Inclusive Diffractive Deep Inelastic Scattering at ZEUS

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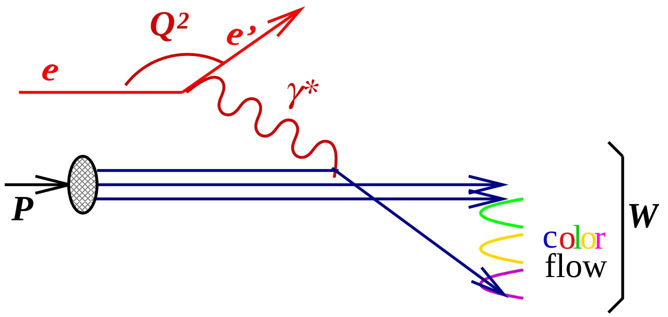
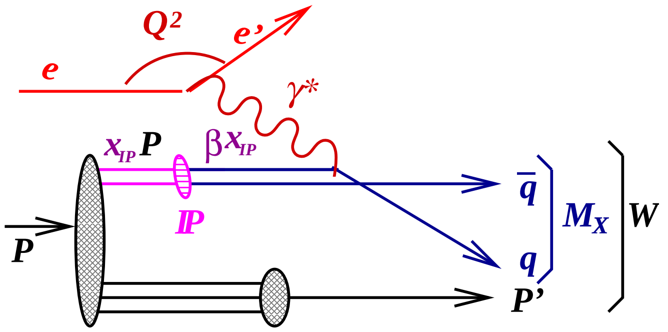
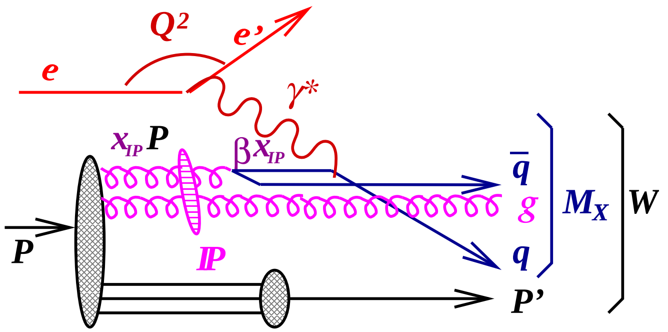
- Introduction
- DIS diffraction with the ZEUS leading proton spectrometer: $F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$ and t dependence
- DIS diffraction from ZEUS with the Forward Plug Calorimeter $d\sigma/dM_X(W, Q^2, M_X)$, $F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$ and $F_2^{D(2)}(\beta, Q^2)$
- Conclusions

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







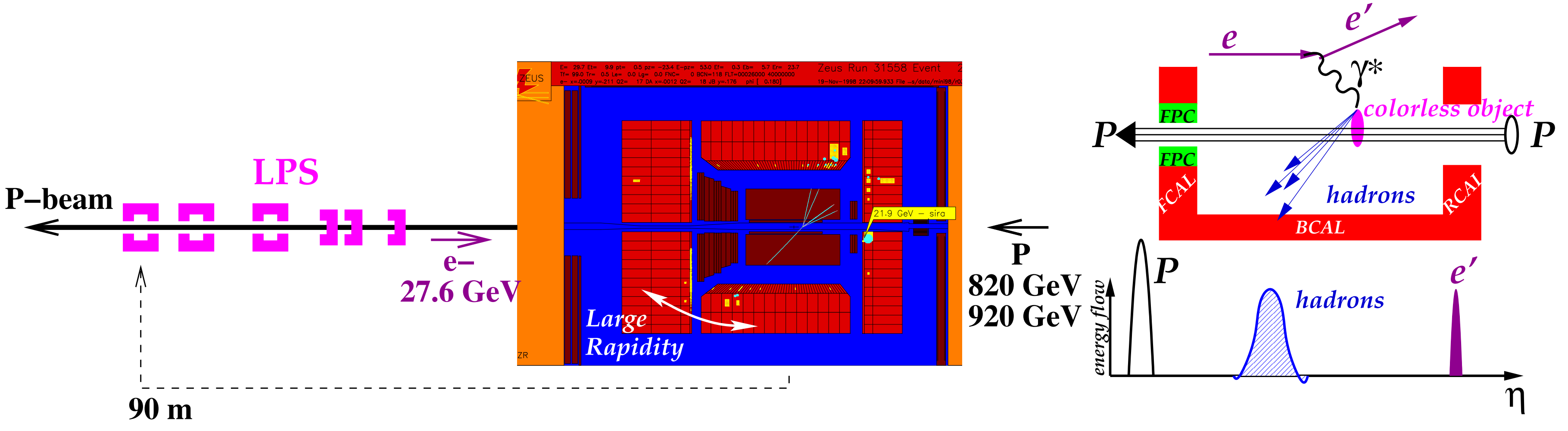
- $Q^2 \;=\; -q^2 \;=\; -(k-k')^2$
- $x \;=\; \dfrac{Q^2}{2q\cdot p}$
- $W \;=\; \sqrt{(p+q)^2} \approx \sqrt{\dfrac{Q^2}{x}}$
- $M_X^2 \;=\; (k-k'+p-p')^2$
- $t \;=\; (p-p')^2$
- $x_{IP} = \dfrac{(p-p')\cdot q}{p\cdot q} \approx \dfrac{M_X^2+Q^2}{W^2+Q^2}$
- $\beta = \dfrac{Q^2}{2(p-p')\cdot q} = \dfrac{x}{x_{IP}} \approx \dfrac{Q^2}{M_X^2+Q^2}$

present data in terms of

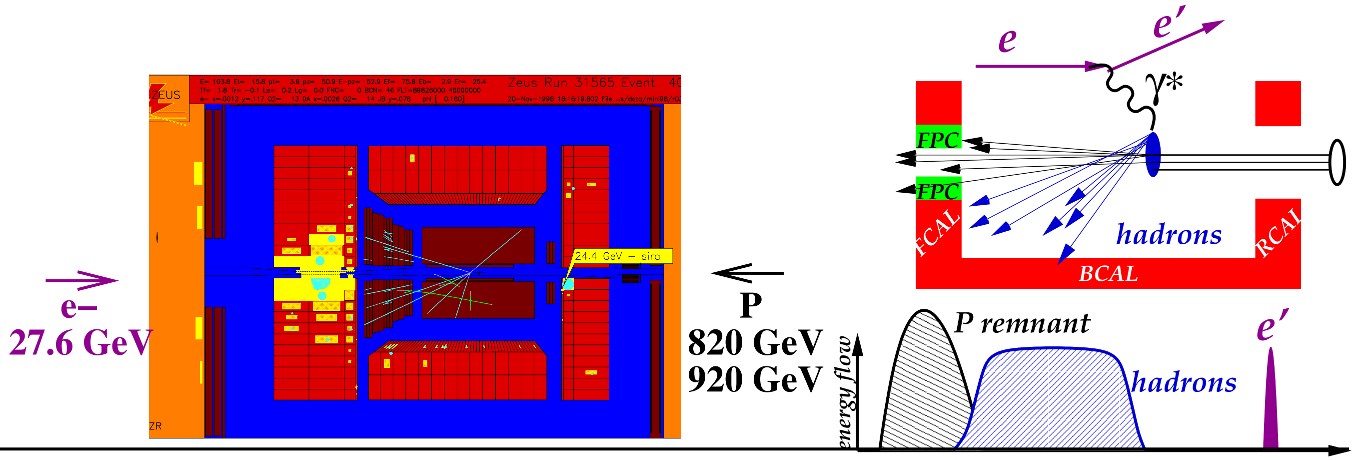
- $d\sigma/dM_X(Q^2, W, M_X)$
- $x_{IP}F_2^{D(3)}(\beta, x_{IP}, Q^2)$

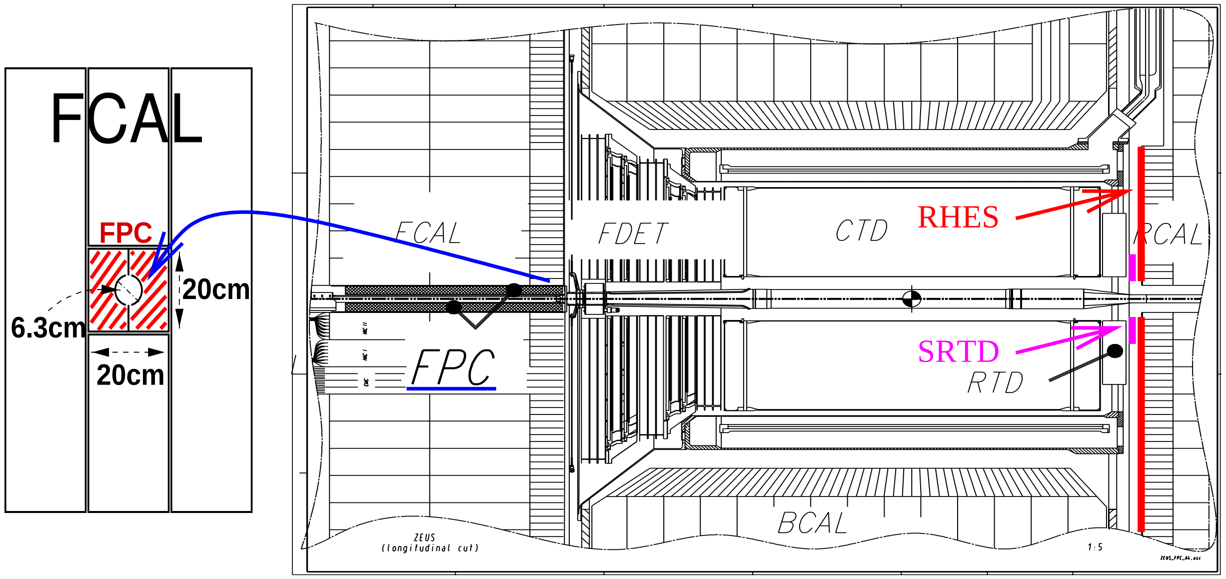
Event Topologies of Diffractive Deep Inelastic Scattering

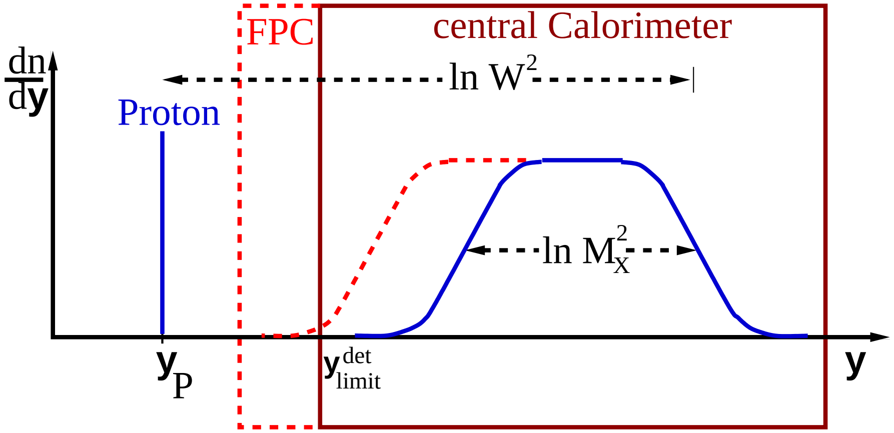
1. Diffractive scattering



2. Non-diffractive scattering







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

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

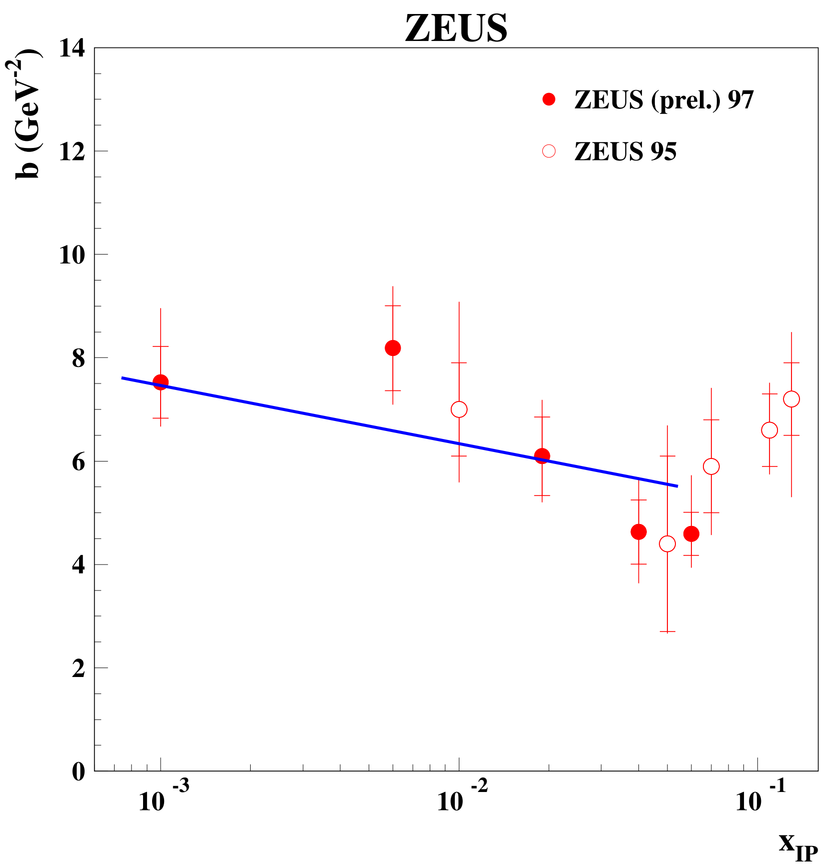
  $\rightarrow$ Increase the accessible M_X range by a factor of 1.7

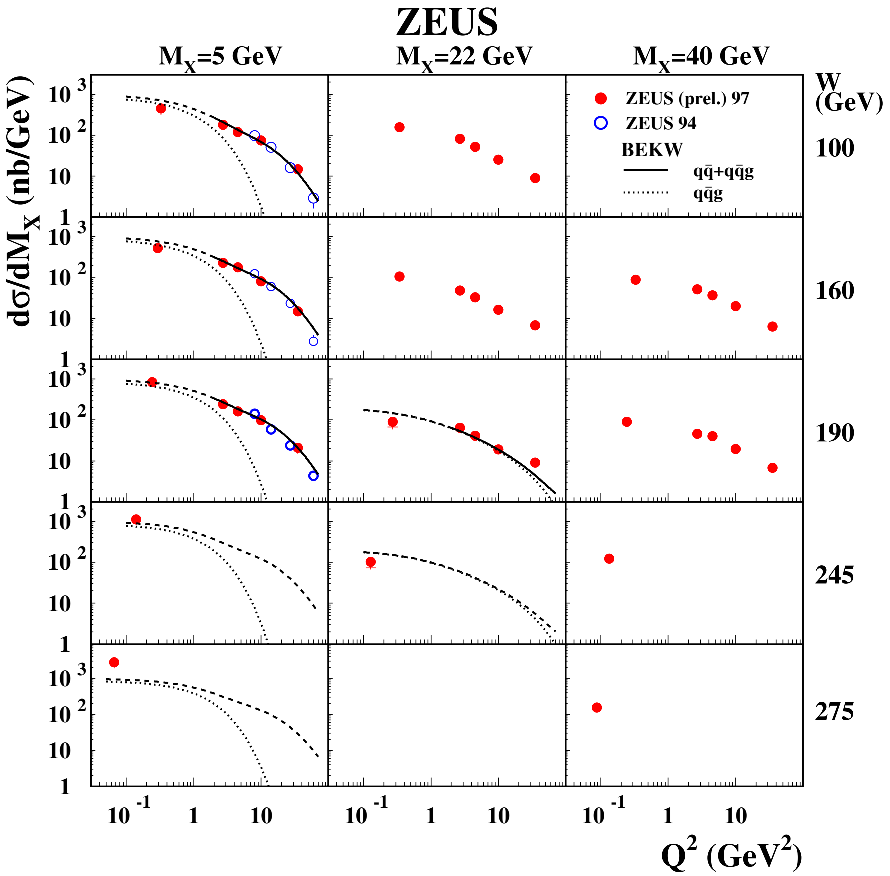
- For 1998-1999

  ◦ FPC $\rightarrow$ higher M_X and lower W

  ◦ Smaller RCAL beamhole $\rightarrow$ lower Q^2 and higher W

Measurement of the t-dependence and $d\sigma/dM_X$ with the LPS

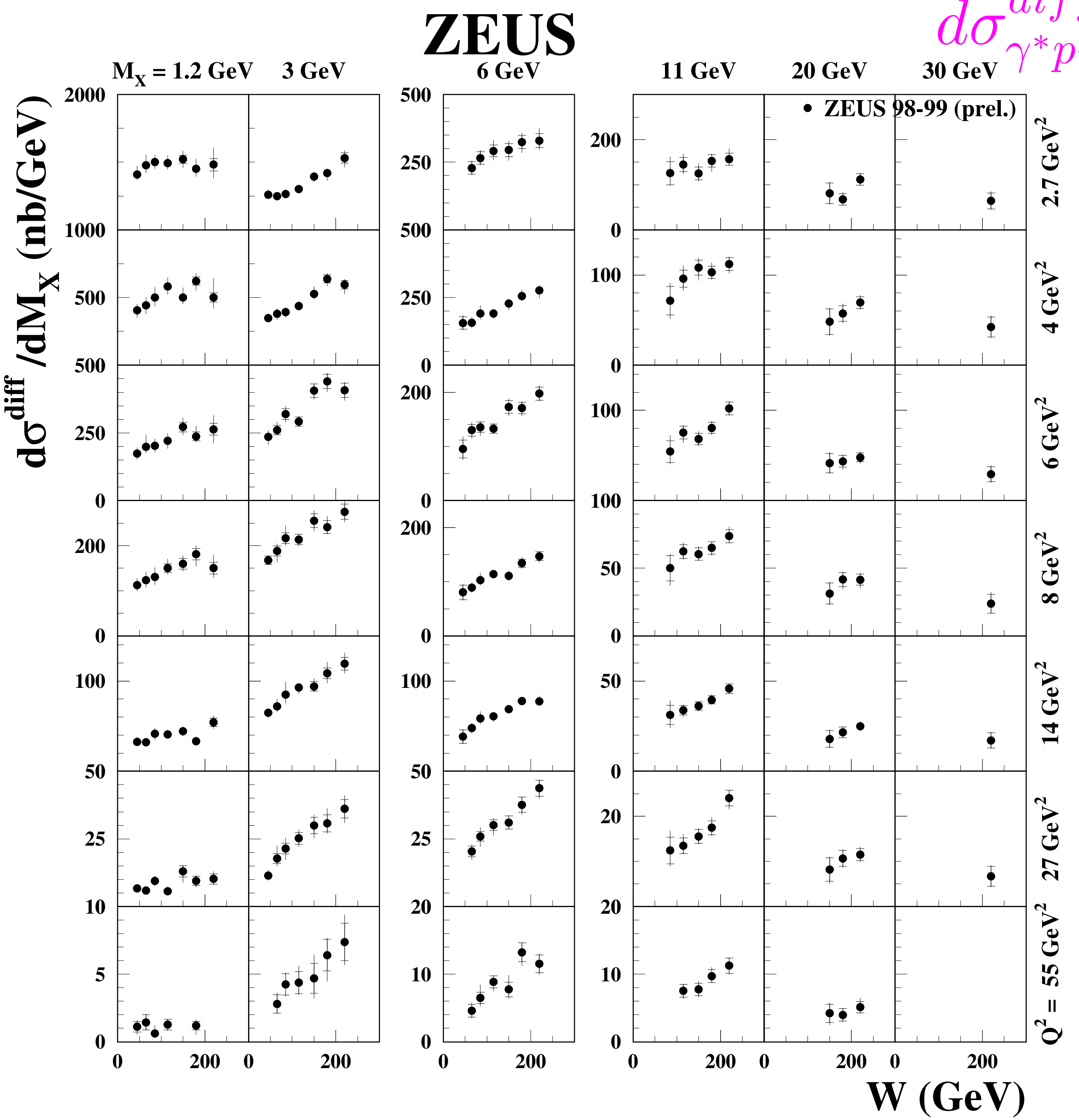




- Fit t distribution to $d\sigma/d|t| \propto exp(-b|t|)$
  $\Longrightarrow b \approx 6-8$ GeV^{-2}
  similar to slopes measured for elastic had-had scattering

- expect shrinkage of diffractive peak (Regge):
  $b = b_0 + 2\alpha' \ln(1/x_{IP})$
  $\rightarrow b$ should rise as $x_{IP} \rightarrow 0$
  dashed line shows expected behaviour for
  $b_0 = 5$GeV^{-2}, $\alpha' = 0.25$ GeV^{-2}
  data cannot yet decide between constant or rising b

- $d\sigma/dM_X$ as function of Q^2
  $\Longrightarrow$ fall-off with Q^2 less steep as M_X increases



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

$M_N < 2.3$ GeV (FPC)

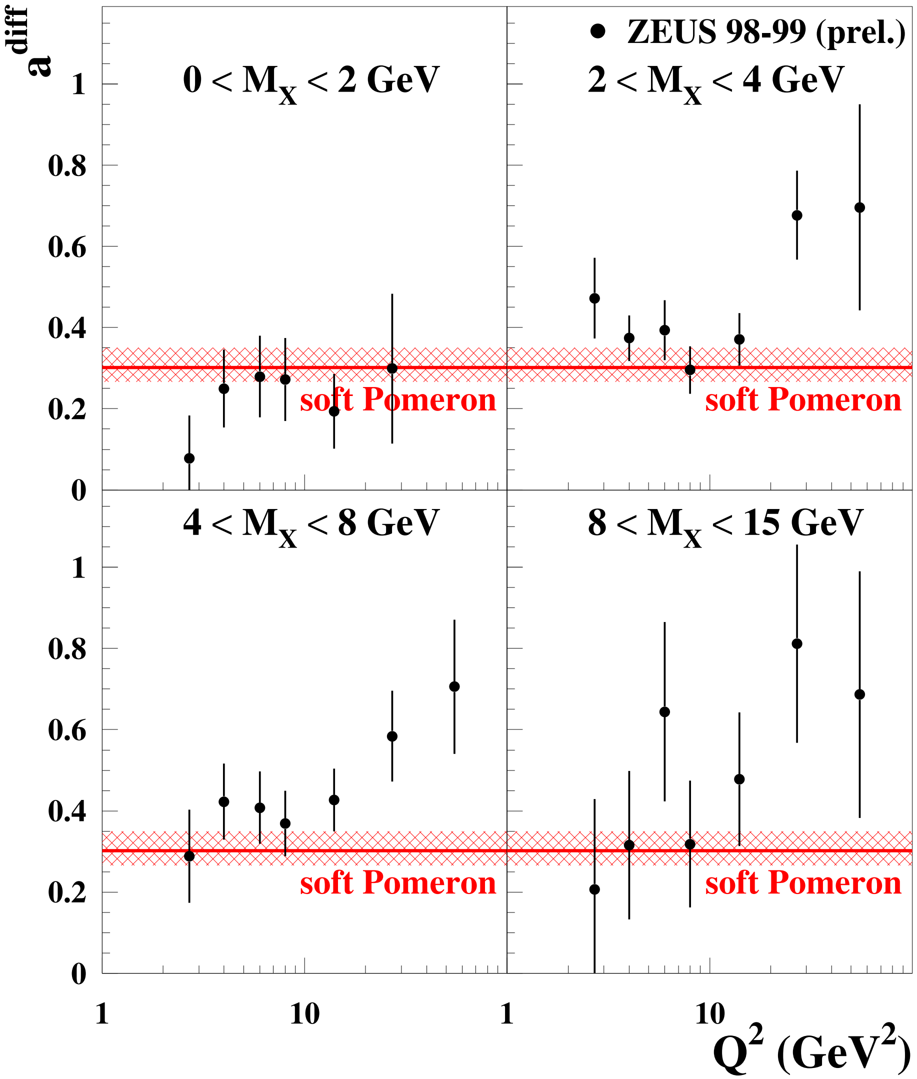
- $M_X < 2$ GeV

  $d\sigma/dM_X$ depends weakly on W .

- $M_X > 2$ 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 $t = 0$:

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

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

3. $M_X < 2$ GeV

a^{diff} as expected for soft Pomeron

4. $M_X > 2$ GeV

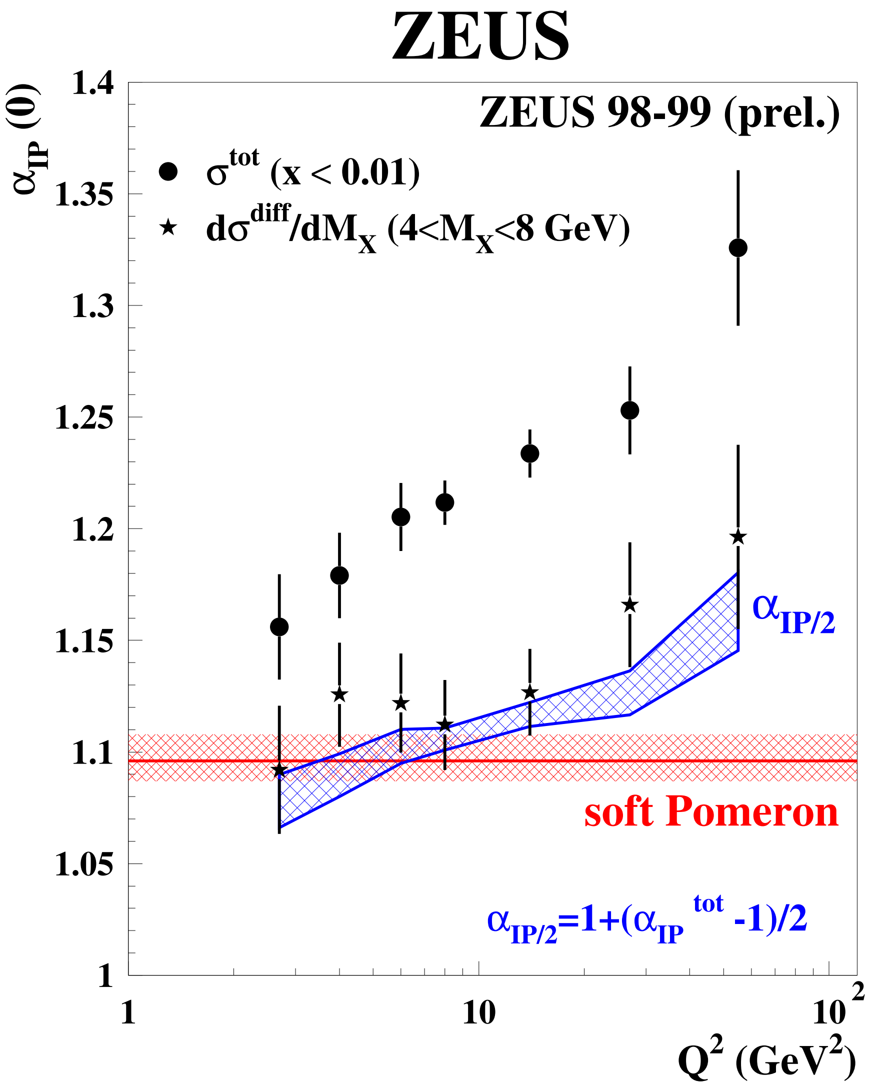
a^{diff} higher than expected for soft Pomeron $\longrightarrow$ clear indication for rise with Q^2 .

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



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

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

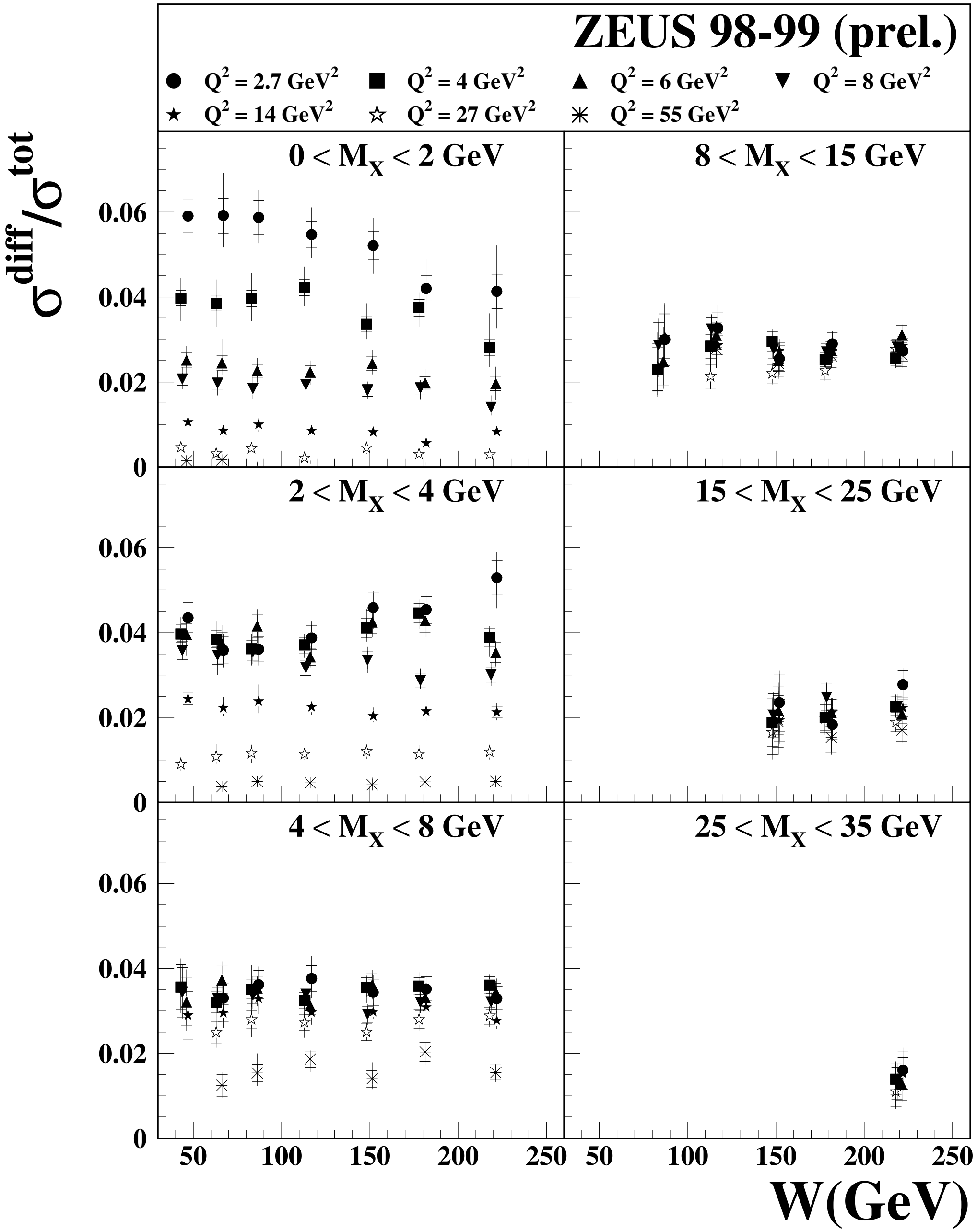
  (Optical theorem)

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

  at $t = 0$

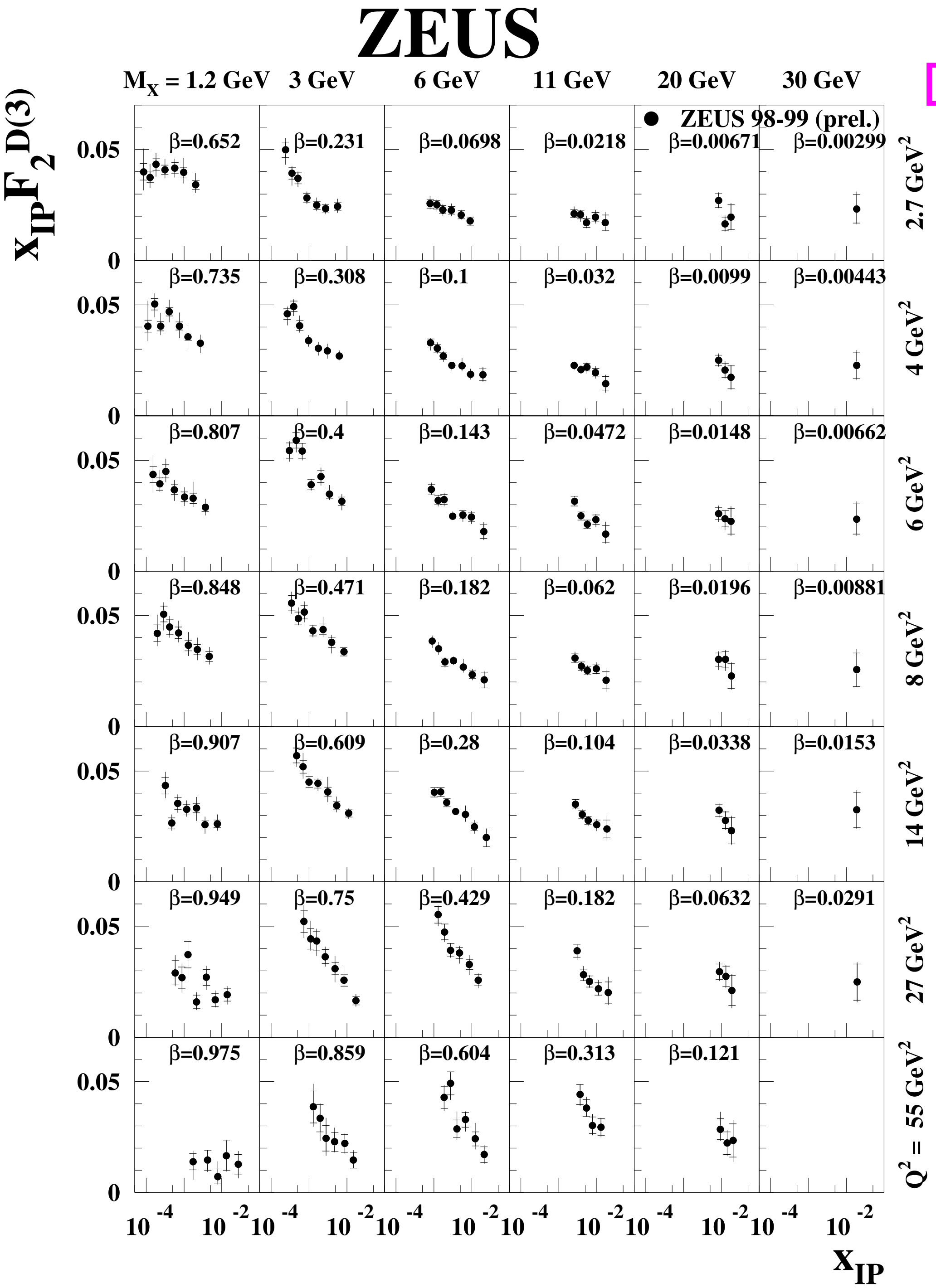
- Data ($4 < M_X < 8$ GeV) show

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

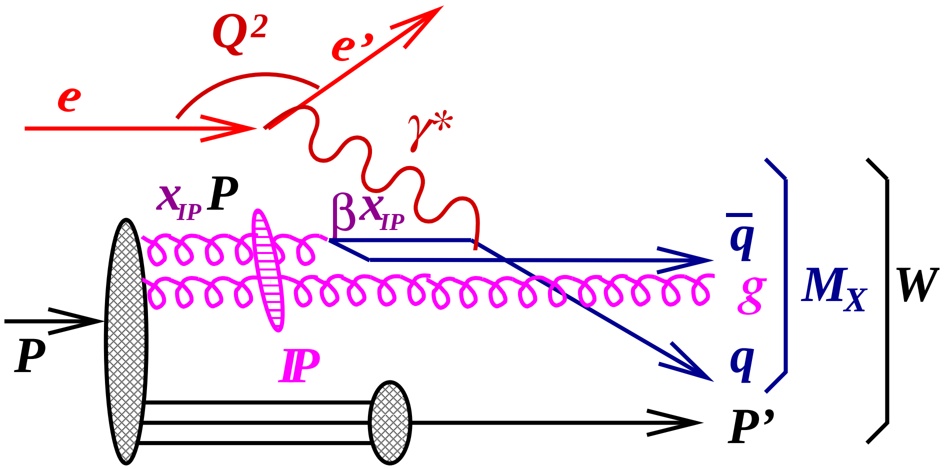


$$r_{tot}^{diff} = \frac{\int_{M_a}^{M_b} dM_X d\sigma^{diff}_{\gamma^* p \to XN, M_N < 2.3GeV}/dM_X}{\sigma^{tot}_{\gamma^* p}}$$

- 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:
  $= 19.8^{+1.5}_{-1.4}\%$ $\quad (Q^2 = 2.7$ GeV^2)
  $= 10.1^{+0.6}_{-0.7}\%$ $\quad (Q^2 = 27$ GeV^2)
  $\Longrightarrow$ Slowly decreasing with Q^2



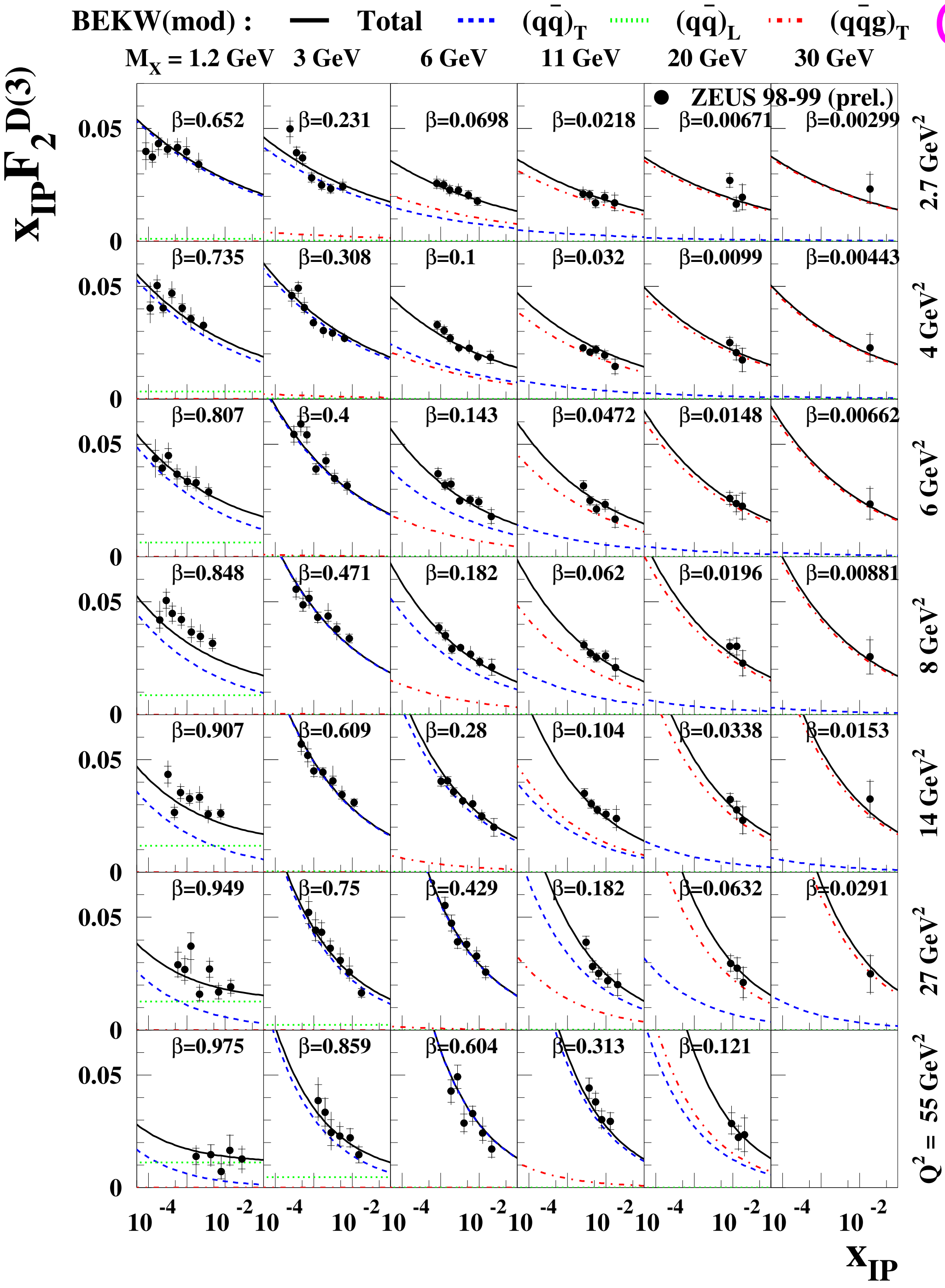
Diffractive structure function $F_2^{D(3)}$ (FPC)



- $$x_{IP} F_2^{D(3)}(\beta, x_{IP}, Q^2) = \frac{1}{4\pi^2\alpha} \cdot \frac{Q^2(Q^2+M_X^2)}{2M_X} \cdot \frac{d\sigma^{diff}_{\gamma^* p \to XN}}{dM_X}$$
- $M_X < 2$ GeV and low Q^2 :

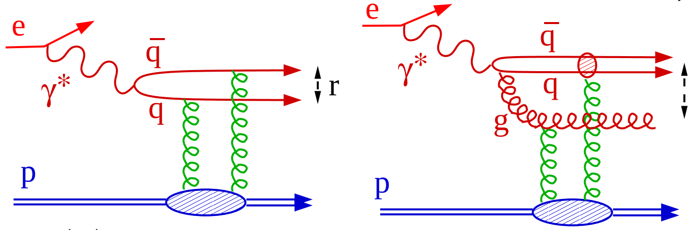
  $x_{IP} F_2^{D(3)} \approx$ constant with x_{IP} .
- $M_X > 2$ GeV: rapid increase as $x_{IP} \to 0$.

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



Comparison with the BEKW model

(Bartels, Ellis, Kowalski and Wüsthoff, 1998)



- $x_{IP} F_2^{D(3)} = c_T \cdot F^T_{q\bar{q}} + c_L \cdot F^L_{q\bar{q}} + c_g \cdot F^T_{q\bar{q}g}$

  $$F^T_{q\bar{q}} = \left(\frac{x_0}{x_{IP}}\right)^{n_T(Q^2)} \cdot \beta(1-\beta)\,,$$

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

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

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

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

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

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

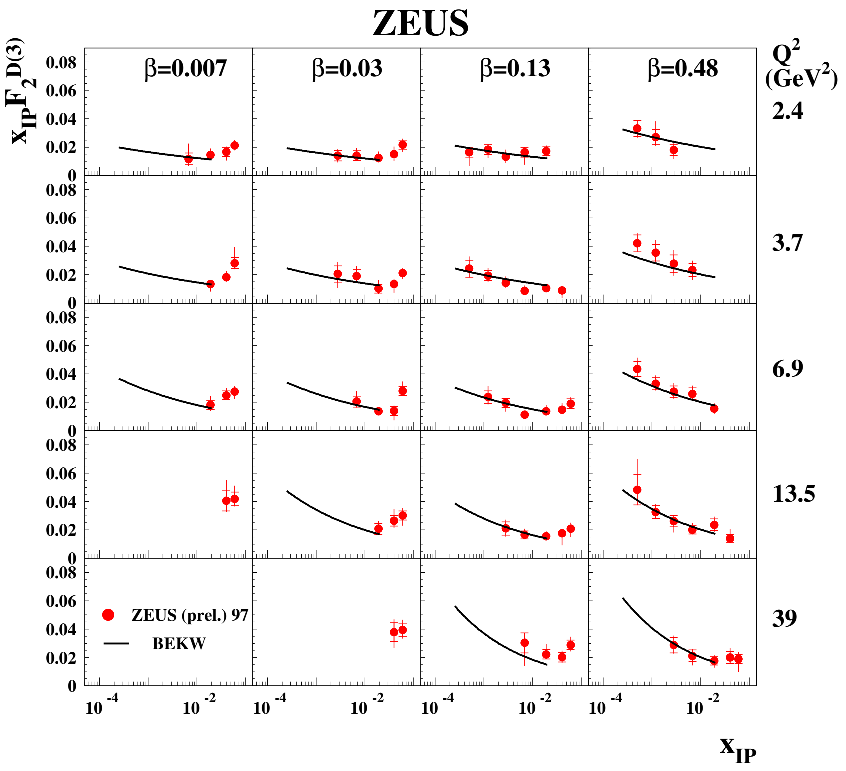
  $\gamma = 8.32 \pm 0.51, \chi^2/\text{ndf} = 132/198$

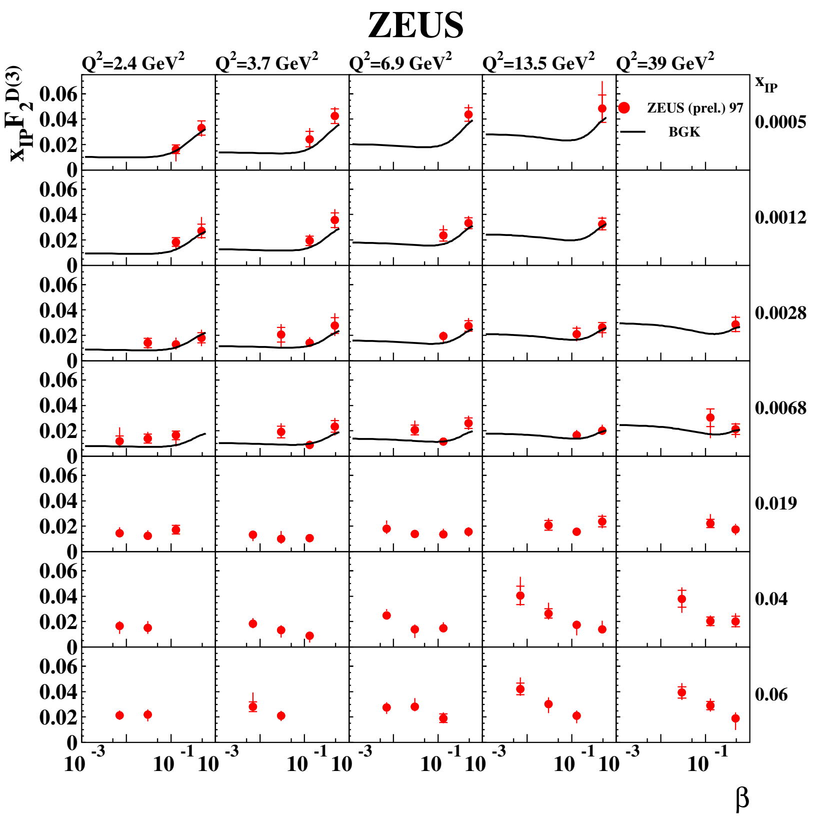
- $(q\bar{q})_L$ only substantial at very large β

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

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

Diffractive structure function $F_2^{D(3)}$ vs $x_{I\!P}$ and β (LPS)

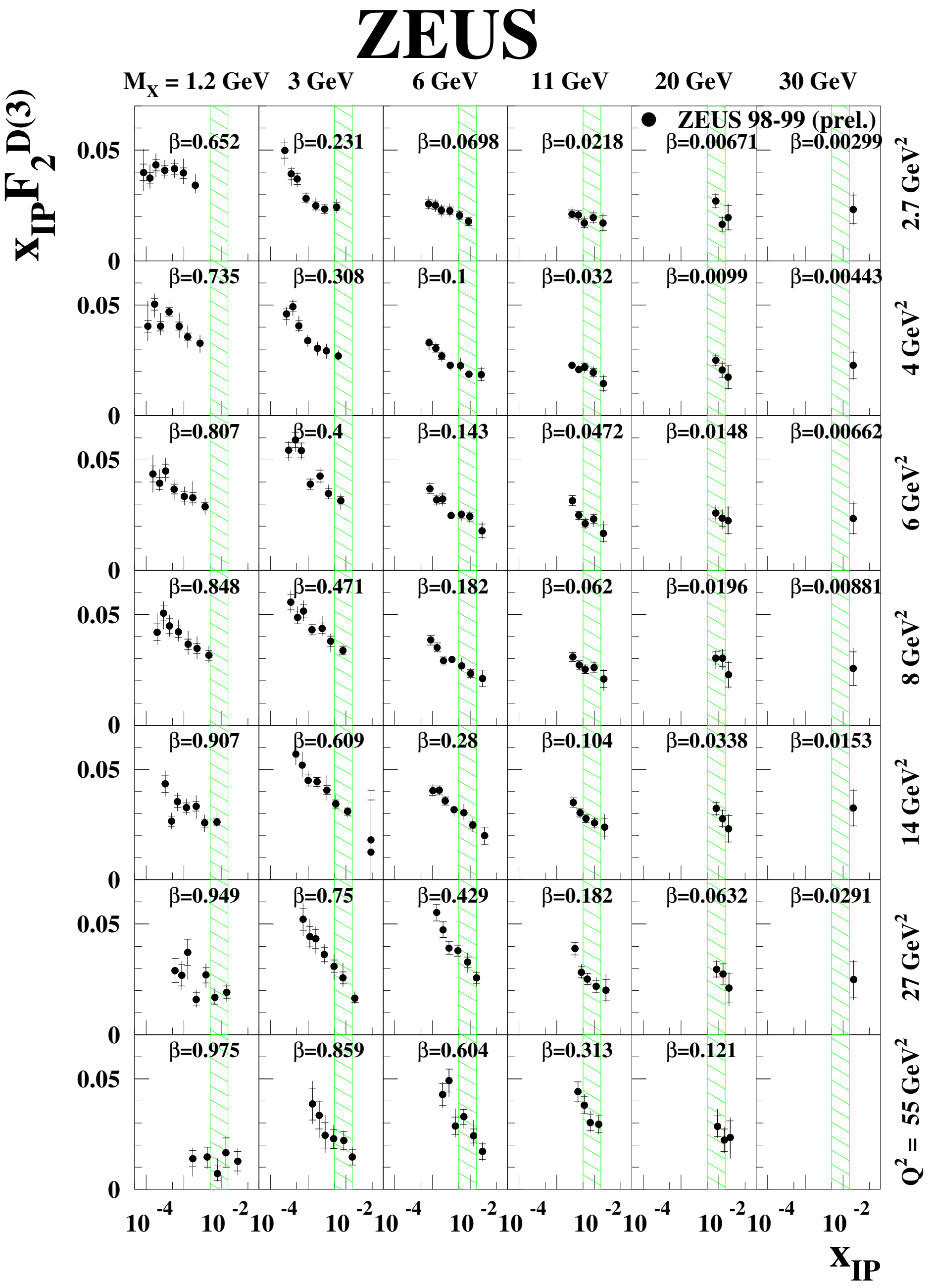




- at fixed β, Q^2
  $x_{I\!P} F_2^{D(3)}(\beta, x_{I\!P}, Q^2)$ rises as $x_{I\!P} \rightarrow 1$
  $\Longrightarrow$ evidence for lower lying
  Regge contributions for $x_{pom} > 0.04$
- curve: BEKW(mod) fit from FPC data * 0.69

  $\Longrightarrow$ the two data sets agree well

- for fixed $x_{I\!P} > 0.04$ and $Q^2 > 13.5$ GeV^2
  $x_{I\!P} F_2^{D(3)}(\beta, x_{I\!P}, Q^2)$ rises as $\beta \rightarrow 0$
  $\Longrightarrow$ contrib. from lower Regge poles?
- curves sat. model (Bartels, Golec-Biernat, Kowalski)



Determine structure function of Pomeron $F_2^{D(2)}$ (FPC)

- Following Ingelman + Schlein,

  diff. struct. function of proton

  = (flux of Pomerons) $\times$ (struct. funct. of Pomeron)

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

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

  For 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 $x_{IP} = 0.01$

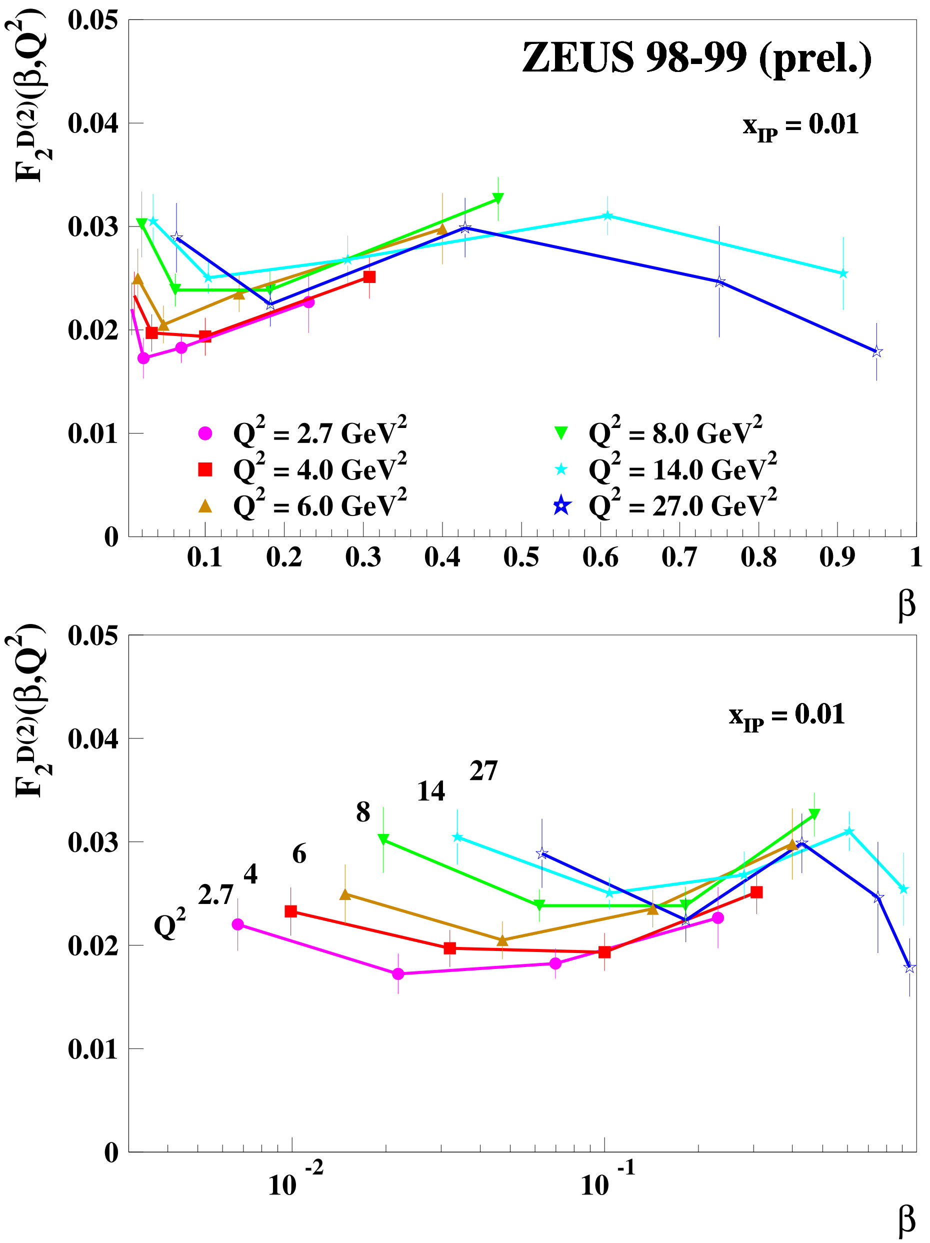
  $\Longrightarrow F_2^{D(2)}(\beta, Q^2) = x_0 F_2^{D(3)}(x_0, \beta, Q^2)$

- use all $x_{IP} F_2^{D(3)}$ data with

  $0.005 < x_{IP} < 0.015$

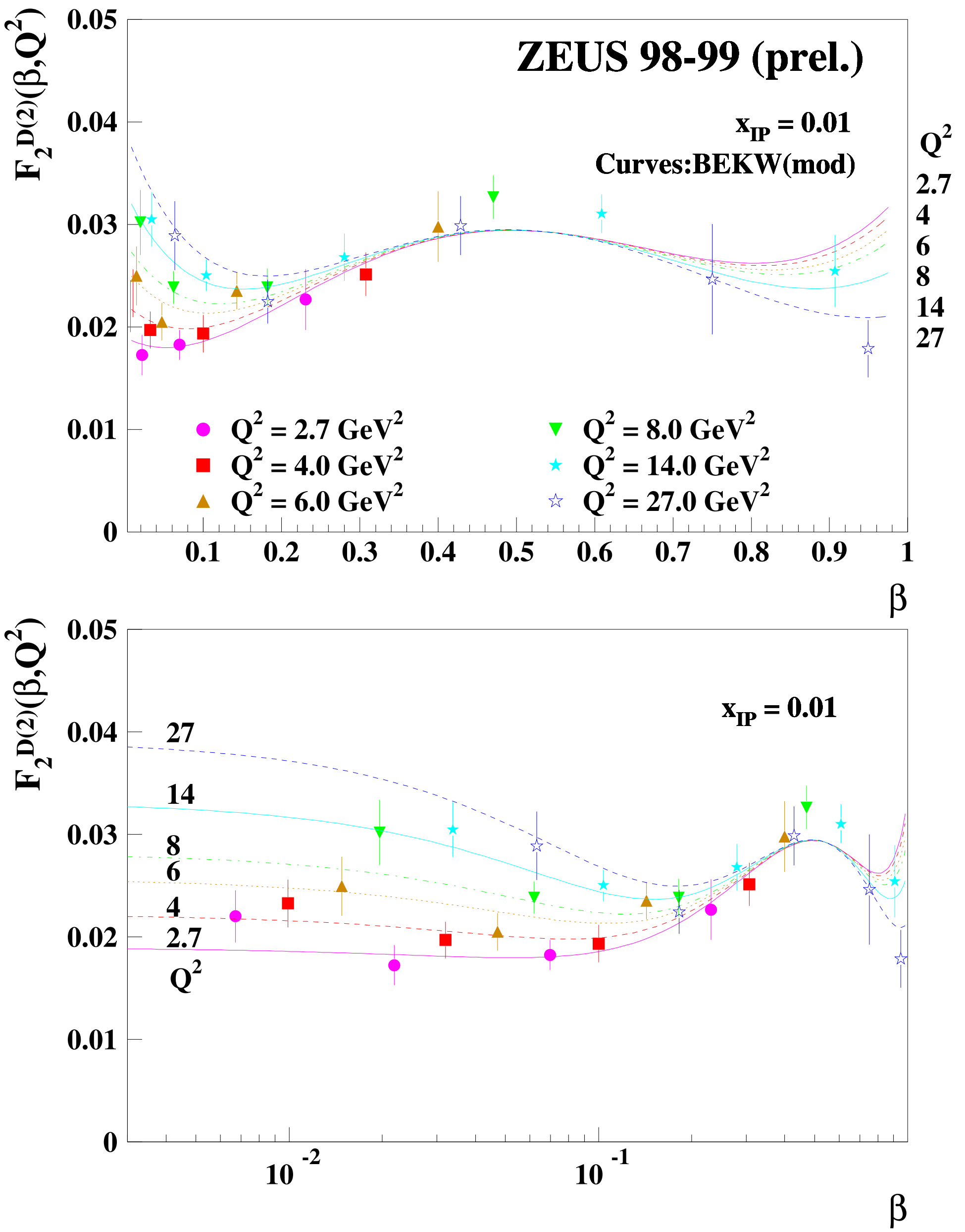
  and transport them to $x_{IP} = 0.01$

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



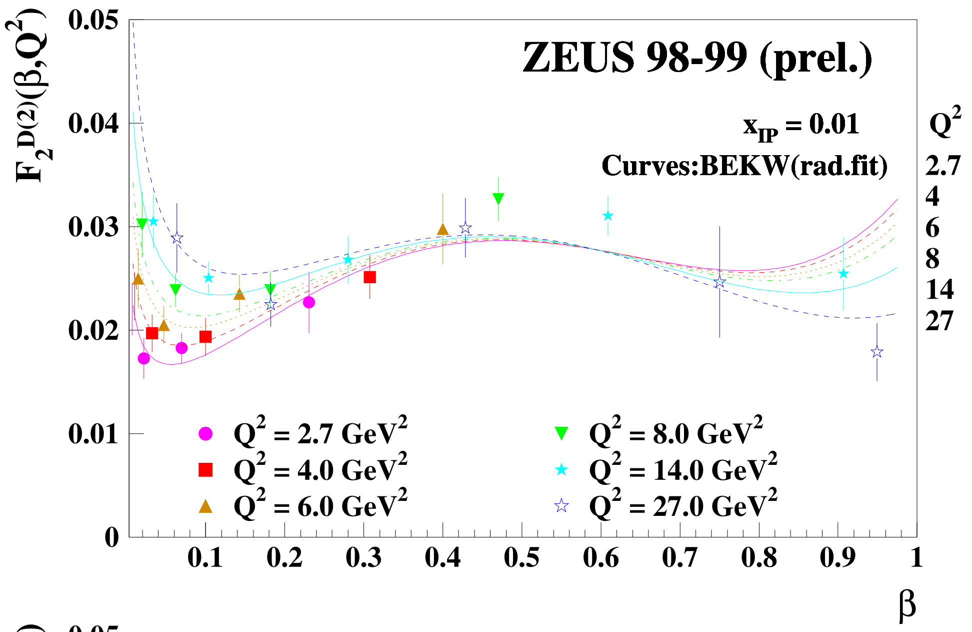
- Structure Function, Proton $x, Q^2 \rightarrow F_2(x, Q^2)$
  Pomeron $\beta, Q^2 \rightarrow F_2^{D(2)}(\beta, Q^2)$
  $\Longrightarrow$ Probability for finding a quark
  with momentum fraction β in Pomeron
- In the "valence" region, $\beta > 0.1$,
  $F_2^{D(2)}$ has a maximum around $\beta = 0.5$
  suggesting that
  main contribution from a Pomeron in a $q\bar{q}$ state
- For high β , $F_2^{D(2)}$ seems to decerase with rising Q^2
- In the "sea" region, $\beta < 0.1$,
  $F_2^{D(2)}$ rises as $\beta \rightarrow 0$ and as Q^2 increases
- $\Longrightarrow$ Evidence for pQCD evolution of the Pomeron structure function with β and Q^2

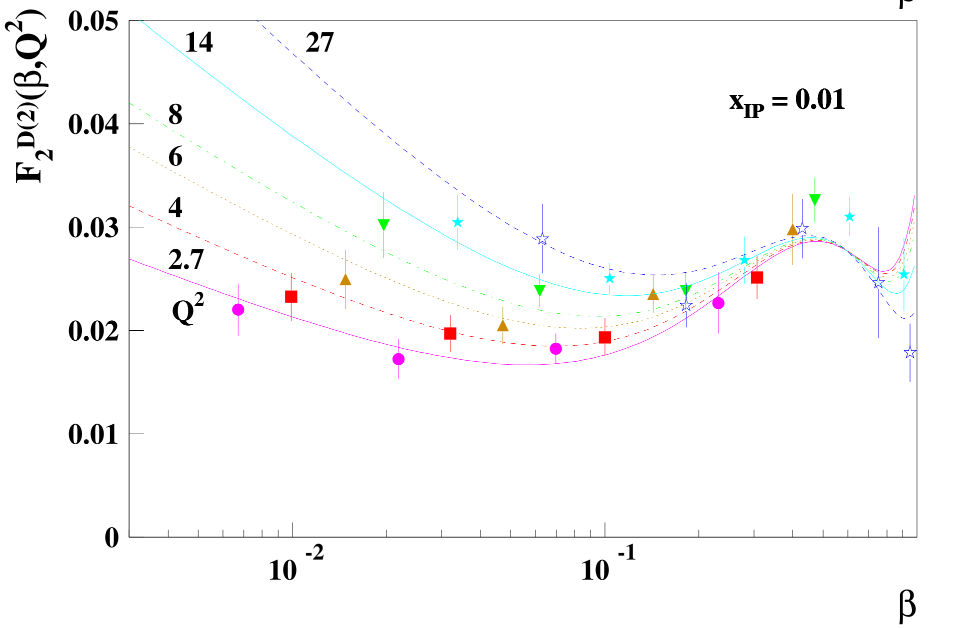
$F_2^{D(2)}(\beta, Q^2)$ including BEKW(mod) fit



- BEKW(mod) fit does not fully 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

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

  $c_{rad} = 0.116 \pm 0.024$

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

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

  $\gamma = 2.90 \pm 0.22$

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

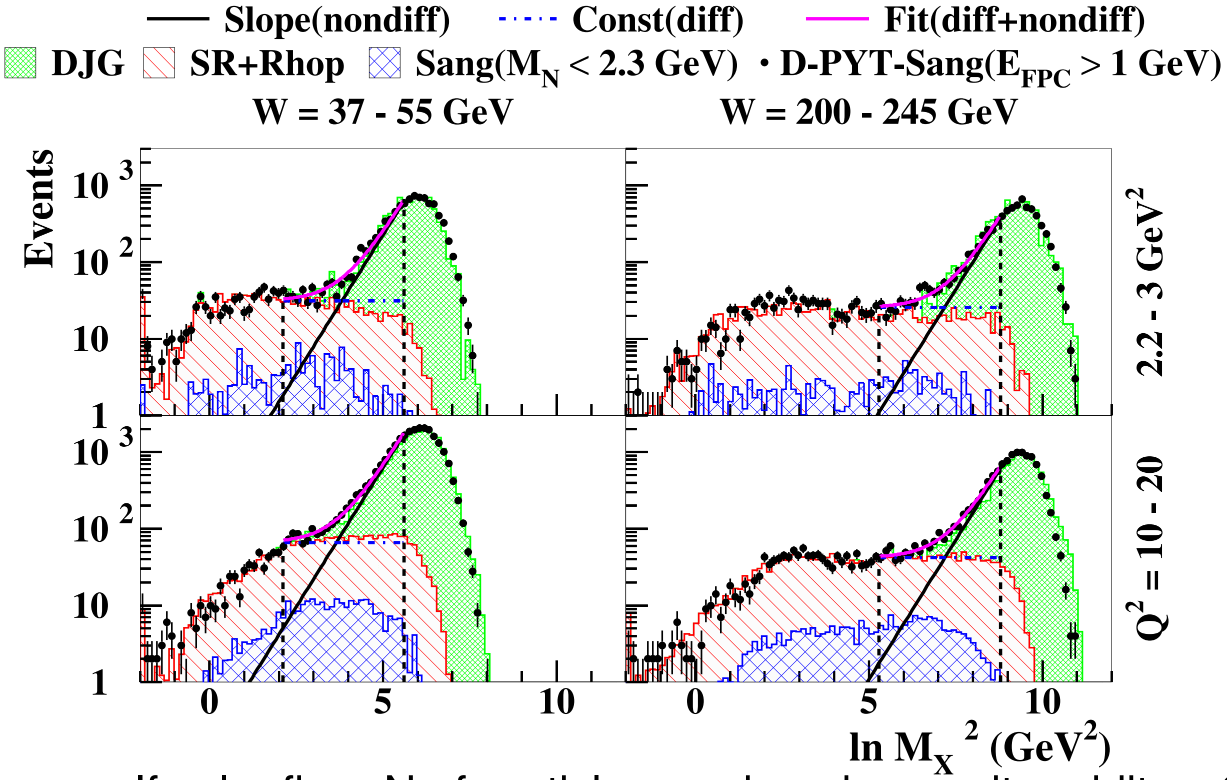
- $\Longrightarrow$ radiation term reproduces trend of the data as $\beta \to 0$ and Q^2 increases

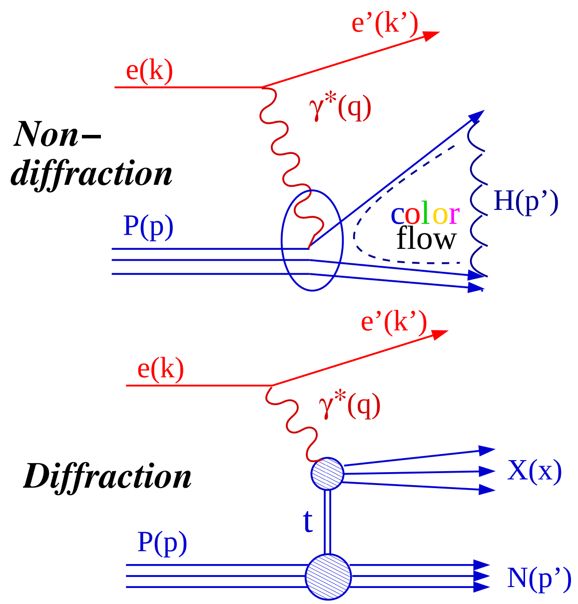
Conclusions

- diffraction contributes a substantial fraction of the total DIS cross section, viz.
  $Q^2 = 2.7$ GeV^2, $\frac{M_X^2}{W^2} < 0.025$: $\sigma^{diff}/\sigma^{tot} = 19.4^{+1.5}_{-1.4}\%$
  $Q^2 = 27$ GeV^2, $\frac{M_X^2}{W^2} < 0.025$: $\sigma^{diff}/\sigma^{tot} = 10.1^{+0.6}_{-0.7}\%$
- strong indication for $\alpha_{I\!P}$ to rise with Q^2 in diffraction: $\alpha_{I\!P}^{diff} \approx 1 + (\alpha_{I\!P}^{tot} - 1/2)$
- diffractive structure function of the proton: $x_{I\!P} F_2^{D(3)}(\beta, x_{I\!P}, Q^2)$ can be factorized as $f(x_{I\!P}, Q^2) \times F(\beta, Q^2)$
- structure function of the pomeron, $F_2^{D(2)}(\beta, Q^2) = x_0 F_2^{D(3)}(x_0, \beta, Q^2)$, x_0 = 0.01, for $\beta > 0.1$ ("valence" region)
  $\Longrightarrow$ has a maximum near $\beta = 0.5$ consistent with a $\beta(1-\beta)$ behaviour
  suggesting main contribution comes from a $(q\bar{q})$ state
  $\Longrightarrow$ for $\beta < 0.1$ ("sea" region) rises as $\beta \rightarrow 0$ and rises as Q^2 increases
  $\Longrightarrow$ suggests for $F_2^{D(2)}$ pQCD like evolution with β and Q^2
- We are making progress in understanding DIS diffraction in terms of quarks and gluons

EXTRA

Extraction of diffractive contribution





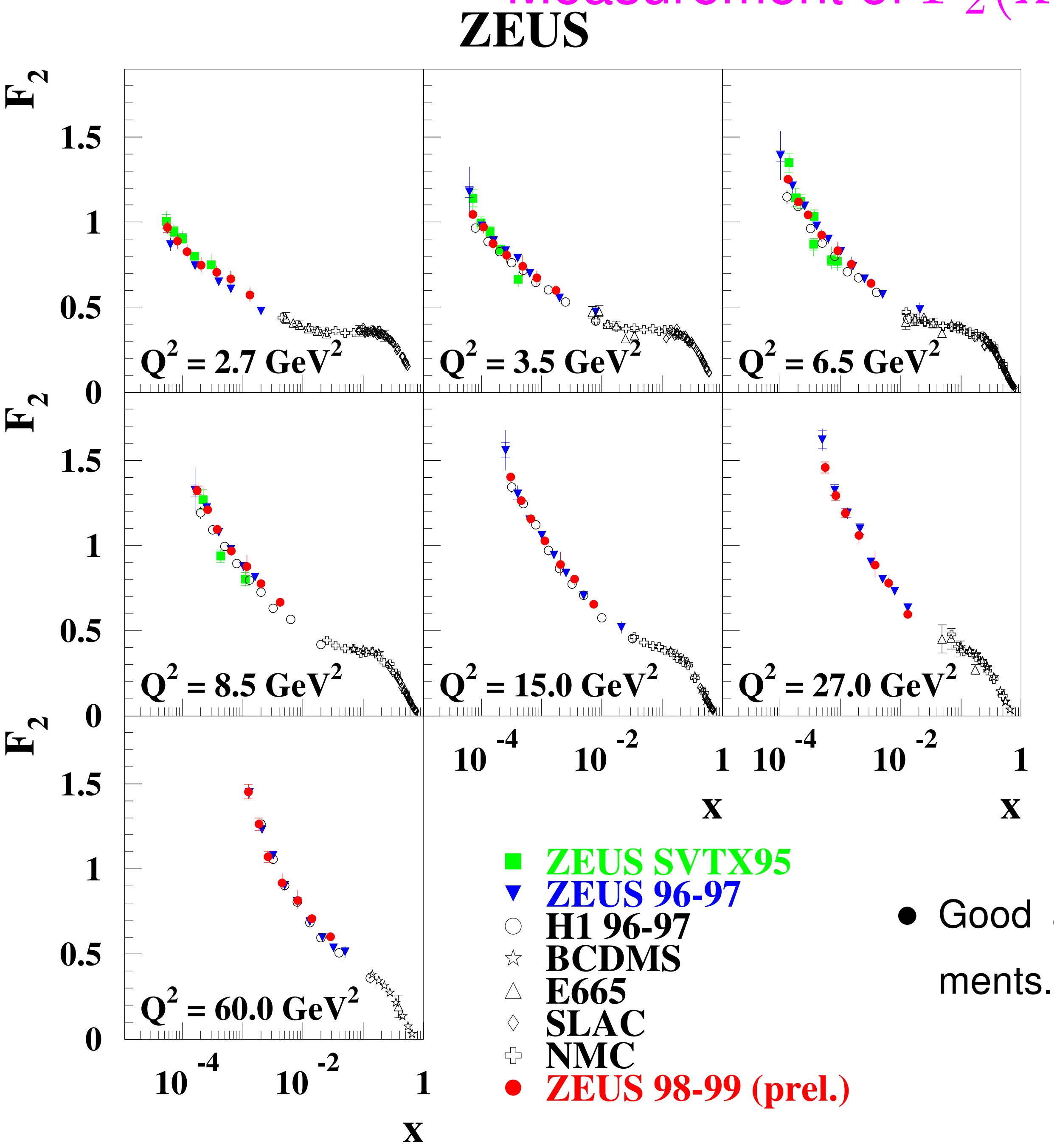
- If color flow, N of particles produced per unit rapidity : $\frac{dn}{d\mathcal{Y}} \approx \lambda \approx$ const
- $$\frac{dN}{d\ln M_X^2} = D + c \cdot \exp(b \cdot \ln M_X^2)$$ with free parameters, D , b and c from fit.
  $$= \text{(Diff)} + \text{(Nondiff)}$$
- diffractive dissocociation of proton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

  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

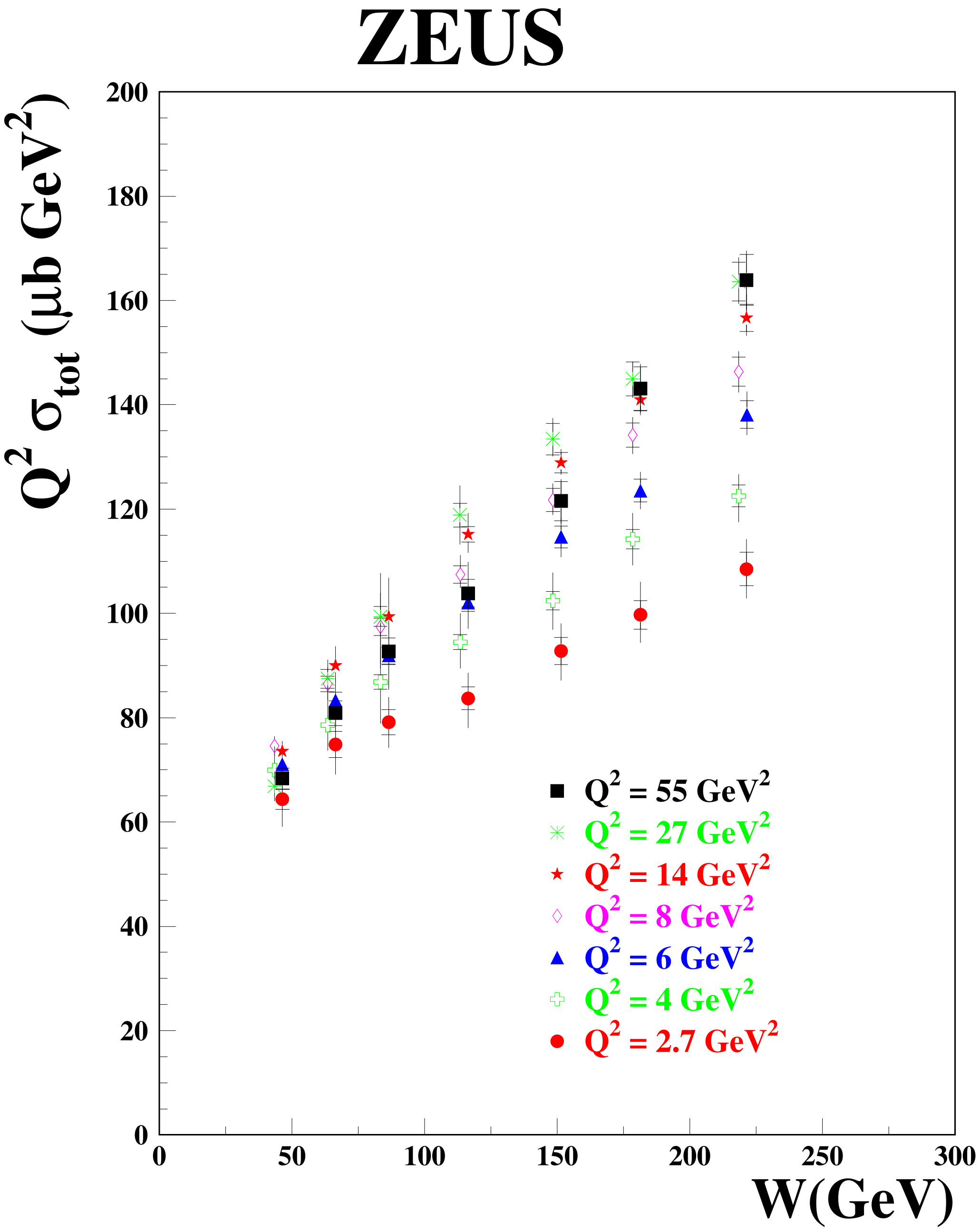
  $\to$ provide $d\sigma^{diff}_{\gamma^* p \to XN}/dM_X$ for $M_N < 2.3$ GeV

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

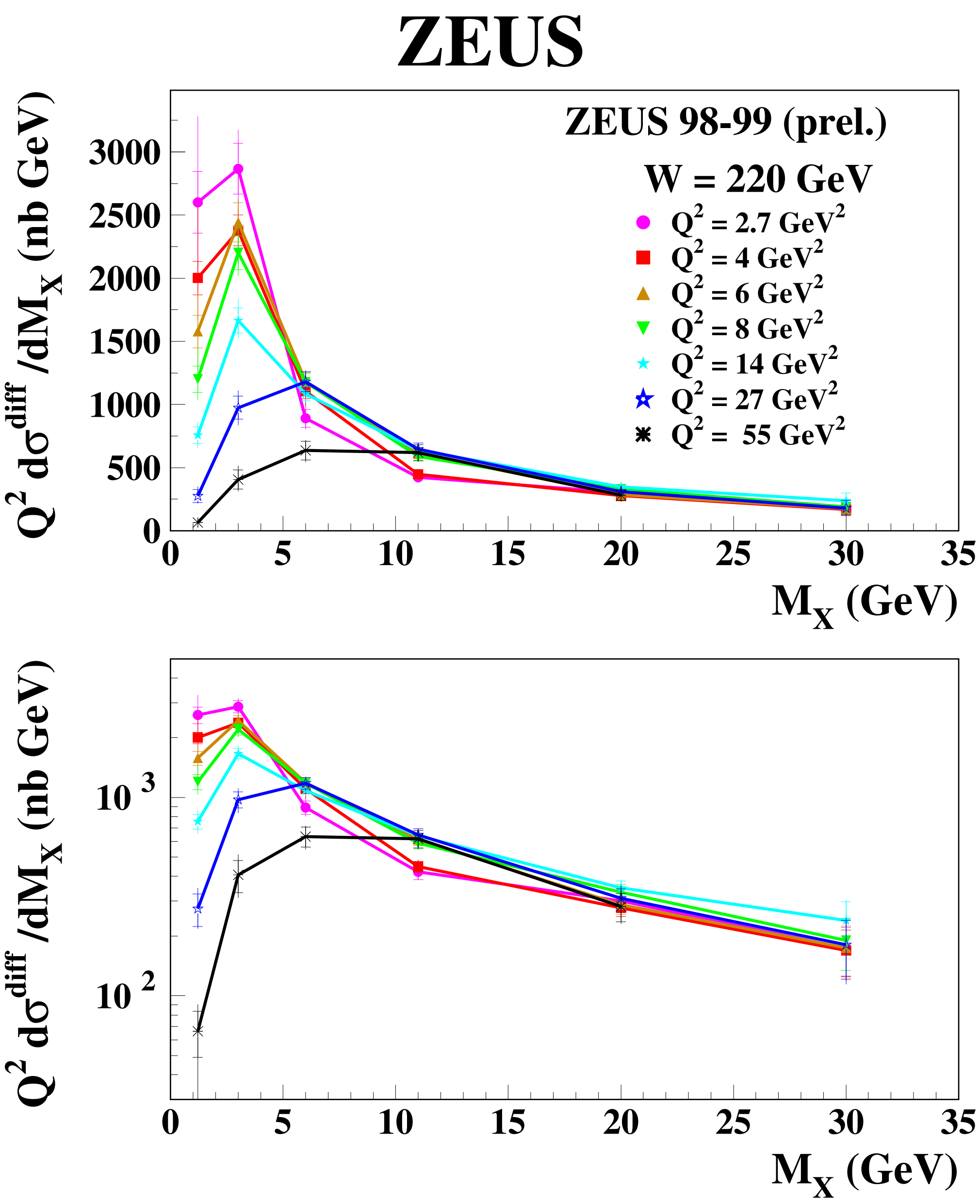


- Good agreement with previous measurements.

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



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



$Q^2 d\sigma^{diff}_{\gamma^* p \to XN}/dM_X$ 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.