Vector meson production at HERA

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On behalf of the H1 and ZEUS Collaborations

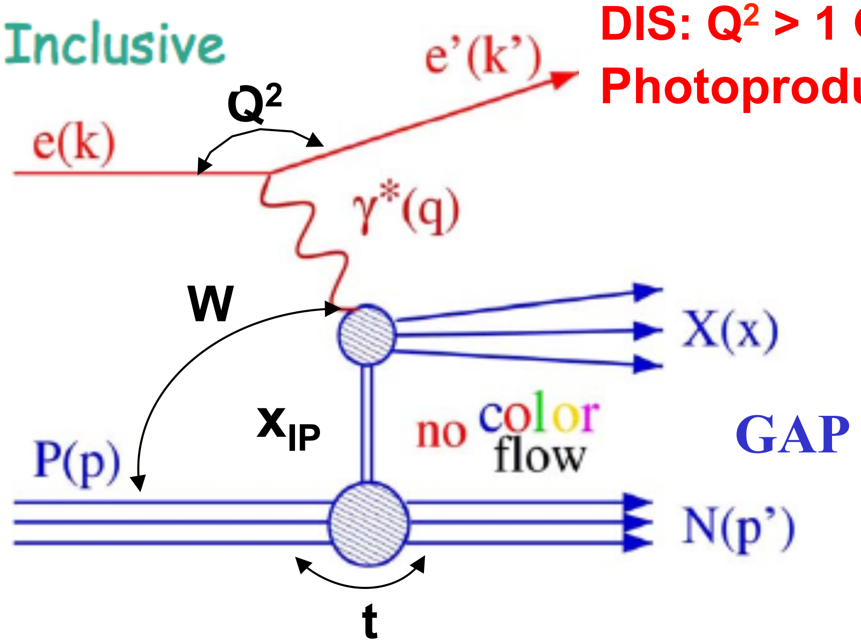
Outline:

- 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

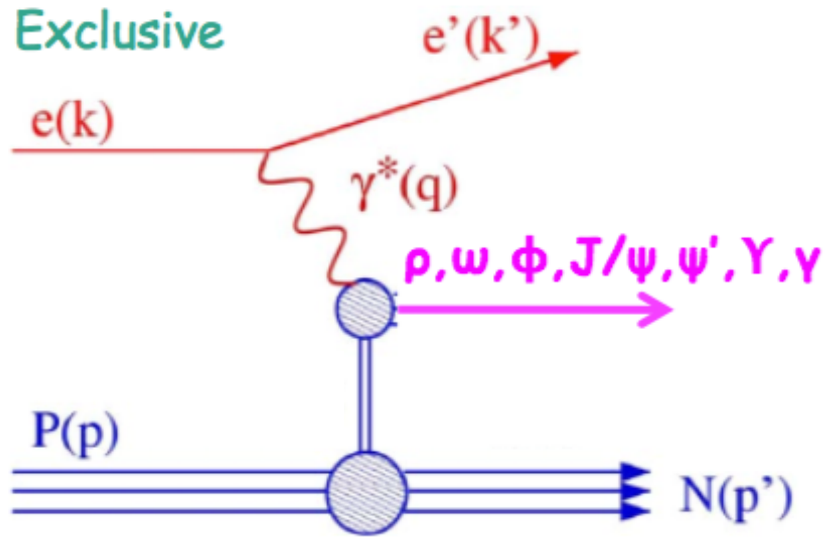
DIS: $Q^2 > 1$ GeV^2
Photoproduction (γp): $Q^2 \sim 0$



Q^2 = virtuality of exchanged photon

W = invariant mass of γ^*-p system

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

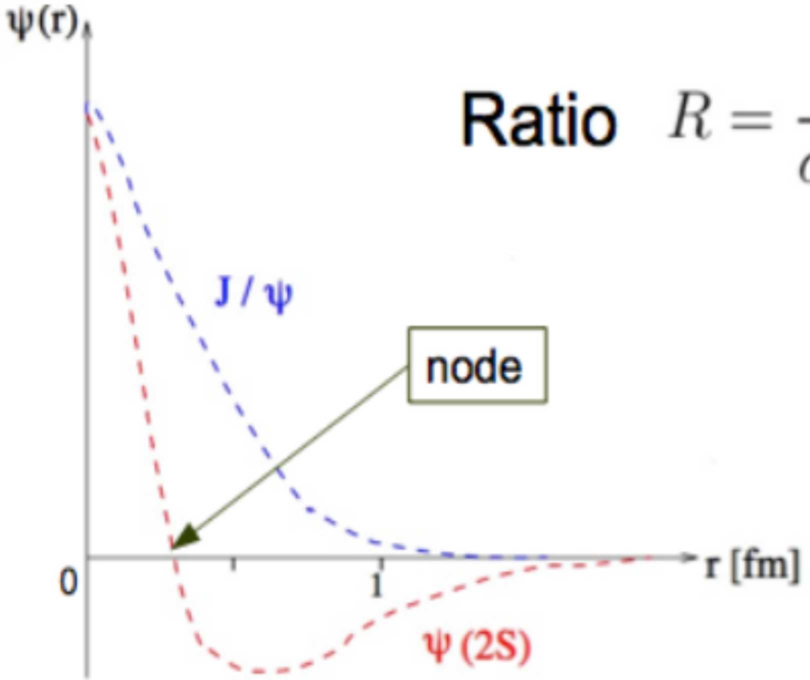


- N = proton -> Elastic events
- N = proton dissociative system

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

Motivation :

Ratio $R = \dfrac{\sigma_{\gamma p \to \psi(2S) p}}{\sigma_{\gamma p \to J/\psi\, p}}$



ψ(2S) wave function different from J/ψ(1S) wave function:

ratio sensitive to radial wave function of charmonium

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

Ψ(2S)/J/Ψ(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}**

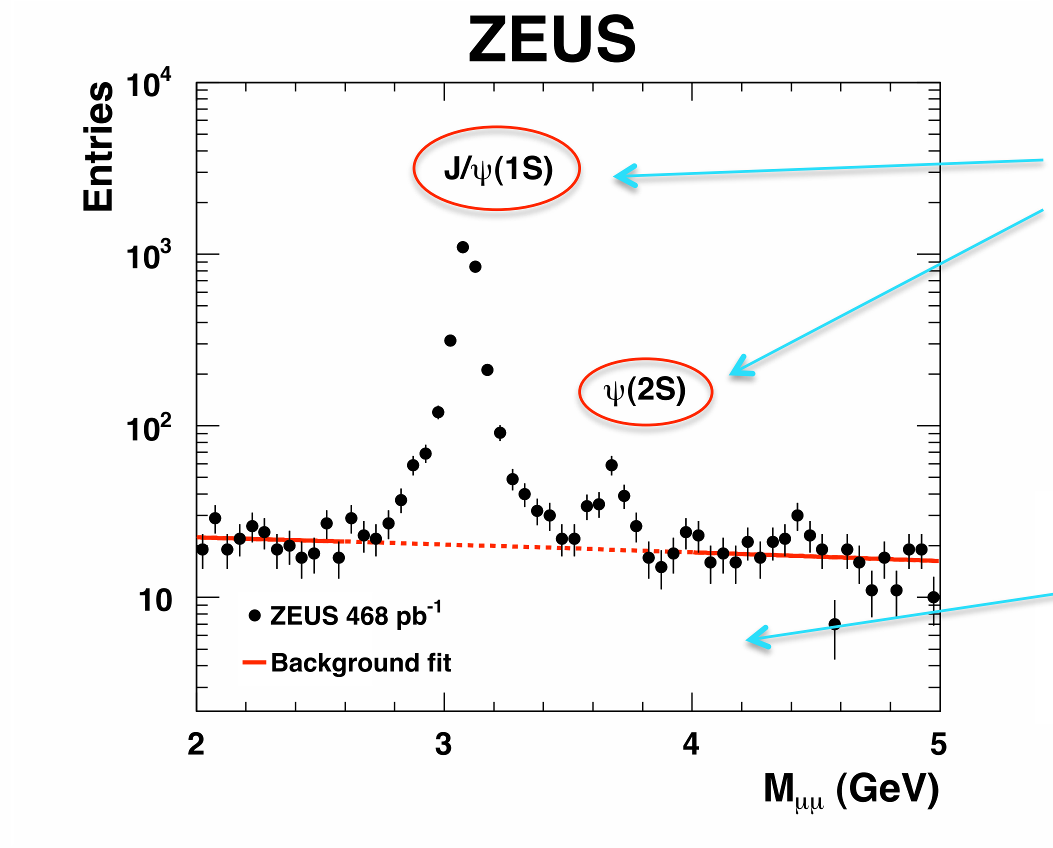
MC :
- Signal – exclusive VM production with DIFFVM
- Background – Bethe-Heither $\mu^+\mu^-$ production with GRAPE

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 background

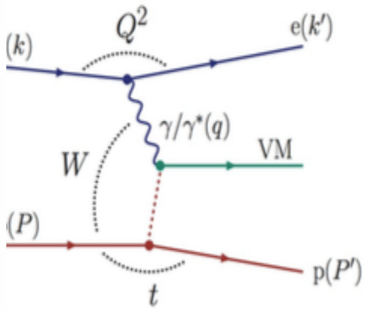
$30 < W < 210$ GeV
$2 < Q^2 < 80$ GeV^2
$|t| < 1$ GeV^2

Ψ(2S)/J/Ψ(1S) in exclusive DIS

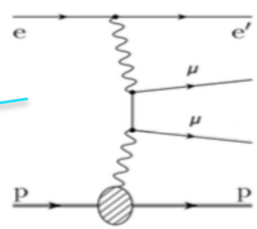
Background subtraction :



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



Bethe-Heither



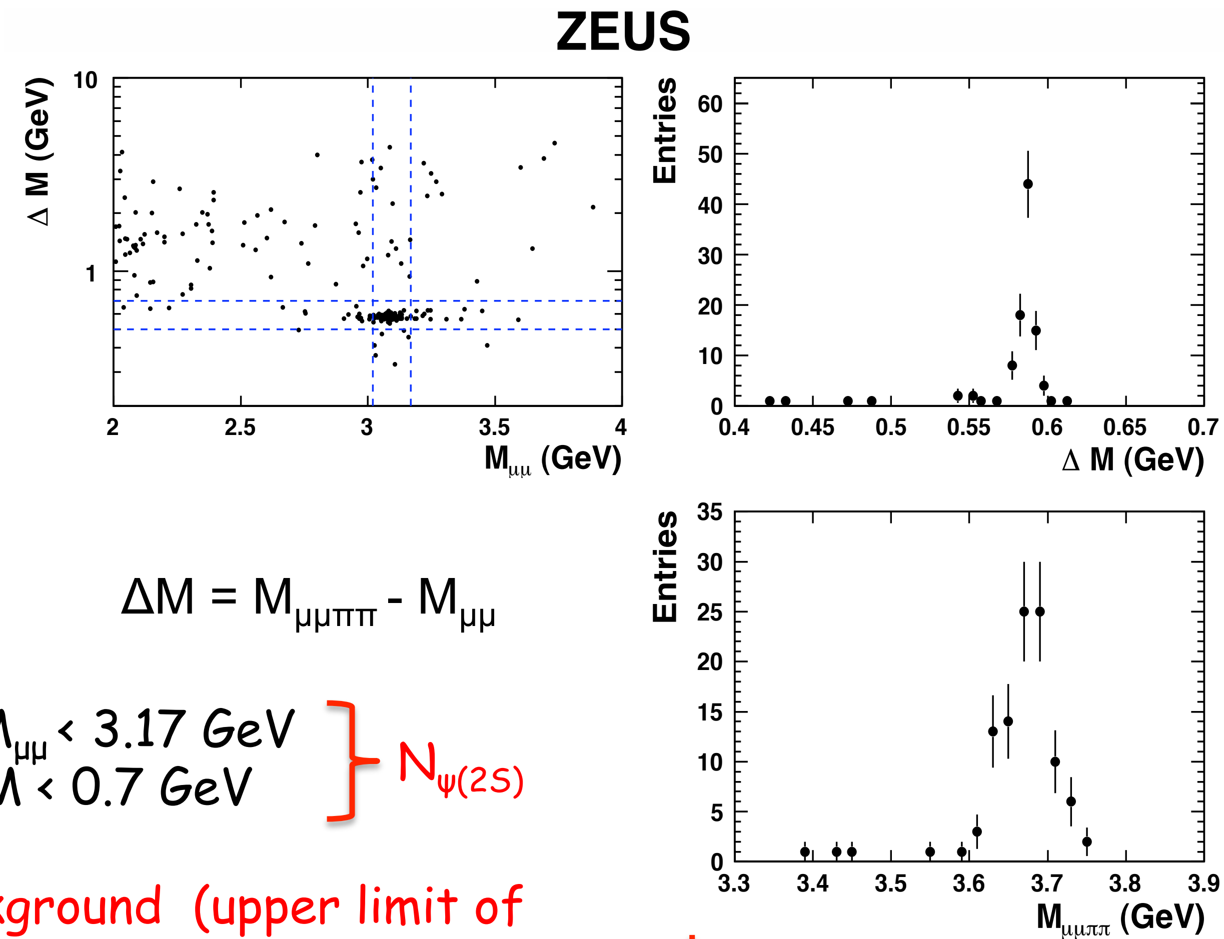
Dimuon background fitted with a straight line for
$2 < M_{\mu+\mu-} < 2.62$ GeV and
$4.05 < M_{\mu+\mu-} < 5$ GeV

Number of events above background :
$3.59 < M_{\mu+\mu-} < 3.79$ GeV → $N_{\psi(2S)}$
$3.02 < M_{\mu+\mu-} < 3.17$ GeV → $N_{J/\psi}$

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

Background subtraction :

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



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

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

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

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 :

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

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

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

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

BR[ψ(2S) → J/ψ ππ] = (33.6±0.4)%

BR[ψ(2S) → μμ] = (7.7±0.8)x10^{-3}%

BR[J/ψ → μμ] = (5.93±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}	$0.26 \pm 0.02^{+0.01}_{-0.01}$
$R_{\psi(2S)}$	$1.1 \pm 0.2^{+0.2}_{-0.1}$

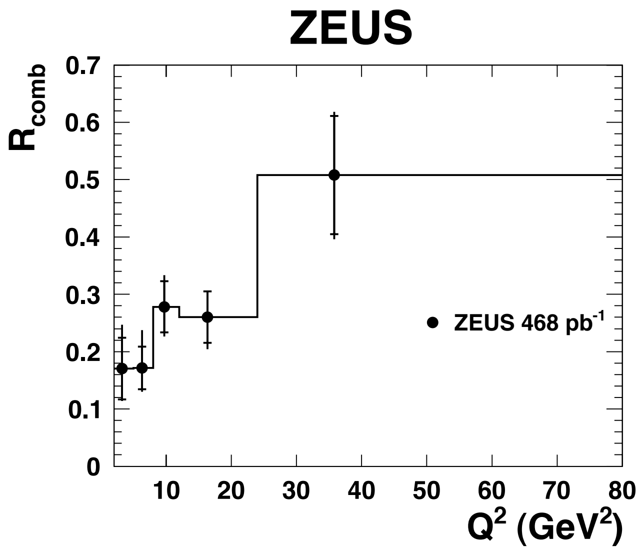
30 < W < 210 GeV
2 < Q^2 < 80 GeV^2
|t| < 1 GeV^2

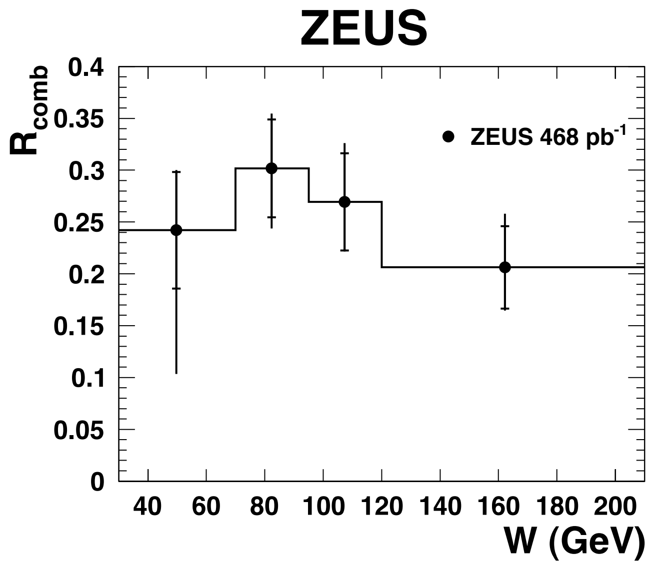
$$R_{\psi(2S)} = R_{J/\psi\,\pi\pi}/R_{\mu\mu}$$

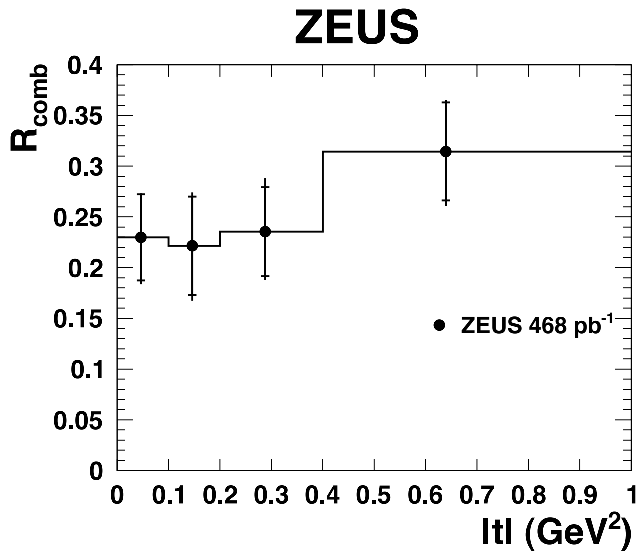
Q^2 (GeV^2)	$R_{J/\psi\pi\pi}$	$R_{\mu\mu}$	R_{comb}	$R_{\psi(2S)}$
$2-5$	$0.21 \pm 0.07^{+0.04}_{-0.03}$	$0.10 \pm 0.09^{+0.09}_{-0.09}$	$0.17 \pm 0.05^{+0.05}_{-0.02}$	–
$5-8$	$0.19 \pm 0.05^{+0.02}_{-0.02}$	$0.13 \pm 0.06^{+0.12}_{-0.03}$	$0.17 \pm 0.04^{+0.05}_{-0.02}$	$1.5 \pm 0.8^{+0.4}_{-0.7}$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

Ψ(2S)/J/Ψ(1S) in exclusive DIS

Ratios vs Q^2, W and t





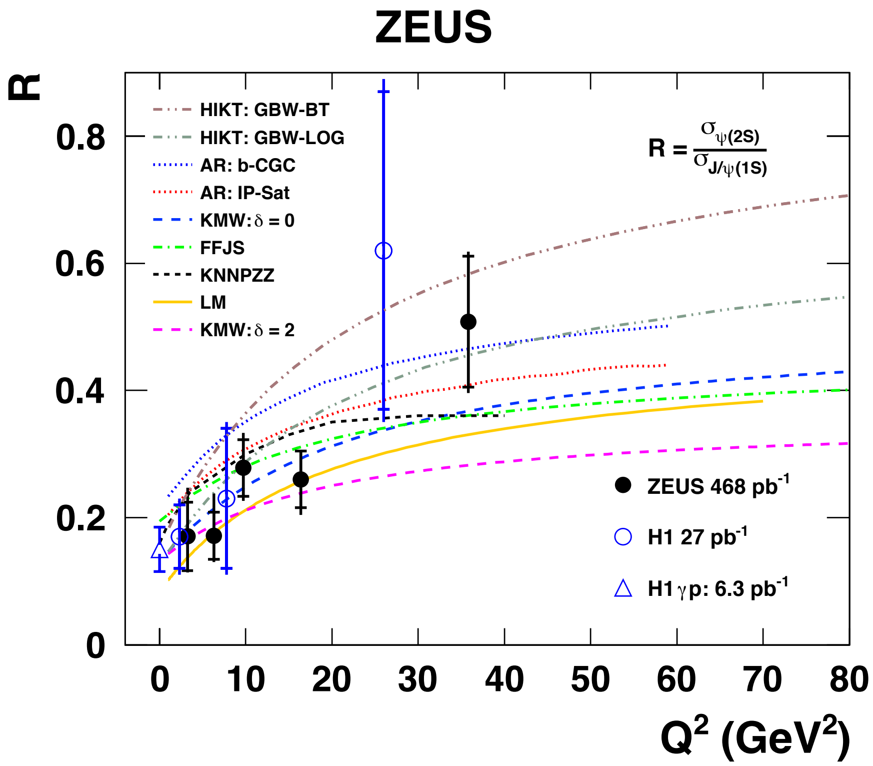


→ Increasing with Q^2

Independent of W and t

Ψ(2S)/J/Ψ(1S) in exclusive DIS

Comparison with H1 earlier measurement and with models



H1, EPJ C10 (1999) 373

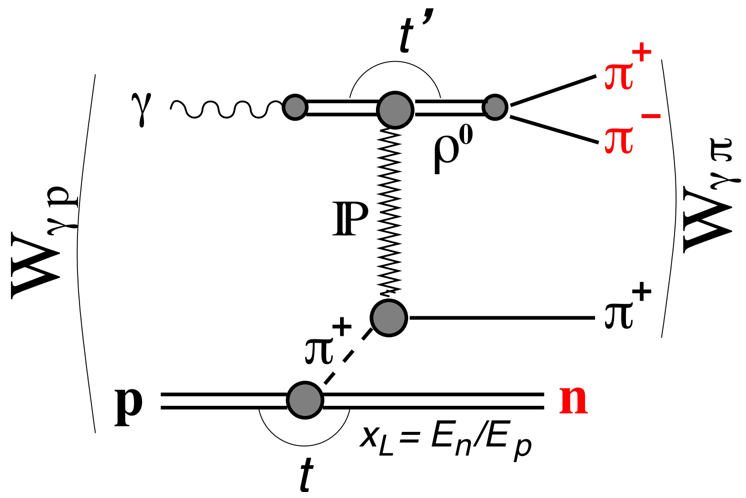
HIKT, Hüfner et al.: dipole model, dipole-proton constrained by inclusive DIS data
AR, Armesto and Rezaeian: impact parameter dependent CGC and IP-Sat model
KMW, Kowalski Motyka Watt: QCD description and universality of quarkonia production
FFJS, Fazio et al.: two component Pomeron model
KNNPZZ, Nemchik 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 ~ 24 GeV → **soft regime**

Regge framework most appropriate :
exchange of two Regge trajectories
in a Double Peripheral Process (DPP)

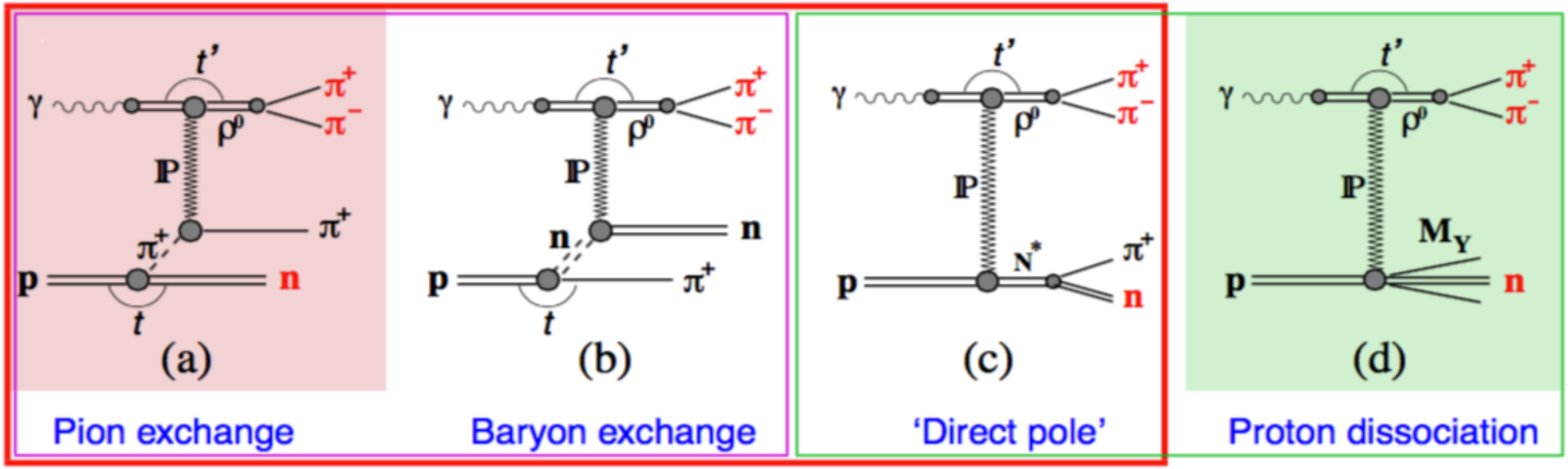
⟹ Constraints to pion flux models

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)

$\sigma(\gamma p \rightarrow \rho^0 n \pi^+) = |A_a + A_b + A_c|^2$ ⟹ **interference effects**

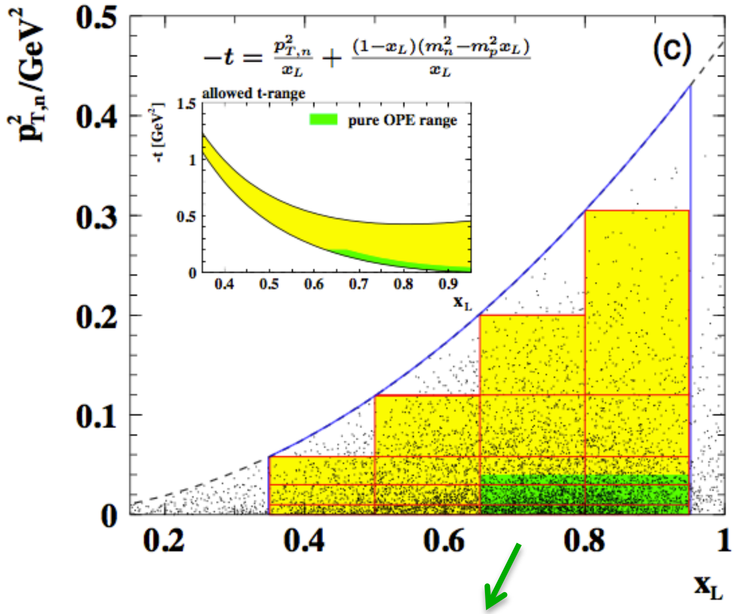
For large s and t' → 0 : pion exchange dominates

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 : <A> ~ 30%
and $p_{T,n} < x_L \cdot 0.69$ 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 GeV

Event selection :

- Scattered positron undetected : < Q^2 > = 0.04 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**)

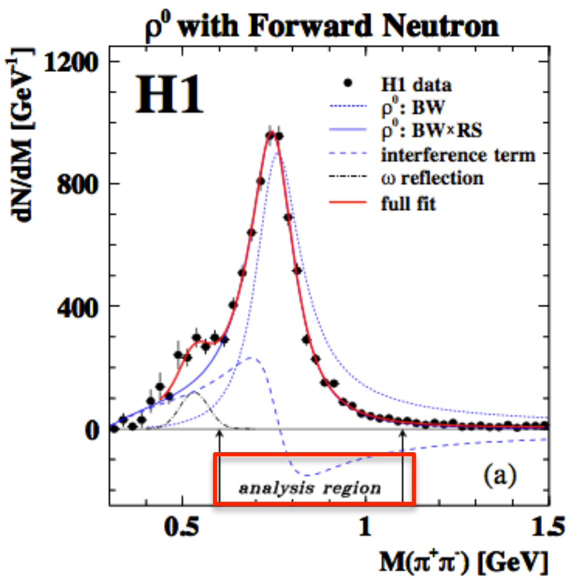
Data :
2006 – 2007 e^+p data, **integrated luminosity 1.16 pb^{-1}**

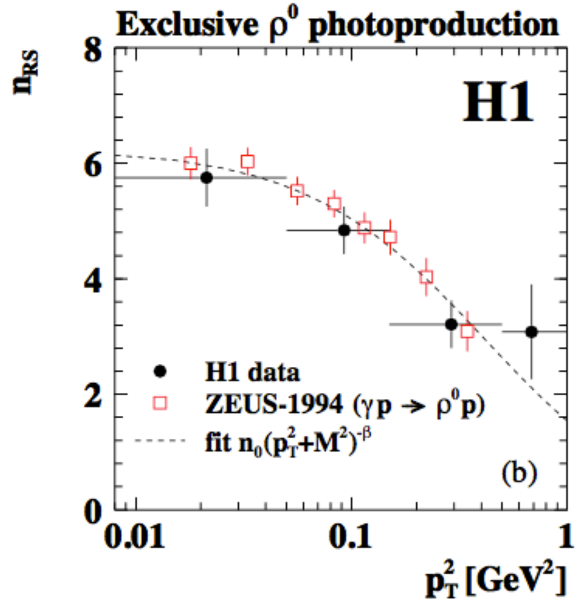
Exclusive ρ^0 photoproduction with a LN

ρ^0 measurement :

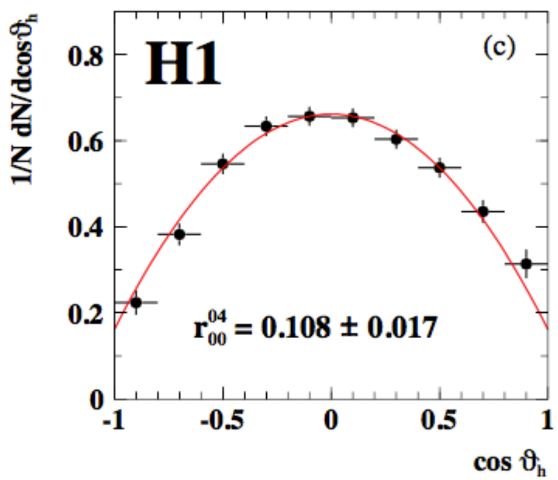
M = 764 ± 3 MeV

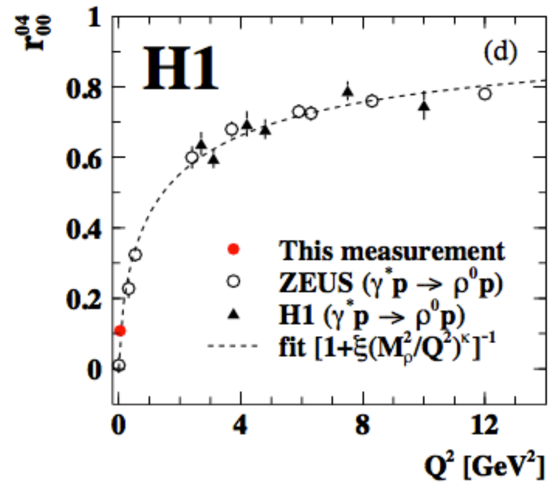
Γ = 155 ± 5 MeV





Ross-Stodolsky skewing par.



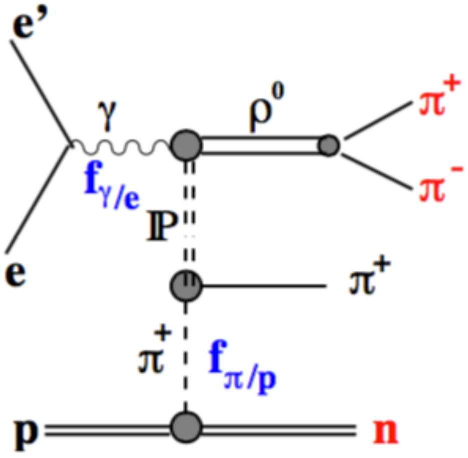


ξ = 1.85 ± 0.10

κ = 0.67 ± 0.03

Exclusive ρ^0 photoproduction with a LN

Cross section measurement :



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

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

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

γp

$\sigma(\gamma p \to \rho^0 n \pi^+) = 310 \pm 6(\text{stat}) \pm 45(\text{syst})$ nb — for $p_{T,n} < x_L \cdot 0.69$ GeV

$\sigma(\gamma p \to \rho^0 n \pi^+) = 130 \pm 3(\text{stat}) \pm 19(\text{syst})$ nb — for $p_{T,n} < 0.2$ GeV

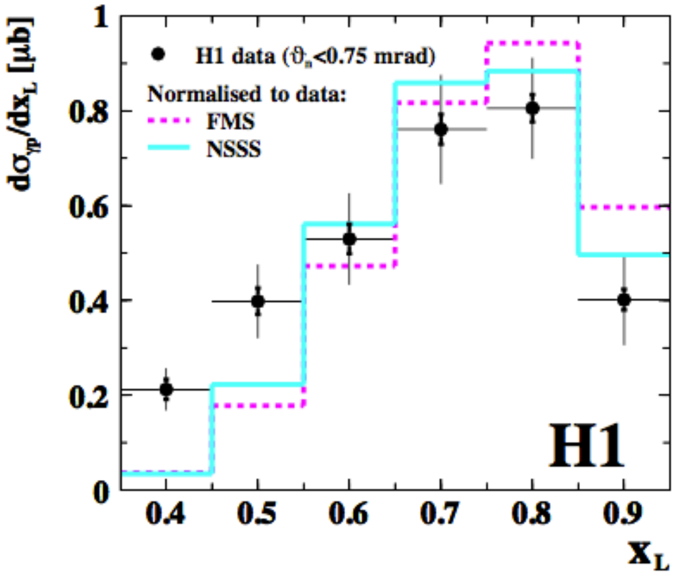
$\gamma\pi$

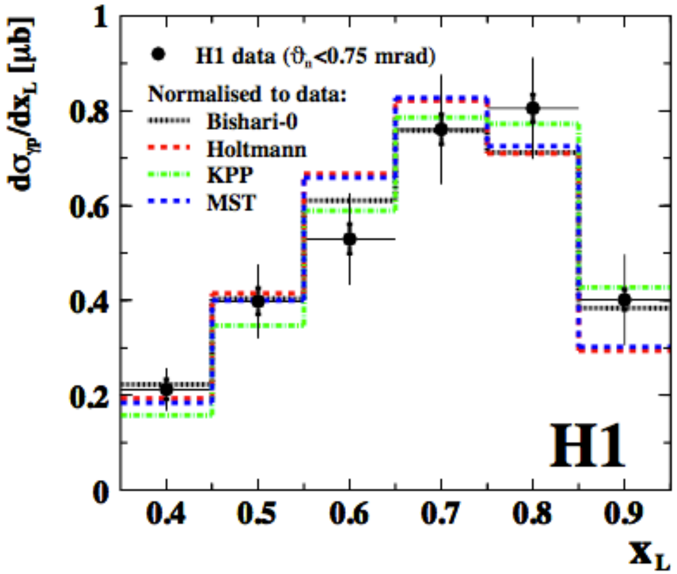
for $< W_{\gamma\pi} > = 24$ GeV

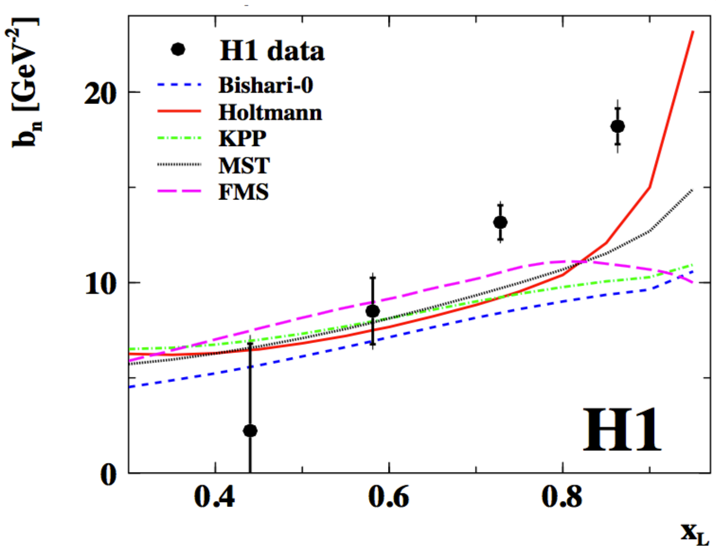
$\sigma_{el}(\gamma\pi^+ \to \rho^0\pi^+) = 2.33 \pm 0.34_{exp}\,(+0.47)(-0.40)_{model}$ μb

Exclusive ρ^0 photoproduction with a LN

Constraining pion flux :





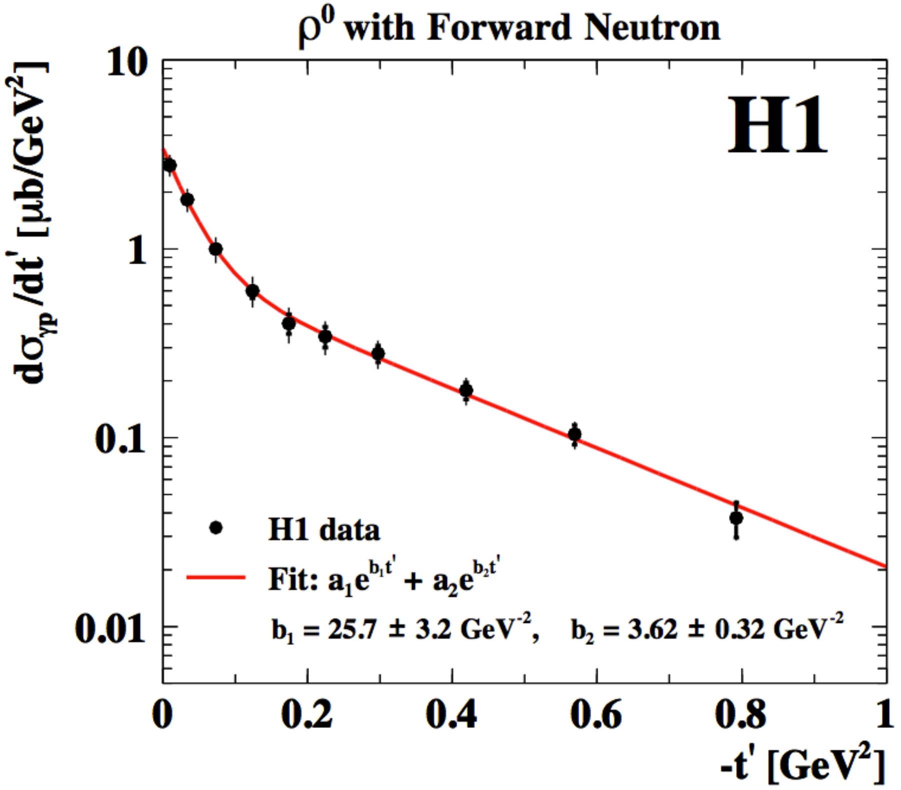


x_L distribution of the leading neutron generally **well described** – some pion fluxes disfavoured

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

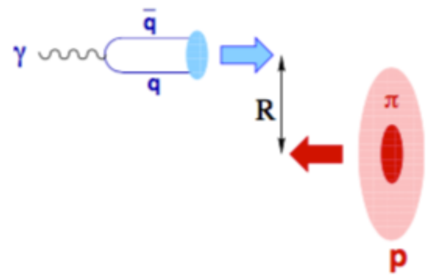
Exclusive ρ^0 photoproduction with a LN

ρ^0 slope :



Geometric interpretation :

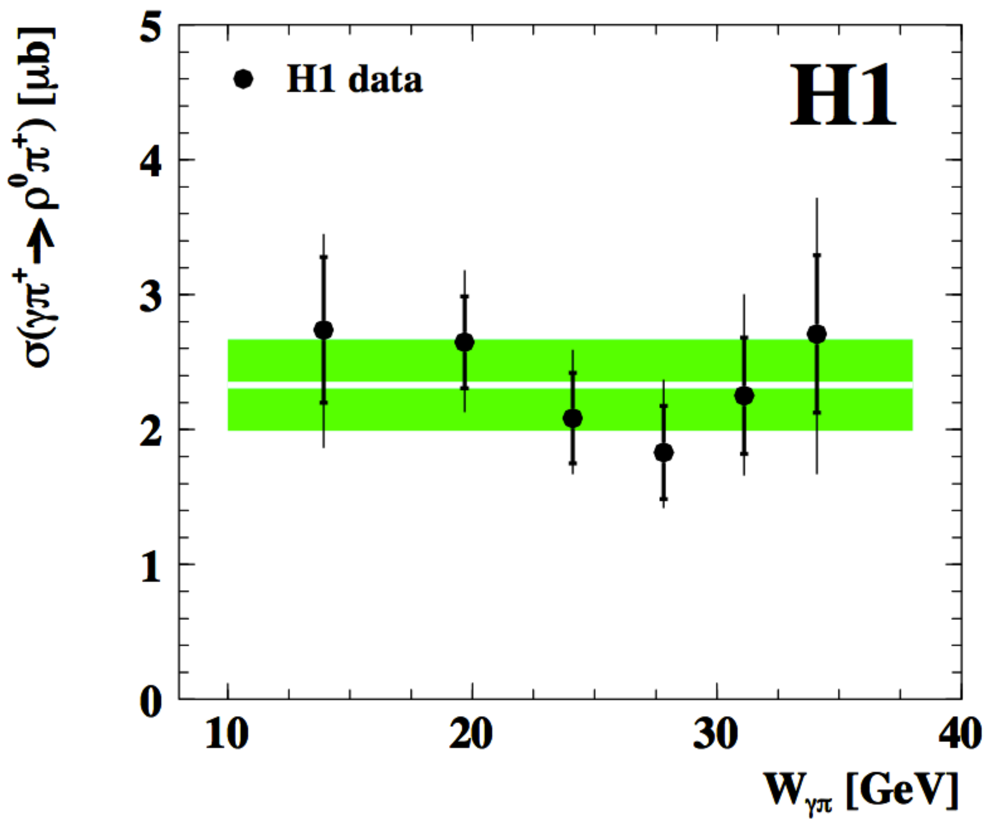
$< r^2 > = 2b_1 \cdot (\hbar c)^2 \sim 2\ \mathrm{fm}^2\ \ (\sim 1.6 R_p)^2$



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 <W> = 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 :

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

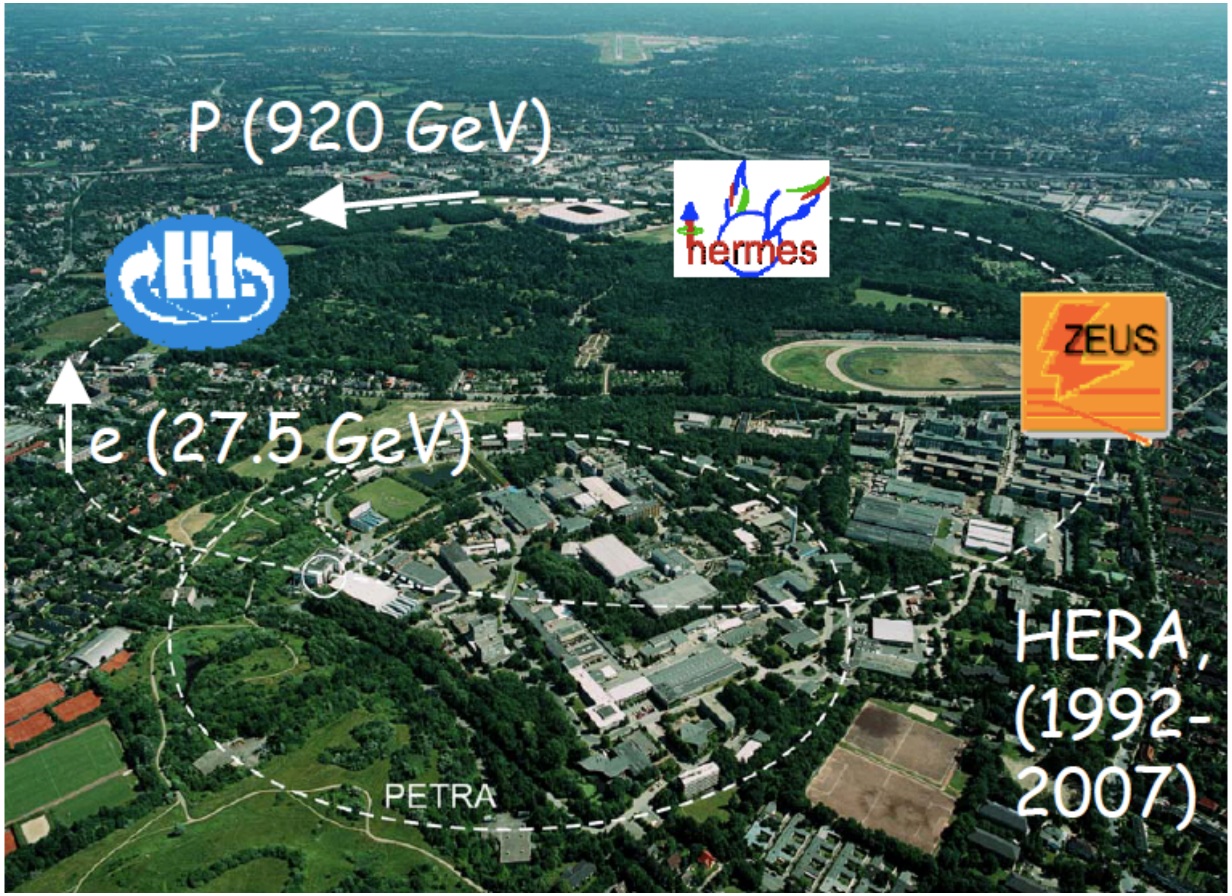
Summary

- **Cross section ratio ψ(2S)/J/ψ(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 dσ/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, $r_{el} = \sigma_{\gamma\pi}/\sigma_{\gamma p} = 0.25 \pm 0.06$, 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

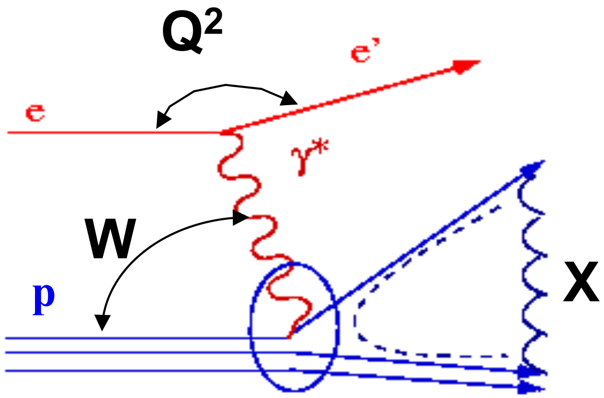
Most of the collected data are at $\sqrt{s}$ = 318 GeV

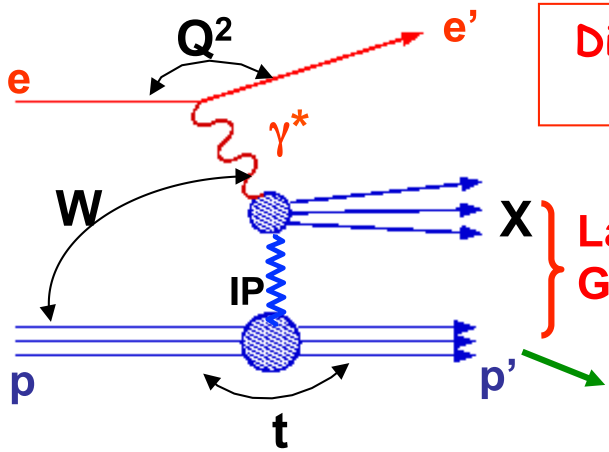
~0.5 fb^{-1} per experiment collected by H1 and ZEUS

Final analyses of HERA data are underway

Diffraction at HERA

Standard DIS
ep → e'X



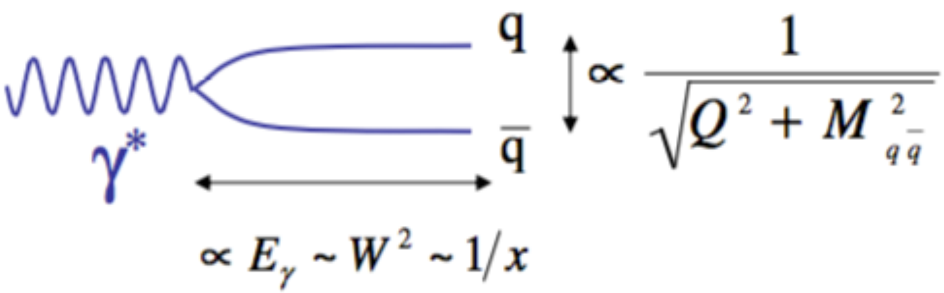


Diffractive DIS
ep → e'Xp'

Large Rapidity Gap (LRG)

Fast proton or low mass diss. system

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



(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_γ ~ 50 TeV at HERA)
→ Dipole interacts hadronically with the proton

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

Ψ(2S)/J/Ψ(1S) : HIKT calculation

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

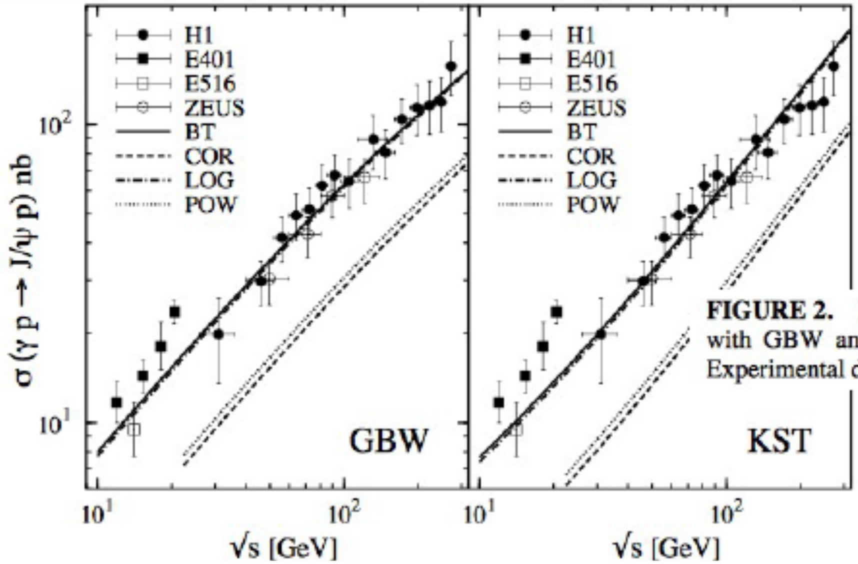
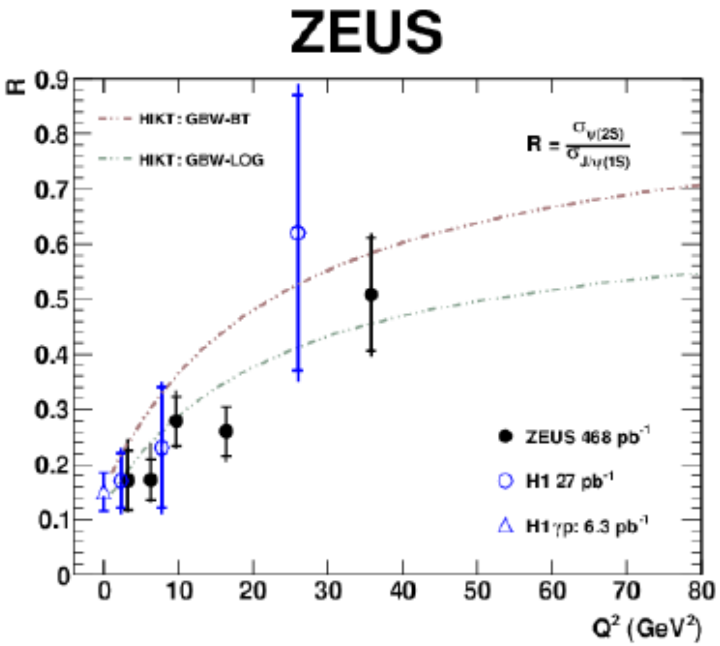


FIGURE 2. Integrated cross section for elastic photoproduction with real photons ($Q^2 = 0$) calculate with GBW and KST dipole cross sections and for four potentials to generate J/ψ wave function Experimental data points from the H1 [20], E401 [21], E516 [22] and ZEUS [23] experiments.



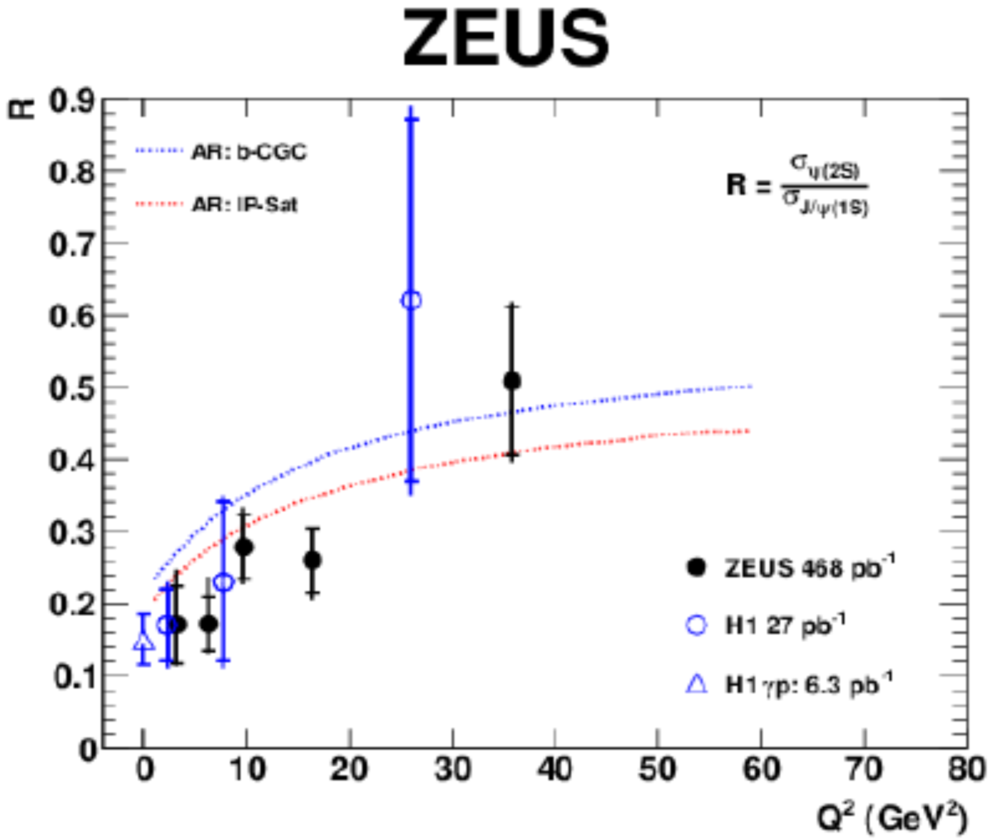
- Two parameterization of the dipole cross section (GBW and KST)

- Four phenomenological potentials of the wave functions:
  - BT, LOG with $m_c \approx 1.5$ GeV
  - COR and POW with $m_c \approx 1.8$ GeV

→ BT predictions larger than the data

Ψ(2S)/J/Ψ(1S) : AR calculation

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

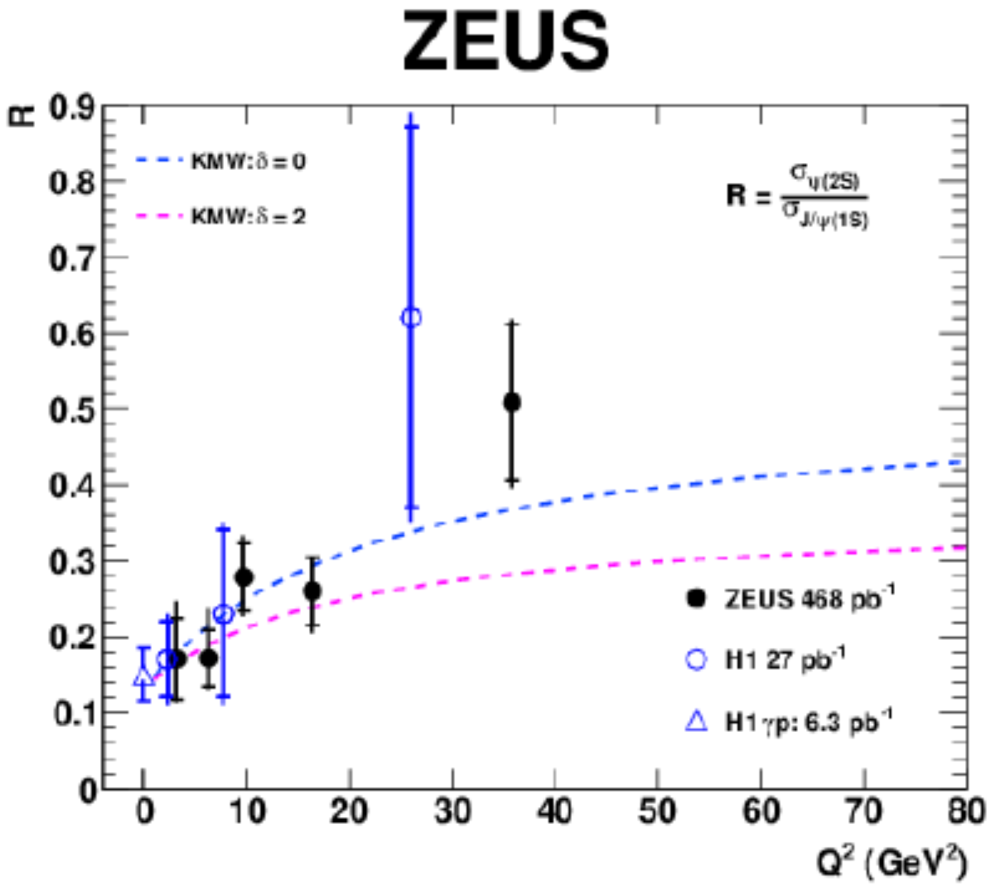


- Impact-parameter-dependent Color Glass Condensate model (b-CGC) or Saturation model (IP-Sat)

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

Ψ(2S)/J/Ψ(1S) : KMW calculation

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



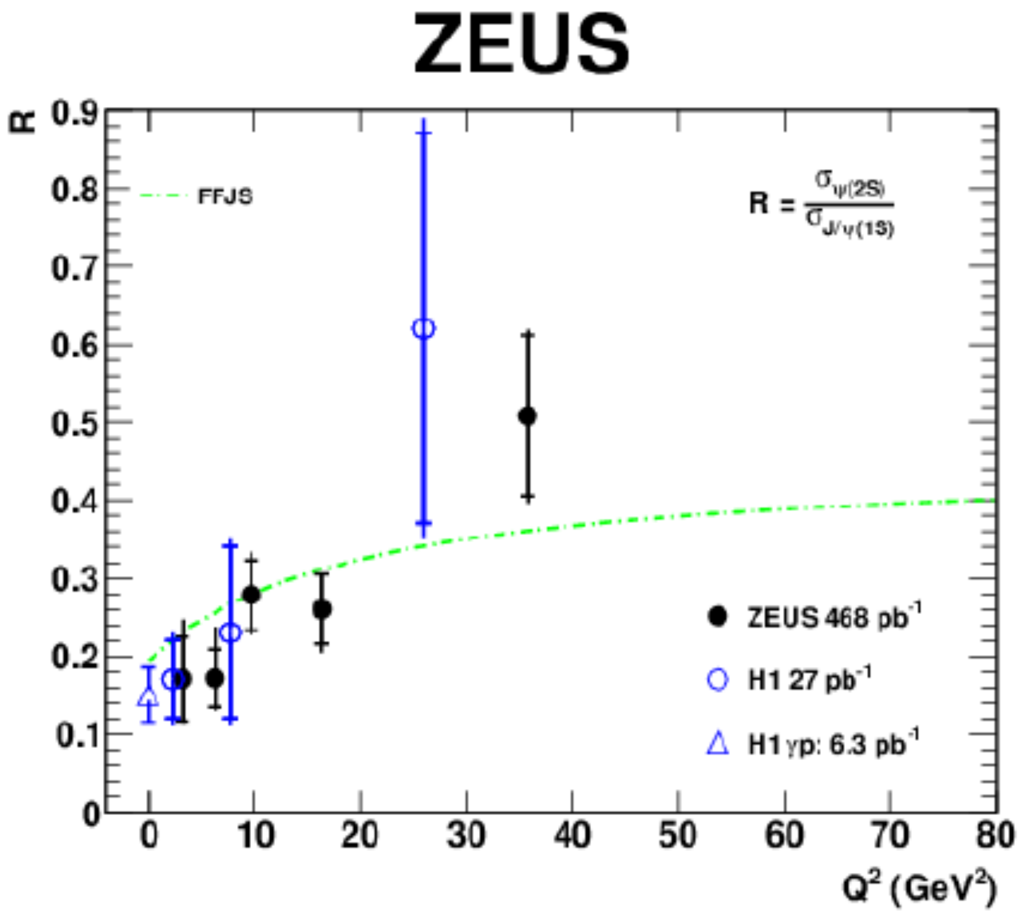
- Assumes universality of production of vector quarkonia states. Parameter δ depends on the choice of the charmonium wave function

→ δ = 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)]

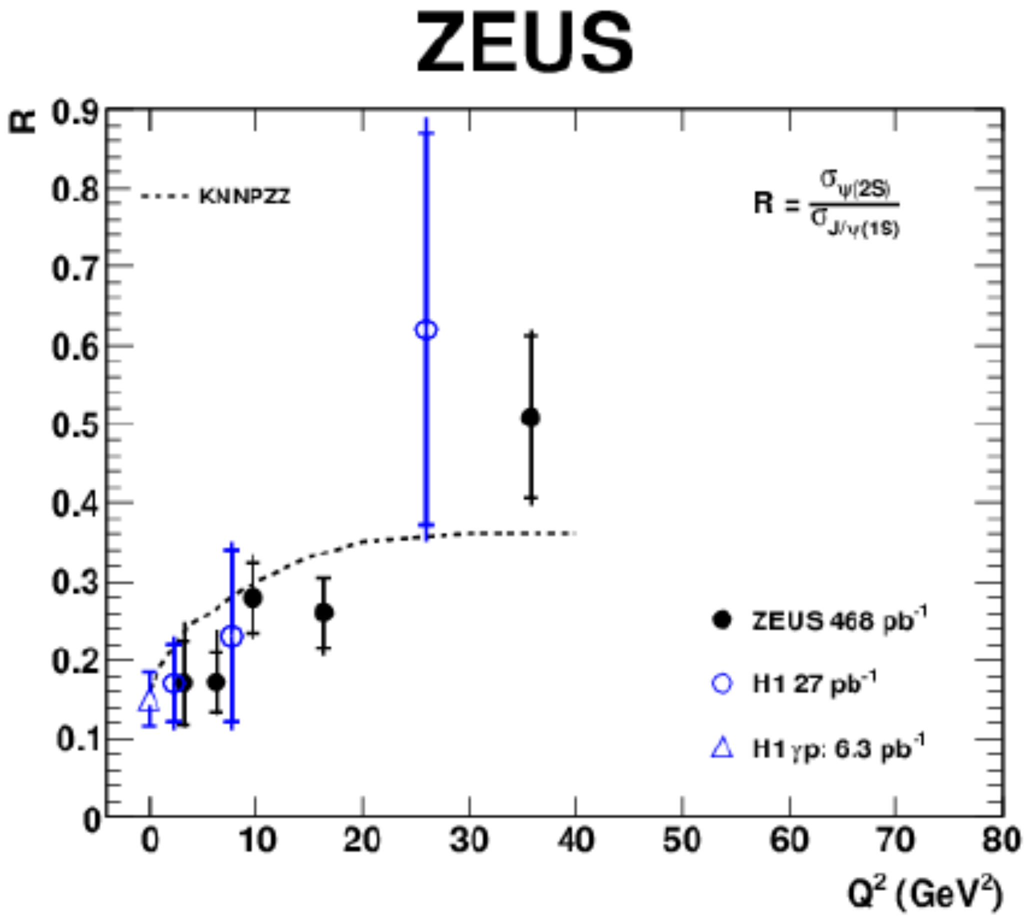
- Two-component Pomeron model



Ψ(2S)/J/Ψ(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)]

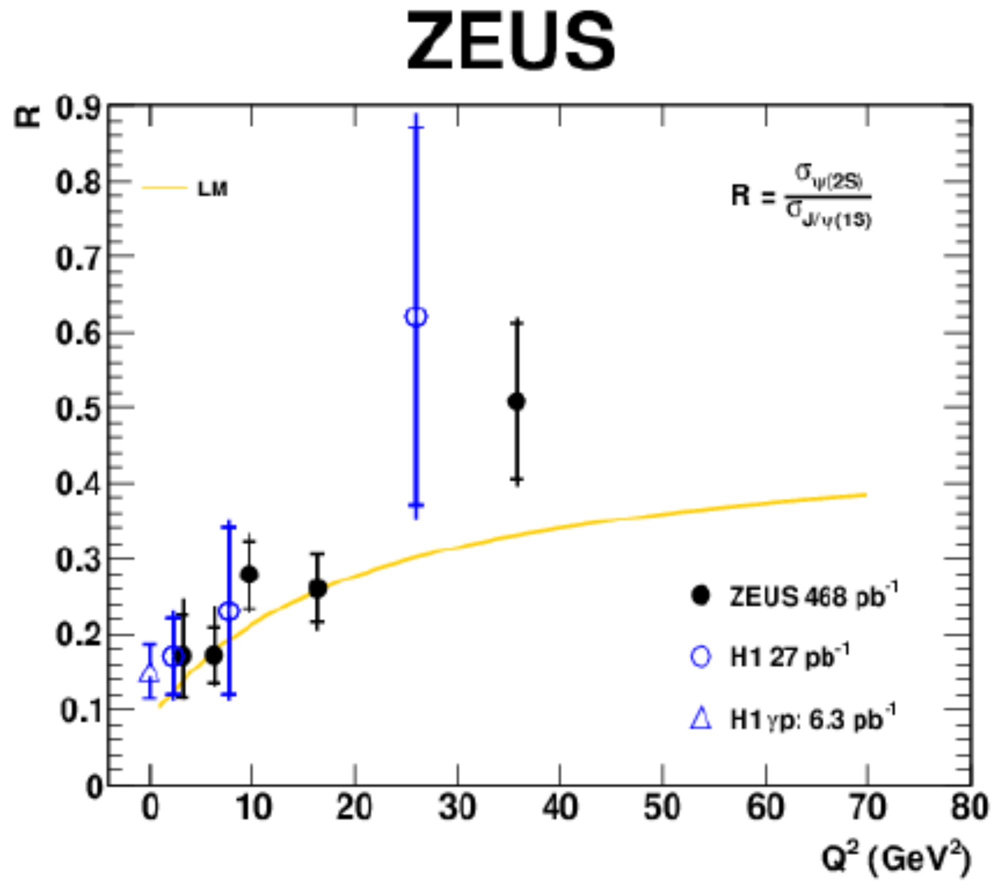
- Generalized BFKL equation for ccbar dipole cross section



Ψ(2S)/J/Ψ(1S) : LM calculation

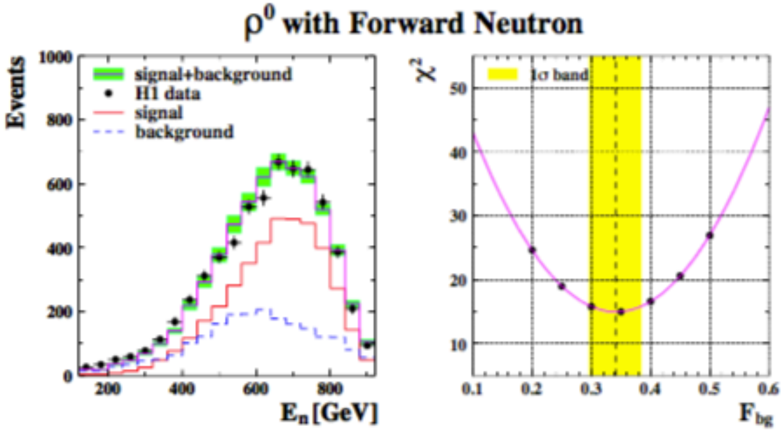
[T. Lappi and H. Mäntysaari, Phys. Rev. C 83, 065202 (2011),
T. Lappi and H. Mäntysaari, PoS (DIS2014), 069 (2014)]

- BFKL equation + IP-Sat mode



Exclusive ρ^0 photoproduction with a LN

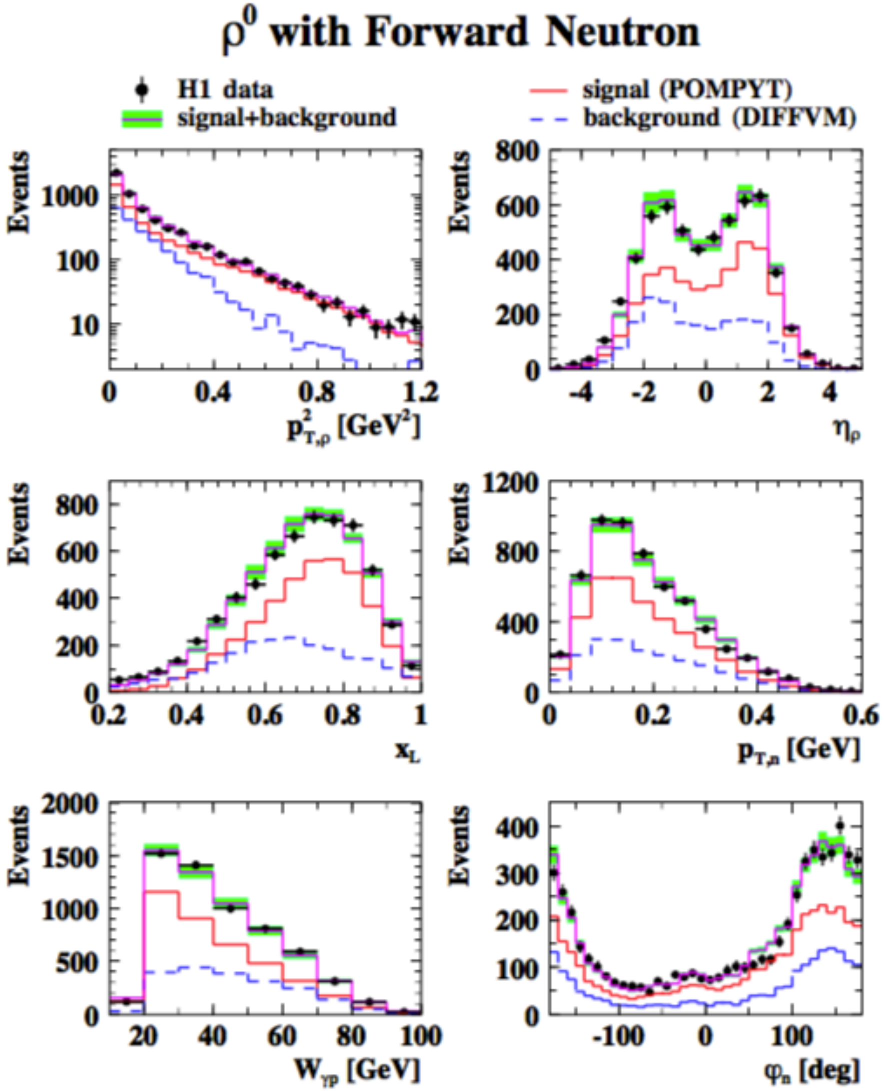
S/B decomposition and control plots :



E_n $B/(S+B)$

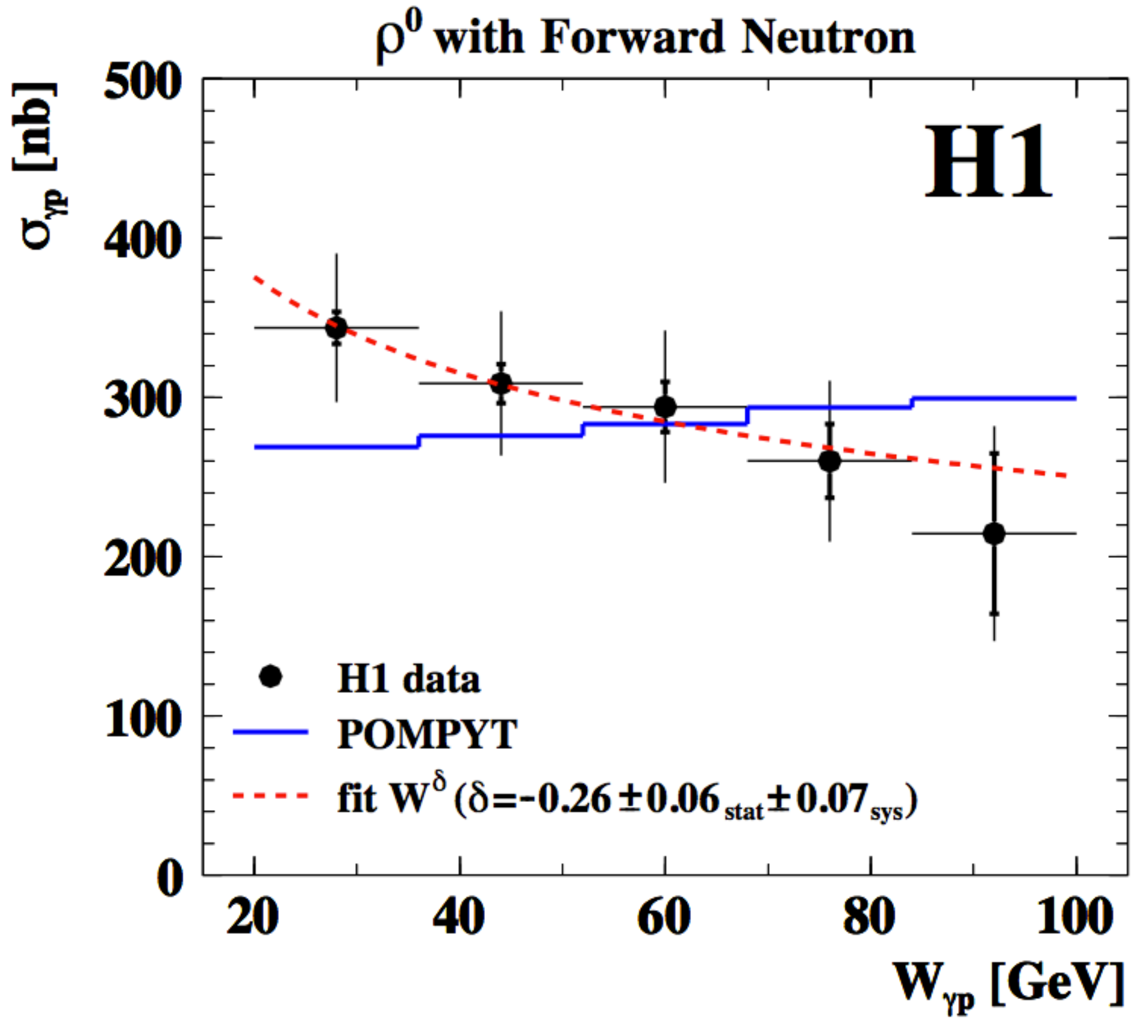
$$F_{bg} = 0.34 \pm 0.05$$

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



Exclusive ρ^0 photoproduction with a LN

Energy dependence :



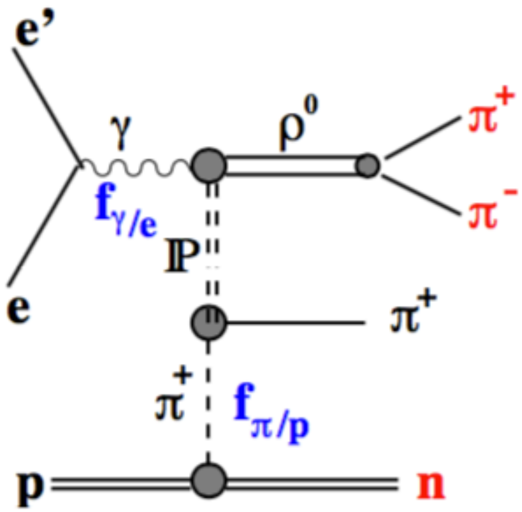
Pomeron exchange alone

Exclusive ρ^0 photoproduction with a LN

Cross section definitions :

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

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



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

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

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

OPE: $$f_{\pi/p}(x_L, t) = \frac{1}{2\pi}\frac{g^2_{p\pi N}}{4\pi}(1-x_L)\frac{-t}{(m^2_\pi - t)^2}\exp\left[-R^2_{\pi n}\frac{m^2_\pi - t}{1-x_L}\right]$$