Measurements of diffraction at HERA

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on behalf of the **H1** and **ZEUS** collaborations

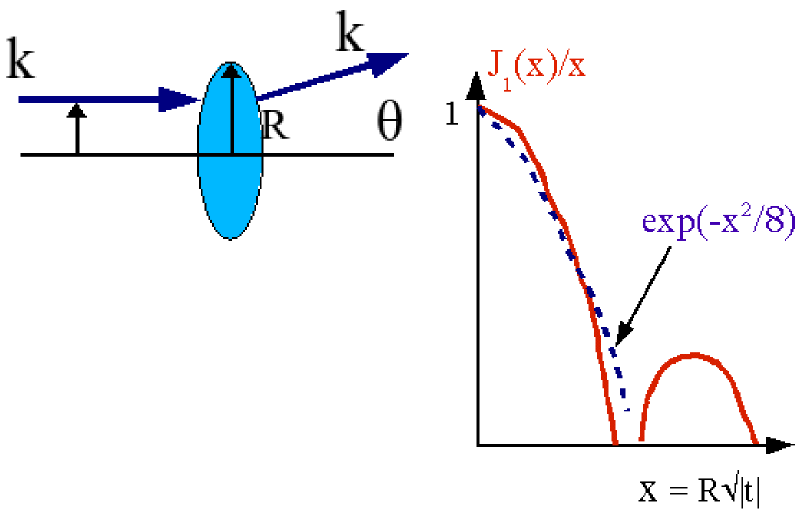
- Introduction to diffraction in h-h and e-p interactions
- Recent results from HERA

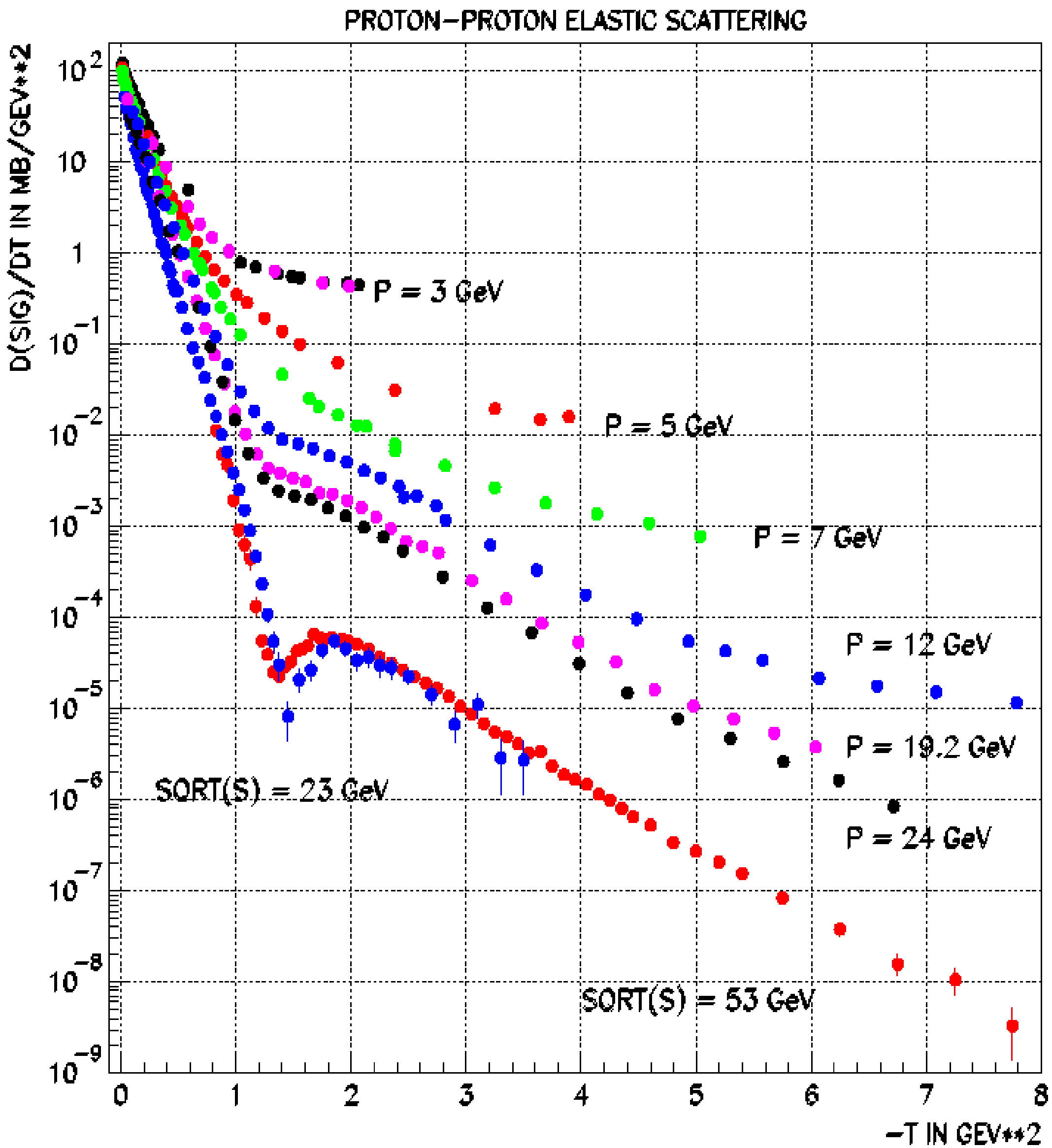
  Exclusive diffraction: vector mesons, DVCS

  Inclusive diffraction

  Diffractive dijet production: QCD factorisation tests
- Summary

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



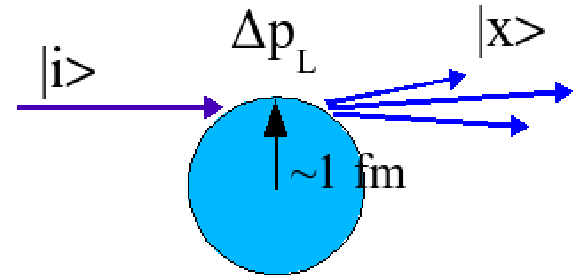


Elastic hadron-hadron scattering:

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

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

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

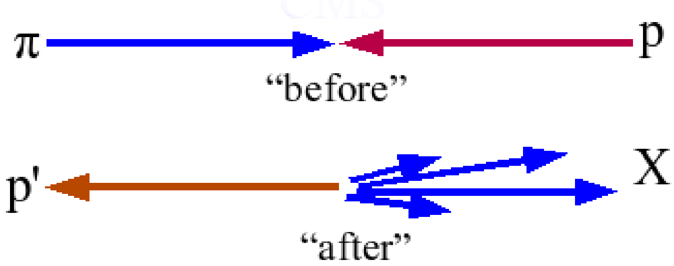


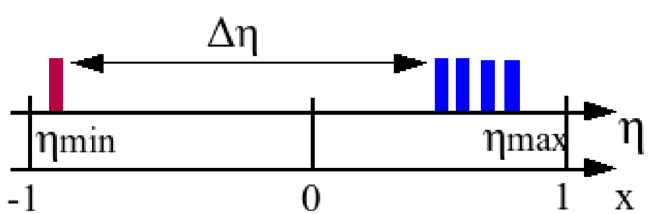
Inelastic hadron diffractive dissociation ↔ coherence condition:

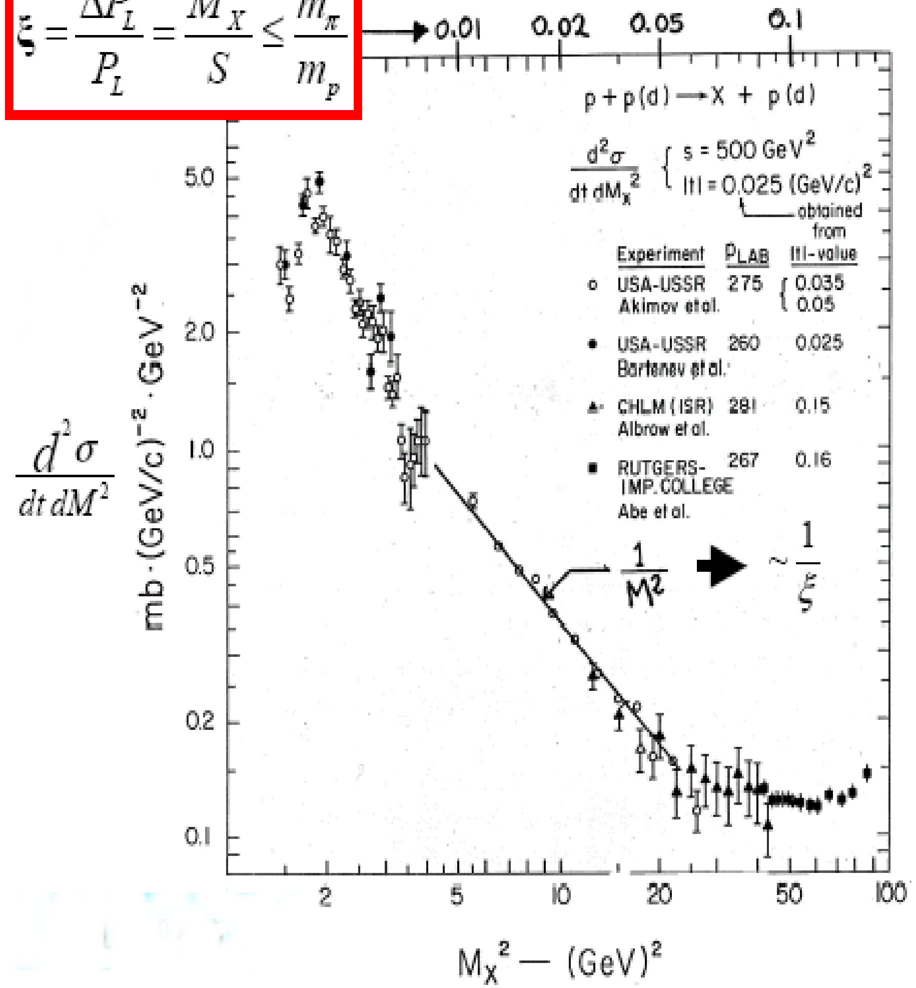
- $\Delta I = \Delta Q = \Delta S = 0, \quad \Delta P = (-1)^J$
- $\xi = M_X^{\,2}/s = \Delta p_L/p_L = 1 - |x| < m_\pi/m_p = 0.15$

  $\Delta\eta = \ln(1/\xi) > 2$, ("large rapidity gap, LRG")

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





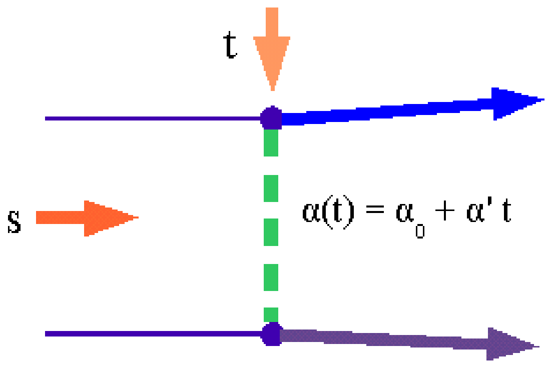


s = squared CMS energy of hadrons
$\eta = -\ln(\tan(\theta/2))$, (pseudo-)rapidity

Diffraction in hadron-hadron interactions (3)

Regge model of hadronic interactions:

two-body reactions: “trajectory” exchange (s → ∞)



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

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

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

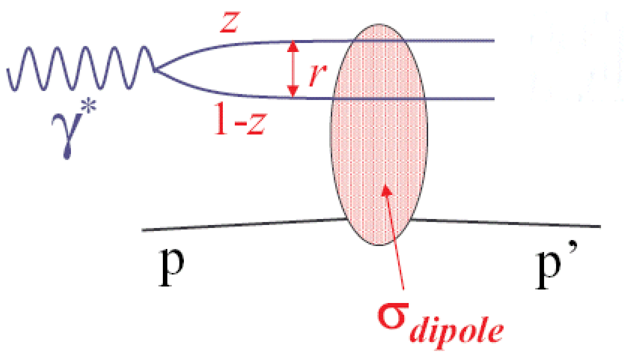
Elastic scattering (→ total cross-section):
exchange of Pomeron IP trajectory (vacuum quantum numbers)

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

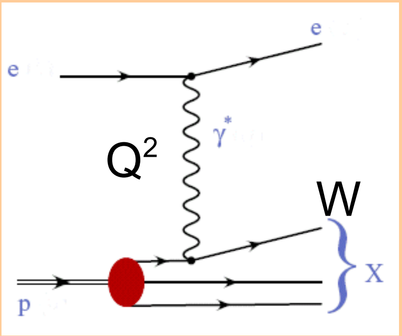
$$\alpha_{IP}(t) = 1.08 + 0.25\, t$$

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

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



Q^2 – γ^* virtuality ($0 - 10^5$ GeV^2)
$s \approx E_e E_p$, $\sqrt{s} \approx 300$ 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

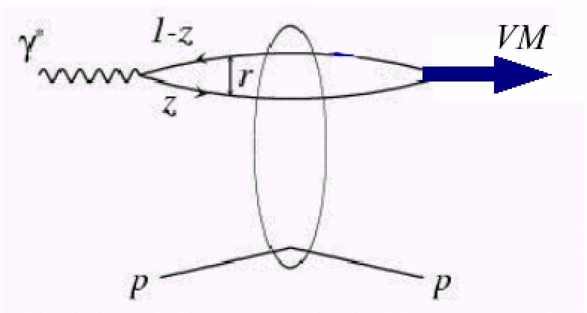


Coherence condition in proton rest frame:

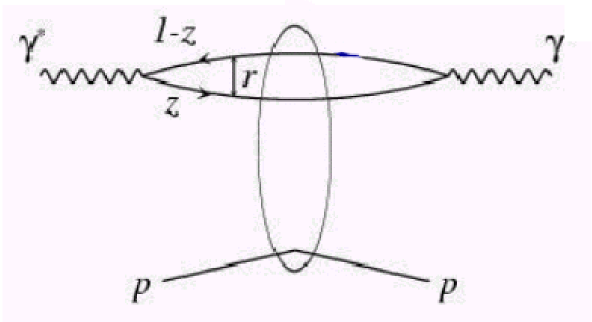
fluctuation length ($\gamma^* \to$ dipol qq) $= 2E_\gamma/(m_{qq}^{\ 2} + Q^2) > 1$ fm

$\to x < 0.01$

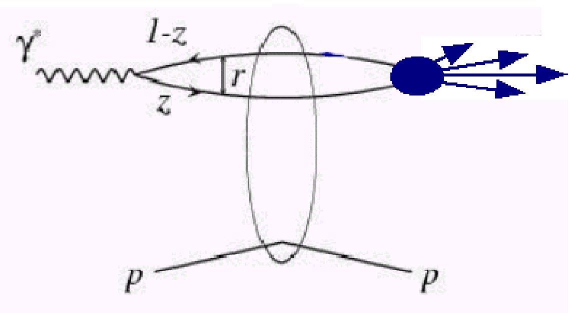
At HERA diffraction is low Bjorken-x phenomenon!



Vector meson production

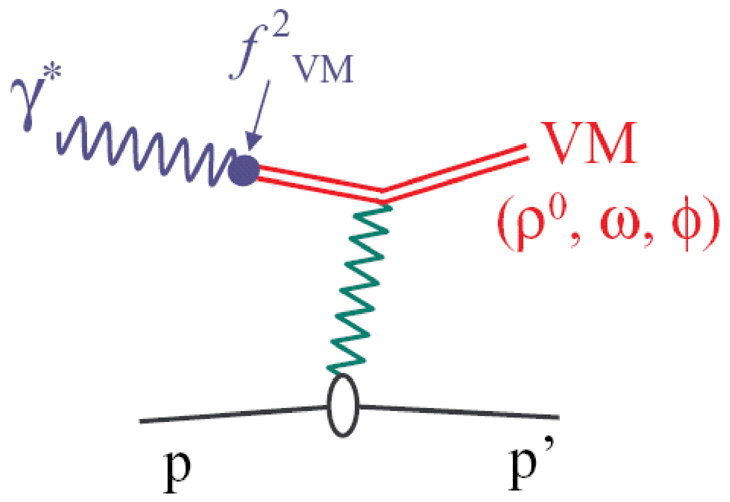


DVCS



inclusive diffraction

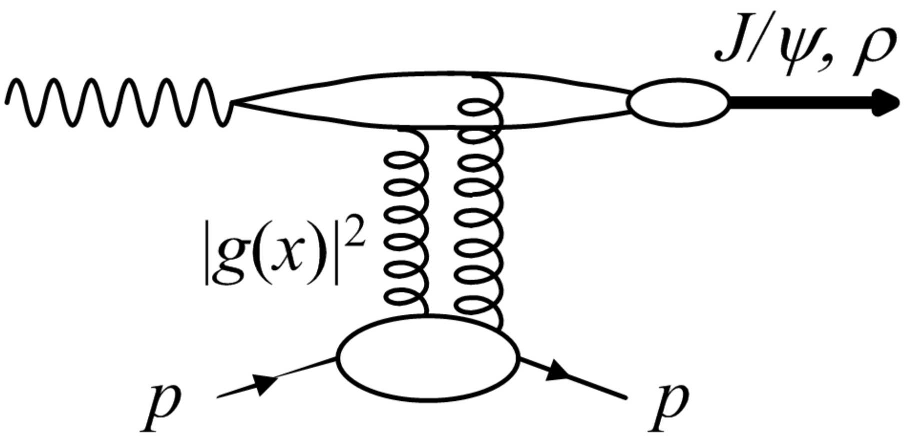
Vector meson production (1)



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
- $d\sigma/dt \sim \exp(-b(W)t), \quad b \sim R_{int}^2 \approx 10$ 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

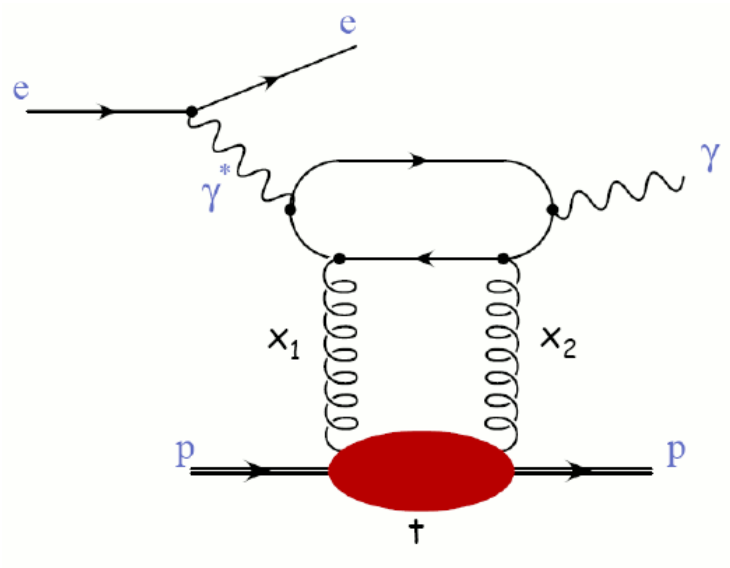
Large Q^2, M_{VM} or $|t|$ $\rightarrow$ small qq dipol

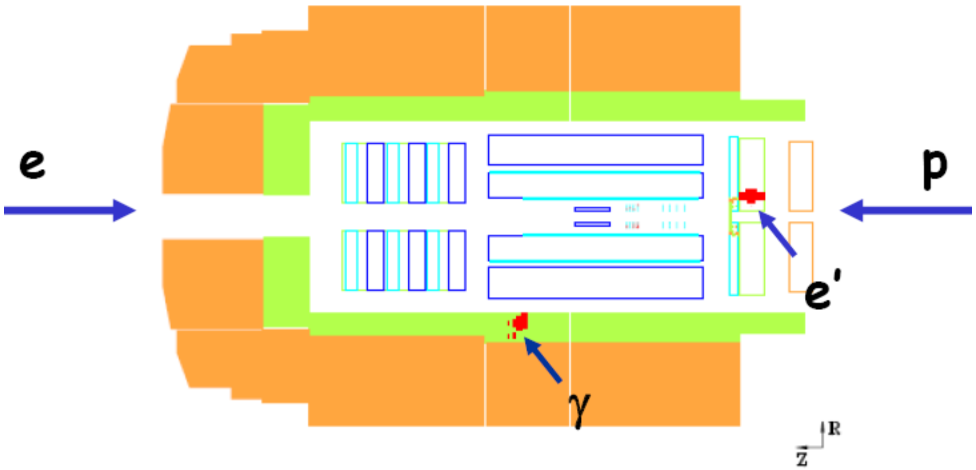
- QCD Pomeron exchange: $\geq$ 2 gluons (colour singlet)
- $\sigma_{VMp} \sim (xg(x))^2 \sim W^{0.7}$!!!
- $b \ll 10$ GeV^{-2}, weak shrinkage

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

Deep virtual Compton Scattering (DVCS)

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





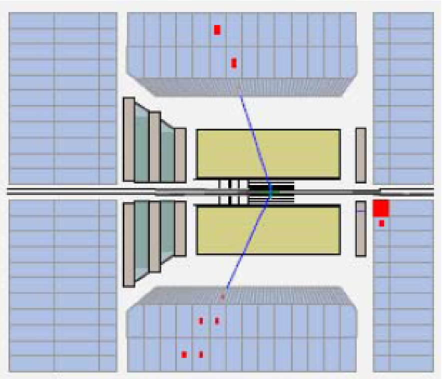
<u>elastic</u> scattering of virtual photon off a proton

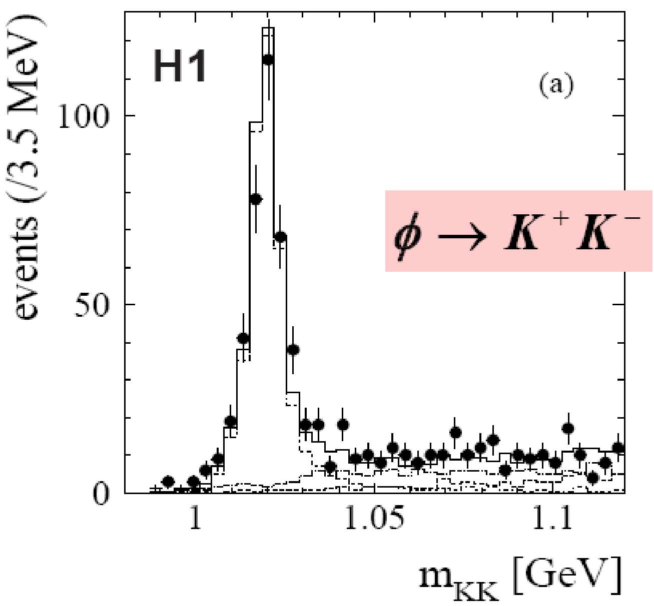
- clean experimental signature
- fully calculable in QCD
- no uncertainty due to VM wave function

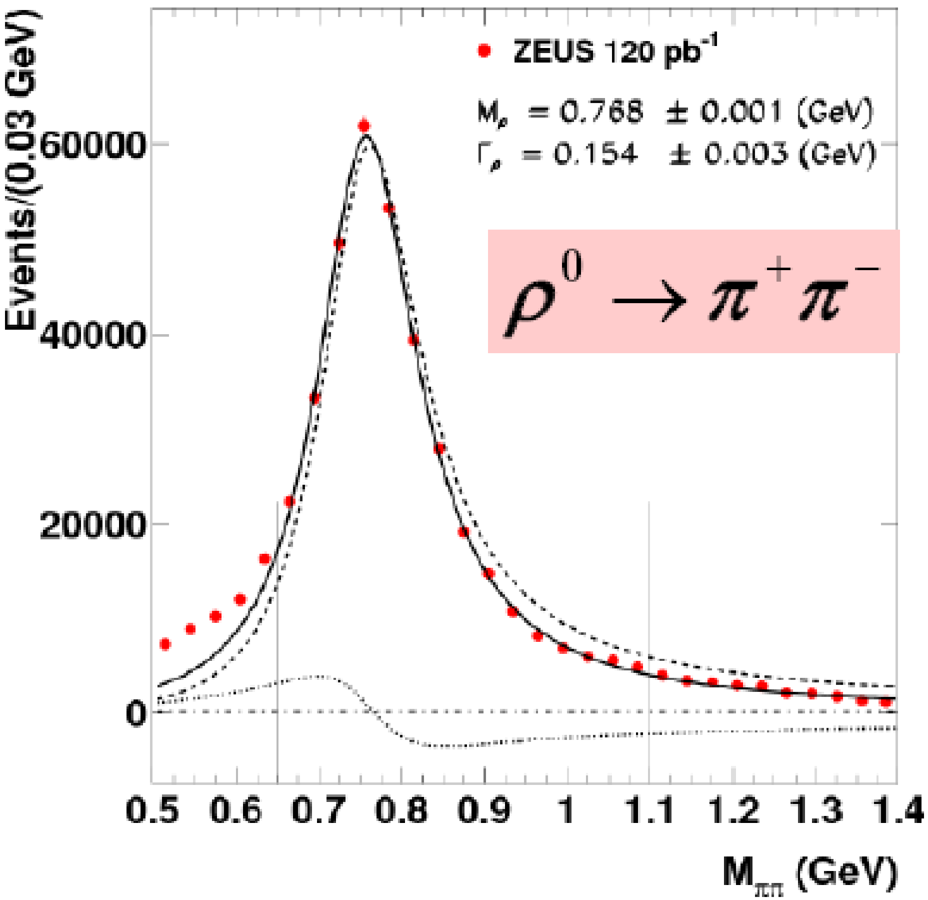
Vector meson production (2)

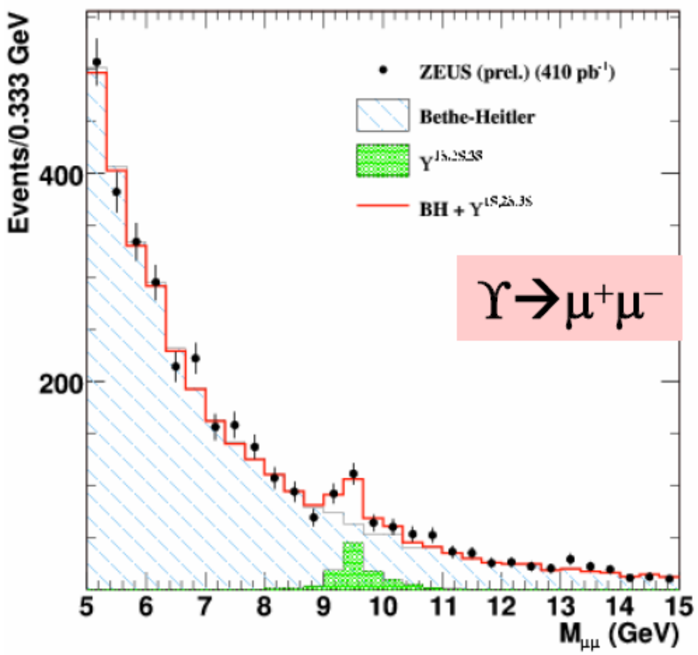
H1prelim-08-013,

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







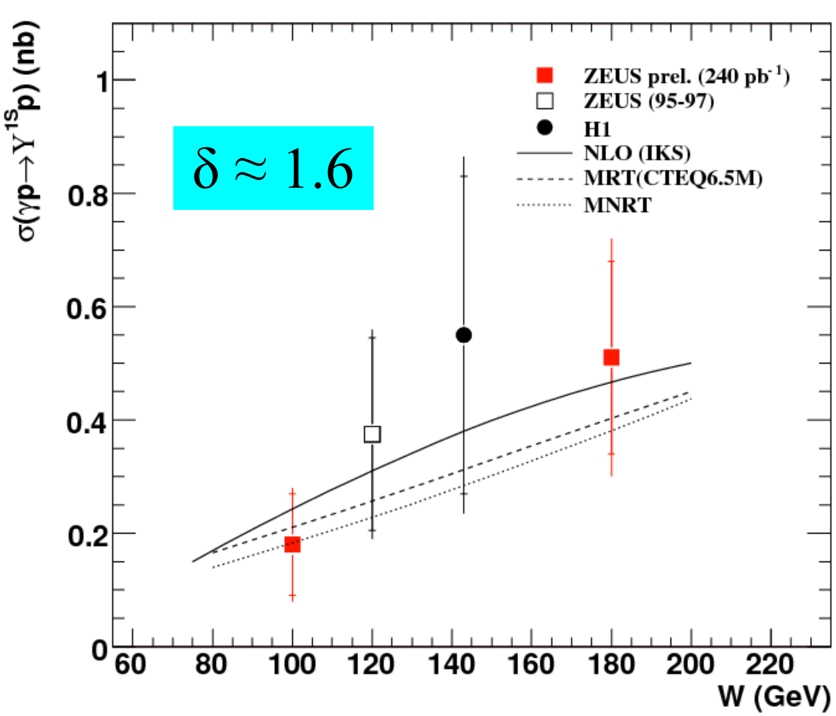


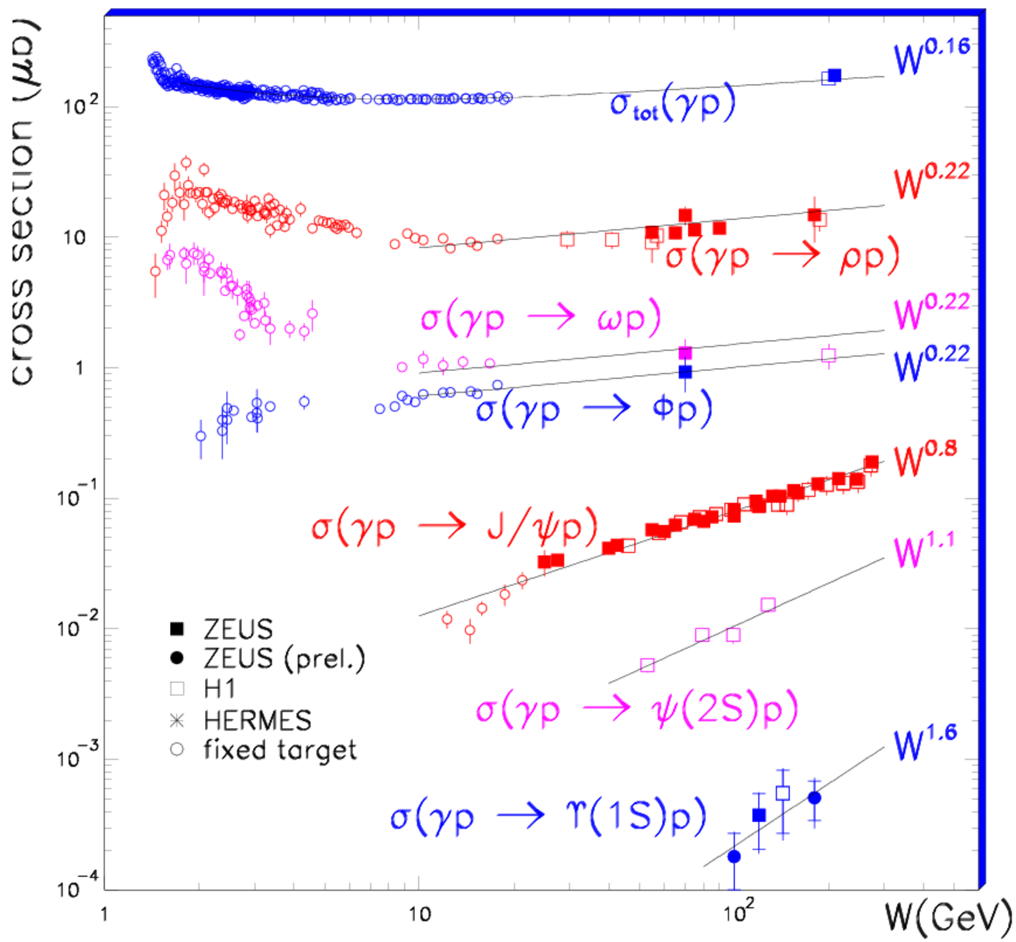
Vector mesons: energy dependence

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

ZEUS-prel-07-015

$\gamma\, p \rightarrow \Upsilon\, p$



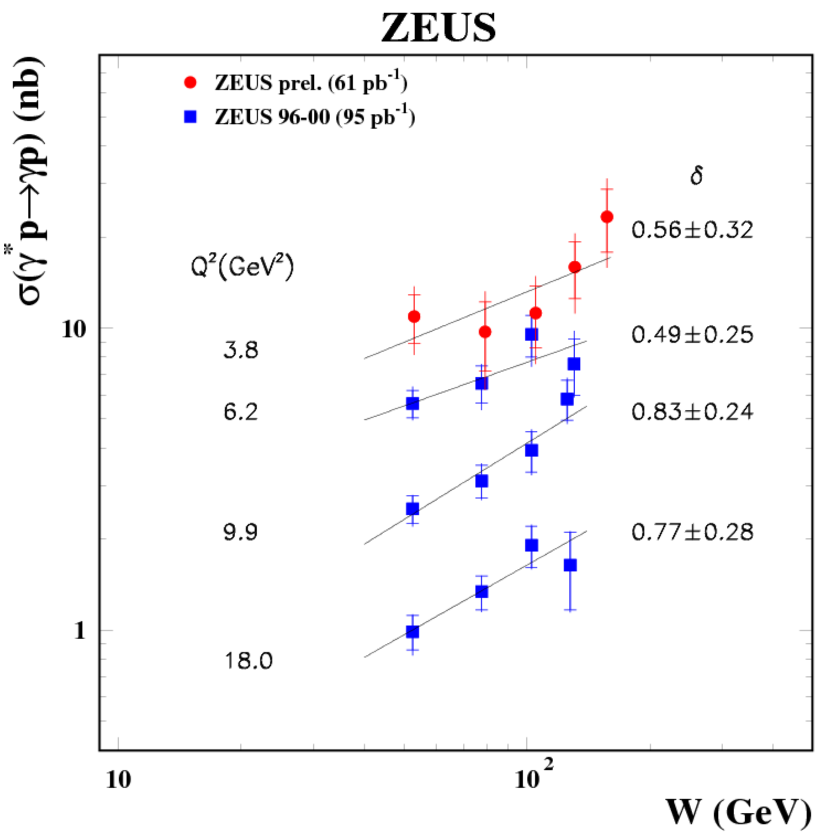


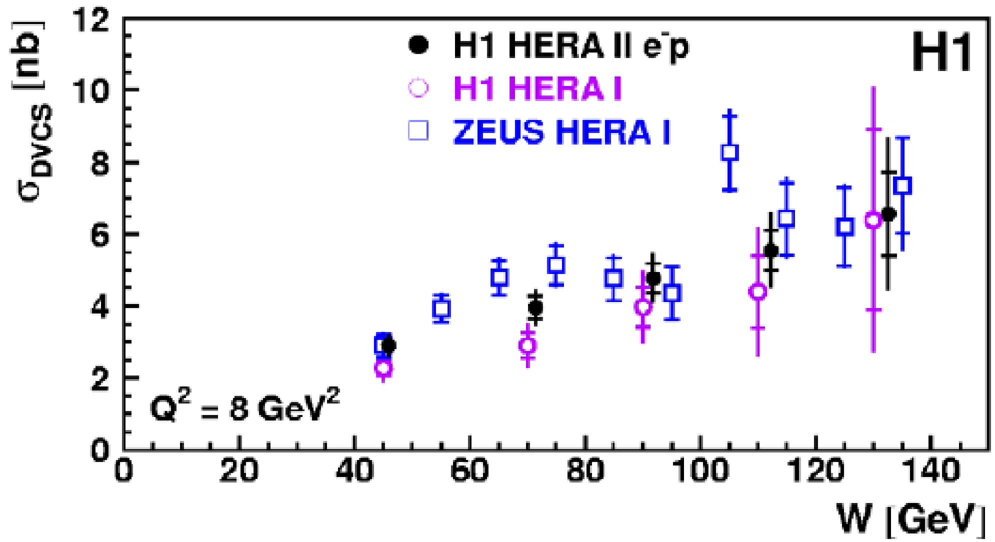
The heavier vector meson –
– the steeper W-dependence

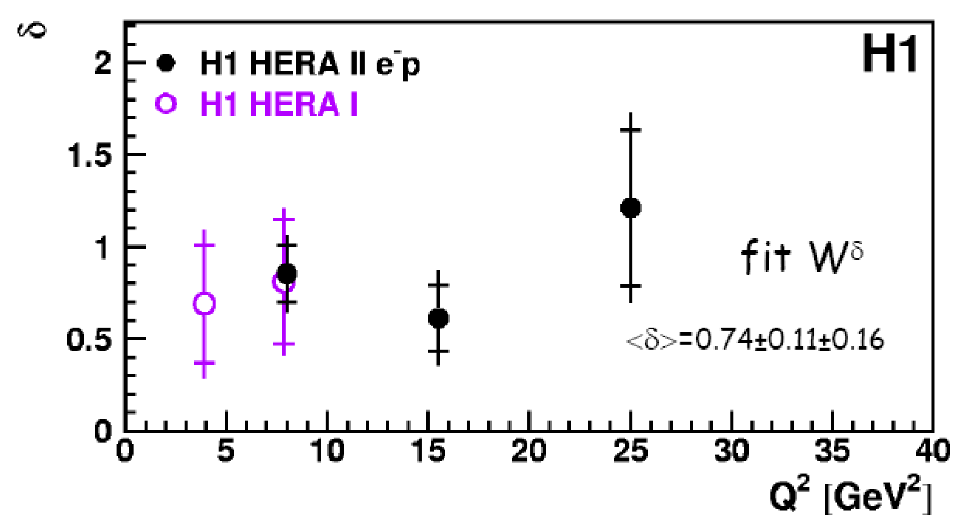
DVCS: energy dependence

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

$$\gamma^* p \longrightarrow \gamma\, p$$

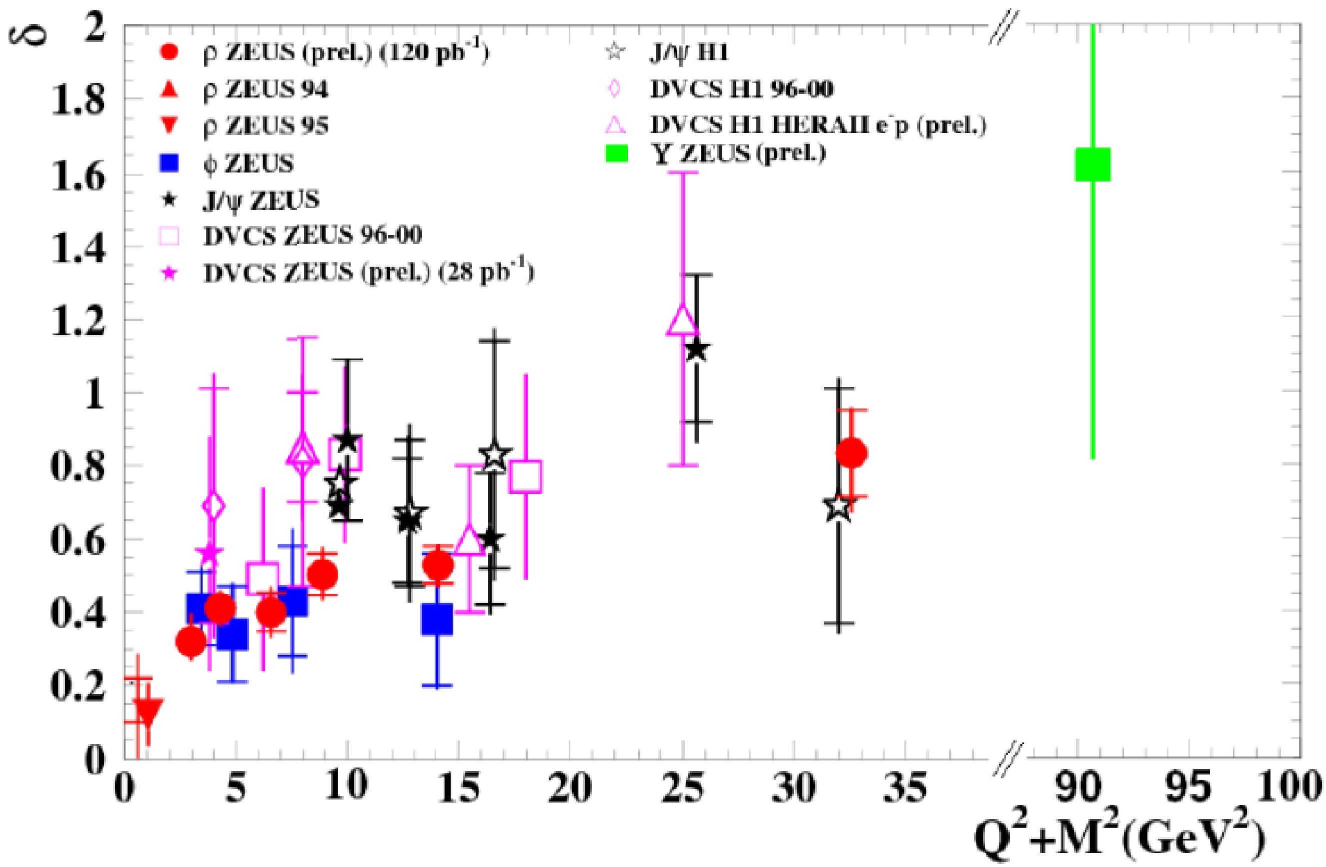






Steep rise with energy, no significant Q^2 dependence

VM and DVCS energy dependence



$\sigma \sim W^{\delta}$

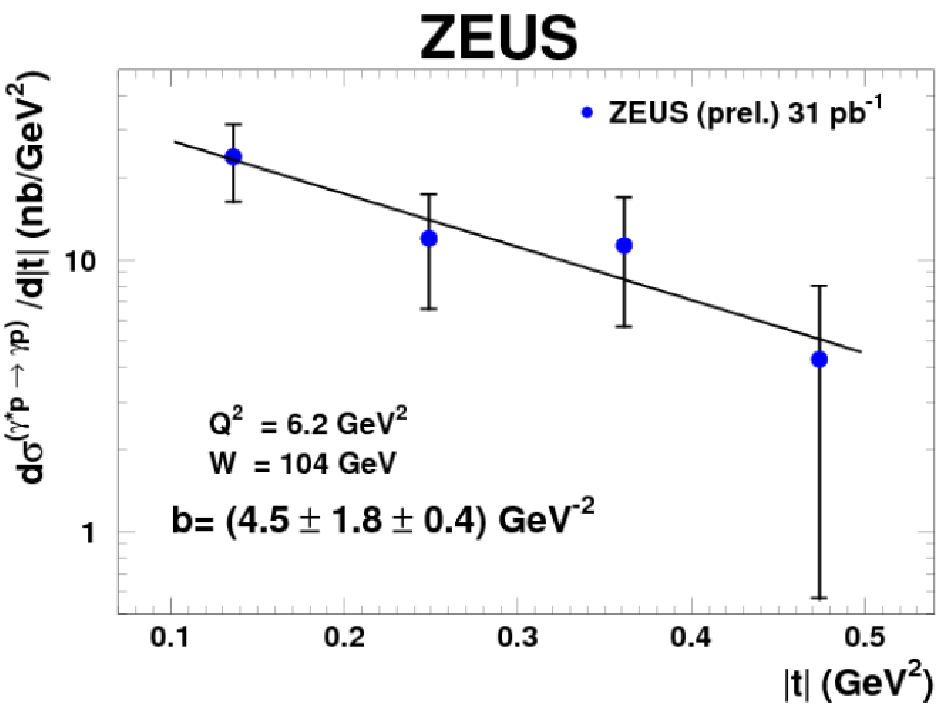
VM-s: bigger "hard" scale Q^2+M^2 – steeper rise with W,
Q^2+M^2 scale governs "soft" – "hard" interaction transition

DVCS: always steep rise with W – "hard" interaction...

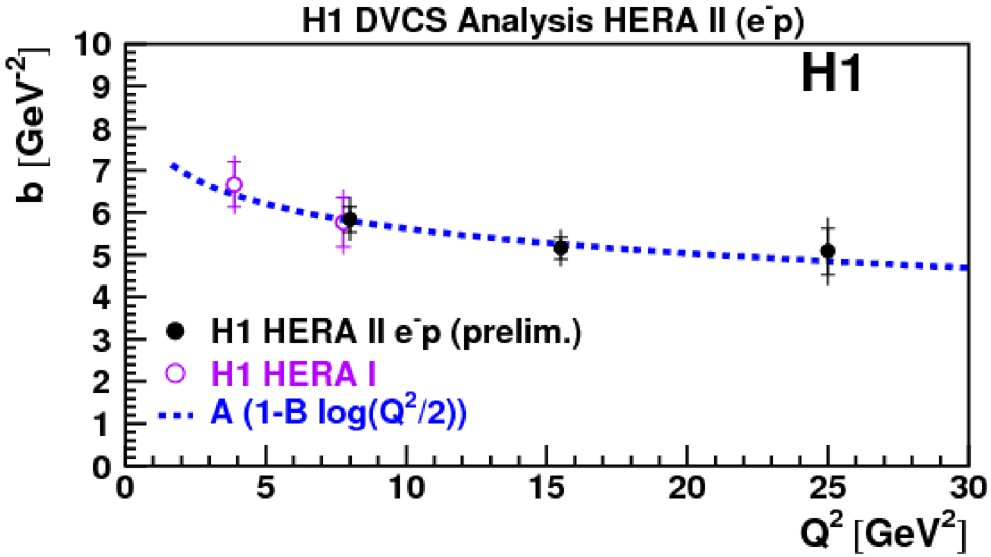
DVCS: t-dependence

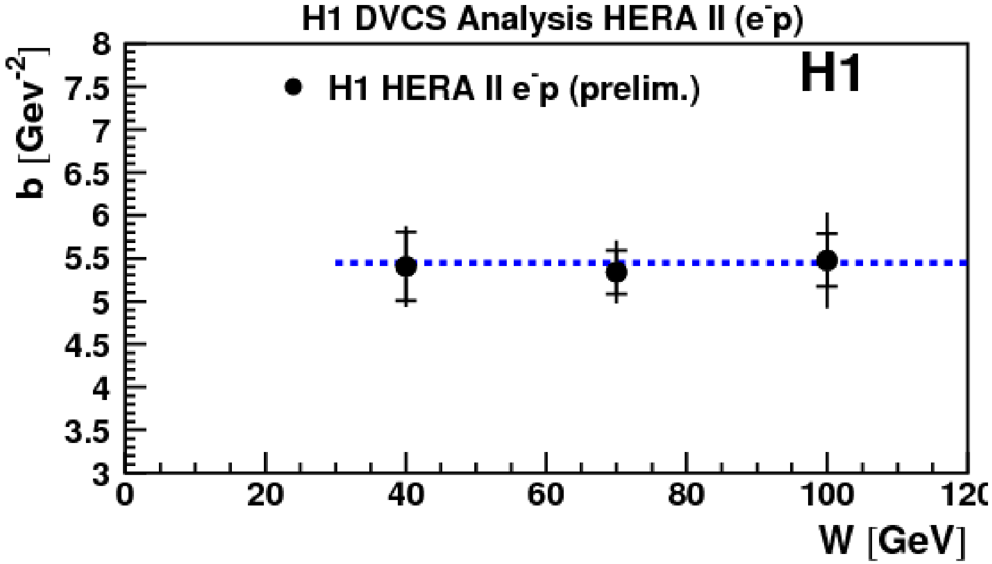
$$d\sigma/dt \sim e^{-b|t|}$$

slope b ~ size of the interaction



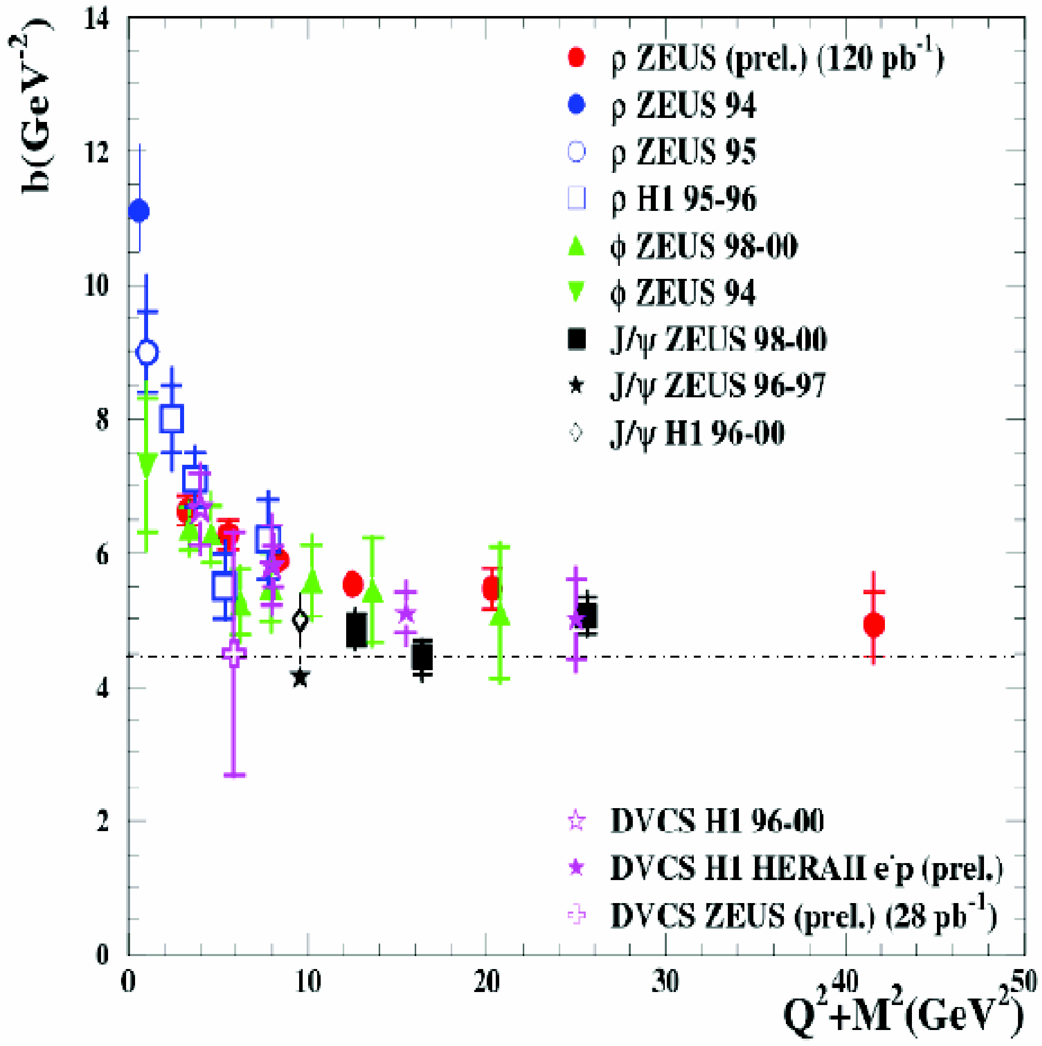
direct measurement with **ZEUS** **L**eading **P**roton **S**pectrometer





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

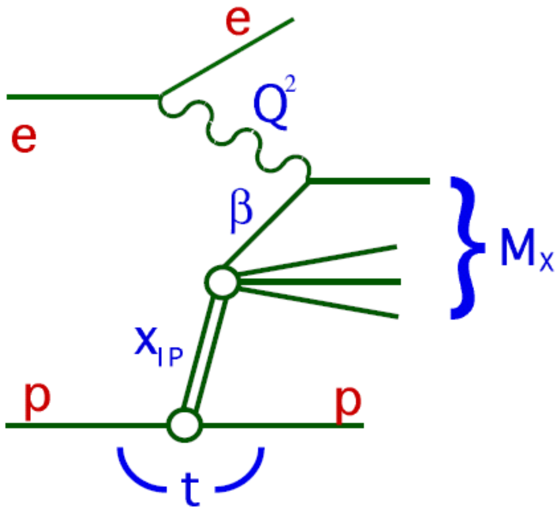
Inclusive diffraction in e-p interactions (1)

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 →

→ ("hard" factorisation + QCD fit) → diffractive PDFs

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

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

"reduced" cross section $\sigma_r^D = F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D \approx F^D_2, \quad y < 1$

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

IPomeron flux

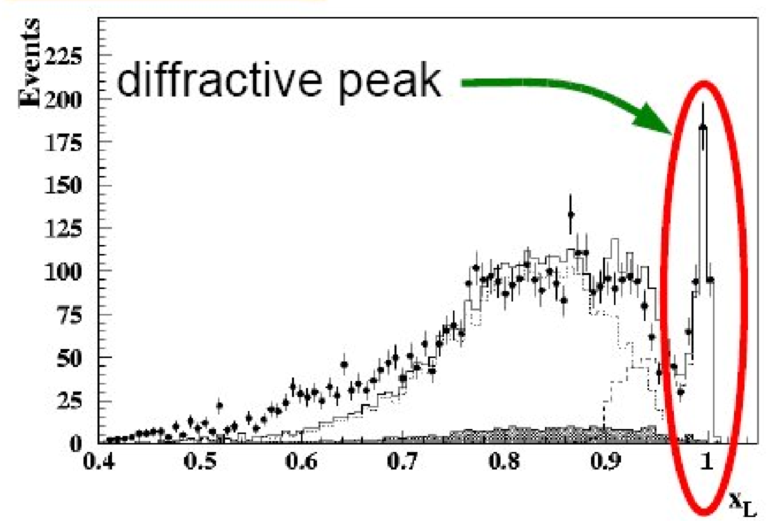
IPomeron structure function

Inclusive diffraction in e-p interactions (2)

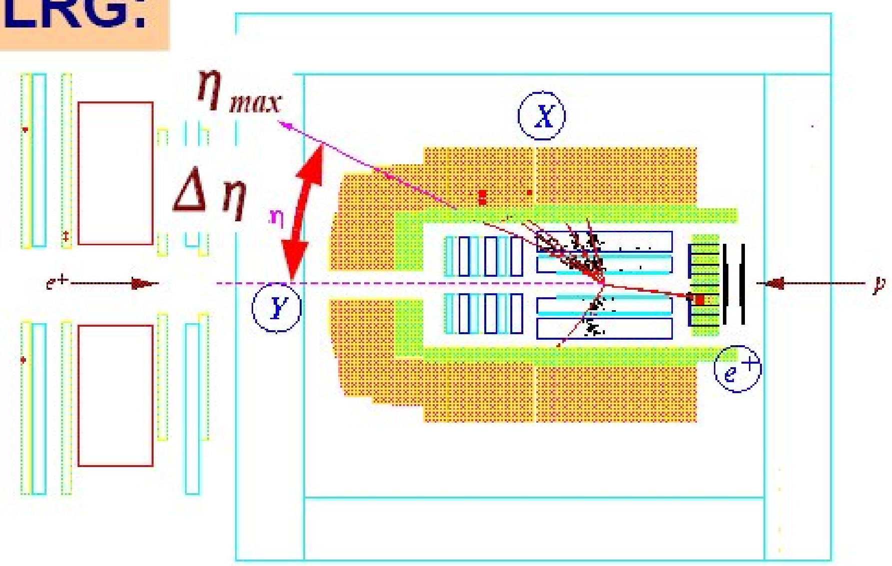
Diffractive selection:

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

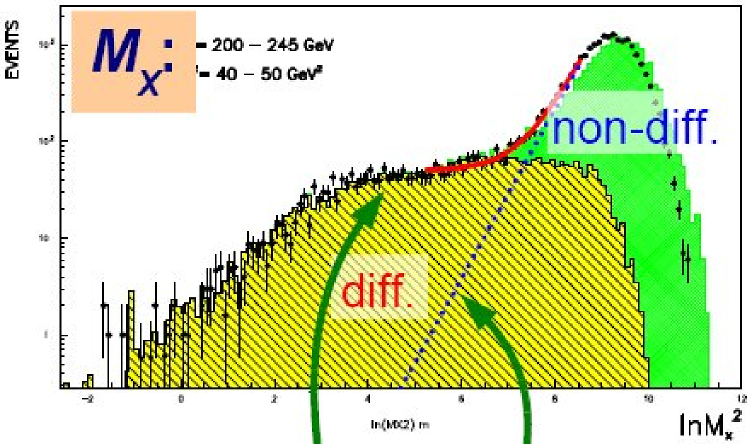
p tagging:



LRG:



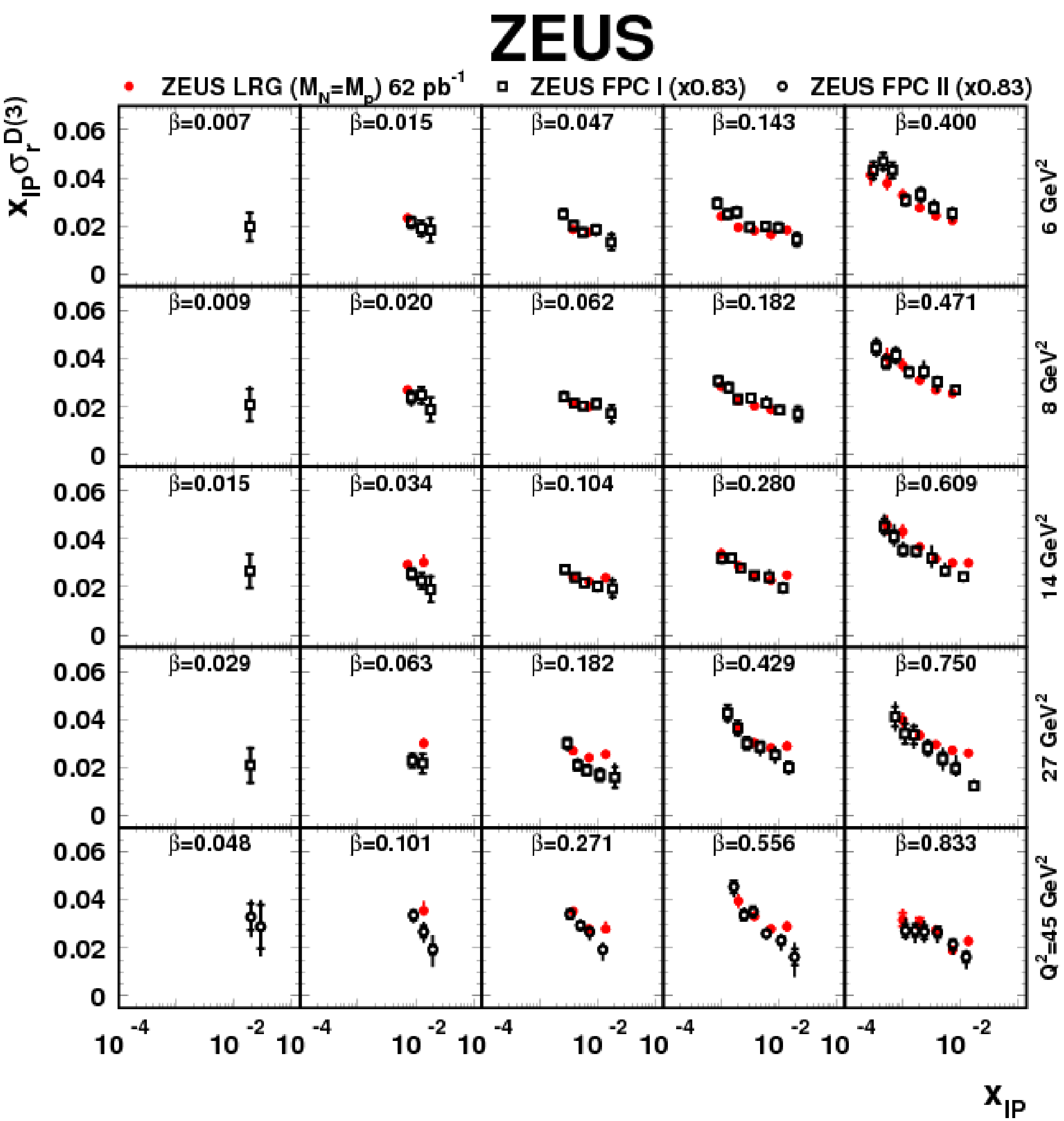
M_X:



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

Inclusive diffraction in e-p interactions (3)

ZEUS: **LRG** vs **M$_X$** method (FPC I, FPC II)

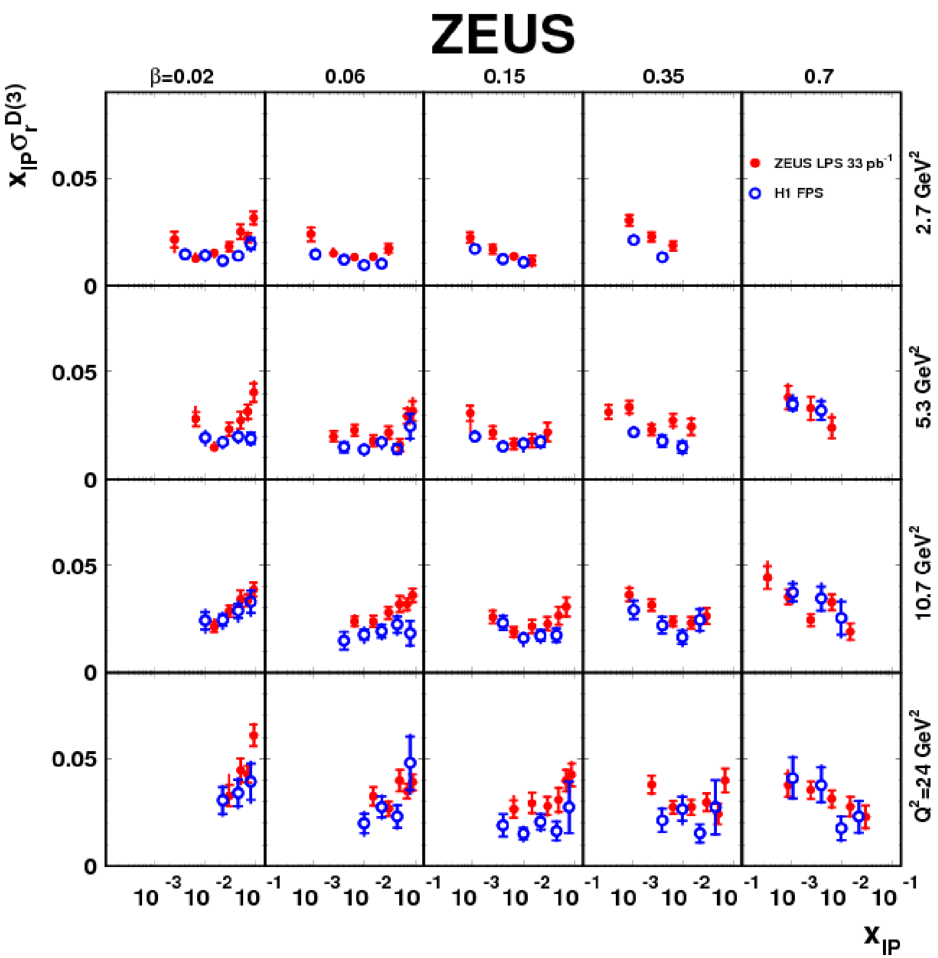


ZEUS-prel-06-024, M. Ruspa DIS2008

Different methods are consistent

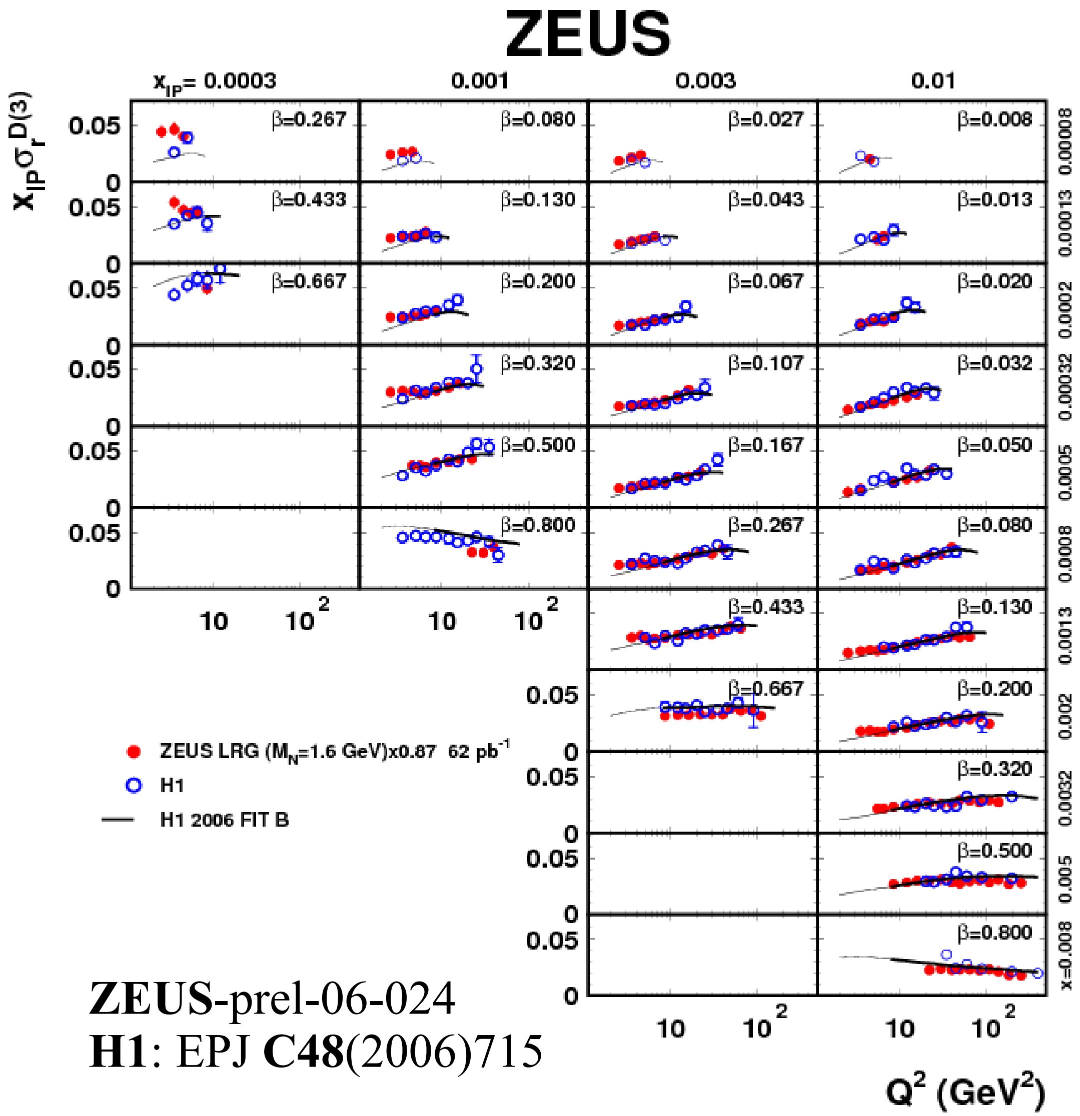
Inclusive diffraction in e-p interactions (4)

proton tagging results:



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

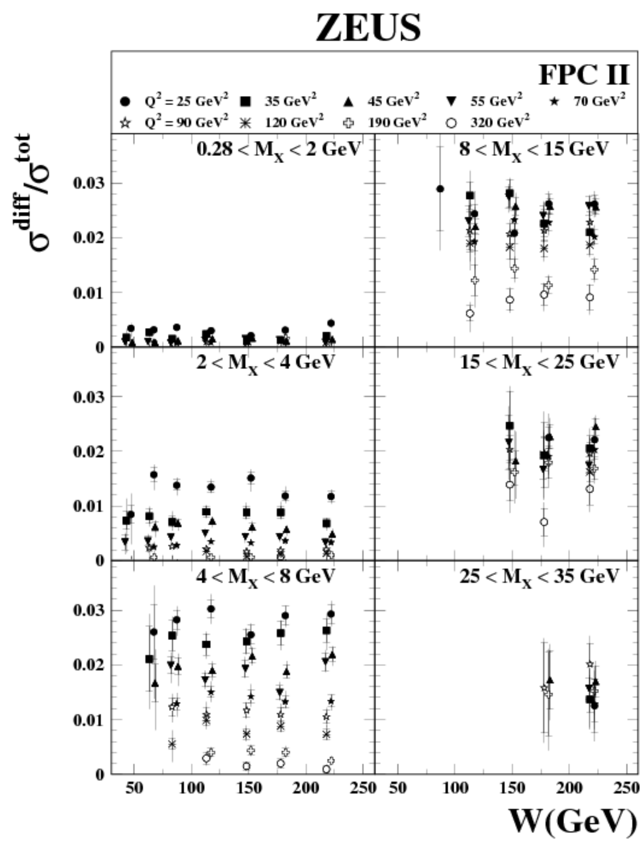
LRG results:

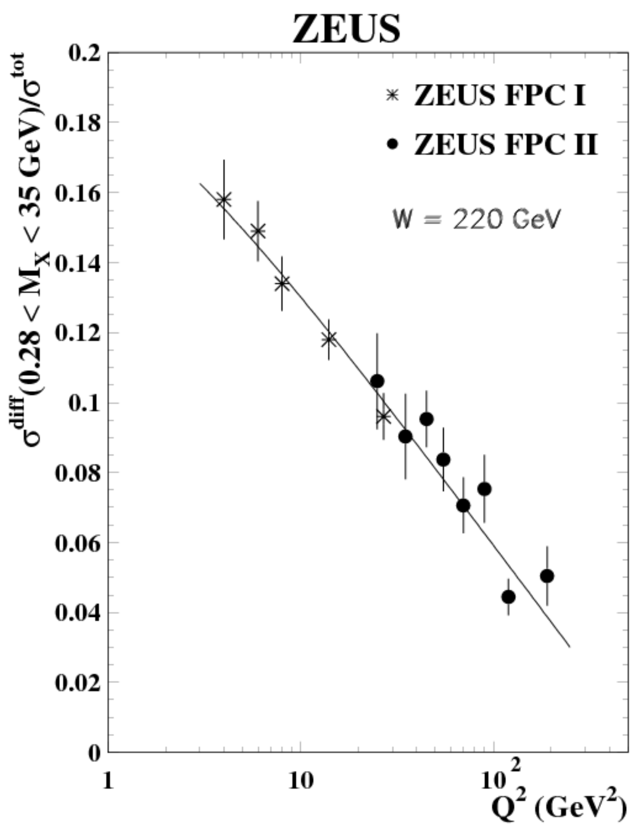


ZEUS-prel-06-024
H1: EPJ **C48**(2006)715

ZEUS consistent with **H1**

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



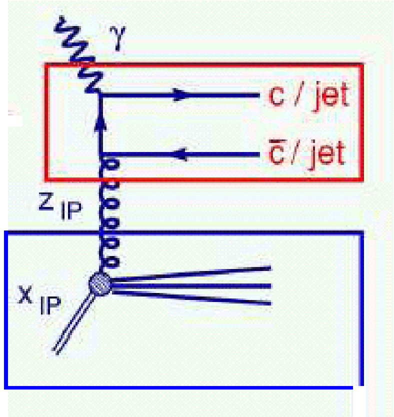


- Diffraction yield (fixed M_X, Q^2) ≈ const (W)
- Diffraction yield (0.28 < M_X < 35 GeV) ≈ a – b ln(1+Q^2)

QCD factorisation tests

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

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



$f_i^{\,D}$ – universal diffractive Parton Distribution Function (dPDF)

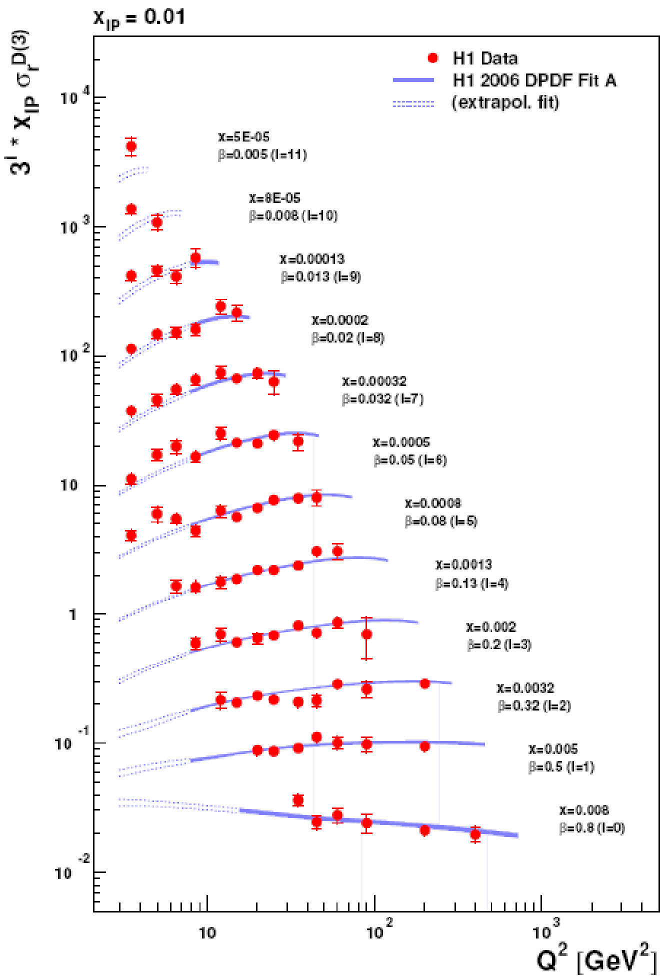
$\sigma_i^{\gamma *}$ – universal (γ* parton) cross-section

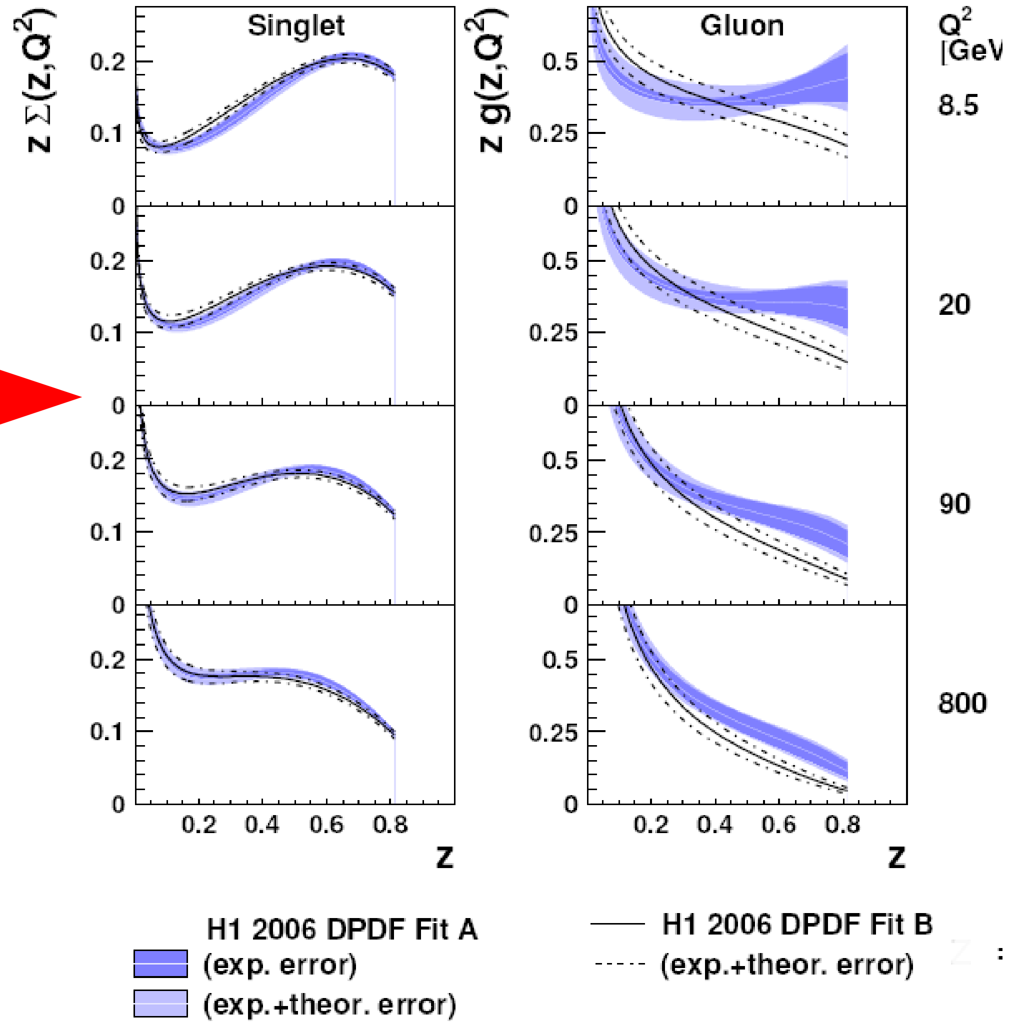
Basic strategy:

- Measure F^D_2 from inclusive diffraction
- Extract diffractive PDFs from NLO DGLAP fit to F^D_2
- calculate $\sigma_i^{\gamma *}$ for semi-inclusive diffractive processes
- convolute with dPDFs (proton vtx factorisation assumed)
- compare the calculations with the measurements...

H1 : $\sigma_R^{D(3)}$ → NLO DGLAP fits (+proton vtx factorisation) → diffractive PDFs

EPJ **C48** (2006) 715





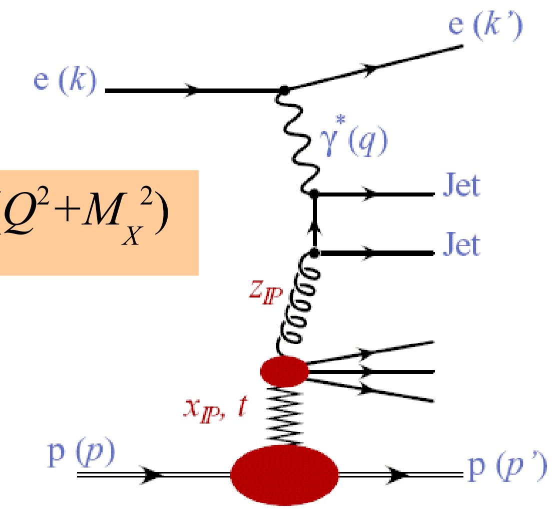
• Gluons weakly constrained, esp. at large z

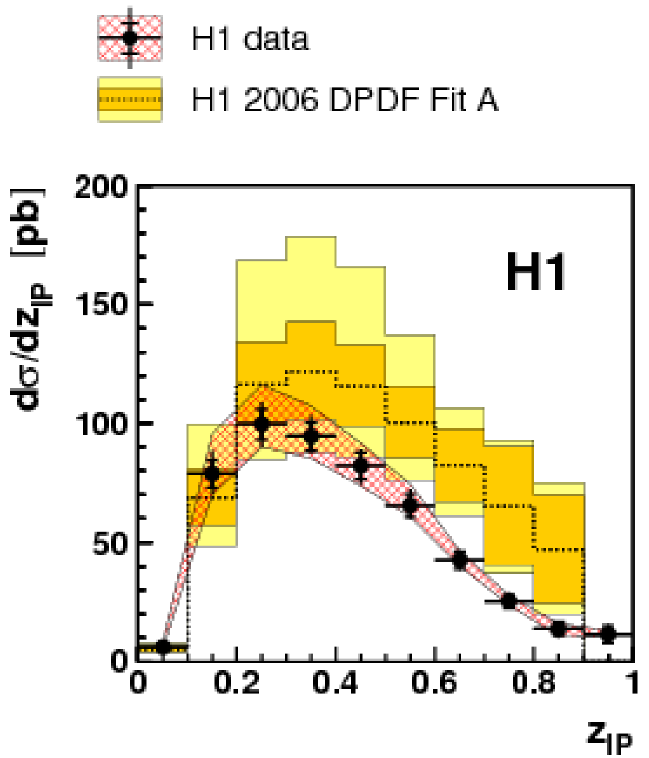
z = fraction of parton momentum in hard scattering/IPomeron

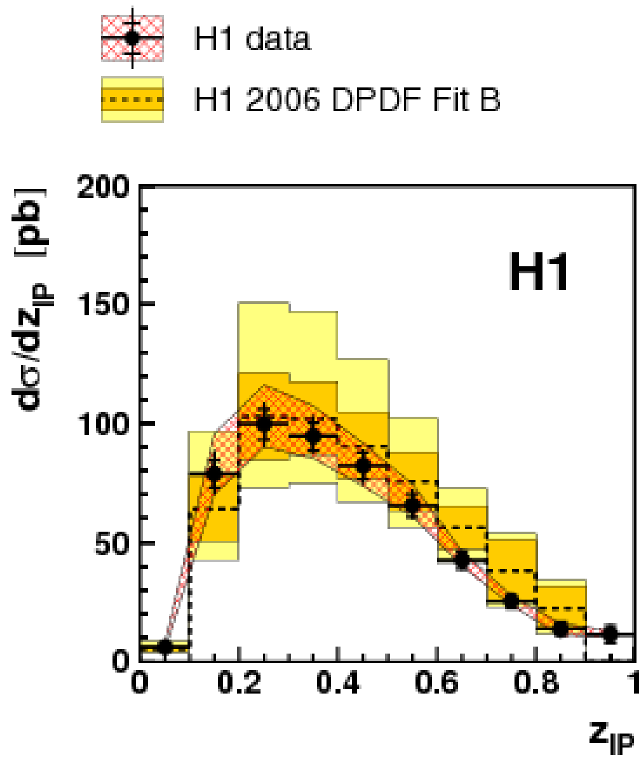
H1: $4 < Q^2 < 80$ GeV^2, $0.1 < y < 0.7$, $x_{IP} < 0.03$

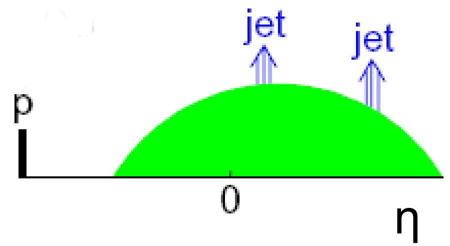
JHEP 0710:042,2007

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



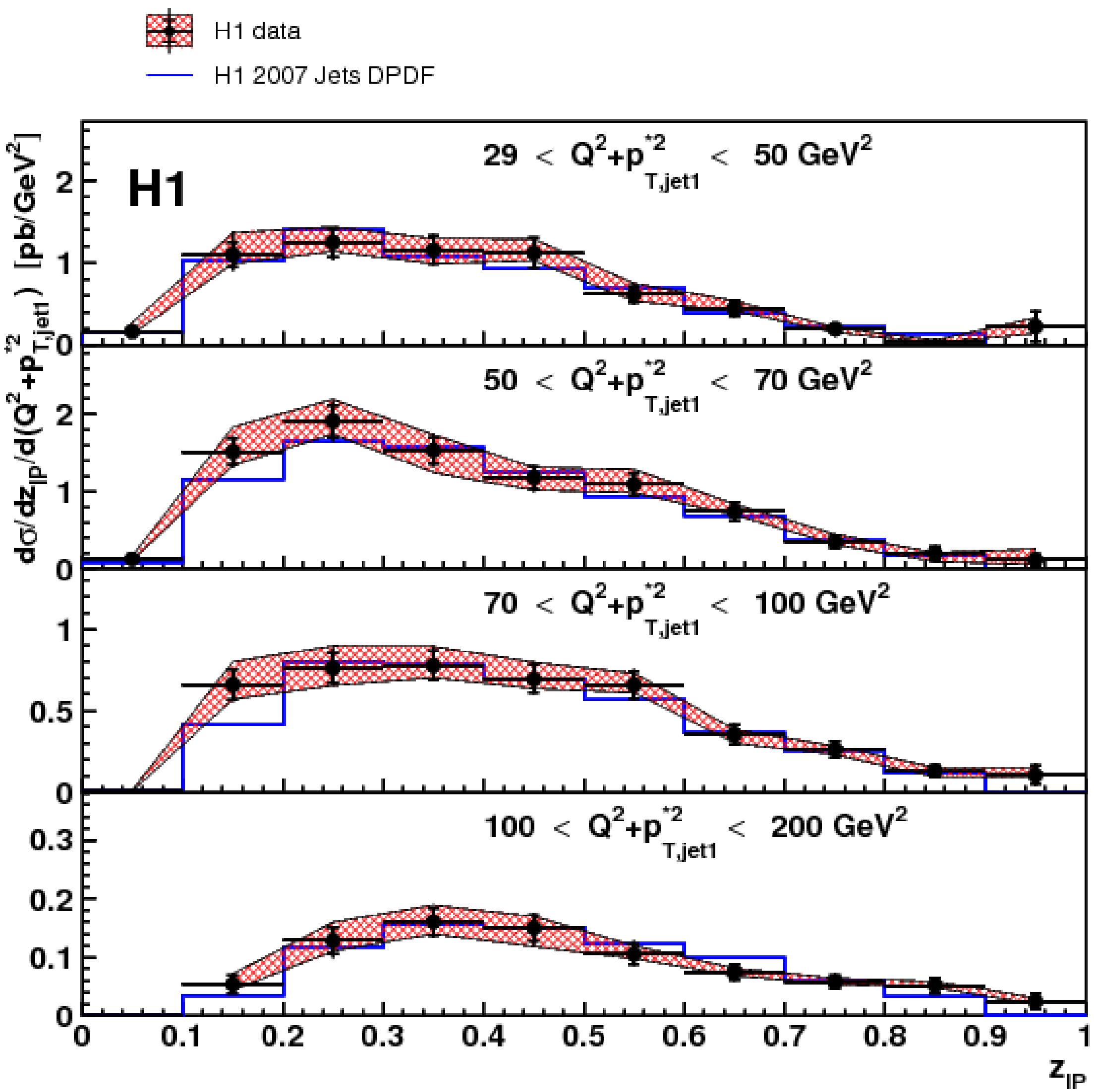






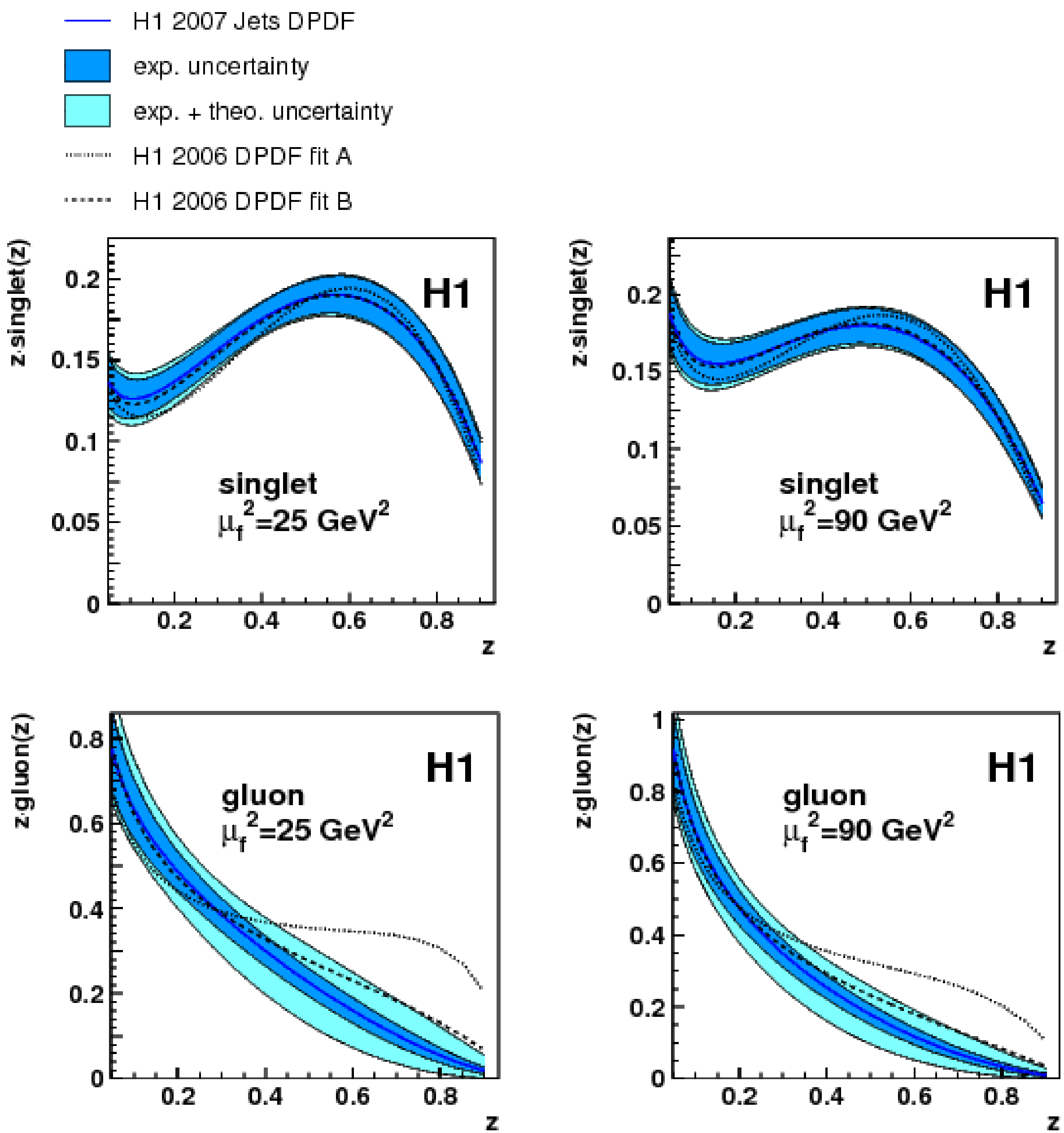
• H1 2006 DPDF fit B gives better agreement with the data

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



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

Factorisation tests: diffr. dijets in DIS (3)



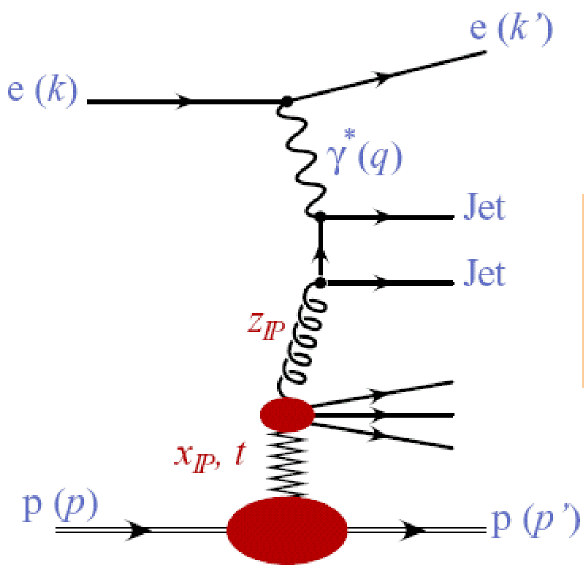
H1 2007 Jets dPDFs

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

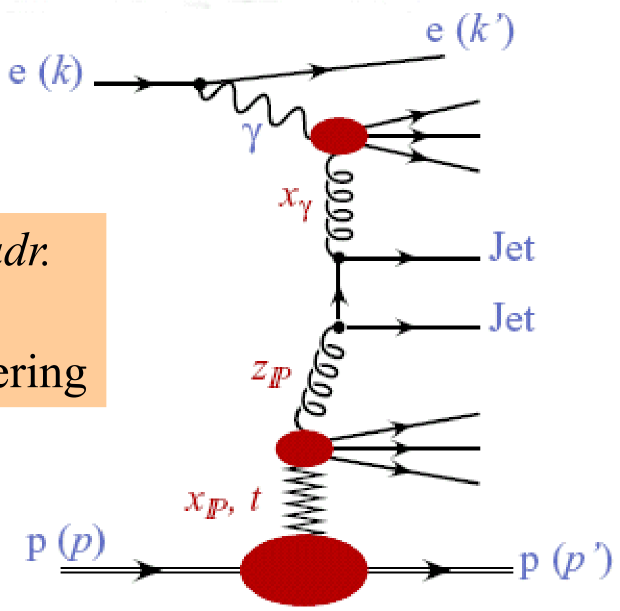
Diffractive dijets in photoproduction (1)

direct photon (like DIS)

resolved photon



$x_\gamma = \Sigma(E\text{-}p_z)jets/\Sigma(E\text{-}p_z)hadr.$
= fraction of photon mom. in hard scattering



$x_\gamma \approx 1$

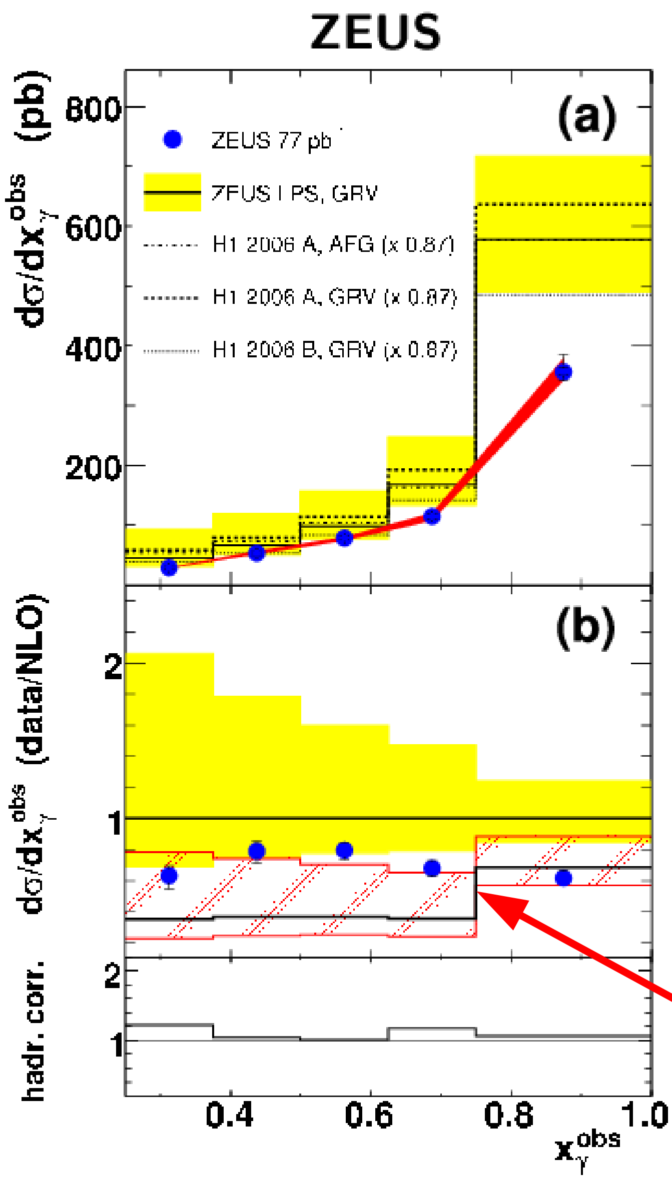
$x_\gamma < 1$

Resolved photon may behave as a hadron →

→ factorisation may be broken (as in p-p)

Diffractive dijets in photoproduction (2)

ZEUS (DESY-07-161):



E_T jet1(2) > 7.5(6.5) GeV ← higher E_T cuts than H1
142 < W < 293 GeV
x_{IP} < 0.025

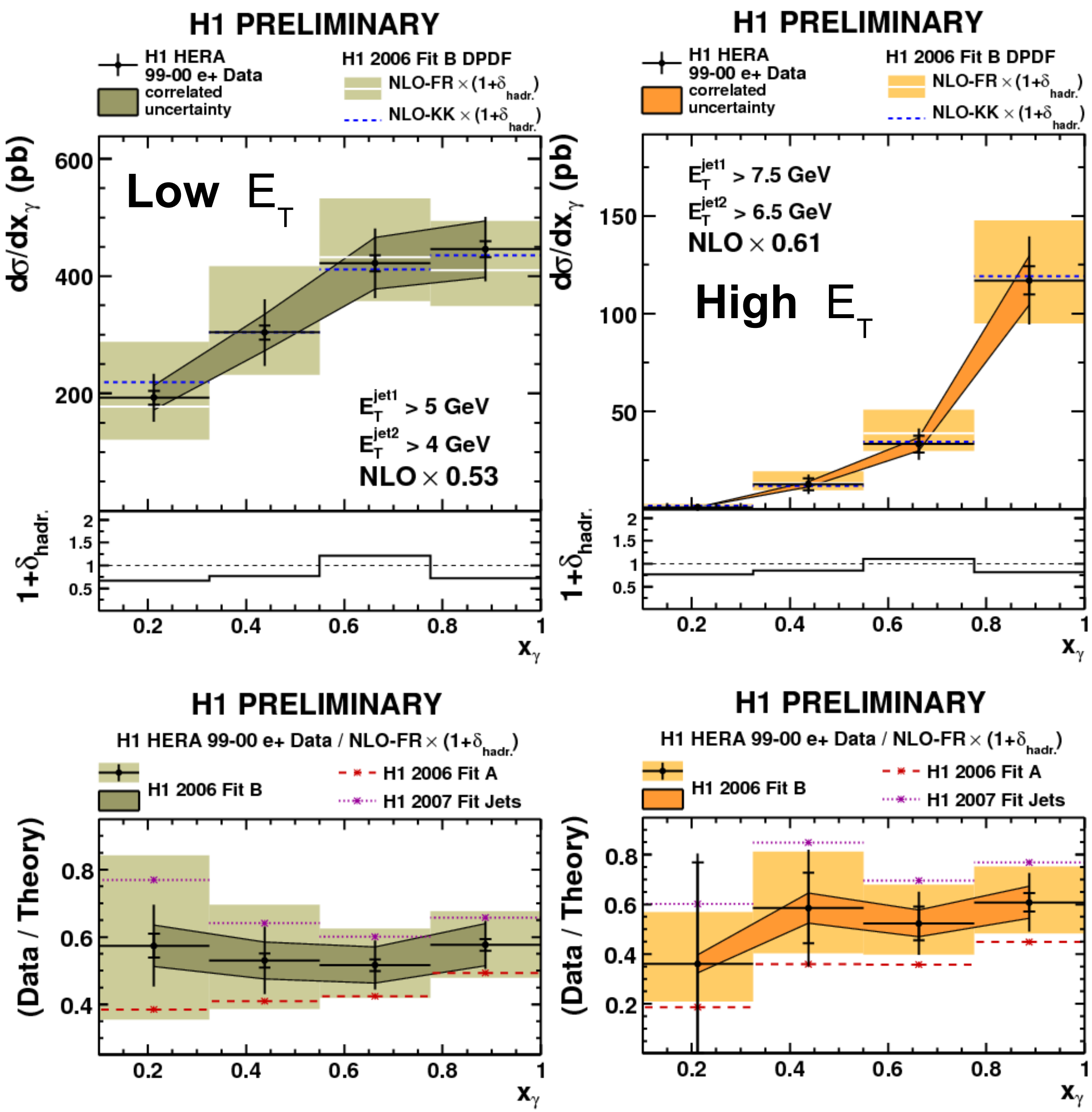
- NLO calculations: Klasen-Kramer
- Diffractive PDFs:
  NLO fits to ZEUS LPS + charm
  H1 2006 Fit A
  H1 2006 Fit B

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

R = 0.34 suppression for resolved γ
(Kaidalov & Khose)

Diffractive dijets in photoproduction (3)

H1-prel-08-012:



γ PDF: GRV-G LO

E_T jets dependence!

Global suppression:

Low E_T:

data/NLO (H1 2006 fit B) =
= 0.54±0.1(syst.)±0.14(scale)

data/NLO (H1 2007 fit Jets) =
= 0.65±0.11

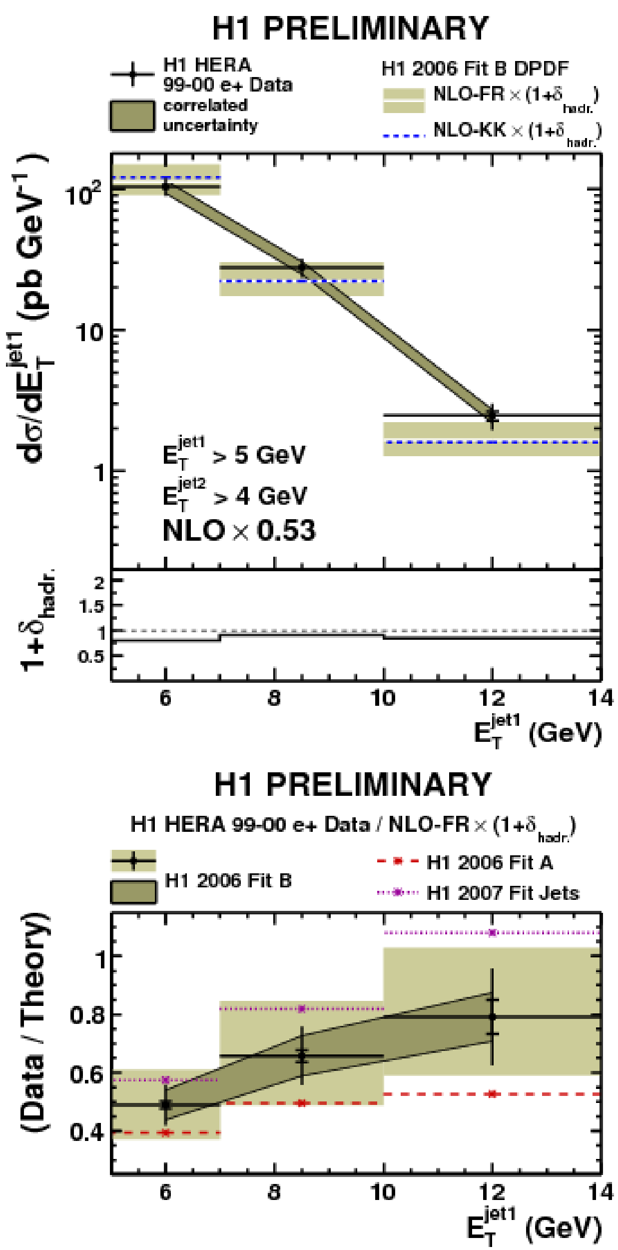
High E_T:

data/NLO (H1 2006 fit B) =
= 0.61±0.13(syst.)±0.15(scale)

data/NLO (H1 2007 fit Jets) =
= 0.79±0.16

~ consistent with ZEUS!

Diffractive 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...