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

Spencer R. Klein  
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Joakim Nystrand  
Department of Physics, University of Bergen  
N-5007 Bergen, Norway

We discuss the photoproduction of Υ and J/ψ at high energy γp, pp and heavy ion colliders. We predict large rates in γp interactions at the Fermilab Tevatron and in pp and heavy-ion interactions at the CERN LHC. The J/ψ is also produced copiously at RHIC. 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 γp 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 γp 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 γp collisions at the Fermilab Tevatron and in pp collisions at the Relativistic Heavy Ion Collider 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 = 1.5 − 5 × 10−3, and at the LHC x = 2 − 7 × 10−4 can be reached. We also discuss the coherent photonic production of Υ in nucleus-nucleus collisions at RHIC and the LHC.

We show that the different CP symmetry between the pp and γp initial states leads to large differences in the transverse momentum, pT 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 parameterizations of the cross sections. The paucity of experimental data on photoproduction of the Υ leads to a relatively large uncertainty in the parameterized cross sections, but is also a strong motivation for investigating new production channels.

The total J/Ψ photon-proton cross section for quasi-real (Q2 ≈ 0) photons has been measured from near threshold up to photon-proton center-of-mass energies, Wγp, up to 200 GeV. The cross section increases with Wγp roughly as Wγp0.8. We parameterize σγp(Wγp) = 1.5 · Wγp0.8 [nb] (W in GeV). A drawback of this parameterization is that there is a discontinuity at the threshold energy, Wγp = mν + mJ/Ψ.

The two measurements of the Υ at HERA both have significant uncertainties. The Zeus collaboration measured σ · Br(Υ → μμ) = 13.3 ± 6.0(stat.) ± 2.3(syst.) pb at a mean center-of-mass energy of ⟨Wγp⟩ = 120 GeV [2]. The H1 collaboration found σ · Br(Υ → μμ) = 19.2 ± 9(stat.) ± 4.8(syst.) pb at ⟨Wγp⟩ = 143 GeV [3]. Both experiments estimate that roughly 70% of the signal comes from the Υ(1S) state.

The leading-order expression for the photoproduction of a vector meson of mass Mν is [3]

\[
\frac{dσ(γp → Vp)}{dt} \bigg|_{t=0} = \frac{α^2 Γ_{ee}^2}{3α M_V^5} 16π^3 [xg(x, M_V^2/4)]^2. \]

Two more sophisticated calculations have considered the use of relativistic wave functions, off-diagonal parton distributions, and NLO contributions [4, 5]. Although the approaches differ, the final results are in good agreement. The cross section for Υ(1S) production scales roughly as Wγp1.7. We use a parameterization which is consistent with both HERA results: σγp(Wγp) = 0.06 · Wγp1.7 [pb] (W in GeV). An alternative method based on parton-hadron duality gives cross sections ≈30-50% larger depending on Wγp [3]. Our calculations are for the Υ(1S).

We estimate the uncertainties in the Υ cross section by fitting the H1 and Zeus data to the function σγp(Wγp) = C · Wγp1.7. 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

\[
σ(p + p → p + p + V) = 2 \int_0^\infty \frac{dk}{dk} σ_{pp}(k) dk. \]

As will be discussed below, quantum mechanical interference alters the transverse momentum (pT) spectrum, but does not affect the total cross section significantly.
We use the photon spectrum from Ref. 7:

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

where $A = 1 + (0.71 GeV^2)/Q_{\text{min}}^2$ and $Q_{\text{min}}^2 \approx (k/\gamma)^2$. It is derived using a proton form factor, $F(Q^2) = 1/(1 + Q^2/(0.71 GeV^2))^2$. This spectrum is close to that of a point charge with a minimum impact parameter of $b_{\text{min}} = 0.7 \, \text{fm}$. It corresponds to emission of a photon with the proton remaining intact. For exclusive vector meson production, the target proton must also 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 a minimum impact parameter of $b_{\text{min}} = 1.0 \, \text{fm}$.

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

$$\frac{d\sigma}{dy} = k \frac{dn}{dk} \sigma_{\gamma,V-A}(k).$$

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 $\sqrt{s} = 500 \, \text{GeV}$ at RHIC, $\sqrt{s} = 1.96 \, \text{TeV}$ at the Tevatron, and $\sqrt{s} = 14 \, \text{TeV}$ at the LHC. The solid and dashed histograms are for the parameterizations $\sigma_{\gamma p}(W_{\gamma p}) = 1.5 \cdot W_{\gamma p}^{0.8} \, \text{[nb]}$ and $\sigma_{\gamma p}(W_{\gamma p}) = 0.06 \cdot W_{\gamma p}^{1.7} \, \text{[pb]}$ for the $J/\Psi$ and $\Upsilon$, respectively. The solid histogram is for the photon spectrum in Eq. 3 while the dashed histogram is for a point charge with a cut-off at $b_{\text{min}} = 1.0 \, \text{fm}$. The grey band shown for the $\Upsilon$ corresponds to the two fits to the data described above (with the photon spectrum of Eq. 3). The sharp cut-off at large rapidities for the $J/\Psi$ is due to the discontinuity at threshold in the parameterization of $\sigma_{\gamma p}$. Using the photon spectrum in Eq. 3, the total cross sections for the $\Upsilon$ are 12 pb, 120 pb, and 3.5 nb at RHIC, the Tevatron, and the LHC, respectively. For the $J/\psi$, the corresponding cross sections are 7.0 nb, 23 nb, and 120 nb.

Exclusive $J/\psi$ production in $pp$ interactions was previously considered by Khoze et al. 8. 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 $p\overline{p}$ at the Tevatron ($2 \times 10^{32} \, \text{cm}^{-2} \, \text{s}^{-1}$) 9, the $\Upsilon$ production rate is 76/hr. Even with the 2.5% per flavor branching ratios to $J/\Psi^- + \phi^0$, good signals should be observable at the Tevatron. For example, in 1 year (8,000 hr) at 33% overall efficiency, 5,000 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, $\Upsilon$ photoproduction could be studied. The situation is better for the $J/\Psi$, where the production rate at RHIC is 250/hr. At the LHC, the $J/\Psi$ and $\Upsilon$ rates are both high.

The mid-rapidity photoproduction cross section for $\Upsilon$ at the Tevatron is about 0.1% of the hadronic inclusive $\Upsilon$ cross section 10. Similarly, the photoproduction cross section at mid-rapidity for the $J/\Psi$ at RHIC is about 0.1% of the hadronic inclusive cross section measured at $\sqrt{s} = 200 \, \text{GeV}$ (the total cross section is expected to be about twice as large at $\sqrt{s} = 500 \, \text{GeV}$) 11.

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 of the 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 $p_T < 1 \, \text{GeV/c}$ (cf. Fig. 2). A $p_T < 1 \, \text{GeV/c}$ cut eliminates about 94% of the hadronproduced $\Upsilon$ at the Tevatron 10, 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 $\langle dn_{\text{ch}}/dy \rangle$, then the probability of having a charged particle free rapidity gap with width $\Delta y$ is $\exp(-\Delta y \cdot \langle dn_{\text{ch}}/dy \rangle)$. The mean particle densities at mid-rapidity are $\langle dn_{\text{ch}}/dy \rangle = 3.0$ at $\sqrt{s} = 500 \, \text{GeV}$, $\langle dn_{\text{ch}}/dy \rangle = 4.0$ at $\sqrt{s} = 1.96 \, \text{TeV}$, and $\langle dn_{\text{ch}}/dy \rangle \approx 5.5$ at $\sqrt{s} = 14 \, \text{TeV}$ (extrapolated), neglecting any possible difference between $p$ and $\overline{p}$. 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.

![FIG. 1: Rapidity distributions for photoproduction of $J/\Psi$ and $\Upsilon(1S)$ mesons in $pp$ and $p\overline{p}$ interactions at RHIC, the Tevatron, and the LHC. The curves are explained in the text.](image-url)
tiles. Because of symmetry, the effect is largest for production is always localized to one of the two perpendicular to the direction of the beams. The impact parameter, $b$, cannot distinguish which proton (or anti-proton) emitted both projectiles can act either as target or photon emitter.

The CDF collaboration has identified a sample of exclusive $J/\psi$ \cite{13}; they do not give a cross section, but expected for photoproduction.

Exclusive vector meson production in $pp$ and $p\bar{p}$ collisions differs from production in $e p$ or $e A$ collisions in that both projectiles can act either as target or photon emitter. For very small momenta of the produced state, one cannot distinguish which proton (or anti-proton) emitted the photon and which acted as target, so adding the cross sections is not justified. This interference was studied for nucleus-nucleus collisions \cite{14}.

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 for $y = 0$.

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, $b$:

$$\frac{d\sigma}{dydt} = \int_{b > b_{\text{min}}} |A_1 + A_2|^2 d^2b. \quad (5)$$

$A_1$ and $A_2$ are the amplitudes for production off each of the two targets. At mid-rapidity, considered here, $|A_1| = |A_2|$. The amplitude is normalized to the cross section for a single source (Eq. 6).

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

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

The sign of the cos-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 $p\bar{p}$ 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 $p\bar{p}$.

The sign in Eq. 6 is “-” in $pp$ collisions (as in nucleus-nucleus collisions \cite{14}) and “+" in $p\bar{p}$ collisions. With adequate statistics, the interference might be used to search for CP violation.

This interference alters the vector meson $p_T$ spectrum near mid-rapidity. 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 \cite{14}. For $p_T > h/|\langle b \rangle|$, the $\cos(\vec{p}_T \cdot \vec{b})$-term in Eq. 6 oscillates rapidly as $b$ varies, and the net contribution to the integral will be zero. For small transverse momenta, however, $p_T \ll 1/|\langle b \rangle|$, $\vec{p} \cdot \vec{b} \approx 0$ 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 $b_{\text{min}} = 1.0$ fm; this has a small effect on the spectrum. The interference is large for $t < 0.05$ GeV$^2$/c$^2$.

The differential cross section in $pp$ and $p\bar{p}$ collisions is clearly visible.

In addition to $pp$ and $p\bar{p}$ interactions, vector mesons are produced in coherent ultra-peripheral nucleus-nucleus collisions \cite{15}. The STAR collaboration has observed $Au + Au \rightarrow Au + Au + p_0$ at RHIC \cite{14}. With 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 $J/\psi$ has a small cross section to interact with a nucleon, hadronic shadowing should be negligible for it. The forward scattering amplitude scales with the number of nucleons, $A$, squared:

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

A Woods-Saxon distribution is used for the nuclear form factor $F(t)$. The total nuclear cross section is the integral of Eq. 7 over all momentum transfers, $t > t_{\text{min}} = [M^2_{\Upsilon}/4k^2]$. The input to the calculation is the parameterizations of the total photon-proton $\Upsilon$ cross section discussed above. 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 $J/\Psi$ production. This leads to a forward scattering amplitude about 5% lower than if the proton form factor above had been used.

With this, and the photon spectrum in \cite{14}, the total cross section and the rapidity distributions can be calculated. Figure 3 shows $d\sigma/dy$ for $\Upsilon$ 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 $\mu$b for Pb+Pb at the LHC.
Because of the low photon flux, the cross section at RHIC is rather low. At design luminosity for Si+Si (4.4 · 10^28 cm⁻²s⁻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 · 10^30 cm⁻²s⁻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 √T \ll 1.

Eq. [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 be a sensitive probe of nuclear gluon shadowing in the range x ≈ 2 × 10⁻³.

The coherent production of Υ at the LHC was studied recently by Frankfurt et al. [17]. 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 dσ/dt in photon-proton interactions. With nuclear gluon shadowing, the cross section at mid-rapidity may be reduced by as much as 50% for Pb+Pb [17].

Photoproduction of other final states should also be accessible at existing and future p\bar{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.

To summarize, we have calculated the cross sections for photoproduction of heavy vector mesons in pp and p\bar{p} collisions. The cross sections are large enough for this reaction channel to be observed experimentally. The dσ/dt is distinctly different in pp and p\bar{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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