ZEUS measurement of the cross-section ratio $\sigma(\psi(2S))/\sigma(J/\psi)$ in exclusive ep scattering at HERA

Grzegorz Grzelak
on behalf of the ZEUS Collaboration

Faculty of Physics
University of Warsaw

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1. Experimental apparatus: the HERA accelerator and the ZEUS detector

2. Introduction: Vector Meson Production in Exclusive Diffraction in $ep$ Scattering

3. Analysis: Events selection and extraction of the signal

4. Results: Cross section ratio $\psi(2S)/J/\psi(1S)$ in DIS (electroproduction)

5. Results: Cross section ratio $\psi(2S)/J/\psi(1S)$ in photoproduction

6. Summary
HERA and ZEUS: 1992 – 2007, DESY, Hamburg

HERA: world’s first and only $e^\pm p$ collider, $E_e = 27.5$ GeV, $E_p = 920$ GeV ($\sqrt{s} = 318$ GeV)

ZEUS: multipurpose, hermetic detector (MVD, CTD, CAL, F/B/RMUON, BAC, ...)
Total luminosity: $\int \mathcal{L} \sim 500$ pb$^{-1}$ collected during HERA I + II running periods
Light Scattering in Fraunhofer approximation (wavelength $\lambda \sim 1/k << R$)

- $|t| = 4k^2 \sin^2(\theta/2)$
- $d\sigma/dt \sim e^{-b|t|}$ (first diffractive peak approximated from Bessel function)
- $b = (R/2)^2 \rightarrow$ transverse size of the target

in the presented studies: target $\equiv$ proton and photon energy $\gg 1$ GeV
Production of Vector Mesons in Exclusive Diffraction in ep Scattering

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

- $M_V^2$ - vector meson mass squared
- $Q^2 (= -q^2 = -(k - k')^2)$ - the photon virtuality (emitted by the incoming electron):
  - $Q^2 \approx 0$ GeV$^2$ PHP (Photoproduction)
  - larger $Q^2$ for DIS (Deep Inelastic Scattering)
- $W = (q + P)^2$ - invariant mass of the $\gamma p$ system
- Process sensitive to the gluon density in the proton
- $|t|$ - 4-momentum transfer at the proton vertex
  $t = (P - P')^2$

Exclusive process: proton stays intact
Proton dissociation also possible $\rightarrow$ background

pQCD: $M_V^2$ and $Q^2$ - set the scale at which the $W$ and $|t|$ are probed
Cross section ratio $\psi(2S)/J/\psi(1S)$: physics motivation

$$\Psi(r)$$

$$\text{Ratio } R = \frac{\sigma_{\gamma p \rightarrow \psi(2S)p}}{\sigma_{\gamma p \rightarrow J/\psi(1S)p}}$$

- sensitive to radial wave function of charmonium
- provides insight into the dynamics of the hard process

- $J/\psi(1S)$ and $\psi(2S)$ have distinctive wave functions
- $\psi(2S)$ has a node at $\approx 0.4$ fm
- $\langle r_{\psi(2S)}^2 \rangle \approx 2 \langle r_{J/\psi(1S)}^2 \rangle$
- pQCD models predict $R \sim 0.17$ in PHP and moderate rise of $R$ with $Q^2$ in DIS
- $\psi'$ cross section is expected to be suppressed w.r.t. the $J/\psi$ production
Investigated decay channels:

- $\psi(2S) \to J/\psi + \pi^+\pi^-$, $\psi(2S) \to \mu^+\mu^-$, $J/\psi(1S) \to \mu^+\mu^-$

HERA I+II: $\mathcal{L} = 468$ pb$^{-1}$ (1996 - 2007) with $5 < Q^2 < 80$ GeV (DIS)

subsample of 114 pb$^{-1}$ (HERA I) with $2 < Q^2 < 5$ GeV (DIS)

HERA II: $\mathcal{L} = 333$ pb$^{-1}$ (2003 - 2007) $Q^2 < 1$ GeV (PHP)

MC Samples: Signal: DIFFVM for exclusive VM production ($J/\psi$ and $\psi'$)

- $ \frac{d\sigma}{dQ^2} \sim \frac{1}{(1+Q^2/M_V^2)^{1.5}}$

- $ \frac{d\sigma}{d|t|} \sim \exp(-b|t|)$,
  $b = 4.0$ GeV$^{-2}$

Background: GRAPE for non resonant muon pair production (Bethe-Heitler process)
Events selection (DIS channel)

\[ \psi(2S) \rightarrow \mu^+ \mu^- \pi^+ \pi^- \Rightarrow \]

- **Event selection:**
  - scattered electron \( E_{e'} > 10\) GeV in CAL
  - 2 (4 for \( \psi(2S) \) 4-prongs decay) non-electron tracks from primary vertex, net charge = 0
  - two tracks identified as muons (CAL, F/B/R/MUO, BAC)
  - no other deposits not matched to tracks (above CAL noise) \( \Rightarrow \) proton remains undetected

- **Kinematic range:**
  - \((2) \leq Q^2 \leq 80\) GeV²
  - \(30 \leq W \leq 210\) GeV
  - \(|t| \leq 1\) GeV²

\[ J/\psi(1S) \rightarrow \mu^+ \mu^- \Rightarrow \]

\[ \psi' \] in exclusive ep by ZEUS
mass intervals for side-band straight-line background fit and signal extraction:

BG: 2.00 – 2.62 GeV and 4.05 – 5.00 GeV

Signal $J/\psi(1S)$: 3.02 – 3.17 GeV, Signal $\psi(2S)$: 3.59 – 3.79 GeV
Selection specific for $\psi(2S) \rightarrow \mu^+ \mu^- \pi^+ \pi^-$ channel

- $\Delta M$ vs. $M_{\mu^+\mu^-}$
  $\Delta M = M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$
  cascade decay of $\psi(2S)$

- $0.5 < \Delta M < 0.7 \text{ GeV}$
  $3.02 < M_{\mu^+\mu^-} < 3.17 \text{ GeV}$

- $M(\mu^+\mu^-\pi^+\pi^-)$ after cleanup
  very clean signature
  ($\leq 3$ background events at 90\% CL)
Cross section ratio \( R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))} \) (DIS) for full kinematic range

For \( 30 \leq W \leq 210 \text{ GeV}, \ 5 \leq Q^2 \leq 80 \text{ GeV}^2, \ |t| \leq 1 \text{ GeV}^2 \)

<table>
<thead>
<tr>
<th>( \psi(2S) ) decay mode</th>
<th>( \psi(2S) ) ( \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^- )</th>
<th>( \psi(2S) ) ( \rightarrow \mu^+\mu^- )</th>
<th>combined</th>
</tr>
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<tbody>
<tr>
<td>( R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))} )</td>
<td>( 0.26 \pm 0.03^{+0.01}_{-0.01} )</td>
<td>( 0.24 \pm 0.05^{+0.02}_{-0.03} )</td>
<td>( 0.26 \pm 0.02^{+0.01}_{-0.01} )</td>
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</tbody>
</table>

Both channels provide consistent results

\[
R_{\psi(2S) \rightarrow J/\psi \pi^+\pi^-} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S) \rightarrow \mu^+\mu^-}}{Acc_{\psi(2S) \rightarrow J/\psi \pi^+\pi^-}} \cdot \frac{1}{BR_{\psi(2S) \rightarrow J/\psi \pi^+\pi^-}}
\]

\[
R_{\psi(2S) \rightarrow \mu^+\mu^-} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S) \rightarrow \mu^+\mu^-}}{Acc_{\psi(2S) \rightarrow \mu^+\mu^-}} \cdot \frac{BR_{J/\psi(1S) \rightarrow \mu^+\mu^-}}{BR_{\psi(2S) \rightarrow \mu^+\mu^-}}
\]

\[
Acc_i = \frac{N_{i\text{reco}}^{i\text{true}}}{N_{i\text{true}}}
\]

\( BR(\psi(2S) \rightarrow J/\psi \pi^+\pi^-) = (33.6 \pm 0.4)\% \), \( BR(\psi(2S) \rightarrow \mu^+\mu^-) = (7.7 \pm 0.8) \times 10^{-3} \),

\( BR(J/\psi \rightarrow \mu^+\mu^-) = (5.93 \pm 0.06)\% \)

Ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ vs. $Q^2$ (DIS: combined 2- and 4-prong channels)

- $R$ rises with $Q^2$

[Graph showing the ratio $R$ vs. $Q^2$ with data points from ZEUS experiment.]
Ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ vs. $W$ (DIS: combined 2- and 4-prong channels)

$\psi'$ in exclusive ep by ZEUS

$R$ independent of $W$
Ratio \( R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))} \) vs. \(|t|\) (DIS: combined 2- and 4-prong channels)

\[ \psi' \text{ in exclusive ep by ZEUS} \]

- \( R \) independent of \(|t|\)

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\[ R_{\text{comb}} \]

\[ |t| \text{ (GeV}^2\text{)} \]

ZEUS 468 pb\(^{-1}\)
ZEUS to H1 comparison: (DIS) full data sample 468 pb$^{-1}$

Both ZEUS and H1 measurements are in agreement: $R$ increases with $Q^2$.

- ZEUS: full HERA I + HERA II data sample (468 pb$^{-1}$) (incl. low-$Q^2$ point)
- both ZEUS and H1 measurements are in agreement: $R$ increases with $Q^2$
- ZEUS improved accuracy due to the increased statistic of HERA I+II data
$Q^2$ dependence: comparison with theoretical models

All models predict the rise of $\sigma(\psi(2S))/\sigma(J/\psi)$ with $Q^2$.

...data begin to discriminate some models (see also backup plots for more details)

**theoretical models:**

Cross section ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ in photoproduction

- Cross section ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ in photoproduction
Event selection (photoproduction channel)

- no scattered electron observed in the calorimeter, otherwise selection very similar to DIS channel
- very clean signature, selection entirely driven by muons starting from trigger
- $30 < W < 180$ GeV (limited by muon chambers)
- experimental challenge: very good understanding of muon efficiency for all components
2-prong sample: $\psi(2S) \rightarrow \mu^+ \mu^-$ (photoproduction)

- $W$ and $M(\mu^+ \mu^-)$ distributions for 3 $W$ intervals (30-80), (80-130), (130-180) GeV
- DIFFVM $J/\psi$, $\psi(2S)$ and GRAPE BH MC normalized to data (fractional fit)
- double Gaussian fit to data for signal extraction

$$W = \sqrt{2E_P(E_{TOT} - P_Z)}, \quad P_Z = p_{\mu^+} \cos(\theta_{\mu^+}) + p_{\mu^-} \cos(\theta_{\mu^-})$$
4-prong sample: $\psi(2S) \rightarrow \mu^+ \mu^- \pi^+ \pi^-$ (photoproduction)

- $W$, $M(\mu^+ \mu^- \pi^+ \pi^-)$ distributions for 3 $W$ intervals (30-80), (80-130), (130-180) GeV
- very clean (almost) background free channel
- DIFFVM $\psi(2S)$ MC normalized to data

$$W = \sqrt{2E_P(E_{TOT} - P_Z)},$$
$$P_Z = p_{\mu^+} \cos(\theta_{\mu^+}) + p_{\mu^-} \cos(\theta_{\mu^-}) + p_{\pi^+} \cos(\theta_{\pi^+}) + p_{\pi^-} \cos(\theta_{\pi^-})$$
\[ R = \frac{\sigma_{\gamma p \rightarrow \psi(2S)p}}{\sigma_{\gamma p \rightarrow J/\psi(1S)p}} \] vs. \( W \) at \( Q^2 = 0 \) GeV² (photoproduction)

**ZEUS Preliminary**

- **average** \( R \) values over 2- and 4-prong channels
- moderate rise of \( R \) with photon-proton centre-of-mass \( W \)
- systematics dominated by 2- and 4-prong channel difference
\[ R = \frac{\sigma_{\gamma p \to \psi(2S)p}}{\sigma_{\gamma p \to J/\psi(1S)p}} \] vs. \( Q^2 \) including new \( Q^2 = 0 \) measurement

**ZEUS preliminary**

- **THEORETICAL MODELS:**

- **HIGHEST PRECISION** \( Q^2 = 0 \) GeV\(^2\) MEASUREMENT

- \( R = 0.1332 \pm 0.0065(\text{stat.}) \pm 0.0270(\text{syst.}) \) (average over full phase space)
• Ratio of $\frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ using HERA I+II data was measured for the first time by ZEUS in the kinematic range: $30 \leq W \leq 210$ GeV, $2 \leq Q^2 \leq 80$ GeV$^2$, $|t| \leq 1$ GeV$^2$ for exclusive DIS and in $30 \leq W \leq 180$ GeV for photoproduction ($Q^2 \approx 0$).

• The accuracy has been improved compared to the H1 HERA I results.

• The ratio increases with $Q^2$ and is constant as a function of $W$ and $|t|$.

• Theoretical calculations of the ratio $\frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ for exclusive vector-meson production have been compared to the experimental data → majority of the predictions are consistent with the data.

• data start to exhibit constraining power.
Thank You For Your Attention
BACKUP PLOTS FOLLOW...
HIKT: Hüfner et al. adopt the light-cone dipole formalism to describe VM production, the dipole-proton interaction cross section is constrained by inclusive low-x DIS data from HERA (BT and Cor: different charmonium potentials with $m_c \approx 1.5$ GeV)

HIKT - BT: overestimates lower $Q^2$ points
Comparison with theoretical models: AR

- AR: Armesto and Rezaeian → two predictions are presented: results from the Impact-Parameter dependent Color Glass Condensate (b-CGC) and the gluon Saturation (IP-Sat) dipole models
- b-CGC overestimates lower $Q^2$ points

$$R_{\psi} = \frac{\sigma(\psi(2S))}{\sigma(J/\psi)}$$

ZEUS

Comparison with theoretical models: KMW

KMW: Kowalski, Motyka, Watt → impact parameter dependent saturated dipole model, based on the QCD description and an assumption of universality of the gluon distribution and proton shape: $\delta = 0$ non-relativistic wave functions, $\delta = 2$ relativistic boosted Gaussian model.
Comparison with theoretical models: FFJS

**FFJS:** Fazio et al. → two component Pomeron model to predict the cross sections for Vector Meson production. The Pomeron is universal, containing two terms, a “soft” and a “hard” one: relative weights: \( \tilde{Q}^2 = Q^2 + M_V^2 \).

\[
R_\psi = \frac{\sigma(\psi(2S))}{\sigma(J/\psi)}
\]

- ZEUS (prel.) 468 pb \(^{-1}\)
- H1 27 pb \(^{-1}\)
- H1 \(\gamma p\): \(Q^2 \approx 0\) GeV \(^2\)

**Figure:**

- **ZEUS**

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\(\psi'\) in exclusive ep by ZEUS  
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KNNPZZ: Kopeliovich et al. → describe the BFKL Pomeron in terms of the colour-dipole cross section which is a solution of the generalized BFKL equations.
Comparison with theoretical models: LM

LM: Lappi and Mäntysaari → use the BFKL evolution as well as the dipole picture in the IP-Sat model to predict VM production.
Control plots for $\psi' \rightarrow \mu^+ \mu^-$ channel

- **ZEUS**

  - $Q^2$ (GeV$^2$) vs. Entries
  - $W$ (GeV) vs. Entries
  - $|t|$ (GeV$^2$) vs. Entries

  - $J/\psi(1S) \rightarrow \mu^+ \mu^-$
  - ZEUS 468 pb$^{-1}$
  - DIFFVM + BH
  - BH

  - MC reweighted in $Q^2$, $|t|$ and $J/\psi$ decay angles to match the data
  - good description $\rightarrow$ detector efficiency calculation
Control plots for $\psi(2S) \rightarrow \mu^+ \mu^-$ channel

ZEUS

- $\psi(2S) \rightarrow \mu^+ \mu^-$
  - ZEUS 468 pb$^{-1}$
  - DIFFVM + BH
  - BH

- MC reweighted in $Q^2$, $|t|$ and $\psi(2S)$ decay angles using $J/\psi \rightarrow \mu^+ \mu^-$ weights
- good description $\rightarrow$ detector efficiency calculation
Control plots for $\psi(2S) \rightarrow \mu^+ \mu^- \pi^+ \pi^-$ channel

**ZEUS**

- $\psi(2S) \rightarrow J/\psi(1S) \pi^+ \pi^-$
- ZEUS 468 pb$^{-1}$
- MC reweighted in $Q^2$ and $|t|$ using $J/\psi \rightarrow \mu^+ \mu^-$ weights
- good description $\rightarrow$ detector efficiency calculation
ZEUS to H1 comparison (in H1 phase space and H1 bins)

- cross check: ZEUS data analyzed in $Q^2$ bins used by H1: [EPJ C10 (1999) 373.]
  - $(5 - 12)$ GeV$^2$ and $(12 - 80)$ GeV$^2$
- $40 < W < 180$ GeV and $1 < Q^2 < 80$ GeV$^2$

Both measurements are in agreement

Improved accuracy due to the increased statistic of HERA II data
Systematics checks (2-prongs and 4-prongs channels)

- varying the $M_{\mu\mu}$ window for signal event counting:
  - for $J/\psi(1S)$: from 3.02 – 3.17 GeV to 3.05 – 3.15 GeV and 2.97 – 3.19 GeV

  changes the values of $R_{\mu\mu}$ by 6% and $R_{J/\psi\pi\pi}$ by 2%

- varying the cut on pions transverse momenta $p_T$ from 0.12 GeV to 0.15 GeV changes the $R_{J/\psi\pi\pi}$ by 4.5%

- changing the background fit function from linear to quadratic changes the values of $R_{\mu\mu}$ by 11% and $R_{J/\psi\pi\pi}$ by 0.5%

- changing the reconstruction of kinematic variables from “constrained” to “electron” method changes the values of $R_{\mu\mu}$ and $R_{J/\psi\pi\pi}$ by 1.5%

- not reweighting the MC samples changes the values of $R_{\mu\mu}$ by 3% and $R_{J/\psi\pi\pi}$ by 1%

- applying more restrictive cuts on the number of (soft/noisy) tracks not associated with the event vertex changes the values of $R_{\mu\mu}$ by 5% and $R_{J/\psi\pi\pi}$ by 3%

**Total systematic uncertainties are:** $\delta R_{\mu\mu} =^{+7}_{-14}\%$, $\delta R_{J/\psi\pi\pi} =^{+4}_{-5}\%$ and $\delta R =^{+3}_{-5}\%$
PHP: Event selection

ψ(2S) → μ⁺μ⁻ channel:

- exclusive muon triggers
- vertex consistent with ep interaction
- $N_{\text{track}} = 2$ (oppositely charged)
- $p_T > 1$ GeV (of each track)
- muon identification:
  - at least one track identified by muon detectors or BAC
  - both tracks matched to MIP clusters in CAL
- no scattered beam-electron in the CAL
- $\cos (\mu^+, \mu^-) > -0.9$ (cosmic rejection)
- elasticity cut (no CAL clusters other then 2 MIPs)
- $30 < W < 180$ GeV, $|t| < 5$ GeV², $2 < M(\mu^+, \mu^-) < 6$ GeV.
$\psi(2S) \rightarrow \mu^+ \mu^- \pi^+ \pi^-$ channel:
(differences w.r.t. the 2-prong channel)

- $N_{\text{track}} = 4$ (two oppositely charged pairs, sorted by $p_T$)
- highest momentum pair: muon candidates
  lowest momentum pair: pion candidates
- transverse momentum of pion candidates: $p_T^\pi > 0.12$ GeV;
- $2.8 < M(\mu^+ \mu^-) < 3.4$ GeV ($J/\psi$ window)
- $M(\mu^+ \mu^- \pi^+ \pi^-) - M(\mu^+ \mu^-)$ in $(0.5 - 0.7)$ GeV window
  (cascade decay of $\psi(2S)$)
\[ R = \frac{\sigma_{\gamma p \rightarrow \psi(2S)p}}{\sigma_{\gamma p \rightarrow J/\psi(1S)p}} \] vs. \( W \) at \( Q^2 = 0 \text{ GeV}^2 \)

\[ R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi)} \bigg|_{Q^2=0} \]

**ZEUS Preliminary**

- **ZEUS (prel.)** 333 pb\(^{-1}\)
- **syst. error**

\[ R \psi(2S) \rightarrow J/\psi \pi^+ \pi^- = \frac{\sigma \psi(2S)}{\sigma J/\psi(1S)} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{\text{Acc} J/\psi(1S) \rightarrow \mu^+ \mu^-}{\text{Acc} \psi(2S) \rightarrow J/\psi \pi^+ \pi^-} \cdot \frac{1}{\text{BR} \psi(2S) \rightarrow J/\psi \pi^+ \pi^-} \]

\[ R \psi(2S) \rightarrow \mu^+ \mu^- = \frac{\sigma \psi(2S)}{\sigma J/\psi(1S)} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{\text{Acc} J/\psi(1S) \rightarrow \mu^+ \mu^-}{\text{Acc} \psi(2S) \rightarrow \mu^+ \mu^-} \cdot \frac{\text{BR} J/\psi(1S) \rightarrow \mu^+ \mu^-}{\text{BR} \psi(2S) \rightarrow \mu^+ \mu^-} \]

\[ \text{BR}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-) = (34.49 \pm 0.3)\%, \text{BR}(\psi(2S) \rightarrow \mu^+ \mu^-) = (7.9 \pm 0.9) \times 10^{-3}, \]
\[ \text{BR}(J/\psi \rightarrow \mu^+ \mu^-) = (5.961 \pm 0.033)\% \]

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G. Grzelak (University of Warsaw)