Upsilon photoproduction at HERA in perturbative QCD

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We estimate the cross section for $\gamma p \to \Upsilon p$ by two independent methods. Both QCD estimates are in good agreement with each other and with the recent measurements of the cross section at HERA and indicate the importance of the real part of the amplitudes as well as of the dynamics from off-diagonal parton distributions.

Recently first measurements of the elastic photoproduction of Υ mesons at HERA have become available. The observed cross section $B\sigma \equiv \sigma(\gamma p \to \Upsilon p)\, B(\Upsilon \to \mu^+\mu^-)$ is found to be rather large: $B\sigma(\Upsilon) = 13.3 \pm 6.0^{+2.7}_{-2.3}$ pb at $\langle W \rangle = 120$ GeV (ZEUS [1]) and $B\sigma(\Upsilon) = 16.0 \pm 7.5 \pm 4.0$ pb at $\langle W \rangle = 160$ GeV (H1 (preliminary) [2]), where Υ stands for the sum over the $\Upsilon(1S), \Upsilon(2S)$ and $\Upsilon(3S)$ states and where $\langle W \rangle$ is the average photon-proton centre-of-mass energy. Here we estimate elastic Υ photoproduction from perturbative QCD by two independent methods.

1. METHOD I

The first method is based on the leading-order expression for the photoproduction of a heavy vector meson of mass M_V [3]

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

where Γ_{ee}^V is the partial width of the $V \to ee$ decay, α_s is the QCD coupling, $\alpha = 1/137$ is the QED coupling and $g(x,\mu^2)$ is the gluon density measured at $x = M_V^2/W^2$ and the scale $\mu = m_Q \simeq M_V/2$. We now briefly discuss four types of corrections to this naive formula.

(a) Relativistic corrections

A non-relativistic wave function for the heavy vector meson was used to derive (1), so first we quantify the size of the relativistic corrections. In the case of J/ψ production the velocity of the charm quarks in the meson can be sizeable $\left(\langle v^2 \rangle \simeq \frac{1}{4}\right)$, leading to corrections in the cross section of about 2 according to [4] or up to a factor of 10 in [5]. However it was shown in [4] that to a good approximation this correction is nullified in the cross section formula (1) since it has been written in terms of the J/ψ mass, instead of the current quark mass $(2m_c < M_\psi)$ which should have been used in perturbative QCD. So it turns out that there are practically no $\langle v^2 \rangle$ corrections to the leading order result (1). This result is consistent with a more detailed study by Hoodbhoy [6], who showed that the total $O(v^2)$ relativistic correction (including corrections to the quark propagator and extra gluons in the J/ψ wave function) to the naive cross section formula (1) amounts to at most only 7% for J/ψ photoproduction. The correction should be even smaller for Υ production. Therefore we neglect these relativistic effects below.

(b) Real part

Only the imaginary part of the $\gamma p \to Vp$ amplitude is expressed in terms of $xg(x,\mu^2)$ in (1). To restore the real part we make use of the approximation $\mathrm{Re}A/\mathrm{Im}A \simeq \pi\lambda/2$ where $\lambda = \partial \log A/\partial \log s$ is obtained as the logarithmic derivative of the gluon distribution $xg(x,\mu^2)$. The real part correction factor is then given by $C_b = \left(1 + \frac{\pi^2\lambda^2}{4}\right) = 1.43\,(1.36)$ or $1.54\,(1.46)$ for $\langle W \rangle = 120\,(160)$ GeV and scale $\mu^2 = 25$ GeV^2, according to whether the MRS(R2) [7] or the GRV [8] gluon distribution is used.

(c) The effect of off-diagonal partons

Strictly speaking the amplitude is proportional to the off-diagonal gluon distribution $x'g(x,x')$,

*In collaboration with A.D. Martin and M.G. Ryskin where the momentum fraction x' carried by the "second" gluon is much smaller than the fraction $x \simeq M_V^2/W^2$ carried by the "first" gluon. The effect, $R = x'g(x,x')/xg(x)$, was estimated in [9]. The correction is small for light mesons, but is much more important for Υ photoproduction since the scale $\mu^2 \simeq M_\Upsilon^2$ and the value of $x = M_\Upsilon^2/W^2$ are much larger. The correction factor to the cross section formula (1) is [9] $C_c = R^2 \simeq (1.4)^2 \simeq 2$.

(d) NLO corrections

Finally we have NLO corrections which come from an explicit integration over the loop which corresponds to the convolution of the exchanged gluons with the vector meson wave function. The integral is not of a pure logarithmic form, which was assumed in deriving the leading order result (1). As discussed in [4] the typical range of integration corresponds to the scale $\mu^2 = \frac{1}{4}M_V^2$ and the correction can be written as $C_d \simeq \left(1 + \alpha_s\left(\frac{1}{4}M_V^2\right)/2\right) \simeq 1.2$.

Assuming that the elastic Υ differential cross section, $d\sigma/dt \sim \exp(bt)$, has a slope $b = 4$ GeV^{-2}, as for elastic J/ψ photoproduction, the leading order formula gives $B\sigma(\Upsilon_{1S})|_{\rm LO} \simeq 1.7$ pb at $\langle W\rangle = 120$ GeV. Taking into account the corrections $C_{b,c,d}$ we obtain $B\sigma(\Upsilon_{1S}) \simeq 6$ pb. However, the cross section measurements of the ZEUS and H1 collaborations did not select the pure $\Upsilon(1S)$ state, but rather the data were integrated over an interval of the $\mu^+\mu^-$ mass which includes at least the $1S$, $2S$ and $3S$ resonances. We estimate the combined contributions of the $2S$ and $3S$ states to be 40% of the $\Upsilon(1S)$ cross section, in agreement with the measurement of the CDF collaboration [10]. Thus we finally get $B\sigma(\Upsilon) = 8.4$ pb, which is compatible with the ZEUS measurement quoted above. Going from $\langle W\rangle = 120$ GeV to 160 GeV, the cross section is predicted to increase by a factor of 1.6, due to the larger gluon density at smaller x, and so our calculation is also in agreement with the preliminary H1 measurement.

2. METHOD II

The second method makes use of parton-hadron duality similar to [11], where ρ electroproduction at HERA was described successfully. The procedure is to calculate the amplitude for open $q\bar{q}$ production, then to project the amplitude onto the $J^P = 1^-$ $q\bar{q}$ state and finally to integrate the cross section over an appropriate interval ΔM of the mass of the $q\bar{q}$ pair which includes the resonance peak(s). Because there are almost no other possibilities for hadronization at $M_{q\bar{q}} \simeq M_V$ we should obtain a reasonable estimate of the cross section for vector meson production. In our numerical calculation all the corrections mentioned above are taken into account, with the exception of the enhancement due to the use of off-diagonal gluons. We therefore include the extra factor $C_c \simeq 2$. In practice we have to extend the formalism of [11] to include the mass of the heavy b quark. For complete formulae and a description of the projection the reader is referred to [12]. Unfortunately the full NLO corrections for diffractive processes are not known yet. Therefore we approximate the NLO corrections by a K factor [11, 13], which was demonstrated to provide a reasonable normalization of the predicted cross sections for both ρ meson and charm ($c\bar{c}$) diffractive leptoproduction. As in [13] the scale in the coupling $\alpha_s(\mu^2)$ was chosen to be $\mu^2 = M^2/4$. This results in a K factor of $2.2 - 2.6$ for the case of Υ production considered here.

To compare with the ZEUS data for $\gamma p \to \Upsilon p$ we integrate over the mass interval 8.9–10.9 GeV. Taking the mass of the b quark to be $m_b = 4.6$ GeV and using the MRS(R2) set of partons [7] we find for our method II $\sigma(\gamma p \to \sum \Upsilon p) \simeq 620$ pb at $\langle W\rangle = 120$ GeV. This should be compared with the value 635 ± 310 pb obtained from the ZEUS measurement by assuming the ratios $B\sigma(\Upsilon_{1S}) : B\sigma(\Upsilon_{2S}) : B\sigma(\Upsilon_{3S}) \simeq 0.7 : 0.15 : 0.15$, which are consistent with the expectations of (1) and with the CDF data [10], and by using the known leptonic branching ratios B of the Υ states.

What is the uncertainty in our cross section estimate due to the choice of m_b? If we were to use $m_b = 4.4$ or 4.8 GeV then the cross section $\sigma(\gamma p \rightarrow \sum \Upsilon p)$ would become 900 or 380 pb, respectively. Concerning uncertainties from the parametrization of the gluon distribution we note that in the case of Υ production we sample the gluon at $x \sim 0.01$ and $Q^2 \sim 25$ GeV^2, where the uncertainties are small.

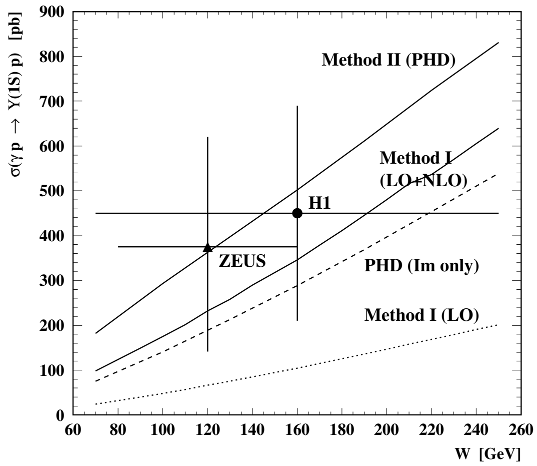

Figure 1. QCD predictions for $\gamma p \rightarrow \Upsilon(1S)p$ as discussed in the text compared with the ZEUS [1] and preliminary H1 [2] measurements.

Fig. 1 shows the ZEUS and H1 data, together with our QCD estimates obtained from the two independent methods (continuous curves). The comparison is given for the $\gamma p \rightarrow \Upsilon(1S)p$ cross section as a function of the photon-proton centre-of-mass energy W. To obtain the $\Upsilon(1S)$ cross section for method II, in which we integrate over the mass interval 8.9–10.9 GeV, we divide the $\gamma p \rightarrow (\sum \Upsilon)p$ result by a factor 1.7 obtained from the ratios $B\sigma(\Upsilon_{1S}) : B\sigma(\Upsilon_{2S}) : B\sigma(\Upsilon_{3S})$ discussed above and the known branching fractions B. For completeness we also show in Fig. 1 the prediction from the naive leading order formula (1) of method I (dotted curve) as well as the result of method II without the corrections from the real part of the amplitudes (dashed curve). We note that the enhancement of about a factor of 2 due to off-diagonal gluon effects appears to be required by the data.

On this conference similar work was reported by M. McDermott [14]. Their procedure is comparable to our method I and also yields a cross section compatible with the HERA data. However, although our final values are similar, there are significant differences in the various component factors like relativistic corrections and contributions from non-forward parton distributions.

We conclude that the recent measurements of elastic Υ photoproduction are in good agreement with the expectations of perturbative QCD. Of course when more precise data become available the effects that are estimated here — relativistic corrections, NLO contributions, off-diagonal parton effects and the contribution of the real part of the amplitude — should be calculated in more detail. The elastic photoproduction of J/ψ and Υ at HERA will be a good laboratory to probe these effects.

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