



Vector meson production at HERA

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On behalf of the H1 and ZEUS Collaborations

Outline:

- Measurement of the cross section ratio $\sigma(\Psi(2S))/\sigma(J/\Psi(1S))$ in deep inelastic exclusive ep scattering at HERA [ZEUS – Nucl. Phys. B909 (2016) 934-953]
- Exclusive ρ^0 meson photoproduction with a leading neutron at HERA [H1 – Eur. Phys. J. C76 (2016) 1-41]

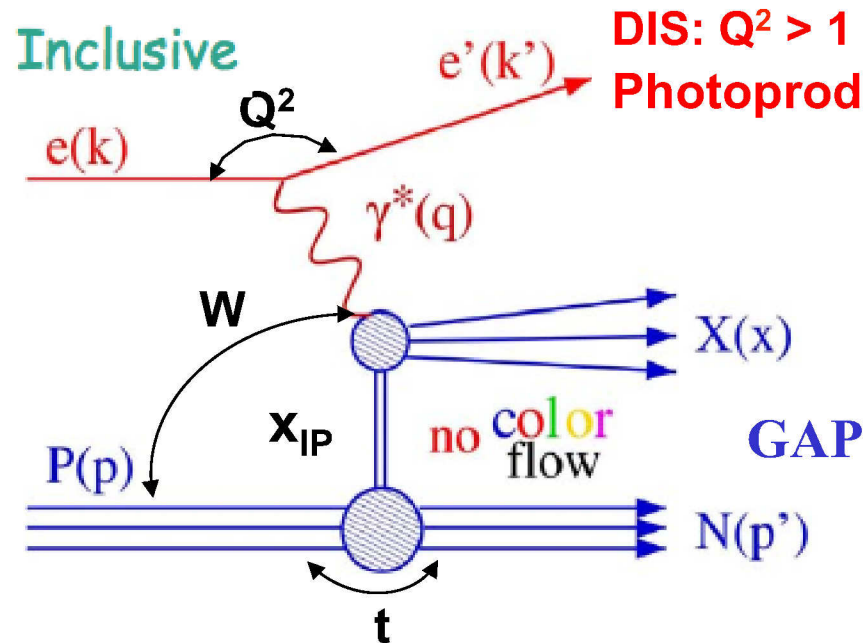
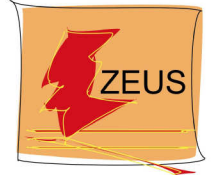


DIFFRACTION 2016





Inclusive and exclusive diffraction



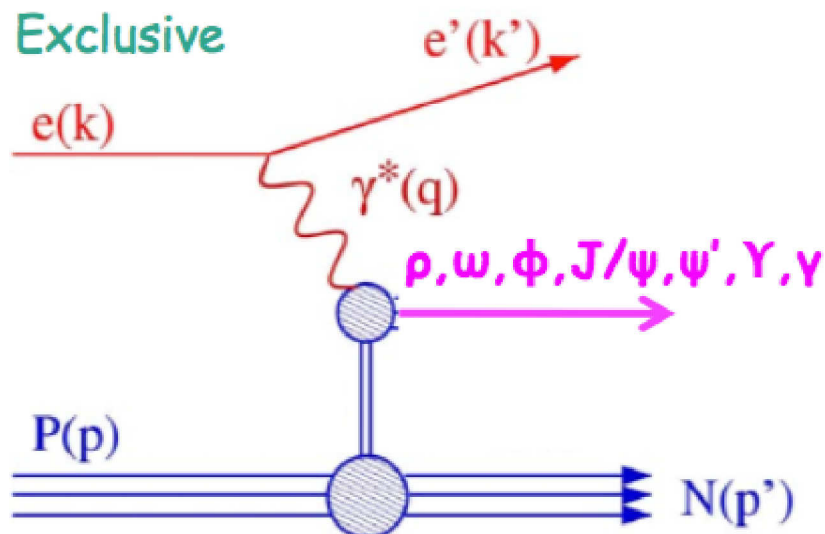
DIS: $Q^2 > 1 \text{ GeV}^2$

Photoproduction (γp): $Q^2 \sim 0$

Q^2 = virtuality of exchanged photon

W = invariant mass of γ^* -p system

t = (4-momentum exchanged at p vertex)²
typically: $|t| < 1 \text{ GeV}^2$

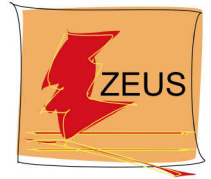


$\Rightarrow N$ = proton $\rightarrow$ Elastic events

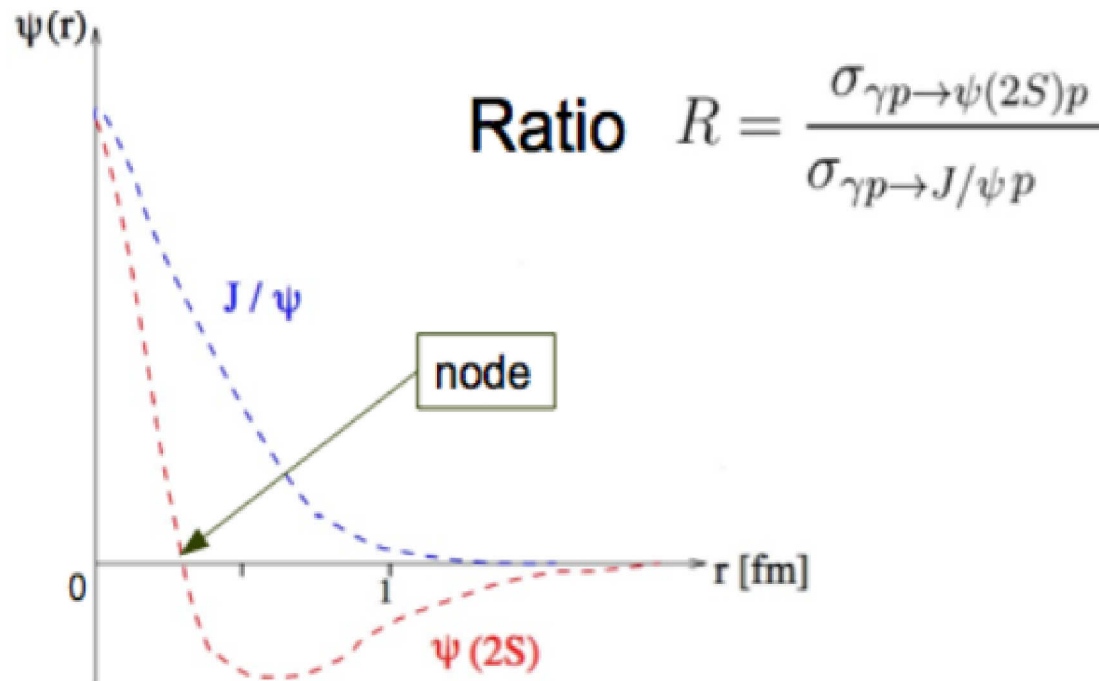
$\Rightarrow N$ = proton dissociative system



$\Psi(2S)/J/\Psi(1S)$ in exclusive DIS



Motivation :



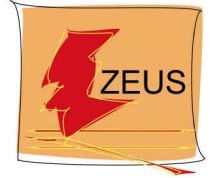
$\psi(2S)$ wave function different from $J/\psi(1S)$ wave function:

ratio sensitive to radial wave function of charmonium

pQCD models predict $R \sim 0.17$ (γp) and rise of R with Q^2 (DIS)



$\Psi(2S)/J/\Psi(1S)$ in exclusive DIS



Samples and event selection :

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

Data : HERA I + HERA II (1996 - 2017) – integrated luminosity 468 pb⁻¹

MC :

- Signal – exclusive VM production with DIFFVM
- Background – Bethe-Heitler $\mu^+\mu^-$ 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 $\mu\mu$ vertex
- Nothing else in the detector above noise
- Proton dissociative events removed above masses $\sim M_N$ 4 GeV

$$\begin{aligned} 30 < W < 210 \text{ GeV} \\ 2 < Q^2 < 80 \text{ GeV}^2 \\ |t| < 1 \text{ GeV}^2 \end{aligned}$$

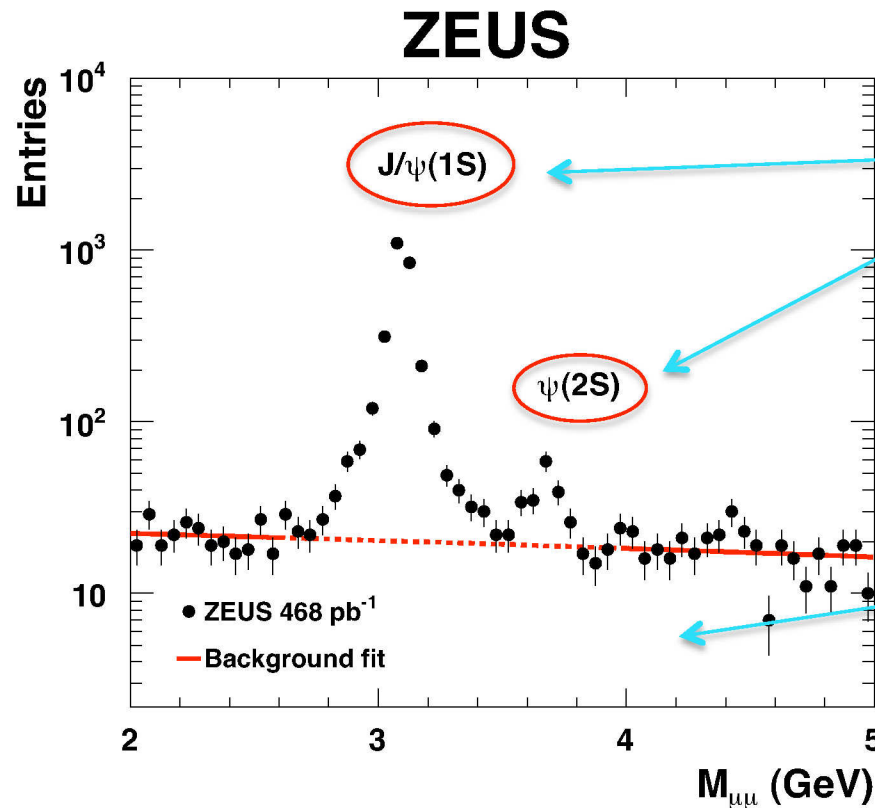
Assuming cross section ratio does not vary with M_N – results not affected by proton dissociation background



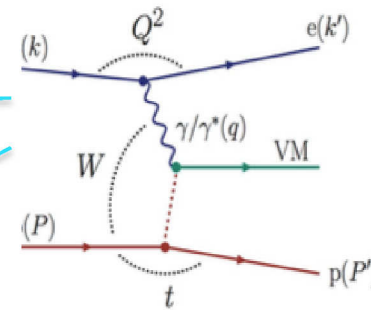
$\Psi(2S)/J/\Psi(1S)$ in exclusive DIS



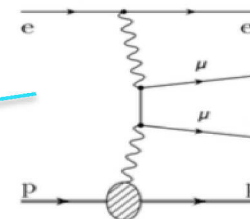
Background subtraction :



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



Bethe-Heitler



Dimuon background fitted with a straight line for
 $2 < M_{\mu+\mu^-} < 2.62$ GeV and
 $4.05 < M_{\mu+\mu^-} < 5$ GeV

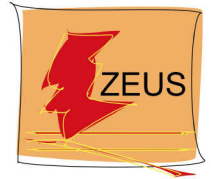
Number of events above background :

$3.59 < M_{\mu+\mu^-} < 3.79$ GeV $\rightarrow N_{\psi(2S)}$

$3.02 < M_{\mu+\mu^-} < 3.17$ GeV $\rightarrow N_{J/\psi}$



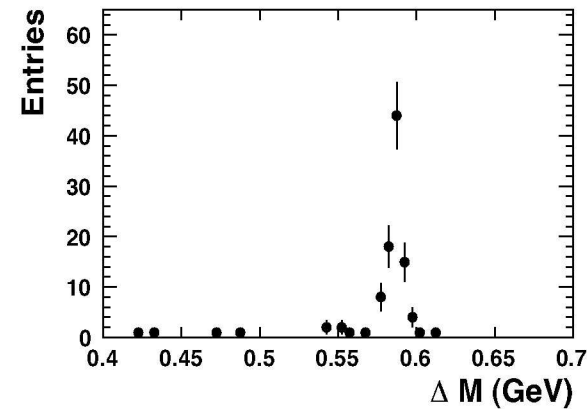
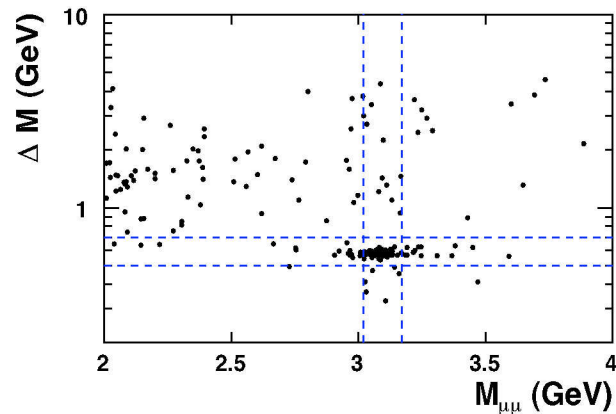
$\Psi(2S)/J/\Psi(1S)$ in exclusive DIS



Background subtraction :

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

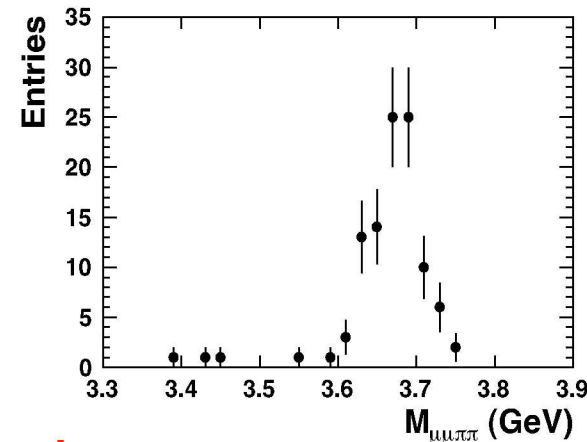
ZEUS



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

$$\left. \begin{array}{l} 3.02 < M_{\mu\mu} < 3.17 \text{ GeV} \\ 0.5 < \Delta M < 0.7 \text{ GeV} \end{array} \right\} N_{\psi(2S)}$$

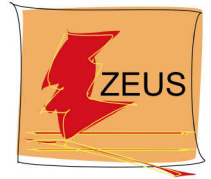
No background (upper limit of 3 events at 90% C.L. estimated)



After cut on $M_{\mu\mu}$



$\Psi(2S)/J/\Psi(1S)$ in exclusive DIS



Measured ratios :

$$R_{J/\psi\pi\pi} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S) \rightarrow \mu^+\mu^-}}{Acc_{\psi(2S) \rightarrow J/\psi\pi^+\pi^-}} \cdot \frac{1}{BR_{\psi(2S) \rightarrow J/\psi\pi^+\pi^-}}$$

$$R_{\mu\mu} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S) \rightarrow \mu^+\mu^-}}{Acc_{\psi(2S) \rightarrow \mu^+\mu^-}} \cdot \frac{BR_{J/\psi(1S) \rightarrow \mu^+\mu^-}}{BR_{\psi(2S) \rightarrow \mu^+\mu^-}}$$

R_{comb} = combination of $R_{J/\psi\pi\pi}$ and $R_{\mu\mu}$

$$Acc_i = \frac{N_i^{reco}}{N_i^{true}}$$

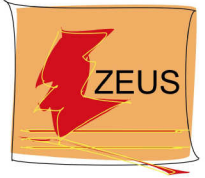
$$BR[\psi(2S) \rightarrow J/\psi \pi\pi] = (33.6 \pm 0.4)\%$$

$$BR[\psi(2S) \rightarrow \mu\mu] = (7.7 \pm 0.8) \times 10^{-3}\%$$

$$BR[J/\psi \rightarrow \mu\mu] = (5.93 \pm 0.06)\%$$



$\Psi(2S)/J/\Psi(1S)$ in exclusive DIS



Measured ratios :

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

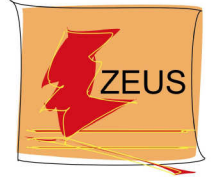
$30 < W < 210 \text{ GeV}$
 $2 < Q^2 < 80 \text{ GeV}^2$
 $|t| < 1 \text{ GeV}^2$

$$R_{\psi(2S)} = R_{J/\psi\pi\pi} / R_{\mu\mu}$$

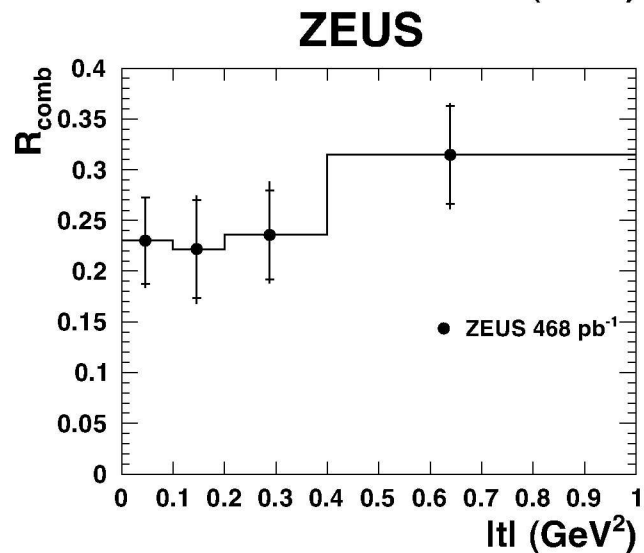
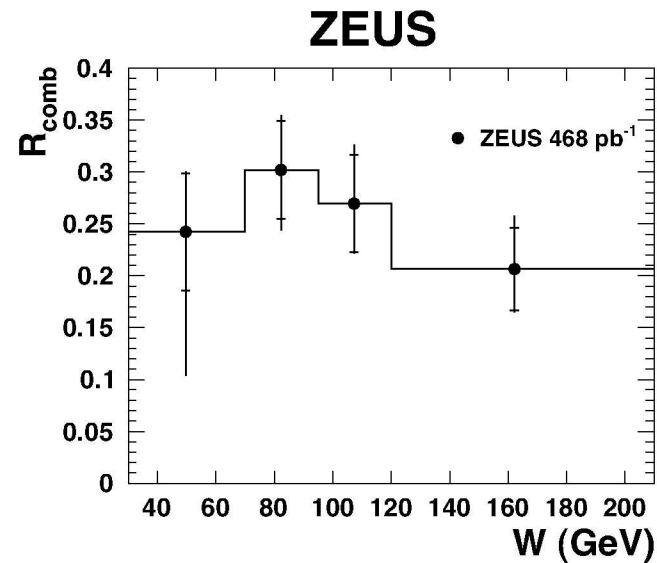
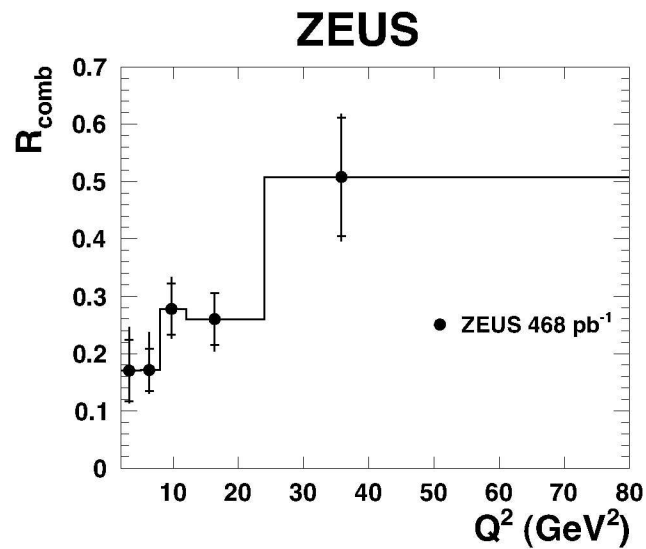
$Q^2 \text{ (GeV}^2\text{)}$	$R_{J/\psi\pi\pi}$	$R_{\mu\mu}$	R_{comb}	$R_{\psi(2S)}$
2 – 5	$0.21 \pm 0.07^{+0.04}_{-0.03}$	$0.10 \pm 0.09^{+0.09}_{-0.09}$	$0.17 \pm 0.05^{+0.05}_{-0.02}$	—
5 – 8	$0.19 \pm 0.05^{+0.02}_{-0.02}$	$0.13 \pm 0.06^{+0.12}_{-0.03}$	$0.17 \pm 0.04^{+0.05}_{-0.02}$	$1.5 \pm 0.8^{+0.4}_{-0.7}$
8 – 12	$0.27 \pm 0.05^{+0.06}_{-0.01}$	$0.29 \pm 0.08^{+0.03}_{-0.08}$	$0.28 \pm 0.05^{+0.03}_{-0.03}$	$0.9 \pm 0.3^{+0.4}_{-0.1}$
12 – 24	$0.27 \pm 0.05^{+0.04}_{-0.03}$	$0.24 \pm 0.08^{+0.01}_{-0.08}$	$0.26 \pm 0.05^{+0.01}_{-0.03}$	$1.1 \pm 0.4^{+0.6}_{-0.1}$
24 – 80	$0.56 \pm 0.13^{+0.04}_{-0.09}$	$0.42 \pm 0.17^{+0.12}_{-0.04}$	$0.51 \pm 0.10^{+0.04}_{-0.04}$	$1.3 \pm 0.6^{+0.3}_{-0.6}$
$W \text{ (GeV)}$	$R_{J/\psi\pi\pi}$	$R_{\mu\mu}$	R_{comb}	$R_{\psi(2S)}$
30 – 70	$0.24 \pm 0.07^{+0.01}_{-0.13}$	$0.24 \pm 0.10^{+0.03}_{-0.14}$	$0.24 \pm 0.06^{+0.01}_{-0.13}$	$1.0 \pm 0.5^{+0.5}_{-0.2}$
70 – 95	$0.30 \pm 0.06^{+0.01}_{-0.04}$	$0.31 \pm 0.09^{+0.09}_{-0.03}$	$0.30 \pm 0.05^{+0.02}_{-0.03}$	$1.0 \pm 0.3^{+0.1}_{-0.2}$
95 – 120	$0.28 \pm 0.06^{+0.05}_{-0.01}$	$0.24 \pm 0.08^{+0.04}_{-0.05}$	$0.27 \pm 0.05^{+0.03}_{-0.01}$	$1.2 \pm 0.5^{+0.5}_{-0.2}$
120 – 210	$0.22 \pm 0.05^{+0.07}_{-0.01}$	$0.17 \pm 0.07^{+0.02}_{-0.05}$	$0.21 \pm 0.04^{+0.03}_{-0.01}$	$1.3 \pm 0.6^{+0.7}_{-0.2}$
$ t \text{ (GeV}^2\text{)}$	$R_{J/\psi\pi\pi}$	$R_{\mu\mu}$	R_{comb}	$R_{\psi(2S)}$
0 – 0.1	$0.23 \pm 0.05^{+0.02}_{-0.02}$	$0.23 \pm 0.09^{+0.04}_{-0.05}$	$0.23 \pm 0.04^{+0.01}_{-0.02}$	$1.0 \pm 0.4^{+0.3}_{-0.2}$
0.1 – 0.2	$0.22 \pm 0.06^{+0.02}_{-0.03}$	$0.23 \pm 0.09^{+0.02}_{-0.06}$	$0.22 \pm 0.05^{+0.02}_{-0.02}$	$0.9 \pm 0.4^{+0.5}_{-0.2}$
0.2 – 0.4	$0.27 \pm 0.06^{+0.06}_{-0.01}$	$0.18 \pm 0.07^{+0.05}_{-0.06}$	$0.24 \pm 0.04^{+0.03}_{-0.02}$	$1.5 \pm 0.6^{+0.5}_{-0.2}$
0.4 – 1	$0.32 \pm 0.06^{+0.05}_{-0.03}$	$0.30 \pm 0.08^{+0.02}_{-0.05}$	$0.32 \pm 0.05^{+0.01}_{-0.02}$	$1.1 \pm 0.3^{+0.3}_{-0.1}$



$\Psi(2S)/J/\Psi(1S)$ in exclusive DIS



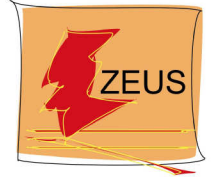
Ratios vs Q^2 , W and t



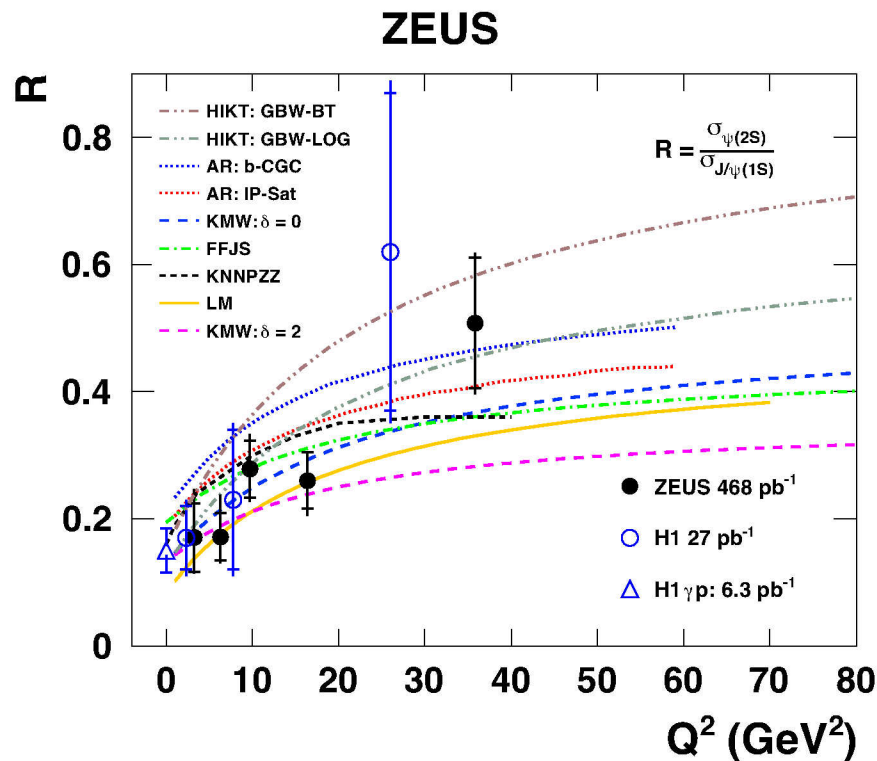
→ Increasing with Q^2
Independent of W and t



$\Psi(2S)/J/\Psi(1S)$ in exclusive DIS



Comparison with H1 earlier measurement and with models

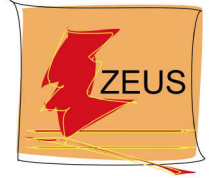


H1, EPJ C10 (1999) 373

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



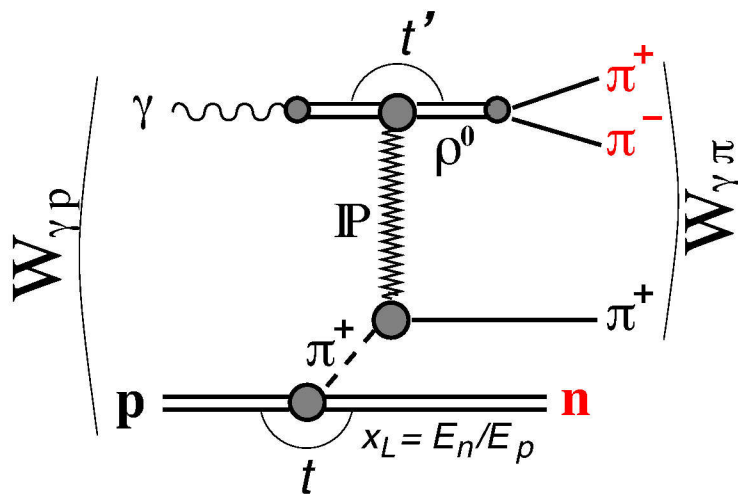
Exclusive ρ^0 photoproduction with a LN



Motivation :

First measurement of ρ^0 photoproduction with a leading neutron at HERA

In $e + p \rightarrow e' + n + X$ the production of neutrons carrying a large fraction of the proton beam momentum is dominated by the **pion exchange process**



⇒ **Extract $\sigma(\gamma\pi^+ \rightarrow \rho^0\pi^+)$**

Mean $W \sim 24$ GeV → **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



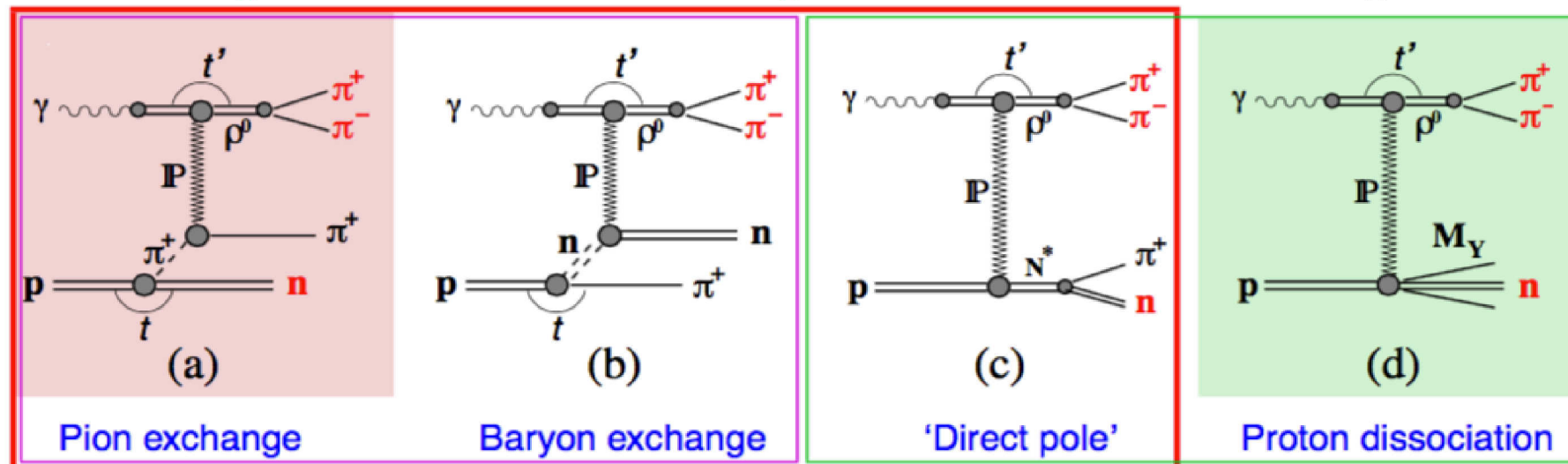
Exclusive ρ^0 photoproduction with a LN



Signal and background diagrams :

Signal : Drell-Hiida-Deck diagrams

Background



(Pompyt MC)

(DiffVM MC)

$$\sigma(\gamma p \rightarrow \rho^0 n \pi^+) = |A_a + A_b + A_c|^2 \implies \text{interference effects}$$

For large s and $t' \rightarrow 0$: pion exchange dominates



Exclusive ρ^0 photoproduction with a LN



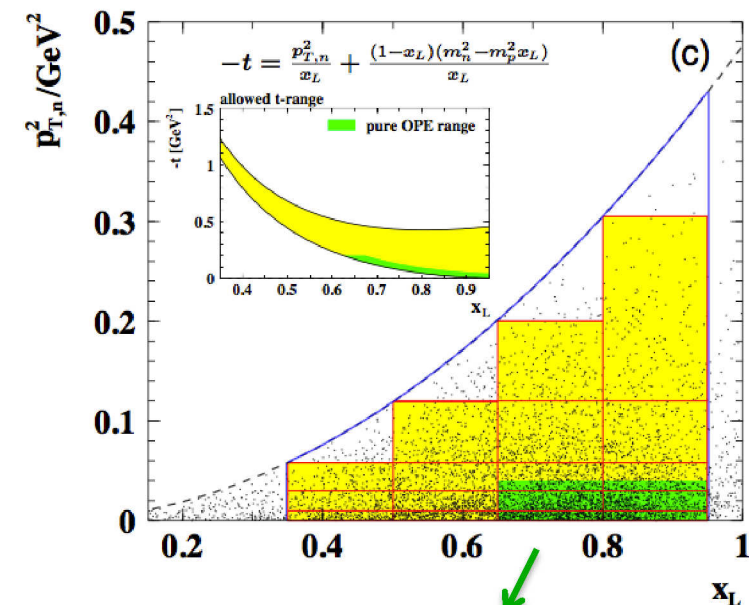
Experimental challenge and data sample :

Forward Neutron Calorimeter (FNC)

to distinguish and measure n and γ/π^0 ,
located at 106 m from the H1 interaction point
– limited acceptance : $\langle A \rangle \sim 30\%$

and $p_{T,n} < x_L \cdot 0.69 \text{ GeV}$ ($x_L = E_n/E_p$)

Fast Track Trigger : special low multiplicity
trigger to collect untagged soft γp events



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

Event selection :

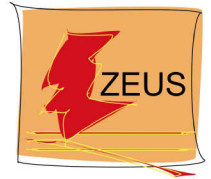
- Scattered positron undetected : $\langle Q^2 \rangle = 0.04 \text{ GeV}^2$ – **photoproduction events**
- Only two oppositely charged pion candidates in the central tracker with $0.3 < M_{\pi\pi} < 1.5$
- A hadronic cluster in the **FNC** with an energy above 120 GeV
- Nothing else in the detector above noise level, in particular in the forward detectors (**LRG**)

Data :

2006 – 2007 e^+p data, **integrated luminosity 1.16 pb^{-1}**



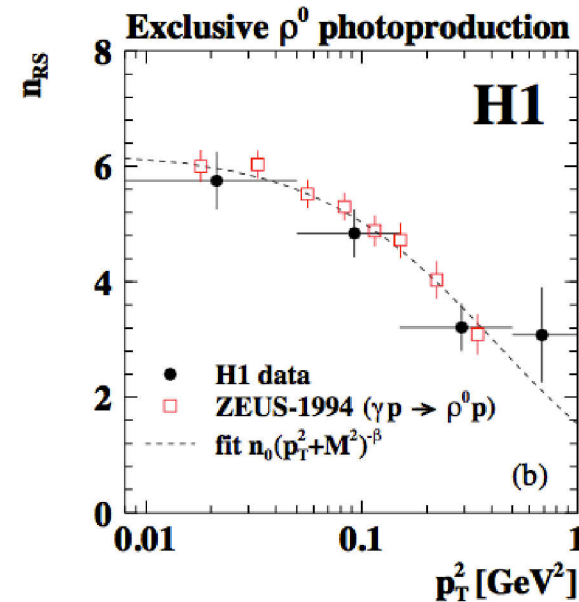
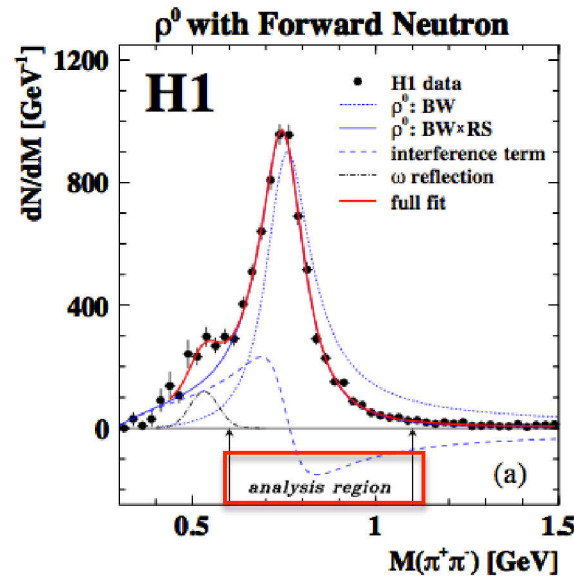
Exclusive ρ^0 photoproduction with a LN



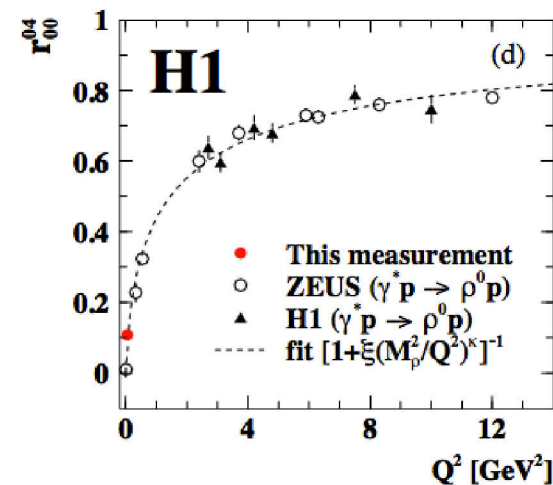
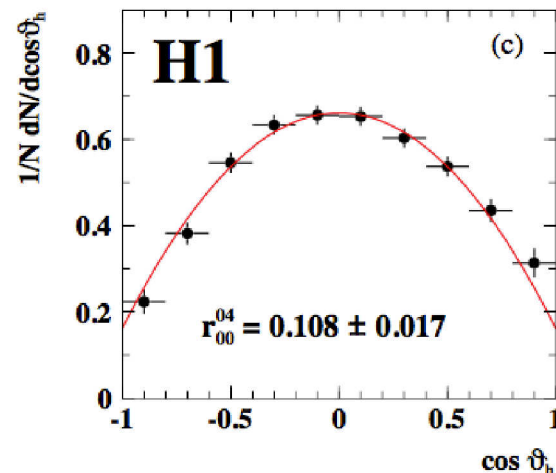
ρ^0 measurement :

$$M = 764 \pm 3 \text{ MeV}$$

$$\Gamma = 155 \pm 5 \text{ MeV}$$



Ross-Stodolsky skewing par.



$$\xi = 1.85 \pm 0.10$$

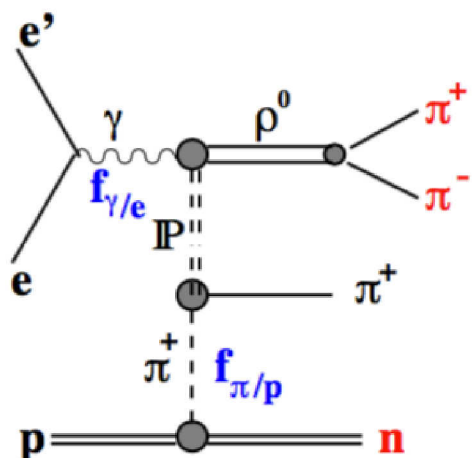
$$\kappa = 0.67 \pm 0.03$$



Exclusive ρ^0 photoproduction with a LN



Cross section measurement :



$$\sigma_{\gamma p} = \frac{\sigma_{ep}}{\int f_{\gamma/e}(y, Q^2) dy dQ^2}$$

$$\sigma_{\gamma\pi}(\langle W_{\gamma\pi} \rangle) = \frac{\sigma_{\gamma p}}{\int f_{\pi^+/p}(x_L, t) dx_L dt},$$

$$\begin{aligned} 20 < W_{\gamma p} < 100 \text{ GeV} \\ 2m_\pi < M_\rho < M_\rho + 5\Gamma_\rho \\ |t'| < 1 \text{ GeV}^2 \\ 0.35 < x_L < 0.95 \\ f_{bg} = 0.34 \pm 0.05 \end{aligned}$$

γp

$$\sigma(\gamma p \rightarrow \rho^0 n \pi^+) = 310 \pm 6(\text{stat}) \pm 45(\text{syst}) \text{ nb}$$

$$\text{for } p_{T,n} < x_L \cdot 0.69 \text{ GeV}$$

$$\sigma(\gamma p \rightarrow \rho^0 n \pi^+) = 130 \pm 3(\text{stat}) \pm 19(\text{syst}) \text{ nb}$$

$$\text{for } p_{T,n} < 0.2 \text{ GeV}$$

$\gamma\pi$

$$\text{for } \langle W_{\gamma\pi} \rangle = 24 \text{ GeV}$$

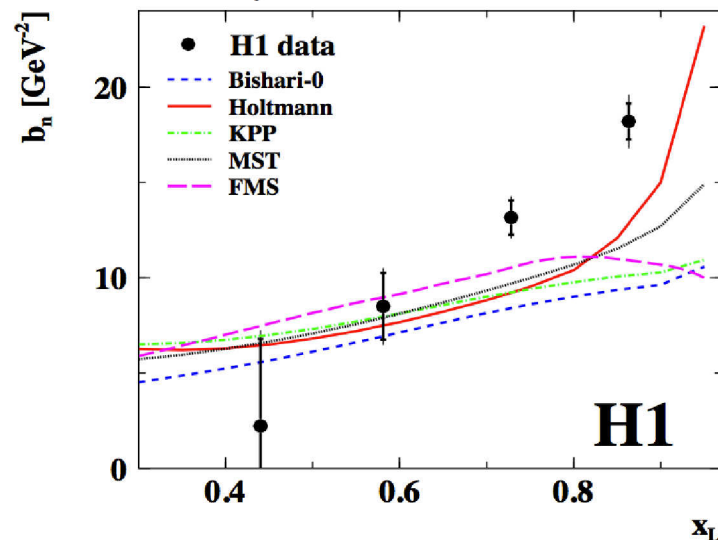
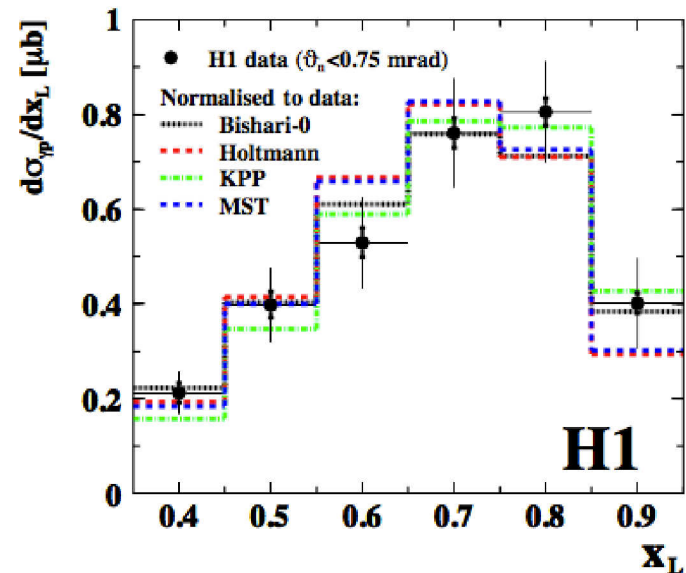
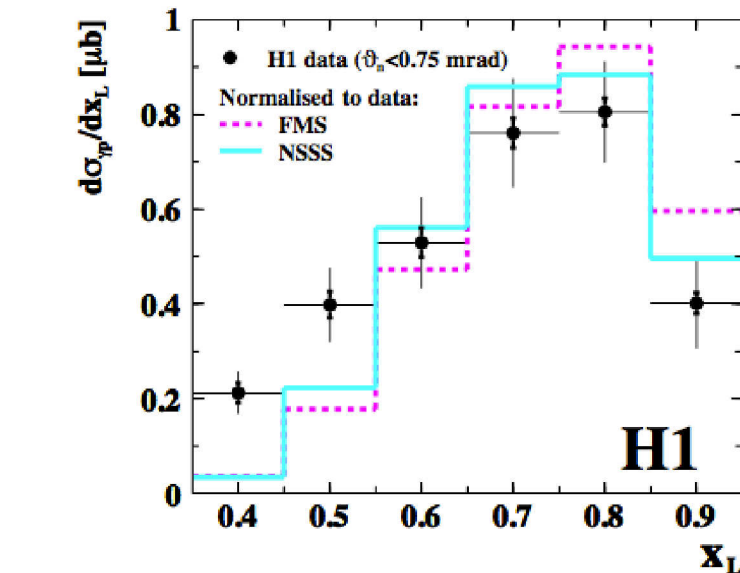
$$\sigma_{el}(\gamma\pi^+ \rightarrow \rho^0 \pi^+) = 2.33 \pm 0.34_{\text{exp}} (+0.47)(-0.40)_{\text{model}} \mu\text{b}$$



Exclusive ρ^0 photoproduction with a LN



Constraining pion flux :

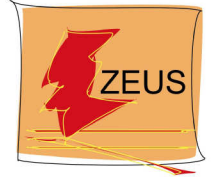


x_L distribution of the leading neutron generally **well described** – some pion fluxes disfavoured

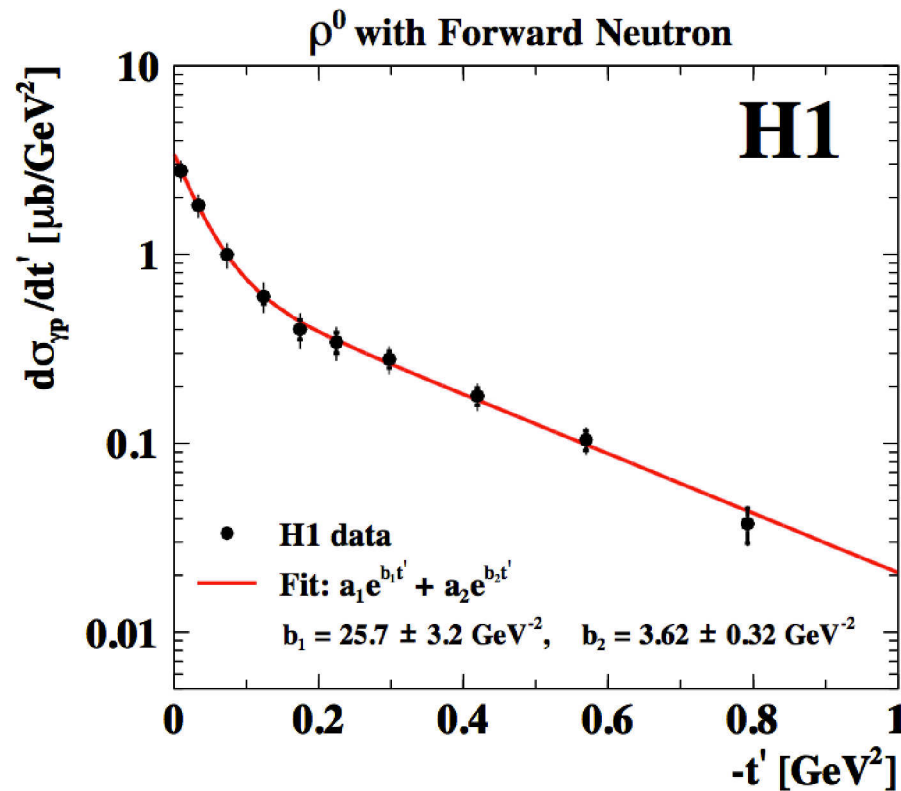
Instead **none of the models can reproduce the t dependence** of the leading neutron – effect of absorptive corrections ?



Exclusive ρ^0 photoproduction with a LN

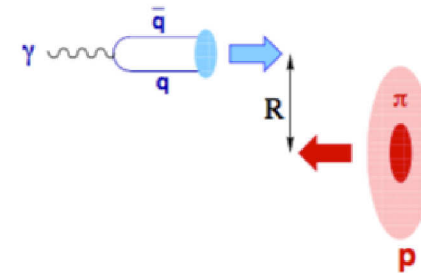


ρ^0 slope :



Geometric interpretation :

$$\langle r^2 \rangle = 2b_1 \cdot (\hbar c)^2 \sim 2 \text{ fm}^2 \quad (\sim 1.6 R_p)^2$$



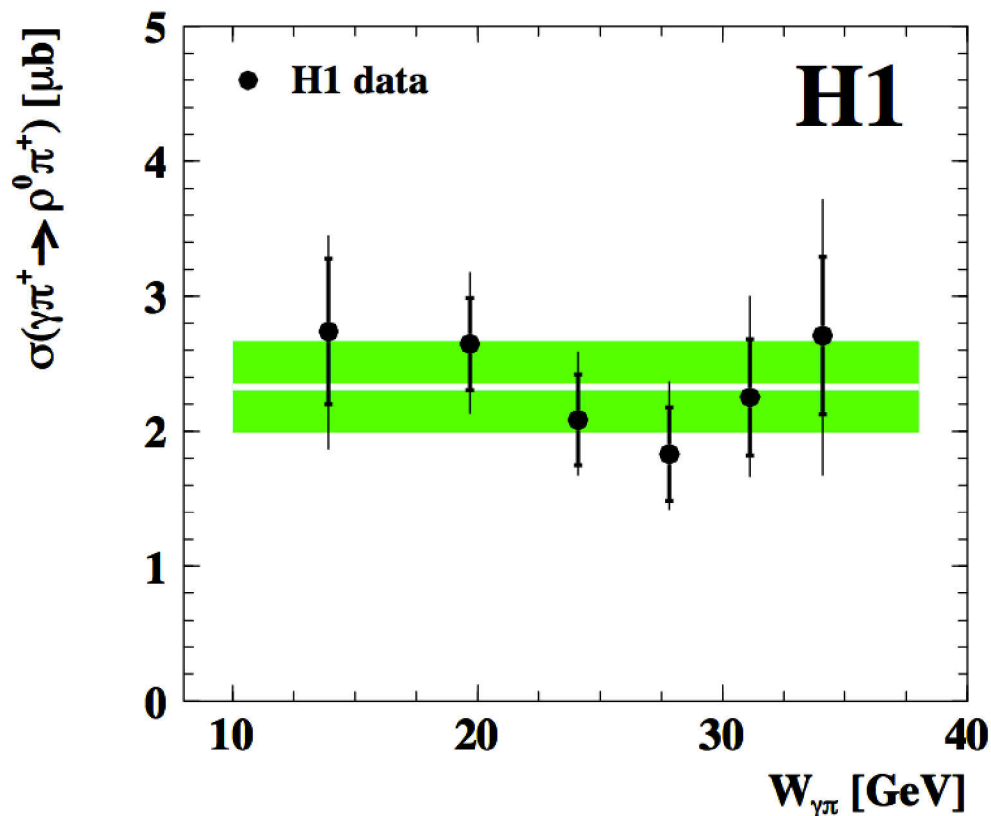
ρ^0 slope strongly changing from low- t' to high- t' region, as expected for a double-peripheral process – slope dependence on the invariant mass of the $(n\pi^+)$ system



Exclusive ρ^0 photoproduction with a LN



$\gamma\pi$ cross section :



Comparing different phase space regions **no evidence for an extra contribution beyond the OPE is found** in the full FNC acceptance range

At $\langle W \rangle = 24$ GeV

$$\sigma(\gamma\pi^+)/\sigma(\gamma p) = 0.25 \pm 0.06$$

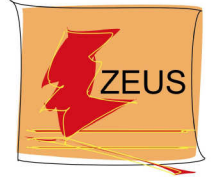
in agreement with a previous ZEUS measurement [ZEUS, NP B637 (2002) 3]

Significantly lower than expected, suggesting large absorption corrections :

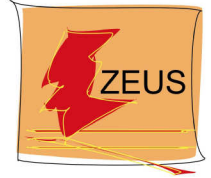
$$K_{\text{abs}} = 0.44 \pm 0.11$$



Summary



- **Cross section ratio $\psi(2S)/J/\psi(1S)$** measured by ZEUS with full HERA statistics
- Ratio grows with Q^2 as predicted by pQCD and is constant with W and t
- Ratio is compared with models of VM production, some discrimination of the different models is possible
- **Exclusive ρ^0 photoproduction associated with a leading neutron** measured by H1 for the first time at HERA
- The differential cross section $d\sigma/dt'$ for the reaction $\gamma p \rightarrow \rho^0 n \pi^+$ shows a behaviour typical for exclusive double peripheral exchange processes
- The elastic photon-pion cross section, $\sigma(\gamma \pi^+ \rightarrow \rho^0 \pi^+)$ at $\langle W_{\gamma\pi} \rangle = 24$ GeV is extracted in the one-pion-exchange approximation
- The estimated cross section ratio for the elastic photoproduction of ρ^0 mesons on the pion and on the proton, $r_{\text{el}} = \sigma_{\gamma\pi}/\sigma_{\gamma p} = 0.25 \pm 0.06$, suggests large absorption corrections



Backup slides



HERA experiments



HERA-I : 1992-2000

p : 820 GeV
920 GeV

HERA-II : 2001-2007

p : 920 GeV
575 GeV
460 GeV

Most of the
collected data are
at $\sqrt{s} = 318$ GeV

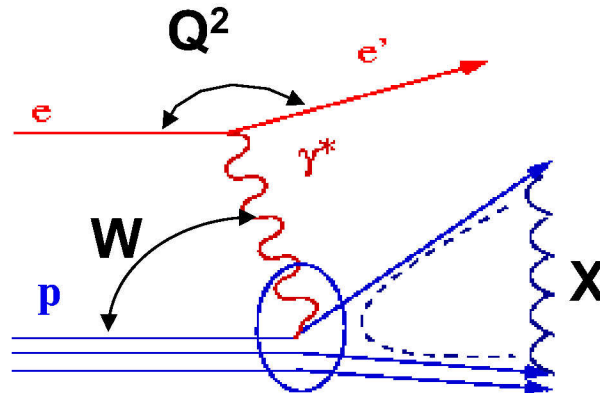
$\sim 0.5 \text{ fb}^{-1}$ per experiment collected by H1 and ZEUS
Final analyses of HERA data are underway



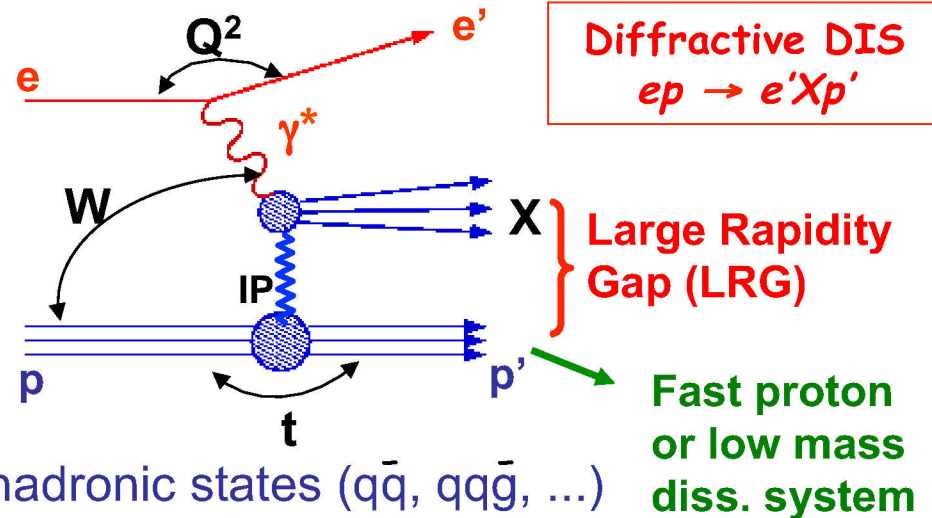
Diffraction at HERA



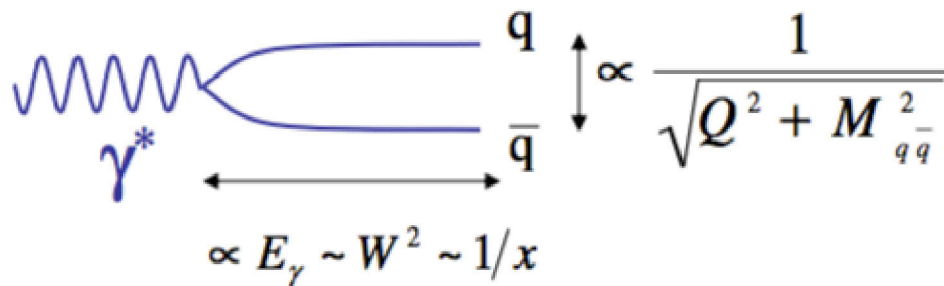
Standard DIS
 $ep \rightarrow e'X$



Diffractive DIS
 $ep \rightarrow e'Xp'$



Real and virtual photons can fluctuate in hadronic states ($q\bar{q}$, $qq\bar{q}$, ...)



(as seen in the proton rest-frame)

Q^2 = photon virtuality

x = Bjorken scaling variable

✓ Lifetime of $q\bar{q}$ dipole (hadron!)
long because of large Lorentz boost
($E_\gamma \sim 50$ TeV at HERA)

→ Dipole interacts hadronically with the proton

✓ Transverse size proportional to $1/\sqrt{(Q^2 + M_{q\bar{q}}^2)}$

→ If dipole size is small, its interaction with the proton **can be treated perturbatively**

Diffractive events contribute up to 15% of the inclusive DIS cross section



$\Psi(2S)/J/\Psi(1S)$: HIKT calculation



[J. Hüfner et al., Phys. Rev. D 62, 094022 (2000)]

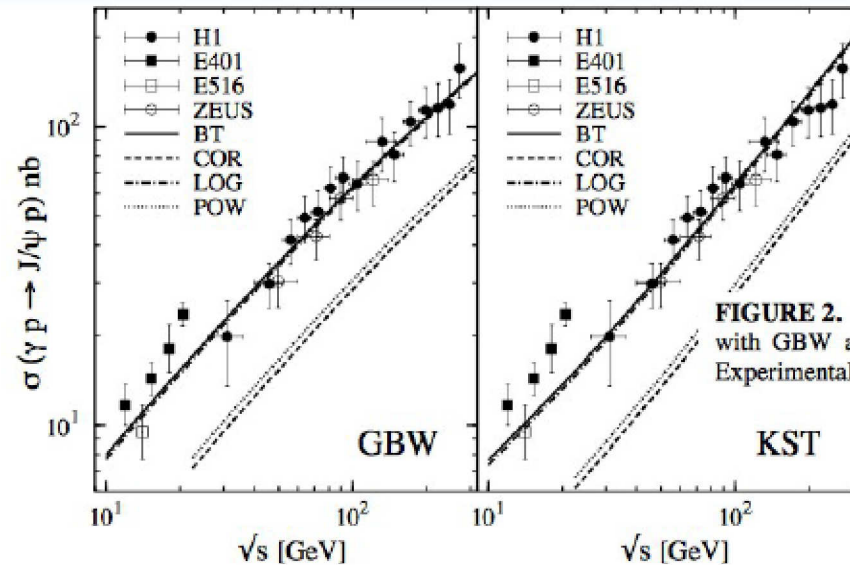
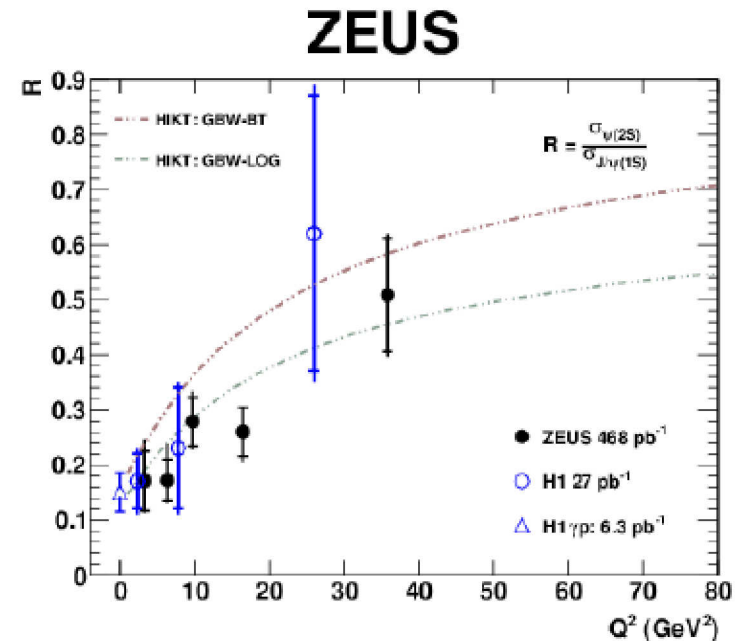


FIGURE 2. Integrated cross section for elastic photoproduction with real photons ($Q^2 = 0$) calculate with GBW and KST dipole cross sections and for four potentials to generate J/ψ wave function. Experimental data points from the H1 [20], E401 [21], E516 [22] and ZEUS [23] experiments.

- Two parameterization of the dipole cross section (GBW and KST)
- Four phenomenological potentials of the wave functions:
 - BT, LOG with $m_c \approx 1.5 \text{ GeV}$
 - COR and POW with $m_c \approx 1.8 \text{ GeV}$

→ BT predictions larger than the data



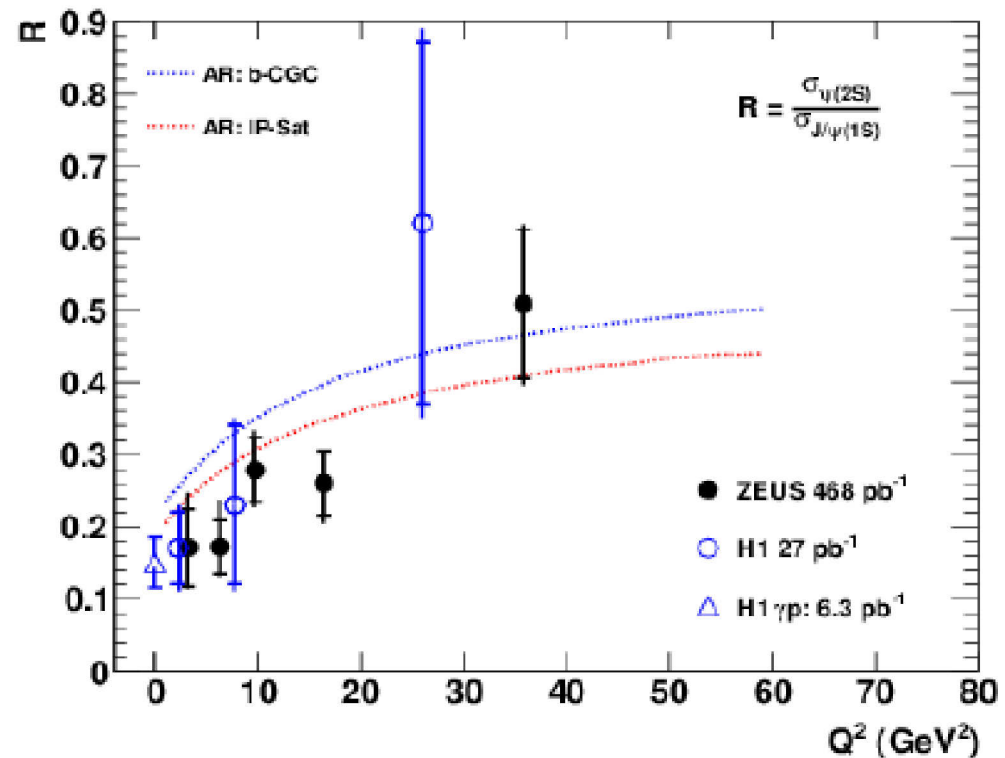


$\Psi(2S)/J/\Psi(1S)$: AR calculation



[N. Armesto and A. H. Reazeian, Phys. Rev. D 90, 054003 (2014)]

ZEUS

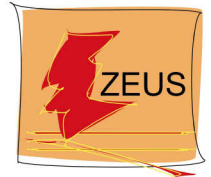


- Impact-parameter-dependent Color Glass Condensate model (b-CGC) or Saturation model (IP-Sat)

→ IP-Sat prediction about 30% lower and gives a better description of the data

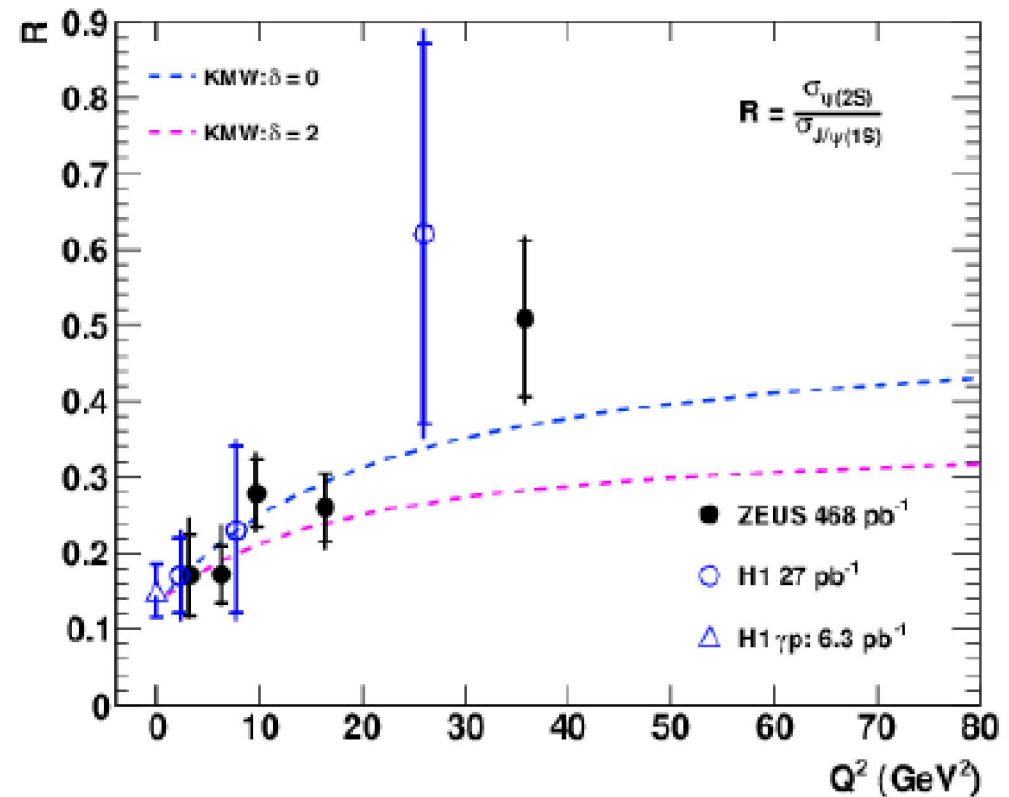


$\Psi(2S)/J/\Psi(1S)$: KMW calculation



[H. Kowalski et al., Phys. Rev. D 74, 074016 (2006)]

ZEUS



- Assumes universality of production of vector quarkonia states.
Parameter δ depends on the choice of the charmonium wave function

→ $\delta = 0$ provides a better description of the data

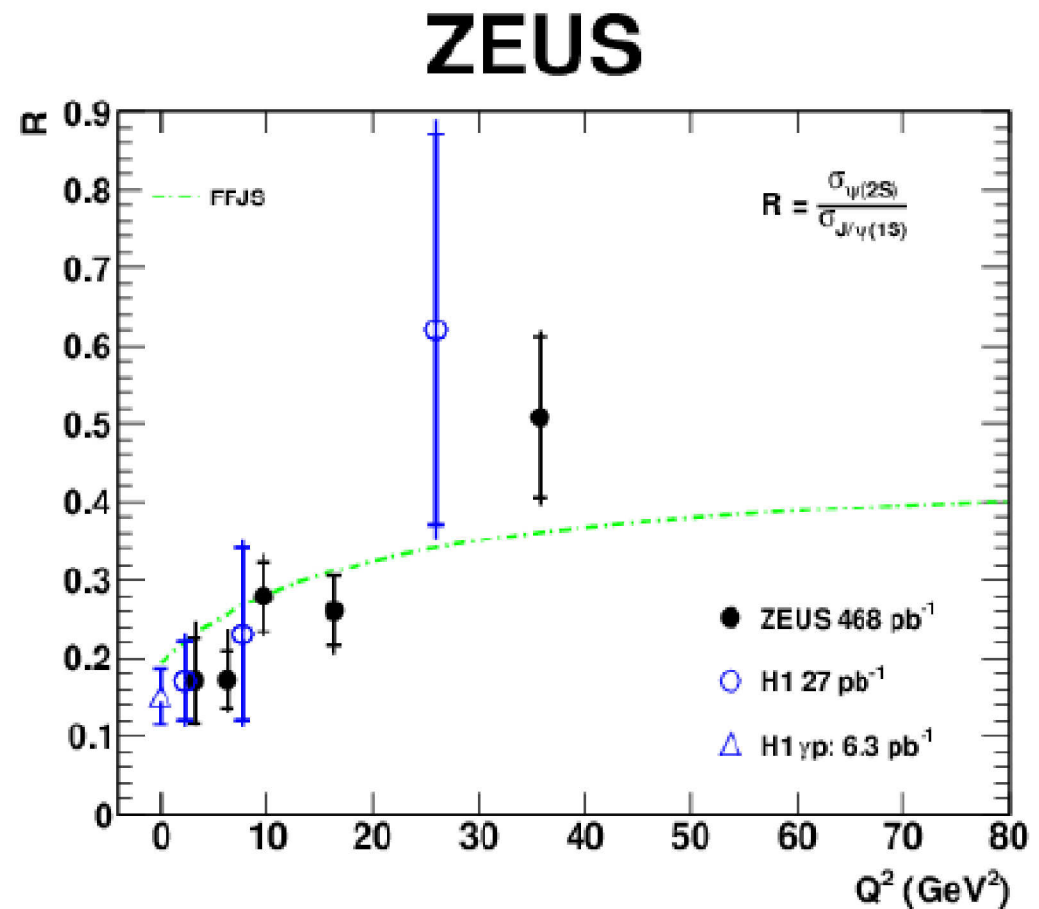


$\Psi(2S)/J/\Psi(1S)$: FFJS calculation



[S. Fazio et al., Phys. Rev. D 90, 016007 (2014)]

- Two-component Pomeron model



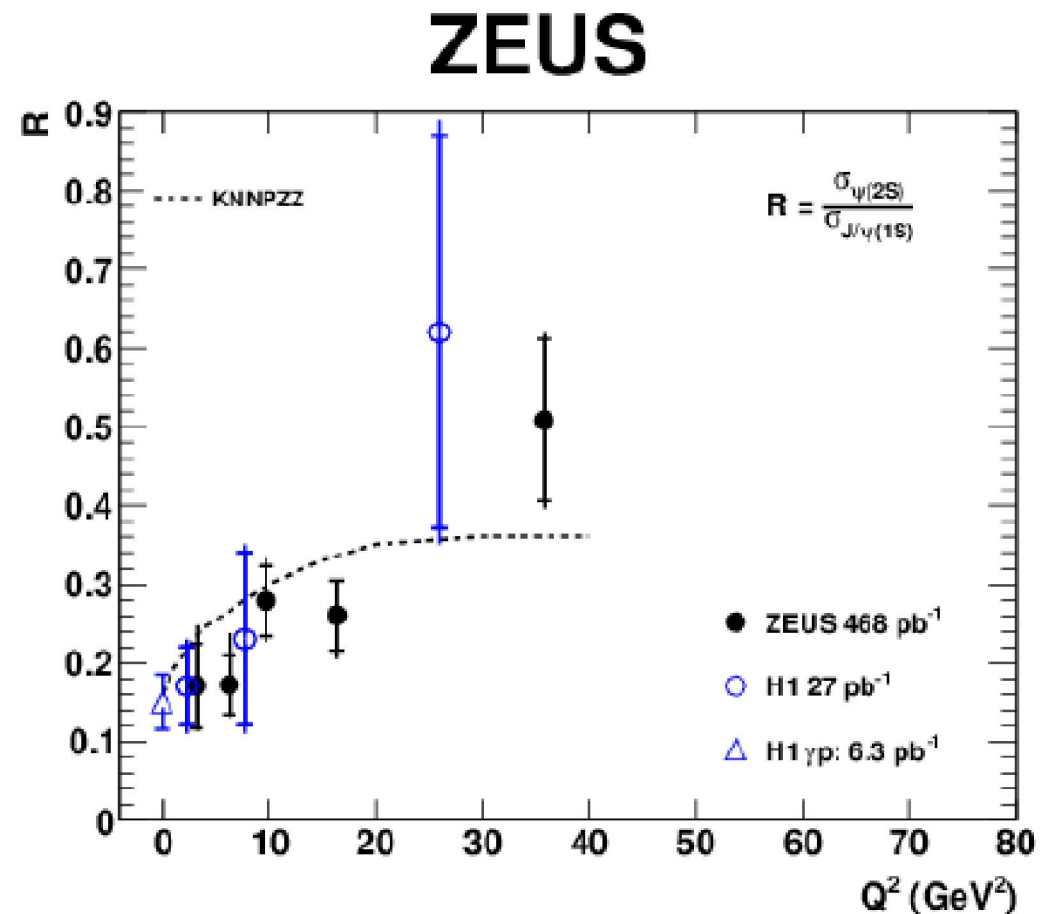


$\Psi(2S)/J/\Psi(1S)$: KNNPZZ calculation



[B. Kopeliovich et al., Phys. Rev D 44, 3466 (1991),
B. Kopeliovich et al., Phys. Lett. B 324, 469 (1994)
J. Nemchik et al., Phys. Lett. B 341, 228 (1994)
J. Nemchik et al., J. Exp. Theor. Phys. 86, 1054 (1998)]

- Generalized BFKL equation for $c\bar{c}$ dipole cross section



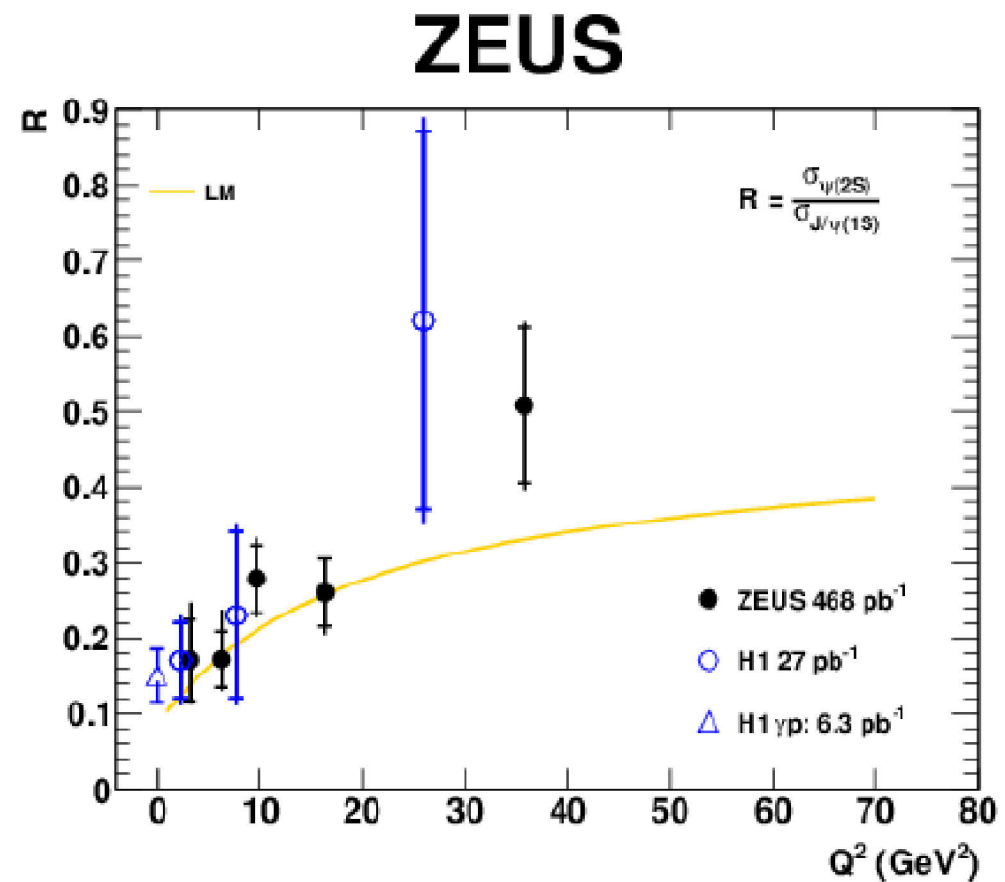


$\Psi(2S)/J/\Psi(1S)$: LM calculation



[T. Lappi and H. Mäntysaari, Phys. Rev. C 83, 065202 (2011),
T. Lappi and H. Mäntysaari, PoS (DIS2014), 069 (2014)]

- BFKL equation + IP-Sat mode

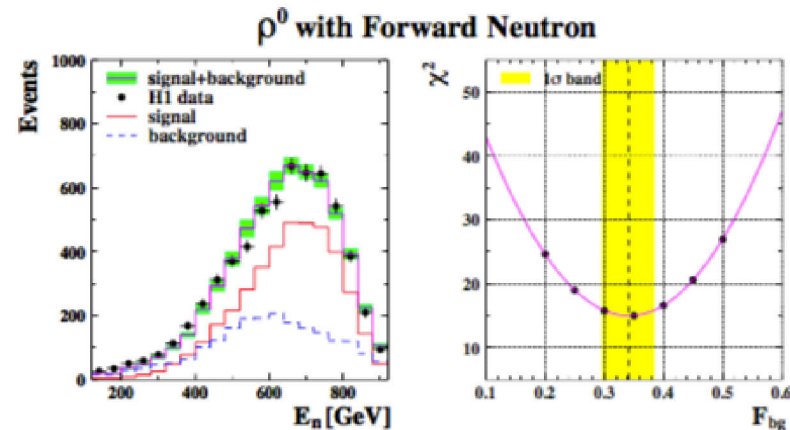




Exclusive ρ^0 photoproduction with a LN



S/B decomposition and control plots :

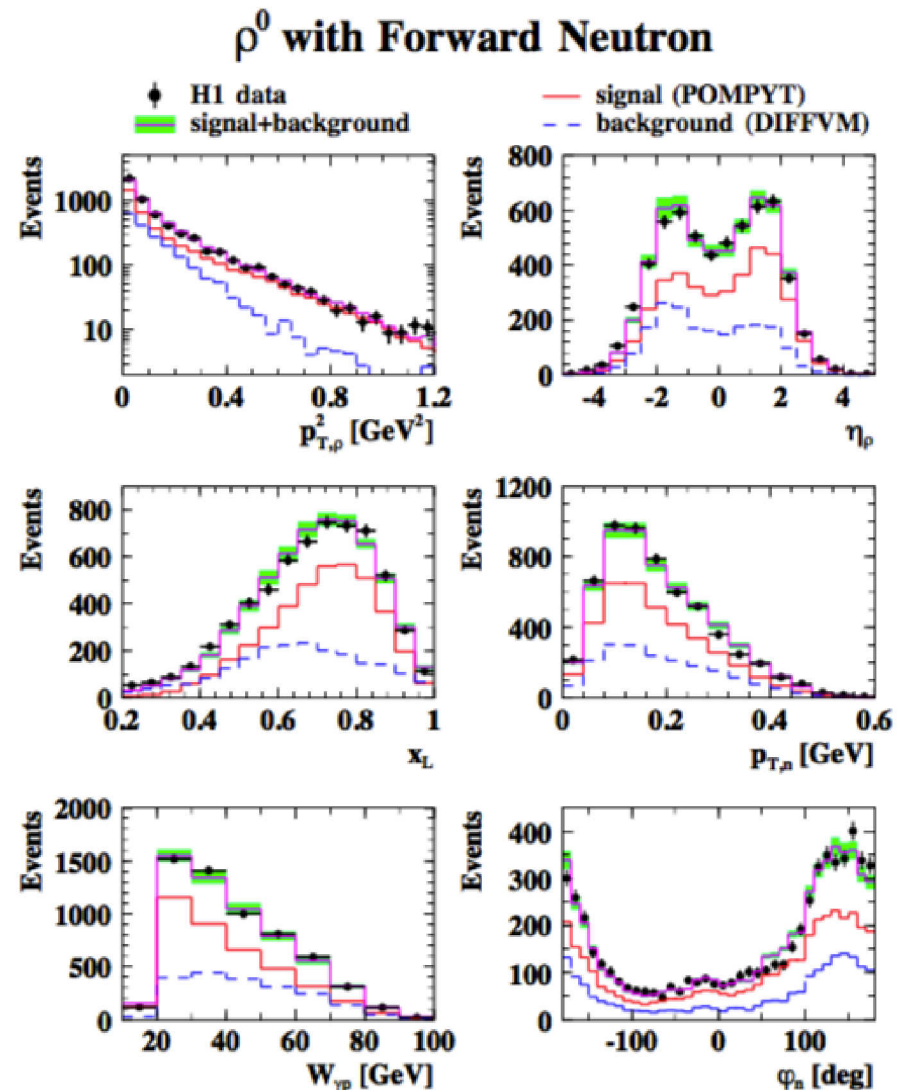


E_n

$B/(S+B)$

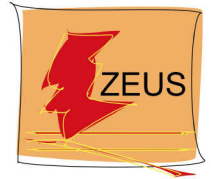
$$F_{bg} = 0.34 \pm 0.05$$

Data points are shown with statistical errors only;
green band represents estimated background fraction uncertainty

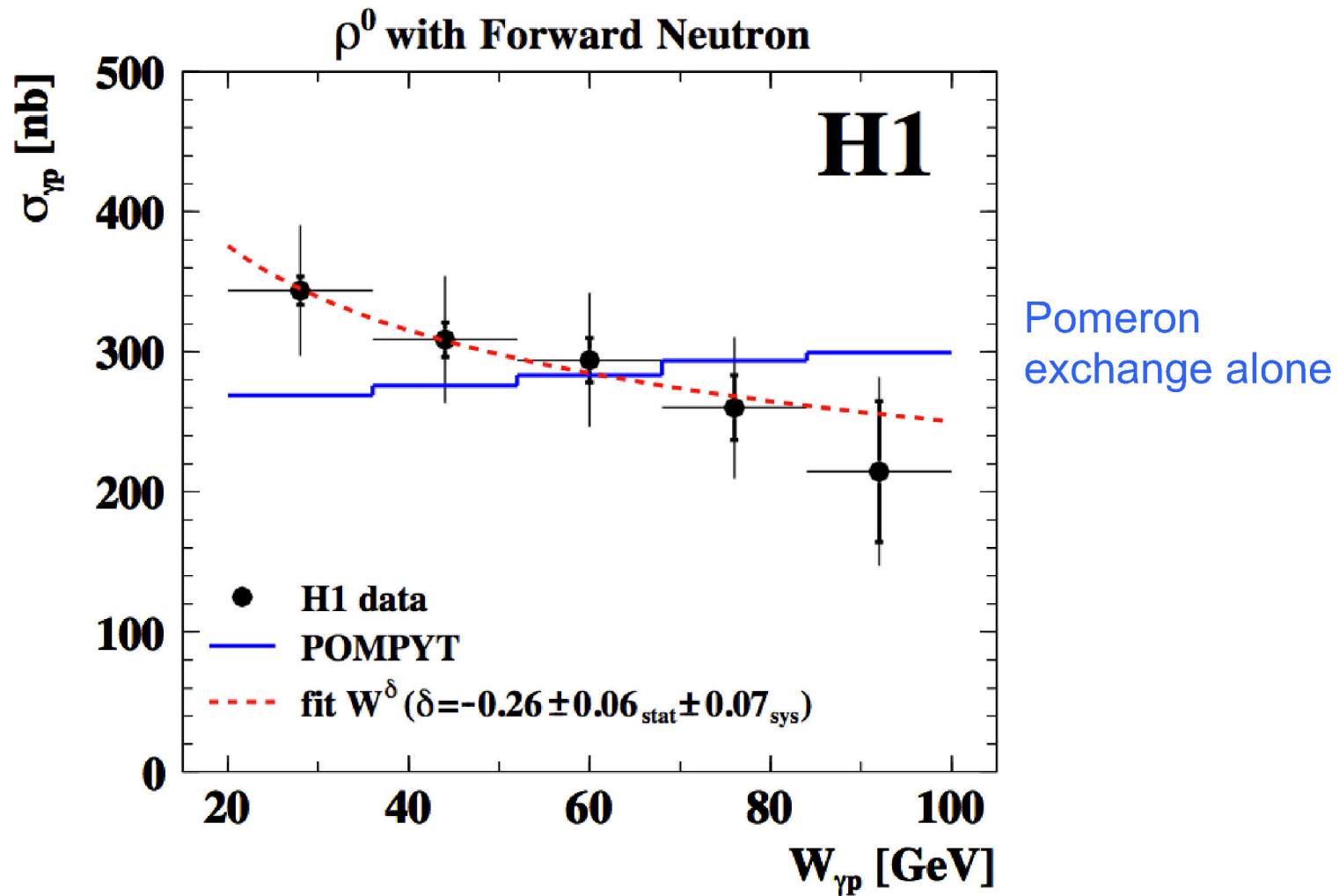




Exclusive ρ^0 photoproduction with a LN



Energy dependence :

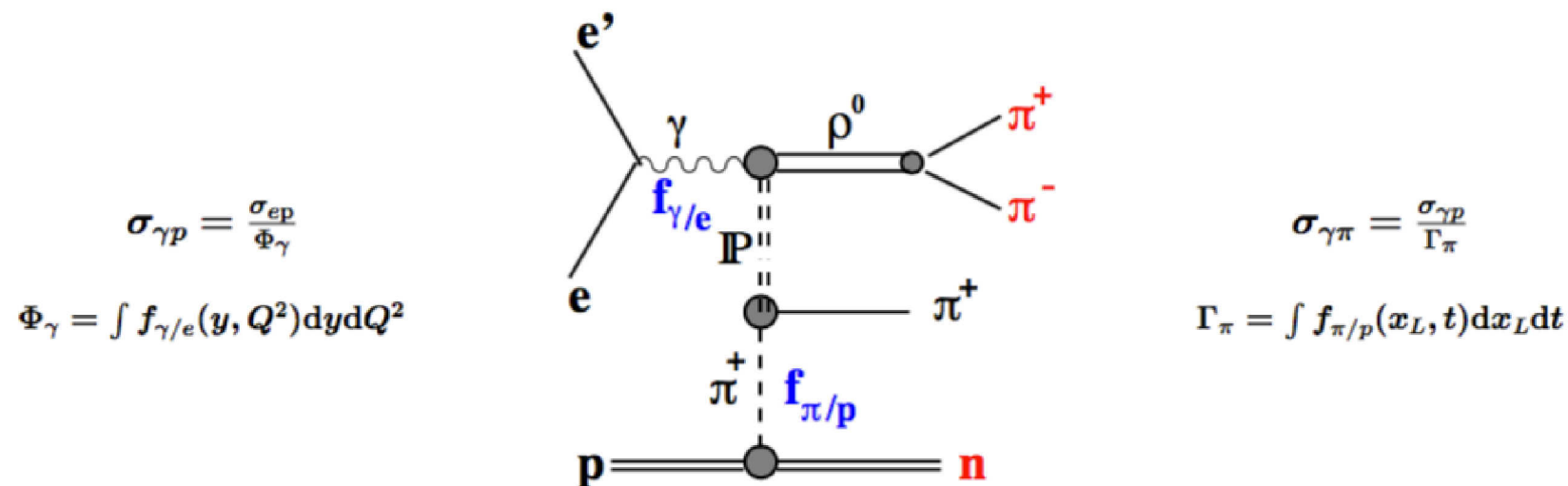




Exclusive ρ^0 photoproduction with a LN



Cross section definitions :



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

OPE:
$$f_{\pi/p}(x_L, t) = \frac{1}{2\pi} \frac{g_{p\pi N}^2}{4\pi} (1-x_L) \frac{-t}{(m_\pi^2 - t)^2} \exp[-R_{\pi n}^2 \frac{m_\pi^2 - t}{1-x_L}]$$