Recent Results on Exclusive Production at HERA

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(on behalf of the H1 and ZEUS Collaborations)

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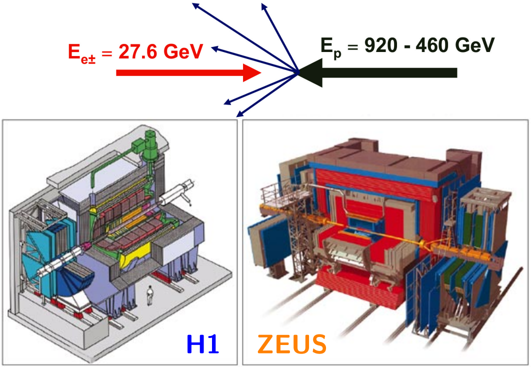
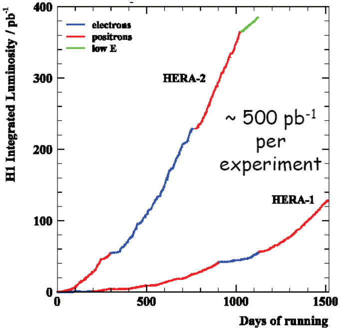
Outline

Recent results on exclusive (photo)production from H1 and ZEUS experiments:

- Exclusive ρ^0 meson photoproduction with a leading neutron at HERA
  H1 Collaboration, Eur. Phys. J. C (2016) 76:41
- Measurement of the cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in exclusive DIS
  ZEUS Collaboration, Nucl. Phys. B909 (2016) 934-953
- Production of exclusive dijets in diffractive DIS at HERA
  ZEUS Collaboration, Eur. Phys. J. C (2016) 76:16



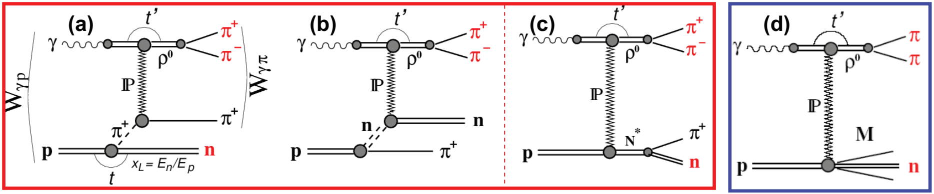


Exclusive ρ^0 photoproduction with a leading neutron

First measurement of exclusive (ρ^0) photoproduction on (virtual) pion.

- The photon from the electron beam scatters elastically on the pion emitted from the proton producing ρ^0: $\boldsymbol{\gamma^{(\star)} + p \rightarrow \rho^0 + \pi^+ + n, \quad \rho^0 \rightarrow \pi^+ + \pi^-}$
- No hard scale present $\Rightarrow$ exchange of two Regge poles in a DPP.
- Processes contributing to the exclusive photoproduction of ρ^0 mesons associated with a leading neutron:

Pion exchange **Neutron exchange** **Direct pole** **Proton dissociation**



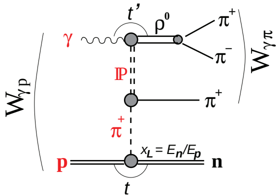
The Drell-Hiida-Deck model (diagrams a, b, c):

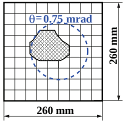
- At large s and small $t \rightarrow 0$ pion exchange dominates as $A_b \approx -A_c$.
- Slope of t' distribution depends on the mass of the $n\pi$ system: $4 < b(m_{n\pi}) < 22$ GeV^{-2}.
- Interference between the amplitudes correspondindg to the first three graphs is necessary to explain the cross section $\sigma(\gamma p \rightarrow \rho^0 n \pi^+) \propto |A_a + A_b + A_c|^2$.

Exclusive ρ^0 photoproduction with a leading neutron

Event selection:

- absence of scattered electron in the calorimeter
  $\Rightarrow$ PHP regime: $Q^2 < 2$ GeV^2, $\langle Q^2 \rangle = 0.04$ GeV^2,
- two oppositely charged tracks with $p_T > 0.2$ GeV originating from a common vertex with $|v_z| < 30$ cm,
- $0.3 < M_{\pi\pi} < 1.5$ GeV and $M_{KK} > 1.04$ GeV,
- leading neutron in FNC with $E_n > 120$ GeV and $\theta_n < 0.75$ mrad,
- no additional signals above noise in the main calorimeters and forward detectors (π^+ escapes detection in the beam pipe).





Monte Carlo simulation:

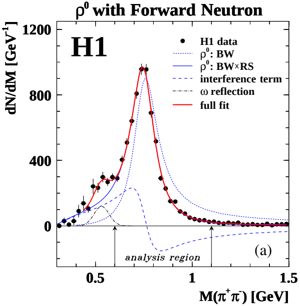
- signal events (a) - POMPYT - virtual pion flux generated according to available parametrisation followed by elastic scattering of pion on photon, thus producing a vector meson (ρ^0).
- background ev. (d) - DIFFVM - based on Regge theory and VDM (elastic, single and double disociation processes); also used for estimation of possible background from $\omega(782)$, $\phi(1020)$ and $\rho'(1450-1700)$.
- both, signal and background events reweighted to relativistic BW shape with additional distortion caused by the interference between resonant and non-resonant $\pi^+\pi^-$ production (see next slide).

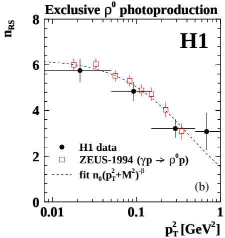
Extraction of the ρ^0 signal

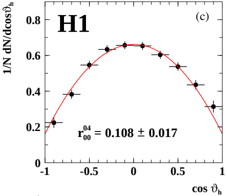
- **Distortion of the ρ^0 mass shape** due to interference between the resonant and non-resonant $\pi^+\pi^-$ production is characterised by the Ross-Stodolsky skewing parameter n_{RS}:

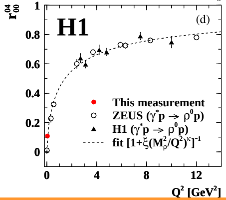
$$\frac{\mathrm{d}N}{\mathrm{d}M_{\pi\pi}} \propto BW_\rho(M_{\pi\pi}) \left(\frac{M_\rho}{M_{\pi\pi}}\right)^{n_{\mathrm{RS}}(p_{\mathrm{T},\rho})}$$

- add contribution for the reflection from $\omega(782) \to \pi^+\pi^-\pi^0$









- Fitted ρ^0 mass and width: $M_\rho = 764 \pm 3$ MeV, $\Gamma_\rho = 155 \pm 5$ MeV

Analysis region ($0.6 < M_{\pi^+\pi^-} < 1.1$ GeV) extrapolated to full range $2m_\pi < M_{\pi\pi} < M_\rho + 5\Gamma_\rho$ using relativistic BW function.

- Skewing parameter n_{RS} dependence on p_{T}^2 of the $\pi^+\pi^-$ system is in agreement with previous ZEUS measurement.
- Polar angle distributions of the π^+ in the helicity frame is in agreement with theory:

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\vartheta_h} \propto 1 - r_{00}^{04} + (3r_{00}^{04} - 1)\cos^2\vartheta_h$$

- Spin-density matrix element r_{00}^{04} (prob. that ρ^0 has helicity 0) obtained from the fit is in agreement with other measurements.

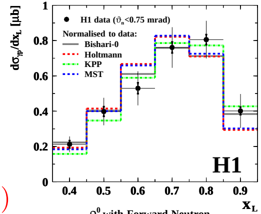
Exclusive ρ^0 photoproduction with a leading neutron

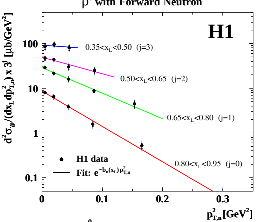
Differential cross sections have been measured at the hadron level in the following kinematic range:

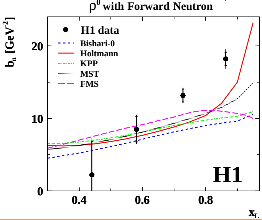
$Q^2 = 0$ GeV^2, $\quad 20 < W_{\gamma p} < 100$ GeV
$t' < 1$ GeV^2, $\quad 2m_\pi < M_\rho < M_\rho + 5\Gamma_\rho$
$0.35 < x_{\mathrm{L}} < 0.95$, $\quad p_{\mathrm{T,n}} < x_{\mathrm{L}} \cdot 0.69$ GeV $(\theta_{\mathrm{n}} < 0.75$ mrad$)$

- γp cross section: $\quad \sigma_{\gamma p} = \dfrac{\sigma_{ep}}{\int f_{\gamma/e}(y, Q^2)\mathrm{d}y\mathrm{d}Q^2}$

  $\sigma(\gamma p \to \rho^0 n \pi^+) = 310 \pm 6\,(\text{stat}) \pm 45\,(\text{sys})$ nb
- shape of x_{L} distribution is well reproduced by most of the pion flux models,
- double differential γp cross section in $(x_{\mathrm{L}}, p^2_{\mathrm{T,n}})$: fit by $\exp\left[-b_n(x_{\mathrm{L}})p^2_{\mathrm{T,n}}\right]$ function in each x_{L} bin,
- none of the models is able to reproduce the x_{L} dependence of the $p^2_{\mathrm{T,n}}$ slope of the leading neutron,
  $\Rightarrow$ possible importance of absorptive corrections leading to increase of the effective b-slope at large x_{L} as compared to pure OPE model.



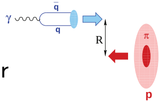




- measured cross section $\sigma_{\gamma p}$ drops with energy $W_{\gamma p}$ in contrast to POMPYT where the whole energy dependnce is driven by Pomeron exchange only; Regge motivated power law fit $\sigma_{\gamma p} \propto W^{\delta}$ yields

  $\delta = -0.26 \pm 0.06$ (stat) ± 0.07 (sys)

- strongly changing slope of $\sigma_{\gamma p}$ between low and high t':
  Geometric picture:
  $\langle R^2 \rangle = 2b_1 \cdot (\hbar c)^2 = 2$ fm$^2 = (1.6\, R_p)^2$
  photons find pions in the cloud extending far beyond the proton radius.



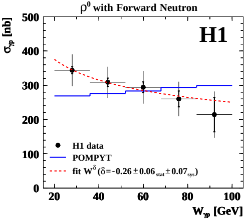
  DPP interpretation: slope of t' depends on mass $m_{n\pi^+}$
  low $m_{n\pi^+}$ $\rightarrow$ large slope, high $m_{n\pi^+}$ $\rightarrow$ less steep;

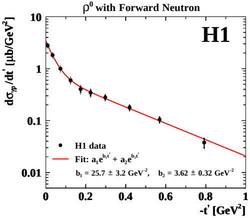
- $\gamma\pi$ cross section: $\sigma_{\gamma\pi}(\langle W_{\gamma\pi}\rangle) = \dfrac{\sigma_{\gamma p}}{\int f_{\pi^+/p}(x_{\mathrm{L}},t)\mathrm{d}x_{\mathrm{L}}\mathrm{d}t}$

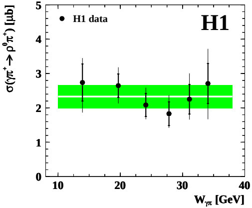
  For $\langle W_{\gamma\pi}\rangle = 24$ GeV the measured cross section is:

  $\sigma_{el}(\gamma\pi^+ \rightarrow \rho^0\pi^+) = 2.33 \pm 0.34\,(exp)^{+0.47}_{-0.40}$ (model) μb

  Measured ratio $r_{el} = \sigma_{el}^{\gamma\pi}/\sigma_{el}^{\gamma p} = 0.25 \pm 0.06$
  is significantly lower than expectation $r_{el}^{\mathrm{th}} = 0.57 \pm 0.03$
  This implies an absorption factor $K_{\mathrm{abs}} = 0.44 \pm 0.11$



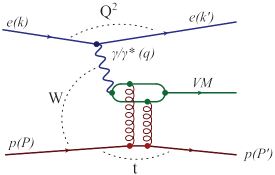


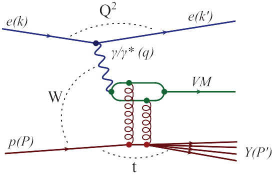


Cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in exclusive DIS

Exclusive diffractive vector meson (VM) production:

- photon fluctuates into $q\bar{q}$ pair which interacts with the proton via colourless exchange, e.g. two-gluon ladder, and then hadronises into the vector meson (VM),
- proton can dissociate into a low mass system.





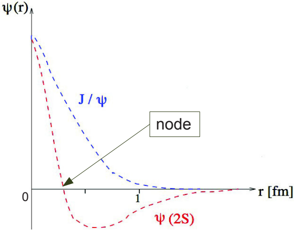
Measure the ratio of the cross sections:

$$R = \frac{\sigma(\gamma^\star p \to \psi(2S)p)}{\sigma(\gamma^\star p \to J/\psi(1S)p)}$$

which is insensitive to many systematic uncertainties.

$\psi(2S)$ and $J/\psi(1S)$ have the same quark content, but different radial wave functions, which means that R is sensitive to the radial wave function of charmonium and provides insight into the dynamics of hard process.

- $\psi(2S)$ has a node at 0.35 fm (typical transverse separation of virtual $c\bar{c}$ pair),
- $\langle r^2_{\psi(2S)}\rangle \approx 2\langle r^2_{J/\psi(1S)}\rangle$
- pQCD predicts rise of R with Q^2 starting from $R(Q^2=0) \approx 0.17$

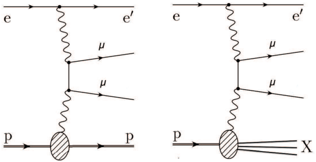


Cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in exclusive DIS

ZEUS data: 468 pb^{-1} $(5 < Q^2 < 80$ GeV$^2)$
+ 114 pb^{-1} $(2 < Q^2 < 5$ GeV$^2)$

Signal MC: DIFFVM (exclusive VM production)

Background MC: GRAPE (Bethe-Heitler elastic and proton dissociative $\mu^+\mu^-$ production)



Event selection:

$E' > 10$ GeV, $|z_{\text{vtx}}| < 30$ cm,
$5\ (2) < Q^2 < 80$ GeV^2, $30 < W < 210$ GeV, $|t| < 1$ GeV^2

Investigated decay channels and their selection:

$\left.\begin{array}{l} \psi(2S) \rightarrow \mu^+\mu^- \\ J/\psi(1S) \rightarrow \mu^+\mu^- \end{array}\right\}$ two tracks identified as muons and nothing else in the detector above noise level are required

$\psi(2S) \rightarrow J/\psi(1S)\pi^+\pi^- \rightarrow \mu^+\mu^-\ \pi^+\pi^- \}$ in addition two pion tracks from the $\mu^+\mu^-$ vertex are required

Measure the ratios:

$$R_{\mu\mu} = \frac{\sigma_{\psi(2S)\rightarrow\mu\mu}}{\sigma_{J/\psi(1S)\rightarrow\mu\mu}} = \left(\frac{N_{\mu\mu}^{\psi(2S)}}{B(\psi(2S)\rightarrow\mu\mu)\cdot A_{\mu\mu}^{\psi(2S)}}\right) \Big/ \left(\frac{N_{\mu\mu}^{J/\psi(1S)}}{B(J/\psi(1S)\rightarrow\mu\mu)\cdot A_{\mu\mu}^{J/\psi(1S)}}\right)$$

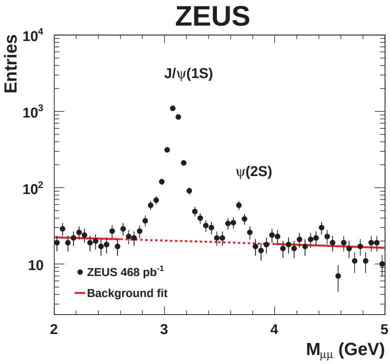
$$R_{J/\psi\pi\pi} = \frac{\sigma_{\psi(2S)\rightarrow J/\psi\,\pi\pi}}{\sigma_{J/\psi(1S)\rightarrow\mu\mu}} = \left(\frac{N_{J/\psi\,\pi\pi}^{\psi(2S)}}{B(\psi(2S)\rightarrow J/\psi(1S)\,\pi\pi)\cdot A_{J/\psi\,\pi\pi}^{\psi(2S)}}\right) \Big/ \left(\frac{N_{\mu\mu}^{J/\psi(1S)}}{A_{\mu\mu}^{J/\psi(1S)}}\right)$$

Cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in exclusive DIS

Background subtraction in $J/\psi \to \mu^+\mu^-$ and $\psi \to \mu^+\mu^-$:

BH dimuon background fit to straight line for $2 < M_{\mu\mu} < 2.62$ GeV and $4.05 < M_{\mu\mu} < 5$ GeV.

J/ψ and ψ signals: numbers of events above background in the range $3.02 < M_{\mu\mu} < 3.17$ GeV and $3.59 < M_{\mu\mu} < 3.79$ GeV, respectively.



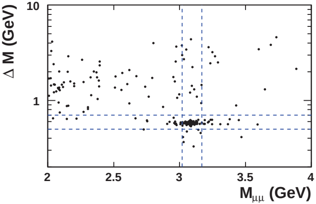
Background subtraction in $\psi(2S) \to J/\psi\,\pi^+\pi^-$:

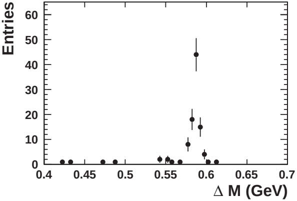
Data show a clear peak on the scatterplot $\Delta M = M_{\mu\mu\pi\pi} - M_{\mu\mu}$ vs. $M_{\mu\mu}$

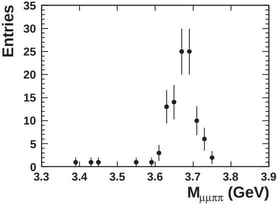
Applied cuts:

$3.02 < M_{\mu\mu} < 3.17$ GeV and $0.5 < \Delta M < 0.7$ GeV

No background (upper limit 3 ev. at 90% CL)







Cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in exclusive DIS

R is measured in the kinematic range:

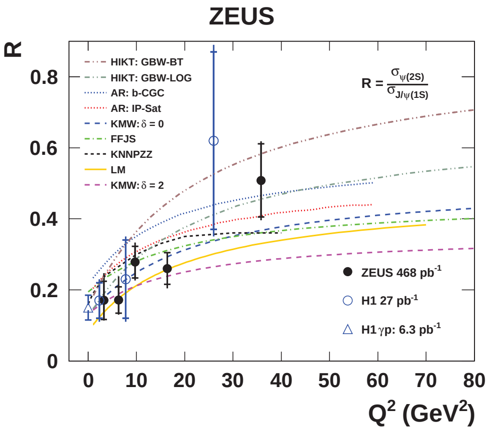
$5\ (2) < Q^2 < 80$ GeV^2
$30 < W < 210$ GeV, $\quad |t| < 1$ GeV^2

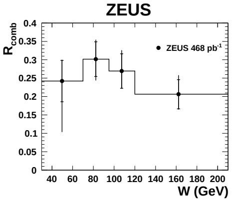
- Data contain proton dissociative background with masses $M_Y < 4$ GeV.
- Assuming that cross section ratio does not vary with M_Y, the results are not affected by proton dissociation backgr.
- Combined ratio R obtained as weighted average of the cross sections determined for the two $\psi(2S)$ decay channels.

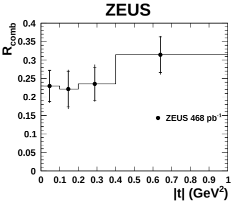
- All models predict rise of R with Q^2:

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 and Watt:
QCD description and universality of quarkonia production
FFJS, Fazio et al.: two component Pomeron model
KNNPZZ, Nemchik et al.:
color-dipol cross section derived from BFKL generalised equation
LM, Lappi and Mäntysaari: dipole picture in IP-Sat model

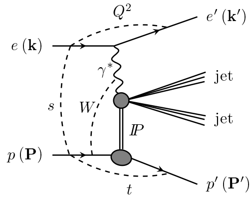
- Good agreement with earlier H1 mesurements (EPJ C10 (1999) 373)
- R is independent of W and $|t|$





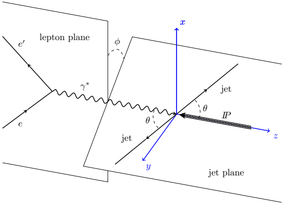


Exclusive dijets in diffractive DIS



Study of the process: $\mathbf{e}+\mathbf{p}\to\mathbf{e}'+\mathbf{p}'+\text{jet}+\text{jet}$

- First measurement of exclusive dijet production in electron-proton scattering (erlier measurement in $p\bar{p}$).
- Sensitive to the nature of the object exchanged between the virtual photon and proton.



ϕ - angle between lepton and jet planes

θ - polar angle of jet in $\gamma^\star I\!P$ CMS

Diffractive DIS selection (main selection cuts):

$E' > 10$ GeV, $\quad 45 < (E-P_Z) < 70$ GeV, $\quad |z_{\text{vtx}}| < 30$ cm,

$Q^2 > 25$ GeV^2, $\quad 90 < W < 250$ GeV,

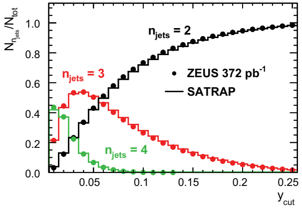
$\eta_{\text{max}} < 2, \quad x_{I\!P} = \frac{Q^2+M_X^2}{Q^2+W^2} < 0.01, \quad M_X > 5$ GeV

Dijet selection (Durham exclusive k_{T} algorithm):

$k^2_{\text{T}\ ij} = 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$

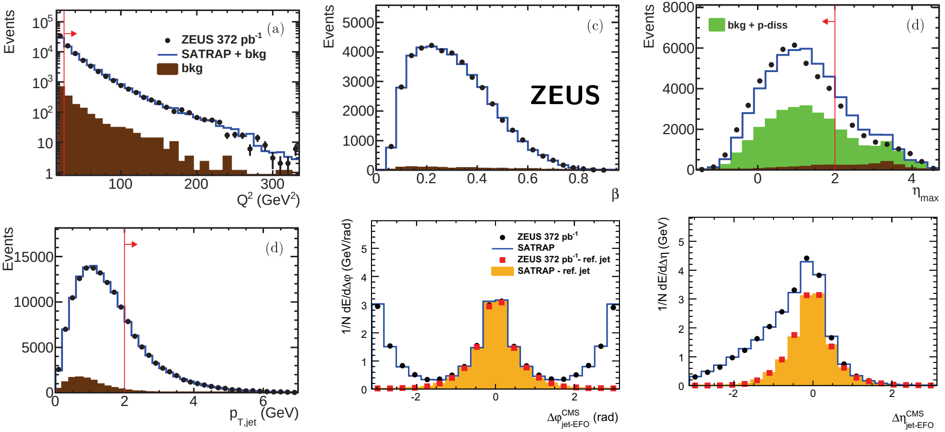
$y_{ij} = \frac{k^2_{\text{T}\ ij}}{M_X^2} < y_{\text{cut}} = 0.15$ - cluster all particles into jets

Select events with exactly 2 jets with $p_{\text{T}} > 2$ GeV in CMS.



Exclusive dijets in diffractive DIS

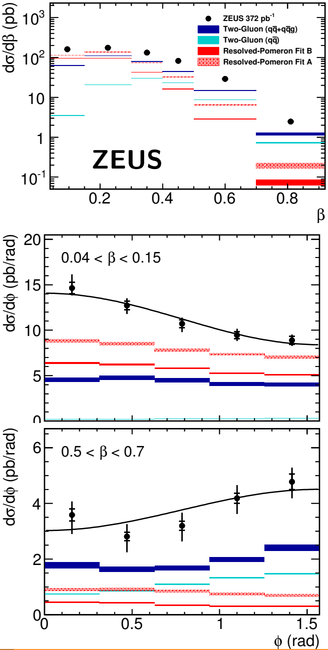
- SATRAP (color dipole model with saturation effects, including $q\bar{q}$ and $q\bar{q}g$ final states) is in good agreement with data and is used for detector level corrections.
- Background processs: non-diffractive DIS (ARIADNE) + diffractive dijet photoproduction (PYTHIA).
- Proton-dissociation: SATRAP with intact proton replaced with a dissociated proton (EPSOFT) and reweighted to data ($f_{\rm diss} = 45 \pm 4$(stat) ± 15(sys)%).



Exclusive dijets in diffractive DIS

Differential cross sections have been measured at the hadron level in the kinematic range:

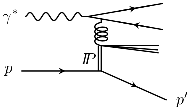
$$Q^2 > 25\ \text{GeV}^2, \qquad 90 < W < 250\ \text{GeV}$$
$$x_{I\!P} < 0.01, \qquad M_X > 5\ \text{GeV}$$
$$N_{\text{jets}} = 2, \qquad p_{\text{T,jet}} > 2\ \text{GeV}$$



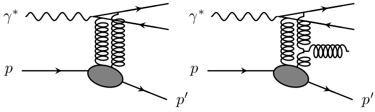
Proton dissociative contribution has been subtracted.

In both, Two Gluon and Resolved Pomeron (BGF) models azimuthal angular distribution behaves like:

$$\frac{d\sigma}{d\phi} \propto 1 + A(p_{\text{T,jets}}) \cos 2\phi$$



Resolved Pomeron
(positive A)



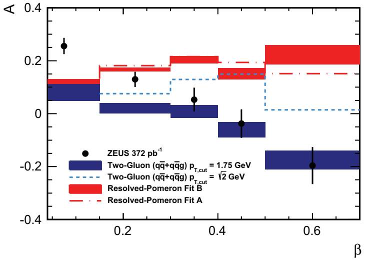
Two Gluon model
(negative A)

Hadron level predictions are based on RapGap MC.

Exclusive dijets in diffractive DIS

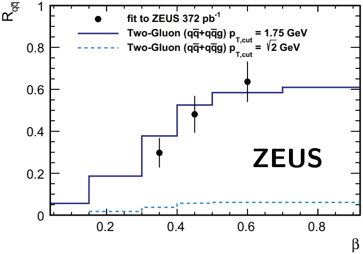
Comparison of the fitted slope parameter A with models:

- Resolved Pomeron - almost constant for all β.
- Two Gluon model:
  - value of A varies from positive to negative,
  - agrees quantitatively with data for $\beta > 0.3$



Measurement of the ratio $R_{q\bar{q}} = \sigma(q\bar{q})/\sigma(q\bar{q}+q\bar{q}g)$:

- theory predictions strongly depend on the cut applied to the parton transverse momentum,
- fit to data suggests $p_{\mathrm{T,cut}} = 1.75$ GeV.



- The measured and predicted cross sections do not agree by factor about 2. Large NLO corrections?
- The Two Gluon model is more successful in data description (region $\beta > 0.3$) than Resolved Pomeron model.

Summary

Experiments H1 and ZEUS at HERA provided new results on exclusive production:

- (H1) First measurement of cross section for exclusive ρ^0 photoproduction with leading neutron: $\gamma p \to \rho^0 n \pi^+$.
- (H1) Differential cross sections for the reaction $\gamma p \to \rho^0 n \pi^+$ show behaviour typical for exclusive double peripheral process.
- (H1) Elastic $\gamma\pi$ cross section, $\sigma(\gamma\pi^+ \to \rho^0\pi^+)$, is extracted in OPE approximation.
- (H1) Estimated ratio $r_{el} = \sigma_{el}^{\gamma\pi}/\sigma_{el}^{\gamma p} = 0.25 \pm 0.06$ sugests large absorption corrections.

- (ZEUS) Measurement of the cross sections ratio $R = \sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in exclusive DIS is in agreement with pQCD predictions regarding its rise with Q^2 and being independent of W and $|t|$.
- (ZEUS) In spite of significantly improved accuracy compared to previous H1 result, only very rough discrimination of models of exclusive VM production is possible.

- (ZEUS) The measured cross sections for exclusive dijet production in diffractive DIS are larger than those predicted at LO by both the Resolved Pomeron or Two Gluon Exchange models.
- (ZEUS) Measurement of exclusive dijet production prefer in LO Two Gluon Exchange to Resolved Pomeron model regarding the shape of the cross section distribution.

Thank you for your attention!

Backup slides

H1 - ρ^0 photoproduction with a leading neutron

The cross section for the process $e(k) + p(P) \to e(k') + \rho^0(V) + n(N) + \pi^+$ reads

$$\frac{\mathrm{d}^2\sigma_{ep}}{\mathrm{d}y\mathrm{d}Q^2} = f_{\gamma/e}(y, Q^2) \cdot \sigma_{\gamma p}(W_{\gamma p}(y))$$

In VDM and taking into account both transversaly and longitudinally polarised virtual photons we have:

$$f_{\gamma/e}(y, Q^2) = \frac{\alpha}{2\pi Q^2 y} \left\{ \left[1 + (1-y)^2 - 2(1-y) \left(\frac{Q^2_{min}}{Q^2} - \frac{Q^2}{M^2_\rho} \right) \right] \left(1 + \frac{Q^2}{M^2_\rho} \right)^{-2} \right\}$$

where $Q^2_{min} = m_e^2 y^2/(1-y)$. In the one-pion-exchange (OPE) approximation, which is valid for small $p^2_{\mathrm{T},n} \sim m^2_\pi$, the photon-proton cross section can be expressed as:

$$\frac{\mathrm{d}^2\sigma_{\gamma p}(W_{\gamma p}, x_L, t)}{\mathrm{d}x_L\mathrm{d}t} = f_{\pi/p}(x_L, t) \cdot \sigma_{\gamma\pi}(W_{\gamma\pi})$$

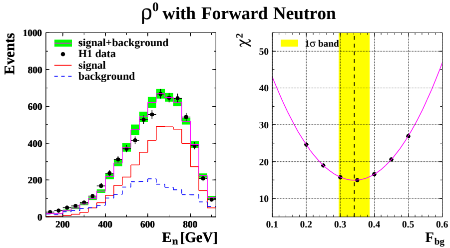
where the pion flux can be written as:

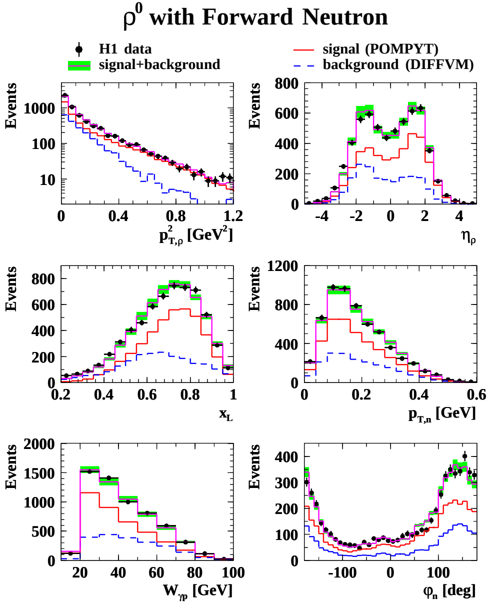
$$f_{\pi/p}(x_L, t) = \frac{1}{2\pi} \frac{g^2_{p\pi n}}{4\pi} (1 - x_L)^{\alpha_{I\!P}(0) - 2\alpha_\pi(t)} \frac{-t}{(m^2_\pi - t)^2} F^2(t, x_L)$$

where $\alpha_\pi(t) = \alpha'_\pi(t - m^2_\pi)$ and $F(t, x_L)$ is a form factor accounting for off mass-shell corrections (normalised to unity at the pion pole).

H1 - ρ^0 photoproduction with leading neutron

Estimation of signal and background contributions from a fit to data.





- Different shapes of leading neutron energy for signal and background (mostly due to proton dissociation).
- Shapes of signal and background modelled by POMPYT and DIFFVM Monte Carlo generators.
- Fit to data gives the background contribution:

$$f_{bg} = B/(S+B) = 0.34 \pm 0.05$$

The following sources of systematic uncertainty were considered:

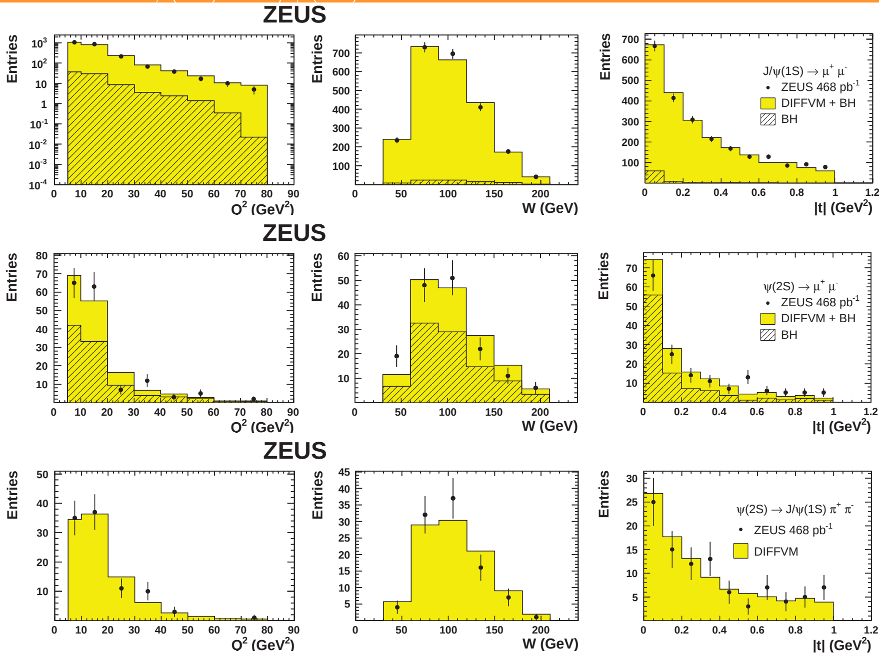
- varying the nominal $M_{\mu\mu}$ window for counting signal events:
  - for $J/\psi(1S)$: from $3.02 - 3.17$ GeV to $3.05 - 3.15$ GeV and $2.97 - 3.22$ GeV
  - for $\psi(2S)$: from $3.59 - 3.79$ GeV to $3.62 - 3.75$ GeV and $3.55 - 3.80$ GeV

  changes the values of $R_{\mu\mu}$ by 2% and 6%, and $R_{J/\psi\pi\pi}$ by 1.5% and -0.5%, respectively;
- changing the cut on the transverse momenta of pion tracks from the nominal value of 0.12 GeV to 0.15 GeV changes the value of $R_{J/\psi\pi\pi}$ by -4.5%;
- changing the background fit function from linear to quadratic changes the values of $R_{\mu\mu}$ by -11% and of $R_{J/\psi\pi\pi}$ by 0.5%;
- changing the reconstruction of kinematic variables from the *constrained* to *electron* method changes the values of both $R_{\mu\mu}$ and $R_{J/\psi\pi\pi}$ by 1.5%;
- not applying the reweighting of the Monte Carlo events changes the values of $R_{\mu\mu}$ by -3% and of $R_{J/\psi\pi\pi}$ by -1%;
- applying different cuts on the total number of tracks, including tracks not associated with the event vertex, changes $R_{\mu\mu}$ by -5% and $R_{J/\psi\pi\pi}$ by 3%.

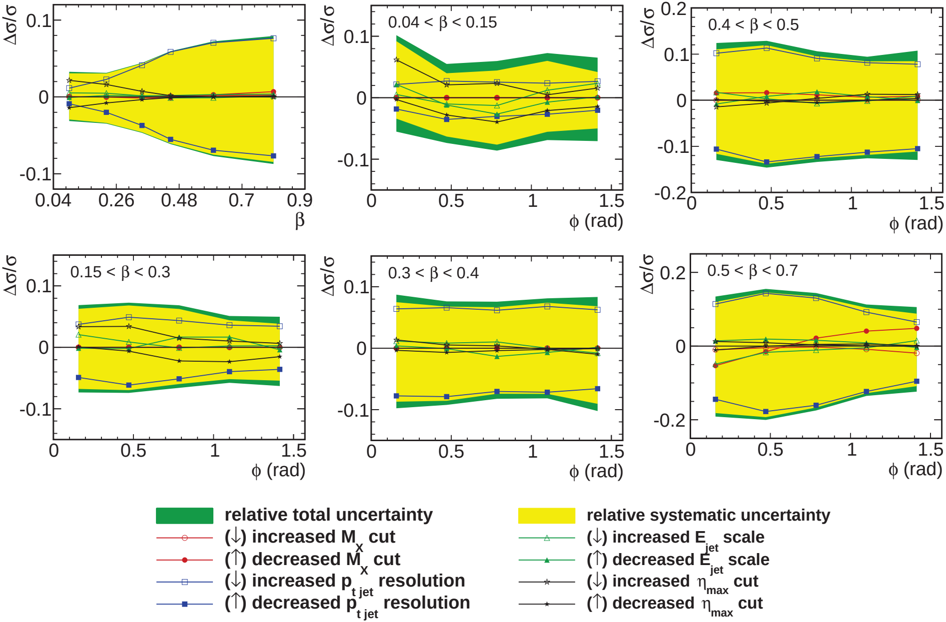
Total systematic uncertainties obtained by separate quadratic sums of the positive and negative changes read:

$$\delta R_{\mu\mu} = ^{+7}_{-14}\,\%, \quad \delta R_{J/\psi\pi\pi} = ^{+4}_{-5}\,\%, \quad \delta R_{\text{comb}} = ^{+3}_{-5}\,\%$$

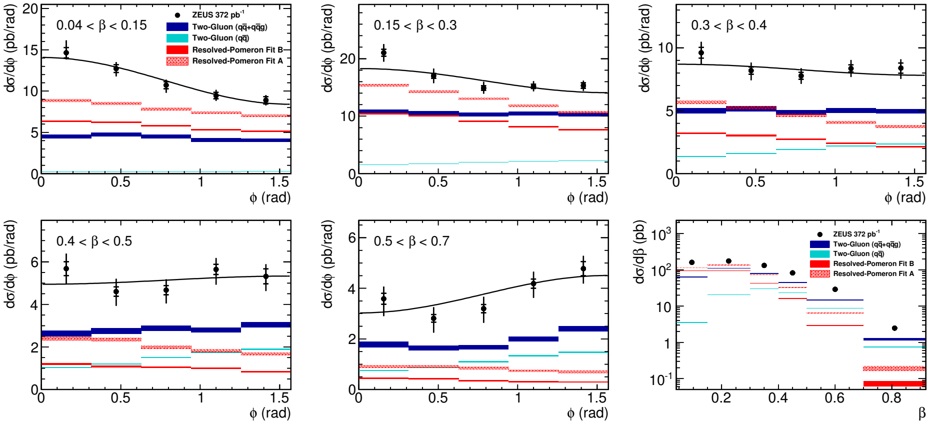
ZEUS - $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ - comparison of data with MC



ZEUS - exclusive dijets - systemaic uncertainties



ZEUS - exclusive dijets - differential cross sections



Differential cross sections in function of ϕ have been fitted with:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} \propto 1 + A(p_{\mathrm{T,jets}}) \cos 2\phi$$