

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

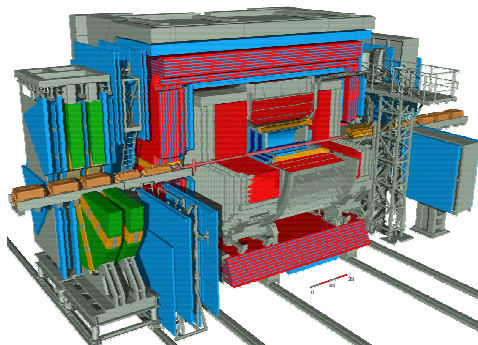
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Newport News, VA USA, April 11th-15th 2011

The ZEUS Detector at the HERA ep Collider in DESY (Hamburg)

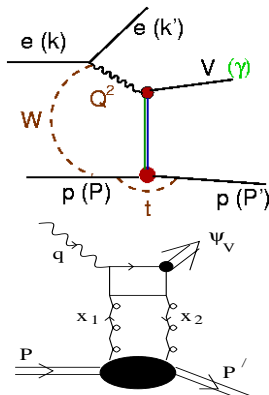


- HERA operated in years 1992-2007
- e^+p and e^-p modes
- $E_e = 27.5$ GeV, $E_p = 920$ GeV
- $E_{CMS} = 318$ GeV
- ZEUS collected $\int L = 468 \text{ pb}^{-1}$

Detector components used in this analysis:

- MVD: Microvertex Detector
- CTD: Central Tracking Detector
- CAL: Uranium Calorimeter
- BAC: Backing Calorimeter
- F/B/R/MUON: Muon Chambers

Production of Vector Mesons in Exclusive Diffraction in ep Scattering



Kinematics of the exclusive process
The proton stays intact !

Kinematics: $M_V^2, Q^2, W, |t|$

M_V^2 - vector meson mass squared

$Q^2 (= -q^2)$ - the photon virtuality
(emitted by the incoming electron):

- $Q^2 \approx 0 \text{ GeV}^2$ PHP (*Photoproduction*)
- larger Q^2 for DIS (*Deep Inelastic Scattering*)

W - invariant mass of the γp system

$$W^2 = (q + P)^2 = 2E_p(E - p_z)_\gamma$$

Process sensitive to the
gluon longitudinal momentum in the proton

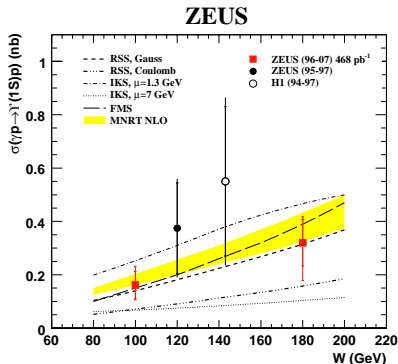
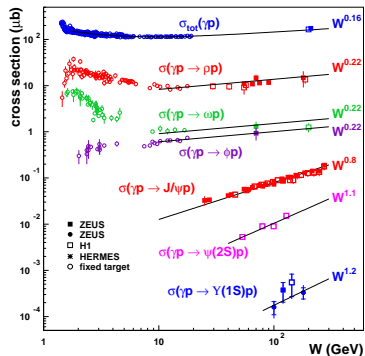
$|t|$ - 4-momentum transfer at the proton vertex

$$|t| = |P' - P|^2 \approx p_{TV}^2 \text{ (approx. true, if } p_{Te}^2 \lesssim 1 \text{ GeV}^2)$$

The cross section $\frac{d\sigma}{d|t|} \sim e^{-b|t|}$, b - gives access
to the **transverse distribution of the gluons** in
the proton

pQCD: M_V^2 and Q^2 - set the scale at which the W and $|t|$ are probed

W-dependence of the VM exclusive cross section for PHP: $\sigma(\gamma p \rightarrow Vp)$



$\sigma \sim W^\delta$, δ rises with M_V^2 from "soft" ($\delta = 0.22$) to "hard" ($\delta \approx 1.0$)
(expected in QCD from the gluon behavior in the proton)

previous ZEUS measurement of Υ meson: $\delta = 1.2 \pm 0.8$ (Phys. Lett. **B 680**, 4 (2009))

- Υ : sensitive to vector meson wave function: seems to prefer Gauss to Coulomb,
- Υ : sensitive to hard scale value: NRQCD NLO scale is between $1.3 < \mu < 7$ GeV,
- Υ : pQCD models W-slope: FMS LO ($\delta=1.7$), other NLO give value $\delta \approx 1.2$

Overview of t -dependence for Vector Mesons

$$\frac{d\sigma}{d|t|} \propto \exp(-b|t|)$$

Geometric picture -
transverse size:

$$b = b_V + b_p$$

Vector Meson tr. size:

$$b_V \sim \frac{1}{Q^2 + M_V^2}$$

Target (proton) tr. size:

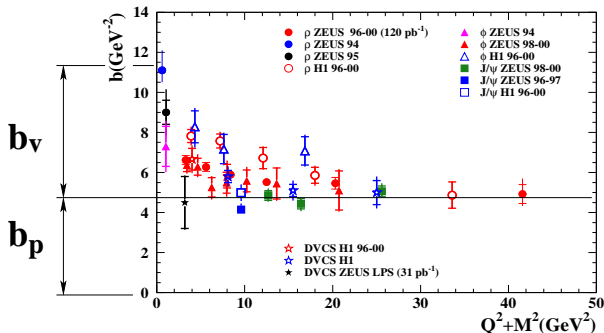
$$b_p \approx 5 \text{ GeV}^{-2}$$

can be interpreted as

$$r_{\text{gluons}} \approx 0.6 \text{ fm}$$

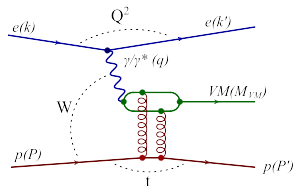
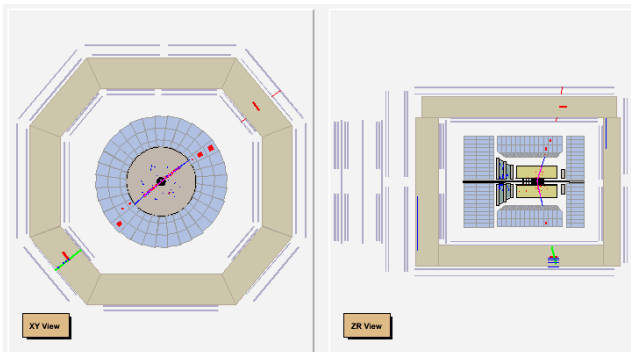
charge radius of the proton

$$r_{\text{em}} \approx 0.8 \text{ fm}$$



The t -slope, b , decreases with the scale $Q^2 + M_V^2$

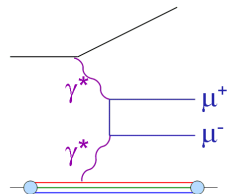
Final State Topology for $ep \rightarrow \Upsilon p, \Upsilon \rightarrow \mu^+ \mu^-$



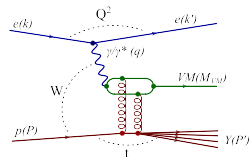
Elastic process, reaction mediated by exchange of **colourless** object. Two gluons in LO QCD or Pomeron in Regge theory.

Υ mesons are detected in the $\mu^+ \mu^-$ decay channel
very clean final state topology: two muons and nothing else !

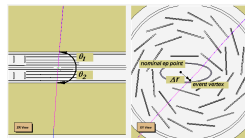
- QED di-muons (like $\gamma^* \gamma^* \rightarrow \mu^+ \mu^-$) from the Bethe-Heitler process



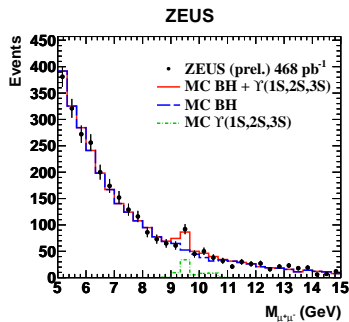
- Υ mesons production with the dissociation of the proton



- Cosmic muons can mimic $\mu^+ \mu^-$ pairs when passing close to the interaction point



- **Muon Triggers** (F/B/R/MUON or BAC)
- **Tracking and Vertex**
 - exactly two, long, oppositely charged tracks matched to the primary vertex
 - $p_T > 1.5$ GeV of each track
 - $|\eta^+ - \eta^-| < 1.5$; to suppress Bethe-Heitler background
 - $|\pi - \alpha| > 0.1$; (anti-collinearity), $\alpha = \angle(\vec{p}^+, \vec{p}^-)$; to further reject cosmic-ray events
 - both tracks identified as a muon (F/B/R/MUON, BAC; 2nd muon at least as CAL MIP)
- **Elasticity and Photoproduction cuts** (on CAL Energy)
 - $E_{\text{clu}} < 0.5$ GeV for clusters not matched to muon (corresponds to an effective cut on $Q^2 < 1$ GeV²)
 - $E_{\text{ir}} < 1$ GeV the sum of the energy in the FCAL around the beam hole; to suppress proton-dissociative events, $ep \rightarrow e\gamma\gamma$ (corresponds to a requirement for $M_Y \lesssim 4$ GeV)
- **Kinematic range:**
 - $Q^2 < 1$ GeV² (median $Q^2 \approx 10^{-3}$ GeV²)
 - $60 < W < 220$ GeV
 - $0 < |t| < 5$ GeV²
 - $5 < M_{\mu^+\mu^-} < 15$ GeV



DIFFVM generator - simulate Vector Meson (J/ψ , Υ) production and decay,

- based on Regge phenomenology and Vector Dominance Model
- both the **elastic and p.diss** production of the Vector Mesons
- assumes S-Channel Helicity Conservation (SCHC)

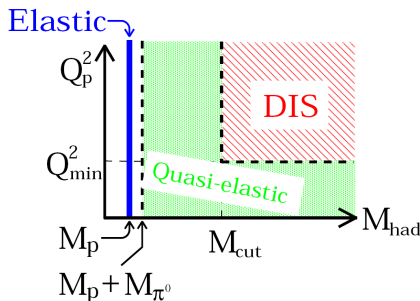
reproduces shape of:

$$\rightarrow \sigma \sim W^\delta, \text{ where } \delta = 4(\alpha_0 - 1)$$

$$\rightarrow \frac{d\sigma}{d|t|} \sim e^{-b|t|}, b = b_0 + \alpha' \left(\ln \frac{W}{W_0} + \ln \frac{M_X}{M_0} \right), \text{ where } \ln \frac{M_X}{M_0} - \text{ for p.diss}$$

Phenomenology \rightarrow no absolute normalisation, correct kinematics

GRAPE generator - simulate QED lepton pair (Bethe-Heitler)



Important for the **shape of the BH $M_{\mu^+\mu^-}$ spectrum** (sidebands)
and for the **BH t -dependence**: low t - elastic BH, higher t - QEL BH

Contribution of the Proton Dissociative Background

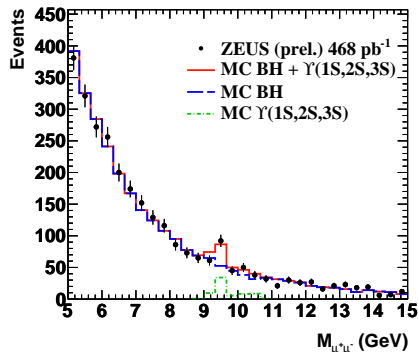
- After all elasticity cuts we still see a mixture of **elastic + p.diss** events,
 - $f_{pdiss} = \frac{p.diss}{ela+p.diss} = ?$
 - has to be determined experimentally
 - this \mathcal{V} analysis has too small statistic
- it has been shown (ZEUS-2000: Eur. Phys. J. **C 14**, 213) that **f_{pdiss} is similar for all Vector Mesons** in diffractive production
- relative contribution also does not depend on event kinematics
- we assume **$f_{pdiss}^{\mathcal{V}} = f_{pdiss}^{J/\psi} = 0.25 \pm 0.05$**

$\frac{d\sigma}{d|t|} \sim e^{-b|t|}$, has two components:

- elastic: $b = b_{el} \approx 4 \div 12 \text{ GeV}^{-2}$, depends on M_V^2 , Q^2
- p.diss: **b_{pdiss} similar for all heavy Vector Mesons**, we assume **$b_{pdiss} \approx 0.65 \text{ GeV}^{-2}$** as for ZEUS J/ψ analysis (Eur. Phys. J. **C 24**, 345)

Υ Signal Extraction: $M_{\mu^+\mu^-}$ Spectrum

ZEUS



Signal $N_{\Upsilon(1S)}$ estimated from:

- MC templates fit in all mass region
- using Υ 1S : 2S : 3S ratio from CDF (Phys. Rev. Lett. **88** 161802 (2002))

$$N_{\Upsilon(1S,2S,3S)} = 64 \pm 16$$

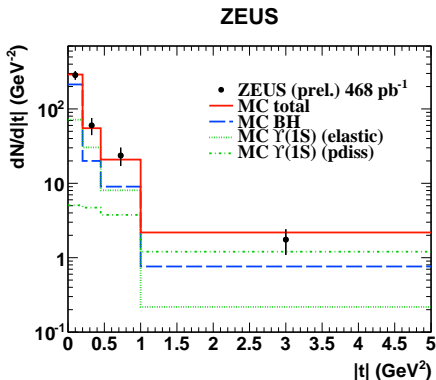
($\times 0.73$ to get 1S)

- Sidebands background normalisation

The data events and BH fraction in
(9.33-9.66) GeV mass range:

- $N_{data} = 92 \pm 9$
- $N_{BH} = 52 \pm 1$

The Elastic t -slope Estimation: Fit to the $dN/d|t|$ distribution



$dN/d|t|$ distribution

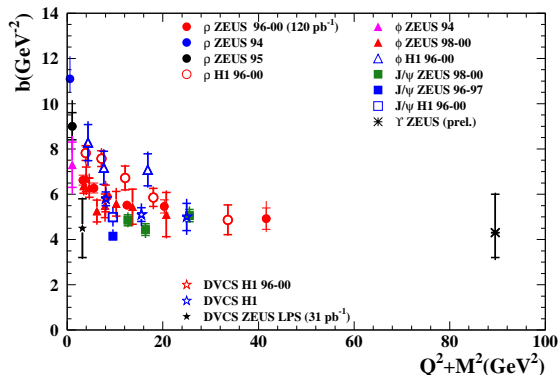
for events in the **mass range (9.33-9.66) GeV**:

- $\gamma(1S)$ signal and BH background normalisation fixed from mass fit
- $\gamma(1S)$ signal splitted between elastic and pdiss (75:25) (syst.)
- $\gamma(1S)$ slope $b_{pdiss} = 0.65 \text{ GeV}^{-2}$ (syst.)
- BH shape is treated as well known (syst.)
- binned maximum log-likelihood fit to **extract the elastic b slope** parameter

The $\Upsilon(1S)$ elastic t -slope b Value

ZEUS Preliminary:

$\Upsilon(1S)$ elastic PHP t -slope: $b = 4.3^{+1.7}_{-1.1} {}^{+0.5}_{-0.5} \text{ (GeV}^{-2}\text{)}$



measurement of the t -slope b for $\Upsilon(1S)$ meson
doubles the scale $Q^2 + M_V^2$ explored by previous studies

- $\Upsilon(1S)$ elastic PHP t -slope: $b = 4.3^{+1.7}_{-1.1} {}^{+0.5}_{-0.5} \text{ (GeV}^{-2}\text{)}$
- measurement was performed at the highest scale
 $Q^2 + M_V^2 = 89.5 \text{ GeV}^2$ achieved for the vector meson
- value of the elastic t -slope parameter b is in agreement with the pQCD predictions and with the expectations implied by the proton radius

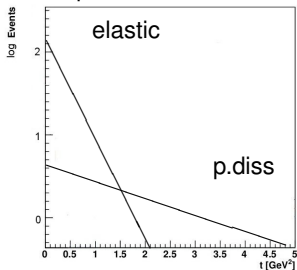
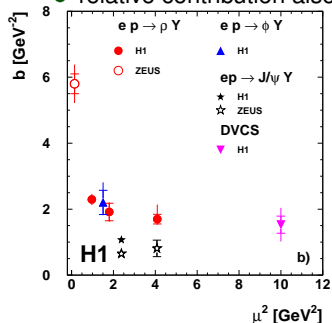
Thank You For Your Attention

BACKUP PLOTS FOLLOWS...

Υ Proton Dissociative t -slope: b_{pdiss}

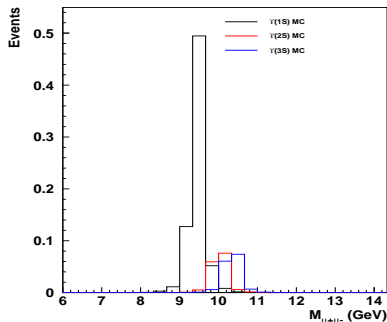
$\frac{d\sigma}{d|t|} \sim e^{-b|t|}$, has two components:

- The "elastic" and "p.diss" events have different t -slopes, b :
- elastic: $b_{el} \approx 4 \div 12 \text{ GeV}^{-2}$, depends on M_V^2 , Q^2
- p.diss: $b_{pdiss} \approx 0.5 \div 2 \text{ GeV}^{-2}$, does not depend on M_V^2 , Q^2
- p.diss: b_{pdiss} similar for all heavy Vector Mesons, we assume $b_{pdiss} \approx 0.65 \text{ GeV}^{-2}$ as for ZEUS J/ψ analysis (Eur. Phys. J. **C 24**, 345)
- relative contribution also does not depend on event kinematics.



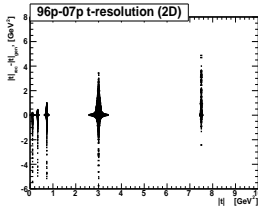
The $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ states:

- ratio 1S:2S:3S = 0.73 : 0.19 : 0.08
(CDF-2002: Phys. Rev. Lett. **88** 161802)
- $M_{\Upsilon(1S)} = 9.46$ GeV,
mass peak width ~ 200 MeV
- Mass window cut at 9.33 to 9.66 was chosen to improve the track resolution (implies t -resolution), and minimise contribution of the background (lower side) and higher excitation states (upper side)
- The mass range (9.33-9.66) GeV contains:
71% (1S), 3.4% (2S), 0.7% (3S).
(relative: 1% (2S), 0.2% (3S))

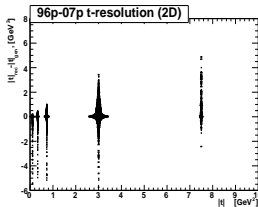
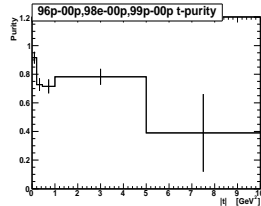
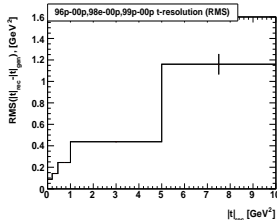


$\Upsilon(3S)$ normalised to $\Upsilon(2S)$
for better visualisation

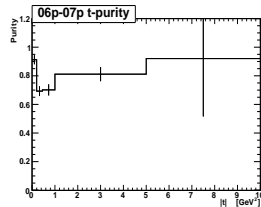
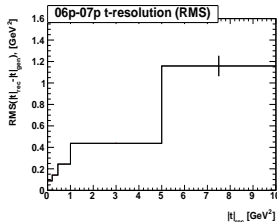
$\Upsilon(1S)$: t -resolution and purity in $|t|$ bins



HERA I

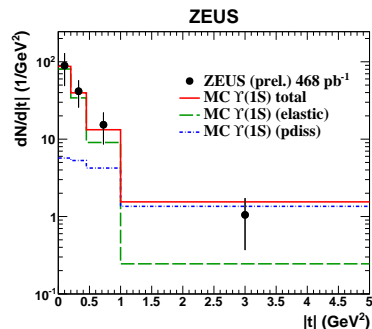


HERA II



t -bin width selected to be $\sim x2$ of the $RMS(t_{rec}-t_{gen})$ in the bin

The t -slope Estimation: BG Subtracted Plot



$$-2 \ln \lambda(\theta) = 2 \sum_{i=1}^N \left[\nu_i(\theta) - n_i + n_i \ln \frac{n_i}{\nu_i(\theta)} \right]$$

$dN/d|t|$ distribution

for events in the **mass range (9.33-9.66) GeV:**

- data: 92 (± 9) events
- BH: expect 52 (± 1) events (syst.)
- the rest splits between $\Upsilon(1S)$: elastic and pdiss (75:25) (syst.)
- BH shape is treated as well known (syst.)
- $\Upsilon(1S)$ $b_{pdiss} = 0.65 \text{ GeV}^{-2}$ (syst.)
- The $\Upsilon(1S)$ b_{el} is iteratively assigned a value in the range from 2.0 to 7.0 GeV^{-2} with an incremental step 0.1 GeV^{-2} (by re-weighting MC, using *generator level* b_{el} value)
- for each iteration a likelihood function was estimated according to the PDG formula.
- Similar LL calculation encoded in TFractionFitter takes into account also statistical errors in MC.

- Υf_{pdiss} : proton dissociative production fraction
(contributes at higher t , $\approx 1 < t < 10 \text{ GeV}^2$)
 - $(25 \pm 5) \% \rightarrow +0.30, -0.25$
- Υ proton dissociative t -slope value b_{pdiss}
 - $(0.65^{+0.70}_{-0.10}) \text{ GeV}^{-2} \rightarrow \begin{matrix} -0.4 \\ +0.1 \end{matrix}$
- BH f_{pdiss} : (variation of QEL/EL BH fraction)
 - variation within it's uncertainty of 3% (data.to.MC t -distribution comparison)
 - less then ± 0.30
- BH relative contribution (in the 9.33-9.66 GeV mass range)
 - $(55.7 \pm 1.2) \% \rightarrow +0.15, -0.10$ (fraction of BH/DATA)