Charged Particle Multiplicity and Open Heavy Flavor Physics in Relativistic Heavy Ion Collisions at the LHC

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Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Graduate School of Arts and Sciences

COLUMBIA UNIVERSITY

2013
ABSTRACT

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In this thesis, two independent measurements are presented: the measurements of centrality dependence and pseudo-rapidity dependence of charged particle multiplicities, and the measurements of centrality dependence of open heavy flavor suppression. These measurements are carried out with the Pb+Pb collisions data at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector. For the charged particle measurements, charged particles are reconstructed with two algorithms (2-point “tracklet” and full tracking) from the pixel detector only. Measurements are presented of the per-event charged particle density distribution, $dN_{ch}/d\eta$ and the average charged particle multiplicity in the pseudo-rapidity interval $|\eta| < 0.5$ in several intervals of collision centrality. The results are compared to previous mid-rapidity measurements at the LHC and RHIC. The variation of the mid-rapidity charged particle yield per colliding nucleon pair with the number of participants is consistent with the lower $\sqrt{s_{NN}}$ results measured at RHIC. The shape of the $dN_{ch}/d\eta$ distribution is found to be independent of centrality within the systematic uncertainties of the measurement. For the open heavy flavor suppression measurements, muons identified by the muon spectrometer are classified as heavy flavor decays and background contributions by using a fitting procedure with templates from Monte Carlo samples. Results
are presented for the per-event muon yield as a function of muon transverse momentum, $p_T$, over the range of $4 < p_T < 14$ GeV. Over that momentum range single muon production results largely from heavy quark decays. The centrality dependence of the muon yields is characterized by the “central to peripheral” ratio, $R_{CP}$. Using this measure, muon production from heavy quark decays is found to be suppressed by a centrality-dependent factor that increases smoothly from peripheral to central collisions. Muon production is suppressed by approximately a factor of two in central collisions relative to peripheral collisions. Within the experimental errors, the observed suppression is independent of muon $p_T$ for all centralities. Furthermore, the $p_T$ dependence of the relative muon yields in Pb+Pb collisions to $p+p$ collisions with the same center of mass collision energy per nucleon is presented by the nuclear modification factor $R_{AA}$, which is defined as the ratio of a spectrum from heavy ion collisions to the same but scaled spectrum from nucleon-nucleon collisions. The observed $R_{AA}$ has little dependence on $p_T$ within the uncertainties quoted here. The results for $R_{AA}$ indicate a factor of about 3 suppression in the yield of muons in the most central (0-10%) collisions compared to the $p+p$ collisions.
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Acknowledgements

I would like to thank my advisor Brian Cole for his invaluable instructions and discussions with me, without whom the thesis could not be possible. His insights always drive me moving forward when things do not look very optimistic.

I would also like to thank Bill Zajc for his help during my graduate study period.

I also want to thank my colleagues at Columbia: Aaron Angerami, Eric Vazquez, Dennis Perepelitsa for their help and useful discussions.

I also want to thank my co-workers in ATLAS HI collaboration, without whose hard work, the ATLAS HI program could not be possible. I am indebted to Peter Steinberg, whose hard work and determination made ATLAS HI program very successful and made the publication of my first thesis topic more smoothly. I am also indebted to Andrzej Olszewski, who helped me with various computing related issues on ATLAS platform and processed my requests as soon as possible.
To my parents Zhi Chen and Huxiang Yu
1

Introduction

This thesis describes the measurements of the pseudo-rapidity dependence of charged particle multiplicities and open heavy flavor suppression through muon decay channel in Pb+Pb collisions with the center of mass energy of $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector.

The Pb+Pb collision data collected at the Large Hadron Collider (LHC) which started to provide heavy ion collision data from November 2010 provide an unique opportunity to study strongly interacting matter at the highest temperatures ever achieved in the laboratory. The heavy ion data at this high energy provide unprecedented conditions for the study of high density, strongly interacting matter which is believed to be a QCD phase that exists in high temperature and high quark density, the Quark Gluon Plasma (QGP). While enormous measurements have been carried out in previous experiments like SPS at CERN and RHIC at BNL, the LHC is another big step forward with both higher energy and dedicated detector systems (ALICE, ATLAS and CMS) that are designed to disentangle the creation and evolution of
On the one hand, measurements of the centrality dependence of charged particle multiplicities and of charged particle pseudo-rapidity densities in Pb+Pb collisions provide essential information on the initial particle production and subsequent evolution in QGP. Results from RHIC over the center of mass energy from 19.6 to 200 GeV indicate that the multiplicity of charged particles per colliding pair has a weak dependence on the collision centrality and that the pseudo-rapidity dependence of the charged particle yield near mid-rapidity is essentially centrality independent. The weak variation of the multiplicity per colliding nucleon pair with centrality at RHIC was initially found to be inconsistent with models such as HIJING which includes a mixture of soft and hard scattering processes with a $p_T$ cutoff on the hard scattering contribution at 2 GeV, or with a beam-energy dependent cutoff in a more recent version. In contrast, calculations based on parton saturation invoking $k_T$ factorization were able to reproduce both the shape and centrality dependence of the RHIC charged particle pseudo-rapidity distributions. However, more recent theoretical studies indicate that $k_T$ factorization may not be applicable to nucleus-nucleus collisions, and improved soft+hard models may be able to describe RHIC multiplicity measurements. At the same time, older hydrodynamical models (e.g. Ref) have had some success describing the energy dependence of the total multiplicity as well as rapidity distributions of identified hadrons, although their domain of applicability is still not fully established. It is thus crucial to have detailed measurements of the centrality dependence of charged particle multiplicities and pseudo-rapidity distributions at the LHC energy. By combing
the results from RHIC, it can provide essential insight on the physics responsible for bulk particle production in ultra-relativistic nuclear collisions. Because hard scattering rates increase rapidly with centrality and center of mass energy, the combined RHIC and LHC measurements should provide a strong constraint on the contribution of hard scattering processes to inclusive hadron production subject to uncertainties regarding the shadowing of nuclear parton distributions at low $x$. Measurements at the LHC can also provide a valuable test of recent parton saturation calculations that still claim to be able to describe inclusive particle production in ultra-relativistic nuclear collisions (28, 29).

On the other hand, measurement of heavy quarks are important to study the interaction between heavy quarks and the QGP medium, thus provide invaluable information about the properties of the QGP medium. High $p_T$ quarks and gluons generated in hard scattering processes during the initial stages of the nuclear collisions are thought to lose energy in the QGP resulting in “jet quenching” (31). Measurement of heavy quarks are an important complement to studies of light quarks and gluon quenching. The contributions from radiative (32) and collisional (33, 34) energy loss in weakly coupled calculations are expected to depend on the heavy quark mass. However, measurements of heavy quark production at RHIC via semi-leptonic decays to electrons showed a combined charm and bottom suppression in Au+Au collisions comparable to that observed for inclusive single hadron production (35, 36, 37, 38). There is disagreement in the theoretical literature regarding the interpretation of the RHIC heavy quark suppression measurements (33, 39, 40, 41), particularly regarding the role of non-perturbative
effects (42, 43, 44). Thus, it is very important to have the measurements of heavy quark quenching at the LHC complementing the measurements of single hadron suppression and jet quenching to provide a comprehensive picture of energy loss mechanism of quarks and gluons in the QGP medium.

The thesis is organized as the following:

- Chapter 2 introduces the heavy ion physics including the physical motivation, theoretical consideration, past experiments and evolution of heavy ion collisions.
- Chapter 3 gives the theoretical aspects of heavy flavor physics including the production of heavy quarks and their interaction with the QGP medium.
- Chapter 4 describes the LHC program and the ATLAS experiments.
- Chapter 5 gives a detailed description of the methods used to measure the centrality and pseudo-rapidity dependence of charged particle multiplicities and open heavy flavor suppression.
- Chapter 6 provides the results from these two measurements.
- Chapter 7 discusses the results of these two measurements and what they can tell us about the QGP medium.
Heavy Ion Physics

The possibility of new states of matter could be formed by exciting nuclei was first put forth in a paper by Lee and Wick (45). In 1974, the famous “Bear Mountain” workshop on BeV collisions of Heavy Ions: How and Why, was held to discuss the possibility to make new form of matter in relativistic heavy ion collisions. Prof. Lee said in his talk “It would be intriguing to explore new phenomena by distributing high energy or high nuclear matter over a relatively large volume”. This leads to the first heavy ion fixed target experiment, Bevelac.

With the discovery of asymptotic freedom in QCD, it was quickly realized that strongly interacting system might have interesting properties at very high temperatures. In the 1980’s first studies of QCD thermodynamics using quenched lattice QCD suggested the possibility of a first order phase transition from ordinary confined matter to a deconfined state (46, 47) that is now referred to as the “quark gluon plasma”, though the nature of this phase transition was later found more likely to be a cross-over instead of
a first order phase transition. Following the idea of Lee and others, it was realized that ultra-high relativistic nuclear collisions might provide the conditions necessary to create the quark gluon plasma.

With the success of SPS and RHIC, the properties of quark gluon plasma were unveiled. The RHIC experiments suggest the discovery of strongly interacting quark gluon plasma, a very high energy state of matter near thermal equilibrium composed of unconfined quarks and gluons (sQGP) (48). The formation of this matter and its subsequent evolution into hadrons bears a close resemblance to the formation of matter and radiation in the early universe. Heavy ion collisions might be the only experimental tools that can be used to study the matter created in the very early universe.

Heavy ion physics was brought to a new high energy regime with the first heavy ion data-taking in December 2010 at the Large Hadron Collider (LHC). A lot of interesting analysis has already provided invaluable information about the QGP (31, 49). With the continuum running of both RHIC and LHC, we expect a rich and prosperous physics results in the coming future provided by their respective heavy ion programs.

2.1 The Big Bang and the Early Universe

The Big Bang theory suggests that the universe has begun from an explosion of a very high energy, high density singular point that occurred about 13.7 billion years ago (50, 51). While the earliest phases of the Big Bang are subject to much speculation, the most common one (ΛCDM model (52, 53)) models the Universe as filled homogeneously and isotropically with an in-
credibly high energy density, huge temperatures and pressures. Very little is known before one Planck time (see appendix A.2 for Planck units) when all of the four fundamental forces (gravity, strong interaction, weak interaction and electromagnetic interaction) are presumed to have been unified into one force. After one Planck time of expansion, a phase transition caused a cosmic inflation, during which the Universe grew exponentially. As the inflationary period ends, the Universe consists of a quark-gluon plasma, which is the main focus of the heavy ion physics. When the expansion continued until the temperature dropped to $10^{13}$ K, quarks started to combine into protons and neutrons and other baryons. As the Universe continued to expand, “The First Three Minutes” as outlined by Steven Weinberg started to play a role in the evolution of the early universe. Figure 2.1 shows the time line of the Big Bang. In this figure, important transition from quantum gravity era to today’s universe including the inflationary epoch is shown. Also, three spontaneous symmetry breaking events which separate the unified force into the four fundamental forces is shown along the time line. The focus of heavy ion physics: the quark-gluon plasma phase which happened around $10^{-6}$ s after the Big Bang is also shown in the figure.

We can have a rough estimate of the energy density when the Universe was in the quark-gluon plasma phase. It is well known that there is 2.7 K cosmic microwave background radiation from the Big Bang. The amount of energy in radiation in today’s universe can be estimated by Stefan-Boltzmann law:

$$ u = \frac{4}{c} \sigma T^4 $$

(2.1)
Figure 2.1: The temperature vs the expansion time of the Universe.
where $u$ denotes the energy density, $\sigma = 5.67 \times 10^{-8} \ J s^{-1} m^{-2} K^{-4}$ is the Stefan-Boltzmann constant and $T$ denotes the temperature. Plug in the $T = 2.7 \ K$, we can get the energy density from photons as:

$$u = 0.25 \text{ MeV/m}^3.$$  \hspace{1cm} (2.2)

There is also background energy in neutrinos which is expected to have a temperature of about 1.9 K. As there are $7/4$ as many of them as photons. The $7/4$ comes from the consideration for the difference in fermions and bosons. So the energy density from neutrinos are:

$$u = 0.25 \times \frac{7}{4} \times \left( \frac{1.9}{2.7} \right)^4 = 0.11 \text{ MeV/m}^3.$$  \hspace{1cm} (2.3)

So the total radiation energy density left in the universe from the Big Bang is about:

$$\epsilon \approx 0.4 \text{ MeV/m}^3.$$  \hspace{1cm} (2.4)

At the beginning of the Big Bang when the universe was dominated by radiation instead of matter, we can have an estimate of the energy density as a function of temperature:

$$\epsilon(T) \approx 0.4 \left( \frac{\text{MeV/m}^3}{2.7K} \right)^4.$$  \hspace{1cm} (2.5)

If we assume the quark confinement happened around the temperature $T \sim$
200 MeV, the energy density of the system is about:

$$\epsilon \approx 0.4 \times 10^{-48} \text{(GeV/fm}^3\text{)}(2 \times 1.16 \times 10^{12}/2.7)^4 = 0.2 \text{(GeV/fm}^3).$$ \hspace{1cm} (2.6)

This is of course a very rough estimate. Now it is calculated from lattice QCD (see 2.2.2) that under the critical temperature $T_c \approx 170 \text{ MeV}$ and the energy density $\epsilon_c \approx 1 \text{ GeV/fm}^3$, color degrees of freedom became confined into color singlet objects, e.g. hadrons.

## 2.2 The QCD Phase Transition

The phase transition from liquid water to solid ice or water stream is observable and understandable in the world. To the contrary, the phase transition of quark matters is not well known, either experimentally or theoretically. Figure 2.2 shows the commonly conjectured form of QCD phase diagram. This diagram is plotted as the chemical potential and temperature of the system, where the chemical potential can be thought as a measure of the imbalance between quarks and anti-quarks in the system. Along the vertical line where the chemical potential is very low, the system goes from confined hadron gas to the quark gluon plasma. This transition is believed to be a smooth crossover at temperature around 190 MeV. Following this path corresponds to traveling far back in time, to the state of the early universe shortly after the big bang when the presence of quarks and anti-quarks are similar. Along the horizontal line where the temperature is very low and the chemical potential increases, there are several phases presented: from
hadron gas to nuclear matter to color-superconductor. The curved solid line starts with zero temperature and a few times nuclear matter density and ends with a red points (labeled as “Critical end point” in the figure) denotes the conjectured boundary between confined hadron gas phase to unconfined quark gluon plasma phase. It is also believed that this is the boundary between the phase where the chiral symmetry is broken (low chemical potential and temperature) and the phase where the chiral symmetry is restored. The dashed line near the solid line describes the nature of the phase transition has changed, where the solid line denotes a first order phase transition and the dashed line denotes a smooth crossover or a second order phase transition. In this figure, some experiments which can be used to explore the QCD phases are also shown. RHIC and LHC can explore the QGP phase space where the temperature is high and the chemical potential is very small and FAIR and low energy RHIC can explore the hadron gas phase of QCD matter.

For a complete description of the phase diagram of QCD matter, thorough understanding of the dense, strongly interacting hadronic matter and strongly interacting quark matter is required from the fundamental QCD theory. The challenge here is the non-perturbative QCD in the low energy regime, which can not be calculated analytically. In this section, we will describe some intuitive consideration as well as numerical calculation from lattice QCD to have a better insight of the phase diagram.
Figure 2.2: Conjectured QCD phases under different chemical potential ($\mu_B$) and temperature ($T$) and the transition between different phases.
2.2.1 Intuitive Consideration

Let’s consider an ideal gas of quarks and gluons in thermal equilibrium. By thermodynamics, the energy density of the partons (species $i$) can be described by the quantum distribution functions:

$$\epsilon_i = \int \frac{d^3p_i}{(2\pi)^3} \frac{E_i}{e^{\beta E_i} \pm 1}$$

(2.7)

where $\beta = 1/k_B T$ and the ‘-’ sign is for bosons and the ‘+’ sign is for fermions. Assuming the mass of quarks and gluons considered here are much less than their energy, we can use $p_i = E_i$. By calculating the above integration, we can get:

$$\epsilon_i = \begin{cases} \frac{\pi^2 T^4}{30} & \text{boson} \\ \frac{7\pi^2 T^4}{8} & \text{fermion} \end{cases}$$

For a system of quarks and gluons, we need to consider all the possible degrees of freedom for each particles:

$$\epsilon = \sum_i g_i \epsilon_i = \left( g_g + \frac{7}{8} (g_q + g_{\bar{q}}) \right) \frac{\pi^2 T^4}{30}$$

(2.8)

where $g_g = 8 \times 2$ is the degrees of freedom for gluons by considering different color and helicity states, and $g_q = g_{\bar{q}} = 3 \times 2 \times 2$ is the degrees of freedom for quarks (anti-quarks) by considering different color, spin and flavor states. Here we only consider the lightest $u$ and $d$ quarks. So the energy density of
quarks and gluons gas can be expressed as:

$$\epsilon = 37 \frac{\pi^2}{30} T^4.$$ \hspace{1cm} (2.9)

The pressure of this system is:

$$P = \frac{1}{3} \epsilon = 37 \frac{\pi^2}{90} T^4.$$ \hspace{1cm} (2.10)

Also, massless quarks contained in hadrons can be described by the Dirac equation, which is the assumption of the MIT bag model (57). The momentum space representation equation for massless fermions is:

$$\gamma^\mu p_\mu \phi = 0.$$ \hspace{1cm} (2.11)

where $\gamma$ are 4*4 matrices and $p$ is the four momentum.

$$\gamma^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix}$$

where $\sigma_i$ are 2*2 Pauli matrices. The equation can be further written as:

$$\begin{pmatrix} p^0 & -\vec{\sigma} \cdot \vec{p} \\ \vec{\sigma} \cdot \vec{p} & -p^0 \end{pmatrix} \begin{pmatrix} \phi_+ \\ \phi_- \end{pmatrix} = 0$$

where $\phi_+$ is the wave function for quarks and $\phi_-$ is the wave function for antiquarks. The above equation can be solved analytically. The lowest energy
solution in space time is:

$$\phi_+(\vec{r}, t) = Ne^{-ip^0t}j_0(p^0r)\chi_+ \quad \phi_-(\vec{r}, t) = Ne^{-ip^0t}\vec{\sigma} \cdot \vec{r} j_1(p^0r)\chi_-$$

where $j_0$ and $j_1$ are the spherical Bessel functions, and $\chi$ are wave functions for spin up and down. To make quarks and anti-quarks confine in the hadrons, we can impose the current flux through the spherical bag surface to be zero, that is:

$$J_\mu = 0. \quad \text{(2.12)}$$

This leads to:

$$\bar{\phi}\phi|_{r=R} = j_0^2(p^0R) - (\vec{\sigma} \cdot \vec{r})^2 j_1^2(p^0R) = 0 \quad \text{(2.13)}$$

The above condition can be fulfilled if $p^0R = 2.04$, which means the energy of quarks and anti-quarks in the bag is: $E = \frac{2.04N}{R}$. For a bag with external pressure $B$, the energy of quarks in the bag becomes:

$$E = \frac{2.04N}{R} + \frac{4\pi R^3}{3}B. \quad \text{(2.14)}$$

Consider the bag in equilibrium, then we have:

$$\frac{\partial E}{\partial R} = 0. \quad \text{(2.15)}$$

That is,

$$B = \frac{2.04N}{4\pi R^4}. \quad \text{(2.16)}$$
For a proton, $N = 3$, $R = 0.8$ fm, the external pressure $B^{1/4} = (\frac{2^{0.43}}{3^{0.14}})^{0.25} \frac{1}{0.8 \text{ fm}} 197.3 \text{ MeV} \cdot \text{ fm}$ ($\hbar c = 197.3 \text{ MeV} \cdot \text{ fm}$), i.e.

$$B^{1/4} = 206 \text{ MeV}$$ (2.17)

Equates the external bag pressure $B$ with the one obtained in 2.10, we can get the critical temperature at which the bag would break:

$$T_c = \left( \frac{90}{37\pi^2} \right)^{1/4} B^{1/4} = 145 \text{ MeV}$$ (2.18)

Based on the above simple consideration, we can see that there is a critical temperature, beyond which the bag will break and release quarks and gluons.

### 2.2.2 The Lattice QCD

The strong interaction dominates the forces between quarks and gluons, which is described by Quantum Chromodynamics (QCD). A key property of this force is asymptotic freedom (58, 59), according to which the coupling strength decreases with the energy transfer of an interaction. Figure 2.3 shows the strong coupling constant, $\alpha_s(Q)$, as a function of the energy transfer as measured from different experiments as well as the calculation from QCD theory. From the figure, we can see that at the energy transfer scale of a few GeV, $\alpha_s(Q)$ is of the order 0.1, thus QCD can be calculated from perturbative theory, which expands the calculation in the order of $\alpha_s$. On the other hand, on the low energy scales of hadron physics the coupling is strong and perturbative calculation is no longer valid. Especially around the
phase transition from hadron gas to quark gluon plasma, the energy scale is of the order 200 MeV as shown in the figure 2.2, perturbative QCD is far from valid. The only known non-perturbative and first principle method to calculate QCD theory is by simulation of lattice gauge theory. The following few chapters will give a brief introduction on this method and the results of this calculation.

Consider a QCD system with temperature \( T = 1/\beta \), the grand canonical partition function is given by \( (60, 61) \):

\[
Z(V, \mu, T) = \text{Tr} \left( e^{-\beta(\hat{H} - \mu \hat{Q})} \right) = \int DAD\bar{\psi}D\psi e^{-S_g[A_\mu]} e^{-S_f[\bar{\psi}, \psi, A_\mu]} \tag{2.19}
\]

with the euclidean gauge and fermion actions:

\[
S_g[A_\mu] = \int_0^\beta dx_0 \int_V d^3x \frac{1}{2} \text{Tr}(F_{\mu\nu}F_{\mu\nu}),
\]

\[
S_f[\bar{\psi}, \psi, A_\mu] = \int_0^\beta dx_0 \int_V d^3x \sum_{f=1}^{N_f} \bar{\psi}_f(\gamma_\mu D_\mu + m^f_\mu - \mu \gamma_0)\psi_f. \tag{2.20}
\]

In the above equations, the thermodynamic parameters are the temperature \( T \), the volume \( V \) and the chemical potential \( \mu \) for quarks. \( A_\mu \) denotes the gluon field and \( \psi, \bar{\psi} \) denote quark, anti-quark field. \( F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + ig[A_\mu, A_\nu] \) denotes the matrix-valued field tensor. It can be seen from above equation the the QCD action depends on the number of quark flavors \( N_f \), their masses \( m^f_\mu \) and the gauge coupling \( g \). In most lattice calculations, the much heavier charm, bottom and top quarks are omitted, and the up and down masses are taken to be the same: \( m_u = m_d \). Two cases are usually
Figure 2.3: Summary of the measurement of the strong coupling constant, $\alpha_s(Q)$, as a function of the energy transfer, $Q$. From [1].
considered by differentiating the case where strange mass equals up and down quark mass (denoted by $N_f = 3$) from the other case where strange mass is not equal to up and down quark mass (denoted by $N_f = 2 + 1$).

By discretizing in space and time, the volume and temperature can be expressed as:

$$
\begin{align*}
V &= (aL)^3 \\
T &= \frac{1}{aN_t},
\end{align*}
$$

(2.21)

where $a$ denotes lattice spacing, $L$ denotes the number of lattice points in space direction and $N_t$ denotes the number of lattice points in time direction. The value of $L$ and $N_t$ defines the computational requirement, and $a$ defines the feasible quark mass on the lattice. After discretization, the fermion fields now live on the lattice points, whereas the gluon fields are represented by link variables ($U$) connecting the points. Because of the limited spacing size and sites, calculations are affected by finite size and cut-off effects. To get the final physical results, calculations are performed for various space size and volumes, and then extrapolated to the thermodynamic ($V \to \infty$) and continuum limits ($a \to 0$), while keeping temperature and other physical parameters fixed. The system where $\mu \neq 0$ is fundamentally difficult to compute with imaginary integration, thus special treatments are required to deal with this case \cite{62, 63}. This is a very hot area of lattice QCD calculation. For the case where $\mu = 0$, Monte Carlo simulation can be used to perform the calculation.
For any observable, \( O \), we want to compute, we can express the average as the following:

\[
\langle O \rangle = \frac{\int DU O[U] e^{-S[U]}}{\int DU e^{-S[U]}}
\]  \hspace{1cm} (2.22)

If simulation is carried out directly according to the above equation, enormous amount of calculation are required and as a result not realistically feasible. Fortunately, classical gluon configurations can be generated on the lattice with the probability distribution according to the Boltzmann factor \( e^{-S[U]} \) (this method is called “importance sampling”), then the actual physical observables can be obtained by averaging over hundreds of thousands of the simulated results:

\[
\langle O \rangle \approx \frac{1}{N} \sum_{i=1}^{N} O(U_i).
\]  \hspace{1cm} (2.23)

The important thermodynamic quantities of the QCD system can be derived from thermodynamics given the partition function.

\[
\begin{align*}
f &= -\frac{T}{V} \ln Z(T,V) \\
\epsilon &= \frac{T^2}{V} \frac{\partial \ln Z(T,V)}{\partial T} \\
P &= T \frac{\partial \ln Z(T,V)}{\partial V}
\end{align*}
\]  \hspace{1cm} (2.24)

where \( f, \epsilon \) and \( P \) denote free energy density, energy density and pressure of the system. For large, homogeneous systems, the pressure can be directly obtained from the free energy density:

\[
P = -f
\]  \hspace{1cm} (2.25)
Using this relation, one can express the entropy density as:

\[ s = \frac{\epsilon + P}{T} = \frac{\partial P}{\partial T} \]  

(2.26)

In lattice QCD, the calculation of the pressure, energy density and entropy density proceeds through the calculation of the trace anomaly in units of the fourth power of the temperature:

\[ \frac{\Theta^{\mu\nu}(T)}{T^4} = \frac{\epsilon - 3P}{T^4} = T \frac{\partial}{\partial T} \left( \frac{P}{T^4} \right) \]  

(2.27)

With the trace anomaly, then we can integrate both sides to get the pressure:

\[ \frac{P(T)}{T^4} - \frac{P(T_0)}{T_0^4} = \int d\tilde{T} \frac{\Theta^{\mu\nu}(\tilde{T})}{\tilde{T}^5} \]  

(2.28)

where \( T_0 \) is an arbitrary temperature value that is usually chosen in the low temperature regime with exponentially suppressed pressure and other thermodynamical quantities due to the Boltzmann factor. In practice, \( T_0 = 0 \) is used and \( \frac{p(T_0)}{T_0^4} = 0 \) in this limit (2.64). With the trace anomaly and pressure, then the energy density and the entropy density can be obtained by the above equations. Figure 2.4 and 2.5 show the energy density, pressure and entropy density as a function of temperature. At low temperature, these quantities are very small. As temperature increases, these quantities increase rapidly over a small range of temperature around 190 MeV. Then the quantities tend to flatten out at higher temperatures. But they are still less than the free Boltzmann gas limit at very high temperature. It should be noted here that the calculation is not extrapolated to physical masses. But the study of the
Figure 2.4: $\epsilon/T^4$ and $3p/T^4$ as a function of temperature calculated from lattice QCD with $N_t = 8$. The Boltzmann limit is shown in the figure as a black line. The vertical band indicates the transition region $185$ MeV $< T < 195$ MeV. The results shown here are not extrapolated to physical pion masses. From [2].

quantities with different $N_t$ setup suggest that the transition is a smooth cross over.

Besides the thermodynamical quantities, another interesting quantity to look at in QCD system is the chiral symmetry in lattice simulation. In the absence of quark masses, the QCD Lagrangian is chirally symmetric, i.e. nature is invariant under separate flavor rotations of right and left-handed
Figure 2.5: $s/T^3$ as a function of temperature calculated from lattice QCD with $N_t = 8$. The Boltzmann limit is shown in the figure as a black line. The vertical band indicates the transition region $185 \text{ MeV} < T < 195 \text{ MeV}$. The results shown here are not extrapolated to physical pion masses. From (2).
quarks. Mathematically, the chiral symmetry can be expressed as:

\[ <\bar{\psi}\psi>_q = \frac{T}{V} \frac{\partial \ln Z}{\partial m_q}, \quad q = l, s \] (2.29)

The derivative here is taken with respect to light quark (up or down quark) or strange quark. And chiral susceptibility is defined as:

\[ \chi_{m,q} = \frac{\partial <\bar{\psi}\psi>_q}{\partial m_q}, \quad q = l, s \] (2.30)

The divergence of \( \chi_{m,q} \) at \( T_c \) in the chiral limit is an unambiguous signal of the chiral phase transition. Figure 2.6 shows the disconnected chiral susceptibility of light quark as a function of temperature from lattice QCD calculation. From this figure, we can see the divergence of \( \chi_l \) happens around 170 MeV and is different with different setup. It should be noted that different lattice QCD groups often give different results because of different methods used. For a detailed review on this, reader can refer to [4].

The nature of the phase transition is very sensitive to the flavors used and their masses considered in the simulation. Figure 2.7 shows the pressure as a function of temperature for the cases with \( N_f = 2, 2 + 1, 3 \) and pure gauge scenario (in which only closed loops are gauge invariant). For \( N_f = 2, 3 \), the quark masses are \( m_q/T_c = 0.4 \) and for \( N_f = 2 + 1 \), the quark masses are \( m_l/T_c = 0.4, m_s/T_c = 1 \). From this figure, we can see rapid increase of pressure over a narrow range of temperature. The pseudo-critical temperature as well as the magnitude of \( p/T^4 \) rise with the increase of the quark degrees of freedom. We may conclude that this signals deconfinement,
Figure 2.6: Chiral susceptibility of light quark as a function of temperature from lattice QCD calculation with physical mass ratio between strange and light quarks. Only disconnected Feynmann diagrams are included in the calculation. From (3).
Figure 2.7: The pressure as a function of temperature with \( N_f = 2, 2+1, 3 \) and pure gauge from lattice QCD calculation with \( N_t = 4 \). Arrows indicate continuum ideal gas limits. From (4, 5).

in which more and lighter degrees of freedom are liberated into the system.

Figure 2.8 shows the schematic QCD phase transition under different quark masses. In the limits of zero and infinite quark masses (lower left and upper right corners), it is believed a first order phase transition can happen. On the other hand, one observes an analytic crossover at intermediate quark masses, with second order boundary lines separating these regions.
**Figure 2.8:** Schematic QCD phase transition behavior of 2+1 quark flavors as a function of quark masses ($m_{u,d}, m_s$). From ([6]).
2.3 Heavy Ion Collisions in the Laboratories

The following section will give a brief summary of experiments that have studied heavy ion collisions in the laboratories, including both fixed target experiments and colliding experiments.

The first heavy ion experiment conducted in the laboratory was Bevalac \(^{[65]}\), which was built with the intention to create the “Lee-Wick” matter in 1971. This experiment was the combination of Bevatron and SuperHILAC linear accelerator, which can accelerate any nuclei in the period table to relativistic energies. These fixed target experiments were able to achieve center-of-mass energies of around 2 GeV per nucleon.

The Alternating Gradient Synchrotron (AGS) has operated since 1960 and it began to accelerate heavy ion particles since 1986. At that time only particles below (including) silicon in periodic table were delivered. And since 1992, it began to deliver much heavier particles (\(\leq\) gold). Now AGS’s primary role is heavy ion and proton injector for RHIC at BNL.

The Super Proton Synchrotron (SPS) was first commissioned on June 17 1976 with 400 GeV accelerating power for protons and electrons. It has carried various experiments to probe different aspects of heavy ion physics. Figure 2.9 shows the heavy ion experiments at SPS and their main physics goals. QGP was believed to be created in the SPS energy, as pointed out in the review paper \(^{[7]}\), “The centrality dependence of J/\(\psi\) production shows a clear onset of anomalous behaviour, indicating the formation of a deconfined partonic medium”. The SPS is now used as the final injector for high intensity proton beams for LHC.
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Observables</th>
<th>Probing</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA34/HELIOS2</td>
<td>hadrons</td>
<td>hadron spectra</td>
</tr>
<tr>
<td>HELIOS3</td>
<td>dimuons</td>
<td>in−medium hadron modifications</td>
</tr>
<tr>
<td>NA35/49</td>
<td>charged hadrons</td>
<td>hadron spectra, correlations, flow abundances, strangeness</td>
</tr>
<tr>
<td></td>
<td>strange hadrons</td>
<td></td>
</tr>
<tr>
<td>NA36</td>
<td>strange hadrons</td>
<td>strangeness production</td>
</tr>
<tr>
<td>NA44</td>
<td>pions and kaons</td>
<td>HBT interferometry, spectra at y = 0</td>
</tr>
<tr>
<td>NA45/CERES</td>
<td>dielectrons</td>
<td>in−medium hadron modifications</td>
</tr>
<tr>
<td></td>
<td>charged hadrons</td>
<td>correlations</td>
</tr>
<tr>
<td>NA38/50</td>
<td>dimuons</td>
<td>$J/\psi$ and Drell–Yan production</td>
</tr>
<tr>
<td>NA60</td>
<td></td>
<td>$\chi_c$ and open charm production</td>
</tr>
<tr>
<td></td>
<td></td>
<td>in − medium hadron modifications</td>
</tr>
<tr>
<td>NA52</td>
<td>low Z/A nuclei</td>
<td>strangelets</td>
</tr>
<tr>
<td>WA80/93/98</td>
<td>photons</td>
<td>thermal photons, pion spectra, flow</td>
</tr>
<tr>
<td>WA85/94/97, NA57</td>
<td>hyperons</td>
<td>strangeness enhancement</td>
</tr>
</tbody>
</table>

**Figure 2.9:** Heavy ion experiments at the CERN-SPS. From (7).
Relativistic Heavy Ion Collider (RHIC) was first in operation in 2000 and was the most powerful heavy ion collider in the world until November 2010 when LHC began delivering heavy ions. Four detectors were built for studying heavy ion physics: STAR [65], PHENIX [67], PHOBOS [68] and BRAHMS [69]. Right now only two of them are operating while PHOBOS completed its operation in 2005 and BRAHMS stopped operating in 2006. Their early physics results were summarized in four white papers [66] [67] [68] [69]. A great variety of colliding nucleon species and collision energies has been studied at RHIC, which has brought out very rich heavy ion physics results like elliptic flow, jet quenching, color glass condensate saturation, particle ratios, etc. By the time the thesis was written, RHIC faces possible termination due to budget reasons.

After years of construction, Large Hadron Collider (LHC) finally began to operate on Nov 23 2009 with the successful delivery of proton proton collisions at the center of mass energy at 900 GeV. Since then the experiment is very successful and it delivered the first heavy ion collisions on November 8 2010 with lead ions with the center of mass energy at 2.76 TeV per nucleon. The energy achieved at LHC is the highest collision energy ever achieved in the laboratory in the human history. There are four detectors operating at LHC: ATLAS, CMS, ALICE and LHCb while the former three have dedicated heavy ion physics program.

Table 2.1 summarizes important heavy ion experiments carried in the laboratories. The years of operation, the name of the program, the detectors, ions used and highest achieved energy are shown in the table.
<table>
<thead>
<tr>
<th>Year</th>
<th>Programme</th>
<th>Detectors</th>
<th>Nuclei</th>
<th>√s or Beam energy (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971 – 1993</td>
<td>LBNL Bevalac</td>
<td>-</td>
<td>Fixed target</td>
<td>∼ 2</td>
</tr>
<tr>
<td>1986</td>
<td>BNL AGS</td>
<td>E802, E810, E814, E859, etc</td>
<td>Fixed target</td>
<td>15</td>
</tr>
<tr>
<td>1984 – 1992</td>
<td>CERN SPS</td>
<td>NA35, NA38, etc</td>
<td>S\textsuperscript{32} \textsubscript{16} etc fixed target</td>
<td>200</td>
</tr>
<tr>
<td>1994 – 2000</td>
<td>CERN SPS</td>
<td>NA49, WA97, etc</td>
<td>Pb\textsuperscript{208} etc fixed target</td>
<td>158</td>
</tr>
<tr>
<td>2000</td>
<td>BNL RHIC</td>
<td>PHENIX, STAR, PHOBOS, etc</td>
<td>Au\textsuperscript{197}, Cu\textsuperscript{64} and others</td>
<td>200</td>
</tr>
<tr>
<td>2010</td>
<td>LHC</td>
<td>ALICE, ATLAS, CMS</td>
<td>Pb\textsuperscript{208}</td>
<td>2760</td>
</tr>
</tbody>
</table>

Table 2.1: A brief summary of heavy ion collisions experiments. Unless otherwise specified as fixed target experiments, the experiments are particle colliders.

2.4 Evolution of Heavy Ion Collisions

It is useful to have a understanding of how heavy ion collisions evolve from the beginning when the collisions just happen to the end when all the hadrons, leptons and photons come out the collisions and are detected by the detectors. The schematic evolution of heavy ion collision in longitudinal space and time has long been suggested by Bjorken (70), and has became more clear to heavy ion physicists as many progress have been made from both theoretical and experimental sides since then. Figure 2.10 shows the schematic evolution of heavy ion collisions. It is believed the evolution can be roughly divided into four stages: pre-equilibrium, QGP state, hadronization and freeze-out. The following few paragraphs will give detailed description of what happened in each stage.
Figure 2.10: Schematic figure of the evolution of heavy ion collisions in space and time.
2.4.1 Pre-equilibrium

With the GeV to TeV kinematic energy per nucleon involved in the collision system, both heavy ion beams are highly squeezed in the z direction by Lorentz contraction. Hard processes happen first and shortly after that soft processes take place. By parton interaction, both high $p_T$ and low $p_T$ objects are created during this process. The multiple scattering among constituent quarks and gluons and between particles created during the collisions lead to a rapid increase in the entropy in the system which could eventually lead to equilibrium in the system. The collisions in this process can be analyzed in several ways.

Glauber Model \((8)\) considers the collisions at the baryon level, which describes the system by geometrical argument. In this model, nucleus collisions are taken as the individual interactions of the constituent nucleons \((9)\). In this model, nucleons are assumed to move independently in the nucleus and be undeflected as the nuclei pass through each other. Figure 2.11 shows a schematic view of two colliding nuclei.

In this figure, $\vec{b}$ (impact parameter) denotes vector from the center of “target” nucleus A to the center of “projectile” nucleus B in the transverse plane, $\vec{s}$ denotes the vector from one nucleon to the center of nucleus A in the transverse plane and $\vec{s} - \vec{b}$ denotes the vector from the same nucleon to the center of nucleus B in the transverse plane. Define $t(\vec{r})d\vec{r}$ as the probability of having a nucleon-nucleon collision when two nucleons are separated with a transverse vector $\vec{r}$. The probability density must satisfy the following
normalization:
\[ \int t(\vec{r})d\vec{r} = 1. \] (2.31)

Let \( \rho(\vec{s}, z) \) denotes the probability density of finding a nucleon near in the volume element \( d\vec{s}dz \), the following normalization must be satisfied for both nuclei.

\[ \int \rho_A(\vec{s}_A, z_A)d\vec{s}_Adz_A = 1, \quad \int \rho_B(\vec{s}_B, z_B)d\vec{s}_Bdz_B = 1 \] (2.32)

With the above notation, the probability of having a non-diffractive inelastic nucleon-nucleon collision for each nucleon from different nuclei can be expressed as:

\[ p = \int \rho_A(\vec{s}_A, z_A)d\vec{s}_Adz_A\rho_B(\vec{s}_B, z_B)d\vec{s}_Bdz_Bt(\vec{b} - \vec{s}_A - \vec{s}_B)\sigma_{in} = T(\vec{b})\sigma_{in} \] (2.33)

where \( \sigma_{in} \) denotes the cross-section of a non-diffractive inelastic nucleon-
nucleon collision, and \( T(\vec{b}) \) is called the thickness function for the two colliding nucle:

\[
T(\vec{b}) = \int \rho_A(\vec{s}_A, z_A) d\vec{s}_A dz_A \rho_B(\vec{s}_B, z_B) d\vec{s}_B dz_B t(\vec{b} - \vec{s}_A - \vec{s}_B) \tag{2.34}
\]

For unpolarized nucleus, the probability should be \( \phi \) independent, so \( T(b) = T(\vec{b}) \). The probability of having \( n \) nucleon-nucleon collision is just the Binomial distribution:

\[
P(n, b) = \binom{AB}{n} p^n (1-p)^{AB-n} = \binom{AB}{n} [T(b)\sigma_{in}]^n [1 - T(b)\sigma_{in}]^{AB-n} \tag{2.35}
\]

The total probability for the occurrence of an inelastic event in the collision of \( A \) and \( B \) can then be expressed as:

\[
\frac{d\sigma_{in}^{AB}}{db} = \sum_{n=1}^{AB} P(n, b) = \sum_{n=0}^{AB} P(n, b) - P(0, b) = 1 - [1 - T(b)\sigma_{in}]^{AB} \tag{2.36}
\]

Therefore, the total inelastic cross section \( \sigma_{in}^{AB} \) for the collision of \( A \) and \( B \) is:

\[
\sigma_{in}^{AB} = \int d\vec{b} \left( 1 - [1 - T(b)\sigma_{in}]^{AB} \right) \tag{2.37}
\]

Another two interesting parameters characterize the collision geometry is the average number of participant \( \langle N_{part} \rangle \) and the average number of binary collisions \( \langle N_{coll} \rangle \). The latter can be easily calculated as the average of \( \langle n \rangle \):

\[
\langle N_{coll} \rangle (b) = \langle n \rangle = \sum_{n=0}^{AB} n P(n, b) = AB \cdot T(b)\sigma_{in} \tag{2.38}
\]

For the calculation of \( \langle N_{part} \rangle \), we can consider the following, the probability
of one nucleon in A at position \((\vec{s}_A, z_A)\) experience one inelastic collision with any nucleon in B is: 

\[
p(\vec{s}_A, z_A; \vec{b}) = \int \rho(\vec{s}_B, z_B) d\vec{s}_B d z_B t(\vec{b} - \vec{s}_A - \vec{s}_B) \sigma_m
\]

(2.39)

so the total probability for this nucleon to experience inelastic collision with nucleus B is: 

\[
P(\vec{s}_A, z_A; \vec{b}) = 1 - \left[1 - p(\vec{s}_A, z_A; \vec{b})\right]^B
\]

(2.40)

we can deduce the average number of nucleons experienced inelastic collisions in nucleus A is: 

\[
\langle N_A(b) \rangle = A \int \rho(\vec{s}_A, z_A) d\vec{s}_A d z_A P(\vec{s}_A, z_A; \vec{b}) = A \int \rho(\vec{s}_A, z_A) d\vec{s}_A d z_A \left(1 - \left[1 - p(\vec{s}_A, z_A; \vec{b})\right]^B\right)
\]

(2.41)

Similarly, we have: 

\[
p(\vec{s}_B, z_B; \vec{b}) = \int \rho(\vec{s}_A, z_A) d\vec{s}_A d z_A t(\vec{b} - \vec{s}_A - \vec{s}_B) \sigma_m
\]

(2.42)

and the average number of nucleons experienced inelastic collision in nucleus B is: 

\[
\langle N_B(b) \rangle = B \int \rho(\vec{s}_B, z_B) d\vec{s}_B d z_B \left(1 - \left[1 - p(\vec{s}_B, z_B; \vec{b})\right]^A\right)
\]

(2.43)
Then the average number of participant is:

$$\langle N_{\text{part}}(b) \rangle = \langle N_A(b) \rangle + \langle N_B(b) \rangle = A \int \rho(\vec{s}_A, z_A) d\vec{s}_A dz_A \left( 1 - [1 - p(\vec{s}_A, z_A; \vec{b})]^B \right)$$

$$+ B \int \rho(\vec{s}_B, z_B) d\vec{s}_B dz_B \left( 1 - [1 - p(\vec{s}_B, z_B; \vec{b})]^A \right)$$

The above consideration is call "Optical Glauber Model". The alternative way is to use Monte Carlo simulation. For details, see [8]. In practice, impact parameter(\(\vec{b}\)), \(\langle N_{\text{part}} \rangle\) and \(\langle N_{\text{coll}} \rangle\) are not directly observable by experiments. A mapping procedure usually is needed to calculate this quantity. This is usually done by defining "centrality classes" for both experiment and phenomenological Glauber model. The mean values are calculated in the corresponding centrality classes. The mapping only works if there is a monotonical relationship between variables calculated in experiments and variables calculated by Glauber model. Usually, charged particle densities or energy densities measured from the experiments are used for the mapping.

An interesting property is the initial energy density involved in the collision system. Bjorken had a very famous estimation of the initial energy [70]. In his estimation, the colliding nuclei transverse each other with only little interaction which deposit only part of their kinetic energy to heat up the central rapidity distribution. Figure 2.12 shows the schematic figure of two colliding nuclei before and after collisions. We can calculate the particle
density deposited in the very small center region around \( z \sim 0 \).

\[
\frac{\Delta N}{A \Delta z} = \frac{1}{A} \frac{|dN/dy|}{dy \, dz}_{|y=0} = \frac{1}{A} \frac{dN}{dy} \frac{1}{\tau_0 \cosh y} |_{y=0} \tag{2.44}
\]

where \( A \) denotes the transverse area, \( y \) denotes the rapidity and \( \tau_0 \) denotes the proper time when quark plasma is produced. See appendix B for the definition. Then the initial energy density can be estimated as:

\[
\epsilon_0 = m_T \cosh y \frac{\Delta N}{A \Delta z} = \frac{m_T}{\tau_0 A} \frac{dN}{dy} |_{y=0} \tag{2.45}
\]

where \( m_T \) is the transverse mass of particles. The equation connects initial energy density with the final particle density which can be measured from the experiment. The main unknown from the above equation is the proper equilibrium time \((\tau_0)\), which Bjorken estimated it as on the scale of 1 fm/c.

Contrary to Bjorken’s assumption, Landau’s model (71) assumed that at some instant in the collisions, some part of the incident kinetic energy is converted into produced particles forming a very high-density matter at rest within a space domain of the longitudinal width of the order of \( 1/\gamma \) fm, where \( \gamma \) is the Lorentz factor of the incident hadrons. The model also assumed that the matter created behaved as a fluid formed by an ideal gas of massless relativistic particles. By using relativistic hydrodynamics, he and others (72 73) derived an approximate formula for the rapidity distribution.
Figure 2.12: Left: Two nuclei $A$ and $B$ before collisions. Right: Nuclei $A$ and $B$ after collisions with energy deposited in region $z \sim 0$. From (9).
and the multiplicity of the charged mesons:

\[
\frac{dN}{dy} = N_{ch} \sqrt{\frac{1}{2\pi \sigma^2}} e^{-y^2/2\sigma^2} \tag{2.46}
\]

with \[N_{ch} = K \sqrt{s} \]

\[\sigma^2 = \frac{8}{3} - \frac{c_s^2}{c_s^2} \ln\left(\frac{\sqrt{s}}{2m_p}\right)\]

where \(N_{ch}\) denotes the number of charged particles, \(\sqrt{s}\) is the center of mass energy of the collision system, \(c_s^2 = dp/d\epsilon\) is the speed of sound in the fluid, \(m_p\) is the proton mass and \(K\) is a parameter depending on the equation of state.

Figure 2.13 is the schematic rapidity distribution before collisions, and after collisions from Landau’s model and from Bjorken’s model. We can clearly see the difference of the two models. Detailed studies (74, 75) show that for higher collision energies, the Landau initial condition can also lead to a plateau type other than a Gaussian type distribution for the rapidity distribution of particles. The recent results (23, 49, 76) at LHC show that Landau initial condition does not work very well.

Another important description of the initial condition of heavy ion collisions is Color Glass Condensate (CGC) which is based on effective field theory. It is observed (10) that the degrees of freedom involved in the early stages of any nucleus-nucleus collisions at sufficiently high energy are partons, mostly gluons, whose density grows as the energy transfer \(Q^2\) increases and their momentum fraction \((x)\) decreases (see appendix C for definition). This phenomenon is clearly shown in the figure 2.14.

At very high energies and small Bjorken x, it is believed that the density of
Figure 2.13: The rapidity distribution of particles in heavy ion collisions. **Top:** Before collisions. **Middle:** After collisions with Landau’s full stopping model. **Bottom:** After collisions with Bjorken’s model.
Figure 2.14: Gluon distributions from HERA experiment as a function of $x$ at three different $Q^2$. From (10).
partons per unit transverse area becomes very large and leads to a saturation of partonic distributions, which is shown in the figure 2.15.

The argument here is that when the scale corresponding to the density per unit transverse area, the saturation scale $Q_s$ becomes large ($Q_s \gg \Lambda_{QCD}$), the coupling constant between partons becomes very small ($\alpha(Q_s) \ll 1$), so that perturbative techniques can be used to study such system. This is called CGC because the system mainly consists of highly dense gluons with color degrees of freedom. And it also resembles the system of actual glasses: a disordered system which evolves very slowly relative to natural time scales and is like a solid on short time scale and like a liquid system on much longer time scale. In the CGC framework, gluon density is calculated to be (77):

\[
\frac{dN}{dyd^2p_T} \sim \frac{\pi R^2 Q_s^4}{\alpha_s p_T^2}, \text{ with } p_T > Q_s \\
\frac{dN}{dyd^2p_T} \sim \frac{\pi R^2}{\alpha_s}, \text{ with } p_T < Q_s
\]  (2.47)

This is of course closely related with final particle density in the heavy ion collisions. So the final multiplicity measurement can be used to test the correctness of this description. It is worth noting that nucleon-nucleus and electron-nucleus collisions may be more promising for this purpose since they are not affected by final state effects occurring in nucleus-nucleus collisions. It also has been argued (78) that open charm may play a role in the description of CGC. When the saturation scale is larger than the charm quark mass, the heavy quark production is similar to that of light quarks, which is suppressed at high $p_T$. So the measurement of open heavy flavor production may also provide information in the understanding of the saturation phenomenon.
Figure 2.15: Schematic figure of gluon saturation in a hadron as $x$ decreases. From [11].
The uncertainty principle says $\Delta t \sim 1/\Delta E$, so high energy particles will be created in a relatively short time scale. So heavy quarks and jets are created in the early stage of heavy ion collisions. Later on, as the collisions evolve, these particles will interact with the QGP medium, thus provide a perfect probe for the medium.

### 2.4.2 QGP Formation and Thermalization

At the time scale of around 1 fm/c, the collision system contains the deconfined quarks and gluons, the QGP forms in the system. A very interesting feature here is for non-central collision where impact parameter is non-zero, the system formed is not symmetric in the $x−y$ plane. Figure 2.16 shows the schematic view of non-central collisions. The reaction plane which is defined as the plane expanded by the direction of the collision nuclei and the impact parameter is also shown in the figure. We can clearly see for the collisions where impact parameter is non-zero, the interaction region is not symmetric in space, instead an almond shape interaction region is formed, and this leads to very interesting expansion pattern for the system, the anisotropic flow.

It is often assumed that local thermodynamic equilibrium is achieved in the system so that relativistic hydrodynamics can be applied to analyze this system. With this assumption, the system can be analyzed by thermodynamics and statistical physics without any assumption on the nature of the particles and fields, or their interactions, that’s why the hydrodynamics is quite popular among theorist. But it should be worth noting that local equilibrium is a very strong assumption. The system can then be fully described
Figure 2.16: Schematic picture of non-central collisions, where an almond interaction region is formed in space.
by the equation of motion, equation of state and initial condition. For ideal fluid in which the viscosity is not present, the equation of motion can be described by the following equations:

\[ \partial_\mu (n u^\mu) = 0 \]
\[ \partial_\mu T^{\mu \nu} = 0 \quad (2.48) \]

where the first equation denotes baryon number conservation and the second equation denotes energy momentum conservation. Here \( n = \frac{N}{V} \) is the baryon number density, \( u^\mu = (\gamma, \gamma \vec{v}) \) is the velocity vector, and \( T^{\mu \nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu \nu} \) is the energy-momentum tensor. The equation of state describes the relation between \( (\epsilon, P, n) \). This is nontrivial for dense systems of strongly interacting particles. In practice, phenomenological model \((12)\) or lattice QCD calculation or hybrid of the two \((79, 80)\) are used to get a reasonable equation of state. Figure 2.17 shows the possible equation of state under different model assumptions with zero net baryon density.

The extend to which the final calculations are sensitive to the choice of the equation of state depends on the physical observables. A realistic equation of state considering the nature of the phase transition and non-zero net baryon density could help to better understand the model and to reduce the model uncertainties. For the initial condition part, it lies outside the domain of applicability of the hydrodynamics. Instead, it must be taken as input to the hydrodynamics. There are various methods to get such initial conditions \((81, 82, 83, 84)\). It is worth mentioning that the Glauber Model introduced in section 2.4.1 can also used to derive the initial conditions \((13)\). In such
Figure 2.17: Nuclear EOS of Hagedorn resonance gas model (12) (EOS H), an ideal gas model (EOS I) and a connection of the two (EOS Q). From (13).
models, the initial entropy density is assumed as the linear combination of soft part and hard part, where soft part is proportional to the average number of participant $\langle N_{\text{part}} \rangle$ and hard part is proportional to the average number of binary collisions $\langle N_{\text{coll}} \rangle$. With the initial conditions, equation of motion and equation of state, the evolution of the system in space-time can then be fully described as long as the system stays in local equilibrium. This is of course not true as time goes by and the system expands in space, so to fully describe the whole system to the final stage, some phenomenological models are needed to model the freeze-out of the system, which will be described in later paragraphs.

As studied by hydrodynamics, the unsymmetry in space is quickly evolved to unsymmetry in the momentum space, so that the thin direction of the almond has higher expansion rate while the long direction of the almond has lower expansion rate. Figure 2.18 shows the pressure gradient is larger in the reaction plane and smaller in the direction perpendicular to the reaction plane.

So as the evolution continues, the system will become more symmetric in space. Figure 2.19 shows the expansion of the system at different time scale by a hydrodynamical model from (13). At earlier times (left), the constant energy density contour is less circular, which denotes the shape in space is less symmetric. And the smaller distance between two neighboring constant energy density contour in the $x$ direction means higher pressure gradient. At later times (right), the contour becomes more circular and the shape is more symmetric because the faster expansion of the system in the $x$ direction.

The amount of deformation in the overlap region can be quantified by the
Figure 2.18: Schematic view of almond expansion with the length of the arrow indicates the expansion rate.

Figure 2.19: Contours of constant energy density in the transverse plane at different times after equilibrium. From [13].
Figure 2.20: Time evolution of spatial eccentricity and momentum anisotropy. From [13].

spatial eccentricity parameter:

$$\epsilon_x(b) = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$  \hspace{1cm} (2.49)

and the momentum anisotropy is defined as:

$$\epsilon_p(\tau) = \frac{\int dxdy(T_{xx} - T_{yy})}{\int dxdy(T_{xx} + T_{yy})}$$  \hspace{1cm} (2.50)

The transformation of anisotropy from space to momentum is clearly shown in the figure 2.20.
2.4.3 Hadronization and Freeze-out

At the time scale of 10 fm/c or so, the temperature of the medium drops down, and when the temperature is below the critical temperature, the quarks and gluons become confined into hadrons. Meanwhile, the expansion and the temperature fall lead to a reduction of the inelastic processes among hadrons until the relative abundance of hadron species is fixed, this is so called ‘chemical freeze-out’ \((85, 86)\). After the chemical freeze-out, the system is dominated by elastic collisions instead of inelastic collisions. These elastic collisions can maintain Boltzmann distribution of momenta, i.e. kinetic equilibrium. Kinetic equilibrium is eventually broken and the final kinematic spectra are fixed, this is so called ‘kinetic freeze-out’ \((87, 88)\).
Heavy Flavor Physics

Heavy flavors, which stand for charm and beauty quarks here because the masses of the up, down and strange quark are significantly lower and the heavier top quark lives too short to form bound state of heavy hadrons are of special interest in heavy ion collisions. Because of their high masses, it requires higher energy transfer to produce them, which makes the production a perturbative QCD process. Also, they are produced in the early stages of the heavy ion collisions, and then interact with the medium and form final heavy hadron, thus they provide invaluable information about the medium. Also, the “dead cone” \( [89] \) effect which states that gluon radiation of a massive parton will be suppressed at small angles leads to smaller energy loss in the medium than their lighter counterparts.
3.1 Production Mechanism

3.1.1 Production

The production of heavy quarks $Q$ with mass $m_Q$ can be evaluated by perturbative QCD. The leading order process (LO) in hadronic collisions is flavor creation: quark-antiquark annihilation and gluon-gluon fusion:

$$q\bar{q} \rightarrow Q\bar{Q} \text{ and } gg \rightarrow Q\bar{Q}$$ (3.1)

The Feynman diagram for $q\bar{q} \rightarrow Q\bar{Q}$ and the corresponding transition matrix is shown in figure 3.1. The Feynman diagrams for $gg \rightarrow Q\bar{Q}$ and the corresponding transition matrix are shown in figures 3.2-3.4.

With the transition matrix, we can integrate over the two-body phase space to get the total partonic cross section at the LO level. The large energy limit of the partonic cross section is (90):

$$\hat{\sigma}(q\bar{q} \rightarrow Q\bar{Q}) \rightarrow \frac{1}{\hat{s}}$$ (3.2)
$$\hat{\sigma}(gg \rightarrow Q\bar{Q}) \rightarrow \frac{1}{\hat{s}} \left( \frac{1}{\beta} \log\left(\frac{1+\beta}{1-\beta}\right) - 1 \right)$$ (3.3)

where $\hat{s} = (p_1 + p_2)^2$ is the center of mass energy available in the partonic system and $\beta = \sqrt{1 - 4m_Q^2/\hat{s}}$ is the velocity of the heavy quark. At high $\hat{s}$ system, the cross section of gluon-gluon fusion process is much higher than quark-antiquark annihilation process, so at the LHC energy, heavy quark production is dominated by gluon-gluon fusion process. Heavy quarks produced by these processes are back-to-back with little combined transverse...
Figure 3.1: LO Feynman diagram and the corresponding transition matrix for $q\bar{q} \rightarrow Q\bar{Q}$. 

\[ i\mathcal{M} = \bar{v}(p_2) (ig\gamma^\mu t^a) u(p_1) \left( \frac{-ig_{\mu\nu}}{q^2} \right) \bar{u}(k_2) (ig\gamma^\nu t^a) v(k_1) \]
Figure 3.2: LO Feynman diagram and the corresponding transition matrix for $gg \rightarrow Q\bar{Q}$, s-channel.

At the next-to-leading order (NLO), contributions of real and virtual emission diagrams have to be taken into account (see figure 3.5).

In addition, heavy quarks can be produced via flavor excitation (see figure 3.6) and gluon splitting processes (see figure 3.7). In the flavor excitation process, the heavy quark is considered to be already present in the incoming hadron. It is excited by the exchange of a gluon with the other hadron and appears on mass-shell in the final state. Since the heavy quark is not a valence quark, it must be produced from the pair production process $g \rightarrow Q\bar{Q}$. The hard scattering in flavor excitation processes must have a virtually above $m_Q^2$ for the heavy quark to be present in the initial state. The heavy quark final states do not need to be back-
to-back as the third parton can carry away some transverse momentum. In the gluon splitting events, the heavy quarks occurs in \( g \to Q\bar{Q} \) events in the initial or final state shower. The resulting heavy flavored final state can carry a large combined transverse momentum and thus be concentrated within a small cone of angular separation. Figure 3.8 shows the charm and bottom cross section as a function of center of mass energy in proton proton collisions as calculated from the paper [14]. The contribution from pair production, flavor excitation and gluon splitting are also shown in the figure.
Figure 3.4: LO Feynman diagram and the corresponding transition matrix for $gg \rightarrow Q\bar{Q}$, $t$-channel.

\[ i\mathcal{M} = \epsilon_{\mu}(p_1)\epsilon_{\nu}(p_2)\bar{u}(k_1) \left( ig\gamma^\nu t^b \right) \frac{i}{q - m} \left( ig\gamma^\mu t^a \right) v(k_2) \]
Figure 3.5: NLO Feynman diagrams of real gluon emissions and virtual gluon emissions.

Figure 3.6: Feynman diagrams of flavor excitation.
Figure 3.7: Feynman diagrams of gluon splitting.

Figure 3.8: Charm (left) and bottom (right) cross section as a function of center of mass energy in proton proton collisions. From [14].
3.1.2 Semi-leptonic decay

In experiments, the presence of hadrons containing heavy quarks is deduced by their decay products. They can decay to other lighter hadrons or to leptons. In a first approximation of heavy-flavored hadron decays, only heavy quark participates in the transition while the other quarks in the hadrons act as spectators. The heavy quarks are decayed through weak interaction. The b quark can decay into a c or a u quark, and c quark can decay into a s or d quark. The charged current couplings for the flavor changing transition between quarks are described by the Cabbibo-Kobayashi-Maskawa (CKM) matrix (91, 92):

\[
V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

The universality of the weak decay is reflected in the unitarity of the CKM matrix, which can be parametrized by three mixing angles and one irreducible phase accounting for the CP violation intrinsic to the weak decay in the Standard Model. The magnitude for the b to c or u quark decay is (93):

\[
|V_{cb}| = (40.9 \pm 1.1) \times 10^{-3}, \quad |V_{ub}| = (4.14 \pm 0.49) \times 10^{-3}
\]

and the magnitude for the c to s or d quark decay is (93):

\[
|V_{cs}| = 1.006 \pm 0.023, \quad |V_{cd}| = 0.230 \pm 0.011
\]
The decay width is proportional to the squared CKM matrix element. So we can see that the b quark decay is highly suppressed and the b quark has a relatively large lifetime of $\tau \sim 10^{-12}$s. Since $|V_{cb}|$ is about an order magnitude larger than $|V_{ub}|$, the preferred decay is $b \to cW^-$ with a branching ratio of almost 100%. We can also see that the c quark can further decay into s and d quark. Semi-leptonic decay of b/c quarks into muons are thoroughly studied in this analysis because the muon provides a clean signature which is relatively easy to detect experimentally. There is about 10% branching ratio of b to muon decays. In addition, about 10% of the subsequent charm decays also have a muon in the final state. The Feynman diagrams of the semi-leptonic decay of a b-hadron with a muon in the final state are shown in figure 3.9.

3.2 Interaction with the Medium

While the heavy quarks are in the medium, they can undergo energy loss by two means: elastic collisions with light partons in the system (collisional
energy loss) and gluon bremsstrahlung (radiative energy loss). The mass-hierarchy of parton energy loss is usually arranged in the following order: $\Delta E(g) > \Delta E(q) > \Delta E(c) > \Delta E(b)$. The first inequality stems from the respective SU(3) Casimirs of the gluons and quarks. The second is present because higher mass of the parton implies a reduction of the formation time and thus leads less radiated field. It is also caused by the “dead cone effect” [89].

It is believed that collisional energy loss dominated in the regime $p_T \leq m_Q$. In theory, this energy loss mechanism was based on the Fokker-Planck equation with drag and diffusion coefficients [95, 96] evaluated from collision energy loss only. The collisional energy loss of heavy quarks through processes such as $Qg \rightarrow Qg$ and $Qq \rightarrow Qq$ depends logarithmically on the extremes of the heavy quark momentum, $-dE/dx \propto \ln(q_{\text{max}}/q_{\text{min}})$. For ultra-relativistic heavy quarks with $p_T \gg m_Q$, the radiative energy loss becomes the dominant mechanism. In this regime, the mass of the quark acts mostly as a collinear regulator. For the most energetic case ($E \gg m_Q$), in-medium formation time of the high energy gluons exceeds the average path length. As a consequence, the average energy loss $\Delta E \propto L^2$ and the dependence on mass appears through a logarithmic factor [97, 98, 99]. It is also pointed out by Dokshitzer and Kharzeev [89] that soft gluon radiation from heavy quarks differs from light quarks by a factor of $(1 + \theta_0/\theta)^2$ with $\theta_0 = m_Q/E$. Thus soft gluon radiation from heavy quarks is suppressed at angles less than $\theta_0$, the dead cone effect. The radiative energy loss could then be quite small. However, Armesto et al. [100] later showed that medium-induced gluon radiation could fill the dead cone, leading to non-negligible
energy loss for heavy flavors. They also found that the energy loss would be larger for charm and bottom quarks. Various theoretical treatments lead to very different results, thus in order to offer inside into the actual mechanism the precise measurement of $R_{AA}$ of heavy flavors could give invaluable insight into the interaction of heavy quarks with the medium.
Experimental Setup

4.1 The Large Hadron Collider

The Large Hadron Collider (LHC) was approved by European Organization for Nuclear Research (CERN) Council in December 1994 with the aim of studying particle physics and nuclear physics with the highest energy ever achieved in the laboratory. It lies in a tunnel of 27 km in circumference, as deep as 175 m beneath the border of France and Switzerland. The full accelerator capability is 7 TeV per beam which leads to a center of mass energy of 14 TeV for proton proton collisions. There are multiple accelerator systems prior to the main accelerator. Taking proton acceleration as an example, the particles are prepared by a series of accelerator LINAC 2 (LINAC 3 for heavy ions) generating 50 MeV protons, which feeds the Proton Synchrotron Booster (PSB). There the protons are accelerated to 1.4 GeV and injected into the Proton Synchrotron (PS), where they are accelerated to 26 GeV. Then the SPS is used to further increase their energy to 450 GeV before
they are injected to the main ring, LHC, in which they can be accelerated to their peak energy at 7 TeV.

The LHC experiment contains seven detectors each designed for specific physics goals: ATLAS, CMS, ALICE, LHCb, TOTEM, LHCf and MoEDAL (see figure 4.1 for location of large detectors).

The ATLAS and CMS are two general purpose detectors which can be used for looking for signals of new physics. They also have the ability to study heavy ion physics. ALICE is the dedicated detector for heavy ion physics. LHCb is designed to investigate the missing antimatter. TOTEM is a small detector designed for the measurement of total cross section, elastic scattering and diffractive processes. LHCf is a small detector designed to
study the particles generated in the forward region of collisions, those almost directly in line with the colliding beams. The prime goal for MoEDAL is to directly search for magnetic monopole and other highly ionizing stable massive particles.

The LHC first circulated proton beams on September 10 2008, but were halted due to a magnet quench incident 9 days later. It then took some time to repair the damage of superconducting magnets. On November 20 2009 proton beams were successfully circulated again, with the first recorded proton proton collisions 3 days later with center of mass energy at 900 GeV. On March 30 2010, the center of mass energy achieved at 7 TeV. On November 8 2010, the first heavy ion collisions recorded at LHC with the center of mass energy 2.76 TeV per nucleon for lead ions. Then the center of mass energy of proton collisions was increased to 8 TeV on April 5 2012. Then on September 12 and September 13 2012, the LHC collided lead ions with protons for the first time. The LHC is scheduled to shutdown for 20 months in early 2013 after heavy ion runs for upgrades to full energy operation at center of mass energy at 14 TeV, with reopening planned for later 2014.

4.2 The ATLAS Experiment

The ATLAS (A Toroidal LHC ApparatuS) detector ([15]) is one of the two general purpose detectors built at the LHC to study $p+p$ and $A+A$ collisions. It is mainly composed of inner detector for tracking, calorimeter for energy measurement, muon spectrometer for muon detection and other forward detectors for triggering.
The coordinate system used to describe the ATLAS detector is the following:

- The coordinate system used to describe the ATLAS detector is the following:

  - $z$–axis is defined in the beam direction and the $x$–$y$ plane is transverse to the beam direction.
  - The positive $x$–axis is defined as pointing from the interaction point to the center of the LHC ring.
  - The positive $y$–axis is defined as pointing upwards.
  - The side-A of the detector is defined as positive $z$ side and side-C is defined as negative $z$ side.
  - The azimuthal angle $\phi$ is measured as usual around the beam axis with respect to the $x$–axis.
  - The polar angle $\theta$ is the angle from the beam axis.

Figure 4.2 shows the overall layout of the ATLAS detector. The inner detector for tracking is surrounded by calorimeters and the outmost detector is the muon spectrometer. For the following few sections, a brief introduction of various parts of the ATLAS detector will be given.

### 4.2.1 Inner Detector

The Inner Detector (ID), which is composed of pixel detector, Semiconductor Tracker (SCT) and Transition Radiation Tracker (TRT), provides measurement of the trajectories of charged particles bending in the (nominal) 2 Tesla solenoidal magnetic field. Each of the sub-detectors have barrel (see figure 4.3).
Figure 4.2: The ATLAS detector.
for the barrel layout) and end-cap components. The ID has an $\eta$ coverage of $-2.5 < \eta < 2.5$. Figure 4.4 shows the inner detector layout. The detector position along with the $\eta$ coverage with respect to nominal interaction position $(0,0,0)$ is also shown in the figure. The main parameters are summarized in the table 4.5.

4.2.1.1 Pixel Detector

The ATLAS pixel detector (101) is composed of a barrel and two end-cap sections. The barrel consists of three cylindrical layers with radii of 50.5 mm.
**Figure 4.4:** The $r-z$ view of ATLAS inner detector with a quarter displayed. Both the barrel and endcap are shown along with their position and $\eta$ coverage.

**Table 1.2:** Main parameters of the inner-detector system.

<table>
<thead>
<tr>
<th>Item</th>
<th>Radial extension (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall ID envelope</td>
<td>$0 &lt; R &lt; 1150$</td>
<td>$0 &lt;</td>
</tr>
<tr>
<td>Beam-pipe</td>
<td>$29 &lt; R &lt; 36$</td>
<td></td>
</tr>
<tr>
<td><strong>Pixel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall envelope</td>
<td>$45.5 &lt; R &lt; 242$</td>
<td>$0 &lt;</td>
</tr>
<tr>
<td>3 cylindrical layers</td>
<td>$50.5 &lt; R &lt; 122.5$</td>
<td>$0 &lt;</td>
</tr>
<tr>
<td>2 × 3 disks</td>
<td>$88.8 &lt; R &lt; 149.6$</td>
<td>$495 &lt;</td>
</tr>
<tr>
<td><strong>SCT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall envelope</td>
<td>$255 &lt; R &lt; 549$ (barrel)</td>
<td>$0 &lt;</td>
</tr>
<tr>
<td>4 cylindrical layers</td>
<td>$251 &lt; R &lt; 610$ (end-cap)</td>
<td>$810 &lt;</td>
</tr>
<tr>
<td>2 × 9 disks</td>
<td>$299 &lt; R &lt; 514$</td>
<td>$0 &lt;</td>
</tr>
<tr>
<td><strong>TRT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall envelope</td>
<td>$554 &lt; R &lt; 1082$ (barrel)</td>
<td>$0 &lt;</td>
</tr>
<tr>
<td>73 straw planes</td>
<td>$617 &lt; R &lt; 1106$ (end-cap)</td>
<td>$827 &lt;</td>
</tr>
<tr>
<td>160 straw planes</td>
<td>$563 &lt; R &lt; 1066$</td>
<td>$0 &lt;</td>
</tr>
<tr>
<td></td>
<td>$644 &lt; R &lt; 1004$</td>
<td>$848 &lt;</td>
</tr>
</tbody>
</table>

**Figure 4.5:** Main parameters of ATLAS inner detector. From [15].
(layer-0), 88.5 mm (layer-1) and 122.5 mm (layer-2), respectively. Each end-cap consists of three disk layers oriented with the plane of the disk perpendicular to the $z$ axis. The end-cap pixel planes are placed symmetrically forward and backward along the $z$ axis at distances with respect to the center of the detector of ±495 mm, ±580 mm and ±650 mm, respectively. The pixel barrel layers are composed of 22, 38 and 52 staves for the inner, middle, and outer layers, respectively. Each stave is composed of 13 pixel sensor modules. The staves are inclined by an azimuthal angle of 20 degrees to insure the most effective overlap region and a proper compensation of the Lorentz angle in order to have the desired charge sharing and cluster size. Each pixel module contains 16 front-end chips (FE) and one Module Control Chip (MCC). One FE chip contains 160 rows and 18 columns of pixel channels i.e. 2880 pixels per FE chip or 46080 pixels per module. The feature size of one pixel channel is 50 $\mu$m $\times$ 400 $\mu$m. Each module has a clearance of 400 $\mu$m between two neighboring front end (FE) chips in both directions. In the long pixel direction ($\eta$ direction) the FE border is extended from 400 $\mu$m to 600 $\mu$m (‘long pixels’), while in the short pixel direction ($\phi$ direction) more complicated approach is used. In this direction, eight rows of pixels in this clearance region, divided into two groups, are connected to the last four odd-numbered rows of the closest FE chips. Those pixels are called ganged pixels and those pixels next to the ganged in the last four rows of the FE chips are inter-ganged. The structure of ganged, inter-ganged and long pixels is shown in the figure 4.6(16).
Figure 4.6: Pixel module structure with ganged, inter-ganged and long pixels. From [16].
4.2.1.2 Semiconductor Tracker

The Semiconductor Tracker (SCT) is the middle component of the inner detector. The SCT system consists of a barrel made of four cylinders and two end-caps each with nine disks. It is similar in concept and function of pixel detector but with long, narrow strips rather than small pixels. Each strip measures 80 mm by 12 cm. The barrel carries 2112 modules and the end-caps have 1976 modules.

4.2.1.3 Transition Radiation Tracker

The TRT is a combination of a straw tracker and transition radiation detector. The detecting elements are drift tubes (straws), each 4 mm in diameter and up to 144 cm long. The barrel contains about 50000 straws, each divided in two at the center and read out at both end to reduce the occupancy. The end-caps contain 320000 radial straws with the readout at the outer radius. The total number of channels that are read out is 420000. Each channel provides a drift time measurement, giving a spatial resolution of 170 mm per straw, and two independent thresholds. These allow the detector to discriminate between tracking hits, which pass the lower threshold, and transition radiation hits, which pass the higher one. The precision of TRT is not as good as pixel detector and SCT, but it was necessary to reduce the cost of covering a larger volume and to have transition radiation detection capability. Since the amount of transition radiation is greatest for highly relativistic particles, and because particles of a particular energy have a higher speed the lighter they are, particle paths with many very strong signals can be
identified as belonging to the lightest charged particles, electrons.

4.2.1.4 Tracking in HI environment

Due to the relatively high occupancy in heavy ion environment, the tracking in heavy ion collisions are very challenging. In order to reduce the combinatorics and the computer time, tracking algorithm has been optimized in heavy ion environment and the $p_T$ threshold for tracking has been to set to 500 MeV. Figure 4.7 4.8 shows the $d_0$ and $z_0 \sin \theta$ distribution from heavy ion collisions for both data and Monte Carlo samples. $d_0$ denotes the transverse distance of the closest point on the track with respect to the vertex position, while $z_0$ denotes the longitudinal position of the closest point on the track with respect to the vertex position. We can see the excellent agreement between data and MC samples.

4.2.2 Calorimeters

The calorimeters are placed outside the inner detector system and the main purpose is to measure the energy from particles by stopping them. Based on how particles interacting with the calorimeter, there are two basic calorimeter systems: an inner electromagnetic calorimeter and an outer hadronic calorimeter with the former absorbing energy mainly by electromagnetic interaction while the latter absorbing energy mainly by hadronic interaction. Based on the materials used for the calorimeters, there are two different techniques: liquid argon calorimeters and tile calorimeters. Both are sampling calorimeters in which the functions of particle absorption and active signal
Figure 4.7: $d_0$ distribution from heavy ion tracking with data (black points) and MC samples (brown shaded area).
Figure 4.8: $z_0 \sin \theta$ from heavy ion tracking with data (black points) and MC samples (brown shaded area).
readout are separated. Liquid argon calorimeters use liquid argon gaps as the active material whereas tile calorimeters use scintillating tiles as the active material to measure the showered energy. The detectors with liquid argon as active material require the cryostats to keep the liquid argon at a temperature of 90 K. The calorimeters closest to the beam-line are housed in three cryostats, one barrel and two end-caps. The barrel cryostat contains the electromagnetic barrel calorimeter, whereas the two end-cap cryostats each contain an electromagnetic endcap calorimeter (EMEC), a hadronic endcap calorimeter (HEC), located behind the EMEC, and a forward calorimeter (FCal) to cover the region closest to the beam. There is no need of cryostat for tile calorimeters. Figure 4.9 shows different components of calorimeters. In this figure, electromagnetic calorimeters are plotted as yellow with one barrel and two end-cap regions. Other parts are hadronic calorimeters. Tile calorimeters are plotted as white color with one barrel and two extended barrel regions. Liquid argon hadronic end-caps are plotted as red while two green areas very close to the beam axis denote liquid argon forward calorimeters.

In total, the calorimeters have very big coverage in space with $|\eta| < 4.9$. Table 4.10 summarizes the main parameters including pseudorapidity coverage, granularity and segmentation for those components.

4.2.2.1 Electromagnetic Calorimeters

The EM calorimeter absorbs energy from particles through electromagnetic interactions, mostly electrons and photons. It has very high precision, both in the amount of energy absorbed and in the precision location of the energy deposited. Layers of lead covered by stainless steel sheets and liquid argon are
Figure 4.9: Schematic view of ATLAS calorimeter with different subdetectors.
<table>
<thead>
<tr>
<th></th>
<th>Barrel</th>
<th>End-cap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EM calorimeter</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of layers and $</td>
<td>\eta</td>
<td>$ coverage</td>
</tr>
<tr>
<td>Presampler</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>$0.025 \times 1.1$</td>
<td>$0.025 \times 0.1$</td>
</tr>
<tr>
<td></td>
<td>$0.025 \times 1.40 &lt;</td>
<td>\eta</td>
</tr>
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<td></td>
<td>$0.025 / 0.1$</td>
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</tr>
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<td></td>
<td>$0.025 / 0.1$</td>
<td>$1.375 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$1.5 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$2.0 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$2.4 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.1 \times 0.1$</td>
<td>$2.5 &lt;</td>
</tr>
<tr>
<td>**Granularity $\Delta \eta \times \Delta \phi$ versus $</td>
<td>\eta</td>
<td>$**</td>
</tr>
<tr>
<td>Presampler</td>
<td>$0.025 \times 0.1$</td>
<td>$0.025 \times 0.1$</td>
</tr>
<tr>
<td>Calorimeter 1st layer</td>
<td>$0.025 / 0.1$</td>
<td>$0.025 / 0.1$</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$1.375 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$1.425 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$1.5 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$2.0 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$2.4 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.1 \times 0.1$</td>
<td>$2.5 &lt;</td>
</tr>
<tr>
<td>Calorimeter 2nd layer</td>
<td>$0.025 / 0.1$</td>
<td>$0.025 / 0.1$</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$0.025 / 0.1$</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$0.025 / 0.1$</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$0.025 / 0.1$</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$1.375 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$1.425 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$1.5 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$2.0 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$2.4 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.1 \times 0.1$</td>
<td>$2.5 &lt;</td>
</tr>
<tr>
<td>Calorimeter 3rd layer</td>
<td>$0.025 / 0.1$</td>
<td>$0.025 / 0.1$</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$0.025 / 0.1$</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$0.025 / 0.1$</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$1.375 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$1.425 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$1.5 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$2.0 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.025 / 0.1$</td>
<td>$2.4 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0.1 \times 0.1$</td>
<td>$2.5 &lt;</td>
</tr>
<tr>
<td><strong>Number of readout channels</strong></td>
<td>7808</td>
<td>1536 (both sides)</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>101760</td>
<td>62208 (both sides)</td>
</tr>
<tr>
<td><strong>LAr hadronic end-cap</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>$ coverage</td>
</tr>
<tr>
<td>Number of layers</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td><strong>Granularity $\Delta \eta \times \Delta \phi$</strong></td>
<td>$0.1 \times 0.1$</td>
<td>$0.1 \times 0.1$</td>
</tr>
<tr>
<td><strong>Readout channels</strong></td>
<td>5632 (both sides)</td>
<td></td>
</tr>
<tr>
<td><strong>LAr forward calorimeter</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>$ coverage</td>
</tr>
<tr>
<td>Number of layers</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Granularity $\Delta \eta \times \Delta \phi$ (cm)</strong></td>
<td>$3.15 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>FCAl1: 3.0 \times 2.6</td>
<td>$3.10 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>FCAl2: 3.3 \times 4.2</td>
<td>$4.30 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>FCAl3: 5.4 \times 4.7</td>
<td>$3.24 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td><strong>Readout channels</strong></td>
<td>3524 (both sides)</td>
<td></td>
</tr>
<tr>
<td><strong>Scintillator tile calorimeter</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>$ coverage</td>
</tr>
<tr>
<td>Number of layers</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Granularity $\Delta \eta \times \Delta \phi$</strong></td>
<td>$0.1 \times 0.1$</td>
<td>$0.1 \times 0.1$</td>
</tr>
<tr>
<td>Last layer</td>
<td>$0.1 \times 0.1$</td>
<td>$0.1 \times 0.1$</td>
</tr>
<tr>
<td><strong>Readout channels</strong></td>
<td>5760</td>
<td>4092 (both sides)</td>
</tr>
</tbody>
</table>

**Figure 4.10:** Main parameters of ATLAS calorimeter. From [15].
interspaced. The lead gives the shower development with its short radiation length and the secondary electrons create ionization in the narrow gaps of liquid argon. An inductive signal from the ionization electrons drifting in the electric field across the gas gap is registered by the copper electrodes.

The EM calorimeters are composed one barrel and two end-cap regions. In order to achieve a full $\phi$ coverage without any cracks and a fast extraction of the signals, an accordion geometry has been chosen for the absorbers and the electrodes (see figure 4.11).

Inside the EM calorimeters, there is a liquid argon pre-sampler detector with thickness of 1.1 cm and 0.5 cm in barrel and end-cap region. There is no lead absorber in front of the pre-sampler. The purpose of this pre-sampler is to correct for the energy lost by electrons and photons upstream of the calorimeter in the inner detector, solenoid and cryostat wall. The barrel of EM calorimeter consists of three sampling layers. The first sampling has a depth of 4.3 radiation lengths and has very thin $\eta$ strips with $\Delta \eta = 0.0031$. This provides an excellent resolution in the $\eta$ direction for photon and $\pi^0$ separation. The second sampling has a radiation lengths of 16, so most energy is deposited in this sampling layer. Clusters with energy below 50 GeV are fully contained and the noise can be reduced by not adding the third sampling layer. This layer has square cells with size of 0.0245 in both $\eta$ and $\phi$ direction. The third layer has cells with size $\Delta \eta \times \Delta \phi = 0.05 \times 0.0245$. For the end-caps of the EM calorimeter, each consists of two co-axial wheels with the boundary located at $|\eta| = 2.5$. In order to achieve precision measurement in lower rapidity region, the inner wheel is divided into three longitudinal layers. Similar to the barrel region, the first layer has long strips in $\eta$ direction, the
Figure 4.11: Sketch of a barrel module with the ganging electrodes in $\phi$. Three layers of EM calorimeters are shown with their granularity.
second layer has square cells with the same size of that in barrel region and the third layer has a twice coarser granularity in $\eta$ direction.

The energy resolution of the EM calorimeter can be expressed as:

$$\frac{\Delta E}{E} = a \sqrt{E} + b + c$$

(4.1)

with energy measured in GeV. The sampling term $a$ is defined by the number of lead/argon layers and is around 10% depending on pseudo-rapidity. Noise influences the resolution at the lowest energies through the term $b$ with is of the order around 400 MeV. The constant term $c$ affects the resolution for high energy clusters and is limited by the calibration of the global energy scale and local variations.

4.2.2.2 Hadronic Calorimeters

Hadronic calorimeters are placed outside electromagnetic calorimeters and they measure particle energy by hadronic interactions. The barrel region uses tile calorimeters while the end-cap region use liquid argon to withstand high level of radiations. The hadronic calorimeters consist of tile calorimeters, liquid argon endcap calorimeters and liquid argon forward calorimeters.

**Tile calorimeter.** Tile calorimeter is composed of central barrel region with $|\eta| < 1.0$ and two extended barrel region with $0.8 < |\eta| < 1.7$. It is a steel matrix with scintillator tiles inserted as active materials. The scintillator tiles are placed such that the shower passes through them from the side to improve $e/h$ ratio. The light created in the scintillators is read out with wavelength shifting fibres to photomultipliers placed
outside of the calorimeter. The fibers absorb the blue light from the
scintillators and reemit it at longer wavelength where it reaches the
photomultipliers through total reflection inside the fibers. The designed
energy resolution for tile calorimeter is $\frac{\%50}{\sqrt{E}} \oplus 3\%$.

**Liquid argon endcap calorimeter.** The HEC consists of two indepen-
dent wheels per end-cap, located behind the end-cap EM calorimeter.
It covers the range of $1.5 < |\eta| < 3.2$ to have an overlap with both the
tile calorimeter and the forward calorimeter. It uses copper plates as
the absorbers placed perpendicular to the beam. The designed energy
resolution for HEC is $\frac{\%50}{\sqrt{E}} \oplus 3\%$.

**Liquid argon forward calorimeter.** The FCal consists of three modules
in each end-cap: the first is made of copper and optimized for elec-
tromagnetic measurements, while the other two are made of tungsten
for hadronic measurements. The choice of copper/tungsten is neces-
sary to limit the width and depth of the showers from high energy jets
close to the beam pipe and to keep the background level low in the
surrounding calorimeters from particles spraying out from the forward
region. The calorimeter is a metal matrix with cylindrical holes filled
with sensitive liquid argon. This geometry allows for excellent control
of the gaps as small as 250 $\mu$m, which limits the sensitivity to pileup
effects and ion buildup. The FCal has coverage over $3.1 < |\eta| < 4.9$.
In Pb+Pb collisions, we use the total transverse energy deposited in
FCal to characterize the geometry (centrality). The designed energy
resolution for FCal is $\frac{\%100}{\sqrt{E}} \oplus 10\%$. 
4.2.3 Muon Spectrometer

The Muon spectrometer is the outmost detector and is mainly used for muon particle tracking. The conceptual design of the muon spectrometer is explained briefly in the following text. For the detailed explanation, please refer to [102]. The Muon Spectrometer is divided into three parts: the barrel part covers $|\eta| < 1.05$ rapidity region and two end-cap region cover $1.0 < |\eta| < 2.7$ rapidity region. Figure 4.12 is a $r - \phi$ view of the Muon Spectrometer. The Muon Spectrometer is immersed in very strong magnetic fields. In the barrel over $|\eta| < 1.4$, the toroid field is produced by eight very large superconducting coils in an open geometry with value between 2 to 5 T·m and large variation as a function of the azimuthal angle $\phi$. In the end-cap region with $1.6 < |\eta| < 2.7$, two identical air core toroids are placed inside the barrel toroid with the same axis. Over the transition region with $1.4 < |\eta| < 1.6$, the magnetic fields are produced by the combination of the barrel and end-cap fields. Depend on different goals, the Muon Spectrometer consists of two kinds of precision tracking chambers and two kinds of trigger chambers. Figure 4.13 shows the four parts chambers in $r - z$ view. The precision tracking chambers are composed of MDT (Monitored Drift Tube) and CSC (Cathode Strip Chamber), covering $|\eta| < 2.7$ and $2.0 < |\eta| < 2.7$ respectively. They are dedicated to the precise measurement of muon transverse momentum ($p_T$) with an accuracy of 2-3% for $p_T < 100$ GeV and around 10% at $p_T = 100$ GeV. The trigger chambers are composed of RPC (Resistive Plate Chamber) and TGC (Thin Gap Chamber), covering $|\eta| < 1.05$ and $1.05 < |\eta| < 2.4$ respectively. They are dedicated to the fast muon trig-
Figure 4.12: R-$\phi$ view of the Muon Spectrometer.

The MDT consists of three barrel layers and four end-cap layers. Each layer of the chamber consists of 16 chambers with 8 small and 8 large chambers alternating each other with a small overlap in the $\phi$ direction to minimize gaps in the detector system (see figure 4.12). For the barrel layers, they are located concentrically around the beam axis at radii of...
Since the completion of the assembly of the Muon Spectrometer in August 2008, combined data taking of the ATLAS detector with cosmic ray muons and the single proton beam has been taking place. Table 1 summarizes the current fraction of active channels, number of channels, and the fraction foreseen at the start of LHC beam in December, 2009.

Table 1. Fractions of active channels (October, 2009) with their number of channels, and fractions foreseen at the start of LHC beam.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Active Channels (%</th>
<th>Number of Channels (k)</th>
<th>Forecasted at December 2009 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPC</td>
<td>97.0%</td>
<td>359k</td>
<td>99.5%</td>
</tr>
<tr>
<td>TGC</td>
<td>99.6%</td>
<td>320k</td>
<td>99.6%</td>
</tr>
<tr>
<td>MDT</td>
<td>99.7%</td>
<td>341k</td>
<td>99.7%</td>
</tr>
<tr>
<td>CSC</td>
<td>98.4%</td>
<td>31k</td>
<td>98.4%</td>
</tr>
</tbody>
</table>

The following article presents in-situ analyses results of the performance of trigger selectivity and momentum resolution obtained with 400 M cosmic ray events and 8 k single proton beam events.

2. Detector Performance

2.1. Trigger Selectivity

The TGCs and RPCs measure the transverse momentum within 2.5 \( \mu \)s using the coincidence logic of on-detector ASICs and FPGAs. By comparing the angular difference between an infinite-momentum track and the one measured (\( \Delta \theta \)), the trigger is satisfied with typical p_{T} thresholds of 6, 8, 10, 12, and 14.

Figure 4.13: R-z view of the Muon Spectrometer.
Figure 4.14: Muon Spectrometer as both high and low momentum trigger.
approximately 5 m, 7.5 m and 10 m. The coverage of the barrel region is $|\eta| < 1.05$ except that in the center of the detector around $|\eta| \approx 0$, a gap in chamber coverage has been left open to allow for services to the solenoid magnet, the calorimeters and the inner detector. In the two end-cap regions, muon chambers form large wheels, perpendicular to the $z$-axis and located at distance of $|z| \approx 7.4$ m, 10.8 m, 14 m and 21.5 from the interaction point. It has a coverage of $1.05 < |\eta| < 2.7$ except for the inner most end-cap layer beyond $|\eta| > 2.0$, they are covered by CSC due to the consideration of high particle fluxes and muon track density (see figure 4.13 for CSC). The basic element of the drift chamber is a drift tube with a diameter of 29.970 mm, operating with Ar/CO$_2$ gas at pressure of 3 bar. In the center of the tube is tungsten-rhenium wire with a diameter of 50 $\mu$m at a potential of 3080 V which is for the collection of ionized electrons.

**CSC** There are two CSC layers, one on each end-cap region with the coverage of $2.0 < |\eta| < 2.7$, where the particle density is very high. As in the case of the MDT’s, the CSC’s are segmented into large and small chambers in $\phi$ with 8 large and 8 small chambers alternating each other. Each chamber contains four CSC planes resulting in four independent measurements in $\eta$ and $\phi$ along each track. The CSC is multi-wire proportional chambers with the wires oriented in the radial direction. It can provide paired measurement of two coordinates with both cathodes segmented, one with the strips perpendicular to the wires and the other parallel to the wires. Good two-track separation and resolution,
good time resolution and low neutron sensitivity are the characteristics of the CSC to do precision tracking in the forward rapidity region with high particle density.

**RPC** The RPC is mostly used for the fast trigger. It consists of three barrel stations with a coverage of $|\eta| < 1.05$. The three concentric cylindrical stations are located around the beam axis at radii of approximately 7.8 m (RPC1), 8.4 m (RPC2) and 10.2 m (RPC3) (see figure 4.14 for location of RPC). The large lever arm between RPC3 and RPC1 permits the trigger to select high momentum tracks in the range of 9–35 GeV, while the two inner stations (RPC1 and RPC2) provide the low $p_T$ trigger in the range of 6–9 GeV. Each RPC station consists of two independent detector layers, each with measurement of $\eta$ and $\phi$. A track going through all three stations thus delivers six measurements. The redundancy in the track measurement can be used to reject fake tracks from noise hits and greatly improve the trigger efficiency in the presence of small chamber inefficiencies. The RPC is a gaseous parallel electrode-plate detector without wires.

**TGC** The TGC consists of six wheels in the end-cap region, with three wheels on each side. It provides both the trigger capability and the azimuthal coordinate measurement to complement the measurement of the MDT in the bending direction. The inner most wheel (MDT1 in figure 4.14) is composed of two layers and radially segmented into two non-overlapping regions. The middle wheel (MDT2) is composed of seven layers. The outer wheel (MDT3) does not provide independent
coordinate measurement because there is no magnetic field between MDT2 and MDT3. Instead, the azimuthal coordinate in the outer MDT wheel is obtained by linear extrapolation of the track from the middle wheel. Like CSC, the TGC is a multi-wire detector.

The main parameters of four sub-detectors are summarized in Table 4.1. In this table, their functionality, coverage, space and time resolution, number of measurements, number of chambers and number of channels are shown in this table.

Table 4.1: Main parameters of four sub-detectors of the muon spectrometer. The quoted spatial resolution does not include chamber alignment uncertainties and time resolution does not include signal propagation and electronics contributions.

<table>
<thead>
<tr>
<th>Detector</th>
<th>MDT</th>
<th>CSC</th>
<th>RPC</th>
<th>TGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function</td>
<td>Precision tracking</td>
<td>Precision tracking</td>
<td>Trigger, tracking</td>
<td>Trigger, tracking</td>
</tr>
<tr>
<td>Coverage</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.7$ inner, $</td>
<td>\eta</td>
</tr>
<tr>
<td>(RMS) $z/R$</td>
<td>$35 , \mu m$ ($z$)</td>
<td>$40 , \mu m$ ($R$)</td>
<td>$10 , mm$ ($z$)</td>
<td>$2-6 , mm$ ($R$)</td>
</tr>
<tr>
<td>(RMS) $\phi$</td>
<td>–</td>
<td>$5 , mm$</td>
<td>$10 , mm$</td>
<td>$3-7 , mm$</td>
</tr>
<tr>
<td>(RMS) time</td>
<td>–</td>
<td>$7 , ns$</td>
<td>$1.5 , ns$</td>
<td>$4 , ns$</td>
</tr>
<tr>
<td>Measurements/track (barrel)</td>
<td>20</td>
<td>–</td>
<td>6</td>
<td>–</td>
</tr>
<tr>
<td>Measurements/track (endcap)</td>
<td>20</td>
<td>4</td>
<td>–</td>
<td>9</td>
</tr>
<tr>
<td>Number of chambers</td>
<td>1150</td>
<td>32</td>
<td>606</td>
<td>3588</td>
</tr>
<tr>
<td>Number of channels</td>
<td>354k</td>
<td>30.7k</td>
<td>373k</td>
<td>318k</td>
</tr>
</tbody>
</table>
4.2.4 Forward detectors

There are three main forward detectors at ATLAS: LUCID (LUminosity measurement using Cherenkov Integrating Detector), ALFA (Absolute Luminosity For ATLAS) and ZDC (Zero Degree Calorimeter). The former two are mainly used for luminosity determination and they are located at $|z| = 17$ m, 240 m respectively. ZDC, which is very important for heavy ion collisions is located at $|z| = 140$ m. The following section will introduce ZDC which is most relevant for heavy ion collisions.

4.2.4.1 Zero Degree Calorimeters

The ZDC has four modules on each arm: one electromagnetic module and three hadronic modules. All modules can provide position information except the EM module on the A-side. The modules are composed of tungsten with an embedded matrix of quartz rods which are observed by photomultiplier tubes. The ZDC resides in a slot in the TAN (Target Absorber Neutral) absorber, which is located at $|z| = 140$ m from the interaction point, at the place where the straight-section of the beam-pipe is divided back into two independent beam-pipes.

The ZDC measures neutral particles produced at small polar angles with respect to the beam axis with $|\eta| > 8.3$. In heavy ion collisions, the dominant contribution to energy at zero degrees is from neutrons that are constituents of the incident lead nuclei that do not participate (undergo a hadronic scattering) during the Pb+Pb collision. The ZDC has been found to be effective in rejecting photo-nuclear collisions that produce particles at mid-rapidity.
but leave one of the nuclei intact.

4.2.5 Trigger System

The ATLAS trigger system has three distinct levels: level one (L1), level two (L2) and event filter (EF). The L2 and EF are also called high level trigger. Each trigger level refines the decisions made at the previous level to further reduce the output. L1 uses a limited amount of the total detector information to make a decision in less than $2.5 \mu s$, reducing the rate to about 75 kHz. L2 uses L1 information to further reduce the event rate to below 3.5 kHz, with an average event processing time of about 40 ms. And EF uses offline analysis procedures on fully built events to reduce the event rate to about 200 Hz, with an average event processing time of approximately 4 s.

The L1 trigger performs the initial event selection based on information from the calorimeters, muon detectors and minimum bias trigger components, which mainly contains information from ID, LUCID, MBTS and ZDC. The MBTS will be explained later. While minimum bias trigger aims for all collisions events without biasing toward any specific physics, triggers on calorimeters and muons are interested in specific physics. The L1 calorimeter trigger aims to identify high $E_T$ objects such as electrons, jets, $\tau$ leptons decaying into hadrons, large missing transverse energy $E_T^{\text{miss}}$ as well as large transverse energy. The L1 muon trigger aims to identify muons by using information from RPC and TGC as explained in §4.2.3. In each event, the L1 trigger also defines one or more Regions-Of-Interest (ROI), i.e. the geographical coordinates in $\eta$ and $\phi$, of those region within the detector where its selection
process has identified interesting features. The ROI is subsequently used by high level trigger.

4.2.5.1 Minimum Bias Trigger Scintillators

The Minimum Bias Trigger Scintillators (MBTS) is composed of two sets of sixteen scintillator counters. They are installed on the inner face of the end-cap calorimeter cryostats and were used to trigger on minimum-bias events in early proton proton and heavy ion runs. Each set of counters are segmented in eight units in $\phi$ and two units in $\eta$. They are located at $z = \pm 3.56$ m, the innermost set covers radii between 153 mm and 426 mm, corresponding to the region $2.82 < |\eta| < 3.84$ and the outermost set covers radii between 426 mm and 890 mm, corresponding to the region $2.09 < |\eta| < 2.82$. It provides both energy and timing information, although during heavy ion runs the MBTS energy was saturated. The MBTS is only supposed to have a short life due to radiation damage from high luminosity runs.
5 Data Analysis

5.1 Charged Particle Multiplicity Measurement

5.1.1 Samples And Event Selection

5.1.1.1 Data And MC Samples

Table 5.1 shows the data and MC data sets used in this analysis. The run number, luminosity, number of selected events (see selection criteria below), and solenoid field configuration are listed for data samples used. For the MC samples, the generator type, tag, number of selected events and solenoid field configuration are provided.

The primary data used for the multiplicity measurement were obtained during zero field operation of the ATLAS detector during the Fall 2010 Pb+Pb LHC run. The data are part of the ATLAS period “data10_hi.periodJ5” which consists of two runs, run 169866 and run 169884. Run 169866 is the
primary data set used for multiplicity measurement described in this note.
For this run, an integrated luminosity of $\int \mathcal{L} \, dt = 484.3 \text{ mb}^{-1}$ spanning the luminosity block range [149, 617] was recorded during stable beams. According to the Good Run List, Luminosity Blocks 194, 173, 200, 453, and 493 were removed from the analysis. Run 169884 was used for a stability check on the multiplicity measurement. An additional run, run 169223, from field-on Pb+Pb running was used in the analysis to obtain the charged particle $p_T$ spectrum for comparison with the spectrum used in Monte Carlo simulations.

The Monte Carlo samples were generated using the HIJING (26) generator and simulated using the ATLAS GEANT simulation package with conditions for the zero-field, data10_hi.periodJ5 period. See section 5.1.1.4 for more details on the generation process. In addition to samples produced using the default geometry and conditions, an additional “extra material” sample was generated. For this sample, the fractional increase in material for different portions of the detector were:

- a 10% increase in the material of the entire ID
- a 20% increase in material associated with Pixel services
- a 20% increase in material associated with SCT services
- a 15% increase in radiation length of material at the end of SCT/TRT end-cap
- 15% increase in radiation length of material at the ID end-plate.
Table 5.1: Dataset and their properties

<table>
<thead>
<tr>
<th>Run number</th>
<th>Luminosity (mb$^{-1}$)</th>
<th>$N_{evt}$</th>
<th>Solenoid</th>
</tr>
</thead>
<tbody>
<tr>
<td>169866 (default)</td>
<td>484.3</td>
<td>1631525</td>
<td>Off</td>
</tr>
<tr>
<td>169884</td>
<td>556.4</td>
<td>130825(partial)</td>
<td>Off</td>
</tr>
<tr>
<td>169223</td>
<td>419.8</td>
<td>986922(partial)</td>
<td>On</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Tag</th>
<th>$N_{evt}$</th>
<th>Solenoid</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIJING (default)</td>
<td>d499_r2183</td>
<td>5592</td>
<td>Off</td>
</tr>
<tr>
<td>HIJING (extra material)</td>
<td>d509_r2273</td>
<td>5594</td>
<td>Off</td>
</tr>
<tr>
<td>Hydjet</td>
<td>d499_r2183</td>
<td>5573</td>
<td>Off</td>
</tr>
<tr>
<td>MC</td>
<td>d443_r1927</td>
<td>27274</td>
<td>On</td>
</tr>
</tbody>
</table>

5.1.1.2 Event Selection

The following event selection requirements or criteria were applied in this analysis:

1. Good lumi block using the results provided by data quality group.


3. A valid time recorded by both MBTS A and C, $time_A \neq 0 \land |time_A| \neq 75$ and $time_C \neq 0 \land |time_C| \neq 75$.

4. An MBTS A-C time difference, $\Delta t_{MBTS} \equiv |time_A - time_C|$, less than 3 ns, $\Delta t_{MBTS} < 3.0$ ns.

5. A reconstructed primary vertex.

6. Primary z vertex position, $v_z$, in the range $|v_z| < 50$ mm.

The last requirement was imposed to limit variations in acceptance due for vertices significantly displaced from the center of the detector that are primarily due to the $z$ coverage of the inner pixel layer.
Figure 5.1: Distribution of MBTS time differences, $\Delta t_{MBTS}$, for events from run 169866 passing trigger and vertex requirements described in the text. The red lines show the applied MBTS time cut, $\Delta t_{MBTS} < 3.0$ ns.

5.1.1.3 MBTS Time Difference Distribution And Vertex Distribution $v_z$

The distribution of MBTS time differences, $\Delta t_{MBTS}$, for events from run 169866 passing the trigger and vertex requirements (criteria 5) described above is shown in figure 5.1. The red lines at $\pm 3$ ns show the applied MBTS $\Delta t_{MBTS}$ cut.

The distributions of $v_z$ from data and MC are shown in the figure 5.2. The black curve is for events from Run 169866 passing the trigger selection and with valid reconstructed vertex. The red line is from the (default) MC samples. Both distributions are normalized to have unit area. Also shown in
Fig. 5.2 as blue curves are the results of Gaussian fits to the data and MC $v_z$ distributions. Because the Monte Carlo $v_z$ distribution does not match that of the data, we re-weight the Monte Carlo events by a $v_z$ dependent factor, $W(v_z)$, obtained from the ratio of the Gaussian fit to the data $v_z$ distribution to the Gaussian fit of the corresponding MC distribution. The resulting re-weighting factor, $W(v_z)$ is shown plotted in Fig. 5.3.

5.1.1.4 MC Samples And Re-weighting Procedure

MC samples are generated by using HIJING event generator which is designed to simulate particle production in $p+p$, $p+A$ and $A+A$ collisions. We used a version of HIJING v1.383b with a few bug fixes relative to the
Figure 5.3: Re-weighting factor, $W(v_z)$ applied to Monte Carlo events to account for difference in data and Monte Carlo $v_z$ distributions (see text for more details).

official distribution. HIJING is a commonly-used event generator for describing heavy ion collisions at the LHC. However, this generation of HIJING has known limitations in describing detailed aspects of the physics because it does not describe the physics that leads to elliptic flow and collective expansion in Pb+Pb collisions. HIJING was run without jet quenching and with standard parameters. Since HIJING does not generate elliptic flow, flow was imposed on the generated events using a post-processing that adjusted particle azimuthal angles to induce a $p_T$ and $\eta$-dependent $\phi$ modulation

$$
\frac{dN}{d\eta d\phi} = \frac{dN}{d\eta} (1 + 2v_2 \cos 2\phi)
$$

(5.1)

with the parameter controlling the amplitude of the modulation, $v_2(\eta, p_T, N_{\text{part}})$, obtained from a parameterization of RHIC elliptic flow results.

Because of the missing physics in the HIJING generator, HIJING arrives
at a very different charged particle transverse momentum spectrum than what is measured in Pb+Pb collisions at the LHC \cite{104}. Fig. 5.4 shows a comparison of the $p_T$ spectrum produced by HIJING to that measured by ALICE for the 10% most central collisions, demonstrating the disagreement. The data from ALICE are restricted to the pseudo-rapidity interval $|\eta| < 0.7$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig5_4.png}
\caption{Comparison of charged particle $p_T$ spectrum generated by HIJING for central (0-10\%) Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (red square) to the spectrum measured by ALICE (black point) for (0-5\%).}
\end{figure}

To evaluate the disagreement between the Monte Carlo spectrum and actual data over $|\eta| < 2$, we have performed an analysis using field on data from run 169223 and using tracks from the pixel tracklets reconstruction to measure the charged particle $p_T$ spectrum down to 100 MeV. The event selection criteria are the same as those listed above. Fig. 5.5 shows the uncorrected $p_T$ spectrum of reconstructed pixel tracks in Pb+Pb collisions for different centrality bins. For additional clarity we show in Fig 5.6 the uncorrected...
$p_T$ spectrum of pixel tracks from both data (black) and MC (red) samples for the top 10% centrality bin. The figure demonstrates both an excess of low momentum particles and a deficit of high $p_T$ particles in the HIJING MC sample compared to the data that will distort results obtained from the Monte Carlo simulations.

Figure 5.5: Raw $p_T$ spectrum of pixel track method with solenoid on sample from different centrality bins.

To account for the discrepancy between the data and Monte Carlo $p_T$ spectra, we apply a $p_T$-dependent re-weighting to the truth particles in the Monte Carlo samples as described below. To obtain the corrections we start from the $p_T$ spectrum of the tracks obtained from the pixel tracklet reconstruction in a given centrality bin to the same spectrum from the Monte Carlo. The centrality bins in the Monte Carlo are matched to that of the data by the number of layer-0 clusters in $\eta < 1.0$ normalized by a factor of 2. The resulting ratios are shown in Fig. 5.7. They are centrality dependent
Figure 5.6: Raw $p_T$ spectrum from pixel track method with solenoid on sample from data (black) and MC (red) for the 0-10% centrality events.

and show the biggest difference between data and MC for the most central events where the physics not included in HIJING has the largest effect on the $p_T$ distribution. Nonetheless, all of the centrality bins show the same general features: the data has a deficit of low $p_T$ particles compared to the Monte Carlo and a excess at higher $p_T$, $p_T \sim 2$ GeV. We use an iterative procedure to determine a re-weighting function that yields the best possible match between Monte Carlo and data pixel tracklet $p_T$ spectra according to the following procedure

1. Parameterize the $p_T$ dependence of the ratio of data and MC pixel tracklet spectra in each centrality bin to produce a weight $W(p_T)$.

2. Apply the above weights in each centrality bin to MC samples. Only pixel tracks with truth associations are given weights and the weights
are applied at the corresponding truth \(p_T\), \(W(p_T^{truth})\). Fake pixel tracks have weight equal to one. Depending on the centrality and \(\eta\), fake rate can range from less than 1% to 30% for most central events in high \(\eta\) region. A track is said to have to truth association when at least two clusters are produced by the same true particles from the generator.

3. Produce the re-weighted MC pixel tracklet \(p_T\) spectra in each centrality bin and re-calculate \(W(p_T)\) from the ration of data to MC \(p_T\) spectra.

4. Iterate this procedure, returning to step 2.

After we do this re-weighting process three times, we get very flat ratios of data to MC \(p_T\) spectrum. For the multiplicity measurement, 99% of particles are with momentum less than 2 GeV, so the weights are only important for low momentum particles. We implement the weights for particles with momentum up to 4 GeV. Fig. 5.8 shows the ratios of data to MC momentum spectrum without (black point) and with (blue square) re-weighting process applied to MC samples three times. It is clear from the histogram that the ratios are flat after the re-weighting process. Fig. 5.9 shows the ratios after applying re-weighting to MC samples three times with vertical scale zoomed in. For the low momentum region which contributes most of the total multiplicity, the ratios are flat within 4%. Fig. 5.10 shows the final weights applied to make the ratio flat. Fig. 5.11 shows the re-weighting function obtained in 0-10% centrality (black line) and ALICE to HIJING spectrum ratio in 0-5% centrality (red point). They are in very good agreement up to 3 GeV. The small discrepancy in high \(p_T\) is probably due to smearing effect.

With the re-weighting functions obtained above, we apply these weights
to MC samples. The weights are applied the same way as above. Tracks or tracklets with truth associations are assigned with weights according the final weights functions with the weights evaluated at associated truth \( p_T \). For tracks or tracklets without truth associations, no extra weights are assigned, how i.e. they have weights equal to one.

![Figure 5.7](image)

**Figure 5.7:** The ratio of data to MC raw pixel tracks \( p_T \) spectrum for solenoid field on configuration.

### 5.1.2 Data Analysis Algorithms

#### 5.1.2.1 Overview Of Charged Particle Reconstruction Algorithms

Before going into the detail of all the charged particle reconstruction algorithms, this paragraph gives an overview of all the algorithms, and their relative advantages and disadvantages. In total, we use four algorithms to measure charged particle multiplicity: pixel tracks, tracklet Method 1, track-
Figure 5.8: The ratio of data to MC pixel tracks $p_T$ spectrum without (black point) and with (blue square) re-weighting process applied to MC samples. **Left:** 0-10%, 10-20%, 20-30% and 30-40% centrality correspondingly. **Right:** 40-50%, 50-60%, 60-70%, 70-80% centrality correspondingly.

Figure 5.9: The ratio of data to MC pixel tracks $p_T$ spectrum with re-weighting procedure applied to MC sample in different centrality bins.
Figure 5.10: The re-weighting function for different centrality bins.

Figure 5.11: The re-weighting function in 0-10% centrality (black line) and ALICE to HIJING $p_T$ spectrum ratio in 0-5% centrality (red points).
let Method 2, and pixel counting. Table 5.2 shows the four algorithms used and their relative advantage to each other. These methods will be explained in later chapters.

<table>
<thead>
<tr>
<th>Method</th>
<th>Behavior in solenoid off field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel track</td>
<td>Efficiency &gt; 50%, fakes &lt; 10%</td>
</tr>
<tr>
<td>Tracklet Method 1</td>
<td>Efficiency &gt; 90%</td>
</tr>
<tr>
<td>Tracklet Method 2</td>
<td>Efficiency &gt; 90%, large number of fakes subtracted by combinatoric approach</td>
</tr>
<tr>
<td>Cluster counting</td>
<td>Efficiency &gt; 90%, cross check on tracklet methods</td>
</tr>
</tbody>
</table>

**Table 5.2:** Algorithms used in this analysis for charged particle finding algorithm and their relative advantages.

For the four methods, not all reconstructed pixel tracks (tracklets or clusters) are used for the analysis, there are some selection criteria imposed to insure their quality. Table 5.3 shows the selection criteria for each algorithm.

<table>
<thead>
<tr>
<th>Method</th>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel track</td>
<td>$</td>
</tr>
<tr>
<td>Tracklet Method 1</td>
<td>None</td>
</tr>
<tr>
<td>Tracklet Method 2</td>
<td>None</td>
</tr>
<tr>
<td>Cluster counting</td>
<td>$E_0(\eta) &gt; -0.013 + 0.048 \cosh(\eta)$</td>
</tr>
</tbody>
</table>

**Table 5.3:** Selection criteria imposed for each object reconstructed by four different algorithms.

5.1.2.2 Standard Algorithm

The NewT package \cite{105,106,107,108} which runs the standard “inside-out” pattern recognition algorithm is used for full track finding algorithm. It uses information from the whole ID, and starts the search for tracks from
pixel detector to SCT and then to TRT (inside-out). The New Tracking algorithm performance in the heavy ion environment is studied throughly in this note \cite{109}. The tracks reconstructed only the pixel detector are called “pixel tracks” in this note.

The primary vertex with full tracks as its input is reconstructed in two steps:

1. Select full tracks compatible with the beam spot to form a vertex seed.

2. Apply an adaptive vertex fitter to fit the vertex parameters from those tracks.

On top of the default primary vertex reconstruction configuration used in ATLAS proton proton collisions \cite{110}, there are several differences in this setup. In the heavy ion environment, only one primary vertex is reconstructed, which is reasonable given the low probability of pile-up events. Also, in the solenoid-off configuration, the $p_T$ requirement is not imposed when selecting full tracks compatible with the beam spot, while in solenoid-on configuration, only $p_T > 500$ MeV full tracks are reconstructed and selected to form vertex seeds.

5.1.2.3 Tracklet Analysis: Cluster Cleaning Cuts

**Removal of duplicate clusters** Duplicate clusters are defined as two or more clusters in the same pixel layer produced by the same particle, which arise from ganged pixels and overlapping sensors. The presence of duplicate clusters not only cause increased combinatoric background and duplicate tracklets, but also cause non-randomness in the “flipped event” for Method
2 (to be explained below). Thus, identifying and removing duplicate clusters before the tracklet reconstruction is essential.

Because of pixel channels sharing the same readout electronics, one channel fired by a real particle induce a hit in the shared channel, thus produce duplicate clusters. The structure of ganged and inter-ganged pixel channels allows us to differentiate clusters produced by real particles from those produced by the sharing of readout electronics. If two clusters use ganged pixels in the same way (i.e. the two clusters match up exactly in their ganged structure) and one cluster has a higher number of pixel channels, then the one with more pixel channels is kept in the analysis and the other discarded as fake. Clusters in the ganged region can be identified as three types by this argument:

1. Real clusters, clusters identified as being fired by real particles.

2. Fake clusters, clusters identified as being artificially caused by the ganged structure.

3. Ambiguity, clusters without enough information to be identified as real or fake.

To illustrate how to identify those ganged clusters as the three types, figure 5.12 shows the fired pixel channels (red) in the ganged area in one pixel module in layer-0 from one heavy ion event. In this figure, the $x$-axis is the row ($\phi$) direction where inter-ganged channels have white shaded color and two channels ganged to each other have the same shaded color, i.e. row 153 is ganged with row 160, row 155 is ganged with row 161, row 154 is inter-ganged channels etc. Fired pixel channels sharing a side or a diagonal side
are formed together as a cluster by the ATLAS default clustering algorithm. As an example, example clusters in the figure are identified as real cluster, fake cluster and ambiguous clusters.

1. Real cluster: the cluster composed of two pixel channels (160,137), (161,137) and labeled as “Real” in the figure.

2. Fake clusters: one composed of one single channel (153, 137) and the other one composed of one single channel (155, 137), labeled as “Fake” in the figure and identified as fakes by using the information from above real cluster.

3. Ambiguous clusters: One cluster composed of two pixel channels (164, 26), (164, 27) and the other cluster composed of two pixel channels (168, 26), (168, 27) (labeled as “Ambiguity”) are duplicates of each other, but there is not enough information to tell which one is real and which one is fake.

In the figure, all clusters labeled with “N” are found to be fakes by our cleaning algorithm. The fake clusters are not used by the tracklet reconstruction procedure. Ambiguous clusters are used in the tracklet reconstruction algorithm and are merged in the tracklet cleaning procedure which will be explained later. After the ganged cluster removal procedure, around 5% clusters are excluded from the tracklet finding process.

Another source of duplicate clusters is caused by the overlap region of the neighboring modules. The duplicate clusters caused by the overlap structure of the pixel neighboring modules in the barrel are removed in the following
Figure 5.12: Column vs row distribution of fired pixel channel in one pixel module in layer-0 of one event, enlarged to ganged region. Inter-ganged channels are denoted with white shaded color and two ganged channel sharing the same readout electronics are denoted with the same shaded color. The fired pixel channels are in red color. Notice the figure has $x-y$ axis interchanged compared with figure ??.

way. We draw a straight line between the vertex and the edge of the inner module in the $x-y$ plane where the overlap occurs. Any clusters in the outer module lays above this line are not used in the tracklet reconstruction process. Fig. 5.13 illustrates how the overlap clusters are dealt with. The figure is a zoom of the overlapping region between layer-0 modules. The red line with $\phi = \phi_0$ shows the line we draw from the vertex to the edge of the inner module. Any clusters in the blue color region are duplicate clusters, thus not used in the tracklet finding process. The duplicate clusters arisen from modules adjacent in the $z$ direction are very small, thus no cleaning procedure is done in the cluster level. After the removal of overlap clusters,
around 5% clusters are excluded from the tracklet finding process.

Although we treat duplicate clusters from both ganged and overlap structure as the same undesirable factors in the tracklet reconstruction algorithm, it should be noted that in the full tracking algorithm, those two kinds of duplication have different effects on the tracking. While duplicate clusters caused by sharing of electronics instead of real particles can impair the precision of track parameters because of the wrong positions, duplicate clusters in the overlap region can provide more information about the particles, thus improve the precision of the reconstructed track parameters.

**Removal of low energy loss clusters** Real particles deposit a small fraction of their energy in the pixel detector when passing through the detector.
The energy loss distribution presents with large tails which are described by Landau distribution and has a sharp cut off at small energy loss side. The $\eta$ of secondary particles produced at displaced secondary vertices are calculated from reconstructed primary vertex, thus some secondary clusters with artificially assigned high $\eta$ value tend to have energy loss less than MIPs at that $\eta$ region. Also, noise hits give an energy measurement much less than clusters produced by real particles and is independent of the cluster $\eta$. Thus, we require the clusters used in tracklet finding algorithm to have a minimal amount of the energy deposition to exclude noise and secondary clusters. The energy deposition cut was obtained in the following way from proton proton collisions:

1. Fit energy loss distribution of tracklet pixel clusters around the peak to Landau distribution ($\mathcal{L}$) in each $\eta$ slice.

2. Find the energy loss position $dE(\eta)$ satisfying $\int_0^{dE} \mathcal{L} \, dx / \int_0^{1.0} \mathcal{L} \, dx = 1.0e - 07$.

3. Fit $dE(\eta)$ to a function $E_i(\eta) = a + b \cosh(\eta)$ for each layer $i$ with $a$, $b$ as the fitted parameter.

Table 5.4 shows the energy loss cut used to exclude noise and secondary clusters. Fig. 5.14 shows the energy loss distribution vs $\eta$ for all the layer-0

<table>
<thead>
<tr>
<th>Layer</th>
<th>$E_0(\eta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer-0</td>
<td>$E_0(\eta) = -0.013 + 0.048 \cosh(\eta)$</td>
</tr>
<tr>
<td>Layer-1</td>
<td>$E_1(\eta) = -0.013 + 0.048 \cosh(\eta)$</td>
</tr>
</tbody>
</table>

**Table 5.4:** Energy loss cut functions for different layers used for noise and secondary clusters removal.
clusters in the most central events. The vertical axis is in linear scale on left histogram and is in log scale on right histogram. We can clearly see the MIP energy loss vary with $\eta$, which is consistent with the fact that the path length of particle incident with different angle is proportional to $\cosh(\eta)$. The energy loss cut used to remove noise and secondaries is also plotted on the histogram as the black line. Clusters with energy loss lower than that line is not used in the tracklet reconstruction. The right histogram (in log scale) emphasizes the low energy loss side where noise and secondaries contribute more. The clusters removed by the energy loss cut corresponds to about $1 \sim 10\%$ of the total clusters depending on pseudo-rapidity. Some clusters produced by primary particles at the edge of the detectors also have very low energy deposition, thus are rejected by the cut. The clusters in pixel barrel region around the edge which is defined by their local position: $locX < -8.2$ or $locX > 8.1$ are less 1% of all the clusters. And the rejected clusters around the pixel module edge are less than 0.1% of all the clusters. Monte Carlo study shows that about 50% of secondary and noise clusters are rejected by this cut, while less than 5% primary clusters are rejected at $|\eta|$ near 2. And about 20% secondaries and noise clusters are rejected while less than 1% primary clusters are rejected near $\eta = 0$. Fig. 5.15 shows the ratio of rejected layer-0 clusters as a function of $\eta$ for both data (black point) and MC (red square) samples. There is 1% difference in the rejection factor. But only 1% to 5% primary clusters from mid-rapidity to high rapidity are rejected, so the difference in rejected primary clusters are in the order of 0.001% to 0.005% from $\eta = 0 - 2$. For more detailed study of energy loss measurement and its application in particle identification, see Ref. (111).
Figure 5.14: Energy loss vs $\eta$ for all layer-0 clusters. The black line is the energy loss cut used to remove noise and secondaries clusters. Y-axis on left histogram is in linear scale and on right histogram is in log scale.

Figure 5.15: Ratio of rejected layer-0 clusters by low energy loss cut for data (black point) and MC (red square).
5.1.2.4 Tracklet Analysis: Reconstruction Algorithm

Tracklet reconstruction algorithms use the reconstructed primary vertex and pixel clusters in the first two barrel layers and performs a simple test to see if the three points are compatible with a straight line. Its conceptual simplicity and high efficiency makes it a popular method for multiplicity measurements in heavy ion collisions. Similar algorithms adapted to specific detector properties for multiplicity measurements in heavy ion collisions can be found in Refs. [19, 22, 112].

Given the reconstructed primary vertex, we calculate the $\eta$ and $\phi$ value of pixel clusters with respect to the vertex, that is

\begin{align}
\eta &= -\ln(\tan(\theta/2)), \\
\phi &= \tan^{-1}\left(\frac{y-v_y}{x-v_x}\right).
\end{align}

with $\theta = \tan^{-1}\left(\frac{|\vec{r} - \vec{v}|}{z-v_z}\right)$ and ($x, y, z$) and ($v_x, v_y, v_z$) are the positions of cluster and reconstructed vertex in the global coordinate system and $\vec{r} = (x, y)$ and $\vec{v} = (v_x, v_y)$ are the position in the transverse plane. In this note, we use the clusters from the first two pixel barrel region (layer-0 and layer-1) which have more than four units $\eta$ coverage for each layer. In the following, the angular parameters of layer-0 clusters are denoted with a subscript 0 and those of layer-1 are denoted with a subscript 1. (e.g. $\eta_0$, $\phi_0$, $\eta_1$, $\phi_1$, etc). For each pair of clusters, one from layer-0 and one from layer-1, we calculate the differences in the $\eta$ and $\phi$ direction: i.e. $\Delta\eta = \eta_1 - \eta_0$ and $\Delta\phi = \phi_1 - \phi_0$. If the differences are less than a chosen cut value, then this pair is kept as a
tracklet candidate: i.e.

\[ dR = \sqrt{\left( \frac{\Delta \eta}{\sigma_{\Delta \eta}} \right)^2 + \left( \frac{\Delta \phi}{\sigma_{\Delta \phi}} \right)^2} < \sqrt{2}N_\sigma. \quad (5.3) \]

Where \( \sigma_{\Delta \eta} \) and \( \sigma_{\Delta \phi} \) are the resolution in \( \Delta \eta \) and \( \Delta \phi \) direction. This elliptical shape cut incorporates the limited resolution of \( \Delta \eta \) and \( \Delta \phi \), primarily from multiple scattering, and \( N_\sigma \) denotes how many times of sigma value to choose for the cut. We use \( N_\sigma = 3 \) as our default value for the algorithm. This is to insure maximum efficiency. In principle, 99% of charged primary particles are within this cut, but some particles are not reconstructed due to dead modules in pixel detector. Once a tracklet candidate is accepted by the above cut, the angular parameters \((\eta, \phi)\) of the tracklet candidate is taken from those for the layer-0 cluster. Fig. 5.16 is the schematic diagram showing how tracklets are defined. On this histogram, three different views are shown, \( x - y \) plane view (top left), \( z - r \) plane view (bottom left) and \( \eta - \phi \) plane view. In the \( x - y \) view, the clusters \( \phi \) values are defined, and in the \( z - r \) view, the clusters \( \theta \), then \( \eta \) values are defined, and in the \( \eta - \phi \) view, the \( \Delta \eta \) and \( \Delta \phi \) of cluster pairs are defined. Fig. 5.17 shows the \( \Delta \phi \) vs \( \Delta \eta \) distribution of all the cluster pairs for the events selected with the selection criteria as described in section 5.1.1.2. The black curve on the histogram shows the cut used to select tracklet candidates at \(|\eta| = 1.0\). The distribution is peaked \( \Delta \eta = 0 \) and \( \Delta \phi = 0 \) since real tracks have a straight trajectory in the absence of solenoid field. However, the distribution is Gaussian in both directions, due to multiple scattering, vertex resolution, and combinatorics. The distribution is not strictly circular in the middle because of different resolution in \( \eta \) and
Fig. 5.18 shows the dR distribution defined from the above equation for any layer-0 and layer-1 cluster pairs. The red line shows our default cut value. It is consistent with the above 2-D histogram where it is populated at small value and has large tails due to combinatorics, the latter clearly indicated by the linear rise at large $dR$.

Figure 5.16: Schematic diagram showing how two-point tracklets are reconstructed. Top left is the x-y view showing how $\phi$ values are defined. Bottom left is the z-r view showing how $\theta$ values are defined. Right is the $\eta$-$\phi$ view showing how tracklets $\Delta \eta$ and $\Delta \phi$ are defined. Layer-0 cluster is denoted with red point, and layer-1 cluster is denoted with blue point.

Several factors can contribute to the limited resolution of $\Delta \eta$ and $\Delta \phi$, e.g. multiple scattering, pixel detector resolution and reconstructed vertex resolution. Furthermore, it is $p_T$, $\eta$ dependent and dominated by the multiple scattering of low momentum particles at large $\eta$. Fig. 5.19 shows both the $\sigma_{\Delta \eta}$ (red square) and $\sigma_{\Delta \phi}$ (black point) as a function of $\eta$ used
in the tracklet finding algorithm. They are estimated from the HIJING sample by studying the clusters from the truth primary particles. Their values are $\eta$ dependent and have higher values at high $\eta$ because of additional material in the detector, increasing the multiple scattering. We apply a fit to parametrize both $\sigma_{\Delta \eta}$ and $\sigma_{\Delta \phi}$ in order to smooth the behavior in $\eta$ direction: 

$$
\sigma_{\Delta \eta}(\eta) = 0.007515 - 0.000376|\eta| + 0.000216|\eta|^2 + 0.000796|\eta|^3,
$$

$$
\sigma_{\Delta \phi}(\eta) = 0.0064 + 0.0007 \cosh(\eta).
$$

As explained above in the discussion of removing duplicate clusters, even after the ganged and overlap clusters are removed, there are still some residual duplicate clusters in the tracklet reconstruction sample. This can cause
Figure 5.18: dR distribution for any layer-0 and layer-1 cluster pairs.

Figure 5.19: $\sigma_{\Delta \eta}$ and $\sigma_{\Delta \phi}$ as a function of $\eta$ used in the tracklet reconstruction algorithm. Red square is for $\sigma_{\Delta \eta}$ and black point is for $\sigma_{\Delta \phi}$. The parametric form is denoted by blue line (see text).

duplicate tracklets which stem from the same particle. To address this, we apply a procedure to remove duplicate tracklets: for each pair of tracklets,
we compare the inner layer clusters and outer layer clusters respectively. If two clusters have the same number of pixel channels and contain only ganged pixel channels in the same way, the two clusters are the duplicate clusters from the ganged structure. If two clusters in the same layer are in different pixel modules and their difference in the angular space satisfies $|\eta^i - \eta^j| < 0.01$ and $|\phi^i - \phi^j| < 0.01$, then the two are overlap clusters. The cut value 0.01 is chosen as the width of the angular difference distribution of the same layer clusters around the zero peak. If two tracklets are found to be overlap or ganged to each other in both layers, the two are taken as duplicates to each other and are merged to form one tracklet, with the angular parameters of the merged tracklet being the “first” one in the list (if both layers involved ganged hits), or the tracklet with the smaller radius in layer-0 (if both layers involve overlapping hits). Around 8% tracklet candidates are removed by this merging procedure.

Fig. 5.20 shows $\phi$ distribution of tracklet candidates with and without the duplicates removal procedure described above. Before any removal of duplicate clusters and tracklets (red line), there are peaks around $\frac{2\pi}{14} \cdot i (i = 0, \pm 1, ...)$, where peaks with even values of $i$ come from ganged structure and peaks with odd values of $i$ arise from overlap regions. The peak height is almost twice the height of the flat $\phi$ region where there are no duplicate clusters from the pixel detector structure itself. With the removal of fake ganged clusters but before the overlap clusters and duplicate tracklets removal (blue line), we can clearly see the reduction of the peaks caused by the ganged fake clusters. There are still some residual counts in the peaks, which is due to the fact that there are still some ambiguous clusters present the tracklet
finding process. The black line shows raw tracklets $\phi$ distribution after the full duplicate removal procedure. The distribution is quite flat along $\phi$ with all the ganged and overlap peaks removed. There are very small dips around the position where the ganged peaks are used to be. This is because two real clusters ganged the same way can happen at the ganged region due to the high particle density. This fraction is less than $10^{-4}$, thus the effect is negligible in multiplicity measurement.

**Figure 5.20:** $\phi$ distribution of tracklet candidates with and without applying the ganged and overlap cluster removal procedure. Red line shows all the tracklet candidates without the ganged and overlap removal procedure. Blue line shows tracklet candidates after the ganged clusters removal procedure. Black line shows tracklet candidates after all the ganged clusters, overlap clusters and the duplicate tracklets removal procedure.

Fig. 5.21 shows the $\phi$ vs $\eta$ distribution of tracklet candidates from data (left) and MC (right) for each step of cleaning procedure. Top panel shows tracklet candidates reconstructed with all available clusters, top middle panel shows tracklet candidates reconstructed with clusters survived ganged clus-
ter removal procedure, bottom middle panel shows tracklet candidates reconstructed with clusters survived ganged and overlap cluster removal procedure. Bottom panel shows the tracklet candidates reconstructed with clusters after ganged and overlap cluster removal procedure and the duplicate merging procedure. After each step of cleaning procedure, we can clearly see the smoothed behavior in $\phi$ direction. Also data and MC are in good agreement with each other in general.

Figure 5.21: Tracklet candidates $\phi$ vs $\eta$ distribution for data (left) and MC (right) for each step of cleaning procedure. Top panel shows tracklet candidates with all clusters. Top middle panel shows tracklet candidates with clusters cleaned by ganged cluster removal procedure. Bottom middle panel shows tracklet candidates with clusters cleaned by ganged and overlap cluster removal procedure. Bottom panel shows tracklet candidates with clusters cleaned by ganged and overlap cluster removal procedure and duplicate tracklet merging procedure.
5.1.2.5 Tracklet Analysis: Method 1 And Method 2

The challenge of heavy ion environment is the large variation in particle density, and especially the high multiplicity events which can cause several clusters in the outer layer to be associated to one cluster in the inner layer when satisfying the given tracklet cut. Depending on the particle density, the percentage of the total layer-0 clusters having two associated layer-1 clusters is found to range from several to 30%. For layer-0 clusters having three and more layer-1 associations, the percentage can range from several percent to 40%. The large number of multiply-associated clusters in central events, has to be dealt with carefully. We have developed two ways to handle this situation, which lead to two different (but complementary) reconstruction methods. The first method (Method 1) treats multiple tracklets associated with the same layer-0 cluster as one tracklets. The second method (Method 2) includes all of the ambiguous cases as separate tracklets, so one cluster in layer-0 associated with multiple clusters in the layer-1 generates multiple tracklets. Fig. 5.22 illustrates how the two methods deal with multiple associations differently. In this diagram, one cluster in layer-0 is associated with three layer-1 clusters in the sense that they satisfy the cuts defined by the equation 5.3. The left figure illustrates how Method 1 treats this as one tracklet candidate and the right figure shows Method 2 treating them as three tracklet candidates. In both cases, the $\eta$ and $\phi$ parameters of all of the reconstructed tracklets are taken from the single layer-0 cluster.

The motivation of Method 1 is obvious in the sense that one particle can only produce one cluster in each layer (except looping electrons, when the
Figure 5.22: Illustrative diagram of three clusters in layer-1 associated to one cluster in layer-0. Left: Method 1 reconstructs one tracklet. Right: Method 2 reconstructs three tracklets.

solenoid is on) if it is not passing through the ganged or overlap region of the pixel detector, which we will discuss later in more detail for this case. By treating multiple associations as one tracklet, we keep the real particles and eliminate most of the combinatorics, at the cost of possibly picking up a wrong association if the multiple scattering is large.

The advantage of Method 2 is that we keep all random combinatorics and so all truth particles are guaranteed to have an associated tracklet, although we have a large fraction of fakes, albeit ones which can be estimated by a data driven method. The number of tracklets coming from random combinations is proportional to the cut area and the cluster density in both layer-0 and layer-1:

\[ N_{\text{comb}} = 9\pi \rho_{n_0} \rho_{n_1} \sigma_{\Delta\eta} \sigma_{\Delta\phi} \]  \hspace{1cm} (5.4)

where \( N_{\text{comb}} \) denotes the number of tracklets arising from pure combinatorics, \( \rho_{n_0} \) and \( \rho_{n_1} \) are cluster densities in layer-0 and layer-1 which can be estimated...
as $n_0/(4 \times 2\pi)$ and $n_1/(4 \times 2\pi)$ with $n_0$ and $n_1$ denoting the number of clusters in layer-0 and layer-1 in $|\eta| < 2.0$ region. For each event, we flip the $z$ position of layer-1 clusters with respect to the reconstructed vertex, i.e. $(z_1 - v_z) \rightarrow -(z_1 - v_z)$, and shift $\phi$ of layer-1 clusters by $\pi$ ($\phi \rightarrow \phi + \pi$ or $\phi \rightarrow \phi - \pi$), then we run tracklet reconstruction algorithm the same way as for the non-flipped signal event. Using this “flipped” sample, which removes all correlations from real tracks, we find combinatoric background which is then subtracted from the signal tracklets on an event-by-event basis in bins of width $\Delta \eta = 0.1$. Fig. 5.23 shows the tracklets in flipped events to those from signal events for data (black point) and MC (red square) for 10-20% centrality bin. The tracklets from the flipped events are combinatorics and proportional to cluster density, so we subtract the same amount of combinatorics for data and MC in the same centrality class. That’s why data and MC agree with each other very well.

5.1.3 Raw Distributions And Comparison To MC

5.1.3.1 Pixel Barrel Dead Channel Map Comparison

Several pixel modules were disabled during the data-taking period. To make sure that the MC samples have good description of the disabled pixel modules, we make a detailed comparison of the pixel barrel cluster distribution. Fig. 5.24 shows the cluster $\phi$ module vs $\eta$ module for data (left) and MC (right) in different barrel layers. There is no difference between data and MC in the totally disabled modules in layer-0 and layer-1. One additional module is in fact disabled in data ($\eta = -5, \phi = 28$) in layer-2, but one
Figure 5.23: Ratio of tracklets in flipped events to those from signal events for data (black point) and MC (red square) for 10-20% centrality bin.

Figure 5.24: Cluster $\phi$ module vs $\eta$ module for data (left) and MC (right) in different layers. Top panels are for layer-0 clusters, middle panels are for layer-1 clusters and bottom panels are for layer-2 clusters.
which is not used in tracklet methods. Also there are some partially disabled modules in data that are not precisely described by data.

To make a clear comparison module by module, we plot the $\phi$ (calculated with respect to 0) distribution of clusters for modules with the same $\eta$ module number layer by layer. Fig. 5.25-5.27 shows the $\phi$ distribution for data (black) and MC (red line) clusters with different $\eta$ module number and in different layers. No difference in entirely dead modules or partially dead modules is found between data and MC in layer-0. For layer-1, there is no difference in entirely dead modules. Two partially-dead modules at $\eta=-1$ and 4 for data sample are not described by MC sample. There is one more entirely dead module for data in layer-2 at $\eta=-5$. Two partially-dead modules at $\eta=-6$ and -1 for data sample is not described by MC sample. In general, the dead channel maps in data are well described by MC, and the discrepancy in the number of clusters affected by the differences is estimated to be less than X%.

5.1.3.2 Raw Distributions

This section shows the raw tracklet angular distributions produced from the reconstruction algorithm but before any corrections are applied. Fig. 5.28 shows the raw tracklet $\eta$ distribution from Method 1 for different centrality bins. From peripheral to central collisions, the number of raw tracklets changes by a factor of 50. Fig. 5.29 shows the raw tracklet distributions from Method 2. The left histograms are from signal samples and the right ones are from background samples in which layer-1 clusters are flipped with respect to reconstructed vertex and their $\phi$ angle is shifted by $\pi$. From peripheral
Figure 5.25: Layer-0 clusters $\phi$ distribution in different $\eta$ modules for data (black line) and MC (red line). Histograms are arranged with increasing $\eta$ module number from -6 to 6. Data and MC are normalized to have the same area.

to central collisions, the number of reconstructed tracklets vary from a few tens to a few thousands for signal events (left). And for background events, they vary from a few to a few thousands from peripheral to central collisions. Fig. 5.30 shows the background to signal ratio of raw tracklet distributions from Method 2 for different centrality bins. We can see the ratio have a very strong centrality and $\eta$ dependence as expected. Because background tracklets are proportional to the number of clusters in both layer 0 and layer-1 and more central events according to centrality definition have more clusters and higher $\eta$ region has more clusters due to extra material in that region. Fig. 5.31 shows the number of raw tracklets in $|\eta| < 1.0$ normalized
Figure 5.26: Layer-1 clusters $\phi$ distribution in different $\eta$ modules for data (black line) and MC (red line). Histograms are arranged with increasing $\eta$ module number from -6 to 6. Data and MC are normalized to have the same area.

by $\eta$ coverage versus the forward calorimeter transverse energy distribution. The red points are plotted for signal events, the black points are plotted for flipped events and the blue points are signal events subtracted by flipped events. The red points shows the distribution of the sum of quadratic combinatorics with the real particles. The black points shows the distribution of the quadratic combinatorics. And the blue points represent the distribution from real particles, thus the number of tracklets is linearly correlated with the forward calorimeter transverse energy. Although the background to signal ratio reach to 60% in mid-rapidity for central events, the real raw signal (blue points) still exhibits the linearity for central events. Fig. 5.32
Figure 5.27: Layer-2 clusters $\phi$ distribution in different $\eta$ modules for data (black line) and MC (red line). Histograms are arranged with increasing $\eta$ module number from -6 to 6. Data and MC are normalized to have the same area.

shows the raw $\eta$ distribution of pixel tracks for different centrality bins. Pixel track algorithm reconstructs less raw candidates than the other two methods because this method requires at least three clusters in different layers thus have lower efficiency, but also a lower fake rate.

5.1.3.3 Comparison Of Data And MC

Fig. 5.33 shows the $\eta$ distribution of data (black point) and MC (yellow shadowed) samples of tracklets constructed by Method 1. Left is from 50-60% centrality events and right is from 0-10% centrality events. Lower panels shows the ratio of data to MC and they agree with each other very well,
Figure 5.28: Raw tracklet distributions from Method 1 for different centrality bins.

Figure 5.29: Raw tracklet distributions from Method 2 for different centrality bins. **Left**: Tracklets from signal samples. **Right**: Tracklets from background samples.

1% within $|\eta| < 1.5$ and reaching to 4% at the edge of the measured interval. Fig. 5.34 shows $\Delta \eta$ distribution of tracklets from Method 1 before (left) and after (right) applying $p_T$ re-weighting process to MC samples for 0-10% centrality events. Data distributions are denoted with black lines and MC
Figure 5.30: Background to signal ratio of raw tracklets from Method 2 for different centrality bins.

Figure 5.31: Number of tracklets from method 2 in $|\eta| < 1.0$ normalized by $\eta$ coverage vs the forward calorimeter transverse energy distribution. The red points are from signal events, the black points are from flipped events, and the blue points are signal events subtracted by flipped events.


**Figure 5.32:** Raw track distributions from pixel tracks reconstruction algorithm for different centrality bins.

Distributions are denoted with yellow shaded area. Data and MC distributions on top panels are normalized by area and lower panels shows the ratio of data to MC. The improvement of the agreement between data and MC is obvious after re-weighting process. Before $p_T$ re-weighting, MC samples show an excess of low momentum particles, thus have more large tails and less tracklets with smaller $\Delta\eta$ value. After the re-weighting process, the ratio shows data and MC have very good agreement with each other. Fig. 5.35 shows $\Delta\phi$ distribution of tracklets from Method 1 for the 0-10% centrality events. MC distribution on left histogram is without re-weighting and the right one is with re-weighting process. It is clear that after the re-weighting, data and MC have quite good agreement with each other. Fig. 5.36 shows the $\eta$ distribution of background subtracted tracklets from Method 2 for 50-60% centrality events (left) and 0-10% centrality events. Data are denoted with
black points and MC are denoted with yellow shaded area. Lower panels show the ratio of MC to data. They agree with each within 6%. Fig. 5.37 (To be updated with new MC) shows the $\eta$ distribution of pixel tracks for 50-60% centrality events (left) and 0-10% centrality events. Data are denoted with black points and MC are denoted with yellow shaded area. Lower panels show the ratio of MC to data. They agree with each other very well within 5%. Finally, Fig. 5.38 shows the $d_0$ distribution of pixel tracks for 0-10% centrality events with data (black line) and MC (yellow shaded area) comparison. MC distribution on left histogram is without $p_T$ re-weighting process and MC distribution on right histogram is with the application of re-weighting process. Lower panels show the ratio of MC to data. After the re-weighting process, data and MC are in good agreement with each other. It should be noted that even though the MC re-weighting process change the distribution $\Delta \eta$, $\Delta \phi$, $d_0$ and $z_0 \sin(\theta)$ by more than 15%, it only changes the final $dN_{ch}/d\eta$ distribution by less than 2%.
Figure 5.33: $\eta$ distribution of tracklets from Method 1 with data (black point) and MC (yellow shaded) comparison. Left is for 50-60% centrality and right is for 0-10% centrality. MC and data distributions are normalized by area. Lower panels show the ratio of MC to data.
Figure 5.34: $\Delta \eta$ distribution of tracklets from Method 1 with data (black line) and MC (yellow shaded) comparison for 0-10% centrality case. MC distribution on left histogram is without $p_T$ re-weighting process, and MC distribution on right histogram is with $p_T$ re-weighting process.
Figure 5.35: $\Delta \phi$ distribution of tracklets from Method 1 with data (black line) and MC (yellow shaded) comparison for 0-10% centrality case. MC distribution on left histogram is without $p_T$ re-weighting process, and MC distribution on right histogram is with $p_T$ re-weighting process.
Figure 5.36: $\eta$ distribution of background subtracted tracklets from Method 2 with data (black point) and MC (yellow shaded) comparison. Left is for 50-60% centrality and right is for 0-10% centrality. MC and data distributions are normalized by area. Lower panels show the ratio of MC to data.
Figure 5.37: $\eta$ distribution of pixel tracks with data (black point) and MC (yellow shaded) comparison. Left is for 50-60% centrality and right is for 0-10% centrality. MC and data distributions are normalized by area. Lower panels show the ratio of MC to data.
**Figure 5.38:** $d_0$ distribution of pixel tracks with data (black point) and MC (yellow shaded) comparison without (left) and with (right) $p_T$ re-weighting process for MC samples. Lower panels show the MC to data ratio.
Figure 5.39: $z_0 \sin(\theta)$ distribution of pixel tracks with data (black point) and MC (yellow shaded) comparison without (left) and with (right) $p_T$ reweighting process for MC samples. Lower panels show the MC to data ratio.
5.1.4 Monte Carlo Study Of Correction Factors

Monte Carlo samples are used to study detector effects. Since the number of produced primary particle varies by large factors in heavy ion collisions, we evaluate efficiencies according to the occupancy in the pixel barrel layer-0: $dN_{clus}^0/d\eta(|\eta| < 1.0)$. Fig 5.40 shows the distribution of the occupancy variable defined above and we slice it into 20 occupancy bins with equal coverage in occupancy space, referred to as “occupancy bin” 1, 2, ..., 20 ordered in increasing occupancy. The bin numbers are indicated in alternate bins in the histogram.

Here we show the reconstruction efficiencies for inclusive charged particles from three different reconstruction algorithms for all of the occupancy bins.

![Figure 5.40](image)

**Figure 5.40:** Distribution of $dN_{clus}^0/d\eta(|\eta| < 1.0)$ which reflects pixel detector occupancy. The distribution is sliced into 20 bins with equal width except the last one. The numbers on the yellow bands are their corresponding occupancy bin numbers.
5.1.4.1 Method 1

We define the correction factor for tracklet Method 1 as following:

$$\epsilon_{reco}(\eta) = \frac{N_{trkl}(\eta)}{N_{primary}(\eta)}$$ (5.5)

where $N_{trkl}$ is the number of reconstructed tracklets and $N_{primary}$ is the number of primary particles produced by the event generator. Fig. 5.41 shows the correction factor for 20 occupancy categories with the MC sample $p_T$ spectrum re-weighting procedure. The change of correction factor from low occupancy to high occupancy is generally because of the contribution from fake tracklets. Because the correction factor combines individual corrections for efficiency, secondary rate and fake rate, they end up greater than one for the high occupancy events. Fig. 5.42 shows the correction factor as a function of occupancy bins in different $\eta$ range. We can see the correction factors increase with occupancy bin and with $|\eta|$, which are due to the increase of combinatorics for high density events in more material region. The increase after occupancy bin 14 is very small due to the ‘saturation’ effect where combinatorics are eliminated by the presence of real particles in their neighborhood defined by the reconstruction cut in equation (5.3). The difference between MC re-weighted correction factor and that without MC re-weighting process is less than 0.5%.
**Figure 5.41:** Correction factor calculated from HIJING with physics flow samples for tracklet Method 1. **Top left:** Occupancy bins 1 to 5, indicated by black point, red square, green triangle, blue reverted triangle and magenta star respectively. **Top right:** Occupancy bins 6 to 10, with the same color convention as previous. **Bottom left:** Occupancy bins 11 to 15. **Bottom right:** Occupancy bins 16 to 20 (i.e. the most central bins)
5.1.4.2 Method 2

Correction factor for tracklet Method 2 algorithm is defined as following:

\[
\epsilon_{\text{reco}}(\eta) = \frac{N_{\text{trkl}}(\eta) - N_{\text{flipped}}(\eta)}{N_{\text{primary}}(\eta)}
\]  

(5.6)

where \(N_{\text{trkl}}\) is the number of tracklets reconstructed in signal events, \(N_{\text{flipped}}\) is the number of tracklets reconstructed in the flipped events and \(N_{\text{primary}}\) is the number of primary particles generated by the event generator. Fig. 5.43 shows the correction factor from tracklet Method 2. The reconstruction efficiencies show very little dependence on centrality, which confirms that the fake tracklets are successfully subtracted from the signal events. Also the correction factors are typically smaller than those in Method 1, because Method...
2 only has to correct for efficiency and secondaries. The correction factors also show unsmooth behavior. This can be caused by the asymmetric pixel detector due to disabled modules. Also the nature of tracklet Method 2 requires subtracting a big number from another big number, which can also contribute to large statistical fluctuations. Fig. 5.44 shows the correction factor as a function of occupancy bin in different $\eta$ region. It has very week dependence on occupancy bins. Most importantly, the difference between MC re-weighted correction factors and those without re-weighting is less than 0.5%.

Figure 5.43: Correction factor calculated from HIJING with physics flow samples for tracklet Method 2. The correction factor for 20 different event categories are organized the same as in the figure 5.41.
Figure 5.44: Correction factor of Method 2 as a function of occupancy bin in different $\eta$ range. Filled points show $0.0 < \eta < 0.1$, filled squares show $0.5 < \eta < 0.6$, filled triangle show $1.0 < \eta < 1.1$, filled inverted triangle show $1.5 < \eta < 1.6$ and open circles show $1.9 < \eta < 2.0$.

5.1.4.3 Pixel Tracking

As explained above, pixel tracks are reconstructed using the main ATLAS tracking package but with space-points restricted to the Pixel detector. Pixel tracks are selected with: $|d_0| < 1.5mm$ and $|z_0 \sin(\theta)| < 1.5mm$ with all parameters evaluated with respect to reconstructed primary vertex. We define the following term to identify different components of reconstructed tracks. Matched primary tracks ($N_{trk}^{matched\ primary}$): tracks matched to primary particles with probability greater than 0.6. Matched secondary tracks ($N_{trk}^{matched\ secondary}$): tracks matched to secondary particles with probability greater than 0.6. Fakes ($N_{trk}^{no\ match}$): tracks that are not matched to any particles. Out-of-kinematic-region tracks ($N_{trk}^{out\ of\ kinematic\ range}$): tracks re-
constructed within our range \((|\eta| < 2.0)\) but matched to truth particles which are outside of the fiducial kinematic range: \(|\eta| > 2.0\). Efficiency, secondary rate, fake rate and out of kinematics rate are defined as following:

\[
\epsilon(\eta) = \frac{N_{\text{matched\,primary}}(\eta)}{N_{\text{primary}}(\eta)},
\]

\[
r_{\text{sec}}(\eta) = \frac{N_{\text{matched\,secondary}}(\eta)}{N_{\text{reco}}(\eta)},
\]

\[
r_{\text{fake}}(\eta) = \frac{N_{\text{no\,match}}(\eta)}{N_{\text{reco}}(\eta)},
\]

\[
r_{\text{okr}}(\eta) = \frac{N_{\text{out\,of\,kinematic\,range}}(\eta)}{N_{\text{reco}}(\eta)}.
\]

Fig. 5.45 shows the efficiency in different occupancy bins. The efficiencies have a weak occupancy dependence, and strong \(\eta\) dependence. For peripheral events where the occupancy is low, the efficiency varies from 70% at \(|\eta| \sim 1.2\) to 50% at the edge \(|\eta| \sim 2.0\). For most central events, the efficiency varies from 60% to 35%. Fig. 5.46 shows the efficiency as a function of occupancy bin in different \(\eta\) region. The efficiency decreases with the occupancy bin and this effect is most obvious for the high \(\eta\) region \((1.9 < \eta < 2.0)\). Fig. 5.47 shows the secondary rate as a function of \(\eta\) in different occupancy bins. The secondary rates shows no occupancy dependence and vary from 2% to 4% from middle to high rapidity region. Fig. 5.48 shows the fake rate as a function of \(\eta\) in different occupancy bins. The fake rates have a very strong occupancy dependence at \(|\eta| > 1.0\) region. For low occupancy events, the fake rates are less than 1% in whole \(\eta\) region. For high occupancy events, the fake rates are also below 1% in \(|\eta| < 1.0\), but rise to 10% at the edge \(|\eta| \sim 2.0\). The out of kinematics rates are only important at the two edge bins.
where reconstructed pixel tracks are matched to true particles with $|\eta| > 2.0$. They are around 3% for the two edge $\eta$ bins, one on each side, while the angular precision of the pixel detector implies that all other bins have zero correction. The difference between MC re-weighted ratios and those without MC re-weighting process is less than 4%.

![Figure 5.45: Efficiency calculated from HIJING with physics flow samples for pixel tracking method. The histogram is organized similarly to figure 5.41.](image)
Figure 5.46: Efficiency of pixel tracks as a function of occupancy bin in different $\eta$ range. Filled points show $0.0 < \eta < 0.1$, filled squares show $0.5 < \eta < 0.6$, filled triangle show $1.0 < \eta < 1.1$, filled inverted triangle show $1.5 < \eta < 1.6$ and open circles show $1.9 < \eta < 2.0$.

Figure 5.47: Secondary rate calculated from HIJING with physics flow samples for pixel tracking method. The histogram is organized as figure 5.41.
Figure 5.48: Fake rate calculated from HIJING with physics flow samples for pixel tracking method. The histogram is organized as figure 5.42.
5.1.5 Correction Procedure

To correct for the tracklet Method 1, each tracklet is evaluated with a weight:

\[ w_{\text{trkl}}(\eta) = \frac{1}{\epsilon_{\text{reco}}(\eta)} \] \hspace{1cm} (5.8)

To correct to tracklet Method 2, each tracklet is evaluated with a weight:

\[ w_{\text{trkl}}(\eta) = \frac{1}{\epsilon_{\text{reco}}(\eta)} \] \hspace{1cm} (5.9)

For pixel tracking, each tracklet is evaluated with the following weight:

\[ w_{\text{trk}}(\eta) = \frac{1 - r_{\text{sec}}(\eta) - r_{\text{fake}}(\eta) - r_{\text{okr}}(\eta)}{\epsilon(\eta)} \] \hspace{1cm} (5.10)

Because we focus on the 80% most central events, there are no events loss caused by our event selection, thus event-level corrections are not needed and not applied.

5.1.6 Systematic Uncertainties Estimate And Cross Checks

Later in this note we will see three methods with results consistent with each other within 2-4% from peripheral to central events, a factor of several hundred in particle density between the two extremes. We choose tracklet Method 1 as our primary method for the final results for the following reasons. Pixel tracks method has the largest correction among the three methods and the fake rate has very large occupancy dependence at large \( \eta \). Moreover, tracklet Method 2 requires layer one of pixel barrel to be flipped in
z direction and shifted in \( \phi \) direction to estimate combinatorial background. To get an accurate estimate bin by bin in each \( \eta \) bin, the layer-1 has to be symmetric with respect to the reconstructed primary vertex. Unfortunately, the disabled pixel modules make the detector asymmetric and can cause an overestimate of the background in the hole region and an underestimate of the background at the other side where the \( \eta \) value is reversed. Also, tracklet Method 2 ultimately subtracts two large numbers, which can introduce some non-trivial statistical fluctuations even with reasonable statistics. Thus, tracklet Method 1 is chosen as our primary method and the following systematic estimates are applied to it.

**MC detector description** Data sample with two more modules partially disabled than MC sample in layer-1 as noted in figure 5.24. We have 13\( \times \)38 modules in layer-1, these two modules corresponds at most \( 2/(13 \times 38) \sim 0.4\% \) difference of the acceptance, we quote this 0.4\% as MC-data acceptance difference uncertainty.

**Extra material** As mentioned in section 5.1.1.1, we use MC samples going through detector with extra material to study the inaccurate description of detector material response. The digitization is re-run with this detector description and the tracklet reconstruction algorithm is re-run with these samples to get correction factors on those samples. The ratio of final results corrected from extra material sample to that of nominal sample is shown is figure 5.49 for different centrality bins. The ratio is very flat along \( \eta \) direction deviates from unity by about 2\%. We assign the uncertainty caused by the description of detector material thus to
be ±2%.

**Figure 5.49:** Ratio of results corrected from extra material sample to that of nominal sample.

**Tracklet method cut** For tracklet methods, we vary our default $3 \sigma (N_\sigma = 3)$ cut to $1.5 \sigma (N_\sigma = 1.5)$. With this tighter cut, we expect much smaller combinatorics and also smaller reconstruction efficiency. While the correction factors of the two cuts differ by more than 20% to 30% from peripheral events to central events in high $\eta$ region, the change of final results is less than 1.0%, this is quoted as the cut uncertainty. Fig. 5.50 shows the correction factor for $1.5 \sigma$ (red square) and $3 \sigma$ (black point) cuts in different occupancy bins from MC samples. Fig. 5.51 shows the ratio of $1.5 \sigma$ result to $3 \sigma$ result for all the centrality considered here. From these two figures, we see that the tracklet results are stable with cut variations. When the correction factor change by more than 10% in mid-rapidity and 30% in high rapidity, the final results change by only about 1% for the most central events at high $\eta$ region. There are almost no changes to
the final results in peripheral centrality bins. The 1% is quoted as the uncertainty for the cut chosen for this analysis.

![Graph](image1)

**Figure 5.50:** Correction factor of 1.5 $\sigma$ cut (red square) to 3 $\sigma$ cut (black point) from tracklet Method 1 for the different occupancy bins obtained from MC samples.

![Graph](image2)

**Figure 5.51:** Ratio of 1.5 $\sigma$ result to 3 $\sigma$ result from tracklet Method 1 for the different centrality events.

$p_T$ re-weighting Although there are very big change in the $p_T$ spectrum before and after the $p_T$ re-weighting process, the $p_T$ re-weighting process introduces less than a 0.5% effect on the correction factor of tracklet
Method 1. This is understood as the independence of $p_T$ and $\eta$ variables. So the systematics caused by this procedure is estimate to be less than 0.5%.

**Hadron composition** We also study the systematics caused by the change of hadron composition. This uncertainty is estimated to be 0.9%, as shown in the appendix [D] so we assign 1% systematic for hadron composition.

**Enhanced $K_s$, $\Lambda$** For the possible enhancement of $K_s$ and $\Lambda$ decays at LHC, we study composition of the matched secondaries from pixel track method in HIJING sample. 50% to 25% matched secondaries from mid-rapidity to high rapidity are from $K_s$ and $\Lambda$ decays. Since we have 2% to 4% secondary efficiency from mid-rapidity to high rapidity, we will get 1% uncertainty if we double the composition of $K_s$ and $\Lambda$. 1% uncertainty is thus assigned for the enhanced $K_s$ and $\Lambda$ decay uncertainty.

**HYDJET sample** We have also generated, simulated and reconstructed samples based on HYDJET [113], another commonly-used heavy ion event generator. These samples have been used to evaluate correction factors as a systematic check. Two limitations of this sample should be pointed out. First, the bookkeeping of primary and secondary particles are wrong. Part of secondary particles are recorded as primary particles in this sample. Thus, correction factor obtained from this sample also correct for some secondaries. Fig 5.52 shows the layer-0 cluster composition as a function of true primary particles from HIJING.
(left) and HYDJET (right) sample. We can clearly see the change of the cluster composition. If the bookkeeping were correct, the secondaries ratio should be roughly the same for different samples. But for the HYDJET sample, some secondary particles are treated as primary particles, this artificially increases the value of x-axis and lower the value of y-axis of the secondary composition in the histogram, and thus makes the secondary ratio lower than the HIJING sample. Another noticeable difference is the unassociated clusters ratio, which are plotted as blue points in the histogram. They differ by more than 20% in the slope, which reflects HYDJET and HIJING have very different description of low momentum X-rays and electrons. Second, the sample

Figure 5.52: Cluster composition of layer-0 clusters as a function of true primary particles for HIJING (left) and HYDJET (right) sample. Black points denote clusters from primary particles, red points denote clusters from secondary particles, and blue points denote unassociated clusters.

underestimates the charged particle production. The highest $dN/d\eta$ in mid-rapidity produced by this generator around is around 1400, so no correction factor can be obtained from this sample for central events. Fig. 5.53 shows the ratio of results corrected from HYDJET sample to that from the default sample. Because the wrong bookkeeping of this
generator, 5% difference is expected solely from this effect. This is also noticed in the figure where in peripheral events (lower panel), the ratio stays at 1.05 and with no $\eta$ dependence (blue dashed line is plotted at 1.05). Taken out the 5% effect, other $\eta$ dependent difference between the two generators is taken as the systematic uncertainty. Red line in the figure shows the fitted variation as a function of $\eta$. For the most central events where HIDYJET provides no information, an extrapolation is used to obtain the systematic uncertainty, where the red line is plotted to show the extrapolated values. This $\eta$ dependent variation is understood as the different physics description of very low momentum X-rays and electrons, where HYDJET sample has much less than HIJING sample.

**Figure 5.53:** Ratio of results corrected from Hydjet to results corrected from the default sample (Black point). The blue dashed lines are plotted at a constant value 1.05, and the red lines show the fitted or extrapolated variation as a function of $\eta$.

**Analysis methods** The difference of three different methods are shown in the figure 6.1 and 6.2. The difference is taken as the systematics from
Table 5.5: Summary of the various sources of systematic uncertainties and their estimated impact on the \(dN_{ch}/d\eta\) measurement in central (0-10%) and peripheral (70-80%) Pb+Pb collisions. Only the uncertainty due to the choice of the event generator is \(\eta\)-dependent.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (0-10%)</th>
<th>(70-80%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC detector description</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Extra material</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>(\Delta R) cut</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>(p_T) re-weighting</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Hadron composition</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Enhanced (K_s, \Lambda)</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>HYDJET</td>
<td>0.5-7.5% vs. (\eta)</td>
<td>0%</td>
</tr>
<tr>
<td>Analysis Method</td>
<td>3.5%</td>
<td>1%</td>
</tr>
<tr>
<td>Combined ((\eta = 0))</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>Combined ((\eta = 2))</td>
<td>8.5%</td>
<td>3%</td>
</tr>
</tbody>
</table>

The total contribution is also shown in this table. We can see that the total systematic uncertainty is around 4% and 3% at mid-rapidity and 8.5% and 3% at high rapidity for most central and most peripheral centrality bin considered here correspondingly.

The following two cross checks are also performed to check the stability of the results. These cross checks demonstrate excellent stability of the analysis and the results.

**Detector stability** Results from different runs are also compared with each other to check the stability of the results. Fig. 5.54 shows the ratio of
Run169884 to Run169866 in different centrality bins. The ratios do not have an $\eta$ dependence and the overall change is less than 2%. Because this run has two more modules enabled than the default run in layer one, a private produced MC sample with the correct pixel detector map is used for the efficiency study.

**Figure 5.54:** Ratio of Run169866 results to the default run results in different centrality bins.

**Pixel cluster counting method** A simple pixel layer-0 cluster counting algorithm is also performed for the multiplicity measurement. The algorithm cleans the clusters with low energy loss cut and then apply the correction factor obtained from MC samples to data. The ratio of pixel counting results to tracklet Method 1 results is shown in figure. The difference between the two methods is around 1% flat in $\eta$ for peripheral events, and around 2% for central events with a small $\eta$ dependence.
Figure 5.55: Ratio of pixel cluster counting method to tracklet Method 1 results in different centrality bins.
5.2 Open Heavy Flavor Suppression Measurement

5.2.1 Samples And Event Selection

5.2.1.1 Data And MC Samples

The experimental data used for this analysis was taken in 2010 during LHC heavy ion runs. All data suitable for physics analysis taken with inner detector magnetic field on are used in this analysis. In total, there are 39 runs corresponding to about $8 \mu b^{-1}$ integrated luminosity.

The Monte Carlo samples used for heavy ion analysis are PYTHIA (114) di-jet embedded with HIJING samples. The J0 to J5 di-jet samples, referred to as the JX di-jet samples, are sampled with non-overlapping parton transverse momenta $\hat{p}_T$. Table 5.6 shows the samples used and their properties.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of events</th>
<th>Cross section (nb)</th>
<th>$\hat{p}_T$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>560000</td>
<td>1.5749e+05</td>
<td>$17 &lt; \hat{p}_T &lt; 35$ GeV</td>
</tr>
<tr>
<td>J2</td>
<td>800000</td>
<td>7086.8</td>
<td>$35 &lt; \hat{p}_T &lt; 70$ GeV</td>
</tr>
<tr>
<td>J3</td>
<td>799950</td>
<td>257.91</td>
<td>$70 &lt; \hat{p}_T &lt; 140$ GeV</td>
</tr>
<tr>
<td>J4</td>
<td>797999</td>
<td>5.8475</td>
<td>$140 &lt; \hat{p}_T &lt; 280$ GeV</td>
</tr>
<tr>
<td>J5</td>
<td>799900</td>
<td>0.061206</td>
<td>$280 &lt; \hat{p}_T &lt; 560$ GeV</td>
</tr>
</tbody>
</table>

5.2.1.2 Event Selection

The following event selection criteria are applied to select good events for physics analysis:
1. Good lumi block provided by the data quality group.

2. Pass ZDC\_AND trigger or ZDC\_A\_C trigger.

3. A valid time recorded by both MBTS A and C, $time_A \neq 0 \land |time_A| \neq 75$ and $time_C \neq 0 \land |time_C| \neq 75$.

4. A MBTS A-C time difference, $\Delta t_{MBTS} \equiv |time_A - time_C|$, less than 3 ns, $\Delta t_{MBTS} < 3.0$ ns.

5. A reconstructed primary vertex.

In total, 53236871 minbias Pb+Pb events are selected for this analysis.

5.2.2 Data Analysis

5.2.2.1 Overview Of Muon Reconstruction Algorithms

Both inner detector and muon spectrometer are used for the muon reconstruction in ATLAS. There are four kinds of muon candidates depending on the way they are reconstructed: stand-alone muon, combined muon, segment tagged muon and calorimeter tagged muon.

**Stand-alone muon:** The muon trajectory is reconstructed in the Muon Spectrometer. The properties of muon candidates are updated by extrapolating the spectrometer trajectory back to the beam line. The parametrized energy loss as a function of momentum and rapidity of the muon in the calorimeter is taken into account in the extrapolation to have a more accurate measurement of the momentum at the interaction point.
**Combined muon:** The Stand-alone muon is combined with the inner detector track to have more precise measurement of muon parameters. The combined fitting of inner detector track and stand-alone muon also provide information about the impact parameters of the muon trajectory with respect to the primary vertex.

**Segment tagged muon:** An inner detector track is identified as a segment tagged muon if the track extrapolated to the Muon Spectrometer can be associated with straight track segments in the precision muon chambers.

**Calorimeter tagged muon:** An inner detector track is identified as a calorimeter tagged muon if the associated energy deposition in the calorimeter is compatible with the hypothesis of a minimum ionizing muon.

There are two muon reconstruction chains: ‘muid’ and ‘staco’. For this analysis, we use ‘muid’ muons as the input.

### 5.2.2.2 Muon Selection

As noted above, the ‘muid’ muons are used for this analysis. To select quality muons for physics analysis, the following criteria are applied:

1. Combined muon

2. $p_T > 4 \text{ GeV}, |\eta| < 2.5$

3. Number of pixel hits greater or equal to one

4. Number of B layer hits greater or equal to one
5. Number of SCT hits greater or equal to seven

6. The sum of pixel holes and SCT holes less than two

7. No SCT holes

8. $|d0_{PV}| < 5 \text{ mm}, |z0_{PV}| < 5 \text{ mm}$

9. Momentum measured by ID $p_{id} > 3 \text{ GeV}$, momentum measured by MS $p_{me} > 0.1 \text{ GeV}$

10. Match $\chi^2/\text{ndof} < 10$

With the above selection criteria, 480097 muons are selected as good muons.

Table 5.7 shows the number of selected muons in each run. The left panel of

\begin{table}[h]
\begin{center}
\begin{tabular}{rrrr}
Run & # of muons & Run & # of muons & Run & # of muons \\
168665 & 149 & 169566 & 7929 & 169964 & 5704 \\
168726 & 10 & 169567 & 4388 & 169966 & 5085 \\
168759 & 596 & 169627 & 22479 & 170002 & 31721 \\
169045 & 4673 & 169648 & 4034 & 170004 & 25882 \\
169136 & 10495 & 169693 & 24352 & 170015 & 14258 \\
169175 & 23352 & 169750 & 12280 & 170016 & 13530 \\
169206 & 11513 & 169751 & 5972 & 170080 & 1723 \\
169207 & 4670 & 169765 & 10012 & 170082 & 8923 \\
169223 & 22388 & 169783 & 1902 & 170398 & 23747 \\
169224 & 2818 & 169839 & 12168 & 170432 & 3971 \\
169226 & 16122 & 169864 & 14083 & 170459 & 15268 \\
169270 & 18439 & 169927 & 32197 & 170467 & 20894 \\
169564 & 7569 & 169961 & 19301 & 170482 & 19161 \\
\end{tabular}
\end{center}
\caption{Number of selected muons in each run.}
\end{table}

figure 5.56 shows the luminosity from the LumiCalc vs the number of selected muons. And the line shows a linear fit of the data. The right panel shows the number of muons per luminosity as a function of the run number and
the line shows a constant fit to the data. Except for a few runs that suffer a tiny fraction loss for unsuccessful jobs on the grid, the two scales with each other very well.

**Figure 5.56**: Left: Luminosity from LumiCalc vs the number of muons selected. The line shows a linear fit line. Right: Number of muons per luminosity vs the run number. The line shows the data fitted to a constant.

Figure 5.57 shows the $\eta$ and $p_T$ distribution of the selected muons. For the $\eta$ distribution, the small inefficiency at $\eta \sim 0$ is caused by the absence of muon detector and the small inefficiency at $|\eta| \sim 1.1$ is because the transition from barrel to endcap. We also see the decrease of muon yield as we go to higher $\eta$ region because we have more material there. For the $p_T$ spectrum, we can see the contribution of $W \to \mu \nu$ at higher $p_T$ values. In this analysis, we constrain the $|\eta| < 1.05$ where the analysis technique is well understood and $4 < p_T < 14 GeV$, where the $W \to \mu \nu$ contamination is much less than 0.1%.
Figure 5.57: Left: $\eta$ distribution of the selected good muons. Right: $p_T$ distribution of the selected good muons.

Figure 5.58 shows the mean and root mean square error (rms) of composite variable (which will be explained later) as a function the run number. It shows the stability of the run conditions.

Figure 5.58: The mean (black points) and rms (red squares) of composite variable as a function of the run number.

Figure 5.59 shows the muon multiplicity distribution in the centrality interval 0-10%. About 2% events with more than one muons.
With the muon selection criteria described above, we can use MC samples to estimate the muon reconstruction efficiency for muons decayed from heavy flavor hadrons. Figure 5.60 shows the muon reconstruction efficiency as a function of $p_T$ in different centrality intervals. We can see that there is very small dependence on centrality and it reaches the plateau very quickly as a function of $p_T$. For the plateau region starting from 5 GeV, we fit a constant line to it. Table 5.8 shows the efficiency values and their relative uncertainties in different $p_T$ and centrality intervals.

### 5.2.2.3 Discriminants For The Analysis

The main goal of this analysis is to separate prompt muons from the muons coming from $\pi/K$ decay in flight and to study the heavy flavor production in heavy ion collisions. The possible backgrounds in the prompt muons are muons from electroweak bosons and light mesons. At transverse momen-
Figure 5.60: Prompt muon reconstruction efficiency vs $p_T$ in different centrality intervals.

Table 5.8: Prompt muon reconstruction efficiencies and their relative uncertainties in different $p_T$ and centrality intervals.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Efficiency</th>
<th>Rel. uncertainty (%)</th>
<th>Efficiency</th>
<th>Rel. uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>63.8%</td>
<td>2.7</td>
<td>78.5%</td>
<td>1.9</td>
</tr>
<tr>
<td>10-20%</td>
<td>64.0%</td>
<td>3.6</td>
<td>79.9%</td>
<td>1.8</td>
</tr>
<tr>
<td>20-40%</td>
<td>68.4%</td>
<td>3.0</td>
<td>79.0%</td>
<td>1.8</td>
</tr>
<tr>
<td>40-60%</td>
<td>66.1%</td>
<td>3.5</td>
<td>78.9%</td>
<td>1.9</td>
</tr>
<tr>
<td>60-80%</td>
<td>66.8%</td>
<td>3.1</td>
<td>79.5%</td>
<td>1.6</td>
</tr>
</tbody>
</table>
tum below $\sim 30$ GeV, electroweak boson production is a negligible source of prompt muons \(^{(115)}\). At transverse momentum greater than 4 GeV, promptly decaying light mesons, such as $\phi \rightarrow \mu^+\mu^-$ is negligible compared to the much larger contribution from b and c quarks. We can therefore associate prompt muons with heavy flavor production in heavy ion collisions. We should be aware of that the $\pi/K \rightarrow \mu$ component is a subset of the light flavor production and its rate is strongly depending on the track quality imposed on the reconstructed muons. And there is no good way to estimate the efficiency of this source.

Based on their different kinematics and interaction with materials in calorimeter, two independent discriminants can be used. One is the momentum balance and the other is the scattering angle significance, both of which will be explained in the following text. Because pions and kaons have relatively long lifetime, they may travel a large part of the detector before decaying into muons. Although the muon is emitted isotropically in the rest frame of the $\pi/K$, the angle between the decaying particle and the muon in the lab system are usually small due to the Lorentz boost and the small mass difference. Because of this, the tracker hits from the two particles may be associated to the same track, which will result in distorted track parameters and can be used for our analysis. Depending on the position they are decayed, $\pi/K$ decays can be divided into three categories:

\textbf{‘Early’ decays:} Decay before first inner detector ( $R \leq 50.5$mm from the beam line).

\textbf{‘Intermediate’ decays:} Decay between inner detector measurements ( $50.5 <
$R < 1082\text{mm from the beam line).}$

**‘Late’ decays:** Decay after the last inner detector measurement ($R \geq 1082\text{mm from the beam line).}$

Early decays are essentially indistinguishable from prompt muons, but they only contribute to a very small fraction given the probability of a decay at such short distance. Their contribution can be estimated with statistical methods described later. For intermediate decays, both track quality selection criteria and their discontinuity in angle and momentum at the decay points give us good tools to discriminate them from prompt muons. The later decays are most likely from $\pi/K$s interacting with calorimeter, resulting in great difference in momentum balance.

As stated above, two independent discriminants can be applied for this analysis: momentum balance and scattering angle significance. Also the combination of the two: the composite discriminant can be used to better identity prompt muons.

**Momentum balance:** For early and intermediate decays, Some fraction of energy will be taken away by neutrinos. For late decays, pions and kaons hitting the calorimeter will be absorbed and only a small fraction of its energy can leak out to the muon spectrometer, resulting in a real muon produced in the calorimeter volume at much lower energy than the $\pi/K$s. So the track parameters measured by the inner detector which correspond to $\pi/K$s before the decays will be very different from track parameters measured in the muon spectrometer which correspond to muons after the decays. So the following discriminant is defined to
take this into account:

\[
\frac{\Delta p_{\text{loss}}}{p_{\text{ID}}} = \frac{p_{\text{ID}} - p_{\text{MS}} - p_{\text{param}(p_{\text{MS}}, \eta, \phi)}}{p_{\text{ID}}}
\]  

(5.11)

where \( p_{\text{ID}} \) is the track momentum measured by the inner detector, \( p_{\text{MS}} \) is the track segment momentum measured by the muon spectrometer and \( p_{\text{param}(p_{\text{MS}}, \eta, \phi)} \) is the parametrized estimation of the minimum ionizing energy loss by a muon crossing the material in the calorimeter, which is a function of \( p_{\text{MS}}, \eta \) and \( \phi \). The parametrized estimation is preferred to the measured energy in the calorimeter because muons considered are usually not isolated.

**Scattering angle significance:** The least-squares track fit includes scattering angle parameters to account for Coulomb scattering in the traversed material. Between the first inner detector measurement and the muon spectrometer, there are approximately 16 scatters. For the inner detector these scatters are mainly at detector layers, where the scattering angles are typically an order of magnitude smaller than the maximum pion decay angle. A decay will in general lie between two measurements, thus two consecutive same sign scattering angle outliers are indicative of a possible decay. A non-zero scattering angle sum in the bending plane is equivalent to a change in curvature. For each scattering center \( i \), the expectation value of the change in angle due to multiple scattering \( (\phi_{\text{msc}})^i \) is evaluated in the same way as in the track fitting using the parametrization described in (116). The signed
residual from the track fitting is defined as:

$$s_i = \frac{q}{\phi_{msc}} \Delta \phi_i$$  \hspace{1cm} (5.12)

where $q$ denote the charge of muon track and $\Delta \phi_i$ is the change in angle measured at scattering center i. At each scattering angle center k, we can define the following variable:

$$S(k) = \frac{1}{\sqrt{n}} \left( \sum_{i=1}^{k} s_i - \sum_{j=k+1}^{n} s_j \right)$$  \hspace{1cm} (5.13)

where n is the total number of scattering centers. Then the scattering angle significance is defined as:

$$S = \max\{|S(k)|, k = 1, 2...n\}$$  \hspace{1cm} (5.14)

It can be found by checking over all the scattering centers of the track trajectory and find the one with the biggest absolute scattering angle change, which is the scattering angle significance.

It approximately takes a 3 GeV muon to penetrate the calorimeter and make a track in the muon spectrometer, the differences in momentum balance between pion decays and prompt muon is too small for the discriminant to be useful for tracks with $p_T < 4$ GeV. And the small mass difference between a $\pi/K$ and a $\mu$ implies that the decay is usually only noticeable as a change in the direction of the track for low momentum particles, so the scattering angle significance discriminant is very useful.
in low momentum region.

**Composite discriminant:** To better differentiate between prompt muons and muons from $\pi/K$ decays, we can use the combination of the above two discriminant:

$$c(r) = \left| \frac{\Delta p_{\text{loss}}}{p_{\text{ID}}} \right| + r|S|$$

(5.15)

where $r$ is the combination coefficient. It was selected by optimizing the separation:

$$s(r) = \int_{-\infty}^{\infty} \frac{(f_{\text{prompt}}(c(r)) - f_{\pi/K}(c(r)))^2}{f_{\text{prompt}}(c(r)) + f_{\pi/K}(c(r))} dc$$

(5.16)

of the composite distribution $c(r)$ for prompt and non-prompt muons in the simulation sample. $f_{\text{prompt}}(c(r))$ denotes the normalized probability density function of composite distribution for prompt muons and $f_{\pi/K}(c(r))$ is the corresponding function for $\pi/K$. The optimization detail can be found in (17). Figure 5.61 shows the optimization of composite distribution. It is very clear from the figure that we can obtain maximum separation between prompt and non-prompt muons at $r = 0.07$. So in this analysis, $r$ is fixed at 0.07.

Figure 5.62 shows the momentum balance distribution in different centrality intervals and in centrality integrated interval (0-80%) for both signal and background muons with momentum in 5 – 6 GeV range. We can clearly see the difference in the signal and background distribution. The signal is more symmetric around 0 where the background distribution is centered around 0.2. Also, we can see there is very little centrality dependence on the
distribution of both signal and background distributions.

Figure 5.61 shows the scattering angle significance distribution in different centrality intervals and in centrality integrated interval (0-80%) for both signal and background. We can see two different distributions for signal and background, but the separation power is not as good as the momentum balance in this low $p_T$ bin. It also explains why the weight for scattering angle significance in the composite distribution is very small (0.07). We also show the scattering angle significance distribution for muons in 10–14 GeV momentum range in figure 5.64. The scattering angle significance has some good separation between signal and background for higher $p_T$ muons.

Figure 5.65 shows the composite distribution of muons with momentum in the range 5 – 6 GeV in different centrality intervals and in centrality integrated interval for both signal and background from MC.
Figure 5.62: Momentum balance distribution in different centrality intervals and in centrality integrated interval for both signal and background for 5 – 6 GeV muons.

5.2.2.4 Template Fitting Procedure

To get the prompt muon fraction in the data, we first have to build templates (probability density functions) for both prompt muons and non-prompt muons from Monte Carlo samples. The JX di-jet samples are used for this purpose. The kernel estimation method (117) is used to build the un-binned probability density function for the two components in different $p_T$ ranges. This is an un-binned non-parametric method where each input point is treated as a gaussian distribution. Figure 5.66 shows the composite distribution in different centrality intervals for muons at $4 < p_T < 5$ GeV. The left histogram
Figure 5.63: Scattering angle significance distribution in different centrality intervals and in centrality integrated interval for both signal and background for 5 – 6 GeV muons.

shows the b/c quark to muon decays and the right histogram shows the π/K to muon decays. The dependence of composite shape on centrality is very small, so the templates are built for muons in different $p_T$ intervals. We also checked the results obtained from templates that are built for each $p_T$ and centrality interval. These templates are built with lower statistics because there are more bins. We found the results are consistent with templates built from integrated centrality interval.

With the templates in different $p_T$ ranges, the data were split into different subsets according to the $p_T$ and centrality values of muons and the subsets
Figure 5.64: Scattering angle significance distribution in centrality integrated interval for both signal and background for 10 – 14 GeV muons.

were fitted to the corresponding templates. Let $S_{pdf}$ denotes the probability density function for the signal component, $B_{pdf}$ denotes the probability density function for the background component and $R$ denotes the ratio of signal component, then the composite density distribution of data samples ($C_{pdf}$) can be written as:

$$C_{pdf}(\text{composite}, R) = RS_{pdf} + (1 - R)B_{pdf}$$  \hspace{1cm} (5.17)

With the measured composite values from data samples, we can construct a likelihood function:

$$\mathcal{L}(R) = \prod_{i=1}^{N} C_{pdf}(\text{composite}_i, R)$$  \hspace{1cm} (5.18)

It can be seen from equation (5.18) that $\text{composite}_i$ are measured from data,
Figure 5.65: Composite distribution in different centrality intervals and in centrality integrated interval for both signal and background for 5 – 6 GeV muons.

$S_{pdf}$ and $B_{pdf}$ are built from Monte Carlo samples, so the only unknown is the signal ratio $R$. In order to get the signal ratio $R$, we have to maximize the maximum likelihood function ($L(R)$). The detail of this is carried through “RooFit” package (118), which uses “MINUIT” fitting package to do the actual fitting (119).

5.2.2.5 Template Building Comparison

As stated above, the kernel estimation can be used to build templates. It suffers from statistical fluctuations so that the templates from this method
Figure 5.66: Composite distribution in different centrality intervals for muons with $4 < p_T < 5$ GeV. The left histogram shows muons from b/c quark hadrons and the right histogram shows muons from $\pi/K$ decays.

is not very smooth. As an alternative, we also used parameterized methods to build templates. In parametrized methods, we define a functional form for the template with several parameters to be valued. We then fit the template to MC samples to get the values of those parameters. For example, one functional form we used is landau distribution convoluted with gaussian distribution:

$$pdf \propto Landau(\mu_l, \sigma_l) \otimes Gauss(\mu_g, \sigma_g)$$

(5.19)

By fitting to the MC samples, we can get the unknown parameters ($\mu_l$, $\sigma_l$, $\mu_g$, $\sigma_g$) for both signal and background contributions. We have tried several parameterized functions, Landau $\otimes$ Gauss, Gauss $\otimes$ Gauss and Gamma $\otimes$ Gauss. Figure 5.67 shows the comparison of templates built from different methods in different $p_T$ intervals for both signal and background contributions. The MC points are also overlaid with the templates. Each panel shows both signal and background components in a specific $p_T$ range. For the signal component, the MC points (black circles), the template from ker-
nel estimation method (red solid line), the template from Landau $\otimes$ Gauss method (blue solid line), the template from Gauss $\otimes$ Gauss method (blue dashed line), and the template from Gamma $\otimes$ Gauss (grey solid line) are shown. For the background component, the MC points (red squares), the template from kernel estimation method (magenta solid line), the template from Gauss $\otimes$ Gauss method (black solid line) and the template from Gamma $\otimes$ Gauss (black dashed line) are shown in each panel. The templates built from kernel estimation method has wiggles here and there for both signal and background in all $p_T$ intervals. For the signal templates, the Landau $\otimes$ Gauss and Gamma $\otimes$ Gauss methods show good agreement to the kernel estimation method and is smooth in all regions. But the templates from Gauss $\otimes$ Gauss have large offset at $\text{composite} = 0$, which is not a desired feature. We use templates built from Gamma $\otimes$ Gauss parametrization as an alternative to the kernel estimation method to cross check the final results. From the histograms, we can also see that parametrized methods can not describe the background very well, so there is no further attempt to use parametrized templates.

5.2.2.6 Shift, Stretch And Smear Effect

By using the kernel estimation methods described above, we have templates built from MC samples. In order to incorporate the uncertainty in shape between data and simulation, the templates are extended with two fitted parameters that model detector effects which are not present in MC simulation. A shift parameter is added to account for uncertainty in the momentum scale (‘shift’), a stretch parameter is added to account for the global broad-
Figure 5.67: Templates built from different methods for signal and background composite distributions in different $p_T$ intervals. The MC points are also overlayed with the templates.
ening/narrowing of the distribution (‘stretch’) and convoluting the template with a gaussian distribution describes a worsening of the momentum resolution (‘smear’). Mathematically, the shift and stretch can be taken into account by the following procedure: instead of evaluating the pdf at the normal composite value, we evaluate the pdf at the following shifted and stretched composite value:

\[
\text{composite}(\text{shift}, \text{stretch}) = \frac{\text{composite} - \text{mean}}{\text{stretch}} + \text{mean} - \text{shift}
\]  

(5.20)

where the left hand side is the new composite value with shift and stretch taken into consideration, \text{composite} is the normal composite value, \text{mean} is the mean value of the composite pdf, and \text{stretch} and \text{shift} are the parameters introduced above. The smear effect is estimated mathematically by convoluting pdf with and gaussian distribution with zero mean and unknow sigma, the smear parameter. This can be written as:

\[
\text{pdf}(\text{composite}(\text{shift}, \text{stretch})) \otimes \text{gauss}(0, \text{smear}).
\]  

(5.21)

So in the fitting procedure, there are four unknowns: prompt muon fraction, shift parameter, stretch parameter and smear parameter. Figure 5.68 to figure 5.70 shows the shift, stretch and gaussian smear parameter as a function of \( p_T \) in different centrality intervals. The shift parameters are around 0.02 and are very stable in different \( p_T \) intervals in different centrality bins. There are about 5% stretch from the fitting. And the gaussian widths are around 0.002. The results from the fitting with shift, stretch and smear effects taken
Figure 5.68: Shift parameter vs $p_T$ in different centrality intervals.

into account are our default results.

5.2.2.7 Fitting to the data

Figures 5.71 to 5.75 show the data composite distribution in different $p_T$ intervals in five centrality intervals between $|\eta| < 1.05$ along with the fittings described above. The data are plotted as black points, the fitted data are plotted as black lines, the fitted signal components are plotted as blue lines and the fitted background components are plotted as green lines. It can be seen from the histograms that the overall fittings are very good.

5.2.3 Total Uncertainties And Cross Checks

In this section, we will summarize the uncertainties on the prompt muon fraction. The parameter error from the fitting procedure, the finite Monte Carlo
Figure 5.69: Stretch parameter vs $p_T$ in different centrality intervals.

Figure 5.70: Gauss smear parameter vs $p_T$ in different centrality intervals.
Figure 5.71: Data composite distributions along with template fittings in different $p_T$ intervals in 0−10% centrality bin. The data are plotted as black points, the fittings to data are plotted as black lines, the fitted signal components are plotted as blue lines and the fitted background components are plotted as green lines.
Figure 5.72: Data composite distributions along with template fittings in different $p_T$ intervals in 10 – 20% centrality bin. The data are plotted as black points, the fittings to data are plotted as black lines, the fitted signal components are plotted as blue lines and the fitted background components are plotted as green lines.
Figure 5.73: Data composite distributions along with template fittings in different $p_T$ intervals in 20 – 40% centrality bin. The data are plotted as black points, the fittings to data are plotted as black lines, the fitted signal components are plotted as blue lines and the fitted background components are plotted as green lines.
Figure 5.74: Data composite distributions along with template fittings in different $p_T$ intervals in 40 − 60% centrality bin. The data are plotted as black points, the fittings to data are plotted as black lines, the fitted signal components are plotted as blue lines and the fitted background components are plotted as green lines.
Figure 5.75: Data composite distributions along with template fittings in different $p_T$ intervals in 60–80% centrality bin. The data are plotted as black points, the fittings to data are plotted as black lines, the fitted signal components are plotted as blue lines and the fitted background components are plotted as green lines.
statistics, $\pi/K$ compositions and the difference in the fitting results by removing the shift, stretch and smear parameters, are studied for this purpose. The effect from those sources are combined quadratically as the uncertainty on the prompt muon fraction, which is shown both in the table 6.2 and in the figure 6.6.

**Parameter error from the fitting procedure** The signal ratio is extracted by a maximum likelihood method, which also gives a confidence interval for the fitted parameter. This error incorporates both the uncertainty from the fitting procedure and the statistical uncertainty from the limited data samples. In the most peripheral interval 60-80%, this error exceeds 10% in the 9 to 10 $p_T$ interval where the data statistics is the lowest. Figure 5.80 shows this uncertainty as a function of muon momentum in different centrality intervals. This uncertainty is mainly caused by the limited data statistics.

**Finite Monte Carlo statistics** The finite statistics in simulation samples create an uncertainty of the shape of the probability for the discriminant which was used as the template in the fitting. By randomly distributing an equal number of muons as was used to build the original template, according to its probability density function, a distribution similar to the original probability function was generated. The new distribution was then used to build an alternative template and was used to fitted to the data to five a new estimation of the signal ratio $R$. This procedure was repeated by 8 times for every original template fit, and the root mean square was used as a systematic uncertainty to
account for the effect from the finite MC sample size. In general, this uncertainty is around 1% and can be as high as 2% in a few bins, which is much smaller than the uncertainty from the parameter of the fitting. Figure 5.77 shows the uncertainty from the limited MC statistics. This uncertainty together with the one from the fitting error introduced above are combined quadratically as the statistical uncertainty on the prompt muon fraction.

π/K composition The uncertainty on the relative fraction of π/K in the real data gives additional source of the uncertainty on the prompt muon fraction. This effect is estimated by doubling the contributions of π and K separately in the simulation and deriving new templates with the modified π and K composition. The new templates are then used to
Figure 5.77: Uncertainty from the limited MC statistics as a function of $p_T$ in different centrality intervals.

fit to the data to obtain the signal fraction in the data samples. The difference of signal ratio obtained by this and the default ones is taken as the systematic uncertainties. This effect is evaluated per template fit. In general, this effect is less than 1%, but at the lowest $p_T$ interval $4 < p_T < 5$ GeV, this can be as high as 3%. Figure 5.78 and figure 5.79 shows the uncertainty from the $\pi/K$ composition.

**Template fit without shift, stretch and smear parameters** Compared with template fitting without any shift, stretch and smear effects, the prompt muon fraction will systematically increase in each $p_T$ intervals and in each centrality intervals with templates taking the shift, stretch and smear parameters into the fitting procedure. Since we do not know for sure whether we should include these parameters in the fitting, the differences in the prompt muon fraction from the fitting
Figure 5.78: Uncertainty from the pion composition as a function of $p_T$ in different centrality intervals.

Figure 5.79: Uncertainty from the kaon composition as a function of $p_T$ in different centrality intervals.
without any extra parameters and the one from the fitting with all the three parameters are taken as a systematic uncertainty. This is the biggest contribution to the total uncertainties. Figure 5.80 shows this uncertainty as a function of $p_T$ in different centrality intervals. This uncertainty together with the uncertainty from the $\pi/K$ composition are combined quadratically as the systematical uncertainties for the prompt muon fraction. When the difference is taken as uncertainty, we can see from the above figure that the values are wiggling around. So we smooth the uncertainty as a function of centrality in each $p_T$ intervals. For the 4 – 5 GeV bin, the error is very smooth, so no attempt is made to smooth it. For 5 – 6 GeV bin, the error is taken as a constant at 5%. For 6 – 7 GeV bin, the error is taken as a constant at 7.5%. For 7 – 8 GeV bin, the error is taken as 5% for 0-60% centrality interval.
and 14\% for 60-80\% centrality interval. For 8 – 9 GeV bin, the error is 
taken as 4\% for 0-60\% centrality interval and 7\% for 60-80\% centrality 
interval. For 8 – 9 GeV and 9 – 14 GeV bins, the error is taken as a 
constant at 4\%.

**Simple cut and count method** Except from the elaborate fitting method, 
we also tried a simple cut and count method. In this method, we define 
a composite cut value (denoted as $Cut$) and estimate the fraction of 
muons that have composite value greater than $Cut$ for both signal and 
background components from the kernel estimated pdfs. We denote 
these fractions as $f_s$ and $f_b$ respectively. Then from the data, we count 
the total number of muons ($N_{total}$) and the number of muons that have 
composite value greater than the $Cut$ ($N_{cut}$). If we denote the number 
of prompt muons and non-prompt muons in data samples as $N_s$ and 
$N_b$ respectively, then we can have the following two equations:

\[
N_{total} = N_s + N_b \tag{5.22}
\]

\[
N_{cut} = N_s f_s + N_b f_b
\]

The prompt muon fraction $R$ then can be calculated as $R = N_s/N_{total}$.

Three different cut values are used to estimate $R$: $Cut = 0.25, 0.20, 0.15$.
The results are averaged and the RMS are taken as the errors for this 
method. Figure 5.81 shows the results from the simple cut and count 
method compared with the results from the kernel estimation method.
without shift, stretch and smear effects. Results from the simple cut and count method are denoted with red squares and results from kernel estimation method are denoted with black points. The error bars on kernel estimation method including all the uncertainties except from the uncertainties coming from shift, stretch and smear effects. From the histograms, we can see very good agreements between these two methods. The difference is taken as systematics. They are on the order of 1%, except for a few peripheral bins, they can be as high as 5%.

Table 5.9 shows a summary of different contribution of systematical uncertainties in two $p_T$ bins and two centrality bins. We can clearly see the biggest contribution is from the fitting with or without taken shift, stretch and smear into consideration. In this table, the uncertainty from muon reconstruction efficiency is also shown, although this is not the uncertainty applied for prompt muon fraction but for the overall muon yields and subsequent ratios among the muon yields. The statistical uncertainties described above are not shown in this table. The statistical and systematical uncertainties are combined quadratically to form the total uncertainties on the prompt muon fraction.

We also performed some cross checks to check the results of this fitting analysis.

**Results from parametrized methods** We also use signal template built from parametrized method: Gamma$\otimes$Gauss as a cross check. By using the templates for prompt muons from the parametrized method and
Figure 5.81: Prompt muon fraction $R$ as a function of $p_T$ in different centrality intervals from the simple cut and count method (red square) and the kernel estimation method without shift, stretch and smear effects (black points).
Table 5.9: Different source of systematics that are relevant for this analysis.

<table>
<thead>
<tr>
<th>$p_T$</th>
<th>Centrality</th>
<th>Systematics (%)</th>
<th>Template</th>
<th>Cut</th>
<th>$\pi/K$</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 – 5</td>
<td>0-10%</td>
<td>4 0 5</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>7 – 8</td>
<td>0-10%</td>
<td>5 0.5 0.5</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>10 – 14</td>
<td>60-80%</td>
<td>18 1 1</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>4 – 5</td>
<td>60-80%</td>
<td>14 5 0.5</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>10 – 14</td>
<td>60-80%</td>
<td>4 4 2</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

the templates for background muons from the default kernel estimation methods, we re-did the whole analysis and compare the results to those from the default kernel estimation method. Figure 5.82 shows the $R_{cp}$ as a function of $p_T$ for different centrality intervals from the default kernel estimation method and the parametrized method. We can see the parametrized method gives larger uncertainties. The two methods give results that are consistent with each other.

**MC closure test** We also did a MC closure test where half of the MC statistics is used for building the template and half of the MC is used as data to be fitted. The fitted value is then compared with the true values. Figure 5.83 shows the signal muon fraction as a function of $p_T$ from fitted methods and the truth. The error bar on the fitted value represents statistical uncertainty. We can clearly see the agreement of fitted values and the true values.

**Fitting momentum balance** As a double check, we also fitted the momentum balance distribution. Figure 5.84 shows the signal muon fraction from fitting composite and fitting momentum balance. We can clearly
Figure 5.82: Heavy flavor $R_{cp}$ as a function of muon transverse momentum $p_T$ in different centrality intervals from default kernel estimation method (black) and parametrized method (red).

Figure 5.83: Signal muon fraction as a function of $p_T$ from fitted methods (black points) and the true values (red squares). Left is in centrality interval 0-40% and right is in centrality interval 40-80%.
see the two results are consistent with each other.

5.2.4 \textit{p}+\textit{p} Baseline Analysis

5.2.4.1 Data Samples and Event Selection

The data of 2.76 TeV proton proton collisions taken in 2011 are taken as the baseline for a $R_{AA}$ measurement. In total there are four runs with this center of mass energy. Heavy Ion D3PD marker is run on the following four ESD datasets to get the D3PDs that are suitable for analysis:

1. data11_2p76TeV.00178163.physics_L1Muon.recon.ESD.f352/
2. data11_2p76TeV.00178211.physics_L1Muon.recon.ESD.f352/
3. data11_2p76TeV.00178229.physics_L1Muon.recon.ESD.f355/
4. data11_2p76TeV.00178264.physics_L1Muon.recon.ESD.f355/

From the name, we can see that those datasets are filtered with a L1 muon trigger. The event selection criteria are the following:

1. Good lumi block is required,
2. L1 Muon0 trigger is required to fire the event,
3. At least one reconstructed primary vertex is required.

5.2.4.2 MC Samples

The MC samples we used are the muon filtered di-jet Pythia samples from J1 to J5. The $p_T$ threshold placed upon muon for the event to be kept during
Figure 5.84: Signal muon fraction as a function of $p_T$ from fitting composite distribution (black points) and fitting momentum balance (red squares).
the event generating process is 3 GeV, that is every filtered event contains a muon with transverse momentum greater than 3 GeV. We filter events with muons above the selected $p_T$ threshold in order to increase the statistics of the MC samples without having to simulate events without the physics we are interested. Each sample contains 1M events. The names for the five samples on the grid are:

1. mc11_2TeV.147709.J1_pythia_jetjet_1muon_3Ptcut. 
   recon.NTUP_HI.e1581_s1310_s1300_r4060/

2. mc11_2TeV.119106.J2_pythia_jetjet_1muon_3Ptcut. 
   recon.NTUP_HI.e1581_s1310_s1300_r4060/

3. mc11_2TeV.147710.J3_pythia_jetjet_1muon_3Ptcut. 
   recon.NTUP_HI.e1581_s1310_s1300_r4060/

4. mc11_2TeV.147711.J4_pythia_jetjet_1muon_3Ptcut. 
   recon.NTUP_HI.e1581_s1310_s1300_r4060/

5. mc11_2TeV.147712.J5_pythia_jetjet_1muon_3Ptcut. 
   recon.NTUP_HI.e1581_s1310_s1300_r4060/

With the above MC samples, we can build the templates to fit the $p+p$ datasets and get the fraction of prompt muons in $p+p$ collisions. Table 5.10 shows the number of signal and background muons in each MC samples selected to build the templates. We can see that the signal muons are much more than the background muons because the filtering on muon enhances the muon composition in the event generator level, there are less $\pi/K$ composition in the generated stable particles.
Table 5.10: Number of signal and background muons selected for each di-jet MC samples.

<table>
<thead>
<tr>
<th>MC sample</th>
<th>Signal muons</th>
<th>Background muons</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>192009</td>
<td>1595</td>
</tr>
<tr>
<td>J2</td>
<td>323283</td>
<td>6013</td>
</tr>
<tr>
<td>J3</td>
<td>434038</td>
<td>14341</td>
</tr>
<tr>
<td>J4</td>
<td>517328</td>
<td>29117</td>
</tr>
<tr>
<td>J5</td>
<td>575448</td>
<td>56958</td>
</tr>
<tr>
<td>Total</td>
<td>2042106</td>
<td>108024</td>
</tr>
</tbody>
</table>

5.2.4.3 Muon Selection

The same muon selection criteria described in section 5.2.2.2 is used for the pp data. There is one more criterion required for the offline muons, they are required to match a Level one MU0 seed. With these selection criteria, the number of muons selected for this analysis is described in the following table 5.11.

Table 5.11: Number of muons selected for each run in 2.76 TeV proton proton collisions.

<table>
<thead>
<tr>
<th>Run number</th>
<th>Number of Muons</th>
</tr>
</thead>
<tbody>
<tr>
<td>178163</td>
<td>51081</td>
</tr>
<tr>
<td>178211</td>
<td>93290</td>
</tr>
<tr>
<td>178299</td>
<td>476361</td>
</tr>
<tr>
<td>178264</td>
<td>132332</td>
</tr>
<tr>
<td>Total</td>
<td>753064</td>
</tr>
</tbody>
</table>

The following figures 5.85, 5.86 give the raw distribution of MBTS timing difference of A and C side, raw $p_T$ distribution and raw $\eta$ distribution correspondingly after the event selection and muon selection criteria are applied. The MBTS timing difference distribution shows it is a very standard gaussian distribution without any extra bumps, which maybe exist if there
are satellite buches collisions in the selected data samples. The raw $p_T$ and $\eta$ distributions of selected muons reflect the composition of different muon sources and the detector geometry respectively.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure5.85}
\caption{Raw MBTS timing difference between A and C side from 2.76 TeV proton proton collisions. Only partial data are used for illustration purpose.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure5.86}
\caption{Left: Raw $p_T$ distribution of muons from 2.76 TeV proton proton collisions. Right: Raw $\eta$ distribution of muons from 2.76 TeV proton proton collisions.}
\end{figure}
5.2.4.4 Trigger Efficiency

As stated in the above, we use Level one MU0 trigger as our event selection, so there is an efficiency associated with this event selection. Multiple attempts are taken to estimates the Level one MU0 efficiency, but we are not successful due to limited statistics. Instead, we decide to use the trigger efficiency measured from 2010 7TeV $p+p$ collisions data as described in the conference note (18). Figure 5.87 shows the efficiency as a function of $p_T$ in mid-rapidity region. The black points show the measured trigger efficiency at each different $p_T$ range. Table 5.12 shows the trigger efficiency and their associated relative uncertainties in different $p_T$ ranges used for this analysis.

![Figure 5.87: L1_MU0 trigger efficiency as a function of $p_T$ measured in 2010 proton proton collisions at $\sqrt{s} = 2.76$ TeV. From (18).](image_url)
Table 5.12: Trigger efficiency and uncertainties used for this analysis.

<table>
<thead>
<tr>
<th>$p_T$ range</th>
<th>Trigger efficiency (%)</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 – 5 GeV</td>
<td>71</td>
<td>5</td>
</tr>
<tr>
<td>5 – 6 GeV</td>
<td>74</td>
<td>5</td>
</tr>
<tr>
<td>6 – 7 GeV</td>
<td>74</td>
<td>5</td>
</tr>
<tr>
<td>7 – 8 GeV</td>
<td>74</td>
<td>5</td>
</tr>
<tr>
<td>8 – 9 GeV</td>
<td>74</td>
<td>5</td>
</tr>
<tr>
<td>9 – 10 GeV</td>
<td>74</td>
<td>5</td>
</tr>
<tr>
<td>10 – 14 GeV</td>
<td>74</td>
<td>5</td>
</tr>
</tbody>
</table>

5.2.4.5 Reconstruction Efficiency

Because there is a difference in the setup of track reconstruction, we re-estimate the muon reconstruction efficiency in $p+p$ reconstruction setup by the MC samples mentioned above. Figure 5.88 shows the reconstruction efficiency of muons in the $p+p$ reconstruction setup. We can see the efficiency reaches plateau at around 6 GeV with efficiency around 85%, which is slightly higher than the heavy ion reconstruction setup (80%). Before the efficiency reaches plateau, it has value of 80% in 4 – 5 GeV and 84% in 5 – 6 GeV bin, respectively. The uncertainty on reconstruction efficiency is less than 1%.

5.2.4.6 Luminosity Measurements

The luminosity for $p+p$ collisions is determined from the 2011 van der Meer scans. For details, please refer to (120). The final measured values are:

$$\mathcal{L} = 200 \pm 6 \text{ nb}^{-1}$$ (5.23)
Figure 5.88: Muon reconstruction efficiency as a function of $p_T$ in $p+p$ reconstruction setup.

5.2.4.7 Templates Fitting

The same fitting procedure is used to fit $p+p$ data as that used in heavy ion data. We use di-jet J1 through J5 Monte Carlo samples to build templates, then the templates for signal and background are used to fit the data to get the prompt muon fraction in the data. Figure 5.89 shows the fitting results in different $p_T$ bins. We can see that the fitting works very well.

5.2.4.8 Uncertainties on $p+p$ measurement

The uncertainties on $p+p$ measurement is re-calculated based on the same consideration of heavy ion measurement. Figure 5.90 shows the systematics for each different contributions. As it was discovered in heavy ion data, the biggest contribution is from the fitting with or without shift, stretch and smear effect. Please refer to the section 5.2.3 for the detailed explanation.
Figure 5.89: Data composite distributions along with template fittings in different $p_T$ intervals for $p+p$ data. The data are plotted as black points, the fittings to data are plotted as black lines, the fitted signal components are plotted as blue lines and the fitted background components are plotted as green lines.
of each different contributions. Compared with the uncertainties from heavy ion data, all errors have been improved by more statistics from both data and Monte Carlo samples.

Figure 5.90: Systematic uncertainties from different sources. From top left to bottom right, the contributions are: 1) parameter error from the fitting procedure, 2) finite Monte Carlo statistics, 3) pion composition, 4) kaon composition, 5) template fitting without shift, stretch and smear effect, and 6) simple cut and count method. See 5.2.3 for explanation of each contribution.
6

Results

6.1 Charged Particle Multiplicity Measurement

Fig. 6.1 - 6.2 show the charged particle pseudo-rapidity distribution of the three methods for the eight most central bins from the three different methods. The histograms are arranged from central to peripheral bins, each with 10% coverage in centrality. The top panel of the histogram shows the $1/N_{evt} dN_{ch}/d\eta$ vs $\eta$ from three different methods, with tracklet Method 1 denoted by black points, tracklet Method 2 denoted by red squares, and pixel track method denoted by blue triangles. The bottom panel of the histogram shows the ratio of different methods, the red squares show the ratio of tracklet Method 2 over tracklet Method 1 ratio and the blue triangle shows the ratio of the pixel track method to tracklet Method 1. The eight centrality bins in those histograms are organized in the same way. We can see that the
three methods agree with each other within 2-4% for all bins from peripheral to central events except a few bins.

To further show how the three methods agree with each other, figure 6.3 shows the raw and corrected charged particle pseudo-rapidity distribution for the most central 10% events on the left panel. The top left panel is the raw distributions from three different methods, we can clearly see the big difference on raw values from three different methods. At the highest $\eta$ value measured here, Method 1 raw yield is more than two times of that given by pixel track method, and Method 2 also has raw yield almost three times of that given by pixel track method. The middle left and middle bottom panels show the corrected yields and their corresponding difference after the correction, this is also shown in the top left panel of figure 6.1. We can see that the corrected yields agree within 5% for most bins, although their raw values differ as much as three times. The right panel shows the corrected $dN_{ch}/d\eta$ distributions from tracklet Method 1 for different centrality bins. The statistical uncertainties are shown as the error bars which is not very visible in log scale, and the total systematic uncertainties described in section 5.1.6 are shown as the shaded band.

It is conventional to characterize particle production in nucleus-nucleus collisions by the mid-rapidity $dN_{ch}/d\eta$, $dN_{ch}/d\eta|_{\eta=0}$, which here is defined to be $dN_{ch}/d\eta$ averaged over $|\eta| < 0.5$. The analysis presented in this paper yields $dN_{ch}/d\eta|_{\eta=0}$ values in central collisions of $1479 \pm 10^{\text{(stat.)}} \pm 63^{\text{(syst.)}}$, $1598 \pm 11^{\text{(stat.)}} \pm 68^{\text{(syst.)}}$, and $1738 \pm 12^{\text{(stat.)}} \pm 75^{\text{(syst.)}}$ for the 0-10%, 0-6%, and 0-2% centrality intervals, respectively. Table 6.1 provides results of the $dN_{ch}/d\eta|_{\eta=0}$ measurements for all centrality bins.
**Figure 6.1:** Charged particle pseudo-rapidity distribution from three different methods: tracklet Method 1 (black points), tracklet Method 2 (red squares) and pixel tracks (blue triangles). The top panel shows the overall distribution and the bottom panel shows the ratio of Method 2 to Method 1 (red square) and track method to Method 1 (blue triangle). The band indicating ±5% deviation from unity are also shown as black dashed line in bottom panel. The top left is for 0 – 10% central events and the top right is for 10 – 20% central events. The bottom left is for 20 – 30%, and the bottom right is for 30 – 40% central events.
Figure 6.2: Charged particle pseudo-rapidity distribution from three different methods. The top left is for 40 – 50%, and the top right is for 50 – 60% central events. The left is for 60 – 70%, and the right is for 70 – 80% central events. The notation is the same as the above figures.
Figure 6.3: Left: Top: uncorrected track/tracklet $dN_{\text{raw}}/d\eta$ distribution from tracklet Method 1 (points), tracklet Method 2 (squares) and pixel tracking (blue triangles) for 0-10% centrality events. Middle: corrected tracklet and track $dN_{\text{ch}}/d\eta$ distributions. Bottom: ratio of $dN_{\text{ch}}/d\eta$ from the tracklet Method 2 (squares) and pixel tracking (triangles) to tracklet Method 1. Right: $dN_{\text{ch}}/d\eta$ distributions from tracklet Method 1 for eight 10% centrality intervals. The statistical errors are shown as bars and the systematic errors are shown as shaded bands.
The top panel of Fig. 6.4 compares the ATLAS measurement to the previously reported ALICE (22) and CMS (23) results for $|\eta| < 0.5$ for the 0-5% centrality interval in terms of $dN_{ch}/d\eta|_{\eta=0}$ per colliding nucleon pair, $dN_{ch}/d\eta|_{\eta=0}/(N_{\text{part}}/2)$, and to other A+A measurements at different $\sqrt{s}$ (see (19) and references therein). The ALICE and CMS 0-5% centrality measurements agree with the result reported here for the 0-6% centrality interval, $8.5 \pm 0.1(\text{stat.}) \pm 0.4(\text{syst.})$, within the quoted errors. The LHC results show that the multiplicity in central A+A collisions rises rapidly with $\sqrt{s}$ above the RHIC top energy of $\sqrt{s}=200$ GeV. The three curves shown in Fig. 6.4 indicate possible variations of $dN_{ch}/d\eta|_{\eta=0}/(N_{\text{part}}/2)$ with $\sqrt{s}$. The dotted curve describes a $\sqrt{s}$ dependence expected from Landau hydrodynamics (24). It is clearly inconsistent with the data. The dot-dashed curve represents a logarithmic extrapolation of RHIC and SPS data (25) that is also excluded by the measurement presented in this paper and by the ALICE and CMS measurements. The dashed curve shows an $s^{0.15}$ dependence suggested by ALICE (22) that is consistent with the ATLAS measurement. Also shown in the top panel in Fig. 6.4 are results from $p+p$ and $\bar{p}+p$ measurements at different $\sqrt{s}$ ((19) and references therein, as well as (20)-(21)). The excess of $dN_{ch}/d\eta|_{\eta=0}/(N_{\text{part}}/2)$ in A+A collisions over $p+p$ collisions observed at RHIC persists and is proportionately larger at the higher $\sqrt{s}$ values of the LHC.

The bottom panel of Fig. 6.4 shows $dN_{ch}/d\eta|_{\eta=0}/(N_{\text{part}}/2)$ as a function of $N_{\text{part}}$ for 2% centrality intervals over 0-20%, and 5% centrality intervals over 20-80%. The values are also reported in Table 6.1. A moderate variation of $dN_{ch}/d\eta|_{\eta=0}/(N_{\text{part}}/2)$ with $N_{\text{part}}$ is observed, from a value of $4.6 \pm 0.1(\text{stat.}) \pm$
Figure 6.4: Top: $\sqrt{s}$ dependence of the charged particle $dN_{ch}/d\eta$ per colliding nucleon pair $dN_{ch}/d\eta|_{\eta=0}/(N_{part}/2)$ from a variety of measurements in $p+p$ and $\bar{p}+p$ (inelastic and non-single diffractive results from [19] and references therein, as well as [20]-[21]) and central A+A collisions, including the ATLAS 0-6% centrality measurement reported here for $|\eta|<0.5$ and the previous 0-5% centrality ALICE [22] and CMS [23] measurements (points shifted horizontally for clarity). The curves show different expectations for the $\sqrt{s}$ dependence in A+A collisions: results of a Landau hydrodynamics calculation [24] (dotted line), an $s^{0.15}$ extrapolation of RHIC and SPS data proposed by ALICE [22] (dashed line), a logarithmic extrapolation of RHIC and SPS data from [24] (solid line). Bottom: $dN_{ch}/d\eta|_{\eta=0}/(N_{part}/2)$ vs $N_{part}$ for 2% centrality intervals over 0-20% and 5% centrality intervals over 20-80%. Error bars represent combined statistical and systematic uncertainties on the $dN_{ch}/d\eta|_{\eta=0}$ measurements, whereas the shaded band indicates the total systematic uncertainty including $N_{part}$ uncertainties. The RHIC measurements (see text) have been multiplied by 2.15 to allow comparison with the $\sqrt{s} = 2.76$ TeV results. The inset shows the $\langle N_{part} \rangle < 60$ region in more detail.
Table 6.1: Tabulation of measurements of $dN_{ch}/d\eta|_{\eta=0}$ evaluated over $|\eta| < 0.5$ and $dN_{ch}/d\eta|_{\eta=0}/(N_{part}/2)$ for the full set of centrality bins considered in the analysis and shown in Fig. 6.4. The uncertainties on $dN_{ch}/d\eta|_{\eta=0}$ include statistical and systematic errors on the multiplicity measurement. The errors reported for $dN_{ch}/d\eta|_{\eta=0}/(N_{part}/2)$ also include systematic uncertainties on the centrality selection and $N_{part}$ determination.
0.6(syst.) at $N_{\text{part}} = 12.3$ (centrality 75-80%) to $8.8 \pm 0.1(\text{stat.}) \pm 0.4(\text{syst.})$ at $N_{\text{part}} = 396$ (centrality 0-2%). The increase of $dN_{\text{ch}}/d\eta|_{\eta=0}/(N_{\text{part}}/2)$ with $N_{\text{part}}$ is monotonic up to the most central interval (0-2%). This demonstrates that, even for the most central collisions, variations in centrality – as characterized by transverse energy depositions well outside the acceptance used for the multiplicity measurement – yield significant changes in the measured final state multiplicity.

The bottom panel of Fig. 6.4 also shows ALICE and CMS measurements of $dN_{\text{ch}}/d\eta|_{\eta=0}$ as a function of $N_{\text{part}}$ that agree with the results presented here for all centrality intervals. Also shown are results from Au+Au collisions at $\sqrt{s} = 200$ GeV obtained from an average of measurements from the four RHIC collaborations (121). Similar to the approach used in Ref. (22), the 200 GeV Au+Au results have been scaled by a factor of 2.15 to allow comparison with the $\sqrt{s} = 2.76$ TeV data. This factor was obtained by matching the most central 200 GeV Au+Au $dN_{\text{ch}}/d\eta$ measurement at $\eta = 0$ to the $dN_{\text{ch}}/d\eta$ measurement from this paper at $\eta = 0$ in the 2-4% centrality interval, the interval that has the closest value of $N_{\text{part}}$ to the most central 200 GeV measurement. After re-scaling, the trend of the 200 GeV data is in good agreement with the 2.76 TeV measurements all the way down to the most peripheral centrality interval reported here. Similar observations have been made previously in comparisons of top energy RHIC data to much lower energies (19). Therefore, this scaling behavior appears to be a robust feature of particle production in heavy ion collisions.

To evaluate the shapes of the measured charged particle $dN_{\text{ch}}/d\eta$ distributions Fig. 6.5 (top) shows the $dN_{\text{ch}}/d\eta$ distribution divided by $dN_{\text{ch}}/d\eta|_{\eta=0}$
Figure 6.5: Top: $dN_{ch}/d\eta$ distributions from tracklet Method 1, scaled by $dN_{ch}/d\eta|_{\eta=0}$, as a function of the pseudorapidity for the 70-80% centrality interval. The statistical errors are shown as error bars. Bottom: Ratio of $dN_{ch}/d\eta/(N_{part}/2)$ measured in different centrality intervals: 0-10% (squares), 20-30% (triangles), 40-50% (inverted triangles) and 60-70% (crosses) to that measured in peripheral collisions (70-80%). Statistical uncertainties are shown as bars while $\eta$-dependent systematic uncertainties are shown as shaded bands.

for the 70-80% centrality interval. For this centrality interval, the $dN_{ch}/d\eta$ increases by $7\% \pm 1\%$ from $\eta = 0$ to $|\eta| > 1$. The bottom panel shows ratios of $dN_{ch}/d\eta/(N_{part}/2)$ for several other 10% centrality intervals to the same quantity in the 70-80% interval. No significant variation of the shape of $dN_{ch}/d\eta$ with centrality is observed within the systematic uncertainties.
6.2 Open Heavy Flavor Suppression Measurement

6.2.1 Prompt Muon Fraction

The fitted signal ratio $R$ can be expressed as a function of $p_T$ and centrality, $R(p_T, cent)$. Figure 6.6 shows the fitted signal ratio as a function of $p_T$ in different centrality intervals for the Pb+Pb collisions. In general, the signal ratio increases with the muon momentum. This is expected because light flavor dominates at low energy and heavy flavor dominates at higher energy. This $p_T$ dependence was also observed in proton-proton collisions [17, 122]. For $p_T > 14$ GeV, the $W \rightarrow \mu \nu$ starts to play a role in the muon spectrum and contributes as prompt muon [115], so no further attempt is made to extract muon fraction above this $p_T$ region. It is also very clear from the table 6.2 and figure 6.6 that the prompt muon fraction increases as we go from peripheral events (60-80%) to more central events (0-10%). This shows that heavy flavor is less suppressed than $\pi/K$ in heavy ion collisions.

The prompt muon fraction for 2.76 $p+p$ data as a function of $p_T$ is shown in the figure 6.7. The same $p_T$ dependence of the fraction of muons from heavy flavor decays is observed as the one in Pb+Pb collisions.

Table 6.2 shows the number of muons ($n_\mu$) and $R$ in different $p_T$ ranges and in different centrality intervals of Pb+Pb collisions and $p+p$ collisions along with the statistical and systematic uncertainties on $R$. 
Figure 6.6: Prompt muon fraction $R$ vs muon momentum $p_T$ estimated from template fitting in different centrality intervals. The total uncertainties are shown as vertical bars and the systematical uncertainties are shown as shaded areas.
Table 6.2: The number of muons $n_\mu$ and prompt muon fraction $R$ in different $p_T$ ranges and in different centrality intervals of Pb+Pb collisions and $p+p$ collisions. Both the statistical and systematic uncertainties on $R$ are also shown in this table.

<table>
<thead>
<tr>
<th>$p_T$ GeV</th>
<th>0-10%</th>
<th>10-20%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n_\mu$</td>
<td>R ± stat. ± syst.</td>
</tr>
<tr>
<td>4 - 5</td>
<td>48687</td>
<td>0.466 ± 0.008 ± 0.029</td>
</tr>
<tr>
<td>5 - 6</td>
<td>19462</td>
<td>0.505 ± 0.008 ± 0.270</td>
</tr>
<tr>
<td>6 - 7</td>
<td>8556</td>
<td>0.569 ± 0.010 ± 0.043</td>
</tr>
<tr>
<td>7 - 8</td>
<td>4143</td>
<td>0.558 ± 0.013 ± 0.028</td>
</tr>
<tr>
<td>8 - 9</td>
<td>2200</td>
<td>0.576 ± 0.015 ± 0.023</td>
</tr>
<tr>
<td>9 - 10</td>
<td>1229</td>
<td>0.636 ± 0.020 ± 0.026</td>
</tr>
<tr>
<td>10 - 14</td>
<td>1687</td>
<td>0.682 ± 0.018 ± 0.029</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$p_T$ GeV</th>
<th>20-40%</th>
<th>40-60%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n_\mu$</td>
<td>R ± stat. ± syst.</td>
</tr>
<tr>
<td>4 - 5</td>
<td>42924</td>
<td>0.445 ± 0.008 ± 0.066</td>
</tr>
<tr>
<td>5 - 6</td>
<td>17995</td>
<td>0.463 ± 0.008 ± 0.025</td>
</tr>
<tr>
<td>6 - 7</td>
<td>8222</td>
<td>0.515 ± 0.009 ± 0.039</td>
</tr>
<tr>
<td>7 - 8</td>
<td>3860</td>
<td>0.524 ± 0.014 ± 0.027</td>
</tr>
<tr>
<td>8 - 9</td>
<td>2102</td>
<td>0.528 ± 0.017 ± 0.021</td>
</tr>
<tr>
<td>9 - 10</td>
<td>1125</td>
<td>0.595 ± 0.022 ± 0.024</td>
</tr>
<tr>
<td>10 - 14</td>
<td>1513</td>
<td>0.683 ± 0.019 ± 0.036</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$p_T$ GeV</th>
<th>60-80%</th>
<th>$p+p$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n_\mu$</td>
<td>R ± stat. ± syst.</td>
</tr>
<tr>
<td>4 - 5</td>
<td>4681</td>
<td>0.385±0.016±0.073</td>
</tr>
<tr>
<td>5 - 6</td>
<td>2050</td>
<td>0.365±0.020±0.021</td>
</tr>
<tr>
<td>6 - 7</td>
<td>929</td>
<td>0.417±0.026±0.032</td>
</tr>
<tr>
<td>7 - 8</td>
<td>460</td>
<td>0.541±0.036±0.082</td>
</tr>
<tr>
<td>8 - 9</td>
<td>215</td>
<td>0.515±0.050±0.037</td>
</tr>
<tr>
<td>9 - 10</td>
<td>126</td>
<td>0.591±0.067±0.024</td>
</tr>
<tr>
<td>10 - 14</td>
<td>147</td>
<td>0.665±0.063±0.043</td>
</tr>
</tbody>
</table>
Figure 6.7: Prompt muon fraction as a function of $p_T$ in $p+p$ fitting procedure. Combined statistical and systematical uncertainties are shown as bars.

6.2.2 Prompt Muon Yield

With the above analysis, it is straightforward to get the per event normalized prompt muon yield in heavy ion collisions:

$$Yield(cent, p_T) = \frac{1}{N_{evt}(cent)} \frac{n_\mu(cent, p_T)R(cent, p_T)}{\epsilon(cent, p_T)}$$  

(6.1)

In this equation, $\epsilon$ is the reconstruction efficiency for muons from heavy flavor decays and is a function of centrality, $p_T$. $N_{evt}$ is the number of events and by construction it is proportional to the centrality interval used. $n_\mu$ and $R$ are the quantities listed in table 6.2.

Figure 6.8 shows the $d^2Yield(cent, p_T)/(p_T dp_T d\eta)$ as a function of muon $p_T$ in different centrality intervals.

For the $p+p$ baseline analysis, we can get the prompt muon cross section
from the prompt muon fraction with the following equation:

$$\frac{d^2\sigma^{HF\rightarrow\mu}_{pp}}{p_Tdp_Td\eta} = \frac{1}{\mathcal{L}\epsilon_{trig}\epsilon_{reco}p_Tdp_Td\eta} N_{\mu}^{total} R$$ \hspace{1cm} (6.2)$$

In the above equation, $\mathcal{L}$ stands for the luminosity of the $p+p$ datasets, $\epsilon_{trig}$ represents the trigger efficiency of muons and $\epsilon_{reco}$ represents the reconstruction efficiency of muons. Figure 6.9 shows the invariant cross section of muons from heavy flavor decays. In this figure, the total uncertainties are shown as bars, which contain the contributions from $R$, $\mathcal{L}$, $\epsilon_{trig}$ and $\epsilon_{reco}$. Their relative uncertainties are added quadratically to form the final total uncertainties on the invariant cross section.
6.2.3 Heavy Flavor Suppression

The prompt muon yield can be used to study the heavy flavor suppression. $R_{cp}$, which is defined as the ratio of prompt muons between central and peripheral events, is a useful quantity to characterize the heavy flavor suppression in heavy ion collisions. In this analysis, the peripheral centrality 60-80% is used as the reference for the calculation. The definition of $R_{cp}$ is as the following:

$$R_{cp} = \frac{\text{Yield}(\text{cent}, p_T)/\langle N_{\text{coll}}(\text{cent}) \rangle}{(\text{Yield}(\text{cent}, p_T)/\langle N_{\text{coll}}(\text{cent}) \rangle)_{\text{cent}=60-80\%}}$$ (6.3)

Intuitively, the equation 6.3 calculates the relative yield of prompt muons in different centrality intervals with the yield scaled by the mean number of binary collisions, which is denoted as $\langle N_{\text{coll}} \rangle$ and is dependent on the
Table 6.3: $R_{coll}$ and their uncertainties in different centrality intervals. The $\langle N_{part} \rangle$ and their uncertainties in different centrality intervals are also shown.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$R_{coll}$</th>
<th>$\langle N_{part} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>56.7 ± 6.2</td>
<td>356.2 ± 2.5</td>
</tr>
<tr>
<td>10-20%</td>
<td>34.9 ± 3.5</td>
<td>260.7 ± 3.6</td>
</tr>
<tr>
<td>20-40%</td>
<td>16.7 ± 1.5</td>
<td>157.9 ± 3.9</td>
</tr>
<tr>
<td>40-60%</td>
<td>4.9 ± 0.2</td>
<td>69.3 ± 3.5</td>
</tr>
<tr>
<td>60-80%</td>
<td>1.0</td>
<td>22.6 ± 2.3</td>
</tr>
</tbody>
</table>

Table 6.4: $R_{coll}$ and their uncertainties in different centrality intervals when 0-10% is used as the reference interval.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$R_{coll}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>1.0</td>
</tr>
<tr>
<td>10-20%</td>
<td>0.615 ± 0.006</td>
</tr>
<tr>
<td>20-40%</td>
<td>0.294 ± 0.009</td>
</tr>
<tr>
<td>40-60%</td>
<td>0.086 ± 0.006</td>
</tr>
<tr>
<td>60-80%</td>
<td>0.018 ± 0.002</td>
</tr>
</tbody>
</table>

centrality interval. $Yield(cent, p_T)$ is defined by the equation 6.1, the prompt muon yield.

Because the mean number of binary collisions in each centrality interval are correlated with each other, we define a new variable to denote the relative ratio of the quantity in central events to peripheral events:

$$R_{coll} = \frac{\langle N_{coll} \rangle^C}{\langle N_{coll} \rangle^P}$$  \hspace{1cm} (6.4)

Table 6.3 shows $R_{coll}$ and their uncertainties in different centrality intervals when 60-80% are used as the reference. The $\langle N_{part} \rangle$ and their uncertainties in different centrality intervals are also shown for later usage.

Figure 6.10 shows the $R_{cp}$ as a function of $p_T$ for different centrality
**Table 6.5:** $R_{\text{coll}}$ and their uncertainties in different centrality intervals when 70-90% is used as the reference interval.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$R_{\text{coll}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>145.89 ± 14%</td>
</tr>
<tr>
<td>0-20%</td>
<td>117.83 ± 14%</td>
</tr>
<tr>
<td>20-40%</td>
<td>42.84 ± 12%</td>
</tr>
<tr>
<td>40-60%</td>
<td>12.55 ± 8%</td>
</tr>
<tr>
<td>60-80%</td>
<td>2.57 ± 3%</td>
</tr>
<tr>
<td>20-90%</td>
<td>16.64 ± 11%</td>
</tr>
<tr>
<td>70-90%</td>
<td>1.0</td>
</tr>
</tbody>
</table>

intervals. It is very flat as a function of $p_T$, except the 7 – 8 GeV bin, which is caused by the peripheral 60-80% fraction.

Figure 6.11 shows the $R_{pc}$ as a function of $p_T$ for different centrality intervals. $R_{pc}$ is defined similar to $R_{cp}$ except that we use 0-10% as the reference. The three more central bins show very flat behavior as a function of $p_T$. The 0-60% bin is almost flat except the 7 – 8 GeV bin, which is slightly higher than other points.

Figure 6.12 shows $R_{cp}$ as a function of $\langle N_{\text{part}} \rangle$ in different $p_T$ intervals. It decreases with increasing $\langle N_{\text{part}} \rangle$, which clearly shows the suppression of heavy flavor muons.

We can calculate the $R_{AA}$ which denotes the relative yield per collision of heavy ion collisions to proton proton collisions by the following equations:

$$R_{AA}(p_T, \text{cent}) = \frac{1}{T_{AA}(\text{cent})} \frac{d^2N_{e}^{AA}(p_T, \text{cent})}{dp_T dq d\eta} \frac{d\sigma_{HF \rightarrow \mu pp}(p_T)}{dp_T dq d\eta}$$

(6.5)

$T_{AA}(\text{cent})$ is called the thickness function and is related to $N_{\text{coll}}$ by the fol-
Figure 6.10: Signal muon $R_{cp}$ as a function of muon transverse momentum $p_T$ in different centrality intervals. Shaded boxes show the correlated systematical errors from $R_{coll}$ and efficiency. The error bars show the combined systematical and statistical errors.

Figure 6.11: Signal muon $R_{pc}$ as a function of muon transverse momentum $p_T$ in different centrality intervals. Shaded boxes show the correlated systematical errors from $R_{coll}$ and efficiency. The error bars show the combined systematical and statistical errors.
Figure 6.12: Heavy flavor $R_{cp}$ as a function of $< N_{part} >$ in different $p_T$ intervals. x-axis for each higher $p_T$ interval is shifted to right by 6 with respect to its neighboring lower $p_T$ interval to make the figure more clear.

Following equation:

$$T_{AA} = \frac{N_{coll}}{\sigma_{pp}^{in}}$$

(6.6)

in which $\sigma_{pp}^{in}$ denotes the total inelastic cross section and is an input of Glauber model with $\sigma_{pp}^{in} = 64$ mb. Table 6.6 shows the $T_{AA}$ in different centrality and their corresponding errors.

**Table 6.6: $T_{AA}$ and the uncertainties**

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$T_{AA}$ (b$^{-1}$)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 10 %</td>
<td>23406 ± 2078</td>
<td></td>
</tr>
<tr>
<td>10 – 20 %</td>
<td>14422 ± 1297</td>
<td></td>
</tr>
<tr>
<td>20 – 40 %</td>
<td>6891 ± 578</td>
<td></td>
</tr>
<tr>
<td>40 – 60 %</td>
<td>2031 ± 156</td>
<td></td>
</tr>
<tr>
<td>60 – 80 %</td>
<td>414 ± 31</td>
<td></td>
</tr>
</tbody>
</table>

The final $R_{AA}$ as a function of $p_T$ in different centrality bins is shown.
in the figure 6.13. The relative uncertainties of each contribution in the equation 6.5 are combined quadratically to form the final uncertainties on the $R_{AA}$ measurements. For some sources contributed to both $p+p$ and Pb+Pb analysis like fitting without shift, smear, streth effect, there are some degree of correlation. Since it is not clear how big is the correlation, adding them quadratically indicate the most conservative estimation of the final uncertainties.
Figure 6.13: $R_{AA}$ as a function of $p_T$ in different centrality bins.
Conclusions

This paper presents results on the measurement of charged particle pseudo-rapidity distributions over $|\eta| < 2$ as a function of collision centrality in a sample of $\sqrt{s} = 2.76$ TeV lead-lead collisions recorded with the ATLAS detector at the LHC. Three different analysis methods are used, based on the pixel detector and using events with the solenoid magnet turned off in order to measure particles with transverse momenta as low as 30 MeV. The charged particle density, normalized by $N_{\text{part}}/2$, is found to increase significantly with beam energy by about a factor of two relative to earlier RHIC data, and is substantially larger than $p+p$ data at the same energy. The relative centrality dependence of $dN_{\text{ch}}/d\eta|_{\eta=0}/(N_{\text{part}}/2)$ agrees well with that observed at RHIC. These results agree well with previous mid-rapidity measurements from ALICE and CMS. Furthermore, the peripheral (70-80%) $dN_{\text{ch}}/d\eta$ distribution shows a significant rise with increasing $|\eta|$ away from $\eta = 0$. No variation of the shape of the $dN_{\text{ch}}/d\eta$ distribution with centrality outside the reported systematic uncertainties is observed.
As it was shown in the paper \cite{22} only very few models can correctly predict the dependence of charged particle multiplicity at mid-rapidity per colliding nucleon on the average number of participants in the system. Although most models are able to tune to the published results, it is desirable to have theoretical calculations that can predict the physical results. This is left for the theoretical physicists to work on.

This paper has also presented ATLAS measurements of muon production and suppression in $\sqrt{s} = 2.76$ TeV Pb+Pb collisions in a transverse momentum range dominated by heavy flavor decays, $4 < p_T < 14$ GeV, and over the pseudo-rapidity range $|\eta| < 1.05$. The fraction of prompt muons was estimated using template fits to the distribution of a quantity capable of distinguishing statistically between signal and background. The $p_T$ spectra of signal muons were evaluated in five centrality bins: 0-10%, 10-20%, 20-40%, 40-60%, and 60-80%. The centrality dependence of muon production was characterized using the central-to-peripheral ratio, $R_{CP}$, calculated using the 60-80% centrality bin as a peripheral reference. The results for $R_{CP}$ indicate a factor of about 2.5 suppression in the yield of muons in the most central (0-10%) collisions compared to the most peripheral collisions included in the analysis (60-80%). No significant variation of $R_{CP}$ with muon $p_T$ is observed. The $R_{CP}$ decreases smoothly from peripheral to central collisions. Furthermore, this paper presented the $R_{AA}$ measurements with 2.76 $p+p$ collision data as the reference. The observed $R_{AA}$ has little dependence on $p_T$ within the uncertainties quoted here. The results for $R_{AA}$ indicate a factor of about 3 suppression in the yield of muons in the most central (0-10%) collisions compared to the $p+p$ collisions.
CMS has previously reported measurements of $R_{AA}$ for non-prompt $J/\psi$ produced in b quark decays in Pb+Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV (123). The $R_{AA}$ in the 0-20% centrality bin ($N_{\text{part}} = 308$) is consistent with the 0-10% ($N_{\text{part}} = 356$) muon $R_{AA}$ presented here in the $10 < p_T < 14$ GeV interval for which the muon yield is expected to be also dominated by b quark decay contributions. However, the non-prompt $J/\psi$ $R_{AA}$ measurement in the 20-100% centrality interval with $N_{\text{part}} = 64$ has $N_{\text{part}}$ value between 40-60% centrality ($N_{\text{part}} = 69.3$) and 60-80% centrality interval ($N_{\text{part}} = 22.6$ ) presented here, the $R_{AA}$ value from CMS measurement is well below the $R_{AA}$ measurements presented here (see figure 7.1) ($R_{AA} = 0.71 \pm 0.09$ for 40-60% and $R_{AA} = 0.83 \pm 0.12$ for 60-80%).

ALICE has previously presented measurements of $R_{AA}$ for muons from heavy flavor decays in forward rapidity range $2.5 < |y| < 4$ with muon momentum in the similar range presented here (124). In general, there is a very good agreement between those two measurements, though the muons are in different rapidity ranges (see figure 7.1).

Comparison of the results presented here with the semi-leptonic electron measurements performed at RHIC may be fruitful, though interpretation of the results must ultimately account for differences in the primordial bottom to charm ratio between RHIC and the LHC. That ratio has not yet been measured in p+p collisions at the LHC. PHENIX has reported a semi-leptonic electron $R_{AA}$ for $p_T > 4$ GeV in the 0-10% centrality bin of $0.30 \pm 0.02(\text{stat}) \pm 0.04(\text{syst})$ (35). STAR has reported similar result for $R_{AA}$ (36). Thus, the RHIC semi-leptonic electron results show more suppression than in the measurements reported here. The difference of $R_{AA}$ in
the same 0-10% centrality interval from these two different measurements was estimated above to be of order 10%. The weaker suppression of semi-leptonic muons at the LHC likely reflects a larger fraction of bottom quark decays in the muon spectrum compared to RHIC and weaker quenching of those quarks.

We compiled the results from different experiments. Figure 7.1 shows the $R_{AA}$ as a function of $\langle N_{\text{part}} \rangle$ for four different experiments: ATLAS, CMS, ALICE and PHENIX. In general, $R_{AA}$ decreases with the $\langle N_{\text{part}} \rangle$ which is expected because heavy quarks are more suppressed at more central collisions. The lower $R_{AA}$ value for the CMS non-prompt $J/\psi$ in the 20-100% centrality is clearly visible in the figure. Also, the sudden drop of $R_{AA}$ value at the most peripheral collisions of PHENIX measurement is quite unexpected.

Figure 7.2 shows the $R_{AA}$ vs $p_T$ for different centrality intervals from different experiments. For the ATLAS and ALICE measurements with center of mass energy at 2.76 TeV, there is very little dependence of $R_{AA}$ on the muon $p_T$, whether the muon is in the middle rapidity range or forward rapidity range. It is also amazing that the two measurements show similar suppression level for middle rapidity and forward rapidity muons from heavy flavor decays. While the ATLAS muon measurement agrees with PHENIX electron measurement within the uncertainties for the 20-40% and 40-60% centrality intervals, there is a very clear difference of suppression between those two measurement at 0-10% centrality intervals. $R_{AA}$ are different both in the values and in their variation with $p_T$. The original of this difference may come from the different contributions of charm and bottom quarks at different collision energies.
Figure 7.1: $R_{AA}$ as a function of $\langle N_{\text{part}} \rangle$ from different experiments. Four different $p_T$ intervals are shown from the ATLAS experiment, with the x-axis value $\langle N_{\text{part}} \rangle$ for higher $p_T$ interval shifted by 6 successively for clear view. The PHENIX non-photonic electron measurement for Au+Au collisions with $\sqrt{s_{NN}} = 0.2$ TeV with electron momentum in the range $4 < p_T < 9$ GeV and electron $|\eta| < 0.35$ is shown in blue square. The CMS non-prompt $J/\psi$ measurement for Pb+Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV with $J/\psi$ momentum ranged from 6.5 to 30 GeV and rapidity ranged in $|y| < 2.4$ is shown in magenta circles. The ALICE $R_{AA}$ measurement for muons from heavy flavor decays in the forward rapidity $2.5 < |y| < 4$ with momentum in the range $6 < p_T < 10$ GeV is shown in open grey cross.
Figure 7.2: $R_{AA}$ as a function of $p_T$. ATLAS shows muons from heavy flavor decays within the pseudorapidity range of $|\eta| < 1.05$, PHENIX shows electrons from heavy flavor decays within the pseudorapidity range of $|\eta| < 0.35$ and ALICE shows muons from heavy flavor decays within the rapidity range of $2.5 < |y| < 4$. Top: ATLAS, PHENIX and ALICE experiments in 0-10% centrality interval. For ATLAS results (filled black circle), the bar is for combined systematical and statistical errors. For PHENIX (blue square) and ALICE (red star) results, bar indicates statistical uncertainty and box indicates systematical uncertainty. Middle: Muon $R_{AA}$ from the ATLAS and electron $R_{AA}$ from the PHENIX for the 20-40% centrality interval. Bottom: Muon $R_{AA}$ from the ATLAS and electron $R_{AA}$ from the PHENIX for the 40-60% centrality interval.
The measured suppression of heavy flavor decay muon production differs appreciably from measurements of single hadron suppression at the LHC at comparable transverse momenta (104, 125, 126). The single hadron $R_{cp}$ value reported by CMS (125) in the 0-5% centrality relative to the 50-90% centrality interval is a factor of about two smaller than the 0-10% muon $R_{cp}$ value reported here while that in the 5-10% centrality bin is lower by about 50%. The single hadron $R_{cp}$ is also observed to vary much more rapidly with $p_T$ than the muon $R_{cp}$ shown here. Interpretation of this difference may be complicated by the indirect relationship between the transverse momentum of the observed particle and the parent parton for both the hadrons and the muons. Nonetheless, the clear difference between between semi-leptonic muon and charged hadron suppression at the LHC should be contrasted with the situation at RHIC where the experimental data do not indicate such a difference (36, 38).

The direct jet suppression measurement (127) also shows there is no obvious dependence on jet $p_T$ for jet suppression as well. While heavy flavor suppression and jet suppression are complemental to each other, the same suppression trend with $p_T$ may require thorough theoretical calculation of parton energy loss mechanism to fully explain the trend.

With more data available from the LHC, the measurements that can separate the contribution from bottom and charm quarks can give more direct interpretation of the heavy quark suppression. Also, the direct measurement of b-jet suppression (which is on-going in the ATLAS collaboration) can lead to more thorough understanding of their interaction with the QGP medium.
References


[124] Betty Abelev et al. *Production of muons from heavy flavour decays at forward rapidity in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*. arXiv:1205.6443


Appendix A

Natural Units And Planck Units

A.1 Natural Units

In high energy physics, ‘natural units’ are usually used to express different scales instead of the international system of units (SI) for the sake of simplicity. In this measure, three physical constants are set exactly to one:

$$\hbar = c = k_B = 1,$$
where $\hbar$ is the reduced Planck constant, $c$ is the speed of light, and $k_B$ is the Boltzmann constant. Their quantities in SI units are:

$$
\begin{align*}
\hbar &= 1.05 \times 10^{-13} \text{ J} \cdot \text{s} = 6.58 \times 10^{-16} \text{ eV} \cdot \text{s} \\
c &= 3.0 \times 10^8 \text{ m} \cdot \text{s}^{-1} \\
k_B &= 1.38 \times 10^{-23} \text{ J} \cdot \text{K}^{-1} = 8.62 \times 10^{-5} \text{ eV} \cdot \text{K}^{-1}
\end{align*}
$$

(A.1)

To fully describe the physical world, four units are required. Electron-volt (eV) is commonly used as well as multiples of eV (KeV, MeV, GeV, TeV, etc.). With this addition unit, any unit can be expressed in terms of eV. Table A.1 shows the transformation from the natural units to the SI units. In this table, $\alpha$ is the fine structure constant, and $\alpha \approx 1/137$.

<table>
<thead>
<tr>
<th>Natural Unit</th>
<th>SI Unit</th>
<th>Derivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 eV$^{-1}$ of length</td>
<td>$1.97 \times 10^{-7}$ m</td>
<td>$(1 \text{ eV}^{-1}) \hbar c$</td>
</tr>
<tr>
<td>1 eV of mass</td>
<td>$1.78 \times 10^{-36}$ kg</td>
<td>$(1 \text{ eV})/c^2$</td>
</tr>
<tr>
<td>1 eV$^{-1}$ of time</td>
<td>$6.58 \times 10^{-16}$ s</td>
<td>$(1 \text{ eV}^{-1}) \hbar$</td>
</tr>
<tr>
<td>1 eV of temperature</td>
<td>$1.16 \times 10^4$ K</td>
<td>$(1 \text{ eV})/k_B$</td>
</tr>
<tr>
<td>1 unit of electric charge</td>
<td>$1.88 \times 10^{-18}$ C</td>
<td>$e/\sqrt{\alpha}$</td>
</tr>
</tbody>
</table>

Table A.1: Natural units to SI units

## A.2 Planck Units

Planck units which are a system of natural units that is not defined in terms of properties of any prototype, physical object, or even elementary particle are commonly used in quantum gravity. In this measure, four physical constants
are set to one:
\[ c = G = \hbar = k_B = 1. \]

Compared with the natural units described above, one more physical constant \( G \) is set to one. \( G \) is the gravitational constant and its value is \( G = 6.67 \times 10^{-11} \text{m}^3\text{kg}^{-1}\text{s}^{-2} \) in the SI units. In the system of Planck units, the Planck base unit of length is known simply as the Planck length, the base unit of time is the Planck time etc. Table A.2 shows the definition of the base Planck units.

<table>
<thead>
<tr>
<th>Planck Unit</th>
<th>SI Unit</th>
<th>Derivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck length</td>
<td>1.62× 10^{-35} m</td>
<td>( l_P = \frac{\hbar G}{c^3} )</td>
</tr>
<tr>
<td>Planck mass</td>
<td>2.18× 10^{-8} kg</td>
<td>( m_P = \sqrt{\frac{\hbar c}{G}} )</td>
</tr>
<tr>
<td>Planck time</td>
<td>5.39× 10^{-44} s</td>
<td>( t_P = \sqrt{\frac{\hbar c}{G}} )</td>
</tr>
<tr>
<td>Planck temperature</td>
<td>1.42× 10^{32} K</td>
<td>( T_P = \sqrt{\frac{\hbar c}{G k_B}} )</td>
</tr>
<tr>
<td>Planck charge</td>
<td>1.88×10^{-18} C</td>
<td>( q_P = e/\sqrt{\alpha} )</td>
</tr>
</tbody>
</table>

Table A.2: Planck units to SI units
Appendix B

Variables Used In High Energy Physics And Their Definitions

The four space-time vector and four momentum vector are denoted as:

\[ x^\mu = (x^0, x^1, x^2, x^3) = (t, \vec{x}) \]
\[ p^\mu = (p^0, p^1, p^2, p^3) = (E, \vec{p}) \]

The product of the above vector:

\[ \tau^2 = t^2 - \vec{x}^2 = x_\mu x^\mu \]
\[ m^2 = E^2 - p^2 = p_\mu p^\mu \]

where \( \tau \) is the proper time and \( m \) is the mass. Both variables are Lorentz invariant. A useful variable that is commonly used in high energy physics is
the rapidity variable:

\[ y = \ln \left( \frac{E + p_z}{E - p_z} \right) \] (B.1)

If we define the transverse mass of a particle:

\[ m_T = \sqrt{m^2 + p_T^2} \] (B.2)

then it is easy to get the following two equations:

\[ E = m_T \cosh(y) \]
\[ p_z = m_T \sinh(y) \] (B.3)

Usually in experiment, it is not very easy to know the particles’ species so that their masses are unknown, then it is useful to have the pseudo-rapidity variable:

\[ \eta = \frac{1}{2} \ln \left( \frac{\vec{p} + p_z}{\vec{p} - p_z} \right) = -\ln (\tan(\theta/2)) \] (B.4)

where \( \theta \) denotes the angle between the particle moving direction and the \( z \) axis. \( \eta \approx 0 \) is called mid-rapidity, which means particles are perpendicular to the \( z \) axis. If particles move in the direction of \( z \) axis, then \( \eta \) will be close to infinity. Also, it is easy to derive the following equations:

\[ \vec{p} = p_T \cosh(\eta) \]
\[ p_z = p_T \sinh(\eta) \] (B.5)

In experiment, \( dN/d\eta \) is usually measured instead of \( dN/dy \). They are con-
nected by the following equation:

\[
\frac{dN}{d\eta} = \sqrt{1 - \frac{m^2}{m_T^2 \cosh^2 y}} \frac{dN}{dy} \quad (B.6)
\]

In Bjorken’s initial condition consideration introduced in 2.4.1, particles are assumed to be streaming out from the origin \((0, \vec{0})\). Then we can have the following equation:

\[
\frac{z}{t} = v_z = \frac{p_z}{E} = \tanh(y) \quad (B.7)
\]

From this, one can write the following:

\[
z = \tau \sinh(y) \]
\[
t = \tau \cosh(y) \quad (B.8)
\]

Then the rapidity can also be written as:

\[
y = \frac{1}{2} \ln \left( \frac{t + z}{t - z} \right) \quad (B.9)
\]
Appendix C

Bjorken $x$ Scaling Variable And Energy Transfer $Q^2$

Bjorken’s $x$ scaling variable was first introduced to describe the deep inelastic scattering where the parton structure of proton was first found and confirmed \cite{128}. The appendix here gives a brief introduction of the variables.

Consider the interaction process of a lepton ($l$) with a nucleon ($N$):

$$l + N \rightarrow l' + H$$  \hspace{1cm} (C.1)

with the final system consisting of another lepton ($l'$) and any hadronic system ($H$). Figure C.1 shows the schematic diagram of this process with labeled four momenta. In this interaction, the energy transfer is defined as:

$$Q^2 = -q^2 = -(p_l - p_{l'})^2 \approx 2E_lE_{l'}(1 - \cos \theta)$$  \hspace{1cm} (C.2)
The energy of the transferred particle in the $N$ rest frame is:

$$\nu = q \cdot p_N / m_N = (p_l - p_{l'}) \cdot p_N / m_N = E_l - E_{l'} \quad (C.3)$$

The dimensionless scaling variable Bjorken $x$ is defined as:

$$x = \frac{Q^2}{2(p_l - p_{l'}) \cdot p_N} = \frac{Q^2}{2m_N \nu} \quad (C.4)$$
Appendix D

Systematic Uncertainty From Hadron Composition

Different particle species have a different efficiency turn on curve as a function of $p_T$, especially at low $p_T$. Fig D.1 shows the efficiency as a function of $p_T$ for three different particle species: pions (black point), kaons (red square) and protons (blue triangle) for the tracklet method. We can see that the three particle species have a different efficiency up to 0.4 GeV. If the relative particle composition in data is different from that in MC, a systematic uncertainty on the final results can be introduced by this difference. In this section, we discuss the systematic uncertainty from the change of the particle composition.

The main components of charged primary particles are charged pions, protons, anti-protons and charged kaons. The efficiency can be expressed as
Figure D.1: Efficiency vs $p_T$ of different particle species from tracklet methods. Black points are for points, red squares are for kaons, and blue triangles are for protons and anti-protons.

the following:

$$
\epsilon = \frac{N_{\text{rec}}}{N_{\text{total}}} = \frac{\epsilon_\pi + \epsilon_k R_k + \epsilon_p R_p}{1 + R_k + R_p} \quad (D.1)
$$

$$
N_{\text{total}} = N_\pi + N_k + N_p = N_\pi (1 + R_k + R_p)
$$

$$
N_{\text{total}}^{\text{rec}} = N_\pi^{\text{rec}} + N_k^{\text{rec}} + N_p^{\text{rec}} = N_\pi (\epsilon_\pi + \epsilon_k R_k + \epsilon_p R_p)
$$

where $N_{\text{total}}, N_\pi, N_k$ and $N_p$ is the total number of charged primary particles, charged pions, charged kaons, and protons (including anti-protons), $N_{\text{total}}^{\text{rec}}, N_\pi^{\text{rec}}, N_k^{\text{rec}}$ and $N_p^{\text{rec}}$ is the reconstructed charged primary particles, charged pions, charged kaons, and protons (including anti-protons), and $R_k = N_k/N_\pi$, $R_p = N_p/N_\pi$ are the ratios of kaons to pions and protons to pions, and $\epsilon_\pi = N_\pi^{\text{rec}}/N_\pi$, $\epsilon_k = N_k^{\text{rec}}/N_k$, $\epsilon_p = N_p^{\text{rec}}/N_p$ are the efficiency of pions, kaons
and protons. From the efficiency expression, we can see that the efficiency is independent of particle composition if \( \epsilon_k = \epsilon_p = \epsilon_\pi \), and any change in the composition will not change the efficiency. So we only have to consider the case up to \( p_T = 0.4 \) GeV. The ratio of kaons to pions and protons to pions can differ between MC and real data. The change in the particle composition ratio can lead to a change in the efficiency:

\[
(d\epsilon)^2 = \left( \frac{\partial \epsilon}{\partial R_k} \right)^2 (dR_k)^2 + \left( \frac{\partial \epsilon}{\partial R_p} \right)^2 (dR_p)^2 \\
= \frac{(\epsilon_k(1+R_p))^2}{(1+R_k+R_p)^4} (dR_k)^2 + \frac{(\epsilon_p(1+R_k))^2}{(1+R_k+R_p)^4} (dR_p)^2 
\]

(D.2)

So the relative change in the efficiency is:

\[
\frac{d\epsilon}{\epsilon_{MC}} = \sqrt{\frac{(\epsilon_k^{MC}(1+R_p^{MC}))^2 (dR_k)^2 + (\epsilon_p^{MC}(1+R_k^{MC}))^2 (dR_p)^2}{(\epsilon_\pi^{MC} + \epsilon_k^{MC} R_k^{MC} + \epsilon_p^{MC} R_p^{MC})(1+R_k^{MC} + R_p^{MC})}} 
\]

(D.3)

The superscript denotes those variables are evaluated from HIJING MC samples.

We do not have the hadron composition in real data by now, so we use the results from the past heavy ion experiments, PHENIX Au-Au collisions with 200 GeV collision energy \(^{[129]}\). In this paper, the ratio of kaons to pions and protons to pions are not directly available at low momentum, so we fit the momentum spectrum and extrapolated to low \( p_T \) and get the ratios we are interested. The ratios of kaons to pions and protons to pions are denoted as \( R_k^{PHENIX} \) and \( R_p^{PHENIX} \). The difference from PHENIX and MC are taken as \( dR_k = R_k^{PHENIX} - R_k^{MC} \), \( dR_p = R_p^{PHENIX} - R_p^{MC} \). The table \(^?\) shows the values of relevant variables and the calculated relative change in
efficiency in each $p_T$ bin.

The particles in the lowest four $p_T$ bins contribute to 0.047, 0.148, 0.172 and 0.150 of the whole particle spectrum. So the final uncertainty to $dn/d\eta$ measurement is: $0.047 \times 0.004 + 0.148 \times 0.016 + 0.172 \times 0.02 + 0.15 \times 0.02 = 0.009 = 0.9\%$. This uncertainty has very weak centrality dependence, so we quote 0.9% uncertainty from particle composition for all centrality events.

**Table D.1**: Relevant variables for the calculation of systematics from particle composition.

<table>
<thead>
<tr>
<th>$p_T$ [GeV]</th>
<th>0-0.1</th>
<th>0.1-0.2</th>
<th>0.2-0.3</th>
<th>0.3-0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon^{MC}$</td>
<td>0.495</td>
<td>0.847</td>
<td>0.873</td>
<td>0.877</td>
</tr>
<tr>
<td>$\epsilon^{MC}_k$</td>
<td>0.086</td>
<td>0.638</td>
<td>0.848</td>
<td>0.874</td>
</tr>
<tr>
<td>$\epsilon^{MC}_p$</td>
<td>0.001</td>
<td>0.329</td>
<td>0.751</td>
<td>0.848</td>
</tr>
<tr>
<td>$R^{MC}$</td>
<td>0.023</td>
<td>0.040</td>
<td>0.064</td>
<td>0.091</td>
</tr>
<tr>
<td>$R^{MC}_k$</td>
<td>0.005</td>
<td>0.009</td>
<td>0.017</td>
<td>0.030</td>
</tr>
<tr>
<td>$R^{PHENIX}_k$</td>
<td>0.049</td>
<td>0.063</td>
<td>0.087</td>
<td>0.116</td>
</tr>
<tr>
<td>$R^{PHENIX}_p$</td>
<td>0.006</td>
<td>0.009</td>
<td>0.013</td>
<td>0.020</td>
</tr>
<tr>
<td>$dR_k$</td>
<td>0.026</td>
<td>0.023</td>
<td>0.023</td>
<td>0.025</td>
</tr>
<tr>
<td>$dR_p$</td>
<td>0.001</td>
<td>0</td>
<td>-0.004</td>
<td>-0.01</td>
</tr>
<tr>
<td>$d\epsilon^{MC}$</td>
<td>0.004</td>
<td>0.016</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>