> **Exclusive results at HERA**

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The world’s only electron/positron-proton collider
- $E_e = 27.6$ GeV, $E_p = 920$ GeV (820, 460, 575 GeV)
- total luminosity $\sim 0.5$ fb$^{-1}$ per experiment
Overview

At HERA exclusive production of VMs, photons and dijets has been investigated

Recent results from H1 and ZEUS:

- $\psi' / J/\psi$ ratio [ZEUS prel-14-003 and prel-15-003]
- $\rho^0$ photoproduction with a leading neutrons [H1 DESY-15-120]
- Exclusive dijet production [ZEUS, arXiv:1505.05783v1]
Exclusive processes – kinematic variables

Exclusive production of Vector mesons, photons, or jets:

- $Q^2$ photon virtuality
- $W$ photon-proton centre-of-mass energy
- $t=(p-p')^2$ – four momentum transfer squared at proton vertex
- $x$–Bjorken $x$–fraction of proton’s momentum carried by struck quark
- $x_{IP}$ – fraction of proton’s momentum carried by exchanged colour singlet

Kinematic variable fully reconstructed, usually measuring scattered electron (in DIS) and vector meson decay products or final photons or jets.

Scattered p detected with lower acceptance
Experimental Methods

- Exclusive processes are very clean experimentally

VFPS

Electron $\rightarrow$ proton $\leftarrow$ scattered electron
Vector Meson production

- Soft physics:
  Vector Dominance Model,
  Regge theory

- In the presence of a hard scale ($M_{VM}$, $Q^2$, $t$) calculations in pQCD are possible. Calculations performed now at NLO. Generalised Parton Distributions relevant here.
> The cross section dependence on $W$ can be parameterised as $\sigma \sim W^{\gamma p \delta}$

The rapid rise of cross section with $W_{\gamma p}$ is related to the increasing gluon density with decreasing of fractional momentum $x \sim 1/W_{\gamma p}^2$. 

Alessia Bruni | Exclusive processes at HERA | QCD@LHC2015, London | 7
VM at NLO and extraction of gluon density at low $x$

“data for $pp \rightarrow pYp$ can now be included in the global PDF fits to determine the gluon in the low $x$ regime”

1507.06942 Jones, Martin, Ryskin, Teubner
Measurement of the cross section ratio $\sigma_{\psi(2s)} / \sigma_{\psi}$ in deep inelastic exclusive ep scattering at HERA I+II and comparison with various theory predictions

ZEUS-prelim-15-003
ψ(2s) and J/ψ(1S) production in DIS

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

- Measurement sensitive to charmonium wave function
- Different rate of ψ(2s) and J/ψ(1S) expected due to different wave function, ratio estimated in QCD models to be \( R \sim 0.17 \), rising with \( Q^2 \)
- Kinematic range: \( 5 < Q^2 < 70 \text{ GeV}^2 \), \( 30 < W < 210 \text{ GeV} \), \(|t| < 1 \text{ GeV}^2 \)

Decays: \( J/\psi \rightarrow \mu\mu \), \( \Psi \rightarrow \mu\mu, \Psi \rightarrow J/\psi\pi\pi \)
\( \psi(2s) / J/\psi(1S) \) ratio vs \( W, t, Q^2 \)

**Ratio:**
- Independent of \( W \)
- Independent of \( t \)
- Increase with \( Q^2 \)

Similar results from H1
ψ(2s) / J/ψ(1S) vs Q², comparison with models

Same quark content and similar mass, but different wave function

pQCD model calculations predict $R \sim 0.17$ in PHP rising with $Q^2$ reaching plateau at $Q^2 \gg M^2 \psi$

HIKT, Hufner 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
Production of exclusive dijets in diffractive DIS at HERA

ZEUS
Exclusive dijets production in diffractive DIS, arXiv:1505.05783

\[ e + p \rightarrow e + \text{jet}1 + \text{jet}2 + p \]

Data 2003-2007, 372 pb^{-1}

Only dijet, scattered electron and proton in the final state

\( Q^2 > 25 \text{ GeV}^2 \)

90 < W > 250 GeV

\( x_P < 0.01 \) – fraction of proton’s momentum carried by exchanged color singlet

Large Rapidity Gap
Exclusive dijet production in diffractive DIS

SATRAP MC model (Golec-Biernat, Wusthoff, 1999):
- 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

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

Jets were found in $\gamma^*-\text{IP}$ rest frame
- using Durham kT jet algorithm in exclusive mode: all objects are merged in jets
- with resolution parameter $y_{\text{cut}} = 0.15$ optimizes efficiency versus purity of jet sample
- $p_T^\text{jet} > 2 \text{ GeV}$ selects hard jets
- $\eta_{\text{jet}} < 2$ select diffractive events with LRG
Exclusive dijets production in diffractive DIS

Test the nature of the object in diffractive interaction by reconstructing the azimuthal angle between lepton and jet plane

\[ \frac{d\sigma}{d\Phi} \sim 1 + A(p_{T\text{jet}}) \cos(2\Phi) \]

J. Bartels et al, PLB386 (1996) 389:

A > 0 for two gluons exchange

A < 0 for \( \bar{q}q \) produced from single gluon
Exclusive dijet production in diffr. DIS, angle between jets

\[ \frac{d\sigma}{d\Phi} \text{ fitted for different } \beta \text{ bins}, \]

\[ \beta = \frac{x}{x_{IP}} \text{ – fraction of Pomeron momentum 'seen' by photon} \]

Normalisation discrepancy of factor two (NLO corr. large?)

The slope of the angular distribution changes sign around \( \beta = 0.4 \)
Exclusive dijet production in diffractive DIS

\[ \frac{d\sigma}{d\Phi} \sim 1 + A(p_{T,\text{jet}}) \cos(2\Phi) \]

A vs \( \beta \), comparison with model predictions

In resolved Pomeron model, the parameter A positive and constant in the whole \( \beta \) range

In two-Gluon-Exchange model value of A varies from positive to negative; it agrees quantitatively with the data in the range \( 0.3 < \beta < 0.7 \)

Data favour the Two-Gluon-Exchange model prediction
Exclusive $\rho^0$ meson photoproduction with a leading neutron at HERA

H1 DESY 15-120, submitted to Eur. Phys. JC
Exclusive PHP of rho mesons with forward neutron

- $\gamma p \rightarrow \rho^0 \pi^+ n$, $\rho^0 \rightarrow \pi^+ \pi^-$

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

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

In One Pion Exchange assumption, factorization of the proton vertex (valid at small $t$):

$$\sigma_{\gamma p} \sim f_{\pi \pi} / p \left( x_L \right) \sigma_{\gamma \pi}$$
Exclusive $\rho$ photoproduction with forward $n$

Kinematic range:
$Q^2 < 2 \text{ GeV}^2$
$|t| < 1 \text{ GeV}^2$
$0.3 < m_{\pi\pi} < 1.5 \text{ GeV}$
$20 < W_{\gamma\pi} < 100 \text{ GeV}$

No hard scale

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

The strength of the distortion is $p_t$ dependent and characterised by the skewing parameter $n_{RS}$
(Ross, Stodolsky 1966)

Property of two-pion system compatible with previous measurements
Exclusive $p$ photoproduction with forward $n$ – slope at $n$ vertex

Slope of momentum transfer at $p$-$n$ vertex vs $x_L = E_n/E_p$

Steep rise with increasing $x_L$ expected from models, but rise is stronger than predicted by various pion-flux parametrisations
Exclusive $\rho$ photoproduction with forward $n$ – slope at $\gamma p$ vertex

$\frac{d\sigma_{\gamma p}}{dp_{t,\rho}}$ vs $t'$, 4-momentum transfer of rho meson

$t'$ - dependence has two components, (two $b$ parameters)

In Double Peripheral Process, this is due to double exchange, IP and $\pi$
Exclusive $\rho$ photoproduction with forward $n$, $\sigma$ vs $W$

The cross section $\gamma p \to \rho^0 \pi^+ n$ is shown in the left graph for $\rho^0$ with forward neutron. The cross section $\gamma \pi \to \rho^0 \pi^+ n$ is shown in the right graph.

$\gamma p$: Regge motivated power low fit $W^\delta$ yields $\delta < 0$.

Using pion-flux parametrisations, the gamma-pion cross section $\gamma \pi$ can be measured.

$\gamma \pi$: cross section independent from $W$ within uncertainties. Ratio $\sigma_{\gamma \pi}/\sigma_{\gamma p} \sim 0.25$, small, indicating rescattering or large absorption corr.
The cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in exclusive DIS has been measured with improved precision, in agreement with QCD models.

First measurement in ep of diffractive production of exclusive dijets in DIS. Production consistent with two gluon exchange.

Photoproduction of exclusive $\rho^0$ associated with leading neutron measured 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.

Process used to extract the elastic photon-pion cross section $\sigma(\gamma\pi \rightarrow \rho^0\pi^+)$ in the OPE approximation. The cross section ratio $\sigma(\gamma\pi) / \sigma(\gamma p)$ suggests large absorption corrections suppressing $\sigma(\gamma p)$.
VM production and DVCS: $b(Q^2+M_{VM}^2)$

- Analysis doubles the explored range
- In agreement with asymptotic behaviour of $Q^2 + M_{VM}^2$
- In optical model approach:
  
  $$b \sim (R_p^2 + R_{VM}^2)/4$$

- The first measurement of $b$-slope:
  
  $$b = 4.3 \pm 2.0-1.2+0.5 -0.6 \text{ GeV}^{-2}$$

- Consistent with predictions based on pQCD models ($b= 3.68 \text{ GeV}-2$)
  
  Cox, Forshaw, Sandapen, JHEP 0906 (2009) 034

- Size of interaction region is getting smaller with $Q^2 + M_{VM}^2$
Vector Meson production

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