# Inclusive Diffraction at HERA

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**[DESY]**

**Representing the**

**Collaborations at HERA**

**ICHEP 2002**
**Amsterdam, July 24th-31st, 2002**

**Parallel Session:**
**QCD - Soft Interactions**

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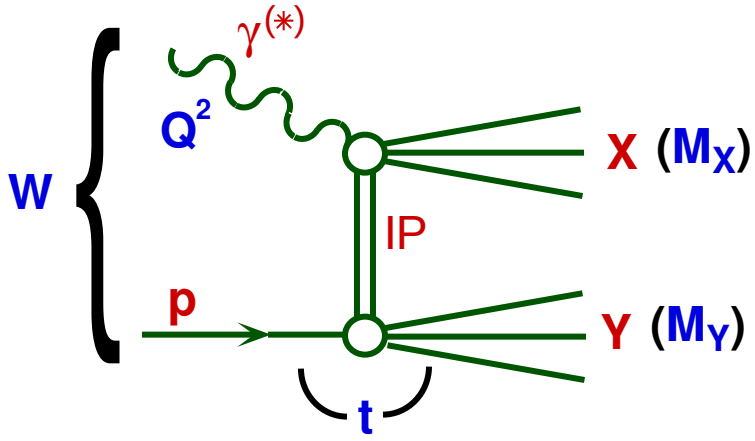



**Highlights:**

- **New generation of high precision data from H1 and ZEUS**
- **NLO QCD interpretation: diffractive parton distributions with uncertainties**

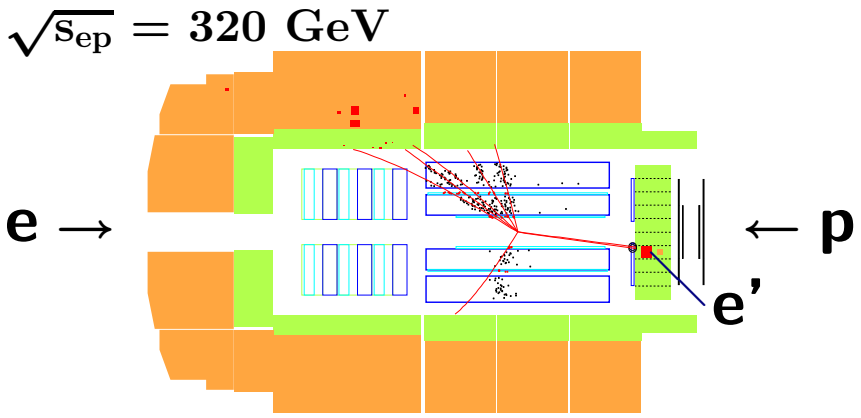
# Introduction

**A challenge in QCD at high energies:**

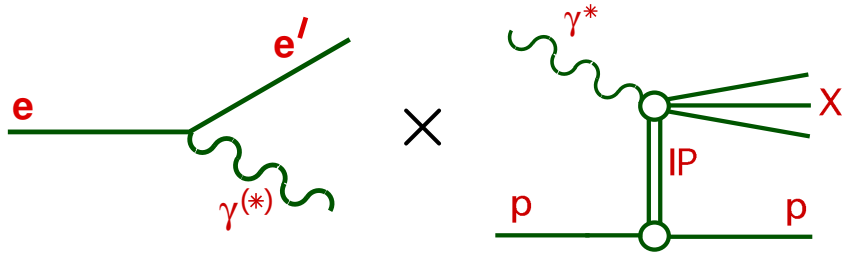
- Description of colour singlet exchange or diffractive processes
- Closely related to rising total cross sections and confinement

**HERA: An ideal laboratory to study hard diffraction:**

**$10\%$ of low-x DIS events are diffractive:**



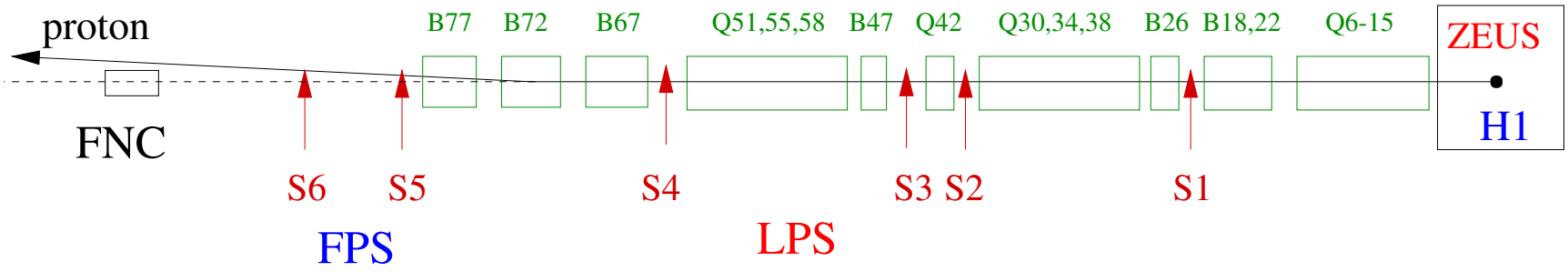

**Can be viewed as diffractive $\gamma^* p$ interaction:**



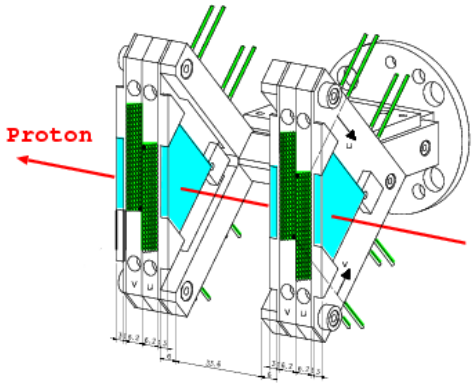

- Probe QCD structure of colour singlet exchange with virtual photon
- In QCD: at least two partons in net colour singlet state (e.g. 2 gluons)
- Increased sensitivity to low-x limit of proton structure

$$W^2_{\gamma p} \sim \frac{1}{x_{bj}}$$

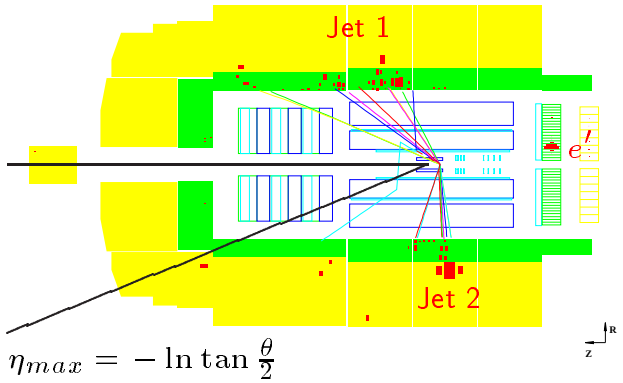
# Experimental Techniques




## Forward Proton Spectrometers at $z = 24...90$ m




## Rapidity Gap Selection in central detector



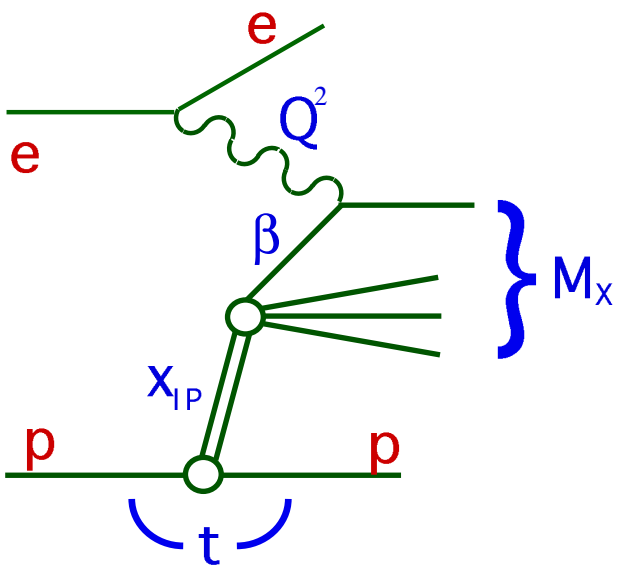

## Measure leading proton

- Free of dissociation bkgd.
- Measure $p$ 4-momentum
- low statistics (acceptance)

## Require large rapidity gap

- $\Delta\eta$ large when $M_{\text{central}} \ll W_{\gamma p}$
- integrate over outgoing $p$ system
- high statistics

# Diffractive Cross section and Structure Functions




$x_{I\!P} = \xi = \frac{Q^2+M_X^2}{Q^2+W^2} = x_{I\!P/p}$
(momentum fraction of colour singlet exchange)

$\beta = \frac{Q^2}{Q^2+M_X^2} = x_{q/I\!P}$
(fraction of exchange momentum of $q$ coupling to $\gamma^*$, $x = x_{I\!P}\beta$)

$t = (p - p')^2$
(4-momentum transfer squared)

**Diffractive reduced cross section $\sigma_r^D$:**

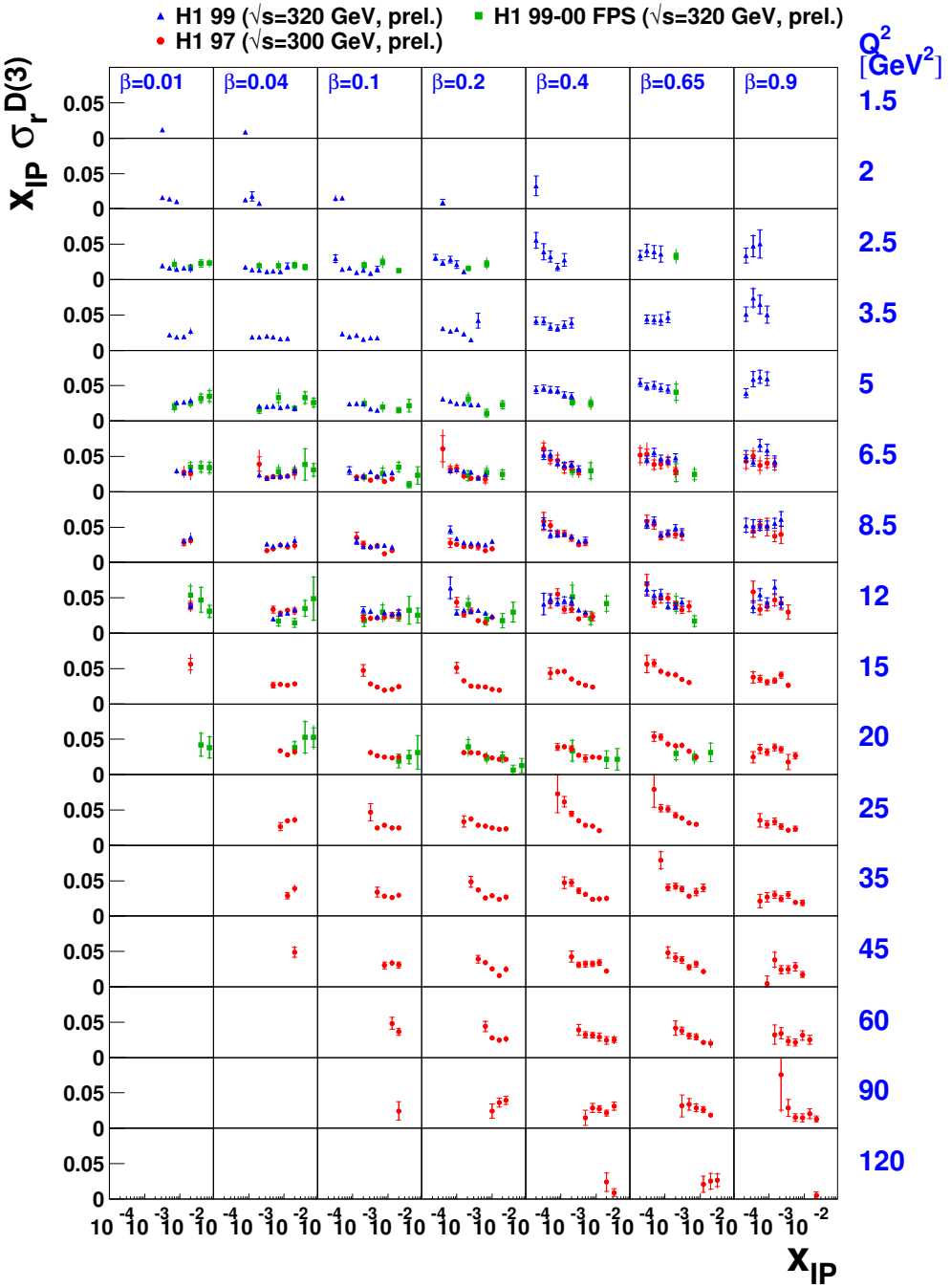
$$\frac{d^4\sigma}{dx_{I\!P}\ dt\ d\beta\ dQ^2} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right)\sigma_r^{D(4)}(x_{I\!P}, t, \beta, Q^2)$$

**Structure functions $F_2^D$ and $F_L^D$:**

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

Integrated over $t$: $F_2^{D(3)} = \int dt\ F_2^{D(4)}$

– Longitudinal $F_L^D$: affects $\sigma_r^D$ at high y [$\gamma$ inelasticity $y = Q^2/sx$]
– If $F_L^D = 0$: $\sigma_r^D = F_2^D$




## New Measurements: H1

- $1.5 < Q^2 < 12$ GeV$^2$
- $6.5 < Q^2 < 120$ GeV$^2$

  New measurements based on rapidity gap method

– Statistics improved by factor 5

- $2.5 < Q^2 < 20$ GeV$^2$

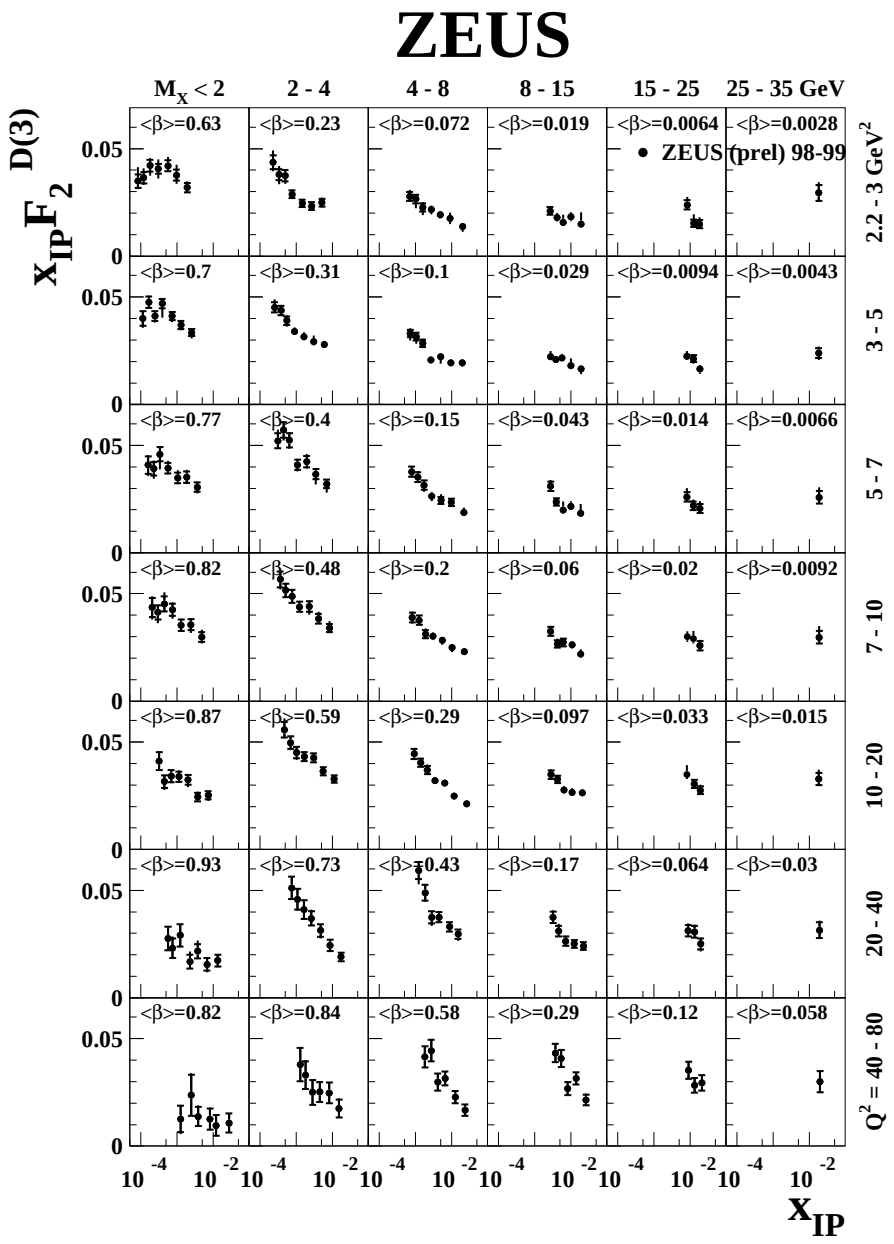
  New measurement using H1 FPS (Forward Proton Spectrometer)

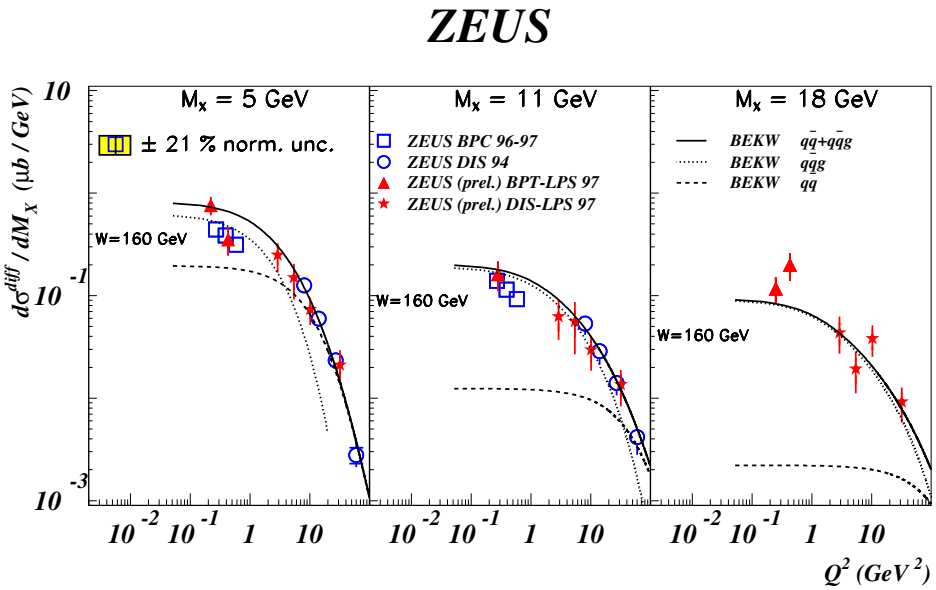
– Agreement between methods

High precision measurements of $\beta$ (or $x$) and $Q^2$ dependences

$\Rightarrow$ DGLAP QCD interpretation

# New Measurements: ZEUS




- **(top) New LPS data**
  **(Leading Proton Spectrometer)**
  **In transition region ($\gamma p$ – DIS)**
  $0.03 < Q^2 < 0.6$ GeV$^2$

- **(left) New data using improved forward calorimeter**
  $2.2 < Q^2 < 80$ GeV$^2$

# Factorization in Diffraction

## Proof of QCD Factorization for diffractive DIS:

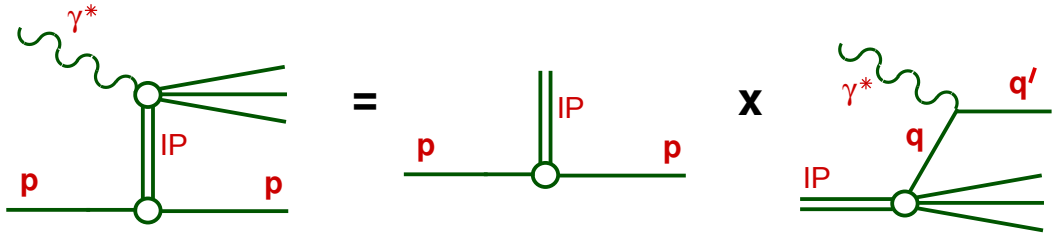
- Diffractive parton distributions (Trentadue, Veneziano, Berera, Soper, Collins, ...):

$$\frac{d^2\sigma(x,Q^2,x_{I\!P},t)^{\gamma^* p\to p' X}}{dx_{I\!P}\ dt} = \sum_i \int_x^{x_{I\!P}} d\xi \hat{\sigma}^{\gamma^* i}(x,Q^2,\xi)\ p_i^D(\xi,Q^2,x_{I\!P},t)$$

- $\hat{\sigma}^{\gamma^* i}$ hard scattering part, as in incl. DIS
- $p_i^D$ diffractive PDF's in proton, conditional probabilities, valid at fixed $x_{I\!P}, t$, obey (NLO) DGLAP

## Regge Factorization / 'Resolved Pomeron' model:

$x_{I\!P}, t$ dependence factorizes out (Donnachie, Landshoff, Ingelman, Schlein, ...):




$$F_2^D(x_{I\!P},t,\beta,Q^2) = f_{I\!P/p}(x_{I\!P},t)\ F_2^{I\!P}(\beta,Q^2)$$

- additional assumption, no proof !
- consistent with present data if sub-leading $I\!R$ included

Shape of diffr. PDF's indep. of $x_{I\!P}, t$, normalization controlled by Regge flux $f_{I\!P/p}$

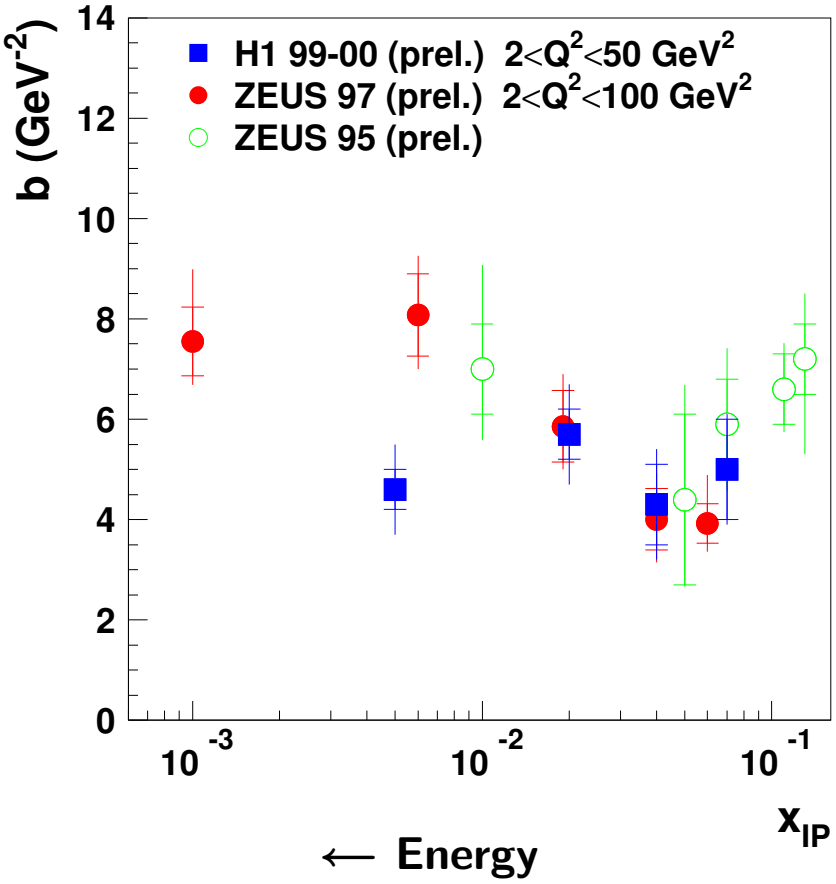
# Forward Proton Detectors: $t$ Measurement

$\frac{d\sigma}{d|t|}$ measured for $-0.4 \lesssim t < |t|_{\min}$

Exponential fit to $t$ distribution:

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

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

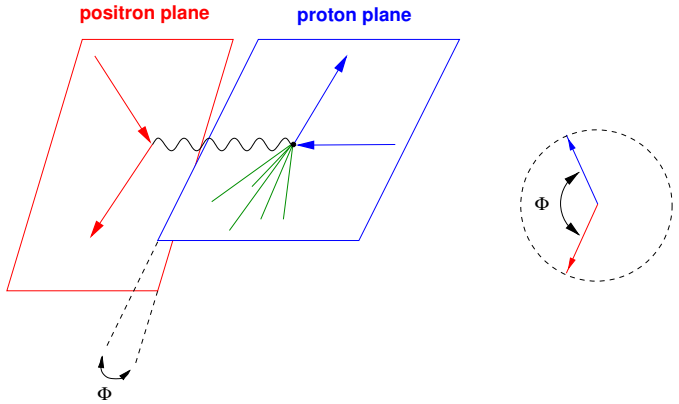



In Regge phenomenology expect 'shrinkage':
(proton gets 'bigger' with increasing energy) $b = b_0 + 2\alpha' \log \frac{1}{x_{I\!P}}$ $x_{I\!P} \sim M_X^2/W_{\gamma p}^2$

So far inconclusive ...

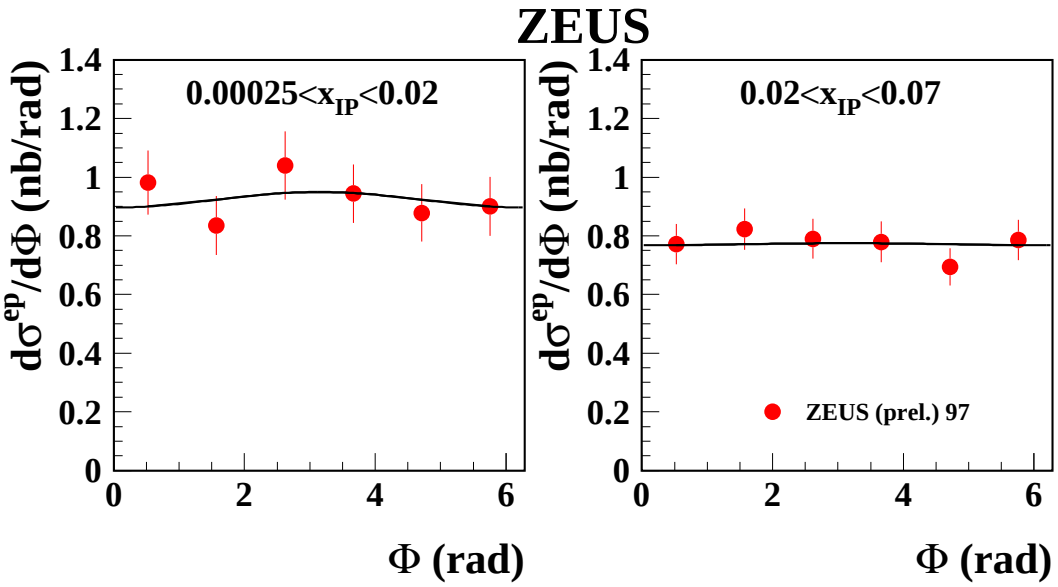
# Forward Proton Detectors: $\phi$ Measurement

**$\Phi$: Azimuthal angle between electron and proton scattering planes**




**$\frac{d\sigma^D}{d\Phi}$ sensitive to $\sigma_L^D$ through interf. term:**

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




**Measured asymmetries from fit $\frac{d\sigma}{d\Phi} \sim 1 + A_{LT}\cos\Phi$:**

$A_{LT} = -0.029 \pm 0.066^{+0.026}_{-0.047}$
$(0 \lesssim x_{I\!P} < 0.02\ ;\ \beta \approx 0.32)$

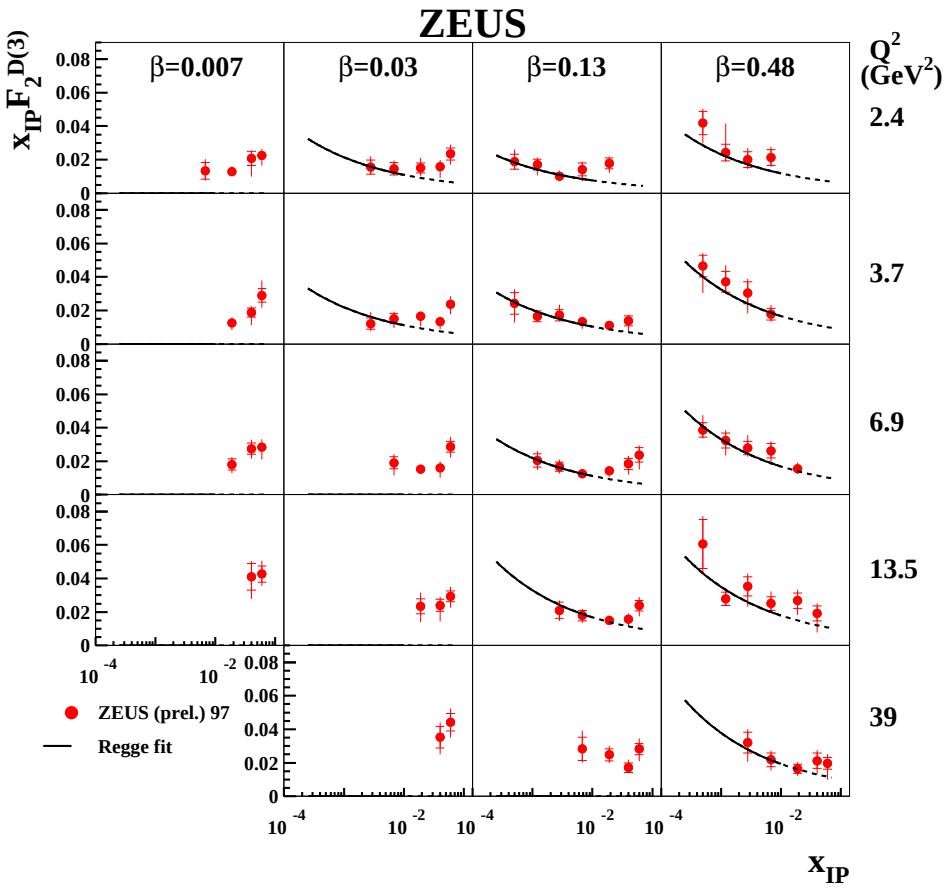
$A_{LT} = -0.005 \pm 0.052^{+0.048}_{-0.047}$
$(0.02 < x_{I\!P} < 0.07\ ;\ \beta \approx 0.1)$

**$\Rightarrow$ Interference term small in measured region**

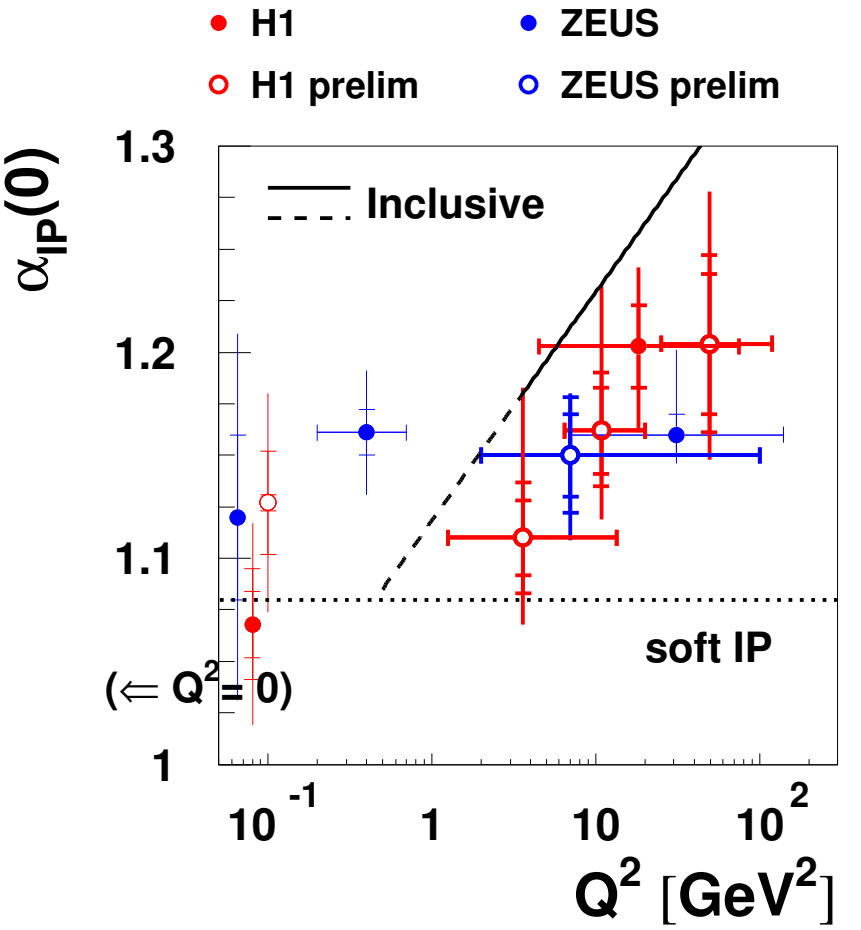
**[Interesting high $\beta$ region (pert. 2-gluon exch. predicts large asymmetry) not yet explored]**

# Energy dependence and $\alpha_{I\!P}(0)$

## Example: ZEUS LPS data




## Diffractive effective $\alpha_{IP}(0)$



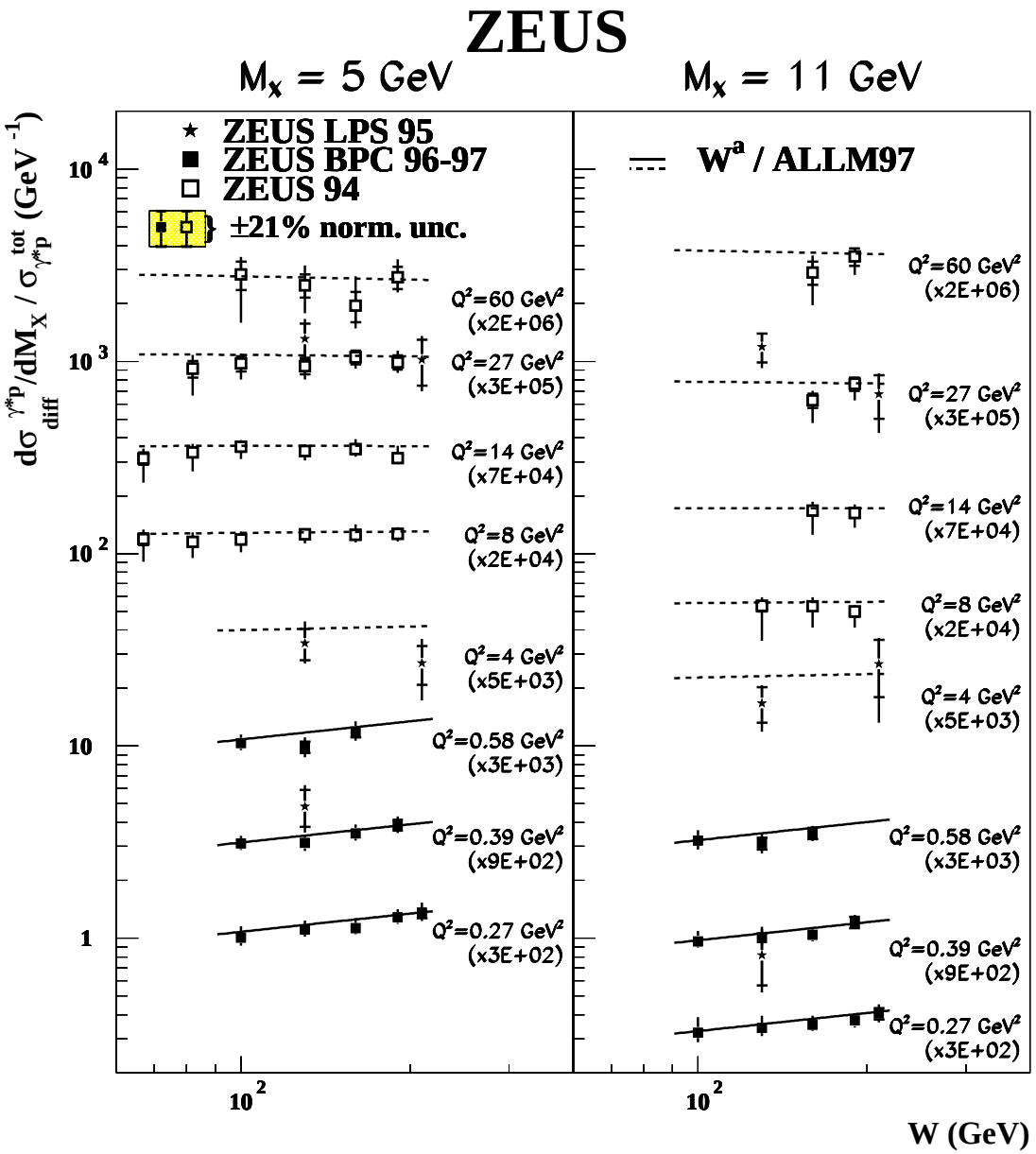

## Fit to $x_{I\!P}$ dependence:

$$F_2^D(x_{I\!P}, \beta, Q^2) = \left(\frac{1}{x_{I\!P}}\right)^{2\overline{\alpha_{I\!P}}-1} \cdot A(\beta, Q^2)$$

## Indications for increase with $Q^2$ ?

Naive expectation $\alpha_{I\!P}^{\mathrm{diff}\cdot}(0) = 2\ \alpha_{I\!P}^{\mathrm{inc}}(0)$ fails in DIS region?

# Ratio Diffractive / Inclusive: Energy Dependence




**Study Ratio $R(W)|_{Mx,Q^2}$:**

$$R = \frac{\int \mathrm{d}t \; (\mathrm{d}\sigma_D^{\gamma p}/\mathrm{d}M_X)}{\sigma_{tot}^{\gamma p}}$$

$$\sim \frac{\left(W^2\right)^{2(\overline{\alpha_{I\!P}}-1)}}{(W^2)^{(\alpha_{I\!P}-1)}} \sim W^{\rho}$$

**– transition region:**

$\rho = 0.24 \pm 0.07$ **(stat.)**

**Steeper for diffractive than inclusive**

**⟶ Regge-like**

**– DIS regime:**

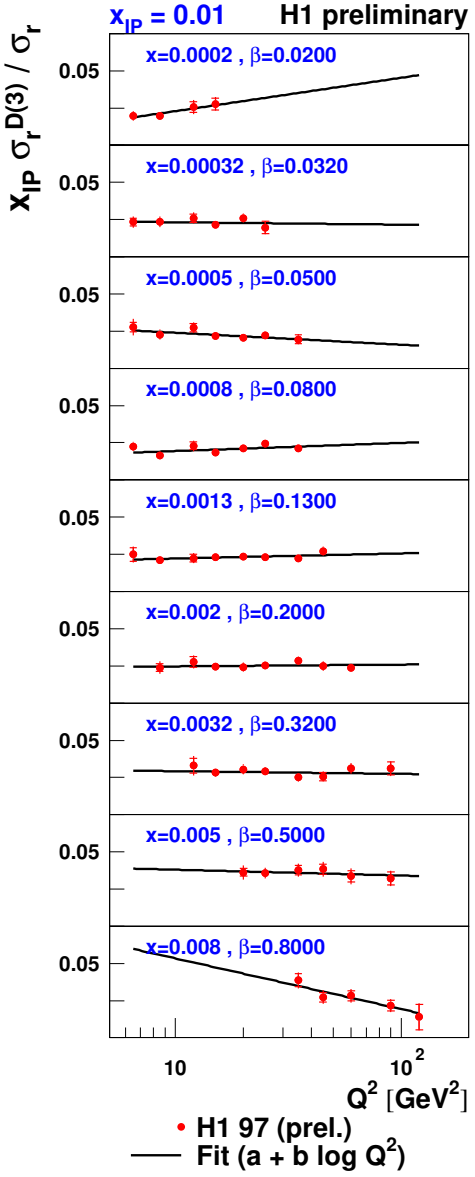
$\rho = 0.00 \pm 0.03$ **(stat.)**

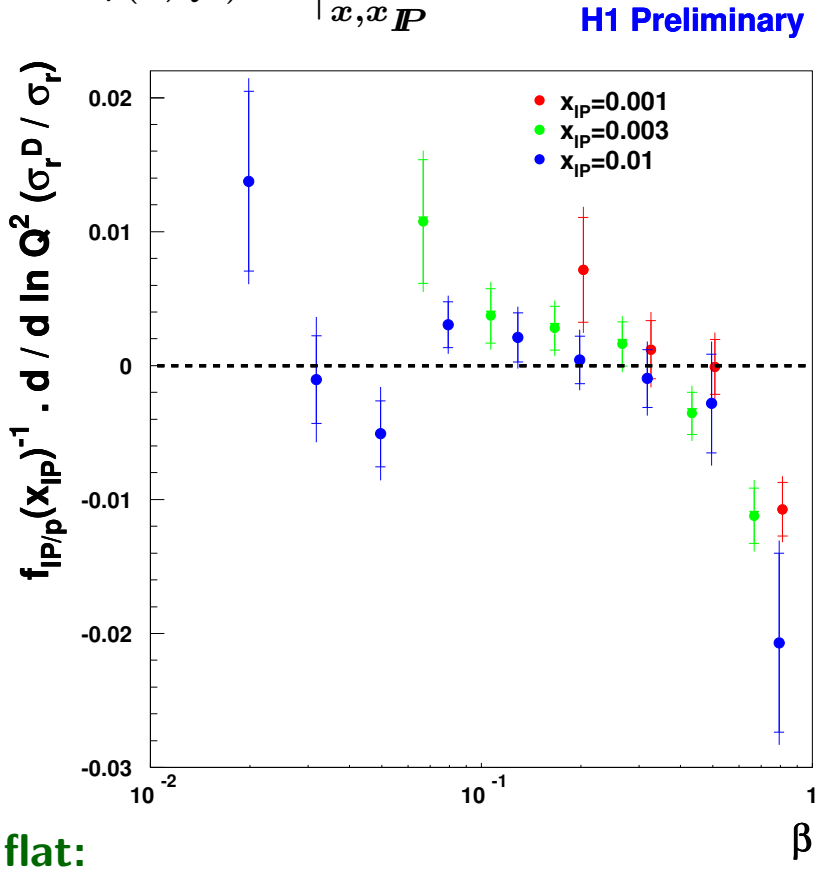
**Same energy dependence**

**⟶ not Regge-like**

# Diffractive / Inclusive: Q2 dependence from H1

**Logarithmic $Q^2$ dependence of the ratio** $\left.\frac{\sigma_r^{D(3)}(x,Q^2,x_{I\!P})}{\sigma_r(x,Q^2)}\right|_{x,x_{I\!P}} \sim A_R + B_R \log Q^2$



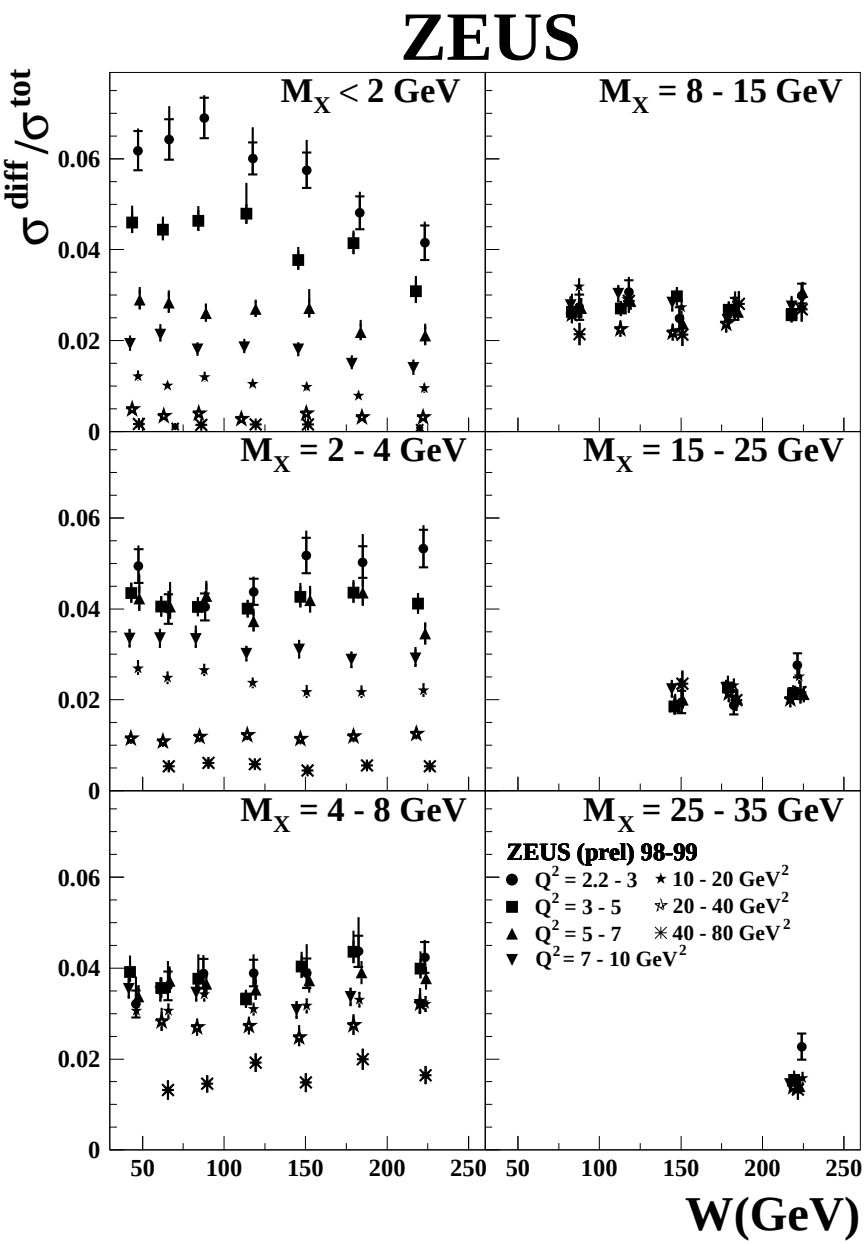




**Low $\beta$: rel. flat:**

- **ratio of diffr. to incl. $g(x, Q^2)$ constant**
- **diple models (IF $\sigma_{dipole} \propto R$)**

**As $\beta = 1$: falling:**

- **$Q^2$-suppressed higher twist (pert. 2-gluon exchange)**
- **DGLAP evolution (gluon radiation)**



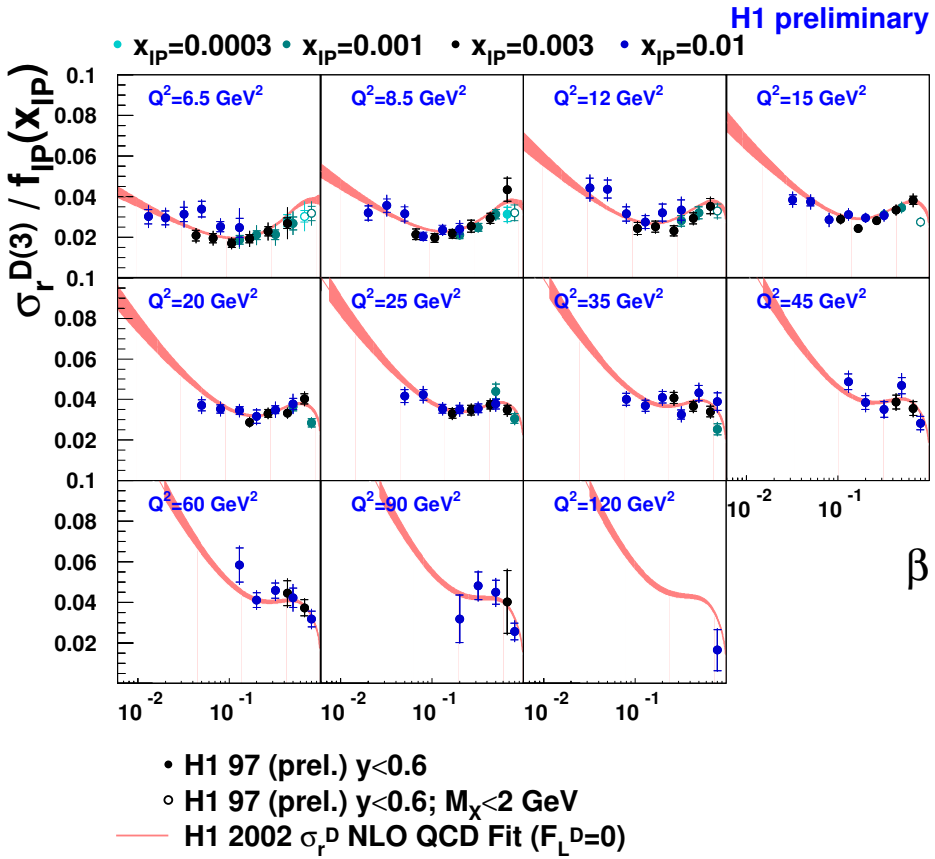

## Ratio from ZEUS

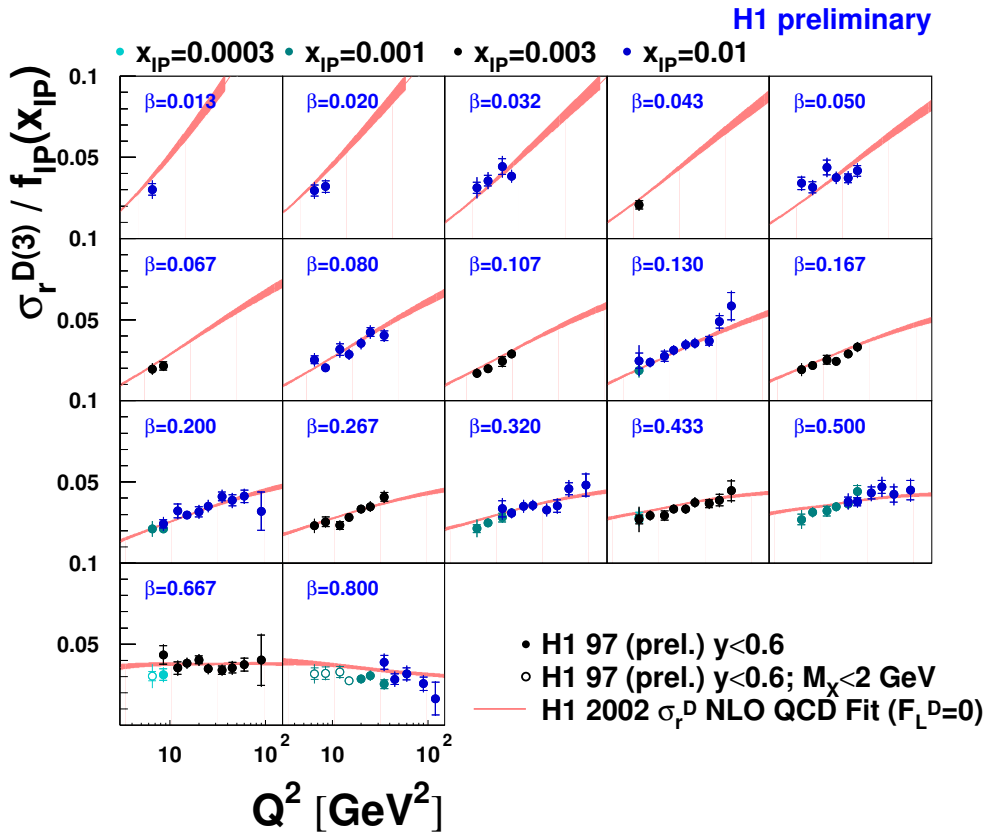
**Similar features observed:**

- little $Q^2$ dependence at high $M_X$ ($\sim$ low $\beta$)
- strong (negative) $Q^2$ dependence at small $M_X$ ($\sim$ high $\beta$)

# Precise H1 Measurement of $\beta$, $Q^2$ dependences

## Prerequisite for NLO DGLAP QCD fit:




$\beta$ dep.: $\sim \sum_i e_i^2 (q_i^D + \bar{q}_i^D)$

$Q^2$ dep.: $\sim \alpha_s \otimes g^D(\beta, Q^2)$

– $x_{I\!P}$ dep. taken out: factorization holds for $x_{I\!P} < 0.01$

– rising for $\beta \longrightarrow 1$ at low $Q^2$

– positive scaling violations expect for largest $\beta$ (gluon dominance)

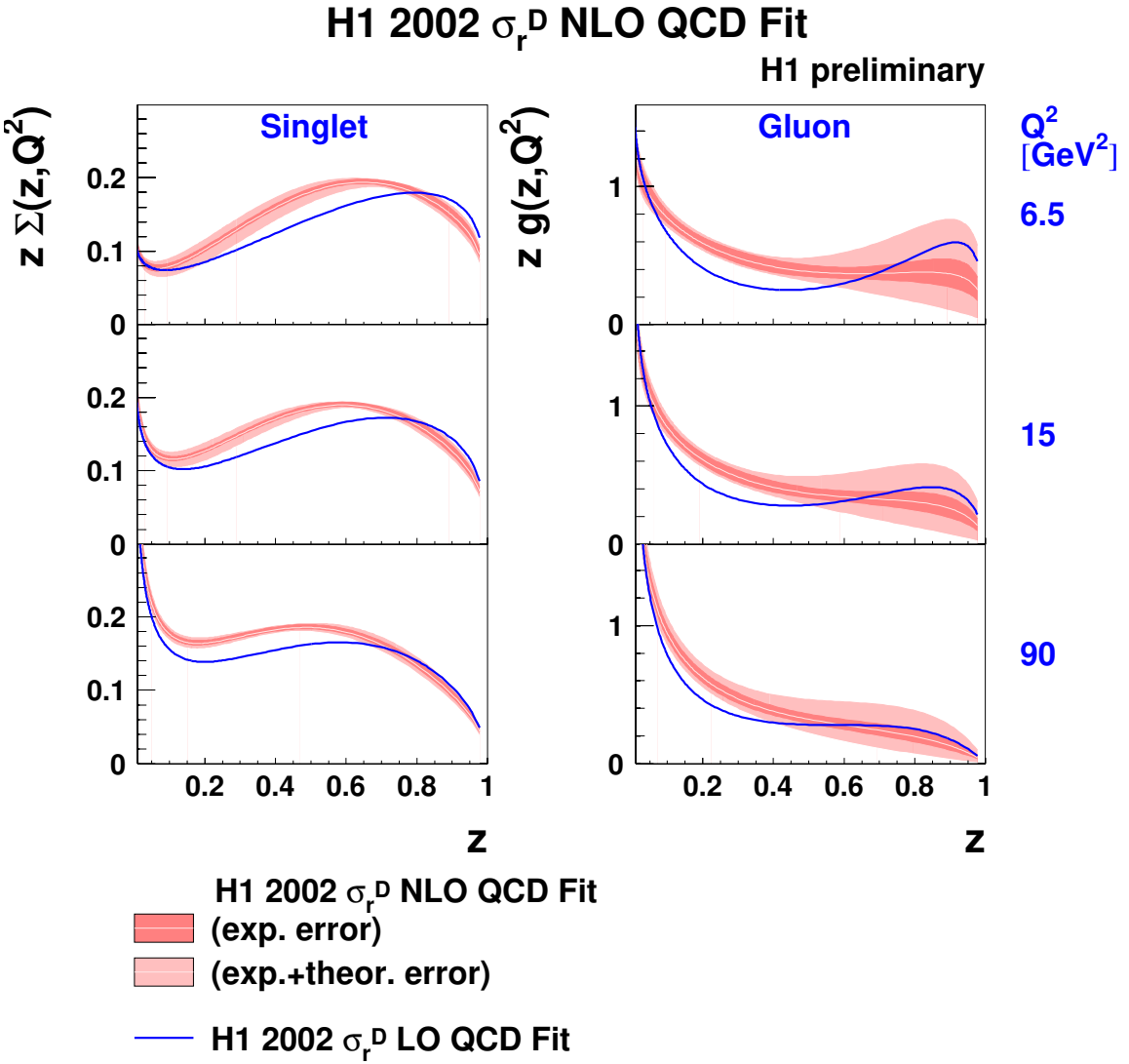
# New NLO DGLAP QCD Fit from H1

## QCD Fit Technique:

- Regge factorization (c.f. data)
- Singlet $\Sigma$ and gluon $g$ parameterized at $Q_0^2 = 3\ \mathrm{GeV}^2$
- NLO DGLAP evolution
- Fit data for $Q^2 > 6.5\mathrm{GeV}^2$, $M_X > 2\ \mathrm{GeV}$
- For first time propagate exp. and theor. uncertainties !

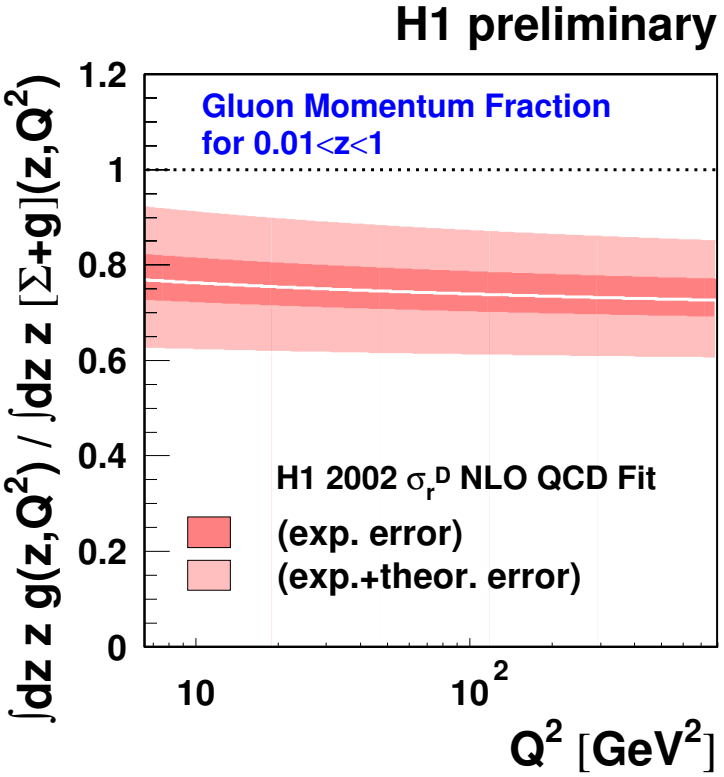
## PDF's of diffractive exchange:

- Extending to large fractional momenta $z$
- Gluon dominated
- $\Sigma$ well constrained
- substantial uncertainty for gluon at highest $z$
- Similar to previous fits



# H1 NLO QCD Fit: Gluon fraction and $F_L^D$

**Integrate PDF's over measured range:**

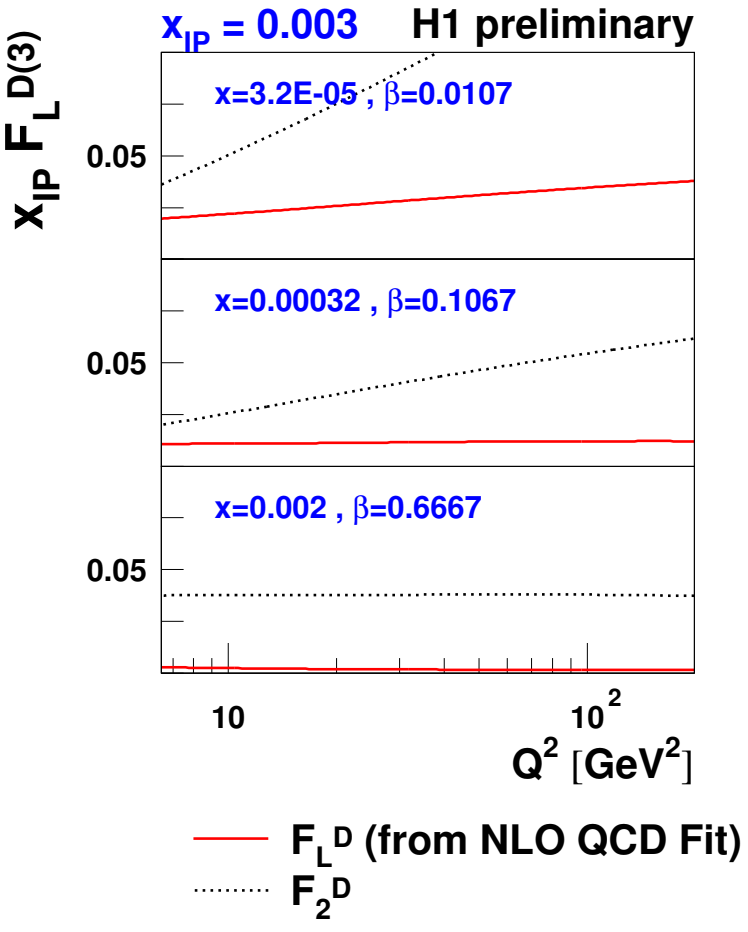



**Momentum fraction of diffractive exchange carried by gluons:**

$$75 \pm 15\%$$

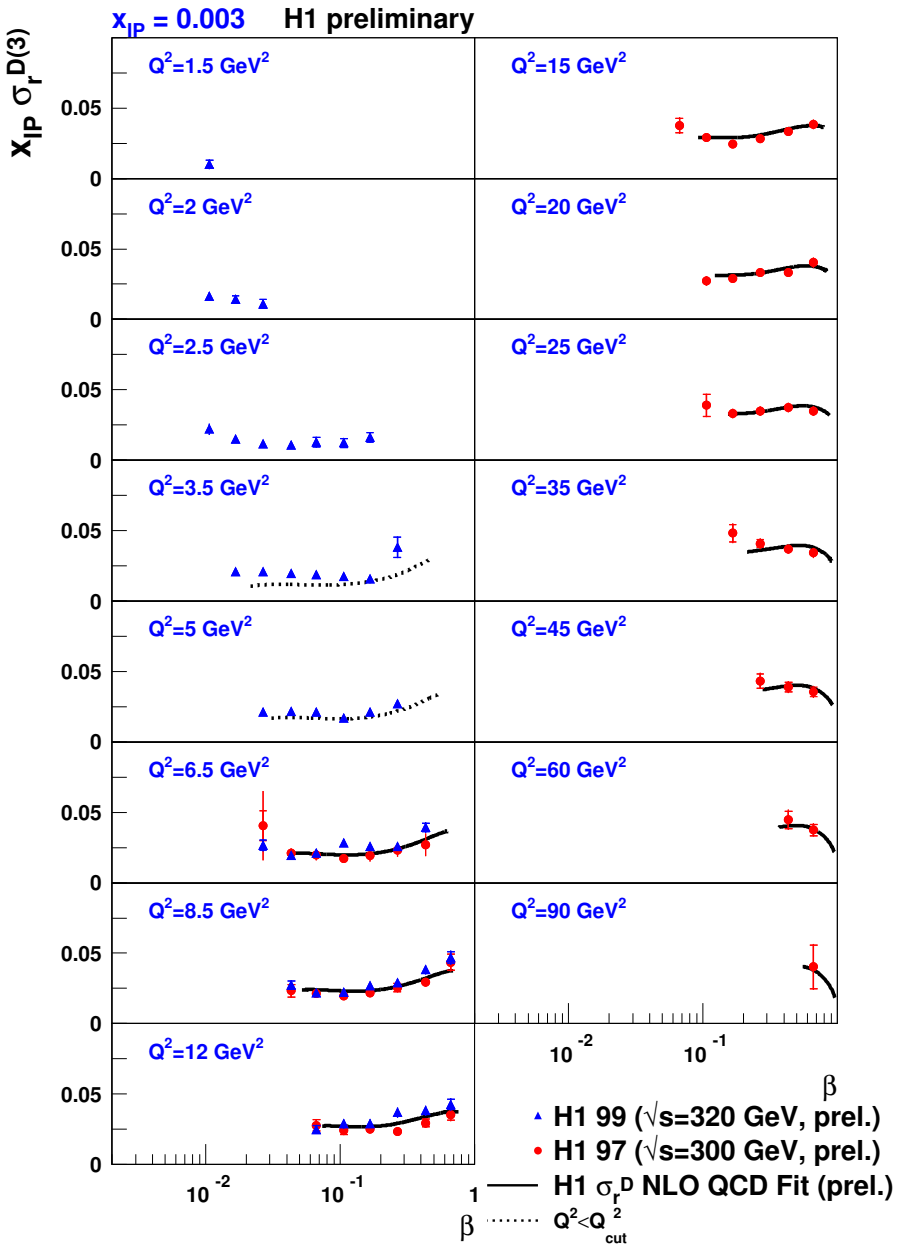
**Longitudinal $F_L^D$:**

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




$\Rightarrow$ $F_L^D$ large at low $Q^2$, low $\beta$

# H1 NLO QCD fit: $\beta$ dependence

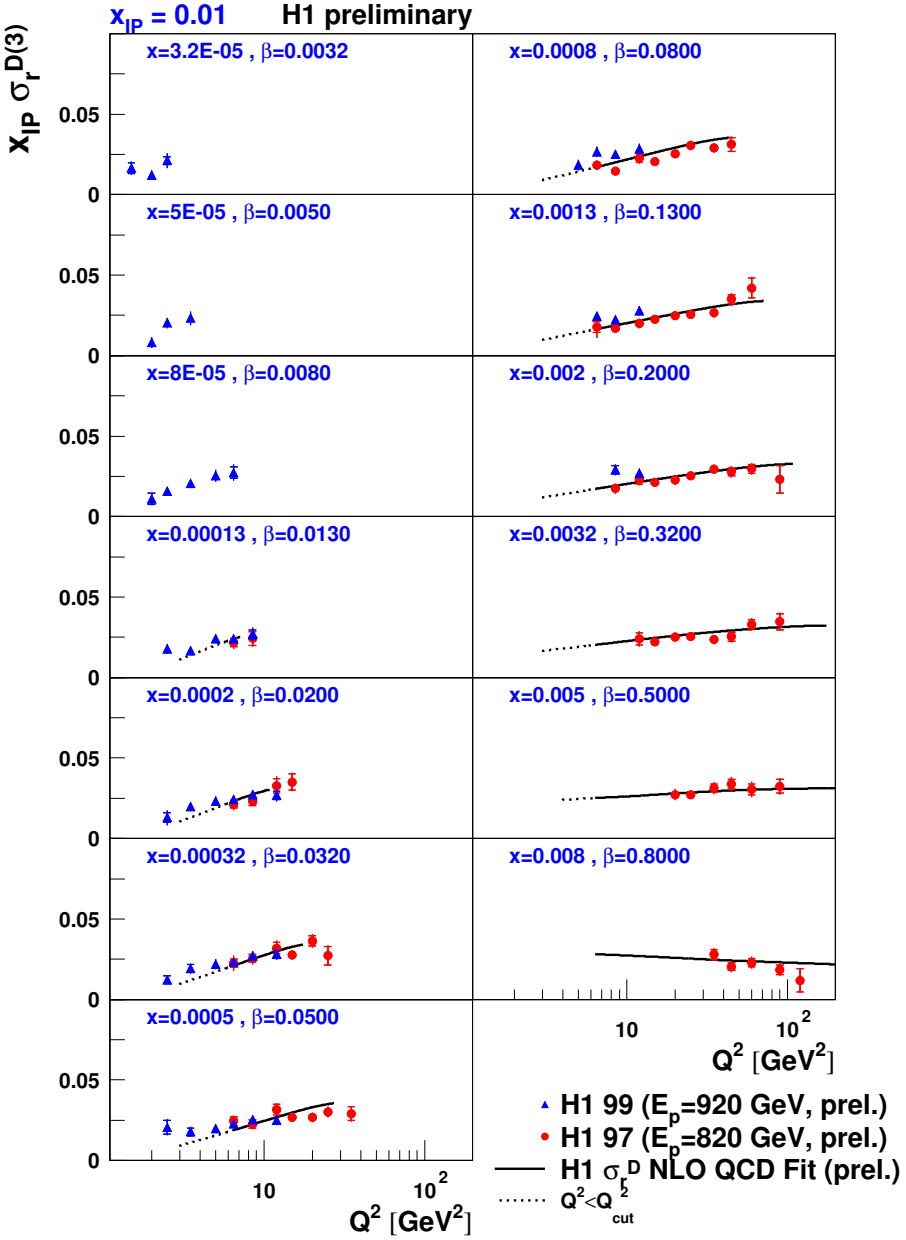



**Example data at $x_{I\!P} = 0.003$:**

- **Rising behaviour for $\beta \longrightarrow 1$ at low $Q^2$, reflected by $\Sigma(\beta, Q^2)$**
- **QCD fit to data for $Q^2 > 6.5$ GeV$^2$**
- **Extension to lower $\beta, Q^2$ with new 99 data! (blue points)**
- **Indication of breakdown of QCD fit at $Q^2 = 3.5$ GeV$^2$**

**$\Rightarrow$ new low $Q^2$ data as additional constraint in future fits!**

# H1 NLO QCD fit: $Q^2$ dependence




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

- **$Q^2$ scaling violations well constrained by data**
- **Rising except at highest $\beta$**
- **Well reproduced by QCD fit for $Q^2 > 3.5$ GeV$^2$**
- **New low $Q^2$ data (blue points) above fit at low $Q^2$ (not included in fit)**

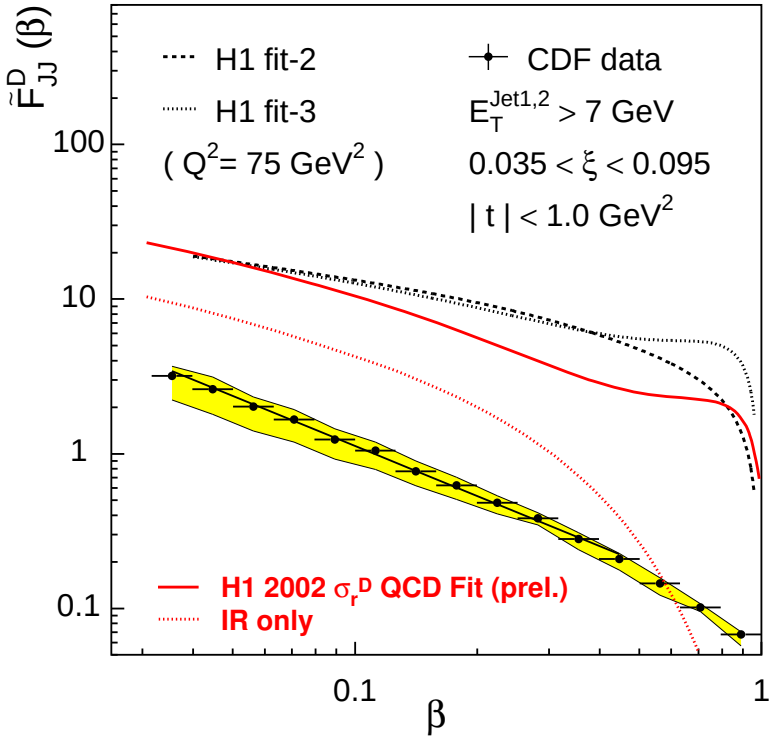
# Factorization Tests

**Use diffractive PDF's to predict diffractive final state cross sections:**

## HERA:

- **Updated comparisons with dijet and charm production in diffractive DIS:**
  **Consistent with factorization** ⇒ **See next talk (A. Savin)**

## Diffractive dijets at the TEVATRON:




- **Prediction based on H1 PDF's one order of magnitude below CDF data**
- **Result of new H1 fit confirms serious breakdown of factorization in diffraction between $\bar{p}p$ and $ep$**

# Summary

**Understanding colour singlet exchange - a major challenge in QCD**

**Diffractive DIS at HERA enables studies of quark / gluon (QCD) structure of diffraction**

- **Several new data samples from H1 and ZEUS:**
  - **Entering an era of high precision in extended kinematic range**
- **Energy dependence: $\alpha_{I\!P}(0)$ in DIS higher than at $Q^2 = 0$**
  - **Diffractive vs inclusive: Simple expectation does not work in DIS**
- **Ratios diffractive to inclusive cross section:**
  - **remarkably flat over wide kinematic range**
  - **high $\beta$: complicated structure (higher twist?)**
- **New H1 NLO DGLAP QCD fit: Diffractive parton distributions including error estimate, dominated by gluon distribution**
  - **used for test of QCD factorization**

**Further information in contributed papers**
**980, 981, 984, 985 (H1) and 821, 822, 823, 828 (ZEUS)**