EXCLUSIVE PHOTOPRODUCTION OF Υ: FROM HERA TO TEVATRON

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The amplitude for photoproduction $\gamma p \rightarrow \Upsilon p$ is calculated in a pQCD $k_T$-factorization approach. The total cross section for diffractive $\Upsilon$s is compared to recent HERA data. The amplitude is used to predict the cross section for exclusive $p\bar{p} \rightarrow p\Upsilon(1S,2S)\bar{p}$ processes in hadronic reactions at Tevatron energies. We also included absorption effects.

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1. Introduction

Exclusive production of heavy $Q\bar{Q}$ vector quarkonium states in hadronic interactions was never measured, but is very attractive from the theoretical side. Due to the negative charge-parity of the vector meson, the Pomeron-Pomeron fusion mechanism of exclusive meson production is not available, and instead the production will proceed via photon–Pomeron fusion. A possible purely hadronic mechanism would involve the elusive Odderon exchange. Currently there is no compelling evidence for the Odderon, and here we restrict ourselves to the photon-Pomeron fusion mechanism. The current experimental analyses at the Tevatron (see, for example, the plenary talk [1]) call for an evaluation of differential distributions including the effects of absorptive corrections. Predictions for Tevatron require the diffractive amplitude for $\gamma p \rightarrow \Upsilon p$. This process has been measured at HERA in the energy range $W \sim 100 - 200$ GeV [2]. This energy range is in fact very much relevant to the exclusive production at Tevatron energies for not too large rapidities of the meson.

2. Photoproduction $\gamma p \rightarrow \Upsilon p$ at HERA

The full amplitude for $\gamma p \rightarrow \Upsilon p$ process can be written as (it is explained in ref. [3])

$$M(W, \Delta^2) = (i + \rho) \Im M(W, \Delta^2 = 0) \exp(-B(W)\Delta^2/2),$$

where $\rho$ is a ratio of real and imaginary part of the amplitude. Imaginary part of the amplitude depends on the light-cone wave function of $\Upsilon$ and the proton’s
Fig. 1. Total cross section for the $\gamma p \rightarrow \Upsilon(1S)p$ as a function of energy. The experimental data are taken from paper [2]. **Left panel**: solid curves - Gaussian (G) wave function, dashed curves - Coulomb (C) wave function. Thick lines were obtained including the NLO correction for the $\Upsilon$ decay width, thin lines are for $K_{NLO} = 1$. **Right panel**: solid curves - $B_0 = 3.5 \text{ GeV}^{-2}$, dashed curves - $B_0 = 4.5 \text{ GeV}^{-2}$. 

unintegrated gluon distribution (taken from Ivanov-Nikolaev [43]. $B(W)$ is slope parameter which depend on energy: $B(W) = B_0 + 2\alpha'_{eff} \log \left( \frac{W^2}{W_0^2} \right)$, with $\alpha'_{eff} = 0.164 \text{ GeV}^{-2}$, $W_0 = 95 \text{ GeV}$ (see ref. [2]). Our amplitude is normalized to the total cross section:

$$
\sigma_{tot}(\gamma p \rightarrow \Upsilon p) = \frac{1 + \rho^2}{16\pi B(W)} \left| 3m \frac{\mathcal{M}(W,0)}{W^2} \right|^2. 
$$

(2)

In our calculations we used two types of models for the wave functions: a Gaussian and a Coulomb-type one, with a power-law tail in momentum space (ref. [34]). Their parameters were fitted to the experimental decay widths $\Upsilon \rightarrow e^+e^-$. The relevant formalism can be found in refs. [13]. It involves the NLO-corrrection factor $K_{NLO}$. We have calculated for two different choices of factors $K_{NLO}$. In leading order $K_{NLO} = 1$, and next to leading order approximation $K_{NLO} = 1 - \frac{35}{3} \alpha_S(m_b^2)$.

In Fig. 1 we show the total cross section for the exclusive photoproduction $\gamma p \rightarrow \Upsilon p$ as a function of the $\gamma - p$ center-of-mass energy $W$. In the left panel we show results for the two different wave functions: Gaussian (solid lines) and Coulomb (dashed lines), without (thin lines) and with QCD corrections for the decay width (thick lines). For $J/\Psi$ photoproduction $B_0$ is $\sim 4.6 \text{ GeV}^{-2}$ (see ref. [6]). It $B_0$ should be somewhat smaller for the $\Upsilon$ meson. We show the sensitivity to the slope parameter $B_0$ in the right panel of Fig. 1. Our predictions are systematically somewhat below the experimental data. The results shown in the right panel of Fig. 1 were obtained for the Gaussian wave function and include QCD corrections for the decay width.
3. Exclusive photoproduction in $p\bar{p}$ collisions

The full amplitude for $p\bar{p} \rightarrow p\bar{p} \ Upsilon$ can be written as

$$\tilde{M}(\tilde{p}_1, \tilde{p}_2) = \int \frac{d^2 \tilde{k}}{(2\pi)^2} S_{el}(\tilde{k}) \tilde{M}^{(0)}(\tilde{p}_1 - \tilde{k}, \tilde{p}_2 + \tilde{k}) = \tilde{M}^{(0)}(\tilde{p}_1, \tilde{p}_2) - \delta \tilde{M}(\tilde{p}_1, \tilde{p}_2),$$  (3)

where

$$S_{el}(\tilde{k}) = (2\pi)^2 \delta^{(2)}(\tilde{k}) - \frac{1}{2} T(\tilde{k}), \quad T(\tilde{k}) = \sigma_{tot}^{pp}(s) \exp(-\frac{1}{2} B_{el} \tilde{k}^2),$$  (4)

with $B_{el} = 17$ GeV$^{-2}$, $\sigma_{tot}^{pp}(s) = 76$ mb (see ref. [3]). Here $\tilde{p}_1$ and $\tilde{p}_2$ are the transverse momenta of outgoing proton and antiproton.

In formula (3) $\tilde{M}^{(0)}(\tilde{p}_1, \tilde{p}_2)$ is the Born-amplitude (without absorptive corrections) for the process $p\bar{p} \rightarrow pUpsilon\bar{p}$ which includes our amplitude for HERA photoproduction and $\delta \tilde{M}(\tilde{p}_1, \tilde{p}_2)$ is the absorptive correction. Notice, that both proton and antiproton can emit the photon, and these two contributions interfere in the differential cross section. In particular, the interference is responsible for a dependence on the azimuthal angle $\phi$ between $\tilde{p}_1$ and $\tilde{p}_2$.

The differential cross section is given in terms of $\tilde{M}$ as

$$d\sigma = \frac{1}{512\pi^3 s^2} |\tilde{M}|^2 \ dy dt_1 dt_2 d\phi,$$  (5)

where $y$ is the rapidity of the vector meson, $t_{1,2} \simeq -\tilde{p}_{1,2}^2$.

The parameters chosen for this calculation correspond to the Gaussian wave function with $K_{NLO}$ included the QCD corrections. In Fig. 2 we show the distribution in rapidity of $\Upsilon(1S)$ (left panel) and $\Upsilon(2S)$ (right panel). Here the absorption effects cause about 20-30% decrease of the cross section.
Fig. 3. Ratio of $d\sigma/dydp_t^2$ with absorptive corrections included/switched off. \textbf{Left panel}: Absorption effect for $\Upsilon(1S)$. \textbf{Right panel}: the same for $\Upsilon(2S)$. The solid line: $y = 0$, dashed line: $y = 2$, dotted line: $y = 4$.

In Fig. 3, we show the ratio of the invariant cross section with to without absorptive corrections as a function of the $\Upsilon$–transverse momentum $p_t$. These results are for different values of rapidity: $y = 0$ (solid lines), $y = 2$ (dashed lines) and $y = 4$ (dotted lines). We can see that absorption effects is bigger for bigger rapidity and also for bigger $p_t$.

4. Conclusions

The results for $\gamma p \to \Upsilon(1S, 2S)p$ production depend on the model of the wave function. We have compared our results with a recent HERA data. Our results are somewhat lower than the experimental data. The amplitudes for the $\gamma p \to \Upsilon p$ process are used next to calculate the amplitude for the $p\bar{p} \to p\bar{p}\Upsilon$ reaction assuming the photon-Pomeron (Pomeron-photon) underlying dynamics. Absorptive corrections have been included, and they affect the shapes of various distributions. The resulting cross sections are of measurable size.

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