Review of Inclusive Diffraction: New Results from HERA

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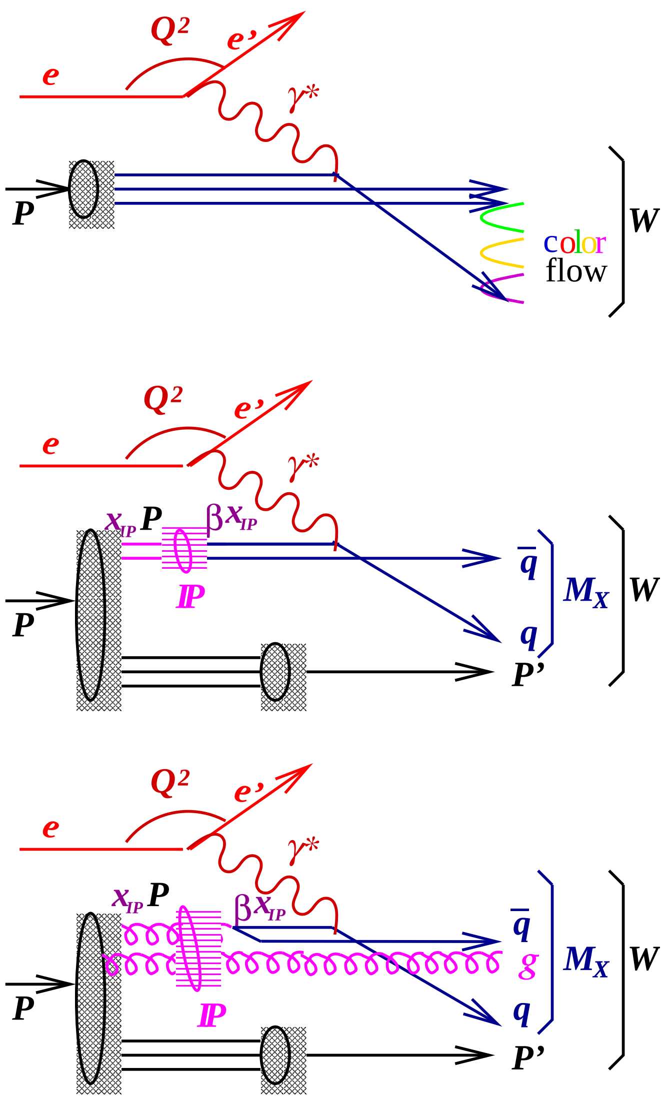
- Introduction
- DIS diffraction with ZEUS leading proton spectrometer: $F_2^{D(3)}(x_{IP}, \beta, Q^2)$ and t dependence
- DIS diffraction from H1: new QCD fit, diffractive parton distributions
  new data at low and very high Q^2
- DIS diffraction from ZEUS with Forward Plug Calorimeter
- Summary

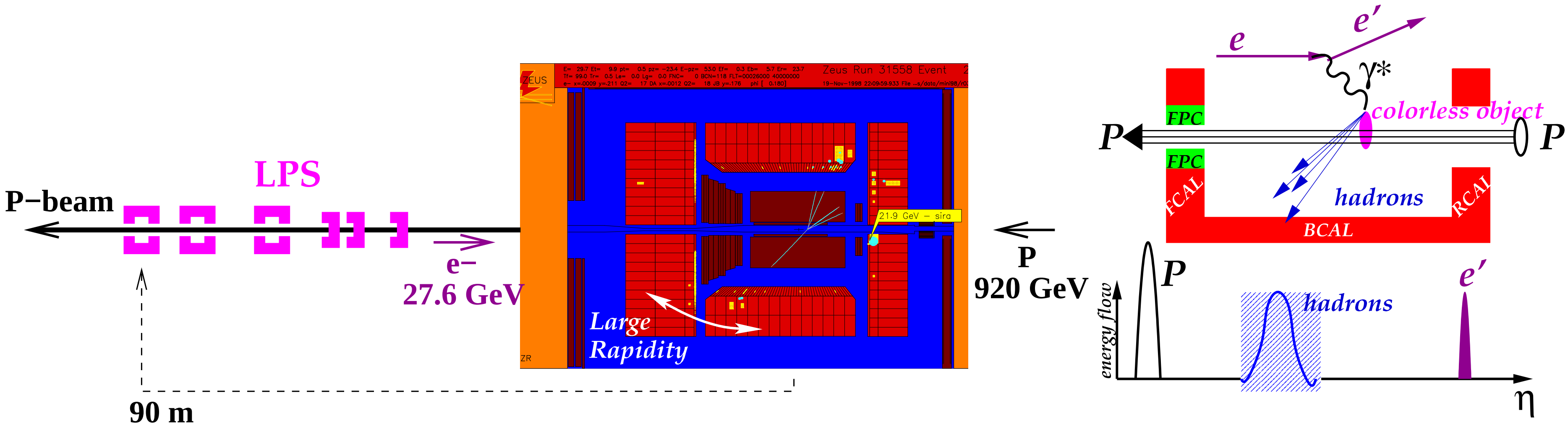
○ Kinematics of $e + p \to e' + X + N$



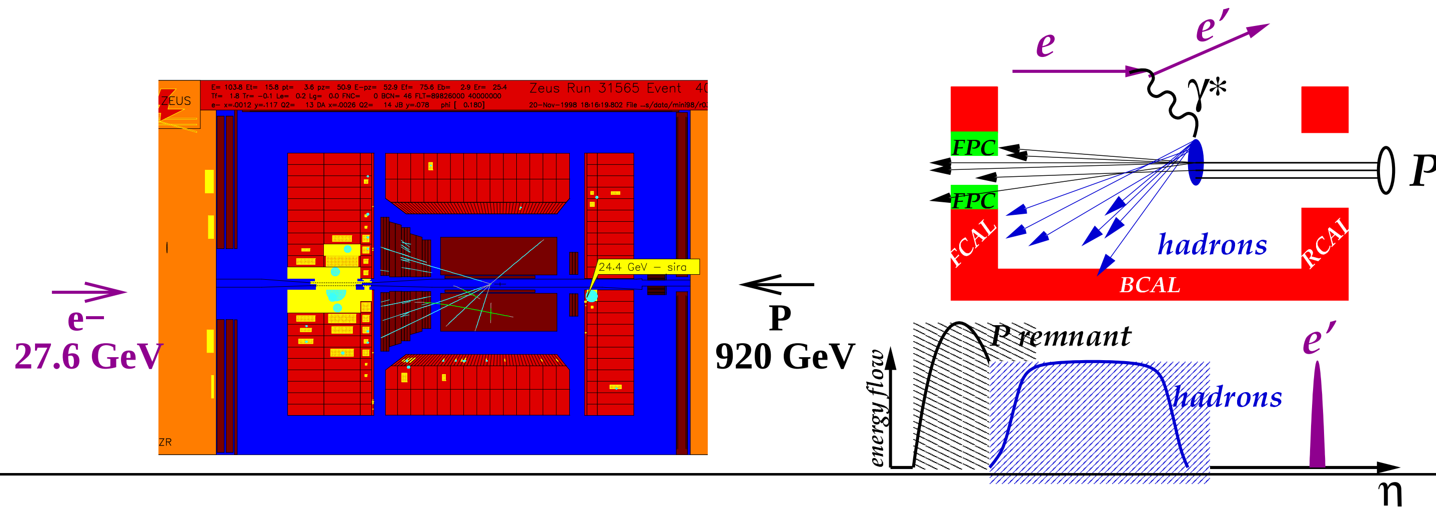
- $Q^2 = -q^2 = -(k-k')^2$
- $x = \dfrac{Q^2}{2q \cdot p}$
- $W = \sqrt{(p+q)^2} \approx \sqrt{\dfrac{Q^2}{x}}$
- $M_X^2 = (k - k' + p - p')^2$
- $x_{IP} = \dfrac{(p-p') \cdot q}{p \cdot q} \approx \dfrac{M_X^2 + Q^2}{W^2 + Q^2}$
- $\beta = \dfrac{Q^2}{2(p-p') \cdot q} = \dfrac{x}{x_{IP}} \approx \dfrac{Q^2}{M_X^2 + Q^2}$

Event Topologies of Diffractive Deep Inelastic Scattering

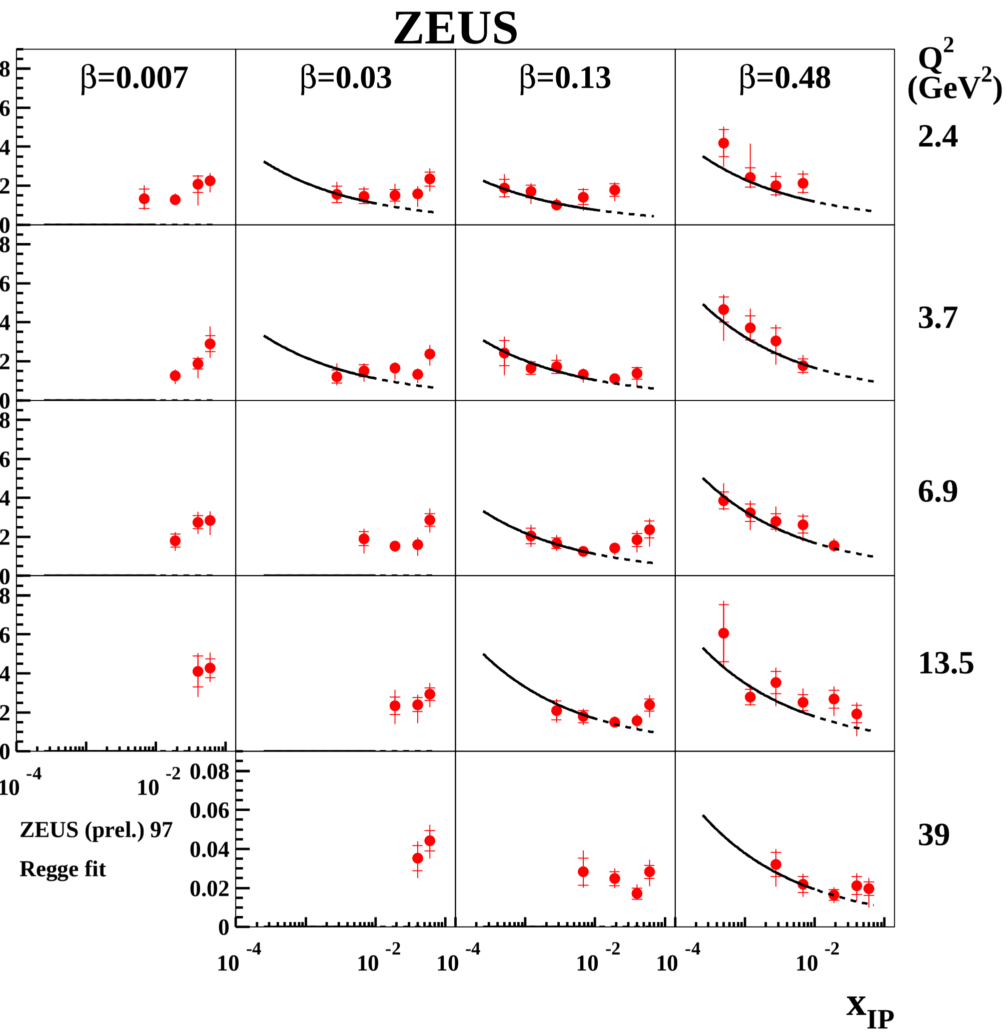
1. Diffractive scattering $(M_X = 5\,\mathrm{GeV},\ Q^2 = 19\,\mathrm{GeV}^2,\ W = 123\,\mathrm{GeV})$



2. Non-diffractive scattering $(M_X = 45\,\mathrm{GeV},\ Q^2 = 13\,\mathrm{GeV}^2,\ W = 93\,\mathrm{GeV})$



ZEUS measurement of $x_{I\!P} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$ with LPS



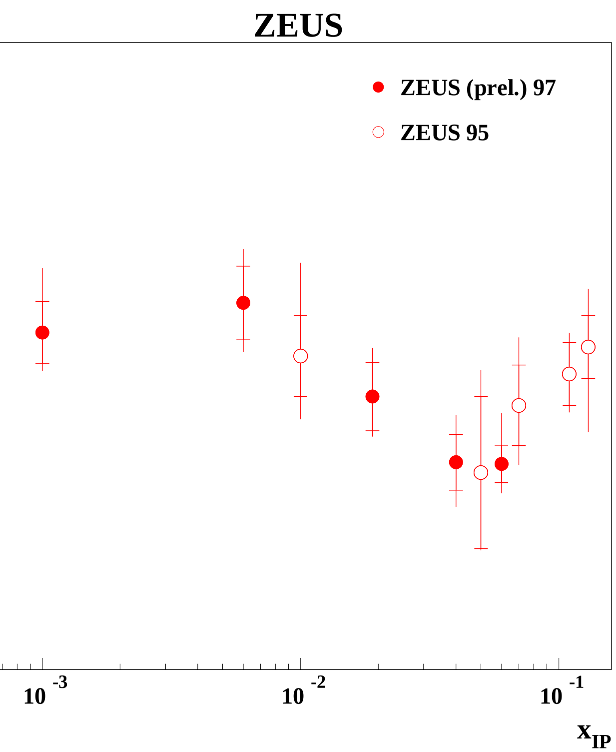
- Fit all data of ($x_{IP} < 0.01$)

  with common Pomeron flux factor

  $$x_{pom} F_2^{D(3)}(x_{IP}, \beta, Q^2) = (1/x_{IP})^{2\alpha_{IP}(0)-1} \cdot F_2^{IP}(\beta, Q^2)$$

  $\alpha_{IP}(0) = 1.173 \pm 0.018(stat) \pm 0.017(sys) \pm ^{(+0.063)}_{(-0.035)}$ (model)

Measurement of $\alpha_{IP}(0)$ from t-dependencewith LPS



- Fit t distribution to $d\sigma/d|t| \propto exp(-b|t|)$

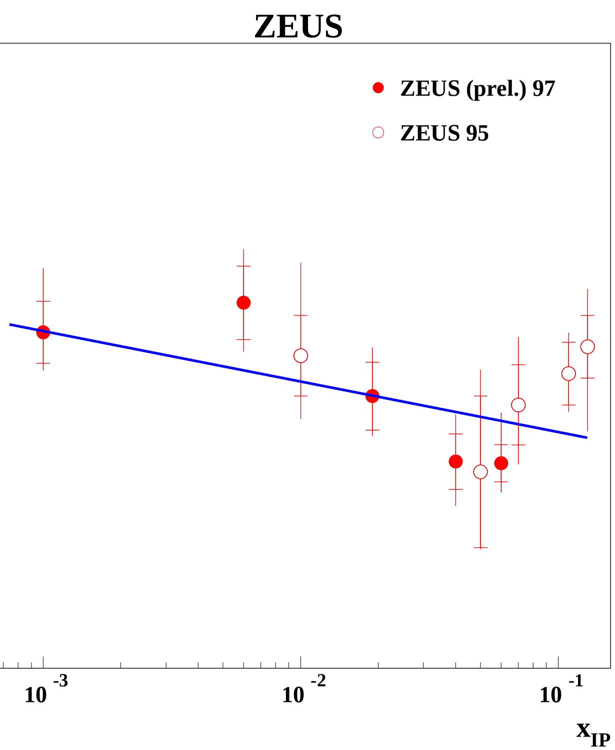
  expect shrinkage of diffractive peak (Regge):

  $b = b_0 + 2\alpha' \ln(1/x_{IP})$

  b should rise as $x_{IP} \to 0$

  data note yet definitive

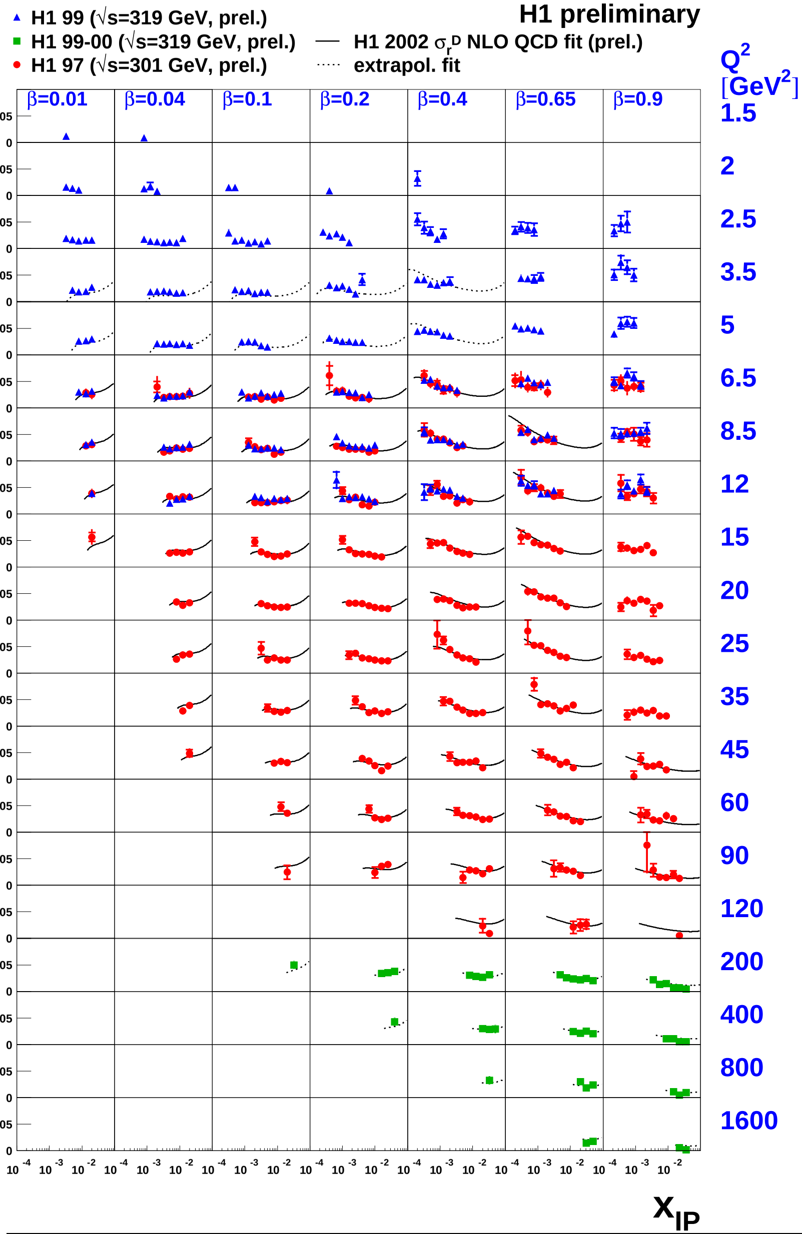
Measurement of $\alpha_{I\!P}(0)$ from t-dependencewith LPS



- line shows expected behaviour

  for $b_0 = 5$ GeV^{-2} and $\alpha' = 0.25$ GeV^{-2}

H1 measurement of $x_{IP} F_2^{D(3)}(x_{IP}, \beta, Q^2)$ and QCD fit



- $\sigma_r^{D(3)} = F_2^{D(3)}(x_{IP}, \beta, Q^2)$

  diffractive structure function of the proton

- new data for $1.5 < Q^2 < 12$ GeV^2

  and $130 < Q^2 < 1600$ GeV^2

- New QCD fit to $F_2^{D(3)}(x_{IP}, \beta, Q^2)$

  use data with $6 < Q^2 < 120$ GeV^2

  assume PDF's independent of x_{IP}

  Pomeron modelled in terms of

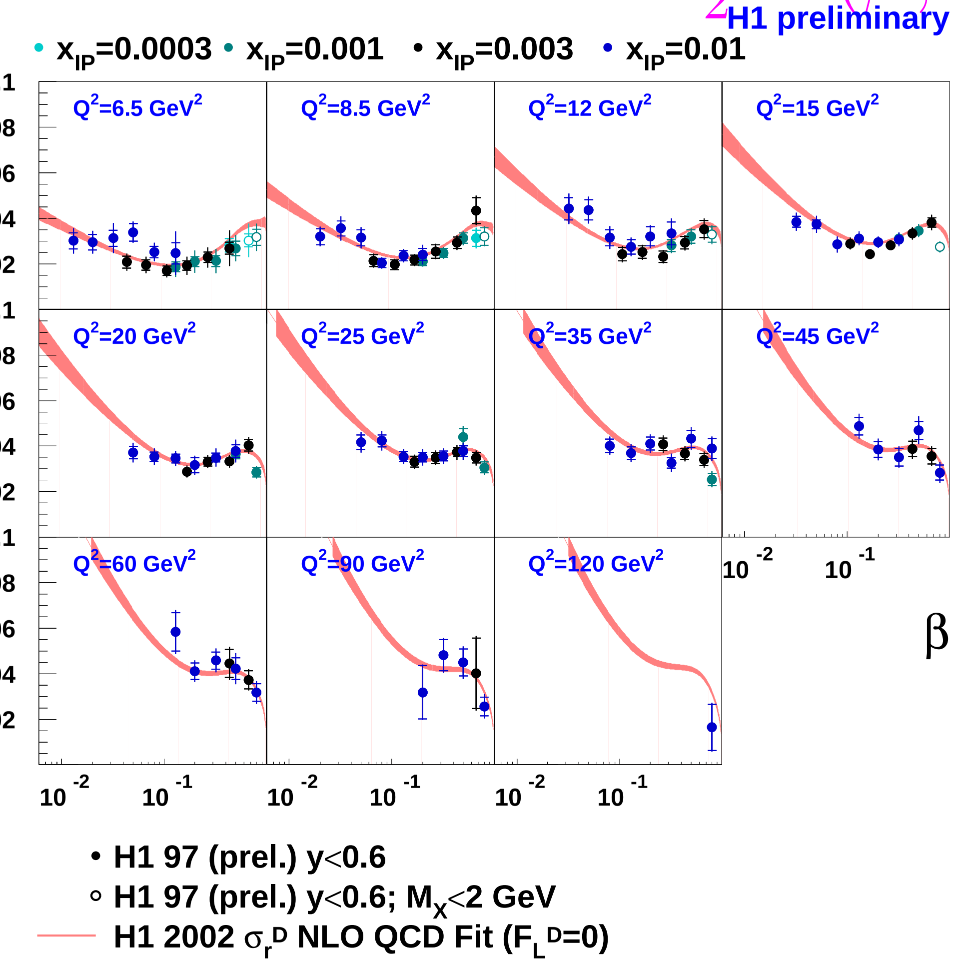
  light quark flavour singlet:

  $\sum(z) = u(z) + d(z) + s(z) + \overline{u(z)} + ..$

  plus gluon distribution:

  $g(z)$

H1 $F_2^{D(2)}(\beta, Q^2)$ and QCD fit



- factorize diff. structure funct. of proton into probability finding Pomeron with fract x_{IP} of proton momentum

  and structure function of the Pomeron:

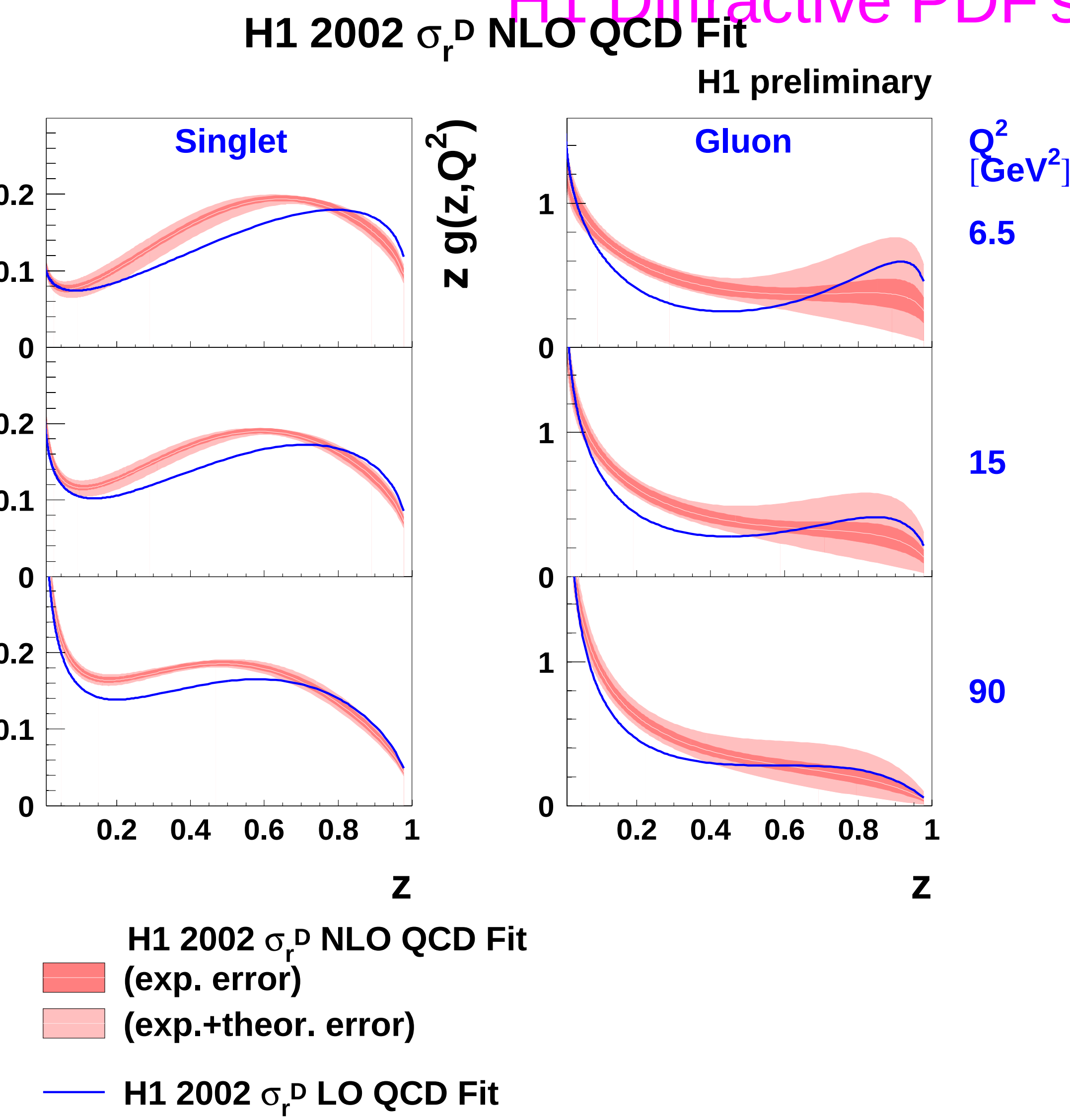
  $$F_2^{D(3)}(x_{IP}, \beta, Q^2) = f_{IP}(x_{pom}) \cdot F_2^{D(2)}(\beta, Q^2)$$

  note

  $$\sigma_r^{D(3)} / f_{IP}(x_{IP}) = F_2^{D(2)}(x_{IP}, Q^2)$$

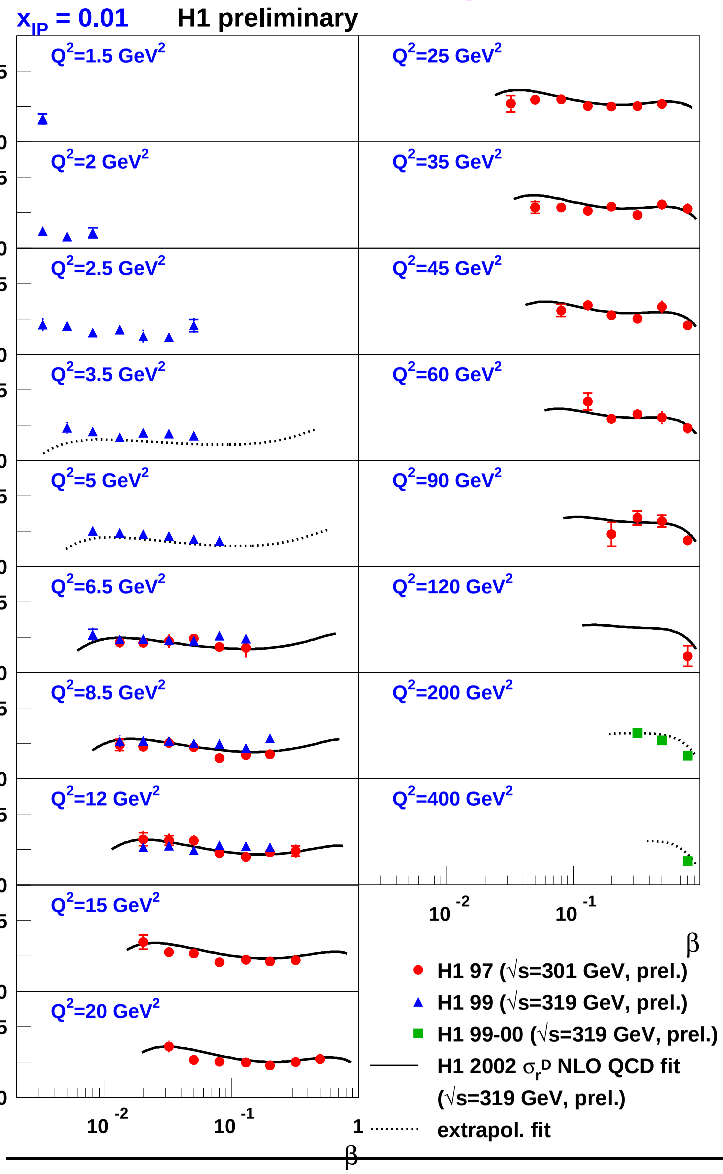
- red band shows result of QCD fit to $F_2^{D(3)}(x_{IP}, \beta, Q^2)$

H1 Diffractive PDF's from QCD fit



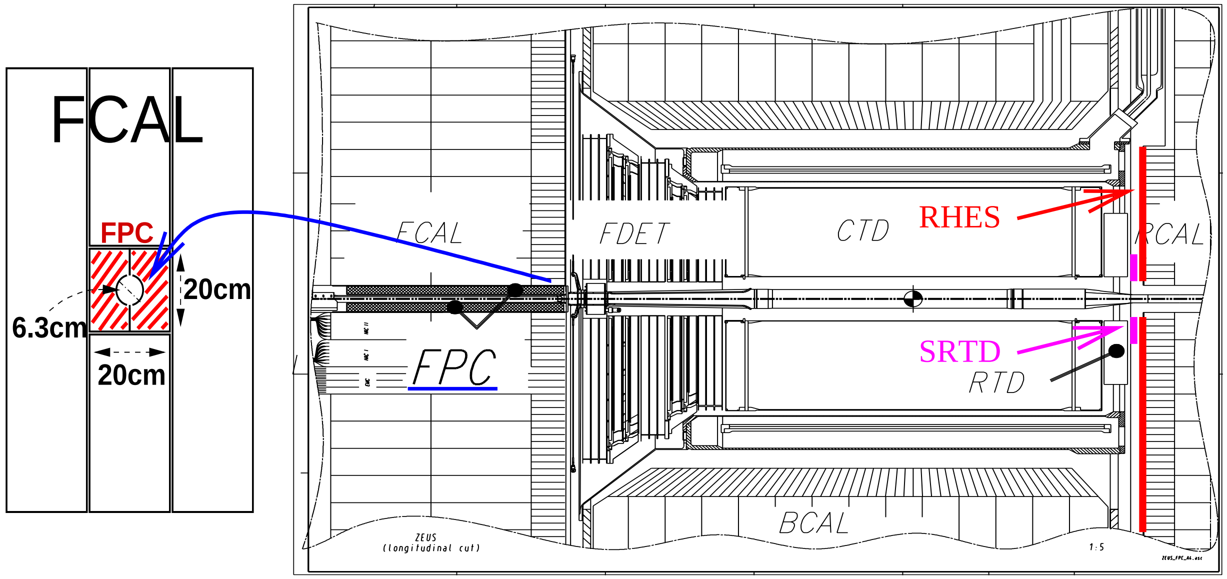
- inner error bands:
  experimental stat + syst errors
  outer error bands:
  include uncertainties from theoretical assumptions
- $75 \pm 15\%$ of Pomeron momentum with $0.01 < z < 1$ is carried by gluons, the rest by quarks
- large uncertainty on $g(z, Q^2)$ at large z

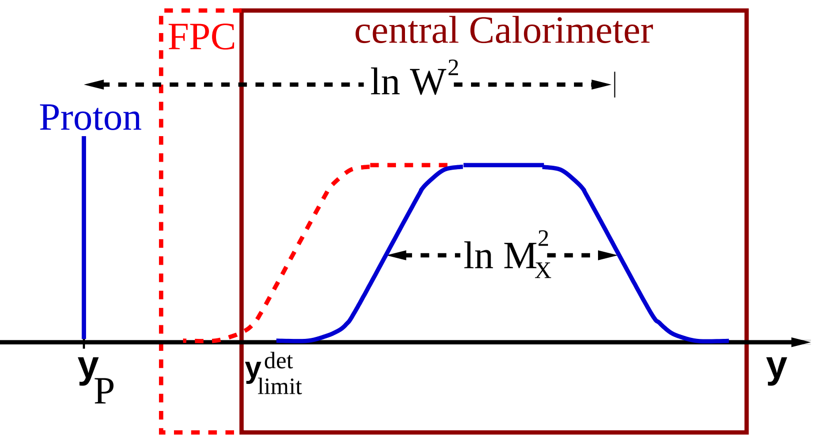
H1 QCD fit compared with $x_{\mathbb{P}} F_2^{D(3)}(x_{\mathbb{P}}, \beta, Q^2)$ data including low and h



- New QCD fit to $F_2^{D(3)}(x_{IP}, \beta, Q^2)$
  fit used data with $6 < Q^2 < 120$ GeV^2

- curves at $Q^2 < 6$ and > 120 GeV^2 are extrapolations of QCD fit





rapidity : $\mathcal{Y} = \frac{1}{2} \ln \frac{E + p_Z}{E - p_Z}$

pseudo-rapidity : $\eta = -\ln \tan(\frac{\theta}{2})$

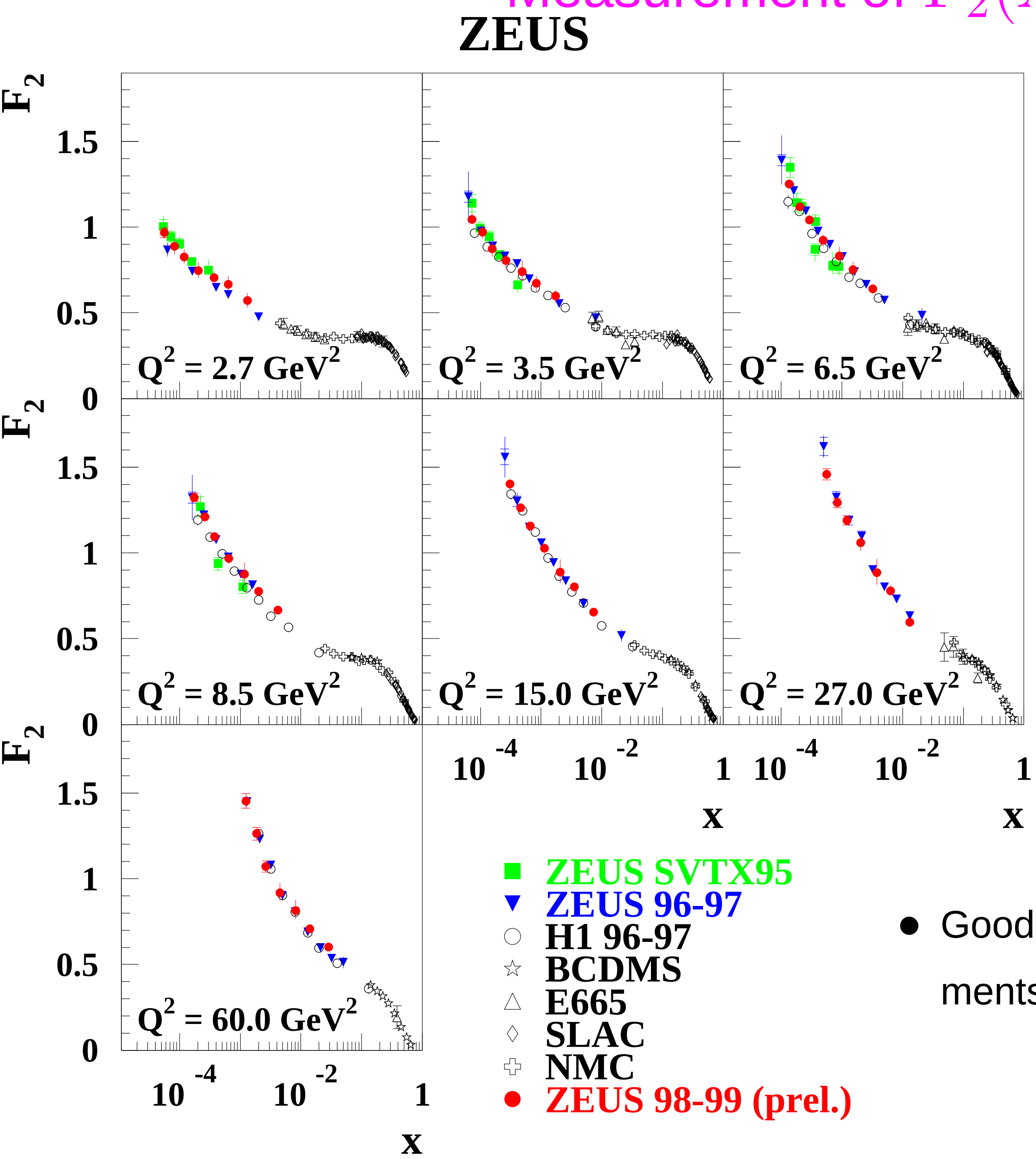
- Forward Plug Calorimter (FPC) : Shashlik type

  → Extend calorimeter acceptance by 1 unit in pseudo-rapidity from η =4 to η =5.

  → Increase the accessible M_X range by a factor of 1.7

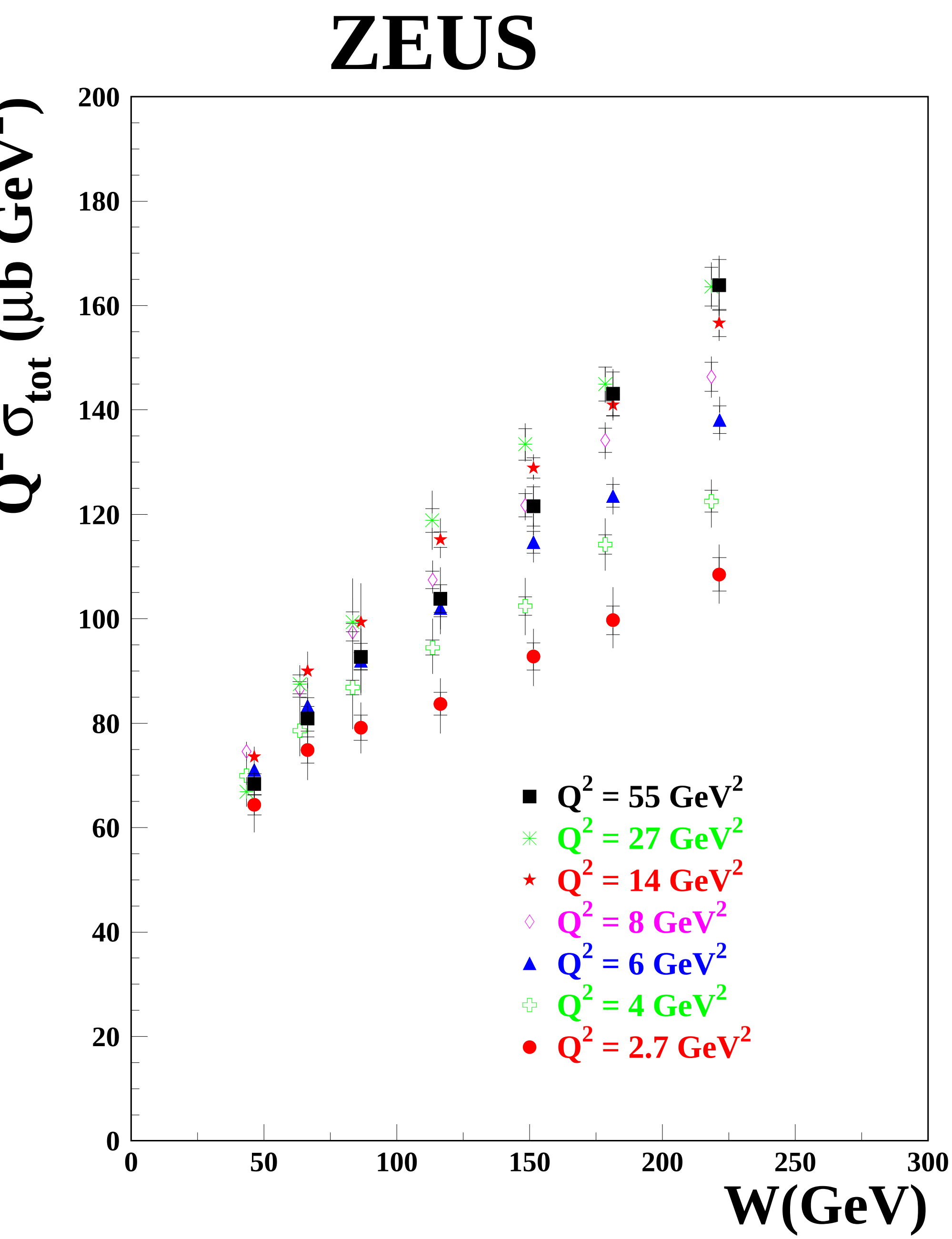
- For 1998-1999,
  - FPC → higher M_X and lower W
  - Smaller RCAL beamhole → lower Q^2 and higher W

Measurement of $F_2(x, Q^2)$



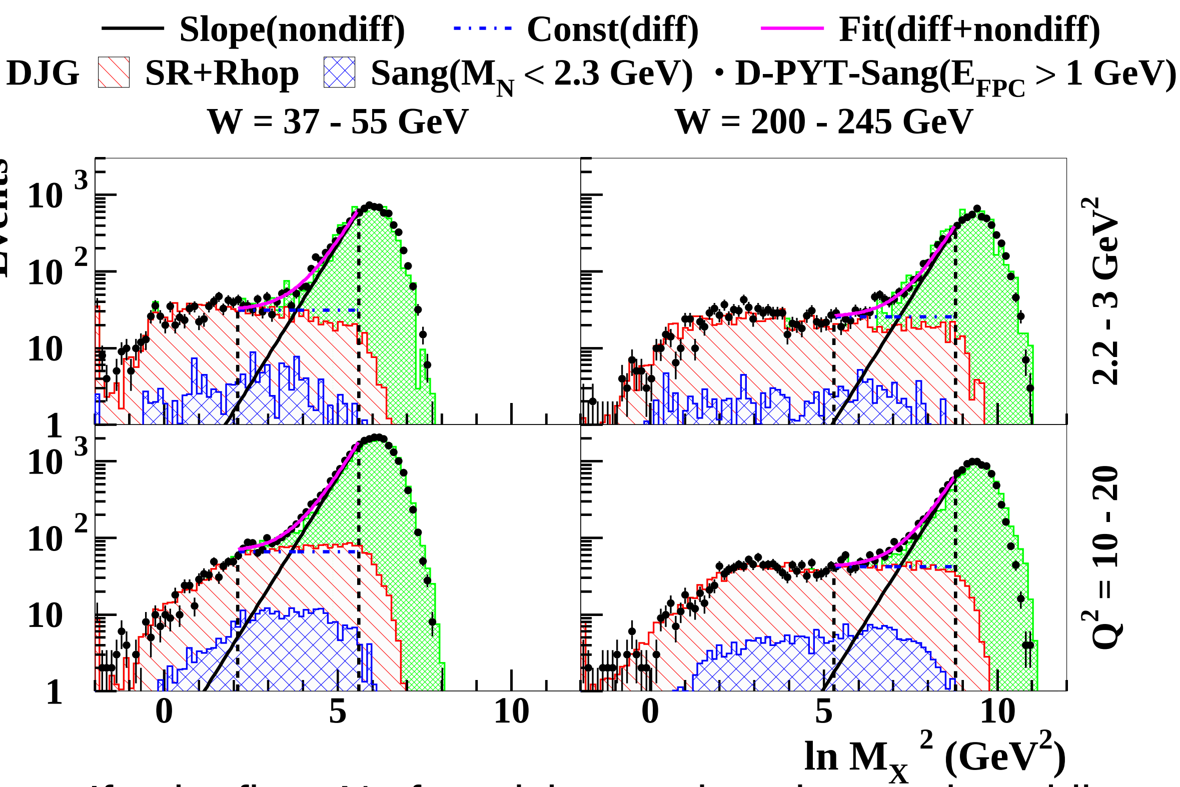
- Good agreement with previous measurements.

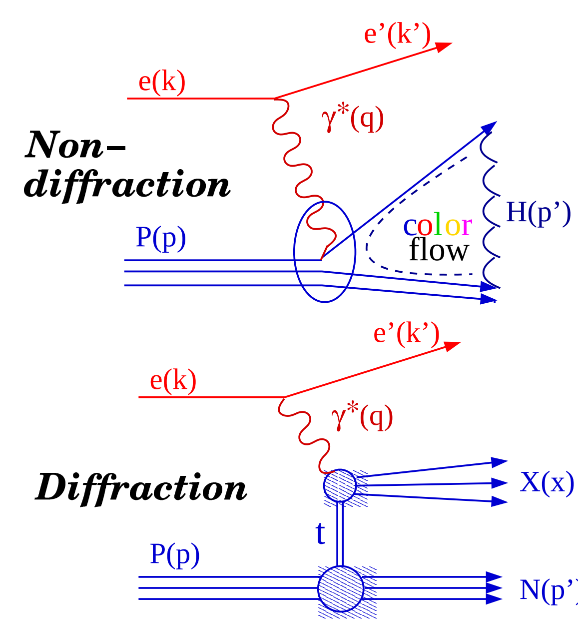
Measurement of $Q^2\sigma^{tot}(W, Q^2)$



- slow rise with Q^2
  $->$ as expected for leading twist
- strong rise as $W \to 0$
  rise accelerates as Q^2 increases
  reflects the rise of F_2 as $x \to 0$
- fit $\sigma^{tot} = c \cdot W^{a^{tot}}$
  note $\alpha_{IP}(0) = 1 + a^{tot}/2$

Extraction of diffractive contribution





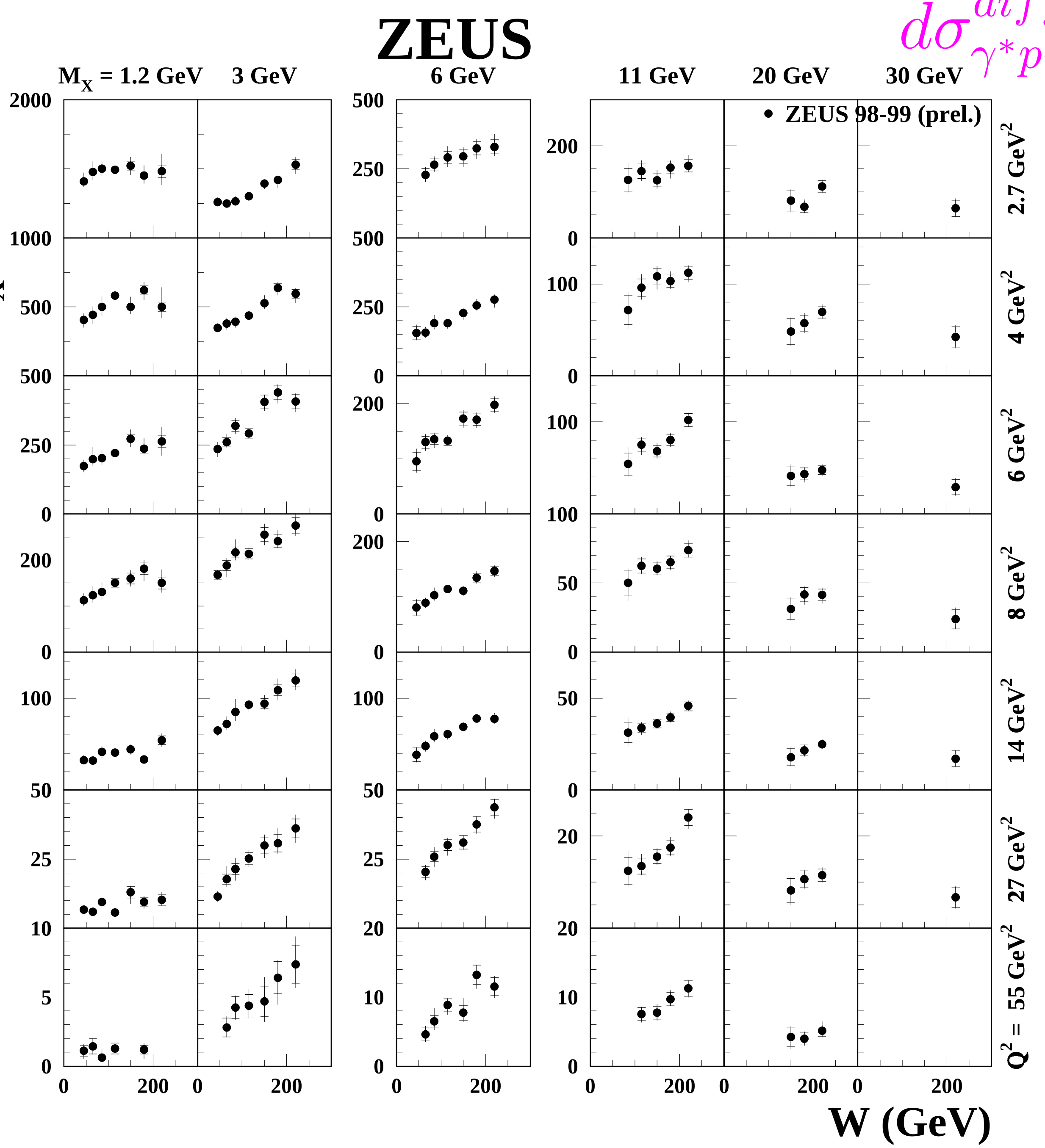
- If color flow, N of particles produced per unit rapidity : $\frac{dn}{d\mathcal{Y}} \approx \lambda \approx$ const
- $$\frac{dN}{d\ln M_X^2} = D + c\cdot\exp(b\cdot\ln M_X^2)$$ with free parameters, D , b and c from fit.
  $$= \text{(Diff)} + \text{(Nondiff)}$$
- diffractive dissocociation of proton $p \to N$

  if $M_N \gtrsim 2.3$ GeV N deposits approx. $E_{FPC} > 1$ GeV $\to$ can recognize in data

  $\to$ use data to adjust M_N spect. of MC $\to$ subtract from data MC contr. with $M_N \gtrsim 2.3$ GeV

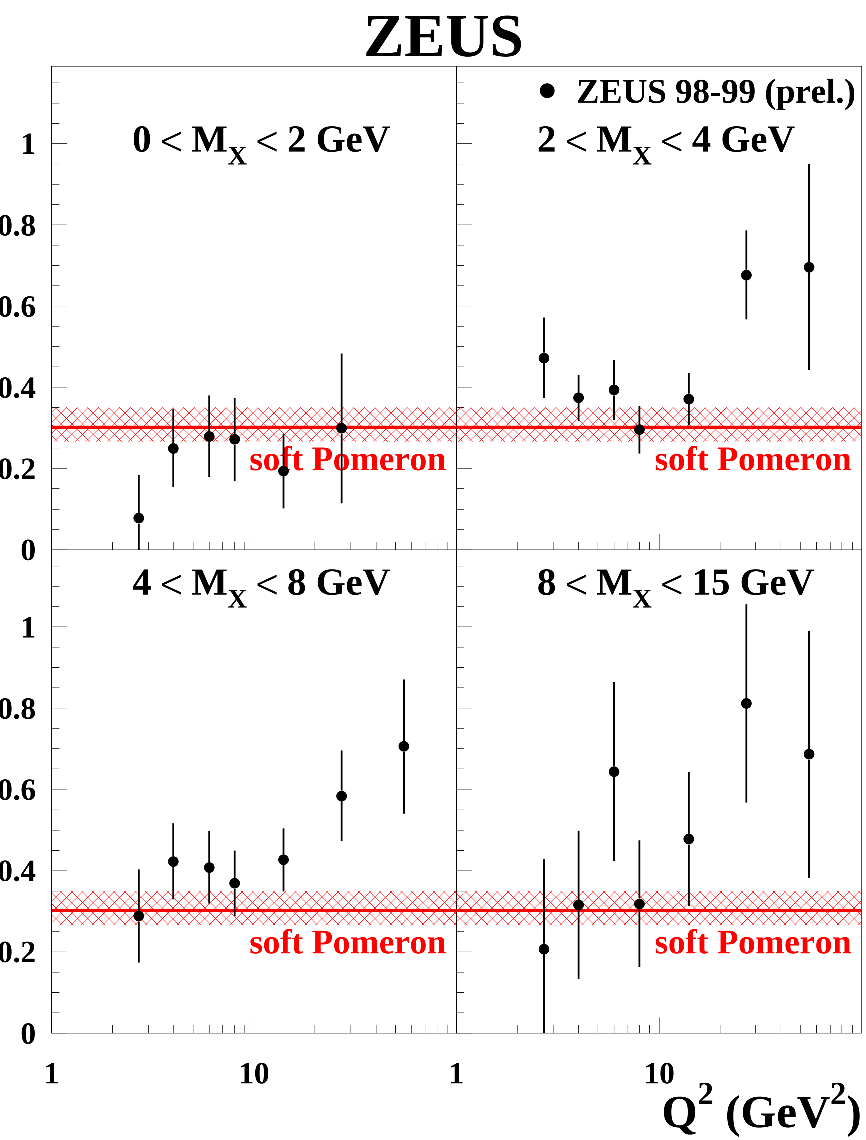
  $\to$ provide $d\sigma^{diff}_{\gamma^* p\to XN}/dM_X$ for $M_N < 2.3$ GeV

$d\sigma^{diff}_{\gamma^* p \to XN}(M_X, W, Q^2)/dM_X$, $M_N < 2.3$ GeV



- For $M_X < 2$ GeV, $d\sigma/dM_X$ depends weakly on W .
- For $M_X > 2$ GeV, $d\sigma/dM_X$ rises rapidly with W .

W dependence of $d\sigma^{diff}_{\gamma^* p \to XN}/dM_X$



1. Fit
   $$\frac{d\sigma^{diff}_{\gamma^* p \to XN}}{dM_X} = h \cdot W^{a^{diff}} \sim (W^2)^{(2\overline{\alpha_{IP}}-2)}$$
   (h , a^{diff} free parameters)

   $\therefore \overline{\alpha_{IP}} = 1 + a^{diff}/4$

2. Compare with soft Pomeron from hadron-hadron scattering at $t = 0$:

   $\alpha^{soft}_{IP}(0) = 1.096^{+0.012}_{-0.009}$ $\quad \therefore a^{soft} = 0.302^{+0.048}_{-0.036}$

   corrected by 0.02($= \delta\alpha_t$) for t distribution

3. For $M_X < 2$ GeV

   a^{diff} as expected for soft Pomeron

4. At higher M_X

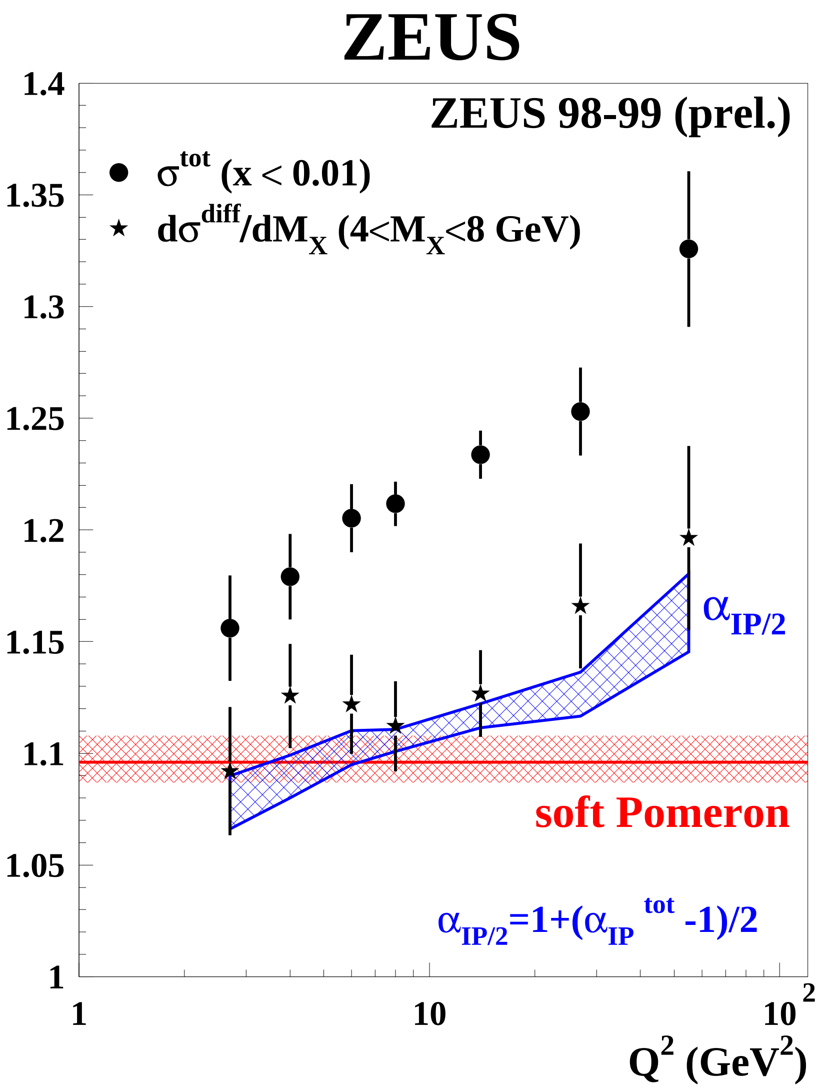
   a^{diff} higher than expected for soft Pomeron $\longrightarrow$ clear indication for rise with Q^2 .

   Note : For $Q^2 > 10$ GeV^2 ,

   Probability that $a^{diff} = a^{soft}$ is < 0.001

$\Longrightarrow$ Strong indication for pQCD

Compare $\alpha_{I\!P}$ for diffractive and total $\gamma^* p$ scattering



- $\sigma^{tot}_{\gamma^* p} = \frac{4\pi^2\alpha}{Q^2} \cdot F_2(x, Q^2)$

  $\sim \frac{1}{W^2} Im T_{\gamma^* p \to \gamma^* p}(W^2, t=0) \sim (W^2)^{\alpha^{tot}_{I\!P}(0)-1}$

  (Optical theorem)

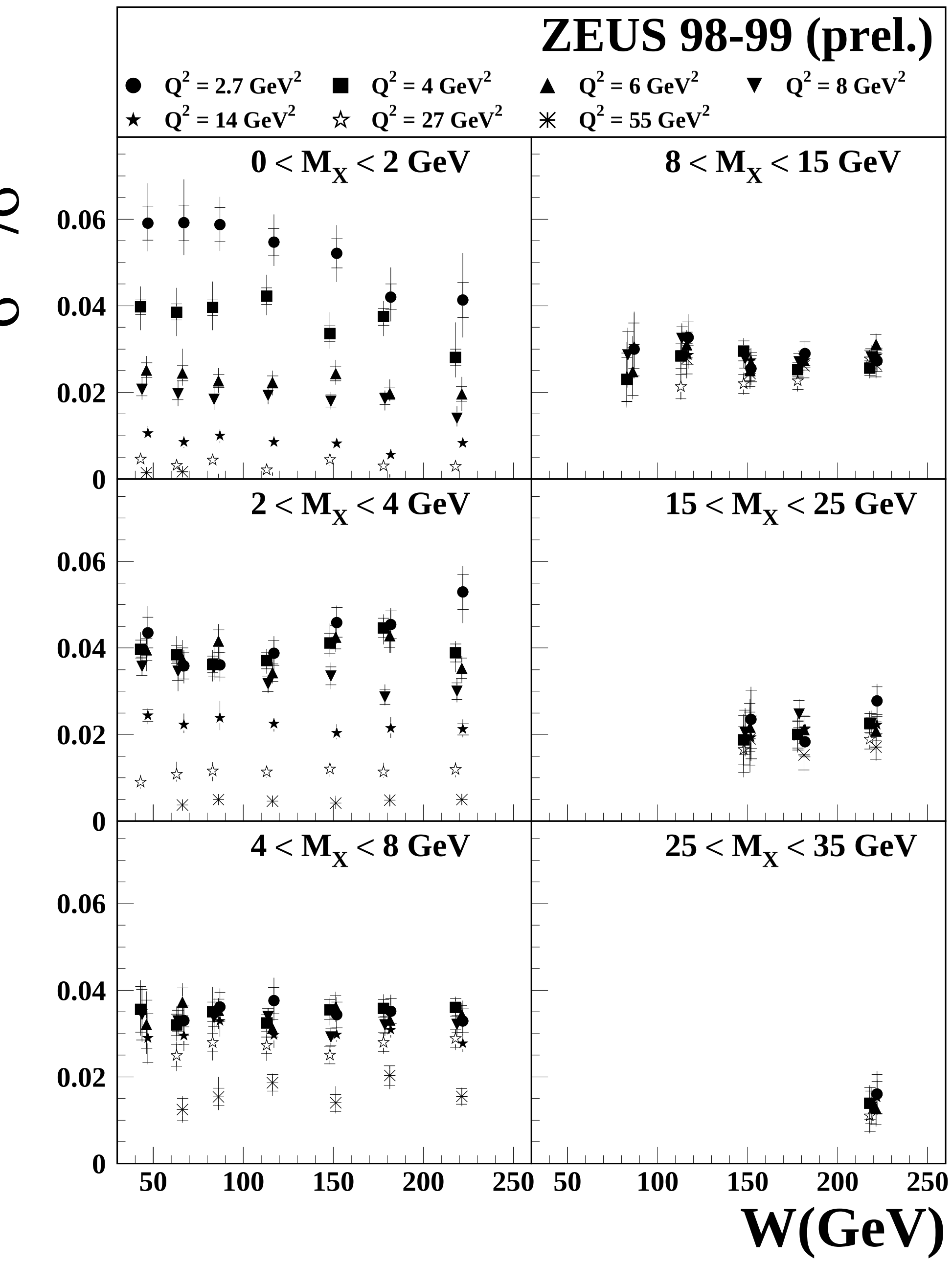
- $\frac{d^2\sigma^{diff}}{dM_X dt} \sim \quad |T_{\gamma^* p \to \gamma^* p}|^2 \quad \sim (W^2)^{2(\alpha^{diff}_{I\!P}(0)-1)}$

  at $t = 0$

- Data ($4 < M_X < 8$ GeV) show

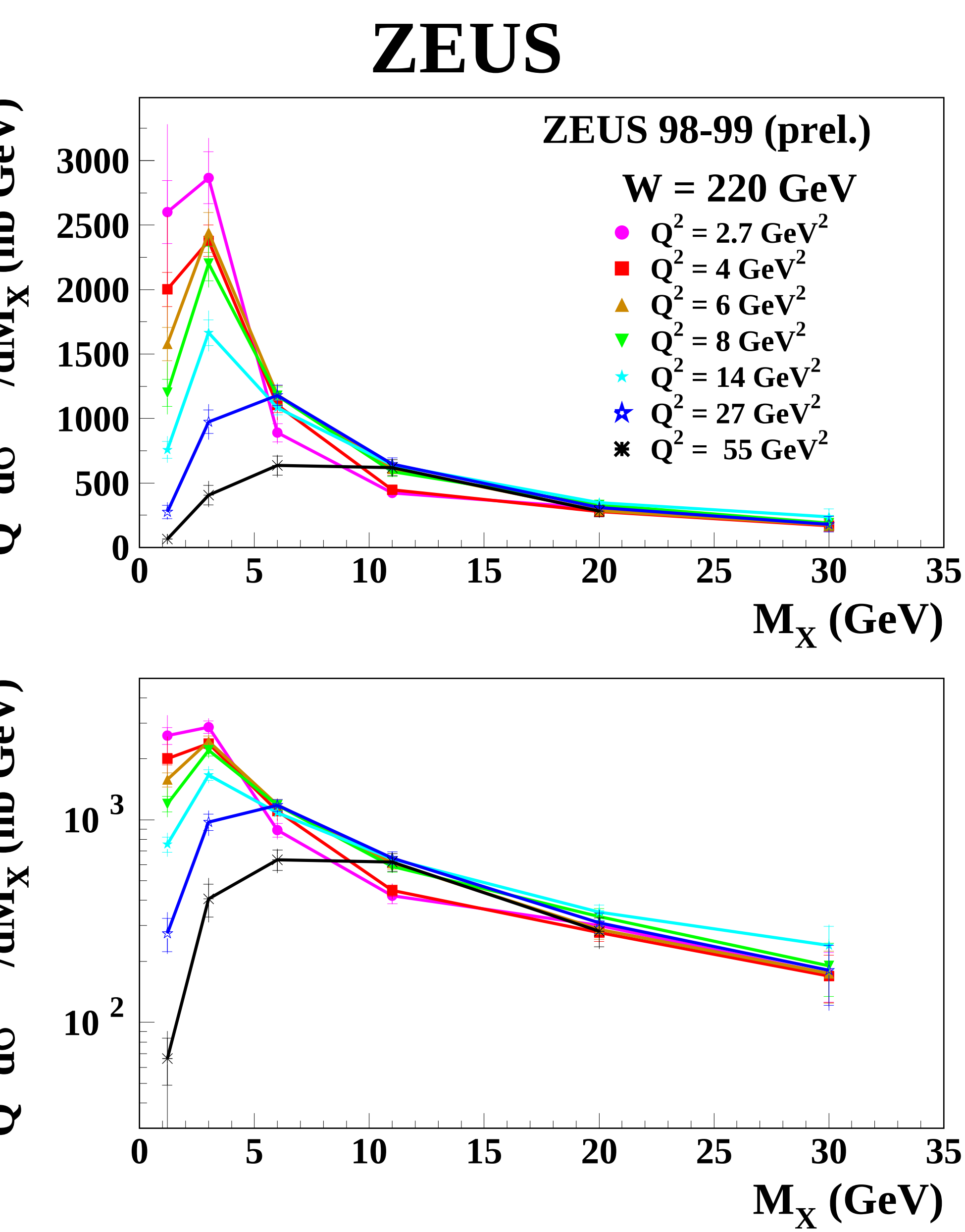
  $\Longrightarrow \alpha^{diff}_{I\!P} \approx 1 + (\alpha^{tot}_{I\!P} - 1)/2$

$$r_{tot}^{diff} = \frac{\int_{M_a}^{M_b} dM_X d\sigma^{diff}_{\gamma^* p \to XN, M_N < 2.3 GeV} / dM_X}{\sigma^{tot}_{\gamma^* p}}$$



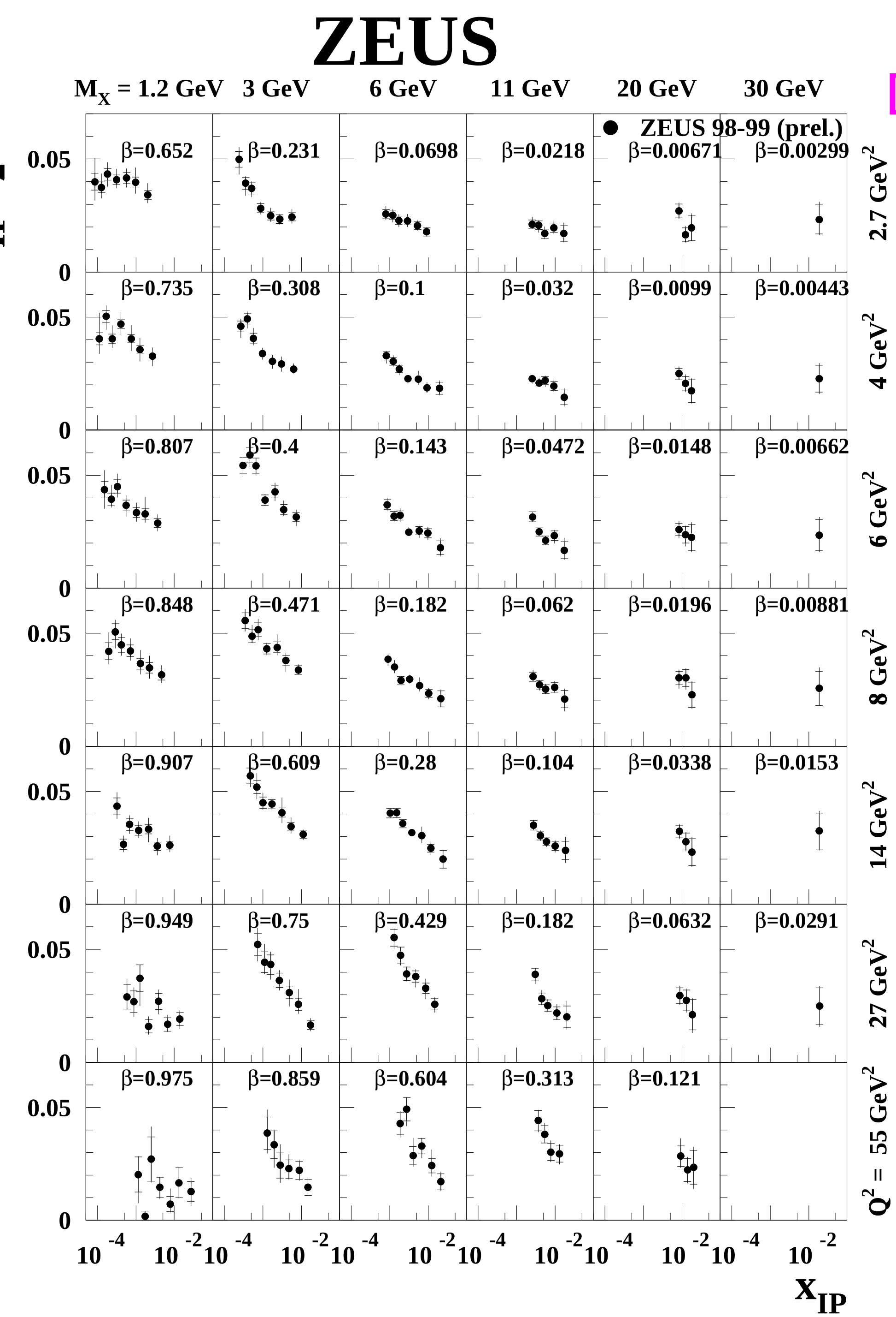
- For $M_X < 2$ GeV, r_{tot}^{diff} is falling with W .
- For $M_X > 2$ GeV, r_{tot}^{diff} is constant with W .
  $\Longrightarrow$ The diffractive cross section has about the same W -dependence as σ^{tot} .
- The low M_X bins exhibit a strong decrease of r_{tot}^{diff} with increasing Q^2 .
- For $M_X > 8$ GeV, no Q^2 dependence is observed.
- $\sigma^{diff}_{(M_X < 35 \text{ GeV})} / \sigma^{tot}$ at $W = 220$ GeV:
  $= 19.8^{+1.5}_{-1.4}\%$ $(Q^2 = 2.7$ GeV^2)
  $= 10.1^{+0.6}_{-0.7}\%$ $(Q^2 = 27$ GeV^2)
  $\Longrightarrow$ Slowly decreasing with Q^2

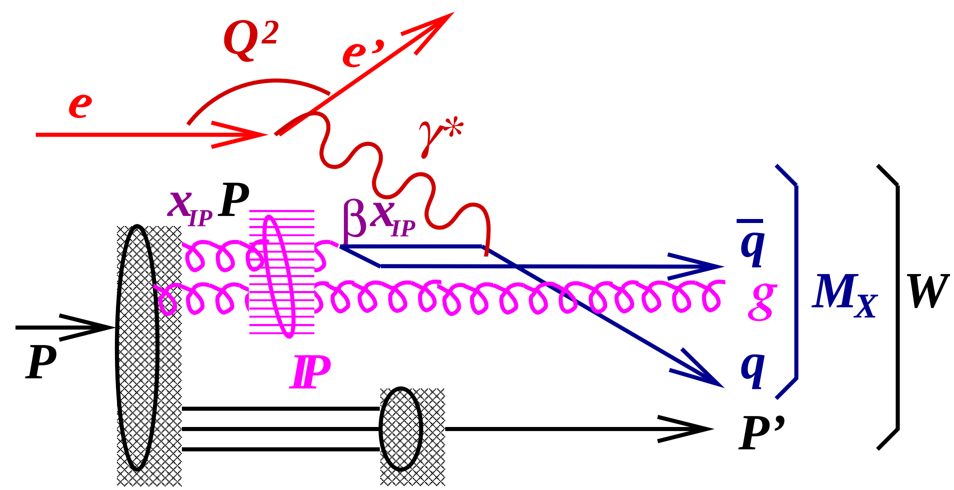
$Q^2 d\sigma^{diff}_{\gamma^* p \to XN}/dM_X$ vs. M_X at $W = 220$ GeV



- Rapid decrease with Q^2 for $M_X < 4$ GeV
  $\Longrightarrow$ predominantly higher twist.
- Constant or slow rise with Q^2 for $M_X > 10$ GeV
  $\Longrightarrow$ leading twist.

Diffractive structure function $F_2^{D(3)}$





- $x_{IP} F_2^{D(3)}(\beta, x_{IP}, Q^2) =$

$$\frac{1}{4\pi^2\alpha} \cdot \frac{Q^2(Q^2+M_X^2)}{2M_X} \cdot \frac{d\sigma^{diff}_{\gamma^* p \to XN}}{dM_X}$$

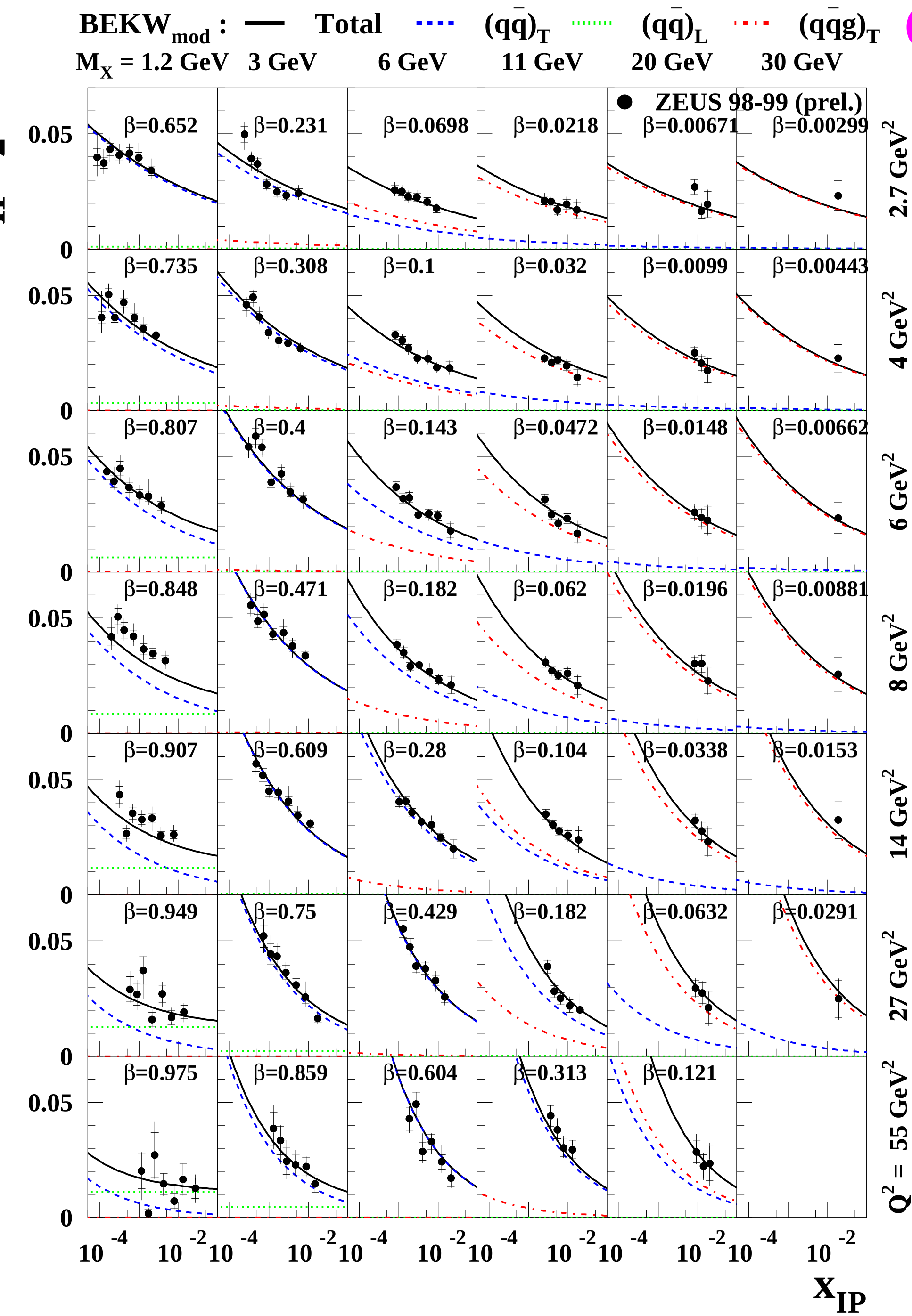
- $M_X < 2$ GeV and low Q^2 :

  $x_{IP} F_2^{D(3)} \approx$ constant with x_{IP} .

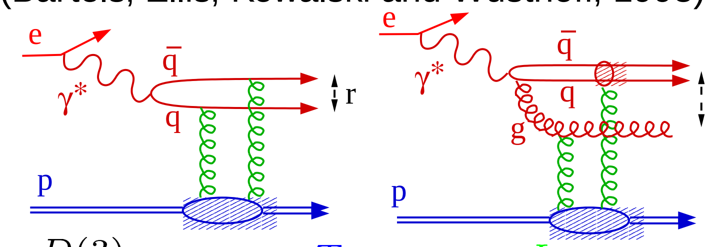
- $M_X > 2$ GeV: rapid increase as $x_{IP} \to 0$.

  $\Longrightarrow$parton evolution as $x_{IP} \to 0$.

Comparison with the BEKW model



(Bartels, Ellis, Kowalski and Wüsthoff, 1998)



- $x_{IP} F_2^{D(3)} = c_T \cdot F_{q\bar{q}}^T + c_L \cdot F_{q\bar{q}}^L + c_g \cdot F_{q\bar{q}g}^T$

$$F_{q\bar{q}}^T = (\frac{x_0}{x_{IP}})^{n_T(Q^2)} \cdot \beta(1-\beta) ,$$

$$F_{q\bar{q}}^L = (\frac{x_0}{x_{IP}})^{n_L(Q^2)} \cdot \frac{Q_0^2}{Q^2+Q_0^2} \cdot [\ln(\frac{7}{4} + \frac{Q^2}{4\beta Q_0^2})]^2 \cdot \beta^3(1-2\beta)^2 ,$$

$$F_{q\bar{q}g}^T = (\frac{x_0}{x_{IP}})^{n_g(Q^2)} \cdot \ln(1+\frac{Q^2}{Q_0^2}) \cdot (1-\beta)^\gamma$$

From data, $n_L(Q^2) \approx 0$ and

$$n_T(Q^2) \approx n_g(Q^2) \approx n_1 \ln(1+\frac{Q^2}{Q_0^2})$$

$\therefore c_T = 0.117 \pm 0.003, c_L = 0.171 \pm 0.012$

$c_g = 0.0093 \pm 0.0003, n_1 = 0.066 \pm 0.003$

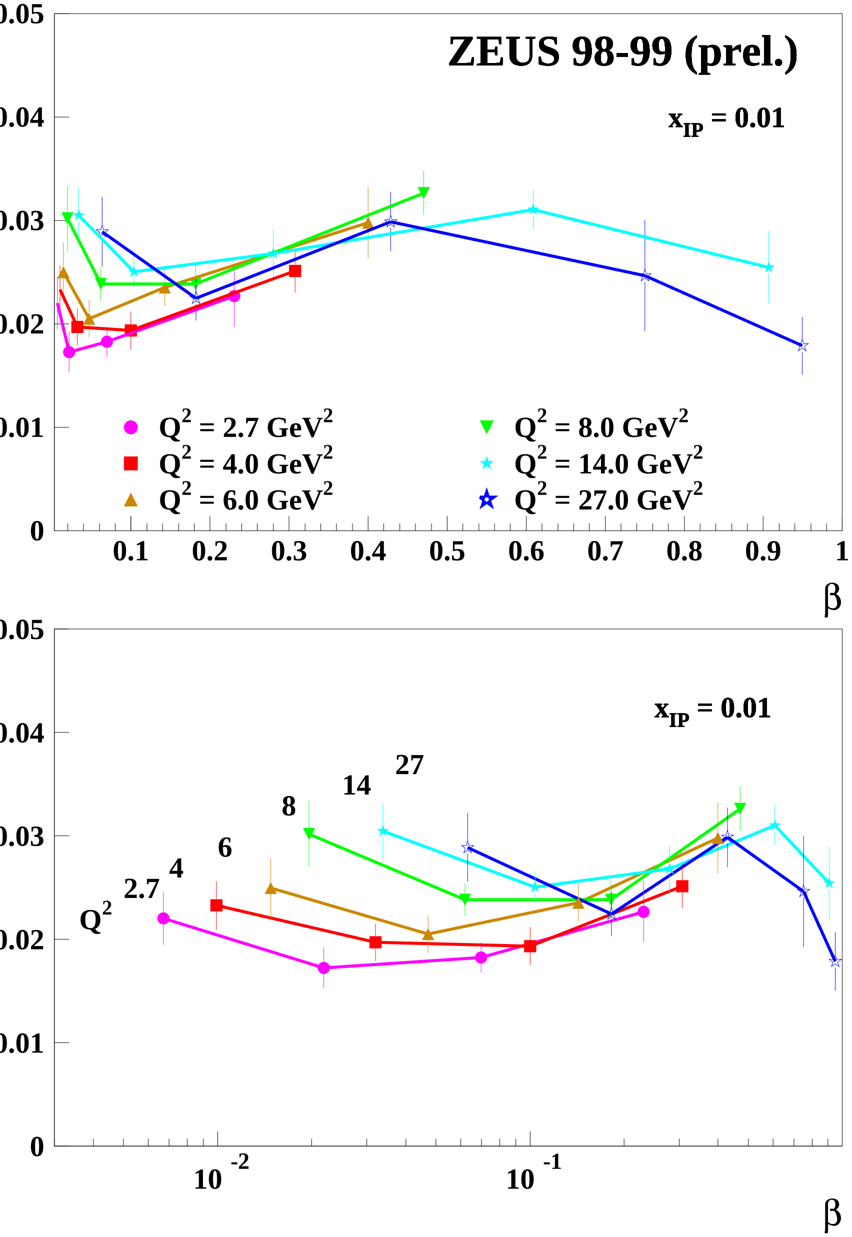
$\gamma = 8.32 \pm 0.51, \chi^2/\text{ndf} = 132/198$

- $(q\bar{q})_L$ only substantial at very large β

  $(q\bar{q})_T$ dominates at $\beta > 0.15$

  $(q\bar{q}g)_T$ dominates at small β

Pomeron structure function $F_2^{D(2)}(\beta, Q^2)$



- Structure Function, Proton $x, Q^2 \rightarrow F_2(x, Q^2)$

  Pomeron $\beta, Q^2 \rightarrow F_2^{D(2)}(\beta, Q^2)$

  $\Longrightarrow$ Probability for finding a quark

  with momentum fraction β in Pomeron

- Following the BEKW model,

  $F_2^{D(3)}(Q^2, \beta, x_{IP}) = f_{IP/p}(x_{IP}, Q^2) \cdot F_2^{D(2)}(\beta, Q^2)$

  $f_{IP/p}(x_{IP}, Q^2)$ Pomeron flux factor

  use ansatz $f_{IP/p}(x_{IP}, Q^2) = \frac{C}{x_{IP}} \cdot (\frac{x_0}{x_{IP}})^{n(Q^2)}$.

- Set $x_0 = 0.01$, $C = 1$

  $\Longrightarrow$ determine $F_2^{D(2)}$ at $x_{IP} = 0.01$

  $\therefore F_2^{D(2)}(\beta, Q^2) = x_0 F_2^{D(3)}(x_0, \beta, Q^2)$

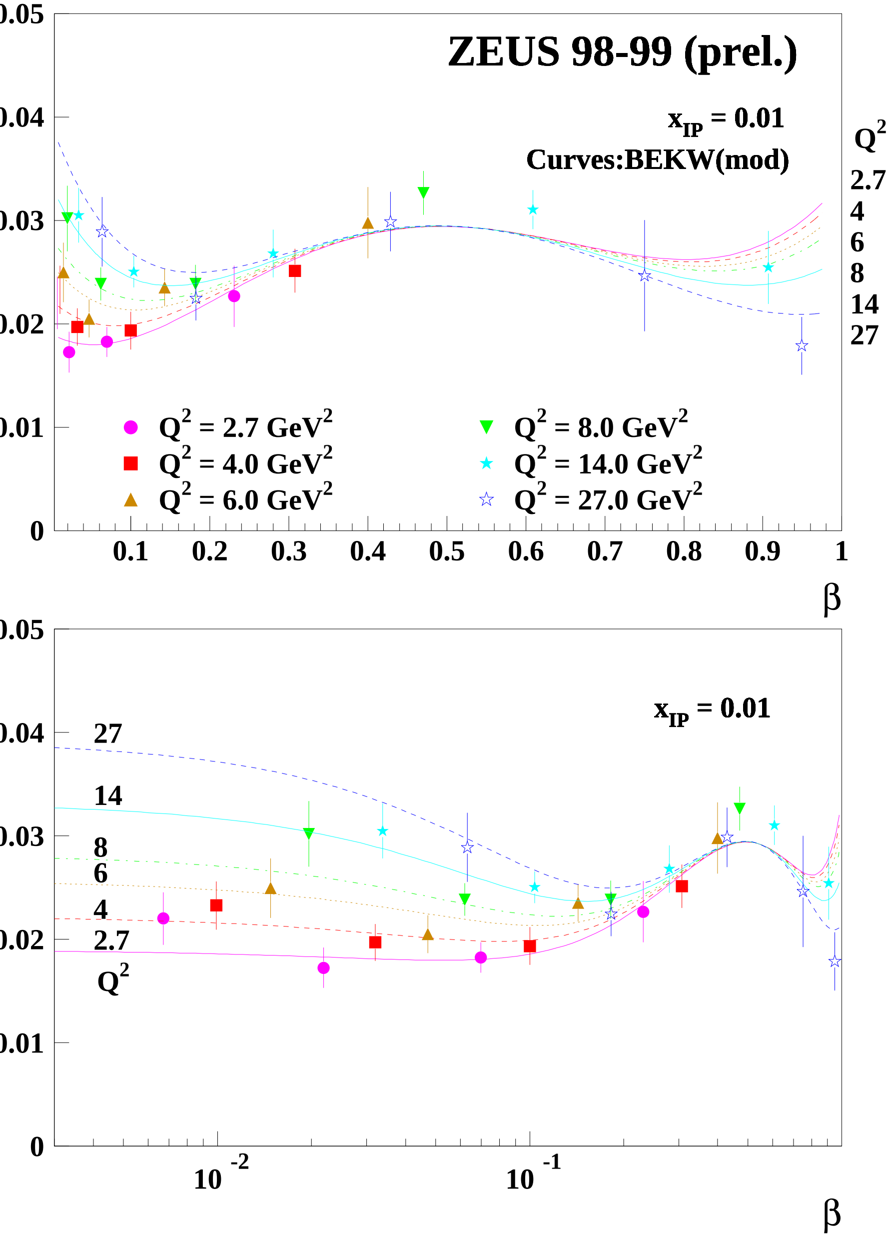
- For high β , $F_2^{D(2)}$ decreases with rising Q^2 .

- As $\beta \rightarrow 0$, $F_2^{D(2)}$ rises.

  The rise becomes stronger as Q^2 increases.

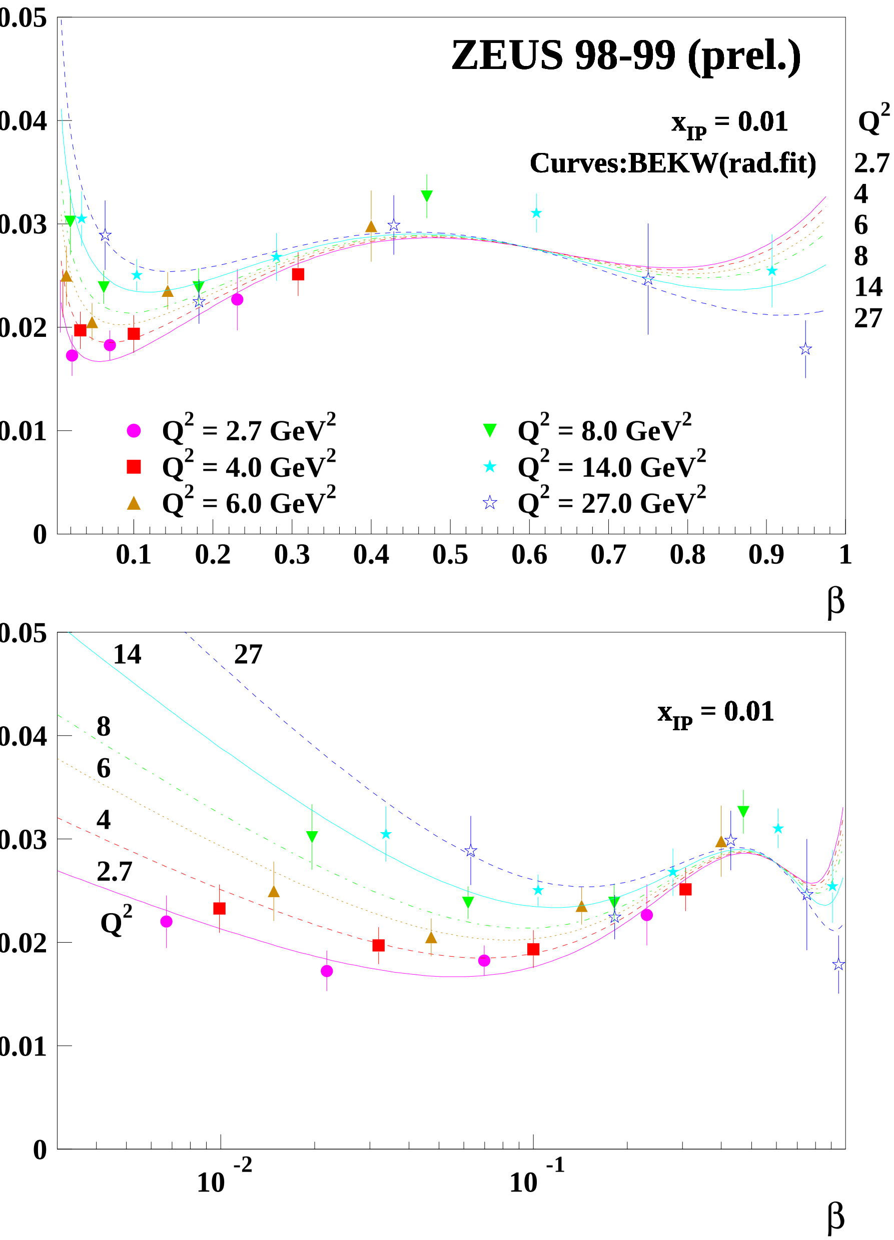
  $\Longrightarrow$ Evidence for pQCD evolution

$F_2^{D(2)}(\beta, Q^2)$ including BEKW(mod) fit



- BEKW(mod) fit does not reproduce the rise of $F_2^{D(2)}$ as $\beta \to 0$

$F_2^{D(2)}(\beta, Q^2)$ including radiation fit



- replace $c_g \cdot F^T_{q\bar{q}g}$ by radiation term:

  $c_{rad} \cdot F_{rad} =$

  $$(c_{rad} \cdot \frac{x_0}{x_{IP}})^{n^{xrad}(Q^2)}$$
  $$\cdot[(1/\beta)^{n^{\beta rad}(Q^2)} - 1)] \cdot (1-\beta)^{\gamma}$$

- from fit to the data

  $c_T = 0.113 \pm 0.001, c_L = 0.178 \pm 0.011$

  $c_{rad} = 0.116 \pm 0.024$

  $n^{xrad} = 0.068 \pm 0.002$

  $n^{\beta rad} = 0.018 \pm 0.003$

  $\gamma = 2.90 \pm 0.22$

  $\chi^2/\text{ndf} = 144/196$

- $\Longrightarrow$ radiation term reproduces trend of the data as $\beta \to 0$ and Q^2 increases

Conclusion

- Data from ZEUS leading proton spectrometer are promising but the measured t dependence is not yet precise enough to measure α' and see shrinkage

- DIS diffraction from H1: QCD-type fit with PDF's for quarks and gluons gives good description of data from $Q^2 = 3.5$ to 400 GeV^2.
  According to the fit, $75 \pm 15\%$ of the Pomeron momentum is carried by gluons

- Results from ZEUS - M_X analysis:

	$M_X < 2$ GeV	$M_X > 2$ GeV
$d\sigma^{diff}/dM_X$	Constant with W	Rising with W
$\alpha_{IP}(0)$	like soft pomeron	For $Q^2 > 10$ GeV^2, above soft pomeron and rising with Q^2
r_{tot}^{diff}	Falling with W Decreasing with Q^2 for $M_X < 8$ GeV	Constant with W Weak Q^2 dependence for $M_X > 8$ GeV
$Q^2 d\sigma^{diff}/dM_X$	Decreasing with Q^2 $\Longrightarrow$ Higher twist	Constant for $M_X > 10$ GeV $\Longrightarrow$ Leading twist
$x_{IP} F_2^{D(3)}$	Constant w.r.t. x_{IP}	Rising as $x_{IP} \to 0$

	"valence region", $\beta > 0.1$	"sea region", $\beta < 0.1$
$F_2^{D(2)}(\beta, Q^2)$	Decreasing with Q^2 Maximum at $\beta \sim 0.5$, $IP = q\bar{q}$	Increasing as $\beta \to 0$ Increasing with Q^2

$\Longrightarrow$ DIS diffractive Scattering : Evidence for QCD evolution in x_{IP} and in β.