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J/ψ as a trigger in $\bar{p}p$ collisions

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We calculate the inclusive ψ cross section in $\bar{p}p$ collisions and emphasize its importance as (i) a unique measure of $b\bar{b}$ production via the decay $B \rightarrow \psi X$, and (ii) a clean and sensitive probe of the small-x gluon distribution via the production mechanism $gg \rightarrow \chi g$ followed by $\chi \rightarrow \psi\gamma$.

It is widely believed[1] that the best signature of heavy-quark ($Q = c, b, \ldots$) production in high-energy $\bar{p}p$ collisions is charged leptons ($l = e$ or μ) originating with large transverse momenta (p_{lT}) relative to the beam axis from the semileptonic decays $Q \rightarrow ql\nu$. Estimates of $c\bar{c}$ and $b\bar{b}$ production at the CERN $\bar{p}p$ collider energy ($\sqrt{s} = 540$ GeV), based on the QCD fusion subprocesses alone (i.e., $gg, q\bar{q} \rightarrow Q\bar{Q}$), give typically[2]

$$\sigma(c\bar{c}) \simeq 0.3 \text{ mb}, \quad \sigma(b\bar{b}) \simeq 6 \ \mu\text{b} \ . \qquad (1)$$

Thus, we anticipate large $c\bar{c}$ and $b\bar{b}$ event rates at the collider (where the present integrated luminosity $L \simeq 100$ nb^{-1}). Unfortunately, the decay leptons occur dominantly at relatively low transverse momenta where the lepton-identification problems are severe. In this respect the most favorable signatures will most likely exploit the identification of muons, which may be observed with momenta as low as $p_{\mu T} \simeq 3$ GeV/c in the UA1 detector.[3] Due to the copious production of hadrons at the collider, the main difficulties are the possibility that a hadron is misidentified as a decay lepton or that the muon from $\pi \rightarrow \mu\nu$ decay, for example, is mistaken with that from a heavy-quark decay $Q \rightarrow q\mu\nu$. Furthermore, it is very difficult to distinguish between the c and b parentage of a decay lepton.

In contrast, "hidden"-flavor J/ψ or Υ production, with subsequent $\mu^+\mu^-$ decay, has an extremely distinctive signature. In particular we emphasize the importance of ψ production at large transverse momenta ($p_{\psi T} \gtrsim 5$ GeV/c) because (i) the experimental signal should be especially free of background, and (ii) in the same region the estimates of the ψ yield based on QCD perturbation theory should be reliable. Here, we address two questions. First, is the inclusive ψ yield large enough to provide a practical event rate at the collider? Second, what type of physics do we expect to explore via the observation of ψ's? As shown in Fig. 1, there are two possible mechanisms for ψ production. The ψ can be produced (A) via $c\bar{c}$ bound-state production, such as

$$gg \rightarrow \chi_J g \text{ with } \chi_J \rightarrow \psi\gamma \ , \qquad (2)$$

or (B) via $b\bar{b}$ production, $b \rightarrow B$ fragmentation, followed by $B \rightarrow \psi X$ decay.[4] A recent measurement[5] from CLEO of the branching ratio for $B \rightarrow \psi X$ gives $(1.0 \pm 0.5)\%$, in reasonable agreement with theoretical predictions (based on the process circled in Fig. 1 with gluon corrections[6]).

We first calculate the ψ yield from mechanism (A). The production of charmonium states ($\psi, \chi_J, \ldots$) directly from the light-quark and gluon constituents of the colliding hadrons is studied in detail in the papers of Baier and Rückl.[7,8] Although estimating the ψ production by hadron interactions has been challenging, its yield at large p_T is now well understood. It is calculated from the dominant $O(\alpha_s^3)$ QCD diagrams shown in Fig. 1. At large p_T, ψ is either produced directly via the subprocess $gg \rightarrow \psi g$ or via $gg, q\bar{q} \rightarrow \chi g$, $qg \rightarrow \chi q$ with subsequent radiative decay $\chi \rightarrow \psi\gamma$ (see Fig. 1). The resulting $p_{\psi T}$ distributions are

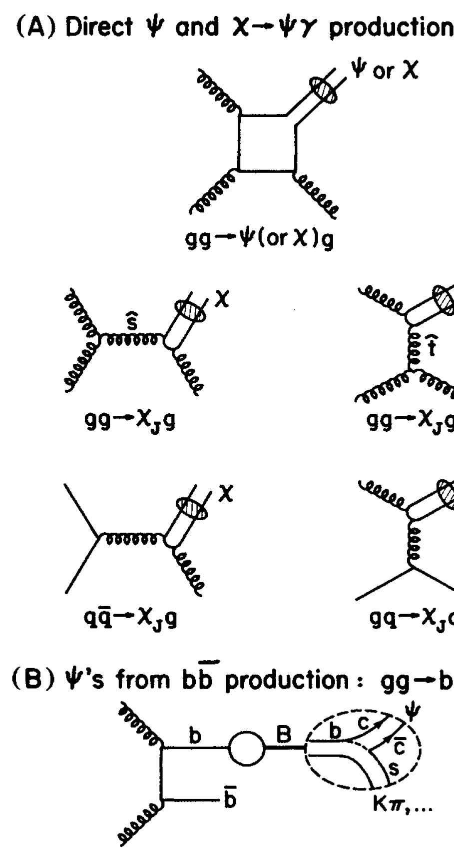

FIG. 1. ψ production (A) via ($c\bar{c}$) bound-state production and $\chi \rightarrow \psi\gamma$, and (B) via $b\bar{b}$ production and $B \rightarrow \psi X$. χ_J denotes the ^3P_J (with $J = 0, 1, 2$) charmonium states. Diagrams with permutation of the gluon lines are implied. The $O(\alpha_s^2)$ subprocesses $gg \rightarrow \chi_{0,2} \rightarrow \psi\gamma$ only produce ψ's of low transverse momenta and are omitted. For mechanisms (B) only one of the possible $gg, q\bar{q} \rightarrow b\bar{b}$ QCD subprocesses is shown.

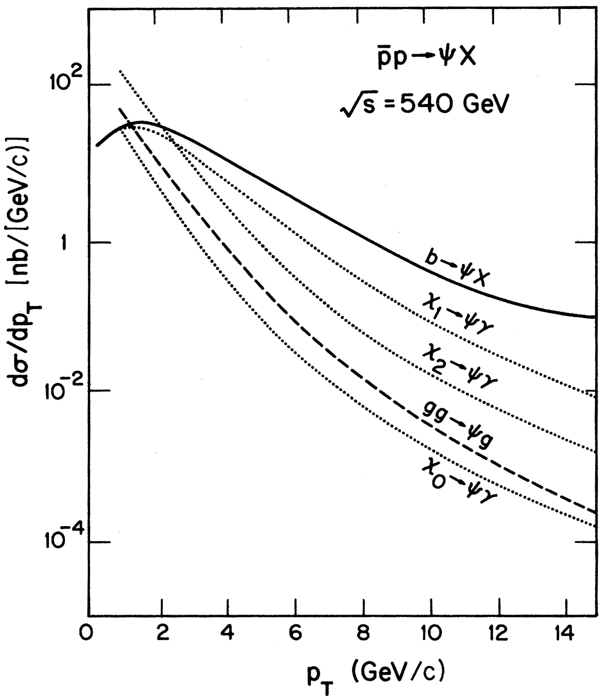

FIG. 2. The ψ transverse-momentum distributions arising from mechanisms (A) and (B) in $\bar{p}p$ collisions at $\sqrt{s}=540$ GeV. We take the branching fractions for $\chi_J \rightarrow \psi\gamma$ to be 0.027, 0.315, 0.154 for $J=0,1,2$, respectively, and for $B \rightarrow \psi X$ to be 0.01. We normalize to $\sigma(b\bar{b})=6.6\ \mu$b. The QCD calculation of the subprocesses which directly involve ψ and χ_J depends, respectively, on the S wave (R_S) and the derivative of the P-wave (R_p') charmonium wave functions at the origin (Refs. 7 and 8). We take $R_S{}^2=0.49$ and $R_p'^2/M_\chi{}^2=0.009$.

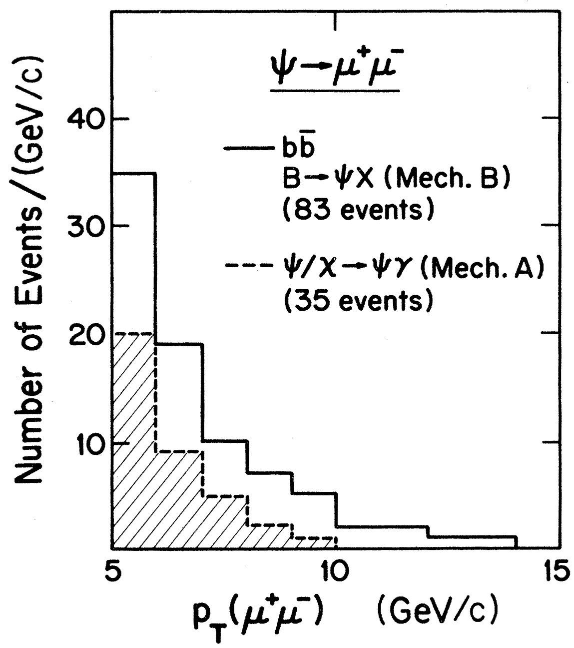

FIG. 3. The number of events per (GeV/c) interval of $P_{\psi T} \equiv p_T(\mu^+\mu^-)$ expected in $\bar{p}p$ collisions at $\sqrt{s}=540$ GeV for an integrated luminosity of 100 nb^{-1} arising from mechanisms (A) and (B) of Fig. 1. The $\psi \rightarrow \mu^+\mu^-$ branching ratio is taken to be 7.4%.

shown in Fig. 2 and the cross sections, integrated over the region $p_{\psi T}>5$ GeV/c, are listed in Table I. At collider energies, for this range of $p_{\psi T}$, we see that of the $O(\alpha_s{}^3)$ processes, the subprocess $gg \rightarrow \chi_1 g$ (followed by $\chi_1 \rightarrow \psi\gamma$) is the dominant source of ψ's. The relative contribution to χ production from the subprocess $q\bar{q} \rightarrow \chi g$ is negligible while that of the subprocesses $qg \rightarrow \chi q$ and $\bar{q}g \rightarrow \chi\bar{q}$ is small; this implies an approximate equality for the χ production rate at pp and $\bar{p}p$ colliders. At small $\hat{s}/M_\chi{}^2$ the contribution from the direct channel $gg \rightarrow \chi g$ is comparably small, too. The main uncertainties in the prediction of the ψ yield are therefore related to the choice of gluon structure functions and to the value of α_s. The quoted yields correspond to using the nonscaling gluon structure functions of Ref. 9 and

$$\alpha_s(Q^2)=\frac{12\pi}{(33-2n_f)\ln(Q^2/\Lambda^2)} , \quad (3)$$

where we put $n_f=4$, $\Lambda=0.3$ GeV, and $Q^2=M_\chi{}^2$ or $M_\psi{}^2$. At the CERN collider energy $\sqrt{s}=540$ GeV, the uncertainty introduced by the gluon distribution functions is of the order of ten for the ψ yield from the subprocesses $gg \rightarrow (\psi,\chi)g$. The highest rate can be achieved by taking scaling glue

$$xg(x)=3(1-x)^5 ;$$

the gluon distribution functions of Ref. 9 predict a rate approximately ten times smaller than that from scaling glue.

To calculate the ψ yield from mechanism (B) we perform a QCD fusion calculation based on the $gg,q\bar{q} \rightarrow b\bar{b}$ subprocesses, folding in a $b \rightarrow B$ fragmentation function of the form given by Peterson, Schlatter, Schmitt, and Zerwas[10] with $\epsilon_b=0.016$. For the $B \rightarrow \psi X$ decay we consider a wide range of two- and three-body (isotropic) decays with $X=K,K^*,K\pi,K^*\pi,\ldots,$ taking $K^*(890)$ and $K^*(1430)$. We find the uncertainties are well encompassed by the allowed range $(1\pm0.5)\%$ of the $B \rightarrow \psi X$ branching ratio.[5] The resulting $p_{\psi T}$ distribution is compared with that for the "direct" and χ-initiated production mechanisms in Fig. 2 and in Table I.

Even though $\sigma(c\bar{c}) >> \sigma(b\bar{b})$ [see Eq. (1)] we find that

TABLE I. Contributions to the J/ψ production cross section (in nb), integrated over the range $p_T>5$ GeV/c, from the mechanisms (A) and (B) of Fig. 1, for $\bar{p}p$ collisions at energy $\sqrt{s}$.

$\sqrt{s}$ (GeV)	$gg \rightarrow \psi g$	Via $\chi_J \rightarrow \psi\gamma$ χ_0	χ_1	χ_2	Via $b\bar{b}$ $B \rightarrow \psi X$	Total σ (nb) for $p_T>5$ GeV/c
540	0.31	0.13	3.9	1.1	11.2	16.6
620	0.42	0.15	4.9	1.4	17.3	24.2
2000	1.1	0.30	13.2	3.0	164.0	181.6

mechanism (B) gives the larger ψ yield, particularly at the larger $p_{\psi T}$ values. This is well illustrated by Fig. 3 which shows the number of $\psi \rightarrow \mu^+\mu^-$ events expected for an integrated $\bar{p}p$ collider luminosity of $L = 100\ \mathrm{nb}^{-1}$, which is approximately equal to the present accumulated luminosity at CERN.

The event rate is such that the proposed $\psi \rightarrow \mu^+\mu^-$ signal should be clearly visible in the $\bar{p}p$ collider data. It should thus allow us to perform a clean measurement of $b\bar{b}$ production. Besides their flatter $p_{\psi T}$ dependence, the $b\bar{b}$-initiated events may also be distinguished by the fact that the ψ will be accompanied by a strange particle [see mechanism (B) of Fig. 1] and recoils against a $\bar{b}$ jet. On the other hand, in the χ-initiated events [mechanism (A)] the ψ should be predominantly accompanied by a relatively slow photon and recoil against a gluon jet.

It might be thought that the corresponding $\Upsilon \rightarrow \mu^+\mu^-$ signal could be exploited to measure $t\bar{t}$ production at the $\bar{p}p$ colliders. Unfortunately, the expected $T \rightarrow \Upsilon X$ branching ratio is much too small. Interestingly, at the current collider energies, the dominant QCD subprocess turns out to be the "direct" reaction $gg \rightarrow \Upsilon g$.

In summary, we should stress the value of measuring ψ production at the $\bar{p}p$ collider. In understanding heavy-flavor production in high-energy $\bar{p}p$ collisions it is important to find a way to unravel b-quark production from the much larger c-quark background. Here, we propose that the $\psi \rightarrow \mu^+\mu^-$ signal (together with a strange particle) offers a unique "clean" trigger for b-quark events. We have seen how it may provide a quantitative test of the QCD fusion mechanism for $b\bar{b}$ production (and in fact it may also reveal whether or not there is a large $b\bar{b}$ diffractive component). The second major mechanism for producing ψ's, which has a steeper $p_{\psi T}$ dependence, is $gg \rightarrow \chi g$ with $\chi \rightarrow \psi\gamma$. Isolation of such events may give a valuable direct measurement of the gluon distribution of the proton at collider energies.

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