Inclusive Diffraction at HERA

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Representing the H1 and ZEUS Collaborations

- Diffraction at HERA
- Selection of diffractive events
- New measurements from H1 and Zeus
- New QCD fits
- Summary

Diffraction in High Energy Physics

- Diffraction in strong interaction physics is essentially the same as optical diffraction.

  Diffraction is elastic (quasi-elastic) scattering.

- It was first observed in hadron-hadron collision ($p-p$, $p-\pi$).

- These data were described by Regge phenomenology.

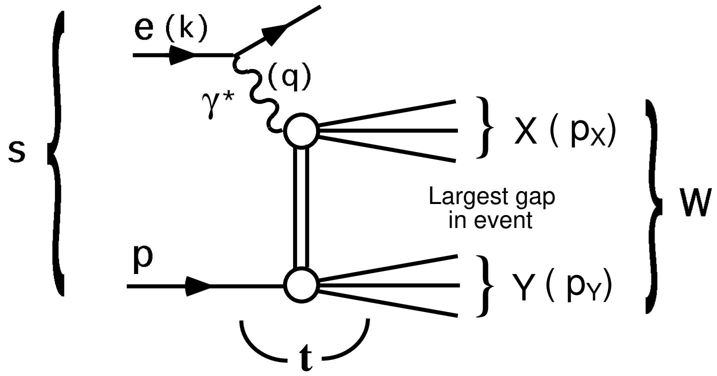
- The pomeron, a colour singlet exchange, was introduced to interpret the rising of the cross-section with the centre of mass energy.

- Diffraction can also be studied at the ep HERA collider.

- The virtuality of the emitted photon permits detailed investigations of QCD.

Diffractive DIS

In Diffractive DIS, two hadronic final states separated by a rapidity gap are formed: $ep \longrightarrow eXY$ + gap

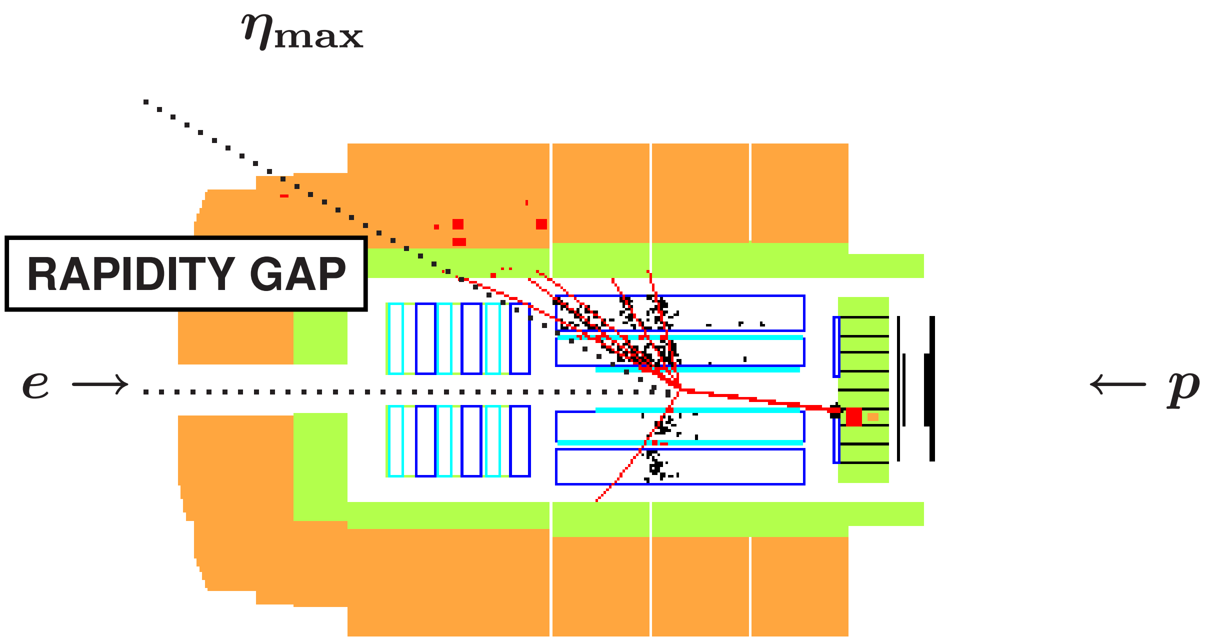


$|t| \sim m_p$

$M_X \ll W^2$

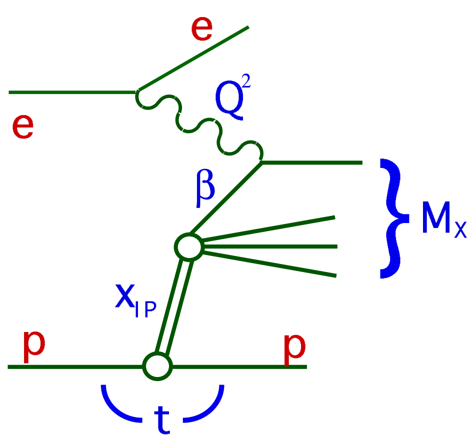
$M_Y \ll W^2$

A typical diffractive event seen in the H1 detector:



$$ep \longrightarrow eXp$$

Diffractive Structure Function



Diffractive kinematics:

- $x_{I\!P} = \frac{q\cdot(p-p')}{q\cdot p} \simeq \frac{Q^2+M_X^2}{Q^2+W^2}$

  Fraction of proton's 4-momentum carried by pomeron ($I\!P$)

- $\beta = \frac{Q^2}{2q\cdot(p-p')} \simeq \frac{Q^2}{Q^2+M_X^2}$ $\quad \beta = \frac{x}{x_{I\!P}}$

  Fraction of pomeron's 4-momentum carried by struck quark

- $t = (p - X)$ momentum transfer at p vertex

Diffractive reduced cross-section:

$$\frac{d^3\sigma}{d\beta dQ^2 dx_{I\!P} dt} = \frac{4\pi\alpha_{em}^2}{\beta Q^4}(1 - y + \frac{y^2}{2})\sigma_r^{D(4)}(\beta, Q^2, x_{I\!P}, t)$$

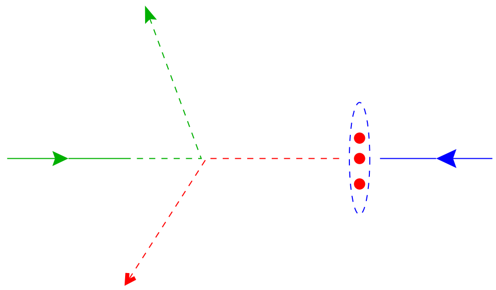
Structure functions F_2^D and F_L^D :

$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{2((1-y+\frac{y^2}{2})} F_L^{D(4)}$$

- Longitunal F_L^D affects σ_r^D at high y
- If $F_L^D = 0$ then $F_2^D = \sigma_r^D$
- Integrate over t when the proton is not tagged $\longrightarrow F_2^{D(3)}$

Main Approaches to Diffraction

1. Factorisation theorem (p.d.f) in the Breit frame



Proton is Lorentz contracted and time dilated.

Hard interaction occurs with one parton.

Might break down at low Q^2 $\longrightarrow$ need measurements.

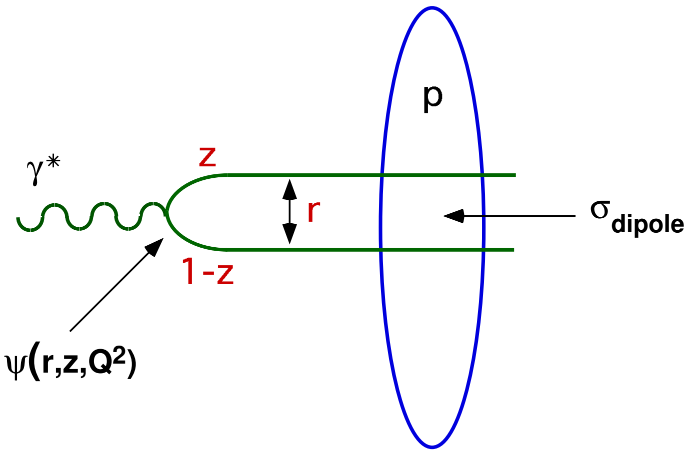
2. Regge theory and factorisation

only valid for soft processes

3. Dipole models

Different approach than 1. $\longrightarrow$ proton rest frame

$\gamma^* \longrightarrow q\bar{q}$ well in advance of target



This is a LLA model, what about NLLA?

4 They are other models...

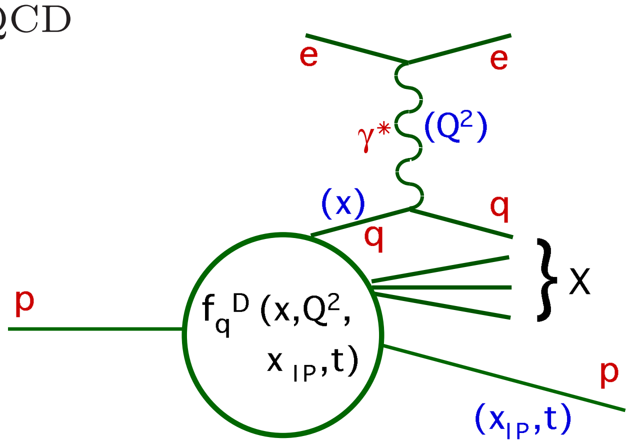
Factorisation Properties of F_2^D

QCD Hard Scattering Factorisation for Semi-Inclusive DIS:-

(Trentadue, Veneziano, Berera, Soper, Collins . . .)

Diffractive parton densities $f_q^D(x_{I\!P}, t, x, Q^2)$ express *conditional* proton parton probability distributions with constraint of final state proton at particular $x_{I\!P}, t \ldots$

$$\sigma^{\mathrm{Dif}} \sim f_q^D(x_{I\!P}, t, x, Q^2) \otimes \hat{\sigma}_{\mathrm{pQCD}}$$



At fixed $x_{I\!P}, t$, $f_q^D(x_{I\!P}, t, x, Q^2)$ evolve with x, Q^2 according to same DGLAP equations as inclusive $f_q(x, Q^2)$

- Diffractive pdf's universal within diffractive DIS.
- As for inclusive DIS, the QCD evolution of σ^{Dif} can be predicted.
- This can be extended to dijet and charm productions in DIS, fits will be shown later!

Regge Theory and Factorisation

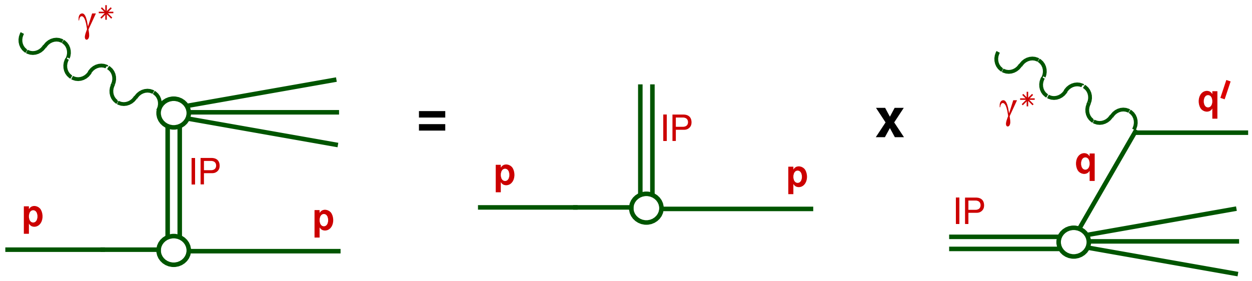
Regge Theory

- Very successfull in soft hadron phenomenology - fits suggests a universal *pomeron* exchange. (Donnachie, Landshoff, ...)
- Regge theory predicts: $\frac{d\sigma}{dt} \sim s^{2(\alpha(0)-1)} e^{2\alpha'(0)t\ln s}$

  The 2nd exp. $\Rightarrow$ diffractive peak becomes narrower as s increases (shrinkage)

'Regge' Factorisation ("resolved $\mathbb{P}$ model"):-

Regge factorisation is an additional assumption, there is no PROOF!



$$\sigma^{\mathrm{Dif}} \quad \sim \quad f_{\mathbb{P}/\mathrm{p}}(x_{I\!P}, t) \quad \times \quad F_2^{\mathbb{P}}(\beta, Q^2)$$

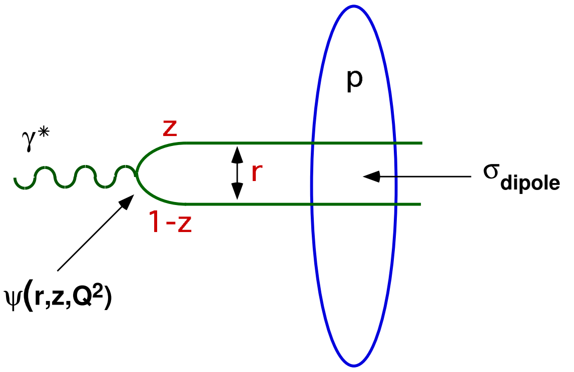
$\mathbb{P}$ flux factors $f_{\mathbb{P}/\mathrm{p}}(x_{I\!P}, t)$ from Regge theory . . .

$$f_{\mathbb{P}/\mathrm{p}}(x_{I\!P}, t) = \frac{e^{Bt}}{x_{I\!P}^{2\alpha(t)-1}} \qquad \text{where} \quad \alpha(t) = \alpha(0) + \alpha' t$$

The shape of σ^{Dif} does not depend on $x_{I\!P}$! (important for later on)

Dipole Models

$\gamma \longrightarrow q\bar{q}$ or $q\bar{q}g$ long before interaction with p:



- $\sigma^{\gamma^* p} \propto$ effective dipole wf $\times$ dipole cross section
- Photon can be L or T polarized
- $\gamma_L \longrightarrow q\bar{q}$ and $\gamma_T \longrightarrow q\bar{q}$ or $q\bar{q}g$
  - $q\bar{q}_L$ dominant at high β
  - $q\bar{q}_T$ dominant at medium β
  - $q\bar{q}g_T$ dominant at low β
- $F_2^D \sim$ 2 gluon exchange, $F_2 \sim$ 1 gluon

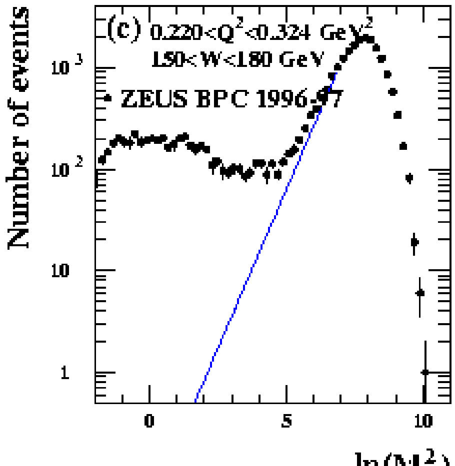
  F_2: $\sigma_{T,L}(x, Q^2) =$
  $$\int \mathrm{d}^2 r \, \mathrm{d}z \quad \left|\psi_{T,L}(r, z, Q^2)\right|^2 \quad \sigma_{\mathrm{dipole}}(x, r)$$
  F_2^D: $\sigma_{T,L}(x, Q^2) =$
  $$\int \mathrm{d}^2 r \, \mathrm{d}z \quad \left|\psi_{T,L}(r, z, Q^2)\right|^2 \quad \sigma^2_{\mathrm{dipole}}(x, r)$$
- Different ansatz exist for σ_{dipole} Golec-Biernat & Wüsthoff, Bartels *et al. (see later),...*

Experimental Diffractive Selection

1. Largest Rapidity Gap (H1, ZEUS)

$$\Delta\eta \text{ large when } M_X, M_Y(M_N) << W$$

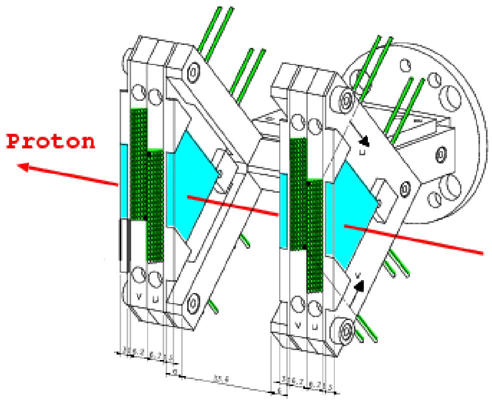
2. Decompose ln M_X^2 distribution (ZEUS)



Decompose into diffractive and non-diffractive contributions

1. and 2. $\longrightarrow$ Large statistics - Integrate over t and MY (M_N)

3. Detect leading protons (H1, ZEUS)



$$x_L = \frac{E_{p'}}{E_p} = 1 - x_{I\!P}$$

for exclusive p

Low statistics due to acceptance - Free of pdiss. background - Measurement of t and ϕ distributions

New Measurements from H1

3 new high precision measurements

New low Q^2 points $\longrightarrow$

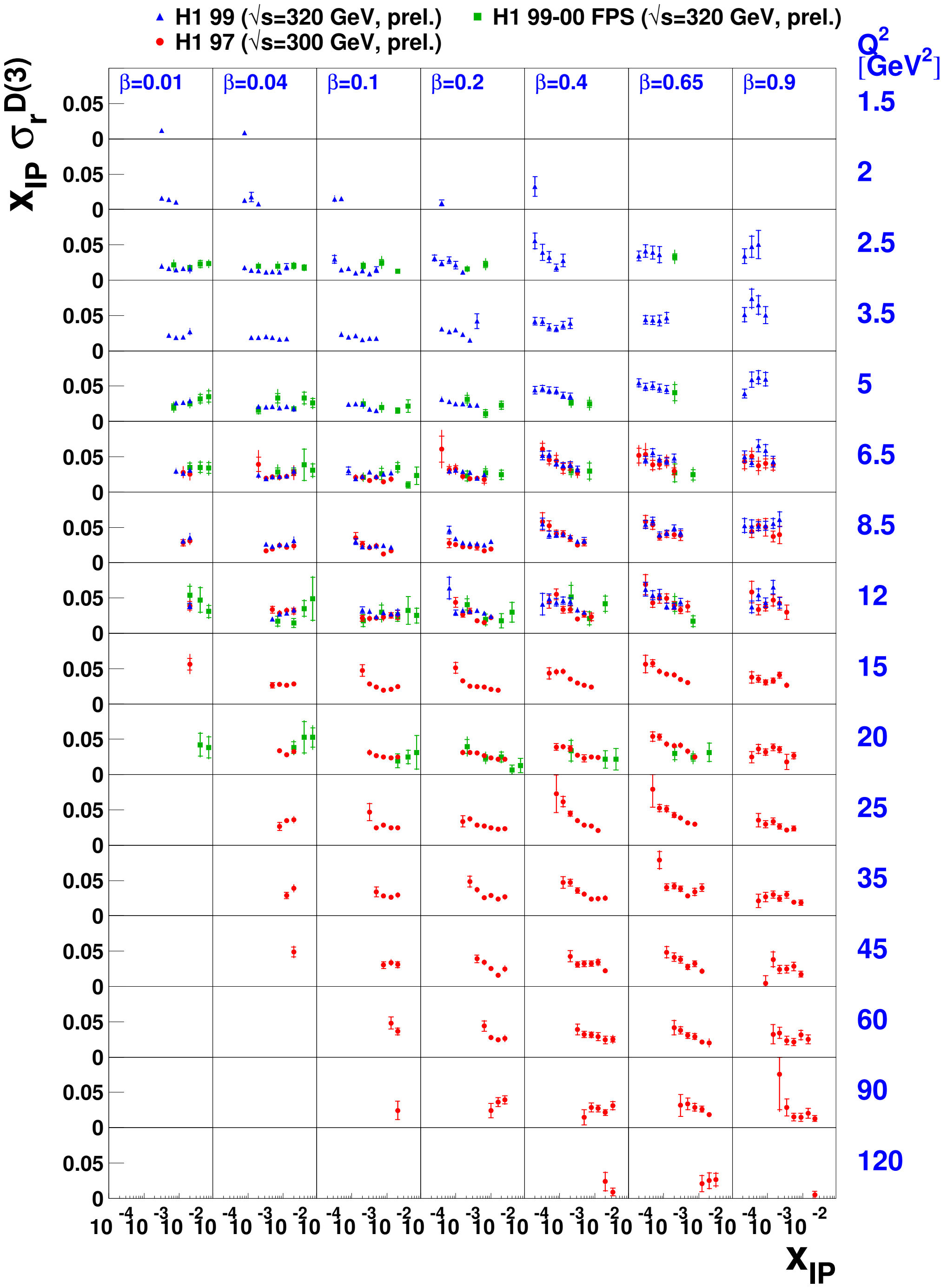
important to

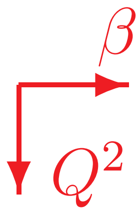
constraint partons

in new fits (see later)

$\sigma_r^{D(3)} \simeq F_2^{D(3)}$

for the y range of meas.

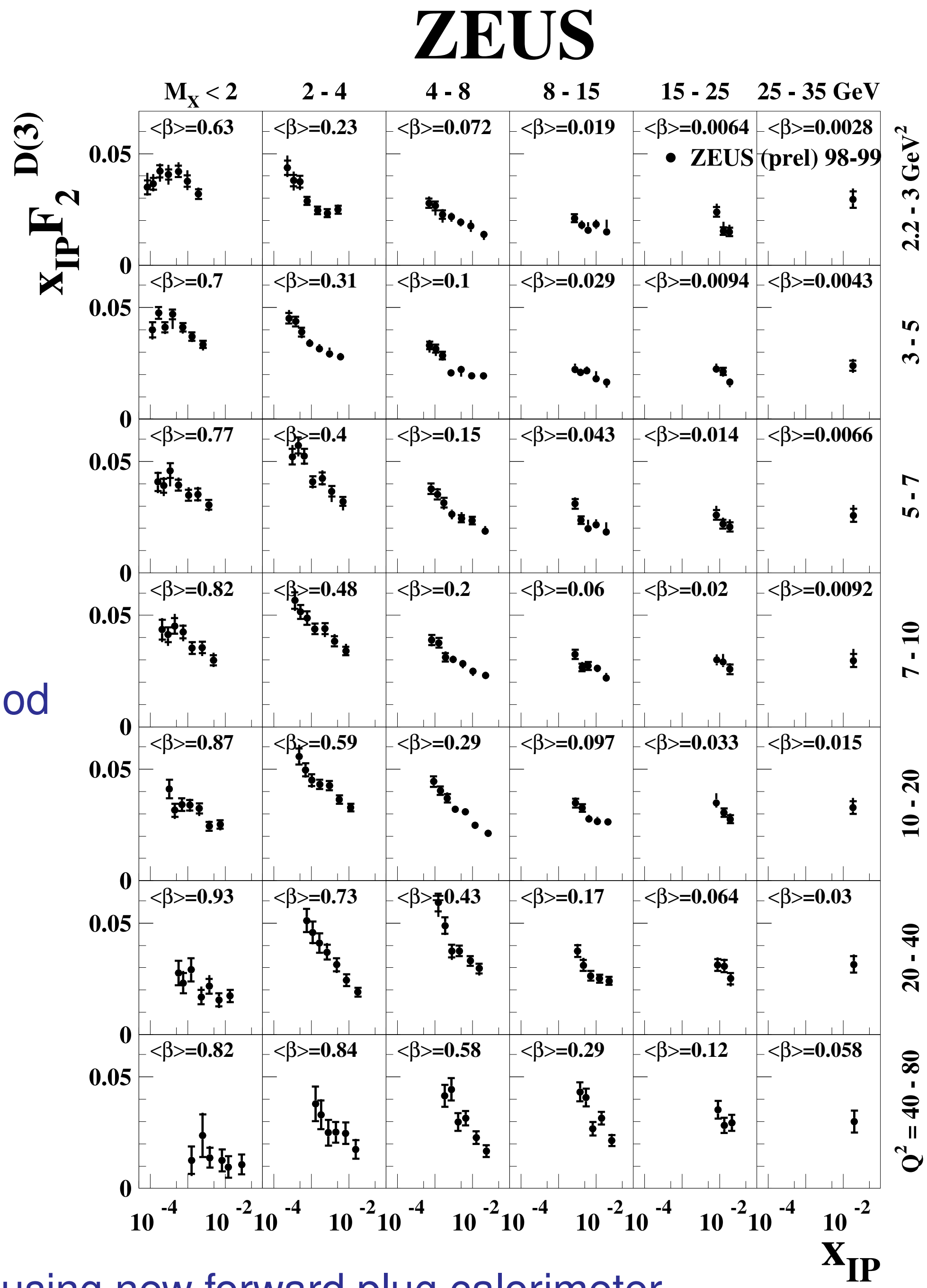




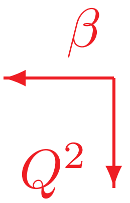
- 5 $\times$ improvement in statistics for measurement with rapidity gap method - $1.5 < Q^2 < 12 geV^2$, $6.5 < Q^2 < 120$ GeV^2
- New measurement with the FPS - $2.5 < Q^2 < 20$ GeV

$\Rightarrow$ Agreement between the two methods

New Measurements from ZEUS



uses MX method



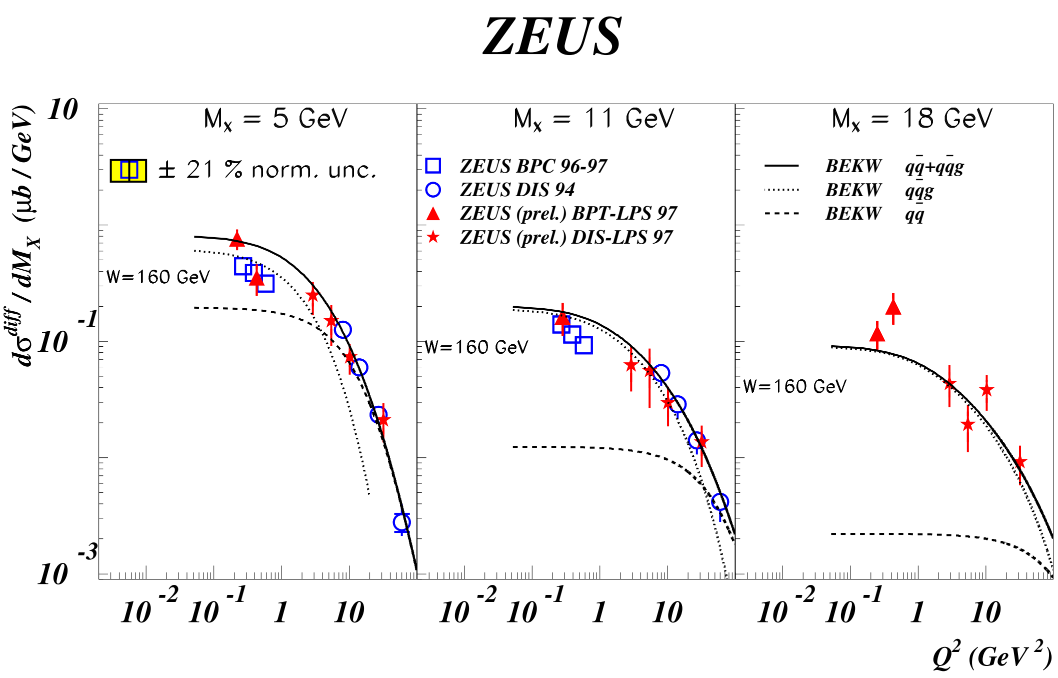
Data using new forward plug calorimeter

$\longrightarrow$ M_X range increased by a factor of 1.7 !!!

$\longrightarrow$ $2.2 < Q^2 < 80$ GeV^2

$\longrightarrow$ Background from double dissociation is reduced.

New FPS Measurements from ZEUS



- This is a very important measurement to study the γ p - DIS transition region!
- $0.03 < Q^2 < 0.6$ GeV^2
- Below $Q^2 \sim 1GeV^2$ cross-section becomes constant.
- At higher Q^2, data shows scaling behaviour $1/Q^2$.
- The data is compared to a dipole model by Bartels *et al.*

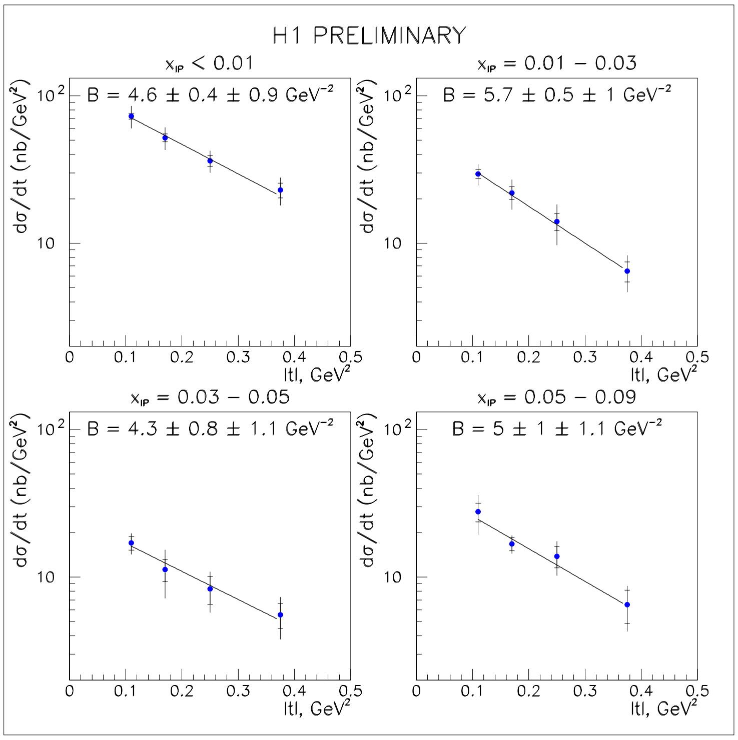
$\longrightarrow$ need both qq and qqg contributions

t measurement

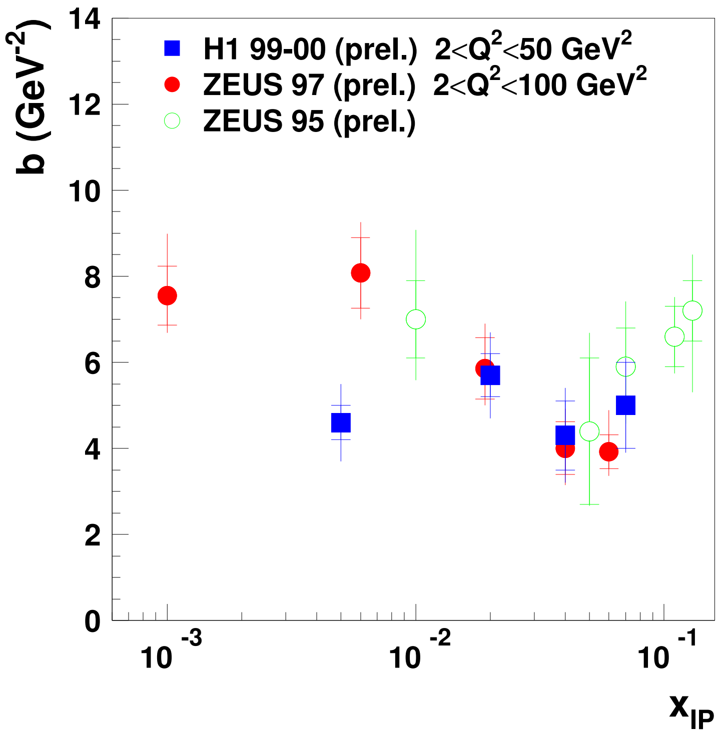
Exponential fit to the t distribution:

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

range of meas. : -0.4 $\lesssim t < |t|_{min}$



b is proportional to the interaction radius: $b = R^2/4$



Regge theory $\longrightarrow$ shrinkage: $b = b_0 + 2\alpha' \log \frac{1}{x_{I\!P}}$ and $x_{I\!P} \sim M_X^2/W_{\gamma p}^2$

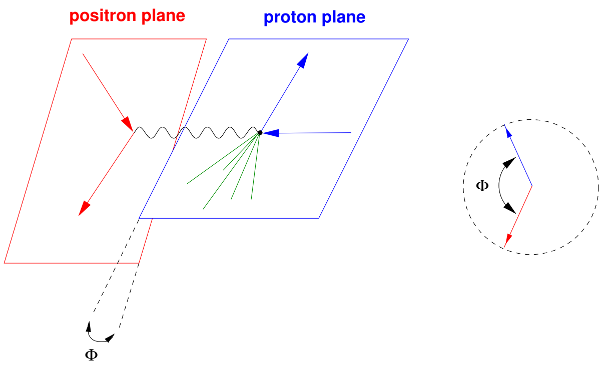
No visible dependence on $x_{I\!P}$ is visible within errors $\longrightarrow$ no shrinkage

ϕ from ZEUS LPS ($Q^2 > 2$ GeV^2)

This measurement gives information on the helicity structure!

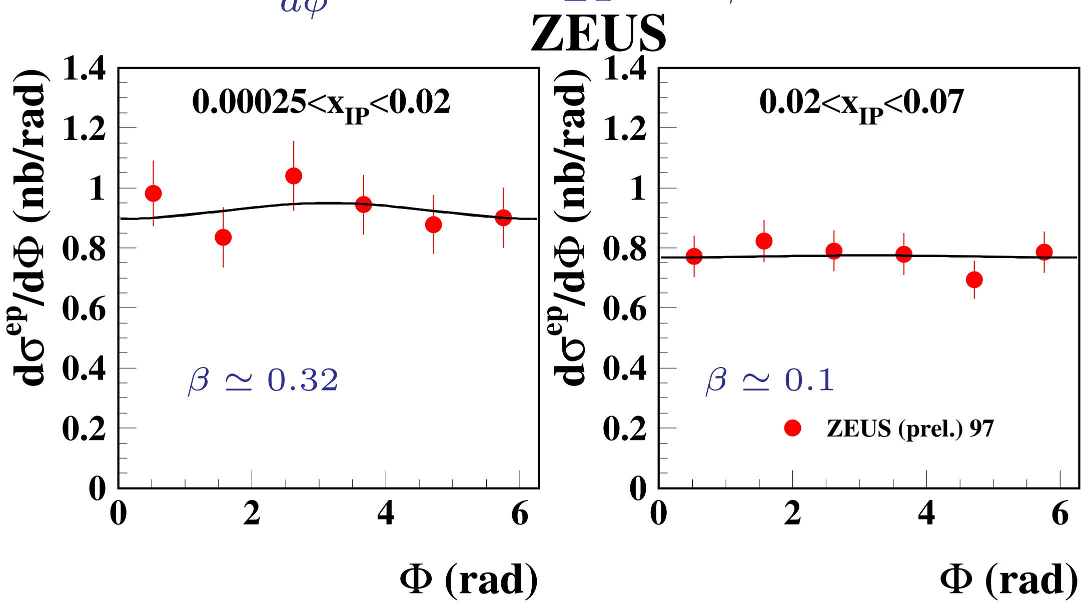
Φ = Azimuthal $\angle$ between

p and e scattering planes



$$\frac{d\sigma^D}{d\phi} \approx \sigma_T^D + \epsilon\sigma_L^D - 2\sqrt{\epsilon(1+\epsilon)}\sigma_{LT}^D \cos\phi - \epsilon\sigma_{TT}^D \cos 2\phi$$

Perform fit: $\frac{d\sigma^D}{d\phi} \approx 1 + A_{LT}\cos\phi$



$A_{LT} = -0.029 \pm 0.066^{+0.026}_{-0.047}$ $A_{LT} = -0.005 \pm 0.052^{+0.048}_{-0.047}$

$\longrightarrow$ The interference between the transverse and longitudinal polarisation of the photon is small in the measured region.

High $\beta (\gtrsim 0.9)$ where theory predicts a large assymmetry is not covered due to the complexity of the measurement.

Pomeron Intercept

Comparison of eff ective $\alpha_{\mathbb{P}}(0)$ from F_2 and F_2^{D3}

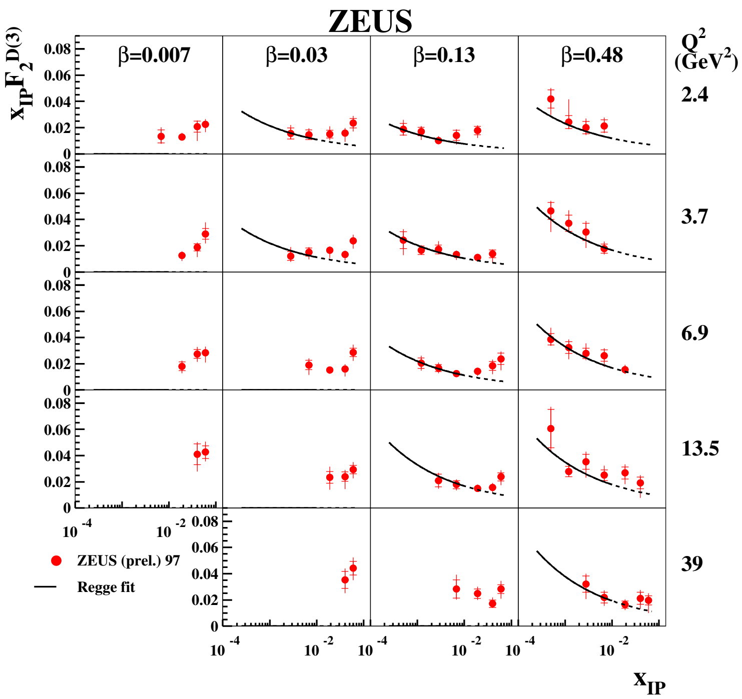
Regge fit

used to extract

$\alpha_{\mathbb{P}}(0)$

subleading exchange

shows up at high $x_{I\!P}$



$F_2 \sim x^{-\lambda}$

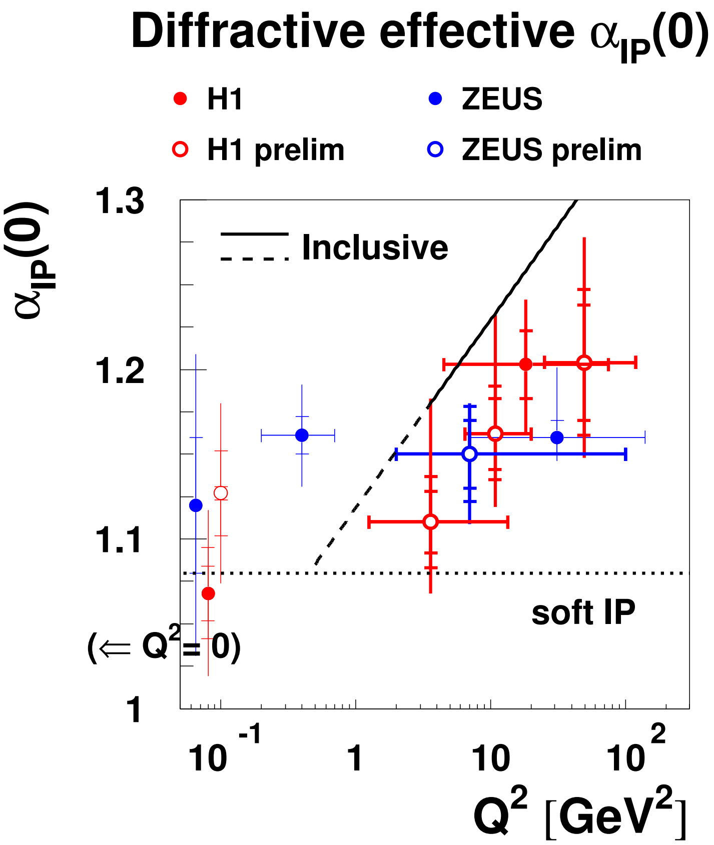
Regge theory

predicts for fixed $<< Q^2$:

$\lambda = \alpha_{\mathbb{P}} - 1 \simeq 0.08$

whereas for diffr.

$x_{I\!P} F_2 \sim x^{-2(\alpha_{x_{I\!P}} - 1)}$



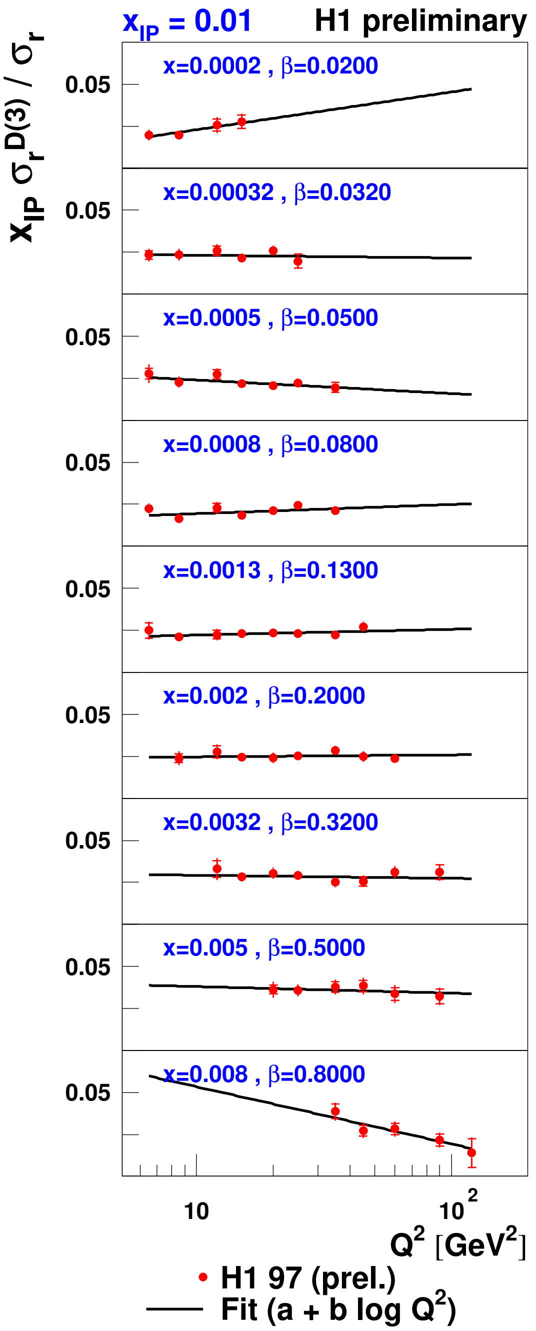
Indications for increase of $\alpha_{\mathbb{P}}(0)$ with Q^2 in diffraction ???

H1 Ratio Diffractive/Inclusive

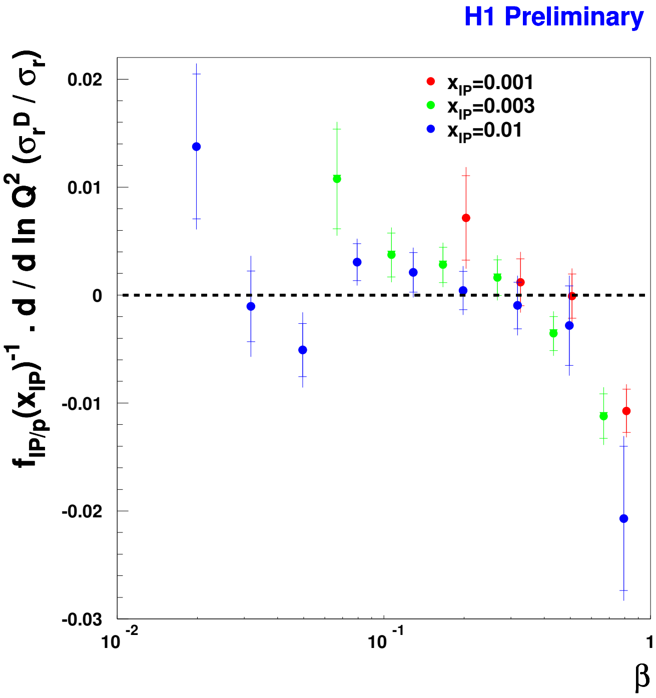
Aim is to compare dynamics of diffr. and non-diffr. scattering

log Q^2 dependence at fixed $x_{\mathbb{P}}$:

$$\frac{\sigma_r^{D(3)}(x,Q^2,x_{\mathbb{P}})}{\sigma_r(x,Q^2)}\Big|_{x,x_{\mathbb{P}}} \sim A_R + B_R \log Q^2$$



$\mathbb{P}$ flux is factored out



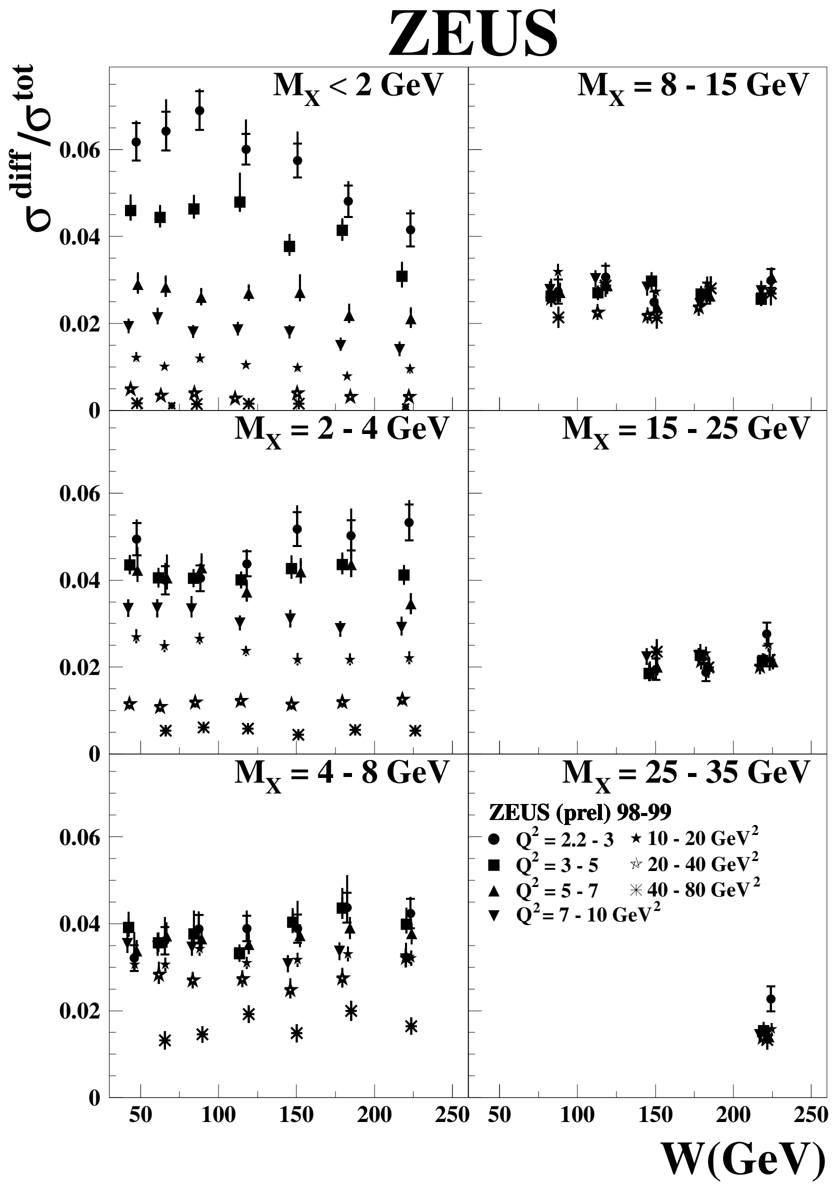
Low $\beta \longrightarrow$ relatively flat:

- ratio of diff. g(x,Q^2) to incl. g(x,Q^2) $\sim$ const
- dipole models ok if $\sigma_{dip.} \propto R$

High $\beta \sim 1 \longrightarrow$ falling:

- Q^2 suppressed higher twist (pert. 2-g exchange)
- DGLAP evolution (g radiation)

ZEUS Ratio Diffractive/Inclusive



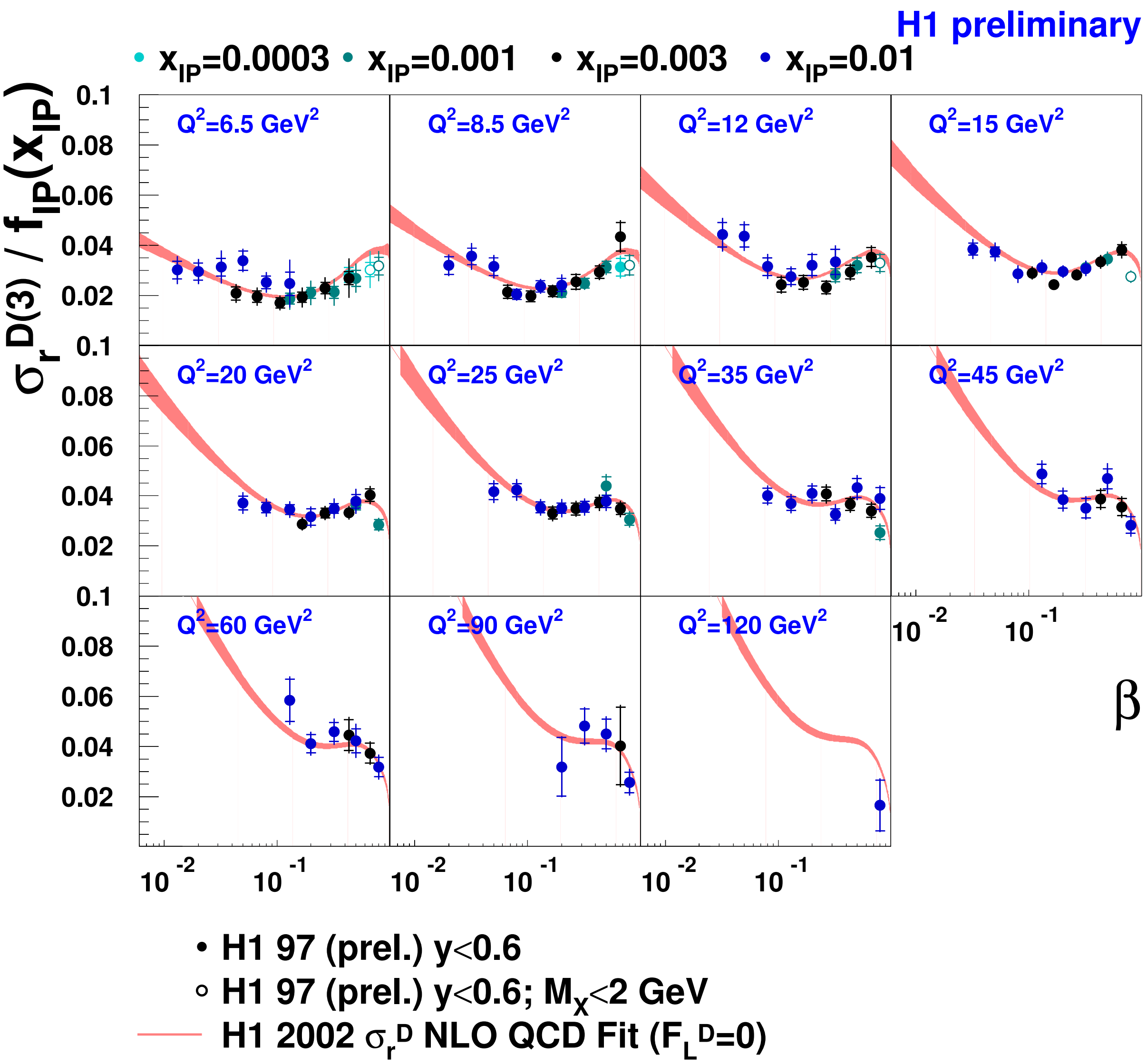
Ratio of diffractive σ to total virtual $\gamma - p$ σ:

Similar features observed as H1:

- Little Q^2 dependence at high M_X ($\sim$ low β)
- Strong Q^2 (negative) dependence at small M_X ($\sim$ high β)

$M_X < 4GeV$ region is presumably dominated by light quark production and for $M_X > 4GeV$ contribution from open charm might be present.

The H1 β, Q^2 dependences and NLO fit



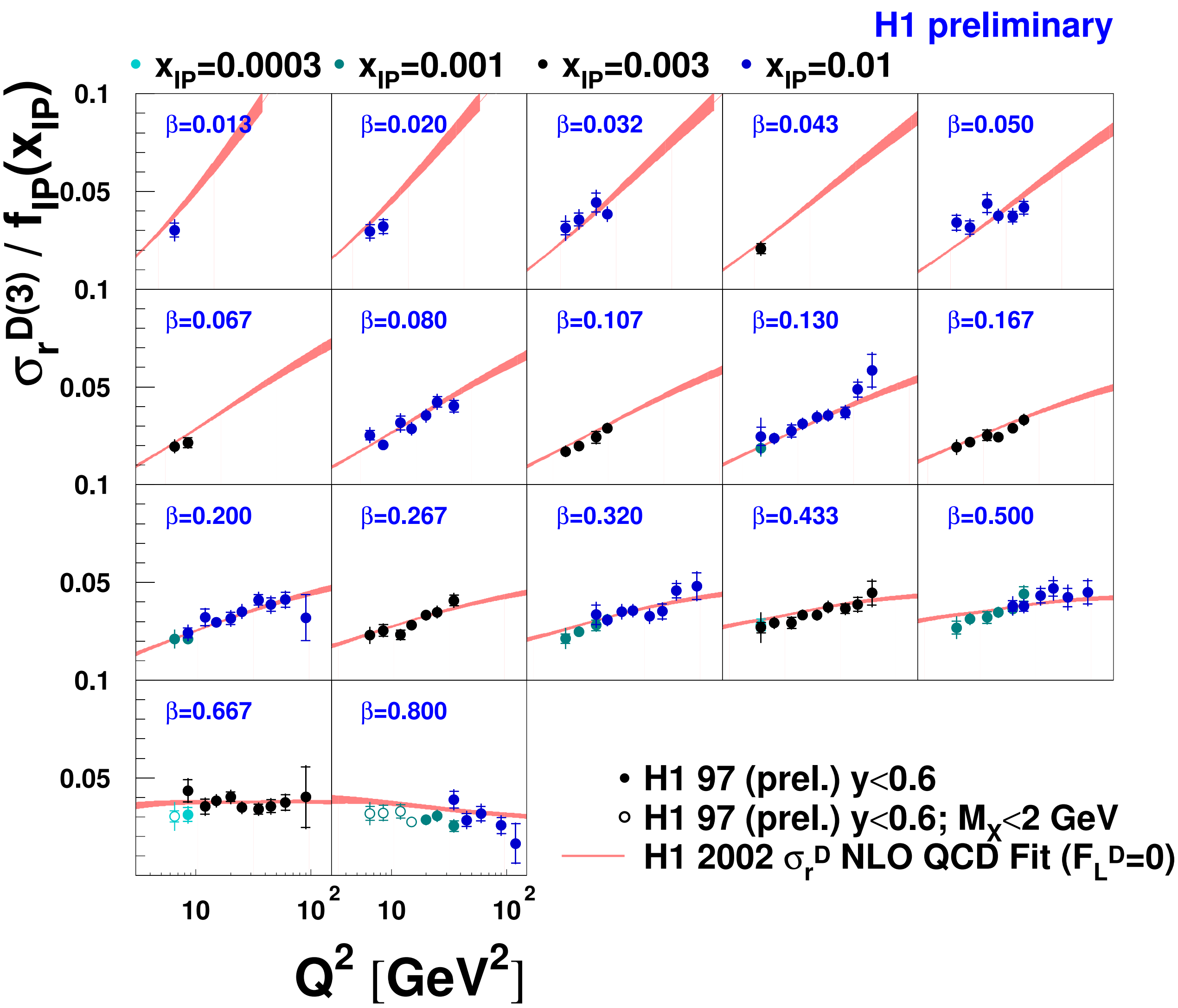
β is equivalent to x in DIS

β dependence $\sim \sum_i e_i^2 (q_i^D + \bar{q}_i^D)$

$x_{I\!P}$ dependence taken out as factor. holds for $x_{I\!P} < 0.01$

NLO DGLAP fit reproduce rising of σ^D at low Q^2 for $\beta \longrightarrow 1$

The H1 β, Q^2 dependences and NLO fit II

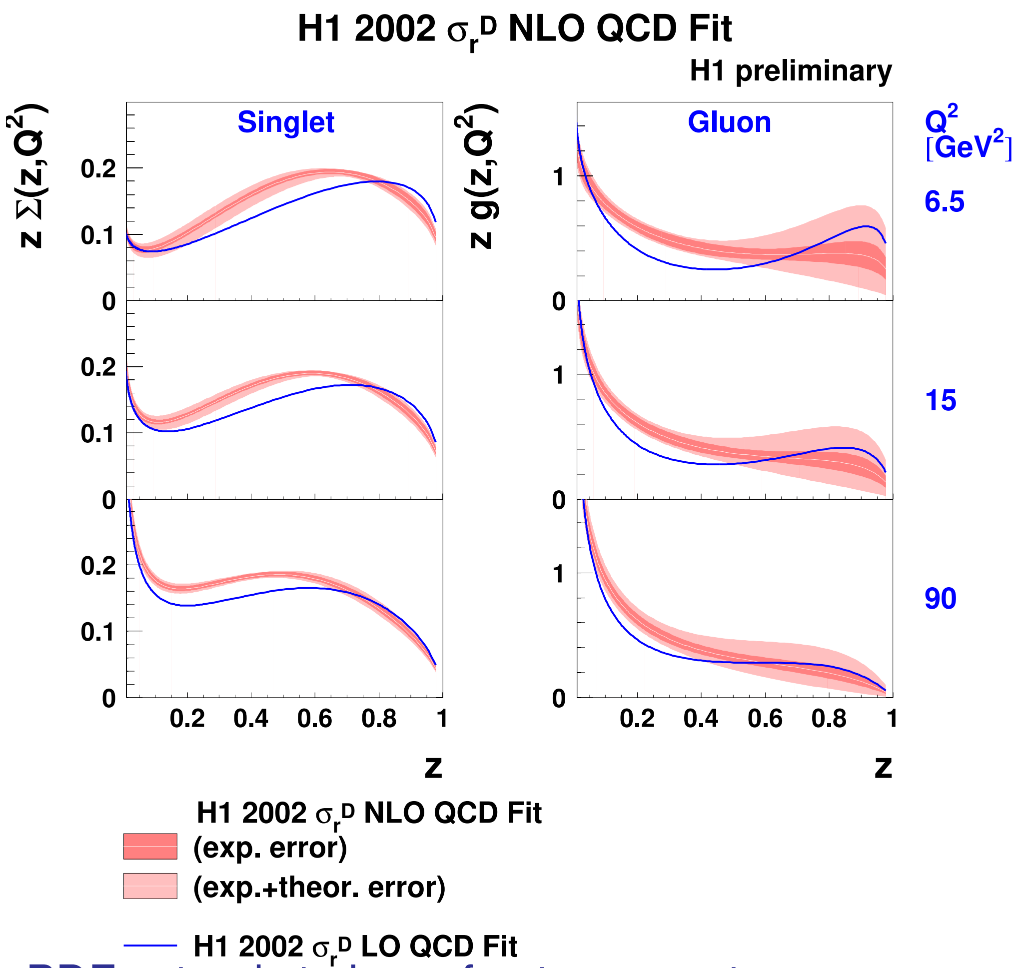


Q^2 dependence $\sim \alpha_s \otimes g^D(\beta, Q^2)$

Positive scaling violation except for largest β.

Diffractive Parton Densities

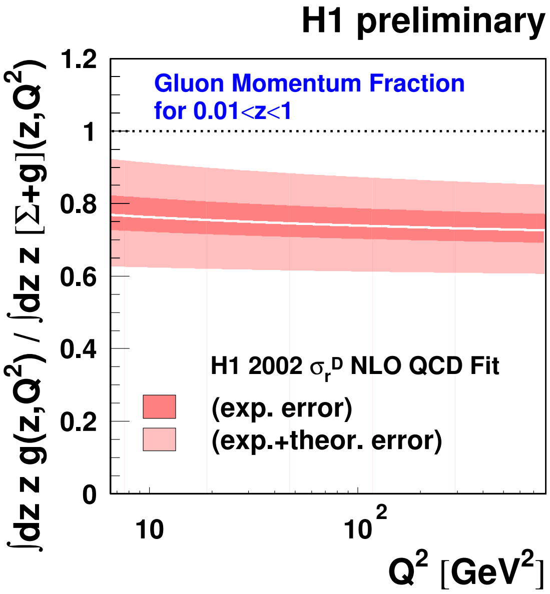
- Usually assume Regge factorisation for $x_{\mathbb{P}}$ dependence.
- Single Σ and gluon g parameterized at $Q_0^2 = 3GeV^2$
- NLO DGLAP evolution - Fit data for $Q_0^2 > 6.5GeV^2$ and $M_X > 2GeV$
- Exp. and theor. uncertainties are propagated for the first time !!!



- PDF extends to large fract. momenta z
- Gluon dominated
- Substantial uncertainty at highest z

Gluon Fraction and F_L^D

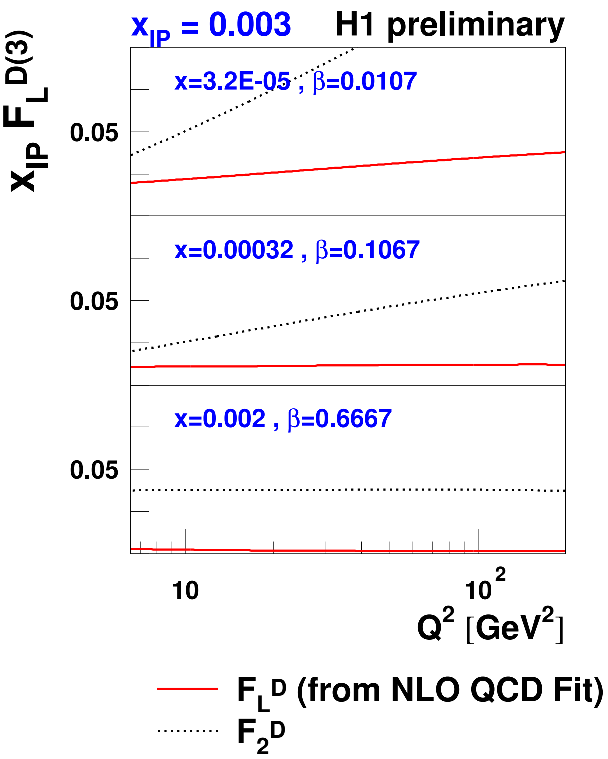
Integrate p.d.f's over measured range:



Momentum fraction of diffractive exchange carried by g:

$$75 \pm 15\%$$

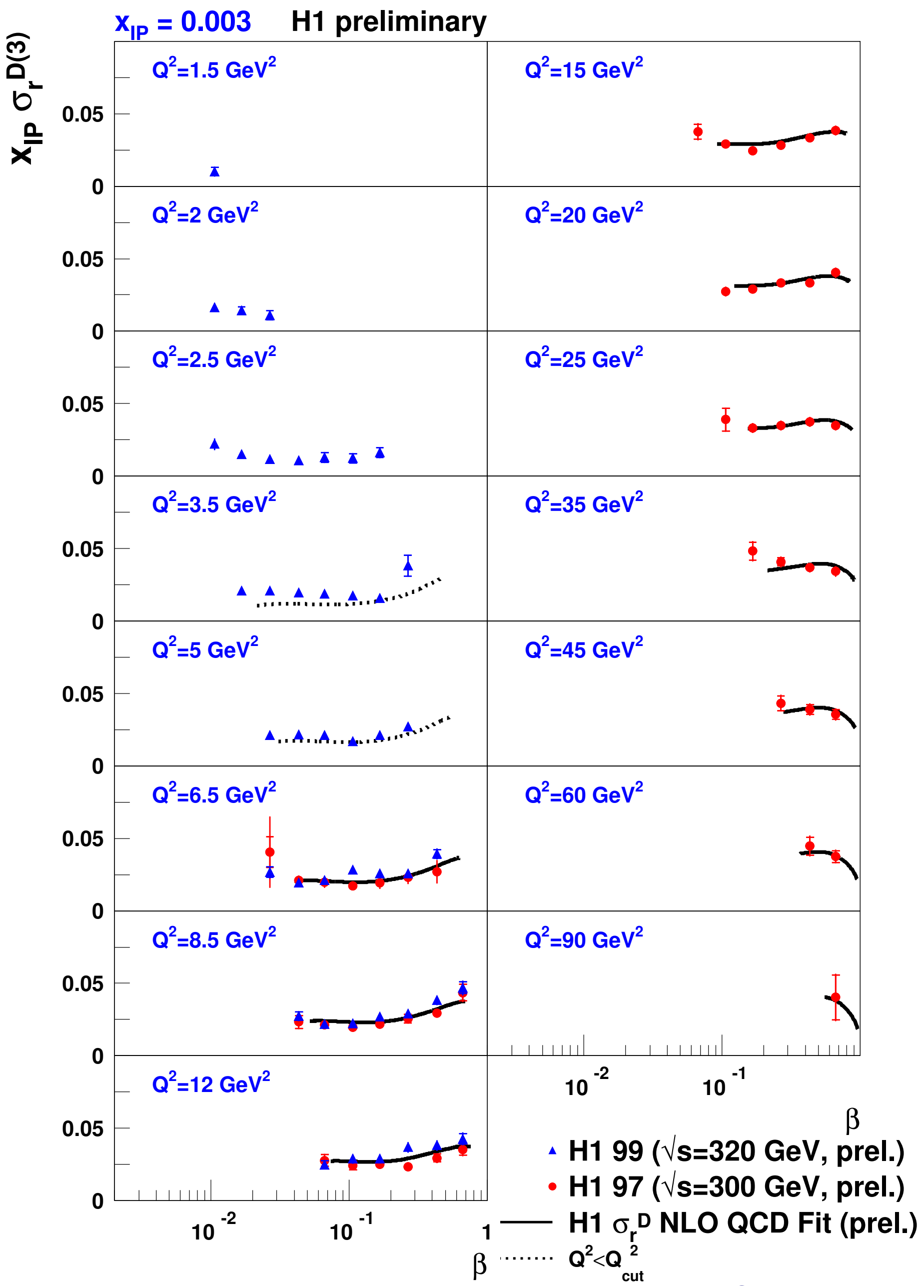
$$F_L^D \sim \frac{\alpha_s}{2\pi}[C_q^L \otimes F_2^D + C_q^L \otimes \sum_i e_i^2 z g^D(z, Q^2))$$



F_L^D large at low Q^2, low β

H1 NLO QCD fit: β dependence

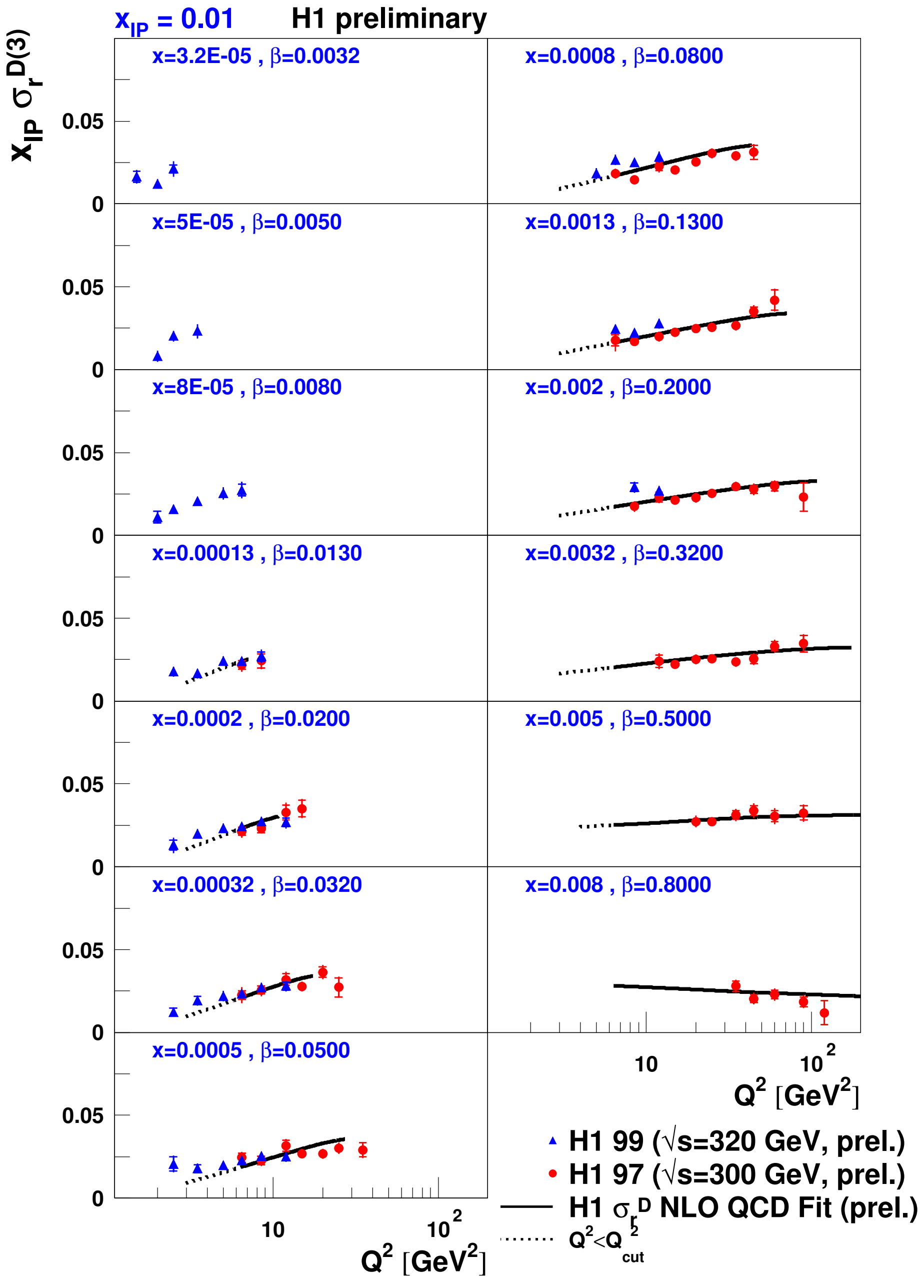
Example: data at $x_{I\!P} = 0.003$



- Rising behaviour for $\beta \to 1$ at low Q^2 reflected by $\Sigma(\beta, Q^2)$.
- QCD fit to data for $Q^2 > 6.5GeV^2$.
- Indication of breakdown of QCD fit at $Q^2 = 3.5GeV^2$.
- need more low Q^2 to getter better constraint.

H1 NLO QCD fit: Q^2 dependence

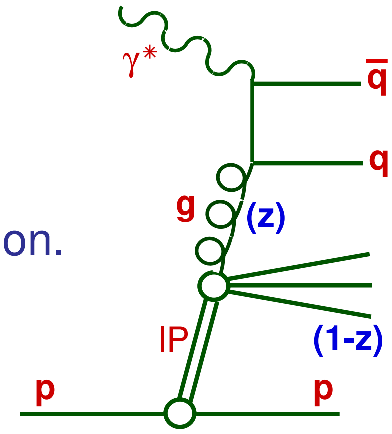
Example data: at $x_{I\!P} = 0.01$



- Q^2 scaling violations are well constrained by the data
- Rising except at highest β
- Well reproduced by QCD fit for $Q^2 > 3.5GeV^2$

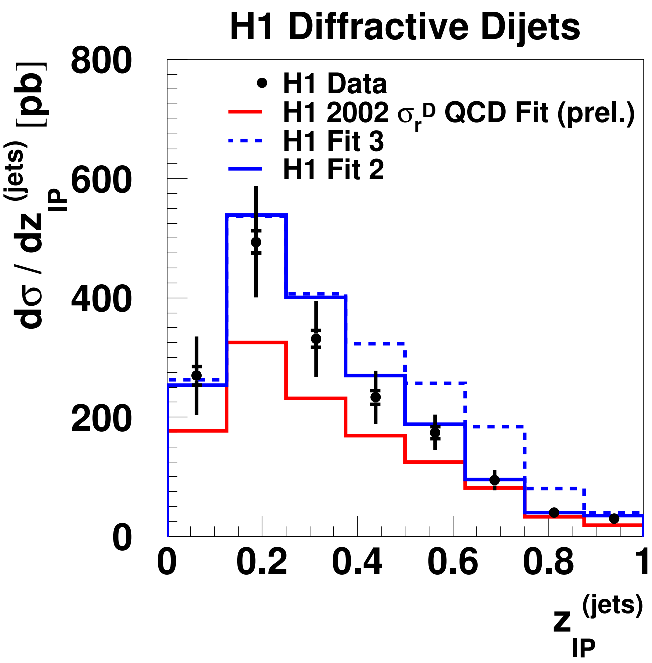
Diffractive Final State Data

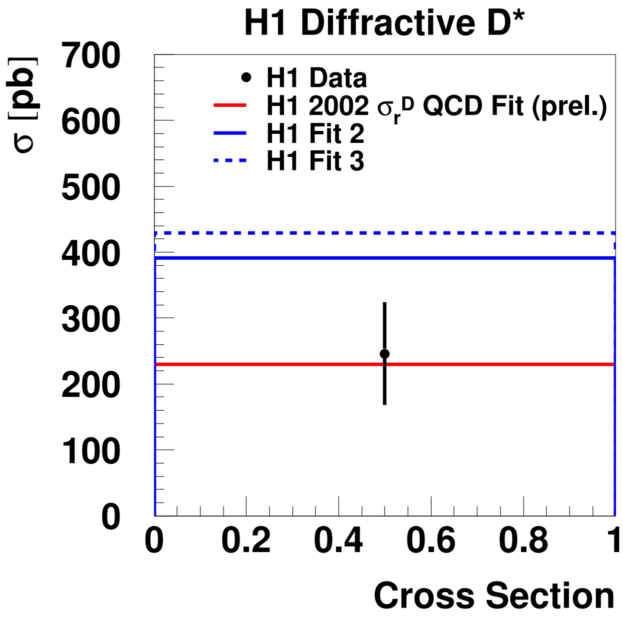
Test factorisation $\Rightarrow$ use p.d.f. from LO fit to predict dijet and open charm cross-sections.



These processes are very sensitive to the gluon density!

Production mechanism is boson-gluon fusion.



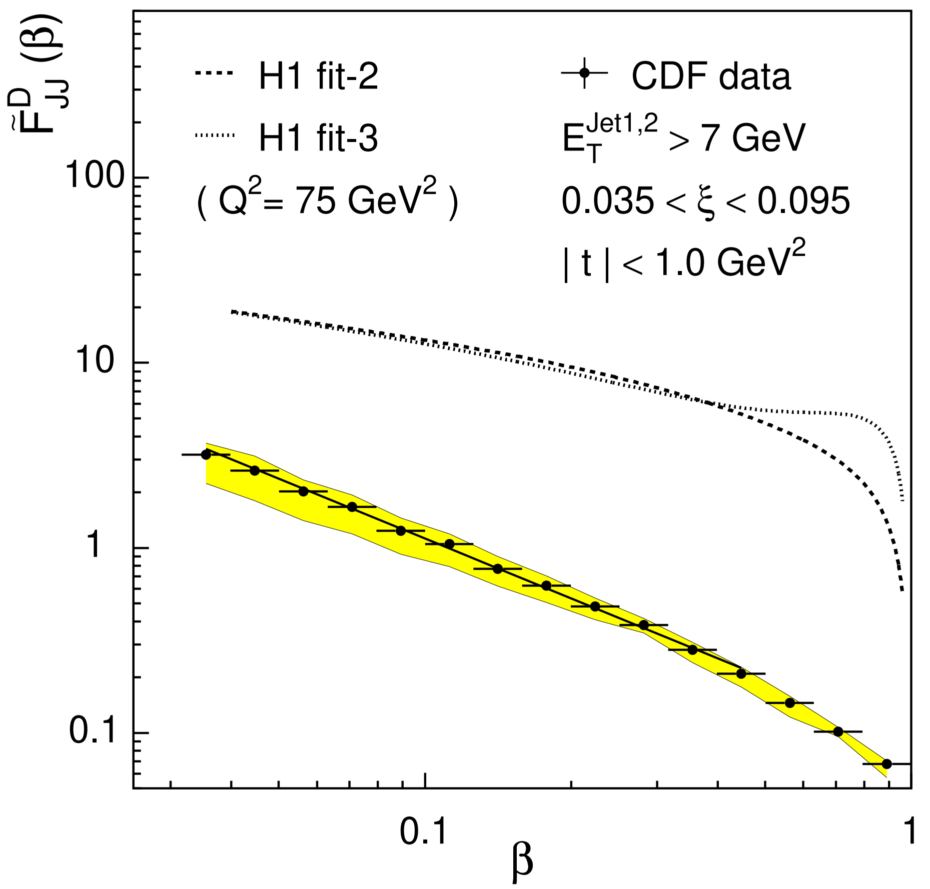


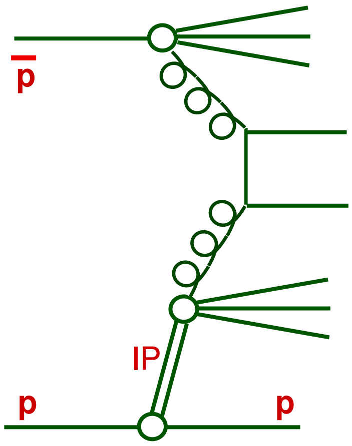
- H1 fit 2 (‘flat’ gluon) works spectacularly well.
- Very good description of the QCD of the D^*
- Good description in shape of the QCD of the dijets

$\Rightarrow$ No evidence of breakdown of factorisation in diffractive DIS!

How Universal are Diffractive Partons?

Model Tevatron diffractive dijets using $\mathbb{P}$ partons from F_2^D.





Prediction inconsistent in both shape and normalisation.

Yet, no conflict with theory: Factorisation is not valid for hadron-hadron collision.

Deeper understanding of 'gap survival' needed to explain connection between diffractive DIS and hadronic diffraction.

Conclusions

- HERA is an ideal laboratory to study hard diffraction. Data from H1 and ZEUS covers a wide kinematic range and is of high precision!
- $\alpha_{\mathbb{P}}(0)$ is higher than the value predicted by Donnachie and Landshoff, might it increase with Q^2?
- The ratio of diffractive to inclusive cross-section is flat over a wide kinematic range except at the highest β, is this due to higher twist effects?
- The QCD factorisation theorem is confirmed by the data.
- p.d.f allow to make powerful predictions and error estimates are now included!
- Diffraction offers still many challenges...