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Inclusive Diffraction at HERA

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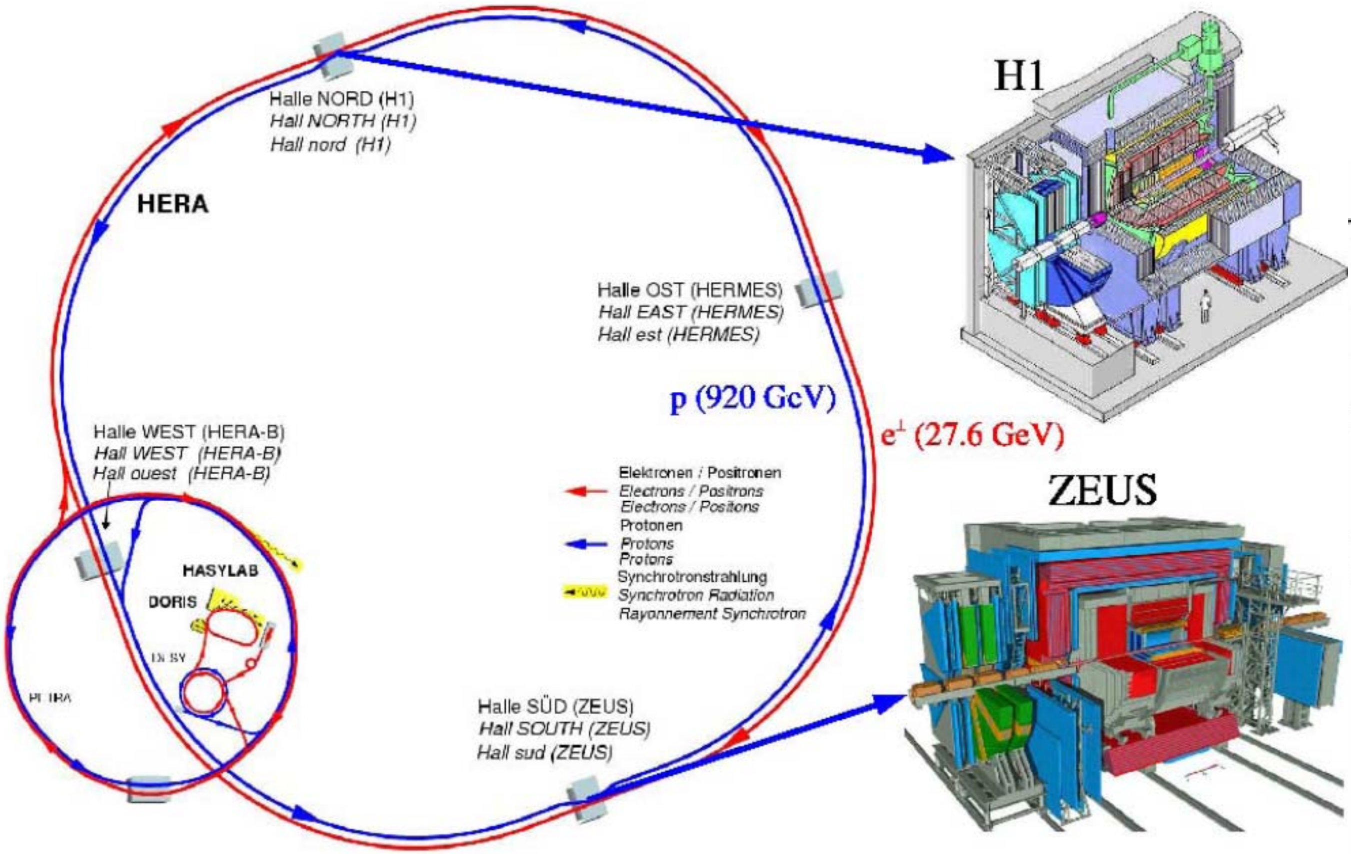
for the H1 and ZEUS Collaborations

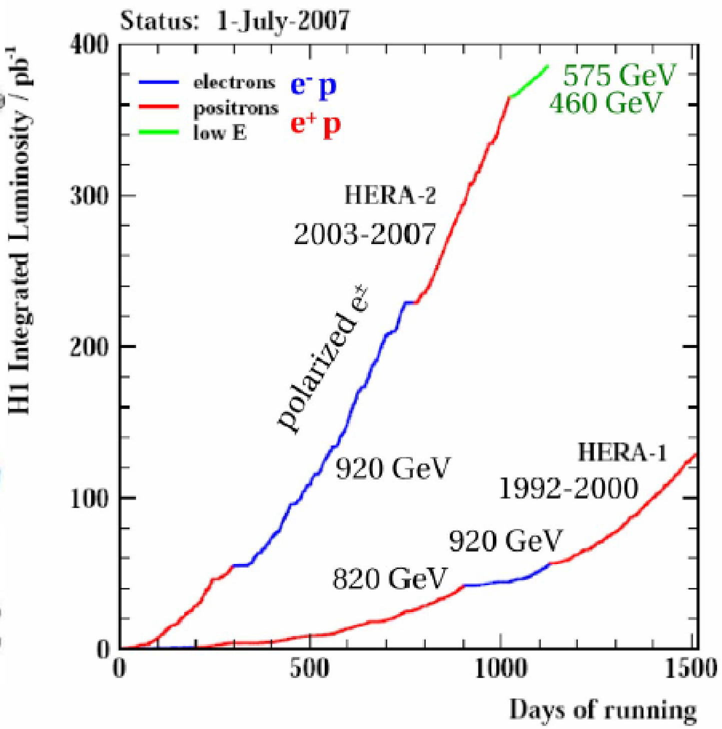
- **Introduction**
- **Diffractive structure functions: comparison of different data**
- **QCD fits and diffractive PDFs**
- **Comparison with diffractive charm production**
- **Diffractive F_L**
- **Factorisation test in diffractive dijet production**
- **Conclusions**

The world's only electron/positron-proton collider at DESY, Hamburg

E_e = 27.6 GeV E_p = 920 GeV (also 820, 460 and 575 GeV)

(total centre-of-mass energy of collision up to $\sqrt{s} \approx 320$ GeV)





Two colliding experiments: H1 and ZEUS

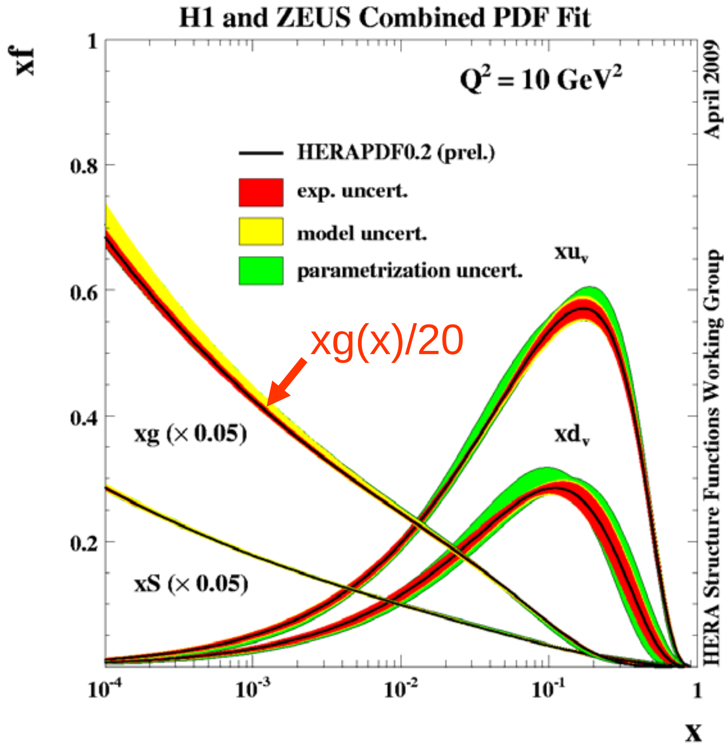
HERA-1: 1992 – 2000

HERA-2: 2003 - 2007

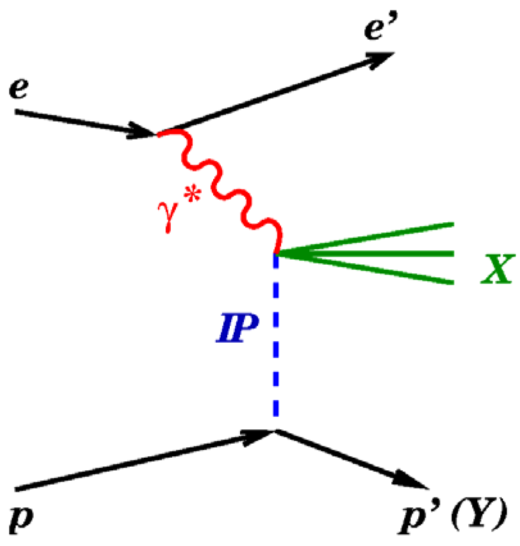
total lumi: 0.5 fb^{-1} per experiment

Low x Physics and Diffraction

Low x physics, as revealed by HERA, is the physics of very large gluon densities

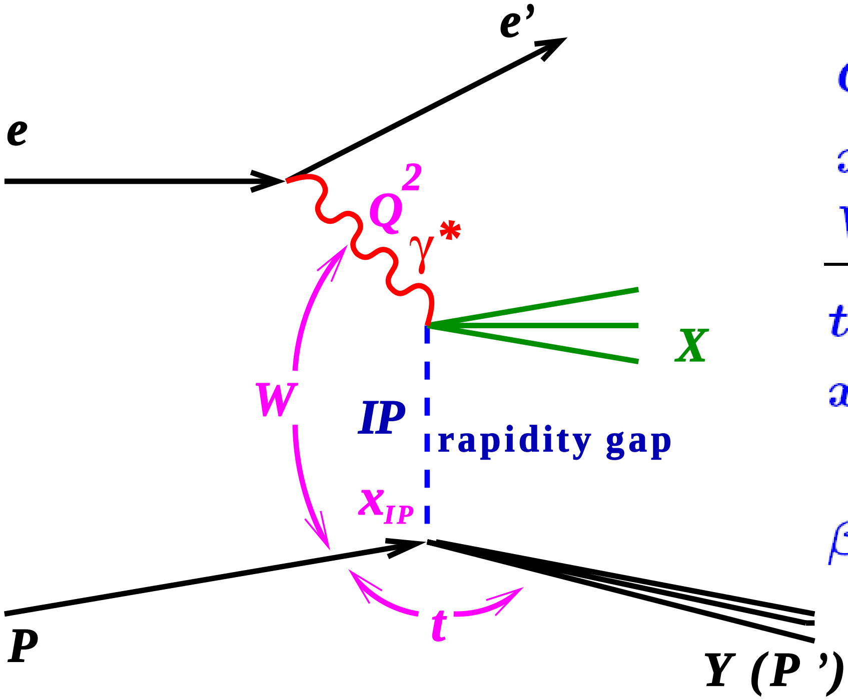


- Associated with a large (> 10%) diffractive content



In $\gamma^*p \rightarrow XY$, virtual photon resolves structure of exchange.
-enormous progress in understanding diffraction in terms of partons
-testing new QCD factorisation ideas
-essential for the predictions of diffractive cross sections at LHC
-related to non-linear evolution (low x saturation), underlying event (gap survival), confinement

Definition of kinematic variables



$$Q^2 = -q^2$$ photon virtuality

$$x = \frac{Q^2}{2q\cdot p}$$ Bjorken scaling variable

$$W^2 = (p+q)^2$$ $\gamma^* p$ CM energy squared

$$t = (p - p_Y)^2$$ 4-momentum transfer squared

$$x_{I\!P} = \frac{q\cdot(p-Y)}{q\cdot p}$$ fraction of p momentum transferred to $I\!P$ ($x_{I\!P} \simeq 1 - E_Y/E_p$)

$$\beta = \frac{Q^2}{2q\cdot(p-Y)}$$ fraction of $I\!P$ momentum carried by struck quark ($x_{I\!P}\beta = x$)

M_X Inv. mass of system X

- t-channel exchange of vacuum quantum numbers
- proton survives the collision intact or dissociates to low mass state, $M_Y \sim O(m_p)$
- large rapidity gap
- small t (four-momentum transfer) and x_{IP} (fraction of proton momentum); $M_X \ll W$

~10% of low-x DIS events at HERA are diffractive

distinguish two classes of events depending on photon virtuality:

$Q^2 \sim 0$ → **photoproduction**

$Q^2 \gg 0$ → **deep inelastic scattering (DIS)**

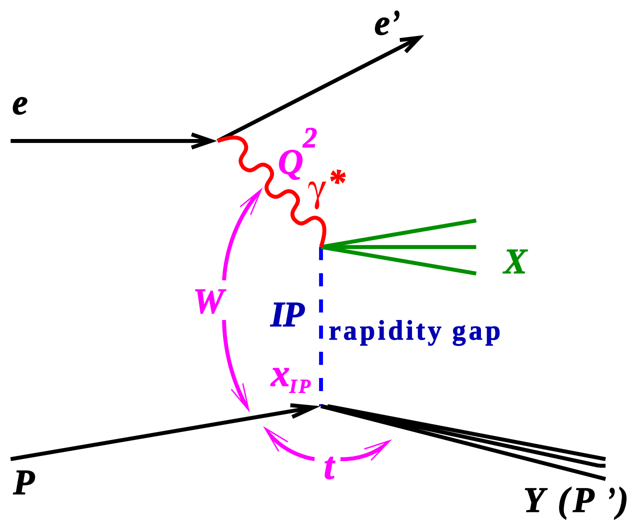
Diffraction at HERA

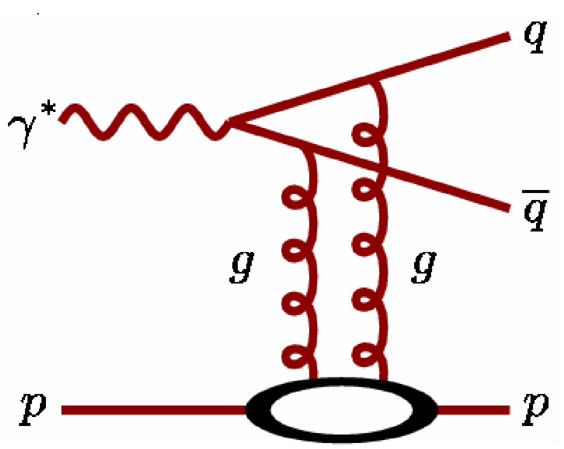
If no hard scale – Q^2, $|t|\approx 0$: similar to soft hadron-hadron interactions
- Regge theory: diffraction is *exchange of Pomeron*

→ **Weak energy dependence**

If hard scale (large Q^2, $|t|$, p_T^{jet}, m_Q) present: study diffractive phenomena in terms of QCD
- Resolved Pomeron: probe the structure of exchanged object
- Colour dipole: diffraction is *exchange of colour singlet gluon ladder* between ($\gamma^* \rightarrow q\bar{q}$, $q\bar{q}g$) and the proton

→ **Steep energy dependence**

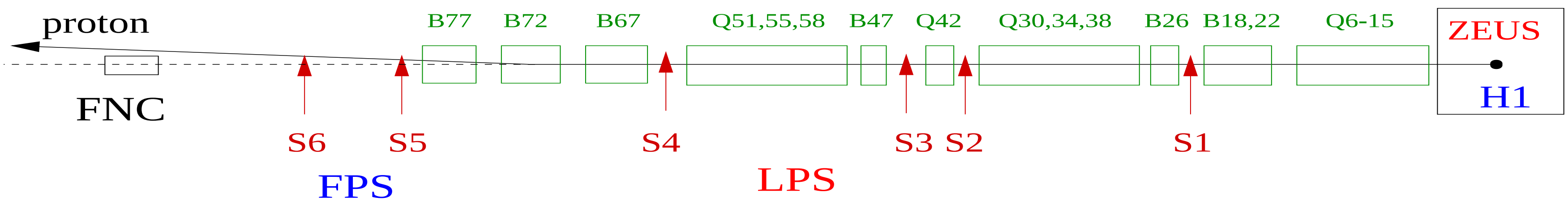




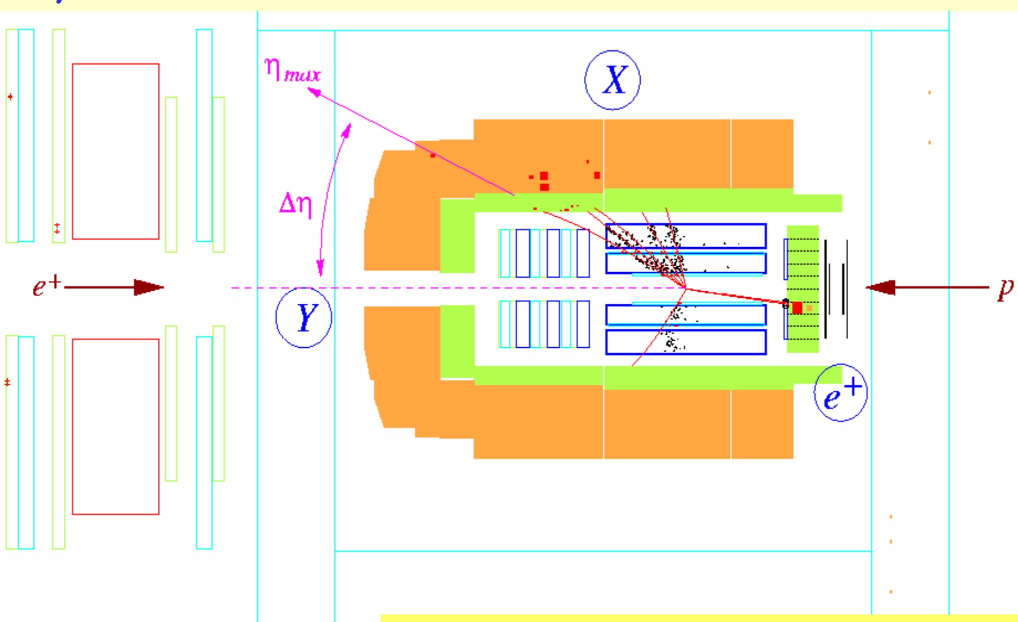
HERA- unique facility to study transition from soft to hard regime and to probe partonic content of diffractive exchange.

Diffractive event selection

➢ **'Leading proton' method (LPS)**– scattered proton detected in 'Roman Pots' (LPS,FPS) free of p-diss.background, t and x_{IP} measurement, but low acceptance/statistics

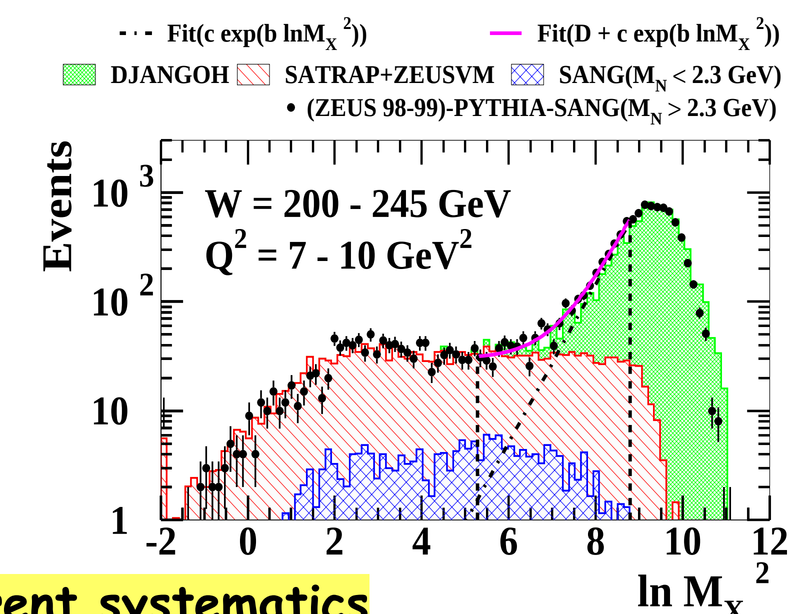


➢ **Large Rapidity Gap' method (LRG)**
t is not measured, some p-diss. background (e.g. for H1 measurements M_Y<1.6 GeV)



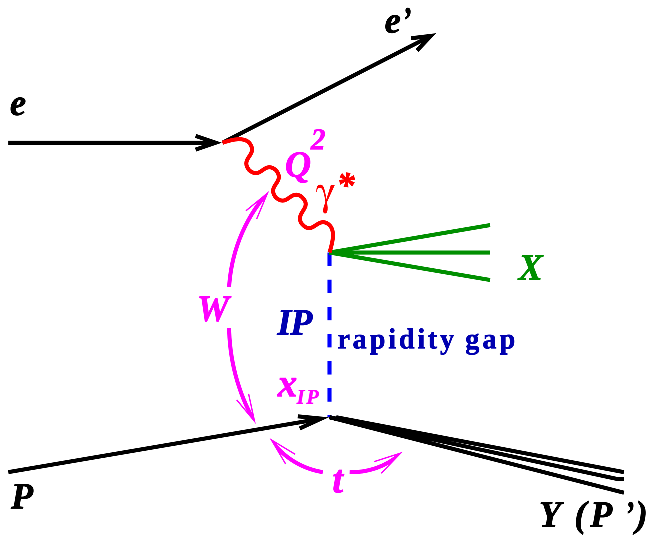
➢ **'M_X' method**- decompose inclusive $\ln(M_X)$ distribution, subtract non-diffractive contribution

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



The methods have very different systematics

Cross-section of inclusive diffractive DIS



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$\beta = \frac{Q^2}{2q \cdot (p-Y)}$	fraction of $I\!P$ momentum carried by struck quark ($x_{I\!P}\beta = x$)

Diffractive DIS cross-section:

$$\frac{d\sigma^D}{d\beta dQ^2 dx_{I\!P} dt} = \frac{2\pi\alpha}{\beta Q^4}(1 - y + y^2/2) \cdot \sigma_R^{D(4)}(\beta, Q^2, x_{I\!P}, t)$$

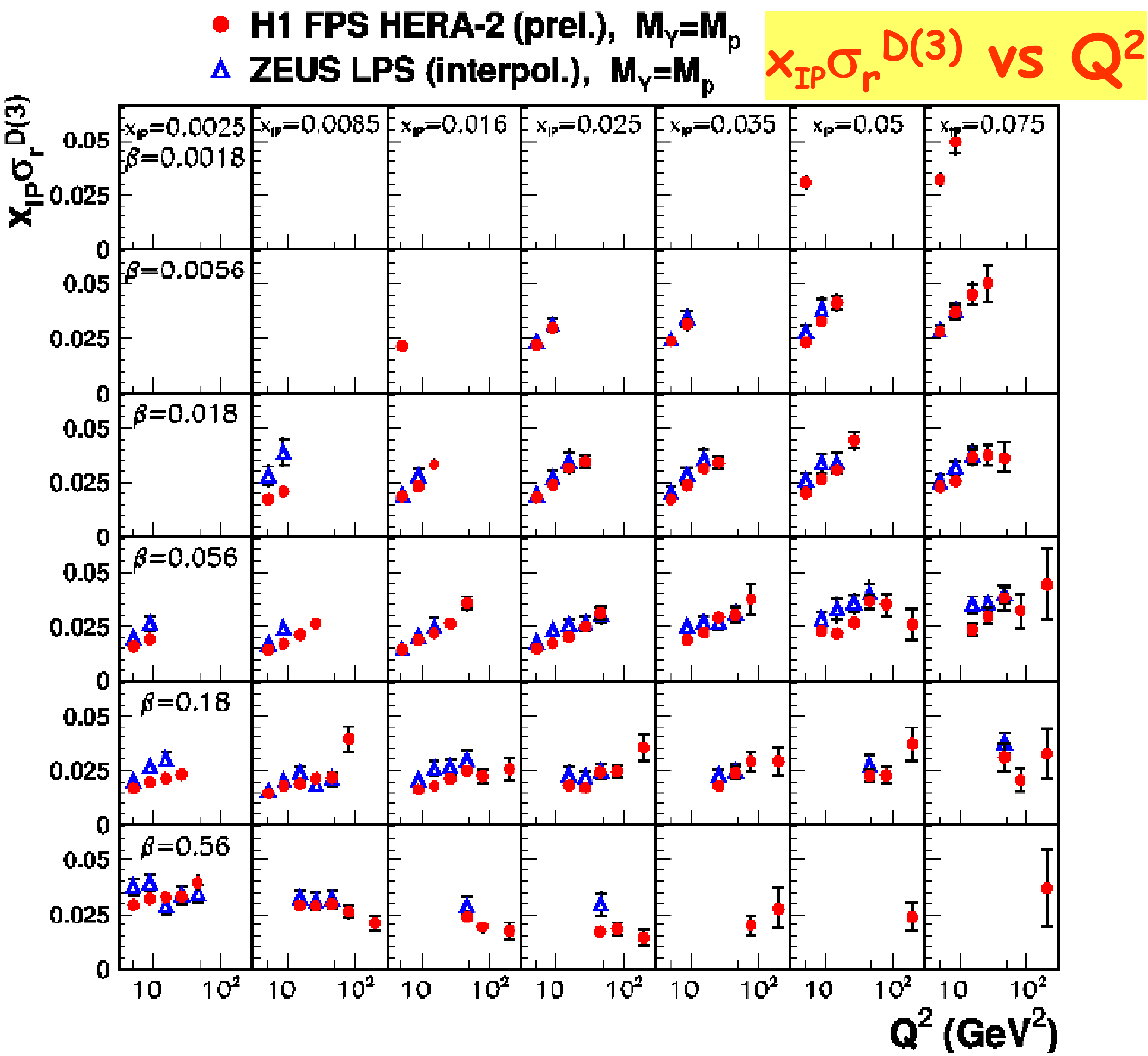
$$\sigma_R^{D(3)}(\beta, Q^2, x_{I\!P}) = \int \sigma_R^{D(4)}(\beta, Q^2, x_{I\!P}, t) \cdot dt$$

Reduced cross-section:

$$\sigma_R^D = F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D \qquad (\sigma_R^D = F_2^D \text{ if } F_L^D = 0)$$

Proton tagged data: ZEUS vs H1

- New H1-FPS HERA-2 data (156 pb^{-1}) improve statistics by factor of 20 and expand phase space to higher Q^2
- Fair agreement between H1-FPS and ZEUS-LPS results (normalisation uncertainties: H1-FPS ~6%, ZEUS-LPS ~10%)



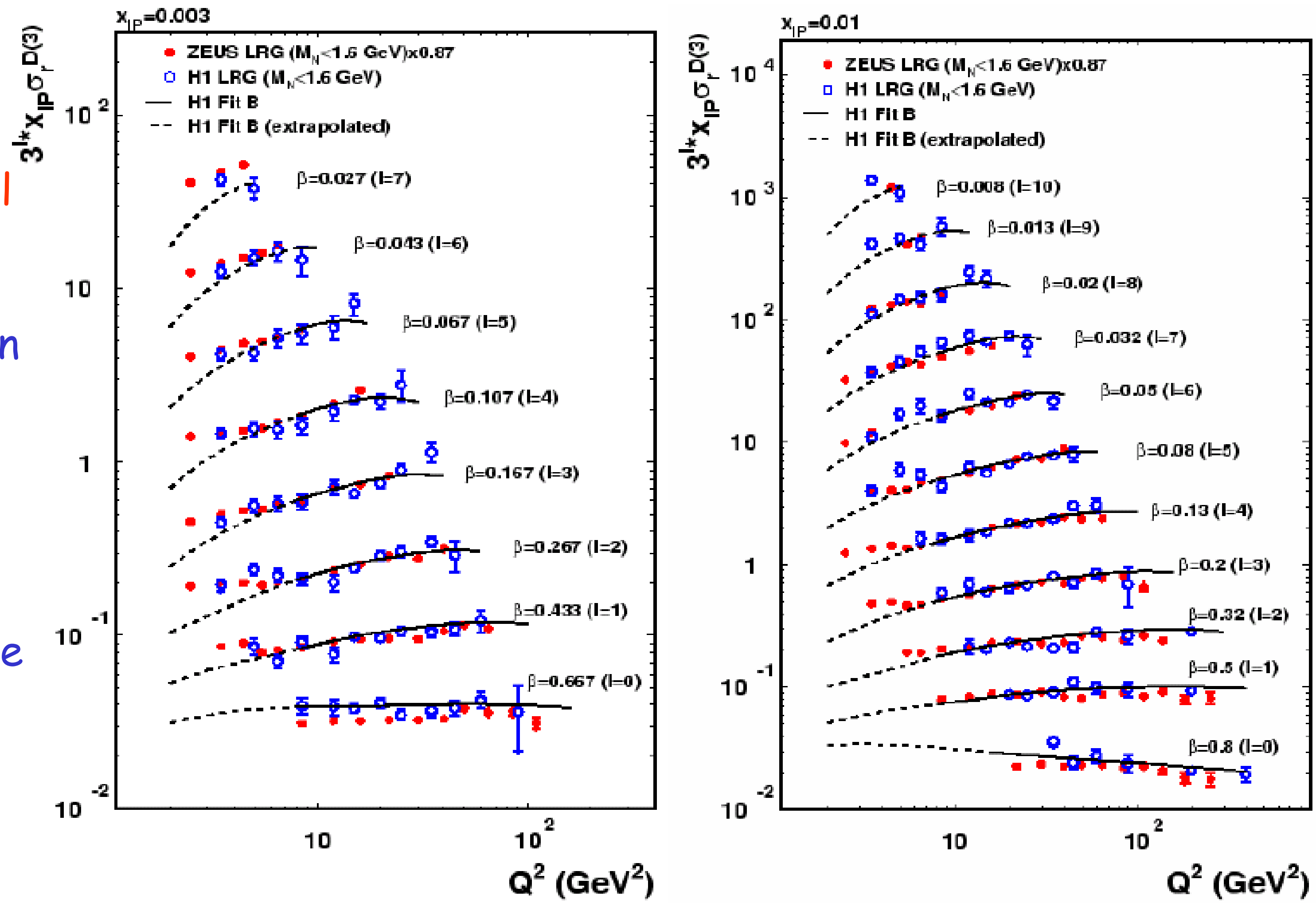
Large Rapidity Gap data : ZEUS vs H1

$\sigma_r^{D(3)}$ at x_{IP}=0.003 and 0.01

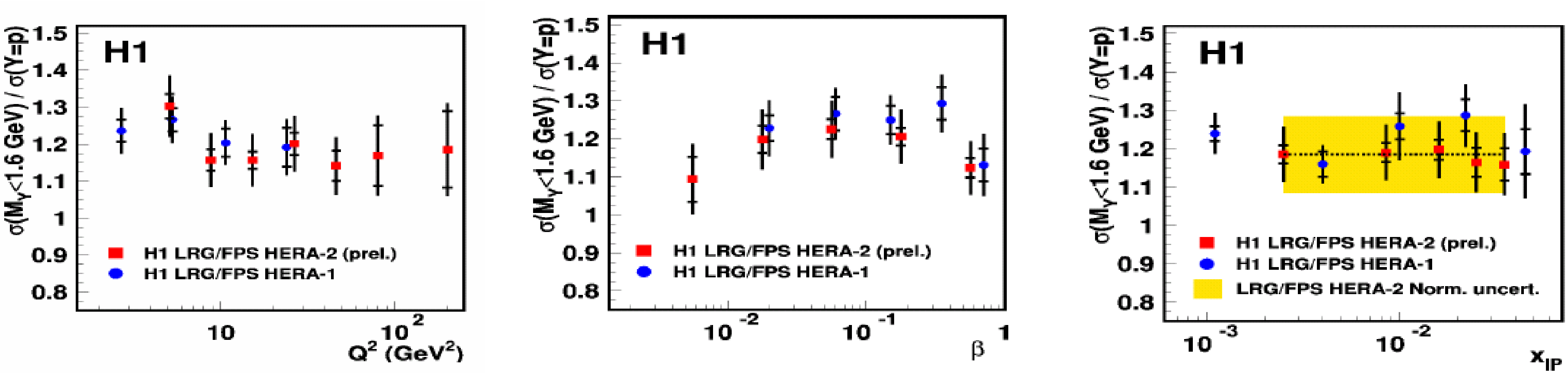
New ZEUS-LRG data ($62 pb^{-1}$) reach new level of statistical precision

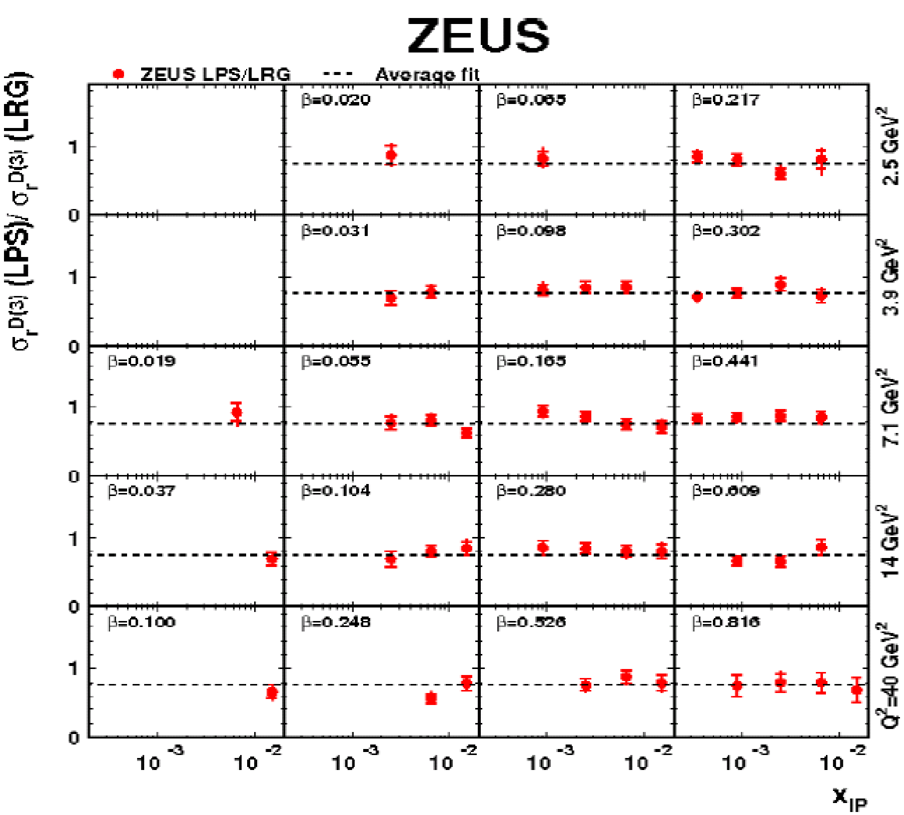
Reasonable agreement in shape in most of phase space

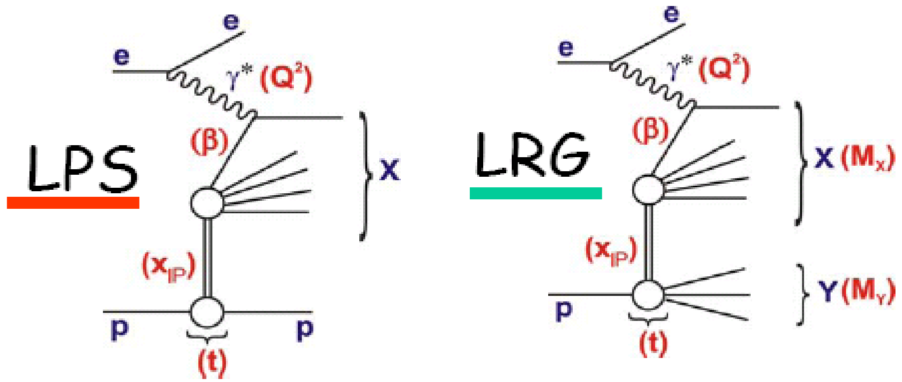
~13% normalisation difference:
both measurements have norm. uncertainties (dominant contribution from p-diss backgrund)



Comparison between methods: proton tagged (LPS,FPS) vs LRG data





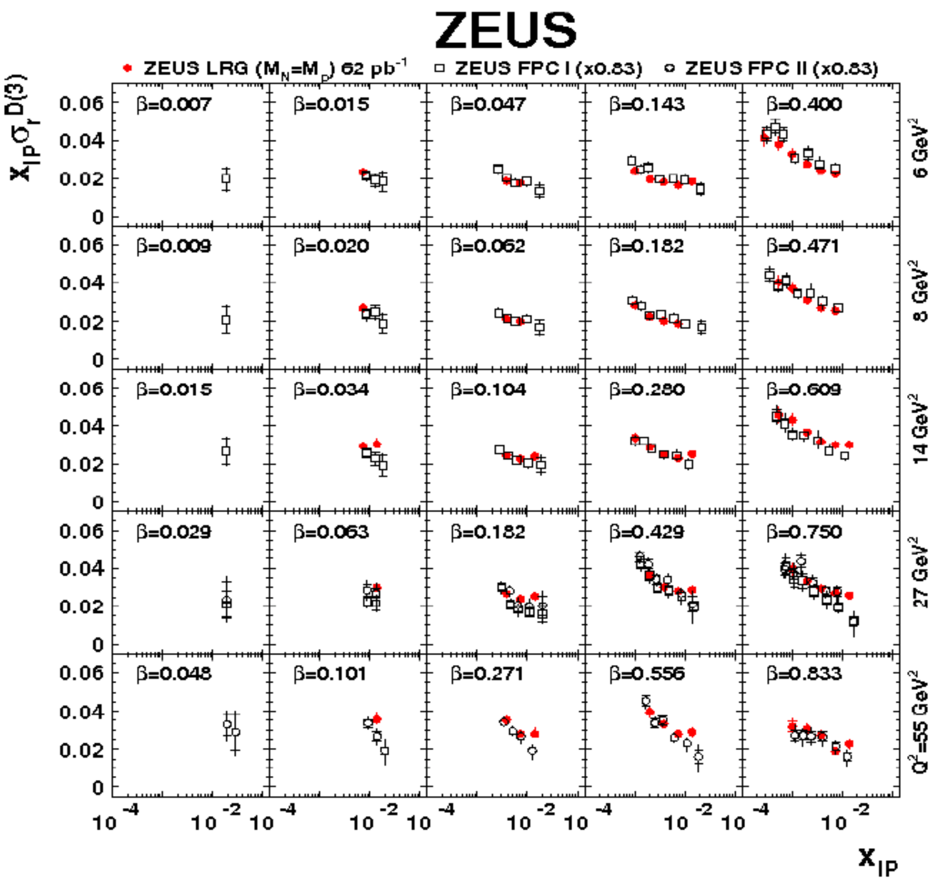


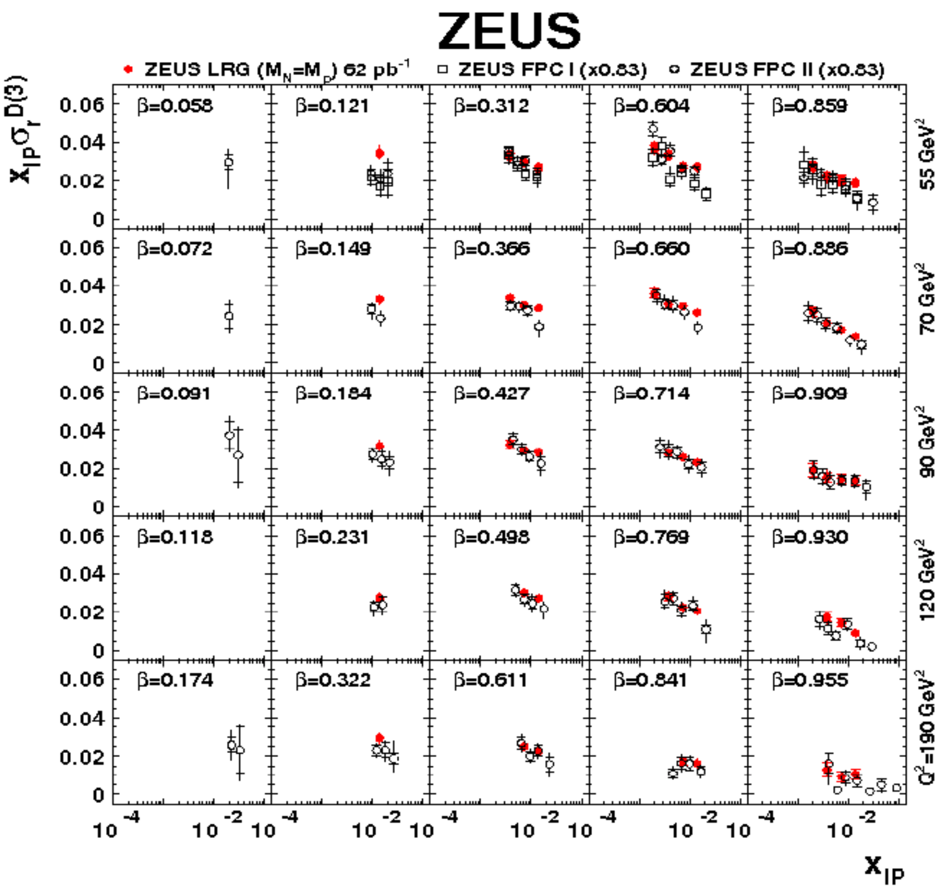
Well controlled, precise measurements

LRG/LPS does not depend on Q^2, β, x_{IP}

LRG data contains sizeable proton dissociative background ~20-30%

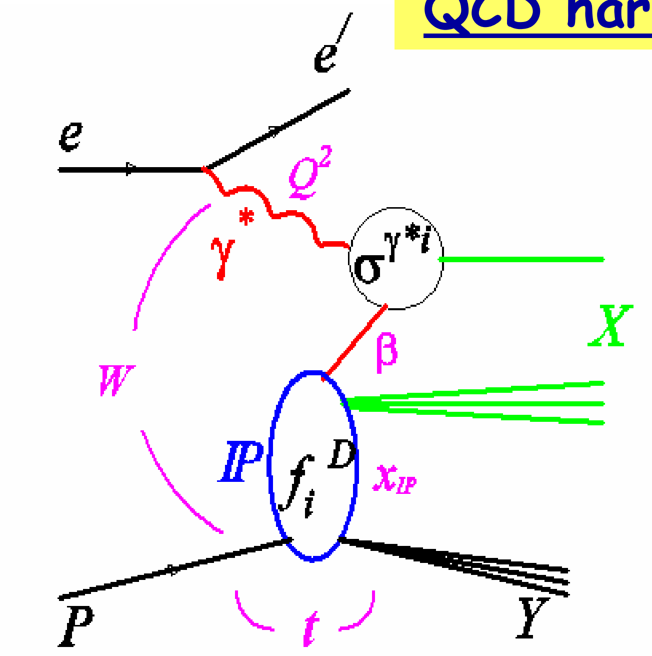
Comparison between methods: LRG vs M_X (ZEUS)





Agreement in shape; ~17% difference in normalisation (p-dissociation)

Factorisation in diffraction



QCD hard scattering collinear factorisation in diffractive DIS

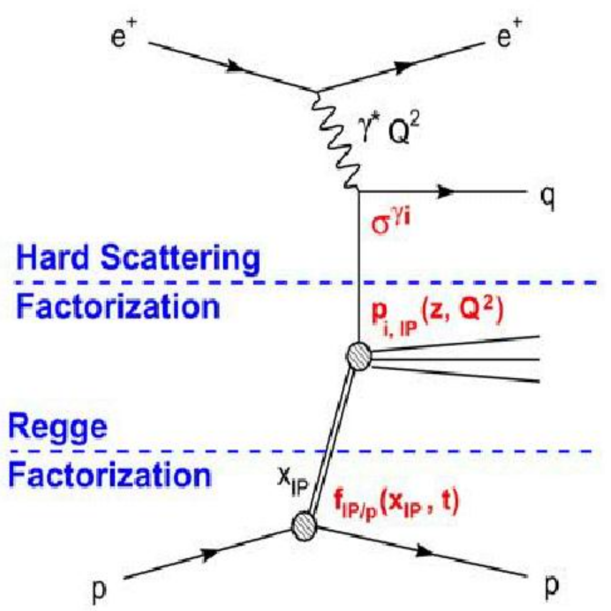
(J.Collins; Phys.Rev.D57 (1998) 3051)

$$\sigma^D(\gamma^* p \to Xp) \propto \sum_i f_i^D(x_{IP}, t, x, Q^2) \otimes \sigma^{\gamma^*,i}(x, Q^2)$$

f_i^D -diffractive parton distribution function – conditional proton parton probability distributions with final state proton at fixed x_{IP},t

$\sigma^{\gamma^*,i}$-universal hard scattering cross section

Should work in diffractive DIS (Collins; Berera, Soper; Trentadue, Veneziano; Kunszt, Stirling)



Proton vertex factorisation (Regge factorisation)

β and Q^2 dependences factorise from x_{IP},t and M_Y

PDF = Pomeron-flux × Pomeron-PDF

$$f_i^D(x_{IP}, t, x, Q^2) = f_{IP/p}(x_{IP}, t) \times f_i^{IP}(\beta = x/x_{IP}, Q^2)$$

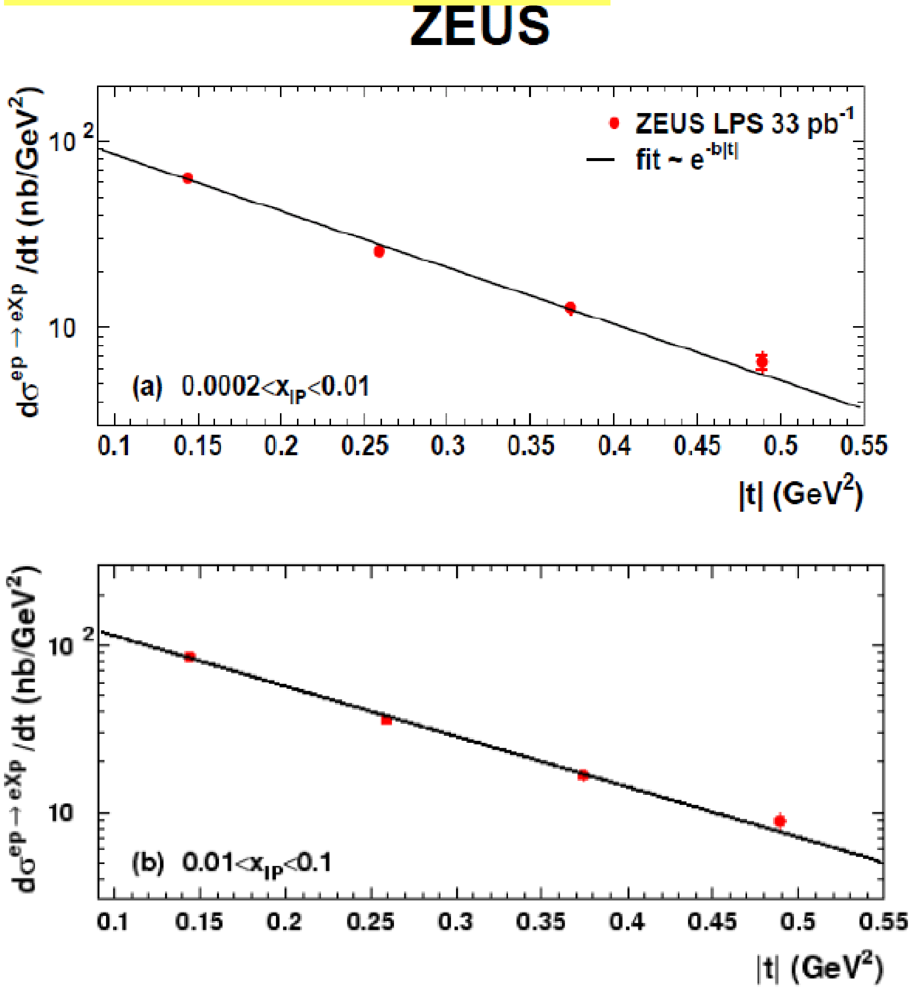
$$f_{IP/p}(x_{IP}, t) = \frac{e^{Bt}}{x_{IP}^{2a(t)-1}}, a(t) = a(0) + a'(t)$$

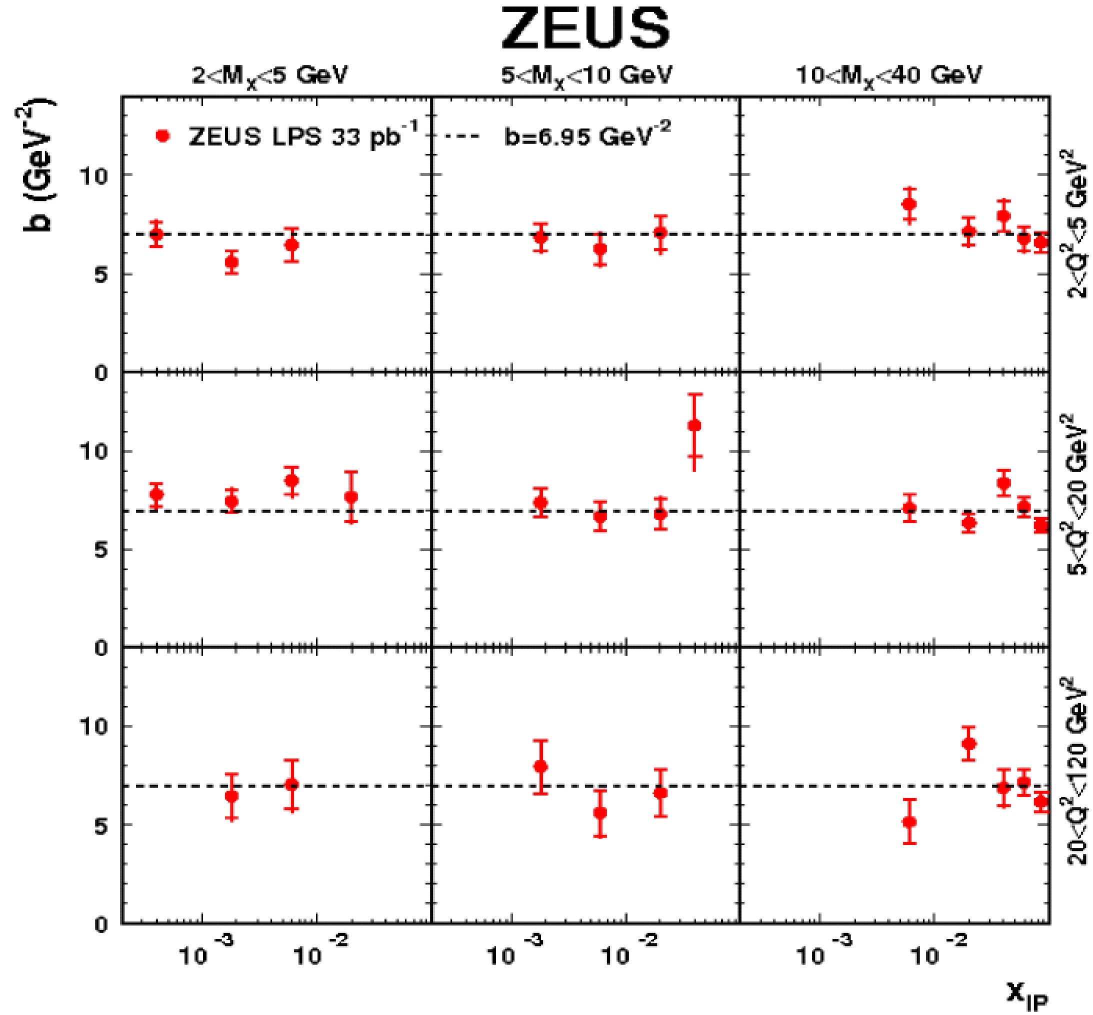
Pomeron flux

➔ assumption; no firm basis in QCD

Proton tagged data: t-dependence

dσ/dt at two x_{IP} bins





- Exponential shape, e^{bt}, with $b=6\div7$ GeV^{-2}
- No dependence on Q^2 and β
- Also very little x_{IP} dependence

Proton tagged data: x_{IP}-dependence

$\sigma_r^{D(4)}$ at two t-values

- low x_{IP}/ high β falling (Pomeron-like) behaviour
- high x_{IP}/ low β rising (Reggeon-like) behaviour

- Compatible x_{IP} dependence in each t bin

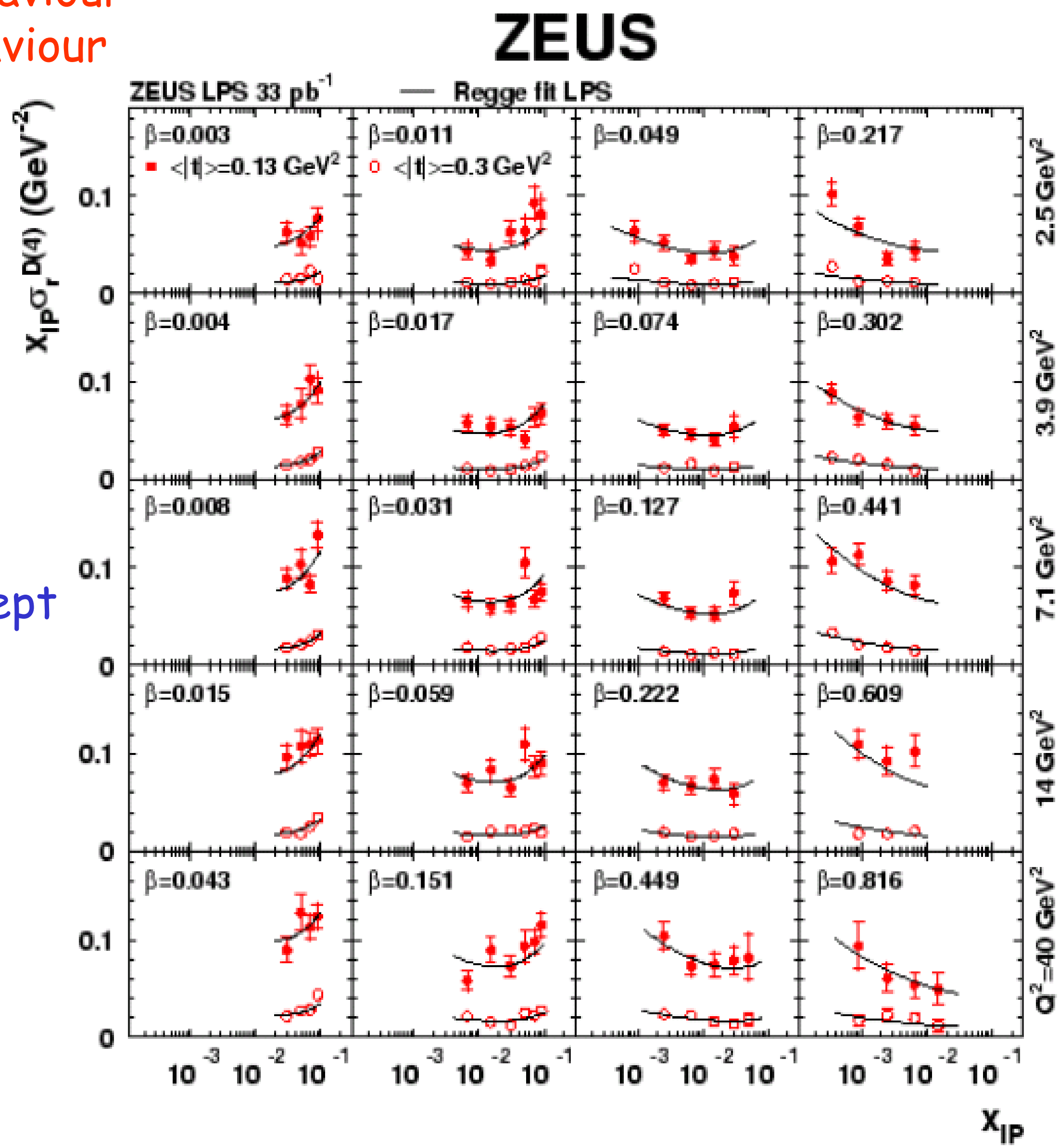
- Regge fit (Pomeron+Reggeon)

ZEUS: $a_{IP}(0)=1.11\pm0.02\pm0.02$
H1: $a_{IP}(0)=1.12\pm0.01\pm0.02$

$a_{IP}(0)$ close to soft 1.08
➔ consistent with soft Pomeron intercept

ZEUS: $a'_{IP}=0.01\pm0.06\pm0.05\ GeV^{-2}$
H1: $a'_{IP}=0.06\pm0.13\ GeV^{-2}$

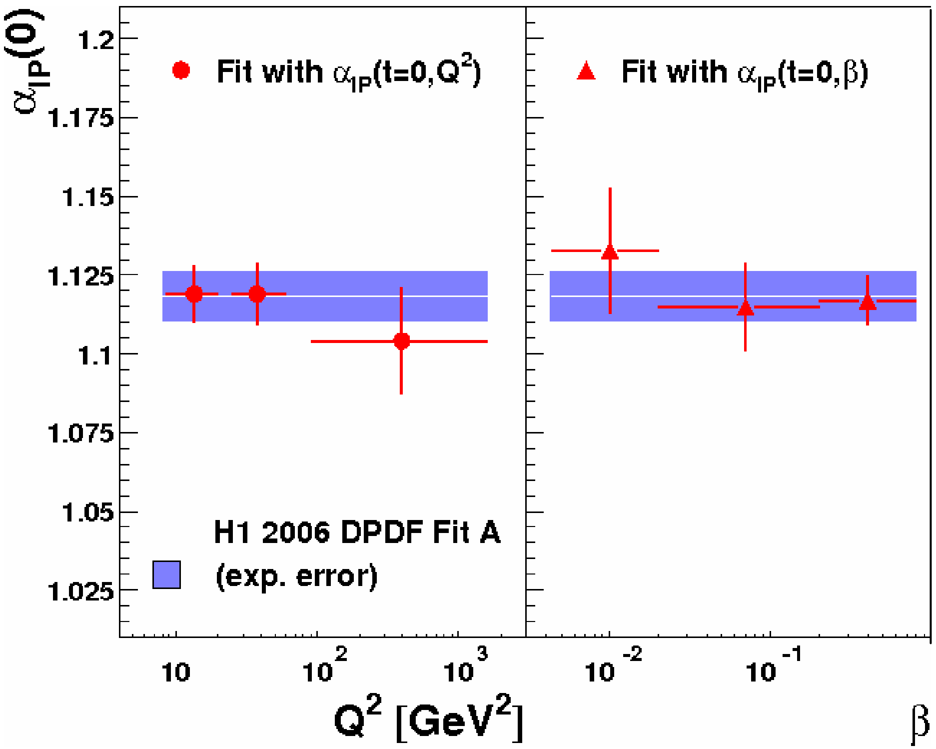
a'_{IP} is not consistent with 0.25 GeV^{-2}
(multi IP, absorption effects ?)

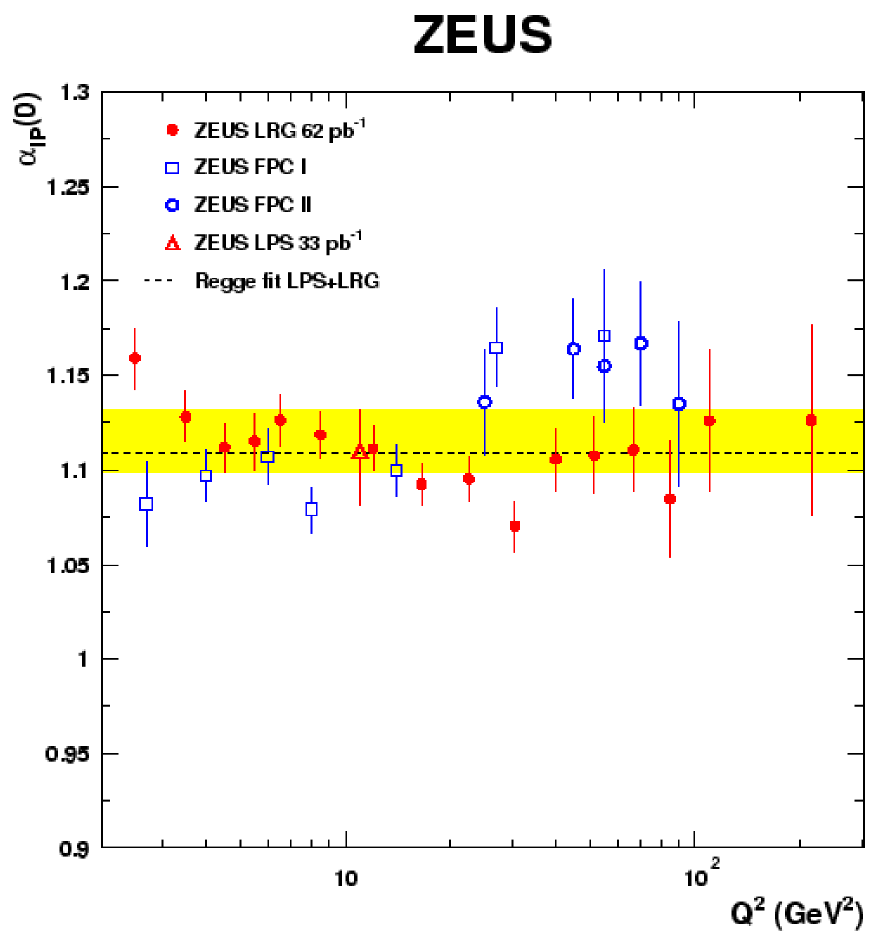


Proton vertex factorisation: Pomeron intercept

Regge fit in different Q^2 bins

No strong evidence for $\alpha_{IP}(0)$ variation
Regge factorisation is a good approximation





- Variables describing proton vertex (x_{IP},t) factorise from those at photon vertex (β,Q^2) to good approximation

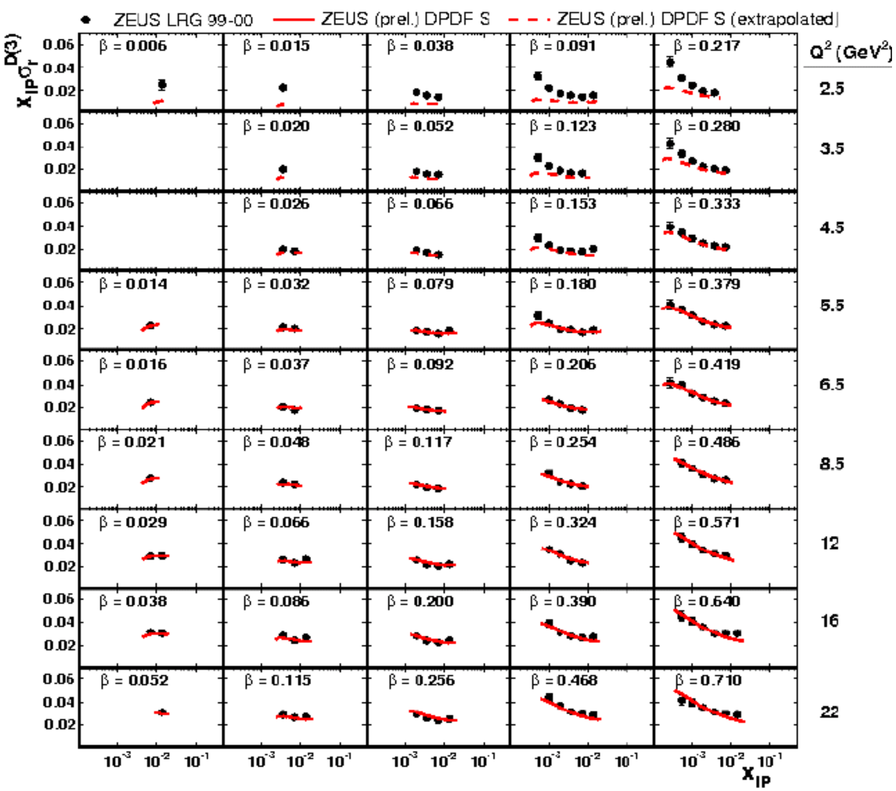
- (β,Q^2) dependence interpreted in terms of **Diffractive Parton Densities (DPDFs),** measuring partonic structure of exchange

QCD fits to diffractive data $\sigma_r^{D(3)}$

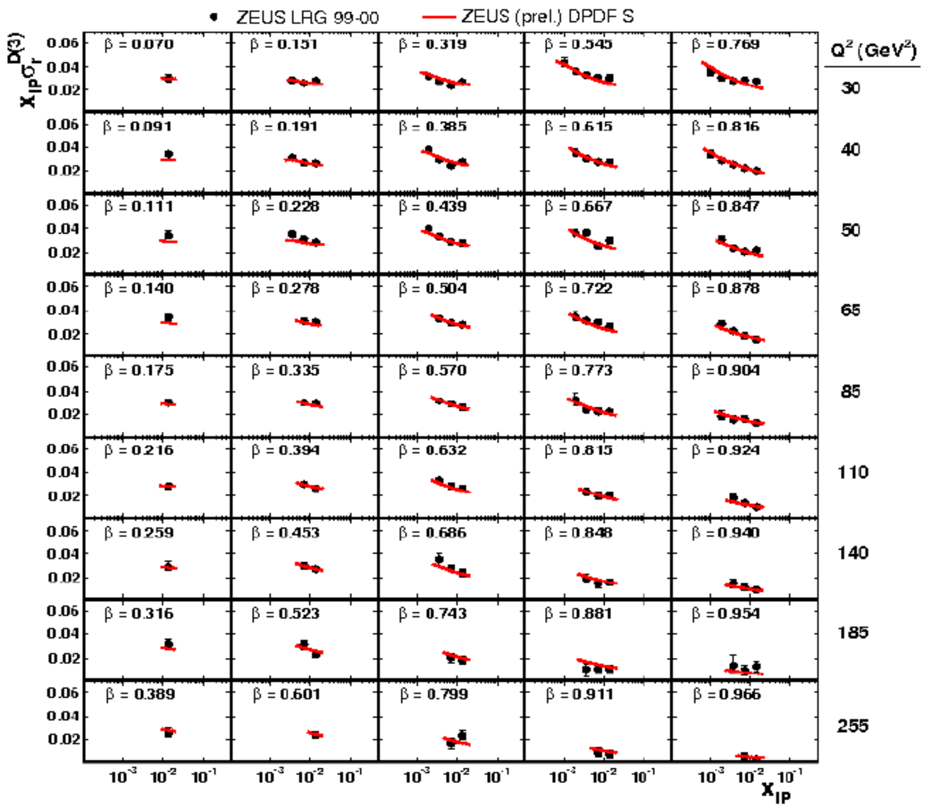
-Use NLO DGLAP evolution analysis technique to Q^2 and β dependences of diffractive cross sections. Extract quark and gluon distributions, with DPDFs parameterised vs z at a starting scale Q_0^2

- Assume Regge factorisation
- Make use of different data sets, theoretical models and approaches
- At fixed x_{IP}, F_2^D constrains quarks; gluons constrained from scaling violation $dF_2^D / d\ln Q^2$

ZEUS vs fit S



ZEUS vs fit C



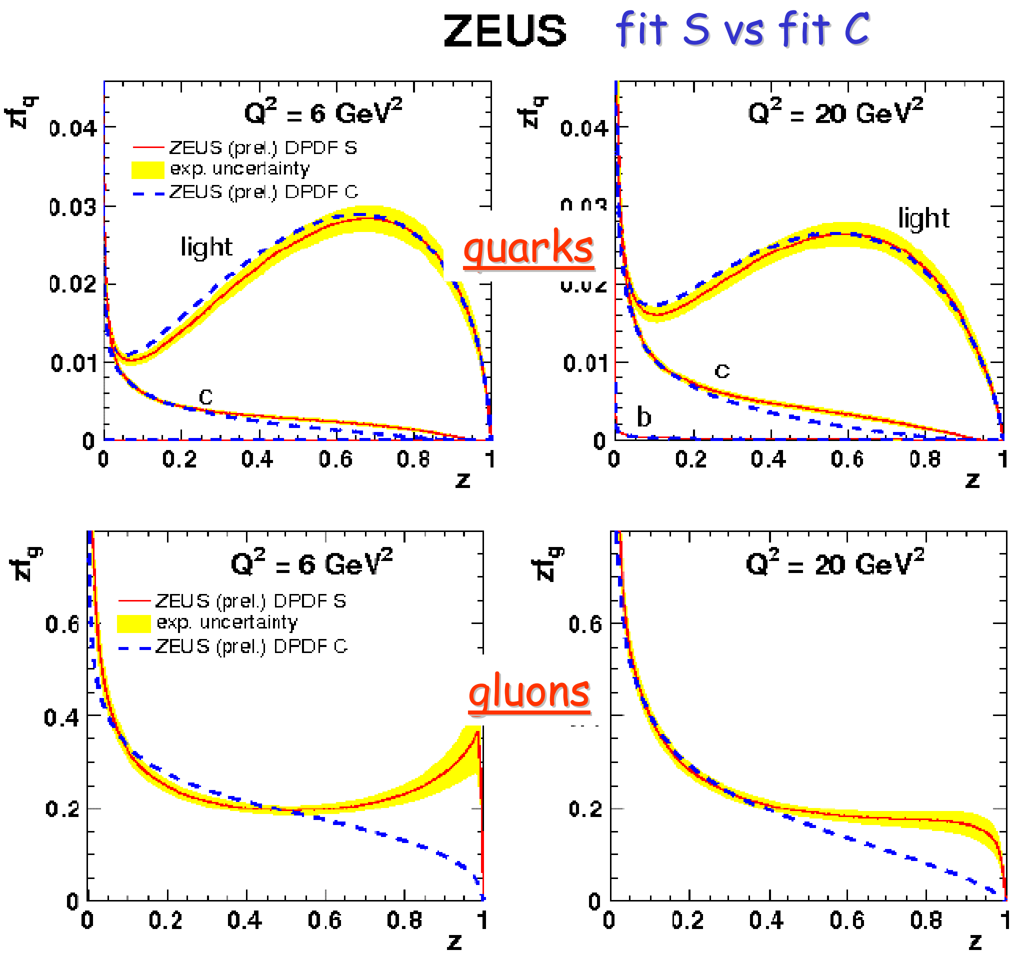
Simultaneous fit to ZEUS LRG and LPS data (Q^2> 5 GeV^2)

Two fit results (fit S, fit C) depending on the starting parameterisations

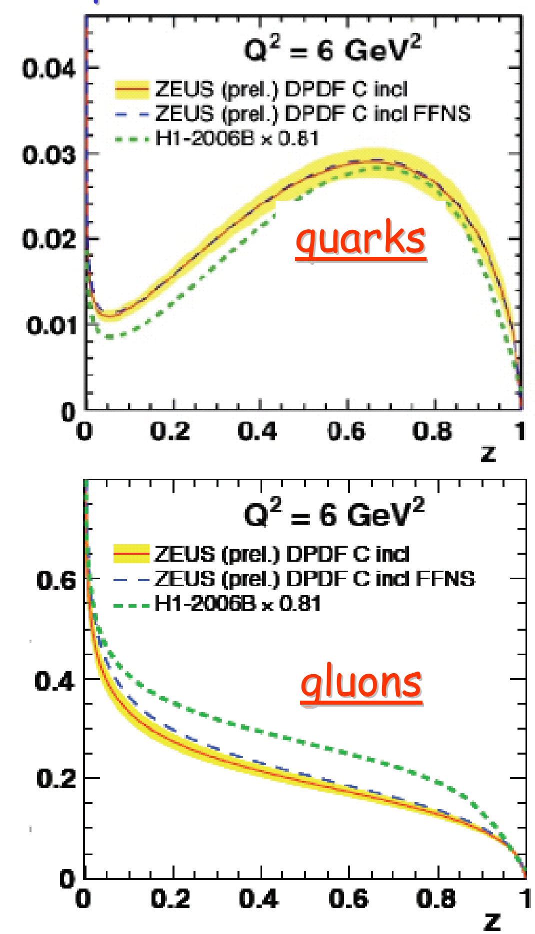
ZEUS DPDFs from inclusive data

- quarks and low-z gluons to few percents (z is long. momentum fraction of exchange)
- gluon dominates
- high-z gluons poor constraint → large uncertainties: low sensitivity of inclusive data to gluons
- reasonable agreement with H1 DPDF fits up to large uncertainty on high-z gluon

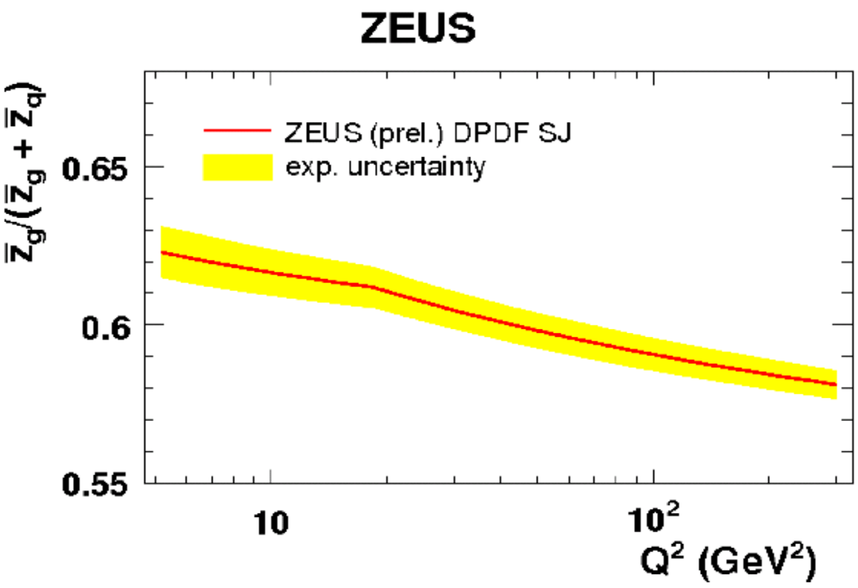
ZEUS fit S vs fit C

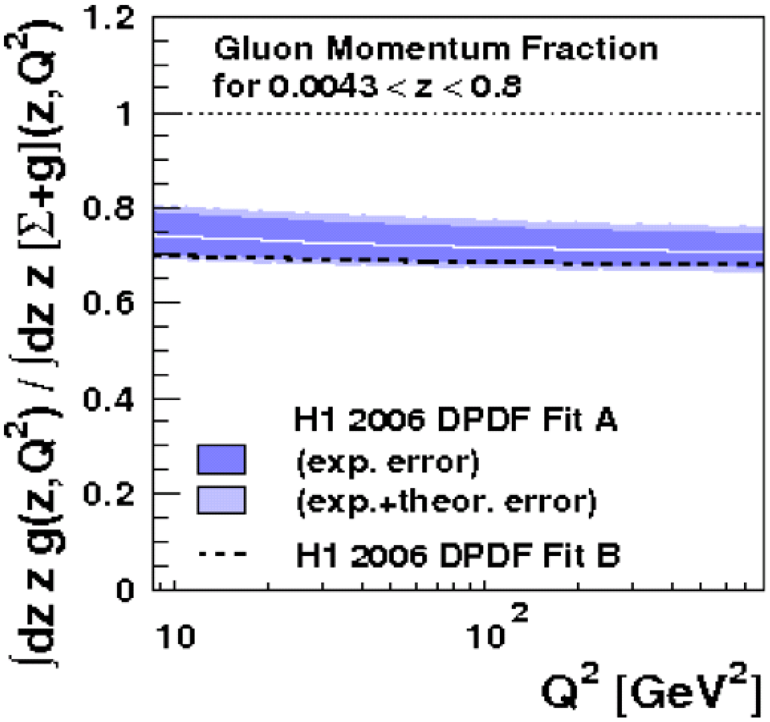


Comparison ZEUS vs H1 DPDFs



Gluon momentum fraction





- Gluon momentum fraction ~ 60-70%

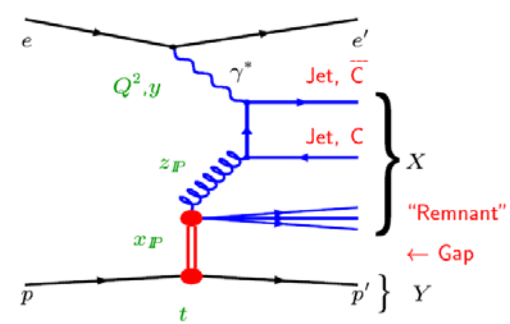
Diffractive Jets at DIS: QCD dijet fit

Jet production: ideal test of underlying dynamics of diffraction:

-Cross sections calculable in pQCD (hard scales: Q^2, p_T^{jet})

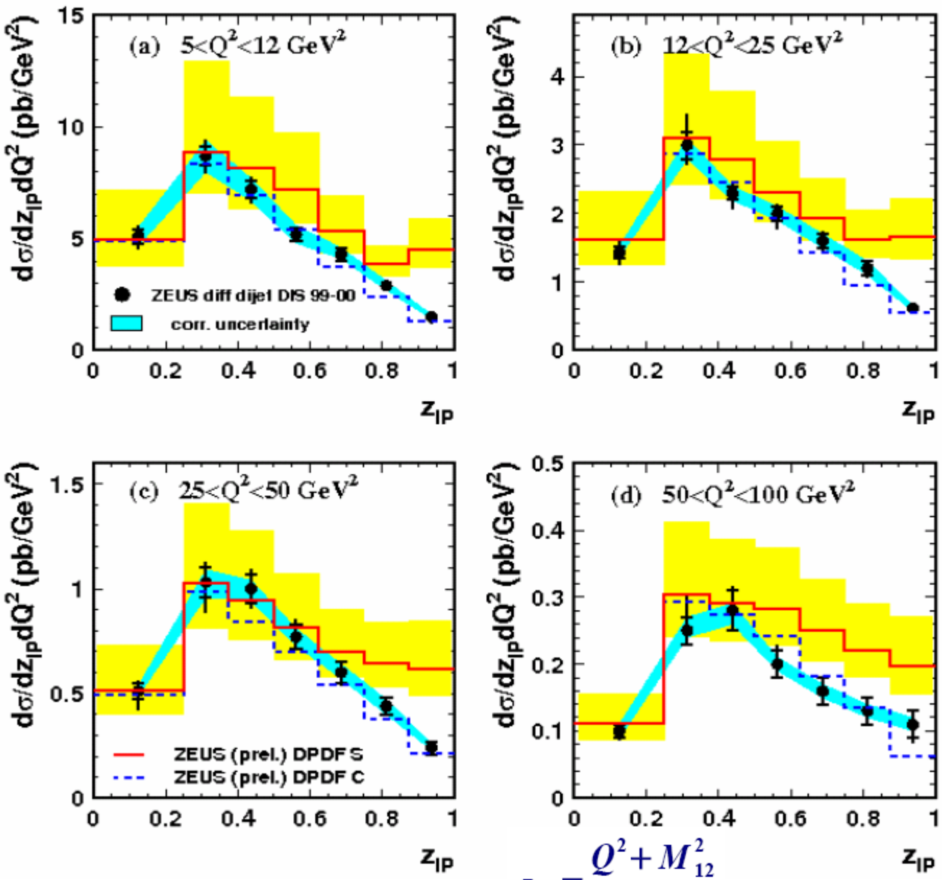
-Production mechanism is directly sensitive to the gluon content

-Test universality of parton distributions (extracted from F_2^D)

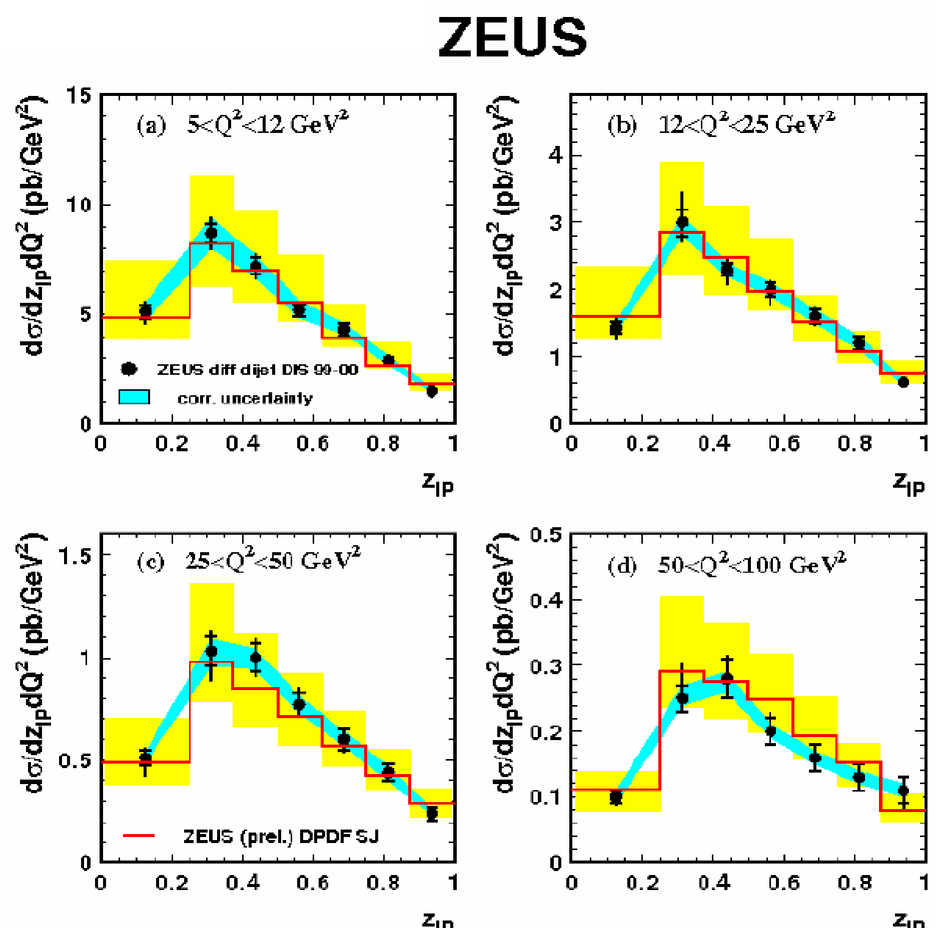


- Fit S fails at high z_{IP} ;Fit C describes dijet data

➔ Dijet cross sections constrain gluon at high z

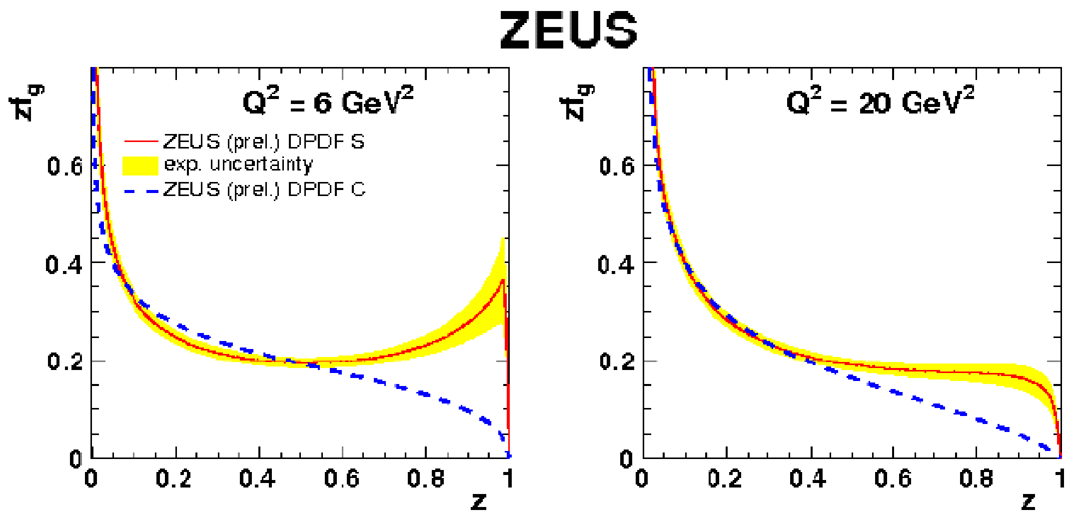


$$z_{IP} = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$



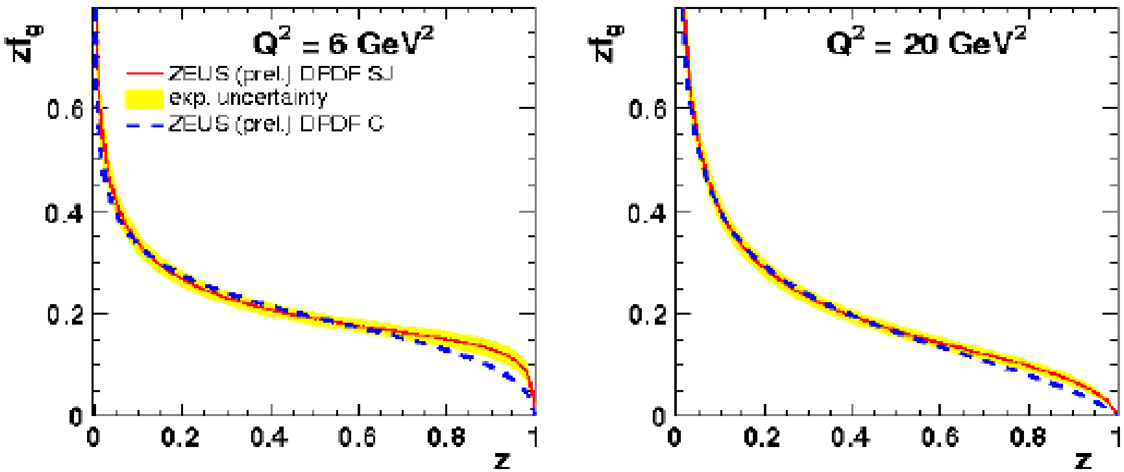
ZEUS fit SJ including jet cross sections

Gluon densities from dijet fit

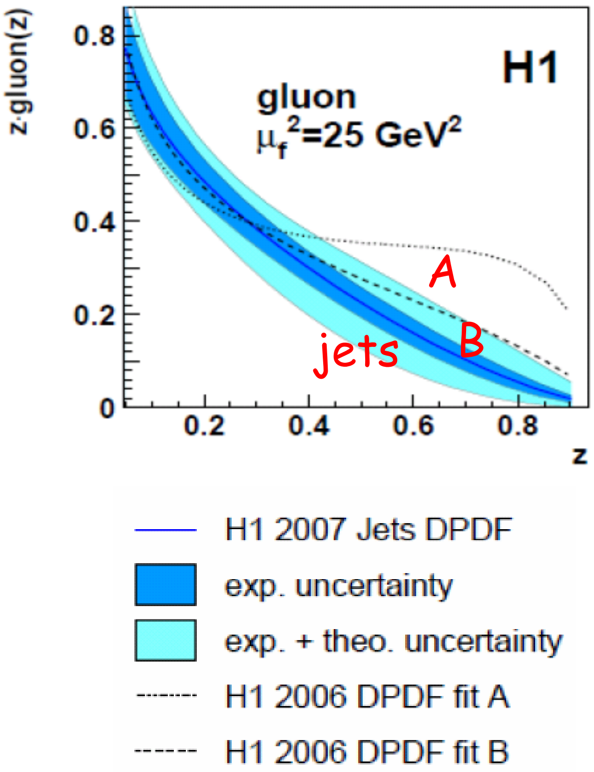


Dijet constrain gluons at high z_{IP} !

ZEUS fit SJ including jet cross sections

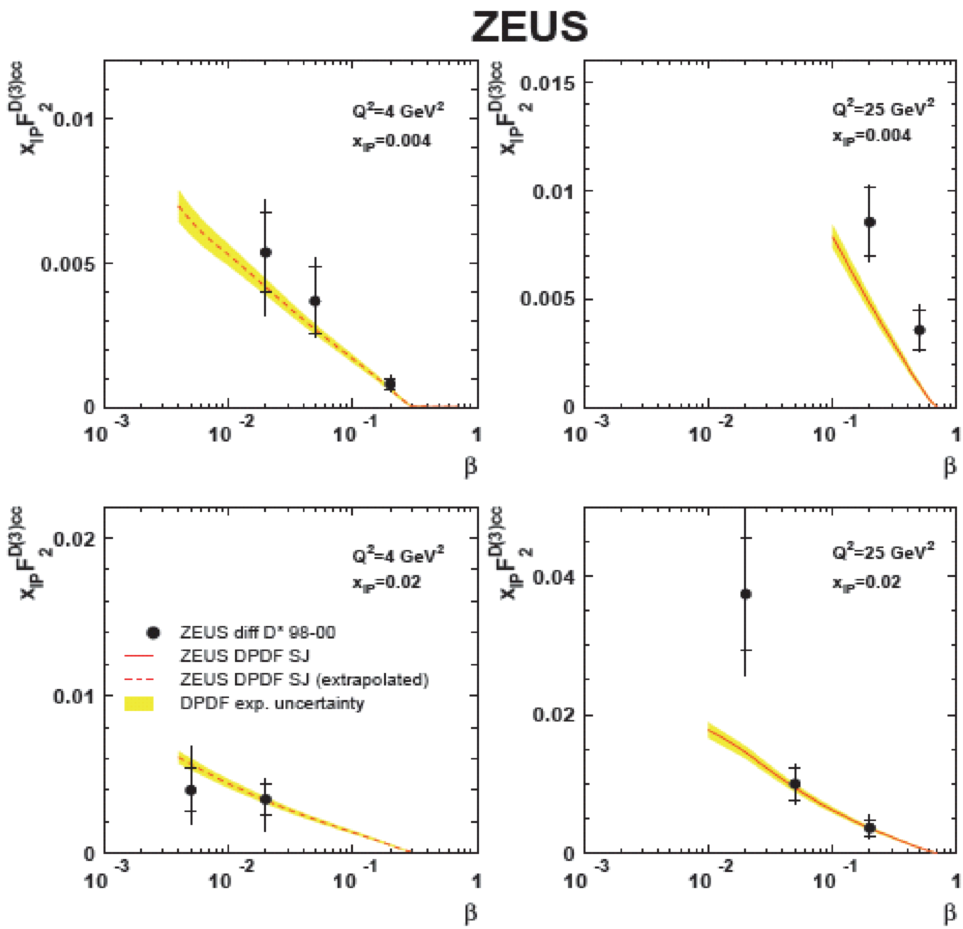


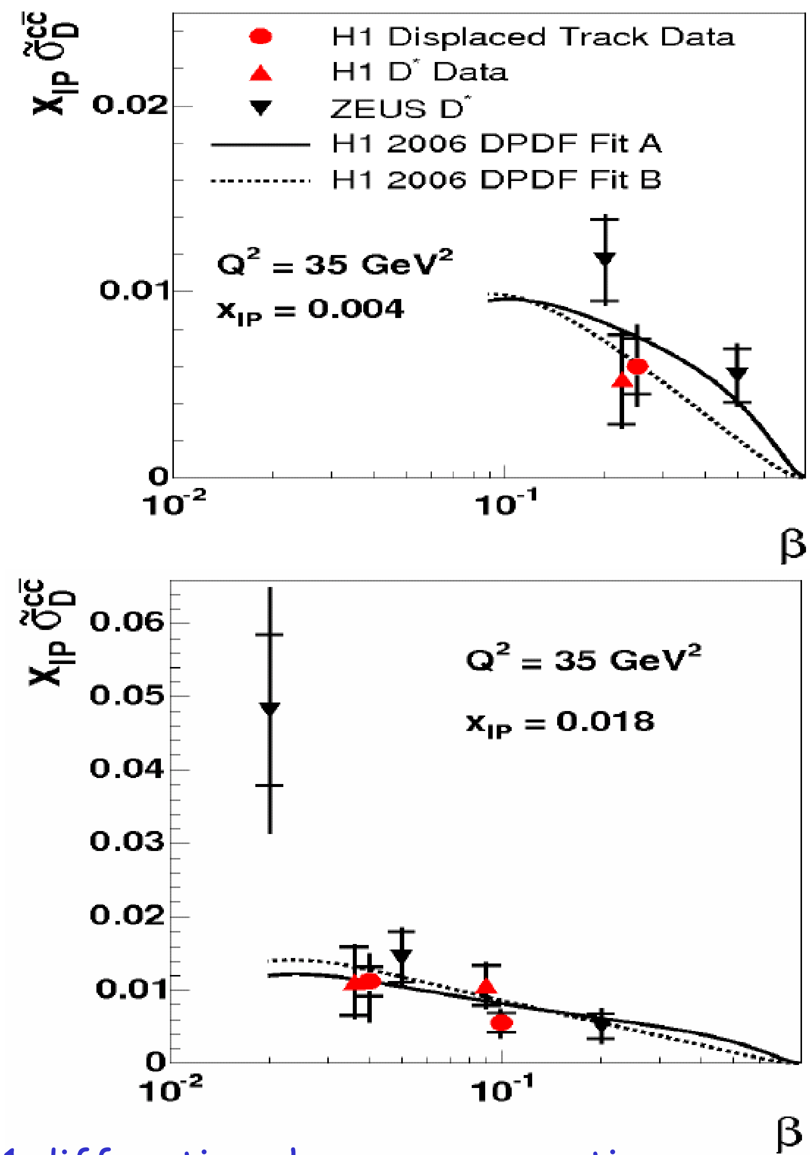
H1 2007 Jets DPDF fit



Describing other diffractive DIS processes: charm production

As well as inclusive cross-sections and jets in DIS, DPDFs describe diffractive charged current, charm, particle flow and spectra





ZEUS DPDF fit SJ predictions compared to charm diffractive structure function $x_{IP}F_2^{D(3)cc}$

H1 diffractive charm cross sections compared to predictions using H1-DPDFs

Fair agreement with data

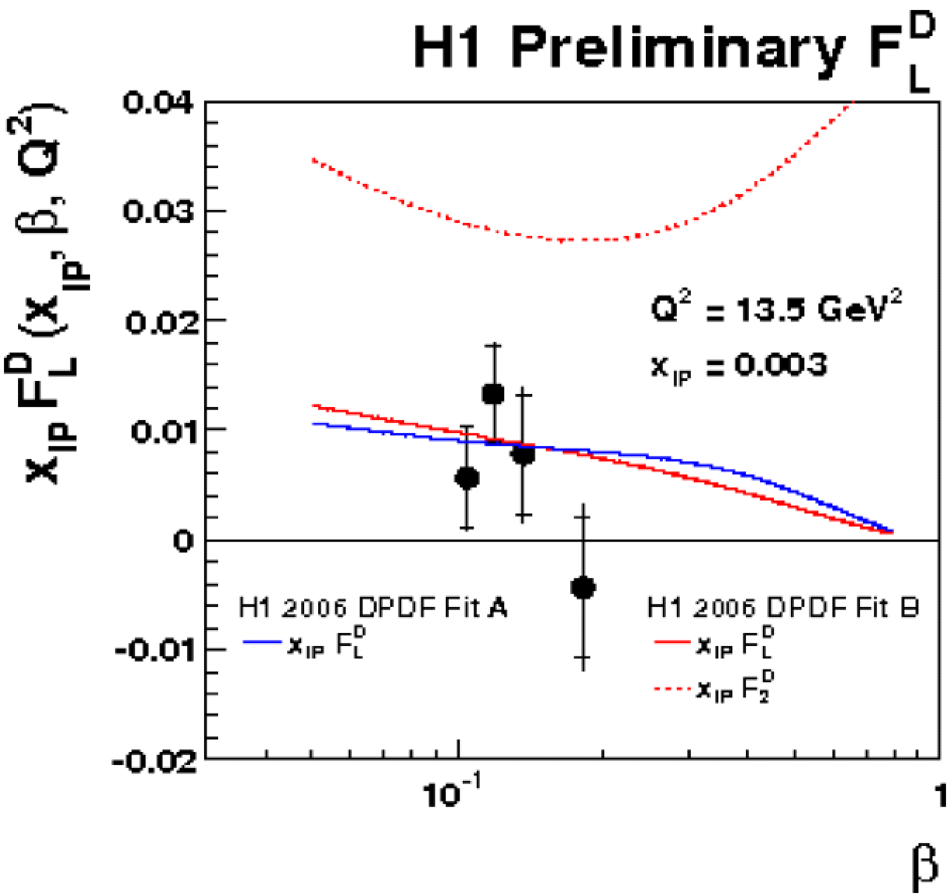
First F_L^D measurement

A new test of diffractive gluon density in DIS

$$\sigma_r^{D(3)}(Q^2, \beta, x_{IP}) = F_2^{D(3)} - \frac{y^2}{2(1-y+y^2/2)} F_L^{D(3)}$$

Explore data at three proton beam energies:
920 GeV (21 pb^{-1})
575 GeV (11 pb^{-1})
460 GeV (6 pb^{-1})

With different beam energies measure $\sigma_r^{D(3)}$ at different y and fixed Q^2, β, x_{IP}



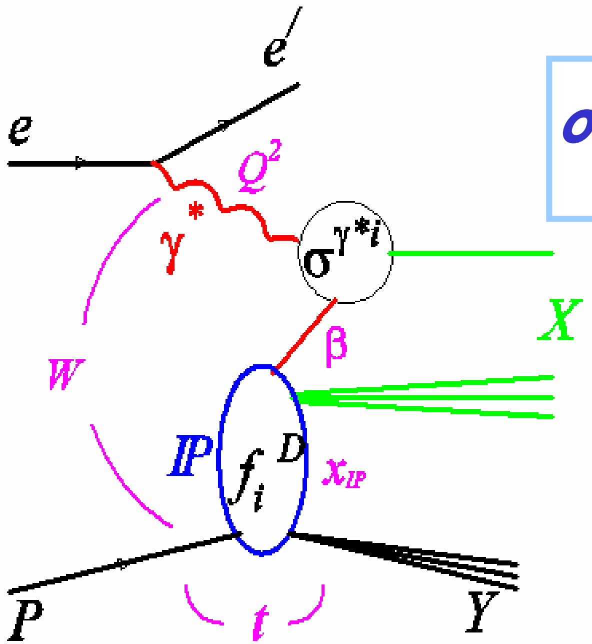
F_L^D measured ~3σ from zero

Results compatible with predictions based on DGLAP fits to F_2^D
$\sigma_L/\sigma_T = F_L^D/(F_2^D - F_L^D) \sim 0.5$

QCD Factorisation in diffraction

QCD hard scattering collinear factorisation in diffractive DIS

(J.Collins; Phys.Rev.D57 (1998) 3051)



$$\sigma^D(\gamma^* p \rightarrow Xp) \propto \sum_i f_i^D(x_{IP}, t, x, Q^2) \otimes \sigma^{\gamma^*, i}(x, Q^2)$$

f_i^D -diffractive parton distribution function – conditional proton parton probability distributions with final state proton at fixed x_{IP}, t

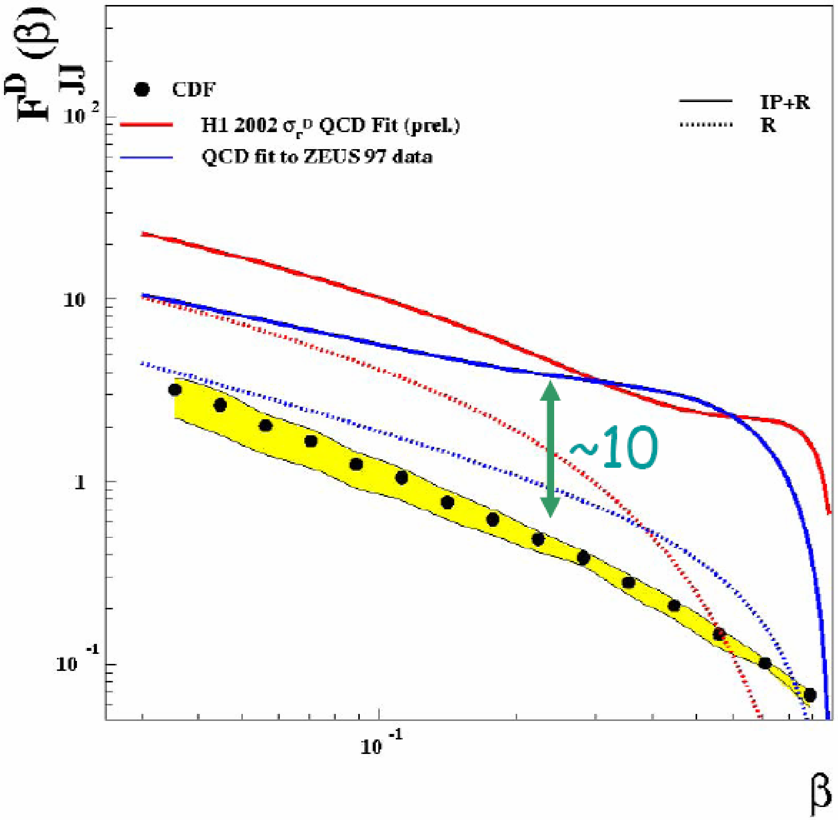
$\sigma^{\gamma^*, i}$ -universal hard scattering cross section

Proven for diffractive DIS.
Is not necessarily true for hadron-hadron collisions

How the QCD factorisation can be studied/tested ?

- extract diffractive PDFs from NLO DGLAP fit to F_2^D from inclusive measurement
- measure an exclusive diffractive final states, open charm and dijets; in pp, DIS and γp
- compare the measurement to theory predictions

Factorisation in diffraction: diffractive jet production at TeVatron



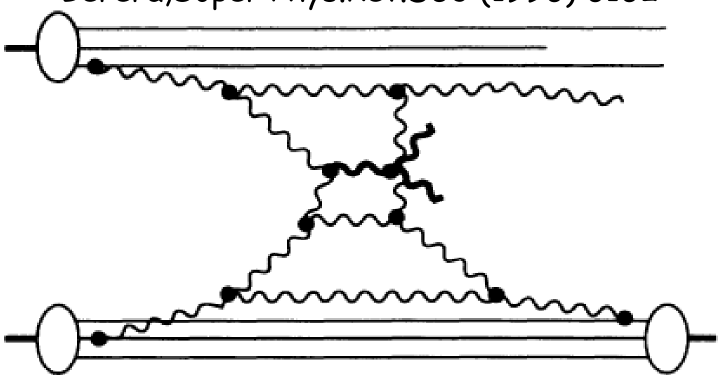
huge difference between the predictions based on the F_2^D fits from HERA and the measurements !

Factorisation is broken in pp

Violation of factorisation can be understood in terms of (soft) rescattering between the two hadrons and their remnants, in initial and final state, suppressing the large rapidity gap

'Gap survival' factor S^2~0.1

Berera,Soper Phys.Rev.D53 (1996) 6162

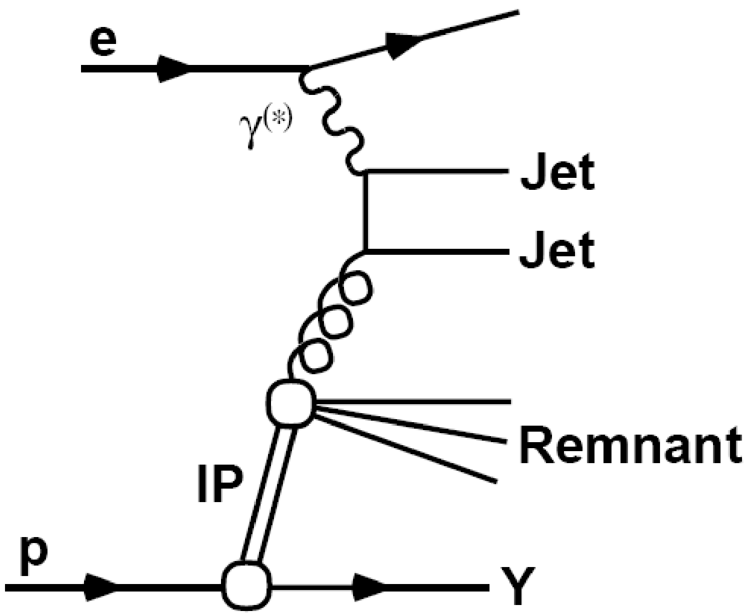


Very essential for the predictions for Diffractive Higgs production at the LHC

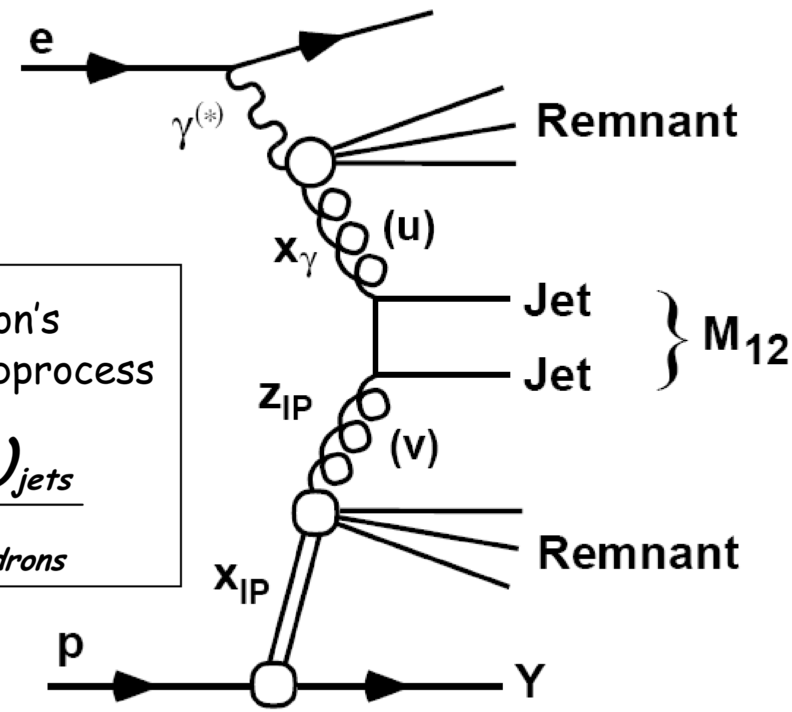
Jets and charm in diffractive photoproduction at HERA

Real photon ($Q^2 \approx 0$) develops hadronic structure

Pointlike (direct) photon



Resolved photon



x_γ - fraction of photon's momentum in hard subprocess

$$x_\gamma^{OBS} = \frac{\sum (E - p_z)_{jets}}{(E - p_z)_{hadrons}}$$

•photon (virtual/real) is directly involved in hard scattering

$x_\gamma = 1$

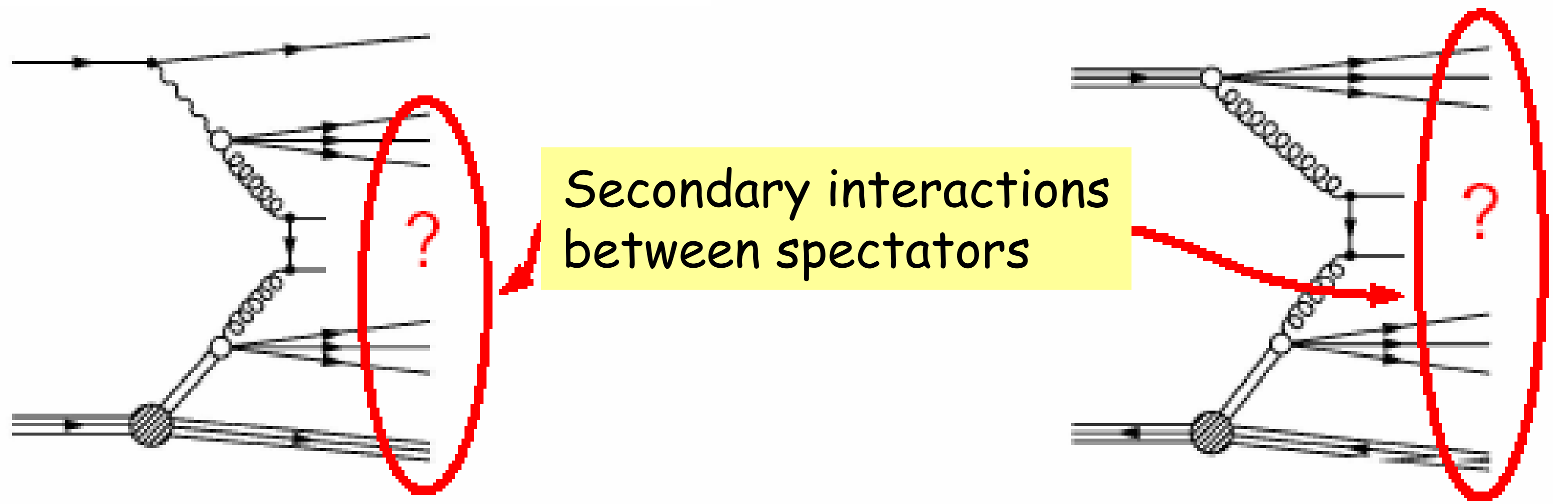
(due to hadronization and resolution not exactly true for measured x_γ)

•photon fluctuates into hadronic system. which takes part into hadronic scattering

$x_\gamma < 1$

Factorisation test: γp – pp analogy

resolved photoproduction γ**p** **pp**

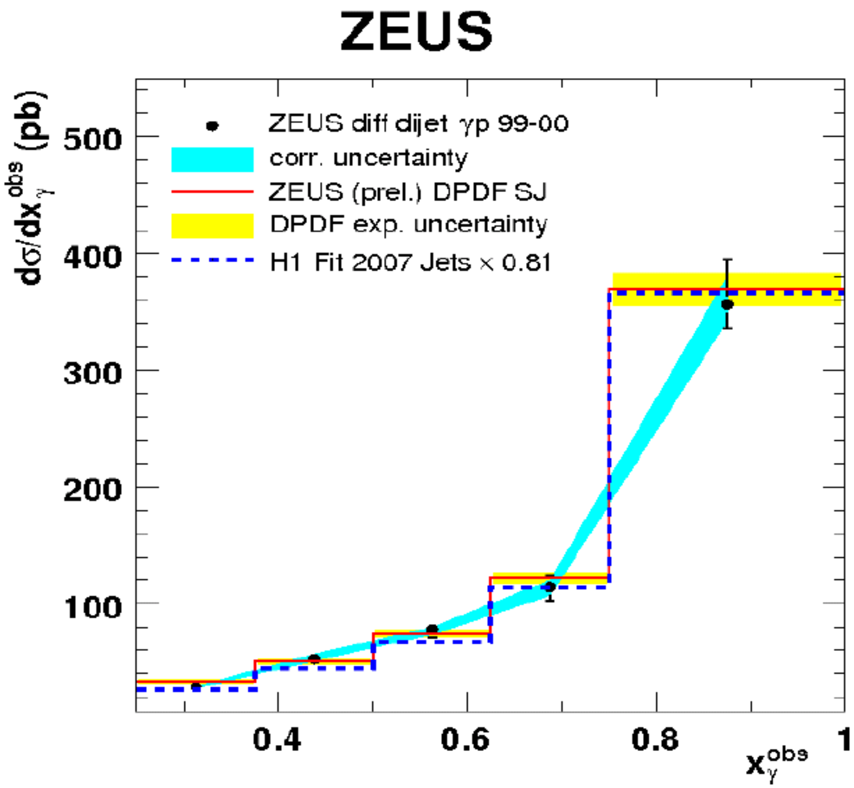


Rescattering leads to factorization breaking and rapidity gap fill up
suppression of cross section = 1–"rap.gap.survival probability"

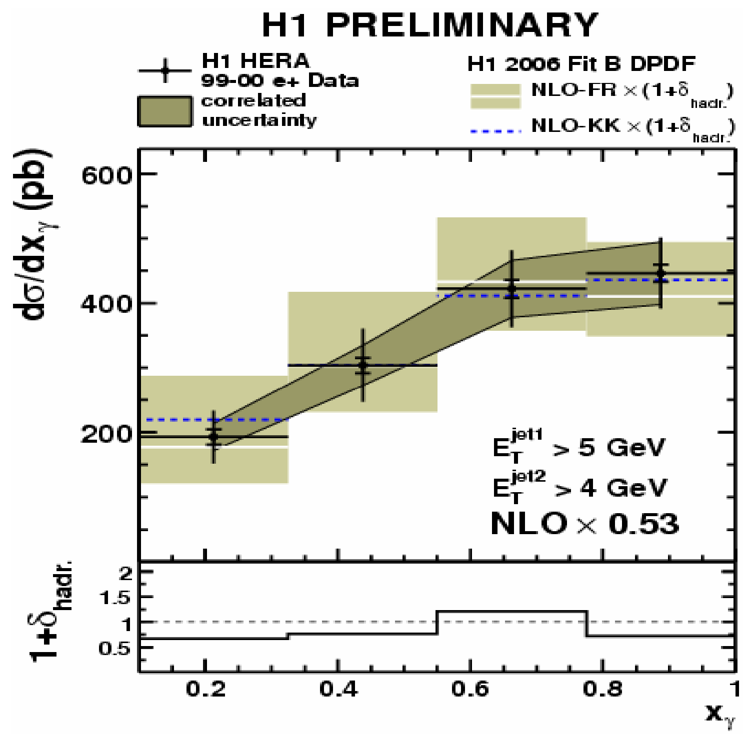
In photoproduction resolved contribution expected to be suppressed
(e.g. suppression~0.34 Kaidalov,Khoze,Martin,Ryskin:Phys.Lett.B567 (2003),61)

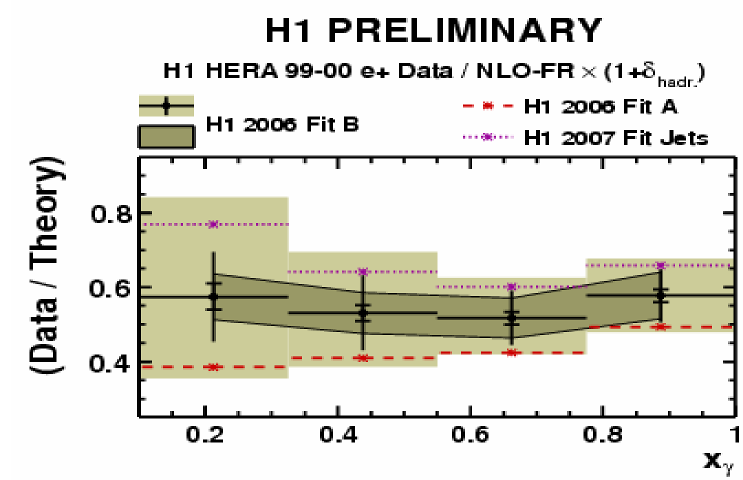
Diffractive dijets in photoproduction

Cross section differential in x_γ



NLO calculations: Frixione/Ridolfi and Klasen/Kramer





- good shape description

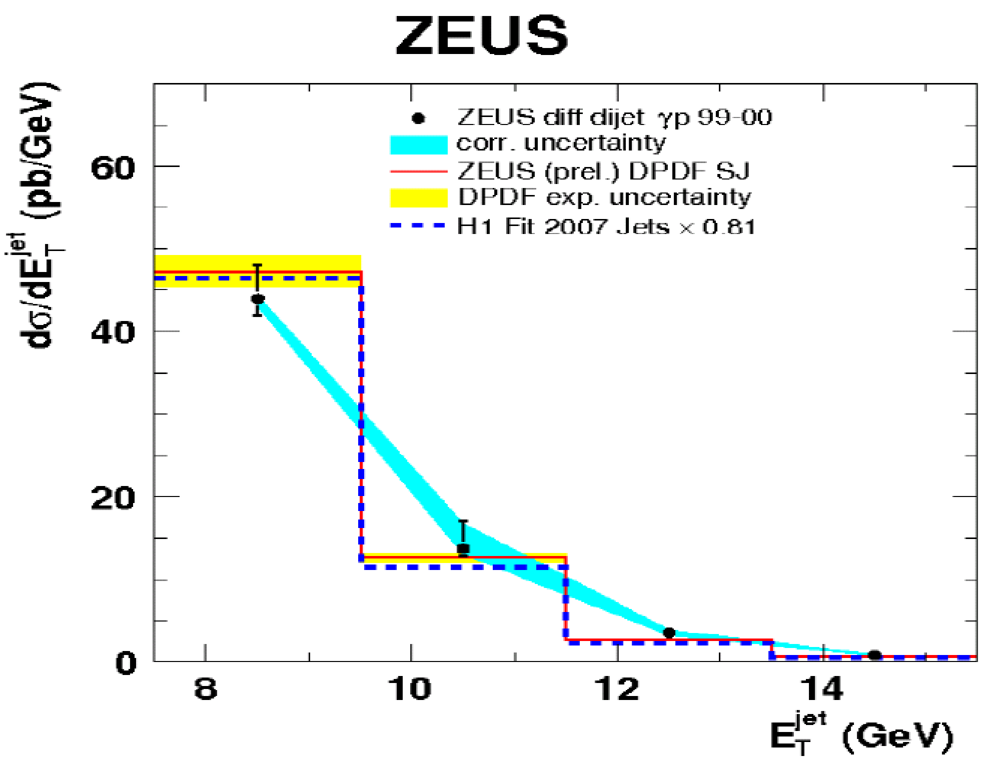
-ZEUS: E_t^{jet1} > 7.5 GeV → good description of jet data.
no suppression

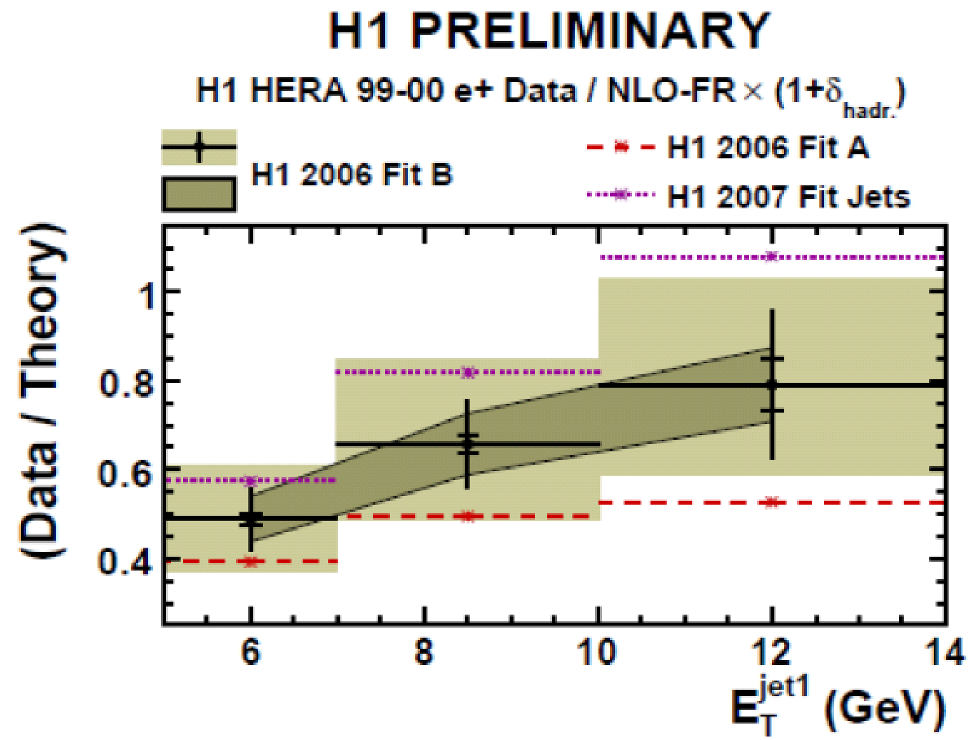
-H1: E_t^{jet1}> 5 GeV → suppression by factor ~2,
no x_γ dependence (suppression also at high x_γ)

- higher E_t → more 'direct-like' events, peak at higher x_γ

Diffractive dijets in photoproduction

Cross section differential in E_T^{jet}

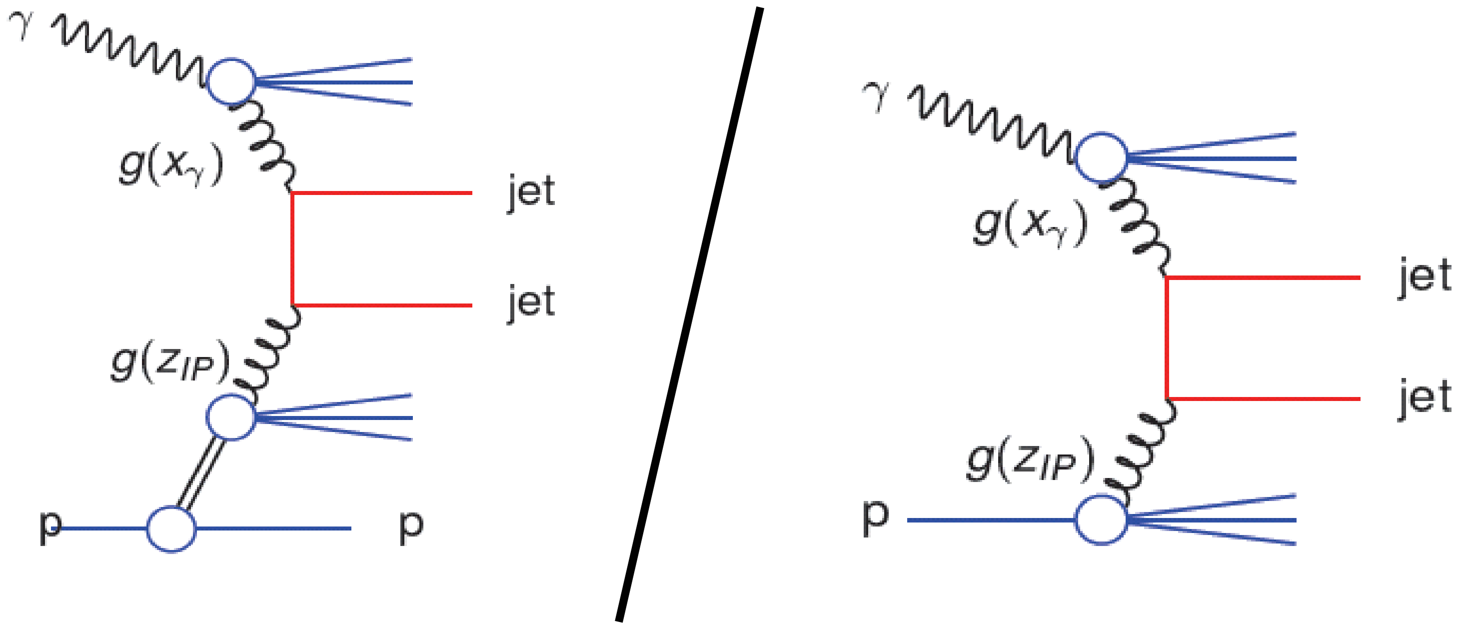




- Suggestions of harder E_t^{jet} dependence in data than NLO theory
  → E_T dependent gap survival probability

- Could rescattering effects for photon depend on E_T, not x_γ ?
- Non-trivial kinematic correlations . Final conclusion pending!

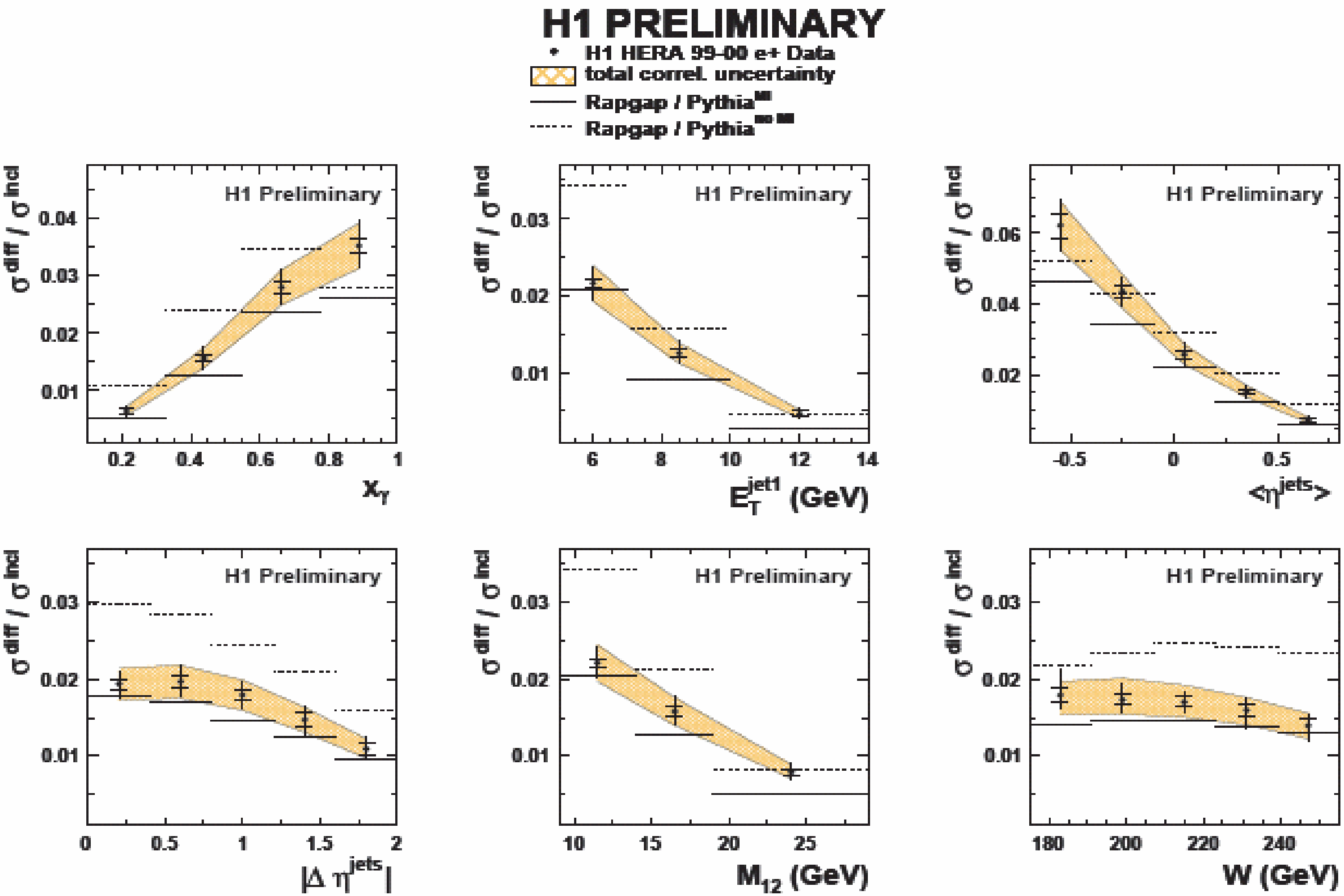
Diffractive to inclusive dijet ratio



Measures the ratio of diffractive gluon to inclusive gluon

- full or partial cancellation of experimental and theoretical uncertainties: photon PDFs, scale uncertainties, jet energy scales
- sensitive to gap survival, but also to difference between phase spaces

Diffractive to inclusive dijet ratio



Use z_{IP}<0.8 to reduce sensitivity to PDF uncertainties

Data compared to RAPGAP/PYTHIA (with and without multi-parton interactions;
we know that multiple interactions are needed to describe the low Pt jet production);

With MI model fair description of data over a large phase space.

Summary

- HERA produced a lot of results on diffraction, more results are coming.

- Agreement between H1 and ZEUS measurement and between different analysis methods used to extract diffraction.

- Regge factorization assumption is a good approximation to describe diffractive data at HERA.

Diffractive PDFs well constrained and tested: DPDFs from HERA are essential ingredients for the prediction of diffractive cross sections at the LHC, e.g. diffractive Higgs production.

- In diffractive DIS, the validity of QCD factorisation confirmed by the measurements of jet and charm production

- In the photoproduction of dijets a large violation of factorisation is observed in H1 data. Suppression is dependent on E_T^{jet} . More investigations needed.

- Ratio of diffractive to inclusive photoproduction dijets cross sections measured. Trend of the data can be interpreted using multiple interactions.