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# Bottom-quark production at hadron colliders

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The recent measurement of the UA1 group of the cross section for bottom-quark production with transverse momentum greater than 5 GeV is found to be in good agreement with the simplest, lowest-order computations in perturbative quantum chromodynamics. This may be contrasted with the well-known disagreement for the much lighter charm quark. Further checks are discussed.

The production of bottom quarks in high-energy hadron collisions is a subject of considerable importance. It serves, first of all, as a test of quantum chromodynamics. Second, it serves to test whether we can accurately predict the cross section for production of heavy particles that carry color. If we *cannot* do so in the case of particles whose properties we know, then we will be hard pressed to use the same theory to place experimental limits on the masses and couplings of hypothetical particles such as gluons or scalar quarks.

Charm-particle production is notorious for being poorly described by the lowest-order perturbative QCD mechanism.[1] The measured cross sections appear to lie an order of magnitude above the lowest-order predictions. This has led to a number of appeals to nonperturbative mechanisms in order to fit the data.[2] However, examination of these mechanisms in light of the structure of low-order perturbative graphs[3] suggests that the usual perturbative picture is valid when the mass of the produced heavy particle is large enough. A recent explicit calculation[4] by Ellis of a subset of the order-$\alpha_s{}^3$ graphs verifies that the infrared-sensitive parts of the cross section do indeed appear as factors associated with the distribution functions of the incoming quarks and gluons, as in the standard perturbative picture.

One expects two kinds of corrections to the lowest-order prediction for the heavy-quark production cross section. The first consists of corrections to the basic formula in which the cross section is written in terms of parton distributions and a hard parton-parton scattering cross section. These corrections should be suppressed by powers of $m/M$, where $M$ is the heavy-particle mass and $m$ is a momentum scale typical of the strong interactions. Unfortunately, there are no quantitative estimates of how big the power-suppressed corrections are, or equivalently, of how large $M$ must be before the corrections are small. Presumably the charm-quark mass, $\sim 1.5$ GeV, is *not* large enough. It seems reasonable (based, say, on the observed jettiness of $e^+e^-$ annihilation events at $Q \approx 10$ GeV) to suppose that the bottom-quark mass, $\sim 5$ GeV, *is* large enough for power corrections to be small. The second kind of correction arises because the hard parton-parton scattering cross section is expanded in a power series in $\alpha_s(M)$. Thus $M$ must be large enough so that $\alpha_s(M)$ is small. Again, the size of the corrections is not known. There was some expectation that the perturbative corrections might be large.[5] However, the class of graphs calculated by Ellis[4] (quark+gluon$\rightarrow$heavy quarks$+X$ at order $\alpha_s{}^3$) was found to give corrections that are *not* particularly large. In summary then, it is reasonable to expect the lowest-order perturbative result to be accurate for the production of bottom quarks or heavier objects.

Recently, the UA1 group has reported a measurement of the cross section for bottom-quark production.[6] Their result is obtained by fitting the production of like- and unlike-sign dileptons to the Drell-Yan process plus heavy-quark decays. Forms are assumed for the fragmentation functions of heavy flavors into leptons, consistent with data from $e^+e^-$ annihilation. Although some uncertainty is involved, the UA1 group extracts a cross section for bottom quarks produced with rapidity $y$ in the range $-2 < y < +2$ and transverse momentum $p_T$ larger than 5 GeV. Their result is

$$\sigma(|y| < 2, p_T > 5\ \text{GeV}) = 1.2 \pm 0.1 \pm 0.2\ \mu\text{b}\ . \quad (1)$$

To see whether this result agrees with the QCD prediction, we use the standard lowest-order hard-scattering cross sections[7] for glue+glue$\rightarrow$heavy-quark pair and quark+antiquark$\rightarrow$heavy-quark pair, together with Duke and Owens distribution functions (set 1).[8] We do not include any charm or other heavy-flavor component in the incident particle distribution functions. We take the bottom-quark mass to be 5.4 GeV. For the scale $Q^2$ in the evolution of structure functions and in the strong-coupling strength $\alpha_s(Q^2)$, we use $Q^2 = \hat{s}$, where, as usual, $\hat{s}$ is the square of the parton-parton center-of-mass energy. We calculate the cross section $\sigma(|y| < 2, p_T > p_{T\min})$ as a function of $p_{T\min}$ for $\sqrt{s} = 630$ GeV. The result is shown in Fig. 1.

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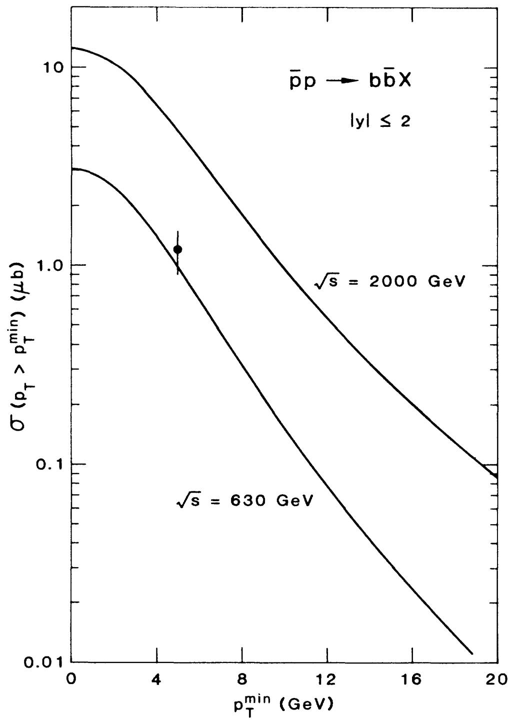


FIG. 1. Cross sections for $b$-quark production in proton-antiproton collisions in the range $p_T > p_{T\min}$, $-2 < y < 2$ as a function of $p_{T\min}$. The cross section is given for the CERN collider, $\sqrt{s} = 630$ GeV, and for the Fermilab Tevatron, $\sqrt{s} = 2000$ GeV. The theoretical curves should be understood to carry a factor of 2 uncertainty arising from unknown higher-order corrections. The result [Eq. (1)] reported by the UA1 group (Ref. 6) at $p_{T\min} = 5$ GeV is also plotted. The $b$-quark mass has been taken to be 5.4 GeV.

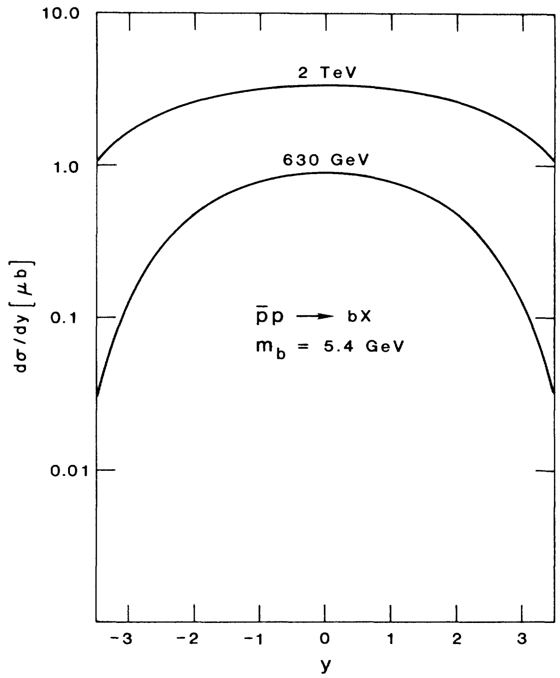


FIG. 2. Distribution in rapidity $d\sigma/dy$ for $\bar{p}p \to bX$ at $\sqrt{s} = 630$ GeV and 2 TeV. These results should be multiplied by 2 if one wishes the cross section for either $b$ or $\bar{b}$.

For $p_{T\min} = 5$ GeV, we obtain $\sigma(|y| < 2, p_T \geq 5 \text{ GeV}) = 1.0\ \mu\text{b}$. Changing the $b$-quark mass to 5.0 GeV, we find that this cross section is increased by 15%. Likewise, using the Eichten-Hinchliffe-Lane-Quigg set 1 structure functions[9] instead of the Duke-Owens set also yields a 15% increase. Changing the scale $Q^2$ from $\hat{s}$ to $4m_b{}^2$ yields an increase of 30%. Overall, we estimate a theoretical uncertainty of a factor 2 in either direction; this uncertainty includes the effect of higher-order corrections. (Compare the "$K$ factor" in the Drell-Yan process at a dimuon mass in the 10-GeV range.) One could get a better value for the cross section and a better estimate of the error if one had a complete third-order calculation of the hard-scattering cross section.

Our calculations and the considerations above lead us to quote a result for $p_{T\min} = 5$ GeV of

$$\sigma(|y| < 2, p_T > 5 \text{ GeV}) = 1.0^{+1.0}_{-0.5}\ \mu\text{b}\ . \qquad (2)$$

An analogous calculation for the Fermilab Tevatron $\sqrt{s} = 2$ TeV is also shown in Fig. 1.

We regard the agreement between Eqs. (1) and (2) as an important experimental confirmation of QCD in an area in which there had been doubts. However, we emphasize that further experimental results are needed. An essential feature of the QCD prediction is that the heavy quarks are produced predominantly with large transverse momentum, $p_T \sim M_Q$. In order to verify this, one would like to know that $\sigma(|y| < 2, p_T > p_{T\min})$ does not continue to rise as $p_{T\min}$ decreases, but levels off when $p_{T\min} < M_Q$, as shown in Fig. 1.

The factorization arguments of Ref. 3 only apply when $p_{T\min}$ is less than or of order $M_Q$. For values of $p_T \gg M_Q$, large contributions to heavy-flavor production are expected from the fragmentation of gluon jets, $g \to b\bar{b}X$, particularly since the subprocess cross section for $gg \to gg$ is very large. This means that Fig. 1 underestimates the large-$p_T$ tail.

Finally, another important feature of the QCD prediction is that heavy quarks are produced predominantly in the central rapidity region, as indicated in the graph of $d\sigma/dy$ (Fig. 2). This feature is contrary to what one finds with strange-quark production.[1] One suspects that strange quarks, once produced, get boosted to large rapidities by their strong interactions with the valence quarks in the proton. This should *not* happen for bottom quarks because they have too much transverse momentum to couple effectively to the quarks in the beam. It will be important to check this feature experimentally.

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