

Measurement of the t -dependence in Exclusive Photoproduction of $\Upsilon(1S)$ Mesons at HERA

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The exclusive photoproduction reaction $\gamma p \rightarrow \Upsilon(1S)p$ has been studied with the ZEUS detector in ep collisions at HERA using an integrated luminosity of 468 pb^{-1} . The measurement covers the kinematic range $60 < W < 220 \text{ GeV}$ and $Q^2 < 1 \text{ GeV}^2$, where W is the photon-proton c.m.s. energy and Q^2 is the photon virtuality. The exponential slope, b , of the t dependence of the cross section, where t is the squared four-momentum transfer at the proton vertex, has been measured, yielding $b = 4.3^{+2.0}_{-1.3}(\text{stat.})^{+0.5}_{-0.6}(\text{syst.}) \text{ GeV}^{-2}$. This constitutes the first measurement of the t dependence of the $\gamma p \rightarrow \Upsilon(1S)p$ cross section.

1 Introduction

In exclusive photoproduction of heavy vector mesons (VM), the mass of the heavy quark provides a hard scale and the process can be described by models based on perturbative QCD (pQCD) [1, 2]. At leading order (Fig. 1) the photon fluctuates into a $q\bar{q}$ state of small transverse size, which interacts with partons in the proton through a two-gluon colour-singlet state, forming a heavy VM. The cross section is proportional to the square of the gluon density in the proton thus heavy vector meson photoproduction exhibits rapid rise of the cross section with the photon-proton c.m.s. energy, W , explained through the increasing gluon density with decreasing fractional momentum, $x \propto 1/W^2$ (at HERA $10^{-4} < x < 10^{-2}$). Prior to this measurement, the ZEUS Collaboration measured the W -dependence of the exclusive photoproduction of $\Upsilon(1S)$ mesons, $\gamma p \rightarrow \Upsilon(1S)p$, parametrised as $\sigma^{\gamma p}(W) \propto W^\delta$, yielding $\delta = 1.2 \pm 0.8$ [3] (Fig. 2), consistent with predictions for exclusive photoproduction of $\Upsilon(1S)$ mesons in leading-order pQCD [4]. Studies of the exclusive photoproduction of vector mesons [5] have shown that the

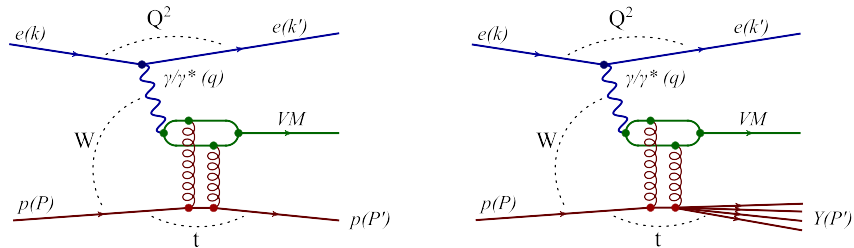


Figure 1: Diagrams for exclusive (left) and proton-dissociative (right) vector-meson photoproduction in ep interactions (see text for description of kinematic variables).

t dependence of the differential cross section may be approximated in the region of small t ($|t| < 1 \text{ GeV}^2$) with a single exponential: $d\sigma/d|t| \propto \exp(-b|t|)$, where t is the four-momentum transfer squared at the proton vertex. The slope parameter, b , measured at ZEUS for exclusive J/ψ production at $W_0 = 90 \text{ GeV}$ is $b = 4.15 \pm 0.05(\text{stat.})^{+0.30}_{-0.18}(\text{syst.}) \text{ GeV}^{-2}$ [6] (and exhibits a logarithmic W variation). In an optical model approach for exclusive production of vector mesons, the slope parameter b is related to the radii of the proton, R_p , and the vector meson, R_{VM} , according to the formula: $b \approx (R_p^2 + R_{VM}^2)/4$. The value of b measured for J/ψ production is approximately equal to that expected from the size of the proton, $b \approx 4 \text{ GeV}^{-2}$, in agreement with calculations based on pQCD [7]. This suggests that the size of the J/ψ meson is small compared to that of the proton. A similar picture is expected in the case of exclusive $\Upsilon(1S)$ production [8, 9].

This contribution reports on the first measurement of b in exclusive $\Upsilon(1S)$ photoproduction, observed in the $\mu^+\mu^-$ decay channel in the kinematic range $60 < W < 220 \text{ GeV}$, using data collected with the ZEUS detector [10], corresponding to an integrated luminosity of 468 pb^{-1} (1996-2007). In the quoted period HERA provided electron and positron beams of energy $E_e = 27.5 \text{ GeV}$ and proton beams of energy $E_p = 920(820) \text{ GeV}$ (c.m.s. energy $\sqrt{s} = 318(300) \text{ GeV}$). The four-momenta of the incoming and outgoing electron and proton are

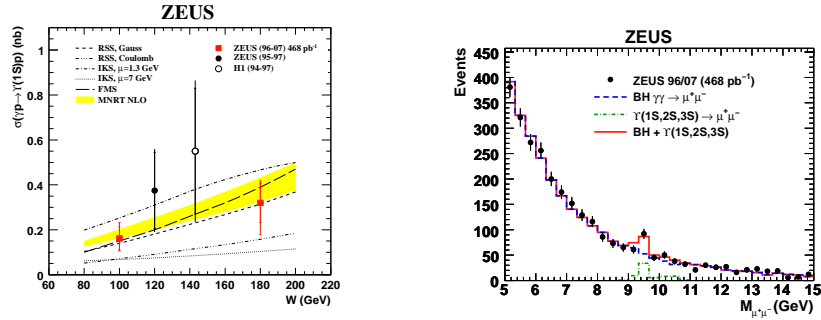


Figure 2: Left: W -dependence of the exclusive photoproduction of $\Upsilon(1S)$ Mesons, $\gamma p \rightarrow \Upsilon(1S)p$, and predictions in leading-order pQCD [4]; right: this analysis - invariant mass distribution of $\mu^+\mu^-$ pairs. The dashed line shows the simulated Bethe-Heitler (BH) (exclusive and proton dissociative) distribution, normalised to the data points in the range $[5 - 15] \text{ GeV}$ with exclusion of the $[9 - 11] \text{ GeV}$ mass window. Simulated contributions of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances is shown as a histogram on the mass axis (dashed-dotted line). The solid line shows the sum of all contributions.

denoted by k , k' , P and P' , respectively. The exclusive reaction $ep \rightarrow e\Upsilon(1S)p$ is described by the following variables (Fig. 1): $s = (k + P)^2$, the c.m.s. energy squared of the electron-proton system; $Q^2 = -q^2 = -(k - k')^2$, the negative four-momentum squared of the exchanged photon; $y = (q \cdot P)/(k \cdot P)$, the fraction of the electron energy transferred to the hadronic final state in the rest frame of the initial-state proton; $W^2 = (q + P)^2 = -Q^2 + 2y(k \cdot P) + m_p^2$, the c.m.s. energy squared of the photon-proton system, where m_p is the proton mass; $M_{\mu^+\mu^-}$, the invariant mass of the $\mu^+\mu^-$ pair; $t = (P - P')^2$, the squared four-momentum transfer at the proton vertex, determined from the approximate formula: $t \approx -(p_x^+ + p_x^-)^2 - (p_y^+ + p_y^-)^2$ where $p_{x,y}^\pm$ are the components of the transverse momentum of the decay muons.

The details of the present analysis can be found elsewhere [11]. Events were restricted to Q^2 values from the kinematic minimum, $Q^2 \approx 10^{-9} \text{ GeV}^2$ to a value at which the scattered electron starts to be observed in the calorimeter (CAL), $Q^2 \approx 1 \text{ GeV}^2$, with an estimated median Q^2 value of 10^{-3} GeV^2 . Exclusive $\mu^+\mu^-$ events in photoproduction were selected online by requiring at least one track associated with a deposit in muon detectors. The main offline selections were as follows: two oppositely charged tracks forming a vertex and no other tracks present in the central tracking system; position of the vertex consistent with an ep interaction; transverse momentum of each track $p_T > 1.5 \text{ GeV}$; at least one track identified as a muon in muon detectors, if not explicitly identified as a muon, the second track had to be associated with a minimum-ionising energy deposit in the CAL; the energy of each CAL cluster not associated to any of the final-state muons was required to be less than 0.5 GeV , in order to be above the noise level of the CAL. It implicitly selected exclusive events with an effective cut $Q^2 < 1 \text{ GeV}^2$; the sum of the energy in the forward CAL modules surrounding the beam hole had to be smaller than 1 GeV to suppress the contamination from proton-dissociative events, $ep \rightarrow e\Upsilon Y$ (Fig. 1). According to a Monte Carlo study, this corresponds to an effective cut on the mass M_Y of the dissociated system originating from the proton, $M_Y < 4 \text{ GeV}$; four-momentum-transfer squared $|t| < 5 \text{ GeV}^2$. The total number of selected $\mu^+\mu^-$ pairs was 2769 (contamination with cosmic ray muons is below 1%).

The invariant-mass distribution of $\mu^+\mu^-$ pairs is shown in Fig. 2 including the simulated contributions from the Bethe-Heitler (exclusive and proton dissociative) process and from the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances. The BH distributions were normalised to the data in the range $[5 - 15] \text{ GeV}$ excluding the $[9 - 11] \text{ GeV}$ mass window. For the determination of the slope parameter for exclusive $\Upsilon(1S)$ production, only events in the mass window $[9.33 - 9.66] \text{ GeV}$ were considered. The width of the mass window was chosen in order to avoid excessive smearing of the t variable and to retain a good signal-to-background ratio (71% of all reconstructed $\Upsilon(1S)$ events are expected in this window and the relative contaminations of $\Upsilon(2S)$ and $\Upsilon(3S)$ states with respect to $\Upsilon(1S)$ are 1.3% and 0.1%, respectively). The contribution from the $\Upsilon(2S)$ and $\Upsilon(3S)$ states was neglected for the extraction of the slope parameter b . The value of the slope parameter for exclusive $\Upsilon(1S)$ production was determined as follows: the sum of simulated distributions of all contributing processes was fitted to the observed event yields in the signal mass window $[9.33 - 9.66] \text{ GeV}$ in the four t bins shown in Fig. 3. A binned Poissonian log-likelihood function was used. The expected number of Bethe-Heitler background events was fixed to the value obtained from the $\mu^+\mu^-$ spectrum outside the signal region. In view of insufficient statistics for a standalone measurement, the contribution of proton-dissociative $\Upsilon(1S)$ events in the final sample was adopted from diffractive J/ψ production [6], 0.25 ± 0.05 .

The values of the slope parameter for the proton dissociative $\Upsilon(1S)$ production in the MC was taken to be $0.65 \pm 0.1 \text{ GeV}^2$ [6]. The fit was performed with two free parameters: the slope b and the number of expected $\Upsilon(1S)$ events in the signal mass window. After evaluation of systematic uncertainties, the slope parameter b for the exclusive production of $\Upsilon(1S)$ mesons was measured to be $b = 4.3_{-1.3}^{+2.0}(\text{stat.})_{-0.6}^{+0.5}(\text{syst.}) \text{ GeV}^{-2}$.

A comparison of all HERA measurements of the slope parameter b for exclusive light and heavy vector meson production and for deeply virtual Compton scattering (DVCS) is shown in Fig. 3. This analysis doubles the range covered by previous measurements in terms of $Q^2 + M_{VM}^2$, where M_{VM} denotes the mass of a vector meson, extending the value of the scale to $\approx 90 \text{ GeV}^2$, the highest achieved to date in the measurement of the t -slope parameter for a vector meson. The measured value is in agreement with an asymptotic behaviour of this dependence, reflecting the proton radius. This was already suggested by earlier measurements and is consistent with

predictions based on pQCD models ($b = 3.68 \text{ GeV}^{-2}$) [12].

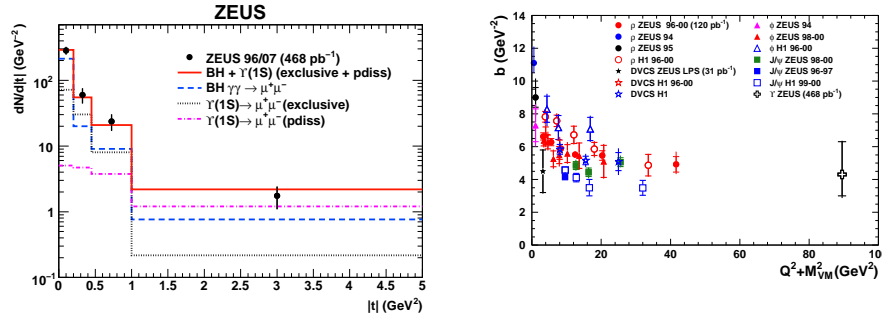


Figure 3: Left: Measured $|t|$ distribution (full dots) with error bars denoting statistical uncertainties. Fitted distributions for simulated events are shown for the Bethe-Heitler (dashed line), exclusive $\Upsilon(1S)$ (dotted line) and proton dissociative $\Upsilon(1S)$ (dashed-dotted line) processes. The solid line shows the sum of all contributions; right: compilation of the HERA measurements of the slope parameter b as a function of the scale $Q^2 + M_{\Upsilon M}^2$, for exclusive $\Upsilon(1S)$ production (the rightmost data point), for other exclusive vector-meson production and for deeply virtual Compton scattering (DVCS) (see [11] for references).

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