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CHARMONIUM PRODUCTION VIA FRAGMENTATION AT p$\bar{\text{p}}$ COLLIDERS

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ABSTRACT

We present the preliminary results of a calculation of the fragmentation contribution to charmonium production at large transverse momentum in $p\bar{p}$ colliders. The fragmentation of gluons and charm quarks is the dominant direct production mechanism for sufficiently large $p_\perp$. We find that for both J/ψ and ψ' production fragmentation dominates over the conventional gluon-gluon fusion mechanism for $p_\perp$ greater than about 6 GeV.

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The study of charmonium production in high energy hadronic collisions provides a fundamental testing ground for perturbative quantum chromodynamics (QCD). Through the comparison of experimental data and theory it is possible to check if the basic ideas used in these calculations are correct. The study of J/ψ production is of particular importance because the decay $B \to \psi + X$ plays a crucial role in the measurements of b quark production and the studies of CP violation in the B meson system. In order to properly understand these phenomena, it is necessary to understand the background due to direct production of χ and ψ.

Previous calculations of direct charmonium production at large $p_\perp$ in $p\bar{p}$ collisions have assumed that the dominant contribution to the cross section comes from those leading order diagrams with gluon-gluon fusion into a charmonium state and a recoiling gluon.[1] These calculations do not reproduce all aspects of the available data,[2] which suggests that there are other important production mechanisms. Recently it was pointed out that there are fragmentation contributions to charmo-

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nium production that come from higher order in the strong coupling constant α_s, but eventually dominate because of a softer $p_\perp$ dependence.[3] In these proceedings we present preliminary results of a project to calculate the fragmentation contributions to charmonium production. Our completed calculations are the fragmentation contributions to the direct production of ψ and ψ'. The ψ' results can be added to the contributions from gluon-gluon fusion and the decay $B \to \psi' + X$ and compared with CDF data on inclusive ψ' production. The inclusive production of the ψ is complicated by the fact that the χ states decay via $\chi \to \psi + \gamma$, so it is important that direct χ production be included when comparing with data on inclusive ψ production. The fragmentation contribution to χ production needs to be calculated before this comparison can be made. We can, however, compare the fragmentation contribution to direct ψ production to the gluon-gluon fusion contribution and determine above what $p_\perp$ the fragmentation contribution dominates.

Fragmentation is the process in which a high $p_\perp$ parton is created and subsequently decays into a hadron. There is a rigorous factorization theorem of perturbative QCD that applies to the inclusive production of such hadrons in e^+e^- annhilation.[4] It states that the differential cross section $d\sigma$ for producing a hadron with large $p_\perp$ factors into differential cross sections $d\hat{\sigma}$ for producing partons with large transverse momentum and fragmentation functions $D(z)$. The fragmentation function gives the probability for the splitting of the parton into the hadron with momentum fraction z, and is universal in the sense that it is independent of the process that produces the fragmenting parton. It has recently been shown that the fragmentation functions $D(z)$ for heavy quarkonium states can be calculated using perturbative QCD.[3] Fragmentation functions for several of these states have been calculated explicitly.[3,5-7]

The factorization theorem for e^+e^- annihilation can be generalized to the inclusive production of a hadron at large $p_\perp$ in $p\bar{p}$ collisions. For sufficiently large $p_\perp$, the differential cross section should have a factorized form in terms of parton distribution functions, hard scattering cross sections, and fragmentation functions. Taking ψ production to be specific, the differential cross section can be written

$$d\sigma(p\bar{p} \to \psi(p_\perp, y) + X) = \sum_i \int_0^1 dz\, d\sigma(p\bar{p} \to i(\frac{p_\perp}{z}, y) + X, \mu)\, D_{i\to\psi}(z, \mu), \tag{1}$$

where the sum is over partons of type i, z is the longitudinal momentum fraction of the ψ relative to the parton, and y is the rapidity of the ψ. $D_{i\to\psi}(z,\mu)$ is the fragmentation function, and μ is the factorization scale which cancels between the two factors. The fragmentation functions can be evolved to any scale via the Altarelli-Parisi evolution equations

$$\mu\frac{\partial}{\partial\mu} D_{i\to\psi}(z,\mu) = \sum_j \int_z^1 \frac{dy}{y}\, P_{i\to j}(z/y,\mu)\, D_{j\to\psi}(y,\mu), \tag{2}$$

where $P_{i\to j}(x,\mu)$ is the Alterelli-Parisi splitting function for the splitting of a parton of type i into a parton of type j with a longitudinal momentum fraction x. The dominant contributions to Eq. (1) come from gluon fragmentation and charm quark fragmentation. At leading order in α_s the hard gluon or charm quark is produced by a hard $2 \to 2$ scattering process and the differential cross section on the right side of Eq. (1), neglecting parton masses, is

$$\frac{d\sigma}{dp_\perp^2 dy}(p\bar{p} \to i(\frac{p_\perp}{z}, y) + X) =$$
$$\sum_{jk} \int_0^1 dx_1\, f_{p\to j}(x_1) \int_0^1 dx_2\, f_{\bar{p}\to k}(x_2)\, \frac{1}{z}\, \delta\left(z - (\frac{e^y}{x_1} + \frac{e^{-y}}{x_2})\frac{p_\perp}{\sqrt{s}}\right) \frac{d\hat{\sigma}}{d\hat{t}}, \tag{3}$$

where x_1 and x_2 are the longitudinal momentum fraction of partons j and k relative to the proton and antiproton, $f_{p\to j}(x_1)$ and $f_{\bar{p}\to k}(x_2)$ are the corresponding parton distribution functions, s is the center of mass energy squared, and $d\hat{\sigma}/d\hat{t}$ is the differential cross section. The differential cross sections $d\hat{\sigma}/d\hat{t}$ for the relevant subprocesses can be found in standard texts.[8] For a given y, $p_\perp$, and s, the delta function in Eq. (3) will translate into a limit on x_1 and x_2, where

$$0 < \frac{e^{-y}}{x_2} + \frac{e^y}{x_1} < \frac{\sqrt{s}}{p_\perp}. \tag{4}$$

The fragmentation functions $D_{g\to\psi}(z,\mu)$ and $D_{c\to\psi}(z,\mu)$ were calculated in Ref. 3 and 5 to leading order in α_s at a scale μ on the order of $2m_c$. We used Eq. (2) to evolve them to the appropriate scale $\mu = p_\perp/z$ set by the transverse momentum of the parton. Only the splitting term $g \to g$ was used in the evolution of $D_{g\to\psi}$, and only the splitting term $c \to c$ was used in the evolution of $D_{c\to\psi}$. It has been pointed out that the $g \to c$ splitting term may be important in the evolution of the gluon fragmentation function.[6]

The evolved fragmentation functions and Eq. (3) were used in Eq. (1) to calculate the fragmentation contribution to direct ψ production. The MRSD0 parton distribution set wes used along with a pseudorapidity cut of $|\eta| < 0.5$, scale $\mu = 2\mu_0$ and a beam energy of 900 GeV. The result of the calculation is shown in figure 1. The gluon fragmentation and charm quark fragmentation contributions are graphed separately and compared with the gluon-gluon fusion contribution. The cross over $p_\perp$ value above which fragmentation dominates is quite low. For gluon fragmentation the cross over $p_\perp$ is about 8 GeV while for charm quark fragmentation it is about 6 GeV. In spite of a suppression by two powers of α_s, the fragmentation contribution dominates at large $p_\perp$ because the subprocess differential cross section $d\hat{\sigma}/d\hat{t}$ scales as $1/p_\perp^4$ whereas for gluon-gluon fusion it scales as $1/p_\perp^8$.

The ψ' fragmentation contribution can be obtained from the ψ fragmentation contribution simply by multiplying by the ratio of their electronic widths. The results at Tevatron energies are shown in figure 2. The parton distribution set, the scale μ_0 and the psuedorapidity cut are the same as those used in the ψ calculation. The two fragmentation contributions are shown as well as the result of the gluon-gluon fusion calculation, the $B \to \psi' + X$ calculation, and the CDF data.[9] The cross over points are the same as those in ψ production. It is clear from the graph that the theoretical predictions do not properly reproduce the shape of the data, a sign that there may still be other production mechanisms that need to be taken into account.

Some important comments about the results of the calculation need to be made. We have demonstrated that although the fragmentation contribution is of higher order in α_s, it will dominate the lower order gluon-gluon fusion process for $p_\perp$ greater than about 6 GeV. This is small enough that the fragmentation contribution is relevant to the analysis of present collider experiments. At higher energies, such as those that may be reached at the LHC and SSC, the fragmentation contribution will be especially important because of the large range of $p_\perp$ that detectors will be able to probe. Another important point is that because of the fragmentation contribution the background to $B \to \psi + X$ from direct ψ or χ production will not vanish at large $p_\perp$, contrary to some previous suggestions. The gluon-gluon fusion contributions fall away rapidly at large $p_\perp$ since they involve parton subprocesses for which $d\hat{\sigma}/d\hat{t}$ scales as $1/p_\perp^8$ for ψ's or $1/p_\perp^6$ for χ's. However the fragmentation contribution involves parton subprocesses for which $d\hat{\sigma}/d\hat{t}$ scales as $1/p_\perp^4$ just like the cross section for b-quark production. A final point that needs to be made is that isolation cuts on the ψ can not eliminate the background to $B \to \psi + X$ from direct ψ production, contrary to previous suggestions. While the gluon-gluon fusion mechanism does produce isolated ψ's and χ's, the fragmentation mechanism produces ψ's and χ's inside gluon jets or charm quark jets.

Once again we want to stress that this is not a complete result for either ψ or ψ'. In the case of ψ production no comparison to data can be made until the contribution from direct χ production is calculated completely, including direct χ's produced from fragmentation. In case of the ψ', we have made a comparison with data and it suggests that there may still be other production mechanisms for charmonium that have not yet been identified.

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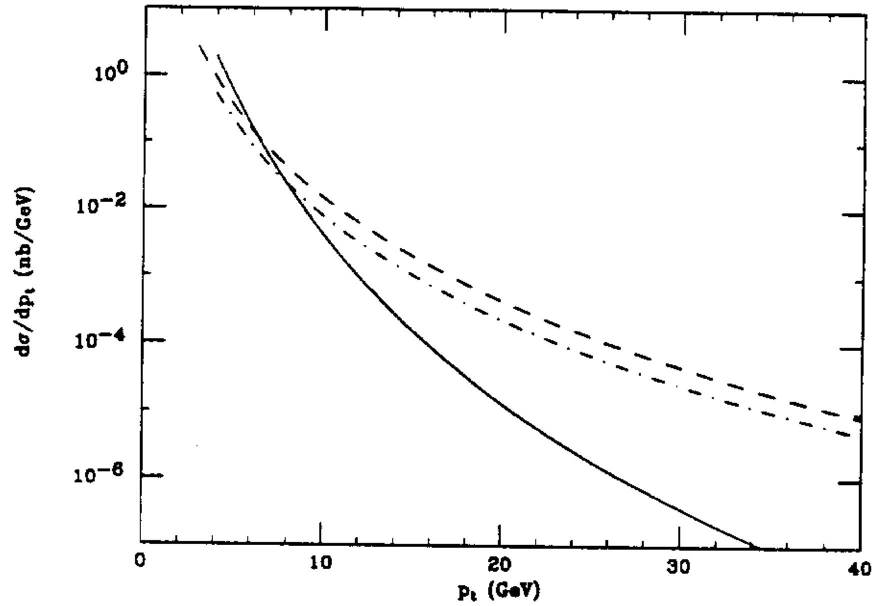

Figure 1: Direct ψ production at the Tevatron. Gluon-gluon fusion with $\mu_0^2 = M_\psi^2 + p_\perp^2$ (solid), gluon fragmentation with $\mu_0 = p_\perp^{gluon}$ (dotdash), charm quark fragmentation with $\mu_0 = p_\perp^{charm}$ (dashes)

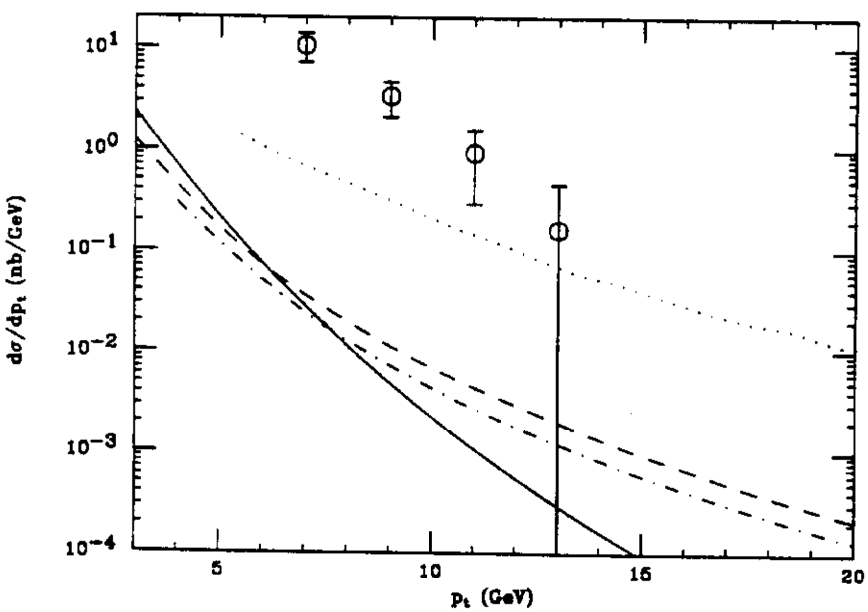

Figure 2: ψ' production at the Tevatron. CDF data (O) compared to gluon-gluon fusion with $\mu_0^2 = M_{\psi'}^2 + p_\perp^2$ (solid), gluon fragmentation with $\mu_0 = p_\perp^{gluon}$ (dotdash), charm quark fragmentation with $\mu_0 = p_\perp^{charm}$ (dashes), and $B \to \psi' + X$ (dots).