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

ZEUS Collaboration

Abstract

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 $60 < W < 220$ 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 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 $b = 4.3^{+2.0}_{-1.3}$ (stat.) $^{+0.5}_{-0.6}$ (syst.) GeV^{-2}. This constitutes the first measurement of the t dependence of the $\gamma\, p \rightarrow \Upsilon(1S)\, p$ cross section.

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1 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 interaction may be viewed at leading order as shown in 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 vector meson. Thus the cross section is proportional to the square of the gluon density in the proton. A characteristic feature of heavy VM photoproduction is the rapid rise of the cross section with the photon–proton centre-of-mass energy, W. This can be explained through the increasing gluon density with decreasing fractional momentum, $x \propto 1/W^2$ (where the x region accessible in heavy-quark production at HERA is $10^{-4} < x < 10^{-2}$). Numerous studies have shown that the dependence of the cross section on W can be parameterised as $\sigma \propto W^\delta$ [3, 4]. Measurements for the J/ψ meson [5, 6] yielded $\delta \approx 0.7$. A higher value of $\delta \approx 1.7$ has been predicted for exclusive photoproduction of $\Upsilon(1S)$ mesons in leading-order pQCD [7], consistent with the recent ZEUS measurement: $\delta = 1.2 \pm 0.8$ [8].

Studies of the exclusive photoproduction of light and heavy vector mesons [3] have shown that the t dependence of the differential cross section may be approximated in the region of small t ($|t| < 1$ 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 [5] at $W_0 = 90$ GeV is $b = 4.15 \pm 0.05$ (stat.) $^{+0.30}_{-0.18}$ (syst.) GeV^{-2} and exhibits a logarithmic variation: $b(W) = b_0 + 2\alpha' \ln(W/W_0)^2$, where $\alpha' \approx 0.1$ GeV^{-2}. In an optical model approach for exclusive production of VMs, the slope parameter b is related to the radii of the proton, R_p, and the vector meson, R_{VM}, according to the approximate 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 ($b \approx 4$ GeV^{-2}), in agreement with calculations based on pQCD [9]. This suggests that the size of the J/ψ is small compared to that of the proton. A similar picture is expected in the case of exclusive $\Upsilon(1S)$ production [10, 11].

The present paper reports on the first measurement of b in exclusive $\Upsilon(1S)$ photoproduction, observed in the $\mu^+\mu^-$ decay channel in the kinematic range $60 < W < 220$ GeV, and complements the previous results [8, 12, 13] on $\Upsilon(1S)$ photoproduction. The data correspond to an integrated luminosity of 468 pb^{-1}, collected in the period 1996–2007.

2 Experimental set-up

In 1998–2007 (1996–1997), HERA provided electron[1] beams of energy $E_e = 27.5$ GeV and proton beams of energy $E_p = 920$ (820) GeV, resulting in a centre-of-mass energy of $\sqrt{s} = 318$ (300) GeV.

A detailed description of the ZEUS detector can be found elsewhere [14]. A brief outline of the components that are most relevant for this analysis is given below.

In the kinematic range of the analysis, charged particles were tracked in the central tracking detector (CTD) [15] and, for the data taken after 2001, also in the microvertex detector (MVD) [16]. These components operated in a magnetic field of 1.43 T provided by a thin superconducting solenoid. The CTD consisted of 72 cylindrical drift chamber layers, organised in nine superlayers covering the polar-angle[2] region $15° < \theta < 164°$. The MVD provided polar angle coverage from $7°$ to $150°$. The transverse-momentum resolution for full-length tracks was $\sigma(p_T)/p_T = 0.0058\,p_T \oplus 0.0065 \oplus 0.0014/p_T$, with p_T in GeV, for data taken before 2001 and $\sigma(p_T)/p_T = 0.0029\,p_T \oplus 0.0081 \oplus 0.0012/p_T$, for data taken after 2001.

The high-resolution uranium–scintillator calorimeter (CAL) [17] consisted of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. Each part was subdivided transversely into towers and longitudinally into one electromagnetic section (EMC) and either one (in RCAL) or two (in BCAL and FCAL) hadronic sections (HAC). The smallest subdivision of the calorimeter is called a cell. The CAL energy resolutions, as measured under test-beam conditions, are $\sigma(E)/E = 0.18/\sqrt{E}$ for electrons and $\sigma(E)/E = 0.35/\sqrt{E}$ for hadrons, with E in GeV.

The muon system consisted of barrel, rear (B/RMUON) [18] and forward (FMUON) [14] tracking detectors. The B/RMUON consisted of limited-streamer (LS) tube chambers placed behind the BCAL (RCAL), both inside and outside the magnetised iron yoke surrounding the CAL. The barrel and rear muon chambers covered polar angles from $34°$ to $135°$ and from $135°$ to $171°$, respectively. The FMUON consisted of six planes of LS tubes and four planes of drift chambers covering the angular region from $5°$ to $32°$. The muon system exploited the magnetic field of the iron yoke and, in the forward direction, of two iron toroids magnetised to 1.6 T to provide an independent measurement of the muon momentum.

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[1] Electrons and positrons are both referred to as electrons in this article.

[2] The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the "forward direction", and the X axis pointing left towards the centre of HERA. The coordinate origin was located at the nominal interaction point for data collected before 2001. After 2001 it was redefined as the centre of the CTD. The polar angle, θ, is measured with respect to the proton beam direction.

The iron yoke surrounding the CAL was instrumented with proportional drift chambers to form the Backing Calorimeter (BAC) [19]. The BAC consisted of 5142 aluminium chambers inserted into the gaps between 7.3 cm thick iron plates (10, 9 and 7 layers in forward, central (barrel) and rear subdetectors, respectively) serving as calorimeter absorber. The chambers were typically 5 m long and had a wire spacing of 1.5 cm. The anode wires were covered by 50 cm long cathode pads. The BAC was equipped with energy readout and position-sensitive readout for muon tracking. The former was based on 1692 pad towers ($50 \times 50 \, \text{cm}^2$), providing an energy resolution $\sigma(E)/E = 1.0/\sqrt{E}$, where E is expressed in GeV. The position information from the wires allowed the reconstruction of muon trajectories in two dimensions (XY in barrel and YZ in endcaps) with a spatial accuracy of a few mm.

The luminosity was measured using the Bethe-Heitler reaction $ep \to e\gamma p$ with the luminosity detector which consisted of independent lead–scintillator calorimeter [20] and magnetic spectrometer [21] systems.

3   Kinematics

The four-momenta of the incoming and outgoing electron and proton are denoted by k, k', P and P', respectively. The exclusive reaction under study

$$ep \to e\Upsilon p \to e\mu^+\mu^- p \tag{1}$$

is described by the following variables (Fig. 1, top):

- $s = (k + P)^2$, the centre-of-mass-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 centre-of-mass-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 reaction $ep \to e\Upsilon Y$, (Fig. 1, bottom), where Y denotes a hadronic state originating from proton dissociation, constitutes an important background. These events mimic exclusive Υ production when the hadrons from proton dissociation remain undetected.

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Events used in the analysis were restricted to Q^2 values from the kinematic minimum, $Q^2_{\min} = m_e^2 y^2/(1-y) \approx 10^{-9}$ GeV^2, where m_e is the electron mass, to a value at which the scattered electron starts to be observed in the CAL, $Q^2_{\max} \approx 1$ GeV^2, with an estimated median Q^2 value of 10^{-3} GeV^2. The photon–proton centre-of-mass energy can then be expressed as:

$$W^2 \approx 4E_p E_e y \approx 2E_p(E - p_Z), \tag{2}$$

where E is the energy and p_Z is the longitudinal momentum of the $\mu^+\mu^-$ pair.

The approximate formula for t introduces dispersion 3 times smaller then that in the experimental resolution of this variable after all event selections; approximation (2) has a negligible effect in the case of W.

4   Event selection

Exclusive $\mu^+\mu^-$ events in photoproduction were selected online by requiring at least one CTD track associated with a F/B/RMUON deposit or with a signal in the BAC consistent with a muon. Owing to the inclusion of muon triggers based on signals in the BAC [22,23], the rate of recorded dimuon events increased by 17% for a third of the data as compared to the previous $\Upsilon(1S)$ analysis [8]. Offline, events were selected 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;

- both tracks were required to have hits in at least 5 CTD superlayers, to ensure a good momentum resolution;

- transverse momentum of each track $p_T > 1.5$ GeV;

- $|\eta^+ - \eta^-| \le 1.5$, where $\eta^\pm$ is the pseudorapidity[3] of a given track, to suppress Bethe-Heitler background (Section 5);

- at least one track identified as a muon in the F/B/RMUON or BAC, whenever available in a given event [24]; if not explicitly identified as a muon, the second track had to be associated with a minimum-ionising energy deposit in the CAL;

- $|\pi - \alpha| > 0.1$, where α is the angle between the momentum vectors of μ^+ and μ^-, to reject cosmic-ray events;

- invariant mass $M_{\mu^+\mu^-}$ in the range between 5 and 15 GeV;

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

- 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 $Q^2 < 1$ GeV^2;

- the sum of the energy in the FCAL modules surrounding the beam hole had to be smaller than 1 GeV [24] to suppress the contamination from proton-dissociative events, $ep \to e\Upsilon Y$. 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, $M_Y \lesssim 4$ GeV;

- photon–proton centre-of-mass energy $60 < W < 220$ GeV and four-momentum-transfer squared $|t| < 5$ GeV^2.

The total number of selected $\mu^+\mu^-$ pairs was 2769. The contamination of this sample with cosmic ray muons is less then 1%.

5   Monte Carlo simulation

The detector and trigger acceptance and the effects due to detector response were determined using samples of Monte Carlo (MC) events. Exclusive and proton-dissociative vector-meson production were simulated with the DIFFVM 2.0 generator [25]. For proton-dissociative events, the simulation was supplemented by the JETSET 7.3 MC package [26]. For exclusive vector-meson production, s-channel helicity conservation (SCHC) was assumed. An exponential dependence, $e^{-b|t|}$, was assumed for the differential cross section in t with a slope parameter $b = 4.5$ GeV^{-2}, consistent with the value obtained for exclusive J/ψ electroproduction [5,6]. The W dependence of the $\gamma p \to \Upsilon p$ cross section was parameterised as $\propto W^\delta$, with $\delta = 1.2$ [8]. Electromagnetic radiative corrections associated with the decay muons are of the order of 1 % [27] and were not included in the simulation.

The non-resonant background, consisting of the exclusive and proton-dissociative Bethe-Heitler (BH) dimuon events, was simulated using the GRAPE v1.1k MC program [28]. After event selection, the contribution of the proton-dissociative events was 25% of the Bethe-Heitler MC sample.

All MC events were generated in the full kinematic range and processed through the simulation of the ZEUS detector based on the GEANT program[4] [29] and were analysed with the same reconstruction and offline procedures as the data. In addition, corrections [24] of the muon-detector efficiencies determined from a data set consisting of J/ψ and Bethe-Heitler exclusive production events were applied.

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[4] Version 3.13 for the 1996–2000 and 3.21 for the 2003–2007 periods, respectively.

6 Determination of the b slope

The invariant-mass distribution of $\mu^+\mu^-$ pairs after applying the selection criteria is shown in Fig. 2. The simulated contributions from the Bethe-Heitler (exclusive and proton dissociative) process and from the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances are also presented[5]. As in the previous paper [8], the BH distributions were normalised to the data in the range [5.0–15.0] GeV excluding the [9.0–11.0] GeV mass window where contributions from the Υ resonances are expected. For the determination of the slope parameter for exclusive $\Upsilon(1S)$ production, only events in the mass window [9.33–9.66] 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. According to MC studies, 71% of all reconstructed $\Upsilon(1S)$ events are expected in this window; 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. After scanning no cosmic ray muon candidates were found in the signal mass window.

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] GeV in the four t bins shown in Fig. 3. A binned Poissonian log-likelihood function, $\ln(L)$, 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 as described earlier. Due to insufficient statistics it was not possible to evaluate the contribution of proton-dissociative $\Upsilon(1S)$ events in the final sample with the present data. However, the fraction of such events, f_{pdiss}, is expected to be similar in all diffractive vector-meson production processes [31]. Therefore, the value $f_{\mathrm{pdiss}} = 0.25 \pm 0.05$, determined for diffractive J/ψ production [5], was used. The values of the slope parameter for the exclusive and proton dissociative $\Upsilon(1S)$ production processes differ [32]; in the MC the value for the latter was taken to be $b_{\mathrm{pdiss}} = 0.65 \pm 0.1$ GeV^{-2} [5].

The fit was performed with two free parameters: the slope b and the number of expected $\Upsilon(1S)$ events in the signal mass window. During the parameter scan, the contribution of the exclusive $\Upsilon(1S)$ production to the t distribution was reweighted at generator level to the function $b \cdot \exp(-b|t|)$. The small statistical uncertainties of the MC sample were neglected in the fit. The fit yielded: $b = 4.3^{+2.0}_{-1.3}$ (stat.) GeV^{-2} and 41 ± 10 $\Upsilon(1S)$ events (44% of the events in this mass window). The fit provides a good description of the data; the equivalent χ^2 is 0.61 for 2 degrees of freedom.

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[5] The ratio of the number of events $N_{\Upsilon(1S)} : N_{\Upsilon(2S)} : N_{\Upsilon(3S)}$ was fixed in the MC to $0.73 : 0.19 : 0.08$ according to a CDF measurement [30] of the production of Υ resonances.

7 Systematic uncertainties

The following sources of systematic uncertainty were considered, where the numbers in parenthesis correspond to the uncertainties on b in GeV^{-2}:

- f_{pdiss} was varied between 0.2 and 0.3, as determined from J/ψ production [5] $\binom{+0.30}{-0.25}$;

- b_{pdiss} was varied by $^{+0.7}_{-0.1}$ GeV^{-2}. In addition to the uncertainty from J/ψ production quoted earlier, the upper variation was extended to the value $b_{\text{pdiss}} = 1.35$ GeV^{-2} obtained for this parameter when it was also fitted $\binom{-0.4}{+0.1}$;

- the contribution of BH events in the mass window [9.33–9.66] GeV was varied between 55.3% and 56.7%, according to the statistical uncertainty of its normalisation $\binom{+0.15}{-0.10}$;

- the fraction of proton-dissociative to all BH events was varied in the range 0.22 to 0.28 (± 0.30).

Variation of the parameter δ between 0.7 and 1.7 and variations of the offline selection cuts lead to a negligible contribution to the b uncertainty. The total systematic uncertainty was determined by adding the individual contributions in quadrature.

8 Result and discussion

The slope parameter b for the exclusive production of $\Upsilon(1S)$ mesons was measured to be $b = 4.3^{+2.0}_{-1.3}$ (stat.) $^{+0.5}_{-0.6}$ (syst.) 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. 4. 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. 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 ($b = 3.68$ GeV^{-2}) [11].

9 Conclusions

The exclusive photoproduction reaction $\gamma p \to \Upsilon(1S)\, p$ was studied with the ZEUS detector in ep collisions at HERA using an integrated luminosity of 468 pb^{-1} collected in the period 1996–2007. The analysis covered the kinematic range $60 < W < 220$ GeV and $Q^2 < 1$ GeV^2. The measurement of the exponential slope of the t dependence yielded $b = 4.3^{+2.0}_{-1.3}$ (stat.) $^{+0.5}_{-0.6}$ (syst.) GeV^{-2}. This is the first determination of the b parameter

for $\Upsilon(1S)$ production. The result is in agreement with expectations of an asymptotic behaviour of the slope parameter as a function of the effective scale present in the process, $Q^2 + M_{VM}^2$. This measurement extends the value of the scale to ≈ 90 GeV^2, the highest achieved to date in the measurement of the t-slope parameter for a vector meson.

Acknowledgments

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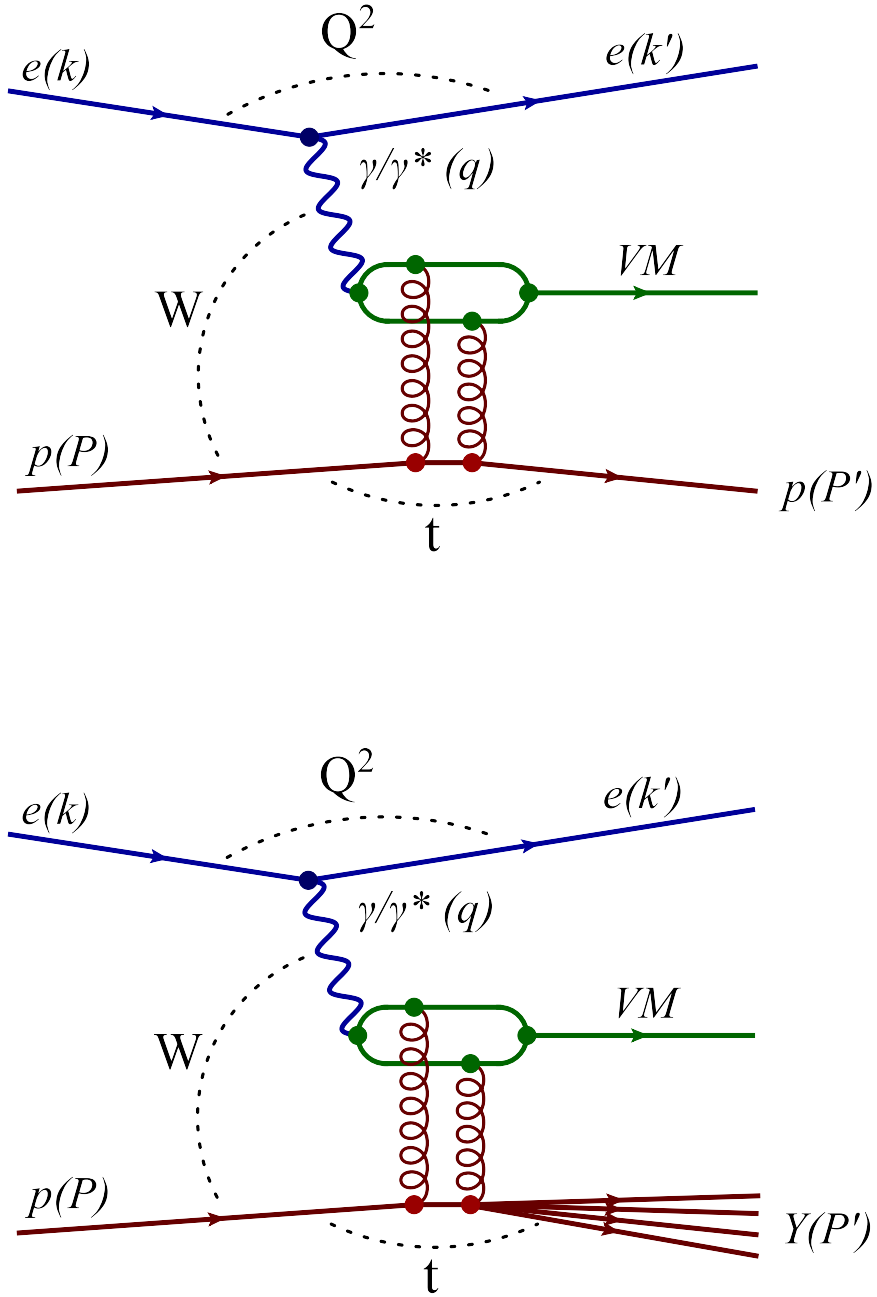**Figure 1:** *Diagrams for (top) exclusive and (bottom) proton-dissociative vector-meson photoproduction in ep interactions. The variables describing the kinematics of both processes are introduced in Section 3.*
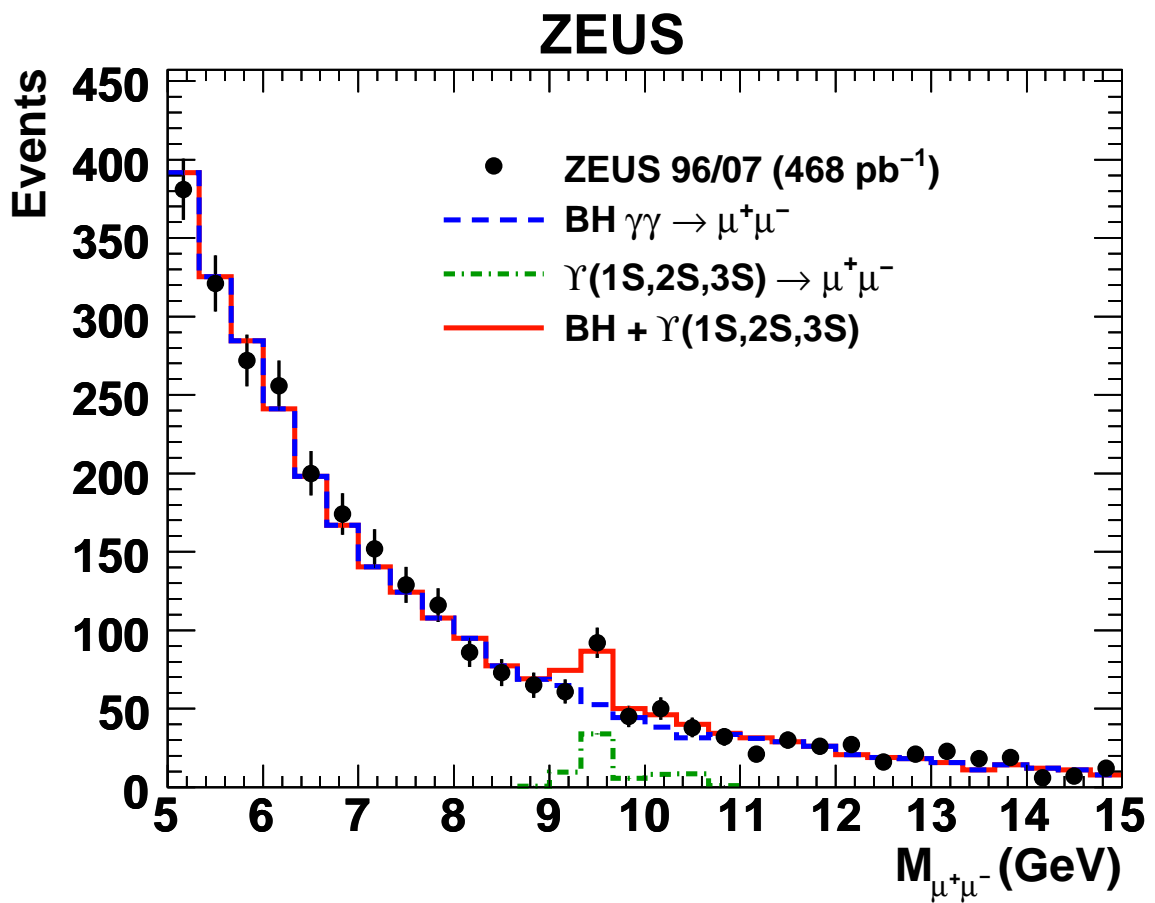
Figure 2: *Invariant mass distribution of $\mu^+\mu^-$ pairs. The dashed line shows the simulated Bethe-Heitler (BH) (exclusive and proton dissociative) distribution, normalised to the data points in the range [5.0–15.0] GeV excluding the [9.0–11.0] GeV mass window. Simulated contributions of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances are shown as a histogram on the mass axis (dashed-dotted line). The solid line shows the sum of all contributions.*
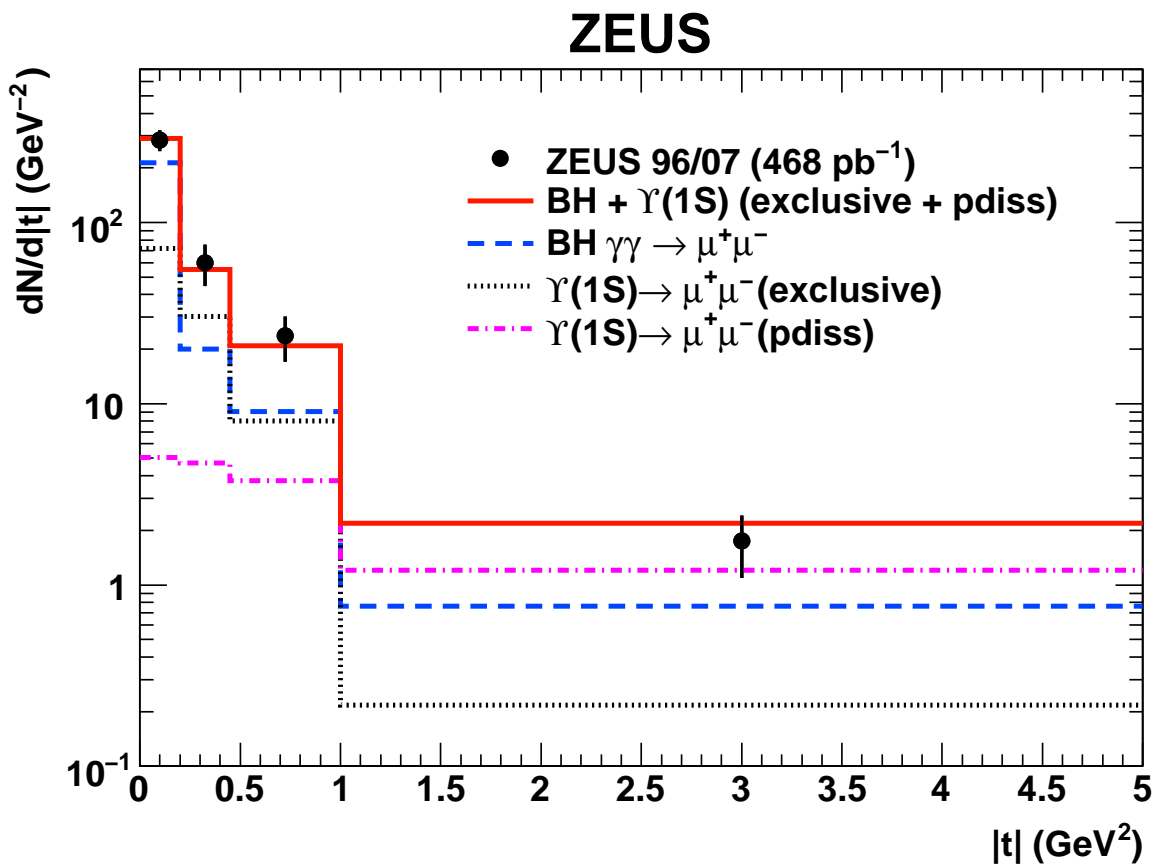
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Figure 3: *Measured |t| distribution (full dots) with error bars denoting statistical uncertainties. Fitted distributions for simulated events are shown for the Bethe-Heitler (dashed line), exclusive $\Upsilon(1S)$ (dotted line) and proton dissociative $\Upsilon(1S)$ (dashed-dotted line) processes. The solid line shows the sum of all contributions.*
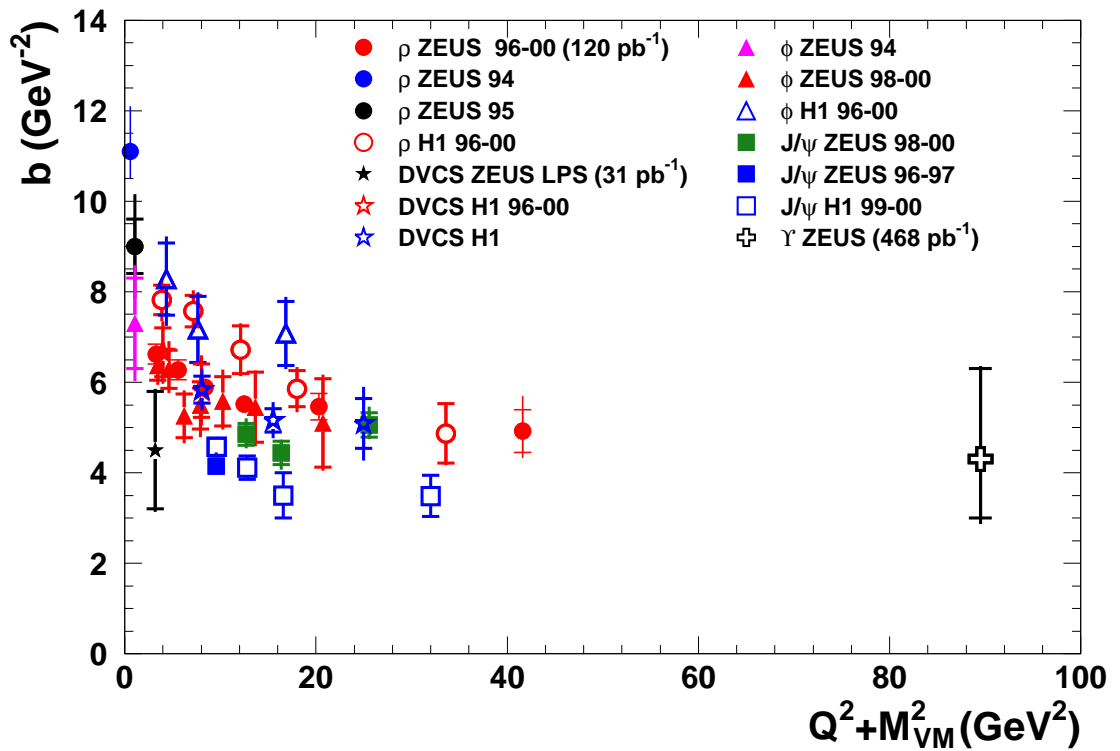
Figure 4: *Comparison of the HERA measurements of the slope parameter b as a function of the scale $Q^2 + M_{VM}^2$ for exclusive $\Upsilon(1S)$ production (the rightmost data point), for other exclusive vector-meson production [5, 6, 32–38] and for deeply virtual Compton scattering (DVCS) [39–41].*

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