Measurement of the cross-section ratio \( \sigma_{\psi(2S)} / \sigma_{J/\psi} \) in deep inelastic exclusive \( ep \) scattering at HERA

Outlines:
- HERA and ZEUS
- Diffractive vector meson production at HERA
- Data selection and signal extraction
- Results
HERA and ZEUS

**HERA**
- *ep collider*
  - Colliding beams:
    - $920 \text{ GeV } p$ and $27.5 \text{ GeV } e^\pm$
    - $\sqrt{s}=318 \text{ GeV}$
  - Data taking: 1992 - 2007

**ZEUS**
- Hermetic multipurpose detector
- Total collected luminosity: $\sim0.5 \text{ fb}^{-1}$
Diffractive vector meson (VM) production at HERA

elastic (exclusive)

proton-dissociative

\[ Q^2 \sim \text{photon virtuality} \]
\[ Q^2 < 1 \text{ GeV}^2 \] — \( \gamma p \)
\[ Q^2 \geq 1 \text{ GeV}^2 \] — DIS

\[ W \sim \text{photon-proton CMS energy} \]

\[ W^2 = (q + P)^2 \]

\[ t \sim \text{4-mom. transfer squared at proton vertex} \]

\[ t = (P - P')^2 \]
Measurement of the cross-section ratio \( \sigma_{\psi(2S)}/\sigma_{J/\psi} \) in DIS

\[
R = \frac{\sigma_{\gamma p \to \psi(2S) p}}{\sigma_{\gamma p \to J/\psi p}}
\]

gives information about the dynamics of hard process sensitive to radial wave function of charmonium

\( \psi(2S) \) wave function different from \( J/\psi \) wave function:
- Has a node at \( \approx 0.35 \text{ fm} \)
- \( \langle r^2 \rangle_{\psi(2S)} \approx 2 \langle r^2 \rangle_{J/\psi} \)

pQCD model calculations predicts \( R \sim 0.17 \) (PhP) and rise of \( R \) with \( Q^2 \) (DIS)
Investigated channels and samples

\[
\begin{align*}
\psi(2S) & \rightarrow J/\psi \pi^+ \pi^-; \quad J/\psi \rightarrow \mu^+ \mu^- \\
\psi(2S) & \rightarrow \mu^+ \mu^- \\
J/\psi & \rightarrow \mu^+ \mu^- 
\end{align*}
\]

Data samples

HERA I + HERA II data (1996 — 2007)
Integrated luminosity: 468 pb$^{-1}$

MC-data samples

**Signal MC:** DIFFVM for exclusive VM production

**Background MC:** GRAPE for Bethe–Heitler mu–pair production
$\psi(2S) \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow \mu^+\mu^-$

- Scattered $e$ with $E > 10$ GeV reconstructed in CAL
- Scattered $p$ undetected
- Two reconstructed tracks identified as muons
  and for $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ additionally two pion tracks from $\mu\mu$ vertex
- Nothing else in detector (above noise)

$30 \leq W \leq 210$ GeV
$2 \leq Q^2 \leq 80$ GeV$^2$
$|t| \leq 1$ GeV$^2$
Sideband of the signal: $2.00 < M_{\mu\mu} < 2.62$ GeV and $4.05 < M_{\mu\mu} < 5.00$ GeV fitted by straight line
\[ \psi(2S) \rightarrow J/\psi \pi^+ \pi^- \]

\[
\begin{align*}
\Delta M &= M_{\mu\mu\pi\pi} - M_{\mu\mu} \\
3.02 &< M_{\mu\mu} < 3.17 \text{ GeV} \\
0.5 &< \Delta M < 0.7 \text{ GeV}
\end{align*}
\]

After cut on \( M_{\mu\mu} \)

\[ \leq 3 \text{ events background} \]

- ZEUS (prel.) 354 pb\(^{-1}\)
### \( \sigma(\psi(2S))/\sigma(J/\psi) \) in full kinematic range

<table>
<thead>
<tr>
<th>( \psi(2S) ) decay mode</th>
<th>( \sigma(\psi(2S))/\sigma(J/\psi(1S)) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^- )</td>
<td>( 0.29 \pm 0.04^{+0.02}_{-0.01} )</td>
</tr>
<tr>
<td>( \rightarrow \mu^+\mu^- )</td>
<td>( 0.25 \pm 0.05^{+0.04}_{-0.02} )</td>
</tr>
<tr>
<td>combined</td>
<td>( 0.28 \pm 0.03^{+0.02}_{-0.01} )</td>
</tr>
</tbody>
</table>

Both ratio measurements agree

#### Method

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

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

\[
BR(\psi(2S)\rightarrow J/\psi\pi^+\pi^-) = (33.6 \pm 0.4) \%
\]

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

\[
BR(\psi(2S)\rightarrow \mu^+\mu^-) = (7.7 \pm 0.8) \times 10^{-3}
\]
$\sigma(\psi(2S))/\sigma(J/\psi)$ vs $Q^2$, $W$ and $|t|$

- Indication of an increase with $Q^2$
- Independent of $W$
- Independent of $|t|$
Results agree - $\sigma(\psi(2S))/\sigma(J/\psi)$ increases with $Q^2$
Significantly improved accuracy thanks to increased integrated luminosity

H1 collaboration:

HIKT — from Hufner et al., use the dipole model to predict VM production, the dipole–proton interaction cross section is constrained by inclusive DIS data from HERA
Model predictions

**ZEUS**

- **AR: b-CGC**
- **AR: IP-Sat**

**$R_\psi$**

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

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

---

**AR** — from Armesto and Rezaeian, two predictions are considered: results from the Impact-Parameter dependent Color Glass Condensate (b-CGC) and the Saturation (IP-Sat) dipole models.
Model predictions

ZEUSS

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

KMW — from Kowalski, Motyka, Watt, based on the QCD description and an assumption of universality of the quarkonia production mechanism
Model predictions

FFJS — from Fazio et al., use a two component Pomeron model to predict the cross sections for VM production.
Model predictions

KNNPZZ — from Nemchik et al., describe the BFKL pomeron in terms of the colour-dipole cross section which is a solution of the generalised BFKL equations.
Model predictions

LM — from Lappi and Mäntysaari, use dipole picture in the IP-Sat model to predict VM production
Model predictions

All models exhibit an increase of $\sigma(\psi(2S))/\sigma(J/\psi)$ with increasing $Q^2$

Theoretical predictions are consistent with the data
Summary and outlook

- Using HERA I+II data $\sigma(\psi(2S))/\sigma(J/\psi)$ in exclusive DIS has been measured for the first time by ZEUS in the kinematic range: $30 \leq W \leq 210 \text{ GeV}$, $2 \leq Q^2 \leq 80 \text{ GeV}^2$, $|t| \leq 1 \text{ GeV}^2$

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

- $\sigma(\psi(2S))/\sigma(J/\psi)$ ratio is compared with models of vector-meson production, all predictions are consistent with the data

- $\sigma(\psi(2S))/\sigma(J/\psi(1S))$: increases with $Q^2$ and independent of $W$ and $|t|$

Thank you very much for your attention!
Backup
Data-MC comparison for J/ψ

Good description of the data by the weighted Monte Carlo

MC weighted in $Q^2$, $|t|$ and J/ψ decay angles to match the data
Data-MC comparison for $\psi(2S) \rightarrow \mu^+ \mu^-$

Good description of the data by the weighted Monte Carlo
Data-MC comparison for \( \psi(2S) \rightarrow J/\psi \, \pi^+ \pi^- \)

Good description of the data by the weighted Monte Carlo