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Production of heavy particles by protons on protons

Y. Afek, B. Margolis, and L. Polvani
Physics Department, McGill University, Montreal, Quebec, Canada
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We calculate the production of heavy particles in the multi-GeV energy range using parton-model and statistical considerations. We discuss both central production and fragmentation. Our picture has implications for the question of the existence of a limiting temperature in hadron interactions.

I. INTRODUCTION

The production of heavy particles and resonances in multi-GeV proton-proton interactions has interesting characteristics. The cross sections fall strongly with increasing mass at fixed energy roughly independent of the flavor of the quarks of which the particles are composed. The particles are produced either centrally, or by fragmentation, or by a combination of the two mechanisms. At laboratory energies of a few hundred GeV, for example, the f_0 and K^* (890) are made predominantly by central production.[1,2] The $N^*(1232)$ is produced mainly by fragmentation.[2] There is evidence that the Λ and Λ_c are produced mainly by fragmentation at the CERN ISR.[3,4]

The particles produced mainly in the central region have cross sections exhibiting the scaling property[2,5]

$$\sigma(m,s)\cong A(m)F_{gg}(m^2/s)\ , \tag{1}$$

where $A(m)$ is some function of m and F_{gg} is the gluon-gluon structure function

$$F_{gg}(\tau)=[\tfrac{1}{2}(n+1)]^2\int_\tau^1 \frac{dx}{x}(1-x)^n(1-\tau/x)^n \tag{2}$$

with $n\simeq 5$.

We propose here to explain central-production features by a combination of parton-model and statistical considerations. We raise the question, in connection with the statistical considerations, of whether there is in fact a limiting temperature in hadron interactions as has been proposed.[6,7] We will then make extension of our picture to the fragmentation process.

II. THE MODEL FOR CENTRAL PRODUCTION

The production cross section away from threshold is described here as follows:

(1) A fireball of mass M is produced through gluon-gluon fusion. The cross section for this process is taken to resemble the result of QCD (Ref. 8) for producing a $Q\bar{Q}$ system of mass M of any flavor. We take this to be

$$\sigma_0(M)\propto \alpha_s{}^2/M^2, \tag{3}$$

where α_s is the strong coupling constant. We will come back to a discussion of this ansatz below.

(2) The fireball of mass M decays into a residual fireball of mass M' and the particle or resonance of mass m. The branching ratio for the decay is taken to be[9] the density of two-body states of mass m and M' in a sphere of hadronic volume V divided by the total density of states of quarks and gluons in a sphere of similar size. For states formed from constituents of mass m_0, say, and with $M>>m_0$ we have[7]

$$\rho(M)\simeq C\exp\left[4\left[\frac{8\pi V}{27h^3}\right]^{1/4}M^{3/4}\right]\ , \tag{4}$$

where C is independent of M. This is an approximation to the phase-space expression

$$\rho(M)=\sum_{n=2}^{\infty}\left[\frac{V}{h^3}\right]^{n-1}\frac{1}{n!}\prod_{i=1}^{n}\int d^3p_i\delta\left[\sum_{i=1}^{n}E_i-M\right]\times\delta^3\left[\sum_{i=1}^{n}\vec{p}_i\right]\ , \tag{5}$$

where $E_i=(\vec{p}_i{}^2+m_i{}^2)^{1/2}$. To get (4) from (5) requires $M>>m_i$ for all i. For a gas made of one type of constituent with mass m_0, $m_i=m_0$.

We have then in our statistical picture (neglecting flavor and baryon quantum-number constraints on the limits of integration which can be included when necessary)

$$\sigma(m,s)=\int_{m^2}^{s}\frac{dM^2}{M^2}F_{gg}(M^2/s)\sigma_0(M)f(M,m)\ , \tag{6}$$

where

$$f(M,m)=\int_0^{M-m} dM' \frac{\rho_f(M')}{\rho_i(M)} \lambda^{1/2}(M^2,M'^2,m^2) \times \frac{M^4-(M'^2-m^2)^2}{M^4} \frac{V}{16\pi^2} . \quad (7)$$

Here we have designated the density of initial and final fireball states by the subscripts i and f. In the case when the fireballs may contain heavy quarks we will allow for the masses of these quarks through adaptations of the general formula (5) for the density of states rather than the form (4) which only holds accurately when $m_i << M$. We have integrated over the density $\rho_f(M')$ of all residual fireballs of mass M' in formula (7). The integrand is $\rho_f(M')$ times the ratio of two-body phase space for particles of mass m and M' divided by the total phase space for total energy M. We adopt the procedure of using the phase space for the two hadrons rather than the phase space of the constituents of the hadrons. This corresponds to the physical situation that the quarks and gluons become hadrons when the fireball has decayed. Formula (4) implies that the temperature of hadronic matter confined to a fixed volume is proportional to $M^{1/4}$ as in black-body radiation. We have in fact

$$T=\frac{1}{4}\left[\frac{27h^3}{8\pi V}\right]^{1/4} M^{1/4} . \quad (8)$$

This has a dramatic effect when compared to the limiting temperature situation of the statistical bootstrap.[6,7] At laboratory energies of the order of 300 GeV we find cross sections for producing particles of mass $m \sim 3$ GeV a few orders of magnitude larger than when we use a limiting temperature

$$T \simeq m_\pi . \quad (9)$$

independent of mass as in the statistical bootstrap.

We note that we have assumed that the emission of the inclusively created particle or resonance of mass m is incoherent with the initial gluon fusion process. We have discussed similar incoherence in more detail in earlier papers.[10]

The results of our calculations of central production of heavy particles of mass m for different values of s in p-p interactions are shown in Fig. 1 using the form (4) for the density of states. We find that it is only for quarks as heavy as bottom that we must use the general form (5) for the density of states. We compare our results with measurements of $\sigma(m,s)$ for particles which are known or thought to be centrally produced. The calculated cross sections are normalized to the data reflecting uncertainty in the precise form of $\sigma_0(M)$ assumed in formula (3).

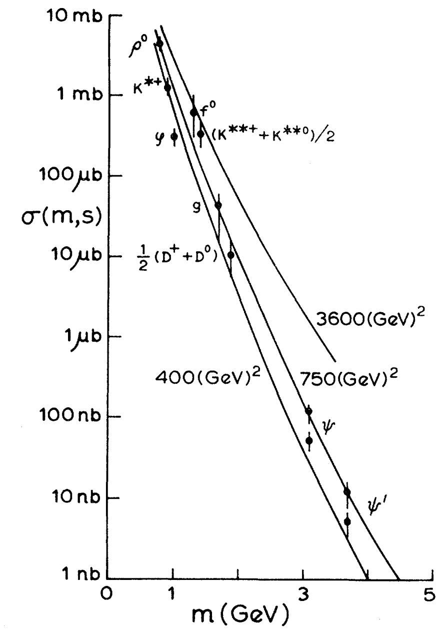

FIG. 1. Calculation of central p-p production cross section $\sigma(m,s)$ of hadrons as a function of mass using formulas (2), (3), (4), (6), and (7) at $s=400$, 750, and 3600 GeV^2 with arbitrary normalization and $V=(4\pi/3)\mu^{-3}$, $\mu=170$ MeV. The experimental data are from compilations of Refs. 1 and 2 and correspond to $s=750$ GeV^2. We divide experimental data by $2J+1$ where J is the spin of the produced particle. The open-charm data point corresponds to central production.

It is interesting that the agreement between theory and experiment is so good up to masses as heavy as those of the ψ family. The statistical considerations applied following gluon-gluon fusion appear to represent adequately the effects of higher-order QCD including confinement or bound-state effects. This is so provided we use the phase space for the density of fireball states calculated with quarks and gluons as the elements. The form for the temperature $T \propto M^{1/4}$ given by Eq. (8) is an essential ingredient. A limiting temperature $T \sim m_\pi$ as given by statistical-bootstrap considerations would lead to cross sections for production of the ψ family of particles several orders of magnitude smaller.

The weighting of fireball masses to relatively small values of M through the gluon-gluon structure function $F_{gg}(M^2/s)$ in formula (6) does not allow for the substantial production of particles of the Υ family from fireball decay at present accelerator energies. Lowest-order QCD plus the use of bound-state wave functions[10] yields a somewhat better result in this case.

We return now to the form for $\sigma_0(M)$, Eq. (3) used above. Lowest-order QCD yields[8]

$$\sigma_{\rm QCD}(M)=\pi/3(\alpha_s{}^2/M^2)G(M^2/4m_q{}^2)\ , \qquad (10)$$

where

$$G(M^2/4m_q{}^2)=\left[1+\frac{4m_q{}^2}{M^2}+\frac{m_q{}^4}{M^4}\right]\ln\left[\frac{1+\lambda}{1-\lambda}\right]\left[7+\frac{31m_q{}^2}{M^2}\right]\frac{\lambda}{4}\ ,\quad \lambda=(1-4m_q{}^2/M^2)^{1/2},\quad M^2>4m_q{}^2\ . \qquad (10a)$$

Fireballs made of quarks of mass m_q will have M values making significant contributions to (6) roughly in the region M of the order of a few times m_q. For $3<M^2/4m_q{}^2<10$, $G(M^2/4m_q{}^2)$ varies by less than a factor of 2. This motivates the use of the approximate form of Eq. (3) for σ_0.

III. PRODUCTION BY FRAGMENTATION

The mechanism for fragmentation is not easily related to QCD parton considerations. However, one has information on diffractive production of mass M in multi-GeV proton-proton interaction up to $s=3600$ GeV^2. Empirically one finds, for the energy range of interest here,[11]

$$\frac{d\sigma_D(M)}{dM^2}\simeq\frac{0.54\ \text{mb}}{M^2}\ . \qquad (11)$$

We assume as in central production, that these masses M are fireballs which decay according to the phase-space considerations above. We write, then,

$$\sigma(m,s)=\int_{m^2}^{m_u{}^2(s)}\frac{d\sigma_D(M)}{dM^2}f(M,m)dM^2\ , \qquad (12)$$

where $f(M,m)$ is given by Eq. (7). We take $m_u{}^2(s)=0.2s$ to correspond to recent experiments.[3] The density of states $\rho_i(M)$ will be dominated by light-parton contributions and so we use the form (4) for it with $m_i=0$. For $\rho_f(M')$ we first of all neglect the quark masses with results for $\sigma(m,s)$ as shown in Figs. 2 and 3. We have also calculated diffractive production taking into account the fact that the residual fireballs with density of states $\rho_f(M')$ contain one strange, charmed, or bottom quark corresponding to diffractive production of a Λ, Λ_c, or Λ_b. Here we use the form (5) for $\rho_f(M')$. These points have been joined by a smooth curve in Figs. 2 and 3. One can then read off from these curves the cross section for diffractive production of D and B as well. We see that the bottom-quark mass reduces the cross section considerably below that for a massless bottom quark.

Unlike for central production we do not expect our considerations for fragmentation to be applicable to the production of bound-charm or -bottom particles without suppression due to quantum-number and other factors. We do not go further into this question here but refer the reader to Ref. 12 where this question is discussed.

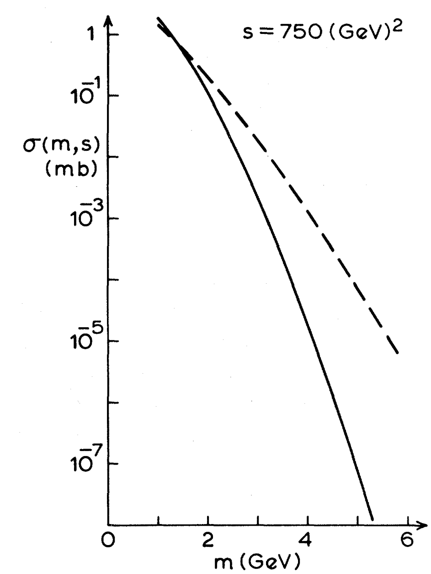

FIG. 2. Calculation of fragmentation production cross section $\sigma(m,s)$ of hadrons as a function of mass at $s=750$ GeV^2 using formulas (7), (11), and (12) with formula (4) (dashed curve) corresponding to neglecting the bottom-quark mass and formula (5) with bottom-quark mass of 4.2 GeV (full curve) as explained in the text.

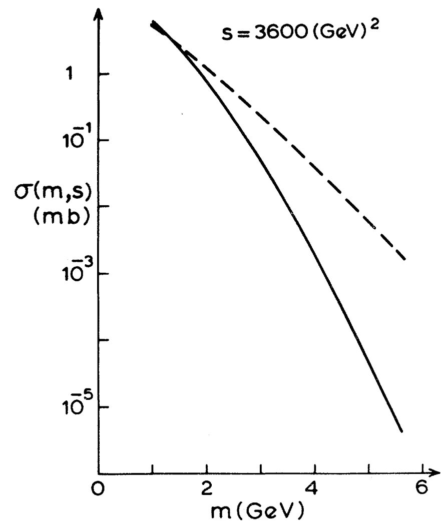

FIG. 3. Calculation of fragmentation production cross section $\sigma(m,s)$ of hadrons as a function of mass at $s=3600$ GeV^2 using formulas (7), (11), and (12) with formula (4) (dashed curve) corresponding to neglecting the bottom-quark mass and formula (5) with bottom-quark mass of 4.2 GeV (full curve) as explained in the text.

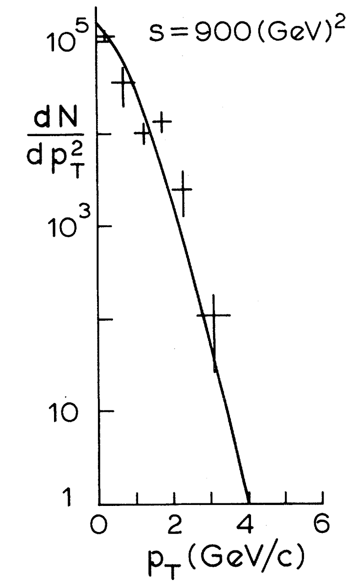

FIG. 4. The p_T distribution for ψ production using formula (13) at $s=900$ GeV^2. Experimental data from Ref. 13. Ordinate units are arbitrary.

IV. DISTRIBUTIONS IN TRANSVERSE MOMENTUM

The distributions in transverse momentum are obtained by suppressing the integration over transverse momentum in the integrand of formula (7). The result is that $f(M,m)$ is replaced by

$$dg(M,m,p_T)=\frac{V}{16\pi^2}2\pi p_T dp_T\int_0^{M_u'}dM'\frac{\rho_f(M')}{\rho(M)}\frac{M^4-(M'^2-m^2)^2}{M^3}\frac{1}{[\lambda(M^2,M'^2,m^2/4M^2-p_T{}^2]^{1/2}}, \tag{13}$$

where $M_u'=\{[M-(m^2+p_T{}^2)^{1/2}]^2-p_T{}^2\}^{1/2}$. Results for central production of the ψ particle are shown in Fig. 4 along with experimental data.[13] Other cases can be calculated similarly. The p_T distribution of fragmentation production requires a convolution with the angular distribution of the fireballs of mass M.

V. DISCUSSION AND CONCLUSIONS

We have presented a model for calculating both central and diffractive production of heavy particles in proton-proton interaction at laboratory energies from a few hundred GeV up. The results agree well with experimental data for central production of particles up to masses in the range of the ψ family. We also have agreement with the large cross sections measured in diffractive production of Λ_c (Refs. 3 and 4) and D (Ref. 14). These cross sections are of the order of a few hundred μb for Λ_c and 1 mb for D production at $s=3600$ GeV^2 and at $s=750$ GeV^2 a factor of eight or so less. For Λ_b production at $s=3600$ GeV^2 we find cross sections of the order of 20 nb. This is much smaller than deduced elsewhere[12] and is due to phase-space considerations arising from the high mass of the bottom quark. The cross section for producing bottom is still of course well within the range of experimental detection. We would be much less optimistic about finding copious numbers of particles containing a top quark in proton-proton interaction since both diffractive- and central-production cross sections are falling very rapidly with increasing mass. At much higher incident proton energies the situation would be different. We would be able to ignore the bottom-quark mass in our calculations and eventually the same for the top quark mass.

The agreement with experiment in the case of central production is evidence for mass dependence of the temperature in hadron interaction of the type exhibited in formula (8). The curvature of the curves in Fig. 1 is the manifestation of this mass dependence. It appears we are seeing a phenomenon in the nature of a phase transition from hadronic to quark-gluon matter[15] at high masses for a fixed volume.

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