Diffraction at HERA

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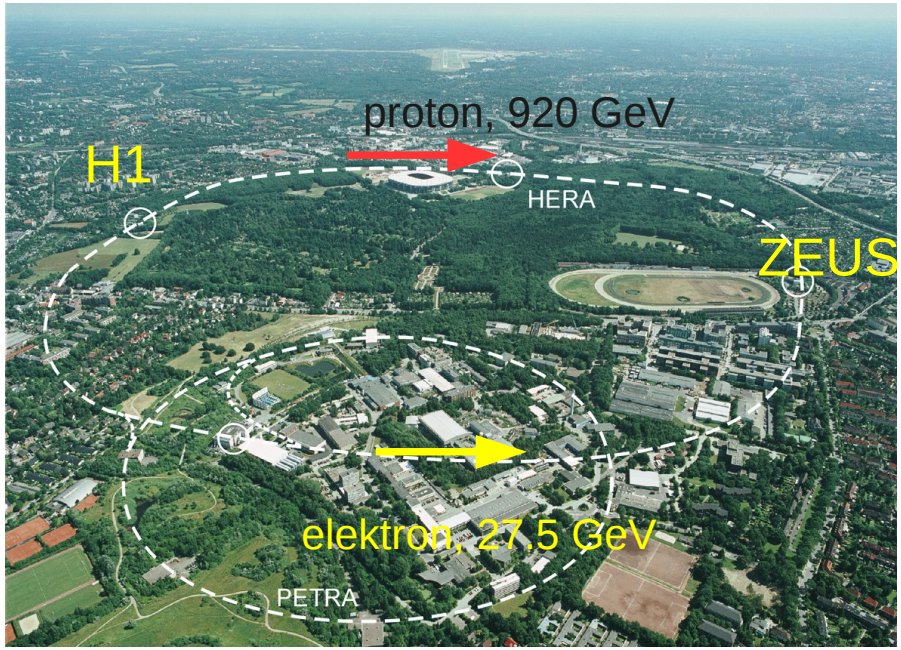
on behalf of the H1 and ZEUS collaborations



... 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

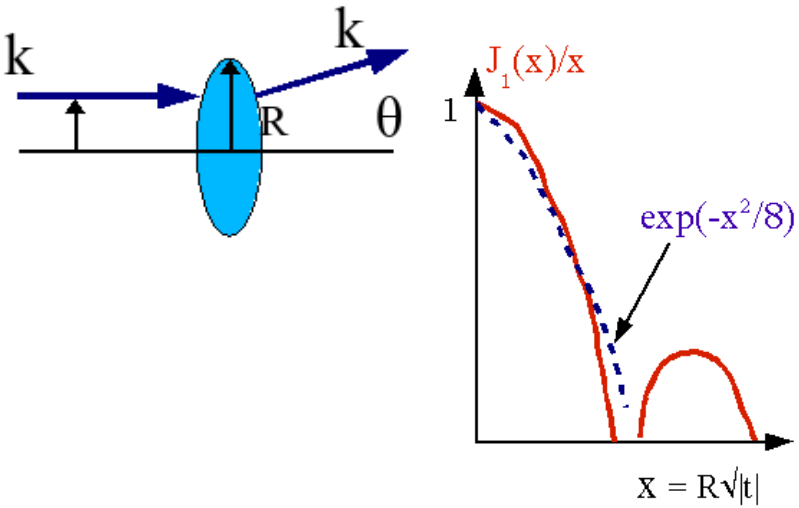
  Inclusive diffraction:

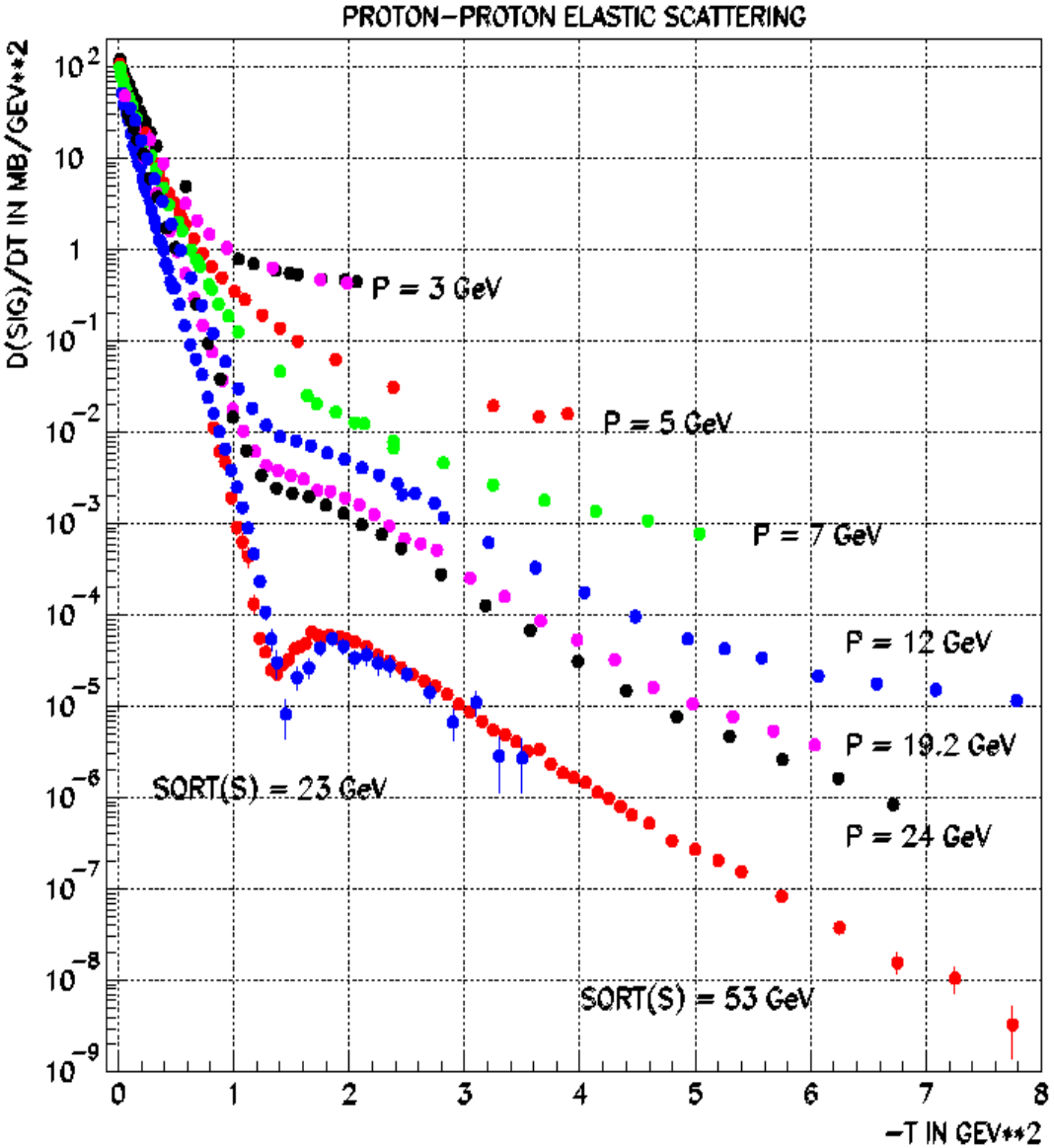
  Diffractive parton distribution functions

  QCD factorisation tests: diffractive dijet production
- Summary

Diffraction in hadron-hadron interactions (1)

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





<u>Elastic</u> hadron-hadron scattering:

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

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

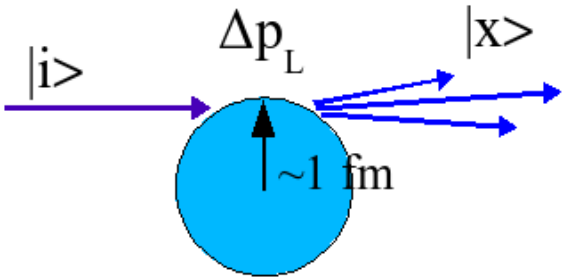
$$b = (R/2)^2 \approx 8\text{ -}10\ \mathrm{GeV}^{-2}$$

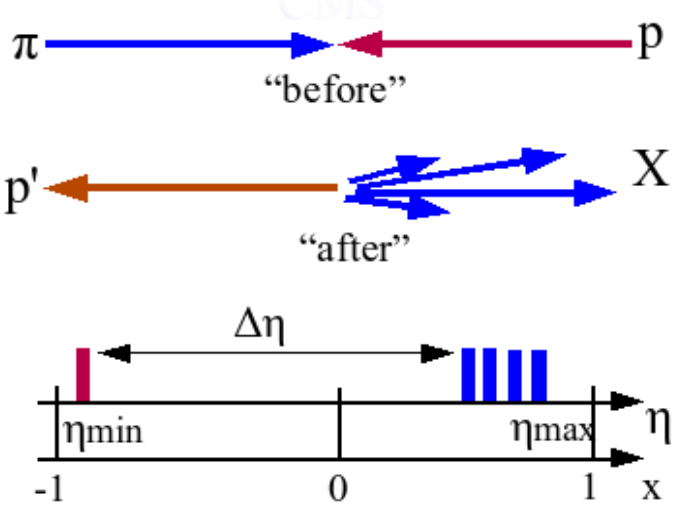
Diffraction in hadron-hadron interactions (2)

<u>Inelastic</u> hadron diffractive dissociation ↔ coherence condition:

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

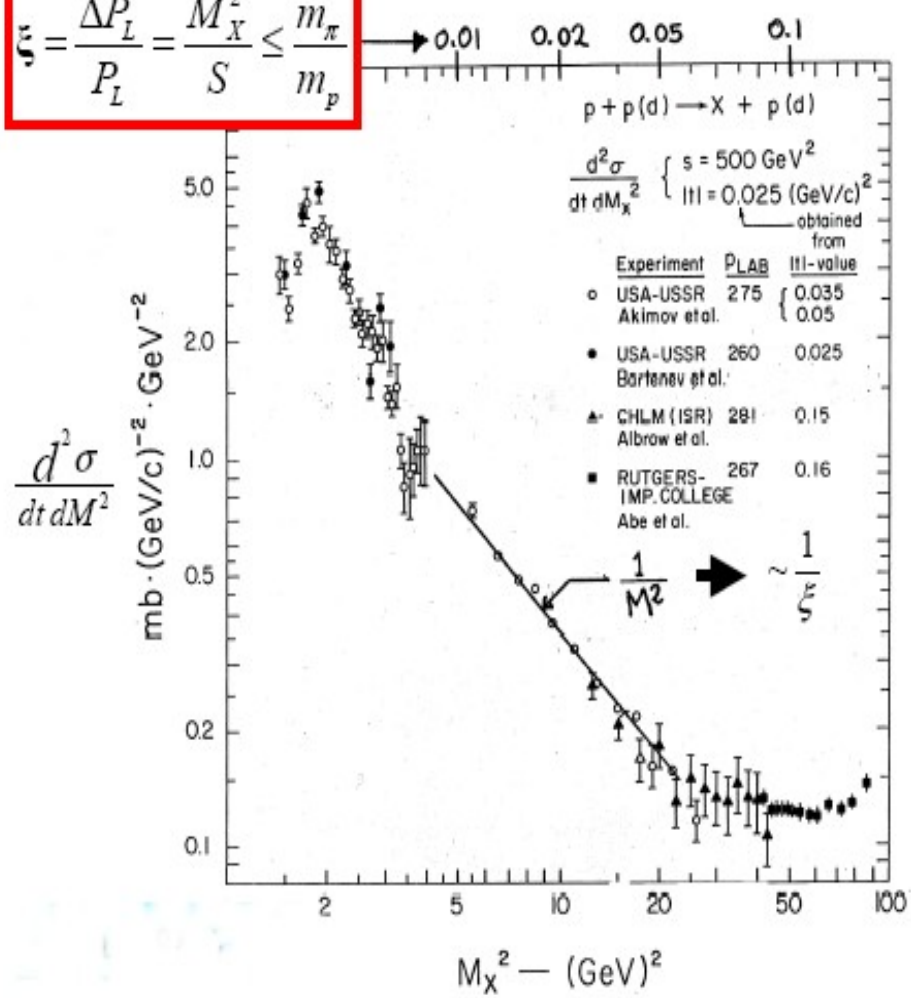
  $\Delta\eta = \ln(1/\xi) > 2$, ("large rapidity gap, LRG")





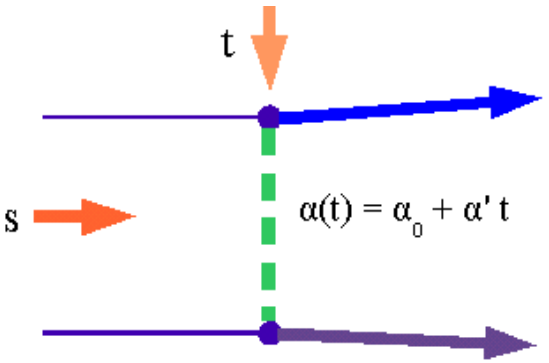
s = squared CMS energy of hadrons
$\eta = -\ln(\tan(\theta/2))$, (pseudo-)rapidity

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



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)

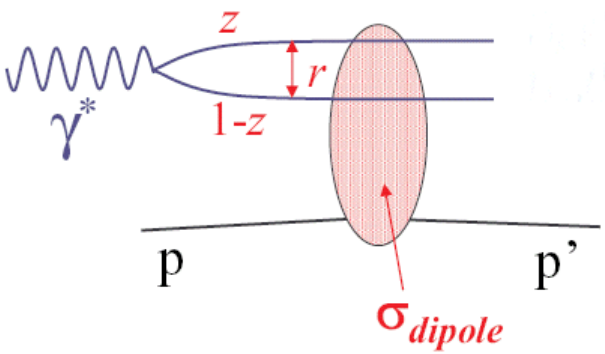
Universal parametrisation of Donnachie-Landshoff ("soft" Pomeron):

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

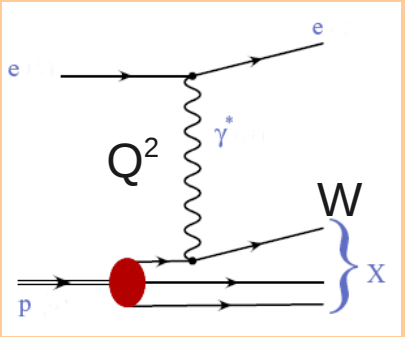
PS: J. D. Bjorken: Regge model foundations are as solid as those of QCD, DIS1994

Diffraction in e-p interactions

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

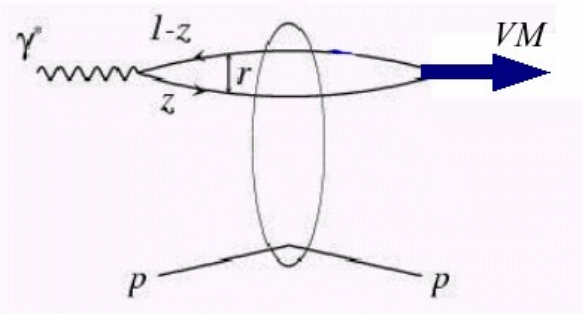


Coherence condition in proton rest frame:

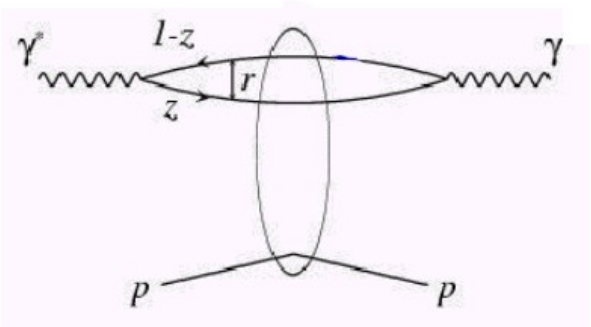
fluctuation length (γ^* → dipol $q\bar{q}$) $= 2E_\gamma/(m_{qq}^2 + Q^2) > 1$ fm

→ $x < 0.01$

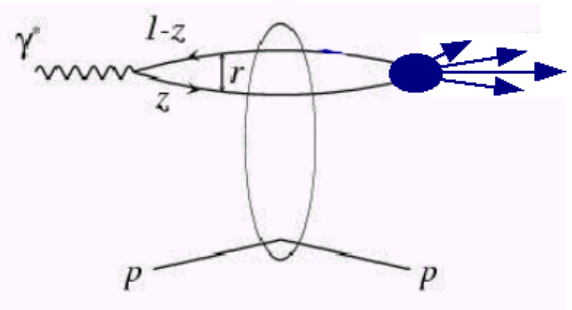
At HERA diffraction is low Bjorken-x phenomenon!



Vector meson production

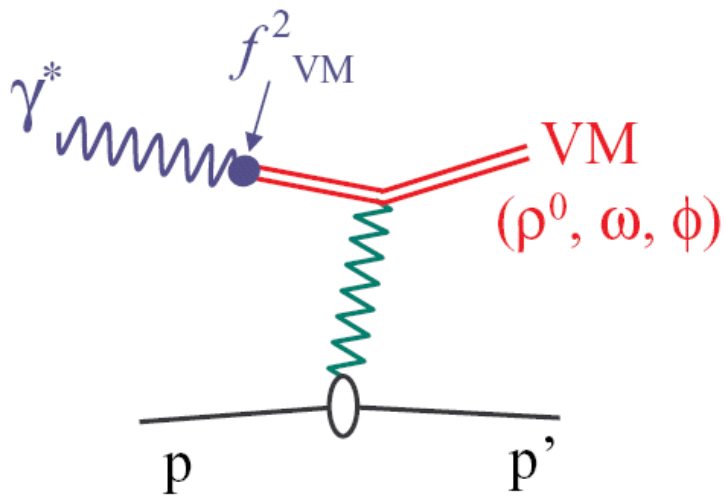


DVCS



inclusive diffraction

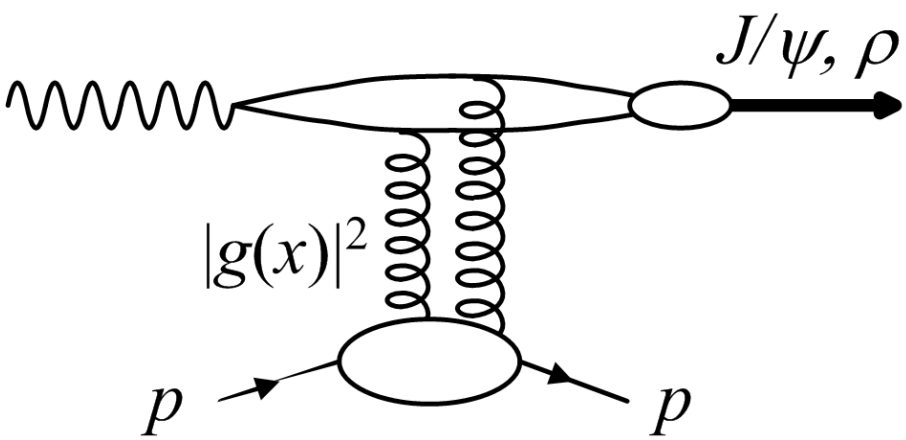
Vector meson production (1)



Vector Dominance Model + Regge

$\gamma^* p \to VM\, p = (\gamma^* \to VM) \otimes (VM\, p \to VM\, p)$

- $VM\, p \to VM\, p \Rightarrow$ DL IPomeron exchange
- $d\sigma/dt \sim \exp(-b(W)t)$, $\quad b \sim R_{int}^{\ 2} \approx 10\ \mathrm{GeV}^{-2}$
- $b(W) = (b_{VM} + b_p + \alpha' \ln(W^2))$ ("shrinkage")
- $\sigma_{VMp} \sim W^{4(\alpha 0-1)}/b(W) \sim W^{\delta}$, $\delta \approx 0.22$



Perturbative QCD

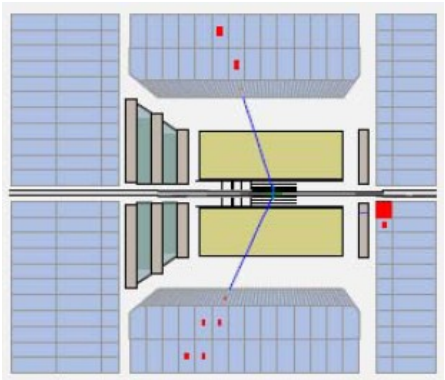
Large Q^2, M_{VM} or $|t|$ $\to$ small qq dipol

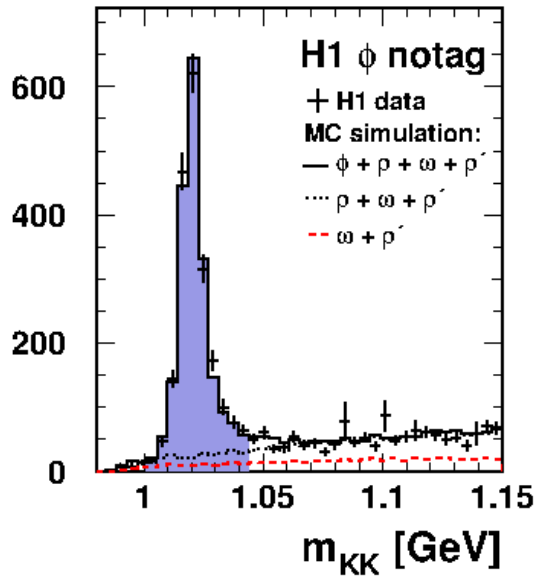
- QCD Pomeron exchange:
  ≥ 2 gluons (colour singlet)
- $\sigma_{VMp} \sim (xg(x))^2 \sim W^{0.7}$!!!
- $b \ll 10\ \mathrm{GeV}^{-2}$, weak shrinkage

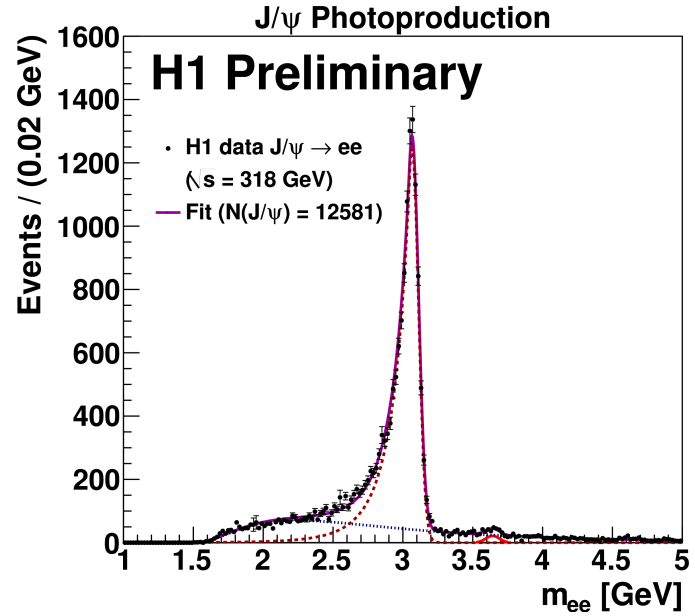
VM at HERA: transition between soft and hard regime; testbed of QCD scales

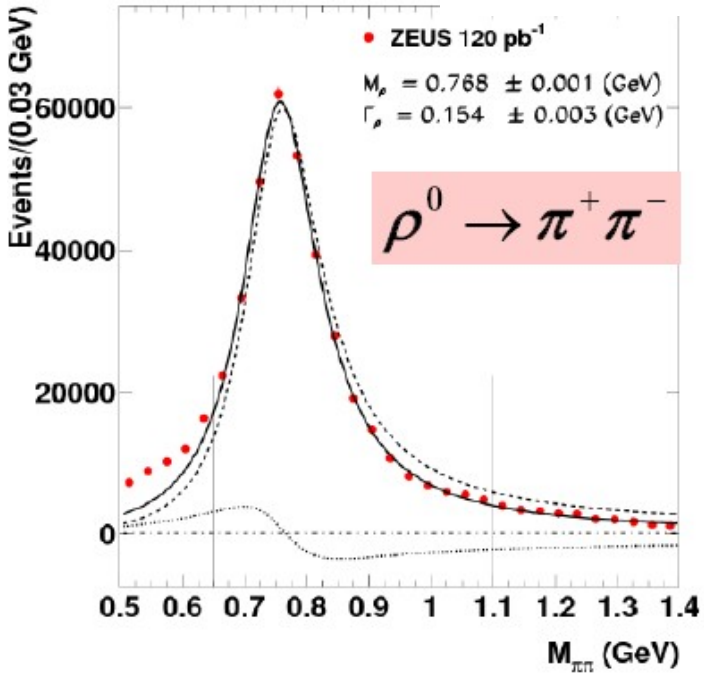
Vector meson production (2)

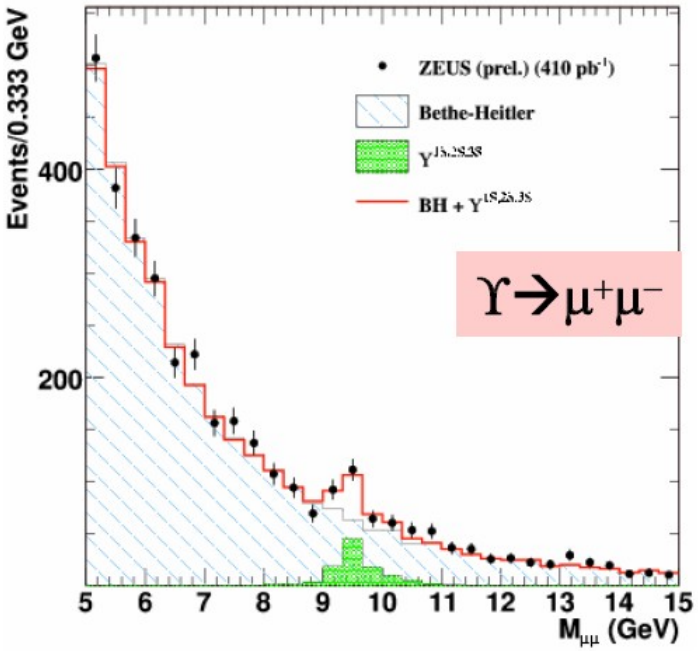
H1, ZEUS





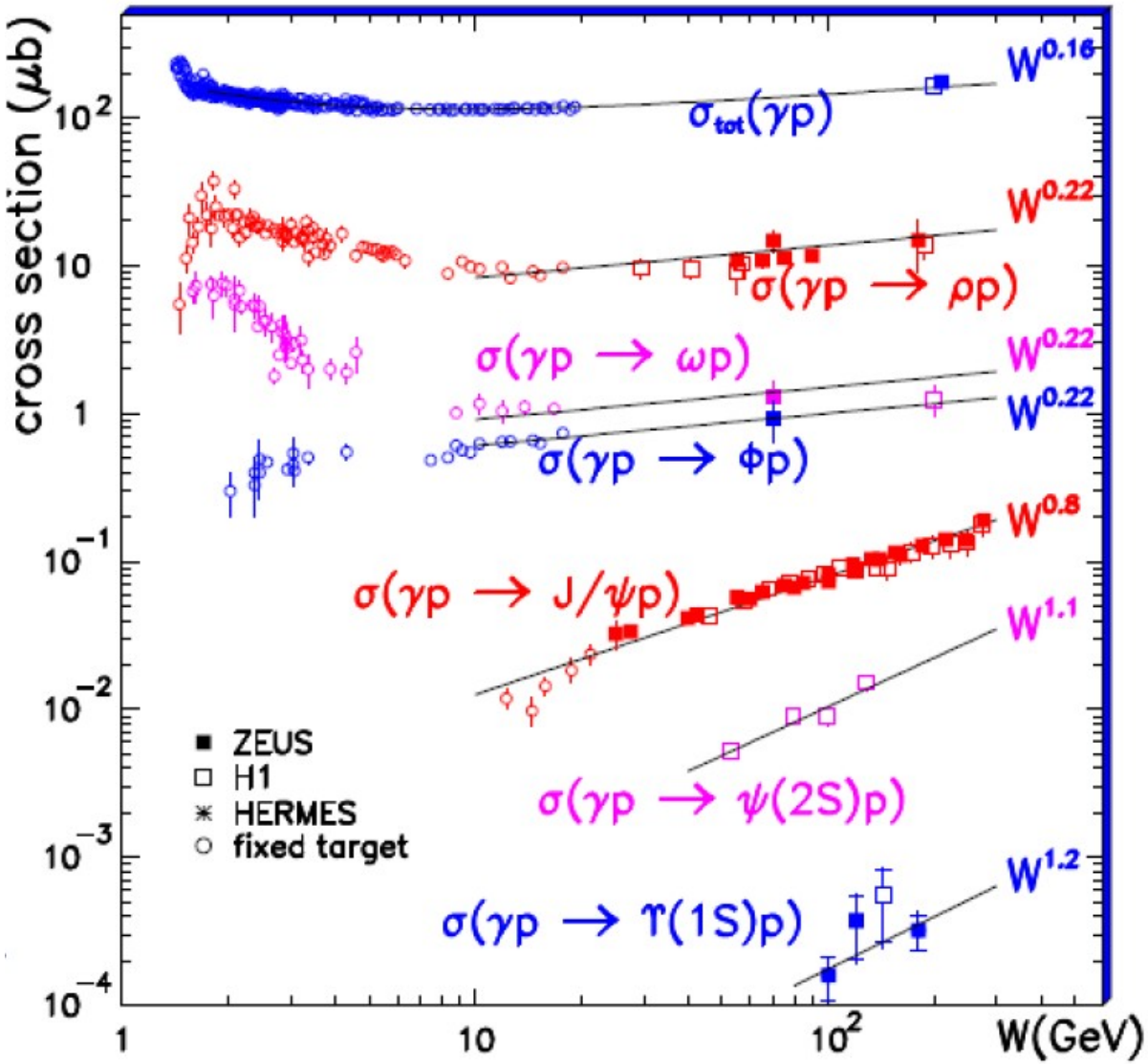






Vector mesons: energy dependence

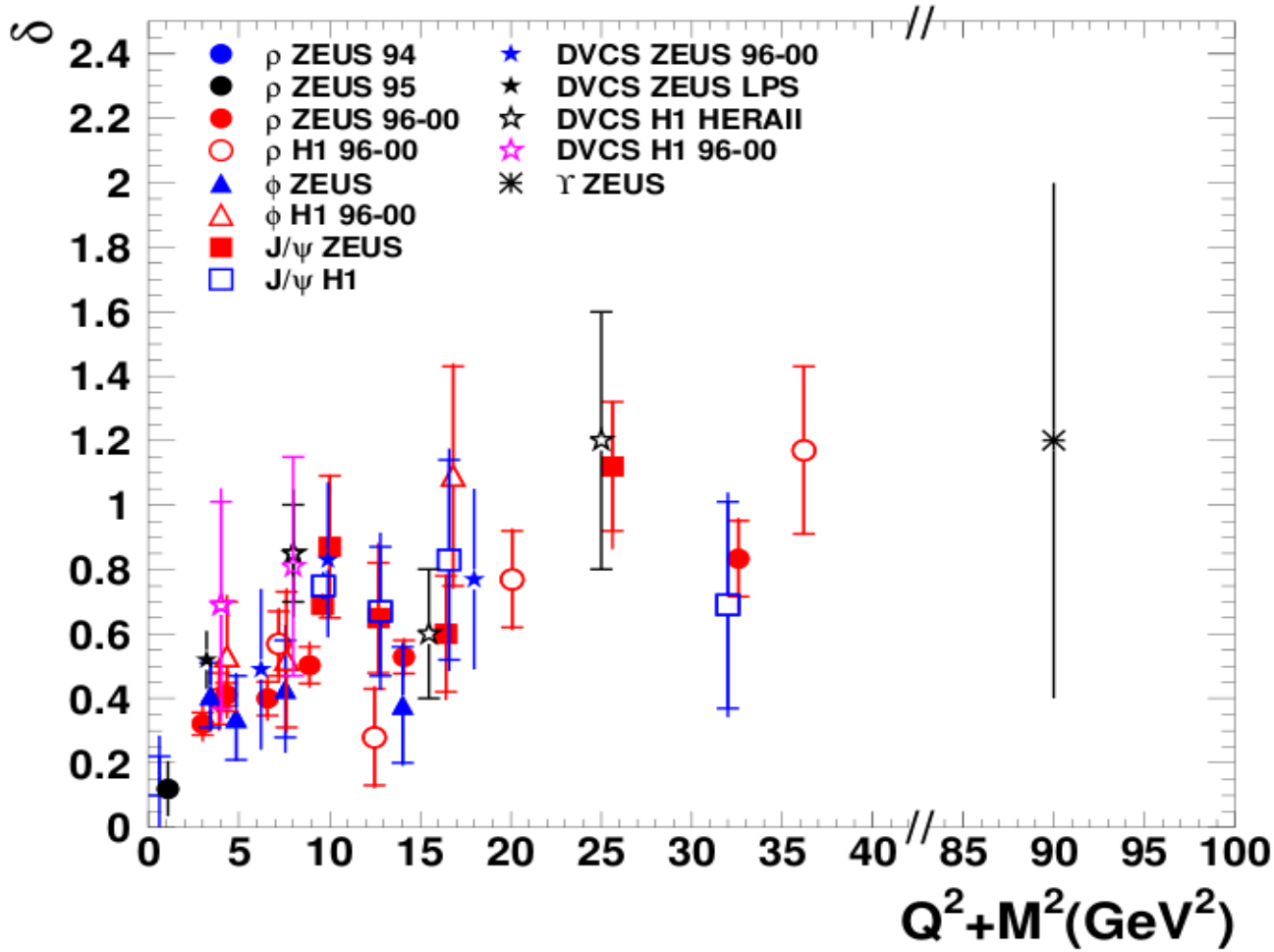
Photoproduction, energy dependence: $\sigma \sim W^{\delta}$



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

VM mass sets QCD scale

VM and DVCS energy dependence

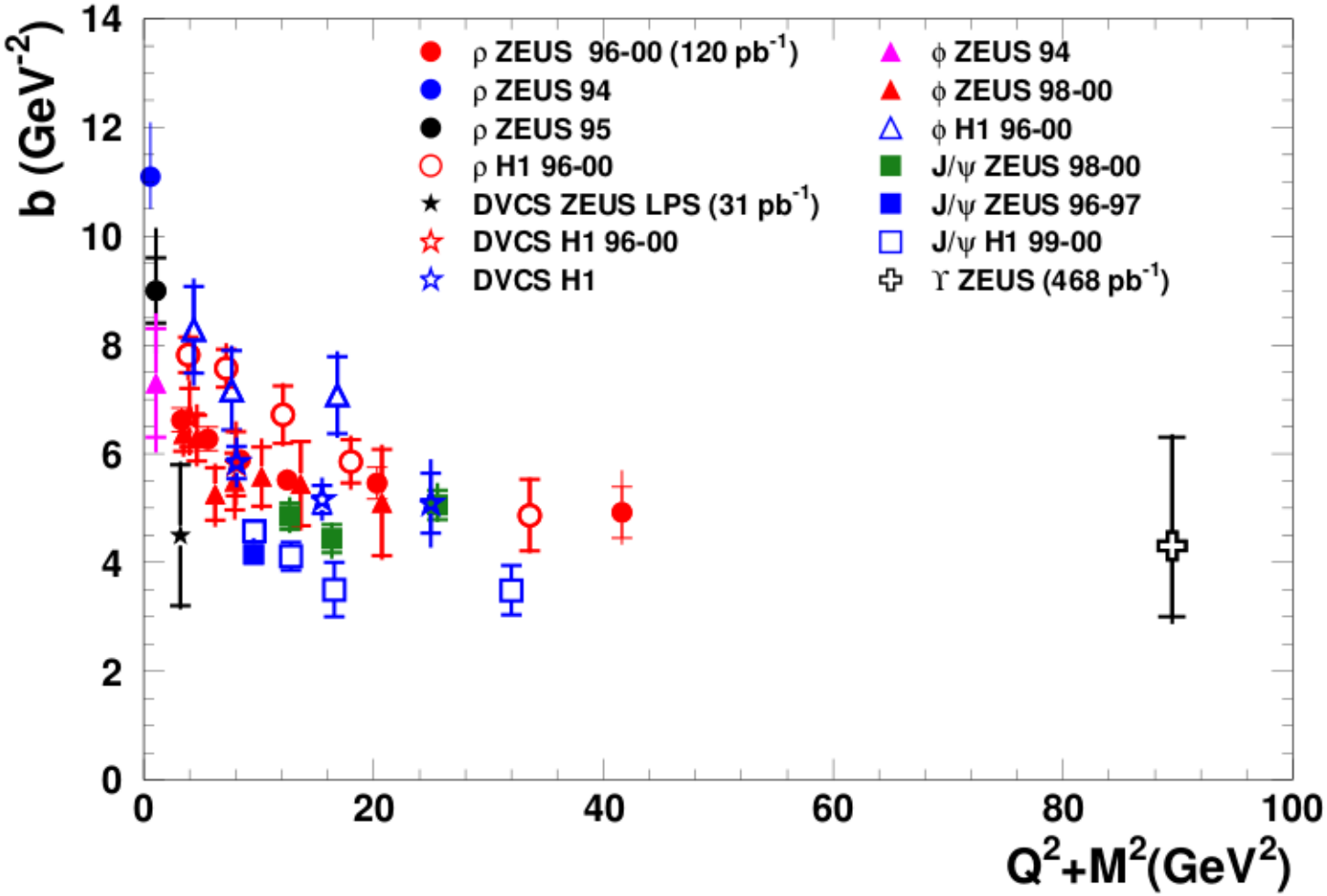


$$\sigma \sim W^{\delta}$$

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)

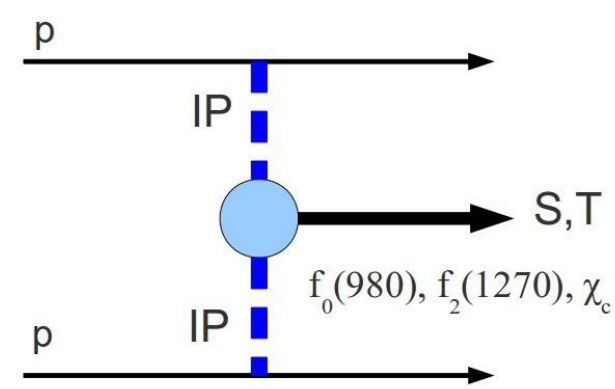
Possible **exchanges**:

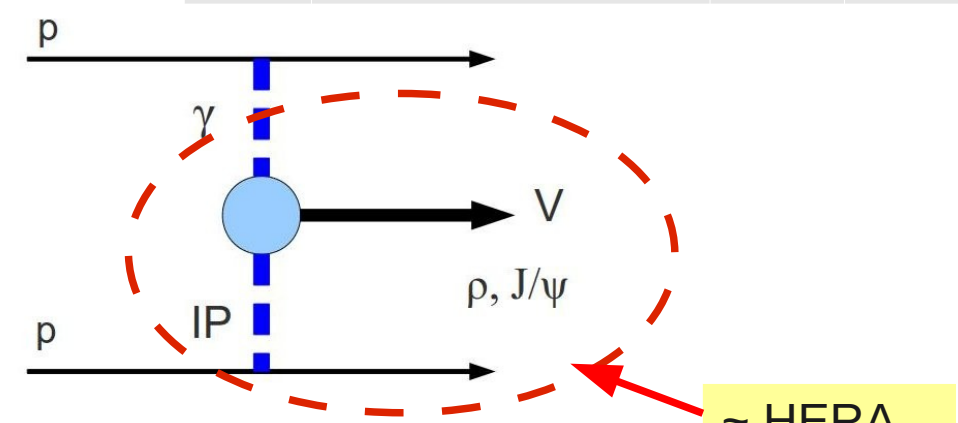
Pomeron (C=+1), QCD: 2 gluons,

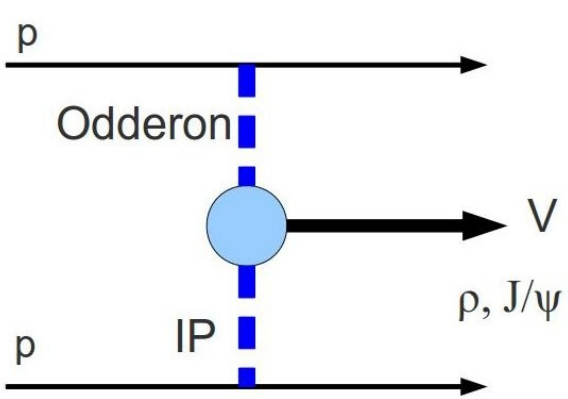
Odderon (C=-1), QCD: 3 gluons

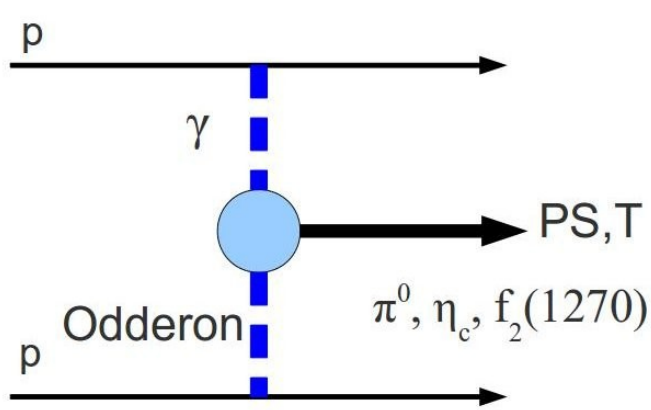
Photon γ (C=-1),

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^{++}





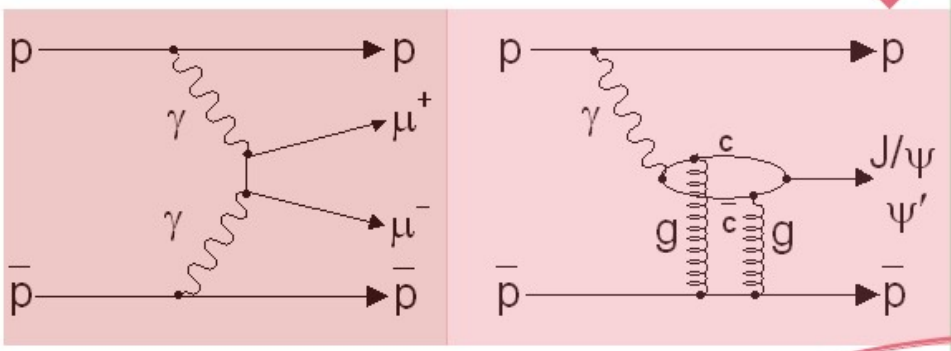


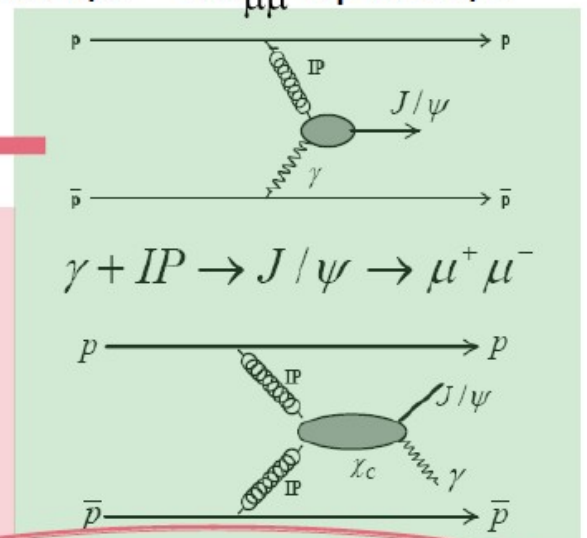


Exclusive Dimuon Production

$\bar{p} + p \rightarrow \bar{p} + \mu^+\mu^- + p$ 3 GeV/c² <$M_{\mu\mu}$<4 GeV/c²

Many Physics Processes in this data:





exclusive χ_c in DPE

- Observation of exclusive χ_c PRL 102 242001 (2009)

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Exclusive J/ψ and ψ(2s)

J/ψ production

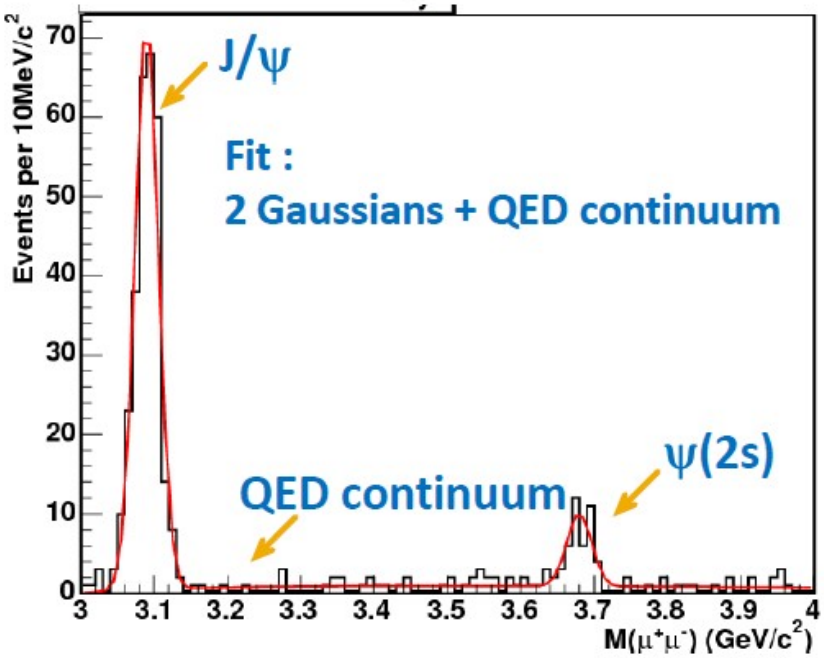
243 ±21 events

$d\sigma/dy|_{y=0}$ = 3.92 ± 0.62 nb

Theoretical Predictions

2.8 nb [Szczurek07,],
2.7 nb [Klein&Nystrand04],
3.0 nb [Conclaves&Machado05], and
3.4 nb [Motkya&Watt08].

PRL 242001 (2009)



Ψ(2s) production

34±7 events

$d\sigma/dy|_{y=0}$ = 0.54 ± 0.15 nb

R = ψ(2s)/J/ψ = 0.14 ± 0.05

In agreement with HERA: R = 0.166 ± 0.012 in a similar kinematic region

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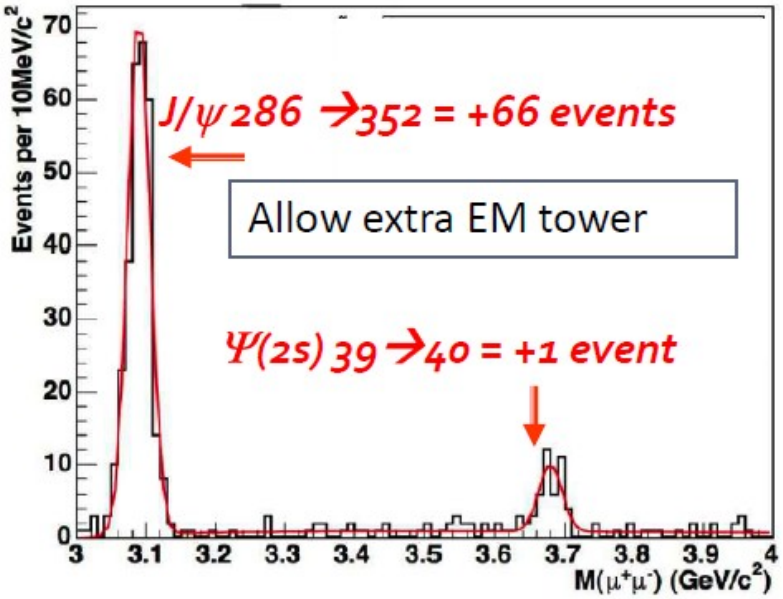
Exclusive $\chi_c \rightarrow J/\psi(\rightarrow \mu^+\mu^-)+\gamma$

PRL 242001 (2009)



➔ Allowing EM towers (E_T>80MeV)

large increase in the J/ψ peak

minor change in the ψ(2s) peak

↓

Evidence for

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

$d\sigma/dy|_{y=0}$ = 75 ± 14 nb,

compatible with theoretical predictions

160 nb (Yuan 01)

90 nb (KMR01)

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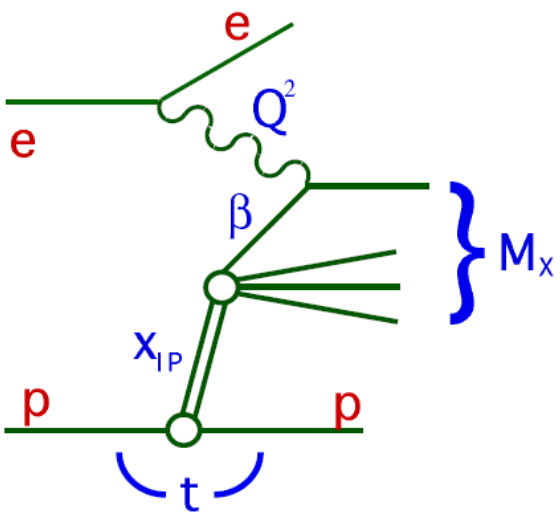
Inclusive diffraction in e-p interactions (1)

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**

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

Regge inspired...

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

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

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

"reduced" cross section $\sigma_r^D = F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D \approx F^D_2$, $y < 1$ ($F^D_L = 0$ at LO)

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

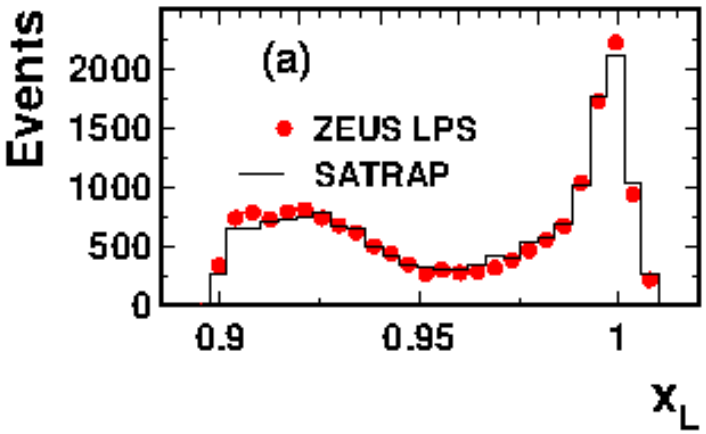
IPomeron flux (Regge form)

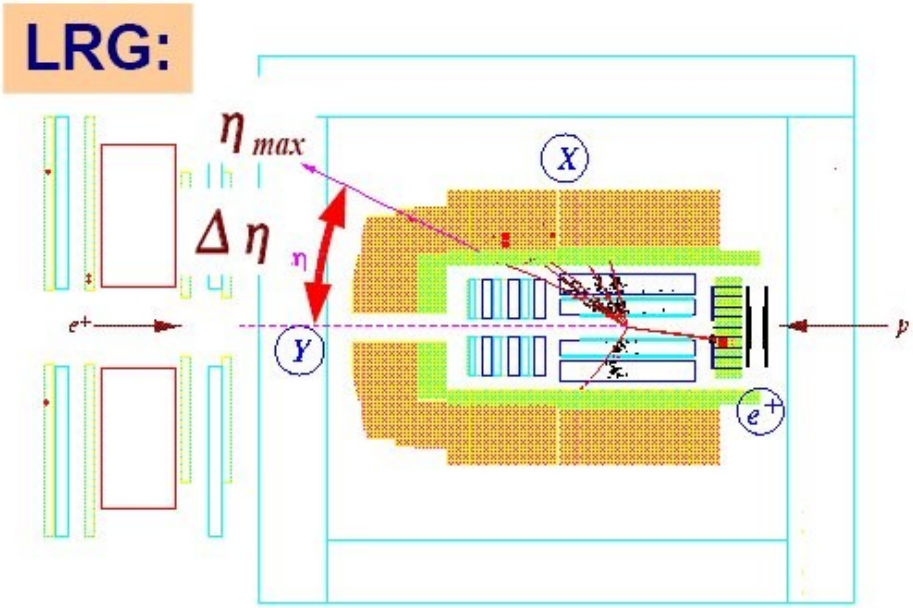
IPomeron structure function !!!

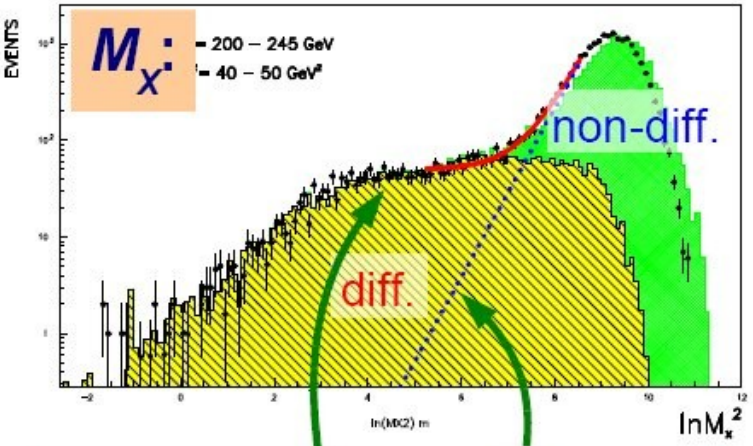
Inclusive diffraction in e-p interactions (2)

Diffractive selection:

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





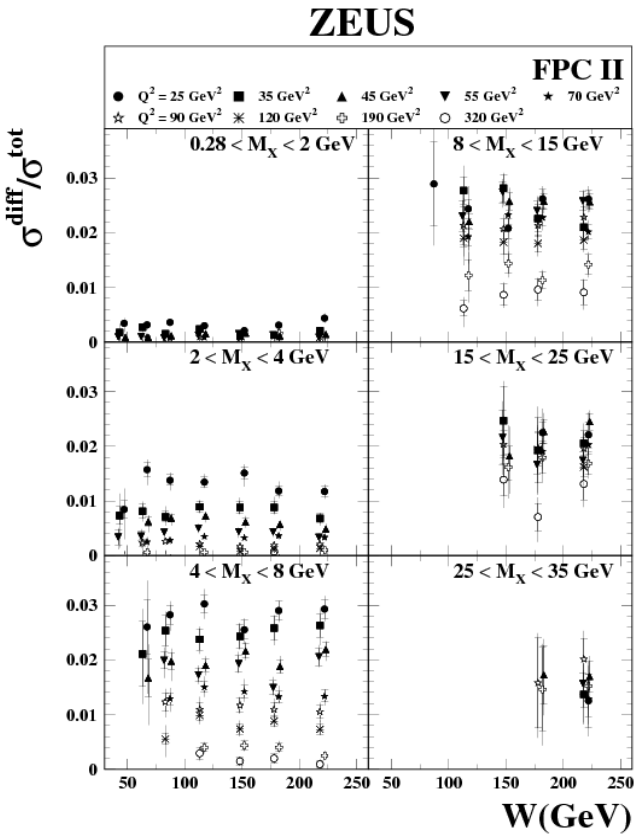


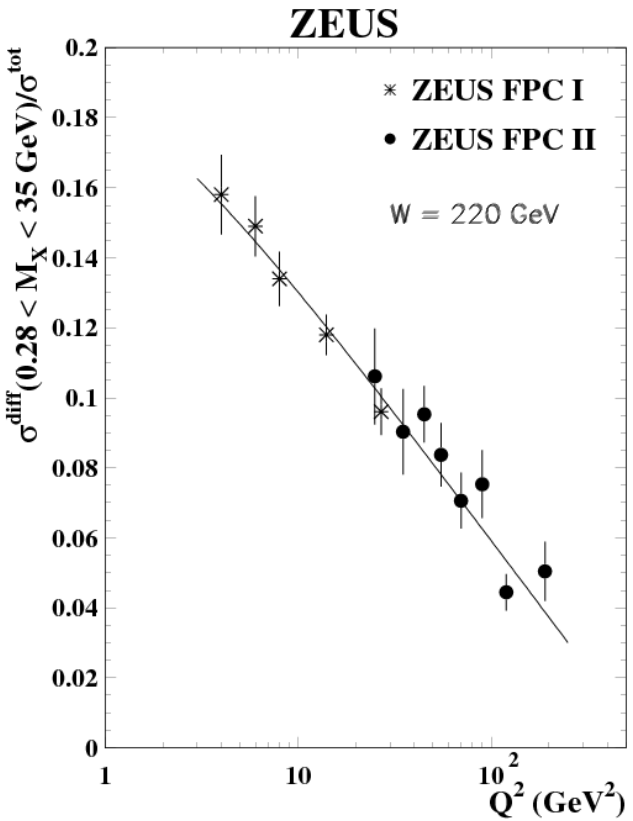
$$\frac{dN}{d\ln(M_X^2)} = D + c\exp(b\ln(M_X^2))$$

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

Inclusive diffraction in e-p interactions (3)

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

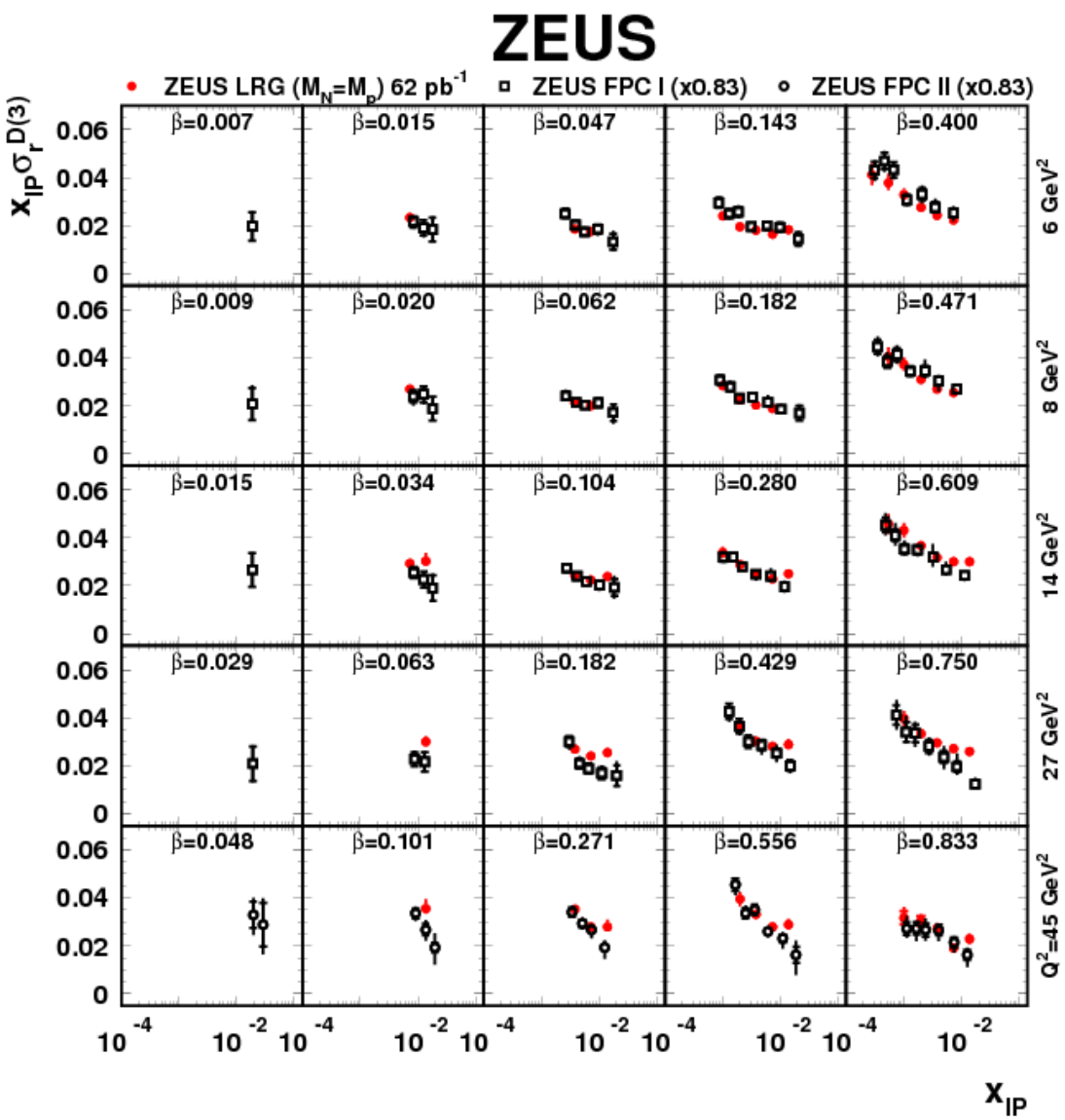




- Diffraction yield (fixed M_X, Q^2) ≈ const (W)
- Diffraction yield ($0.28 < M_X < 35$ GeV) ≈ $a - b \ln(1+Q^2)$

Inclusive diffraction in e-p interactions (4)

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

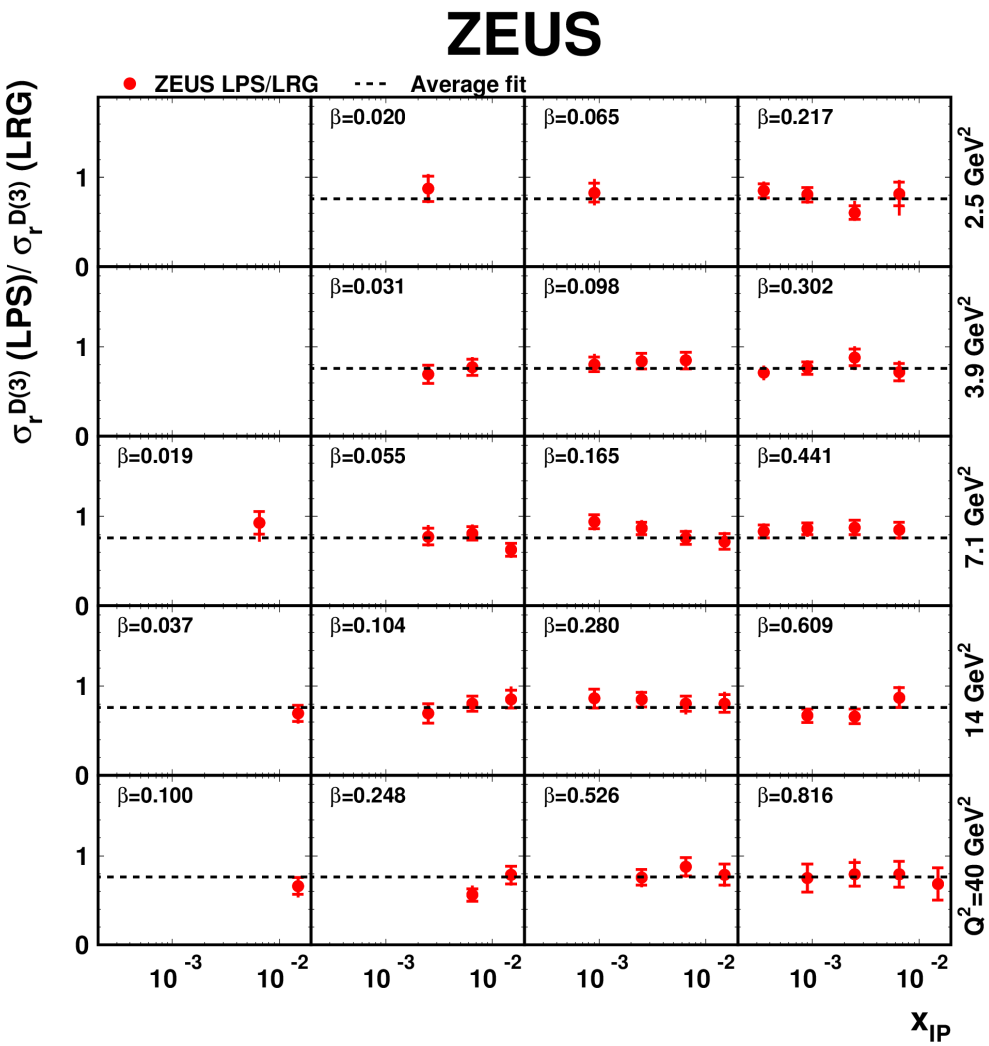


ZEUS Nucl.Phys. **B816** (2009) 1

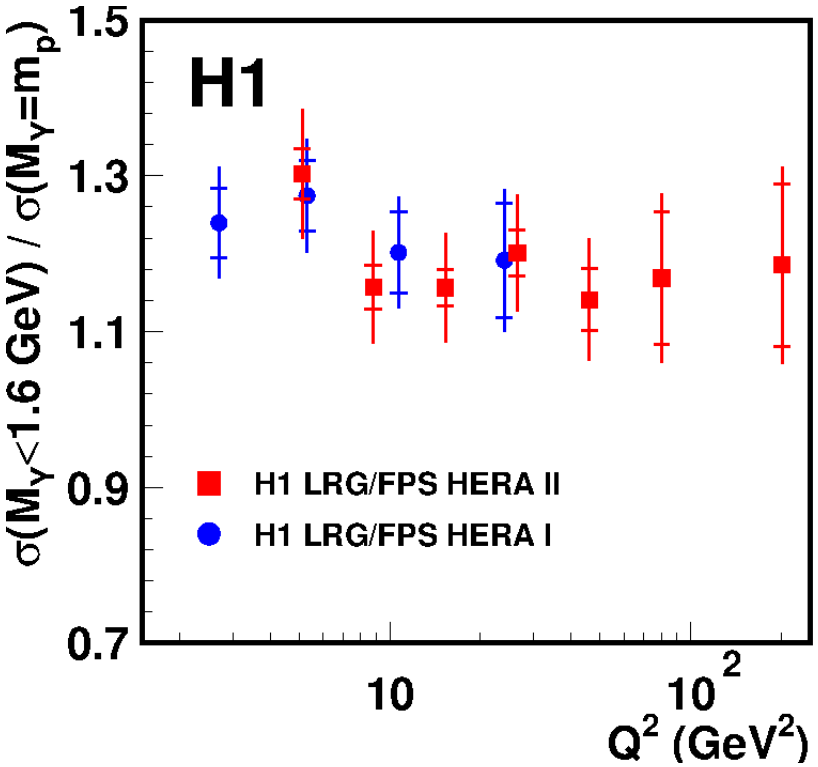
Different methods are consistent

Inclusive diffraction in e-p interactions (5)

LPS vs **LRG** method



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



H1 EPJ **C71** (2011) 1578

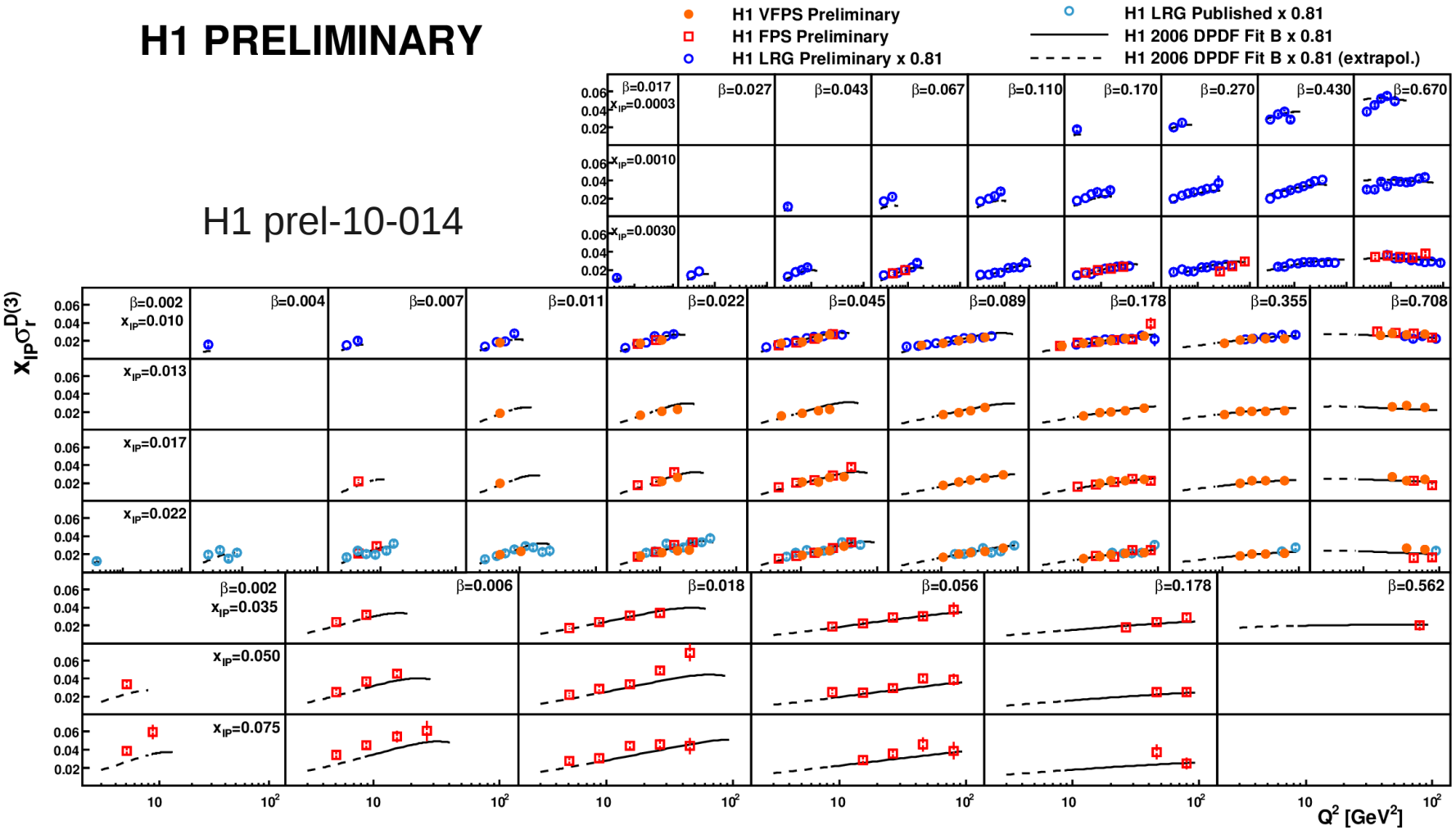
- LRG data contain ~20% of p-diss.
- No significant dep. on Q^2, β, x_{IP}

Inclusive diffraction in e-p interactions (6)

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

H1 PRELIMINARY

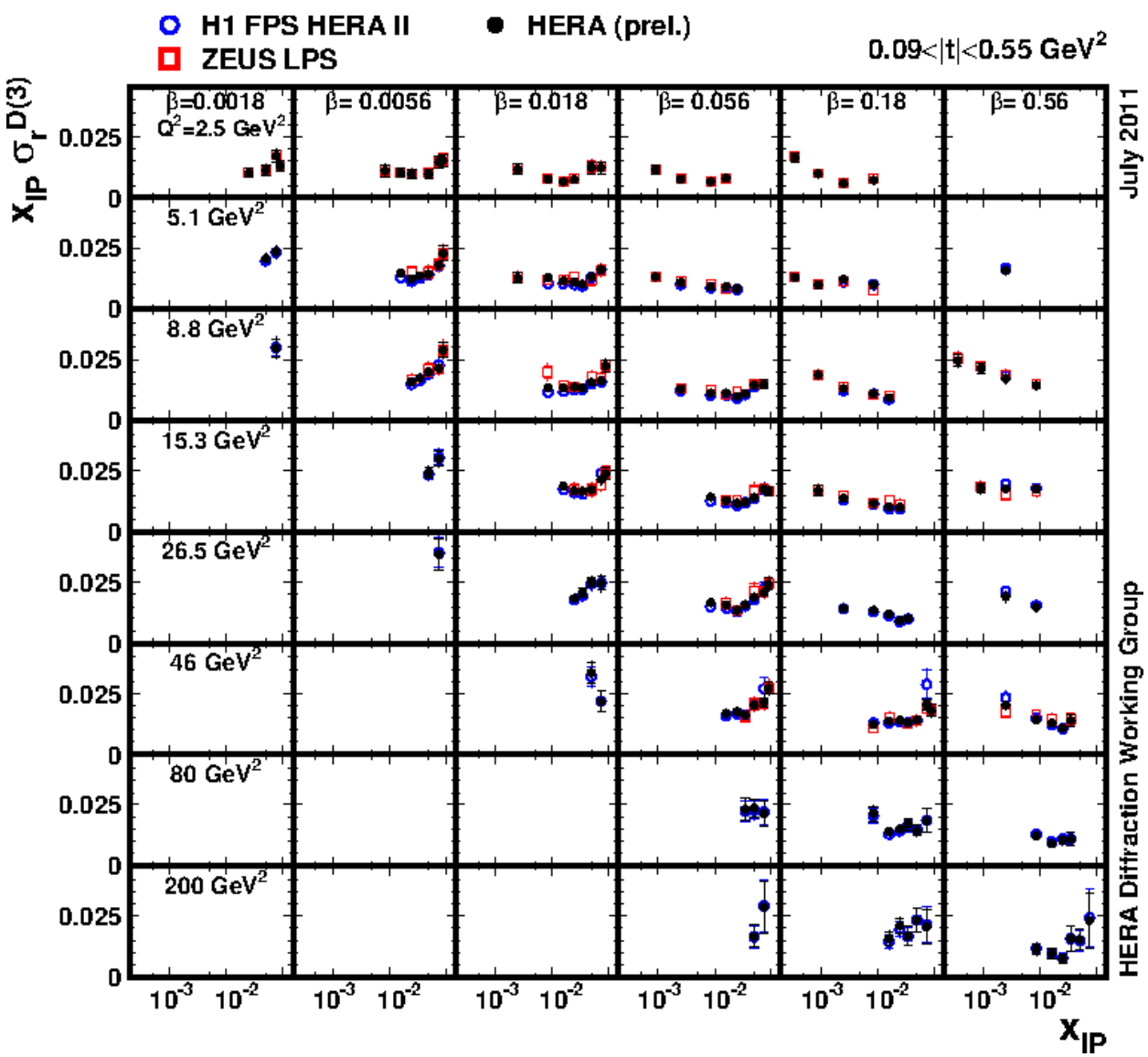
H1 prel-10-014



VFPS ≈ 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 ⇒

⇒ Combine!

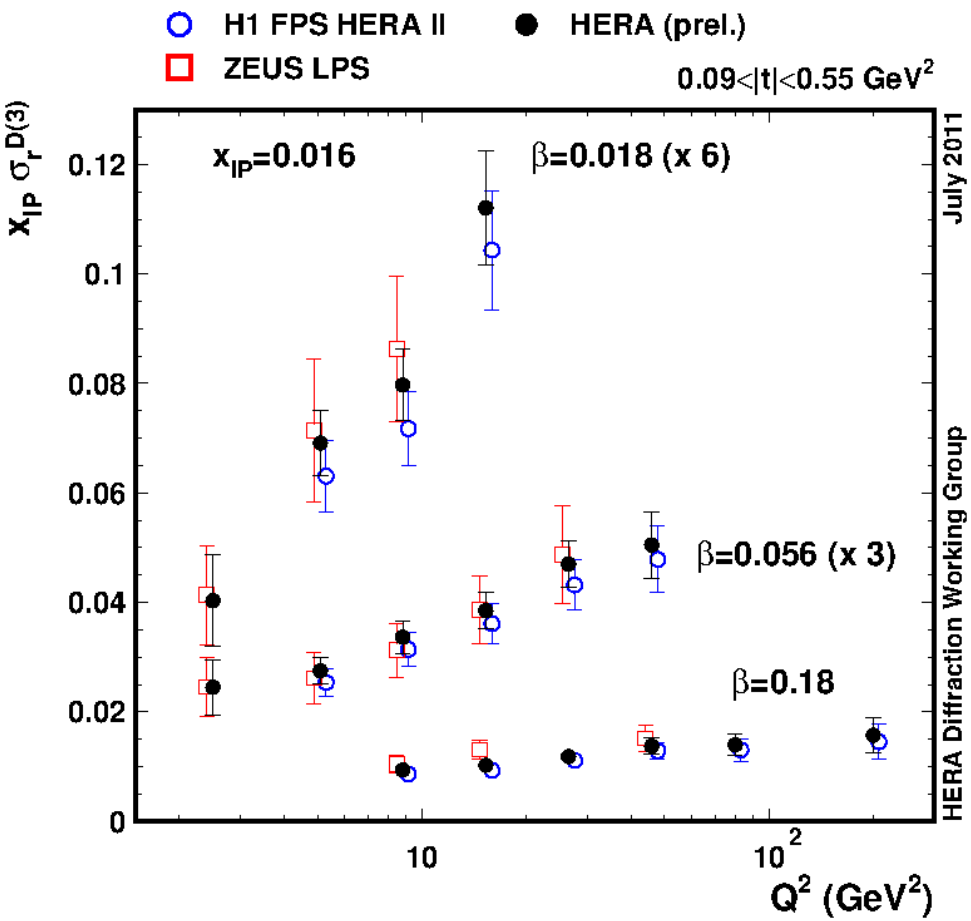
extend phase space,

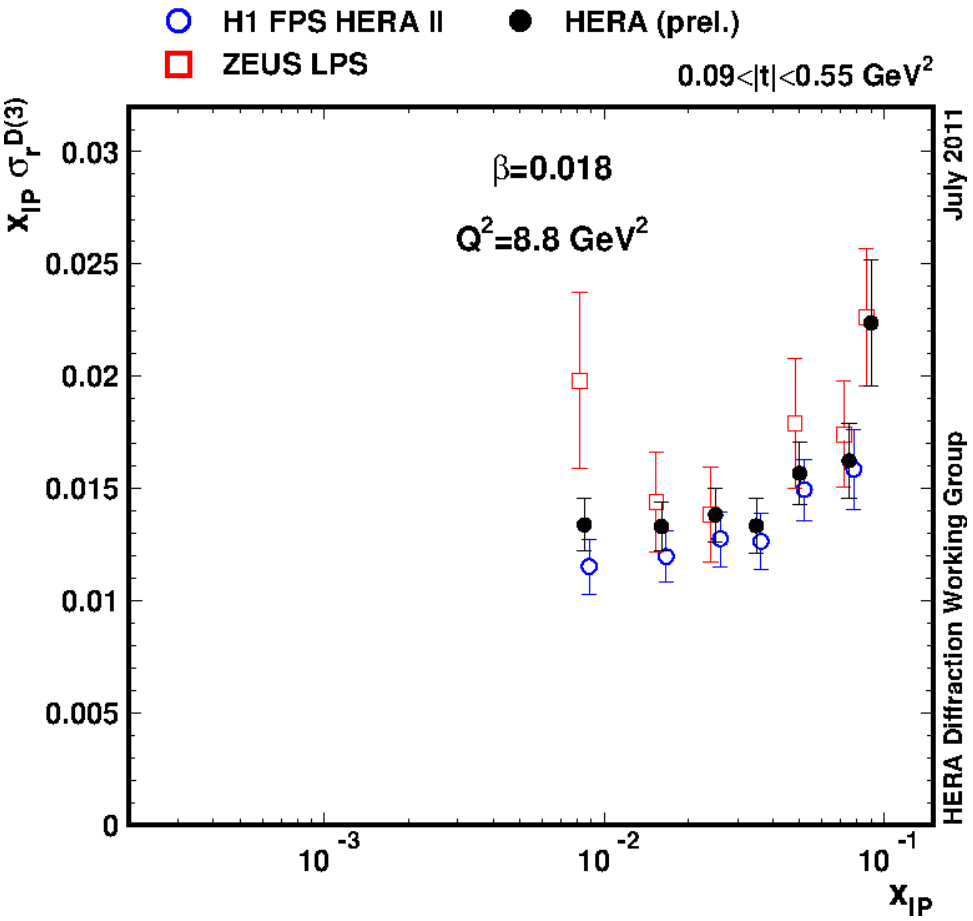
reduce uncertainties

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

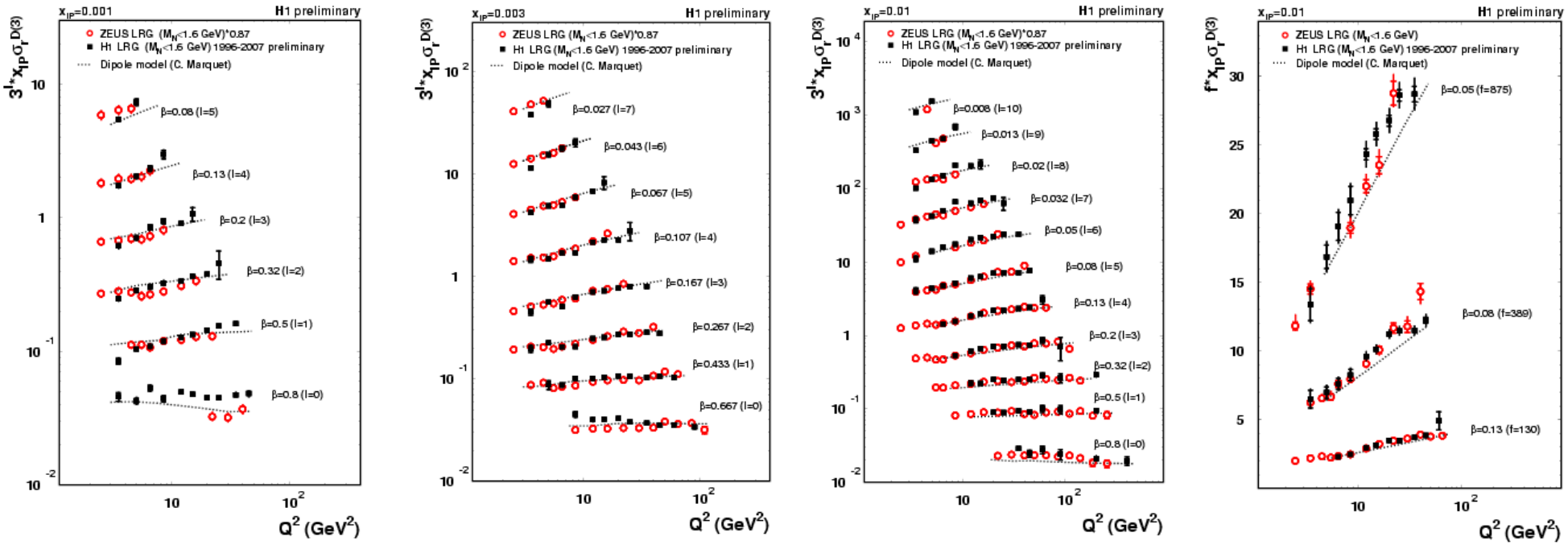




Combined data have ~20% smaller uncertainties than H1 or ZEUS data

Inclusive diffraction in e-p interactions (9)

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



H1 prel-10-011

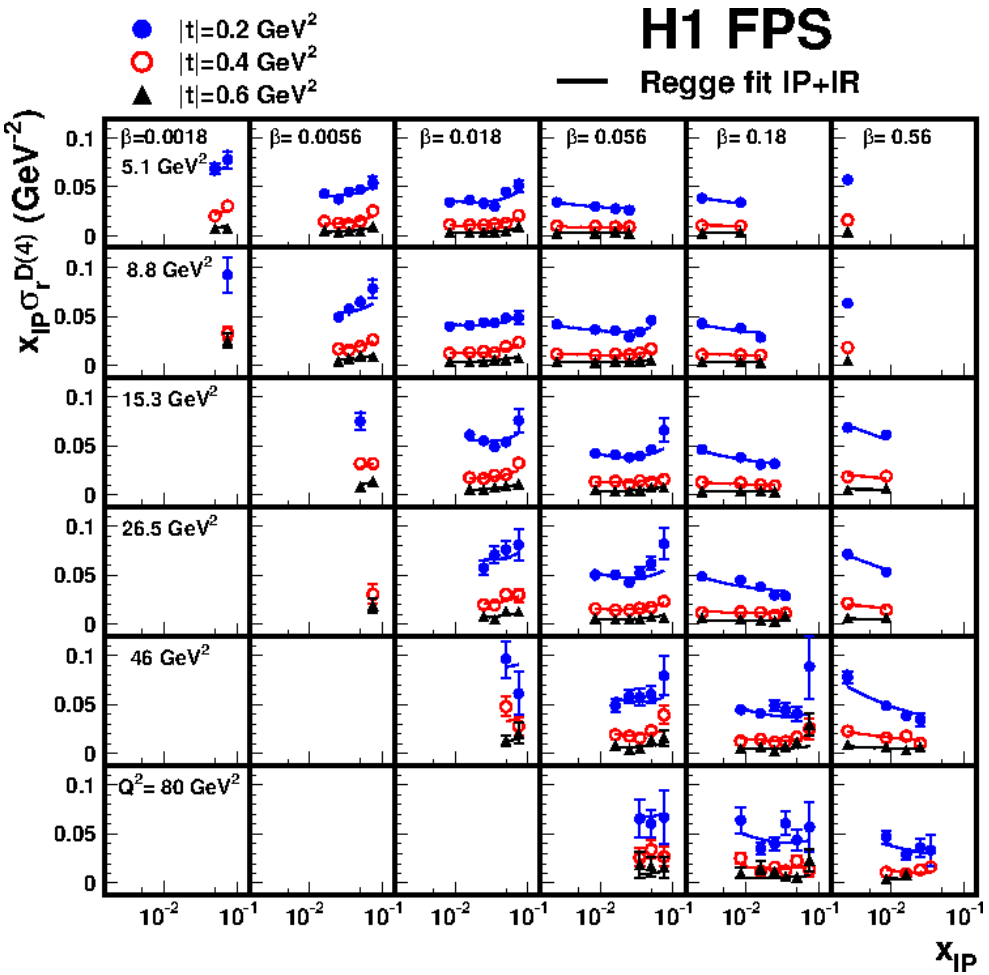
Compared H1 LRG (HERA-1, HERA-2) and ZEUS LRG (HERA-1) data

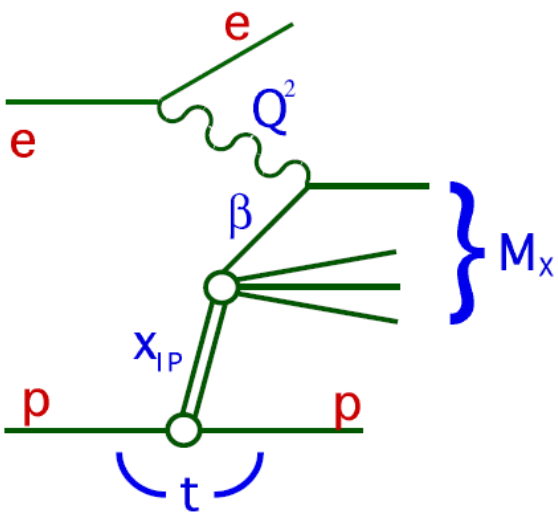
→ reasonable agreement

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 (?):

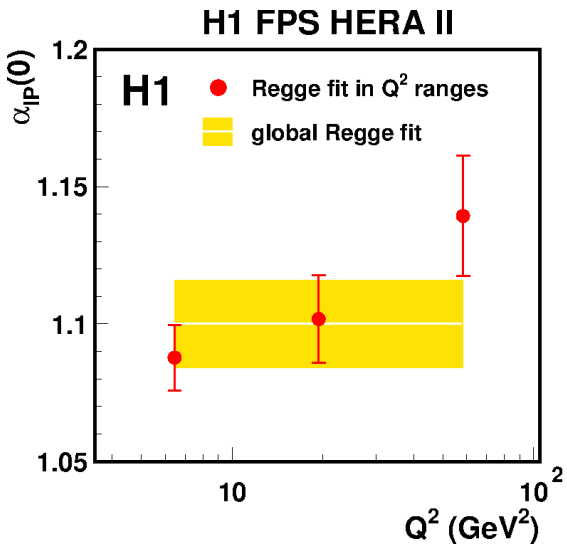
$$F_2^{D(4)}(\beta, Q^2, x_{IP}, t) = f_{IP}(x_{IP}, t)\, F_2^{IP}(\beta, Q^2)$$

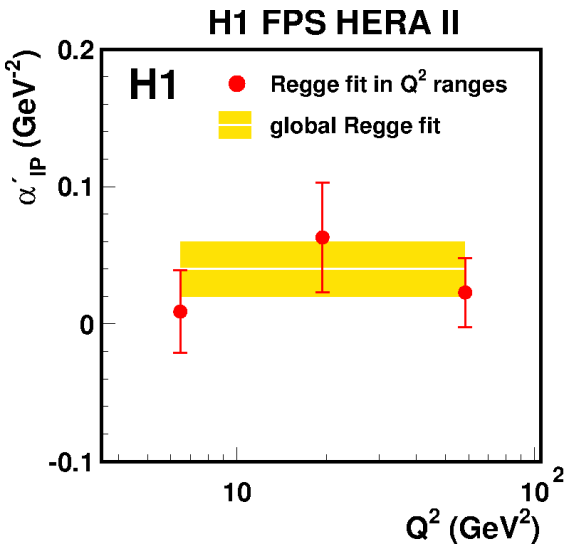
(Sub-leading IR term omitted...)

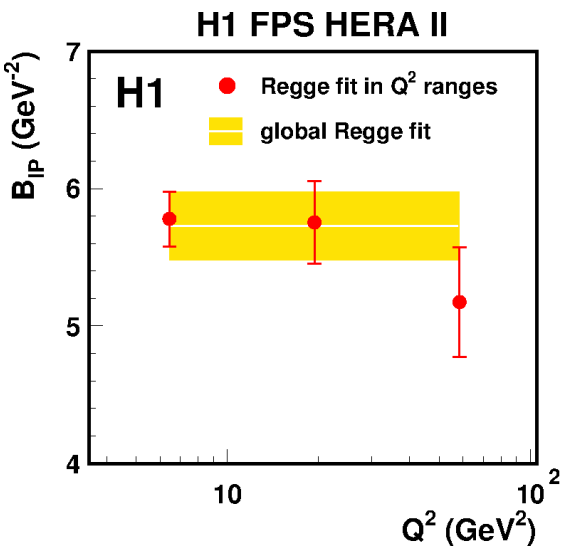
Inclusive diffraction in e-p interactions (10)

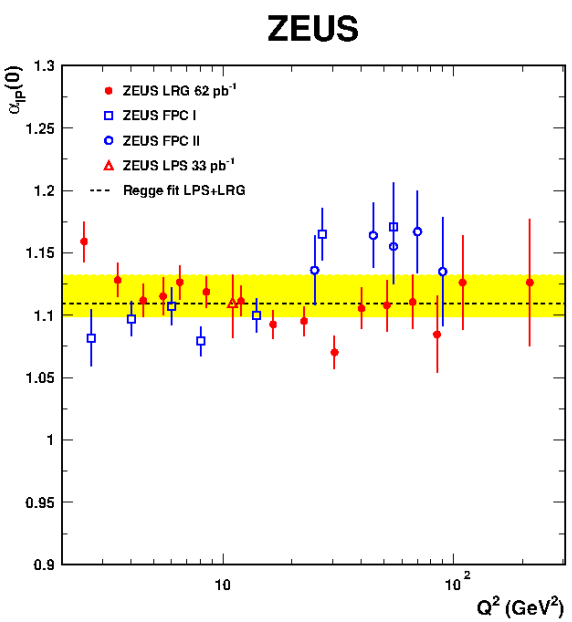
$$x_{IP}\sigma_r^{D(4)}(\beta,Q^2,x_{IP},t)$$

H1, EPJ **C71** (2011) 1578,
ZEUS, NP **B816** (2009) 1









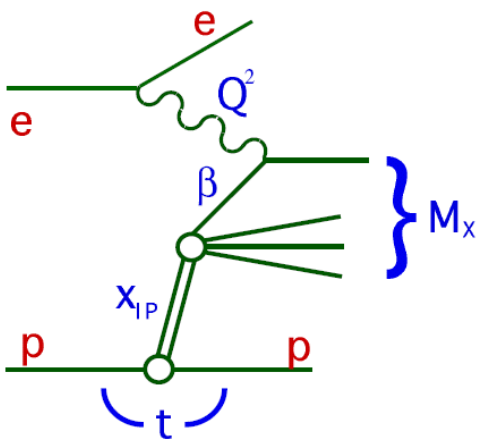
- $\alpha_{IP}(0) \simeq 1.10$ in agreement with α_{IP} (soft)~1.08
- $\alpha'_{IP} \simeq 0 \rightarrow$ no "shrinkage" < α'_{IP} (soft)~0.25 GeV-2 (B_{IP} consistent with hard process)
- no strong dependence of $\alpha_{IP}(0)$, α'_{IP}, B_{IP} on Q^2
- Proton vertex factorization holds within uncertainties

QCD factorisation tests

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

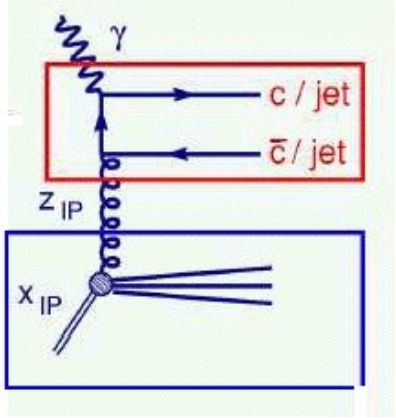
$$\sigma^D = \Sigma\, f_i^{\,D} \otimes \sigma_i^{\gamma^*}$$

$f_i^{\,D}$ – universal diffractive Parton Distribution Function (dPDF)
$\sigma_i^{\gamma^*}$ – universal (γ^* parton) cross-section



Basic strategy:

- **Inclusive diffraction:**
  Measure diffractive structure function F^D_2
  Extract dPDFs (quarks and gluons) from F^D_2 :
  NLO DGLAP fit to F^D_2, (polynomials at Q_0^2),
  proton vertex factorisation, Regge approximation,
- **Semi-inclusive diffractive process:**
  Calculate partonic $\sigma_i^{\gamma^*}$,
  convolute with dPDFs → cross-section

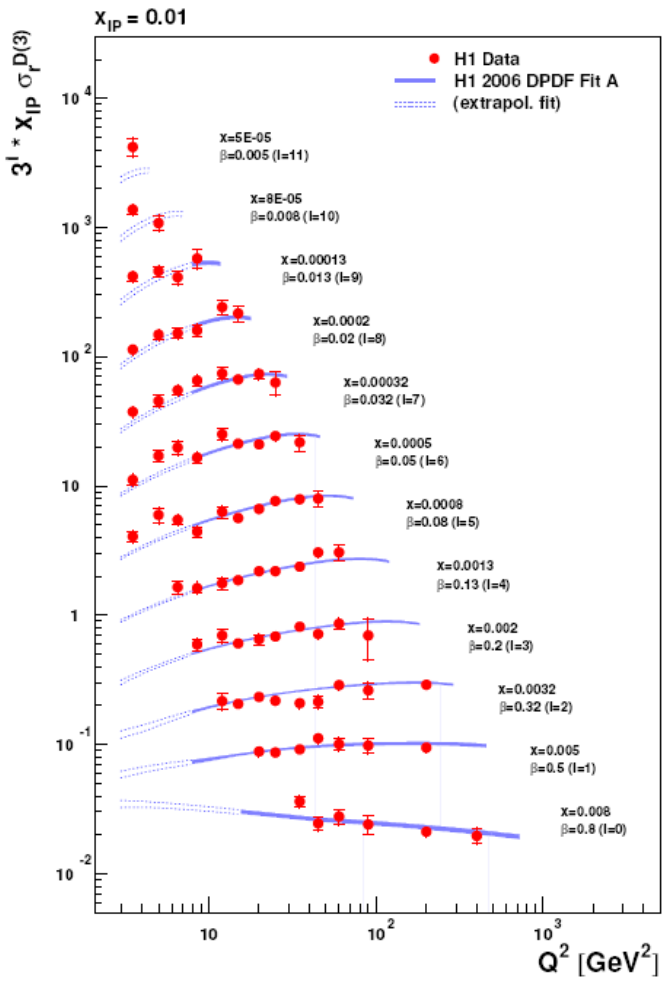


⇉ compare the calculations with experiment...

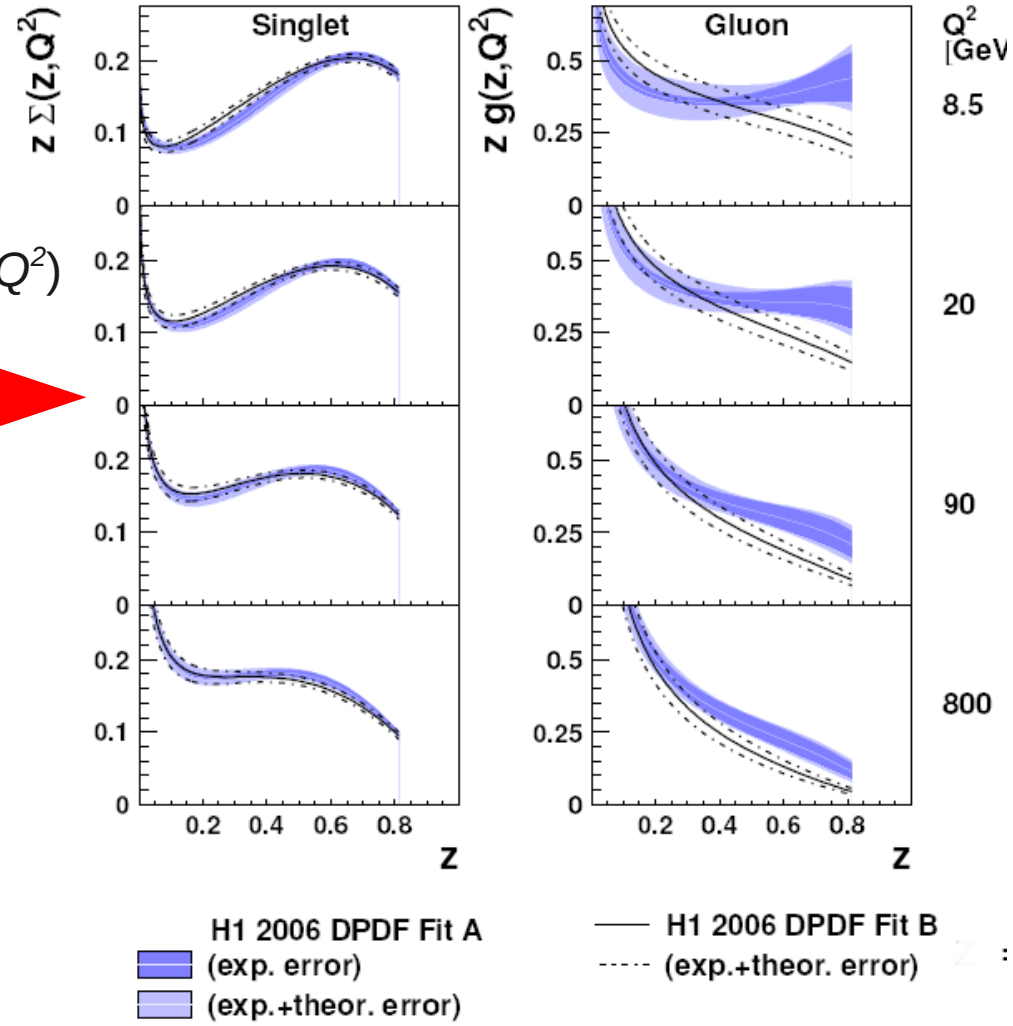
Diffractive PDFs (1)

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

EPJ **C48** (2006) 715



$F^{IP}_2(z,Q^2)$



- Gluons weakly constrained, esp. at large z

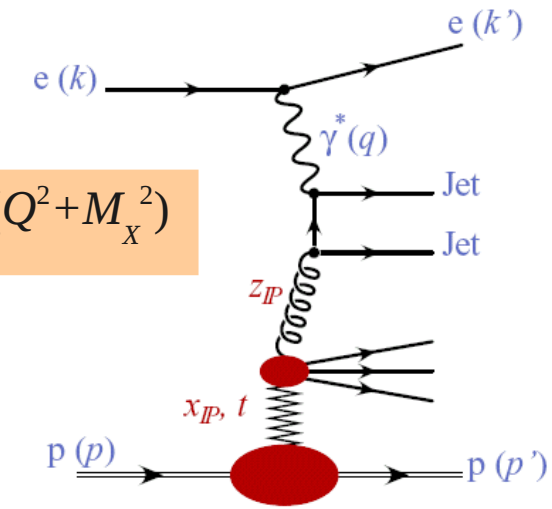
z = fraction of parton momentum in hard scattering/IPomeron (= β)

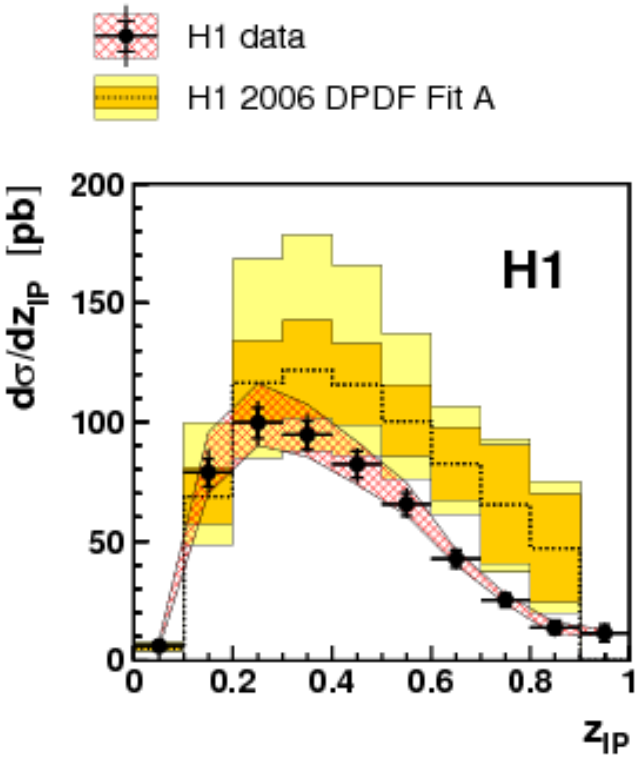
Diffractive PDFs (2)

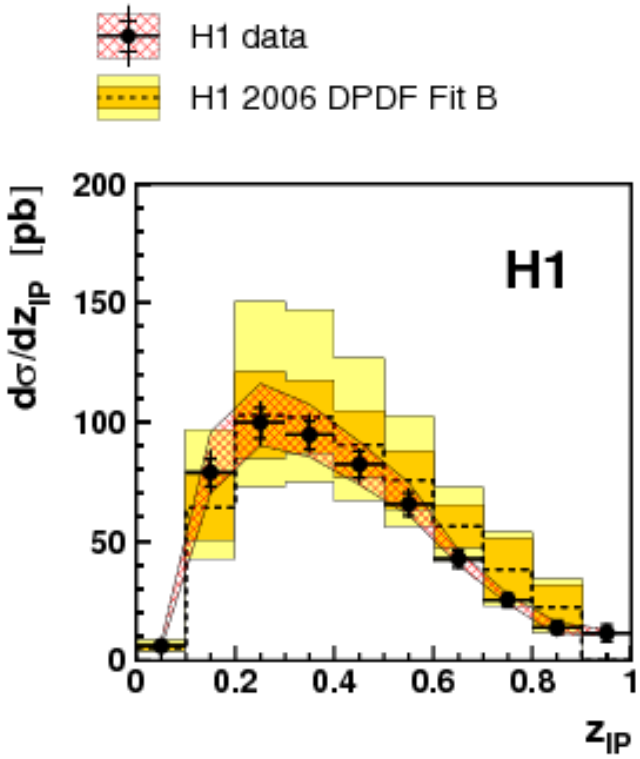
H1, diffractive di-jets in **DIS**: JHEP 0710:042,2007

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

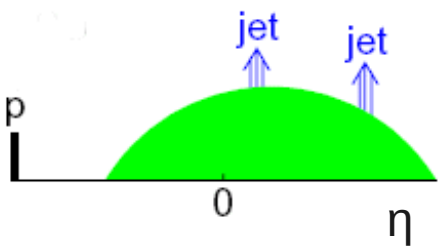
$$z_{IP} = (Q^2+M_{JJ}^{\ 2})/(Q^2+M_X^{\ 2})$$







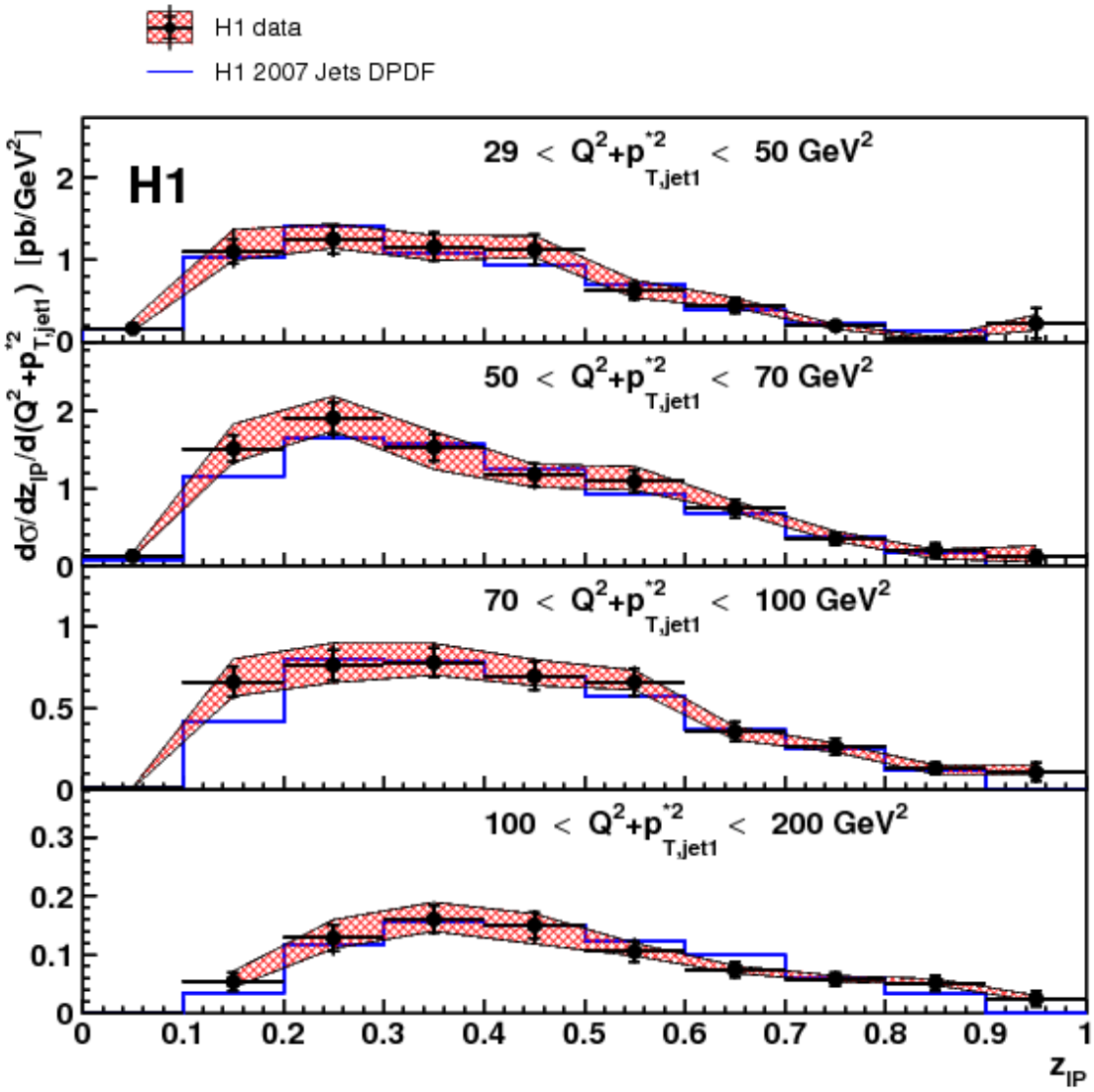
(= z)



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

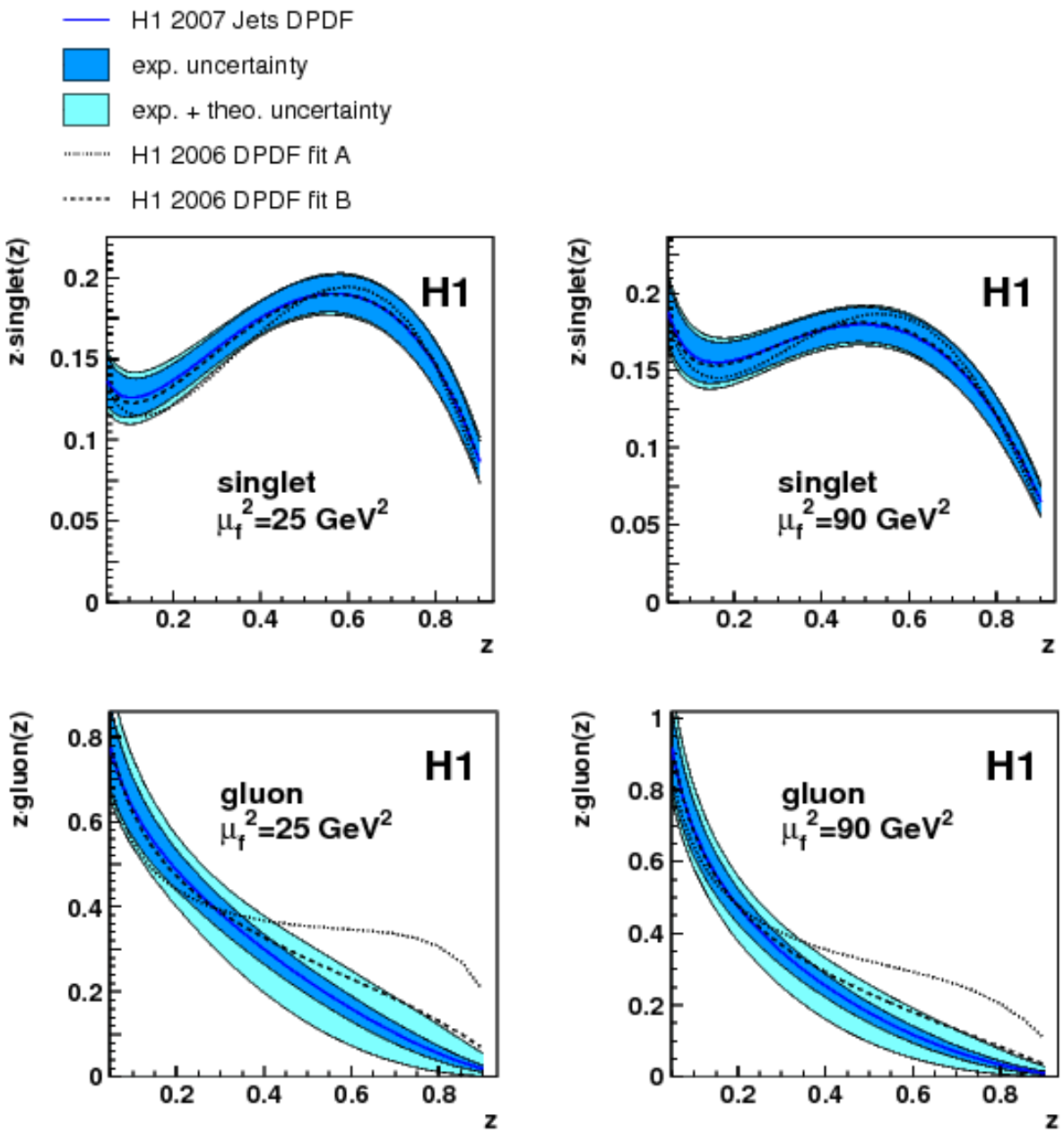
Diffractive PDFs (3)

H1: diffractive di-jets in **DIS**



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

Diffractive PDFs (4)



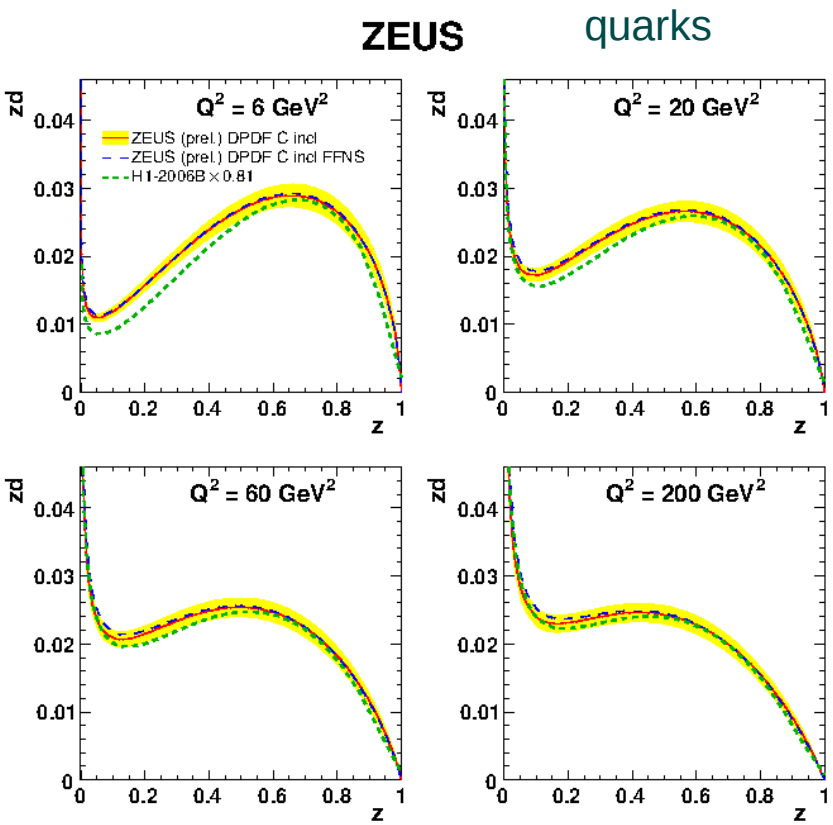
H1 2007 Jets dPDFs

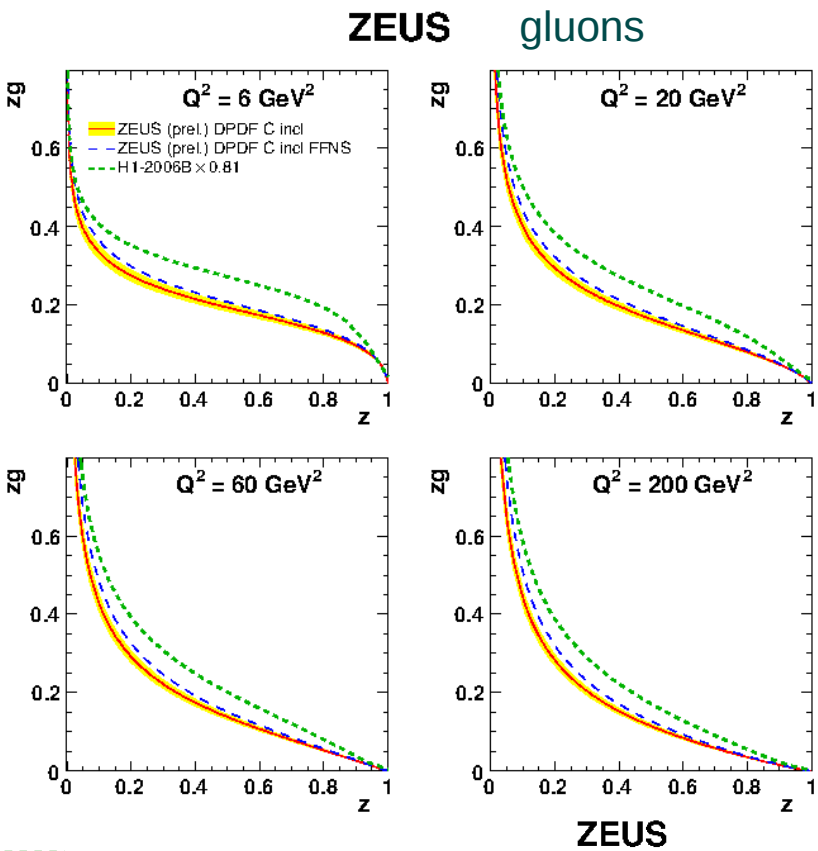
- H1 2007 Jets DPDF <u>close</u> to H1 2006 DPDF fit B
- Common diffractive DIS and diffractive dijets PDFs →
  → factorisation holds

Diffractive PDFs (5)

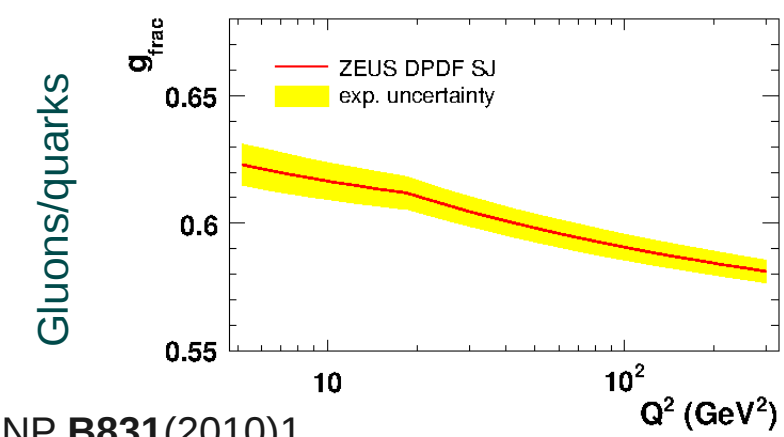
ZEUS DPDF fits (ZEUS-prel-09-004):

LRG & **LPS** & **diffractive Dijet** DIS





H1 2006B

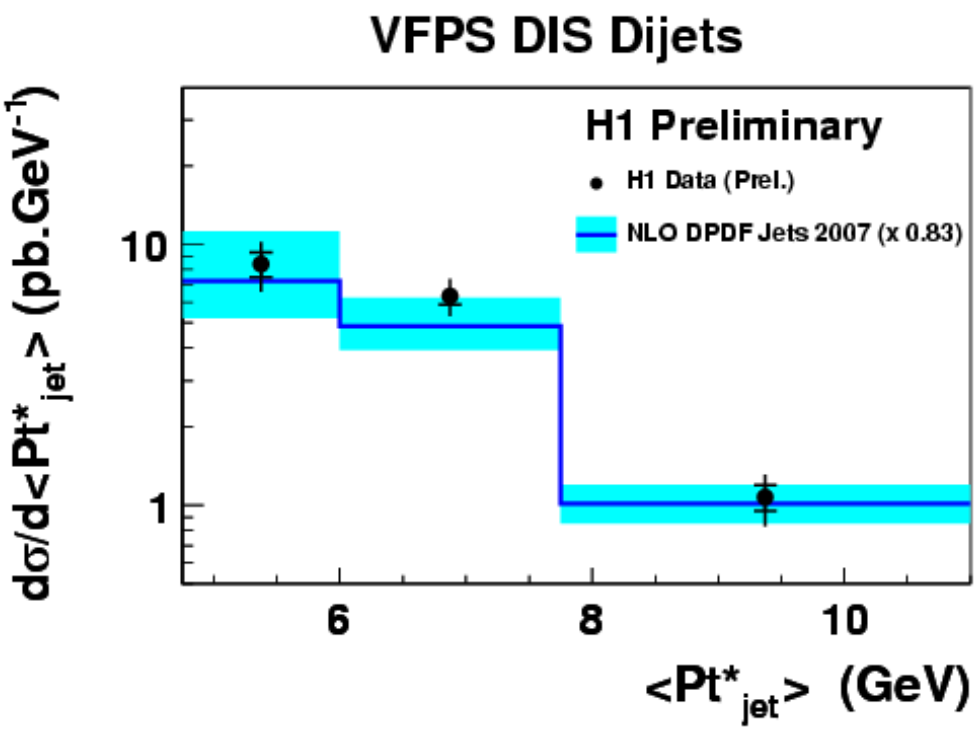


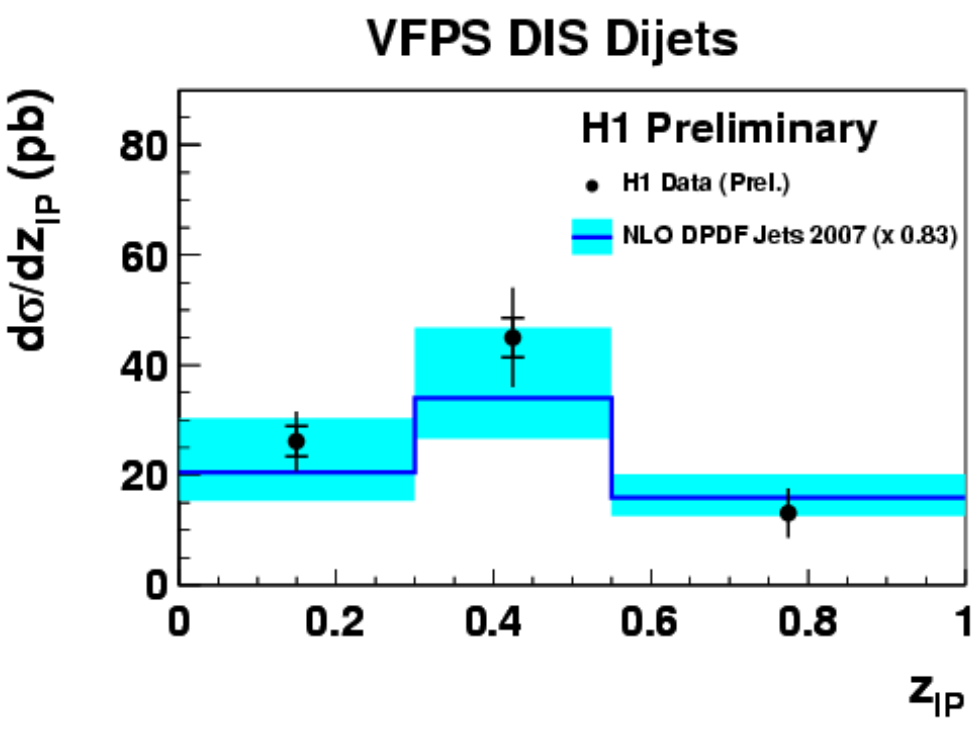
ZEUS,NP **B831**(2010)1

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

QCD factorization test: dijets in D-DIS

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

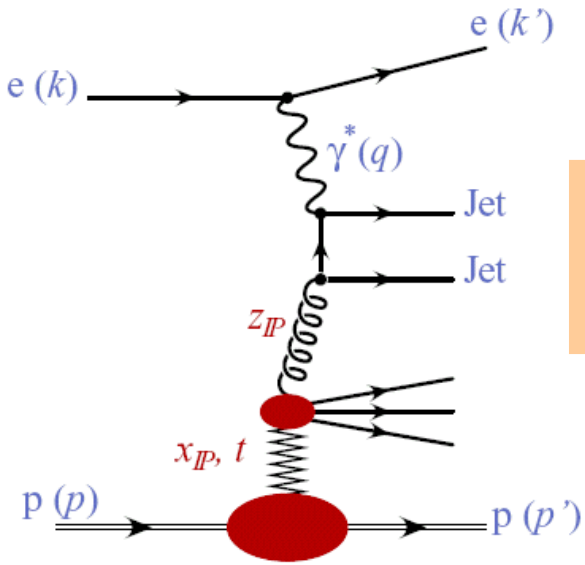




NLO predictions using **H1** Jets 2007 DPDFs describe dijet production in DIS with tagged proton → QCD factorisation holds...

Diffractive dijets in photoproduction (1)

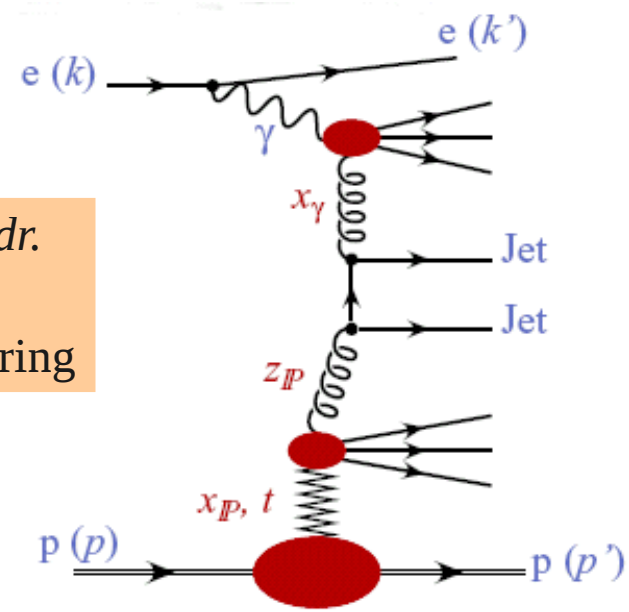
direct photon (like DIS)



$x_\gamma \approx 1$

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

resolved photon



$x_\gamma < 1$

Resolved photon may behave as a hadron → factorization may be broken

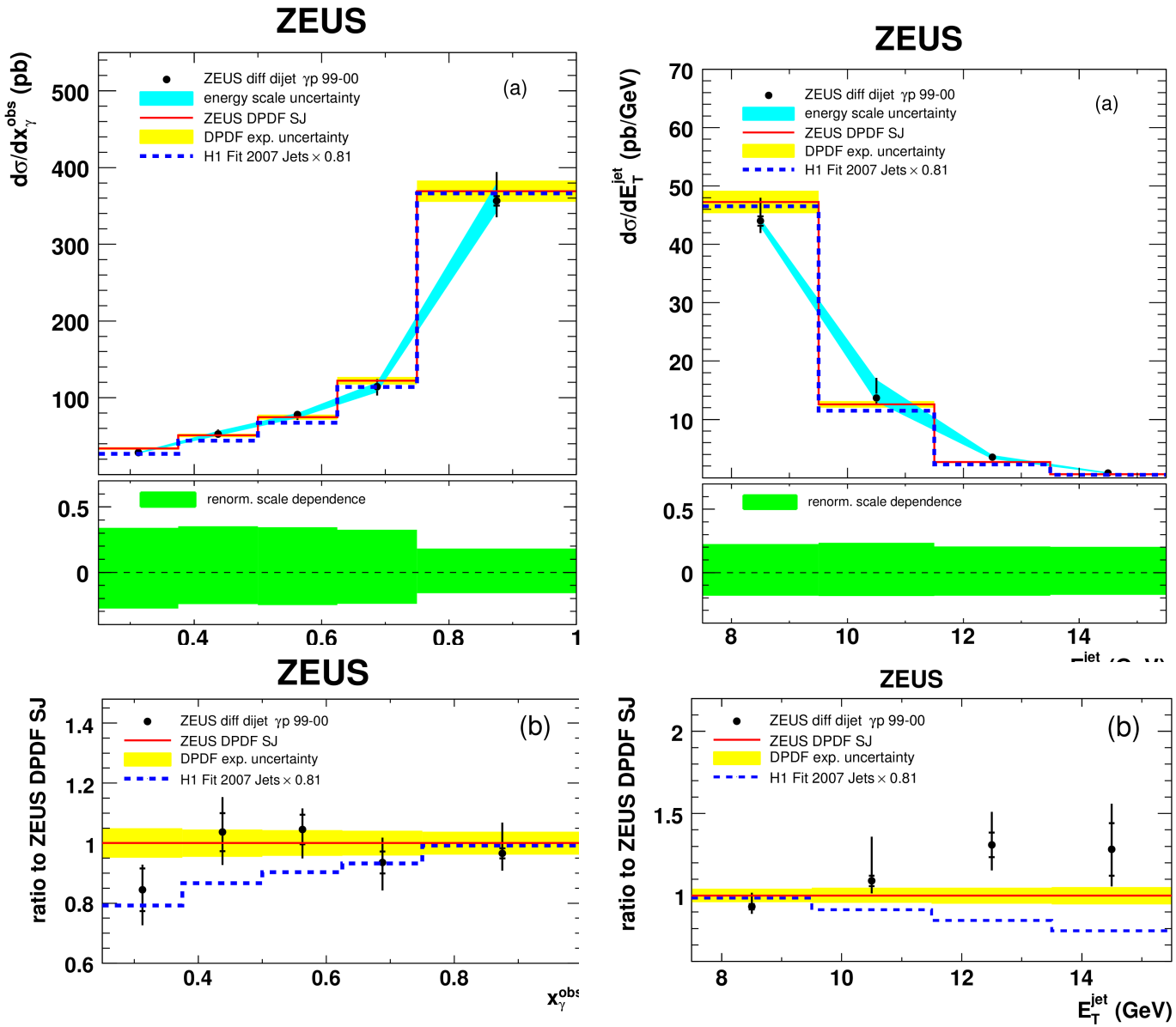
(as in p-p, secondary re-scattering, multi-pomeron exchanges)

→ "gap survival probability..."

Diffractive dijets in photoproduction (2)

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

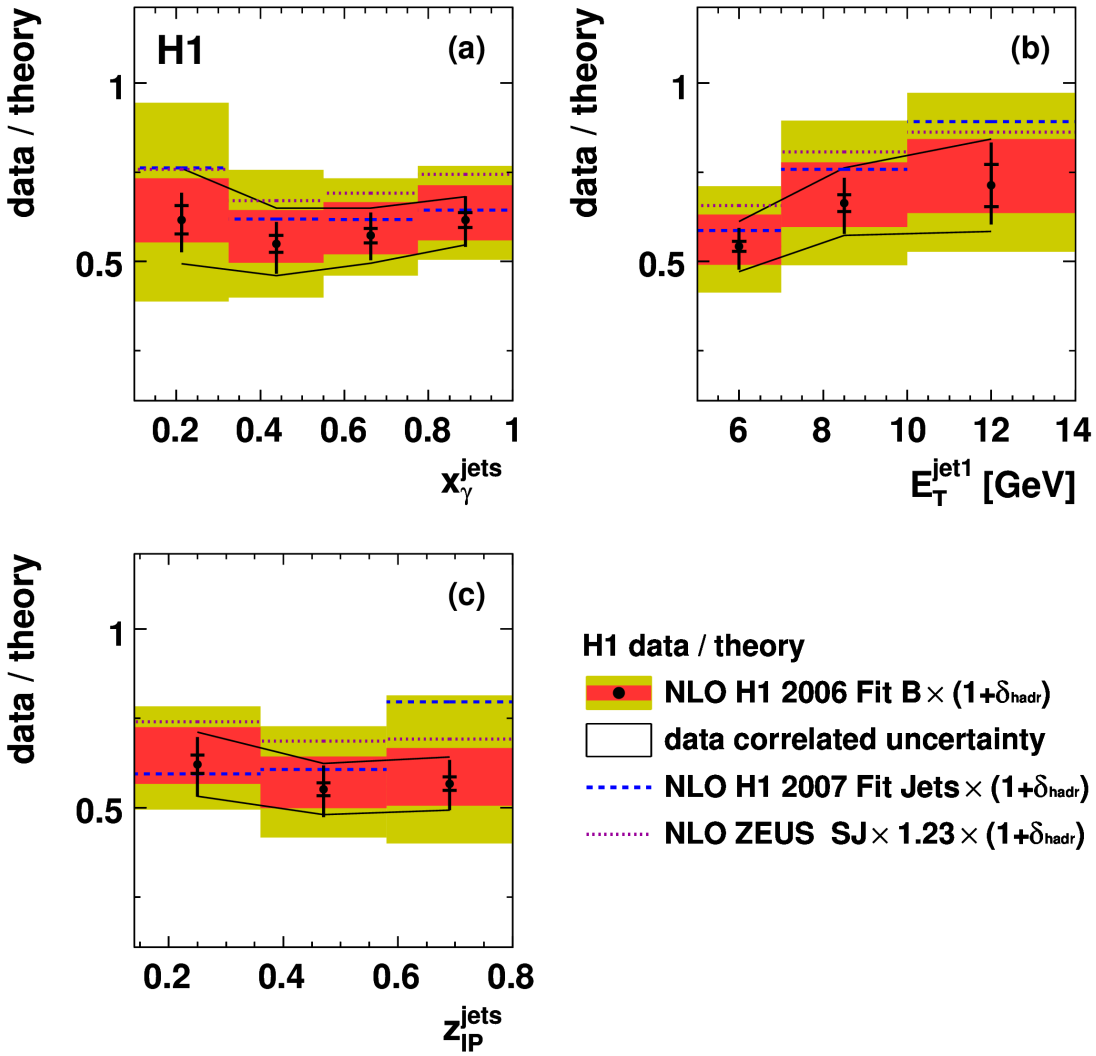
E_T jet > 7.5 GeV



- No supression ⇒ QCD factorization holds?...
- Inconsistency with H1 DPDF...

Diffractive dijets in photoproduction (3)

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



E_T jet > 5 GeV

"~ Gap survival probability"

H1-data/NLO = 0.58±012(exp.)

±0.14(scale)±0.09(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 comparisson inconclusive
- Theoretical uncertainties of QCD calculations are larger than experimental errors...
- Diffractive analyses at HERA are still ongoing...