



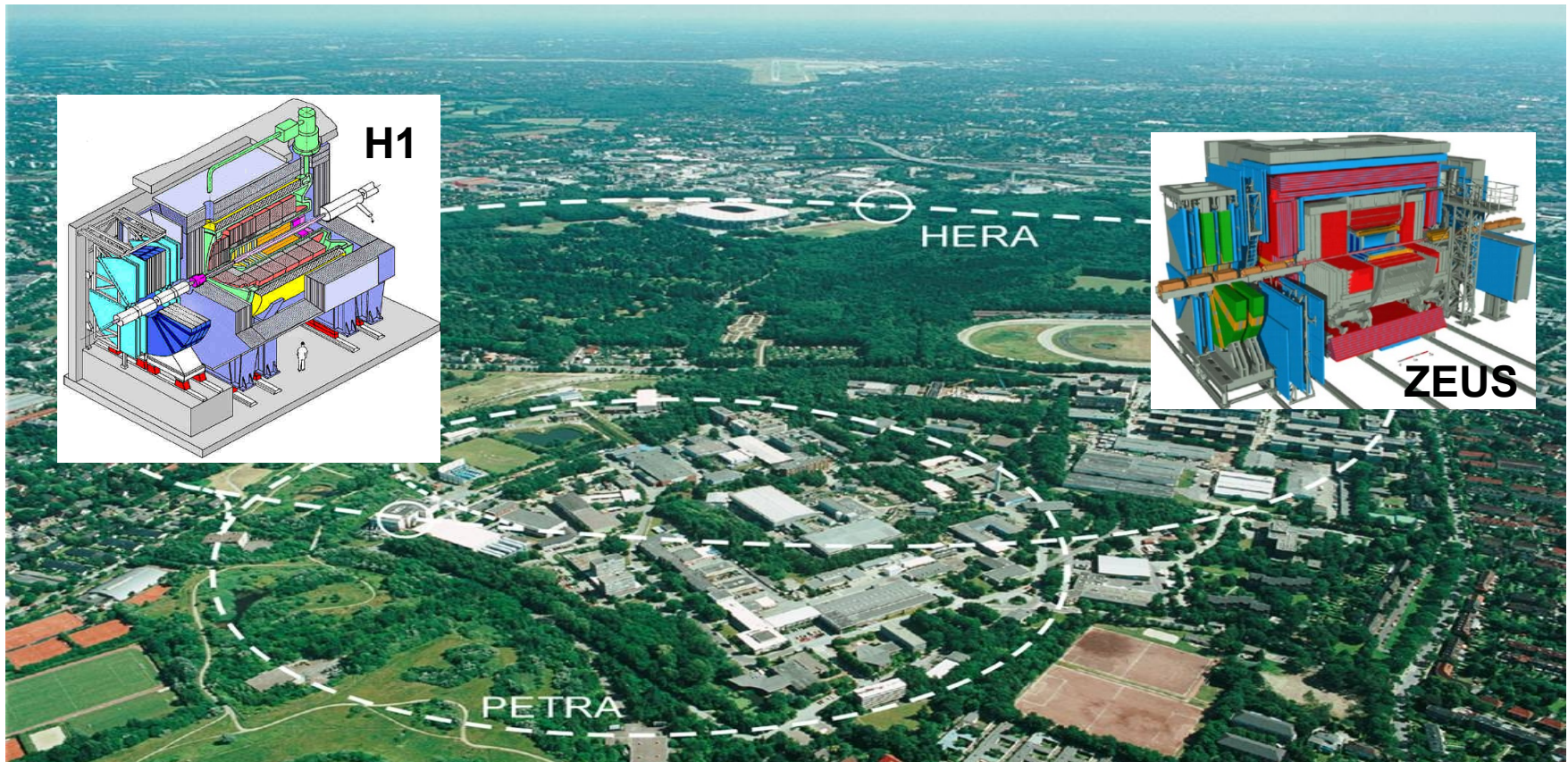
- > **Exclusive results at HERA**
- > Alessia Bruni, Istituto Nazionale di Fisica Nucleare
- > on behalf of H1 and ZEUS Collaborations



QCD@LHC, London, 1-5 September 2015

# HERA ep collider 1992 – 2007, DESY, Hamburg

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

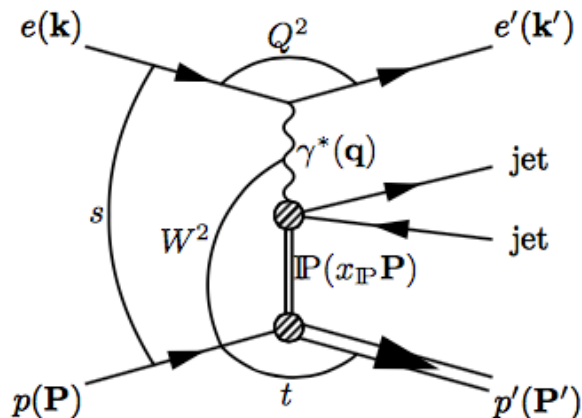
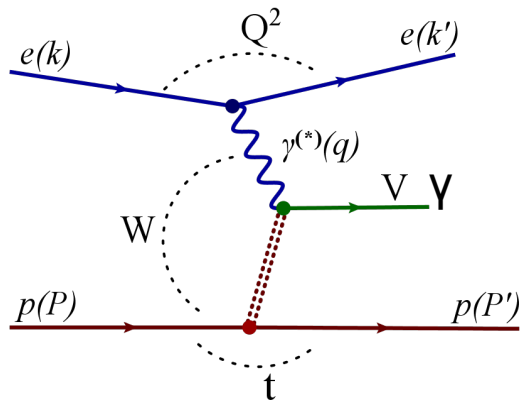


At HERA exclusive production of VMs, photons and dijets has been investigated

Recent results from H1 and ZEUS:

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

# Exclusive processes – kinematic variables



Exclusive production of Vector mesons, photons, or jets:

$Q^2$  photon virtuality

$W$  photon-proton centre-of-mass energy

$t=(p-p')^2$  – four momentum transfer squared at proton vertex

$x$ –Bjorken  $x$ –fraction of proton's momentum carried by struck quark

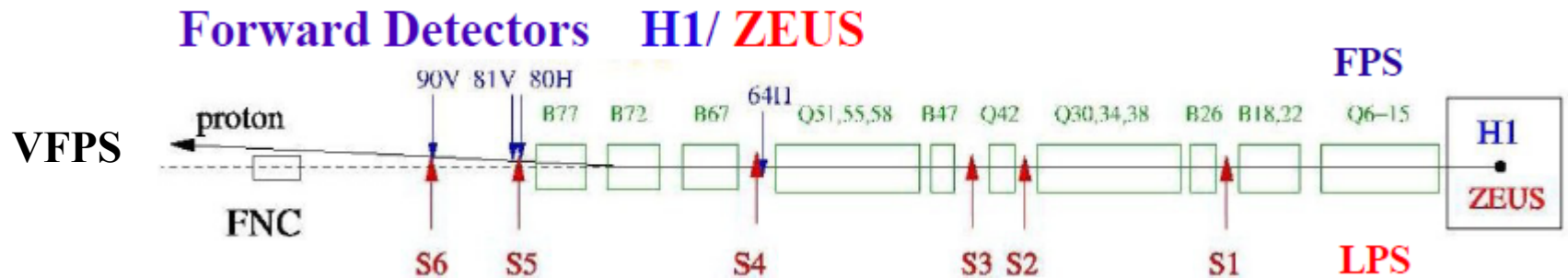
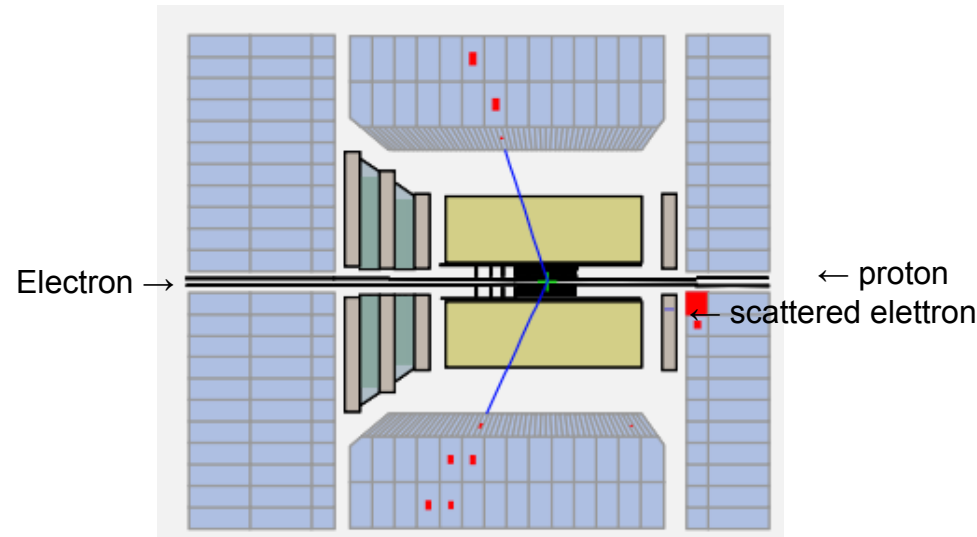
$x_{IP}$  – fraction of proton's momentum carried by exchanged colour singlet

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

Scattered  $p$  detected with lower acceptance

# Experimental Methods

- > Exclusive processes are very clean experimentally
- >
- >

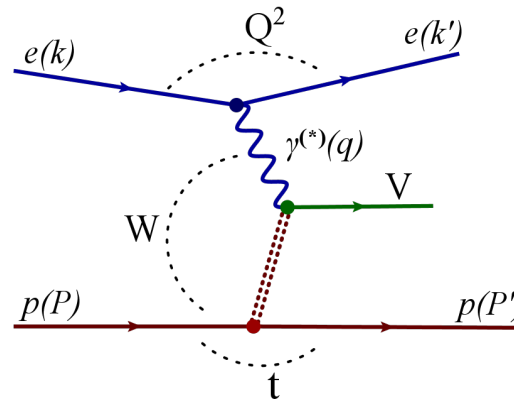


# Vector Meson production

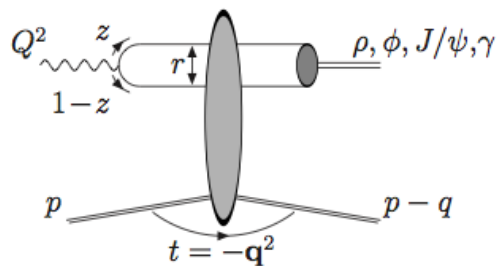
- Soft physics:

Vector Dominance Model,

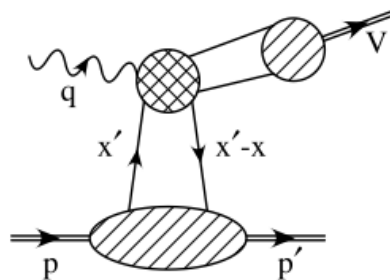
Regge theory



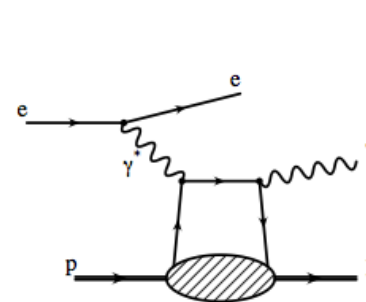
- In the presence of a hard scale ( $M_{VM}$ ,  $Q^2$ ,  $t$ ) calculations in pQCD are possible. Calculations performed now at NLO. Generalised Parton Distributions relevant here.



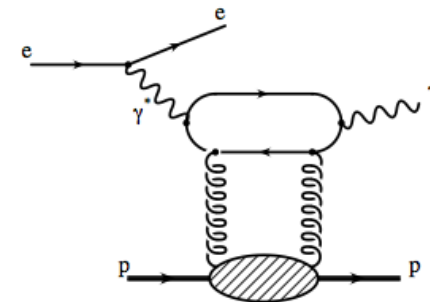
Dipole approach



GPDs



LO

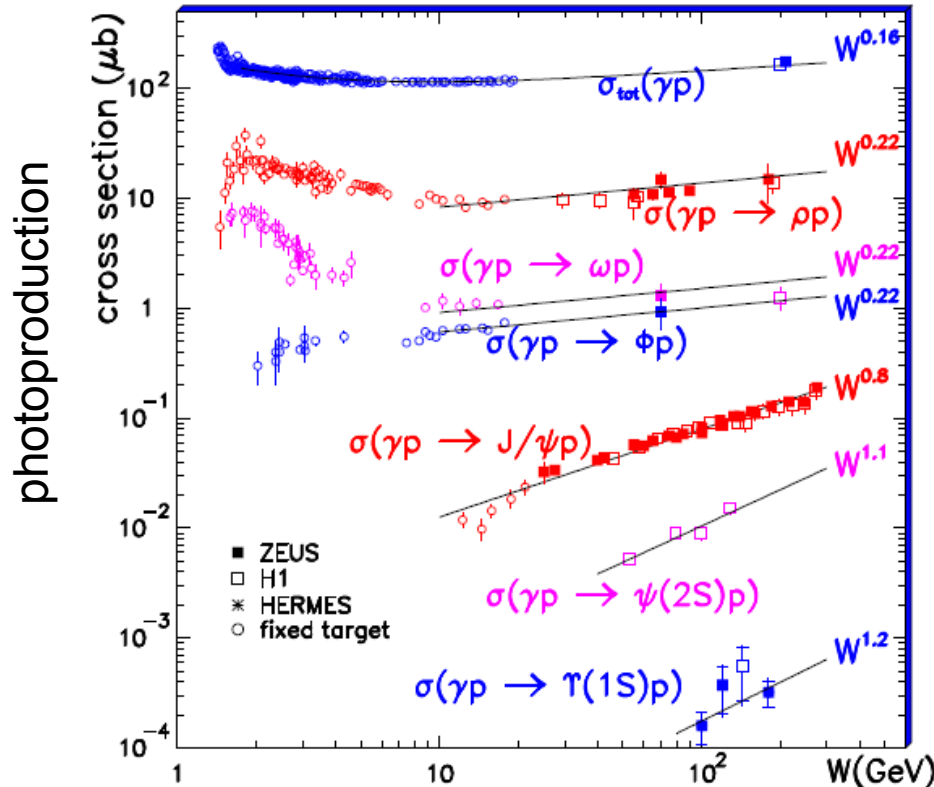


NLO

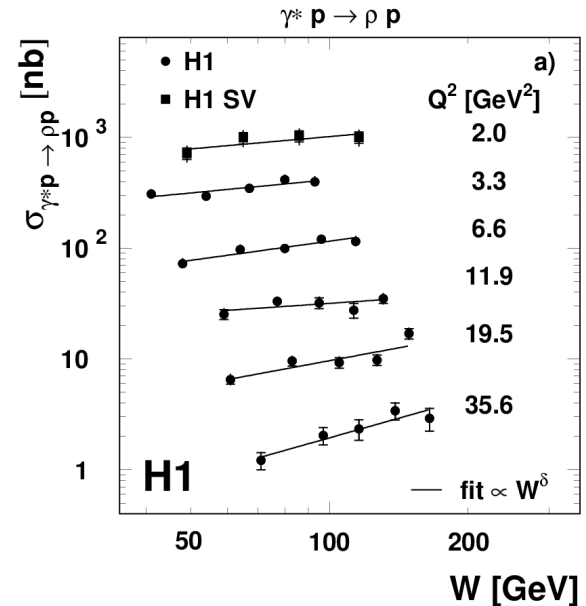


# Vector Meson production: W-dependence

- The cross section dependence on  $W$  can be parameterised as  $\sigma \sim W \gamma p^\delta$

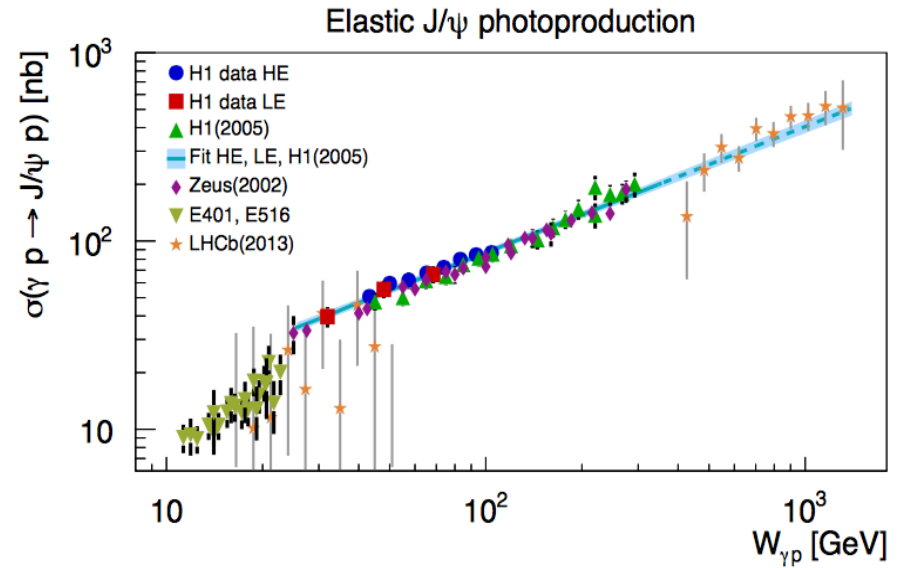
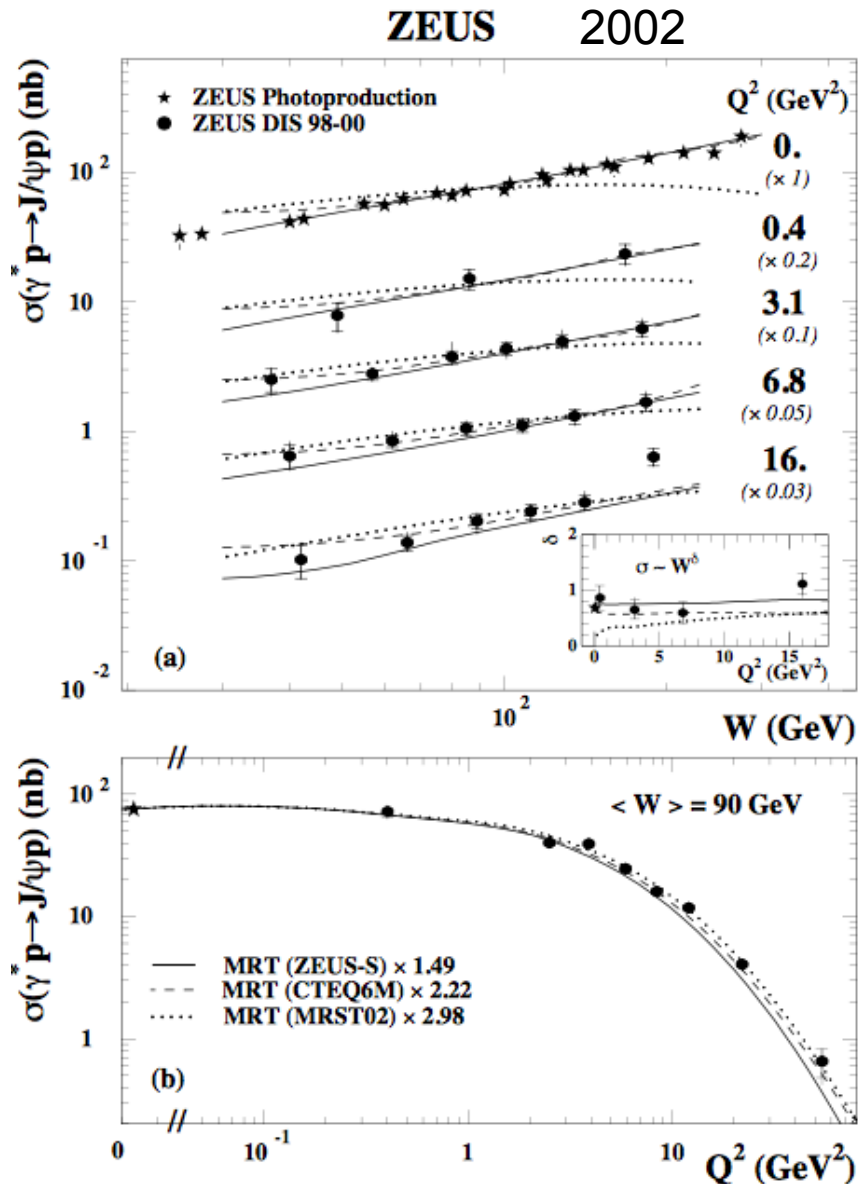


electroproduction (DIS)



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

# VM at NLO and extraction of gluon density at low x



*“data for  $pp \rightarrow pYp$  can now be included in the global PDF fits to determine the gluon in the low  $x$  regime”*  
 1507.06942 Jones, Martin, Ryskin, Teubner

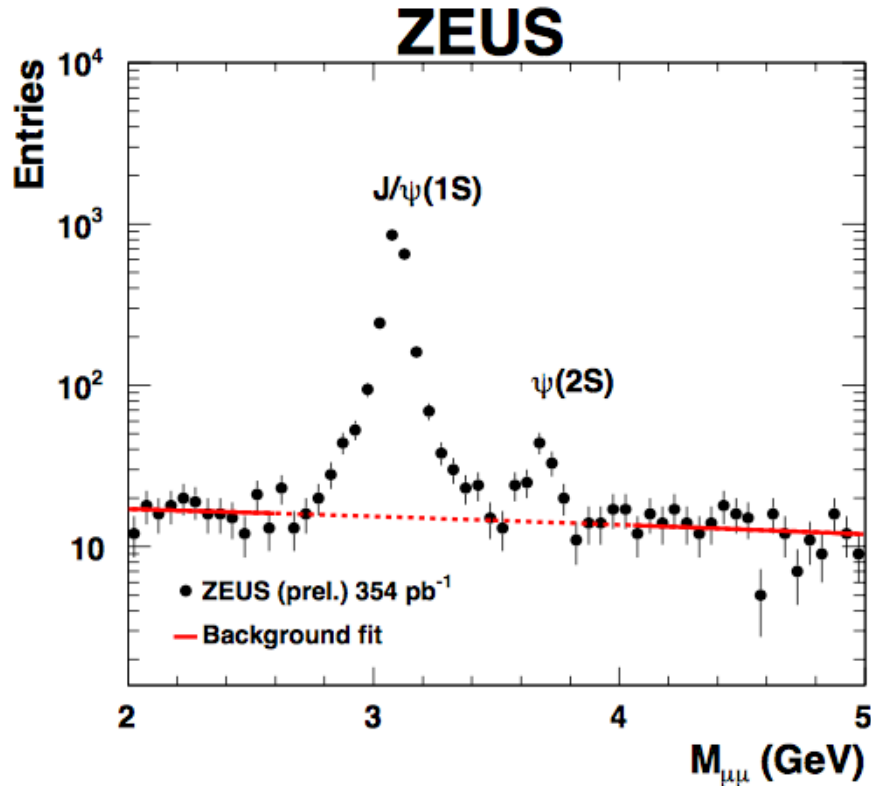


Measurement of the cross section ratio  $\sigma_{\psi(2s)}/\sigma_{J/\psi}$  in deep inelastic exclusive ep scattering at HERA I+II and comparison with various theory predictions

ZEUS-prelim-15-003

# $\psi(2s)$ and $J/\psi(1S)$ production in DIS

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



Decays:  $J/\psi \rightarrow \mu\mu$   
 $\Psi \rightarrow \mu\mu, \Psi \rightarrow J/\psi \pi\pi\pi$

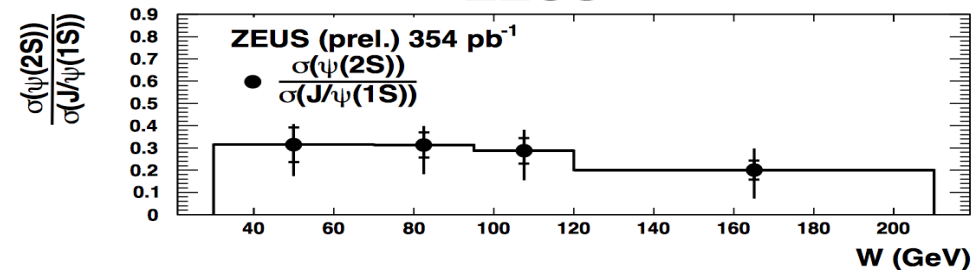
- Measurement sensitive to charmonium wave function
- Different rate of  $\psi(2s)$  and  $J/\psi(1s)$  expected due to different wave function, ratio estimated in QCD models to be  $R \sim 0.17$ , rising with  $Q^2$
- Kinematic range:  
 $5 < Q^2 < 70 \text{ GeV}^2$ ,  
 $30 < W < 210 \text{ GeV}$ ,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

# $\psi(2s) / J/\psi(1S)$ ratio vs $W$ , $t$ , $Q^2$

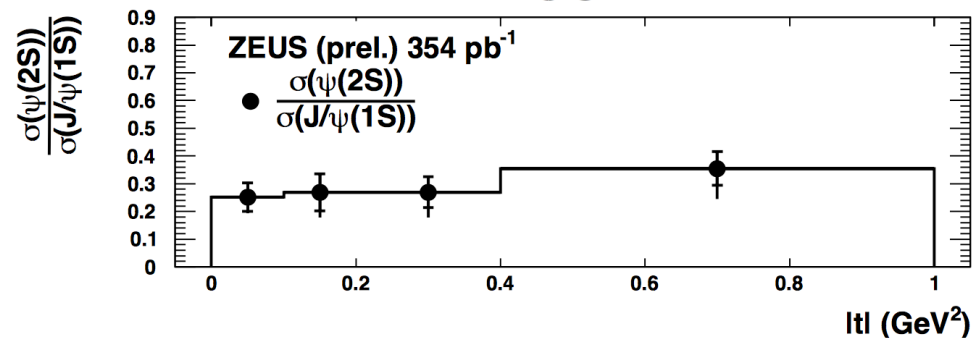
Ratio:

- Independent of  $W$
- Independent of  $t$
- Increase with  $Q^2$

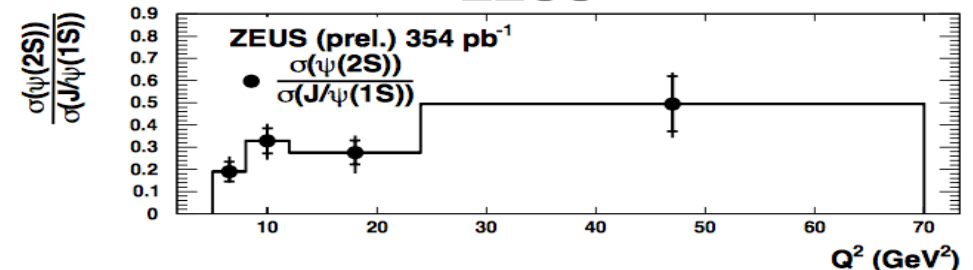
**ZEUS**



**ZEUS**

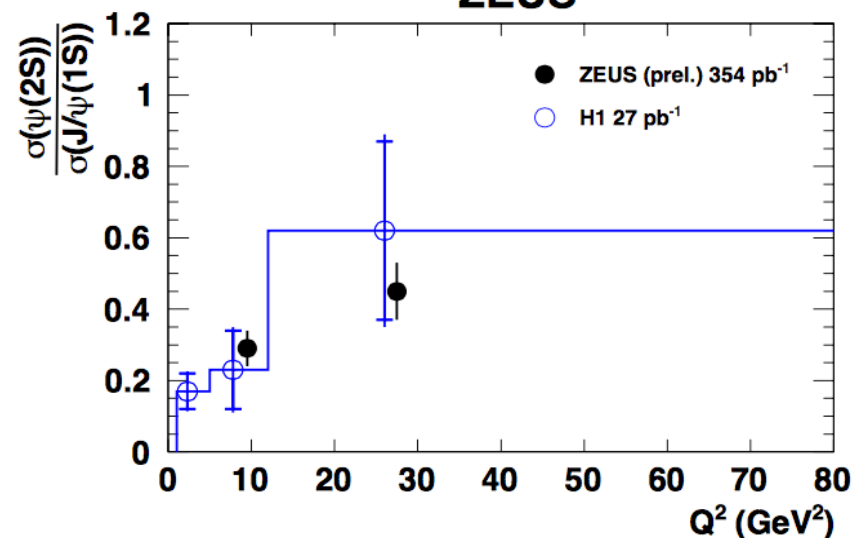


**ZEUS**



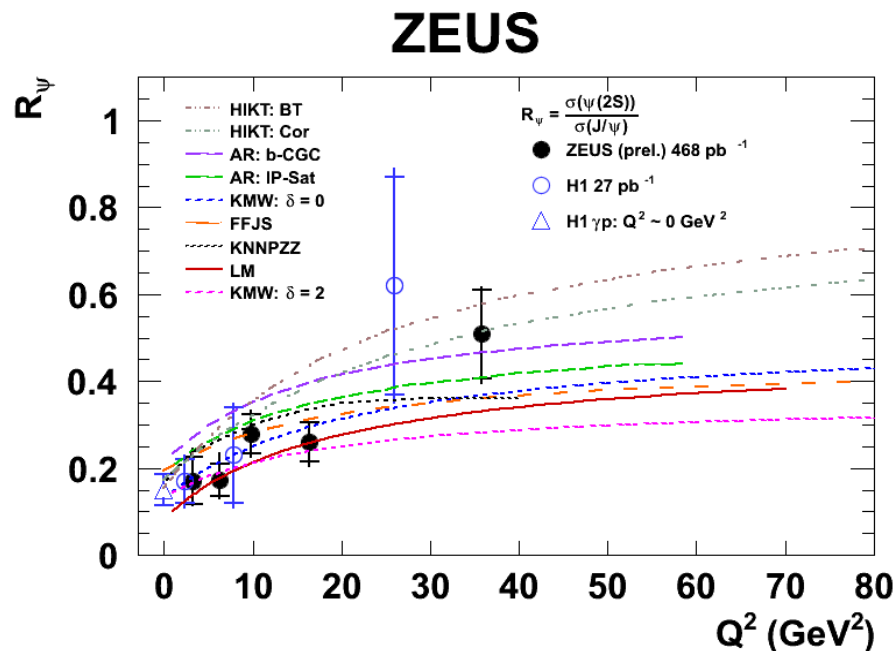
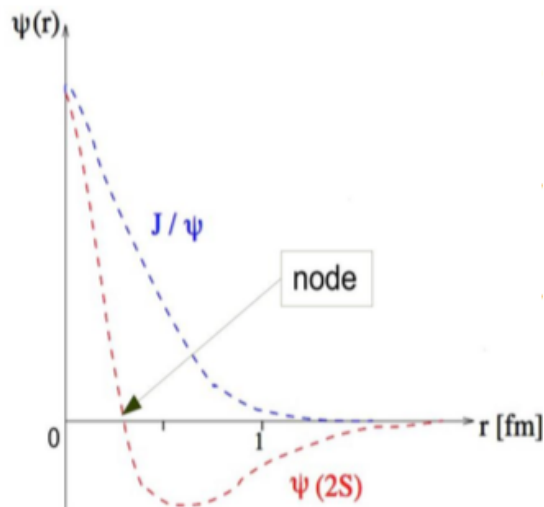
Similar results from H1

**ZEUS**



# $\psi(2s) / J/\psi(1S)$ vs $Q^2$ , comparison with models

Same quark content and similar mass, but different wave function



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

HIKT, Hufner et al.: dipole model, dipole-proton constrained by inclusive DIS data

AR, Armesto and Rezaeian: impact parameter dependent CGC and IP-Sat model

KMW, Kowalski Motyka Watt: QCD description and universality of quarkonia production

FFJS, Fazio et al.: two component Pomeron model

KNNPZZ, Nemchik et al.: color-dipole cross section derived from BFKL generalised eq. LM,

Lappi and Mäntysaari: dipole picture in IP-Sat model

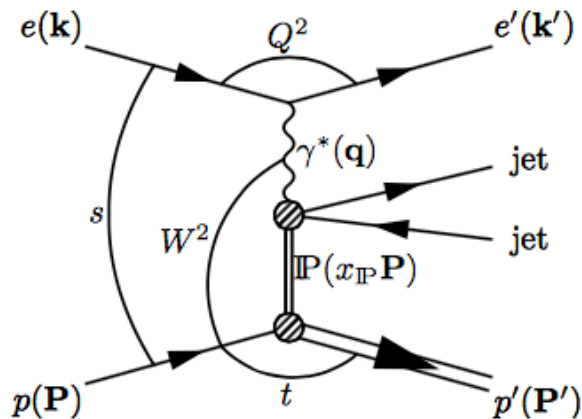
# Production of exclusive dijets in diffractive DIS at HERA

ZEUS

DESY-15-070, arXiv:1505.05783

# Exclusive dijets production in diffractive DIS, arXiv:1505.05783

$e + p \rightarrow e + \text{jet1} + \text{jet2} + p$



Data 2003-2007,  $372 \text{ pb}^{-1}$

Only dijet, scattered electron and proton in the final state

$Q^2 > 25 \text{ GeV}^2$

$90 < W < 250 \text{ GeV}$

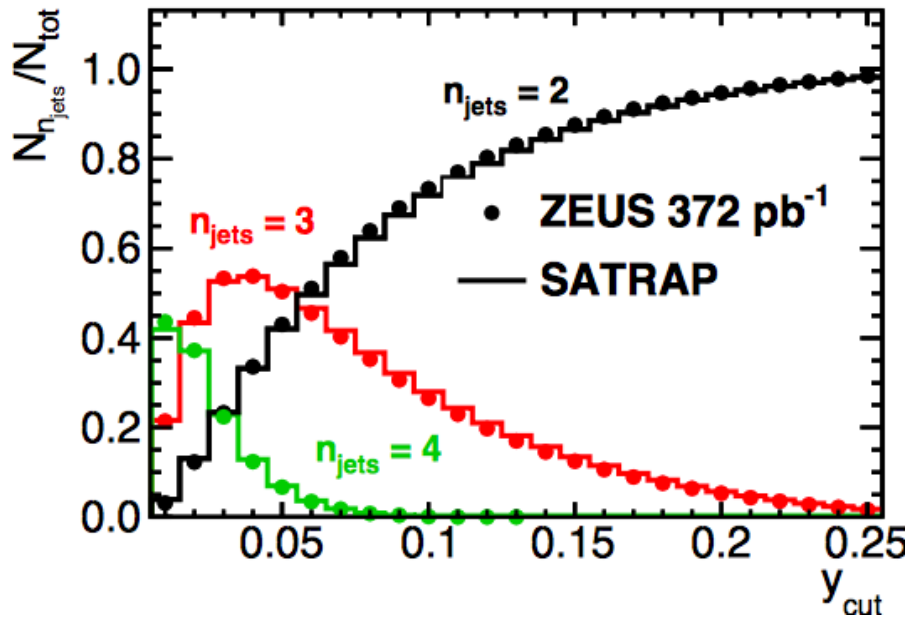
$x_{\mathbb{P}} < 0.01$  – fraction of proton's momentum carried by exchanged color singlet

Large Rapidity Gap



# Exclusive dijet production in diffractive DIS

ZEUS



SATRAP MC model

(Golec-Biernat, Wustoff, 1999):

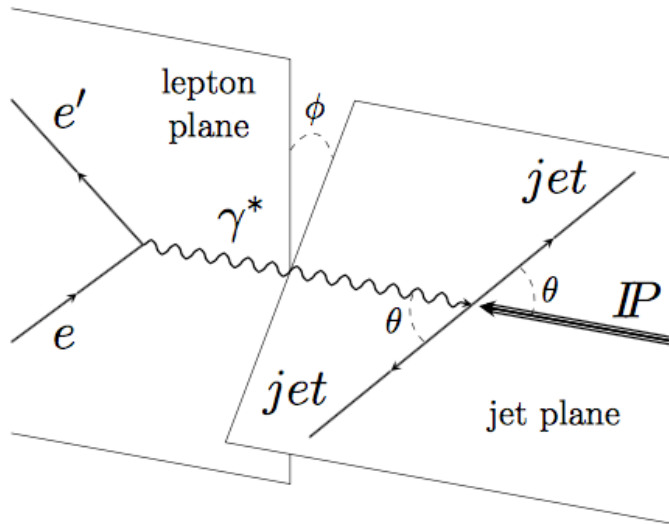
- color dipole model with saturation
- $q\bar{q}$  and  $q\bar{q}g$  in a final state
- good agreement with data, used for detector level

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

Jets were found in  $\gamma^*$ -IP rest frame

- using Durham kT jet algorithm in exclusive mode: all objects are merged in jets
- with resolution parameter  $y_{cut} = 0.15$  optimizes efficiency versus purity of jet sample
- $p_{T,jet} > 2$  GeV selects hard jets
- $n_{jet} < 2$  select diffractive events with LRG

# Exclusive dijets production in diffractive DIS



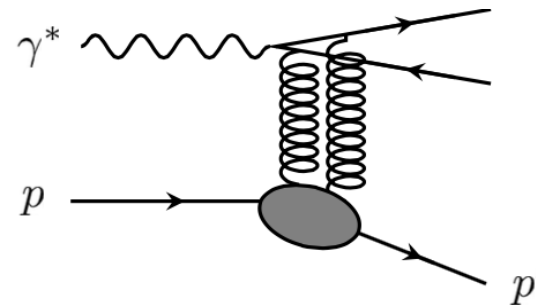
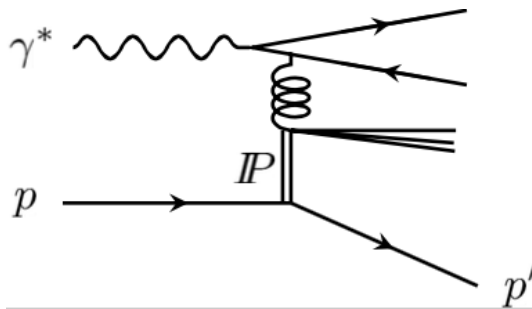
Test the nature of the object in diffractive interaction by reconstructing the azimuthal angle between lepton and jet plane

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

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

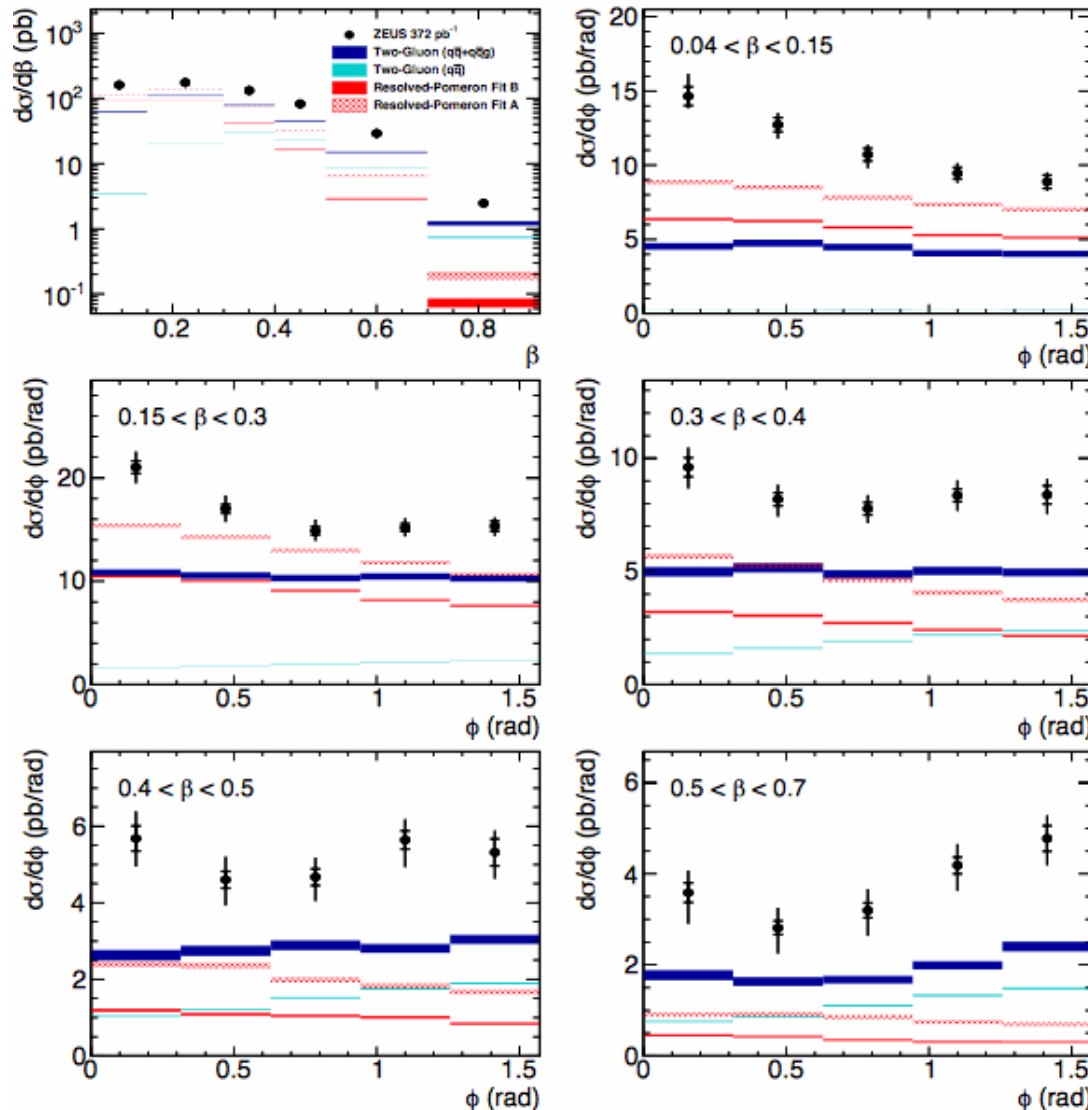
$A < 0$  for two gluons exchange

$A > 0$  for  $q\bar{q}$  produced from single gluon



# Exclusive dijet production in diffr. DIS, angle between jets

## ZEUS



$d\sigma/d\Phi$  fitted for different  $\beta$  bins,  
 $\beta = x / x_{IP}$  – fraction of Pomeron  
 momentum ‘seen’ by photon

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

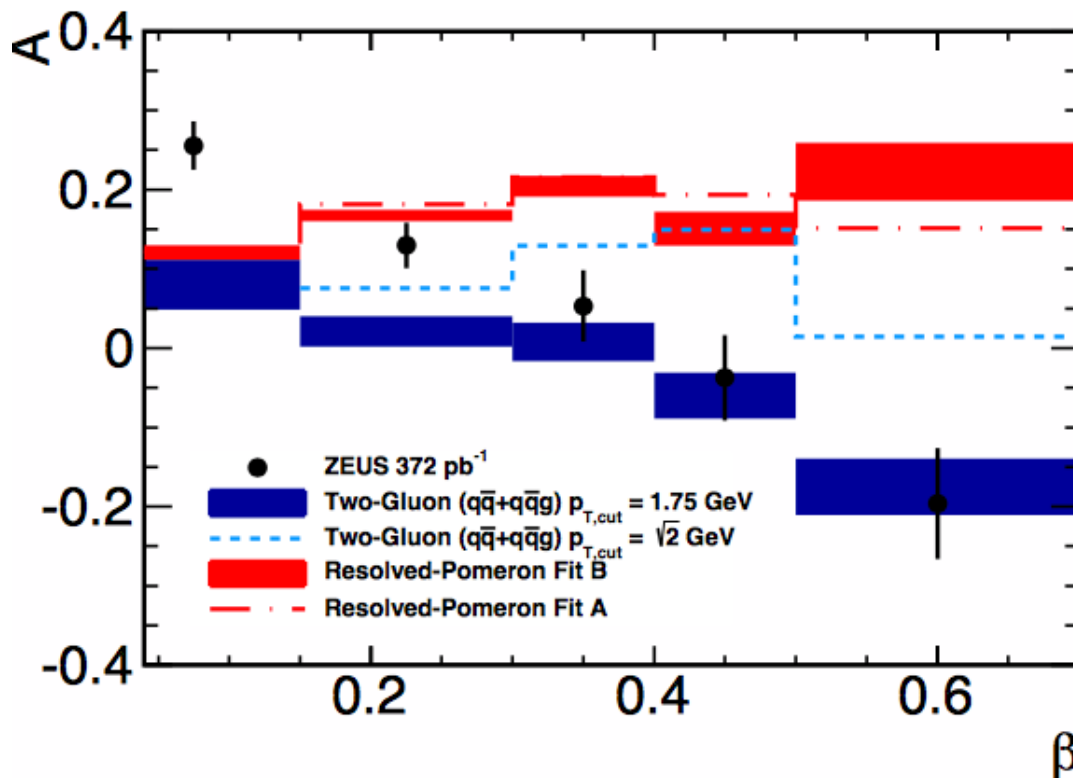
The slope of the angular  
 distribution changes sign  
 around  $\beta = 0.4$

# Exclusive dijet production in diffractive DIS

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

A vs  $\beta$ , comparison with model predictions

## ZEUS



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

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

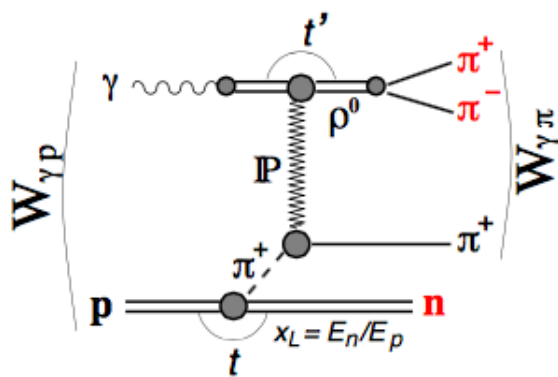
Data favour the Two-Gluon-Exchange model prediction

Exclusive  $\rho^0$  meson photoproduction with a leading neutron at HERA

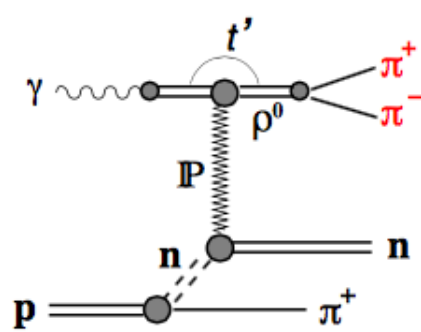
H1 DESY 15-120, submitted to Eur. Phys. JC

# Exclusive PHP of rho mesons with forward neutron

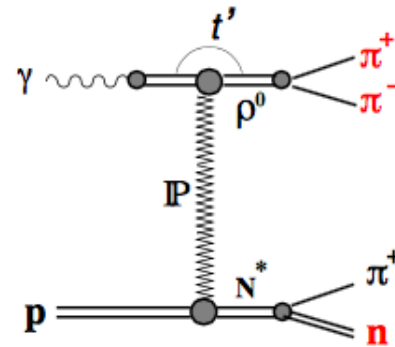
- $\gamma p \rightarrow \rho^0 \pi^+ n, \rho^0 \rightarrow \pi^+ \pi^-$



One Pion Exchange



additional contributions



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

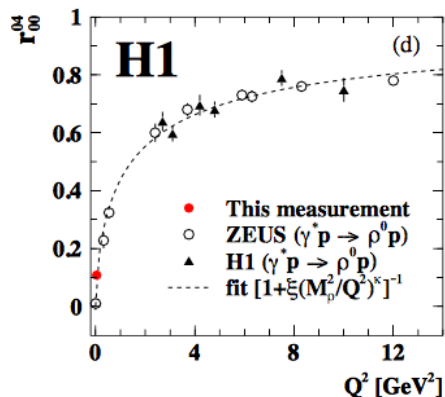
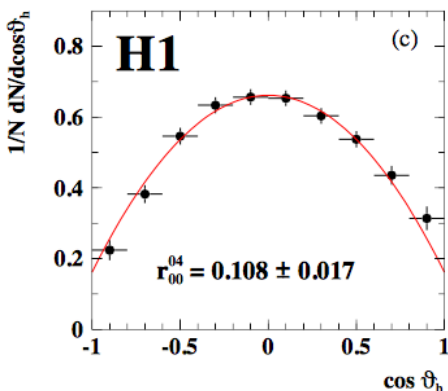
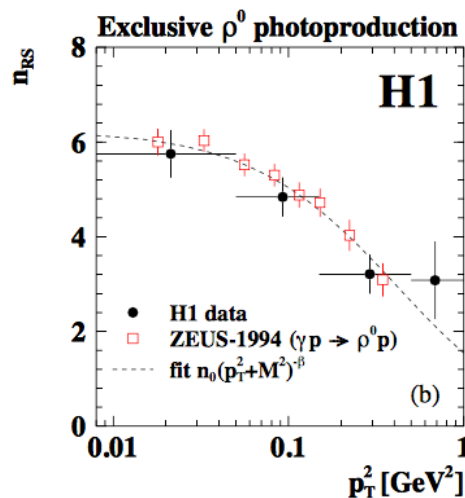
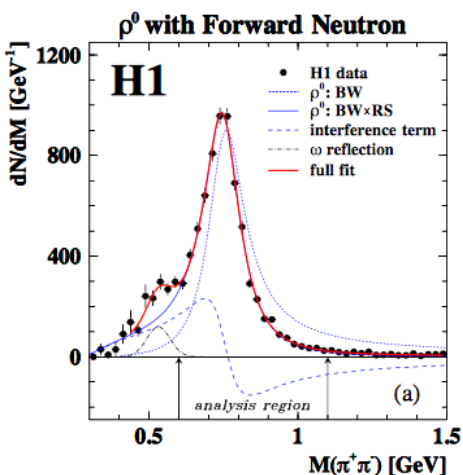
Key observables :

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

In One Pion Exchange assumption, factorization of the proton vertex (valid at small  $t$ )  $\rightarrow \sigma_{\gamma p} \sim f_\pi / p(x_L) \sigma_{\gamma \pi}$



# Exclusive $\rho$ photoproduction with forward n



Kinematic range:

$$Q^2 < 2 \text{ GeV}^2$$

$$|t| < 1 \text{ GeV}^{-2}$$

$$0.3 < m_{\pi\pi} < 1.5 \text{ GeV}$$

$$20 < W_{\gamma\pi} < 100 \text{ GeV}$$

No hard scale

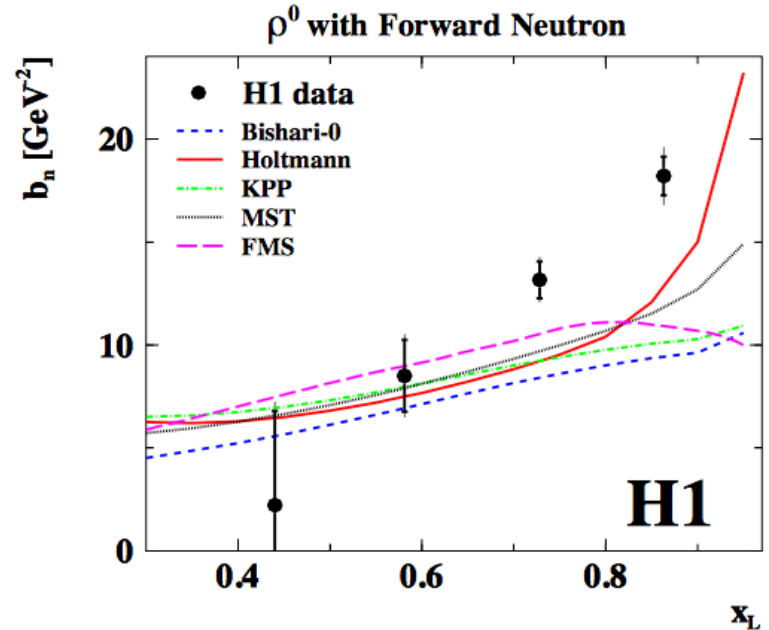
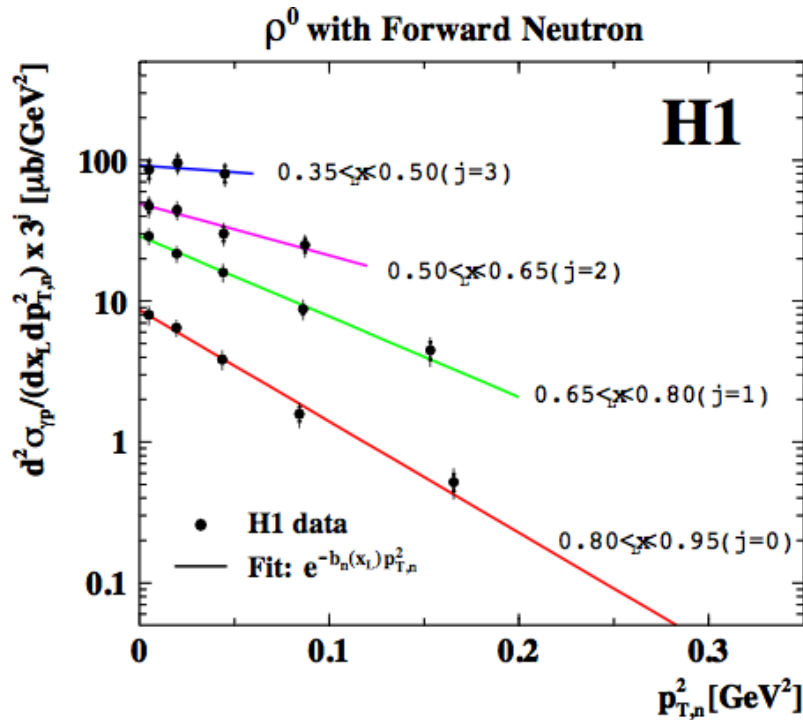
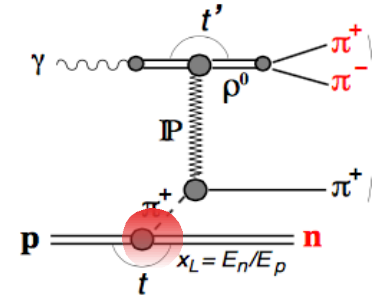
The BW shape is distorted due to interference with non-resonant  $\pi\pi\pi$  production amplitude

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

Property of two-pion system compatible with previous measurements

# Exclusive $\rho$ photoproduction with forward n – slope at n vertex

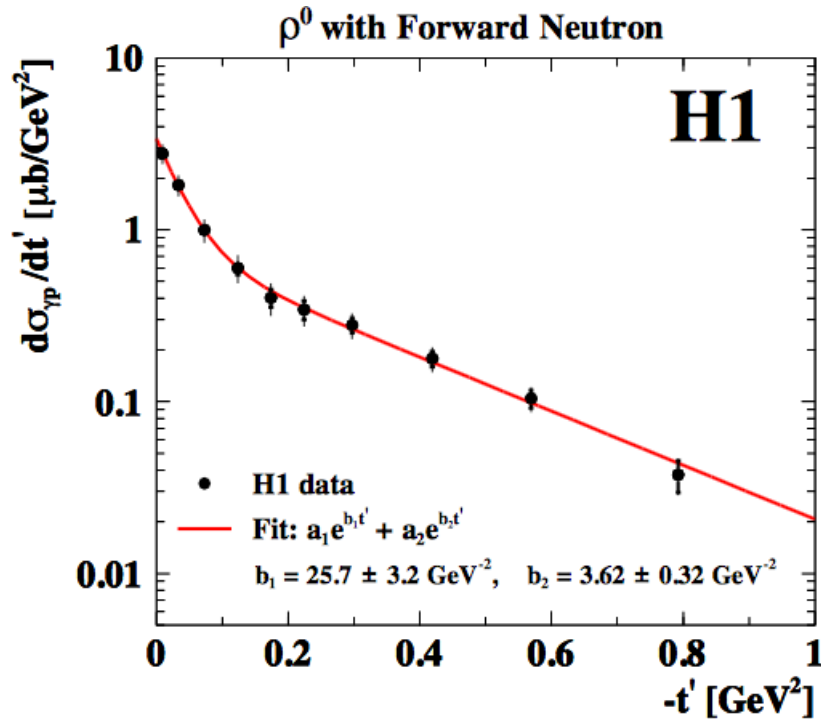
Slope of momentum transfer at p-n vertex vs  $x_L = E_n/E_p$



Step rise with increasing  $x_L$  expected from models, but rise is stronger than predicted by various pion-flux parametrisations

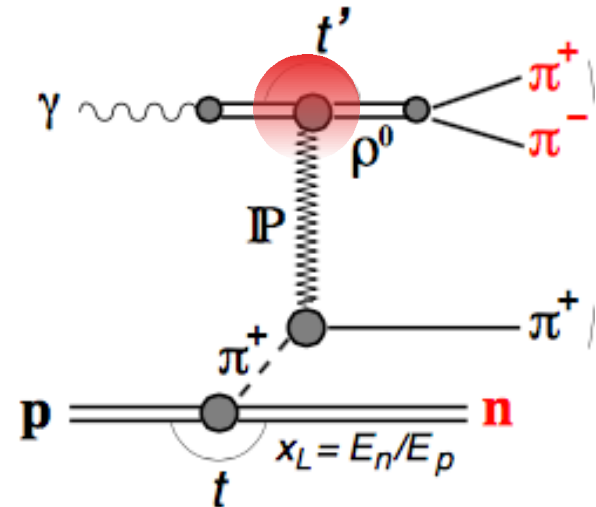
# Exclusive $\rho$ photoproduction with forward n – slope at $\gamma p$ vertex

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



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

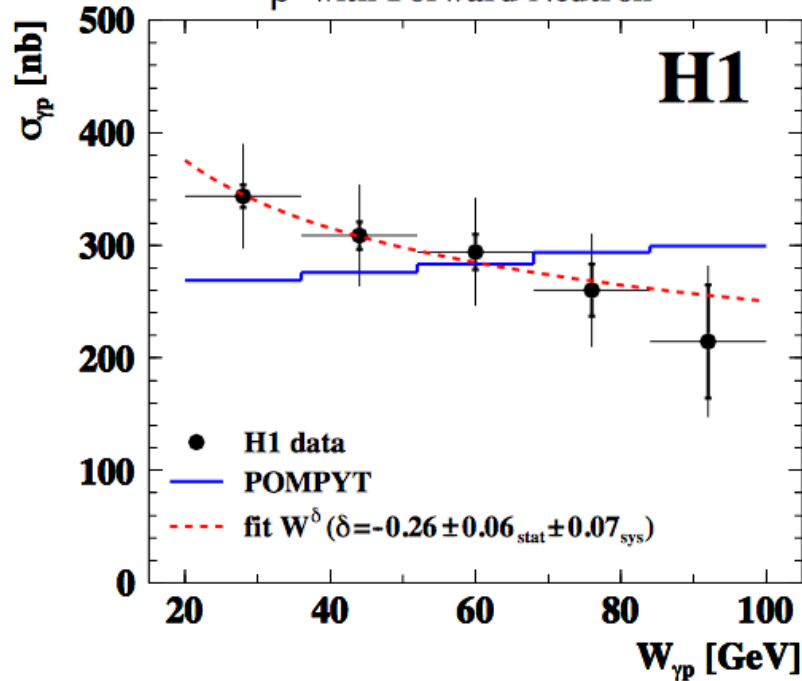
In Double Peripheral Process, this is due to double exchange, IP and  $\pi$



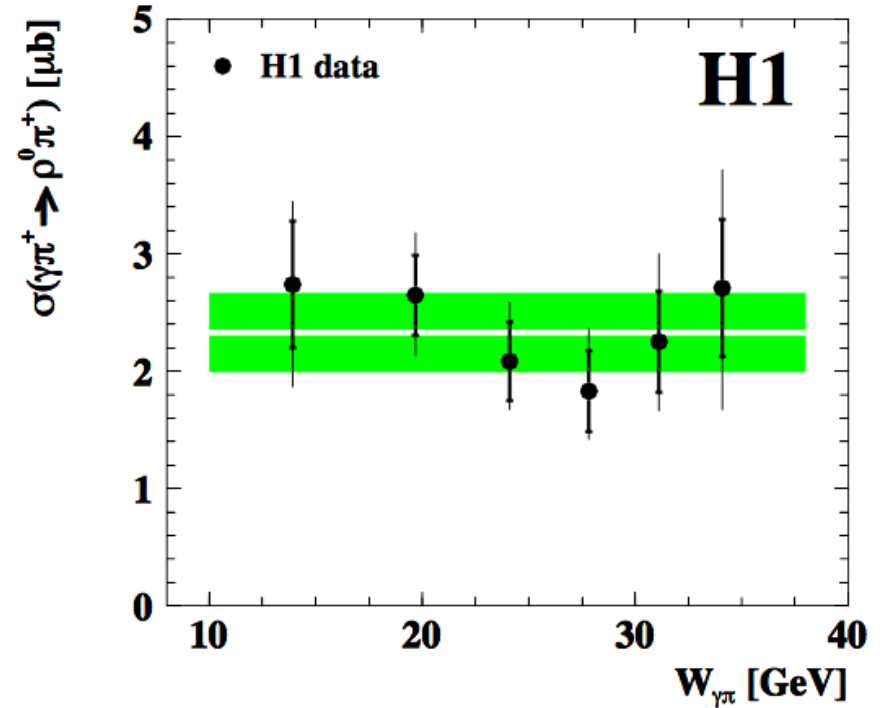
# Exclusive $\rho$ photoproduction with forward $n$ , $\sigma$ vs $W$

cross section  $\gamma p \rightarrow \rho^0 \pi^+ n$

$\rho^0$  with Forward Neutron



cross section  $\gamma \pi \rightarrow \rho^0 \pi^+ n$



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

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

$\gamma \pi$ : cross section independent from  $W$  within uncertainties

Ratio  $\sigma_{\gamma \pi} / \sigma_{\gamma p} \sim 0.25$ , small, indicating rescattering or large absorption corr.

# Summary

- > The cross section ratio  $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$  in exclusive DIS has been measured with improved precision, in agreement with QCD models
- > First measurement in ep of diffractive production of exclusive dijets in DIS. Production consistent with two gluon exchange.
- > Photoproduction of exclusive  $\rho^0$  associated with leading neutron measured for the first time at HERA.
- > Differential cross sections for the reaction  $\gamma p \rightarrow \rho^0 n \pi^+$  exhibit features typical for exclusive double peripheral process.
- > Process used to extract the elastic photon-pion cross section  $\sigma(\gamma\pi \rightarrow \rho^0\pi^+)$  in the OPE approximation.  
The cross section ratio  $\sigma(\gamma\pi) / \sigma(\gamma p)$  suggests large absorption corrections suppressing  $\sigma(\gamma p)$

# VM production and DVCS: $b(Q^2+M_{VM}^2)$

Phys.Lett.B 708 (2012) 14

- > Analysis doubles the explored range
- > In agreement with asymptotic behaviour of  $Q^2 + M_{VM}^2$

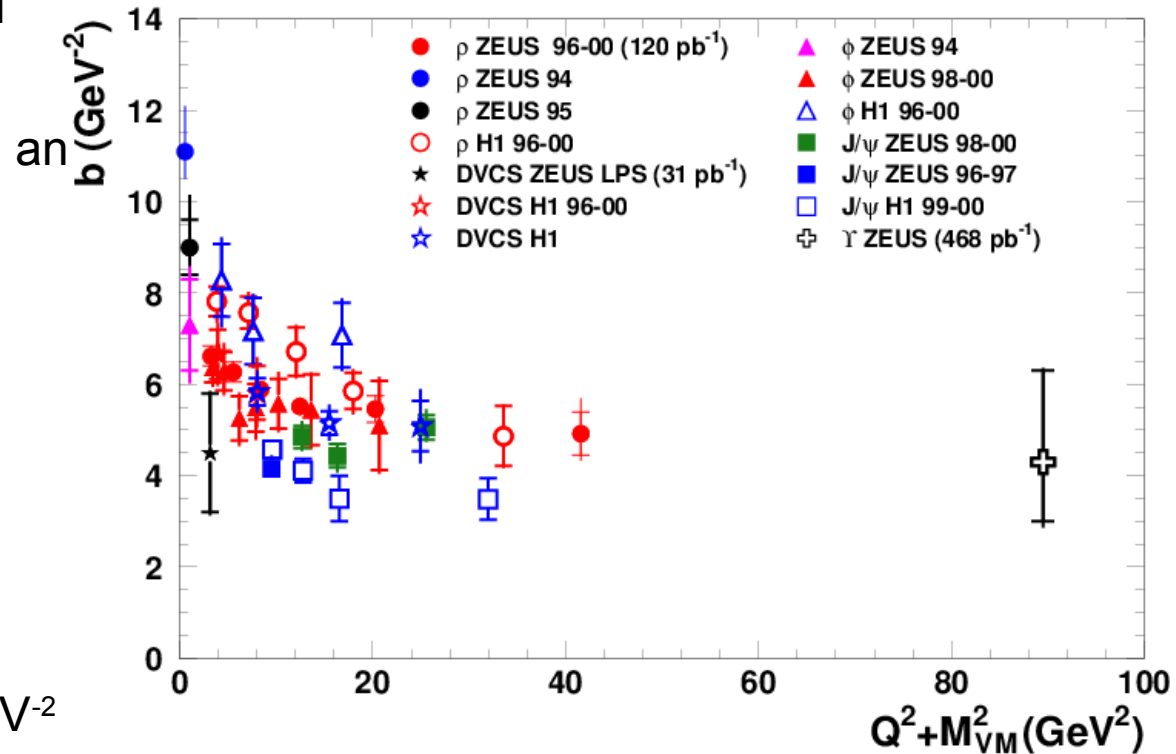
- > In optical model approach:

$$b \sim (R_p^2 + R_{VM}^2)/4$$

- > The first measurement of

b-slope:

$$b = 4.3 +2.0-1.2+0.5 -0.6 \text{ GeV}^{-2}$$



- > consistent with predictions based on pQCD models ( $b= 3.68 \text{ GeV}^{-2}$ )

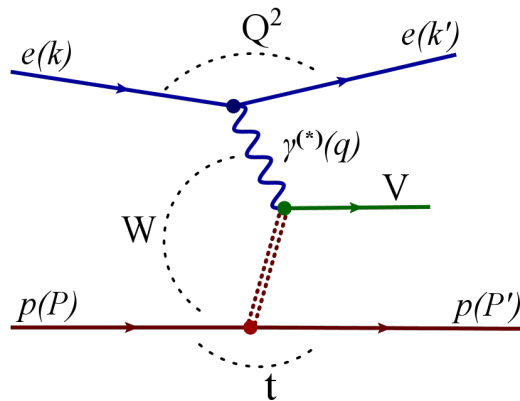
Cox, Forshaw, Sandapen, JHEP 0906 (2009) 034

- > size of interaction region is getting smaller with  $Q^2 + M_{VM}^2$



# Vector Meson production

- Soft physics: Vector Dominance Model, Regge theory



- In the presence of a hard scale ( $M_{VM}$ ,  $Q^2$ ,  $t$ ) calculations in pQCD are possible. Calculations performed now at NLO. GPDs relevant here.

