Exclusive Processes at HERA

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Recent H1 and ZEUS results on exclusive production:

• Measurement of the cross section ratio $\sigma(\Psi(2S))/\sigma(J/\Psi(1S))$ in deep inelastic exclusive ep scattering at HERA
  

• Production of exclusive dijets in diffractive deep inelastic scattering at HERA
  

• Exclusive $\rho^0$ meson photoproduction with a leading neutron at HERA
  
**Inclusive and Exclusive Diffraction**

**Inclusive**

- $e(k)$
- $\gamma^*(q)$
- $X(x)$
- $P(p)$
- $N(p')$

**Exclusive**

- $e(k)$
- $\gamma^*(q)$
- $\rho, \omega, \phi, J/\psi, \psi', \gamma, \gamma$
- $P(p)$
- $N(p')$

**Quantities**

- $Q^2$: virtuality of photon = $\left(\text{4-momentum exchanged at } e \text{ vertex}\right)^2$
- $W$: invariant mass of $\gamma^*-p$ system
- $t$: $\left(\text{4-momentum exchanged at } p \text{ vertex}\right)^2$ typically: $|t|<1 \text{ GeV}^2$

**Formulas**

- $M_X$: invariant mass of $\gamma^*-\text{IP system}$
- $x_{\text{IP}}$: fraction of proton's momentum carried by IP
- $\beta$: Bjorken's variable for the IP

**DIS:** $Q^2 > 1 \text{ GeV}^2$

**Photoproduction ($\gamma p$):** $Q^2 \sim 0$

**other:** $N=\text{proton - elastic process}$

**other:** $N=\text{dissociated proton system - pdiss process}$
Motivation:

The ratio \( R = \frac{\sigma_{\gamma p \to \psi(2S)p}}{\sigma_{\gamma p \to J/\psi p}} \) is sensitive to the radial wave function of charmonium. The \( \psi(2S) \) wave function differs from the \( J/\psi \) wave function:

- Has a node at \( \sim 0.35 \text{ fm} \)
- \( \langle r^2 \psi(2S) \rangle \approx 2 \langle r^2 J/\psi \rangle \)

pQCD calculations predict: \( R \sim 0.17 \) (PhP) and rise of \( R \) with \( Q^2 \) (DIS)
**Samples and event selection:**

**Data:** Full statistics of HERA I and HERA II (1996 – 2007)
Integrated luminosity 468/pb

**Decay channels:**
- $J/\psi \rightarrow \mu^+\mu^-$
- $\psi(2S) \rightarrow \mu^+\mu^-$
- $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$, $J/\psi \rightarrow \mu^+\mu^-$

**Monte Carlo samples:**
- Signal – exclusive VM production with DIFFVM
- Background – Bethe-Heither $\mu^+\mu^-$ production with GRAPE

**Event selection:**
- Scattered electron with $E > 10$ GeV measured in CAL
- Two reconstructed tracks identified as muons
- for $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ additionally two pion tracks from $\mu\mu$ vertex
- Nothing else in the detector (above noise)

Scattered proton undetected, contribution from proton dissociative events with $M_N < 4$ GeV. Assuming cross section ratio does not vary with $M_N$ – results not affected by proton dissociation background.
$\Psi(2S)/J/\Psi(1S)$ ratio in exclusive DIS

Mass spectra and background subtraction, 2-track sample:

$J/\psi \rightarrow \mu^+\mu^-$
$\psi(2S) \rightarrow \mu^+\mu^-$

Non-resonant di-muon background fitted with a straight line in the sideband regions:
- $2.99 < M_{\mu^+\mu^-} < 2.62$ GeV
- $4.05 < M_{\mu^+\mu^-} < 5.00$ GeV

then subtracted from the signal regions:
- $3.59 < M_{\mu^+\mu^-} < 3.79$ GeV
- $3.02 < M_{\mu^+\mu^-} < 3.17$ GeV
$\Psi(2S)/J/\Psi(1S)$ ratio in exclusive DIS

Mass spectra and background subtraction, 4-track sample:

ZEUS

$\psi(2S) \rightarrow J/\psi \pi^+\pi^-$

$J/\psi \rightarrow \mu^+\mu^-$

$\Delta M = M_{\mu\mu\pi\pi} - M_{\mu\mu}$

No background events in the $\psi(2S)$ signal region:

$3.02 < M_{\mu\mu} < 3.17$ GeV

$0.5 < \Delta M < 0.7$ GeV

(upper limit of 3 events at 90% C.L. estimated)
\( \Psi(2S)/J/\Psi(1S) \) ratio in exclusive DIS

**Ratios vs \( Q^2 \), \( W \) and \( t \):**

- Increasing with \( Q^2 \)
- Independent of \( W \) and \( t \)
Ψ(2S)/J/Ψ(1S) ratio in exclusive DIS

Comparison with theory predictions:

HIKT, Hüfner et al.: dipole model, dipole-proton constrained by inclusive DIS data
AR, Armesto and Rezaeian: impact parameter dependent CGC and IP-Sat model
KMW, Kowalski Motyka Watt: QCD description and universality of quarkonia production
FFJS, Fazio et al.: two component Pomeron model
KNNPZZ, Nemchik et al.: color-dipole cross section derived from BFKL generalised eq.
LM, Lappi and Mäntysaari: dipole picture in IP-Sat model

All models describe the increase of the $\sigma(\psi(2S))/\sigma(J/\psi)$ ratio with $Q^2$
Exclusive dijet production in DIS

Motivation:

Resolved Pomeron model

Two-Gluon Exchange model

Resolved pomeron model in DDIS describes well various event observables in dijet production
Two-gluon exchange well suited for exclusive dijets

Distribution of angle $\phi$ between the lepton and dijet production planes allows to distinguish between both theoretical approaches.

$$\frac{d\sigma}{d\phi} \propto 1 + A \cos(2\phi)$$

A > 0 in Resolved Pomeron model
A < 0 in Two-Gluon Exchange model

J. Bartels et al., PLB 386 (1996) 389
Exclusive dijet production in DIS

**Data sample and event selection:**

**Data:** Full statistics of HERA II (2003 – 2007), Integrated luminosity 372/pb

**Monte Carlo:**
- SATRAP for diffractive sample and detector level corrections
- ARIADNE and PYTHIA6.2 for nondiffractive and PhP backgrounds
- RAPGAP for model predictions at hadron level: Resolved Pomeron (G. Ingeman and P. Schlein) and Two-Gluon Exchange (J. Bartels and H. Jung)

**Jet reconstruction:**
- Durham jet algorithm in $\gamma^*IP$ rest frame in exclusive mode – all objects in jets
- Resolution parameter - $y_{min}=0.15$

**Kinematic region:**
- $Q^2 > 25 \text{ GeV}^2$
- $90 < W < 250 \text{ GeV}$
- $x_{IP} < 0.01$
- $M_X > 5 \text{ GeV}$
- $N_{jets} = 2$ (with $y_{cut} = 0.15$)
- $p_{T,jet} > 2 \text{ GeV}$.

Proton dissociation background $f_{pdiss} = 45\% \pm 4\% \text{ (stat)} \pm 15\% \text{ (sys)}$
Exclusive dijet production in DIS

Cross sections $d\sigma/d\beta$ and $d\sigma/d\phi$ in bins of $\beta$:

$\beta = x / x_{IP}$ – Pomeron momentum fraction entering hard subprocess

$d\sigma/d\phi$ cross section fitted with:

$$1 + A \cos 2\phi$$

→ $\beta$ dependence of $A$ parameter
Exclusive dijet production in DIS

Comparison to theory predictions:

Data vs Resolved Pomeron and Two-Gluon Exchange models:

- None of the models predicts correctly the magnitude of cross section. Factor of 2 difference $\rightarrow$ NLO?
- Resolved Pomeron model does not reproduce $A(\beta)$, Two-Gluon Exchange successful for $\beta > 0.3$
**Motivation:**

First measurement of $\rho^0$ photoproduction with a leading neutron at HERA

A presence of the neutron carrying a large fraction of the proton beam momentum $x_L$ is accompanied by the pion exchange process

→ measure $\gamma\pi^+ \rightarrow \rho^0\pi^+$ cross section

Mean $W \sim 24$ GeV is low → soft regime, Regge framework most appropriate:

- exchange of two Regge trajectories in a Double Peripheral Process (DPP)

Constraints to pion flux models

Study of absorption effects in leading baryon production
**Signal and background processes:**

**Signal : Drell-Hiida-Deck diagrams**

(a) pion exchange: \( \gamma p \rightarrow \rho^0 n \pi^+ \)

(b) neutron exchange: \( \gamma p \rightarrow \rho^0 n \pi^- \)

(c) "direct pole": \( \gamma p \rightarrow \rho^0 n \pi^+ \)

**Background**

(d) proton dissociation: \( \gamma p \rightarrow \rho^0 n Y \pi^+ \)

\[ f_{bg} = 0.34 \pm 0.05 \]

\[ \sigma(\gamma p \rightarrow \rho^0 n \pi^+) = |Aa + Ab + Ac|^2: \text{interference effects} \]

For large \( s \) and \( t' \rightarrow 0 \): pion exchange dominates.
Exclusive $\rho^0$ photoproduction with a LN

Samples and event selection:

Data: 2006 – 2007 $e^+p$ data, integrated luminosity $1.16/pb$

LN detection: Forward Neutron Calorimeter (FNC) located at 106 m from the H1 interaction point.
Limited acceptance: $< A > \sim 30\%$
$p_{T,n} < xL \cdot 0.69 \text{ GeV} (\theta_n < 0.75 \text{ mrad})$

OPE dominant range: $p_{T,n} < 0.2 \text{ GeV}$

Event selection:

- Scattered positron undetected:
  $< Q^2 > = 0.04 \text{ GeV}^2$ – photoproduction events
- Only two oppositely charged pion candidates in the central tracker with $0.3 < M\pi\pi < 1.5 \text{ GeV}$
- A hadronic cluster in the FNC with $E_n > 120 \text{ GeV}$
- Nothing else in the detector (above noise level)

All properties of the selected $\pi^+\pi^-$ are consistent with $\rho^0$ photoproduction.
Exclusive $\rho^0$ photoproduction with a LN

Cross section measurement:

\[
\sigma_{\gamma p} = \frac{\sigma_{ep}}{\int f_{\gamma/e}(y, Q^2)dydQ^2}
\]

\[
\sigma(\gamma p \rightarrow \rho^0 n\pi^+) = 310 \pm 6\,\text{(stat)} \pm 45\,\text{(syst)} \, \text{nb} \quad (\theta_n < 0.75 \, \text{mrad})
\]

\[
\sigma(\gamma p \rightarrow \rho^0 n\pi^+) = 130 \pm 3\,\text{(stat)} \pm 19\,\text{(syst)} \, \text{nb} \quad (p_{T,n} < 0.2 \, \text{GeV})
\]

Kinematic region:

- $20 < W_{\gamma p} < 100 \, \text{GeV}$
- $2m_\pi < M_p < M_p + 5\Gamma_{\rho}$
- $|t'| < 1 \, \text{GeV}^2$
- $0.35 < x_L < 0.95$

\[
\sigma_{\gamma\pi}(\langle W_{\gamma\pi} \rangle) = \frac{\sigma_{\gamma p}}{\int f_{\pi^+/p}(x_L, t)dx_Ldt'}
\]

\[
\sigma(\gamma\pi^+ \rightarrow \rho_0\pi^+) = 2.33 \pm 0.34 \, \text{(exp)}^{+0.47}_{-0.40} \, \text{(model)} \, \mu\text{b}
\]

for $\langle W_{\gamma\pi} \rangle = 24 \, \text{GeV}$
Contraining pion flux:

- $x_L$ distribution of the leading neutron generally well described
- FMS and NSSS pion fluxes disfavoured
- None of the models can reproduce the $t$ dependence of the leading neutron - effect of absorptive corrections?
**Exclusive $\rho^0$ photoproduction with a LN**

**Differential cross section $d\sigma_{\gamma p}/dt'$ of $\rho^0$ meson:**

- $\rho^0$ slope strongly changing from low-$t'$ to high-$t'$ region, as expected for a double-peripheral process – slope dependence on the invariant mass of the $n\pi^+$ system.

- Geometric picture: Photon finds pion in a cloud which extends far beyond the proton radius.

- $< r^2 > = 2b_1 \cdot (hc)^2 \sim 2 \text{ fm}^2 \sim (1.6R_p)^2$
Exclusive $\rho^0$ photoproduction with a LN

$$\gamma\pi^+ \rightarrow \rho^0\pi^+$$
cross section:

Compare $\gamma\pi^+ \rightarrow \rho^0\pi^+$ and $\gamma p \rightarrow \rho^0 p$ cross sections:

$$\frac{\sigma(\gamma\pi^+)}{\sigma(\gamma p)} = 0.25 \pm 0.06 \text{ at } \langle W \rangle = 24 \text{ GeV}$$

in agreement with a previous ZEUS measurement (NPB 637 (2002) 3). Significantly lower than expected $\rightarrow$ large absorption corrections: $k_{\text{abs}} = 0.44 \pm 0.11$
Summary

- Cross section ratio $\psi(2S)/J/\psi(1S)$ measured by ZEUS
  - The ratio grows with $Q^2$ and is constant with $W$ and $t$
  - Comparison with model predictions: all predictions are consistent with the data, some discrimination between the models possible

- First measurement of exclusive dijets in diffractive DIS by ZEUS
  - Cross section significantly larger than predicted by models
  - Two-gluon-exchange model more successful in describing the data at high $\beta$ than resolved Pomeron model

- Exclusive $\rho^0$ photoproduction associated with a leading neutron measured for the first time at HERA by H1
  - The $t$-dependence of the $\gamma p \rightarrow \rho^0 n \pi^+$ cross section shows a behaviour typical for exclusive double peripheral exchange processes
  - The elastic photon-pion cross section, $\sigma(\gamma\pi^+ \rightarrow \rho^0\pi^+)$ at $<W_{\gamma\pi}> = 24$ GeV extracted in the one-pion-exchange approximation
  - The cross section ratio for elastic photoproduction of the $\rho^0$ meson on the pion and on the proton suggest large absorption corrections.

Thank you for your attention!
Backup slides
Exclusive $\rho^0$ photoproduction with a LN

All properties of the selected $\pi^+\pi^-$ are consistent with $\rho 0$ photoproduction

R. Ciesielski, Exclusive Processes at HERA