Photoproduction of Quarkonium in Proton-Proton and Nucleus-Nucleus Collisions

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We discuss the photoproduction of Υ and J/ψ at high energy $\overline{p}p$, pp, and heavy ion colliders. We predict large rates in $\overline{p}p$ interactions at the Fermilab Tevatron and in pp and heavy ion interactions at the CERN Large Hadron Collider. The J/ψ is also produced copiously at the Relativistic Heavy Ion Collider. These reactions can be used to study the gluon distribution in protons and heavy nuclei. We also show that the different CP symmetries of the initial states lead to large differences in the transverse momentum spectra of mesons produced in $\overline{p}p$ vs pp collisions.

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Photoproduction has traditionally been studied with fixed target photon beams, at electron-proton colliders and, to a limited extent, at relativistic heavy ion colliders. However, energetic protons also have large electromagnetic fields, and high energy pp and $\overline{p}p$ colliders can be used to study photoproduction, at photon energies higher than are currently accessible. These photoproduction reactions are of interest as a way to measure the gluon distribution in protons at low Feynman x.

In this Letter, we study photoproduction of heavy quark vector mesons in $\overline{p}p$ collisions at the Fermilab Tevatron and in pp collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven and at the Large Hadron Collider (LHC) at CERN. At the Tevatron, the high rates allow for detailed measurements of gluon distributions around $x \approx (1.5–5) \times 10^{-3}$, and at the LHC $x \approx (2–7) \times 10^{-4}$ can be reached. We also discuss the coherent photonuclear production of Υ in nucleus-nucleus collisions at RHIC and the LHC.

We show that the different CP symmetry between the pp and $\overline{p}p$ initial states leads to large differences in the transverse momentum, p_T spectra of the produced mesons. Finally, we discuss how these events can be separated from purely hadronic interactions.

We use data from HERA and fixed target experiments on exclusive photoproduction of heavy vector mesons in photon-proton interactions [1] as input to our calculations. Because data on the Υ is limited, we use QCD based models as a basis for parametrizations of the cross sections. The paucity of experimental data on photoproduction of the Υ leads to a relatively large uncertainty in the parametrized cross sections, but is also a strong motivation for investigating new production channels.

The total J/Ψ photon-proton cross section for quasireal ($Q^2 \approx 0$) photons has been measured for photon-proton center-of-mass energies, $W_{\gamma p}$, from near threshold up to 200 GeV. The cross section increases with $W_{\gamma p}$ roughly as $W_{\gamma p}^{0.8}$. We parametrize $\sigma_{\gamma p}(W_{\gamma p}) = 1.5W^{0.8}$ [nb] (W in GeV). A drawback of this parametrization is that there is a discontinuity at the threshold energy, $W_{\gamma p} = m_p + m_{J/\Psi}$.

The two measurements of the Υ at HERA both have significant uncertainties. The ZEUS collaboration measured $\sigma B(\Upsilon \rightarrow \mu\mu) = 13.3 \pm 6.0(\text{stat}) + 2.7 - 2.3(\text{syst})$ pb at a mean center-of-mass energy of $\langle W_{\gamma p}\rangle = 120$ GeV [2]. The H1 collaboration found $\sigma B(\Upsilon \rightarrow \mu\mu) = 19.2 \pm 9.9(\text{stat}) \pm 4.8(\text{syst})$ pb at $\langle W_{\gamma p}\rangle = 143$ GeV [3]. Both experiments estimate that roughly 70% of the signal comes from the $\Upsilon(1S)$ state.

The leading-order expression for the photoproduction of a vector meson of mass M_V is [4]

$$\frac{d\sigma(\gamma p \rightarrow Vp)}{dt}\bigg|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xg(x, M_V^2/4)]^2. \quad (1)$$

Two more sophisticated calculations have considered the use of relativistic wave functions, off-diagonal parton distributions, and next-to-leading order contributions [5,6]. Although the approaches differ, the final results agree. The cross section for $\Upsilon(1S)$ production scales roughly as $W_{\gamma p}^{1.7}$. We use a parametrization which is consistent with both HERA results: $\sigma_{\gamma p}(W_{\gamma p}) = 0.06W_{\gamma p}^{1.7}$ [pb] (W in GeV). An alternative method based on parton-hadron duality gives cross sections ~(30–50)% larger depending on $W_{\gamma p}$ [6]. Our calculations are for the $\Upsilon(1S)$.

We estimate the uncertainties in the Υ cross section by fitting the H1 and ZEUS data to the function $\sigma_{\gamma p}(W_{\gamma p}) = CW_{\gamma p}^{1.7}$. The constant C is determined from two fits, one with the experimental errors (quadratic sum of statistical and systematical) added to the measured value and the other with the experimental errors subtracted. These fits give $C = 0.175$ [pb] and $C = 0.054$ [pb], respectively.

The cross section to produce a vector meson in a proton-proton collision is

$$\sigma(p + p \rightarrow p + p + V) = 2\int_0^\infty \frac{dn}{dk}\sigma_{\gamma p}(k)\,dk. \quad (2)$$

As will be discussed below, quantum mechanical interference alters the transverse momentum (p_T) spectrum, but does not affect the total cross section significantly.

We use the photon spectrum from Ref. [7]:

$$\frac{dn}{dk} = \frac{\alpha}{2\pi k}\left[1 + \left(1 - \frac{2k}{\sqrt{s}}\right)^2\right] \times \left(\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\right), \qquad (3)$$

where k is the photon energy in the center-of-mass frame, where $A = 1 + (0.71\ \mathrm{GeV}^2)/Q^2_{\min}$ and $Q^2_{\min} \approx (k/\gamma)^2$. It is derived using a proton form factor, $F(Q^2) = 1/[1 + Q^2/(0.71\ \mathrm{GeV}^2)]^2$. The effect of the magnetic form factor of the proton is important only at very high photon energies, as was pointed out by Kniehl [8], and is neglected here. The photon spectrum is close to that of a point charge with a minimum impact parameter of $b_{\min} = 0.7$ fm. It corresponds to emission of a photon with the proton remaining intact. The photon flux increases if the proton is allowed to break up [9]. For exclusive vector meson production, both protons must remain intact. This stricter requirement slightly decreases the effective photon flux. To estimate this uncertainty, we have also performed calculations with a photon spectrum corresponding to a point charge with $b_{\min} = 1.0$ fm.

The rapidity y of a produced state with mass M_V is related to the photon energy through $y = \ln(2k/M_V)$. Using this relation in Eq. (2) and differentiating gives

$$\frac{d\sigma}{dy} = k\frac{dn}{dk}\sigma_{\gamma A \to VA}(k). \qquad (4)$$

Interchanging the photon emitter and target corresponds to a reflection around $y = 0$; the total cross section is the sum of the two possibilities. The rapidity distributions are shown in Fig. 1. The calculations are for collision energies of $\sqrt{s} = 500$ GeV at RHIC, $\sqrt{s} = 1.96$ TeV at the Tevatron, and $\sqrt{s} = 14$ TeV at the LHC. The solid and dashed histograms are for the parametrizations $\sigma_{\gamma p}(W_{\gamma p}) = 1.5 W_{\gamma p}^{0.8}$ [nb] and $\sigma_{\gamma p}(W_{\gamma p}) = 0.06 W_{\gamma p}^{1.7}$ [pb] for the J/Ψ and Υ, respectively. The solid histogram is for the photon spectrum in Eq. (3), while the dashed histogram is for a point charge with a cutoff at $b_{\min} = 1.0$ fm. The grey band shown for the Υ corresponds to the two fits to the data described above [with the photon spectrum of Eq. (3)]. The sharp cutoff at large rapidities for the J/Ψ is due to the discontinuity at threshold in the parametrization of $\sigma_{\gamma p}$. Using the photon spectrum in Eq. (3), the total cross sections for the Υ are 12, 120, and 3500 pb at RHIC, the Tevatron, and the LHC, respectively. For the J/ψ, the corresponding cross sections are 7.0, 23, and 120 nb.

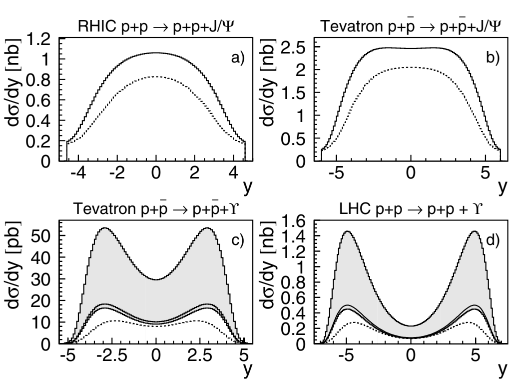

FIG. 1. Rapidity distributions for photoproduction of J/Ψ and $\Upsilon(1S)$ mesons in pp and $\overline{p}p$ interactions at RHIC, the Tevatron, and the LHC. The curves are explained in the text.

Exclusive J/ψ production in pp interactions was previously considered by Khoze *et al.* [10]. They use a very different approach, based on the proton energy lost. Analytical or numerical comparisons between their results and ours are therefore difficult.

At the design luminosity for $\overline{p}p$ at the Tevatron ($2 \times 10^{32}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) [11], the Υ production rate is 76/h. Even with the 2.5% per flavor branching ratios to l^+l^-, good signals should be observable at the Tevatron. For example, in 1 yr (8000 h) at 33% overall efficiency, 5000 decays should be observable in each of the e^+e^- and $\mu^+\mu^-$ channels. At RHIC, the lower energy, luminosity, and shorter pp running time decrease the signal. However, with the planned RHIC II luminosity upgrade, Υ photoproduction could be studied. The situation is better for the J/Ψ, where the production rate at RHIC is 250/h. At the LHC, the J/Ψ and Υ rates are both high.

The midrapidity photoproduction cross section for Υ at the Tevatron is about 0.1% of the hadronic inclusive Υ cross section [12]. Similarly, the photoproduction cross section at midrapidity for the J/Ψ at RHIC is about 0.1% of the hadronic inclusive cross section measured at $\sqrt{s} = 200$ GeV (the total cross section is expected to be about twice as large at $\sqrt{s} = 500$ GeV) [13].

Although the photoproduction cross section is a small fraction of the hadronic cross section, separation of this reaction channel seems possible given the very different character of the photon induced events. We will discuss some selection criteria, and estimate their effectiveness at rejecting hadronic events.

Hadronically produced vector mesons have $p_T \sim M_V$. In contrast, almost all of the photoproduced mesons have $p_T < 1$ GeV/c (cf. Fig. 2). A $p_T < 1$ GeV/c cut eliminates about 94% of the hadroproduced Υ at the Tevatron [12], while retaining almost all of the photoproduction.

As long as both protons remain intact, the vector meson will not be accompanied by any other particles in the same event. In contrast, in hadronic events, the produced particles are distributed over the available phase space. If the average charged particle multiplicity is $\langle dn_{\mathrm{ch}}/dy\rangle$, then the probability of having a charged particle free rapidity gap with width Δy is $\exp(-\Delta y\langle dn_{\mathrm{ch}}/dy\rangle)$. The mean particle densities at

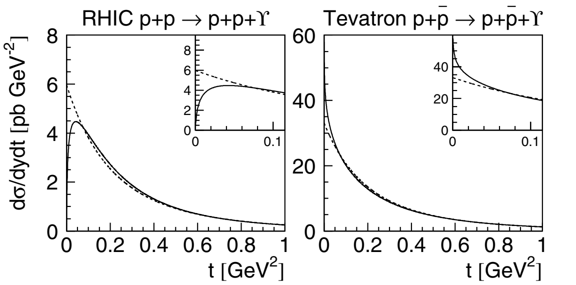

FIG. 2. $d\sigma/dydt$ for photoproduced $\Upsilon(1S)$ mesons at midrapidity in pp and $\overline{p}p$ collisions at RHIC and the Tevatron. The inset has an expanded t scale.

midrapidity are $\langle dn_{\rm ch}/dy \rangle = 3.0$ at $\sqrt{s} = 500$ GeV, $\langle dn_{\rm ch}/dy \rangle = 4.0$ at $\sqrt{s} = 1.96$ TeV, and $\langle dn_{\rm ch}/dy \rangle \approx 5.5$ at $\sqrt{s} = 14$ TeV (extrapolated), neglecting any possible difference between p and $\overline{p}$ [14]. Requiring that the vector meson be surrounded by particle free regions (rapidity gaps) with a total width $\Delta y = 3.0$ will reduce the background by a factor of $\approx 10^{-4}$ at RHIC, $\approx 10^{-5}$ at the Tevatron, and $\approx 10^{-7}$ at the LHC. The total width can be split between two or more gaps, e.g., two gaps of width 1.5, or one of width 3.0. These gaps fit within the acceptance of existing and planned detectors, and provide more rejection power than is needed. The selection could be improved by using calorimetry to detect neutral particles in the gaps.

The CDF collaboration has identified a sample of exclusive J/ψ [15]; they do not give a cross section, but most of the yield is in the region $p_T < 1$ GeV$/c$, as expected for photoproduction.

Photoproduction in pp and $\overline{p}p$ collisions differs from production in ep or eA collisions in that both projectiles can act either as a target or a photon emitter. For very small momenta of the produced state, one cannot distinguish which proton (or antiproton) emitted the photon and which acted as target, so adding the cross sections is not justified. This interference was studied for nucleus-nucleus collisions [16].

The interference is best understood in a plane perpendicular to the direction of the beams. The impact parameters for photoproduction are typically a few fm because of the long range of the electromagnetic force, but the production is always localized to one of the two projectiles. Because of symmetry, the effect is largest at midrapidity, $y = 0$.

The differential cross section, $d\sigma/dydt$, where t is the momentum transfer from the target ($t \approx p_T^2$), may be written as an integral over the impact parameter, b:

$$\frac{d\sigma}{dy\,dt} = \int_{b>b_{\rm min}} |A_1 + A_2|^2 d^2\vec{b}. \quad (5)$$

A_1 and A_2 are the amplitudes for production off each of the two targets. At $y = 0$, $|A_1| = |A_2|$. The amplitude is normalized to the cross section for a single source [Eq. (4)].

If the produced vector mesons are treated as plane waves, $A_i = A_0 \exp(i\vec{p} \cdot \vec{x})$, the total amplitude is

$$|A_1 + A_2|^2 = 2|A_1|^2[1 \pm \cos(\vec{p}_T \cdot \vec{b})]. \quad (6)$$

The sign of the cosine term depends on the symmetry of the system. In a pp collision, moving the vector meson emission (scattering) from one proton to the other corresponds to a parity transform. In a $\overline{p}p$ collision, however, it corresponds to a charge-parity (CP) operation. Since the vector meson has quantum numbers $J^{PC} = 1^{--}$, the interference is destructive for pp and constructive for $\overline{p}p$. The sign in Eq. (6) is "$-$" in pp collisions (as in nucleus-nucleus collisions [16]) and "$+$" in $\overline{p}p$ collisions. With adequate statistics, the interference might be used to search for CP violation.

Without interference, the p_T spectrum is that for production off a single (anti)proton. This spectrum is the convolution of the photon transverse momentum spectrum with the spectrum of transverse momentum transfers from the target [16]. For $p_T > \hbar/\langle b \rangle$, the $\cos(\vec{p}_T \cdot \vec{b})$ term in Eq. (6) oscillates rapidly as b varies, and the net contribution to the integral is zero. For small transverse momenta, however, $\vec{p} \cdot \vec{b} < \hbar$ for all relevant impact parameters, and interference alters the spectrum. This is illustrated in Fig. 2, which compares $d\sigma/dydt$ with and without interference at RHIC and the Tevatron. For Fig. 2, we imposed a cut $b_{\rm min} = 1.0$ fm; this has a small effect on the spectrum. The interference is large for $t < 0.05$ GeV$^2/c^2$. The different sign of the interference in pp and $\overline{p}p$ is clearly visible.

In addition to pp and $\overline{p}p$ interactions, vector mesons are produced in coherent ultraperipheral nucleus-nucleus collisions [17]. The STAR collaboration has observed Au + Au → Au + Au + ρ^0 at RHIC [18]. With a cut on $p_T < 100$ MeV$/c$, the signals were quite clean.

For coherent production, the momentum transfer from the nucleus to the vector meson is determined by the nuclear form factor. Since the $\Upsilon(1S)$ has a small cross section to interact with a nucleon, hadronic shadowing should be negligible. The forward scattering amplitude scales with the number of nucleons, A, squared:

$$\frac{d\sigma(\gamma A \to \Upsilon A)}{dt} = A^2 \frac{d\sigma(\gamma p \to \Upsilon p)}{dt}\bigg|_{t=0} |F(t)|^2. \quad (7)$$

A Woods-Saxon distribution is used for the nuclear form factor $F(t)$. The total photonuclear cross section is the integral of Eq. (7) over all momentum transfers, $t > t_{\rm min} = [M_\Upsilon^2/4k\gamma]^2$. The input to the calculation is again the parametrizations of the total photon-proton Υ cross section. When determining the forward scattering amplitude from the total photon-proton cross section, an exponential t dependence is assumed with the same slope, 4 GeV^{-2}, as for J/Ψ production. This leads to a forward

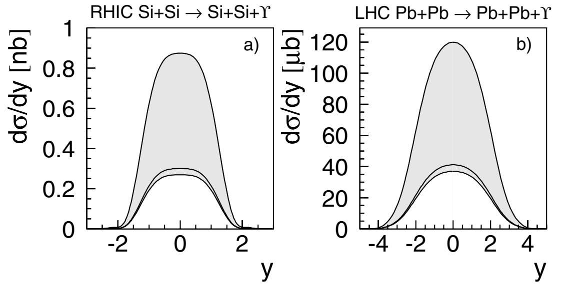

FIG. 3. Rapidity distributions of ϒ mesons produced in coherent photonuclear interactions at RHIC and the LHC. The solid curves correspond to the parametrization $\sigma_{\gamma p}(W_{\gamma p}) = 0.06W^{1.7}$ [pb], and the grey bands show the uncertainty in $\sigma_{\gamma p}$.

scattering amplitude about 5% lower than if the proton form factor above had been used.

With this, and the photon spectrum in [17], the total cross section and the rapidity distributions can be calculated. Figure 3 shows $d\sigma/dy$ for ϒ production in Si + Si interactions at RHIC ($\gamma = 135$) and Pb + Pb interactions at the LHC ($\gamma = 2940$). The total cross section (solid curve) is 0.72 nb for Si + Si at RHIC and 170 μb for Pb + Pb at the LHC.

The cross section at RHIC is rather low. At design luminosity for Si + Si (4.4×10^{28} cm^{-2} s^{-1}), about 300 ϒs are produced in a RHIC year (10^7 s). The situation is better with Pb ions at the LHC. The design luminosity (1×10^{26} cm^{-2} s^{-1}) corresponds to a production rate of about 0.02 Hz or roughly 60 ϒs per hour. The experimental identification in heavy ion interactions is relatively easy because of the coherence requirement, which limits production to $p_T < \sqrt{2}\hbar/R$ [18].

Equation (1) shows that the forward scattering amplitude for ϒ production is proportional to the gluon density squared. A 30% reduction in the nuclear gluon density would roughly halve the cross section. Photonuclear ϒ production at the LHC should measure gluon shadowing in the range $x \approx 2 \times 10^{-3}$.

The coherent production of ϒ at the LHC was studied recently by Frankfurt *et al.* [19]. Our result (solid curve in Fig. 3) is about 10% higher than their result for the impulse approximation (no shadowing). The difference may be due to the slightly different photon spectrum and slope of $d\sigma/dt$ in photon-proton interactions.

Photoproduction of other final states should also be accessible at existing and future $\bar{p}p$ and pp colliders. For example, photoproduction of open charm and bottom could be used to measure gluon distributions. These events would have only a single rapidity gap, but the experimental techniques should be similar.

In summary, we have calculated the cross sections for photoproduction of heavy vector mesons in pp and $\bar{p}p$ collisions. The cross sections are large enough for this reaction channel to be observed experimentally. The $d\sigma/dt$ is distinctly different in pp and $\bar{p}p$ collisions because of the interference between the production sources. The cross section for producing ϒ mesons in coherent photonuclear Pb + Pb interactions at the LHC is large. Because of the distinctive experimental signature, these reactions should be easy to detect.

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