Exclusive Processes at HERA

Olga Lukina
SINP MSU
On behalf of the H1 and ZEUS
Overview

New analyses from H1 and ZEUS experiments

- **ZEUS**: Exclusive dijet production in diffractive DIS at HERA

- **ZEUS**: Measurement of the cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in deep inelastic exclusive ep scattering at HERA I+II

- **H1**: Exclusive photoproduction of $\rho^0$ with forward neutron

- **H1**: Measurement of Feynman-$x$ spectra of photons and neutrons in the very forward direction in DIS
HERA

920 GeV proton and 27.6 GeV electron/positron
HERA I \[ L \sim 100 \text{ pb}^{-1} \]
HERA II \[ L \sim 400 \text{ pb}^{-1} \]
Total integrated luminosity \[ 0.5 \text{ fb}^{-1} \]
Production of exclusive dijets in diffractive DIS

DESY-15-070
arXiv:1505.05783
Exclusive dijet production in diffractive DIS

\[ e + p \rightarrow e + jet1 + jet2 + p \]

Data 2003 – 2007  372 pb\(^{-1}\)

- \( Q^2 = - q^2 > 25 \text{ GeV}^2 \) - virtuality of the photon
- \( 90 < W < 250 \text{ GeV} \) - photon-proton center-of-energy
- \( x \) – Bjorken \( x \) – fraction of proton’s momentum carried by struk quark
- \( x_{IP} < 0.01 \) – fraction of proton’s momentum carried by exchanged color singlet
- \( t = (p-p')^2 \) – four momentum transfer squared at proton vertex
- \( \beta = x / x_{IP} \) – fraction of Pomeron momentum ‘seen’ by photon
- only dijet, scattered electron and proton in the final state

Select two hard jets may to allow comparison pQCD models

Models predict different shape for dijet azimuthal angular distribution
Exclusive dijet production in diffractive DIS

$\Phi$ - angle between $\gamma^*$-dijet and $\gamma^*$-e$^\pm$ planes in the rest frame of the diffractive final state

$\Phi$ distribution is parameterised by $1 + A (p_{T\text{jet}}) \cos (2\Phi)$

Parameter $A$ sensitive to the nature of the object exchanged between the virtual photon and the proton
Exclusive dijet production in diffractive DIS

Jets were found in $\gamma^*-\text{IP CMF}$

Exclusive $k_T$ jet algorithm: objects are merged as long as $k_T < y_{\text{cut}} \cdot M_x^2$

Exclusive dijet may originate from two, three, many parton states

Resolution parameter $y_{\text{cut}} = 0.15$ optimizes efficiency versus purity of jet sample

SATRAP MC model:

- color dipole model with saturation
- $q\bar{q}$ and $q\bar{q}g$ in a final state
- good agreement with data
- used for detector level

$p_{T\text{jet}} > 2$ GeV selects hard jets

$\eta_{\text{jet}} < 2$ select diffractive events with LRG
Exclusive dijet production in diffractive DIS

Differential cross sections
Φ distribution well described by theoretically predicted

$$1 + A \cos(2\Phi)$$

The shape of the Φ distribution varies when going from small to large values of β and the slope of the angular distribution changes sign around β = 0.4
Exclusive dijet production in diffractive DIS

d\sigma/d\beta : comparison with model predictions

Resolved Pomeron model
Prediction decreases with increasing $\beta$ faster than data

Two-Gluon-Exchange model
Reasonable description of the shape of the $\beta$ distribution
Exclusive dijet production in diffractive DIS

\[ 1 + A \cos(2\Phi) \]: comparison with model predictions

**Resolved Pomeron model**
Almost constant,
Positive value of \( A \) in the whole \( \beta \) range

**Two-Gluon-Exchange model**
Value of \( A \) varies from positive to negative
Model agrees quantitatively with the data in the range \( 0.3 < \beta < 0.7 \)

Data favour the Two-Gluon-Exchange model prediction
Measurement of the cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in deep inelastic exclusive $ep$ scattering at HERA I+II and comparison with various theory predictions

ZEUS-prelim-15-003
$\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}}$ in exclusive DIS

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

- gives information about the dynamics of hard processes
- sensitive to radial wave function of charmonium
- insensitive to many systematic uncertainties
- pQCD model calculations predict rise of $R$ with $Q^2$ reaching plateau at $Q^2 \gg M_{\psi^2}$

- $J/\psi(1S)$ and $\psi(2S)$ have the same quark content,
  - similar masses, but different wave functions
- $\psi(2S)$ has a node at $\approx 0.35$ fm
- $\langle r^2_{\psi(2S)} \rangle \approx 2 \langle r^2_{J/\psi} \rangle$
$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in exclusive DIS

Channels:
- $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$; $J/\psi \rightarrow \mu^+\mu^-$
- $\psi(2S) \rightarrow \mu^+\mu^-$
- $J/\psi \rightarrow \mu^+\mu^-$

Kinematic range:
- $2 < Q^2 < 80$ GeV$^2$
- $30 < W < 210$ GeV
- $|t| \leq 1$ GeV$^2$

$\Delta M = M(\mu\mu\pi\pi) - M(\mu\mu)$
\[ \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}} \text{ in exclusive DIS} \]

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

Both ratio measurements agree

\[ R_{\mu\mu} = \left( \frac{N_{\psi(2S)}^{\psi(2S)}}{BR_{\mu\mu}^{\psi(2S)} \cdot Acc_{\mu\mu}^{\psi(2S)}} \right) / \left( \frac{N_{J/\psi(1S)}^{J/\psi(1S)}}{BR_{\mu\mu}^{J/\psi(1S)} \cdot Acc_{\mu\mu}^{J/\psi(1S)}} \right) \]

\[ R_{J/\psi \pi\pi} = \left( \frac{N_{\psi(2S)}^{J/\psi \pi\pi}}{BR_{\psi(2S)}^{J/\psi \pi\pi} \cdot Acc_{\psi(2S)}^{J/\psi \pi\pi}} \right) / \left( \frac{N_{J/\psi(1S)}^{J/\psi(1S)}}{Acc_{\mu\mu}^{J/\psi(1S)}} \right), \]

\[ BR(J/\psi(1S) \rightarrow \mu^+\mu^-) = (5.93 \pm 0.06)\%. \]
\[ BR(\psi(2S) \rightarrow \mu^+\mu^-) = (0.77 \pm 0.08)\% \]
\[ BR(\psi(2S) \rightarrow J/\psi \pi^+\pi^-) = (33.6 \pm 0.4)\% \]
$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in DIS vs $W$ and $|t|$ 

Independent of $W$ and $|t|$
$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs $Q^2$ – model predictions

**ZEUS**

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

ZEUS & H1: Ratio increases with $Q^2$
All theoretical models exhibit an increase of the ratio with $Q^2$
Exclusive photoproduction of $\rho^0$ with forward neutron at HERA

H1 prelim–14-013
Exclusive photoproduction of $\rho^0$ with forward neutron

H1 Forward Neutron Calorimeter FNC

106 m from IP

Distinguish and measure neutral particles $N$ and $\gamma/\pi^0$

Limited acceptance for forward $\pi$ and $N$ ($\eta_{lab} \geq 6$)
Exclusive photoproduction of $\rho^0$ with forward neutron

$$\gamma^* + p \rightarrow \rho^0 + \pi^+ + n$$

$$\rho^0 \rightarrow \pi^+ + \pi^-$$

- the photon from the electron beam scatters elastically on the pion emitted from the proton producing $\rho^0$

- theoretical model: exchange of two Regge trajectories in a double-peripheral scattering process DPP

Key observables:

- $x_L = E_n / E_p$ (or $x_\pi = 1 - x_L$) distribution: $\sim f_{n/p}(x_L)$
- $W$ dependence: $\sim W^\delta$ - nature of exchange objects
- $t$-slope of $\rho^0$ ($b \sim R^2$ in geometric picture)

DATA sample: 2006-2007 e+ run 1.16 pb

No hard scale present

Regge framework is most appropriate

- $Q^2 < 2 \text{ GeV}^2$
- $|t| < 1 \text{ GeV}^2$
- $0.3 < m_{\pi\pi} < 1.5 \text{ GeV}$
- $20 < W_{\gamma\pi} < 100 \text{ GeV}$
- $E_n > 120 \text{ GeV}$, $\theta_n < 0.75 \text{ mrad}$
- $0.35 < x_L = E_n / E_p < 0.95$

analysis phase space
Exclusive photoproduction of $\rho^0$ with forward neutron

The $BW$ shape is distorted due to interference with non-resonant $\pi\pi$ production amplitude

$M = 764 \pm 3$ MeV  
$\Gamma = 154 \pm 5$ MeV  
n$_{RS} = 4.17 \pm 0.27$

The strength of the distortion is $p_t$ dependent and characterised by the skewing parameter $n_{RS}$
Exclusive photoproduction of $\rho^0$ with forward neutron

- $d\sigma_{\gamma p} / dx_L$
- Shape well described by model predictions
- Models differ in calculating the pion flux
Exclusive photoproduction of $\rho^0$ with forward neutron

Total $\gamma p$ and $\gamma \pi$ cross sections vs $W$

Regge motivated power law fit $W^\delta$ yields $\delta < 0$

Holtmann pion flux used $\frac{\sigma^\text{el}_{\gamma \pi}}{\sigma^\text{el}_{\gamma p}} = 0.21 \pm 0.06$ at $W = 22$ GeV
Exclusive photoproduction of $\rho^0$ with forward neutron

\[ \frac{d\sigma_{\gamma p}}{dp_{t,\rho}} \]

IP and $\pi$ exchange

Two slopes as predicted for a double-peripheral process:
low mass $\pi^+N$ state $\rightarrow$ large slope
high masses $\rightarrow$ less steep slope
Measurement of Feynman-x Spectra of Photons and Neutrons in the Very Forward Direction in Deep-Inelastic Scattering at HERA

DESY 14-035
Feynman-x Spectra of Photons and Neutrons

Energetic forward particles are produced at very small angles via

- Photons - from proton fragmentation (mainly from $\pi^0$ decay)
- Neutrons - from proton fragmentation AND from pion exchange

leading n's & $\gamma$'s are detected in FNC

$$Q^2 = -q^2 = -(k-k')^2$$ photon virtuality
$$y = (q \cdot p) / (k \cdot p)$$ inelasticity
$$W^2 = (q+p)^2$$ $\gamma^*p$ CM energy

$$x_L = E_{n,\gamma} / E_p$$ long.momentum fraction
$$x_F = p^* \parallel / p^* \parallel_{max} = 2p^* \parallel / W$$ Feynman x

$$x_F \approx x_L$$ for very forward particles
Feynman-x Spectra of Photons and Neutrons

HERA II (2006-2007) \( L = 131 \text{ pb}^{-1} \)

230k events with neutrons
83k events with photons

**NC DIS Selection**

<table>
<thead>
<tr>
<th>6 ( &lt; Q^2 ) ( &lt; 100 \text{ GeV}^2 )</th>
<th>0.05 ( &lt; y ) ( &lt; 0.6 )</th>
<th>70 ( &lt; W ) ( &lt; 245 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward photons ( \eta &gt; 7.9 )</td>
<td>Forward neutrons ( \eta &gt; 7.9 )</td>
<td>( 0.1 \leq x_F \leq 0.7 )</td>
</tr>
</tbody>
</table>
| \( 0 < p_T^\gamma \leq 0.4 \text{ GeV} \) | \( 0 < p_T^n \leq 0.6 \text{ GeV} \)

Cross sections are normalised to the total DIS cross section \( \sigma_{\text{DIS}} \)

At high \( x_L \) many photon candidates FNC clusters originate from more than one photon

\( x_L < 0.7 \) to suppress multi-photon events
Feynman-x Spectra of Photons and Neutrons

Normalised cross sections as a function of W

Fraction of forward photons & neutrons in DIS independent of W → limiting fragmentation

LEPTO and CDM predict too high rate of photons, by ~70%
LEPTO predicts the neutron rate rather well, CDM has too low rate
CR models predict too high rate of forward photons, by 30-40% 
Large spread in the forward neutron predictions ( EPOS LHC closest, but still different ) 
CR models indicate a $W$-dependence for photons, but less so for neutrons
Feynman-$x$ Spectra of Photons and Neutrons

Normalised cross sections as a function of $x_F$ in $W$ intervals

**70<W1<130 GeV**

**130<W2<190 GeV**

**190<W3<250 GeV**

LEPTO and CDM — both overestimate the photon rate significantly.
LEPTO describes the shape of photon $x_F$ spectra well, CDM is too hard.
Neutron $x_F$ spectra well described by Combination of MC models.
Feynman-x Spectra of Photons and Neutrons

Test of Feynman Scaling: Photons: Fragmentation models

FS: Expect Feynman-x distributions to stay uncharged in the high energy limit

DATA and Fragmentation models are compatible with Feynman Scaling
Feynman-x Spectra of Photons and Neutrons

Test of Feynman Scaling: Photons & Neutrons: CR models

**DATA: γ's & N's:**

- Ratios are consistent with unity and with being \(\text{const}\)
- \(\downarrow\) FS in the fragmentation region holds

**CR:γ's:**

- FS violated (lower rates with \(W\) rise)
- Effect strongest for SIBYLL&QGSJET
- EPOS LHC closer to data

**CR:N's:**

- Compatible with FS except SYBILL
The first measurement of diffractive production of exclusive dijets in DIS has been reported by ZEUS. The shape of $\Phi$ distribution was parameterised as motivated by theory by $1+\text{Acos}(2\Phi)$ and measured value of parameter $\text{A}$ is predominantly consistent with the two gluon exchange.

The cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in exclusive DIS has been measured for the first time by ZEUS with improved precision and agrees with models of VM production.

Photoproduction of exclusive $\rho^0$ associated with leading neutron, measured by H1, was used to extract the elastic photon-pion cross section $\sigma(\gamma\pi\rightarrow\rho^0\pi^+)$ in the OPE approximation for the first time at HERA. Differential cross sections for the reaction $\gamma p \rightarrow \rho^0 n\pi^+$ exhibit features typical for exclusive double peripheral process.

Precise measurements of high energy forward neutrons and photons has been performed with the FNC by H1. The measured cross sections are consistent with hypotheses of limiting fragmentation and Feynman scaling in $W$ range 70 - 245 GeV.
**Exclusive dijet production in diffractive DIS**

**Resolved – Pomeron model**
(G. Ingelman and P. Schlein et al.)

- Gluon emitted from the Pomeron $q\bar{q}$
- produced via Boson Gluon Fusion
- Positive parameter $A$
- Cross section sensitive to the diffractive gluon distribution in the proton
- Pomeron remnant contributes to production

**Two-Gluon-Exchange model**
(J. Bartels and H. Jung et al.)

- Virtual photon fluctuates into a $q\bar{q}$
- Two gluons from the proton couples to $q\bar{q}$
- Negative parameter $A$
- Cross section sensitive to the gluon distribution in the proton
- Emission of additional gluon also contributes to production of $q\bar{q}$
Parameter $A$ decreases with increasing $\beta$ and changes sign around $\beta = 0.4$.
Exclusive dijet production in diffractive DIS

Two-Gluon-Exchange model: $q\bar{q}$ dijet component

$\Phi$ distribution predicted to and $q\bar{q}g$ have different shape

Ratio

$$R_{q\bar{q}} = \frac{\sigma(q\bar{q})}{\sigma(q\bar{q}) + \sigma(q\bar{q}g)}$$

can be determined by studying the measured $\Phi$ distribution

Predicted $R_{q\bar{q}}$ depends on the applied $p_{T\text{cut}}$

The $p_{T\text{cut}}$ value of $\sqrt{2}$ GeV used in the original calculation significantly underestimated the ratio

The measured ratio can be well described with $p_{T\text{cut}} = 1.75$ GeV
\[ \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}} \text{ in DIS vs } Q^2 \]

**Graph:**
- **ZEUS + H1:** Ratio increases with \( Q^2 \)
- **ZEUS (prel.) 468 pb\(^{-1} \)**
- **H1 27 pb\(^{-1} \)**
- **H1 \gamma p: Q^2 \sim 0 GeV\(^2 \)**

**References:**

---

**ZEUS**

**HERA I + HERA II**
Feynman-$x$ Spectra of Photons and Neutrons

Normalised cross sections as a function of $x_F$:

**Neutrons**

$130<W2<190$ GeV

CR models predict very different neutron rates

$x_F$ dependence:

- QGSJET models are too hard and predict too high rates
- SIBYLL 2.1 describes the shape of the $x_F$ dependence, but too low rate
- EPOS LHC gives reasonable description, except at highest $x_F$ values
Feynman-x Spectra of Photons and Neutrons

Normalised cross sections as a function of $x_F$:

Photons

$130 < W < 190$ GeV

CR: in general predict γ’s rates which are closer to DATA than standard DIS models

$x_F$ dependence:

QGSJET models are too soft

SYBILL2.1  -  is too hard

EPOS LHC gives the best description, but also too hard