

# Measurements of diffraction at HERA



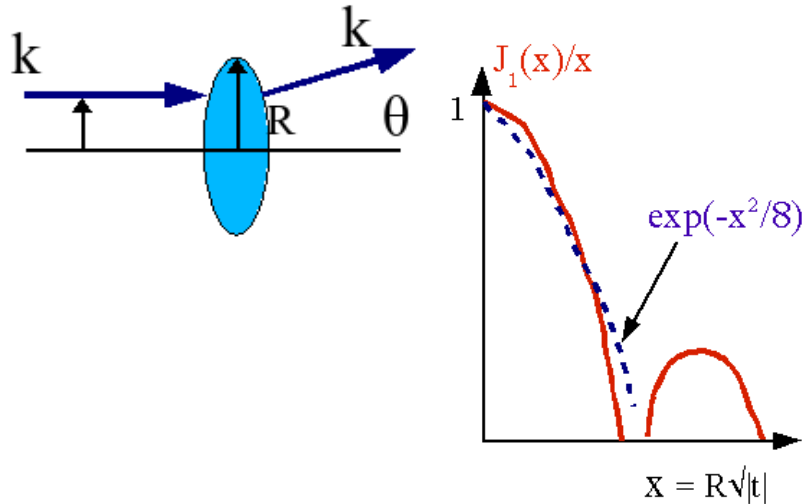
Jan Figiel  
Institute of Nuclear Physics, Kraków  
on behalf of the **H1** and **ZEUS** collaborations



- Introduction to diffraction in h-h and e-p interactions
- Recent results from HERA
  - Exclusive diffraction: vector mesons, DVCS
  - Inclusive diffraction
  - Diffractive dijet production: QCD factorisation tests
- Summary

# Diffraction in hadron-hadron interactions (1)

Light scattering: Fraunhofer diffraction ( $1/k \ll R$ )

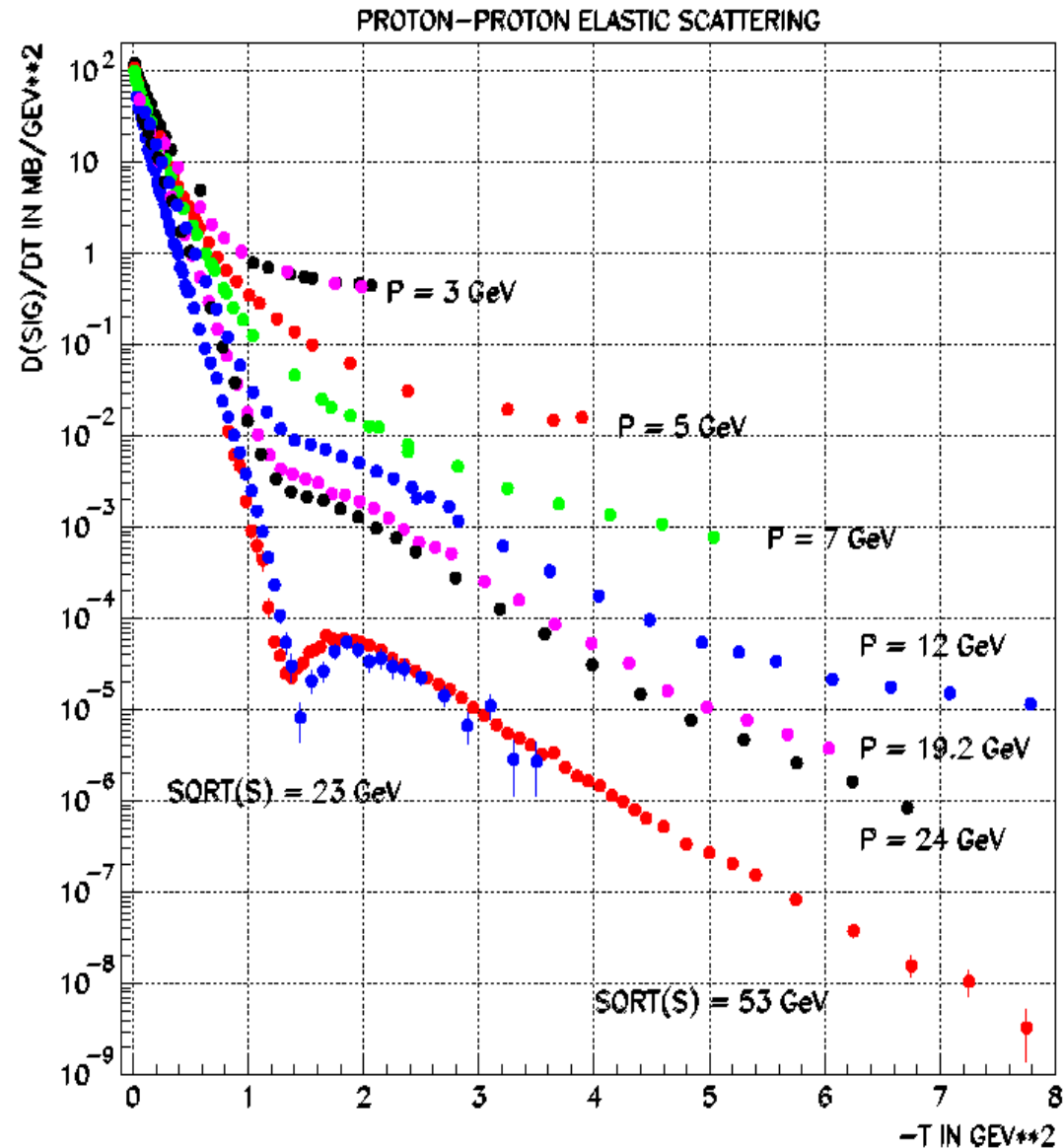


Elastic hadron-hadron scattering:

$$|t| = 4k^2 \sin^2(\theta/2),$$

$$d\sigma/dt \sim \exp(-b|t|),$$

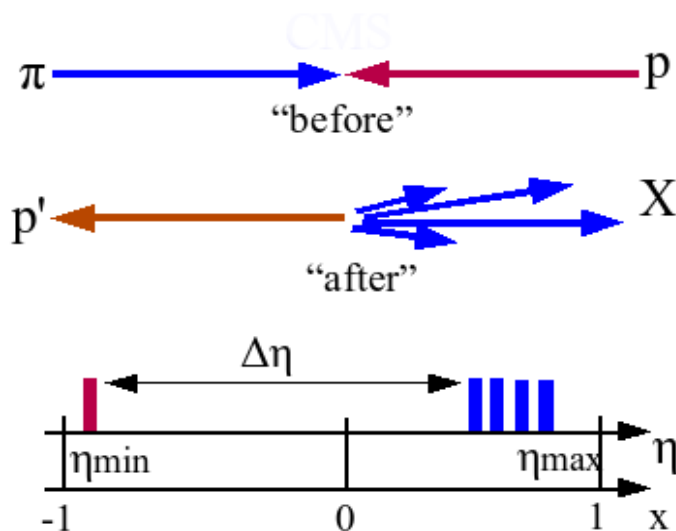
$$b = (R/2)^2 \approx 8 - 10 \text{ GeV}^{-2}$$



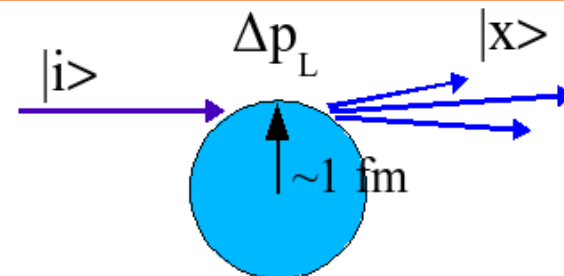
# Diffraction in hadron-hadron interactions (2)

Inelastic hadron diffractive dissociation  $\leftrightarrow$  coherence condition:

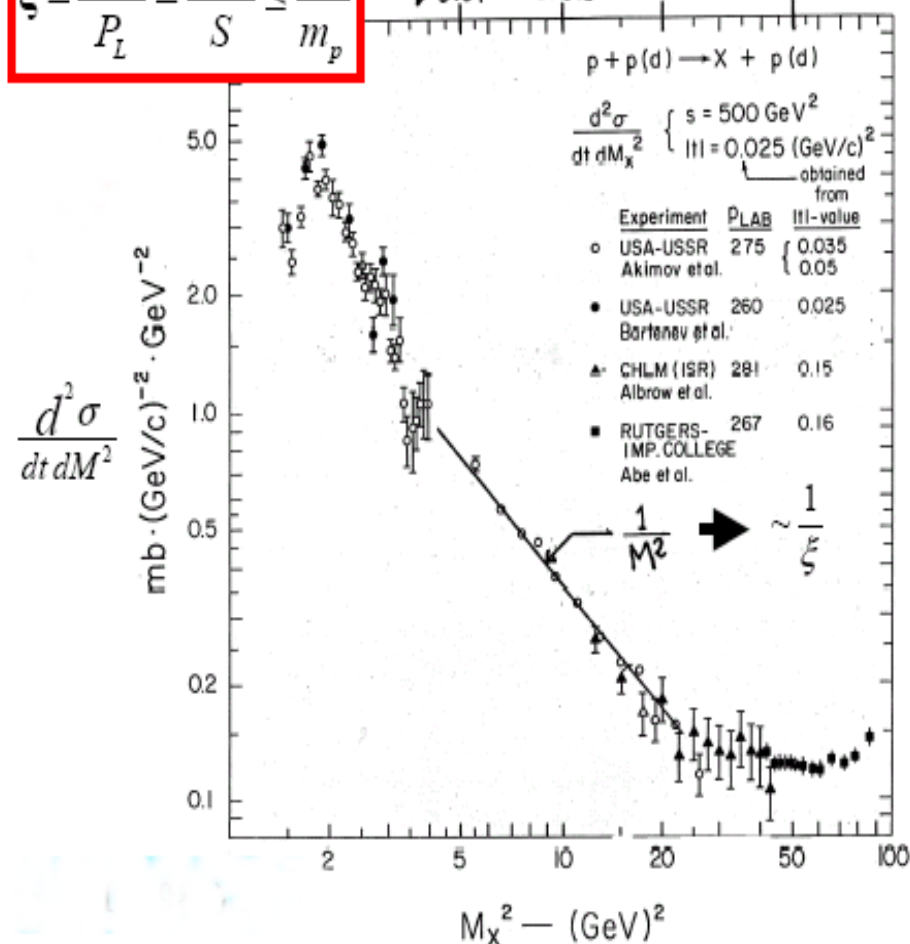
- $\Delta I = \Delta Q = \Delta S = 0, \quad \Delta P = (-1)^J$
- $\xi = M_X^2/s = \Delta p_L/p_L = 1 - |x| < m_\pi/m_p = 0.15$
- $\Delta\eta = \ln(1/\xi) > 2$ , (“large rapidity gap, LRG”)



$s$  = squared CMS energy of hadrons  
 $\eta = -\ln(\tan(\theta/2))$ , (pseudo-)rapidity



$$\xi = \frac{\Delta P_L}{P_L} = \frac{M_X^2}{S} \leq \frac{m_\pi}{m_p}$$



# Diffraction in hadron-hadron interactions (3)

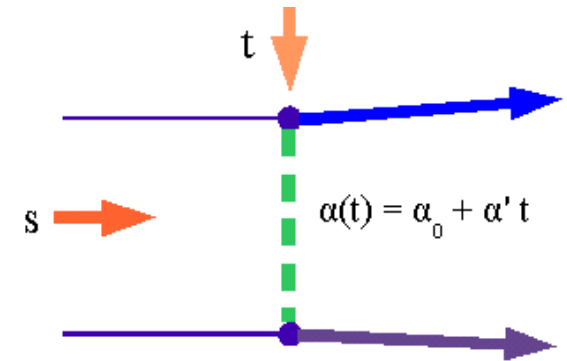
**Regge model** of hadronic interactions:

two-body reactions: “trajectory” exchange ( $s \rightarrow \infty$ )

$$\alpha(t) = \alpha_0 + \alpha' t$$

$$d\sigma/dt \sim F(t) s^{2\alpha(t)-2} = F(t) s^{2\alpha(0)-2} \exp(2\alpha' \log(s) t)$$

$$\sigma_{tot} \sim s^{\alpha(0)-1}$$



Elastic scattering ( $\rightarrow$  total cross-section):

exchange of Pomeron IP trajectory (vacuum quantum numbers)

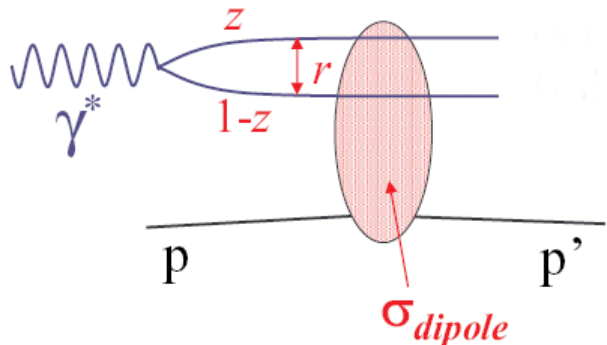
Universal parametrisation of Donnachie-Landshoff (“soft” Pomeron):

$$\alpha_{IP}(t) = 1.08 + 0.25 t$$

PS: J. D. Bjorken: Regge model foundations are as solid as those of QCD, DIS1994

# Diffraction in e-p interactions

HERA:  $e^\pm$  (27.5 GeV) – p (820/920 GeV)  $\rightarrow \gamma^* p \rightarrow \text{hadrons}$



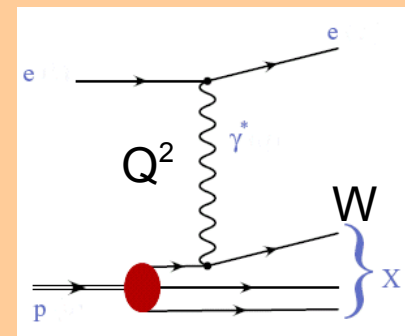
$Q^2$  –  $\gamma^*$  virtuality ( $0 - 10^5 \text{ GeV}^2$ )

$s \approx E_e E_p$ ,  $\sqrt{s} \approx 300 \text{ GeV}$

$W$  –  $\gamma^* p$  CMS energy (20 -290 GeV)

$x \approx Q^2/W^2$  – Bjorken  $x$  = fractional parton momentum in proton Breit frame

$y \approx Q^2/(sx)$  – fractional energy transfer to  $p$

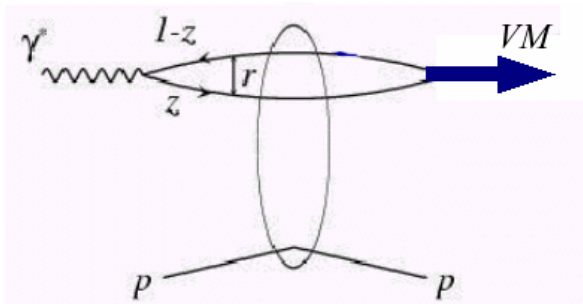


Coherence condition in proton rest frame:

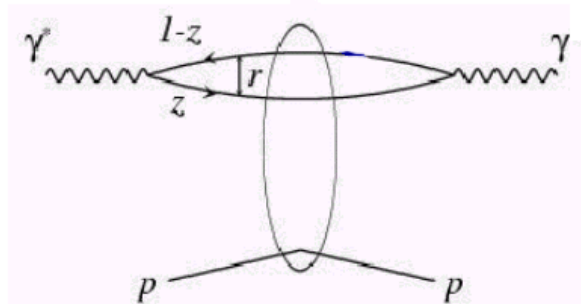
$$\text{fluctuation length } (\gamma^* \rightarrow \text{dipol } qq) = 2E_\gamma / (m_{qq}^2 + Q^2) > 1 \text{ fm}$$

$$\rightarrow x < 0.01$$

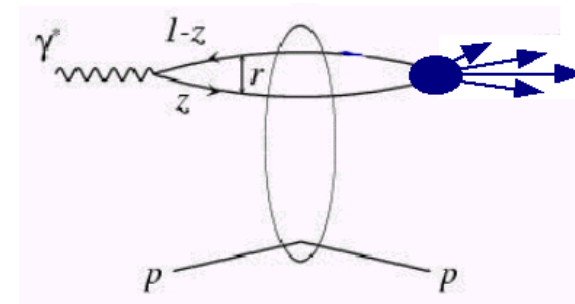
**At HERA diffraction is low Bjorken-x phenomenon!**



Vector meson production



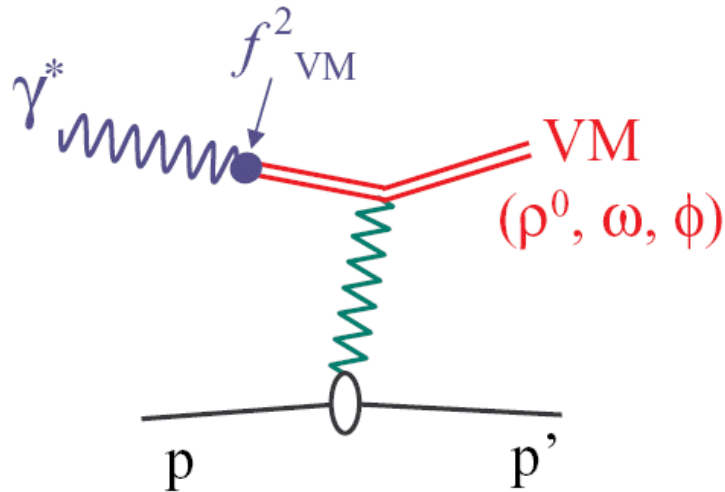
DVCS



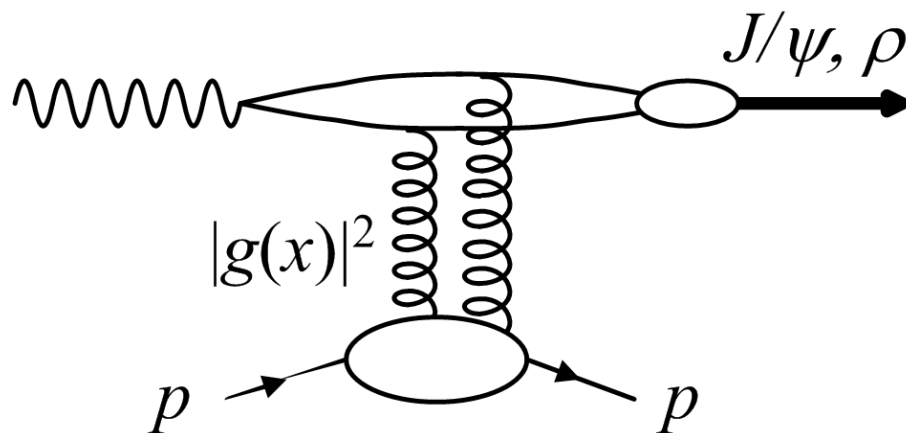
inclusive diffraction

# Vector meson production (1)

## Vector Dominance Model + Regge



- $\gamma^* p \rightarrow VM p = (\gamma^* \rightarrow VM) \otimes (VM p \rightarrow VM p)$
- $VM p \rightarrow VM p \Rightarrow$  DL IPomeron exchange
  - $d\sigma/dt \sim \exp(-b(W)t)$ ,  $b \sim R_{int}^2 \approx 10 \text{ GeV}^{-2}$
  - $b(W) = (b_{VM} + b_p + \alpha' \ln(W^2))$  (“shrinkage”)
  - $\sigma_{VMp} \sim W^{4(\alpha_0-1)}/b(W) \sim W^\delta$ ,  $\delta \approx 0.22$



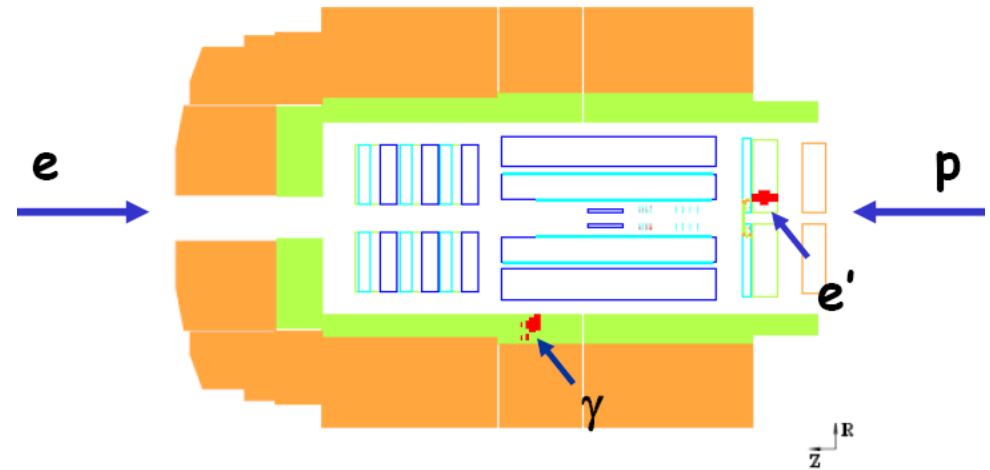
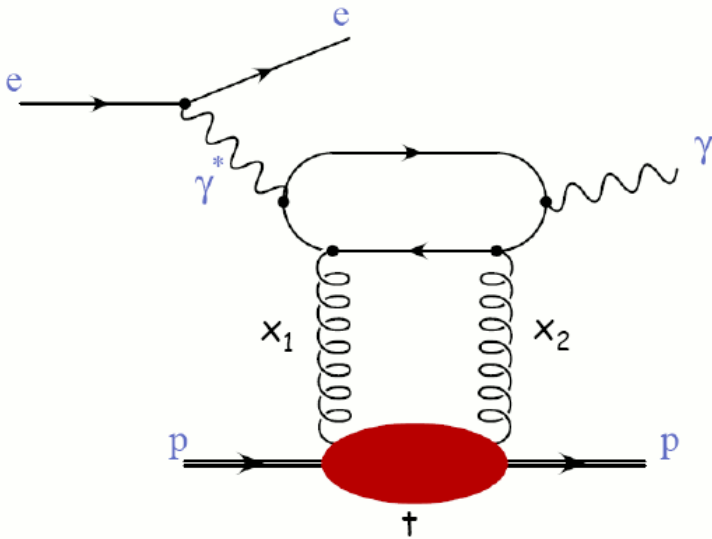
## Perturbative QCD

- Large  $Q^2$ ,  $M_{VM}$  or  $|t| \rightarrow$  small qq dipol
- QCD Pomeron exchange:  
 $\geq 2$  gluons (colour singlet)
  - $\sigma_{VMp} \sim (xg(x))^2 \sim W^{0.7} !!!$
  - $b \ll 10 \text{ GeV}^{-2}$ , weak shrinkage

VM at HERA: transition between soft and hard regime; testbed of QCD scales

# Deep virtual Compton Scattering (DVCS)

$$\gamma^* p \rightarrow \gamma p$$



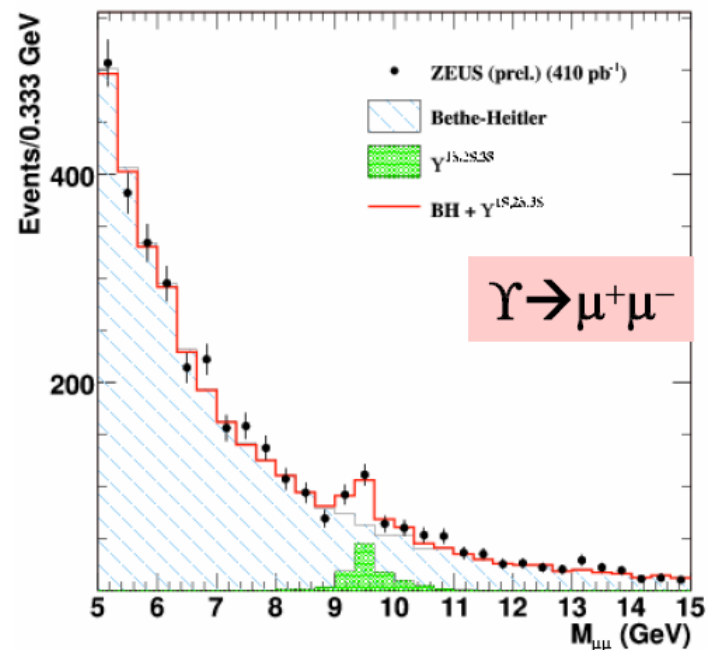
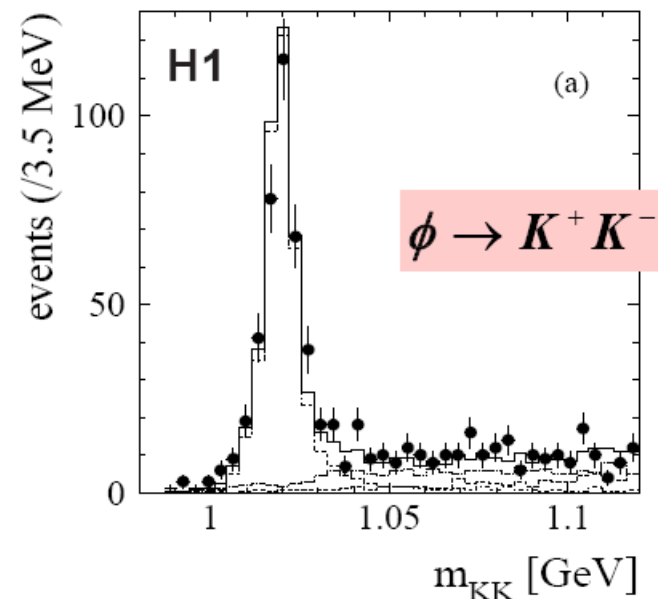
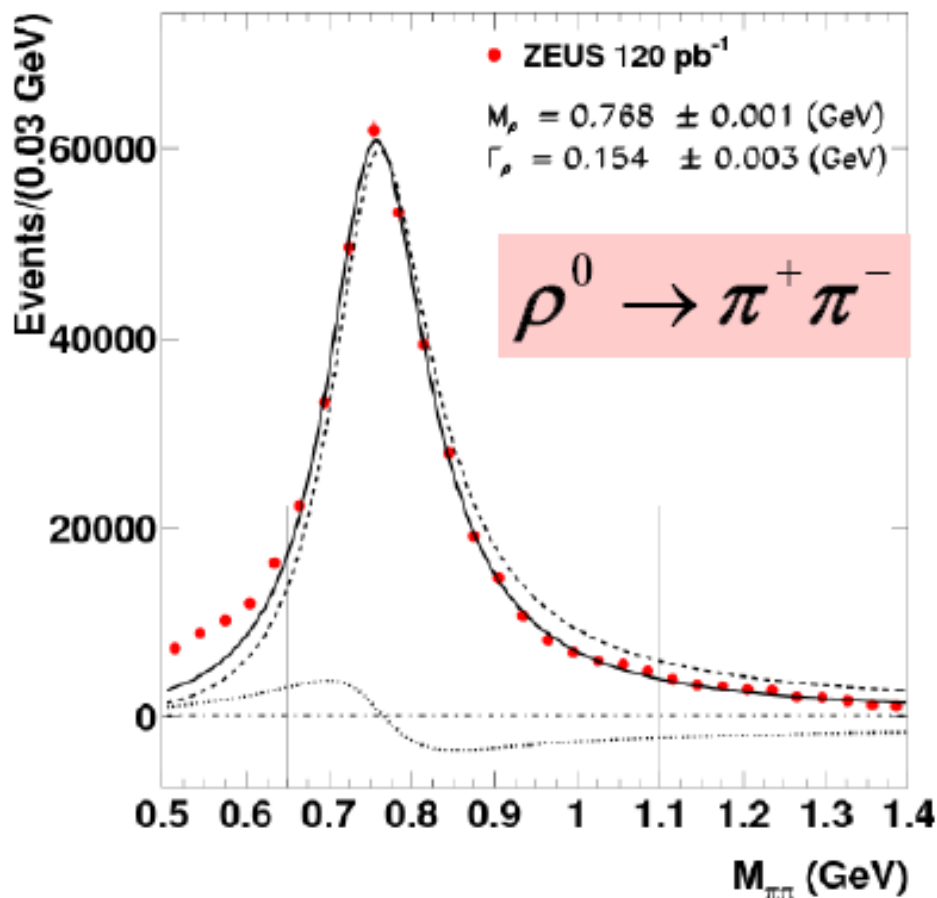
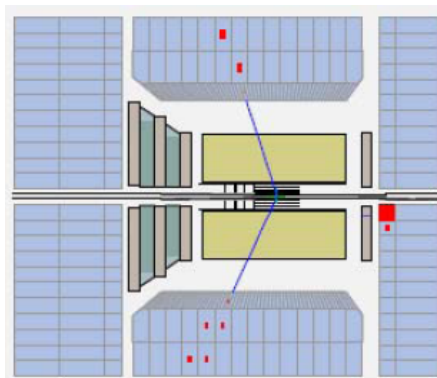
elastic scattering of virtual photon off a proton

- clean experimental signature
- fully calculable in QCD
- no uncertainty due to VM wave function

# Vector meson production (2)

H1prelim-08-013,

ZEUS: PMC Physics A1:6  
doi:10.186/1754-0410-1-6



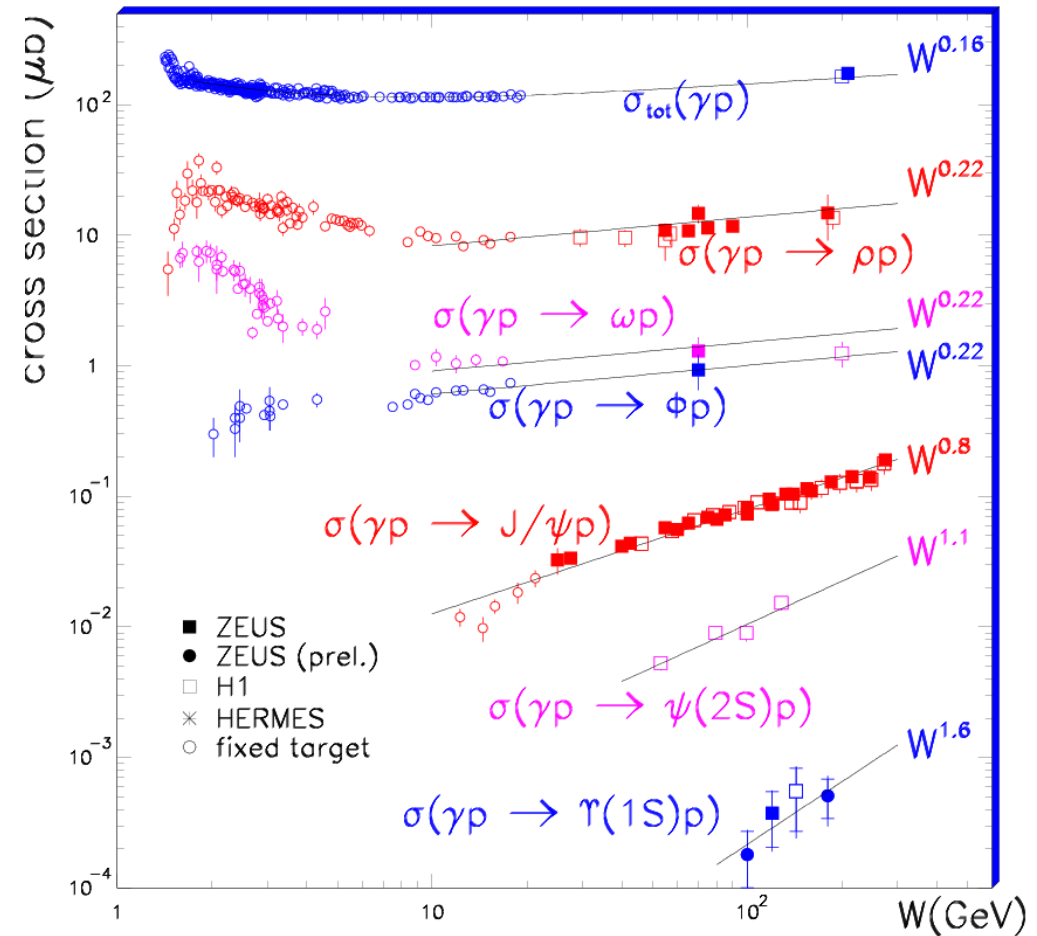
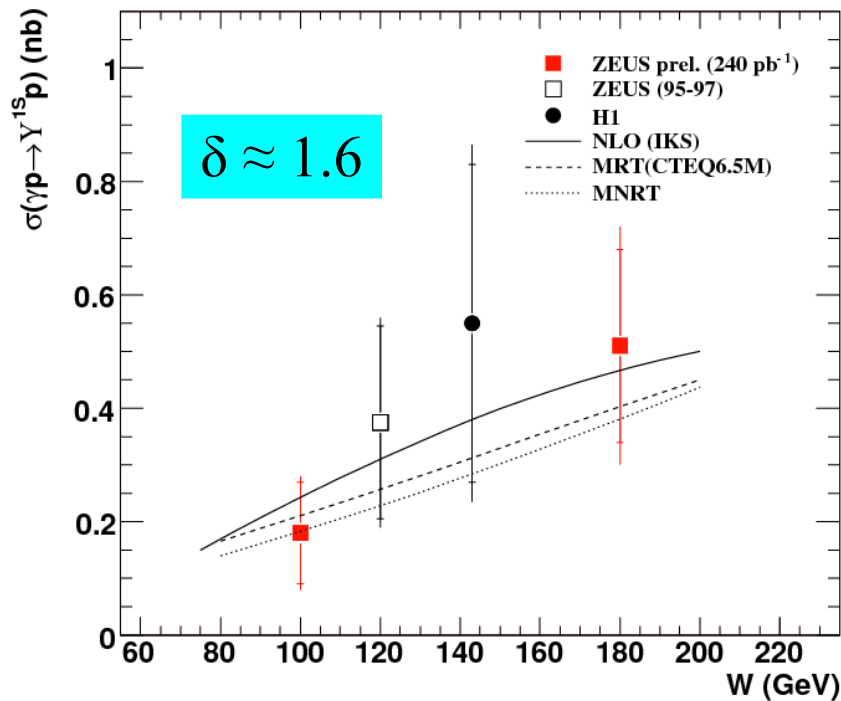


# Vector mesons: energy dependence

Photoproduction, energy dependence:  $\sigma \sim W^\delta$

ZEUS-prel-07-015

$$\gamma p \rightarrow \gamma p$$

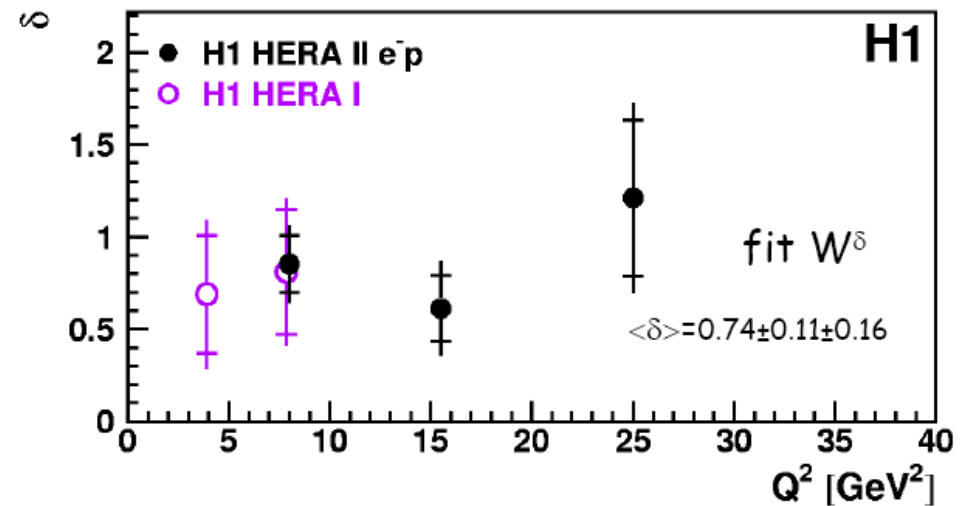
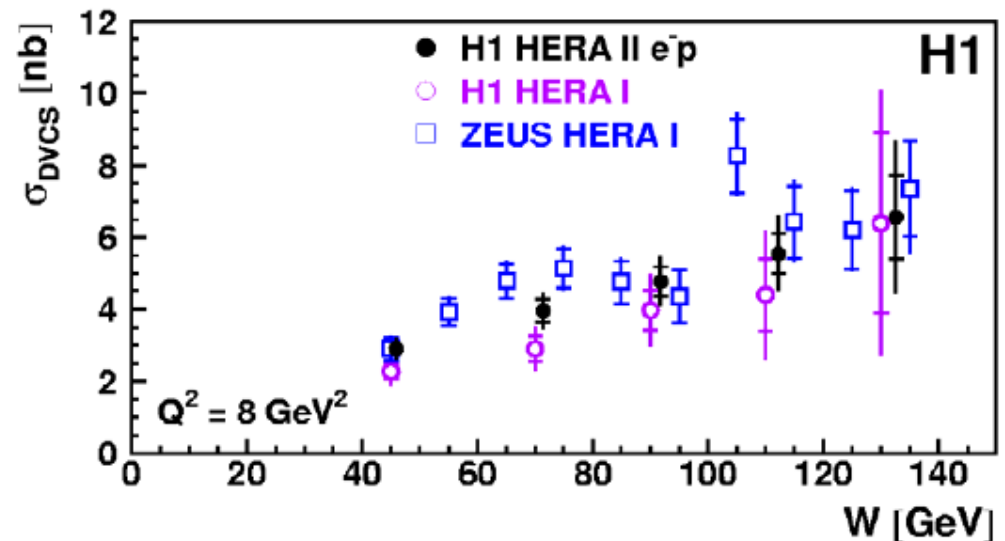
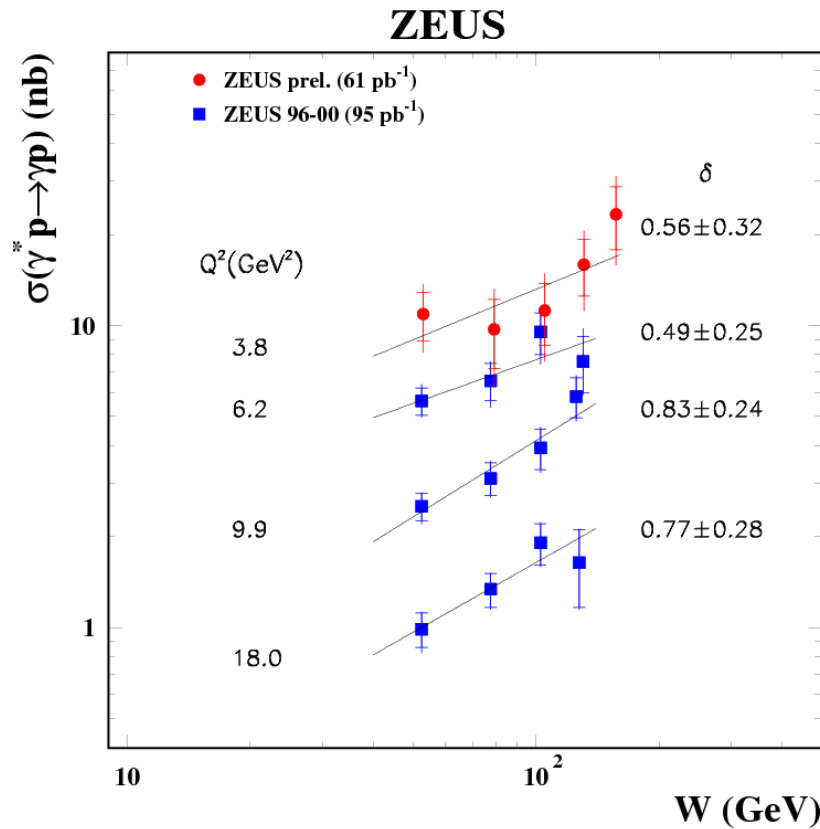


The heavier vector meson –  
– the steeper  $W$ -dependence

# DVCS: energy dependence

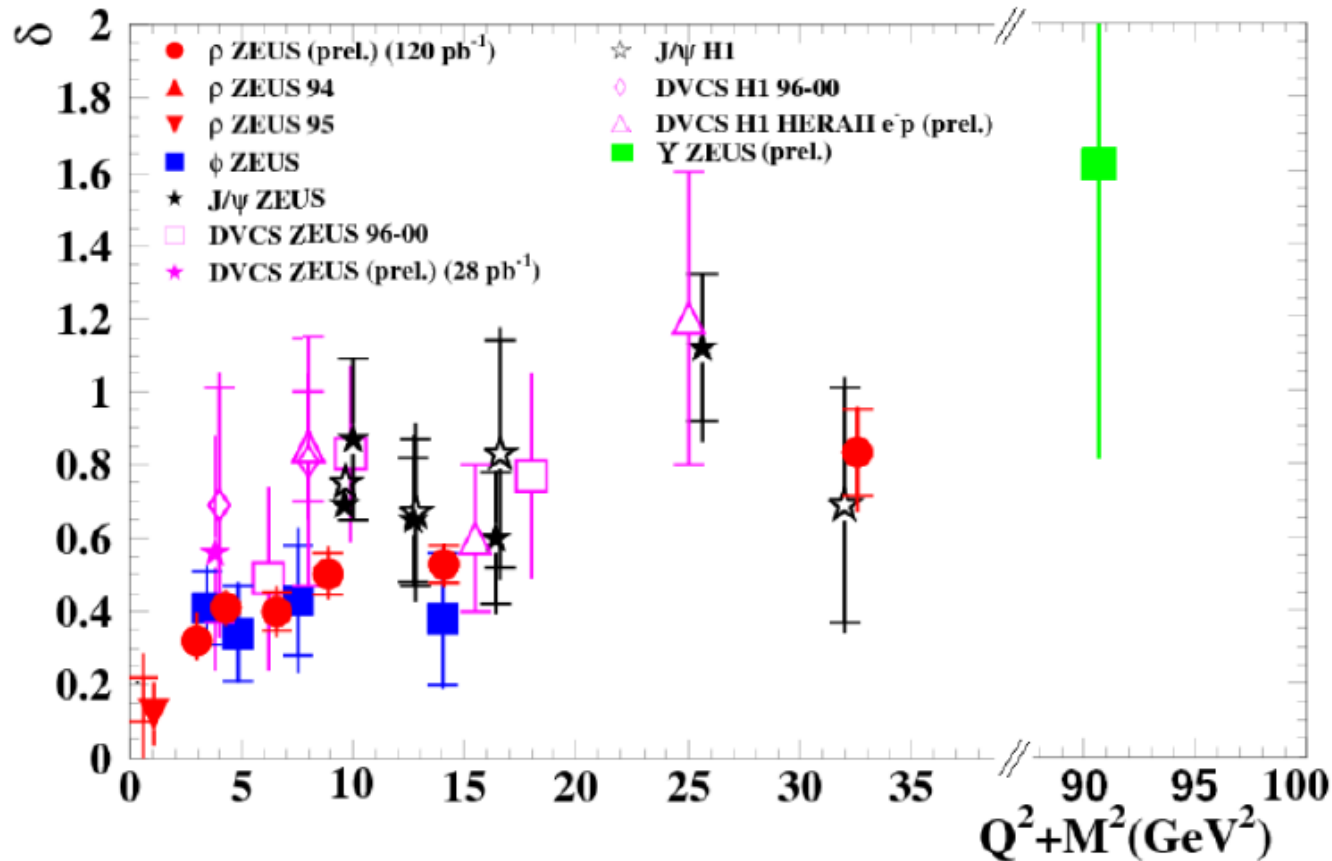
ZEUS-prel-07-016, H1: DESY-07-142

$$\gamma^* p \rightarrow \gamma p$$



Steep rise with energy, no significant  $Q^2$  dependence

# VM and DVCS energy dependence



$$\sigma \sim W^\delta$$

VM-s: bigger “hard” scale  $Q^2 + M^2$  – steeper rise with  $W$ ,  
 $Q^2 + M^2$  scale governs “soft” – “hard” interaction transition

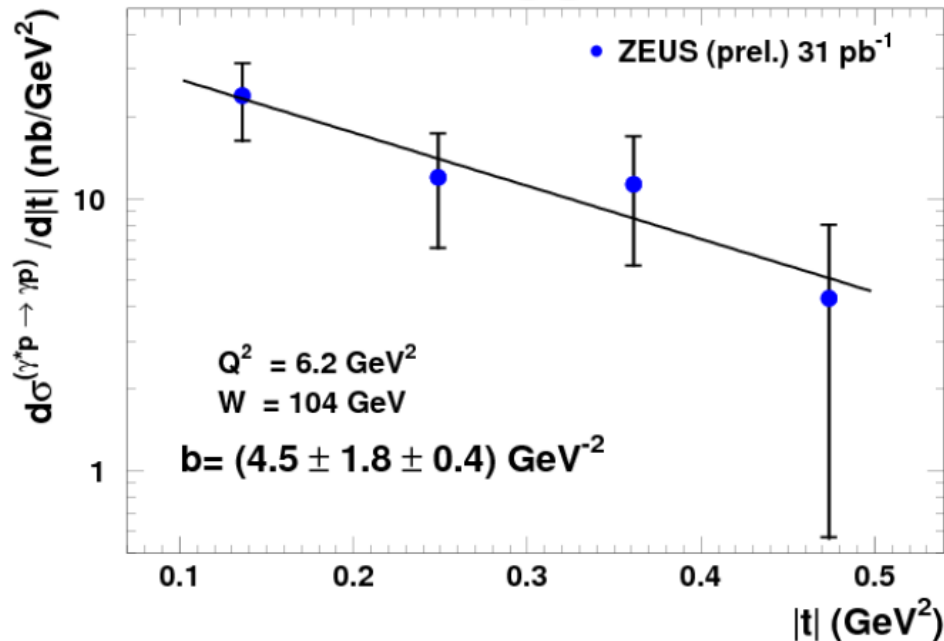
DVCS: always steep rise with  $W$  – “hard” interaction...

# DVCS: t-dependence

$$d\sigma/dt \sim e^{-b|t|}$$

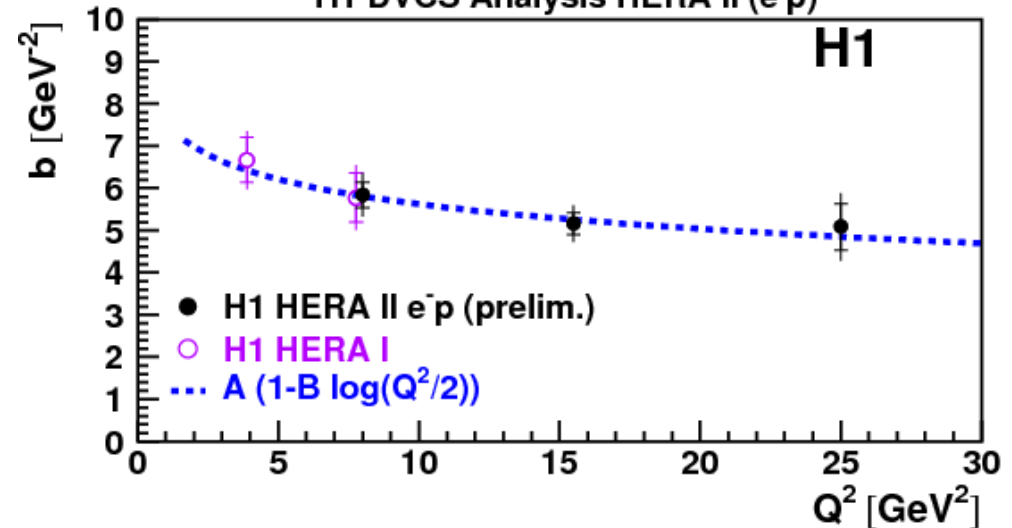
slope  $b \sim$  size of the interaction

**ZEUS**

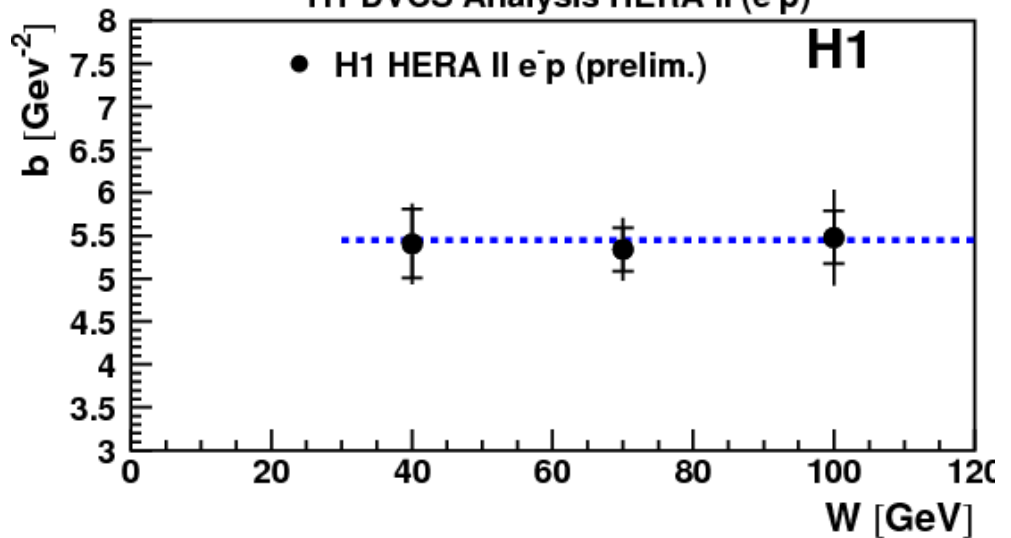


direct measurement with **ZEUS**  
Leading Proton Spectrometer

H1 DVCS Analysis HERA II (e<sup>-</sup>p)

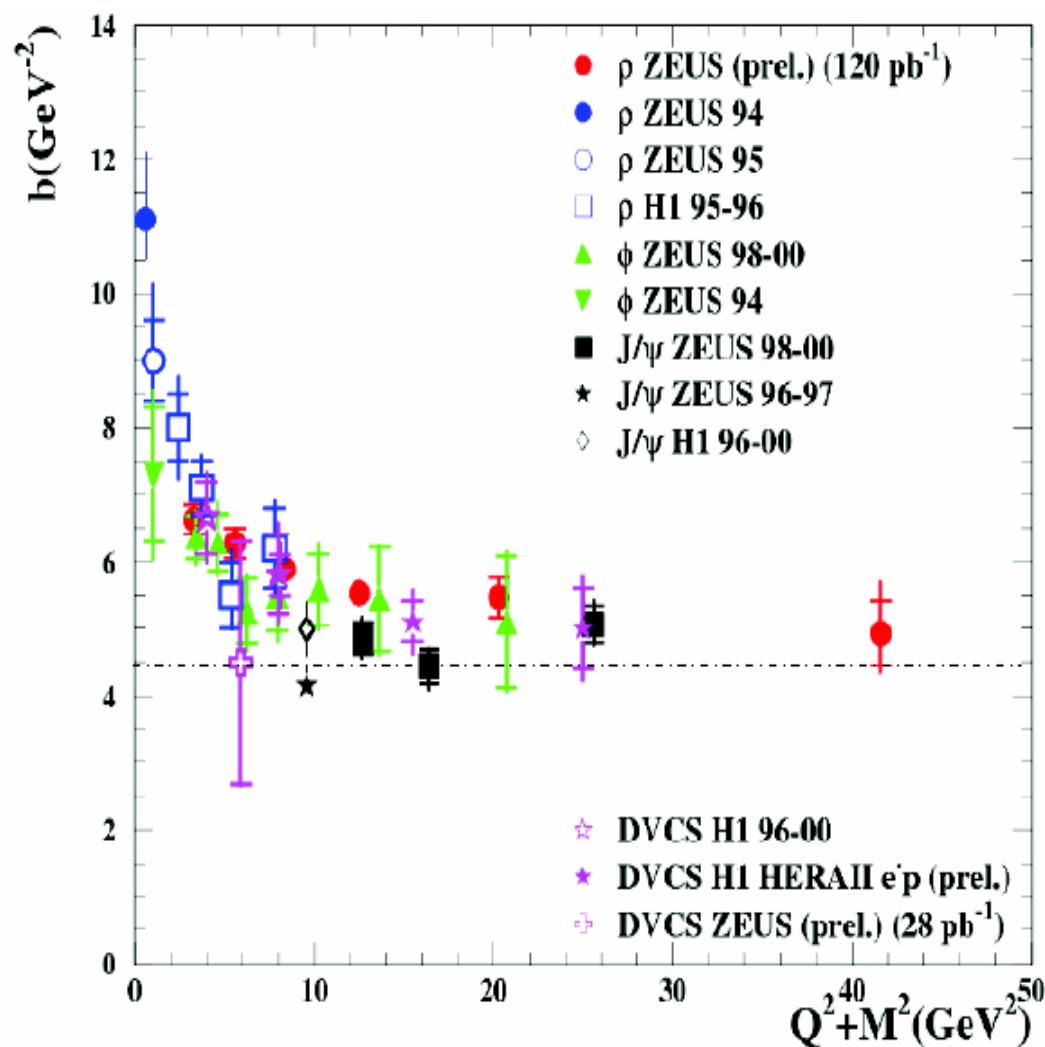


H1 DVCS Analysis HERA II (e<sup>-</sup>p)



# VM and DVCS: t-slope compilation

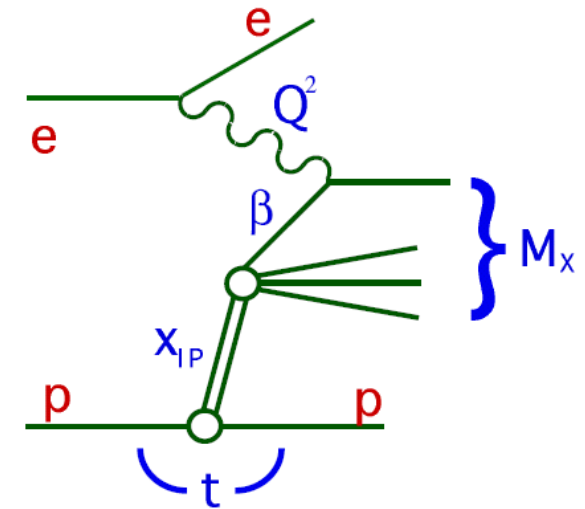
$$d\sigma/dt \sim e^{-b|t|}$$



Decreasing slope (and interaction size) with rising scale  $Q^2 + M^2$  -  
- transition between “soft” and “hard” interaction

# Inclusive diffraction in e-p interactions (1)

$M_X$  – mass of diffractive system (without  $p'$ )  
 $x_{IP} = (Q^2 + M_X^2)/(Q^2 + W^2)$ , relative momentum  $IP/p$   
 $\beta = Q^2/(Q^2 + M_X^2) \approx x/x_{IP}$ , relative momentum  $q/IP$   
 $t$  – squared 4-momentum transfer  $p - p'$



Diffractive structure functions  $\rightarrow$

$\rightarrow$  (“hard” factorisation + QCD fit)  $\rightarrow$  diffractive PDFs

$$\frac{d^4 \sigma_{y^*p}^D}{dQ^2 d\beta dx_{IP} dt} = \frac{2\pi \alpha_{em}^2}{\beta Q^4} \left(1 + (1-y)^2\right) F_2^{D(4)}(Q^2, \beta, x_{IP}, t)$$

If  $t$  not measured  $\rightarrow F_2^{D(3)}(Q^2, \beta, x_{IP})$

“reduced” cross section  $\sigma_r^D = F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D \approx F_2^D, \quad y < 1$

proton vertex factorization (?):  $F_2^{D(4)}(\beta, Q^2, x_{IP}, t) = f_{IP}(x_{IP}, t) F_2^{IP}(\beta, Q^2)$

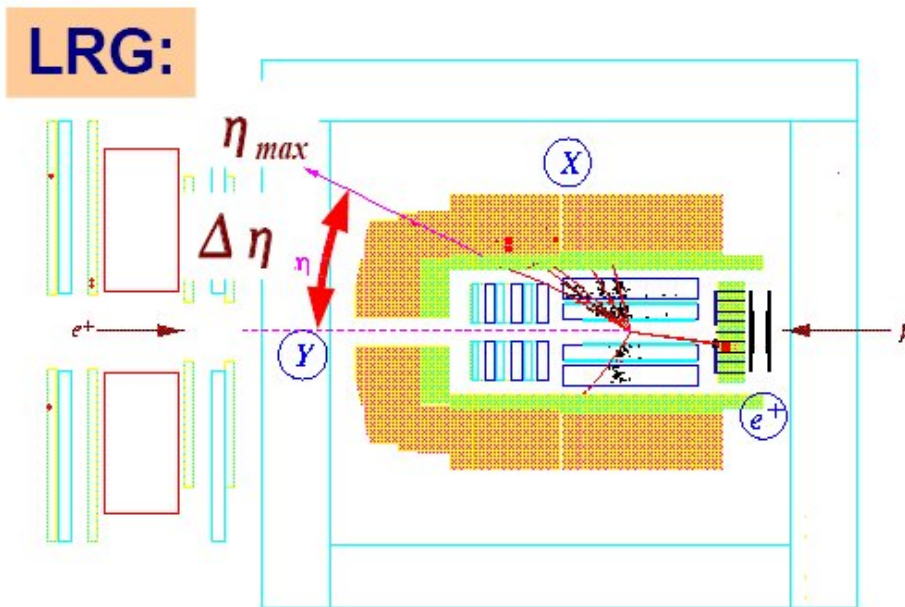
IPomeron flux

IPomeron structure function

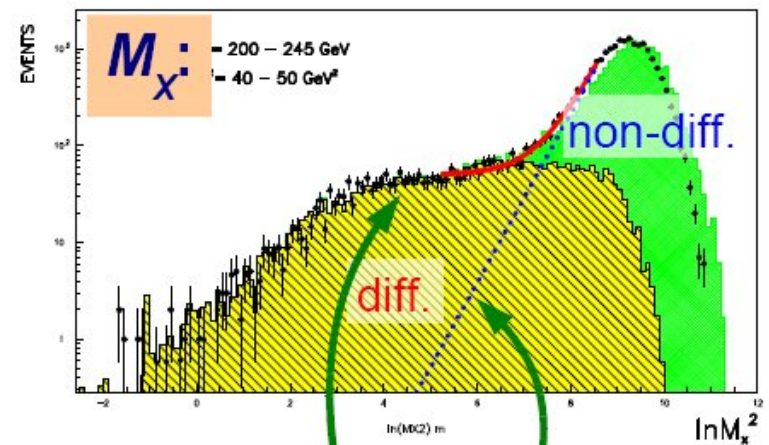
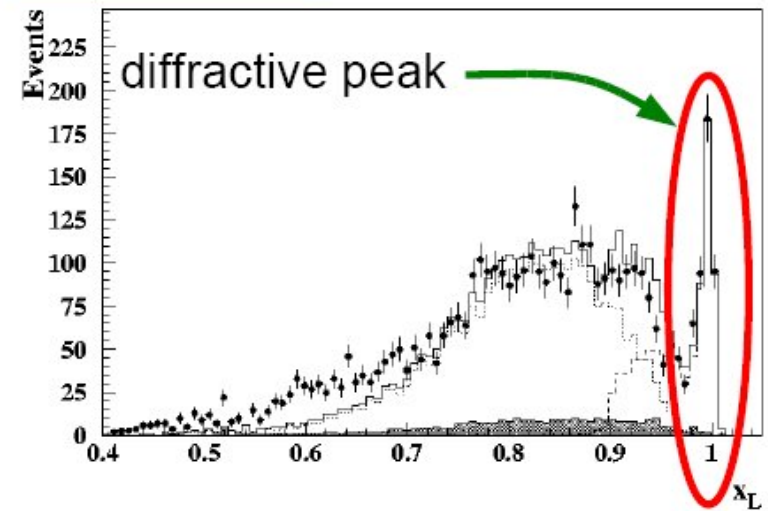
# Inclusive diffraction in e-p interactions (2)

Diffractive selection:

- proton tagging, LPS(**ZEUS**), FPS(**H1**)
- Large Rapidity Gap
- $M_X$  method



**p tagging:** ZEUS 1994

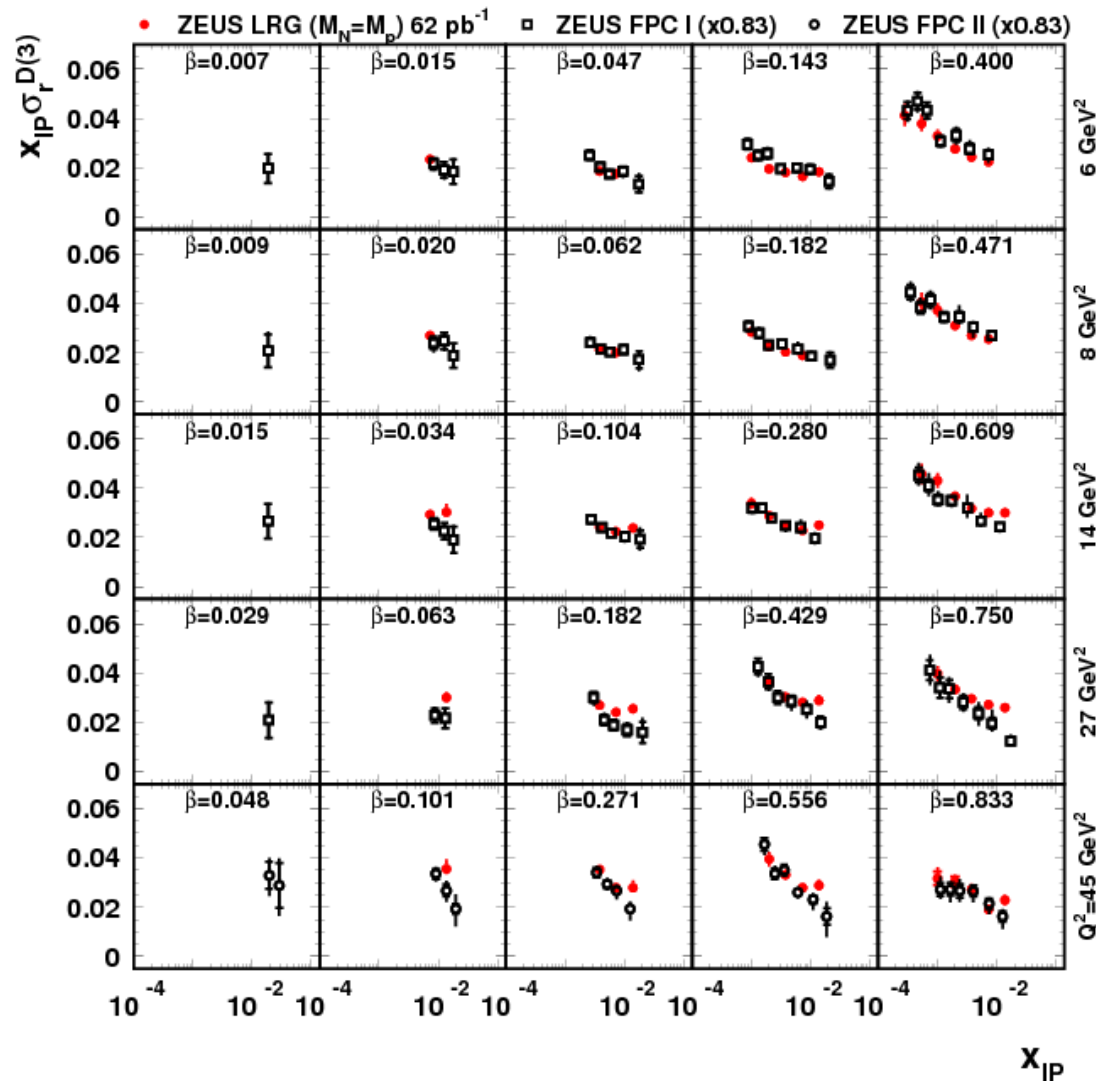


$$\frac{dN}{d \ln(M_X^2)} = D + c \exp(b \ln(M_X^2))$$

# Inclusive diffraction in e-p interactions (3)

ZEUS: LRG vs  $M_x$  method (FPC I, FPC II)

ZEUS



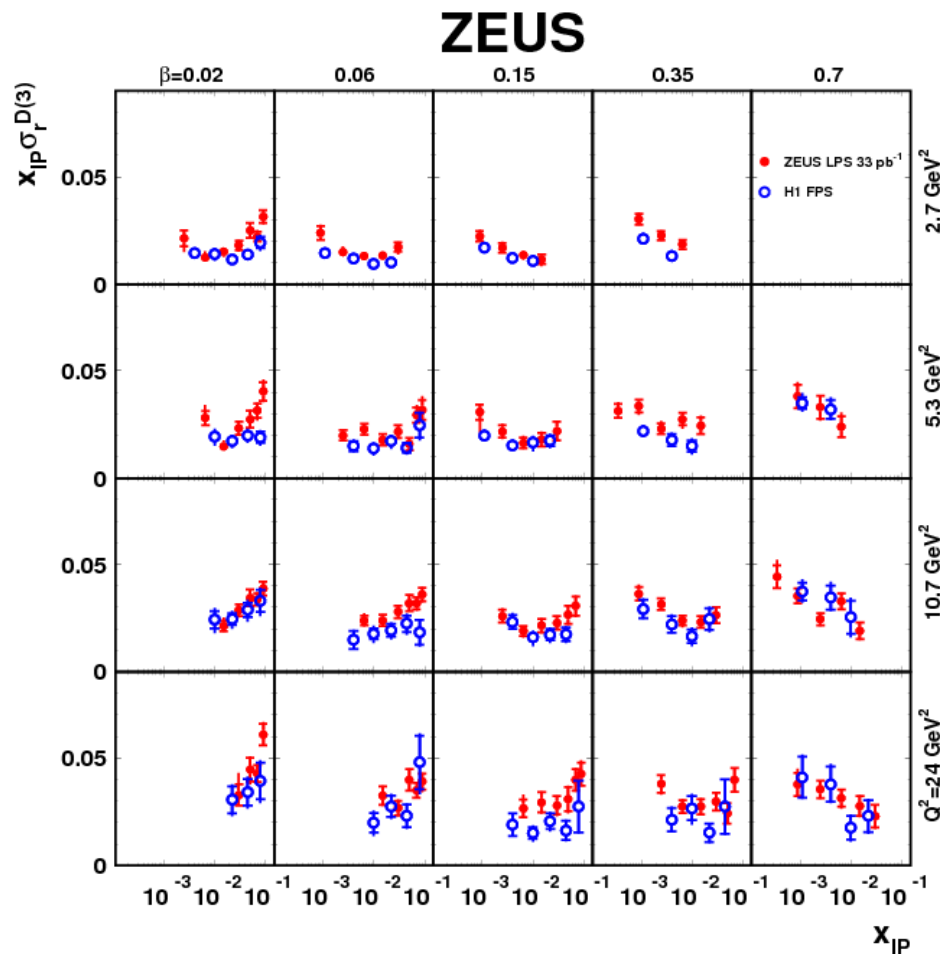
ZEUS-prel-06-024, M. Ruspa DIS2008

Different methods are consistent



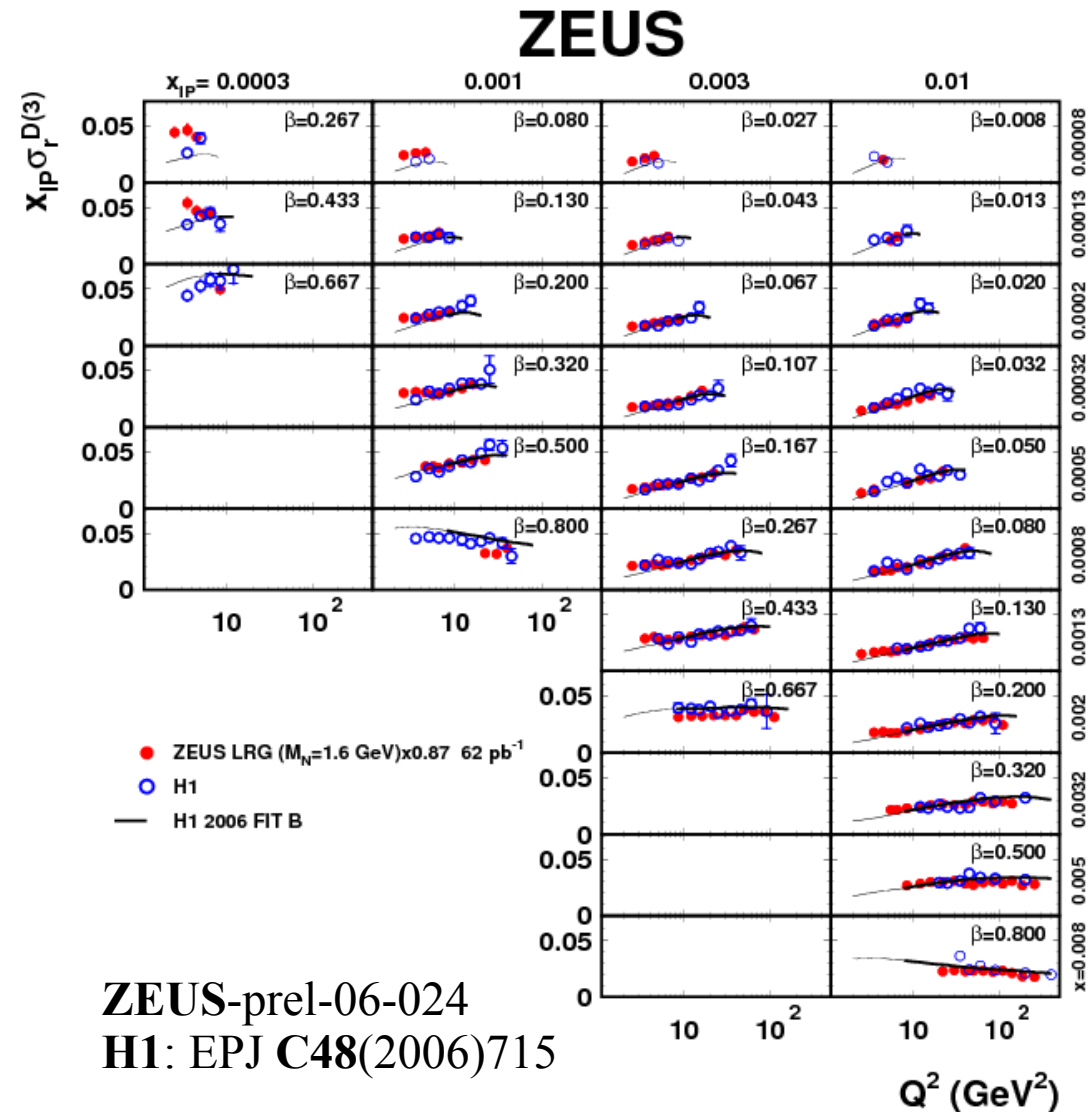
# Inclusive diffraction in e-p interactions (4)

proton tagging results:



**ZEUS LPS:** M. Ruspa DIS2008  
**H1 FPS:** EPJ C48(2006)749

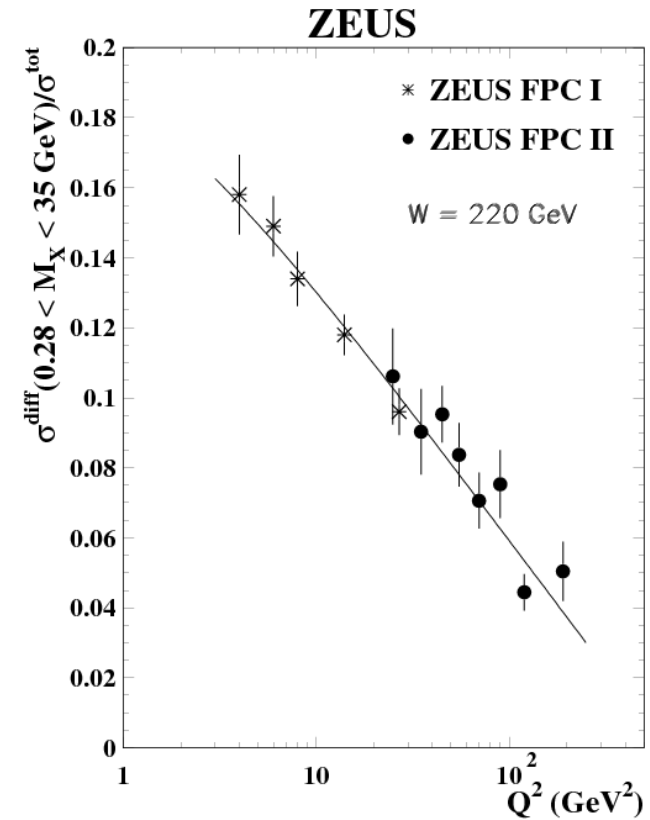
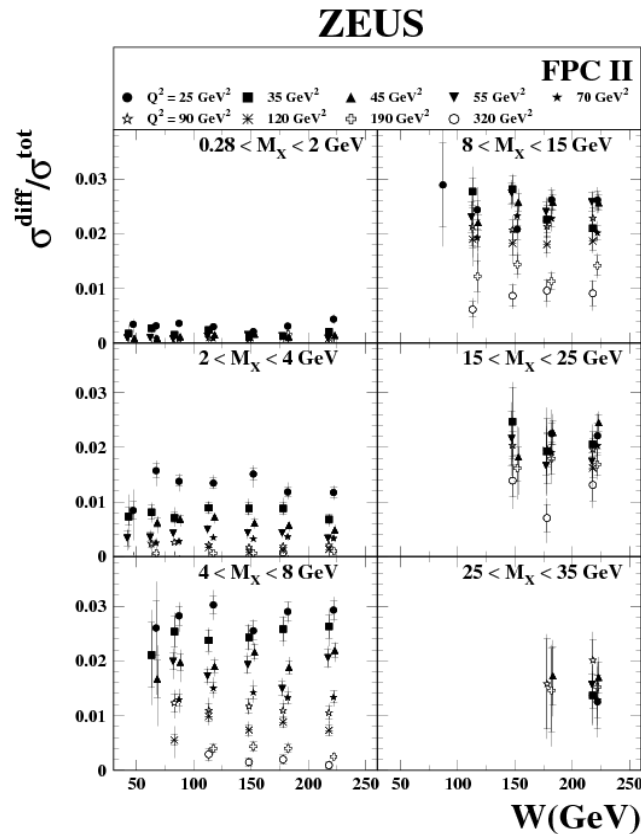
LRG results:



**ZEUS consistent with H1**

# Inclusive diffraction in e-p interactions (5)

**ZEUS (DESY -08-011) FPC II** results ( $M_X$  method):



- Diffraction yield (fixed  $M_X$ ,  $Q^2$ )  $\approx \text{const}(W)$
- Diffraction yield ( $0.28 < M_X < 35 \text{ GeV}$ )  $\approx a - b \ln(1+Q^2)$

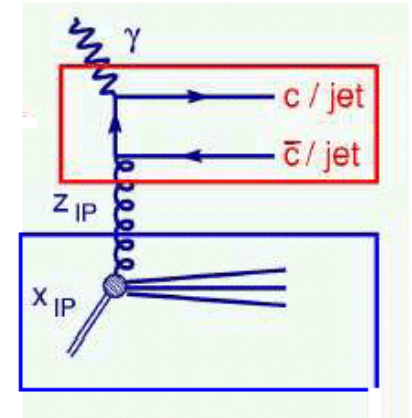
# QCD factorisation tests

Collinear factorisation theorem (lepton-proton, DIS, perturbative QCD)

$$\sigma^D = \sum f_i^D \otimes \sigma_i^{\gamma^*}$$

$f_i^D$  – universal diffractive Parton Distribution Function (dPDF)

$\sigma_i^{\gamma^*}$  – universal ( $\gamma^*$  parton) cross-section

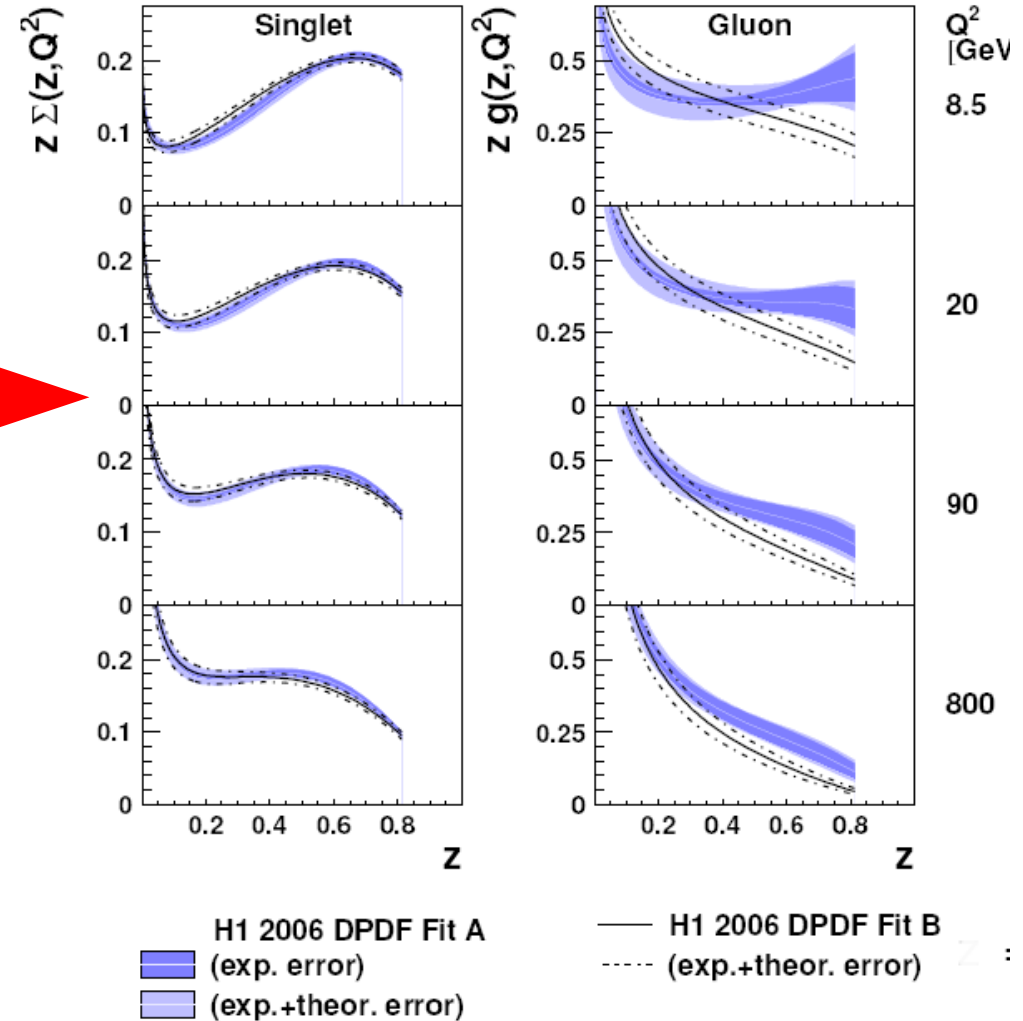
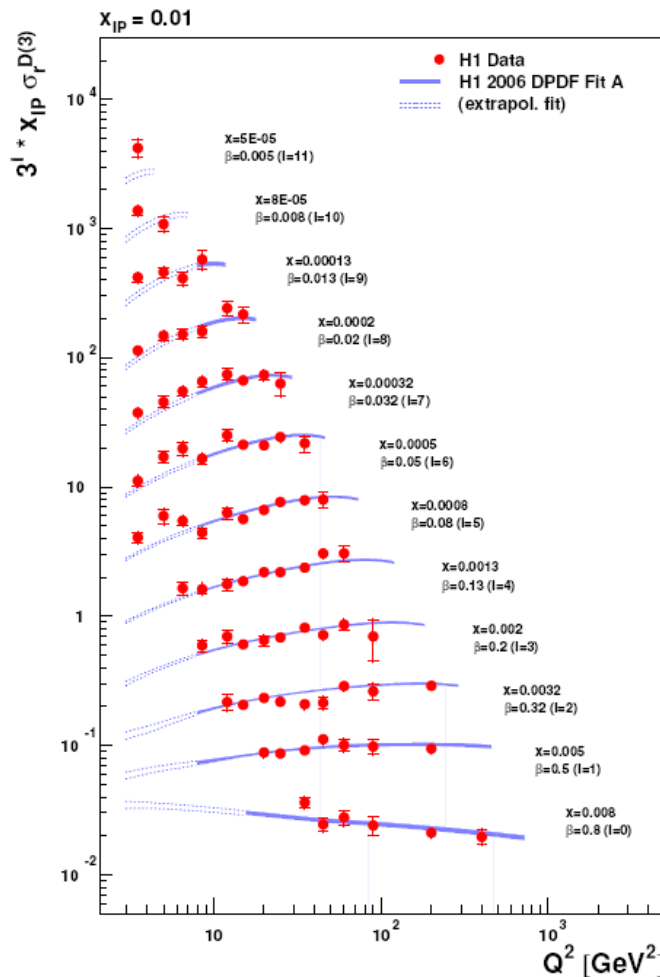


## Basic strategy:

- Measure  $F_2^D$  from inclusive diffraction
- Extract diffractive PDFs from NLO DGLAP fit to  $F_2^D$
- calculate  $\sigma_i^{\gamma^*}$  for semi-inclusive diffractive processes
- convolute with dPDFs (proton vtx factorisation assumed)
- compare the calculations with the measurements...

# Inclusive diffraction in e-p interactions (5)

**H1** :  $\sigma_R^{D(3)} \rightarrow$  NLO DGLAP fits (+proton vtx factorisation)  $\rightarrow$  diffractive PDFs  
 EPJ C48 (2006) 715



• Gluons weakly constrained, esp. at large  $z$

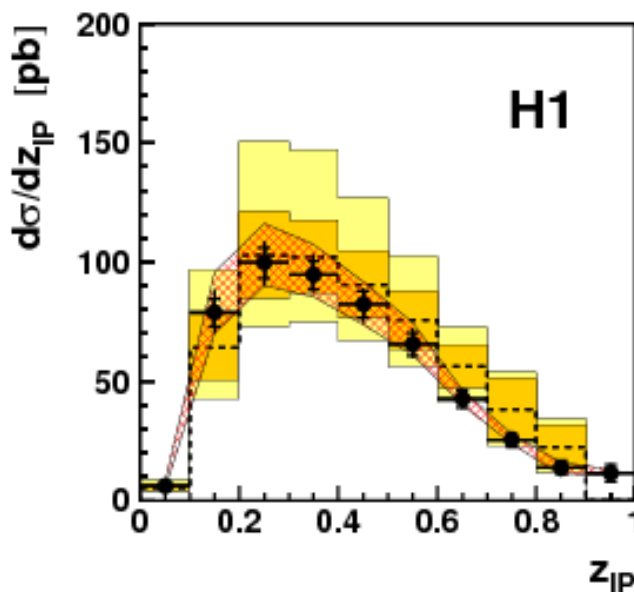
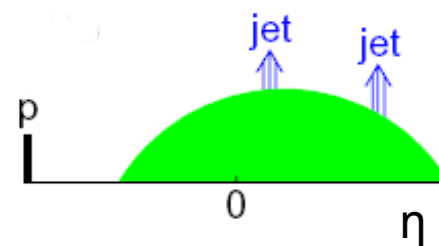
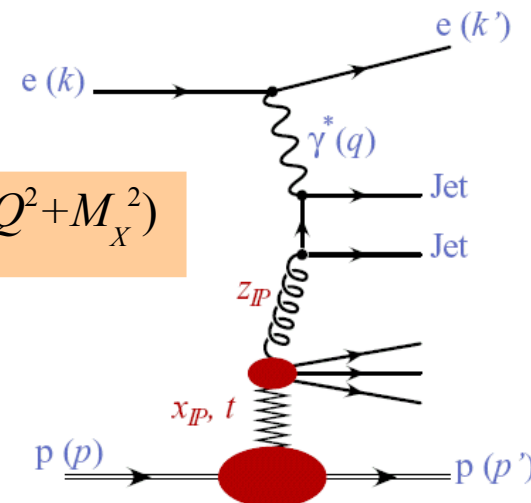
$z$  = fraction of parton momentum  
 in hard scattering/IPomeron

# Factorisation tests: diff. dijets in DIS (1)

**H1:**  $4 < Q^2 < 80 \text{ GeV}^2$ ,  
 $0.1 < y < 0.7$ ,  $x_{IP} < 0.03$

JHEP 0710:042,2007

$$z_{IP} = (Q^2 + M_{JJ}^2)/(Q^2 + M_X^2)$$

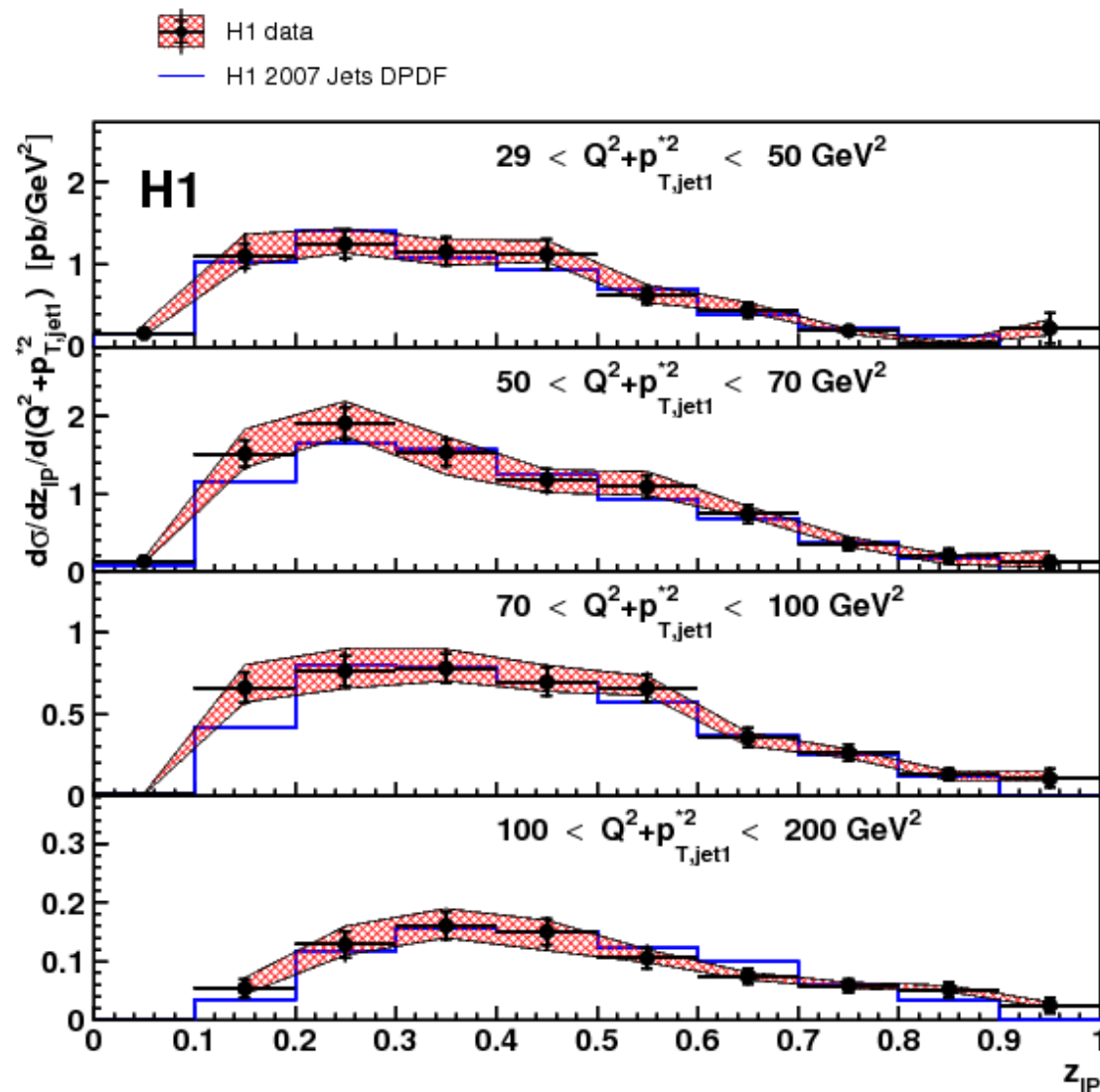


- H1 2006 DPDF fit B gives better agreement with the data

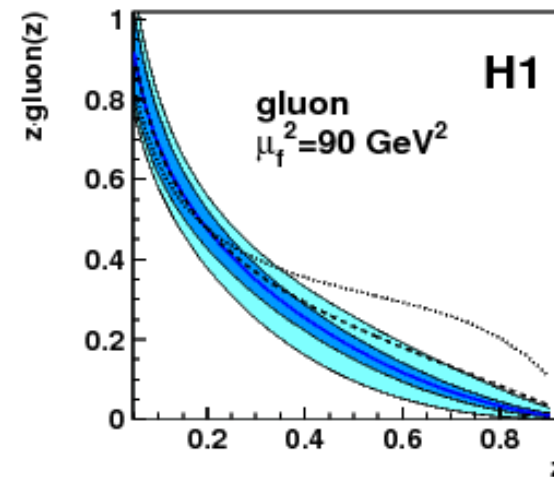
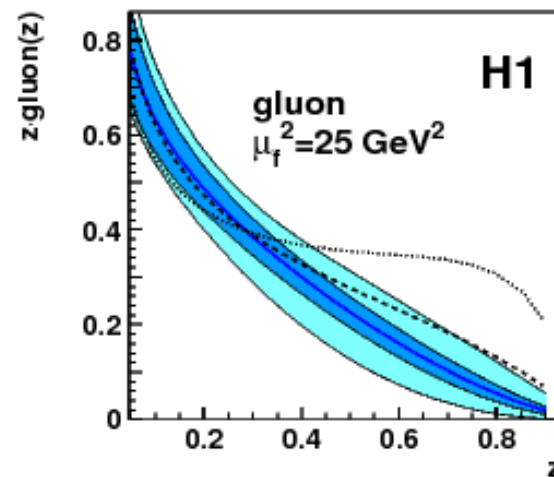
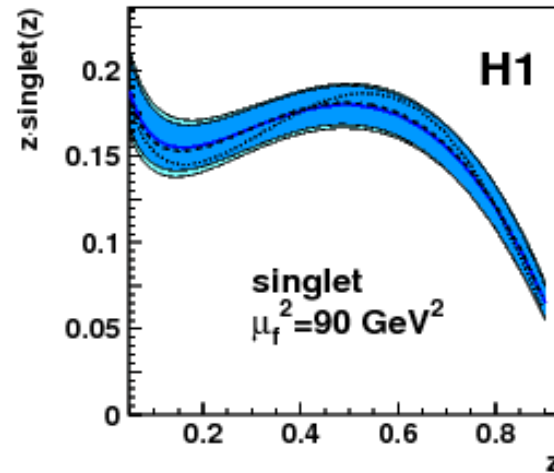
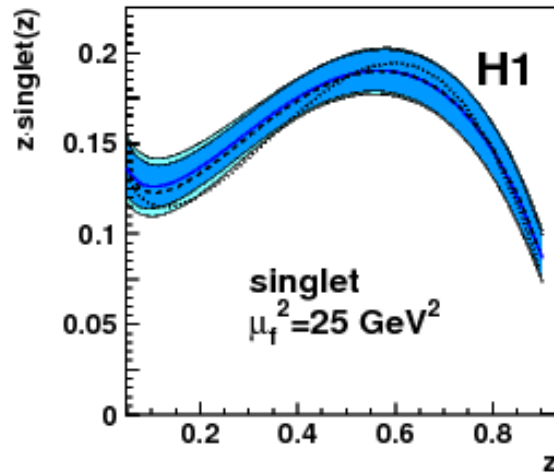
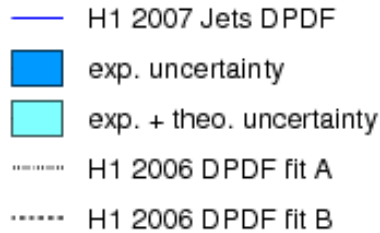
# Factorisation tests: diffr. dijets in DIS (2)

**H1:**  $4 < Q^2 < 80 \text{ GeV}^2$ ,  
 $0.1 < y < 0.7$ ,  $x_{\text{IP}} < 0.03$

Combined QCD fit to dijets and  
inclusive diffraction to constrain  
gluon distribution at high  $z \rightarrow$   
H1 2007 Jets dPDFs



# Factorisation tests: diffr. dijets in DIS (3)

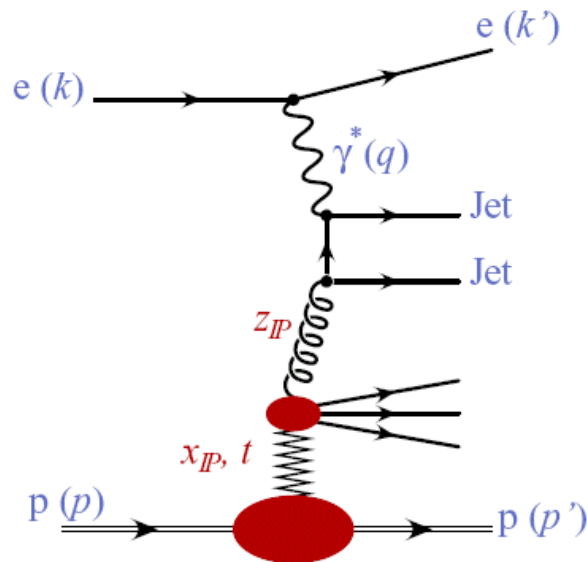


## H1 2007 Jets dPDFs

- H1 2007 Jets DPDF close to H1 2006 DPDF fit B
- Common diffractive DIS and diffractive dijets PDFs  $\rightarrow$   
 $\rightarrow$  factorisation holds

# Diffractive dijets in photoproduction (1)

direct photon (like DIS)

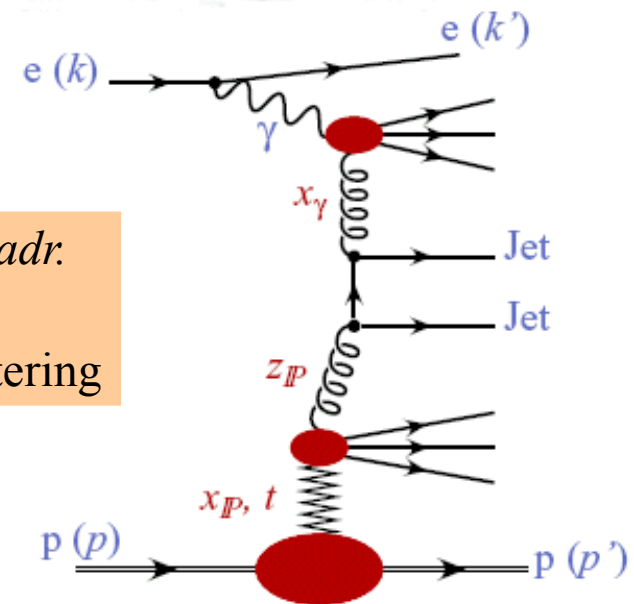


$$x_{\gamma} \approx 1$$

$$x_{\gamma} = \Sigma(E-p_{\perp})_{jets} / \Sigma(E-p_{\perp})_{hadr.}$$

= fraction of photon  
mom. in hard scattering

resolved photon



$$x_{\gamma} < 1$$

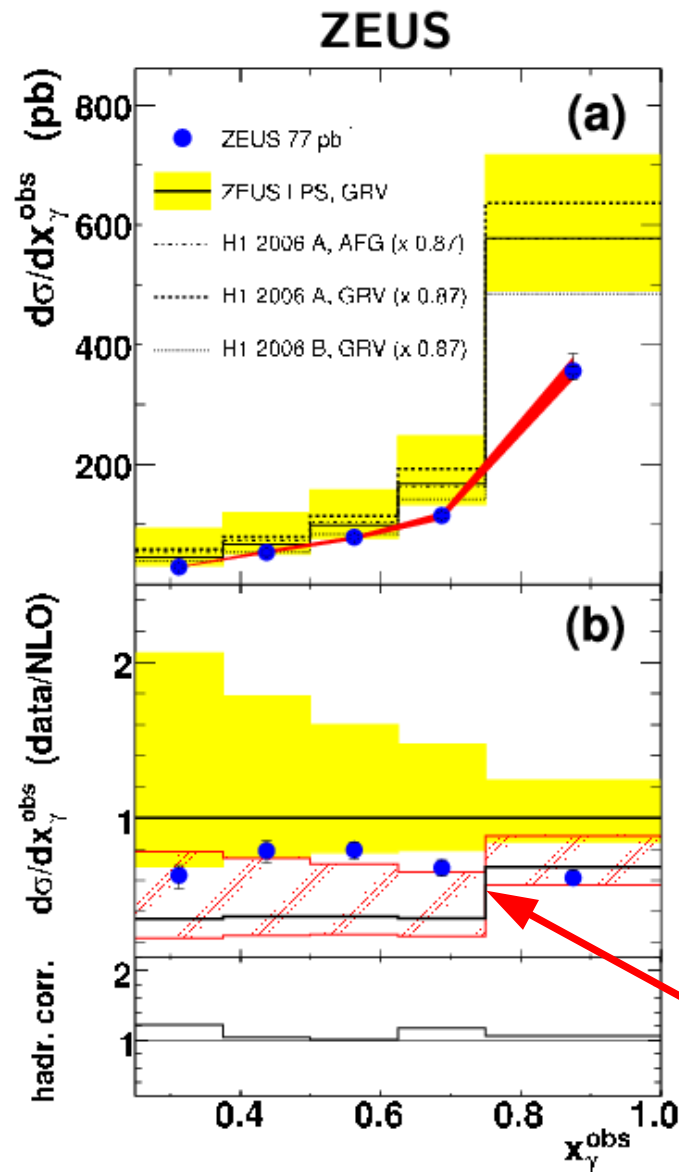
Resolved photon may behave as a hadron →  
→ factorisation may be broken (as in p-p)



# Diffraction dijets in photoproduction (2)

ZEUS (DESY-07-161):

$E_{T,jet1(2)} > 7.5(6.5) \text{ GeV} \leftarrow \text{higher } E_T \text{ cuts than H1}$   
 $142 < W < 293 \text{ GeV}$   
 $x_{IP} < 0.025$



- NLO calculations: Klasen-Kramer
- Diffractive PDFs:  
 NLO fits to ZEUS LPS + charm  
 H1 2006 Fit A  
 H1 2006 Fit B

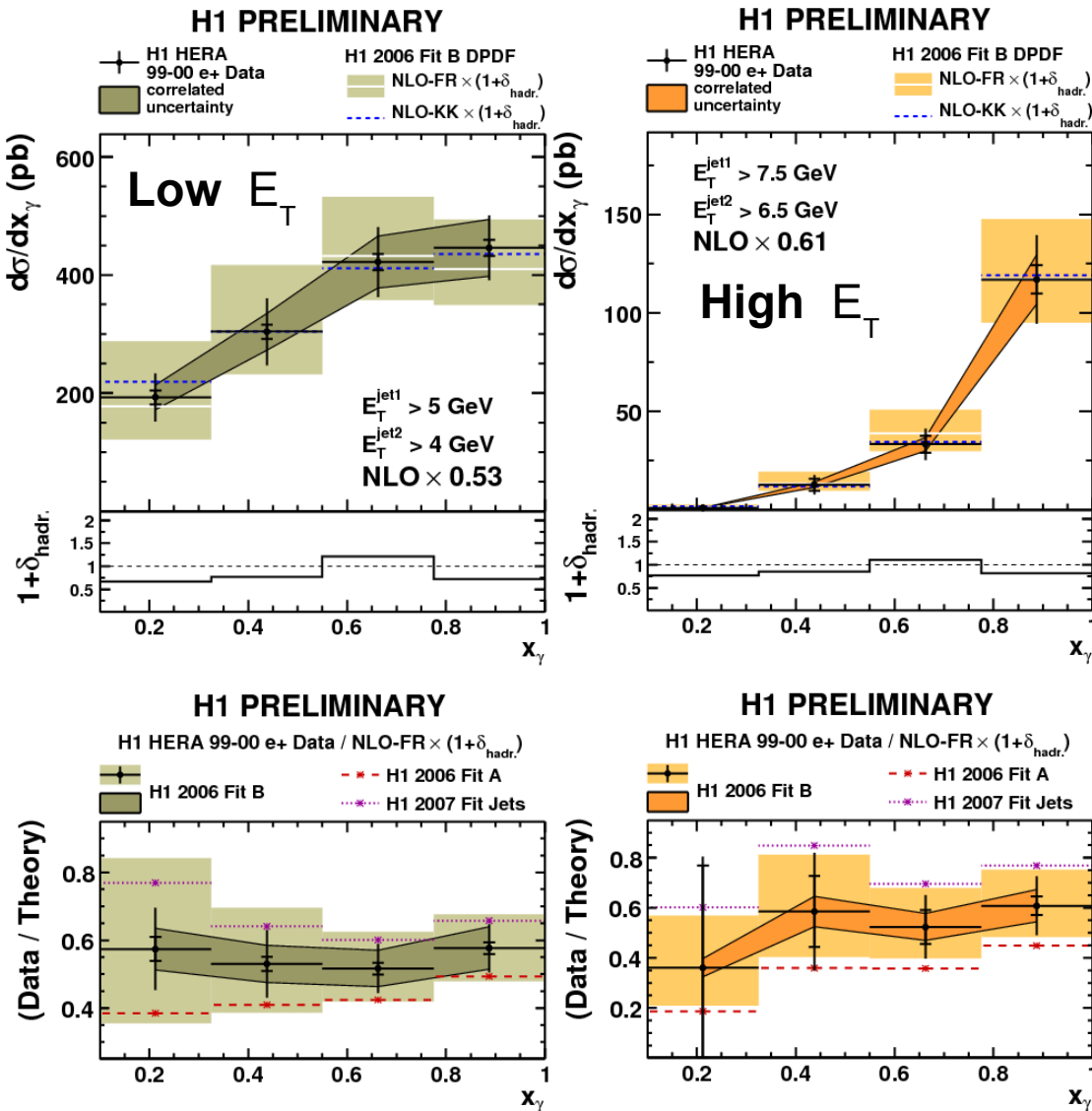
- Global, independent of  $x_\gamma$ , suppression:  
 data/NLO (ZEUS LPS+charm)  $\sim 0.7$   
 data/NLO (H1 2006 fit B)  $\sim 0.9$
- Factorization holds within large theoretical errors ( $\sim 30\%$ )

$R = 0.34$  suppression for resolved  $\gamma$   
 (Kaidalov & Khose)

# Diffractional dijets in photoproduction (3)

H1-prel-08-012:

$E_T$  jets dependence!



$\gamma$  PDF: GRV-G LO

Global suppression:

**Low  $E_T$ :**

data/NLO (H1 2006 fit B) =  
 $= 0.54 \pm 0.1(\text{syst.}) \pm 0.14(\text{scale})$   
 data/NLO (H1 2007 fit Jets) =  
 $= 0.65 \pm 0.11$

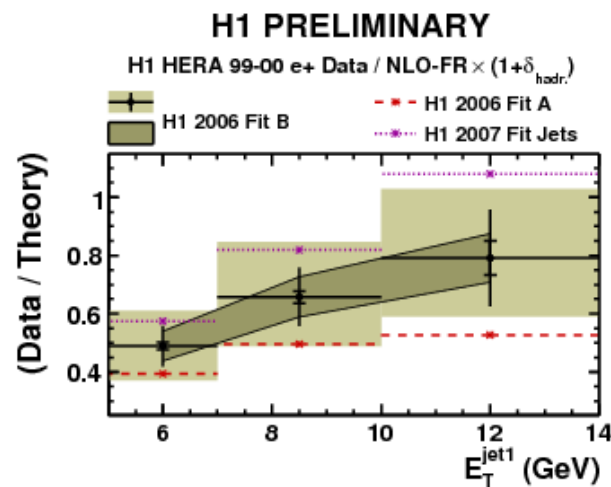
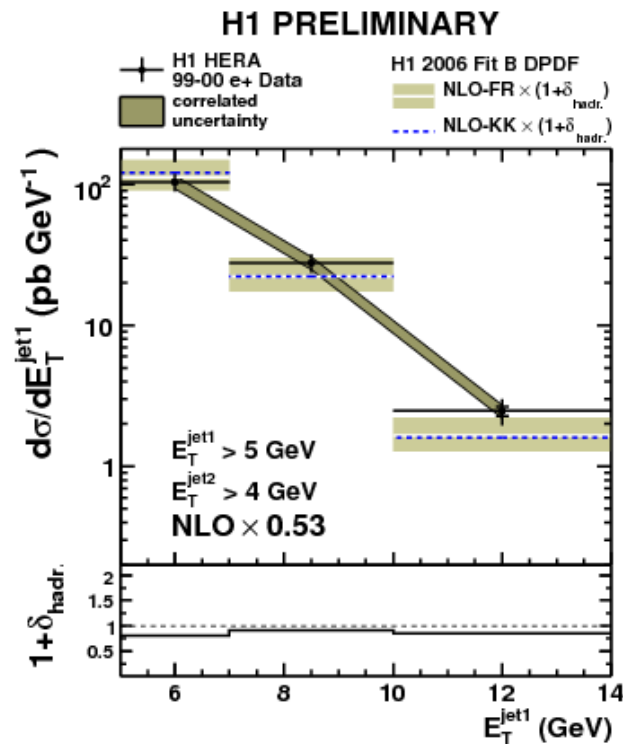
**High  $E_T$ :**

data/NLO (H1 2006 fit B) =  
 $= 0.61 \pm 0.13(\text{syst.}) \pm 0.15(\text{scale})$   
 data/NLO (H1 2007 fit Jets) =  
 $= 0.79 \pm 0.16$

~ consistent with ZEUS!

# Diffractional dijets in photoproduction (4)

$E_T$  jets dependence



Factorisation breaking decreases  
with increasing  $E_T$  jet?

# Summary

- Many new, precise measurements of diffraction at HERA
- Consistent picture of VM production within QCD framework
- DVCS measurements open new testbed for pQCD
- New diffractive PDFs from inclusive and semi-inclusive measurements with several methods
- QCD hard factorization holds in diffractive dijet production in DIS but seems to be broken in PHP, at least at low  $E_T$
- Theoretical uncertainties of QCD calculations are larger than experimental errors...