Diffraction in Deep Inelastic Scattering: Results obtained with the $\ln M_X$ method by ZEUS

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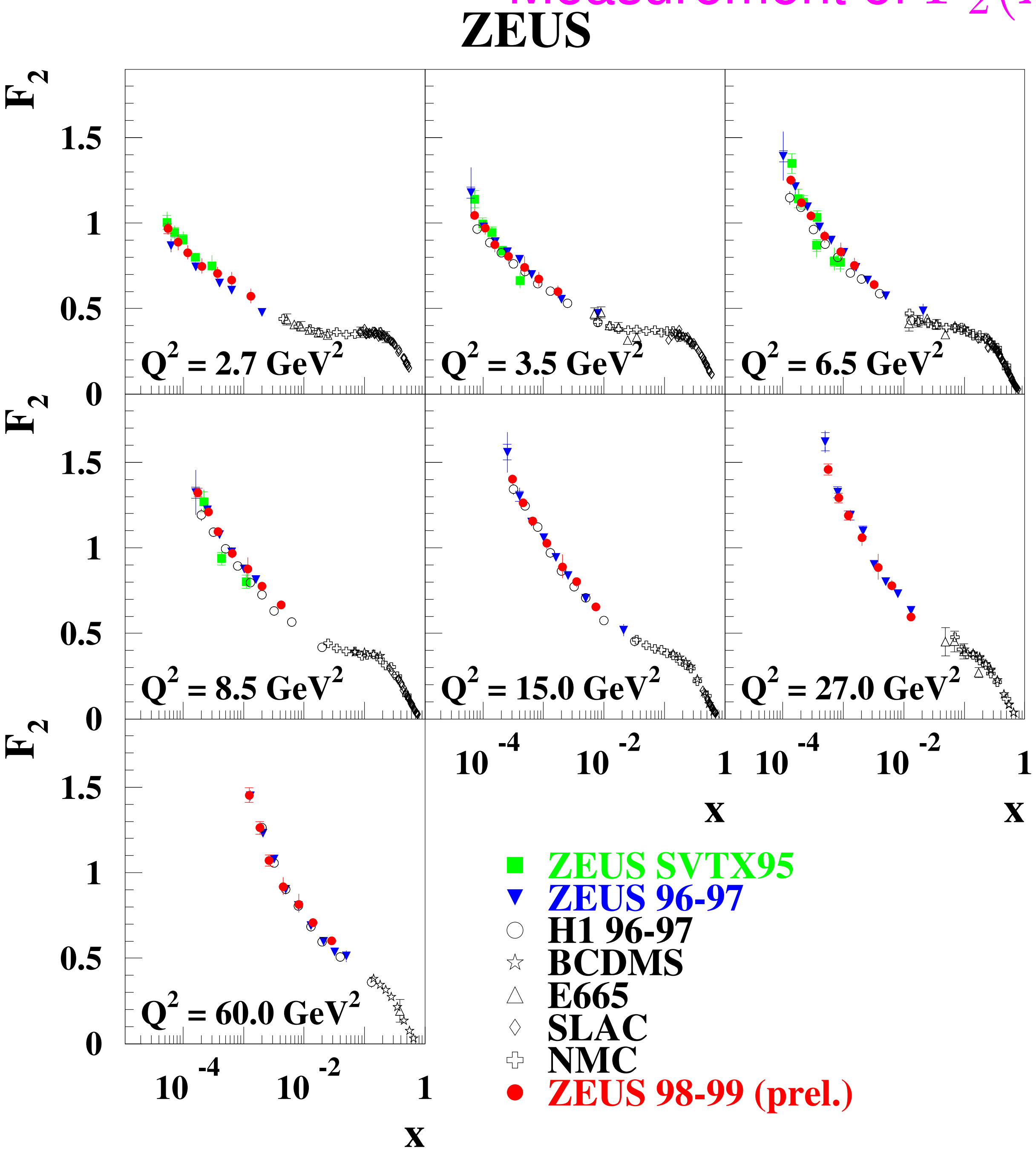
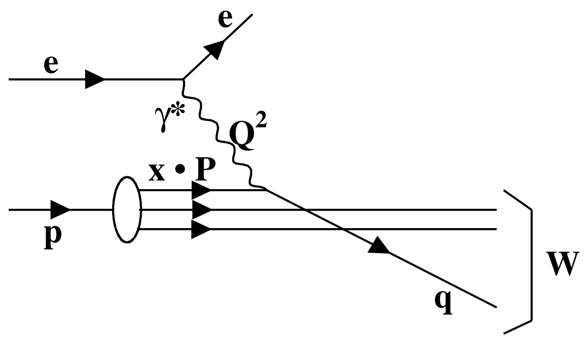
- Introduction
- Diffractive scattering: $\ln M_X$ - method
- Inclusive results
- Diffractive cross sections
- Diffractive structure functions
- Summary

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

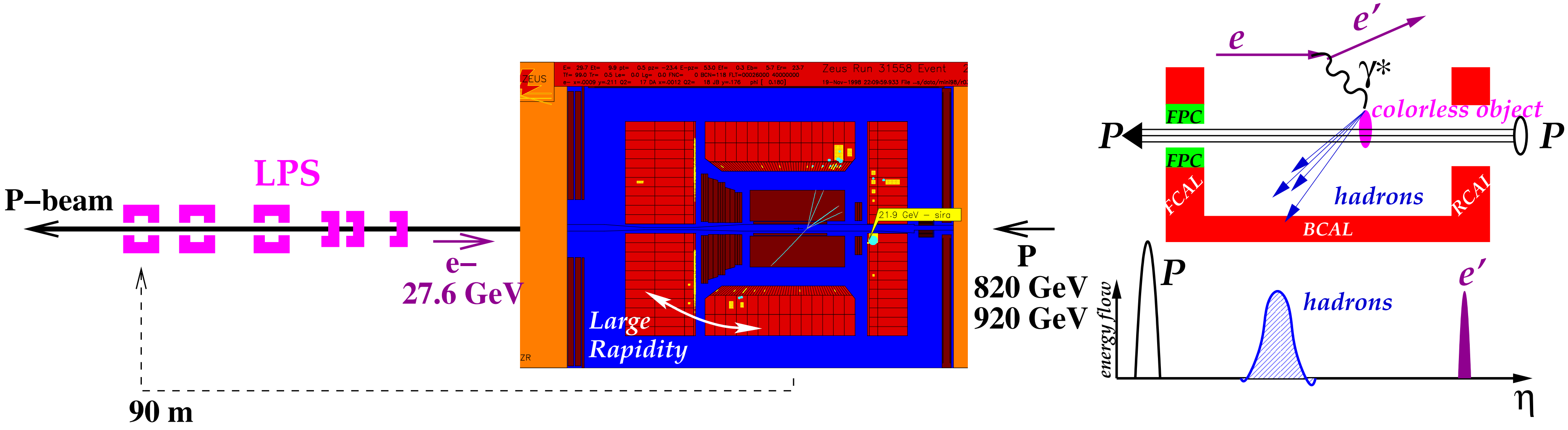




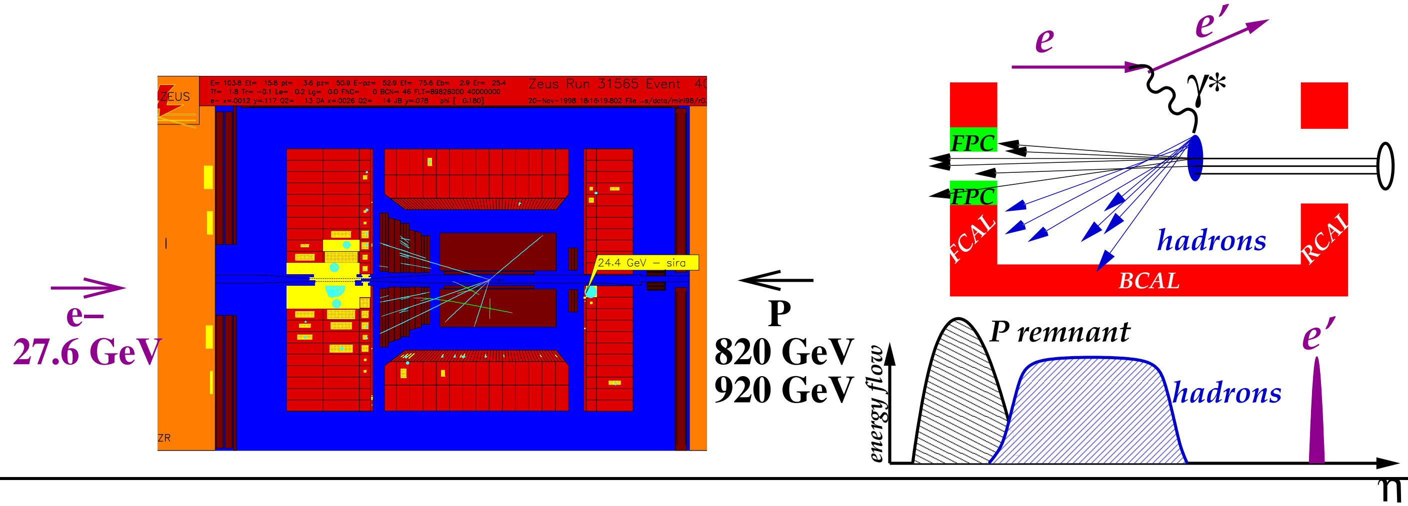
- $F_2(x, Q^2) = \sum_q e_q^2 \cdot q(x, Q^2)$

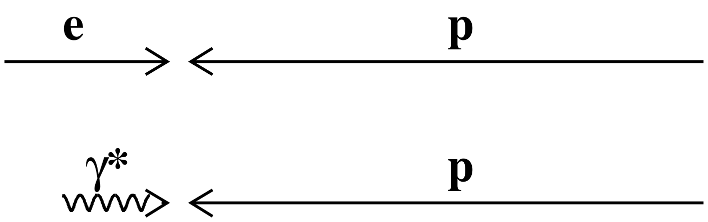
Event Topologies of Deep Inelastic Scattering

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



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





Kinematics in lab. system

$$W^2 = (\gamma^* + p)^2 \approx -Q^2 + m_p^2 + 4E_{\gamma^*}E_p^{beam} \approx 4E_{\gamma^*}E_p^{beam}$$

rapidity: $y = \frac{1}{2}\ln\frac{E+P_L}{E-P_L}$

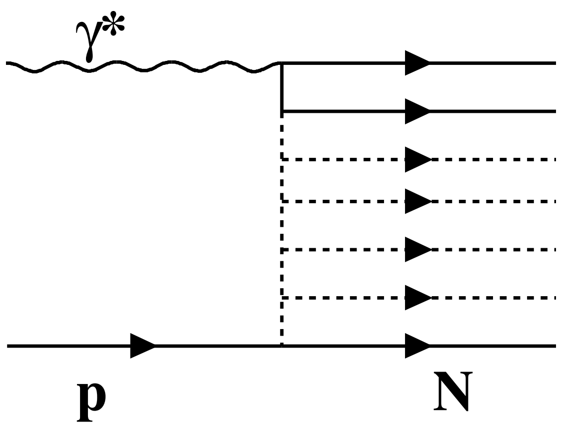
y_{max}, y_{min}:

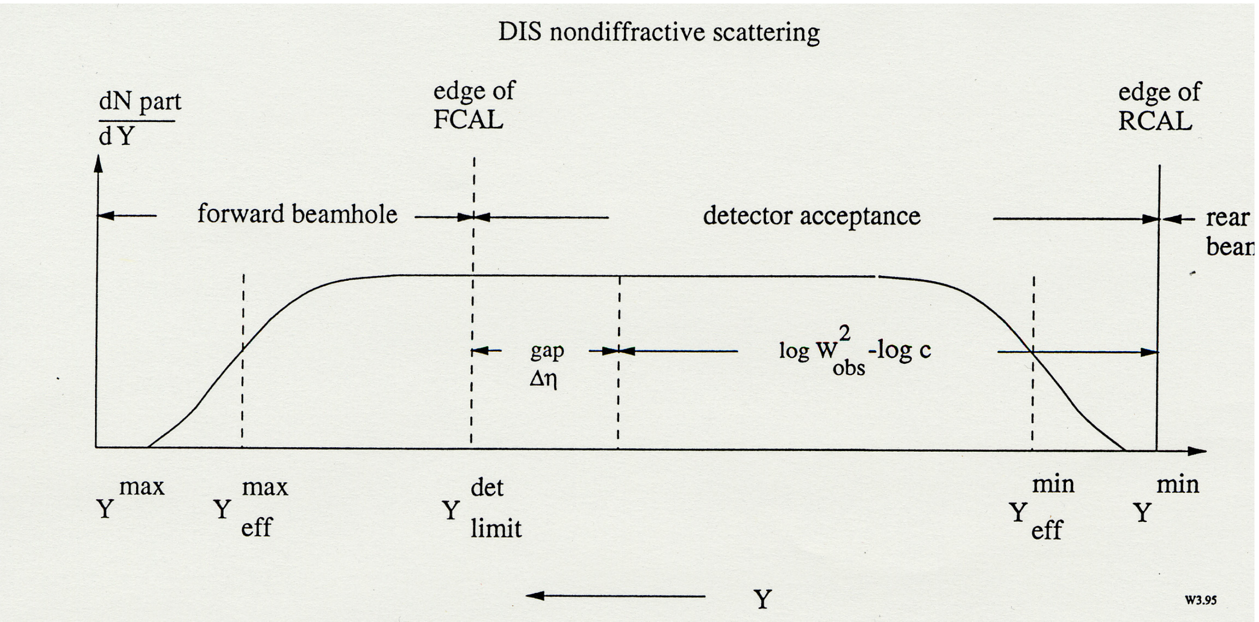
proton: $y_{max} = \frac{1}{2}\ln\frac{E_p^{beam}+P_{pL}^{beam}}{E_p^{beam}-P_{pL}^{beam}} \approx \frac{1}{2}\ln\frac{2E_p^{beam}}{\frac{m_p^2}{2E_p^{beam}}} = \ln(2E_p^{beam}/m_p)$

pion with energy of γ^*, $E_\pi = E_{\gamma^*}$: $y_{min} \approx ln(m_\pi/2E_{\gamma^*})$

$$y_{max} - y_{min} = \ln\frac{4\cdot E_p^{beam}E_{\gamma^*}}{m_p\cdot m_\pi} = \ln\frac{W^2}{m_p\cdot m_\pi}$$

$W^2 \approx c_0 \cdot exp(y_{max} - y_{min})$ with $c_0 = m_p \cdot m_\pi$





$$W^2 \approx c_0 \cdot exp(y_{max} - y_{min})$$

$$\longrightarrow M_X^2 \approx c_0 \cdot exp(y_{limit}^{det} - y_{min}) = W^2 \cdot exp(y_{limit}^{det} - y_{max})$$

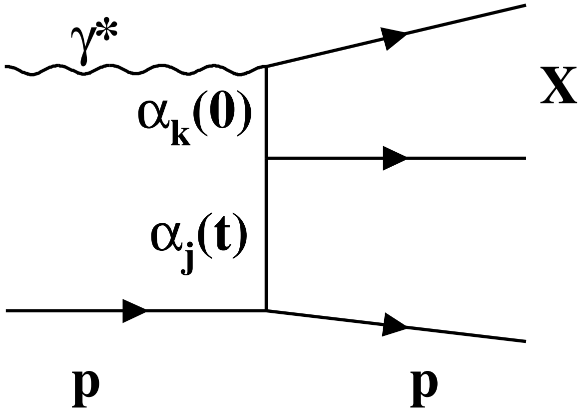
Prob. that no particles emitted between y_{limit}^{det} and $(y_{limit}^{det} - \Delta y)$: $P(\Delta y) = exp(-\lambda \Delta y)$

$\longrightarrow$ exponential fall-off of the $\ln M_X^2$ distribution:

$$\frac{dN^{inclusive}}{d \ln M_X^2} = c \cdot exp(b \cdot \ln M_X^2)$$

QCD-models: $b \approx 2$

Diffractive contribution



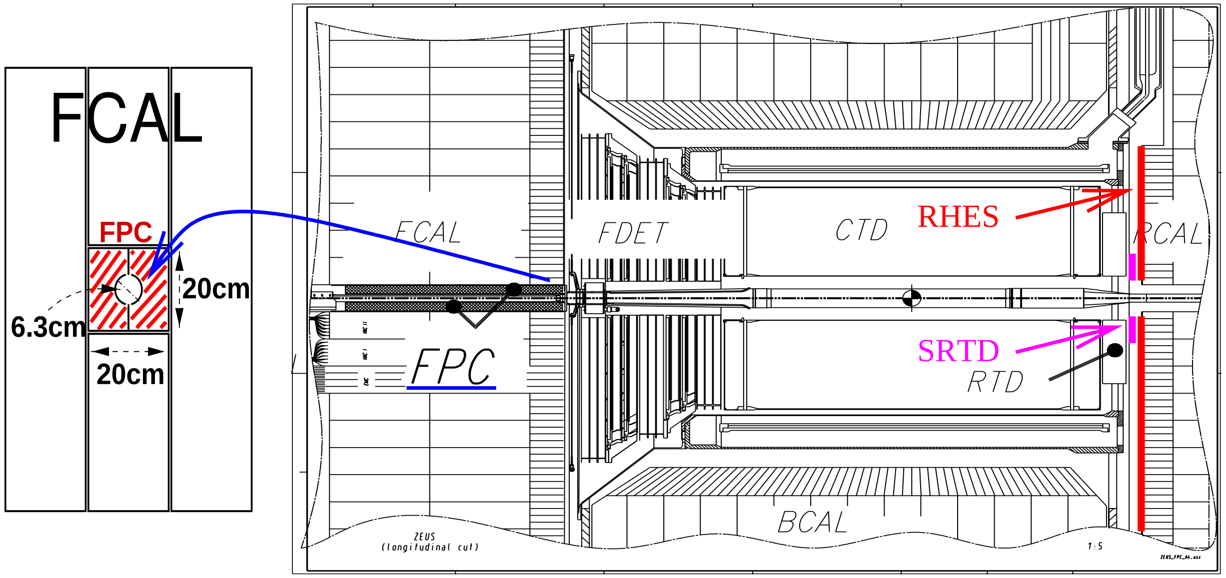
- in triple Regge model $$\frac{d\sigma^{diff}_{\gamma * p \to XN}}{d\ln M_X^2} \propto exp[(1+\alpha_k(0) - 2\overline{\alpha_j}) \cdot \ln M_X^2].$$
- for large M_X expect $\alpha_k(0) = 1$
- hence, Pomeron exchange in t-channel with $\overline{\alpha_j} \approx 1$ leads to $1 + \alpha_k(0) - 2\overline{\alpha_j} = 0$

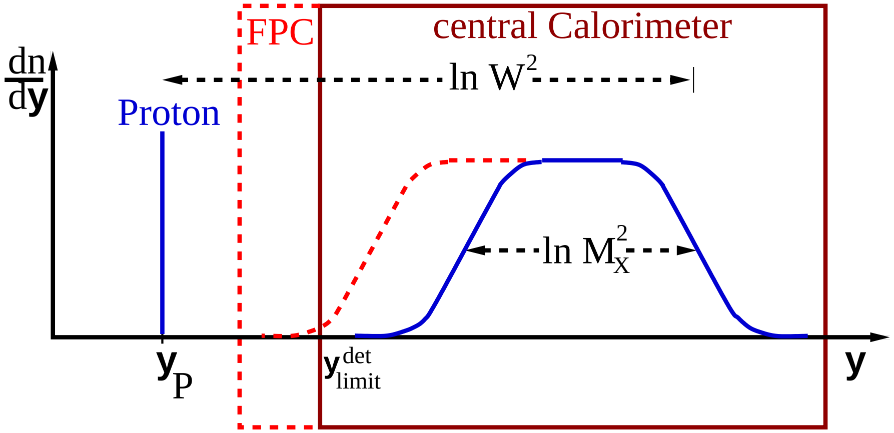
  and to a constant $\ln M_X^2$ spectrum: $$\frac{d\sigma^{diff}_{\gamma * p \to XN}}{d\ln M_X^2} = \mathrm{const}$$
- Reggeon exchange in t-channel with $\overline{\alpha_j} = 0.5$ leads to $1 + \alpha_k(0) - 2\overline{\alpha_j} = 1$

  and to

$$\frac{d\sigma^{diff}_{\gamma * p \to XN}}{d\ln M_X^2} \propto exp(b_R \cdot \ln M_X^2), \quad b_R \approx 1$$

Forward Plug Calorimeter





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

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

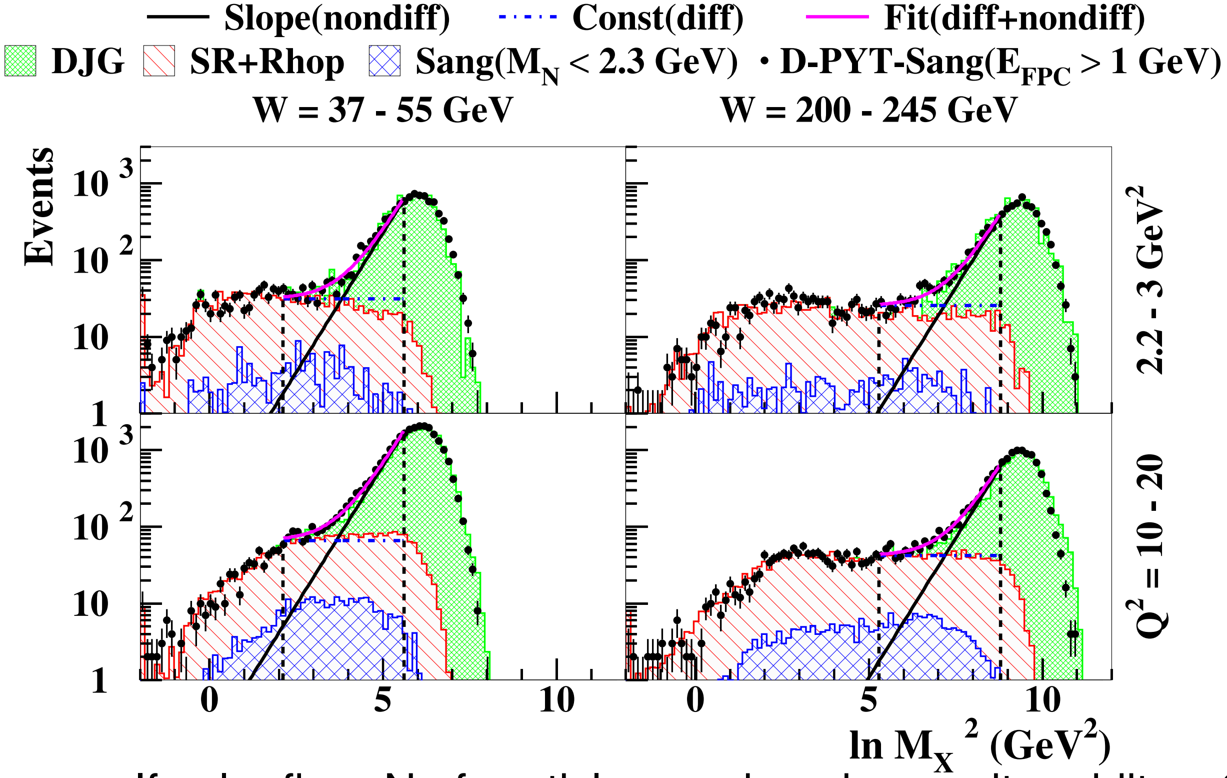
- Forward Plug Calorimter (FPC) : Shashlik type

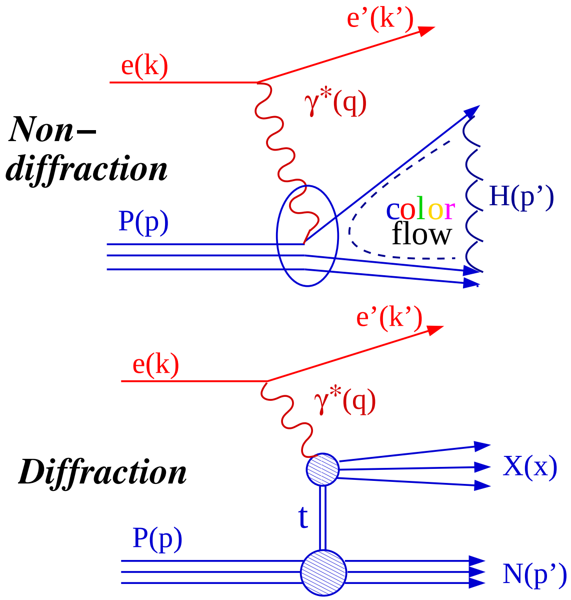
  $\rightarrow$ Extend calorimeter acceptance by 1 unit in pseudo-rapidity from η =4 to η =5.

  $\rightarrow$ 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

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 $p \rightarrow N$

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

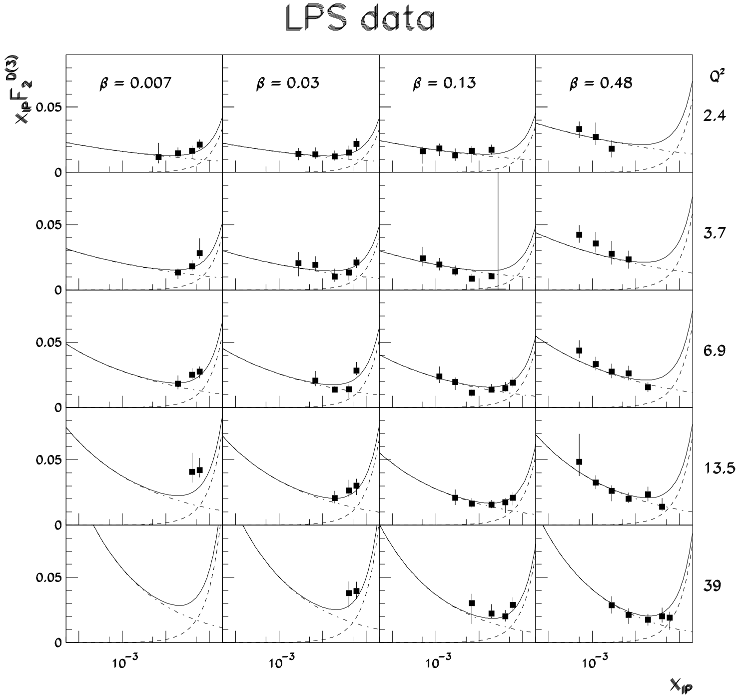
  $\rightarrow$ use data to adjust M_N spect. of MC $\rightarrow$ subtract from data MC contr. with $M_N \gtrsim 2.3$ GeV

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

Use ZEUS - LPS data for $\gamma p \to pX$ to estimate Reggeon contribution

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

Fit yields $c_{pom} = 0.68$, $c_{regge} = 0.58$ and $\chi^2/nd = 1.02$.



dash-dotted: pom   dashed: regge   solid: pom+regge

LPS studies $\gamma^* p \to Xp$
$t-$channel exchanges are Pomeron, R^0
where $R = \rho^0, \omega, f \ldots$

FPC studies $\gamma^* p \to XN$
possible $t-$channel exchanges are Pomeron, $R^{+,-,0}$,
where $R = \rho, \omega, f, \ldots$

$\gamma^* p \to XN$: different R-charge states lead to different N in the final state:
e.g. R^+ emission from the proton can lead to $p \to n$ while R^- requires $p \to N^{++}$

expect $\sigma^R_{\gamma^* p \to XN(FPC)} = 2 - 3 \cdot \sigma^R_{\gamma^* p(LPS)}$

assume $\sigma^R_{\gamma^* p \to XN(FPC)} = 2.5 \cdot \sigma^R_{\gamma^* p(LPS)}$

Compute neutral + charged reggeon contribution to $\ln M_X^2$ distribution

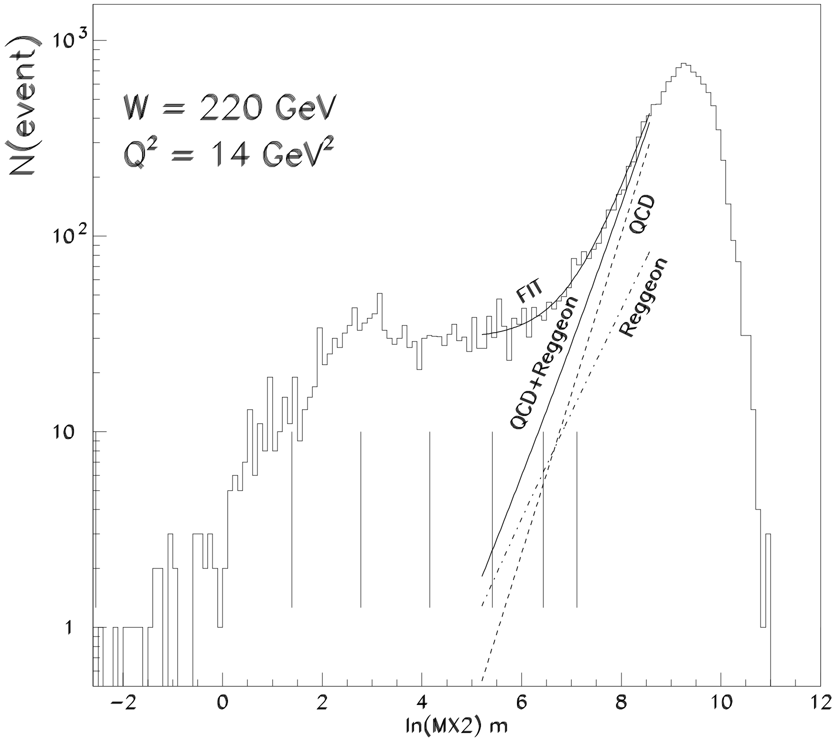
describe inclusive DIS without contributions

from diffraction +reggeon exchange by

$$\frac{dN^{QCD}}{dlnMX^2} = c \cdot exp(b^{QCD} \cdot lnMX^2)$$

take b^{QCD} from MC: DJANGOH:

$b^{QCD} = 1.88 \pm 0.05$



dashed: QCD dash-dotted: Reggeon

dashed solid: QCD+Reggeon also solid: fit

Conclusions:

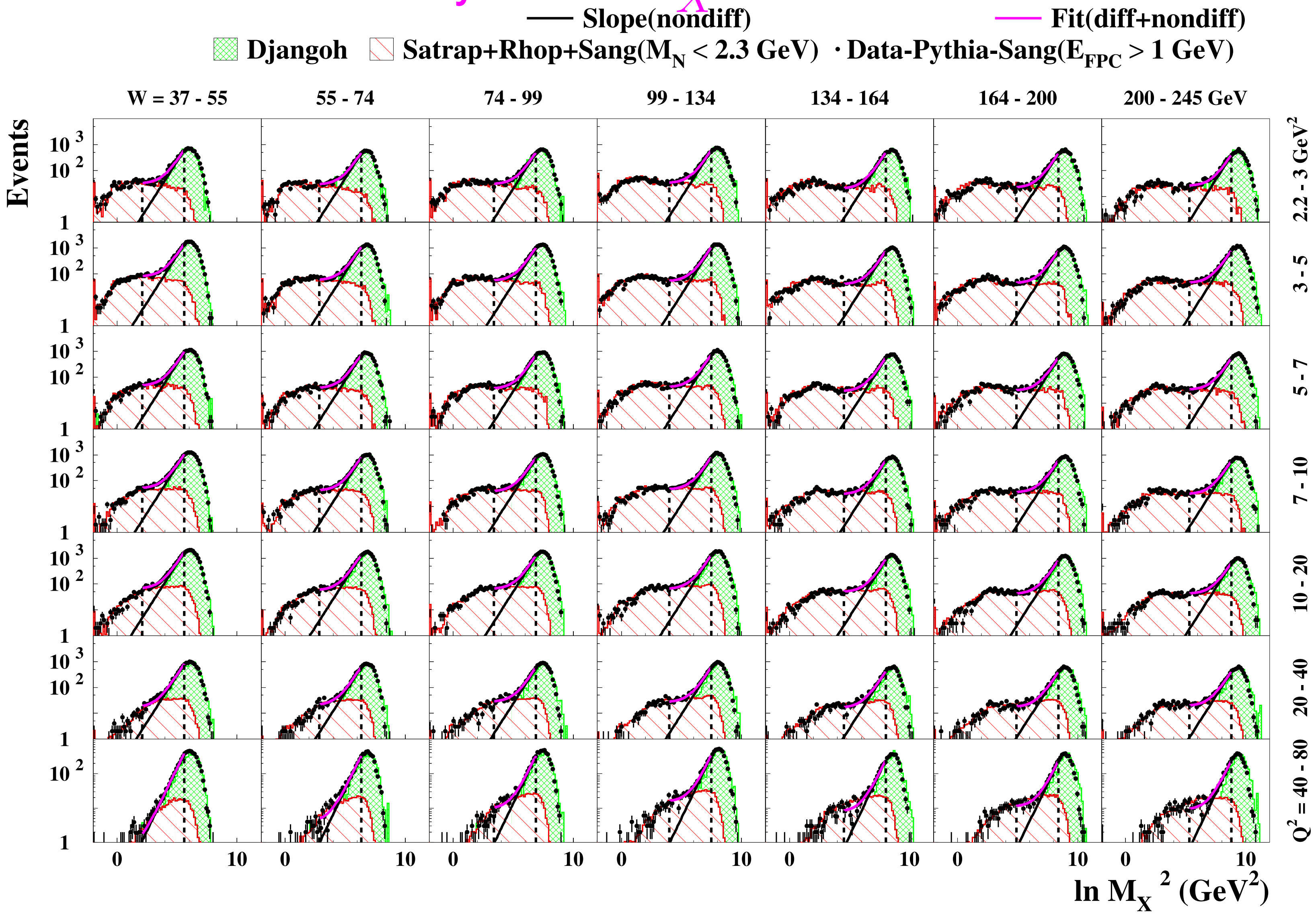
reggeon contribution falls exponentially

reggeon is below the nondiffractive contribution from fit

using the lnM_X method, reggeon is part of nondiff contribution determined by fit

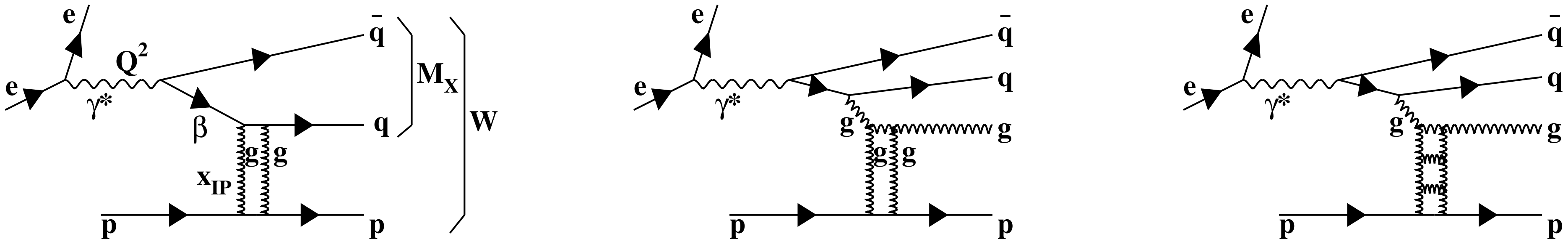
the lnM_X method extracts the diffractive contribution

Summary of $\ln M_X^2$ distributions

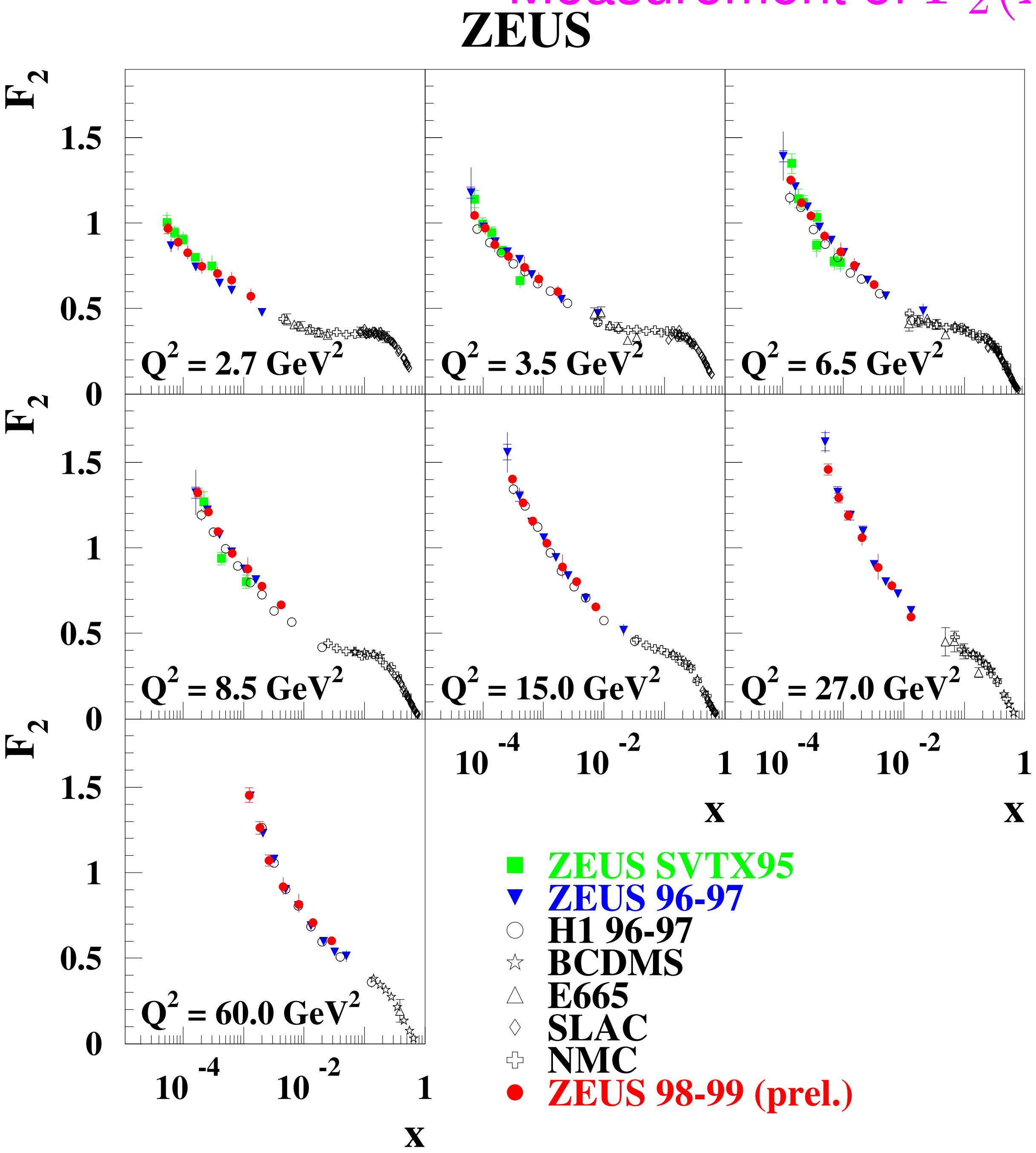


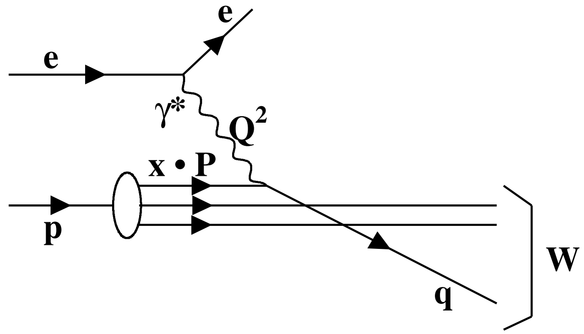
Kinematic region of FPC analysis

Q^2 (GeV^2)	2.2 - 3	3 - 5	5 - 7	7 - 10	10 - 20	20 - 40	40 - 80
Q^2_{ref} (GeV^2)	2.7	4	6	8	14	27	55
W (GEV)	37 - 55	55 - 74	74 - 99	99 - 134	134 - 164	164 - 200	200 - 245
W_{ref} (GEV)	45	65	85	115	150	180	220
M_X (GEV)	0.28 - 2	2 - 4	4 - 8	8 - 15	15 - 25	25 - 35	
M_{Xref} (GEV)	1.2	3	6	11	20	30	



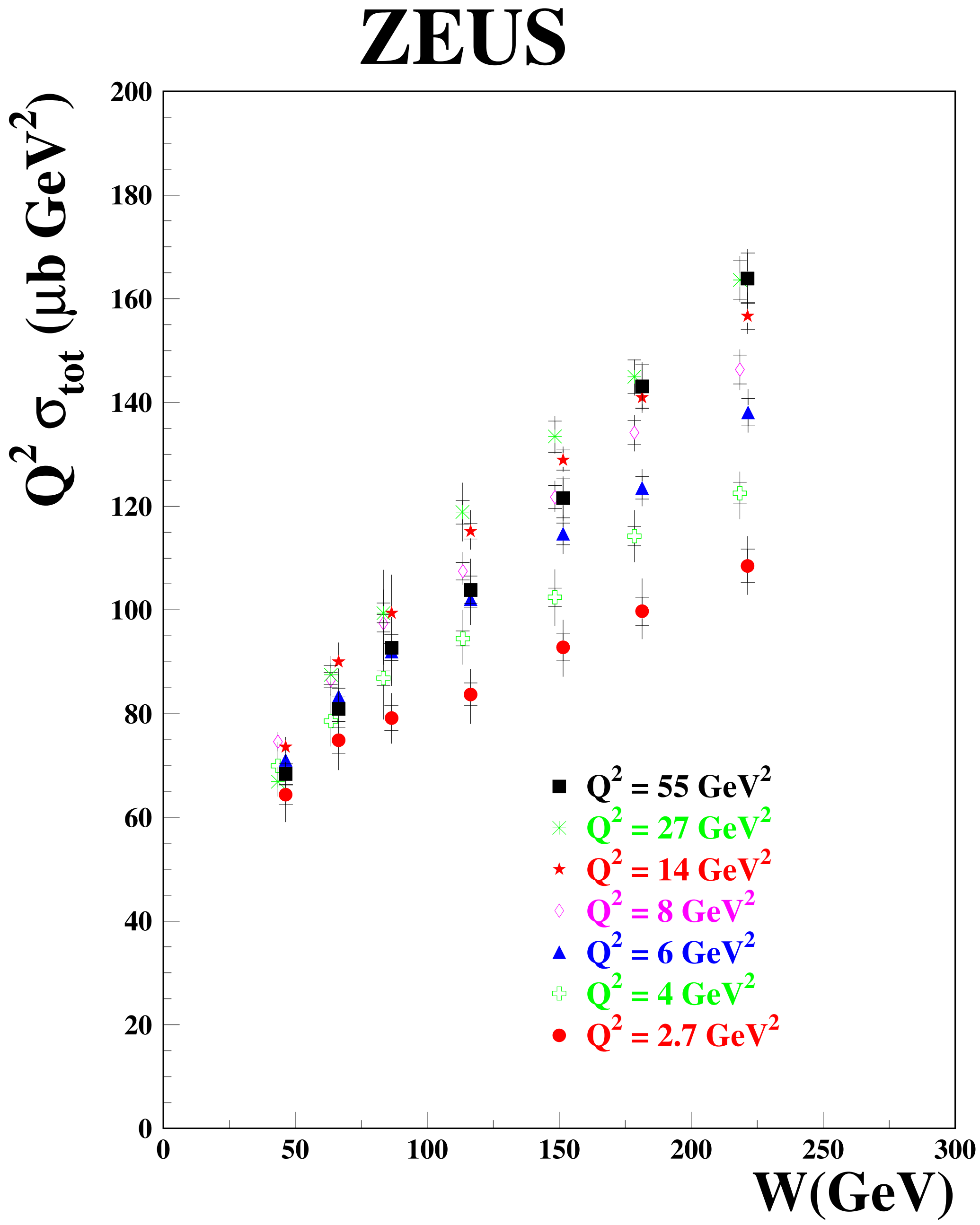
Measurement of $F_2(x, Q^2)$





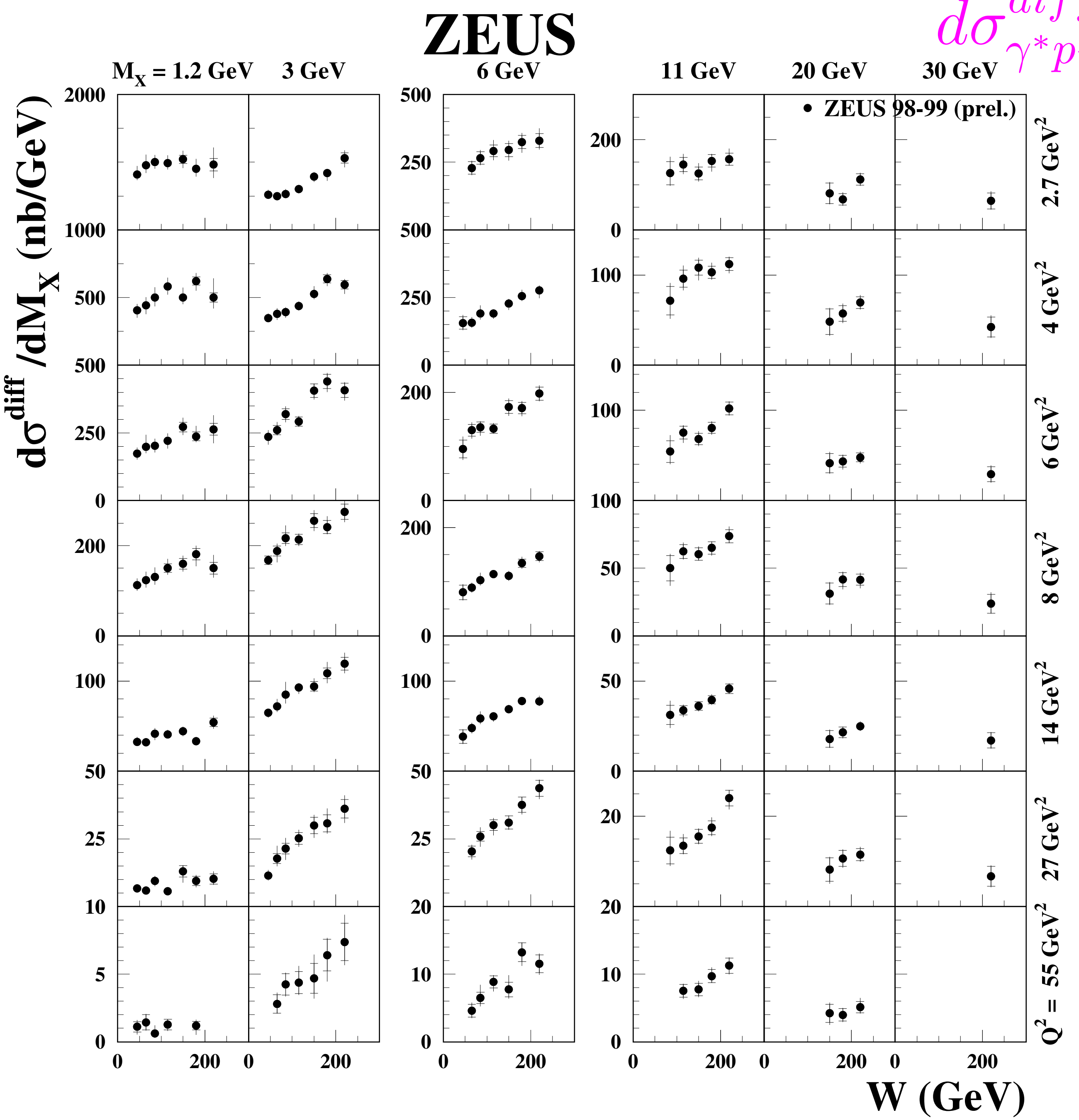
- $F_2(x, Q^2) = \sum_q e_q^2 \cdot q(x, Q^2)$
- Good agreement with previous measurements.
- Steep rise of F_2 as $x \longrightarrow 0$
  rise accelerates as Q^2 increases
- Observe evolution of parton densities $q(x, Q^2)$

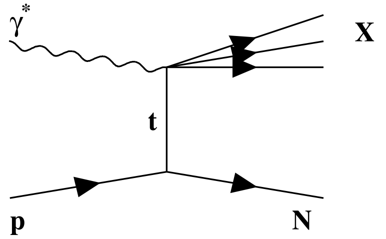
Measurement of $\mathrm{Q}^2\sigma^{\mathrm{tot}}(\mathrm{W}, \mathrm{Q}^2)$



- 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 $\alpha_{I\!P}(0) = 1 + a^{tot}/2$
  $\alpha_{I\!P}(0) \approx 1.15$ at $Q^2 = 2.7$ GeV^2
  ≈ 1.33 at $Q^2 = 55$ GeV^2
- W dependence quite different from behaviour of $\sigma^{tot}_{p \cdot \overline{p}}$
- a Pomeron intercept, rising with Q^2, violates the assumption of single Pomeron exchange plus factorisation of the vertex functions

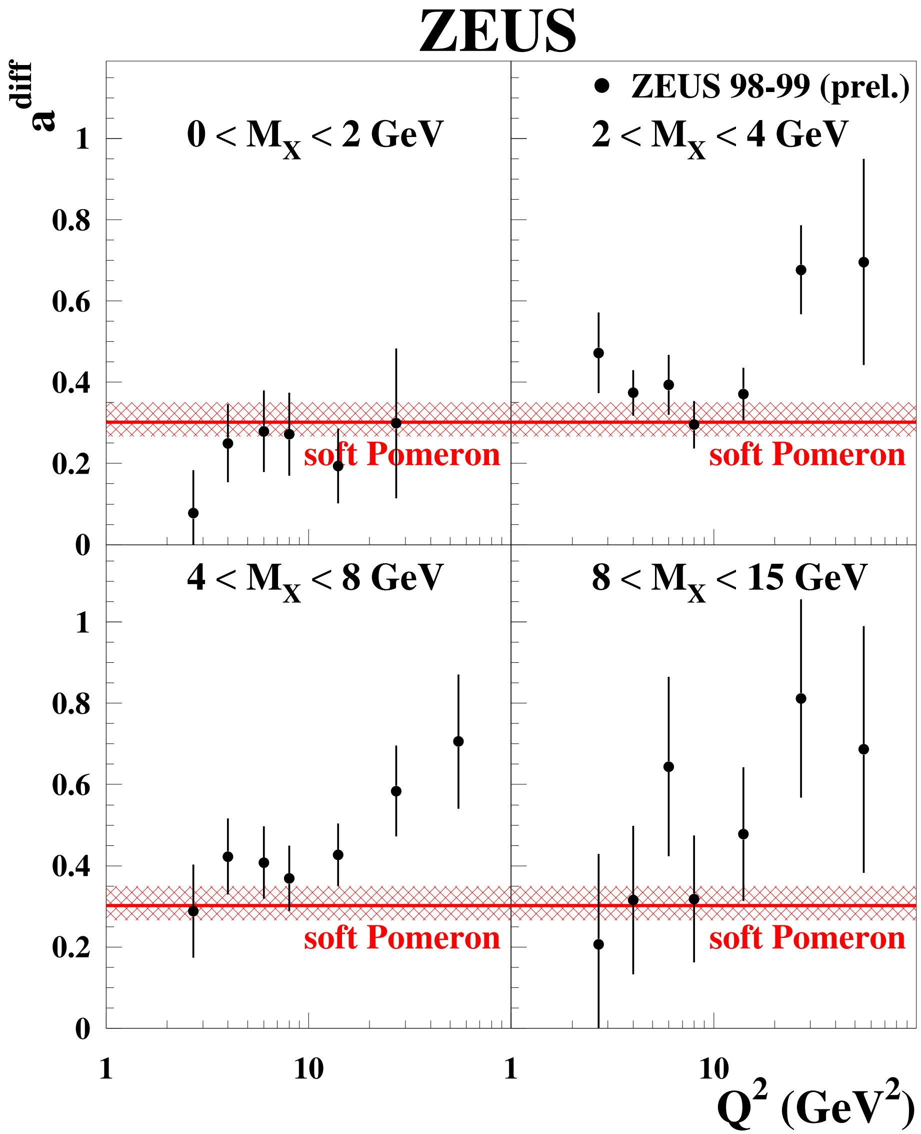
$$d\sigma^{diff}_{\gamma^* p \to XN}(M_X, W, Q^2)/dM_X,$$
$$M_N < 2.3 \text{ GeV}$$





- 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

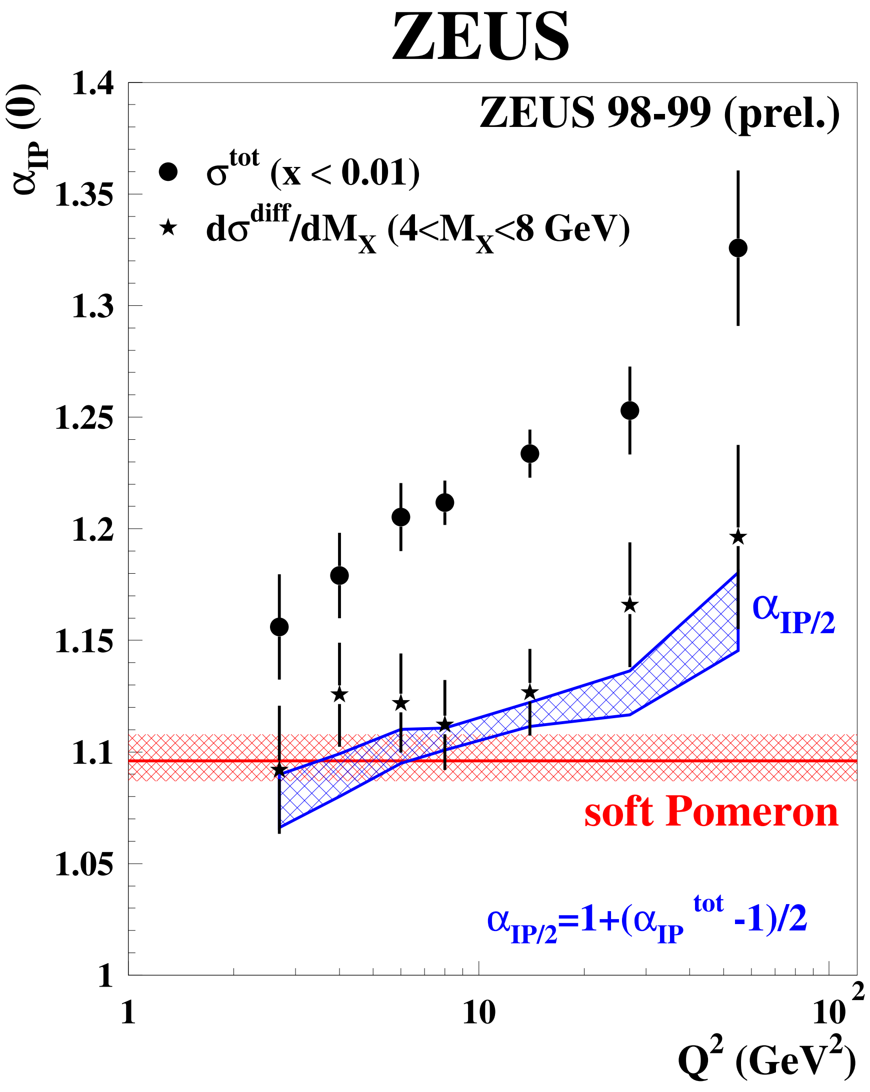
a^{diff} higher than expected for soft Pomeron $\longrightarrow$ clear indication for rise with Q^2 .

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

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

$\Longrightarrow$ Strong indication for pQCD

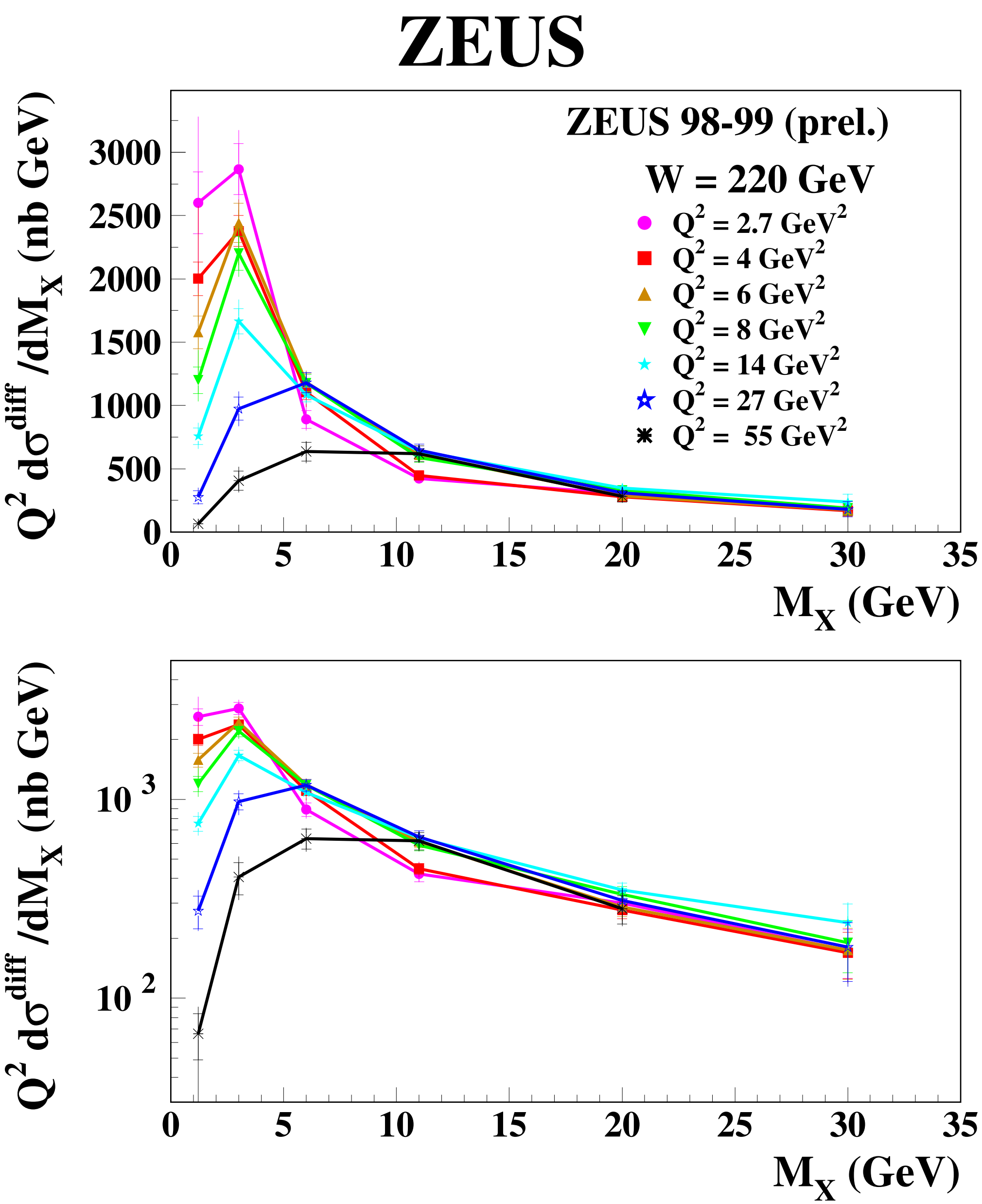
Compare α_{IP} for diffractive and total $\gamma^* p$ scattering



- $\sigma^{tot}_{\gamma^* p} = \frac{4\pi^2\alpha}{Q^2} \cdot F_2(x, Q^2)$
  $$\sim \frac{1}{W^2} Im T_{\gamma^* p \to \gamma^* p}(W^2, t = 0) \sim (W^2)^{\alpha^{tot}_{IP}(0)-1}$$
  (Optical theorem)

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

- Data ($4 < M_X < 8$ GeV) show
  $$\Longrightarrow \alpha^{diff}_{IP} \approx 1 + (\alpha^{tot}_{IP} - 1)/2$$

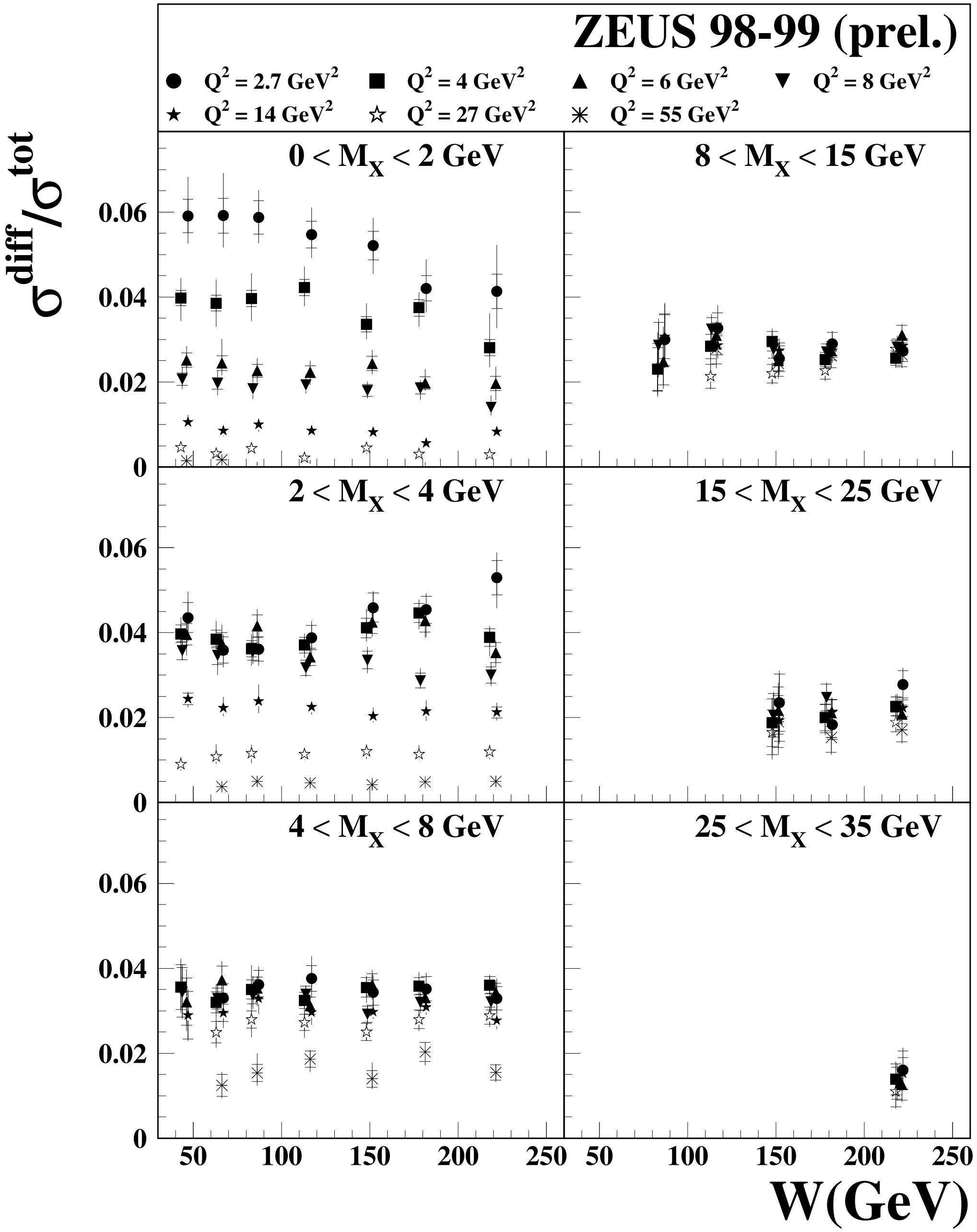


$Q^2 d\sigma^{diff}_{\gamma^* p \to XN}/dM_X$ vs. M_X
at $W = 220$ GeV

- 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

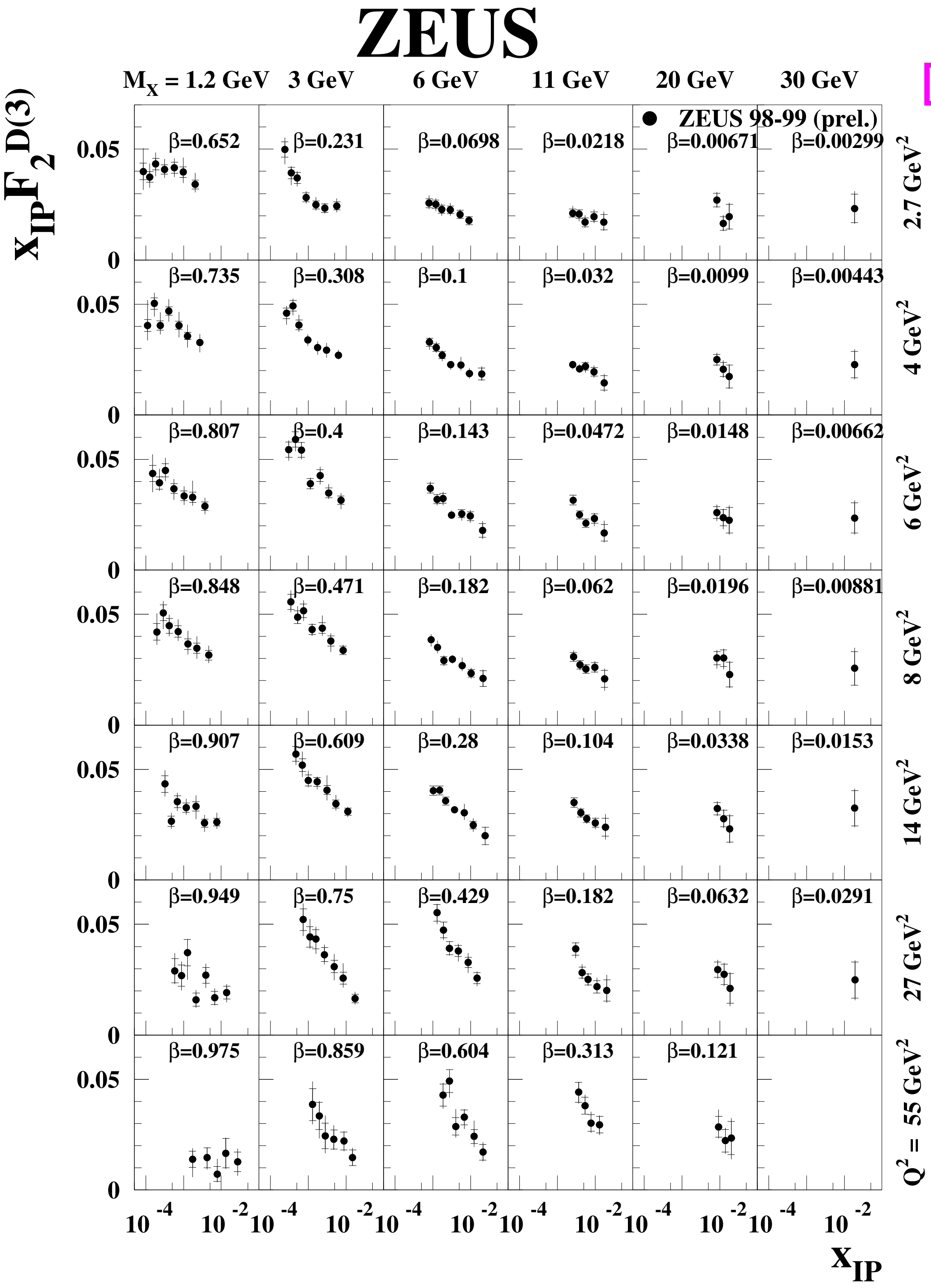
therefore:

can expect substantial diffractive contributions even at Q^2 values much higher than studied here

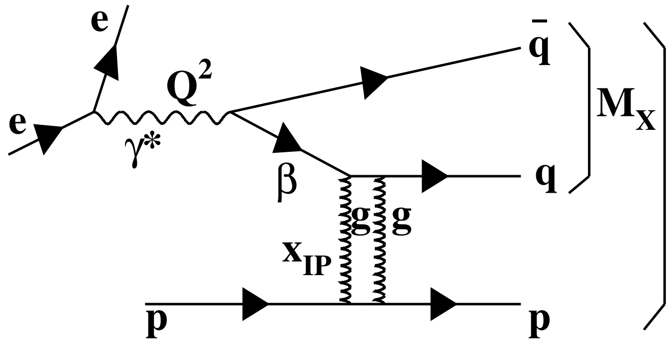


$$r^{diff}_{tot} = \frac{\int_{M_a}^{M_b} dM_X d\sigma^{diff}_{\gamma^* p \to XN, M_N < 2.3GeV}/dM_X}{\sigma^{tot}_{\gamma^* p}}$$

- The diffractive cross section has about the same W-dependence as σ^{tot} .
- The low M_X bins indicates a decrease of r^{diff}_{tot} with increasing Q^2 .
- For $M_X > 8$ GeV: no Q^2 dependence.
- $\sigma^{diff}_{(M_X<35\ \text{GeV})}/\sigma^{tot}$ 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
- Diffraction is a substantial part of deep inelastic scattering



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



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

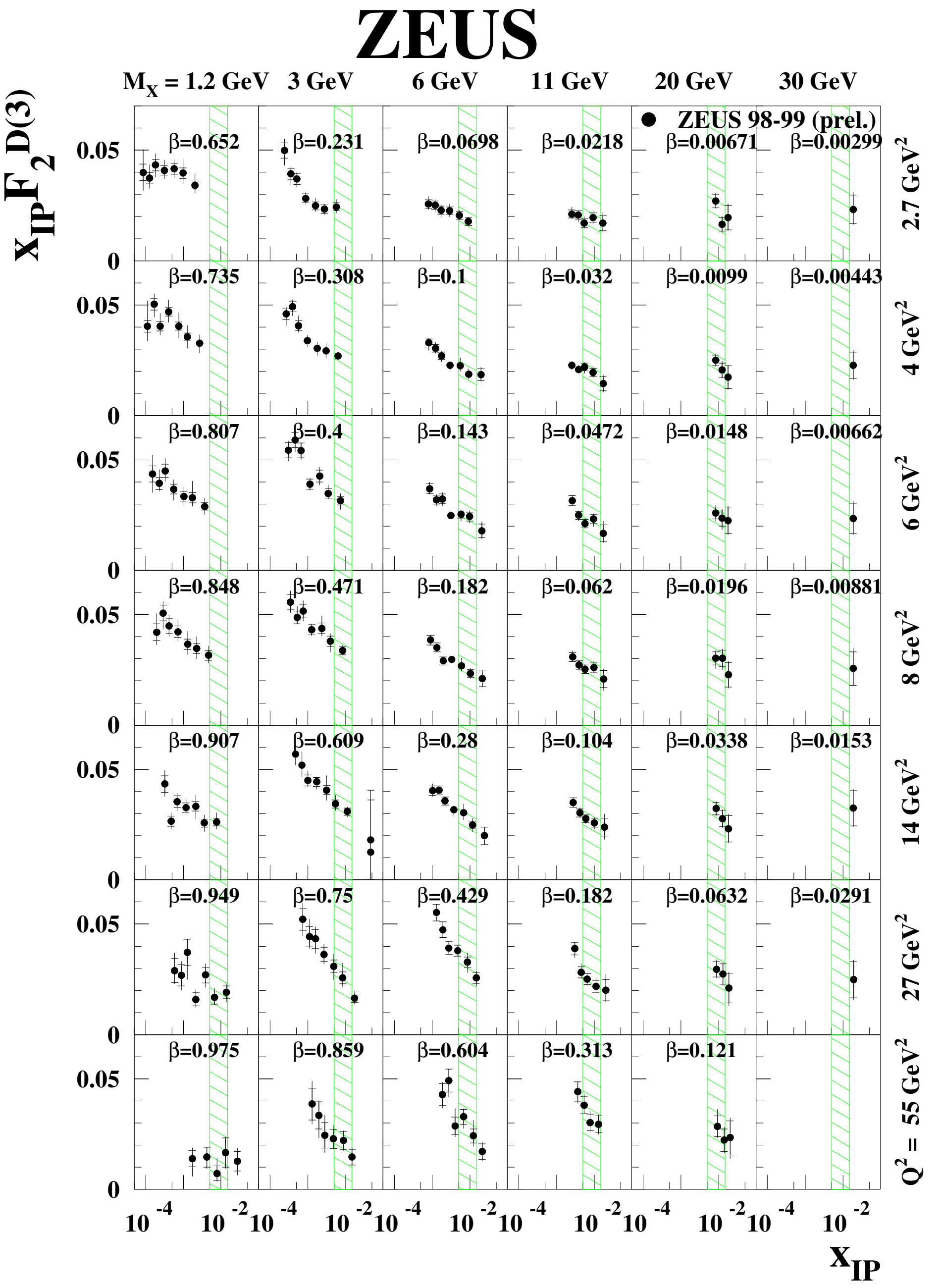
$$\frac{1}{4\pi^2\alpha} \cdot \frac{Q^2(Q^2+M_X^2)}{2M_X} \cdot \frac{d\sigma^{diff}_{\gamma^* p \to XN}}{dM_X}$$

- $M_X < 2$ 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 $x_{IP} \to 0$.



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} = x_0 = 0.01

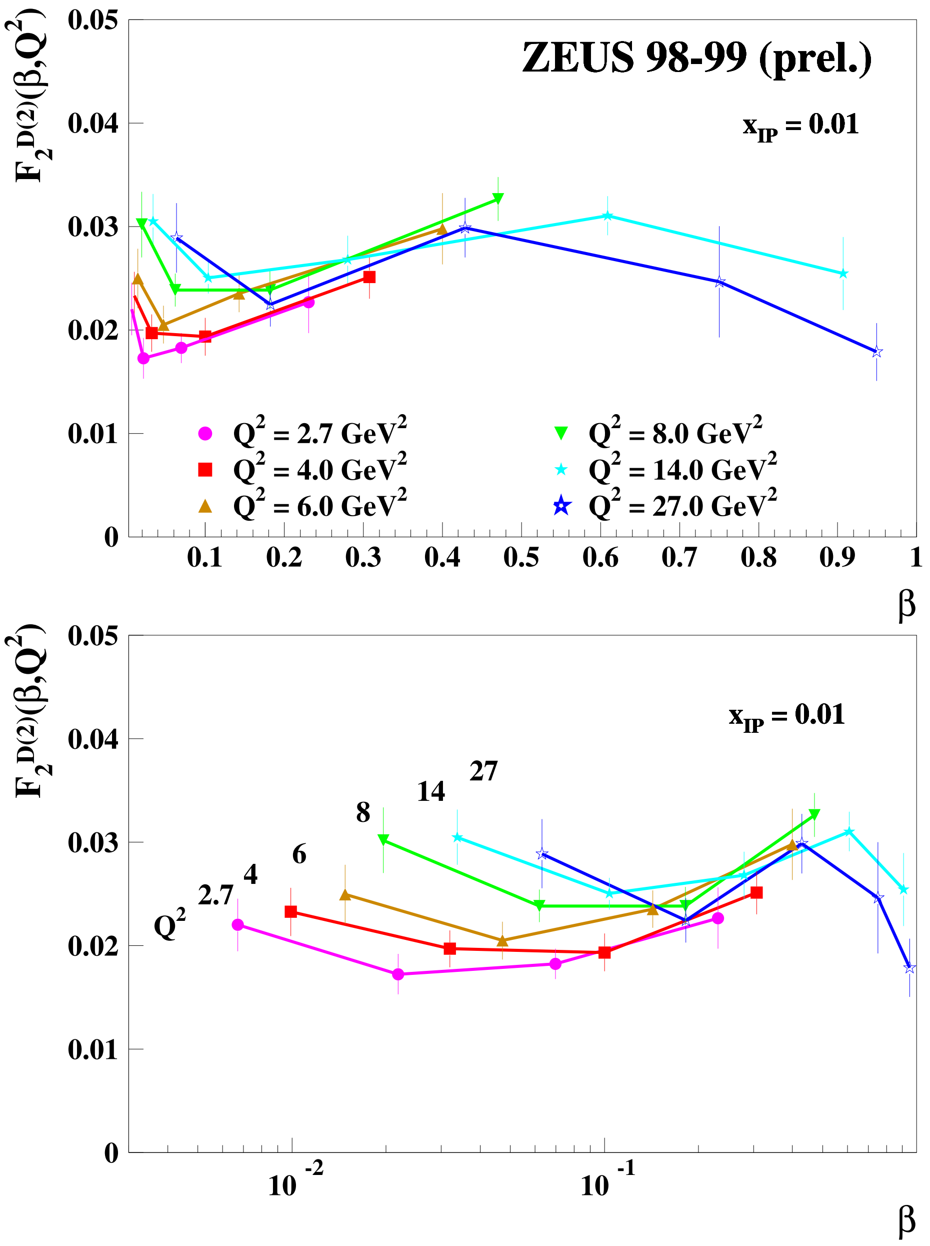
  $\Longrightarrow F_2^{D(2)}(\beta, Q^2) = x_0 F_2^{D(3)}(x_0, \beta, Q^2)$

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

  $0.005 < x_{IP} < 0.015$

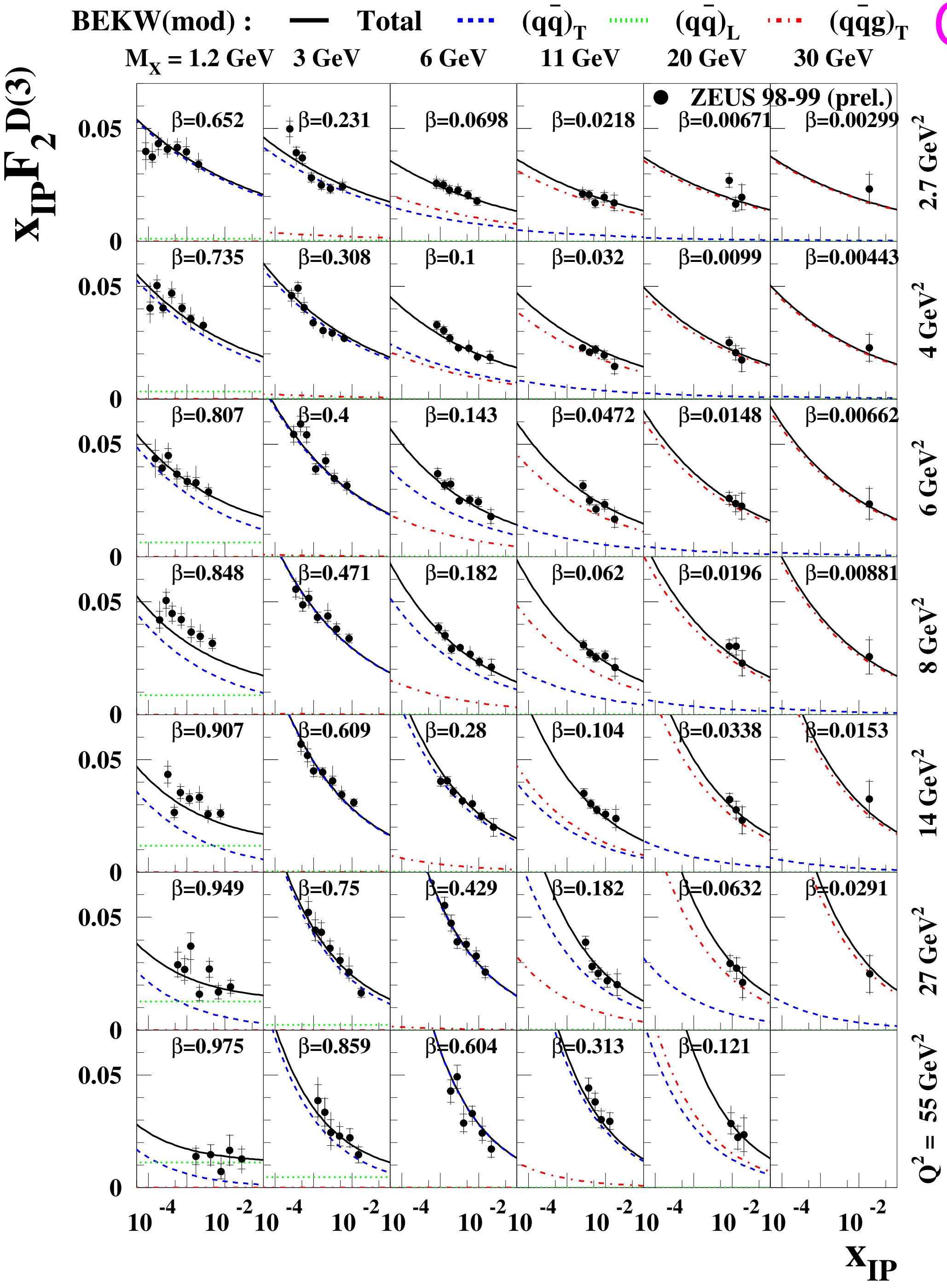
  and transport them to $x_{IP} = 0.01$

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

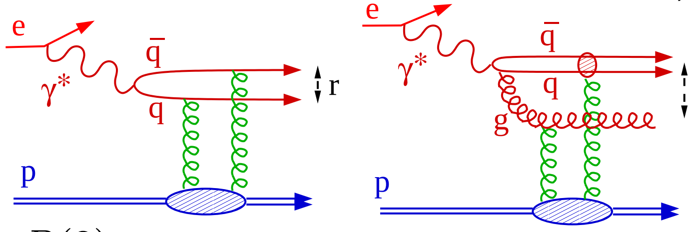


- Structure Function, Proton $x, Q^2 \rightarrow F_2(x, Q^2)$
  Pomeron $\beta, Q^2 \rightarrow F_2^{D(2)}(\beta, Q^2)$
  $\Longrightarrow$ Probability for finding a quark
  with momentum fraction β in Pomeron
- In the "valence" region, $\beta > 0.1$,
  $F_2^{D(2)}$ has a maximum around $\beta = 0.5$
  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

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

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

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

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

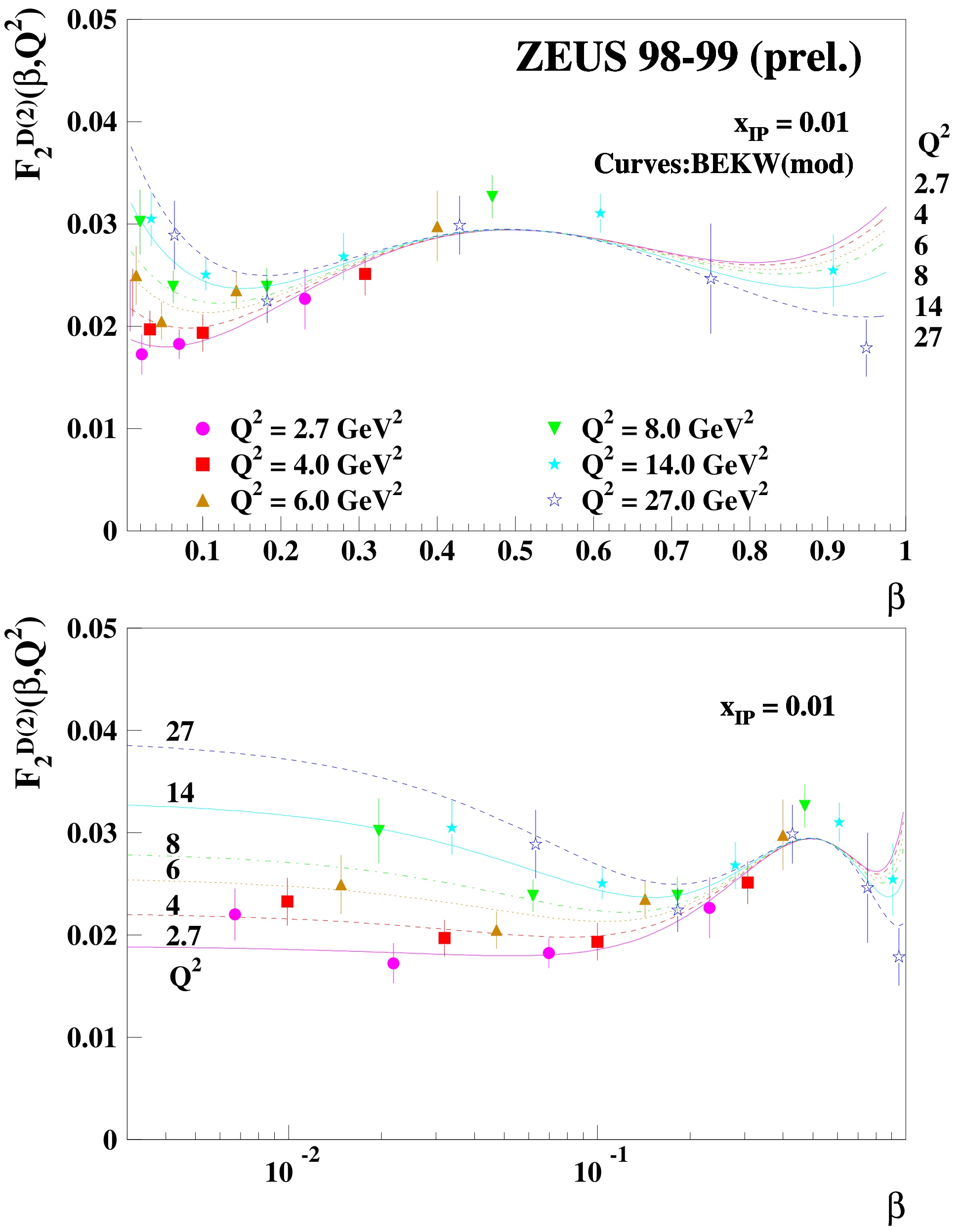
$\gamma = 8.32 \pm 0.51, \chi^2/\text{ndf} = 132/198$

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

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

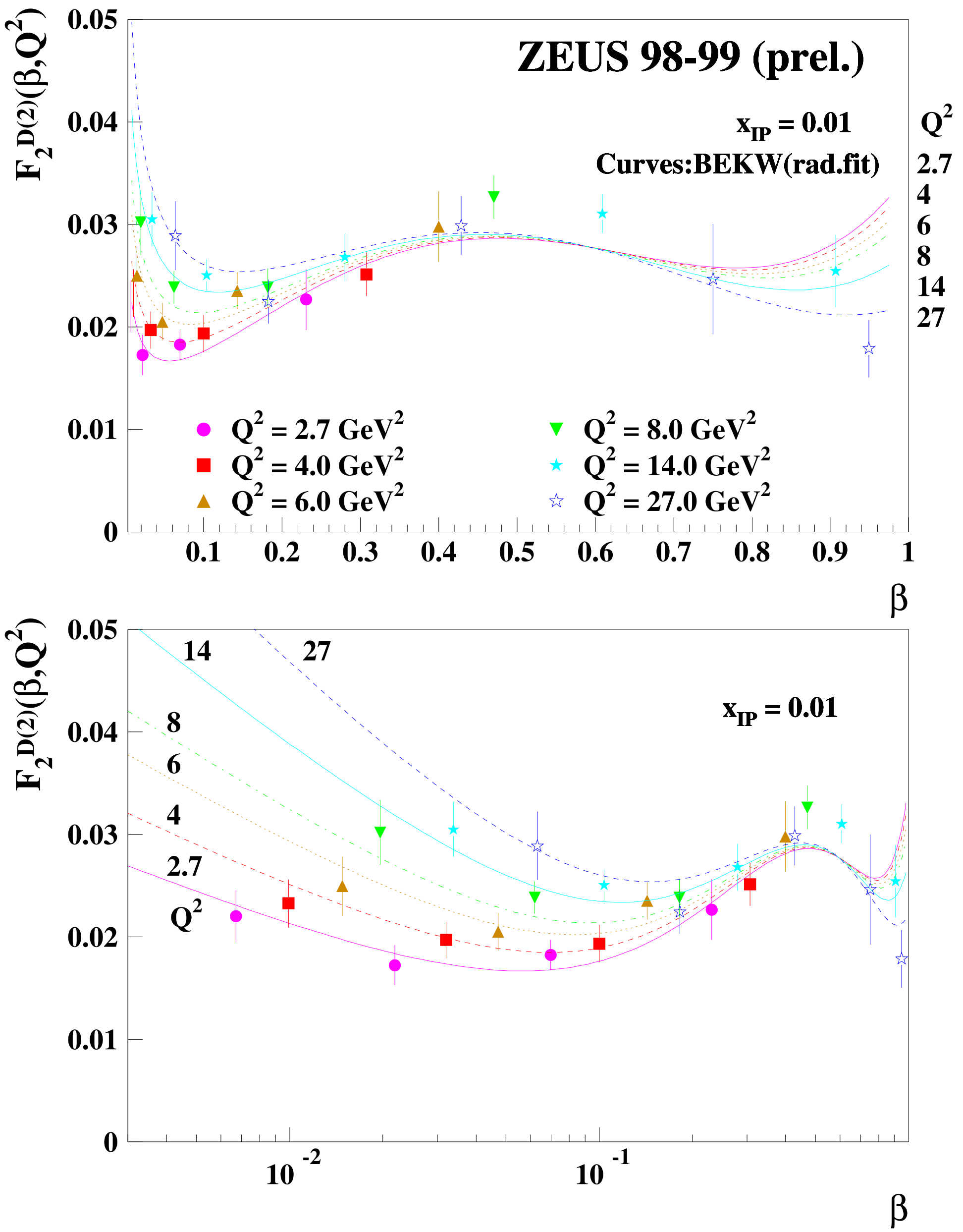
  $(q\bar{q}g)_T$ dominates at small β

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

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

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

- 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 $\beta \rightarrow 0$ 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, $\frac{M_X^2}{W^2} < 0.025$: $\sigma^{diff}/\sigma^{tot} = 10.1^{+0.6}_{-0.7}\%$
  $\Longrightarrow$ may require special treatment of the diffractive contribution when extracting the parton distribution functions of the proton via DGLAP type fits

- strong indication for $\alpha_{I\!P}$ to rise with Q^2 also in diffraction: $\alpha_{I\!P}^{diff} \approx 1 + (\alpha_{I\!P}^{tot} - 1/2)$

- diff. struct. funct. of proton: $x_{I\!P} F_2^{D(3)}$ for $M_X > 2$ GeV rises strongly as $x_{I\!P} \to 0$
  can be factorized as $f(x_{I\!P}, Q^2) \times F_2^{D(2)}(\beta, Q^2)$

- structure function of the pomeron, $F_2^{D(2)}(\beta, Q^2) \equiv x_0 F_2^{D(3)}(x_0, \beta, Q^2)$, x_0 = 0.01,
  for $0.9 > \beta > 0.1$ ("valence" region)
    has a maximum near $\beta = 0.5$ consistent with a $\beta(1-\beta)$ behaviour
    main contribution expected from $\gamma_T \to q\bar{q}$ diffractively scattering on proton
  for $\beta < 0.1$ ("sea" region):
    $F_2^{D(2)}$ rises as $\beta \to 0$ and rises as Q^2 increases,
    main contrib. expected from $\gamma_T \to q\bar{q}g(+g..)$ diff. scattering on the proton
    $\Longrightarrow$ data suggest for $F_2^{D(2)}$ a pQCD like evolution with β and Q^2

- We are making progress in understanding DIS diffraction in terms of quarks and gluons