Exclusive Production at HERA

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Overview

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

Resent results from ZEUS and H1:

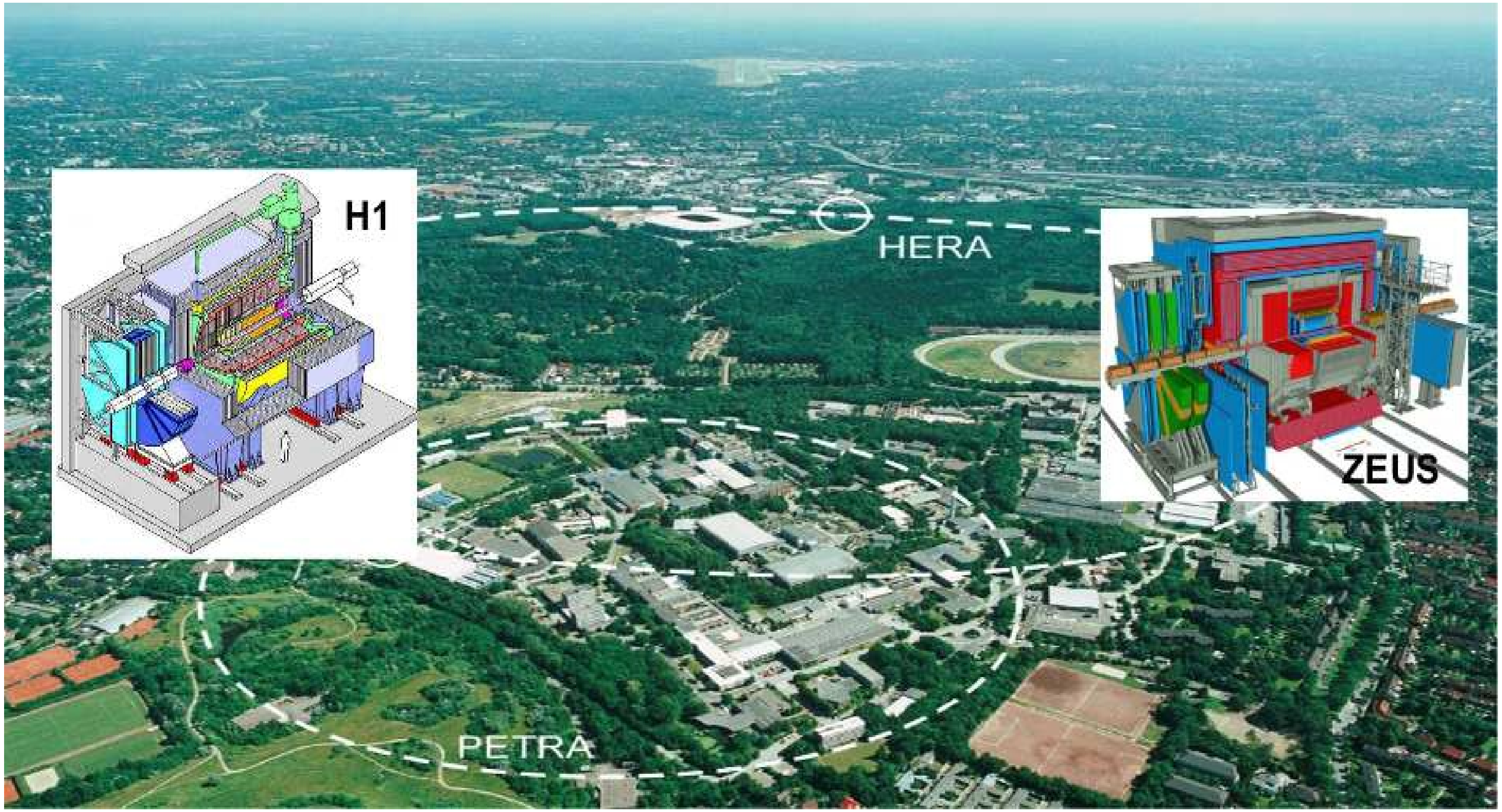
ZEUS: Production of exclusive dijets in diffractive DIS at HERA
ZEUS Collaboration, Eur. Phys. J. C (2016) 76:16

ZEUS: Measurement of the cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in exclusive DIS
ZEUS Collaboration, Nucl. Phys. B909 (2016) 934-953

H1: Exclusive ρ^0 meson photoproduction with leading neutron at HERA
H1 Collaboration, Eur. Phys. J. C 92016) 76:41

HERA *ep collider 1992 - 2007, DESY*

27.6 GeV electrons/positrons on 920 GeV protons
$\rightarrow \sqrt{s}$=318 GeV
HERA I+II: ~ 500 pb^{-1} per experiment
H1 & ZEUS — 4π detectors

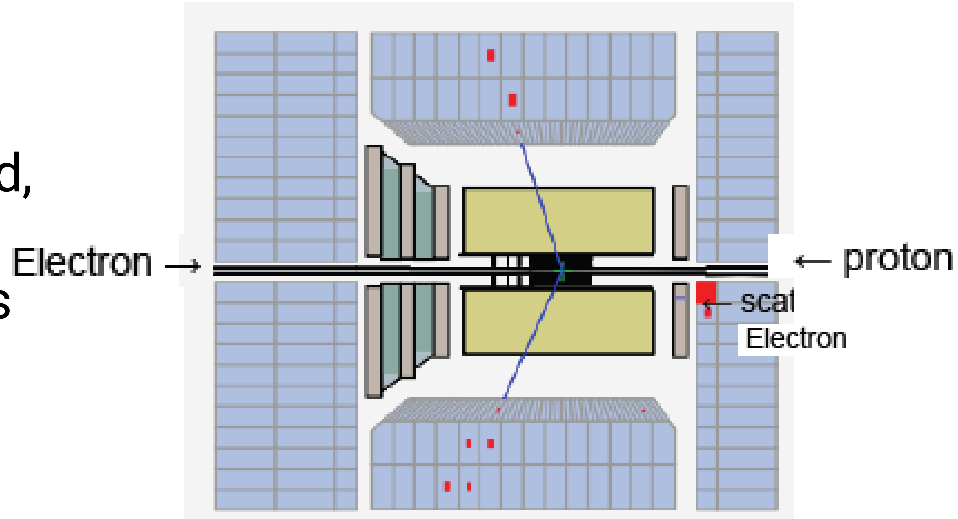


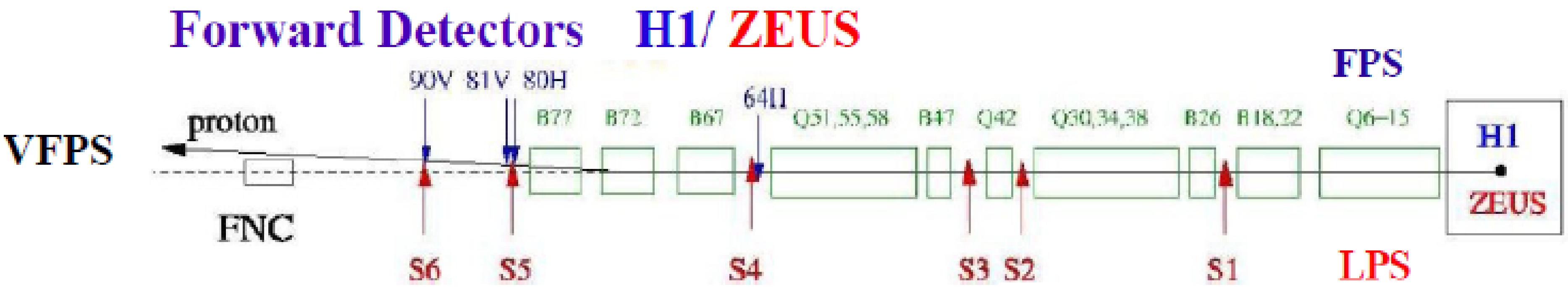
Selection of exclusive processes

Exclusive processes are very clean experimentally

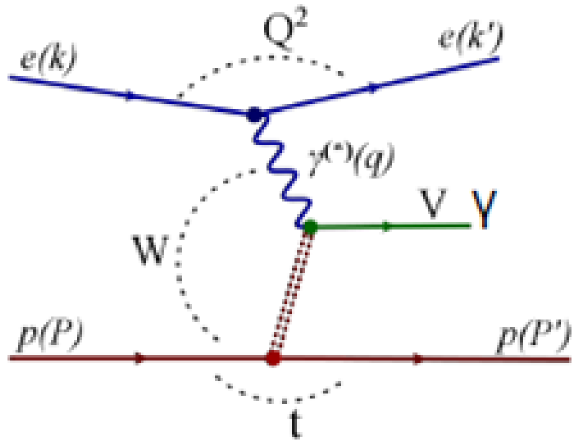
Kinematic variables fully reconstructed, usually measuring scattered electron (in DIS) and VM decay products or jets

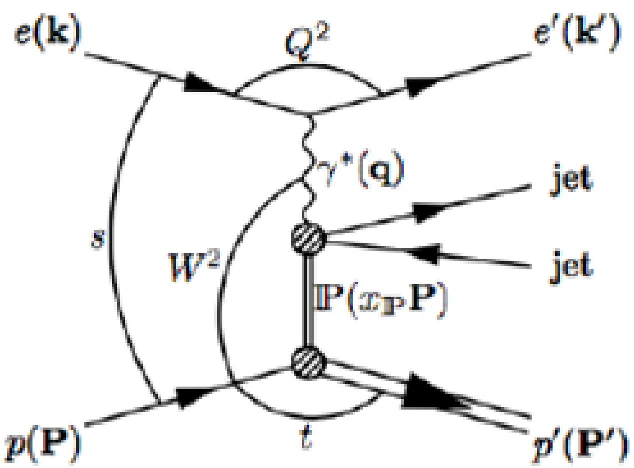
Scattered proton detected with lower acceptance by forward detectors





Exclusive processes – kinematic variables





Q^2 - photon virtuality, [0 – 100 GeV^2]

W – photon-proton centre-of-mass energy
[20 – 300 GeV]

$t=(p-p')^2$ - four momentum transfer squared
at proton vertex [$-t < 30$ GeV^2]

x-Bjorken – fraction of proton's momentum carried by struck quark, $x = Q^2/(Q^2+W^2)$
[10^{-2} - 10^{-4}]

x_{IP} – fraction of proton's momentum carried by exchanged colour singlet

$\beta = x / x_{IP}$ - fraction of Pomeron momentum 'seen' by photon

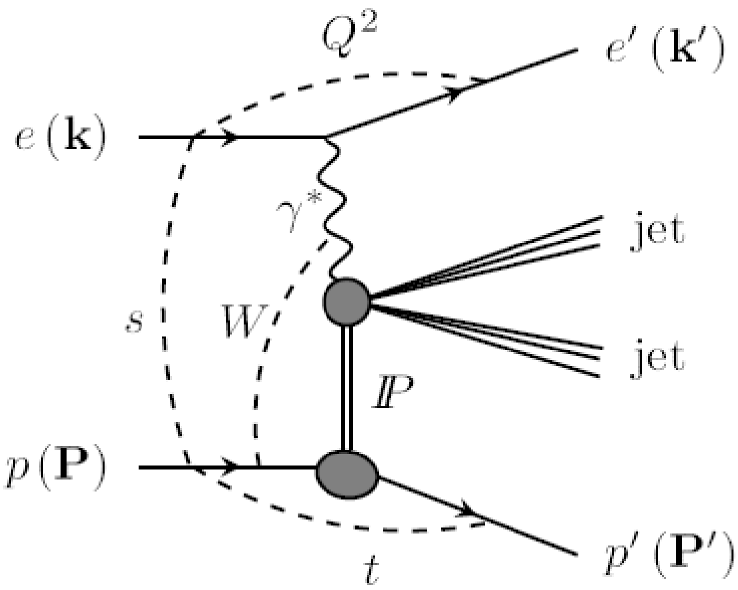
Production of exclusive dijets in diffractive DIS at HERA

ZEUS Collaboration
Eur. Phys. J. C (2016) 76:16

Exclusive dijets production in diffractive DIS

e + p → e′ + jet1 + jet2 + p′

is sensitive to the nature of the object exchanged between the virtual photon and proton



Data 2003 – 2007 372 pb⁻¹

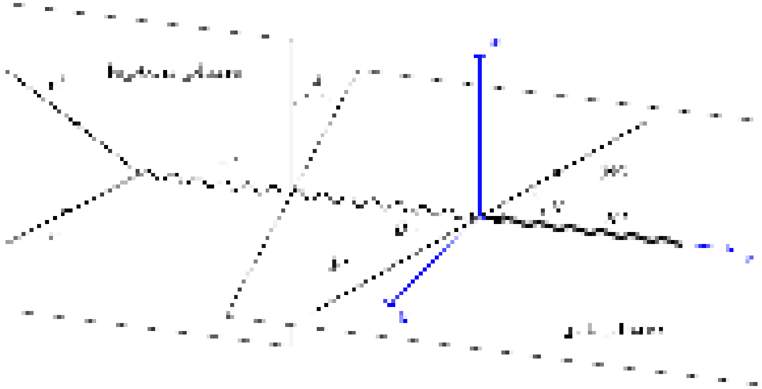
Only dijet, scattered electron and proton in the final state, LRG

Diffractive DIS selection (main selection cuts)

- E'> 10 GeV, 45 < ($E-P_Z$) < 70 GeV, M_X > 5GeV
- $Q^2 = -q^2 > 25$ GeV² - virtuality of the photon
- 90 < W > 250 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
- $0.5 < \beta < 0.7$, $\beta = x / x_{IP}$ – fraction of Pomeron momentum ' seen' by photon

Exclusive dijets production in diffractive DI

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

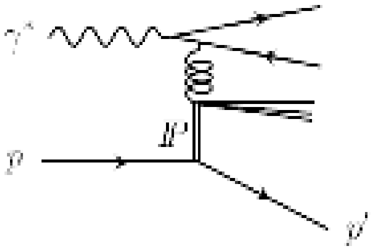


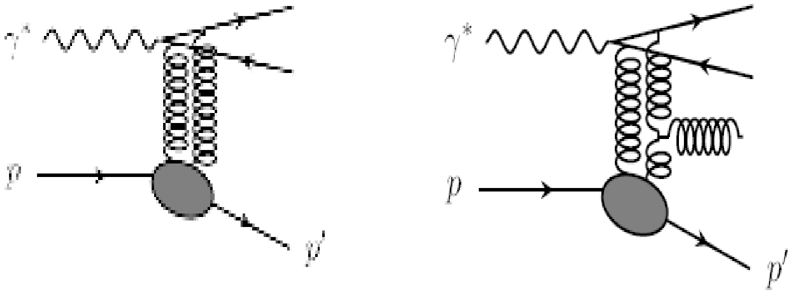
In Resolved Pomeron and Two Gluon Exchange models azimuthal angular distribution behaves like

$$d\sigma/d\Phi \sim 1 + A\ (p_{T,\,jets})\ \cos(2\Phi)$$

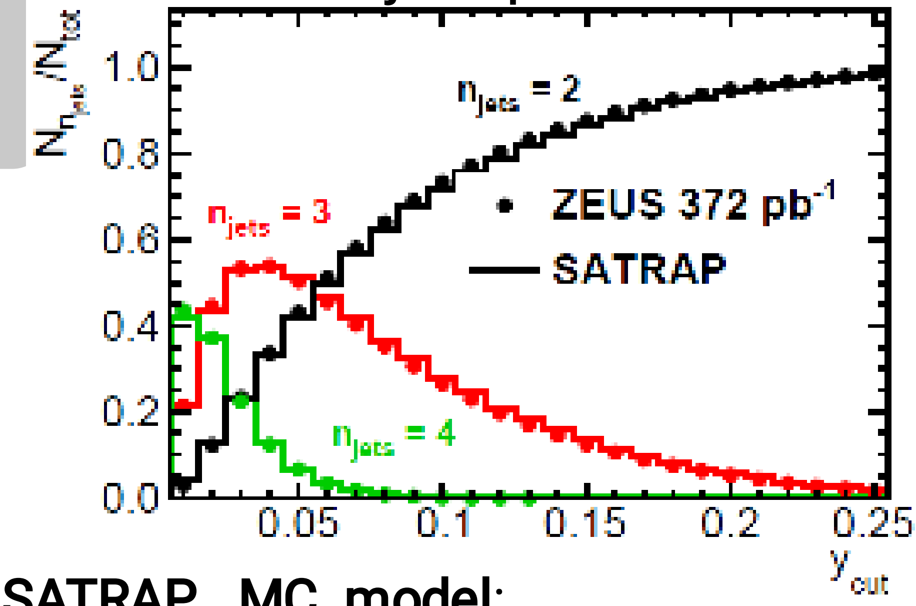
Resolved Pomeron
(A positive)
for $q\bar{q}$ produced from single gluon

Two-Gluon-Exchange model
(A negative)
for two gluons exchange





Exclusive dijets production in diffractive D



Jets were found in γ*-IP rest frame

- using Durham exclusive kT jet algorithm all objects are merged in jets

$k_{T\,ij}^2 \quad 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$

$y_{ij} \quad \frac{k_{T\,ij}^2}{M_X^2} < y_{cut}$ 0.15 - cluster all particles into jets

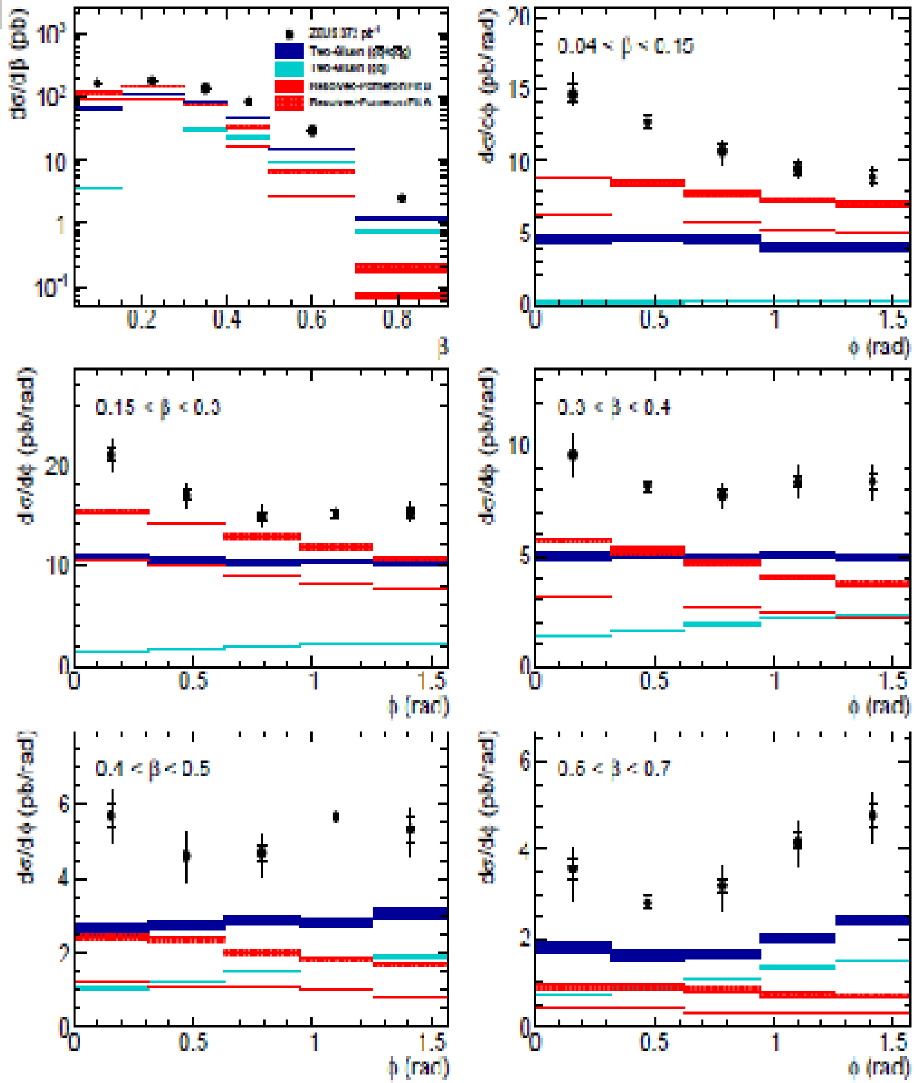
- with resolution parameter y_{cut} = 0.15 optimizes efficiency versus purity of jet sample
- $\eta_{jet} < 2$ select diffractive events with LRG
- select events with exactly 2 jets with $p_{Tjet} > 2$ GeV in CMS

SATRAP MC model:
(Golec-Biermat, Wustoff, 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

Proton-dissociation:SATRAP with intact proton replaced with a dissociated proton (EPSOFT) and reweighted to data (F_diss = 45±4(stat)±15(sys)%).

Exclusive dijets production in diffractive



dσ/dβ : comparison with model predictions

Differential cross sections
dσ/dΦ have been fitted for different β bins,
$\sim 1 + A\cos(2\Phi)$

The slope parameter of the angular distribution changes sign around β = 0.4

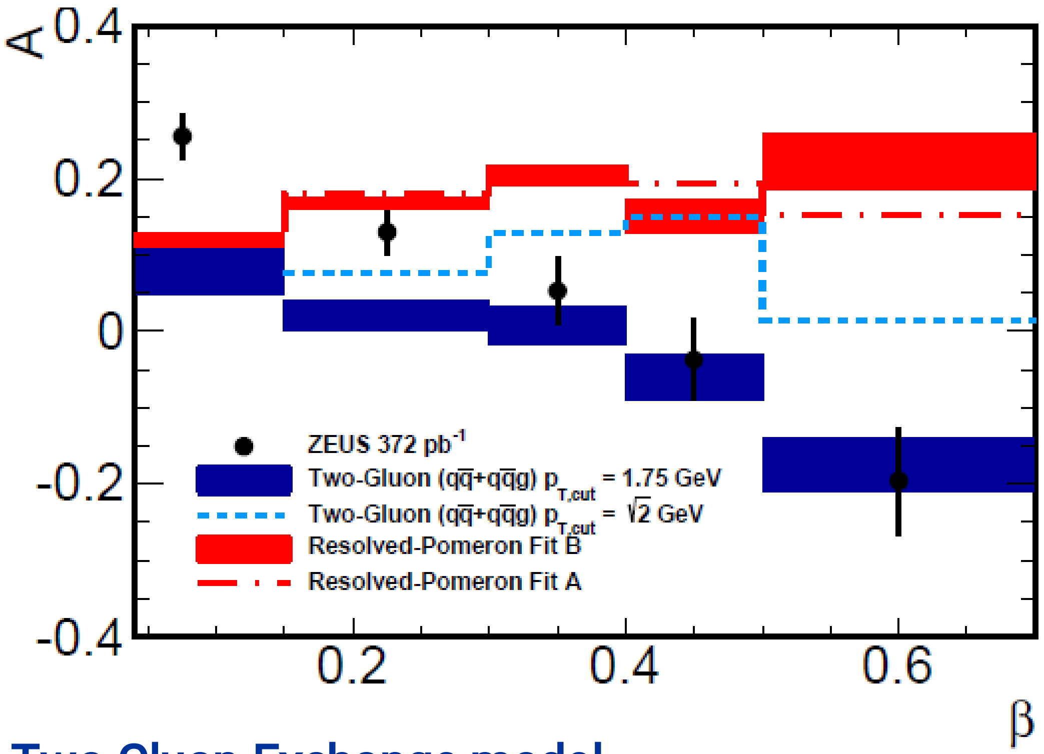
Resolved Pomeron model
Prediction decreases with increasing β faster than data

Two-Gluon-Exchange model
Reasonable description of the shape of the β distribution

Normalization discrepancy of factor two
Large NLO corrections ?

Exclusive dijet production in diffractive D

$d\sigma/d\Phi \sim 1 + A(p_{T,jet})\cos(2\Phi)$: A vs β, comparison with model predictions



Resolved Pomeron model

The parameter A almost constant for all β,
Positive value of A in the whole β range

Two-Gluon-Exchange model

Value of parameter A varies from positive to negative
Model agrees quantitatively with the data for β > 0.3
The Two Gluon Exchange model is more successful in data description (region β > 0.3) than Resolved Pomeron model

Measurement of the cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in deep inelastic exclusive ep scattering at HERA

ZEUS Collaboration
Nucl. Phys. B909 (2016) 934-953

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

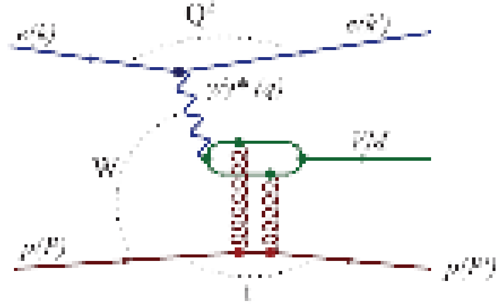
Measure the ratio of the cross sections :

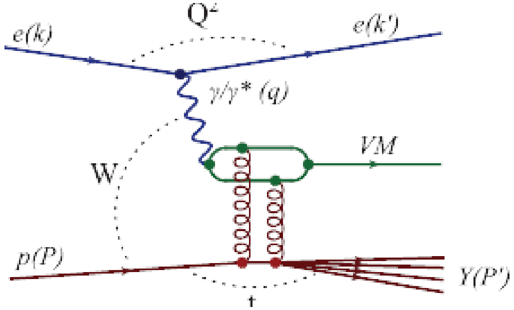
$$R = \sigma(\gamma^* p \rightarrow \psi(2S)\, p) \,/\, \sigma(\gamma^* p \rightarrow J/\psi(1S)\, p)$$

- sensitive to charmonium wave function
- insensitive to many systematic uncertainties.
  ψ(2S) and J/ψ(1S) have the same quark content, similar masses, but different radial wave functions

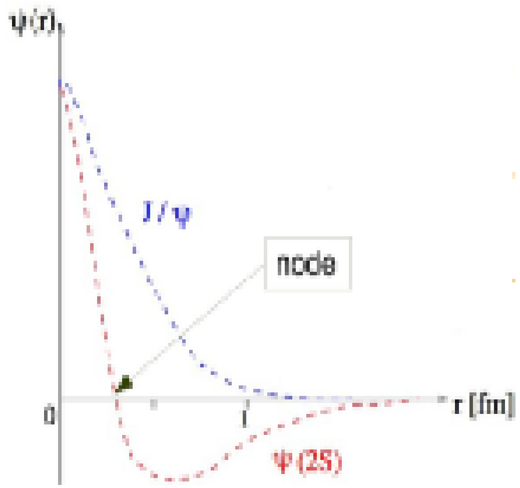
=>Different rate of ψ(2S) and J/ψ(1S) expected due to the different wave function

=>Ratio estimated in QCD models to be R~0.17, rising with Q^2





Photon 'transverse size' decreases with Q^2
=> Large for photoproduction O (1 fm)
=> Small for high-Q^2 DIS << 1 fm
- ψ(2S) has a node at 0.35 fm
- < r^2ψ(2S)> ≈ 2< r^2J/ψ(1S)>



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

- Channels: $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$; $J/\psi \rightarrow \mu^+\mu^-$
  $\psi(2S) \rightarrow \mu^+\mu^-$
  $J/\psi(1S) \rightarrow \mu^+\mu^-$
- Data : HERA I+HERA II integrated luminosity 468 pb^{-1}

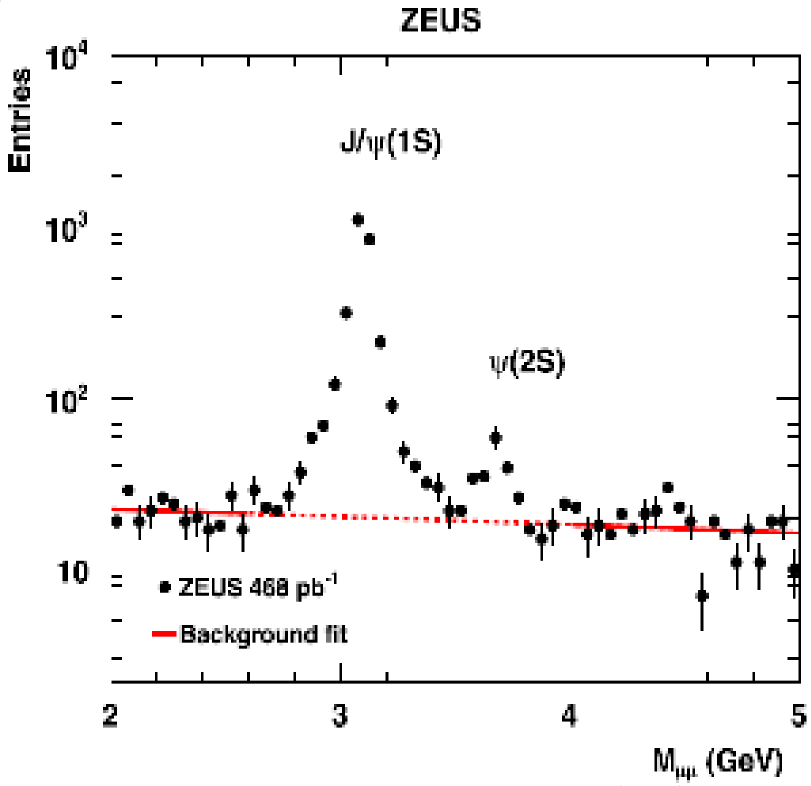
Kinematic range:
$30 < W < 210$ GeV
$2 < Q^2 < 80$ GeV^2
$|t| < 1$ GeV^2

MC :
- Signal — exclusive VM production with DIFFVM
- BG — Bethe-Heither elastic and proton dissociative $\mu^+\mu^-$ production with GRAPE

Event selection :
- Scattered electron with E>10 GeV measured in CAL
- Scattered proton undetected
- Two reconstructed tracks identified as muons and for $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ additionally two pion tracks from μμ vertex
- Nothing else in the detector above noise
- Proton dissociative events removed above masses ~ M_N= 4 GeV

Assuming cross section ratio does not vary with M_N — results not affected by proton dissociation BG

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



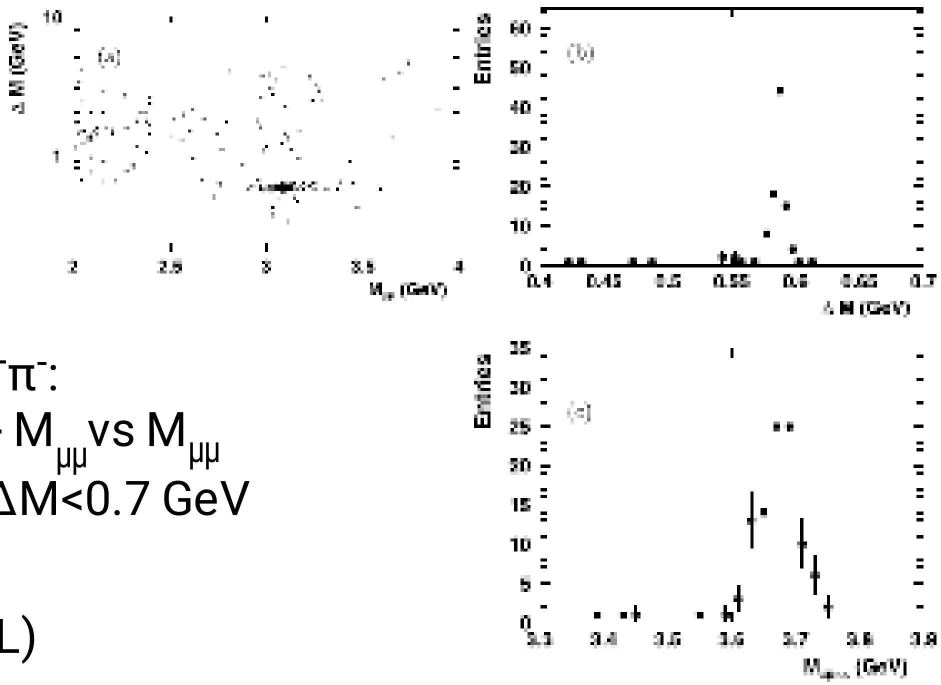
- BG subtraction in $J/\psi \rightarrow \mu^+\mu^-$, $\psi(2S) \rightarrow \mu^+\mu^-$: BH dimuon background fit to straight line for

  $2 < M_{\mu\mu} < 2.62$ GeV; $4.05 < M_{\mu\mu} < 5$ GeV

  Number of events above background:

  $3.59 < M_{\mu\mu} < 3.79$ GeV → $N_{\psi(2S)}$

  $3.02 < M_{\mu\mu} < 3.17$ GeV → $N_{J/\psi(1S)}$



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

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

=> $N_{\psi(2S)}$

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

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

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

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

R_{comb} — obtained as weighted average of the cross sections determined for the two ψ(2S) decay channels (combination of $R_{\mu\mu}$ and $R_{J/\psi\pi\pi}$)

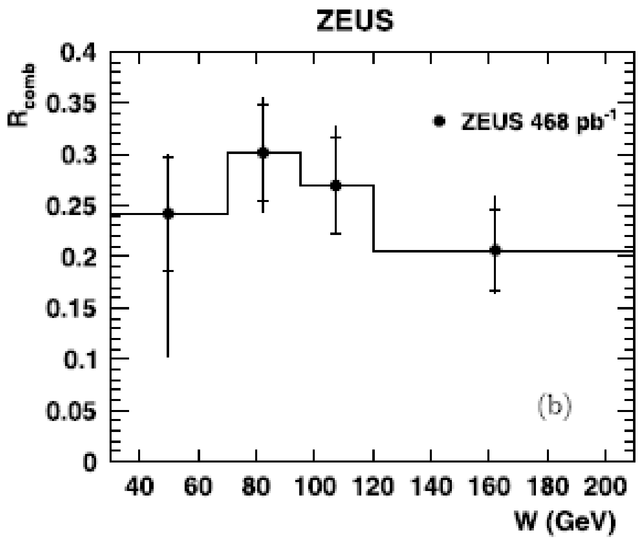
$A_i = N_i^{reco} / N_i^{true}$

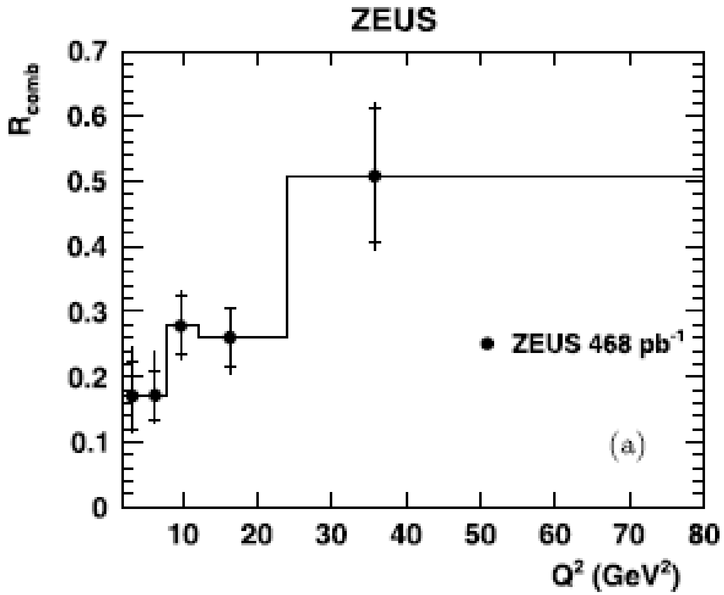
$Br[\psi(2S) \to J/\Psi\pi\pi] = (33.6 \pm 0.4)\%$
$Br[\psi(2S) \to \mu\mu] = (7.7 \pm 0.8)\text{x}10^{-3}\%$
$Br[J/\psi(1S) \to \mu\mu] = (5.93 \pm 0.06)\%$

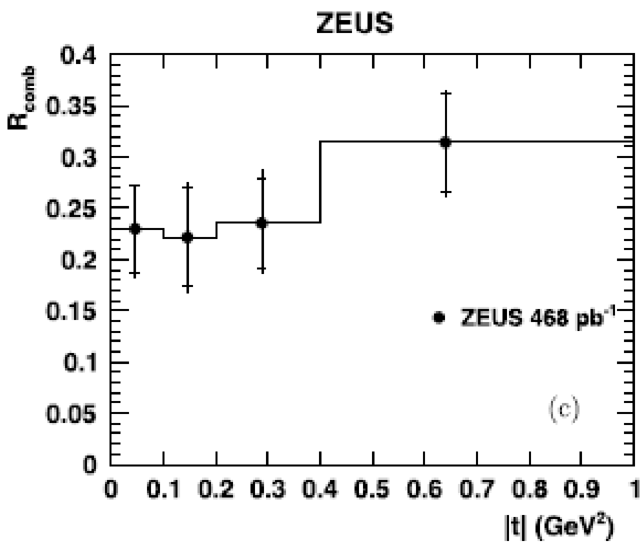
In the kinematic range:
$30 < W < 210$ GeV
$2 < Q^2 < 80$ GeV^2, $|t| < 1$ GeV^2
Measured ratio $R_{\psi(2S)} = R_{J/\psi\pi\pi} / R_{\mu\mu}$

$R_{J/\psi\pi\pi}$	$0.26 \pm 0.03^{+0.01}_{-0.01}$
$R_{\mu\mu}$	$0.24 \pm 0.05^{+0.02}_{-0.03}$
R_{comb}	$0.26 \pm 0.02^{+0.01}_{-0.01}$
$R_{\psi(2S)}$	$1.1 \pm 0.2^{+0.2}_{-0.1}$

Cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ vs W, |t|, Q^2





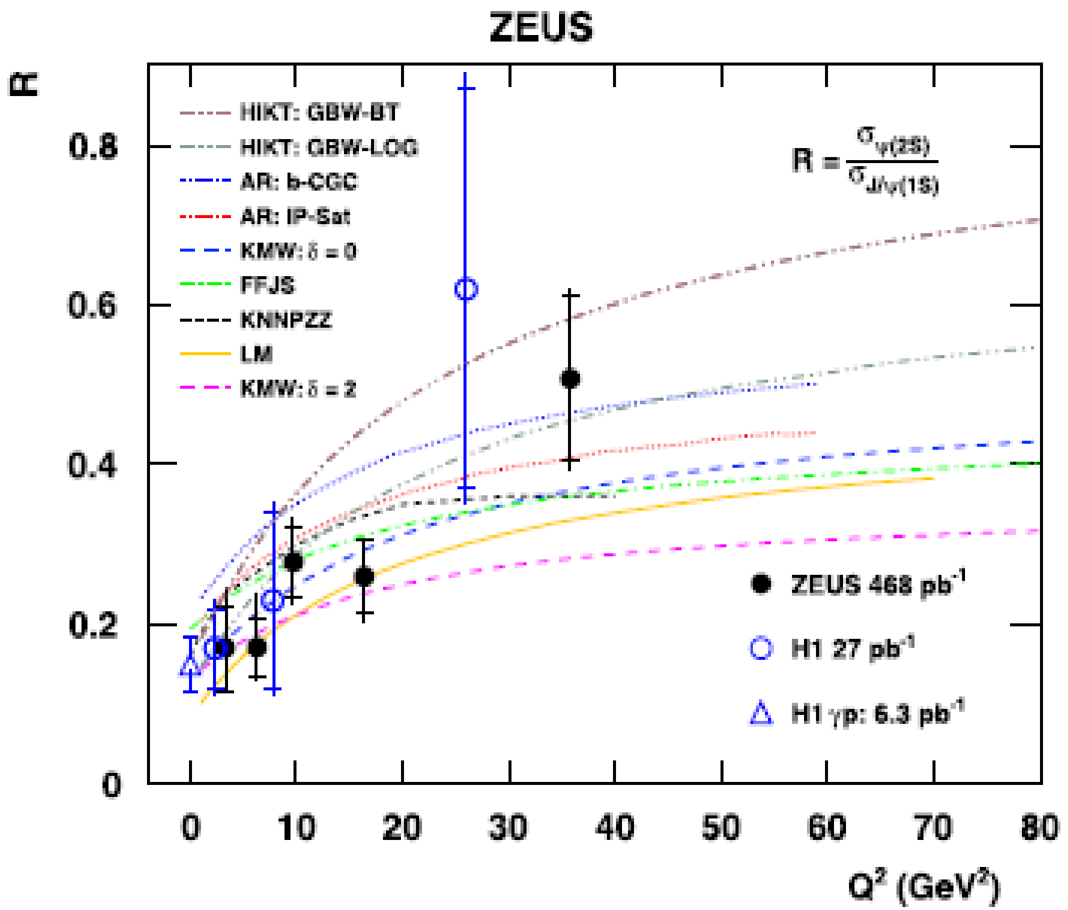


No significant dependence on:

-W - γ^*p centre-of-mass energy
-t - momentum transfer from the proton
(that stay intact)

Apart from Q^2, i.e. the transverse size of γ^*

Cross section ratio $R = \sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ vs Q^2



Good agreement with earlier H1 measurement
(EPJ C10 (1999) 373)

Most of the models reproduces the behaviour

Models with very slow rise not favour

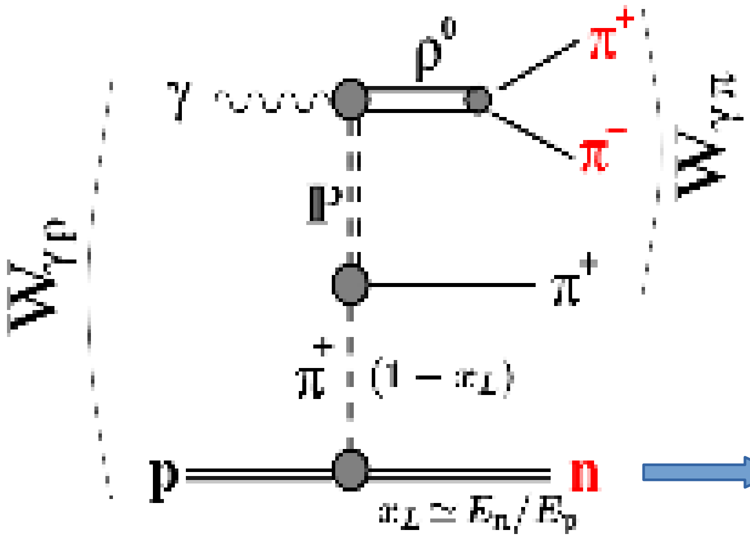
Steep increase with Q^2 from photoproduction to DIS regime

Exclusive ρ^0 meson photoproduction with a leading neutron at HERA

H1 Collaboration
Eur. Phys. J. C (2016) 76:41

Exclusive ρ^0 photoproduction with a LN

First measurement of exclusive ρ^0 photoproduction with a leading neutron at HERA.
In **$e+p \to e' + n + X$** the production of neutrons carrying a large fraction of the proton beam momentum is dominated by the **pion exchange process**



First extraction of elastic $\sigma(\gamma\pi^+ \to \rho^0\pi^+)$

A virtual photon emitted from the electron interacts with a virtual pion from the proton cloud
producing ρ^0: $\gamma^{(*)} + p \to \rho^0 + \pi^+ + n$
$\rho^0 \to \pi^+ + \pi^-$

NO hard scale present : Mean W ~ 24 GeV
Soft regime: Regge framework most appreciate: measurement of the DPP mediated by exchange of two, pion and Pomeron, Regge trajectories

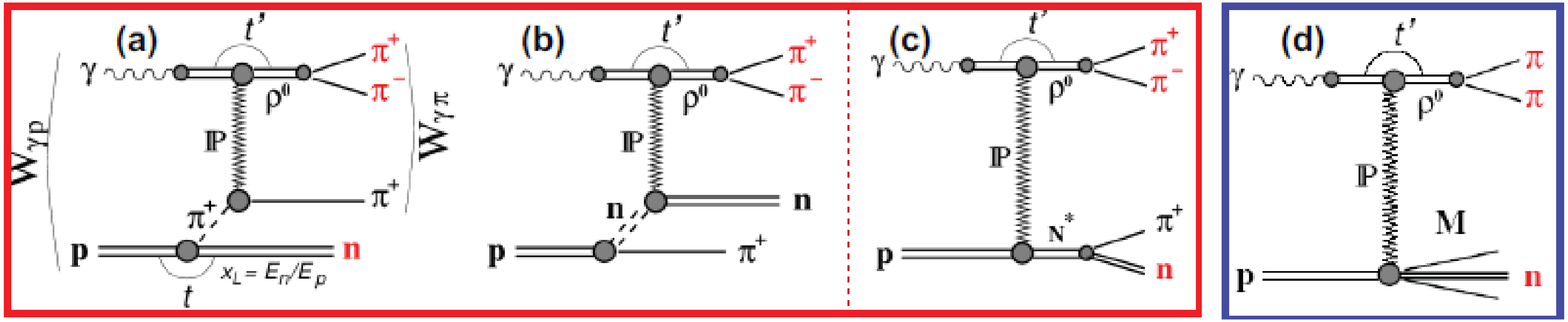
Key observables:

- $x_L = E_n / E_p$ (or $x_\pi = 1 - x_L$)
- W dependence : ~ W^δ – nature of exchange objects
- t-slope of ρ^0 (b ~ R^2 in geometric picture)

Exclusive ρ^0 photoproduction with a LN

Processes contributing to the exclusive photoproduction of ρ^0 meson associated with a leading neutron:

Pion exchange | Neutron exchange | Direct pole | Proton dissociation



Signal : Drell-Hiida-Deck diagrams
Pompyt MC

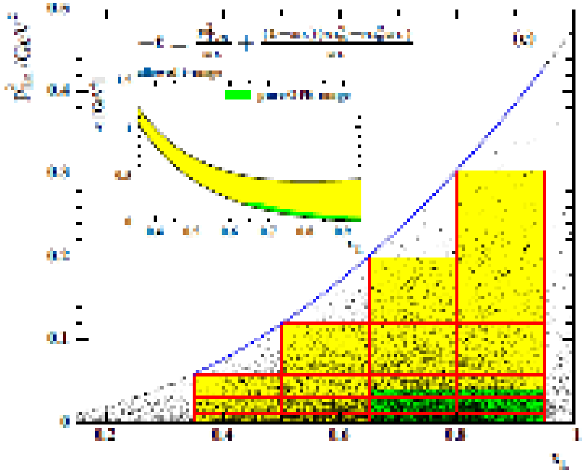
Background
DiffVM MC

- At large *s* and small $t \rightarrow 0$ pion exchange dominates as $A_b \approx - A_c$ (cancelling)
- 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 corresponding to the first three graphs is necessary to explain the cross section $\sigma(\gamma p \rightarrow \rho^0 n \pi^+) = |A_a + A_b + A_c|^2$.

Exclusive ρ^0 photoproduction with a LN

Data: 2006-2007 e^+p data, integrated luminosity 1.16 pb^{-1}
~ 7000 events

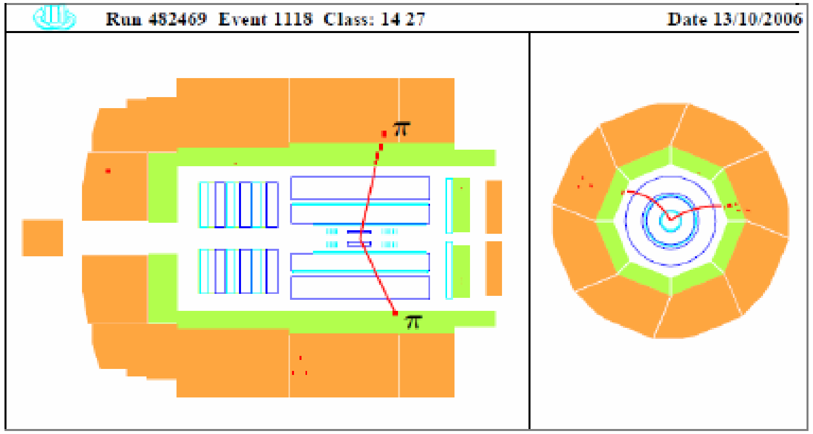
Forward Neutron Calorimeter (FNC) -
lead-sandwich calorimeter at 106 m from IP
to distinguish and measure n and γ/π^0,
Limited acceptance : <A> ~ 30%
and $p_{T,n} < x_L \cdot 0.69$ GeV ($x_L = E_n/E_p$)



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

Selection of exclusive events in untagged (scattered e^+ not detected) photoproduction:

- Only two oppositely charged tracks in the Central Tracker with $0.3 < M_{\pi\pi} < 1.5$ GeV
- A hadronic cluster in the FNC with energy above 120 GeV (forward π^+ from proton vertex not measured)
- No additional signals above noise in the main H1 calorimeter and forward detectors (LRG)



Exclusive ρ^0 photoproduction with a LN

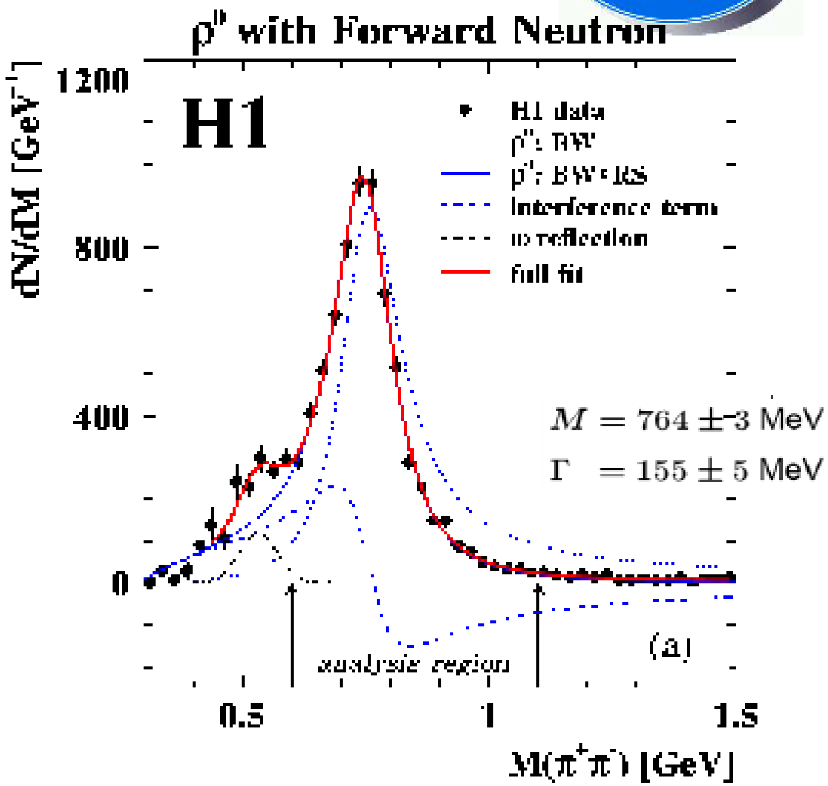
Monte Carlo simulation:

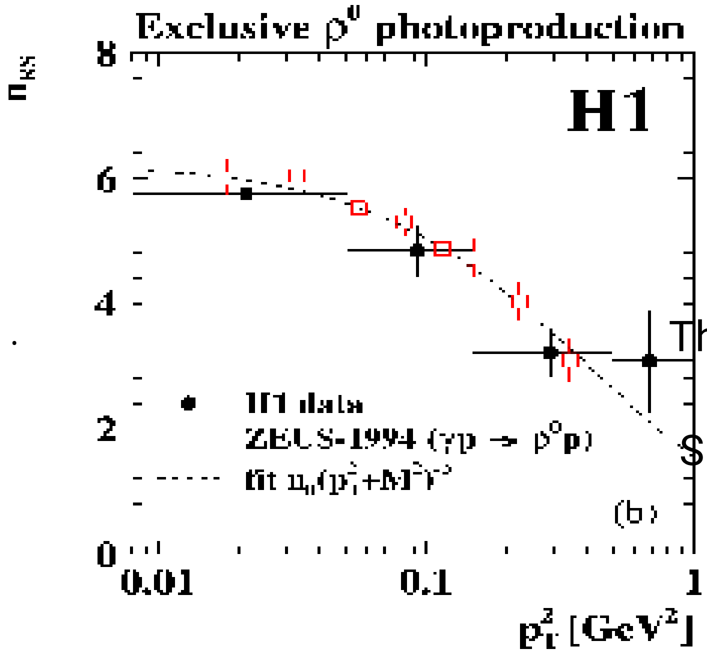
- Signal events (a) — POMPYT — virtual pion flux generated according to available parametrisation followed by elastic scattering of pion on photon, thus producing a vector meson (ρ^0)
- Background events (d) — DIFFVM — based on Regge theory and VDM (elastic, single and double dissociation processes); also used for estimation of possible background from ω(782), φ(1020) and ρ'(1450-1700)
- Both, signal and background events reweighted to relativistic BW shape with additional distertion caused by the interference between resonant and non-resonant $\pi^+\pi^-$ production

Exclusive ρ^0 photoproduction with a LN

- 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}

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





The strength of the distortion is p_T - dependent

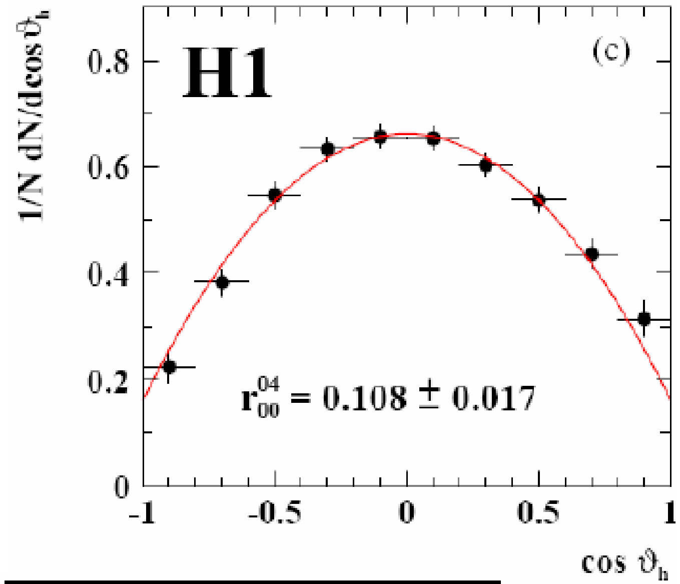
Skewing parameter n_{RS} vs. p_T^2 of the $\pi^+\pi^-$ sytem is in agreement with ZEUS value (from $\gamma p \rightarrow \rho^0 p$)

Exclusive ρ^0 photoproduction with a LN

Property of two-pion system compatible
with previous measurements

- Polar angle distribution of the π^+ in the helicity frame is in agreement with theory:

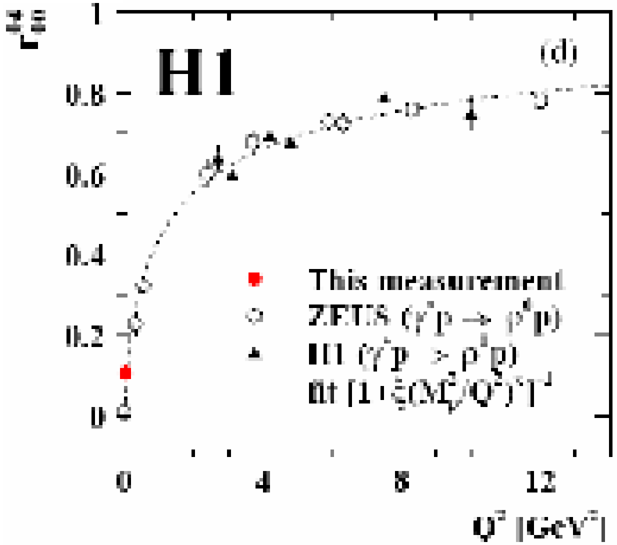
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_h} \propto 1 - r^{04}_{00} + (3r^{04}_{00} - 1)\cos^2\theta_h$$



- Spin-density matrix element r^{04}_{00} ,probability that ρ^0 has helicity 0, obtained from the fit is in agreement with other measurements in diffractive ρ^0 photo- and electro-production at HERA

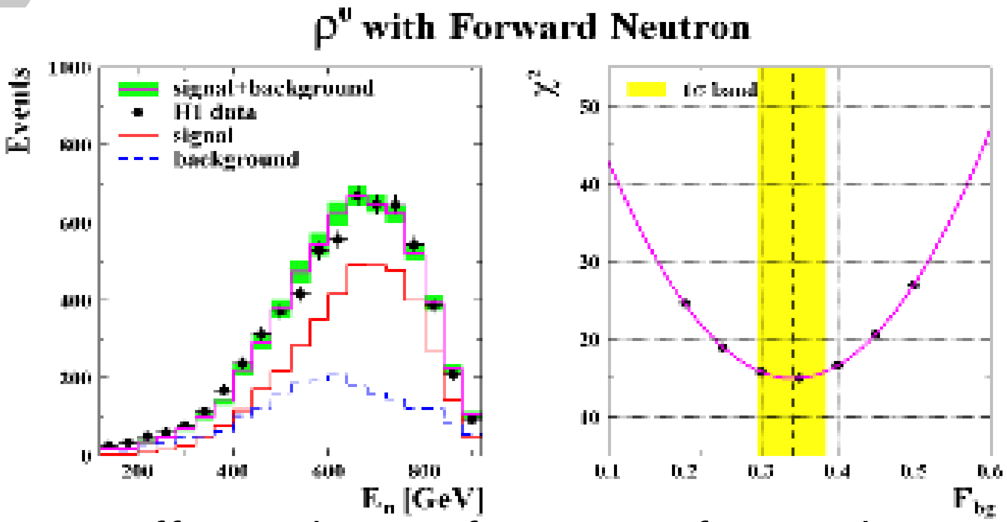
Empiric fit :

$$r^{04}_{00} = \frac{1}{1+\xi(M^2_\rho/Q^2)^\kappa}$$



Exclusive ρ^0 photoproduction with a LN

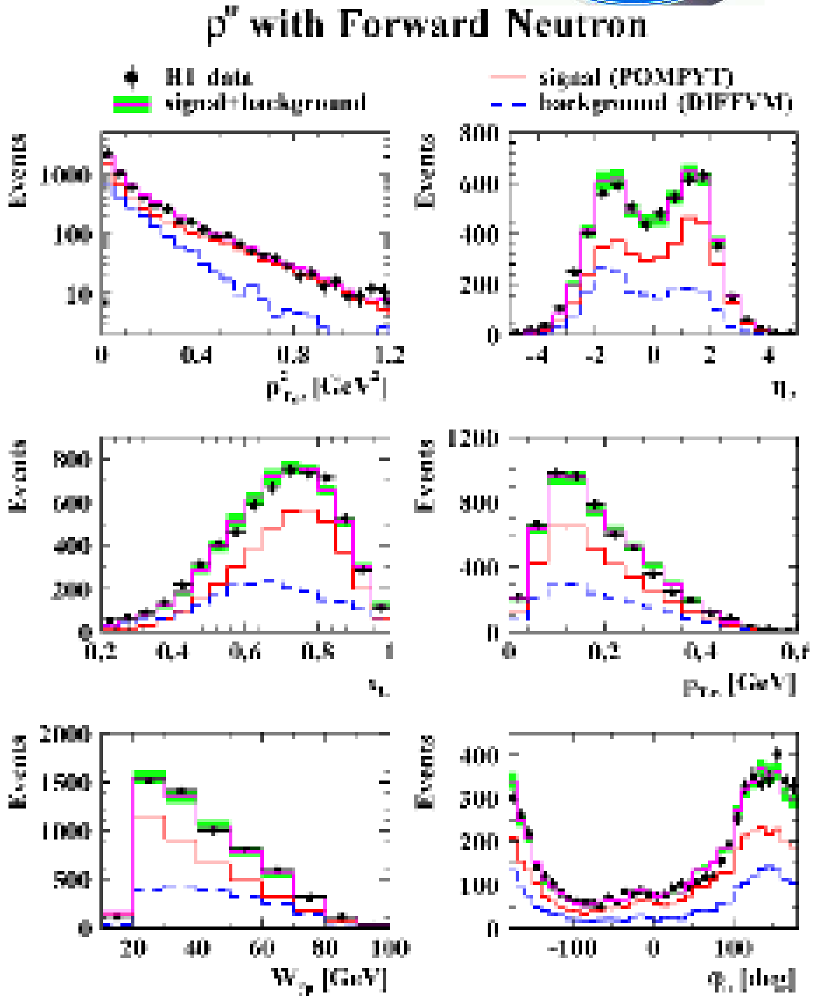
ρ^0 + n : Backgroud substraction



- Different shapes of LN energy for signal and background
- Background mostly due to proton dissociation
- Shape of signal and background modelled by POMPYT and DIFFVM MC

Background fraction fit to the data :

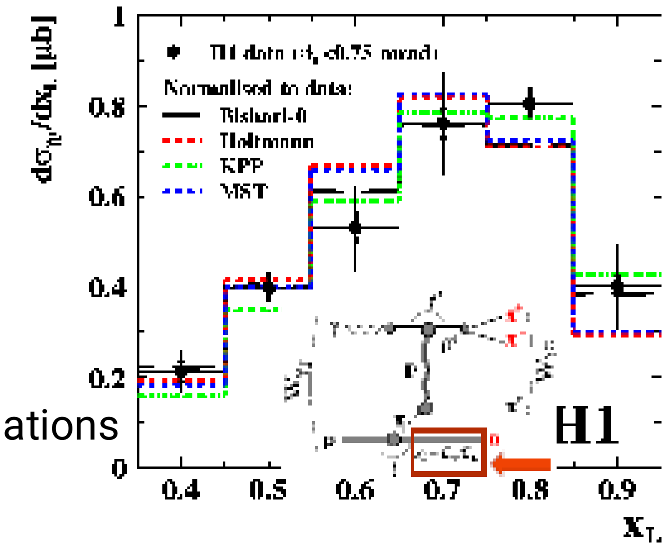
F_{bg} = B / (S + B) = 0.34 ± 0.05



Good description of data with thus determined background fraction

Exclusive ρ^0 photoproduction with a LN

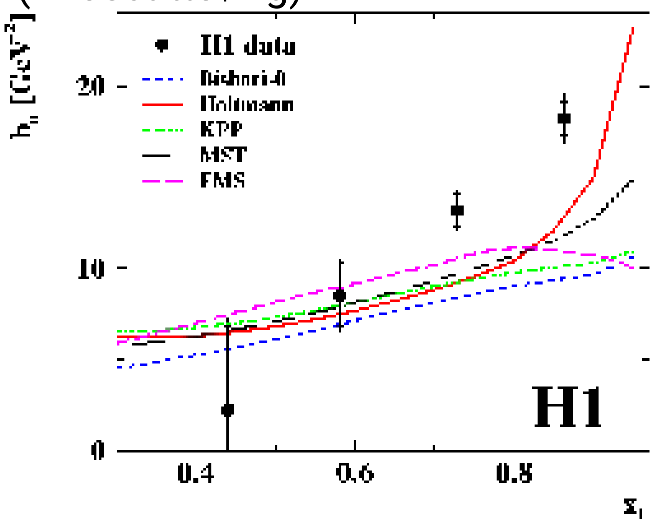
- Shape of x_L distribution is well reproduced by most of the pion flux models

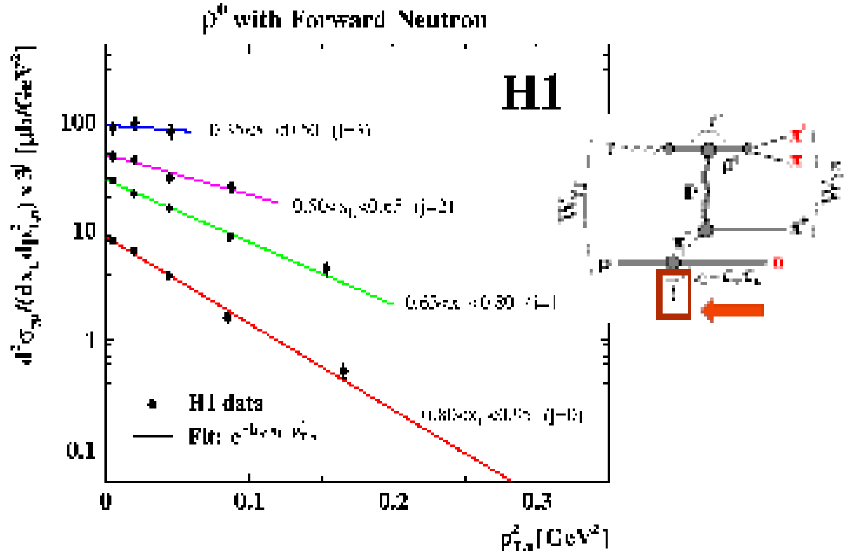


- double differential γp cross section in (x_L, $p_{T,n}^2$):fit by $\exp[-b_n(x_L)\, p_{T,n}^2]$ function in each x_L bin
  - steeply falling (i.e.high b parameter) at very high x_L

- Steep rise with increasing x_L expected from models, but rise is stronger than predicted by various pion-flux approximations

- Failure to describe $b_n(x_L)$ suggests strong absorptive effect (n rescattering)





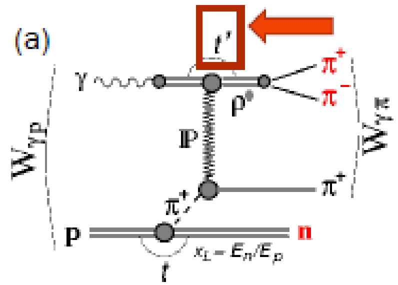
Exclusive ρ^0 photoproduction with LN

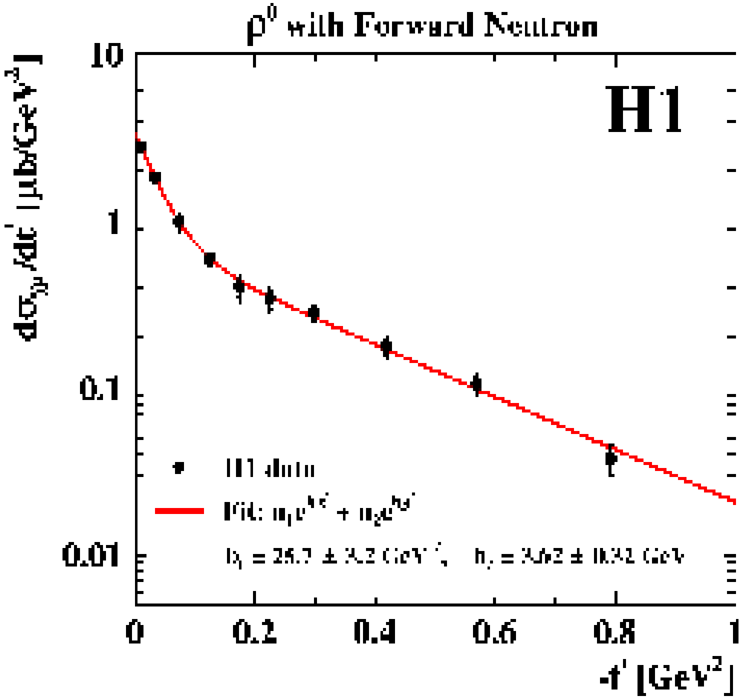
ρ^0 slope :

ρ^0 slope strongly changing from
low-t' to hight-t' region
=> two b parameters:
$b_1 \sim 25\ GeV^{-2}$ — very peripheral scattering;
⇒Photons find pions in the cloud extending
far beyond the proton radius

In DPP this is due to double exchange,
IP and π

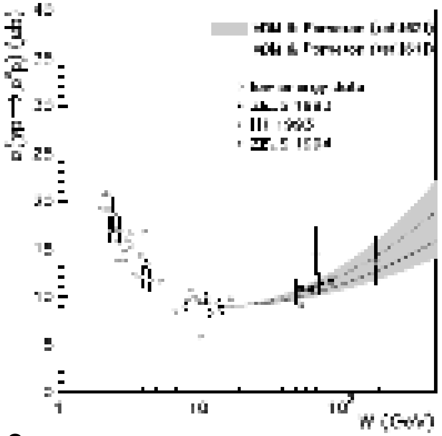
DPP interpretation — slope t' depends
on the invariant mass of the $(n\pi^+)$ system:
low mass $\pi^+ n$ state → large slope,
high masses → less steep slope





Exclusive ρ^0 photoproduction with a LN

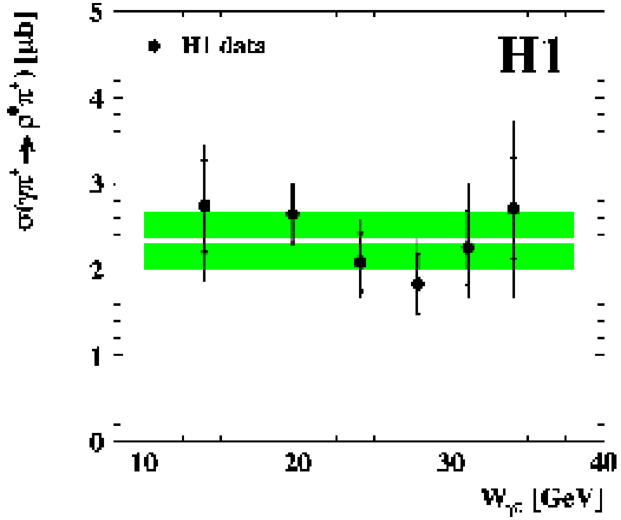
W dependence:



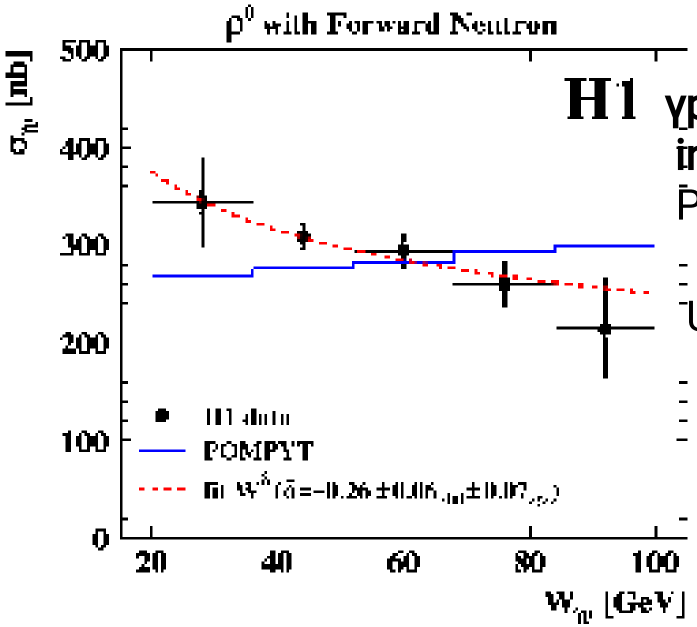
$\gamma p \to \rho^0 p$ at HERA prefers to **increase with W**

Pomeron trajectory : $\delta \approx 0.08$

$\gamma\pi \to \rho^o\pi+$



$\gamma p \to \rho^o\pi+n$



Using pion-flux parametrization, $\sigma_{\gamma\pi}$ can be measured;

measured **$\sigma_{\gamma\pi}$ independent from $W_{\gamma\pi}$**

$\sigma_{el}(\gamma\pi^+)/\sigma_{el}(\gamma p) = 0.25 \pm 0.06$ - agrees with ZEUS(2002)

$\sigma(\gamma\pi^+)/\sigma(\gamma p)_{theor.} = 0.57 \pm 0.06$ =>

$K_{abs} = 0.44 \pm 0.11$

$\sigma_{\gamma p}$ drops with energy in contrast with POMPYT
where the whole energy dependence is driven by
Pomeron exchange only; Regge motivated power law fit by W^{δ} describes the data

Summary

H1 and ZEUS at HERA provided new results on exclusive production

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

- 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

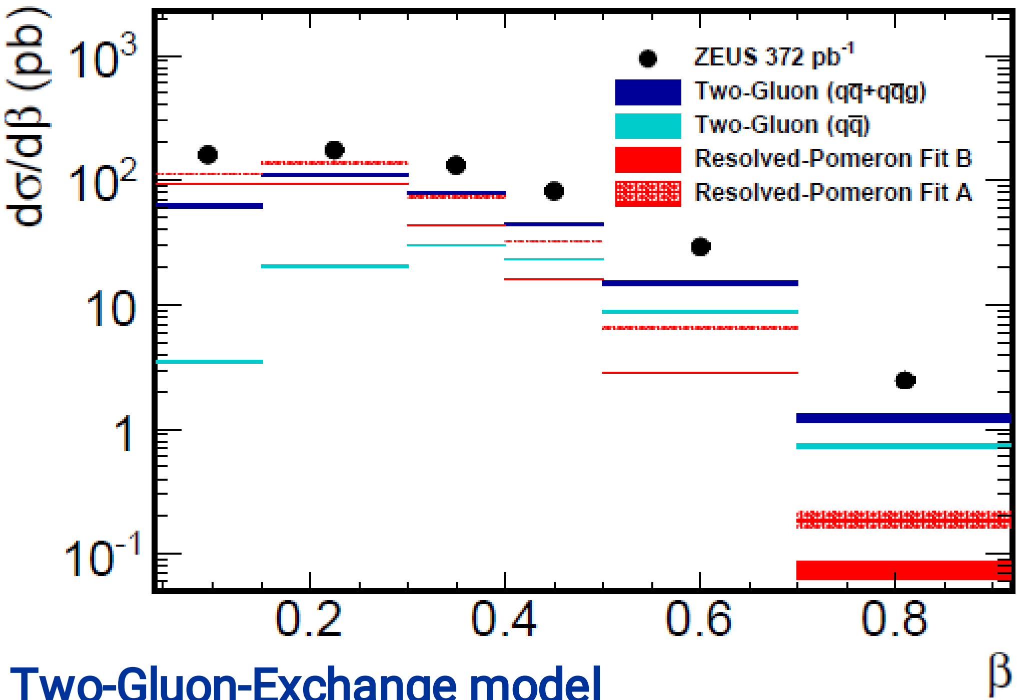
- Photoproduction of exclusive ρ^0 associated with leading neutron measured first time at HERA
  Differential cross sections for the reaction $\gamma p \rightarrow \rho^0 n \pi^+$ exhibit features typical for exclusive DPP
  Process used to extract the elastic photon-pion cross section σ_{el} $(\gamma\pi \rightarrow \rho^0\pi^+)$ in the OPE approximation
  The cross section ratio $\sigma(\gamma\pi)/\sigma(\gamma p)$ suggests large absorption correction suppressing $\sigma(\gamma p)$

- Studies of the exclusive state production performed at HERA still inspiring for QCD theory and LHC experiments

Backup

Exclusive dijet production in diffractive DI

dσ/dβ : comparison with model predictions



Resolved Pomeron model

Prediction decreases with increasing β faster than data

Difference between data and prediction is less pronounced for Fit A than for FitB

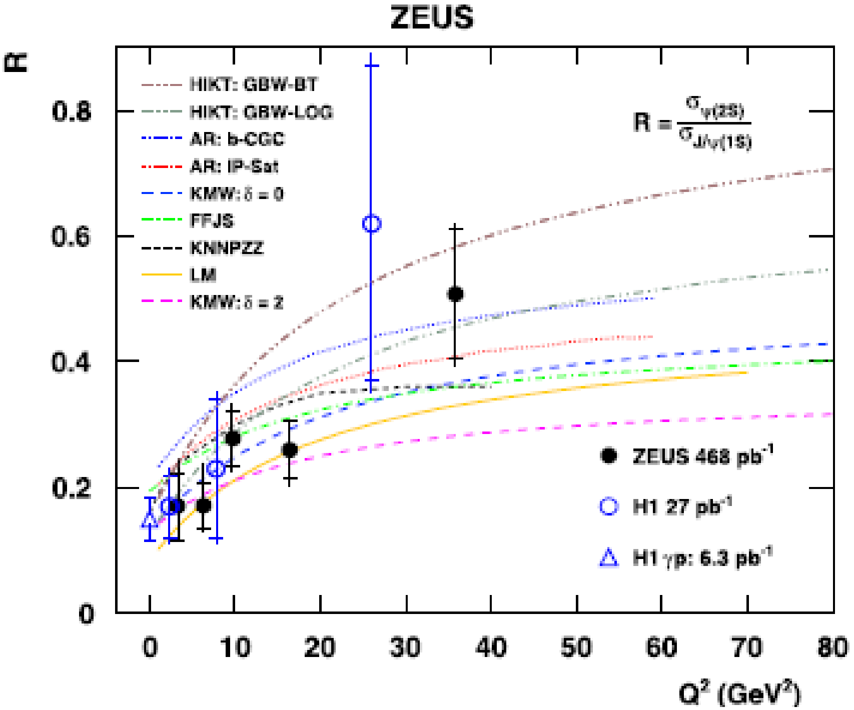
Two-Gluon-Exchange model

Reasonable description of the shape of the β distribution

Large difference in normalization could indicate that the NLO corrections are large or effect of the off-diagonal gluon distribution is significant

Howerever large uncertainty due to the p-diss subtraction makes the difference not significant

Cross section ratio $R = \sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs Q^2



Good agreement with earlier H1 measurement (EPJ C10 (1999) 373)

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

Exclusive ρ^0 photoproduction with a LN

Cross section measurement:

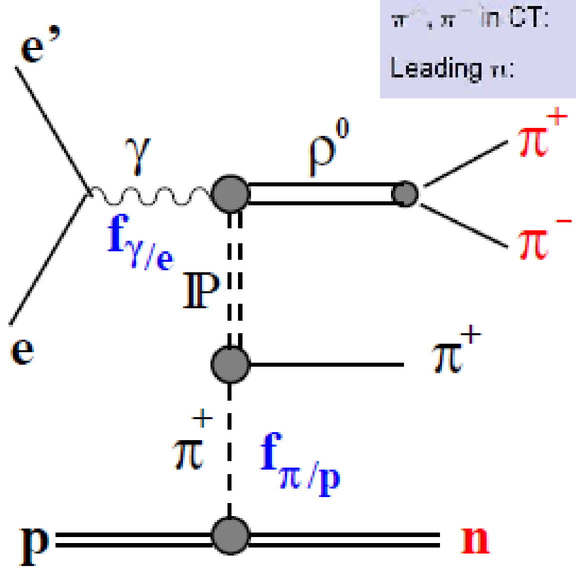
Photoproduction:	$Q^2 < 2$ GeV^2	($\langle Q^2 \rangle = 0.04$ GeV^2)
Low p_t:	$\lvert t \rvert < 1$ GeV^2	($\langle \lvert t \rvert \rangle = 0.20$ GeV^2)
Small mass:	$0.3 < m_{\pi\pi} < 1.5$ GeV	(m_ρ)
π^+, π^- in CT:	$20 < W_{\gamma p} < 100$ GeV	($\langle W_{\gamma p} \rangle = 45$ GeV)
Leading n:	$E_n > 120$ GeV;	$\theta_n < 0.75$ mrad

$$\sigma_{\gamma p} = \frac{\sigma_{ep}}{\Phi_\gamma}$$

$$\Phi_\gamma = \int f_{\gamma/e}(y, Q^2)\mathrm{d}y\mathrm{d}Q^2$$

$$\sigma_{\gamma\pi} = \frac{\sigma_{\gamma p}}{\Gamma_\pi}$$

$$\Gamma_\pi = \int f_{\pi/p}(x_L, t)\mathrm{d}x_L\mathrm{d}t$$



γp: $\sigma(\gamma p \rightarrow \rho^o n \pi^+) = 310 \pm 6(\text{stat}) \pm 45(\text{stat})$ nb for $p_{T,n} < x_L \cdot 0.69$ GeV

$\sigma(\gamma p \rightarrow \rho^o n \pi^+) = 130 \pm 3(\text{stat}) \pm 19(\text{stat})$ nb for $p_{T,n} < 0.2$ GeV

γπ: $\sigma_{el}(\gamma\pi^+ \rightarrow \rho^0\pi^+) = 2.33 \pm 0.34_{exp}(+0.47)(-0.40)_{model}$ μb for $< W_{\gamma\pi} > = 24$ GeV

Exclusive ρ^0 photoproduction with a LN

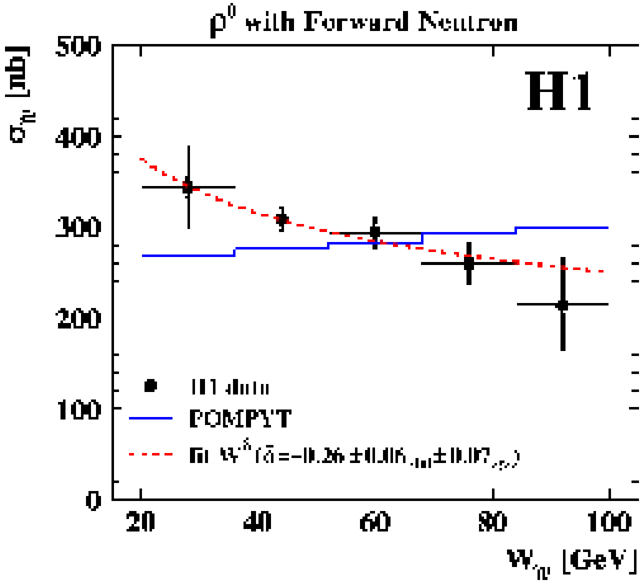
Cross section measurement:

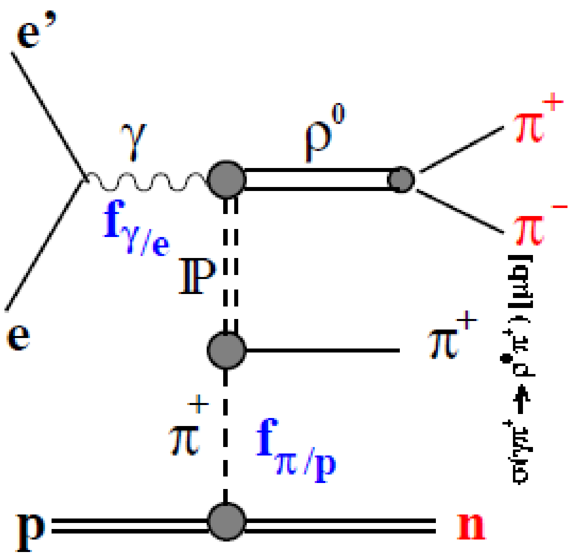
$$\sigma_{\gamma p} = \frac{\sigma_{ep}}{\Phi_\gamma}$$

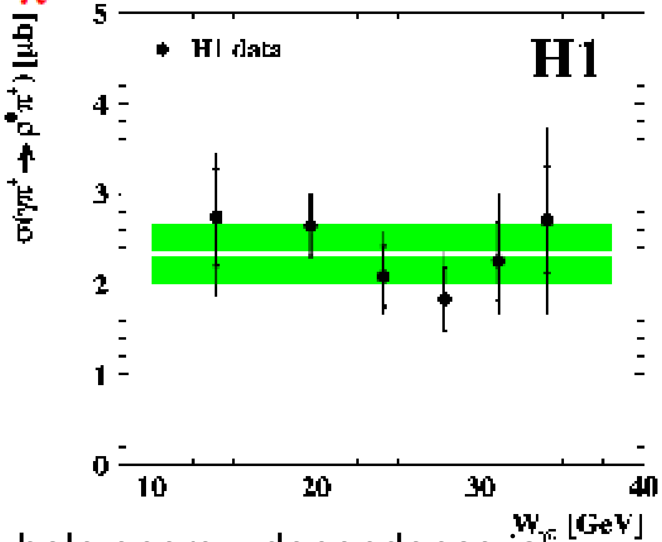
$$\Phi_\gamma = \int f_{\gamma/e}(y, Q^2)\mathrm{d}y\mathrm{d}Q^2$$

$$\sigma_{\gamma\pi} = \frac{\sigma_{\gamma p}}{\Gamma_\pi}$$

$$\Gamma_\pi = \int f_{\pi/p}(x_L, t)\mathrm{d}x_L\mathrm{d}t$$







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