

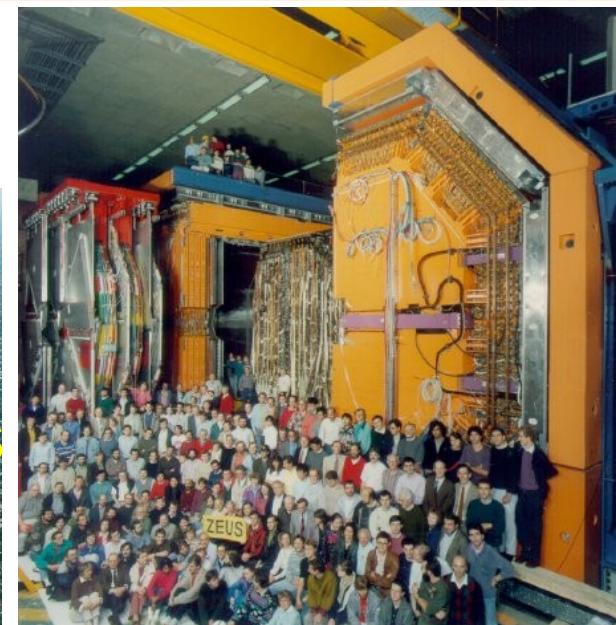
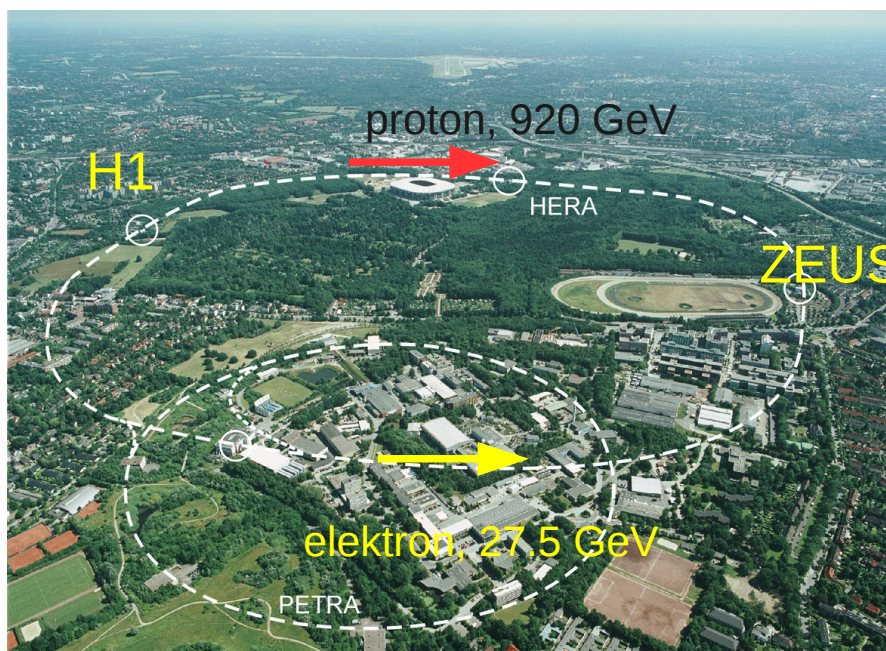


Diffraction at HERA



Jan Figiel

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



... we investigate the **fundamental forces** and **particles** in $e p$ collisions at highest energies – quark and gluon interactions, we verify the Standard Model and seek „new physics” ...
... among the other - studying **diffractive** processes ...





Outline

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

Exclusive diffraction: vector meson production

Inclusive diffraction:

Diffraction parton distribution functions

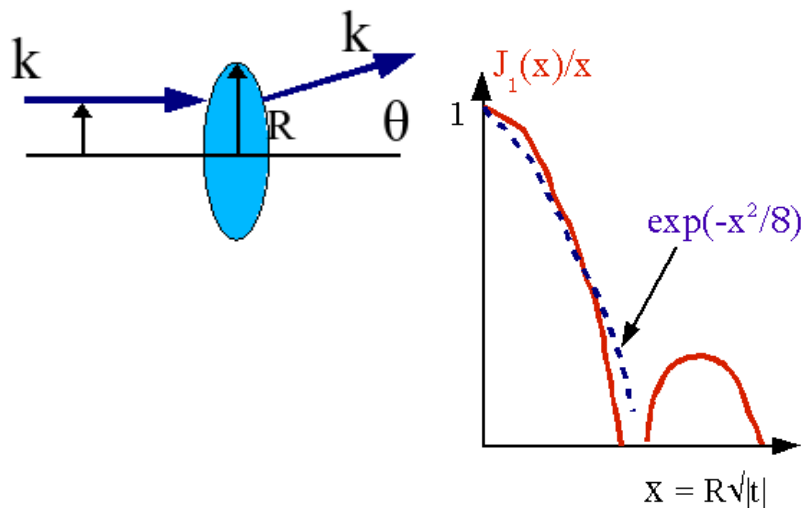
QCD factorisation tests: diffractive dijet production

- Summary



Diffraction in hadron-hadron interactions (1)

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

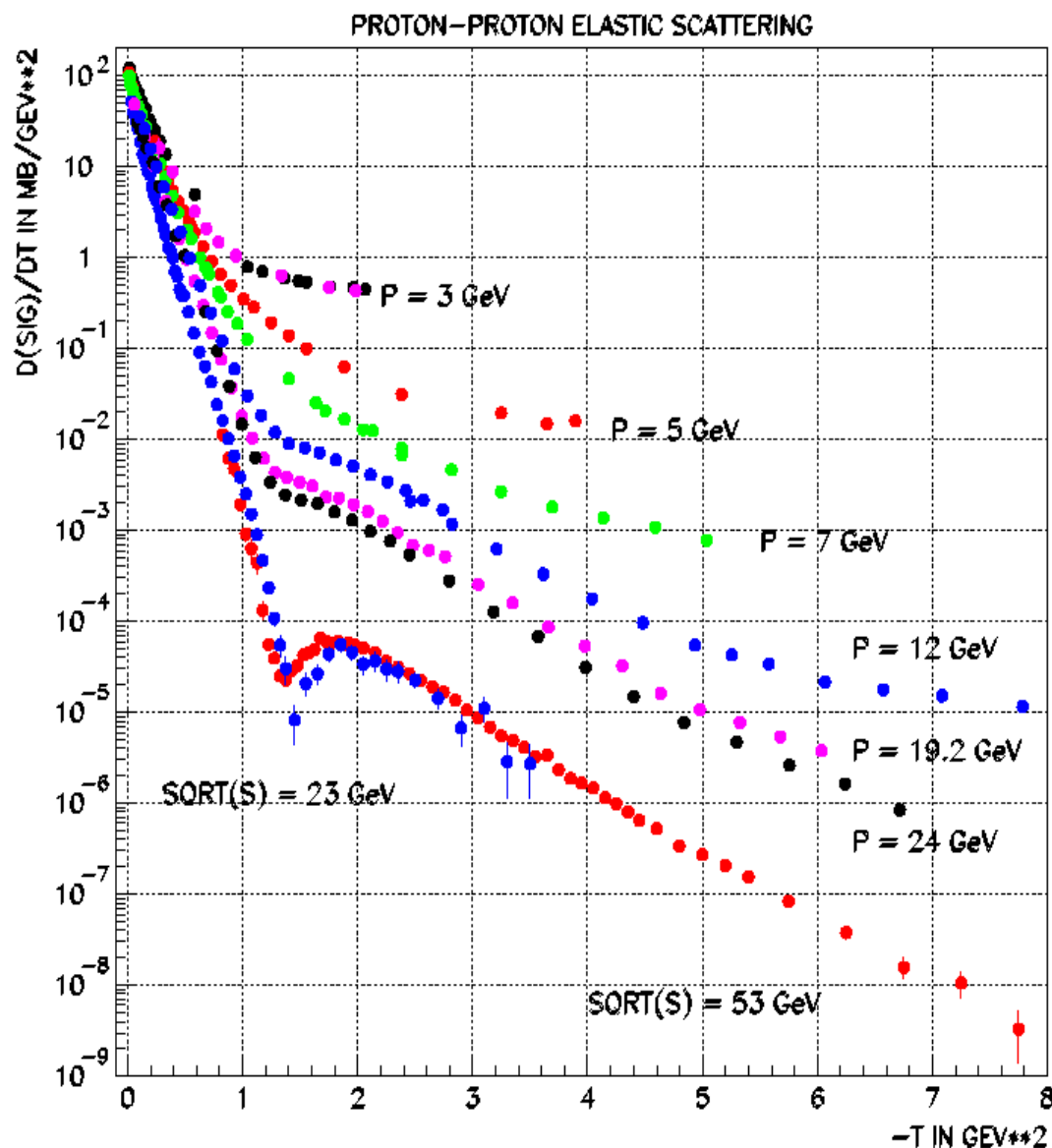


Elastic hadron-hadron scattering:

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

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

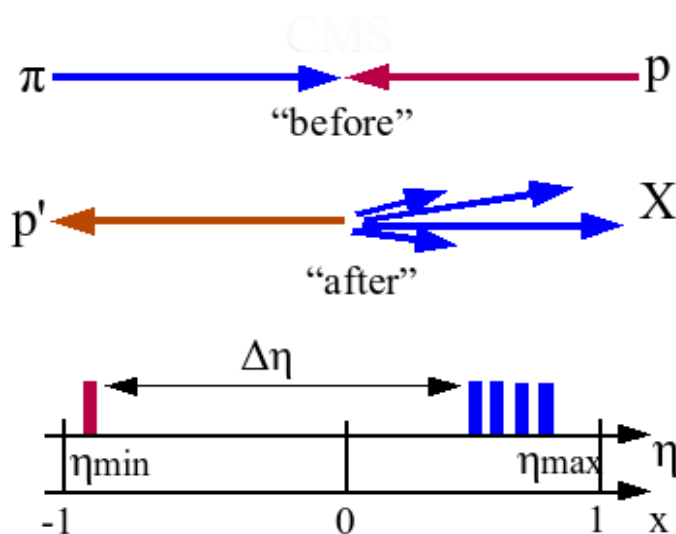
$$b = (R/2)^2 \approx 8 - 10 \text{ GeV}^{-2}$$



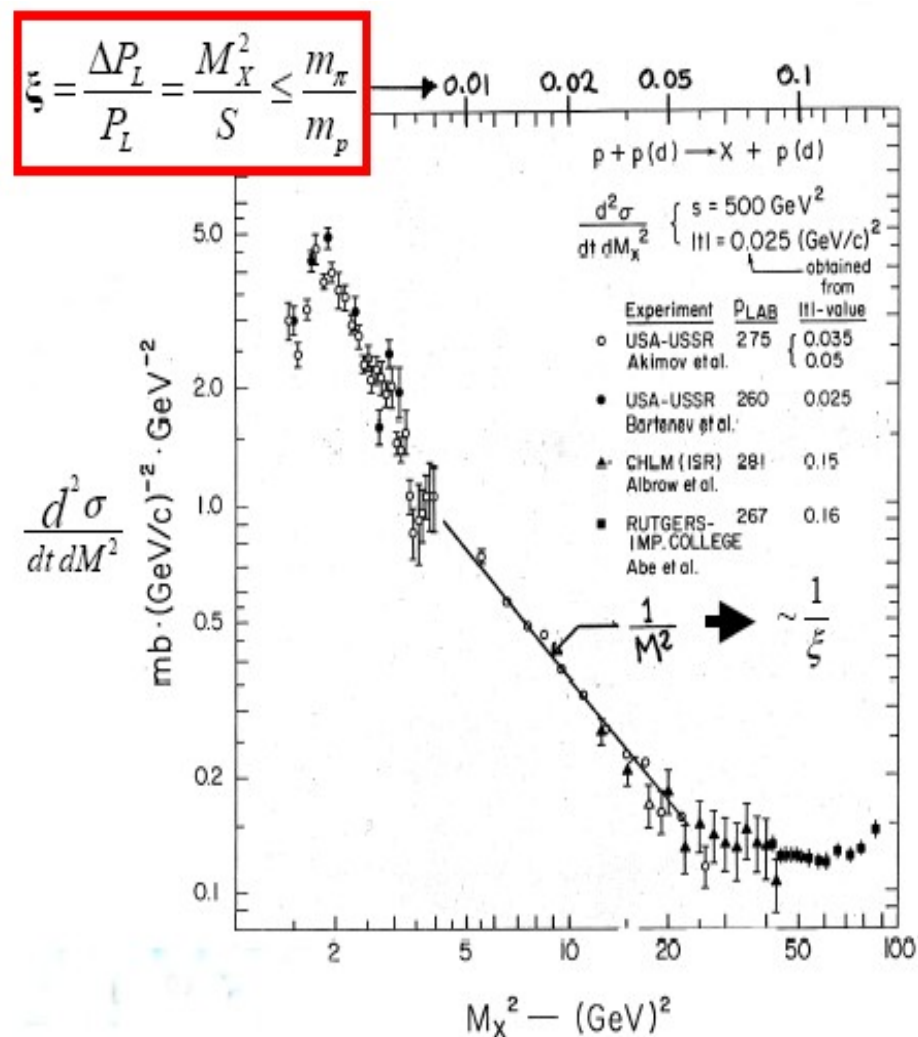
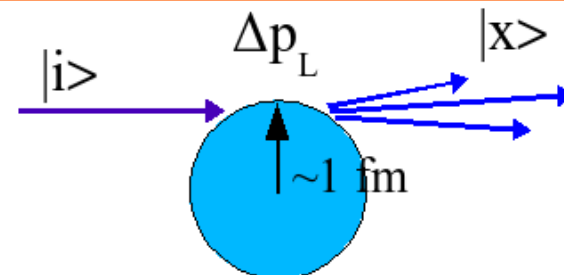
Diffraction in hadron-hadron interactions (2)

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



Diffraction in hadron-hadron interactions (3)

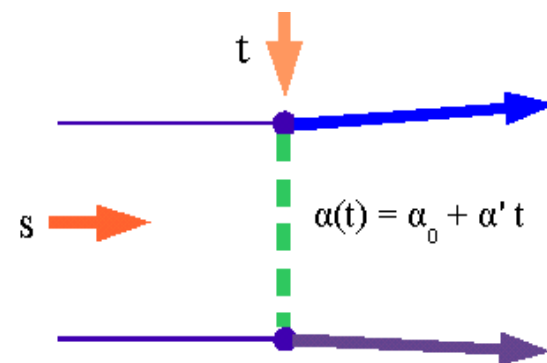
Regge model of hadronic interactions:

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)

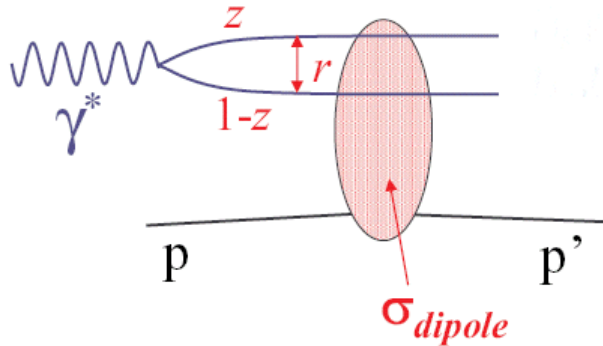
Universal parametrisation of Donnachie-Landshoff (“soft” Pomeron):

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

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) $\rightarrow \gamma^* p \rightarrow$ hadrons



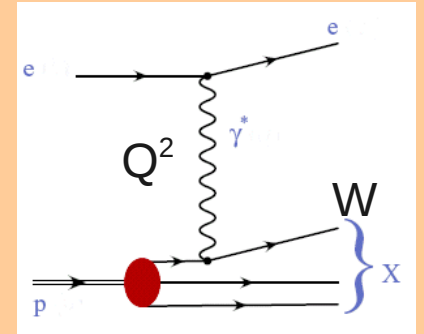
Q^2 – γ^* virtuality ($0 - 10^5 \text{ GeV}^2$)

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

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

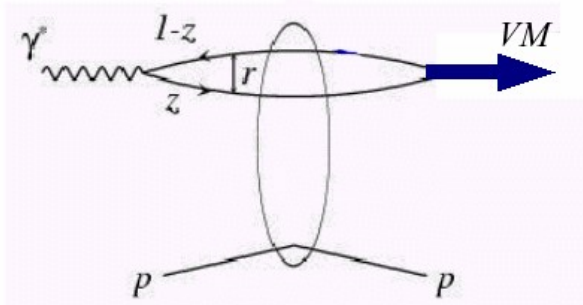


Coherence condition in proton rest frame:

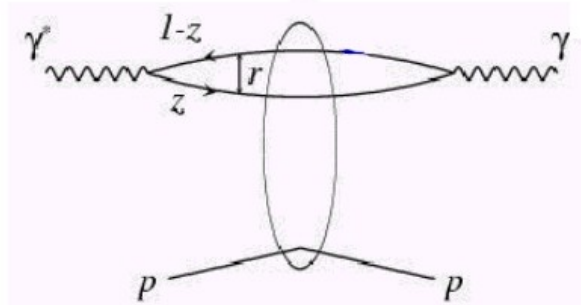
fluctuation length ($\gamma^* \rightarrow \text{dipol } q\bar{q}$) = $2E_\gamma / (m_{q\bar{q}}^2 + Q^2) > 1 \text{ fm}$

$\rightarrow x < 0.01$

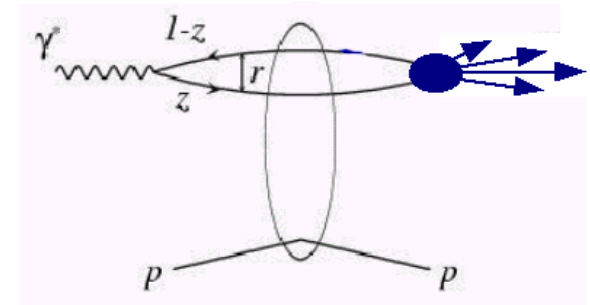
At HERA diffraction is low Bjorken-x phenomenon!



Vector meson production



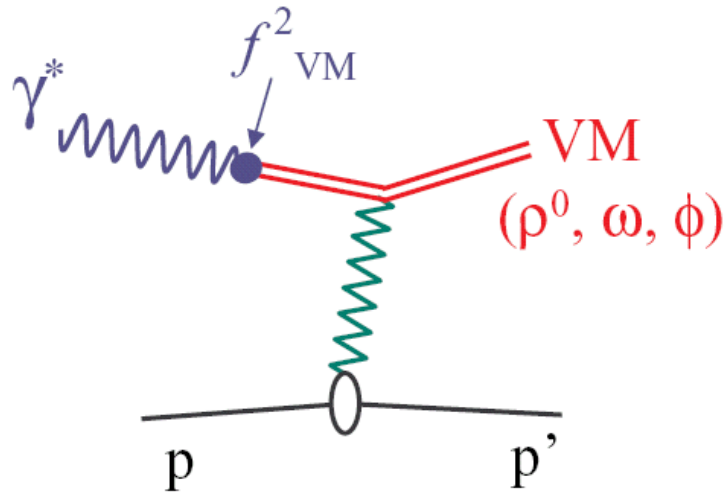
DVCS



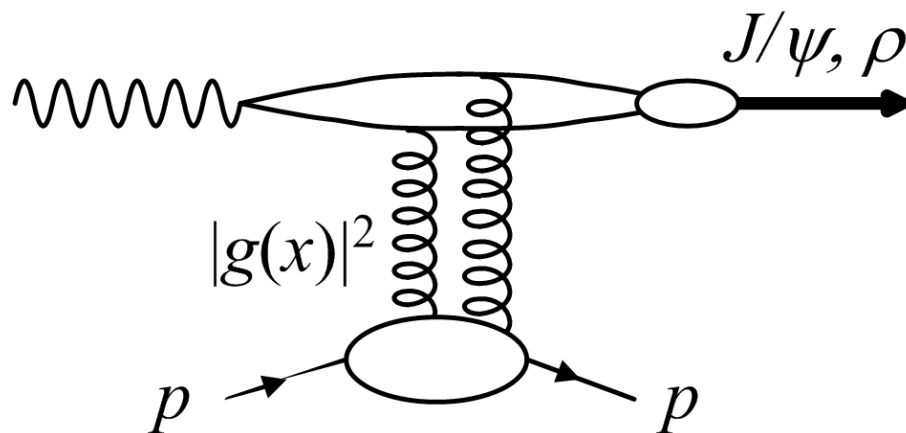
inclusive diffraction

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”)
 - $\sigma_{VMp} \sim W^{4(\alpha_0-1)}/b(W) \sim W^\delta$, $\delta \approx 0.22$



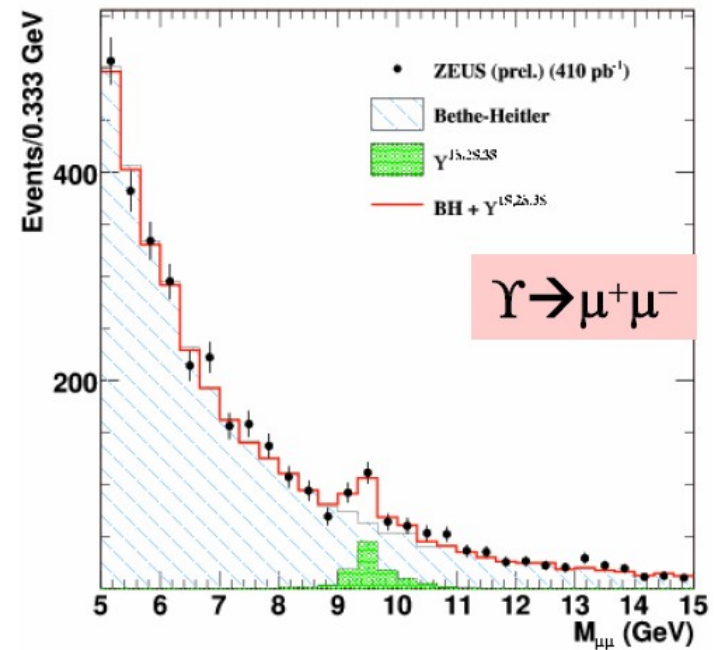
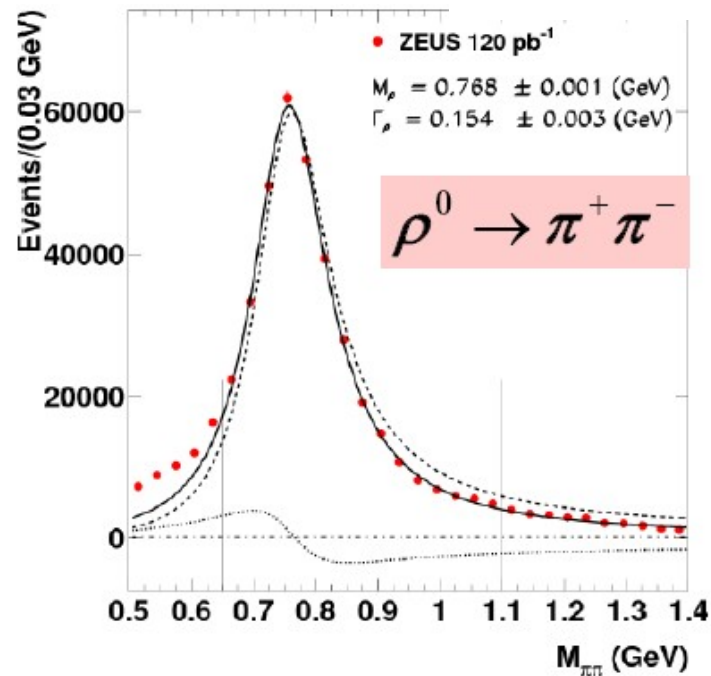
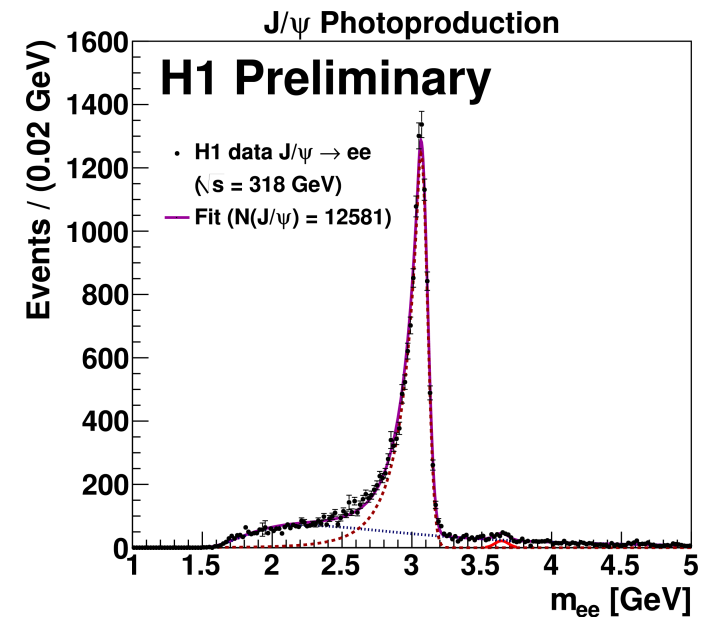
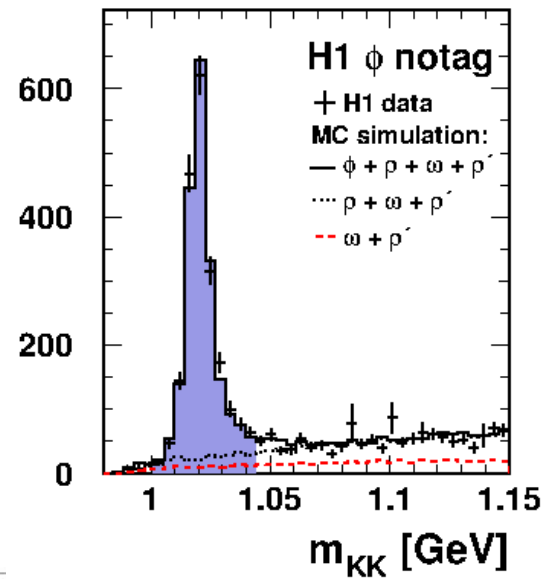
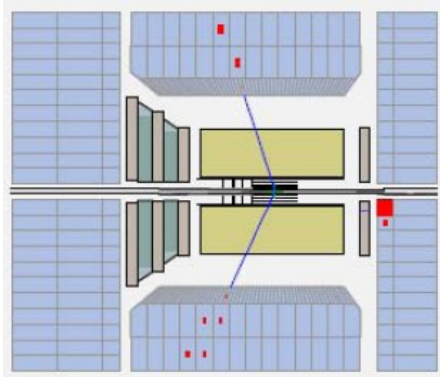
Perturbative QCD

- Large Q^2 , M_{VM} or $|t| \rightarrow$ small qq dipol
- QCD Pomeron exchange:
 ≥ 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

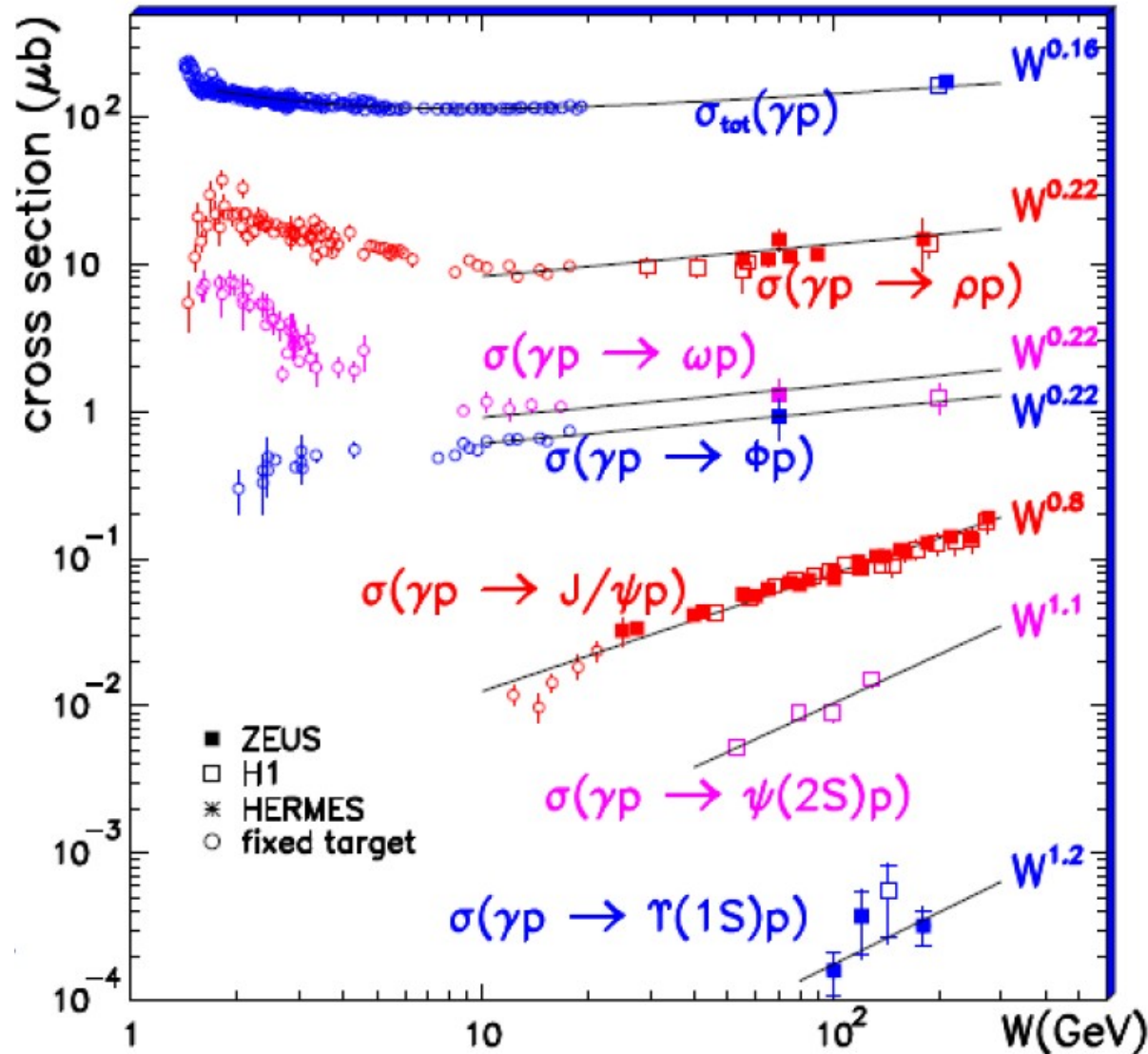
Vector meson production (2)

H1, ZEUS



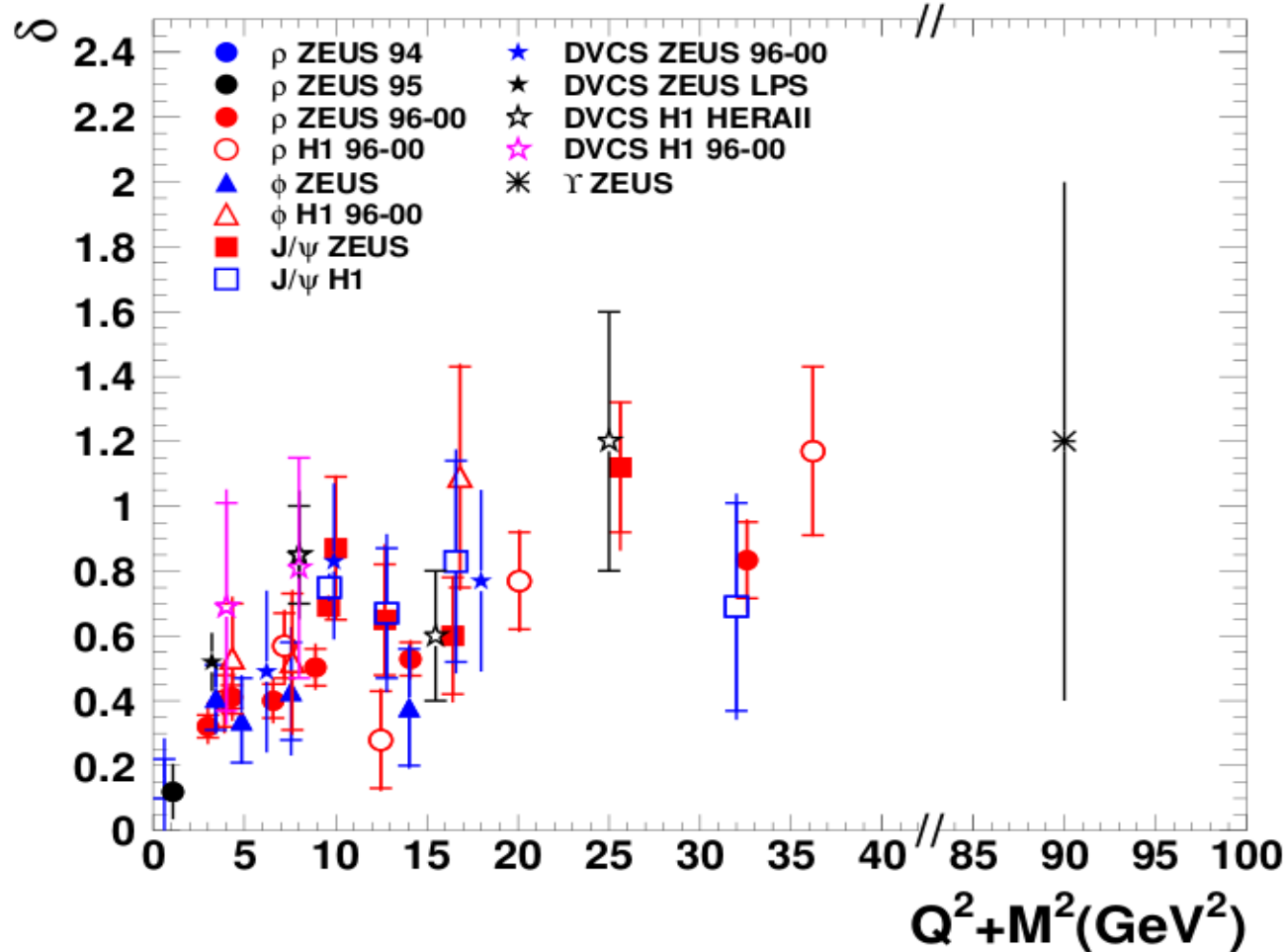
Vector mesons: energy dependence

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



The heavier vector meson –
– the steeper W -dependence.
VM mass sets QCD scale

VM and DVCS energy dependence

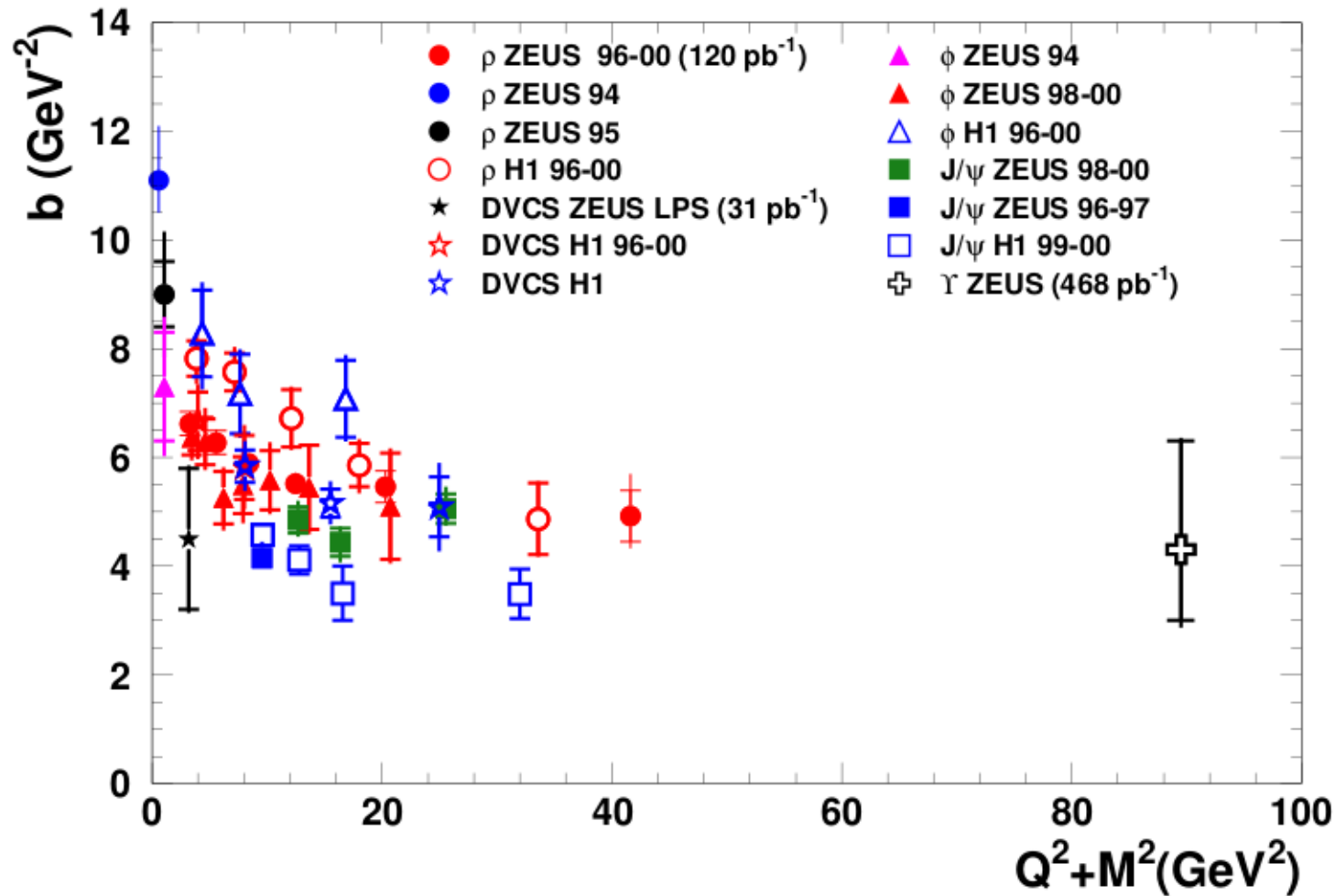


$$\sigma \sim W^\delta$$

VMs: 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...

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

Central, exclusive diffraction in (anti-)pp collisions (1)

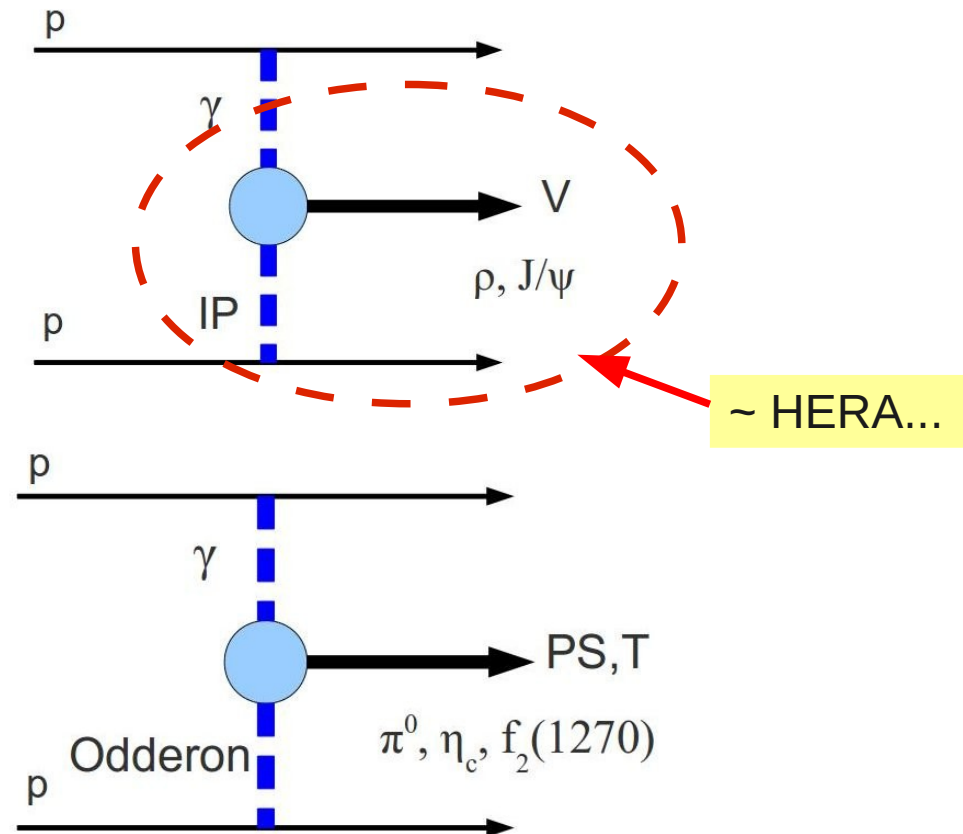
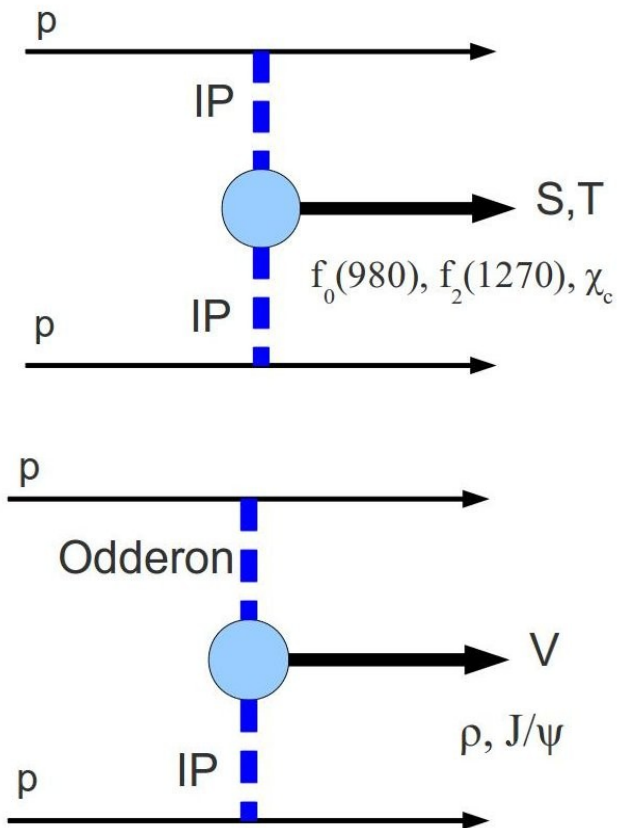
Possible **exchanges**:

Pomeron ($C=+1$), QCD: 2 gluons,

Odderon ($C=-1$), QCD: 3 gluons

Photon γ ($C=-1$),

Type	Meson	I^G	J^{PC}
S	$f_0/\sigma(600)$, $f_0(980)$, χ_c	0^+	0^{++}
PS	π^0 , η_c	1^-0^+	0^+
V	ρ^0 , J/ψ	1^+0^-	1^-
T	$f_2(1270)$	0^+	2^{++}

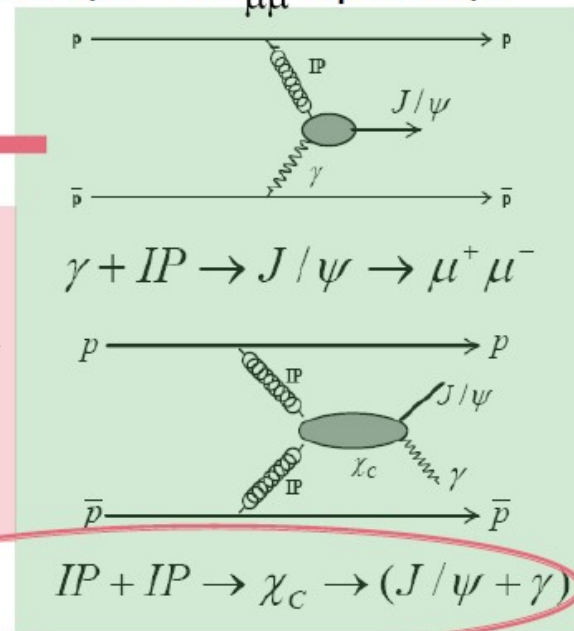
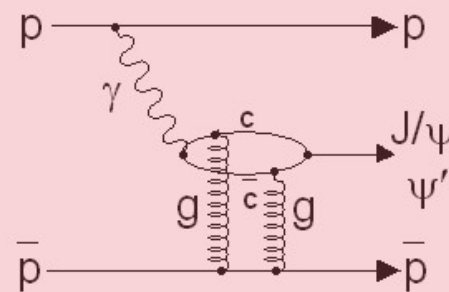
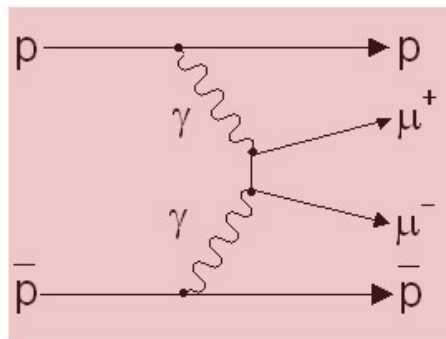


Exclusive Dimuon Production



$$\bar{p} + p \rightarrow \bar{p} + \mu^+ \mu^- + p \quad 3 \text{ GeV}/c^2 < M_{\mu\mu} < 4 \text{ GeV}/c^2$$

Many Physics Processes in this data:



exclusive χ_c in DPE

- Observation of exclusive χ_c PRL 102 242001 (2009)

Exclusive J/ψ and $\psi(2s)$



J/ψ production

243 ± 21 events

$$d\sigma/dy|_{y=0} = 3.92 \pm 0.62 \text{ nb}$$

Theoretical Predictions

- 2.8 nb [Szcureko7,],
- 2.7 nb [Klein&Nystrando4],
- 3.0 nb [Conclaves&Machado05], and
- 3.4 nb [Motkya&Watto8].

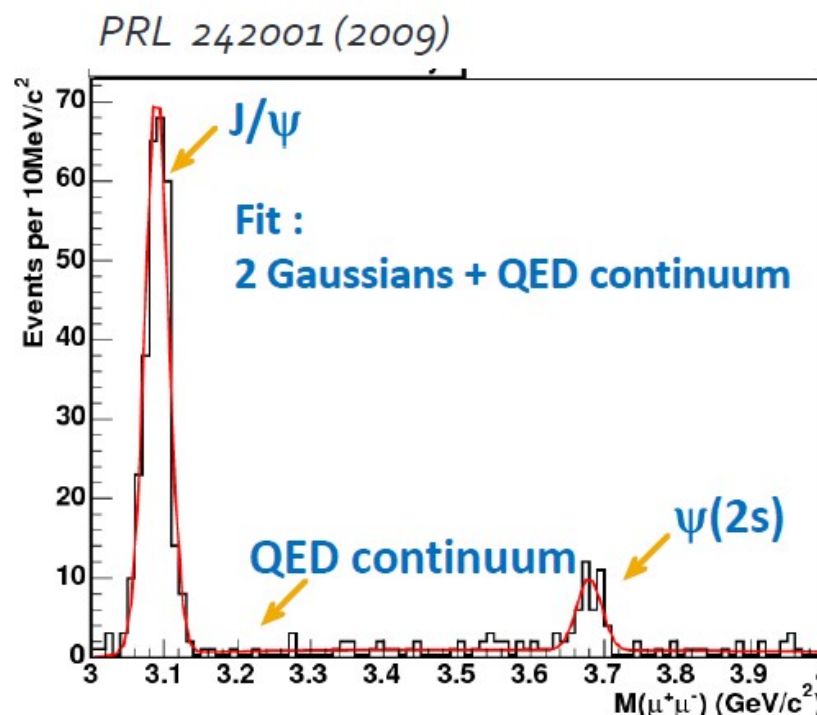
$\Psi(2s)$ production

34 ± 7 events

$$d\sigma/dy|_{y=0} = 0.54 \pm 0.15 \text{ nb}$$

$$R = \psi(2s)/J/\psi = 0.14 \pm 0.05$$

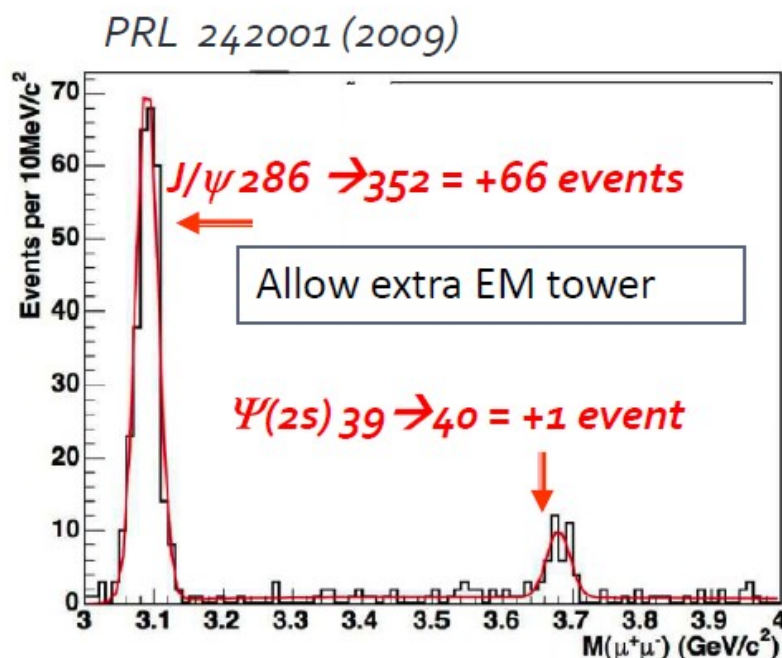
In agreement with HERA: $R = 0.166 \pm 0.012$ in a similar kinematic region



Central, exclusive diffraction in (anti-)pp collisions (4)



Exclusive $\chi_c \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) + \gamma$



→ Allowing EM towers ($E_T > 80 \text{ MeV}$)

large increase in the J/ψ peak
minor change in the $\psi(2s)$ peak



Evidence for
 $\chi_c \rightarrow J/\psi + \gamma$ production

$d\sigma/dy|_{y=0} = 75 \pm 14 \text{ nb}$,
compatible with theoretical predictions
160 nb (Yuan 01)
90 nb (KMR01)

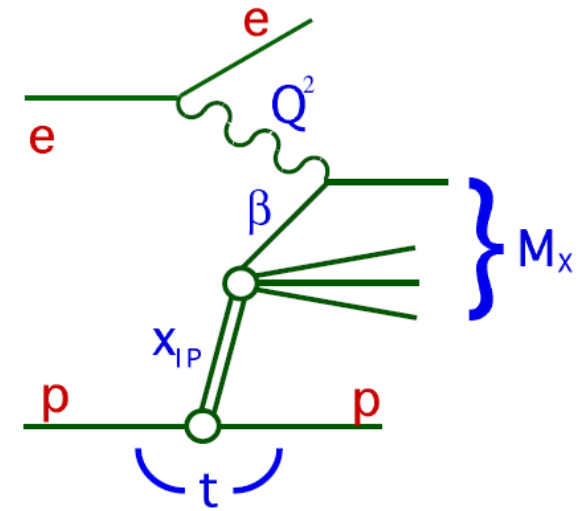
Inclusive diffraction in e-p interactions (1)

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**

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

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

“reduced” cross section $\underline{\sigma_r^D} = F_2^D - \frac{y^2}{1 + (1-y)^2} F_L^D \approx F_2^D, \quad y < 1 \quad (F_L^D = 0 \text{ at LO})$

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

IPomeron flux
(Regge form)

**IPomeron structure
function !!!**

Regge inspired...

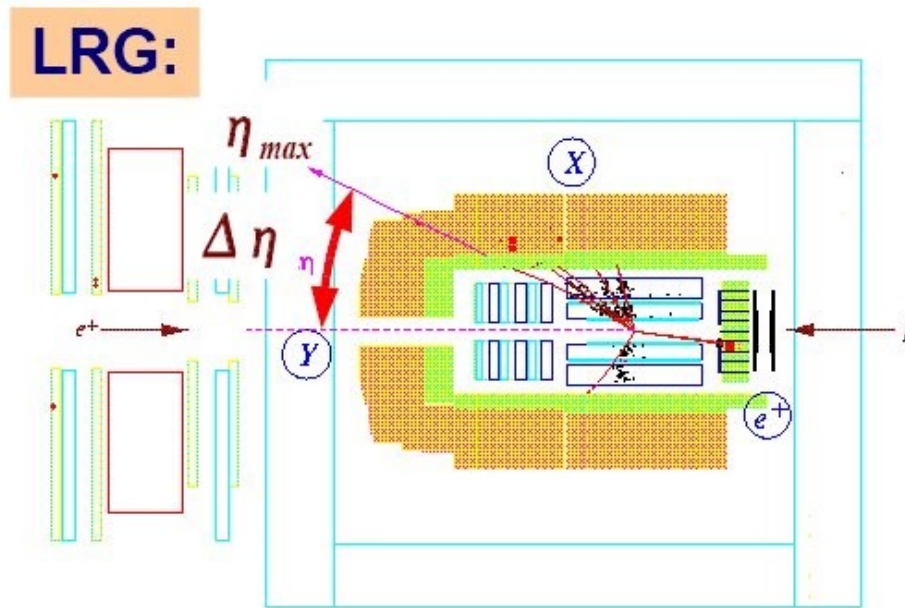
$$f_{IP}(x_{IP}, t) = A(1/x_{IP})^{2\alpha(t)-1} \exp(Bt)$$

$$F_2^{IP}(z, Q^2) = A z^B (1-z)^C$$

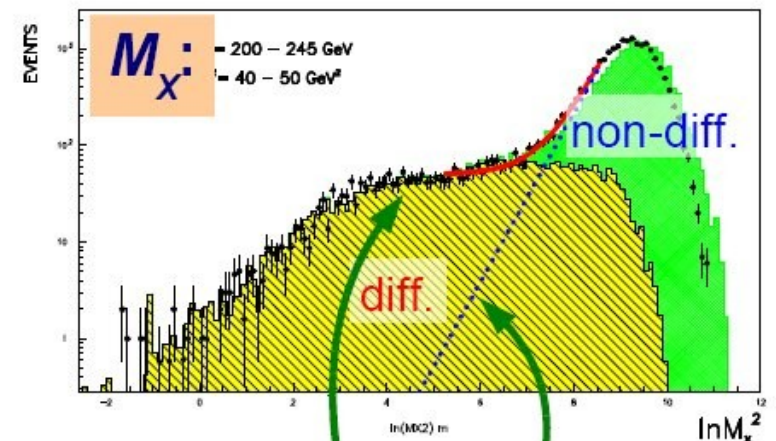
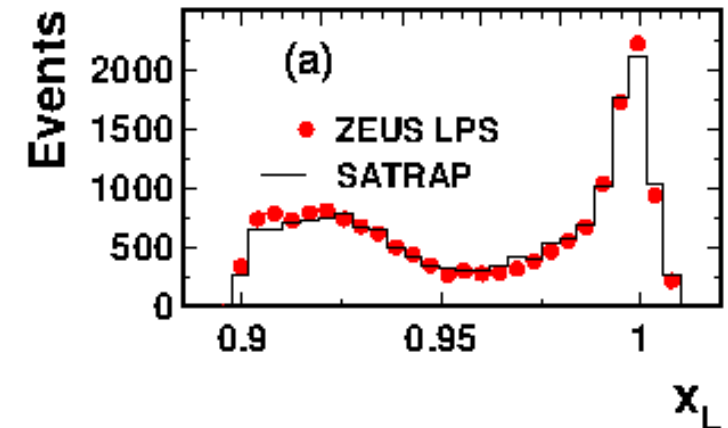
Inclusive diffraction in e-p interactions (2)

Diffractive selection:

- proton tagging, LPS(**ZEUS**), FPS, VFPS(**H1**)
- Large Rapidity Gap (p-dissociation ..!)
- M_X method (p-dissociation ..!)



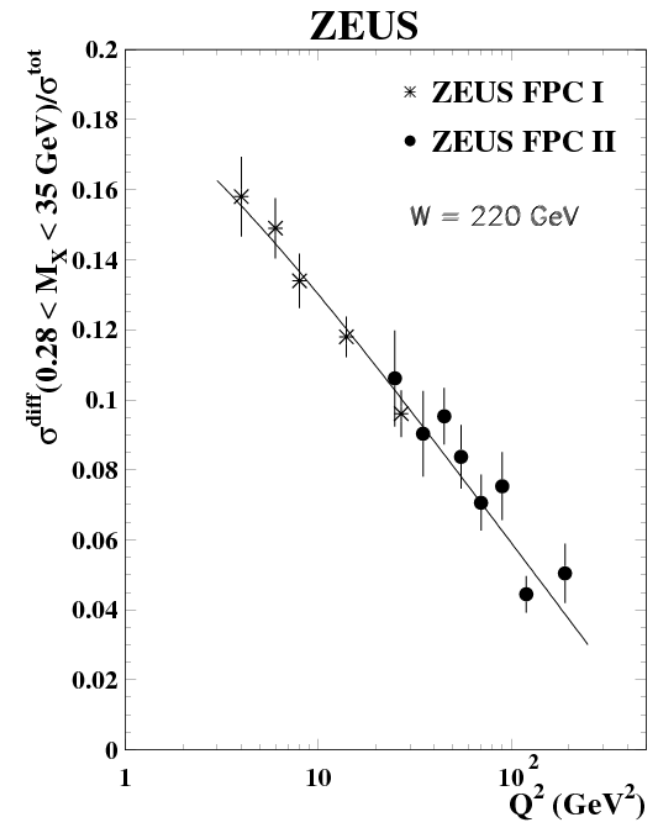
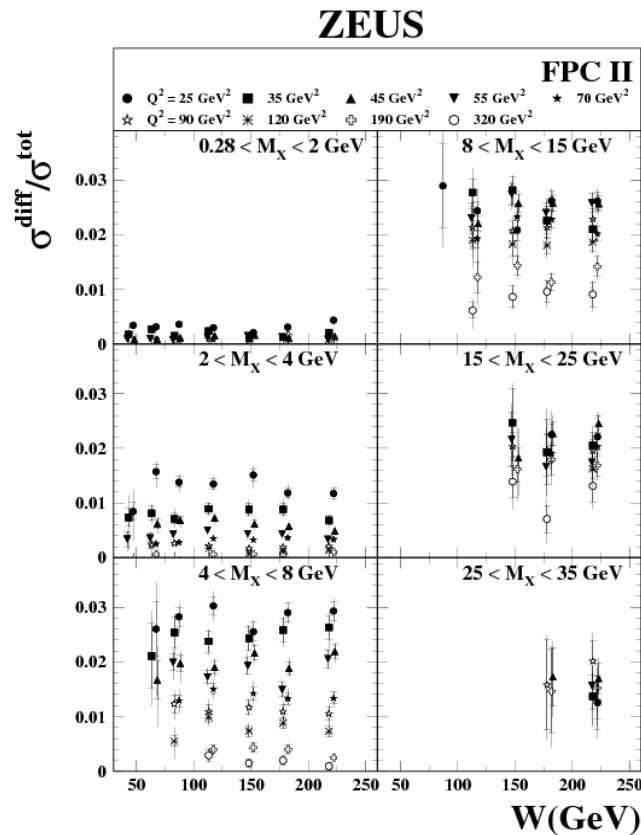
$$3.3 < \eta < 7.5, \quad \eta_{max} < 3$$



$$\frac{dN}{d \ln(M_X^2)} = \underbrace{D + c \exp(b \ln(M_X^2))}_{\text{diff.}}$$

Inclusive diffraction in e-p interactions (3)

ZEUS (Nucl. Phys. **B800** (2008) 1) **FPC II** results (M_X method):

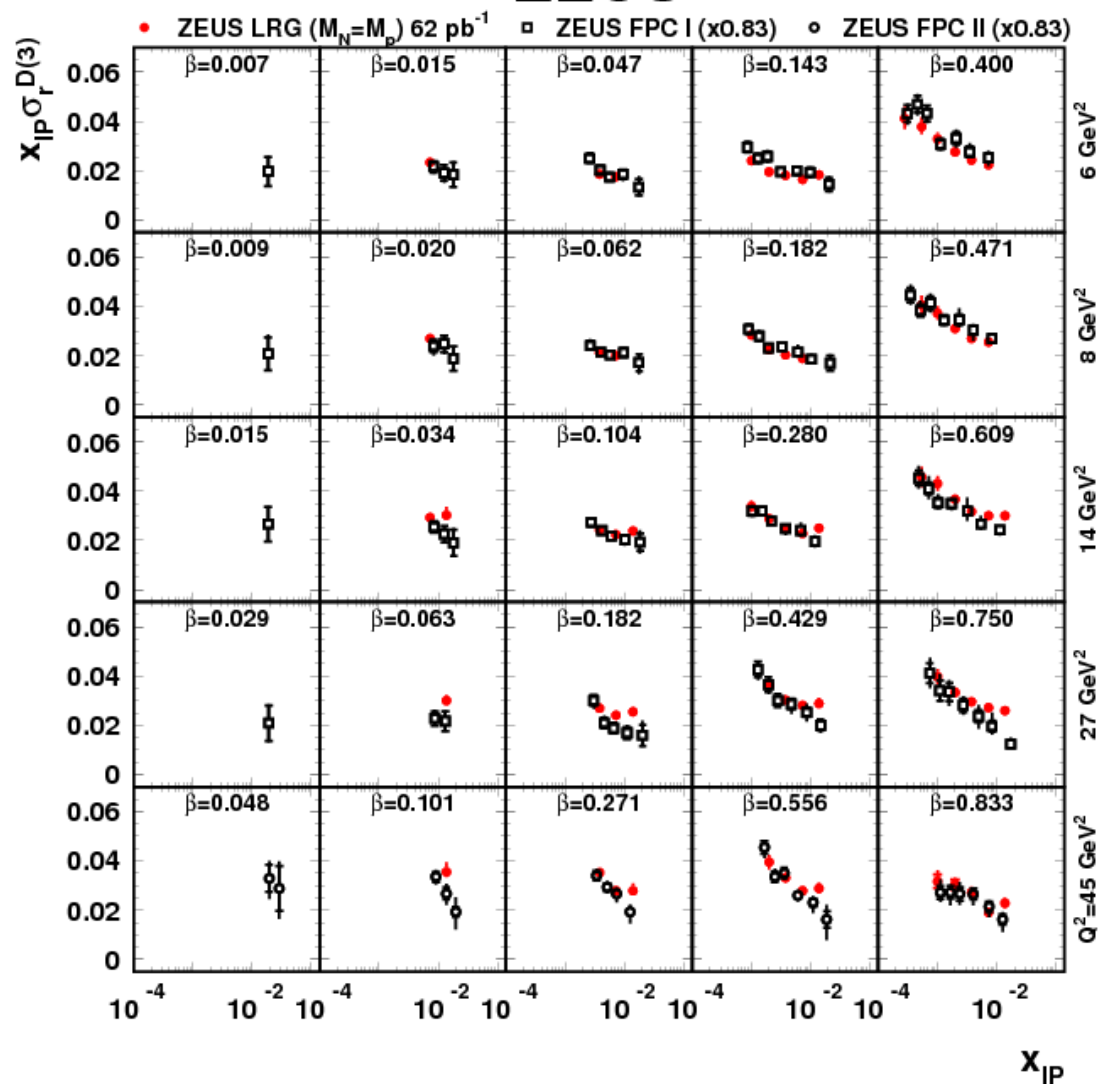


- Diffraction yield (fixed M_X , Q^2) $\approx \text{const}(W)$
- Diffraction yield ($0.28 < M_X < 35 \text{ GeV}$) $\approx a - b \ln(1+Q^2)$

Inclusive diffraction in e-p interactions (4)

ZEUS: LRG vs M_X method (FPC I, FPC II)

ZEUS



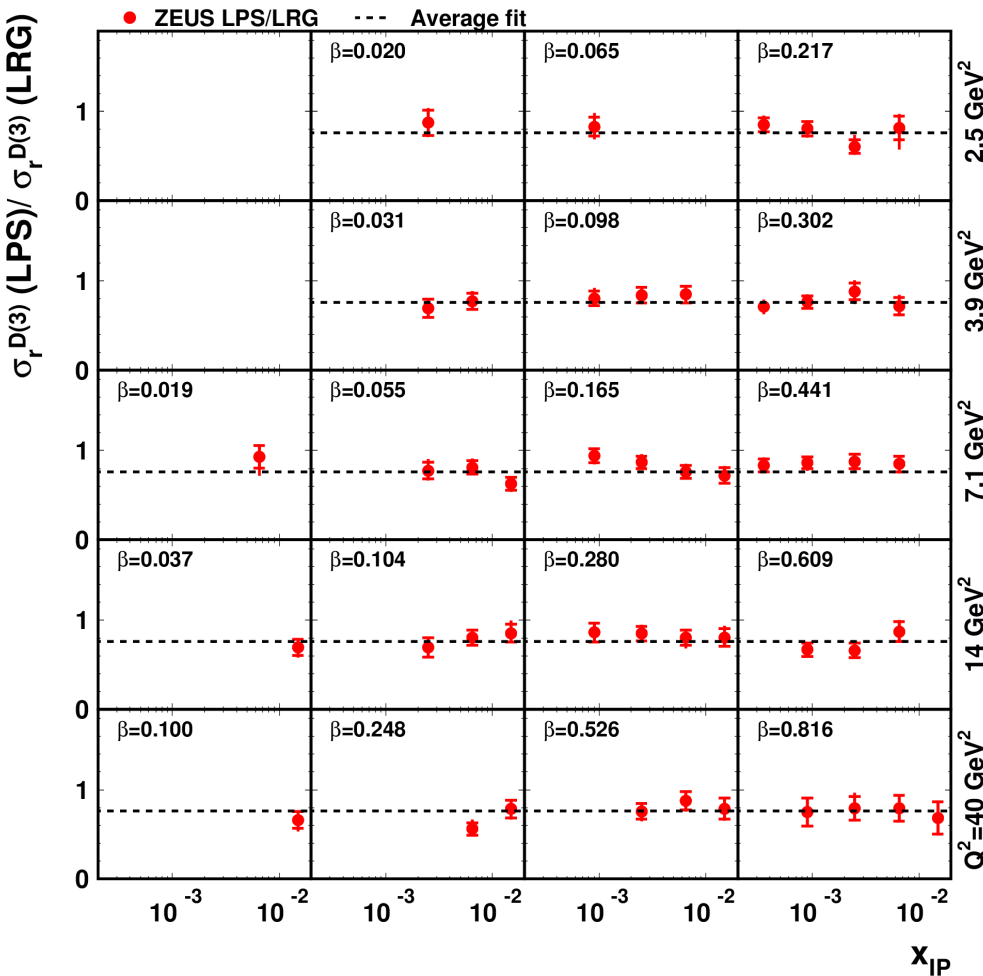
ZEUS Nucl.Phys. **B816** (2009) 1

Different methods are consistent

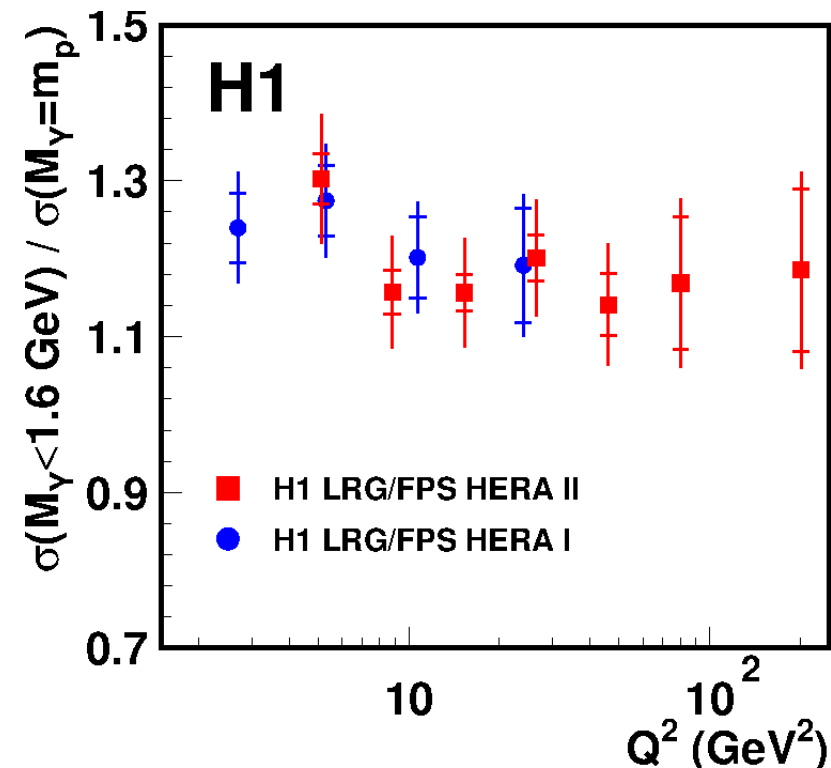
Inclusive diffraction in e-p interactions (5)

LPS vs LRG method

ZEUS



ZEUS Nucl.Phys. **B816** (2009) 1



H1 EPJ C71 (2011) 1578

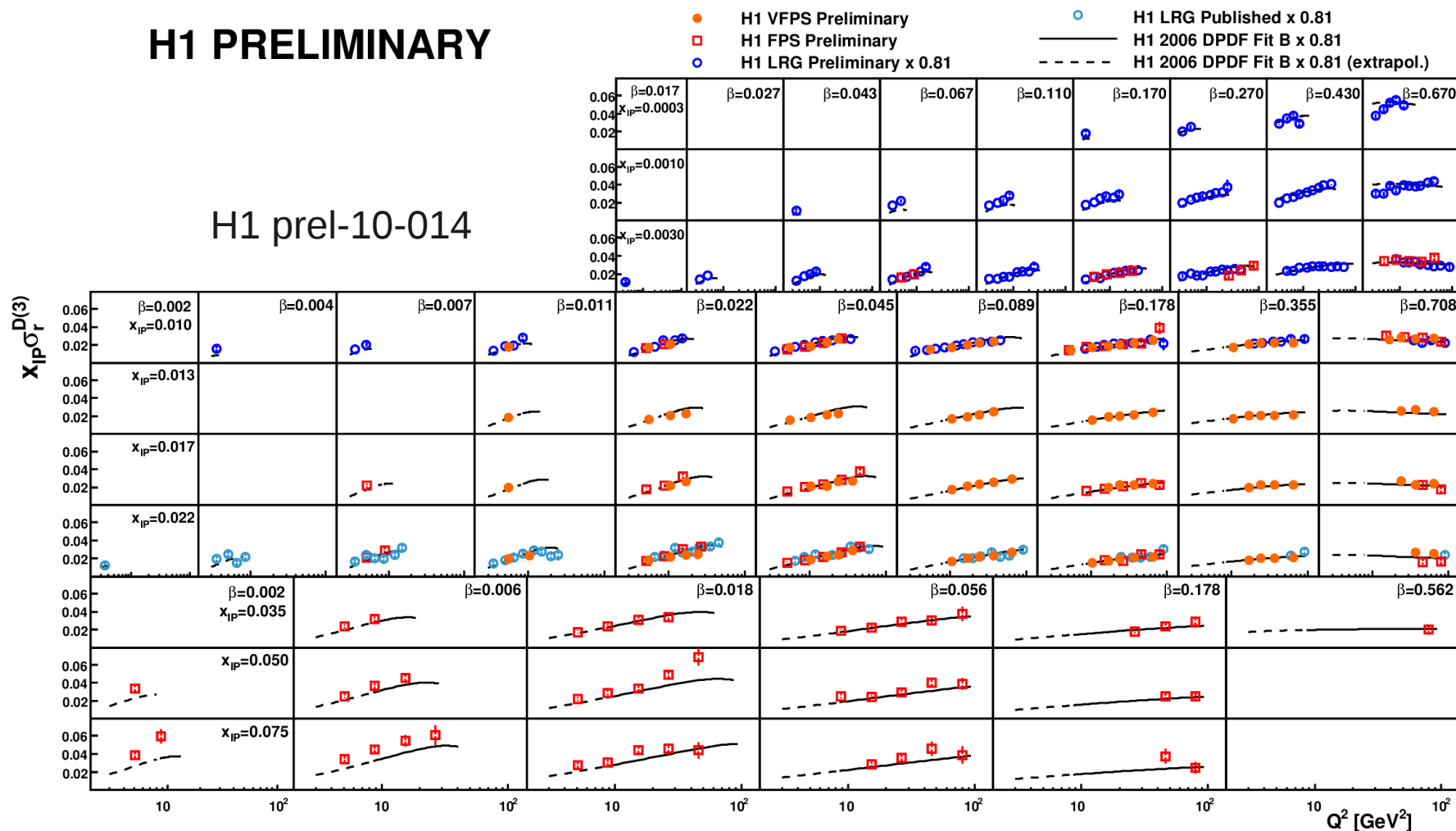
- LRG data contain ~20% of p-diss.
- No significant dep. on Q^2 , β , x_{IP}

Inclusive diffraction in e-p interactions (6)

$$\sigma_r^{D(3)} : \text{VFPS vs FPS vs LRG}$$

H1 PRELIMINARY

H1 prel-10-014

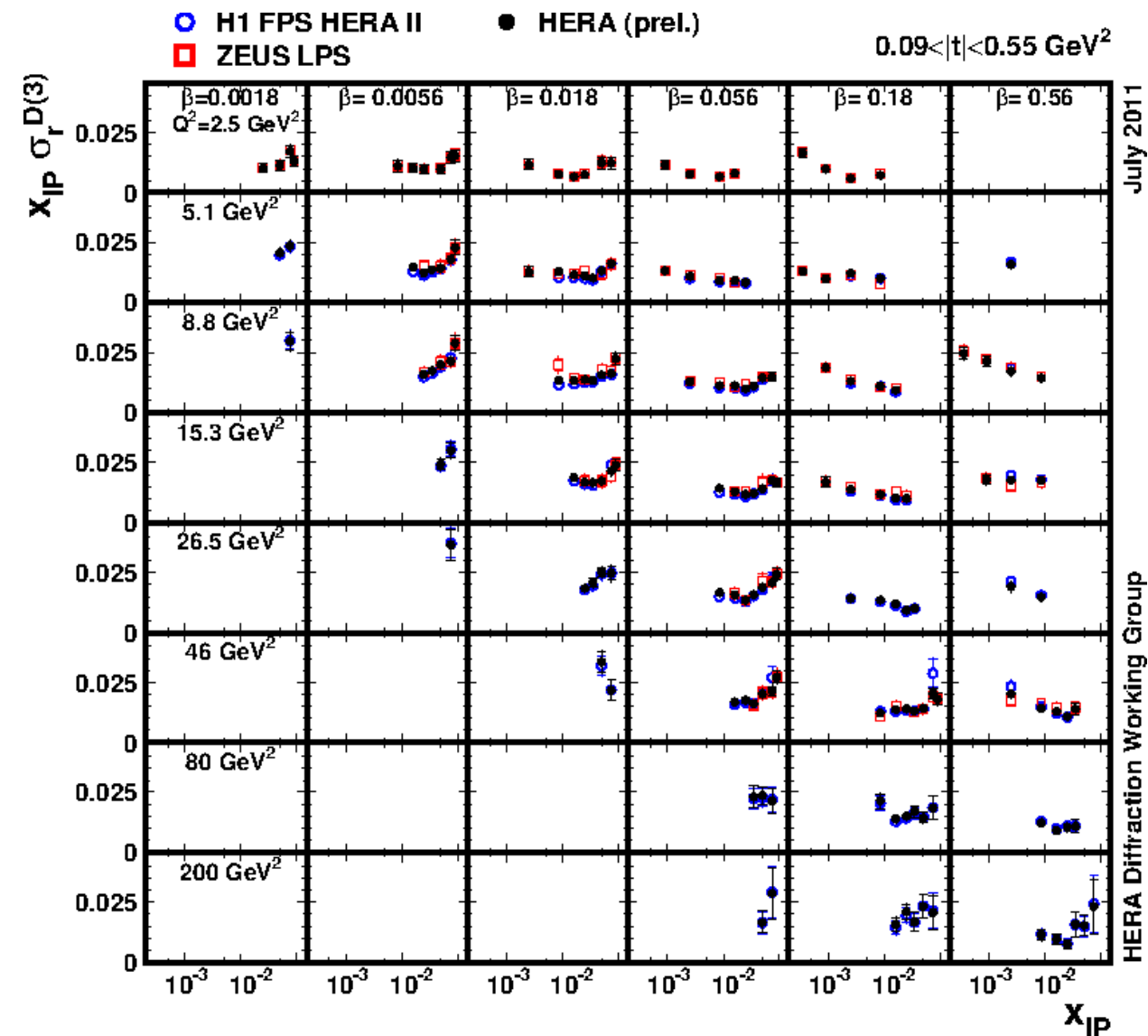


VFPS \approx FPS within the errors...

Inclusive diffraction in e-p interactions (7)

$\sigma_r^{D(3)}$: H1 FPS vs ZEUS LPS

H1 prel-11-111, ZEUS prel-11-011



Reasonable agreement
of H1 and ZEUS data \Rightarrow

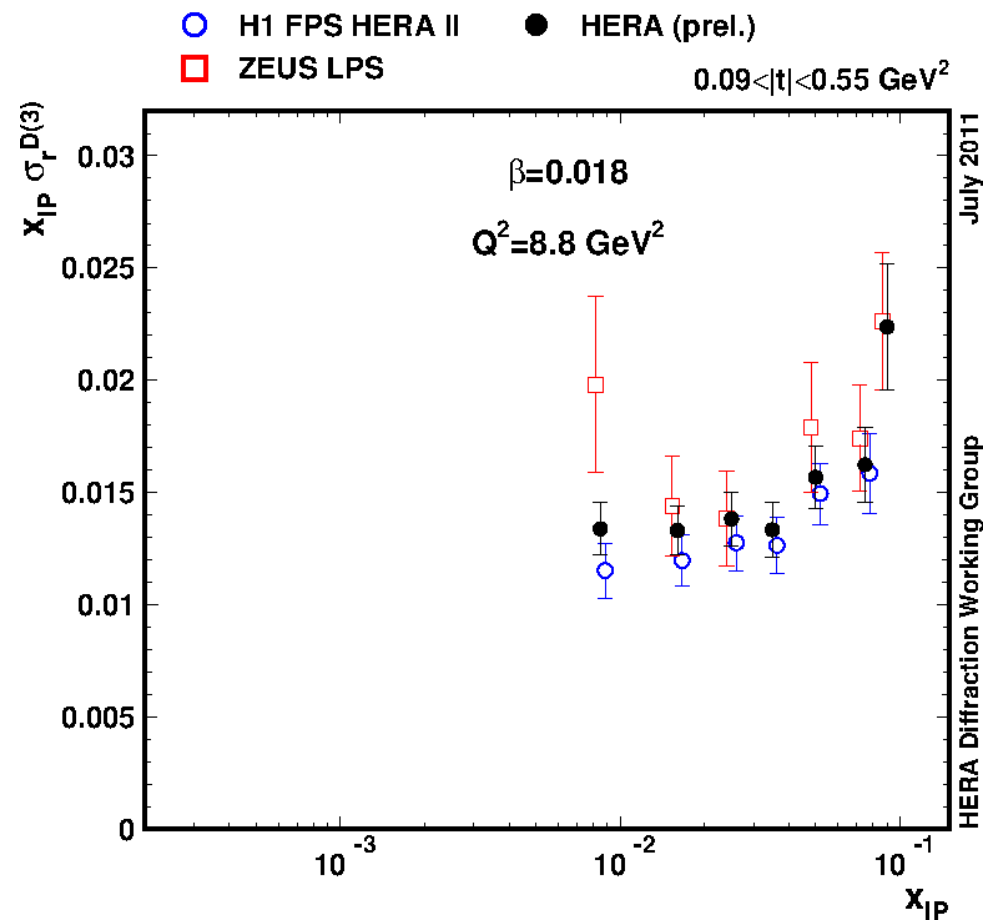
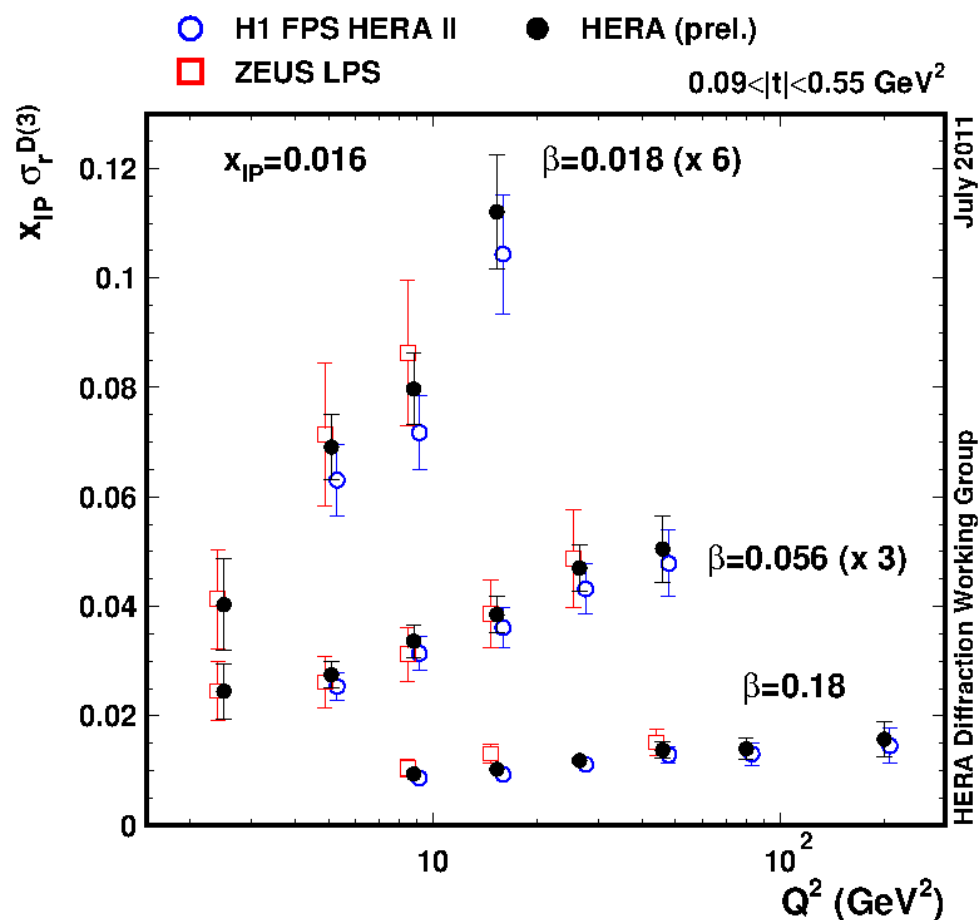
\Rightarrow **Combine!**

extend phase space,
reduce uncertainties

Inclusive diffraction in e-p interactions (8)

$\sigma_r^{D(3)}$: H1 FPS and ZEUS LPS combination...

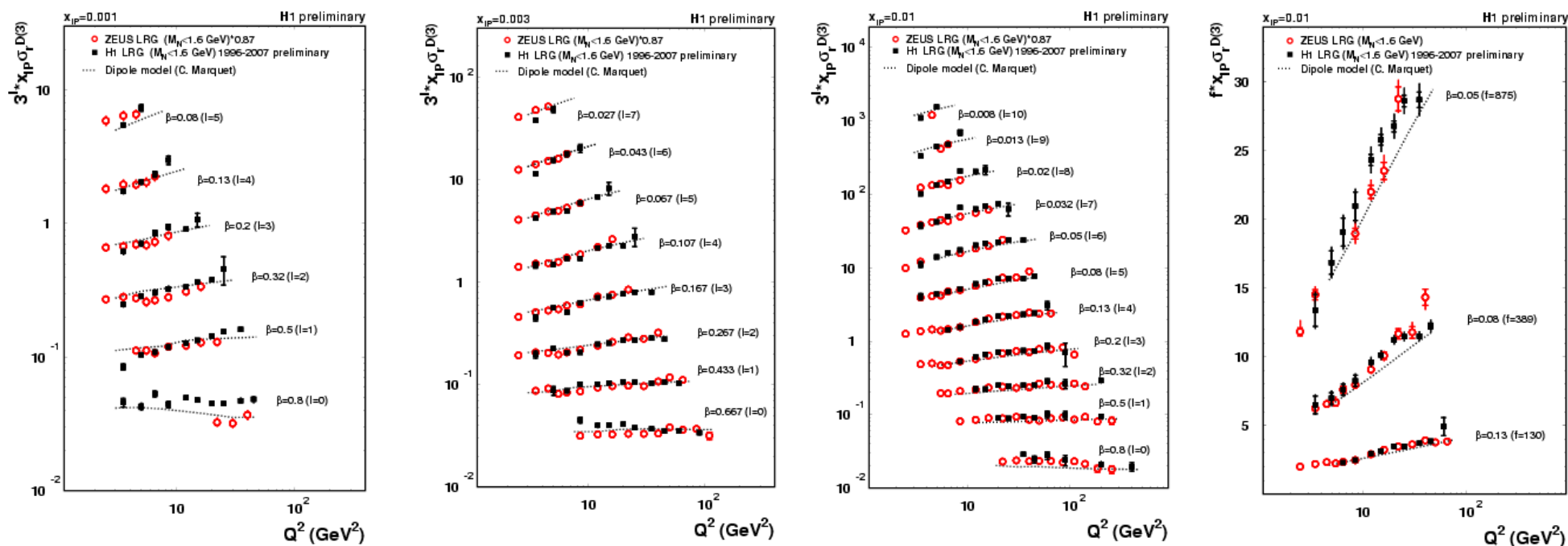
H1 prel-11-111,
ZEUS prel-11-011



Combined data have $\sim 20\%$ smaller uncertainties than H1 or ZEUS data

Inclusive diffraction in e-p interactions (9)

LRG $\sigma_r^{D(3)}$: H1 vs ZEUS



H1 prel-10-011

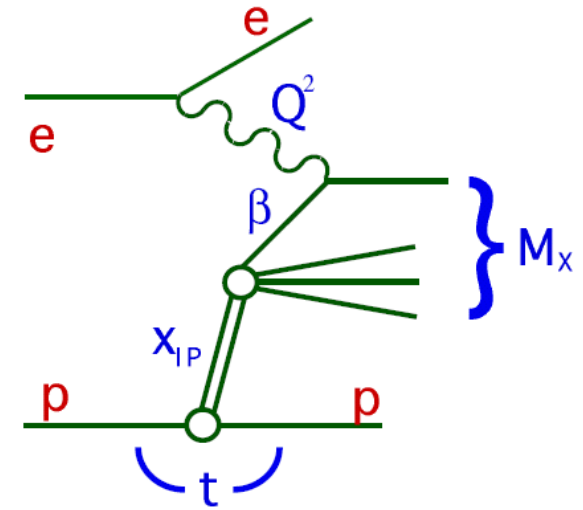
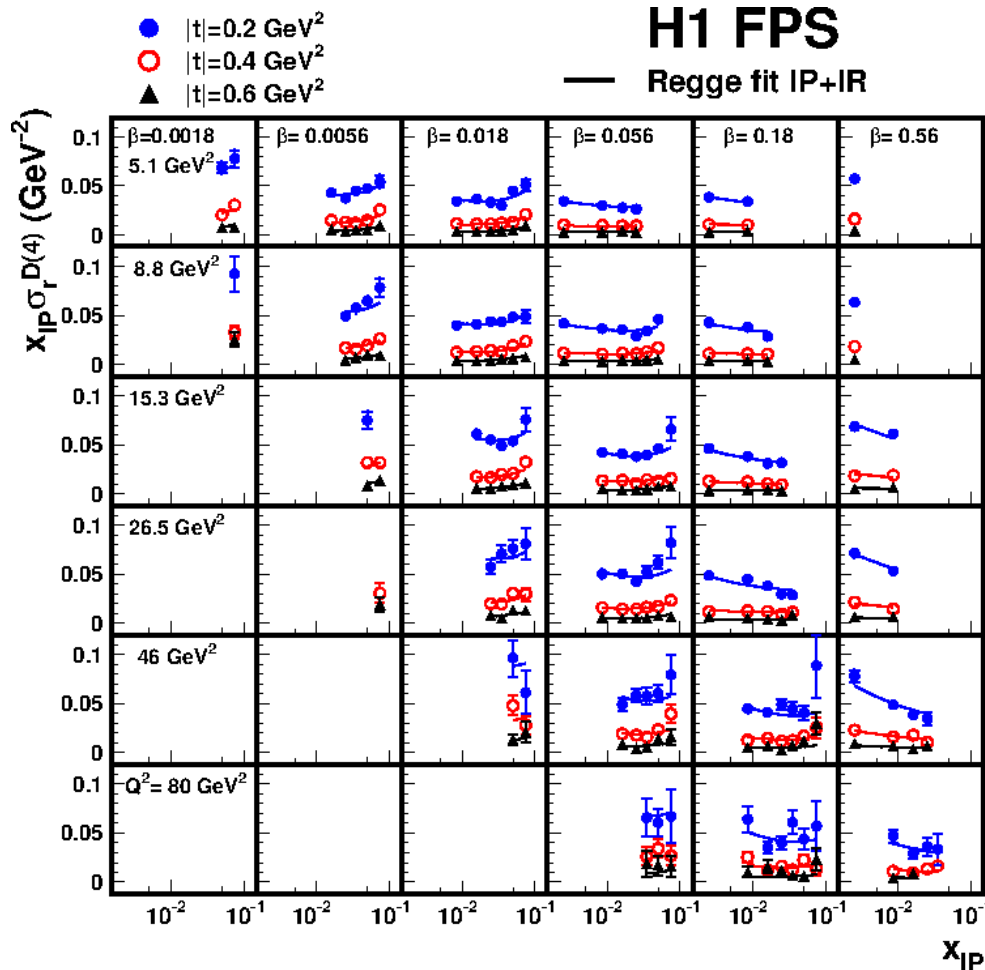
Compared H1 LRG (HERA-1, HERA-2) and ZEUS LRG (HERA-1) data

→ reasonable agreement

Inclusive diffraction in e-p interactions (10)

$$x_{IP} \sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t)$$

H1, EPJ C71 (2011) 1578,



$$f_{IP}(x_{IP}, t) = A(1/x_{IP})^{2\alpha(t)-1} \exp(B t)$$

$$B = B_{IP} + 2\alpha'_{IP} \ln(1/x_{IP})$$

$$F_2^{IP}(z, Q^2) = A z^B (1-z)^C$$

Regge..

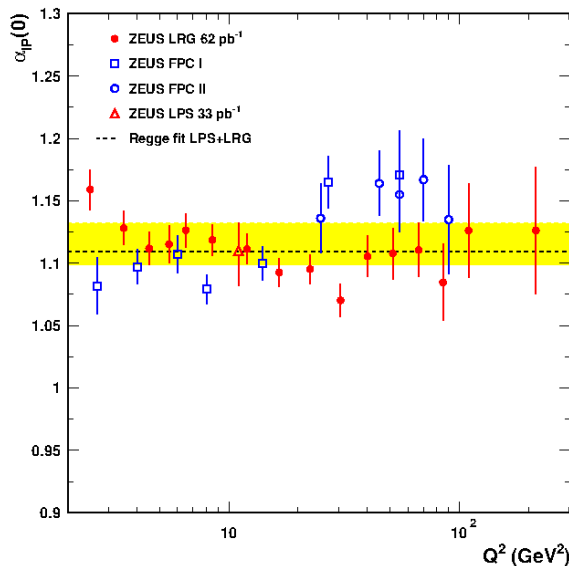
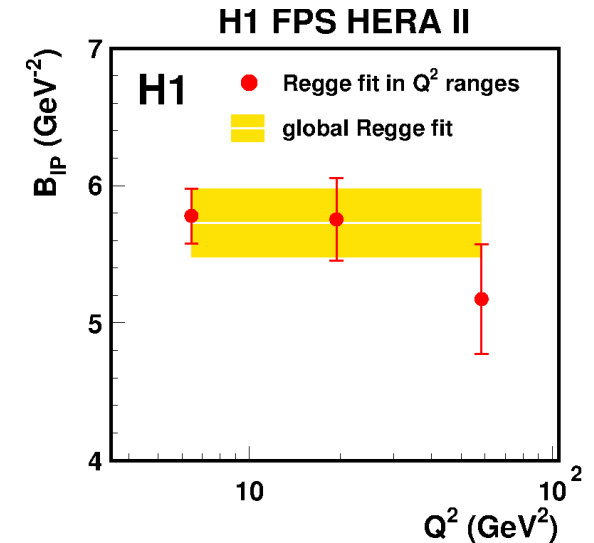
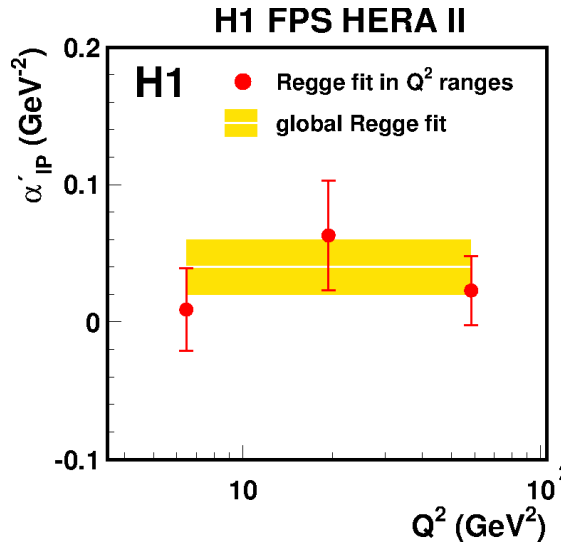
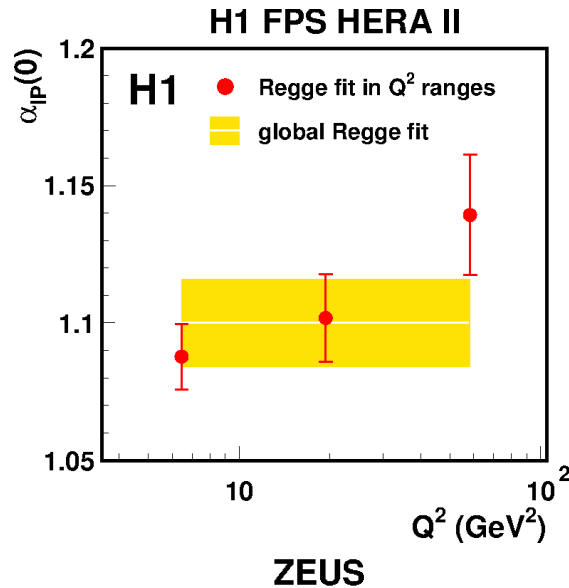
proton vertex factorization. Regge flux approximation (?):

$$F_2^{D(4)}(\beta, Q^2, x_{IP}, t) = f_{IP}(x_{IP}, t) F_2^{IP}(\beta, Q^2) \quad (\text{Sub-leading IR term omitted...})$$

Inclusive diffraction in e-p interactions (10)

$$x_{IP} \sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t)$$

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ZEUS, NP **B816** (2009) 1



- $\alpha_{IP}(0) \approx 1.10$ in agreement with α_{IP} (soft)~1.08
- $\alpha'_{IP} \approx 0 \rightarrow$ no “shrinkage” < α'_{IP} (soft)~0.25 GeV⁻²
(B_{IP} consistent with hard process)
- no strong dependence of $\alpha_{IP}(0)$, α'_{IP} , B_{IP} on Q^2
- Proton vertex factorization holds within uncertainties

QCD factorisation tests

Collinear **factorization** theorem (lepton-proton, DIS, **perturbative QCD**)

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

f_i^D – universal diffractive **P**arton **D**istribution **F**unction (dPDF)
 $\sigma_i^{\gamma^*}$ – universal (γ^* parton) cross-section

Basic strategy:

- **Inclusive diffraction:**

Measure diffractive structure function F_2^D

Extract dPDFs (quarks and gluons) from F_2^D :

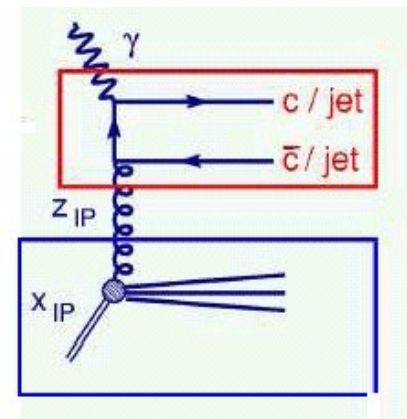
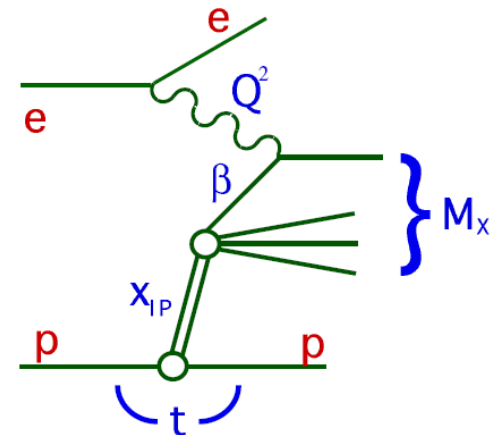
NLO DGLAP fit to F_2^D , (polynomials at Q_0^2),
 proton vertex factorisation, Regge approximation,

- **Semi-inclusive diffractive process:**

Calculate partonic $\sigma_i^{\gamma^*}$,

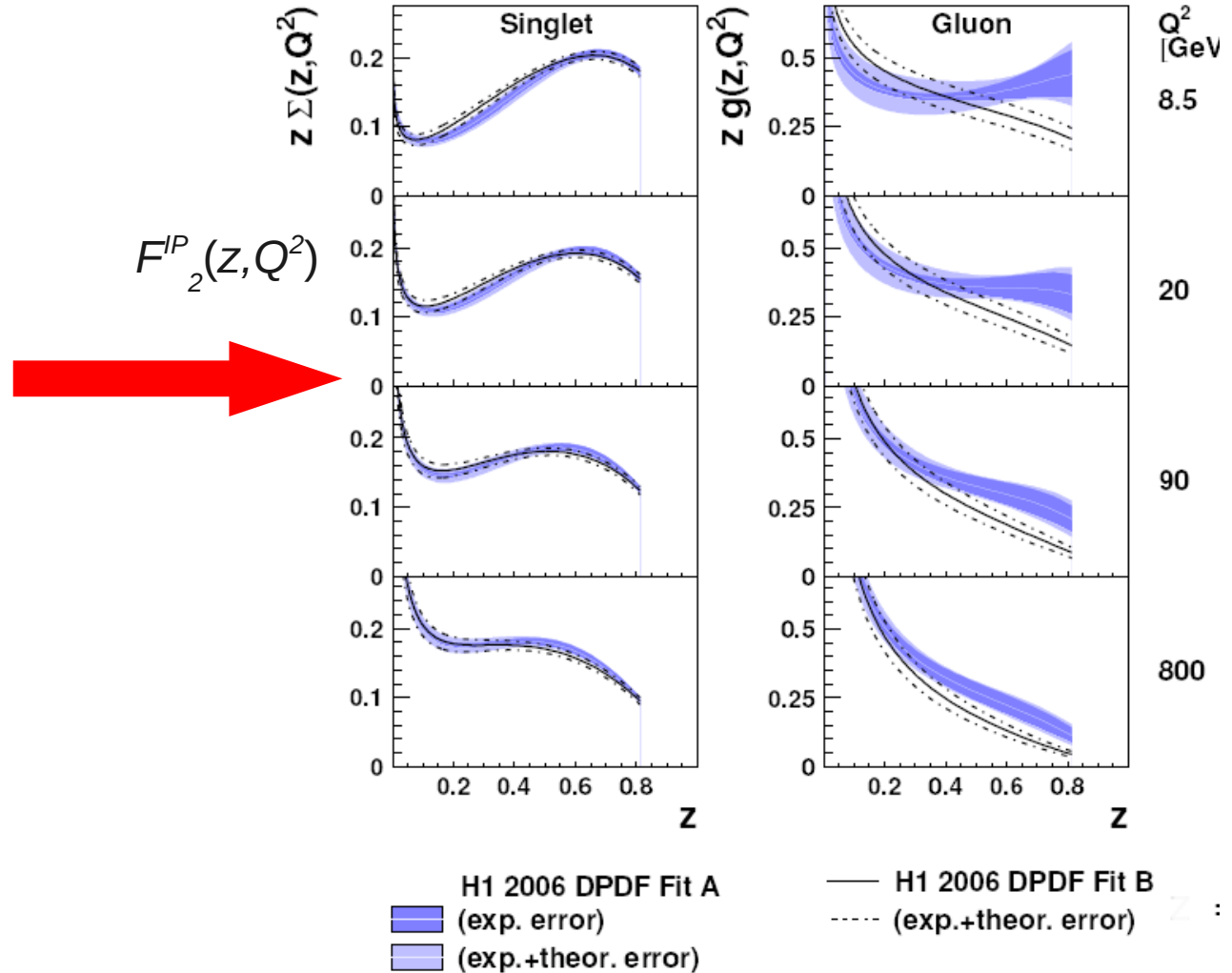
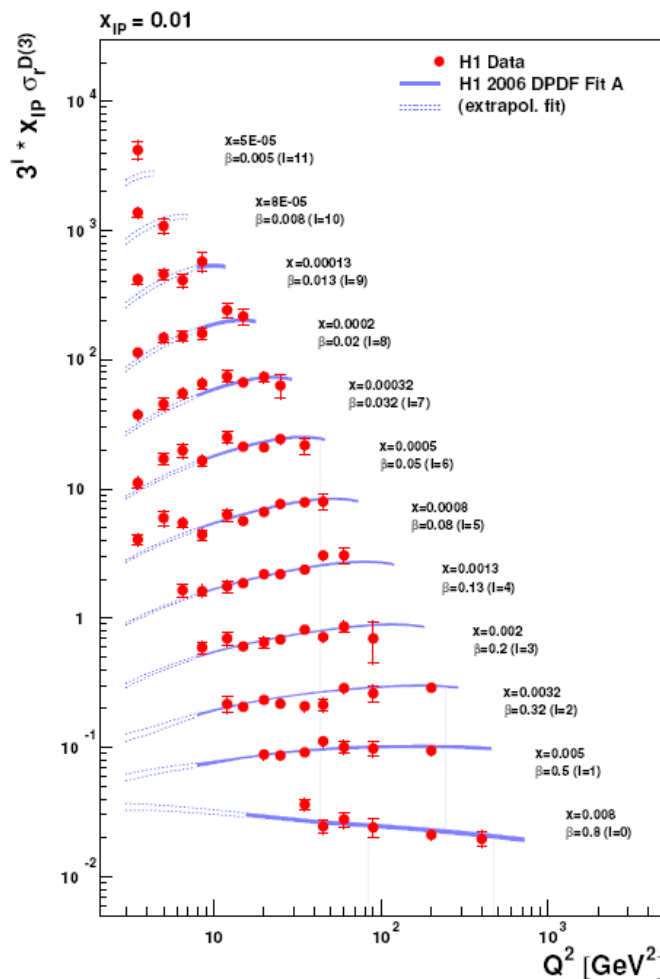
convolute with dPDFs \rightarrow cross-section

\Rightarrow compare the calculations with experiment...



Diffractive PDFs (1)

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

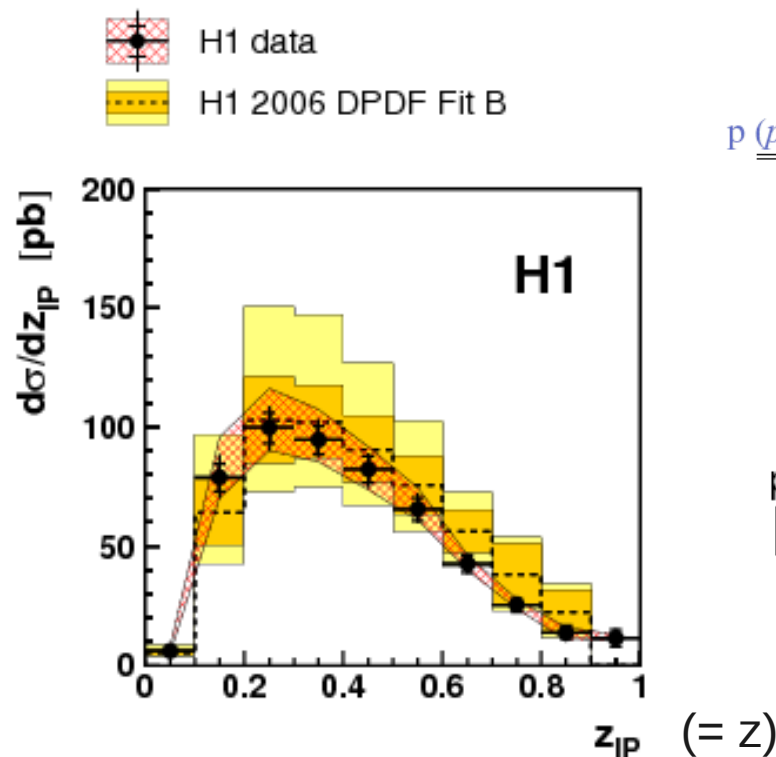
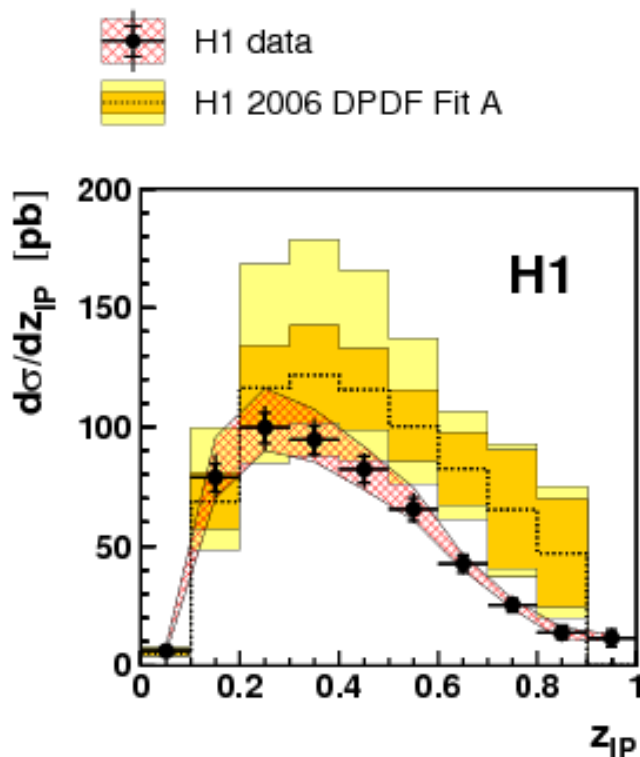
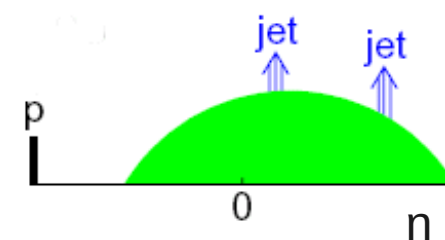
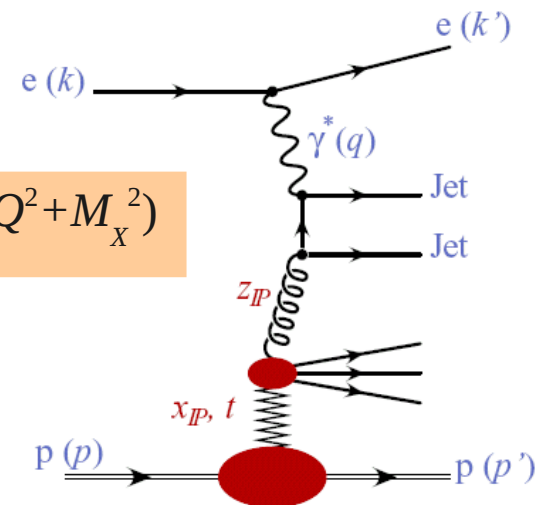
z = fraction of parton momentum
 in hard scattering/IPomeron ($= \beta$)

Diffraction PDFs (2)

H1, diffractive di-jets in **DIS**: JHEP 0710:042,2007

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

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

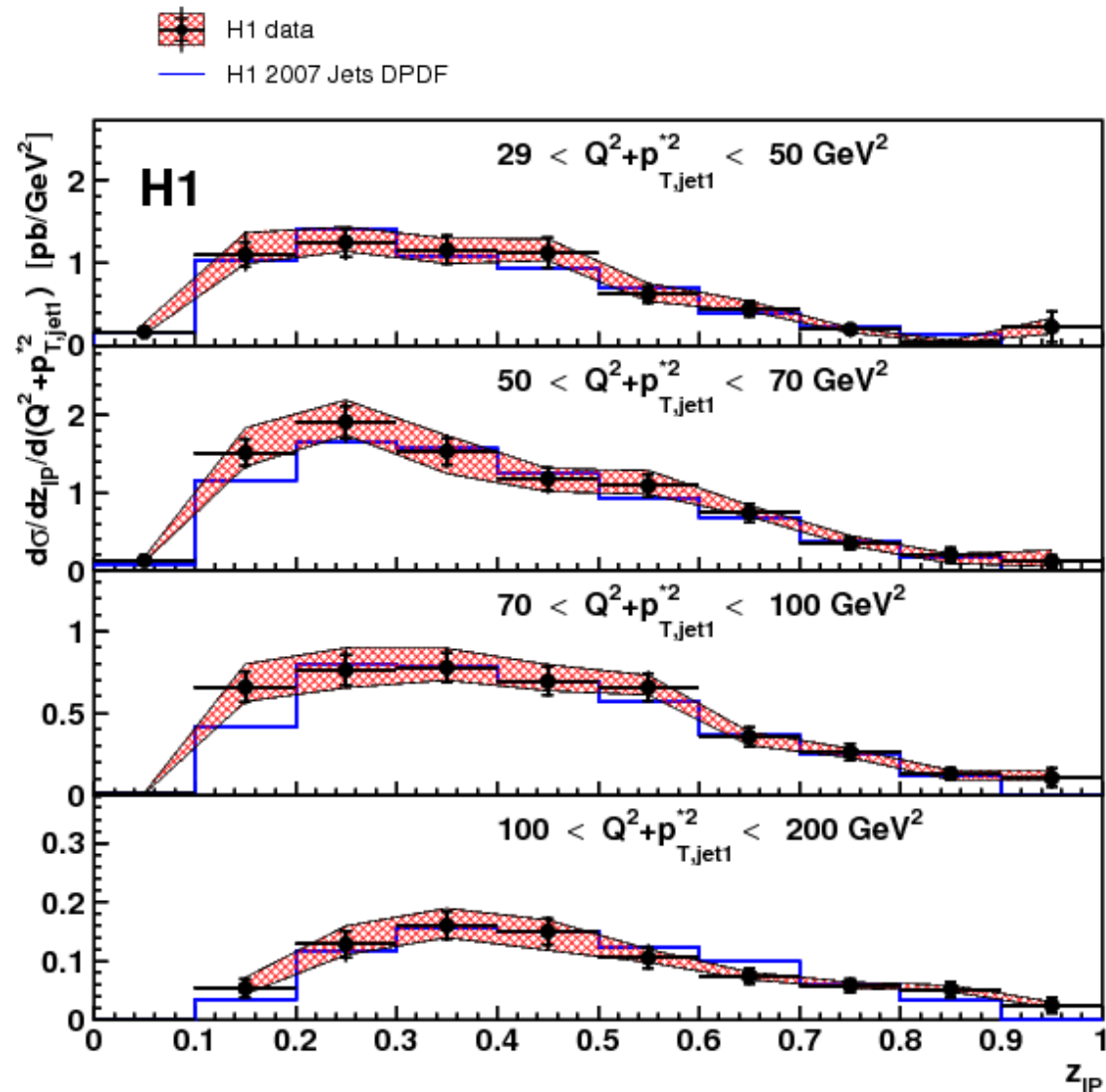


- H1 2006 DPDF fit B gives better agreement with the data

Diffraction PDFs (3)

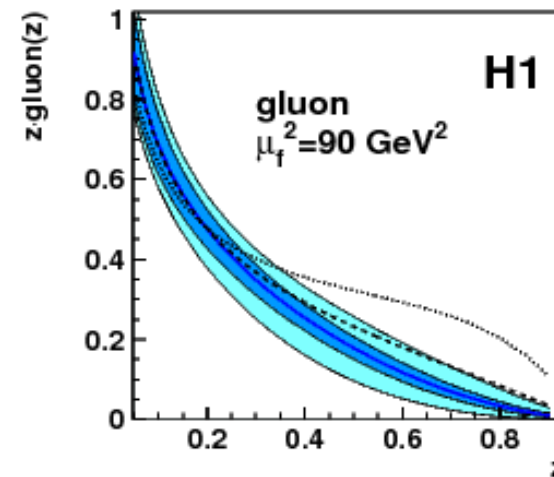
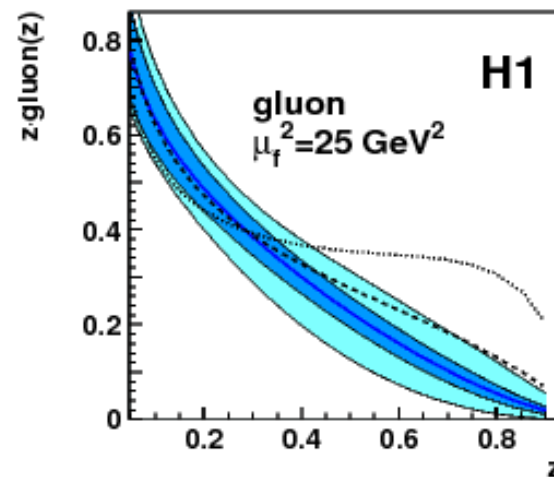
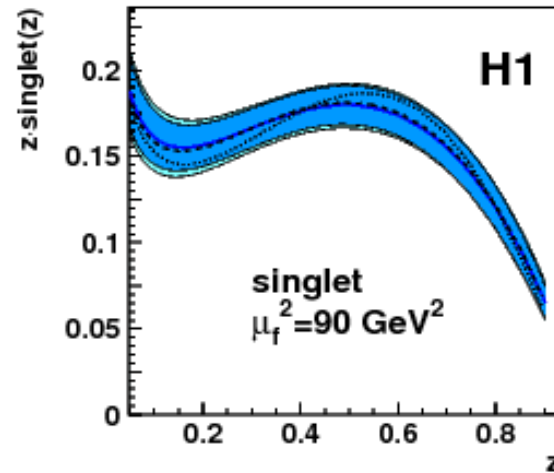
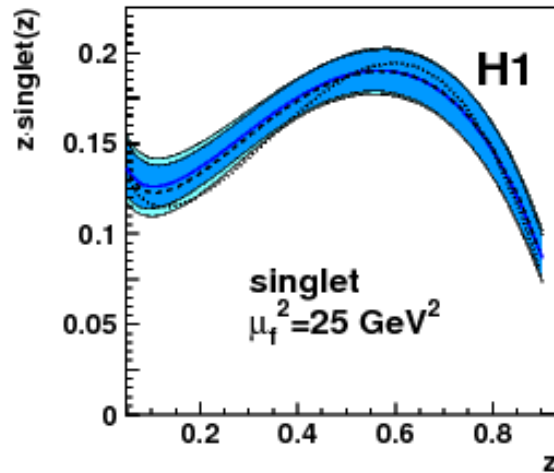
H1: diffractive di-jets in DIS

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



Diffractive PDFs (4)

- H1 2007 Jets DPDF
- exp. uncertainty
- exp. + theo. uncertainty
- H1 2006 DPDF fit A
- H1 2006 DPDF fit B



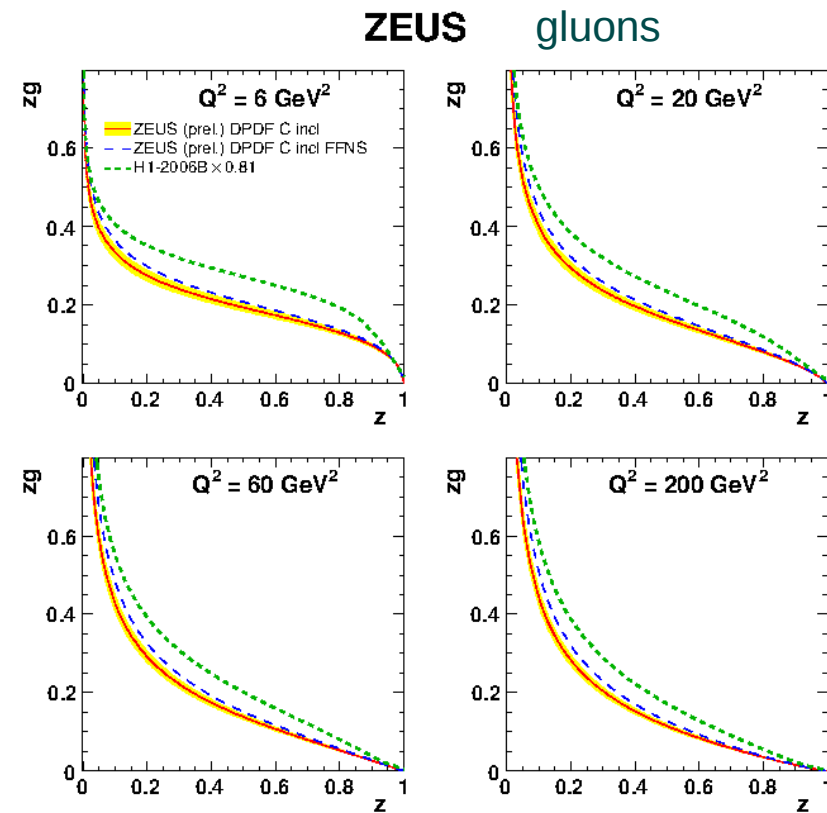
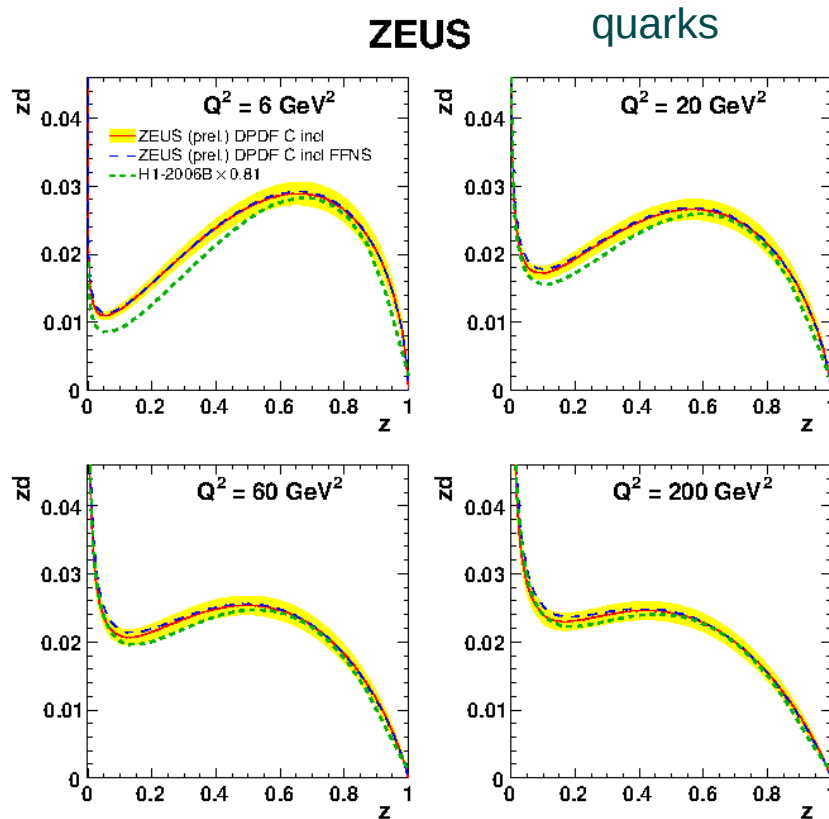
H1 2007 Jets dPDFs

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

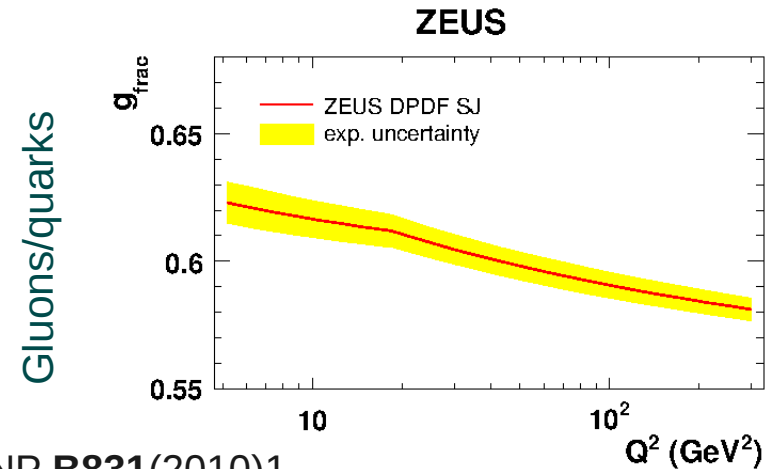
Diffraction PDFs (5)

ZEUS DPDF fits (ZEUS-prel-09-004):

LRG & LPS & diffractive Dijet DIS



H1 2006B

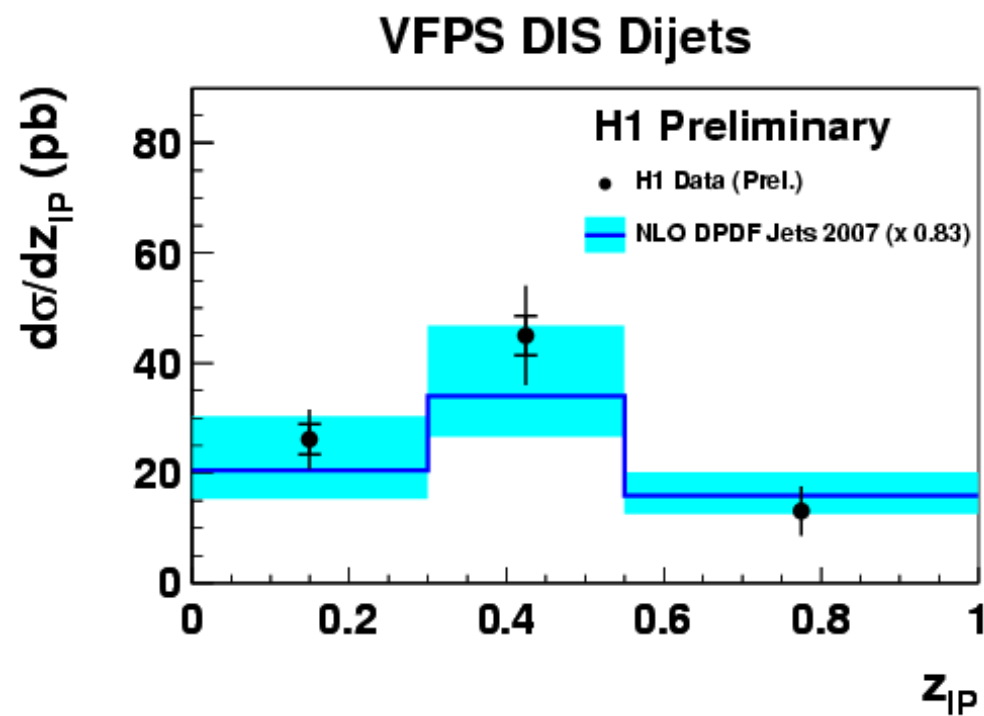
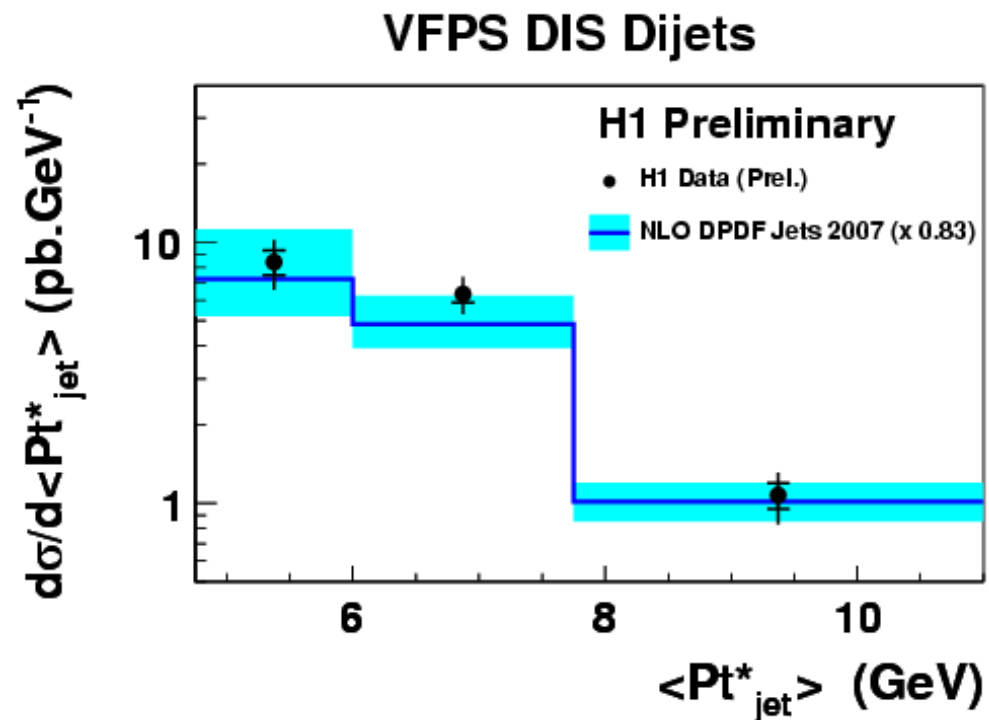


ZEUS and H1 2006B DPDF fits
are consistent up to normalisation

ZEUS, NP **B831**(2010)1

QCD factorization test: dijets in D-DIS

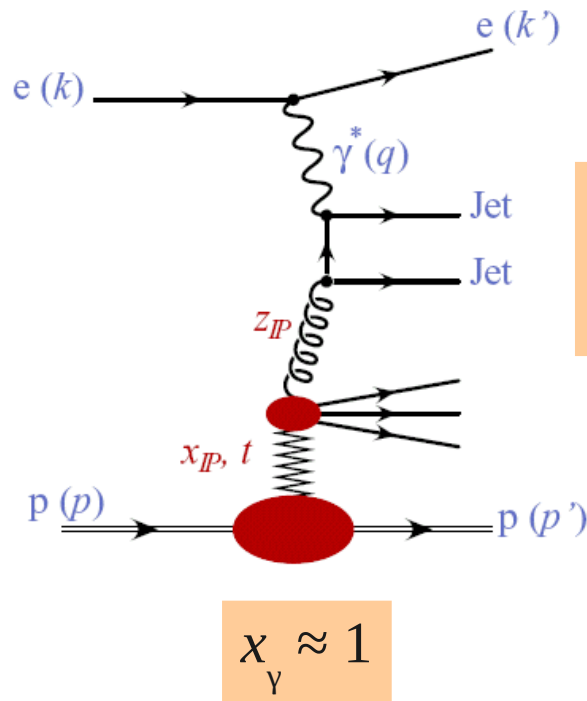
H1: 2 jets in diffractive DIS with leading proton **VFPS** (H1 prel-11-013)



NLO predictions using **H1** Jets 2007 DPDFs describe dijet production in DIS with tagged proton → QCD factorisation holds...

Diffractive dijets in photoproduction (1)

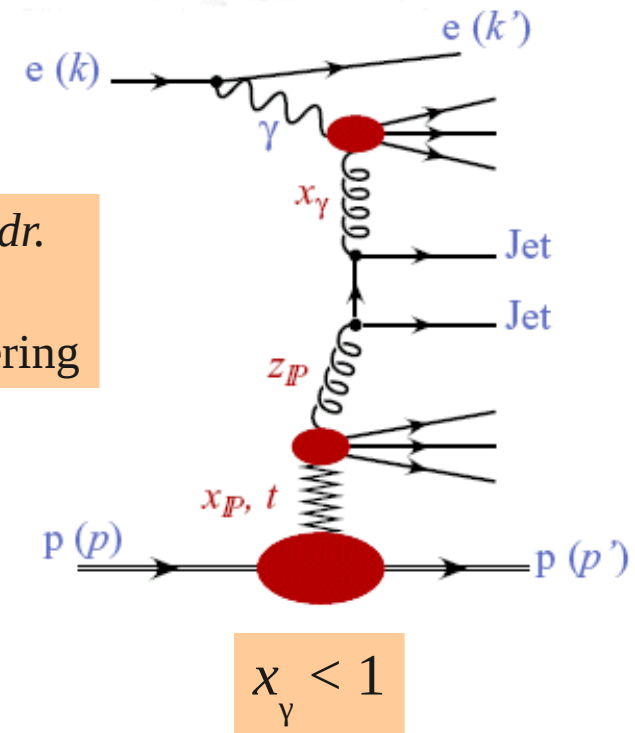
direct photon (like DIS)



$$x_\gamma = \Sigma(E-p_z)jets / \Sigma(E-p_z)hadr.$$

= fraction of photon
mom. in hard scattering

resolved photon

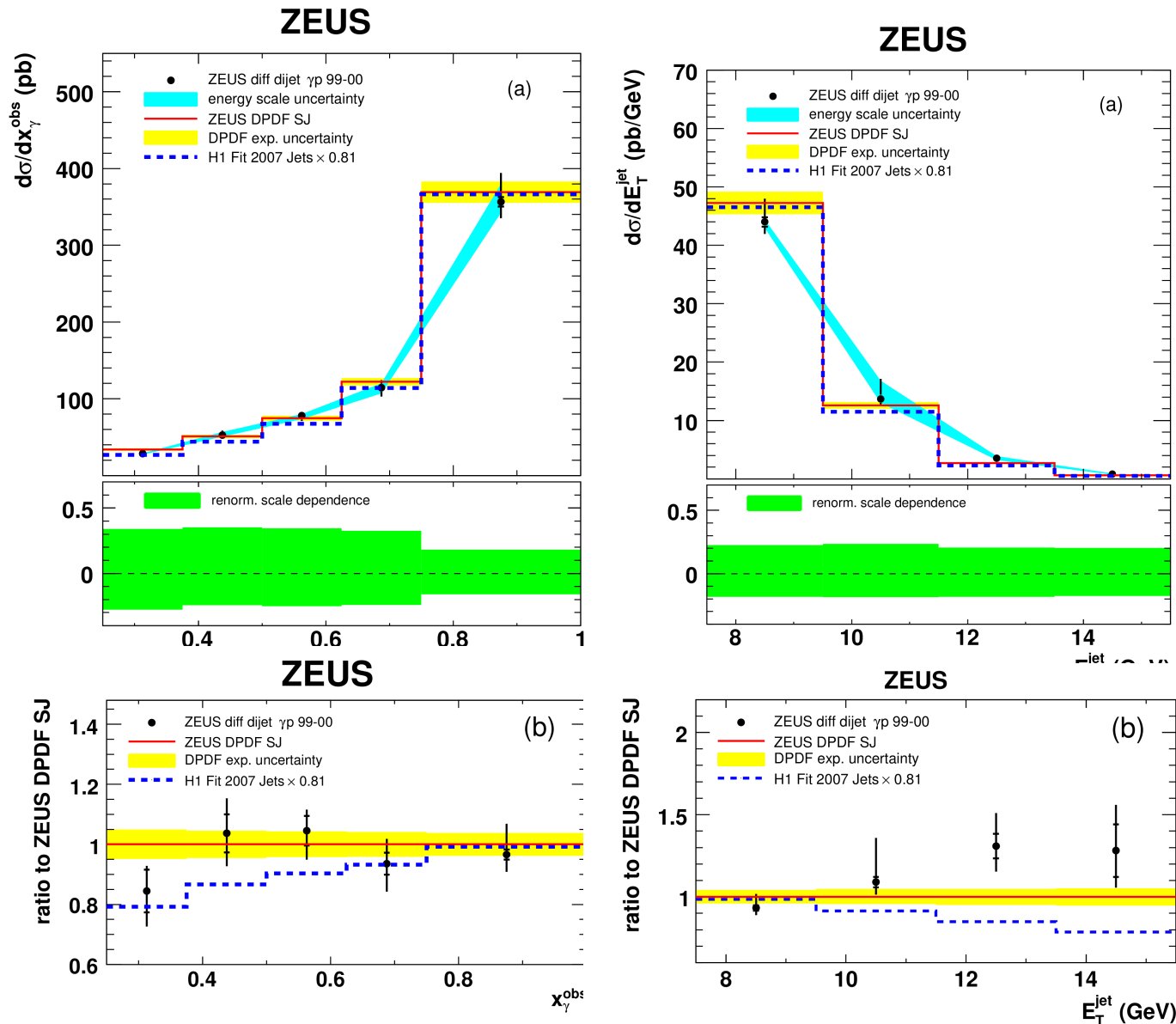


Resolved photon may behave as a hadron → factorization may be **broken**
(as in p-p, secondary re-scattering, multi-pomeron exchanges)
→ “**gap survival** probability...”

Diffractional dijets in photoproduction (2)

ZEUS: diffractive (LRG+LPS) dijets in photoproduction (NP B831 (2010) 1)

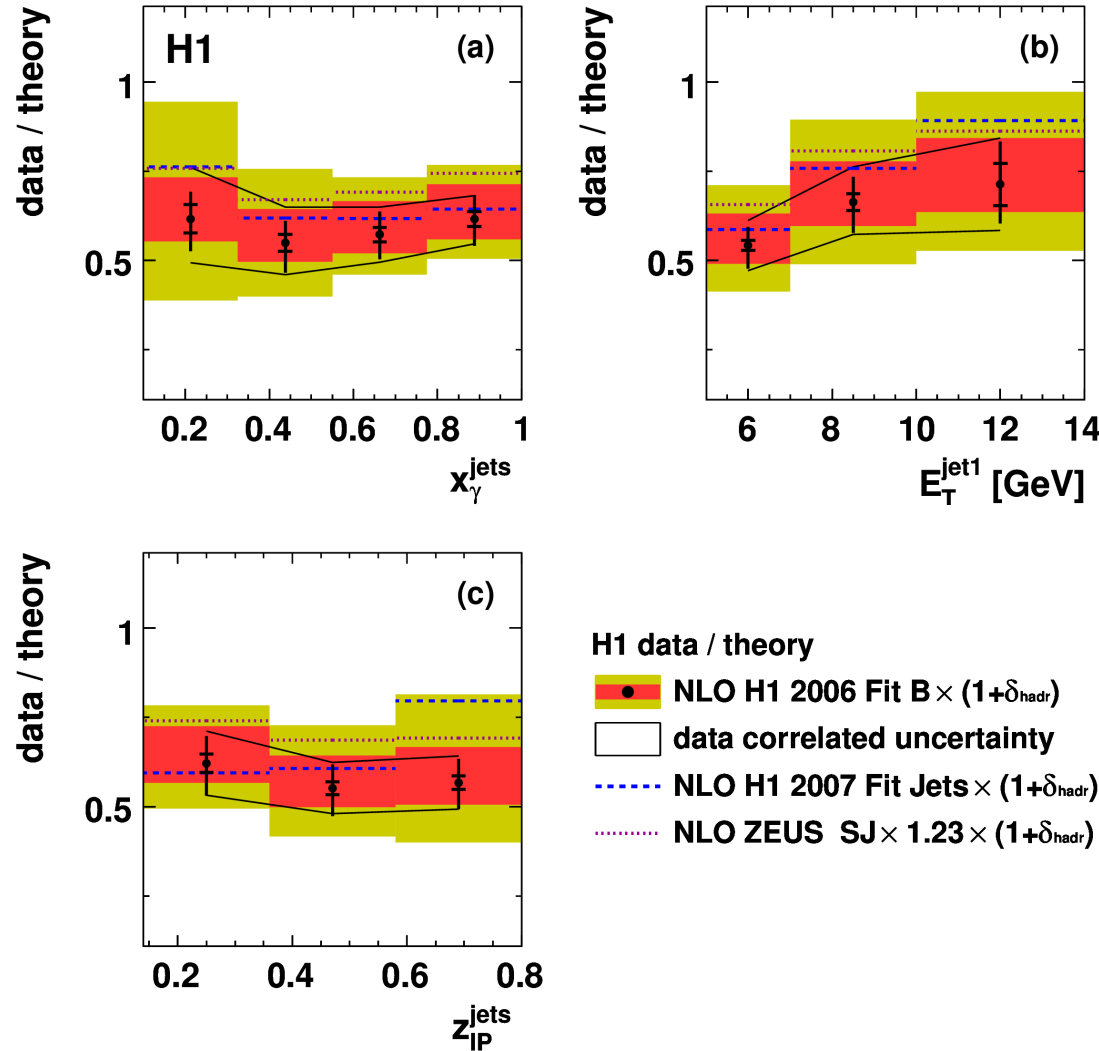
$E_T^{\text{jet}} > 7.5 \text{ GeV}$



- No suppression \Rightarrow QCD factorization holds?...
- Inconsistency with H1 DPDF...

Diffraction dijets in photoproduction (3)

H1: diffractive (**LRG**) dijets in photoproduction (EPJ **C70** (2010) 15)



$E_{\text{T jet}} > 5 \text{ GeV}$

“~ Gap survival probability”
H1-data/NLO = $0.58 \pm 0.12(\text{exp.})$
 $\pm 0.14(\text{scale}) \pm 0.09(\text{DPDF})$

- Weak dependence on x_{γ} (?)
- hint of jet E_{T} dependence
- dependence on DPDF...

Summary

- Still new, precise measurements of diffraction at HERA
- Consistent picture of VM production within QCD framework
- New diffractive PDFs from inclusive and semi-inclusive measurements, with several methods - consistent
- First combination of H1 and ZEUS diffractive data with tagged proton gives consistent results
- QCD hard factorization holds in diffractive dijet production in DIS but may be broken in PHP, H1 - ZEUS comparison inconclusive
- Theoretical uncertainties of QCD calculations are larger than experimental errors...
- Diffractive analyses at HERA are still ongoing...