Yields of heavy quarks at high energies

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(Submitted 19 February 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 6, 276–279 (25 March 1991)

The relative yields of c and b quarks at energies $\sqrt{s} \gtrsim 0.5$ TeV are studied in the framework of the phenomenology of semihard processes. Absorption corrections must slow the growth of the c-quark production cross section. Consequently, the b-quark production cross sections determined from the data on the yields of muons or J/ψ mesons are larger than the parton model predictions used to analyze the experimental results.

The cross sections for heavy quark (c and b) production in $\bar{p}p$ collisions at high energies have recently been extracted by analyzing the data on the inclusive cross sections for direct lepton (mainly muons) or J/ψ-meson production. This work has given rise to the problem of separating the c- and b-quark contributions. It is usually assumed that the transverse momentum distributions of these quarks are described well by the parton model. However, partons with transverse momenta which are not very large must undergo multiple rescatterings on numerous soft gluons of the initial hadrons. A quantitative estimate of these rescatterings can be obtained using the theory of semihard processes.[1,2] According to this theory, secondary interactions can be ignored for particles with transverse momenta q_T such that the square of their transverse mass $m_T^2 = m^2 + q_T^2 > q_0^2$, since their rescattering cross sections $\sigma_r \sim \alpha_s/m_T^2$ are already rather small. According to Refs. 1 and 2, q_0 increases with increasing energy, reaching the value $q_0 = 2.5$ GeV at $\sqrt{s} = 0.54$ TeV and $q_0 = 7$ GeV at $\sqrt{s} = 40$ TeV. For small q_T, where the squared transverse mass of the quark Q is such that $m_T^2 = m_Q^2 + q_T^2 < q_0^2$, the corrections for rescattering and the resulting screening must be included.

Estimates indicate that beginning at $\sqrt{s} \sim 0.5$ TeV such corrections become important in the case of c-quark production, while for b quarks this happens at $\sqrt{s} \sim 20$ TeV. Here the role of corrections mainly reduces to stopping the growth of the cross section $d\sigma/dq_T^2$ with energy in the range $m_T < q_0$, while this growth continues for large q_T. As a result, the shape of the distributions $d\sigma dq_T^2$ begins to change and gradually acquires a quite unusual form with weak dependence on q_T in the region[1)] $q_T^2 < q_0^2$ (the specific form of this dependence can differ in different models). As an illustration, in Fig. 1 we give the calculated cross sections $d\sigma/dq_T^2$ for c and b quarks produced at the energy $\sqrt{s} = 1.8$ TeV. The details of the calculations are discussed in Ref. 4. The solid lines show the cross sections $d\sigma/dq_T^2$ calculated using QCD, without allowance for the screening discussed above. Their form is quite close to the well-known predictions of the parton model (see, for example, Ref. 5). The dashed lines show the same cross sections, taking the screening into account.

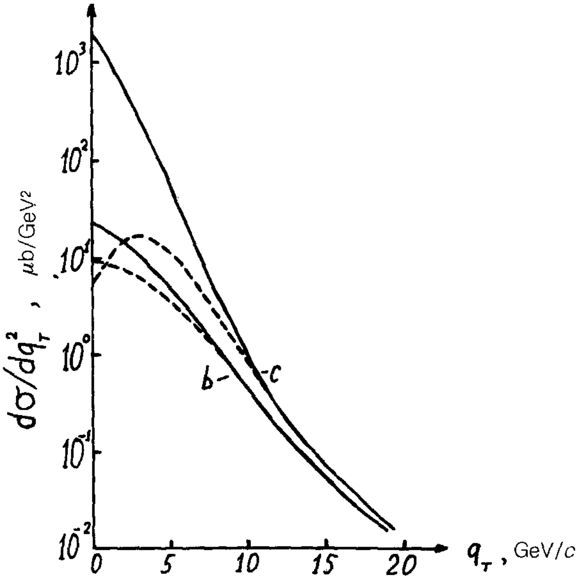

FIG. 1. Calculated cross sections for c- and b-quark production at $\sqrt{s} = 1.8$ TeV, taking into account the screening effects (dashed lines) and ignoring them (solid lines).

Therefore, when rescattering effects are included, the ratio of the c- and b-quark production cross sections must be decreased in the region $m_T \lesssim q_0$. The decrease of the relative charm fraction tends to increase the B-meson production cross section extracted from the data on muon or J/ψ-meson yields. The discussion of this question is the main purpose of the present study.

First of all, let us explain what can cause the suppression of processes that produce particles with small q_T. The main cause is apparently a phenomenon analogous to the Landau–Pomeranchuk effect.[6,7] The time for the formation of a $\bar{Q}Q$ pair by a parent gluon is $\tau \sim E/(2m_T^2)$. In the case $m_T < q_0$ the gluon during this time undergoes several rescatterings on the slow partons of the target nucleon, changing its color charge in each (see Fig. 2, in which the rescatterings are shown by the dashed lines). We note that the quantity[1,2] q_0 is such that for $m_T \sim q_0$ the number of rescatterings $n \sim 1$, i.e., the average mean free path $l \sim \tau c$. The change in the color of the parent gluon (for example, because of exchange of another gluon in the rescattering) leads not to coherent emission during the entire time τ, but to $n = \tau c/l$ incoherent ampli-

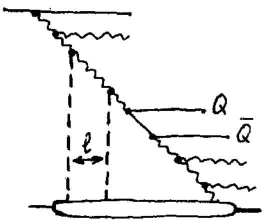

FIG. 2. Gluon rescatterings (dashed lines), which account for the decrease in the cross section for heavy quark production.

tudes for $\bar{Q}Q$ pair production in each individual interval between rescatterings. As a result, the cross section turns out to be proportional to the number of such intervals $n = \tau c/l$, instead of $\sigma \sim n^2$ in the coherent case. Compared to the ordinary parton model, which disregards rescattering, the cross section is decreased by a factor of n.

We cannot sum all the possible graphs responsible for absorption corrections in the range $m_T \lesssim q_0$, so, for example, the calculation shown in Fig. 1 is model-dependent. To most easily estimate the influence of these effects on the value of the b-quark production cross section extracted from experiment, we make the very simple assumption that the cross section $d\sigma(\bar{Q}Q)/dq_T^2$ has the form

$$\frac{d\sigma(\bar{Q}Q)}{dq_T^2} = \left(\frac{d\sigma(\bar{Q}Q)}{dq_T^2}\right)_{q_T=0} \begin{cases} 1, & m_T < q_0 \\ (q_0/m_T)^4, & m_T > q_0 \end{cases}. \tag{1}$$

Let us see what this leads to in the case of B-meson production at $\sqrt{s} = 1.8$ TeV.

The CDF group extracts the value of $\sigma(B)$ by measuring the J/ψ production cross section and assuming, in accordance with the parton model calculations, that 30% of the J/ψ mesons are formed as a result of B-meson decay, while the remaining 70% are produced in $\bar{c}c$-pair production processes by recombination. However, the inclusion of rescattering effects markedly affects this ratio. The fraction of J/ψ mesons formed in $\bar{c}c$-pair production decreases for two reasons. First, the cross section for c-quark production itself decreases, and, second, the probability for their recombination into a J/ψ meson decreases because of the increase of the average c-quark transverse momentum.

Let us assume that the probability for this recombination is proportional to m_T^{-2}. This hypothesis to some degree corresponds to the spirit of the estimate which follows from the QCD sum rules. The probability for J/ψ-meson formation due to c-quark production will then be proportional to

$$w = \int \frac{d\sigma(\bar{c}c)}{dq_T^2} \Big/ \left(\frac{d\sigma(\bar{c}c)}{dq_T^2}\right)_{q_T=0} \frac{dq_T^2}{m_T^2} = \frac{1}{2} + \ln(q_0^2/m_c^2). \tag{2}$$

For $m_c = 1.5$ GeV and $\sqrt{s} = 1.8$ TeV, when $q_0 \simeq 3.1$ GeV, the factor w turns out to be 1.95, which is 4.7 times smaller than in the case where rescattering is absent $[d\sigma(\bar{c}c)/dq_T^2 \sim (q_0/m_T)^4$ in the entire range of $q_T]$.

In other words, the inclusion of absorption corrections in c-quark production changes the ratio 30%: 70% of the fractions of J/ψ particles due to b- and c-quark production to 67%: 33%. Then the B-meson production cross section should be increased by a factor of 2.2 compared to the result obtained using the parton model. If we assume that the probability for recombination $\bar{c}c \to J/\psi$ is proportional to $1/(q_T^2 - \langle R_\psi^2 \rangle^{-1})$, then w is changed even more and instead of the ratio 30%: 70% we obtain 74%: 26% for $\langle R_\psi^2 = 0.08$ F^2, i.e., the B-meson production cross section should be increased by a factor of 2.5.

We note that the numerical value of these effects depends essentially on the transverse momentum range in which the J/ψ mesons are detected. For example, if we restrict the analysis to the range $q_T > 10$ GeV/c, where rescattering effects are nearly absent, the correct cross section $\sigma(B)$ is obtained. This result, however, gives rise to uncertainties related to the extrapolation of the measured cross sections to the full phase space. Nevertheless, the imposition of systematic cutoffs on the transverse momentum of the detected muon or the J/ψ meson makes it possible in principle to experimentally determine the absorption effects in question.

In conclusion, we note that gluon rescattering effects can play a very important role in heavy quark production processes. The heavy quark production cross sections at energies $\sqrt{s} \gtrsim 0.5$–1 TeV can turn out to be much larger than assumed here. In particular, the preliminary results we have obtained using the theory of semihard processes, $\sigma(\bar{p}p \to \bar{b}b) \simeq 200\ \mu b$ at $\sqrt{s} = 1.8$ TeV, agree with the CDF data after these corrections are taken into account. It is desirable to carry out more detailed calculations of absorption effects using realistic models.

[1)] We immediately note that in the case of light quarks (u, d, s) it is virtually impossible to observe the effects of such screening, because of the background from the fragmentation of soft bremsstrahlung gluons, and because of the absence of the leading effect[3] for hadrons composed of light quarks.

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Translated by Patricia Millard