Exclusive Processes at HERA

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On behalf of the H1 and ZEUS

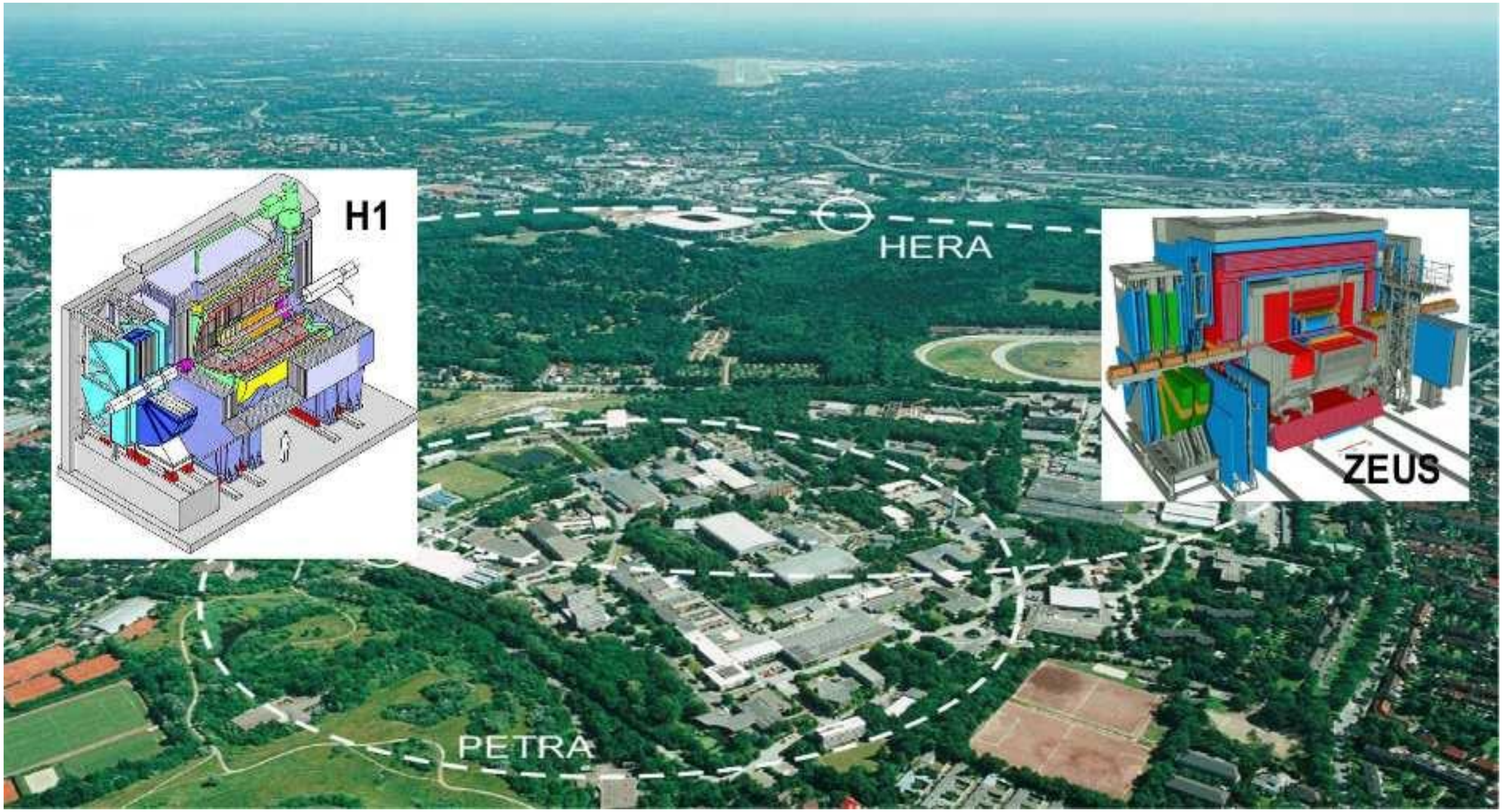
Overview

New analyses from H1 and ZEUS experiments

- **ZEUS:** Exclusive dijet production in diffractive DIS at HERA
- **ZEUS:** Measurement of the cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in deep inelastic exclusive ep scattering at HERA I+II
- **H1:** Exclusive photoproduction of ρ^{0} with forward neutron
- **H1:** Measurement of Feynman-x spectra of photons and neutrons in the very forward direction in DIS

HERA

920 GeV proton and 27.6 GeV electron/positron
HERA I L ~ 100 pb^{-1}
HERA II L ~ 400 pb^{-1}
Total integrated luminosity 0.5 fb^{-1}

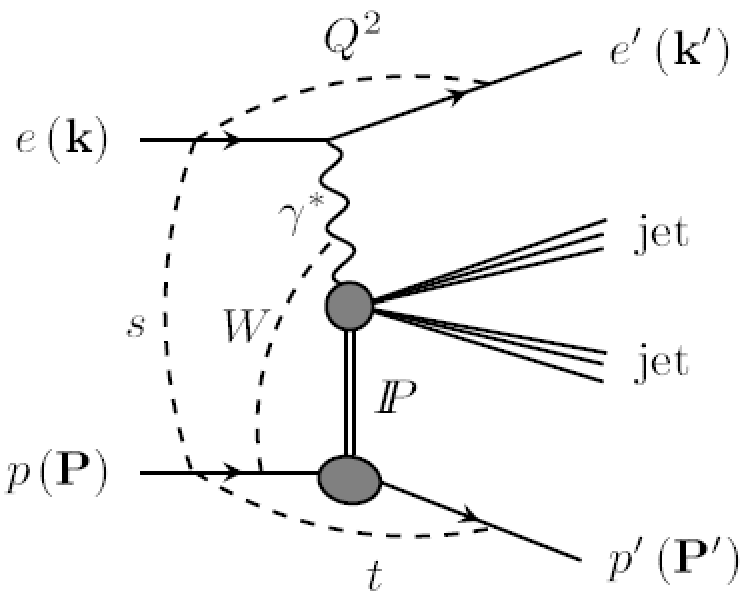


Production of exclusive dijets in diffractive DIS

DESY-15-070
arXiv:1505.05783

Exclusive dijet production in diffractive DIS

e + p → e + jet1 + jet2 + p



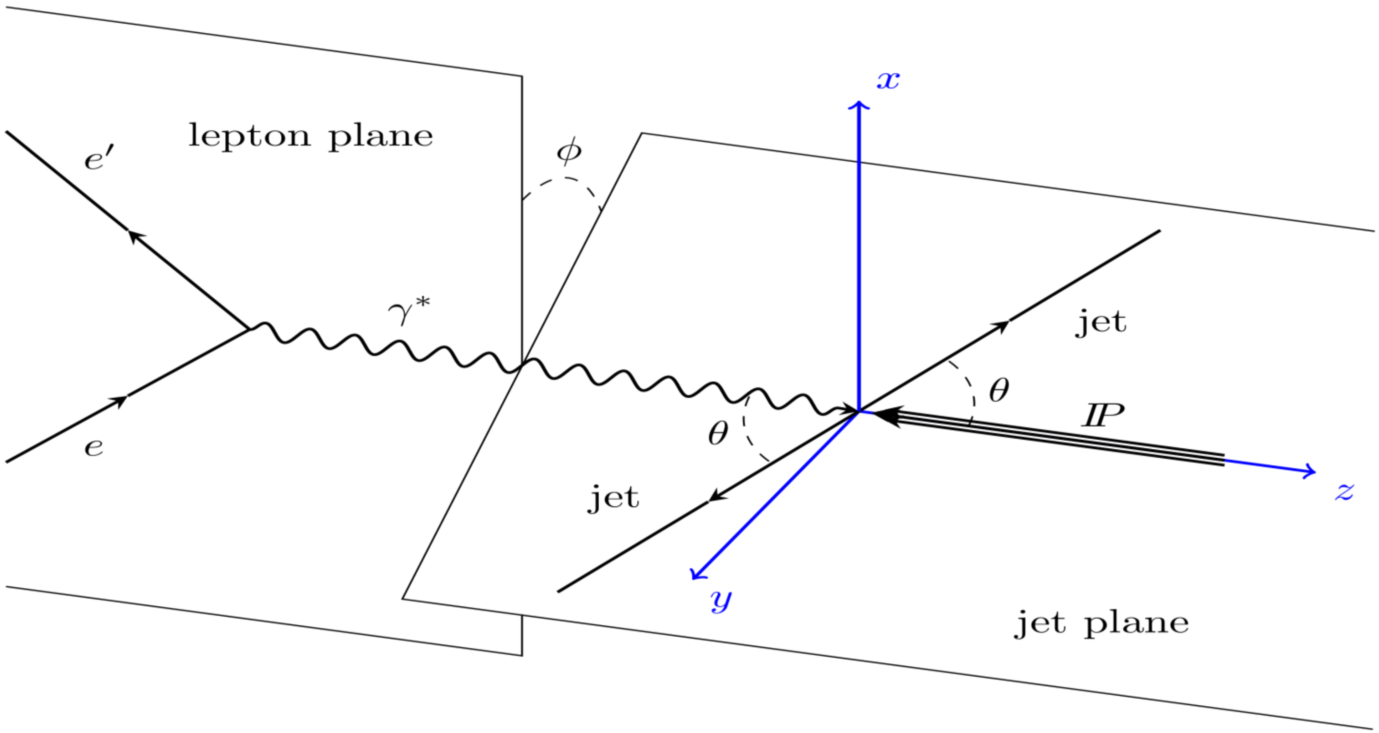
Data 2003 – 2007   372 pb⁻¹

- $Q^2 = -q^2 > 25$ 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
- $\beta = x / x_{IP}$ – fraction of Pomeron momentum ' seen' by photon
- only dijet, scattered electron and proton in the final state

Select two hard jets may to allow comparison pQCD models

Models predict different shape for dijet azimuthal angular distribution

Exclusive dijet production in diffractive DIS

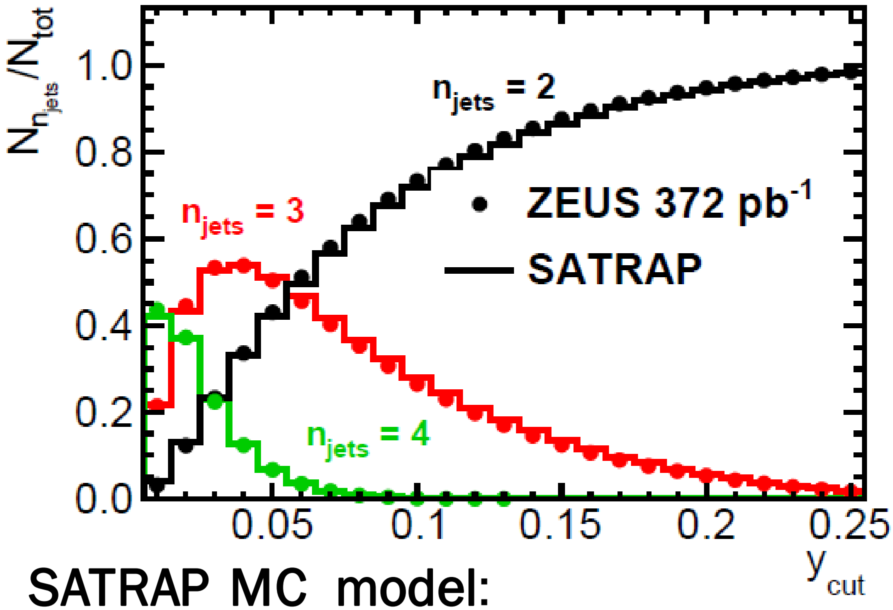


Φ - angle between γ*- dijet and γ*- e± planes in the rest frame of the diffractive final state

Φ distribution is parameterised by $1+A\,(p_{Tjet})\cos(2\Phi)$

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

Exclusive dijet production in diffractive DIS



Jets were found in γ*-IP CMF

Exclusive k_T jet algorithm: objects are merged as long as $k_T < y_{cut} M_x{}^2$

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

Resolution parameter $y_{cut} = 0.15$ optimizes efficiency versus purity of jet sample

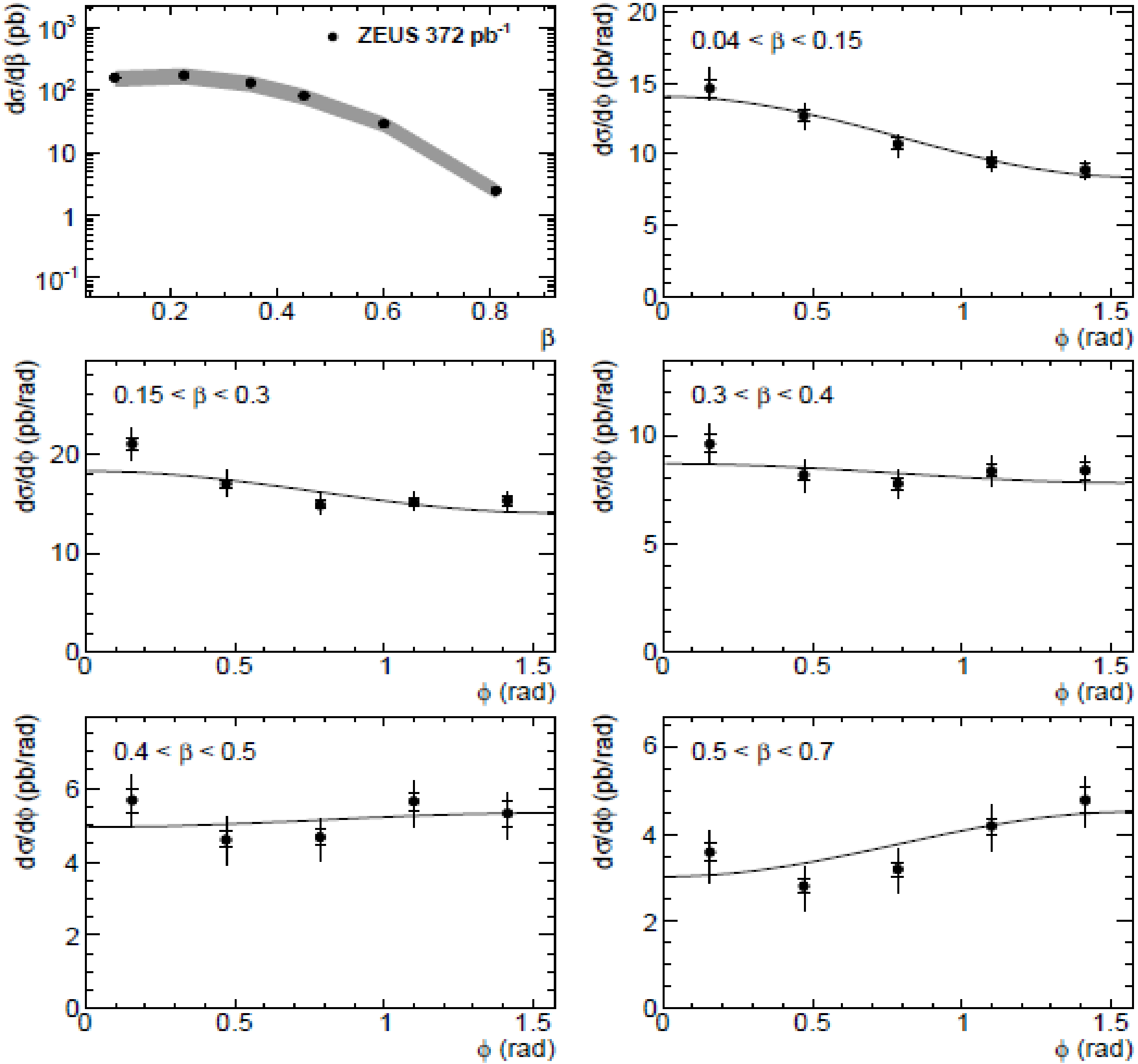
$p_{Tjet} > 2$ GeV selects hard jets

$\eta_{jet} < 2$ select diffractive events with LRG

SATRAP MC model:

- 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 production in diffractive DIS

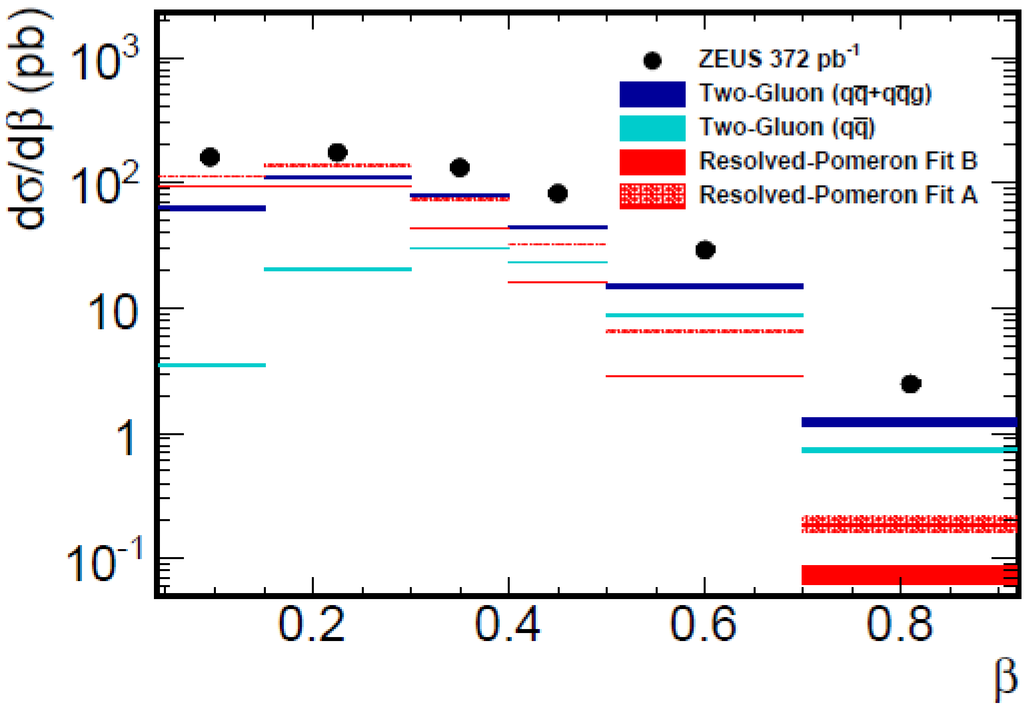


Differential cross sections
Φ distribution well described by theoretically predicted $1 + A \cos(2\Phi)$

The shape of the Φ distribution varies when going from small to large values of β and the slope of the angular distribution changes sign around $\beta = 0.4$

Exclusive dijet production in diffractive DIS

dσ/dβ : comparison with model predictions



Resolved Pomeron model

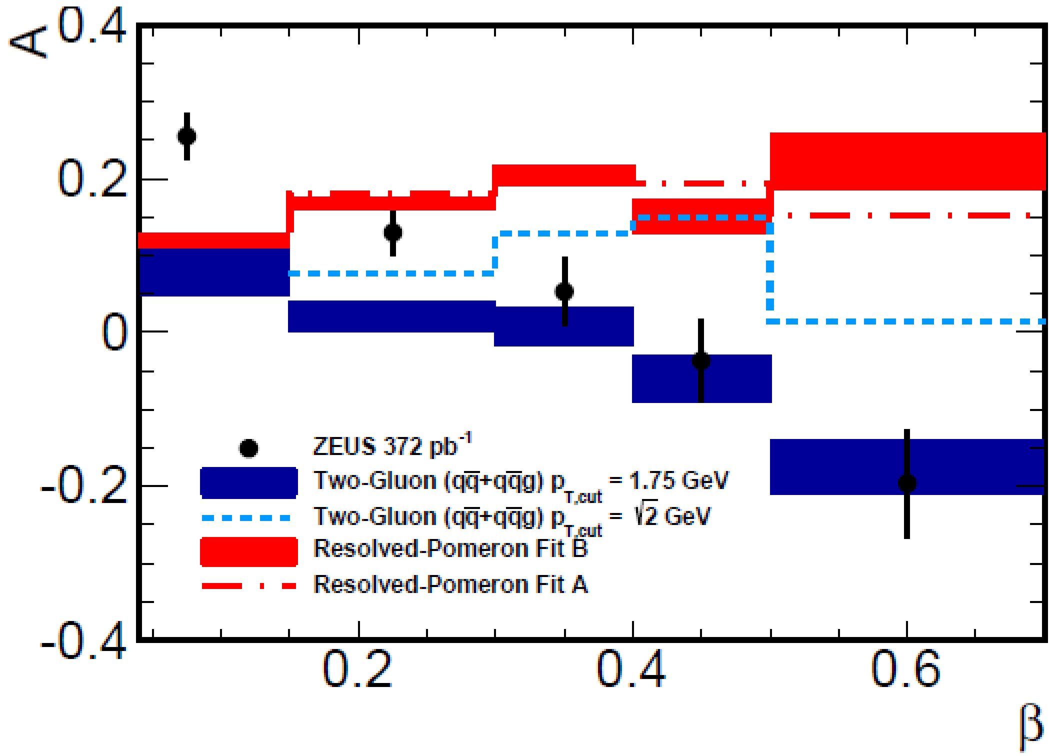
Prediction decreases with increasing β faster than data

Two-Gluon-Exchange model

Reasonable description of the shape of the β distribution

Exclusive dijet production in diffractive DIS

$1 + A\cos(2\Phi)$: comparison with model predictions



Resolved Pomeron model

Almost constant,
Positive value of A in the whole β range

Two-Gluon-Exchange model

Value of A varies from positive to negative

Model agrees quantitatively with the data in the range $0.3 < \beta < 0.7$

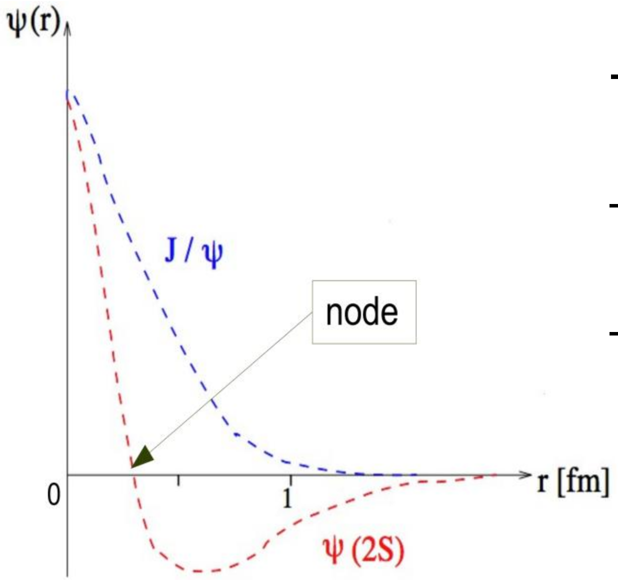
Data favour the Two-Gluon-Exchange model prediction

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

$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in exclusive DIS

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



- gives information about the dynamics of hard process

- sensitive to radial wave function of charmonuim

- insensitive to many systematic uncertainties

- pQCD model calculations predict rise of R with Q^2 reaching plateau at $Q^2 >> M_\psi^2$

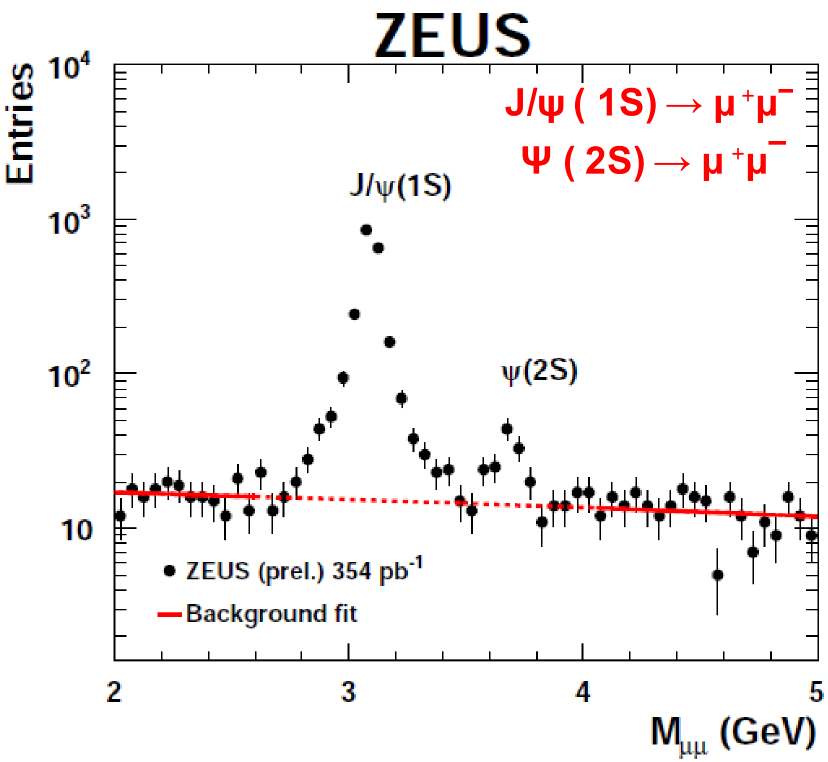
- J/ψ(1S) and ψ(2S) have the same quark content, similar masses, but different wave functions
- ψ(2S) has a node at ≈ 0.35 fm
- $< r^2_{\psi(2S)} > \approx 2 < r^2_{J/\psi} >$

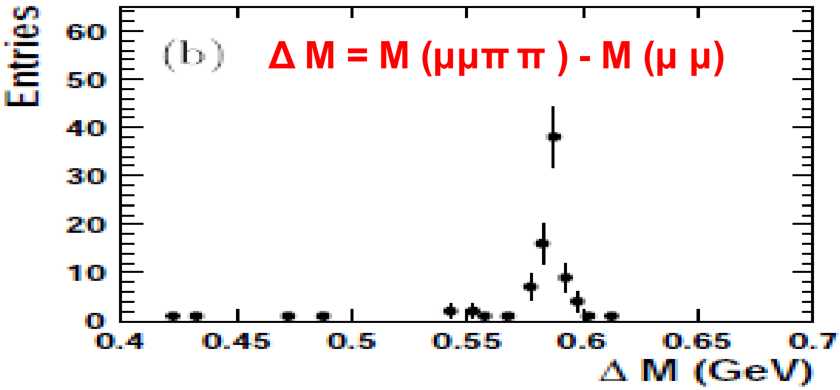
$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in exclusive DIS

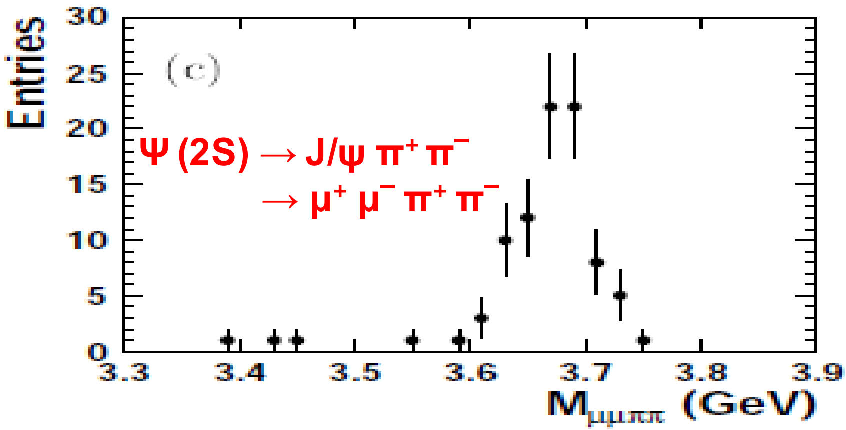
no activity in CTD in addition to scattered e' and decay product of ψ(2S) and J/ψ(1S)

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

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







$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in exclusive DIS

$\psi(2S)$ decay mode	$\sigma(\psi(2S))/\sigma(J/\psi(1S))$
$J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$	$0.29 \pm 0.04^{+0.02}_{-0.01}$
$\mu^+\mu^-$	$0.25 \pm 0.05^{+0.04}_{-0.02}$
combined	$0.28 \pm 0.03^{+0.02}_{-0.01}$

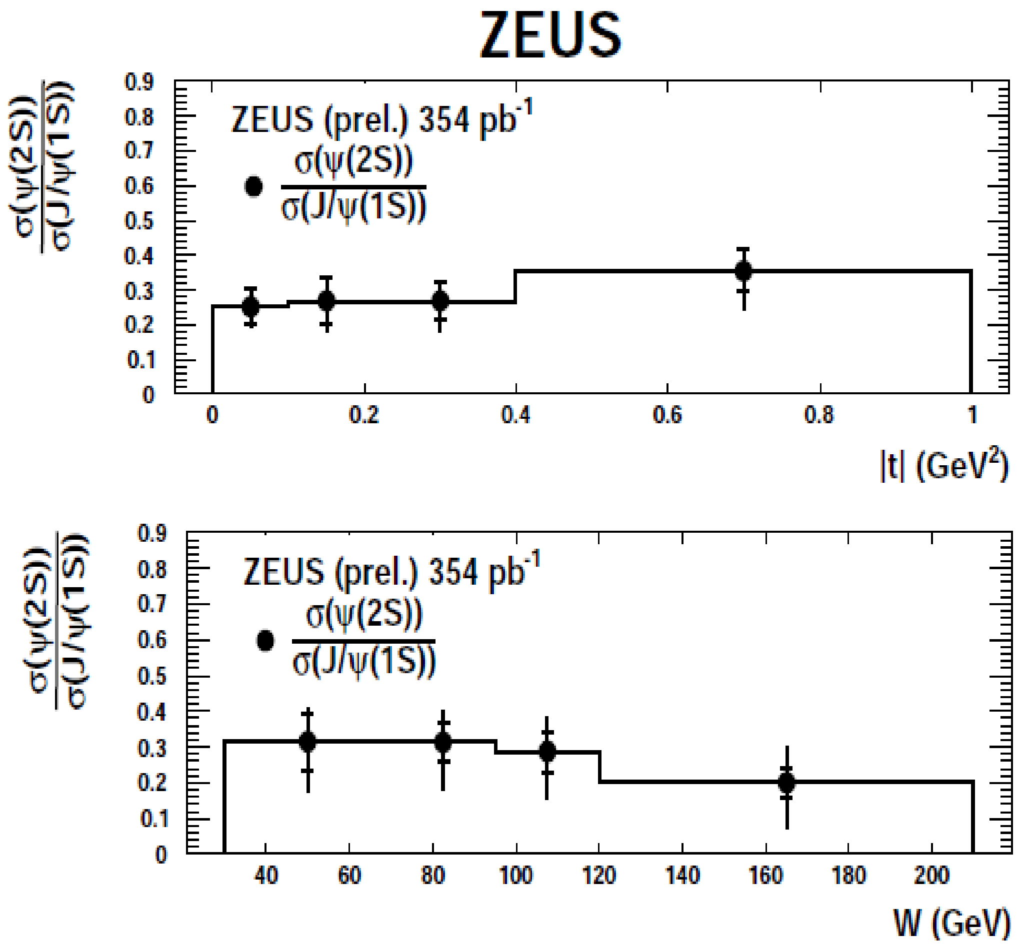
Both ratio measurements agree

$$R_{\mu\mu} = \left(\frac{N_{\mu\mu}^{\psi(2S)}}{BR_{\mu\mu}^{\psi(2S)} \cdot Acc_{\mu\mu}^{\psi(2S)}}\right) / \left(\frac{N_{\mu\mu}^{J/\psi(1S)}}{BR_{\mu\mu}^{J/\psi(1S)} \cdot Acc_{\mu\mu}^{J/\psi(1S)}}\right)$$

$$R_{J/\psi\,\pi\pi} = \left(\frac{N_{J/\psi\,\pi\pi}^{\psi(2S)}}{BR_{J/\psi\,\pi\pi}^{\psi(2S)} \cdot Acc_{J/\psi\,\pi\pi}^{\psi(2S)}}\right) / \left(\frac{N_{\mu\mu}^{J/\psi(1S)}}{Acc_{\mu\mu}^{J/\psi(1S)}}\right),$$

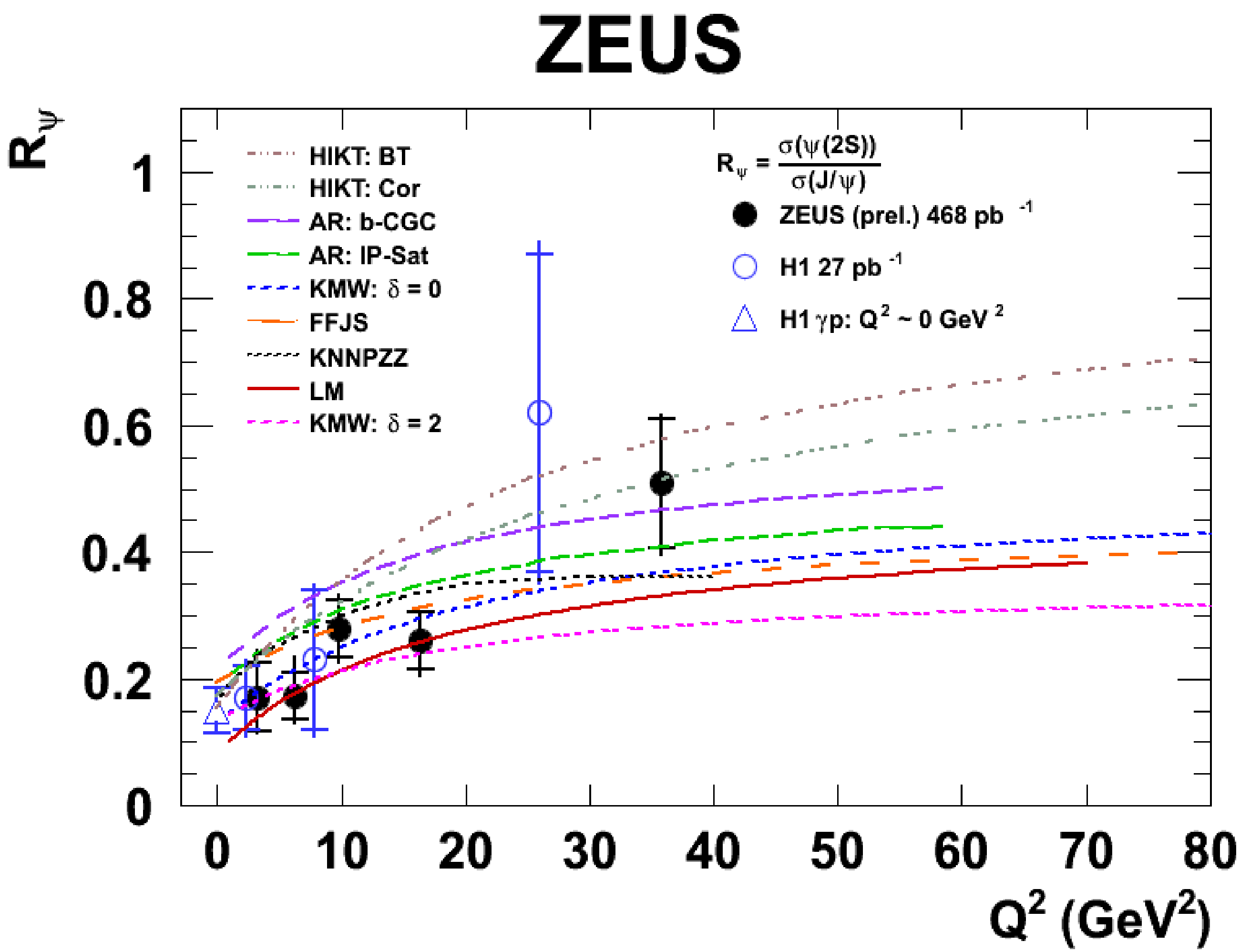
$$BR(J/\psi(1S) \rightarrow \mu^+\mu^-) = (5.93 \pm 0.06)\%,$$
$$BR(\psi(2S) \rightarrow \mu^+\mu^-) = (0.77 \pm 0.08)\%$$
$$BR(\psi(2S) \rightarrow J/\psi\,\pi^+\pi^-) = (33.6 \pm 0.4)\%$$

$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in DIS vs W and | t |



Independent of W and | t |

$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs Q^2 – model predictions



ZEUS & H1 : Ratio increases with Q^2

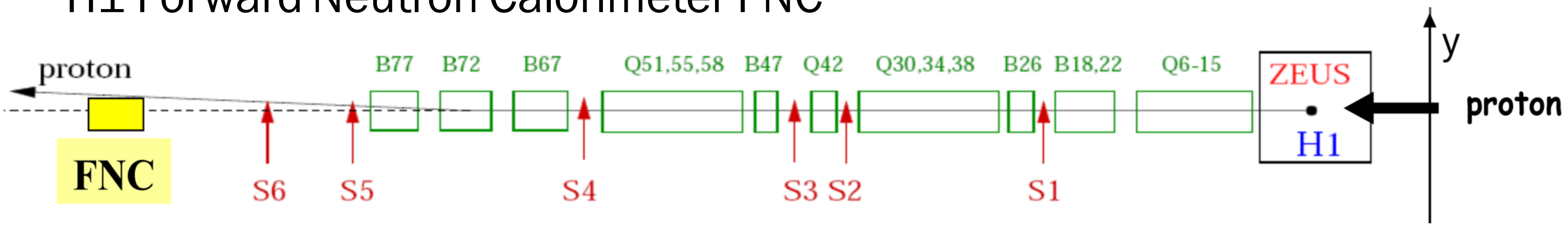
All theoretical models exibit an increase of the ratio with Q^2

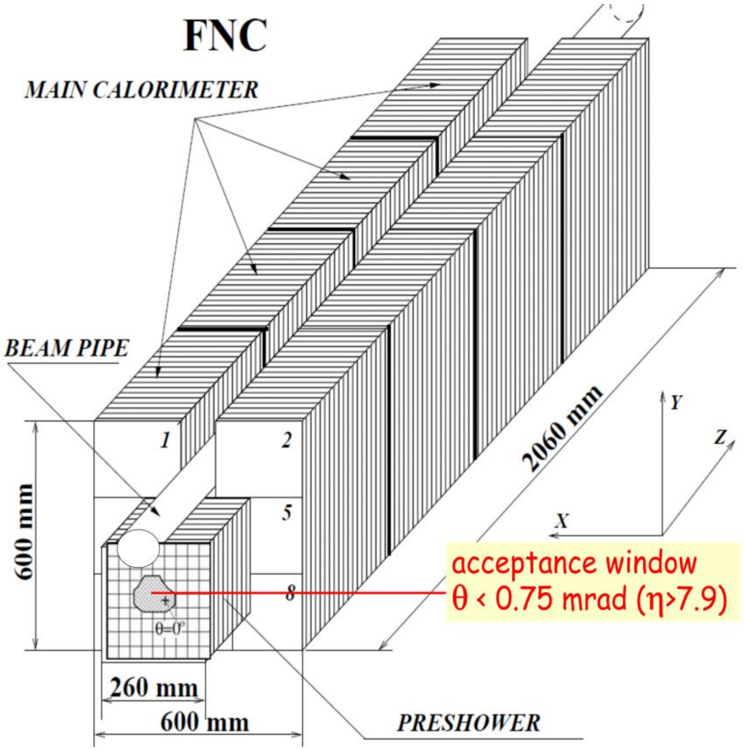
Exclusive photoproduction of ρ^0 with forward neutron at HERA

H1 prelim – 14-013

Exclusive photoproduction of ρ^0 with forward neutron

H1 Forward Neutron Calorimeter FNC





106 m from IP

Distinguish and measure neutral particles N and γ/π^o

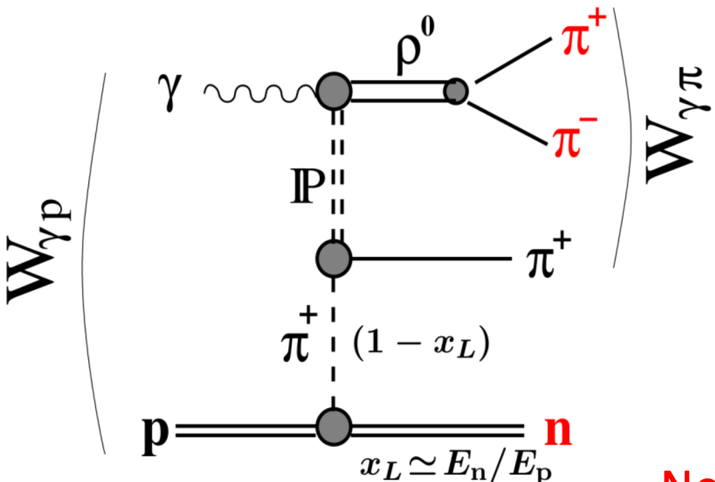
Limited acceptance for forward

π and N ($\eta_{lab} \geq 6$)

Exclusive photoproduction of ρ^0 with forward neutron

DATA sample:
2006-2007 e+ run
$1.16\ \mathrm{pb}^{-1}$

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



$$W_{\gamma p} \simeq \sqrt{2(E - p_z)_\rho E_p}$$

$$W_{\gamma\pi} \simeq W_{\gamma p}\sqrt{1 - x_L}$$

- the photon from the electron beam scatters elastically on the pion emitted from the proton producing ρ^o

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

$Q^2 < 2\ \mathrm{GeV}^2$
$\lvert t \rvert < 1\ \mathrm{GeV}^2$
$0.3 < m_{\pi\pi} < 1.5\ \mathrm{GeV}$
$20 < W_{\gamma\pi} < 100\ \mathrm{GeV}$
$E_n > 120\ \mathrm{GeV};\ \theta_n < 0.75\ \mathrm{mrad}$
$0.35 < x_L = E_n/E_p < 0.95$

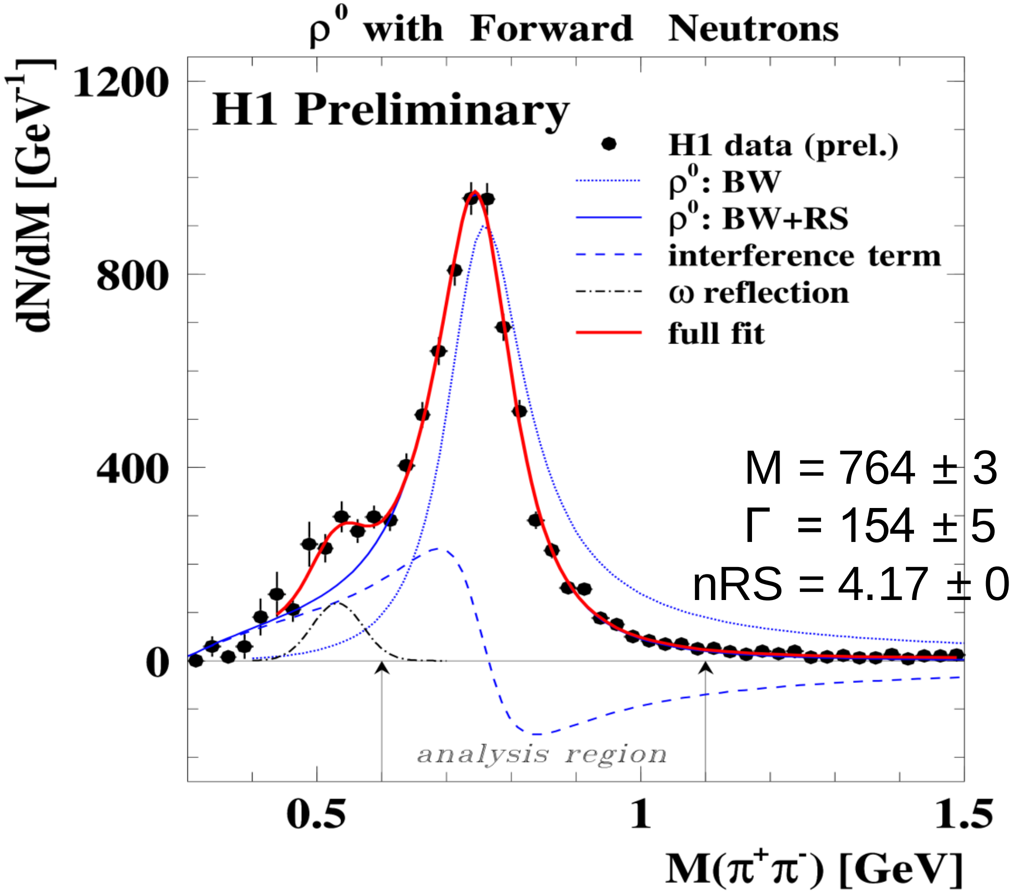
analysis phase space

No hard scale present
Regge framework
is most appropriate

Key observables:

- $x_L = E_n / E_p$ (or $x_\pi = 1 - x_L$) distribution: $\sim f_{\pi/p}(x_L)$
- W dependence: $\sim W^\delta$ - nature of exchange objects
- t-slope of ρ^o ($b \sim R^2$ in geometric picture)

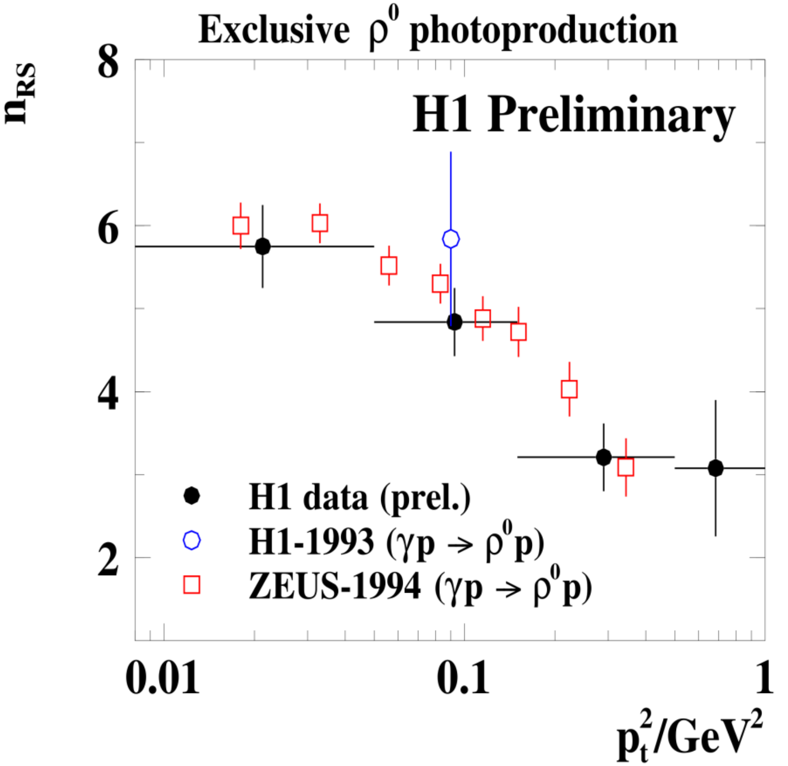
Exclusive photoproduction of ρ^0 with forward neutron



M = 764 ± 3 MeV
Γ = 154 ± 5 MeV
nRS = 4.17 ± 0.27

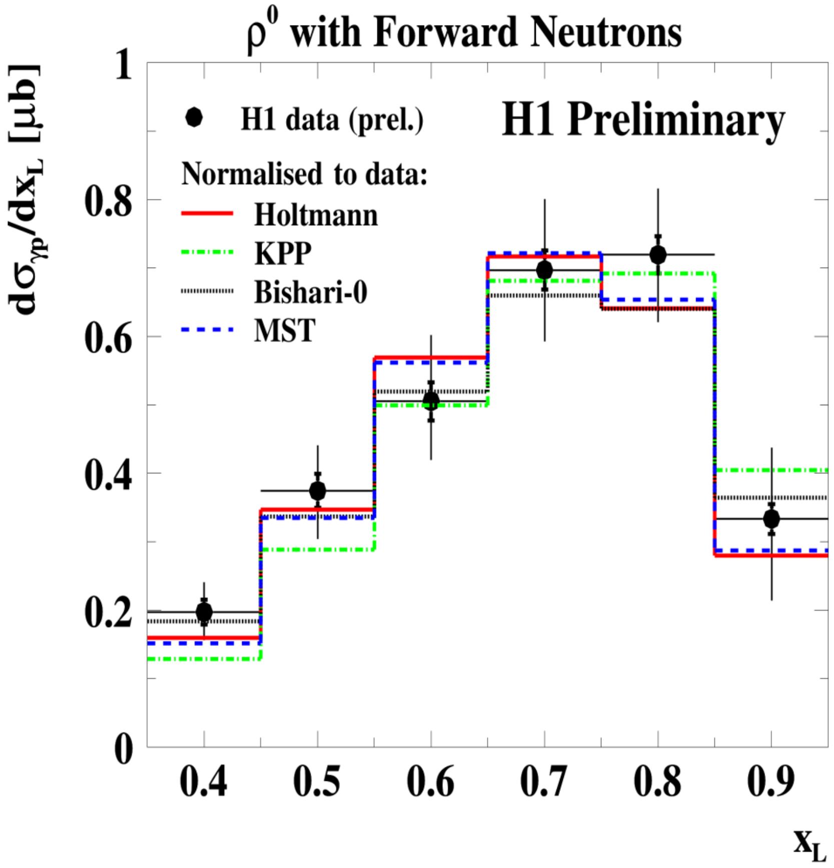
$$\frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} \propto BW_\rho(M_{\pi\pi}) \left(\frac{M_\rho}{M_{\pi\pi}}\right)^{n_{RS}}$$

The strength of the distortion is p_t dependent and characterised by the skewing parameter n_{RS}



The BW shape is distorted due to interference with non-resonant ππ production amplitude

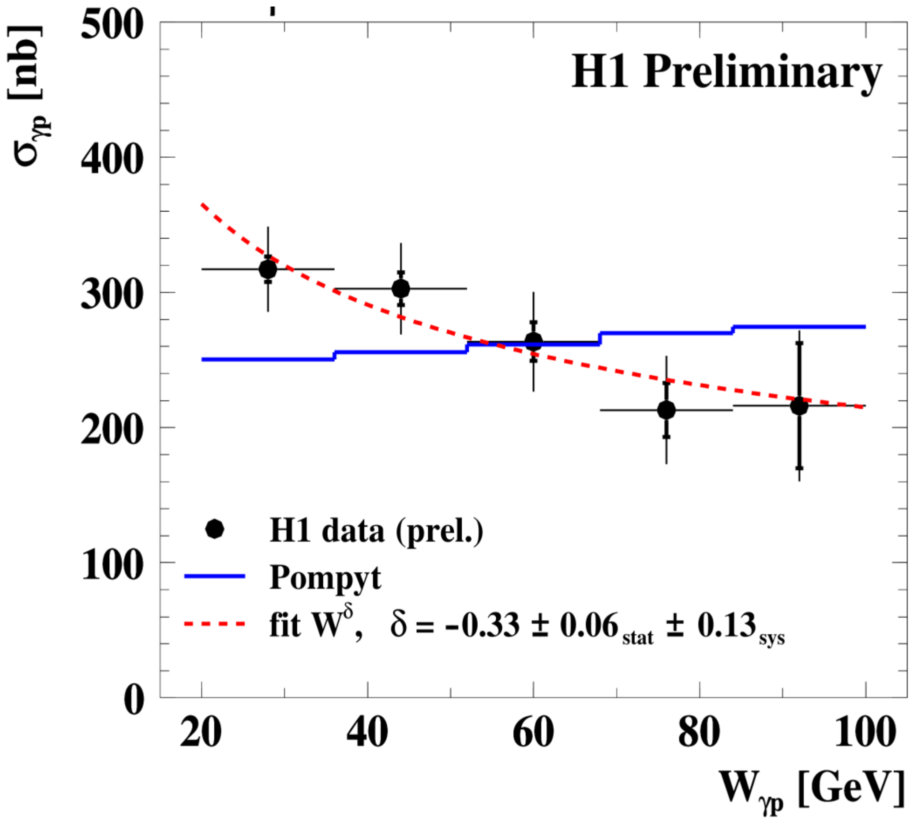
Exclusive photoproduction of ρ^0 with forward neutron

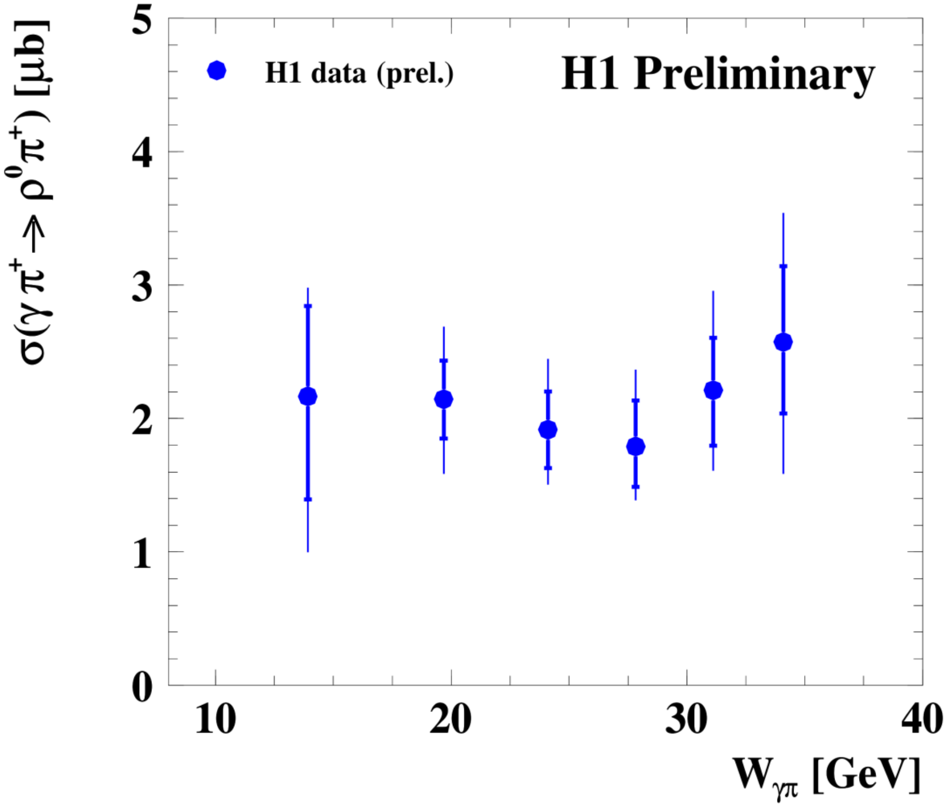


- $d\sigma_{\gamma p} / dx_L$
- Shape well described by model predictions
- Models differ in calculating the pion flux

Exclusive photoproduction of ρ^0 with forward neutron

Total γp and $\gamma\pi$ cross sections vs W





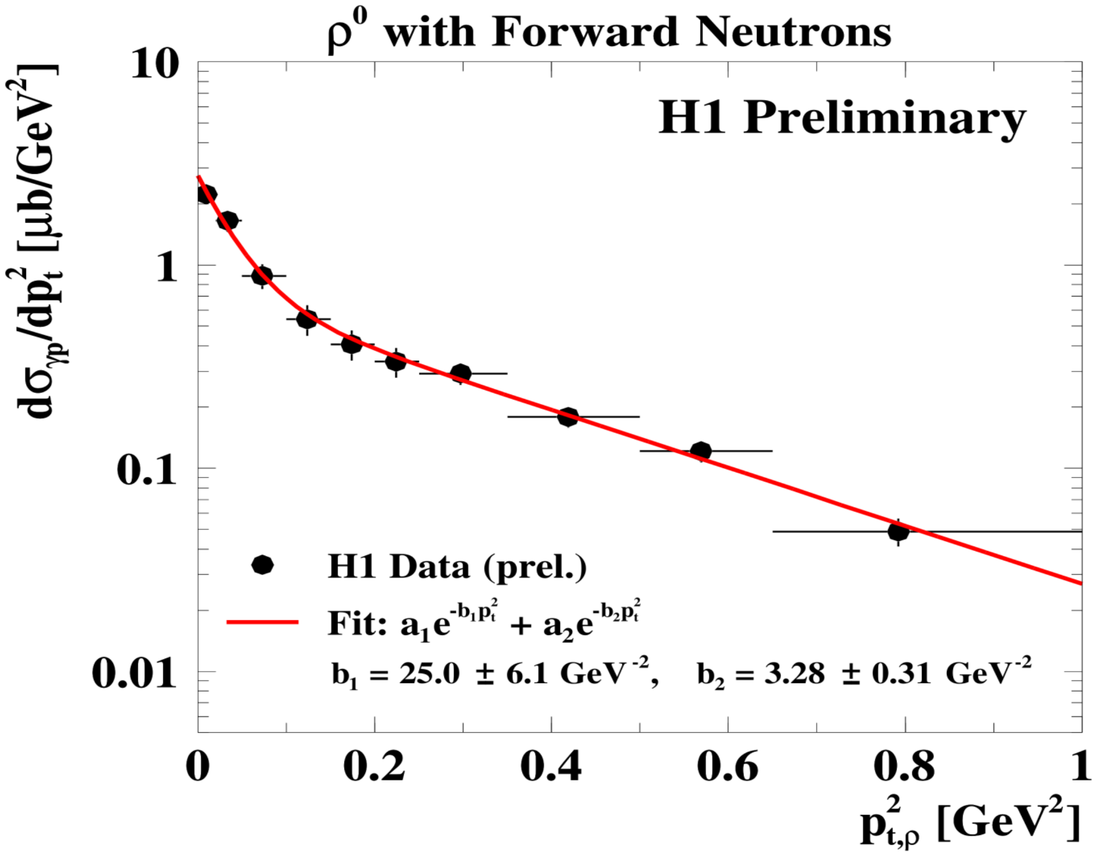
Holtmann pion flux used

$\sigma^{el}_{\gamma\pi} / \sigma^{el}_{\gamma p} = 0.21 \pm 0.06$

at W = 22 GeV

Regge motivated power low fit W^{δ} yelds $\delta < 0$

Exclusive photoproduction of ρ^0 with forward neutron



$d\sigma_{\gamma p} / dp_{t,\rho}$

IP and π exchange

Two slopes as predicted for
a double-peripheral process:
low mass π^+N state $\longrightarrow$ large slope
high masses $\longrightarrow$ less steep slope

Measurement of Feynman-x Spectra of Photons and Neutrons in the Very Forward Direction in Deep-Inelastic Scattering at HERA

DESY 14-035

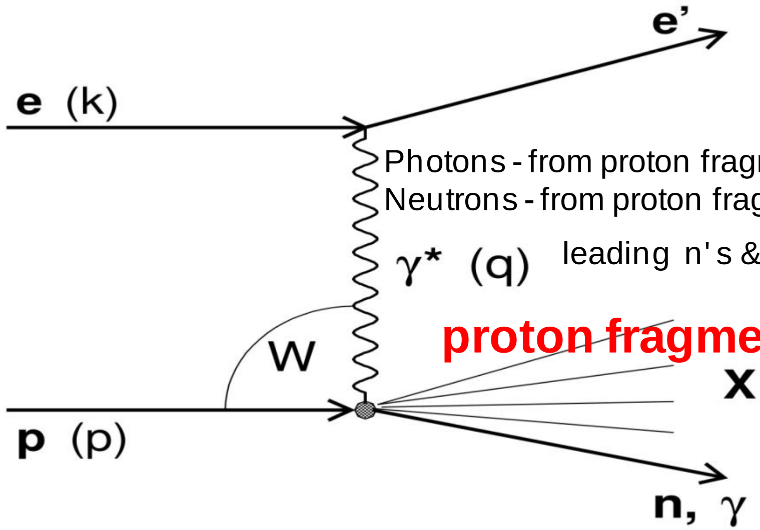
Eur.Phys.J.C74(2014)2915

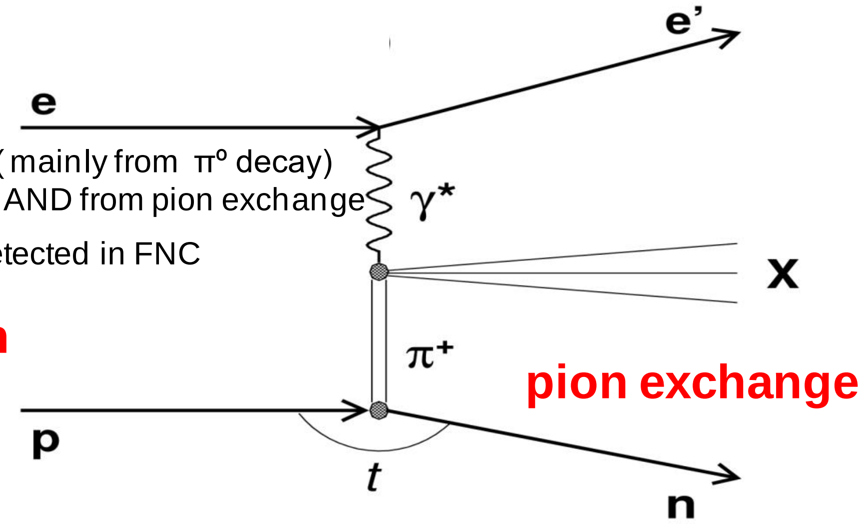
Feynman-x Spectra of Photons and Neutrons

Energetic forward particles are produced at very small angles via

Photons - from proton fragmantation (mainly from π^o decay)
Neutrons - from proton fragmentation AND from pion exchange

leading n's & γ's are detected in FNC



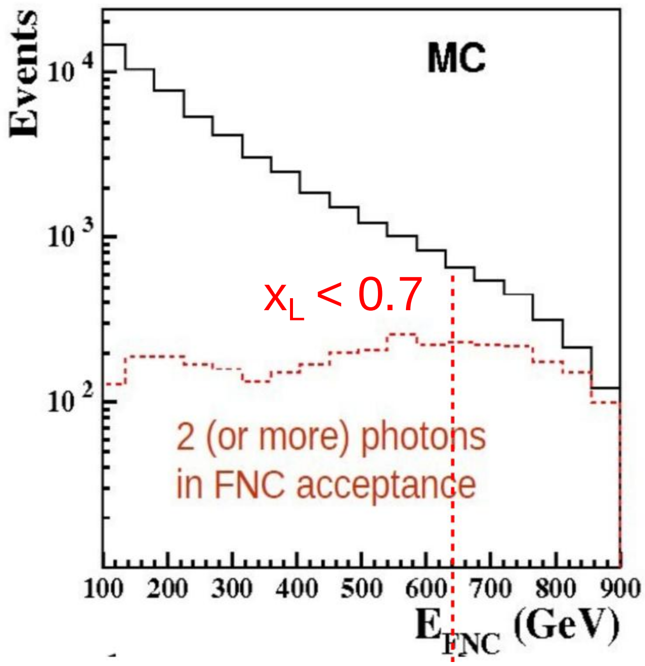


$Q^2 = -q^2 = -(k-k')^2$	photon virtuality	$x_L = E_{n,\gamma}/E_p$	long.momentum fraction
$y = (q \cdot p) / (k \cdot p)$	inelasticity	$x_F = p^*_{\parallel} / p^*_{\parallel max} = 2p^*_{\parallel} / W$	Feynman x
$W^2 = (q+p)^2$	γ^*p CM energy	$x_F \approx x_L$	for very forward particles

Feynman-x Spectra of Photons and Neutrons

HERA II (2006-2007) L = 131 pb [1]
230k events with neutrons
83k events with photons

NC DIS Selection	
$6 < Q^2 < 100$ GeV^2	
$0.05 < y < 0.6$	
$70 < W < 245$ GeV	
Forward photons	**Forward neutrons**
$\eta > 7.9$	$\eta > 7.9$
$0.1 < x_F < 0.7$	$0.1 < x_F < 0.94$
$0 < p_T^* < 0.4$ GeV	$0 < p_T^* < 0.6$ GeV
W **ranges for cross sections** $\frac{1}{\sigma_{DIS}}\frac{d\sigma}{dx_F}$	
$70 < W < 130$ GeV	
$130 < W < 190$ GeV	
$190 < W < 245$ GeV	



At high x_L many photon candidates FNC clusters originate from more than one photon

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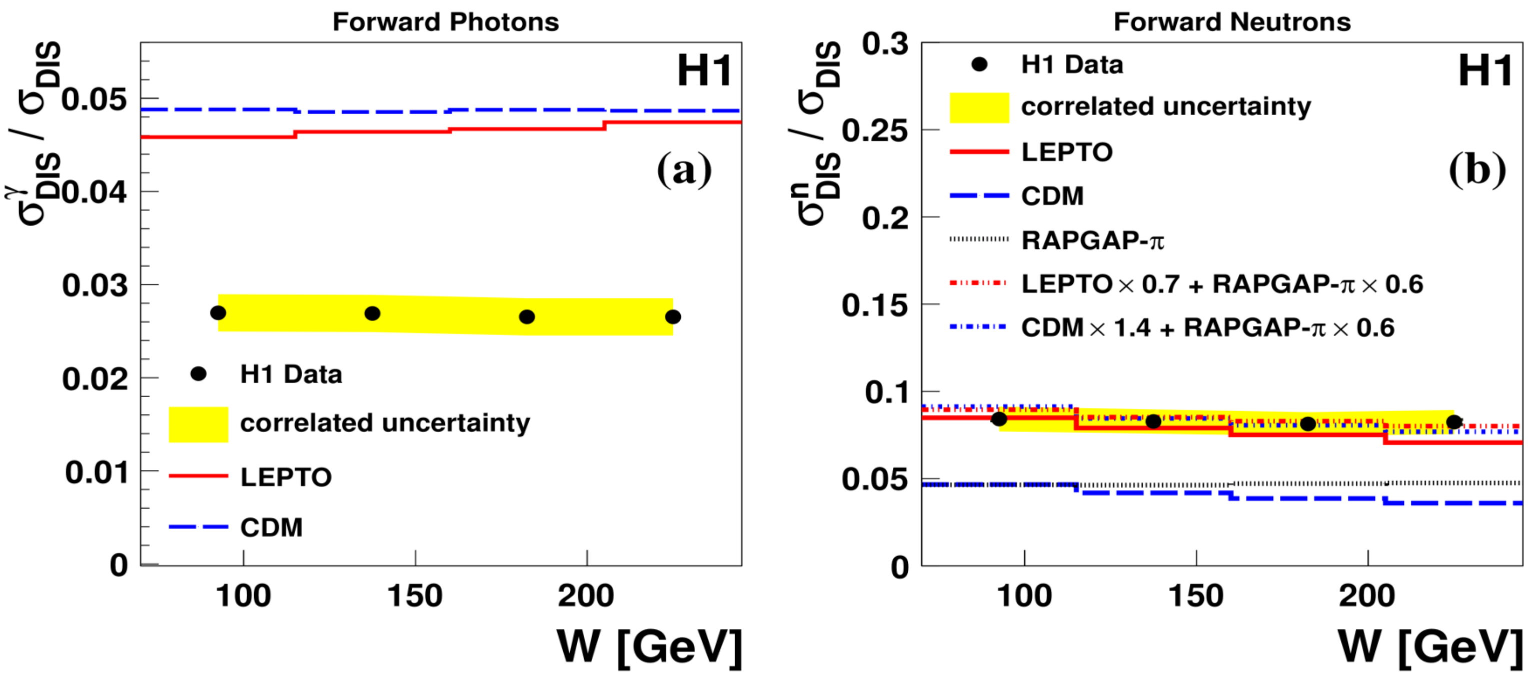
cut $x_L < 0.7$ to suppress multi-photon events

Cross sections are normalised to the total DIS cross section σ_{DIS}

Feynman-x Spectra of Photons and Neutrons

Normalised cross sections as a function of W



Fraction of forward photons & neutrons in DIS independent of W

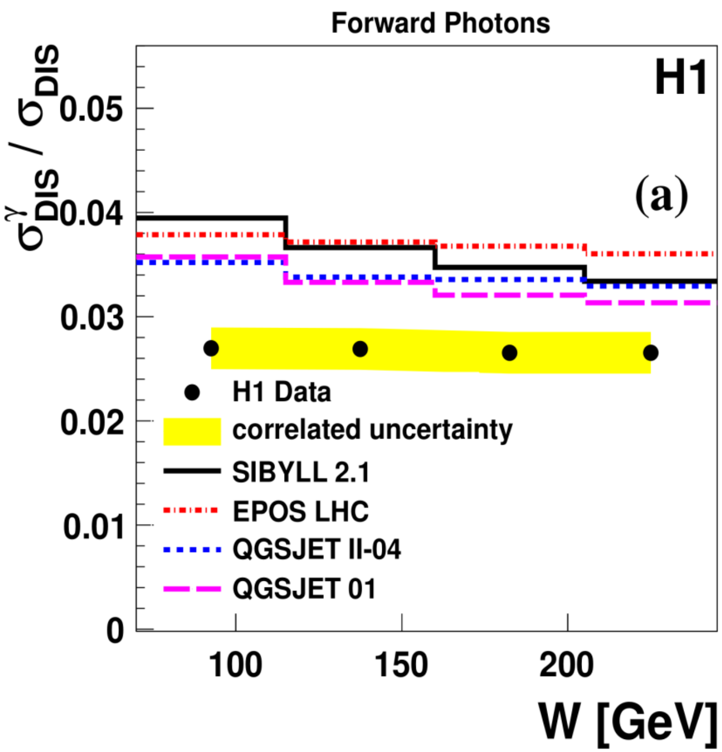
$\longrightarrow$ limiting fragmentation

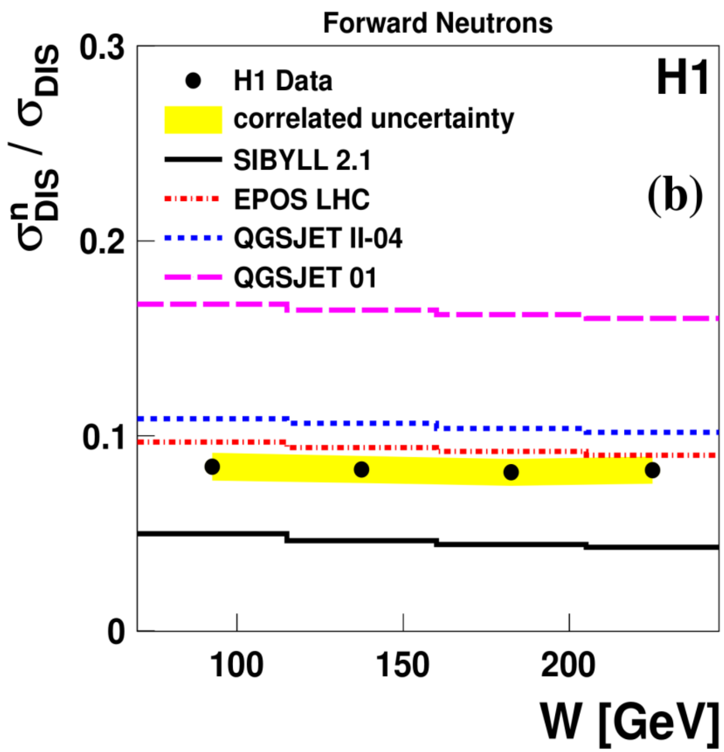
LEPTO and CDM predict too high rate of photons, by ~70%

LEPTO predicts the neutron rate rather well, CDM has too low rate

Feynman-x Spectra of Photons and Neutrons

Normalised cross sections as a function of W



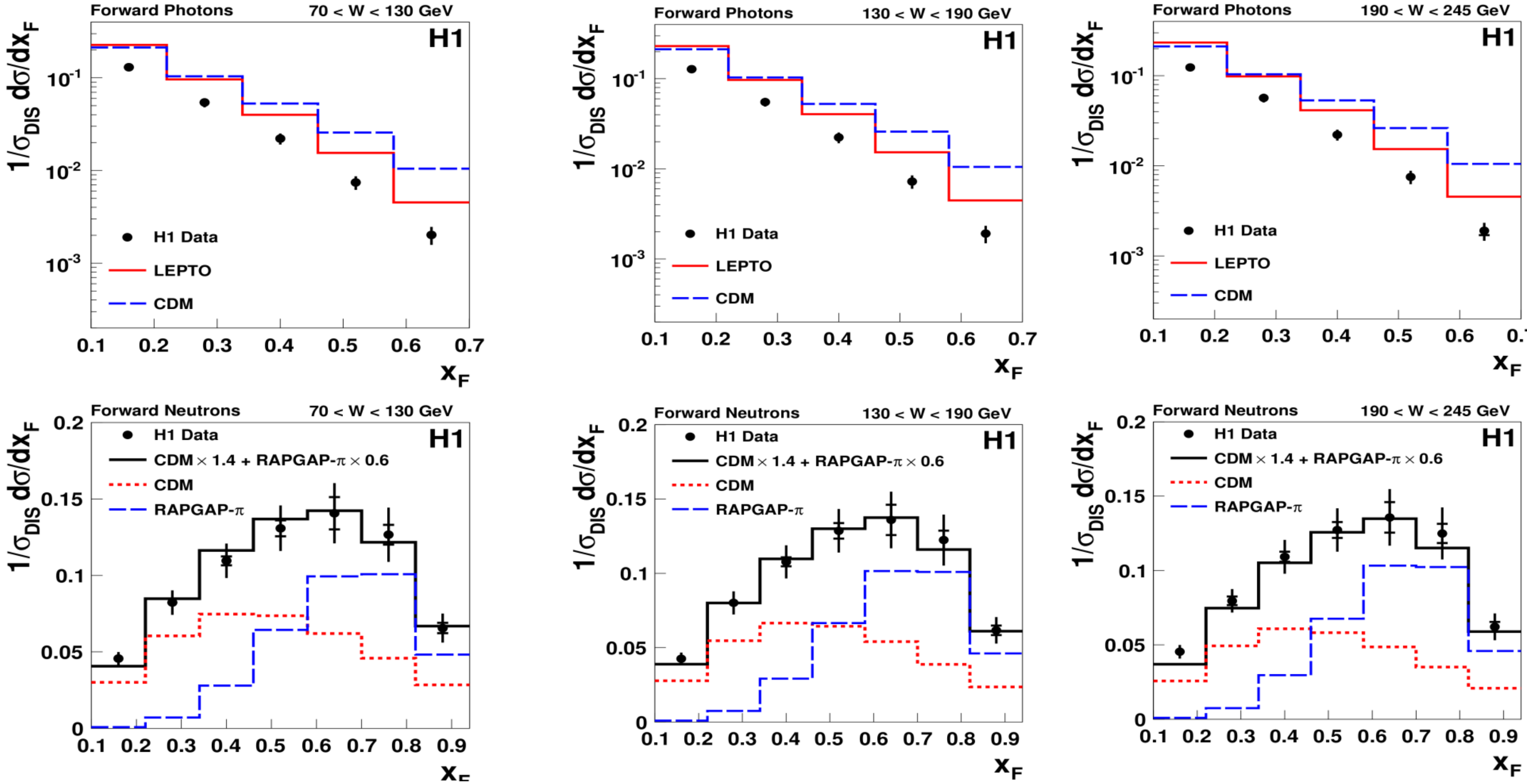


CR models predict too high rate of forward photons, by 30-40%
Large spread in the forward neutron predictions (EPOS LHC closest, but still different)
CR models indicate a W-dependence for photons, but less so for neutrons

Feynman-x Spectra of Photons and Neutrons

Normalised cross sections as a function of x_F in W intervals

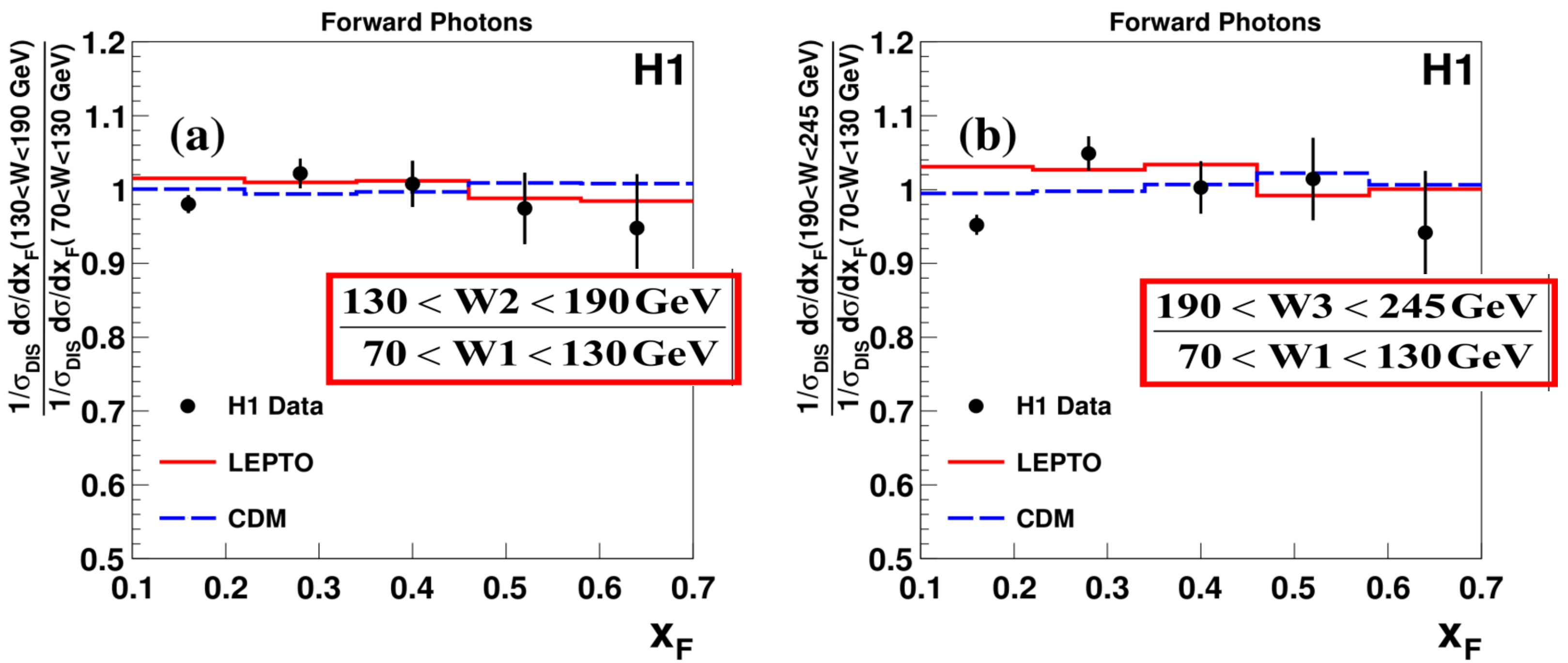
70<W1<130 GeV | 130<W2<190 GeV | 190<W3<250 GeV



- LEPTO and CDM — both overestimate the photon rate significantly
- LEPTO describes the shape of photon x_F spectra well, CDM is too hard
- Neutron x_F spectra well desribed by Combination of MC models

Feynman-x Spectra of Photons and Neutrons

Test of Feynman Scaling : Photons : Fragmentation models

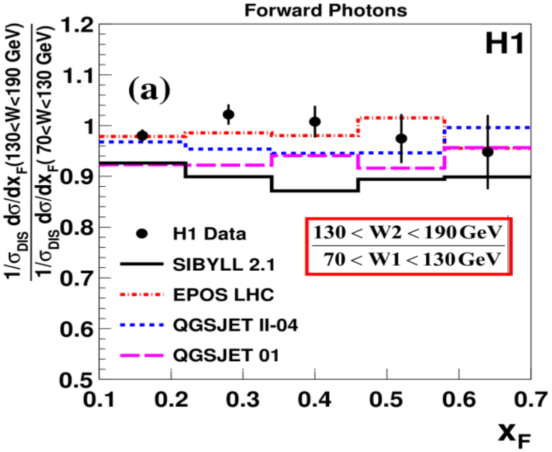


FS: Expect Feynman-x distributions to stay uncharged in the high energy limit

DATA and Fragmentation models are compartible with Feynman Scaling

Feynman-x Spectra of Photons and Neutrons

Test of Feynman Scaling : Photons & Neutrons: CR models



DATA: γ′ s & N′ s:

ratios are consistent with unity and with being *const*

↓

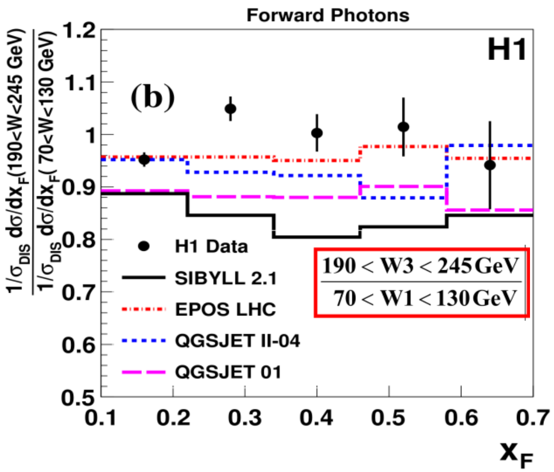
FS in the fragmentation region holds

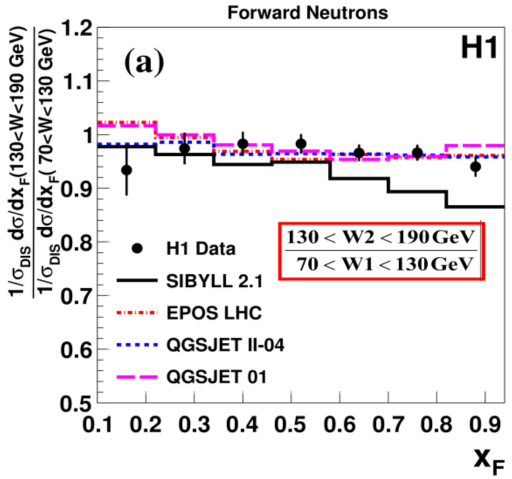
CR: γ′ s:

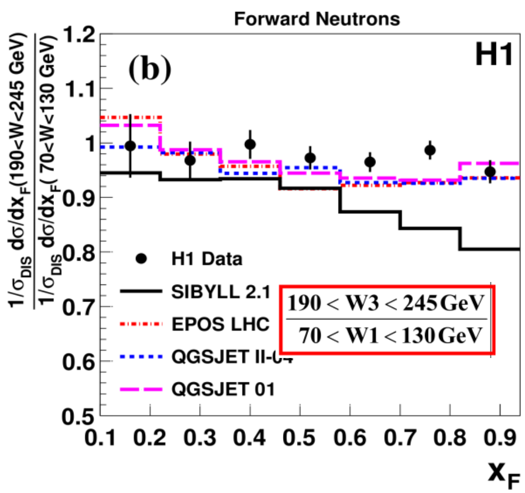
- FS violated (lower rates with W rise)
- effect strongest for SIBYLL&QGSJET
- EPOS LHC closer to data

CR: N′ s:

- Compartible with FS except SYBILL







Summary

- The first measurement of diffractive production of exclusive dijets in DIS has been reported by ZEUS. The shape of Φ distribution was parameterised as motivated by theory by $1+A\cos(2\Phi)$ and measured value of parameter A is predominantly consistent with the two gluon exchange.

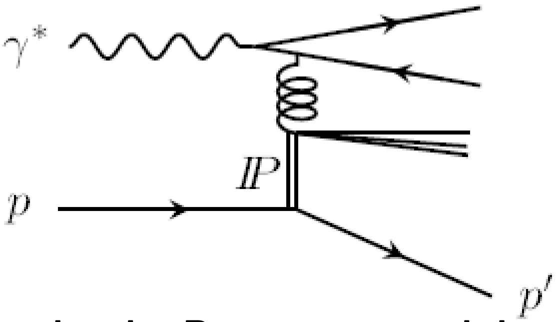
- The cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in exclusive DIS has been measured for the first time by ZEUS with improved precision and agrees with models of VM production.

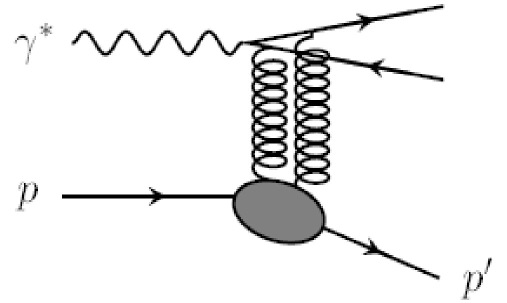
- Photoproduction of excusive ρ^{o} associated with leading neutron, measured by H1, was used to extract the elastic photon-pion cross section $\sigma(\gamma\pi \rightarrow \rho^{o}\pi^{+})$ in the OPE approximation for the first time at HERA. Differential cross sections for the reaction $\gamma p \rightarrow \rho^{o} n \pi^{+}$ exhibit features typical for exclusive double peripheral process.

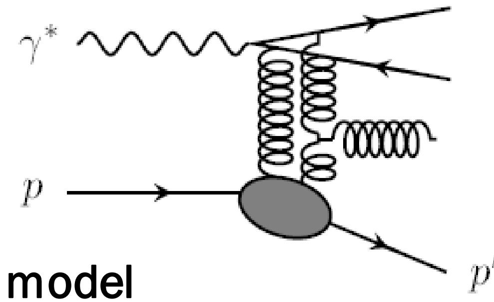
- Precise measurements of high energy forward neutrons and photons has been performed with the FNC by H1. The measured cross sections are consistent with hypotheses of limiting fragmentation and Feynman scaling in W range 70 - 245 GeV.

BACKUP

Exclusive dijet production in diffractive DIS







Resolved – Pomeron model
(G.Ingelman and P.Schlein et al.)

Gluon emitted from the Pomeron

$q\bar{q}$ produced via Boson Gluon Fusion

Positive parameter A

Cross section sensitive to the diffractive gluon distribution in the proton

Pomeron remnant contributes to $q\bar{q}$ production

Two-Gluon-Exchange model
(J.Bartels and H.Jung et al.)

Virtual photon fluctuates into a $q\bar{q}$.

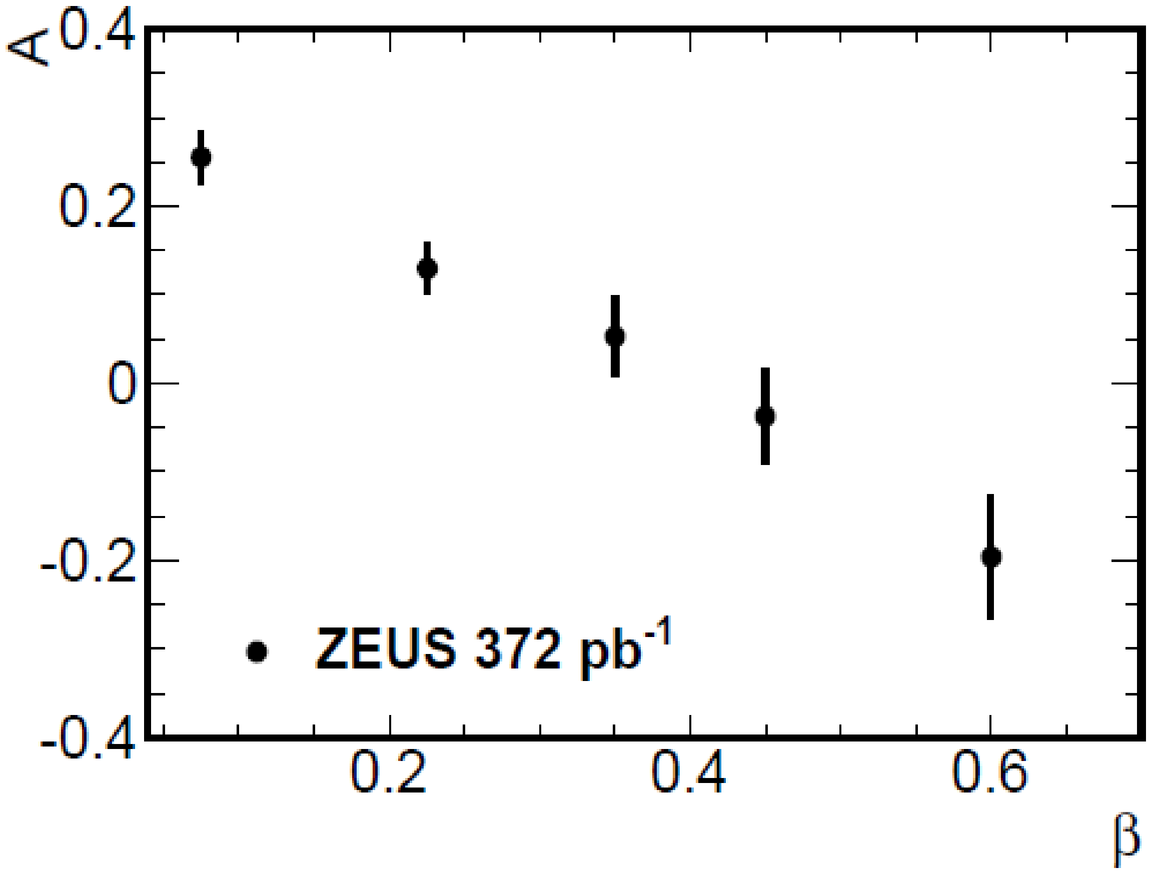
Two gluons from the proton couples to $q\bar{q}$.

Negative parameter A

Cross section sensitive to the gluon distribution in the proton

Emission of additional gluon also contributes to production of $q\bar{q}$.

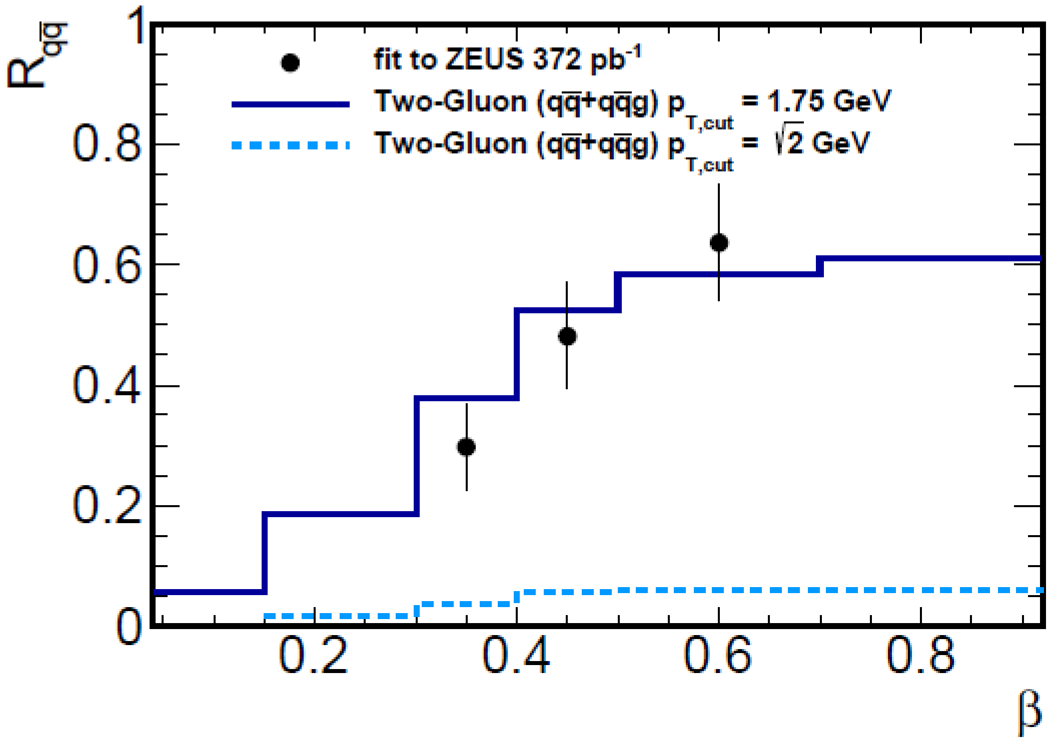
Exclusive dijet production in diffractive DIS



Parameter A decreases with increasing β and changes sign around β = 0.4

Exclusive dijet production in diffractive DIS

Two – Gluon - Exchange model: $q\bar{q}$ dijet component



Φ distribution predicted to $q\bar{q}$

and $q\bar{q}g$ have different shape

Ratio $R_{q\bar{q}} = \sigma(q\bar{q})/(\sigma(q\bar{q}) + \sigma(q\bar{q}g))$

can be determined by studying the measured Φ distribution

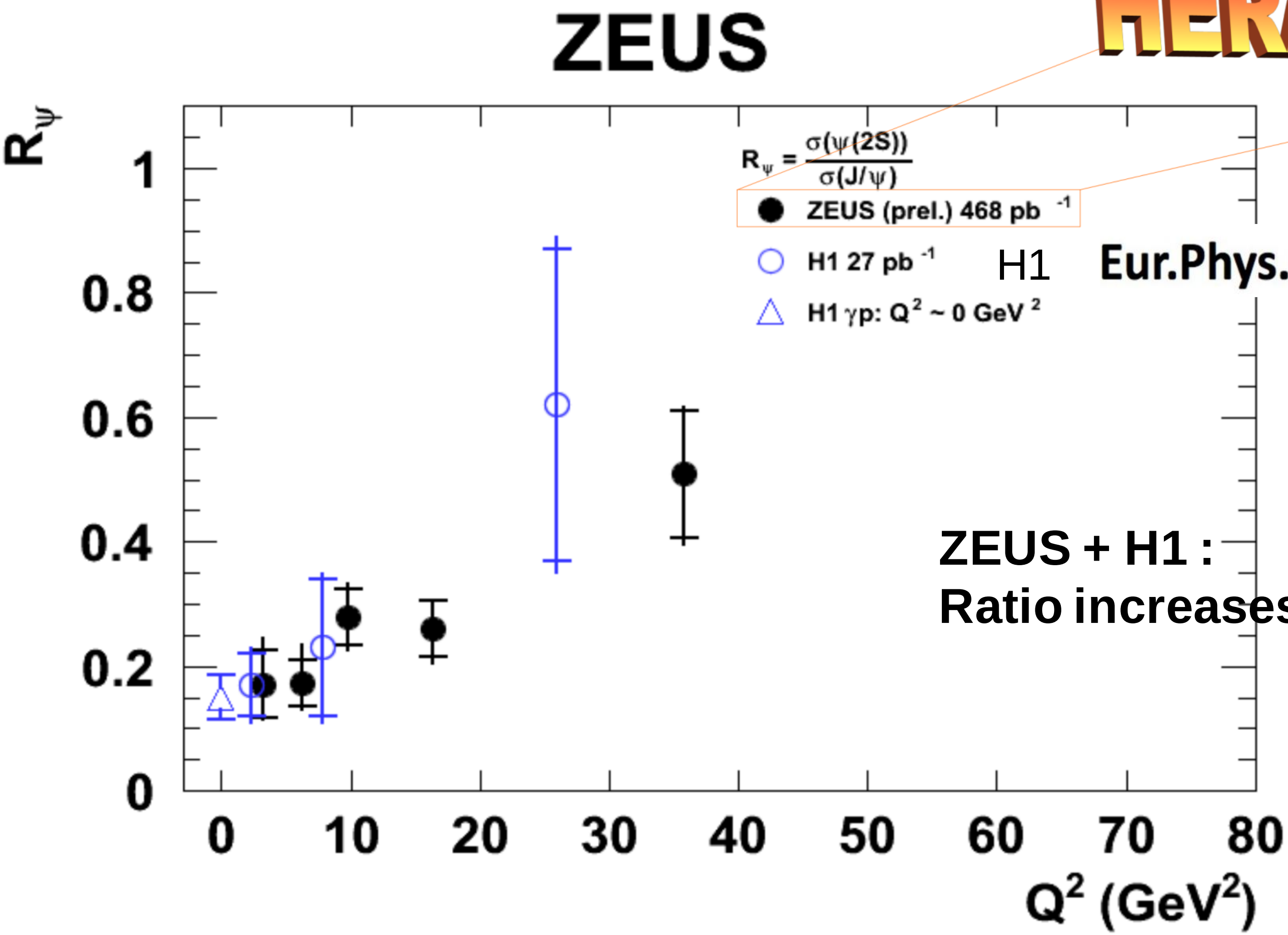
Predicted $R_{q\bar{q}}$ depends on the applied p_{Tcut}

The p_{Tcut} value of √2 GeV used in the original calculation significantly underestimated the ratio

The measured ratio can be well described with p_{Tcut} = 1.75 GeV

$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in DIS vs Q^2

HERA I+HERA II



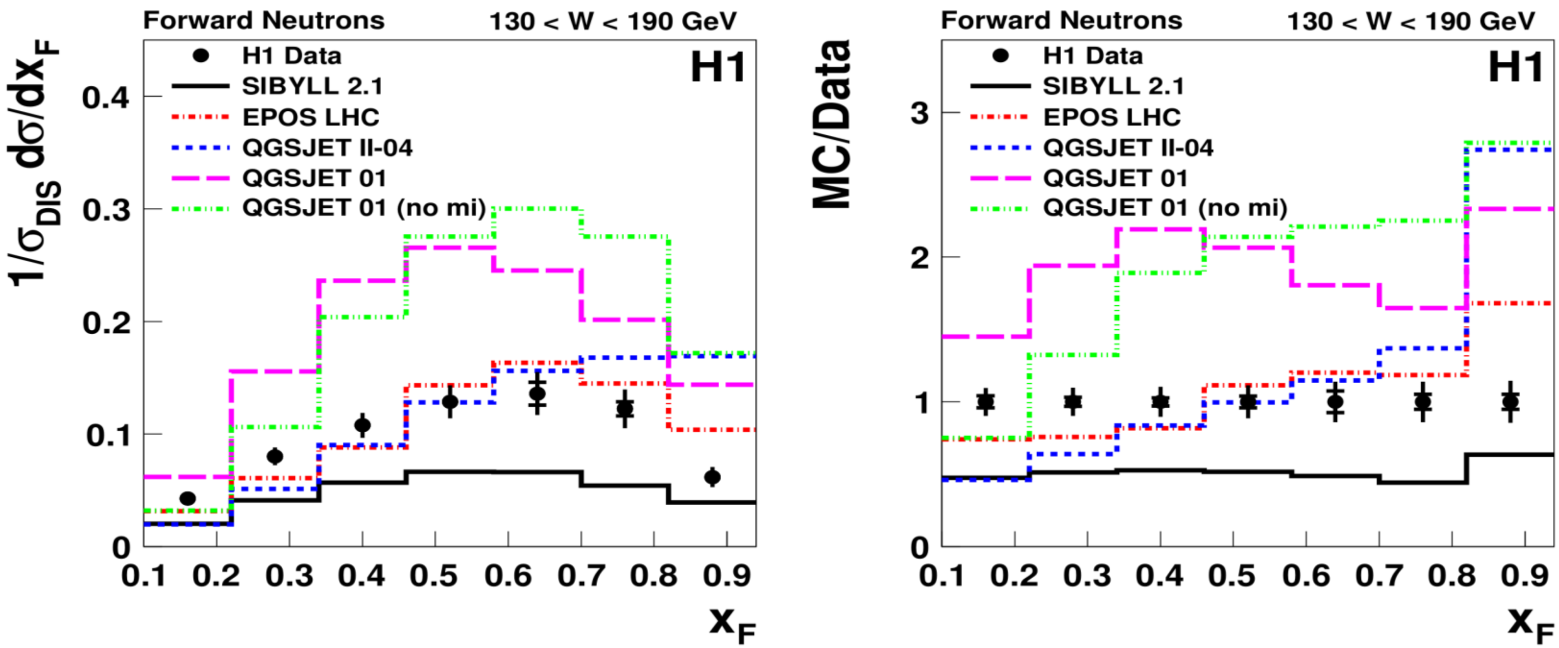
H1 Eur.Phys.J.C10:373-393,1999

ZEUS + H1 :
Ratio increases with Q^2

Feynman-x Spectra of Photons and Neutrons

Normalised cross sections as a function of x_F : Neutrons

130<W2<190 GeV



CR models predict very different neutron rates

x_F dependence:

QGSJET models are too hard and predict too high rates

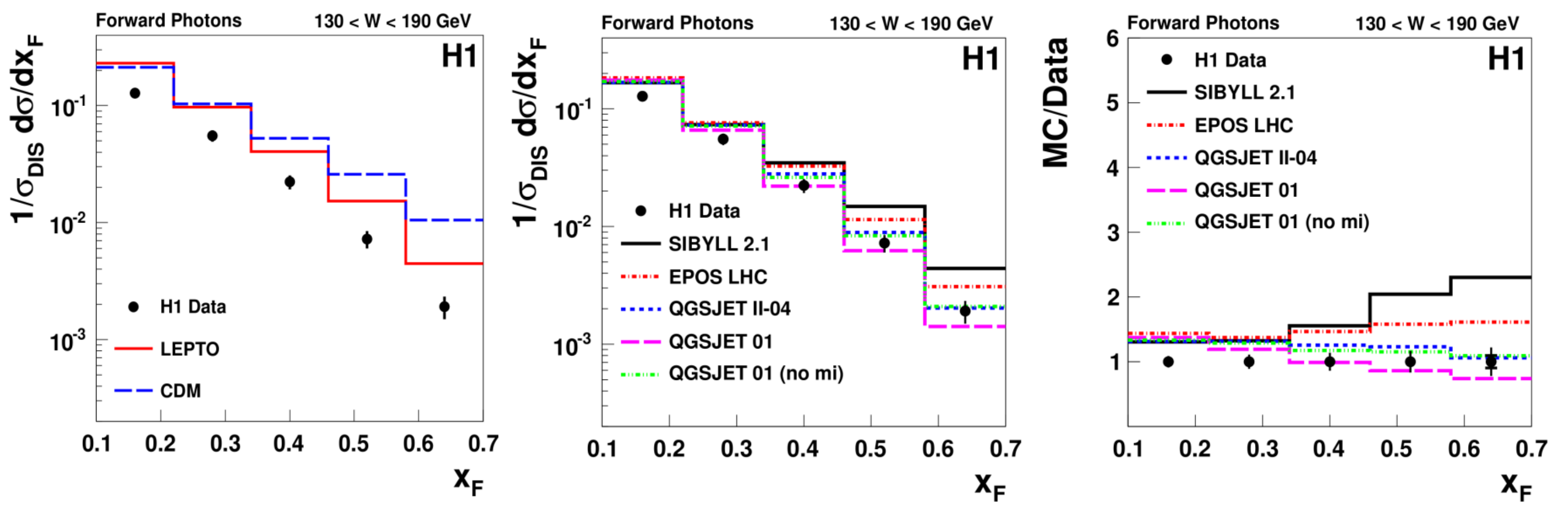
SIBYLL 2.1 describes the shape of the xF dependence, but too low rate

EPOS LHC gives reasonable description, exept at highest x_F values

Feynman-x Spectra of Photons and Neutrons

Normalised cross sections as a function of x_F : Photons

130<W2<190 GeV



CR: in general predict γ´s rates which are closer to DATA than standard DIS models

x_F dependence :

QGSJET models are too soft

SYBILL2.1 - is too hard

EPOS LHC gives the best description, but also too hard