Measurement of the t-dependence in exclusive photoproduction of $\Upsilon(1S)$ mesons at HERA

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Abstract. The exclusive photoproduction reaction $\gamma p \to \Upsilon(1S)\, p$ 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 $60 < W < 220$ GeV and $Q^2 < 1$ GeV^2, where W is the photon–proton centre-of-mass energy and Q^2 is the photon virtuality. The slope of the t-dependence of the cross section $\propto \exp(-b|t|)$, where t is the squared four-momentum transfer at the proton vertex, has been measured, yielding $b = (4.3^{+1.7}_{-1.1}\ \text{(stat.)}\ ^{+0.5}_{-0.5}\ \text{(syst.)})$ GeV^{-2} (prel.). This constitutes the first measurement of the t-dependence of the $\gamma p \to \Upsilon(1S)\, p$ cross section.

Keywords: heavy vector mesons, exclusive photoproduction, HERA, ZEUS
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INTRODUCTION

In exclusive photoproduction of heavy vector mesons (VMs), J/ψ and Υ, the masses of the charm and the bottom quarks provide a hard scale and the process can be described by models based on perturbative QCD (pQCD) [1, 2]. The photon-proton interaction may be viewed at leading order as shown in Fig. 1: the photon fluctuates into a $q\bar{q}$ pair, which then interacts through a two-gluon colour-singlet state with partons in the proton and a heavy vector meson is formed.

The differential cross section may be approximated in the region of small t ($|t| < 1$ GeV^2) using a single exponential: $d\sigma/d|t| \propto \exp(-b|t|)$, where t is the four-momentum transfer squared at the proton vertex. In exclusive production of VMs, the slope parameter, b, is related to the radii of the proton and the vector meson according to the approximate formula: $b \approx (R_p^2 + R_{VM}^2)/4$, where R_p and R_{VM} are the radii of a vector meson and proton, respectively. The value of b measured for J/ψ production [3] is approximately equal to that expected from the size of the proton ($b \approx 4$ GeV^{-2}). This suggests that the size of the heavy VM is small compared to that of the proton. A similar picture is expected in the case of exclusive Υ(1S) production.

In this note we report on the first measurement of b in exclusive $\Upsilon(1S)$ photoproduction, observed in the $\mu^+\mu^-$ decay channel in the kinematic range $60 < W < 220$ GeV using a data sample corresponding to the integated luminosity of 468 pb^{-1}, collected in the period 1996–2007 with the ZEUS detector in ep collisions at HERA.

KINEMATICS AND EVENT SELECTION

The four-momenta of the incoming electron and proton, and the scattered electron and proton are denoted by k, P, k' and P', respectively. The exclusive reaction under study $ep \to e\Upsilon p \to e\mu^+\mu^- p$, is described by the following variables (Fig. 1, left):

- $Q^2 = -q^2 = -(k-k')^2$, the four-momentum squared of the exchanged photon;
- $W^2 = (q+P)^2 = -Q^2 + 2y(k\cdot P) + m_p^2$, the centre-of-mass energy squared of the photon–proton system, where m_p is the proton mass; determined from the approximate formula, valid for small Q^2 values: $W^2 \approx 4E_pE_ey \approx 2E_p(E-p_Z)$, where E is the energy and p_Z is the longitudinal momentum 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 reaction $ep \to e\Upsilon Y$, (Fig. 1, right), where Y denotes a hadronic state originating from proton dissociation, constitutes an important source of background. These events mimic the exclusive Υ production when hadrons from proton dissociation remain undetected.

Exclusive $\mu^+\mu^-$ events in photoproduction were selected using dedicated triggers and offline selection cuts:

- a primary vertex position consistent with ep interaction;
- exactly two oppositely charged long tracks matched to the vertex;
- transverse momentum of each track $p_T > 1.5$ GeV;
- $|\eta^+ - \eta^-| \leq 1.5$, where $\eta^{\pm}$ is the pseudorapidity[1] of a given track, to suppress Bethe-Heitler background;
- at least one track identified as a muon, if not explicitly identified as a muon, the second track had to be consistent with being a minimum-ionising particle (MIP);
- invariant mass of the muon pair $M_{\mu^+\mu^-}$ in the range between 5 and 15 GeV;
- elasticity cuts on calorimeter deposits not associated with the $\mu^+\mu^-$ pair.

The events were selected in the kinematic range $60 < W < 220$ GeV, $Q^2 < 1$ GeV^2 and $|t| < 5$ GeV^2.

DETERMINATION OF THE t-SLOPE PARAMETER b

The invariant mass distribution of $\mu^+\mu^-$ pairs after applying the selection criteria is shown in Fig. 2 (left). Elastic and proton dissociative vector meson production was simulated using the DIFFVM 2.0 generator [4]. The non-resonant background, consisting of the elastic and proton dissociative Bethe-Heitler (BH) dimuon events, was simulated using the GRAPE v1.1k MC program [5].

The distribution of the $|t|$ variable for the data and simulated events, using the final fit results discussed below, is shown in Fig. 2 (right). The fraction of proton-dissociative

[1] Pseudorapidity is defined as $\eta = -\ln(\tan\frac{\theta}{2})$.

events in the final sample is expected to be similar for all heavy VMs and was assumed to be $f_{\text{pdiss}} = 0.25 \pm 0.05$ [6]. The values of the slope parameter b for the elastic and proton dissociative $\Upsilon(1S)$ production differ [7], the value for the latter was taken to be $b_{\text{pdiss}} = 0.65^{+0.1}_{-0.1}\text{GeV}^{-2}$ [3] in the signal MC. In order to determine the slope parameter for elastic $\Upsilon(1S)$ production, events from the mass window [9.33–9.66] GeV were considered. The width of the mass window was limited to 0.33 GeV in order to avoid excessive smearing of the t-variable and to retain a good signal to background ratio.

The sum of simulated distributions of all contributing processes was fitted to the observed event numbers in the signal mass window in the four t-bins shown in Fig. 2 (right). A binned Poissonian log-likelihood function, $\ln(L)$, was used. The expected number of $\Upsilon(1S)$ signal and Bethe-Heitler background events was constrained to the value obtained from the fit to the $\mu^+\mu^-$ mass spectrum.

RESULT AND DISCUSSION

Taking into account the statistical errors from the fit and the systematic uncertainties the slope parameter b for the elastic production of $\Upsilon(1S)$ mesons was measured to be $b = (4.3^{+1.7}_{-1.1}\,(\text{stat.})\,^{+0.5}_{-0.5}\,(\text{syst.}))\,\text{GeV}^{-2}$ (prel.). A comparison of all HERA measurements of the slope parameter b for exclusive light and heavy vector meson production and as well as for deeply virtual Compton scattering (DVCS) is shown in Fig. 3. This analysis doubles the range covered by previous measurements in terms of the $Q^2 + M_{VM}^2$ scale, where M_{VM} denotes the mass of a vector meson VM. The measured value is in agreement with an asymptotic behaviour of this dependence, already suggested by earlier measurements, $b \approx 4 - 5\ \text{GeV}^{-2}$, in agreement with expectations implied by the proton radius and predictions based on pQCD models ($b = 3.68\ \text{GeV}^{-2}$) [8].

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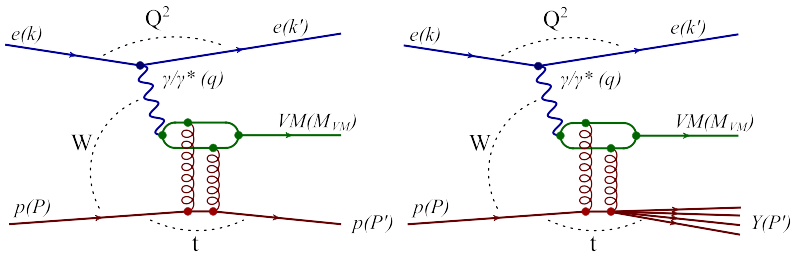

FIGURE 1. Diagrams for the vector meson elastic (left) and proton dissociative (right) photoproduction in ep interactions. Variables describing the kinematics of the process are introduced in the text.

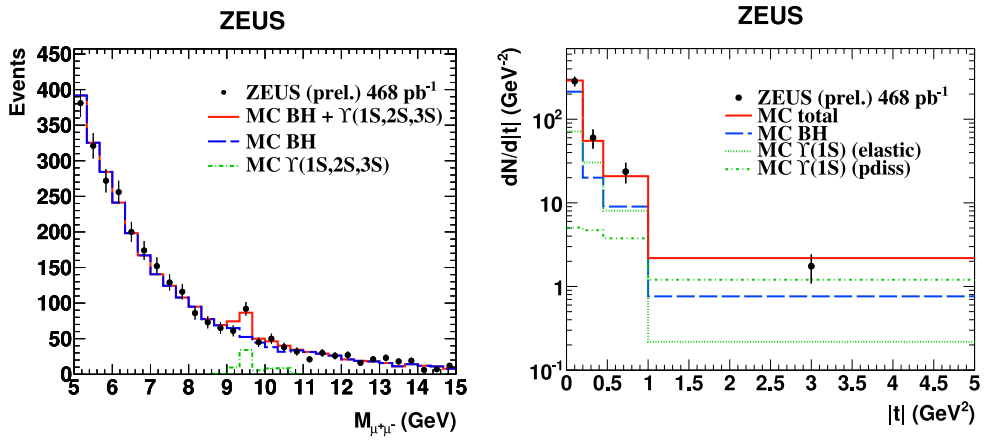

FIGURE 2. Left: Invariant mass distribution of $\mu^+\mu^-$ pairs after all event selections. Right: The measured distribution of the $|t|$ variable for events from the [9.33–9.66] GeV signal mass window. Simulated MC distributions of the contributing processes using the final fit results are described in the legends.

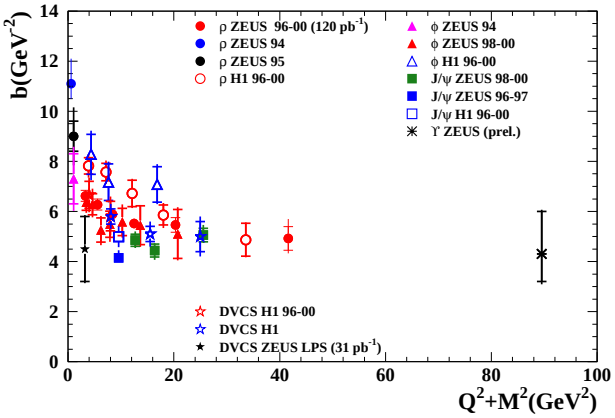

FIGURE 3. Comparison of the HERA measurements of the slope parameter b as a function of the scale $Q^2 + M_{VM}^2$ for elastic, light and heavy vector meson production [9, 10, 11, 7, 12, 13, 14, 3, 15] and for the deeply virtual Compton scattering (DVCS) [16, 17, 18].