New Trends in HERA Physics
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Diffractive structure functions and QCD fits

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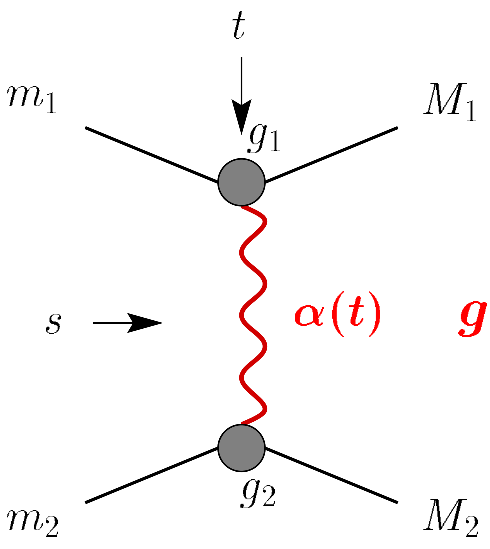
Representing

- Introduction
- Experimental Techniques and Data Samples
- Cross section measurements
- Interpretation in terms of models and QCD fits
- Summary

Two approaches to Strong Interactions

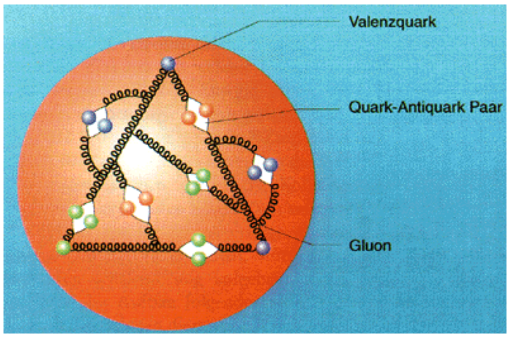
1. Regge Pole Model ⇒ RFT



$$A(s,t) = g_1(m_1, M_1, t)g_2(m_2, M_2, t)\frac{s^{\alpha(t)} \pm (-s)^{\alpha(t)}}{\sin(\pi\alpha(t))}$$

hadronic language

2. Quark-Parton Model ⇒ QCD



$$\sigma_{ab} = \int f_{i/a}(x_i, \mu^2) \cdot f_{j/b}(x_j, \mu^2) \cdot \hat{\sigma}_{ij}(x_i, x_j, \mu^2)$$

sub-hadronic language

RFT: soft hh scattering vs QCD: deep inelastic ep scattering

RFT: soft hh scattering

- Hadronic degrees of freedom
- Validity: large $s \gg t$
- $I\!P$ dominates: $\alpha_{I\!P}(0) > \alpha_{I\!R}(0)$
  $\rightarrow \sigma_{\text{tot}} \propto s^{\alpha_{I\!P}(0)-1}$
- Unitarity corrections unavoidable
  ($\sigma_{\text{tot}} \leq \ln^2(s/s_0)$ at $s \rightarrow \infty$)
- When? $s_{sat} =?$
- First to be seen in diffraction: $\sigma_D \propto s^{2(\alpha-1)}$

QCD: deep inelastic ep scattering

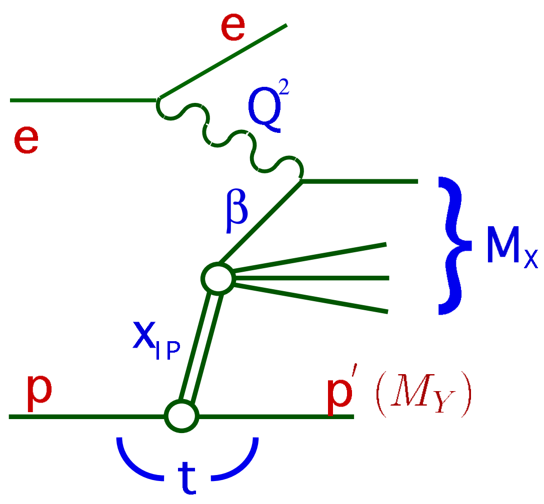
- Partonic degrees of freedom
- Low x: $W^2 \gg Q^2, t \; (Q^2/W^2 \simeq x \ll 1)$
- gluons dominate: $xg(x) \gg xq_{val}(x)$
  $F_2(x, Q^2) \propto xg(x) \sim x^{-\lambda}$
- Saturation of the $xg(x)$
- $x_{sat} =?$
- First to be seen in diffraction: $\sigma_D \propto |xg(x)|^2$

$\Rightarrow$ Diffraction $\equiv$ Physics of the Pomeron, the essence of strong interactions

$\Rightarrow$ Diffraction $\equiv$ Gluodynamics, the essence of QCD

in high energy limit

Diffractive Kinematics and Cross Section



$$x_{I\!P} = \frac{Q^2+M_X^2}{Q^2+W^2}$$

(momentum fraction of colour singlet exchange)

$$\beta = \frac{Q^2}{Q^2+M_X^2} = x_{q/I\!P} = \frac{x}{x_{I\!P}}$$

(fraction of exchange momentum, coupling to γ^*)

$$t = (p - p')^2$$

(4-momentum transfer squared)

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

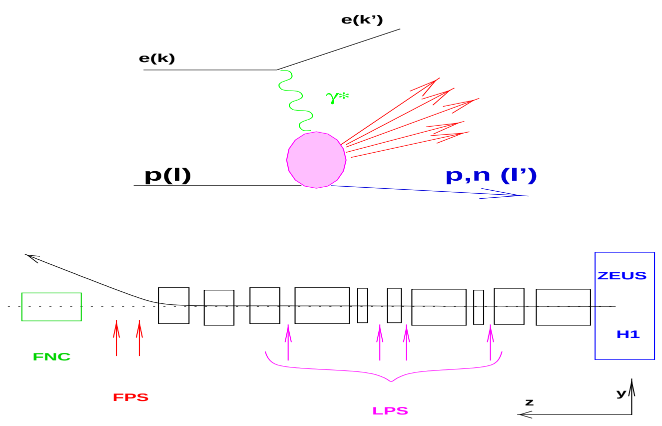
$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{2(1-y+y^2/2)}F_L^{D(4)} \quad \Rightarrow \quad F_2^{D(3)} = \int dt\, F_2^{D(4)}$$

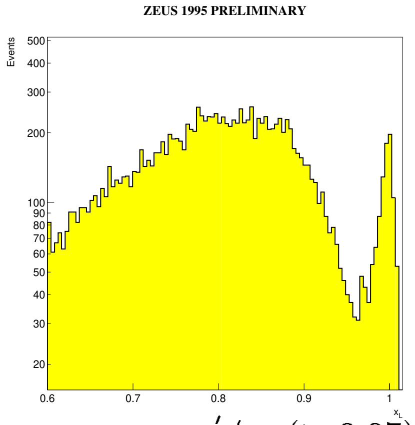
Selecting Diffractive Events

Three methods to isolate diffractive processes are used based on the kinematical properties of the final state

- tagging intact scattered proton
- requiring large rapidity gap in the event
- analysing hadronic mass distribution of the final state

- Tagging leading protons by Roman Pots (H1-FPS, ZEUS-LPS)



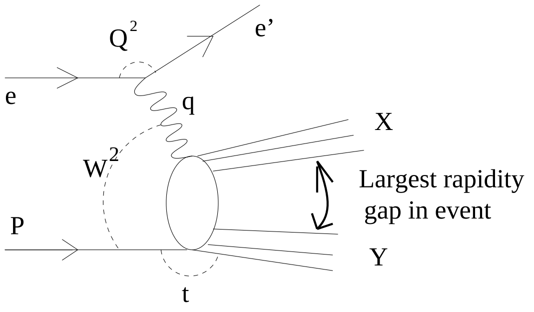


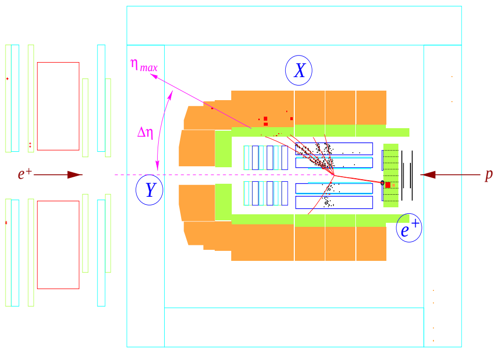
$x_L = p'/p \quad (> 0.97)$

- clean sample free of p-dissociation bgr.
- provides t measurement
- low statistics (acceptance, beam conditions)

Selecting Diffractive Events

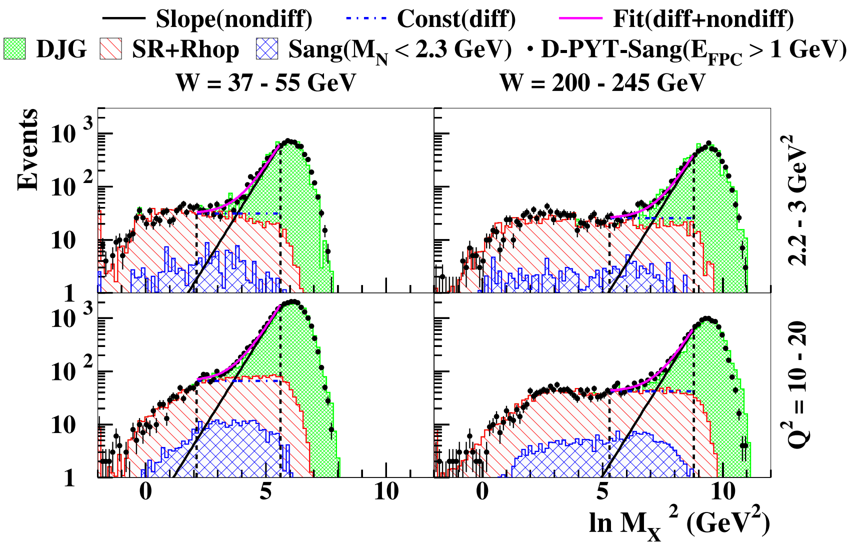
- Select Large Rapidity Gap (LRG) events, $3.2 < \eta_{gap} < 7.5$ (H1)





$$M_Y < 1.6 \text{ GeV} \quad \text{and} \quad t > -1 \text{ GeV}^2$$

- Analysing mass distribution of the hadronic final state (ZEUS)



1998-1999:

improved Forward calorimeter

increased η acceptance by 1 unit

$\rightarrow$ increased M_X range by factor 1.7

$$M_Y < 2.3 \text{ GeV} \quad \text{and} \quad t > -1 \text{ GeV}^2$$

- large statistics
- some dissociative admixture remains; integrate over t

New Data Samples

LPS (FPS)

ZEUS [1]

3.6 pb^{-1} $0.03 < Q^2 < 0.6$ GeV^2

12.8 pb^{-1} $2 < Q^2 < 100$ GeV^2

H1 [3]

28.8 pb^{-1} $2 < Q^2 < 50$ GeV^2

M_X (LRG)

ZEUS [2]

4.2 pb^{-1} $2.2 < Q^2 < 80$ GeV^2

H1 [4–6]

3.4 pb^{-1} $1.5 < Q^2 < 12$ GeV^2

10.6 pb^{-1} $6.5 < Q^2 < 120$ GeV^2

63 pb^{-1} $200 < Q^2 < 1600$ GeV^2

$\Rightarrow$ Significant improvement in statistics and covered phase space compared to previous generation of published data

[1] *ZEUS Coll., EPS01, Abs. 566; EPS03, Abs. 540.*

[2] *ZEUS Coll., ICHEP02, Abs.822; EPS03, Abs. 538.*

[3] *H1 Coll.. ICHEP02, Abs.984. http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-01-112.long.html*

[4] *H1 Coll., EPS03, Abs.88. http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-02-112.long.html*

[5] *H1 Coll., EPS03, Abs.89. http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-01-111.long.html*

[6] *H1 Coll., EPS03, Abs.90. http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-03-011.long.html*

Understanding Diffraction in DIS

- Model independent approach using the concept of diffractive PDF's

- Three types of (phenomenological) models
  - ▷ Regge motivated models with factorizable Pomeron
  - ▷ Colour dipole and 2-gluon exchange models
  - ▷ Non-pomeron mechanisms, generating large rapidity gap events

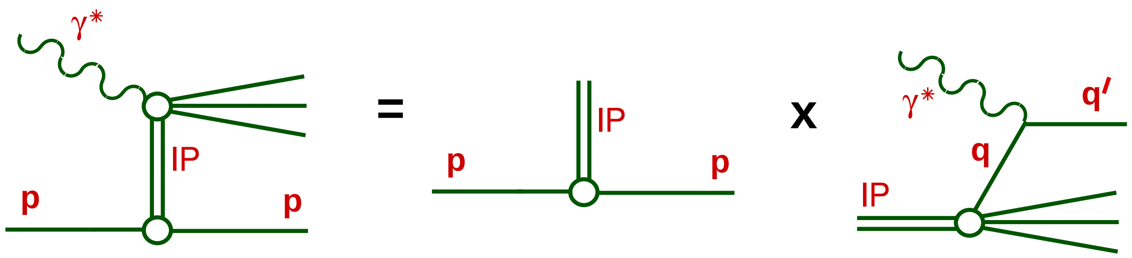
Diffractive parton distributions are based on rigorously proven (by Collins et al) QCD factorization for diffractive DIS, $\gamma^* p \to p^{'} X$

$$\frac{d^2\sigma(x, Q^2, x_{I\!P}, t)}{dx_{I\!P}\, dt} = \sum_i \int_x^{x_{I\!P}} d\xi \hat{\sigma}^{\gamma^* i}(x, Q^2, \xi) p_i^D(\xi, Q^2, x_{I\!P}, t)$$

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

Resolved Pomeron Model

Assuming Regge factorization



$$F_2^{D(4)}(x_{I\!P}, t, \beta, Q^2) = \Phi(x_{I\!P}, t) \cdot F_2^{I\!P}(\beta, Q^2)$$

(e.g. Ingelmann, Schlein or Donnachie, Landshoff, ...)

- Consistent with present data if in addition to $I\!P$ term also sub-leading $I\!R$ contribution is included
- In this case shape of diffractive PDF's is independent of $x_{I\!P}, t$ while normalization is controlled by Regge flux $\Phi(x_{I\!P}, t)$

Q: Does this factorization hold (universal property) or does it break (where, why)? $\Rightarrow$ Test it in

- other (exclusive) DIS processes (so far OK)
- other ep scattering, e.g. photoproduction (seems to be OK)
- non-ep processes, e.g. hh (breaks severely, mechanism?)

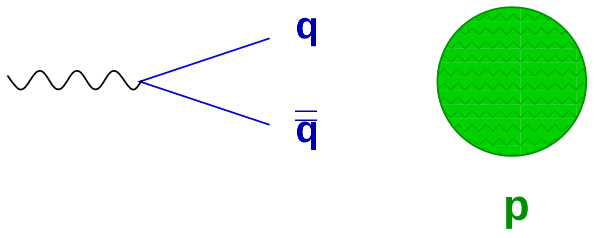
$\Rightarrow$ for details see talk of N.Vlasov

Colour dipole approach to DIS

Goal: Combine both soft and hard (inclusive and diffractive) processes within a common framework

Basic idea: (B.L.Ioffe in 1969, S.Brodsky et al. in 1992, J.D.Bjorken in 1993, ...)
Consider DIS in a proton rest frame.

At low x $\tau \approx \frac{1}{xM_p}$ $\Rightarrow \sim 1000$ fm at HERA

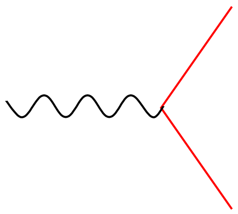


$\Rightarrow$ factorizes into $\Psi_{q\bar{q}} \times \sigma_{(q\bar{q})p}$

$|\gamma> \; = q\bar{q} + q\bar{q}g + \ldots$ Fock states

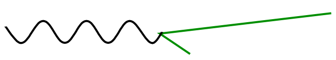
(diffraction is then modelled as colour singlet exchange between the dipole and p, e.g. $2g$)

Hard interactions:



Large $k_\perp$ = small dipole size
$\rightarrow$ small cross section (σ_L)

Soft interactions:

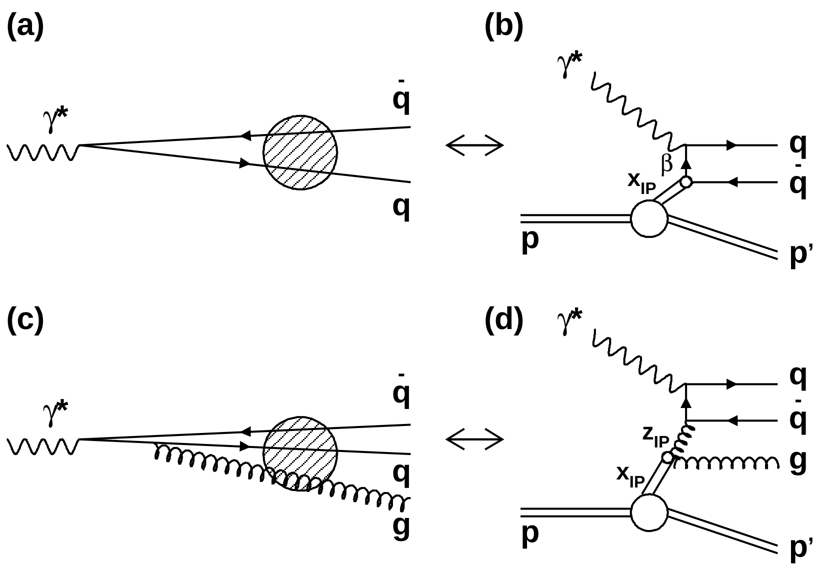


Small $k_\perp$ = large dipole size
$\rightarrow$ large cross section (σ_T)

$$\sigma_{\rm DIS}(Q^2) = \Psi^{\rm hard}_{q\bar{q}}(Q^2) \cdot \sigma_L(Q^2) + \Psi^{\rm soft}_{q\bar{q}}(Q^2) \cdot \sigma_T(Q^2)$$

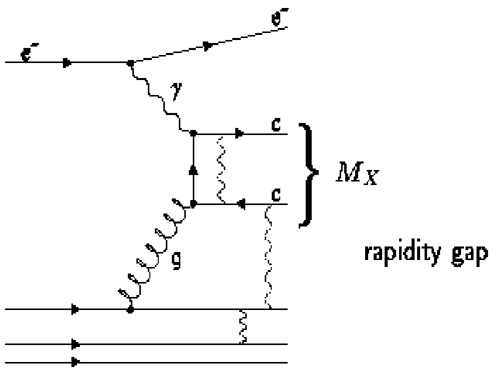
Models continued

Proton rest frame vs proton infinite momentum frame



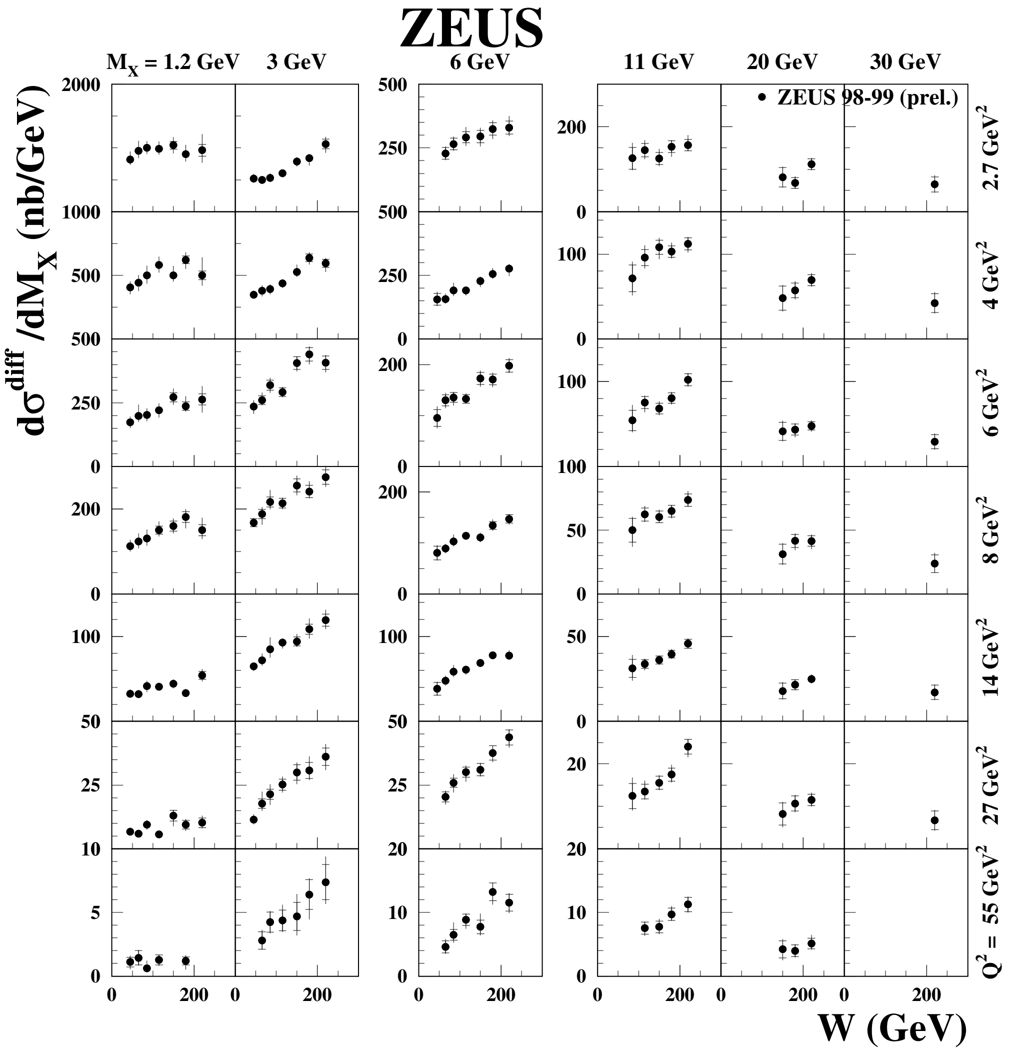
(examples: semi-classical model of BGH, sat. model of GW, BGK, BEKW)

• Soft Colour Interactions (e.g. Ingelmann, Rastman)



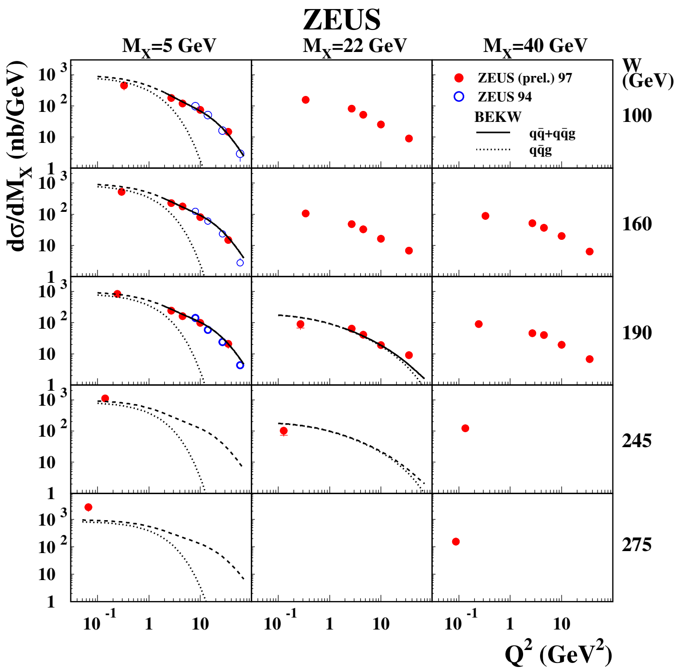
Mimic non-perturbative effects:
LRG are produced by the normal BGF with additional emittion of soft gluons, neutralizing the colour flow. ⇒ **leading gluon behaviour**

ZEUS Measurements

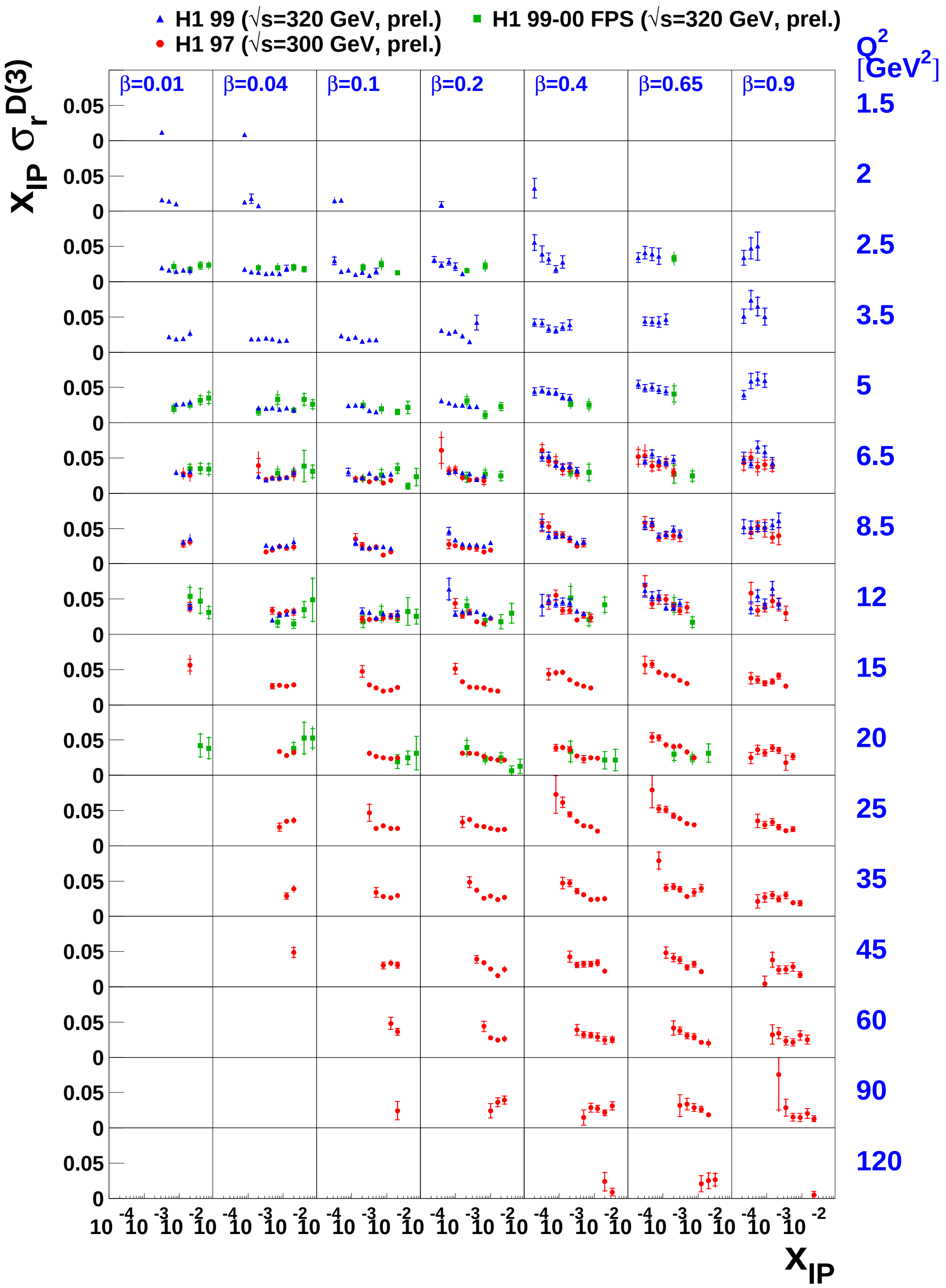


(left) Data using new forward calorimeter: $d\sigma/dM_X$ rapidly rises with W, for $M_X > 2$ GeV and shows weak W-dependence for $M_X < 2$ GeV.

(bottom) New LPS data cover transition region Q^2 behaviour is similar to that of total $\gamma^* p$ and can be described by colour dipole model with $q\bar{q} + q\bar{q}g$ comp.

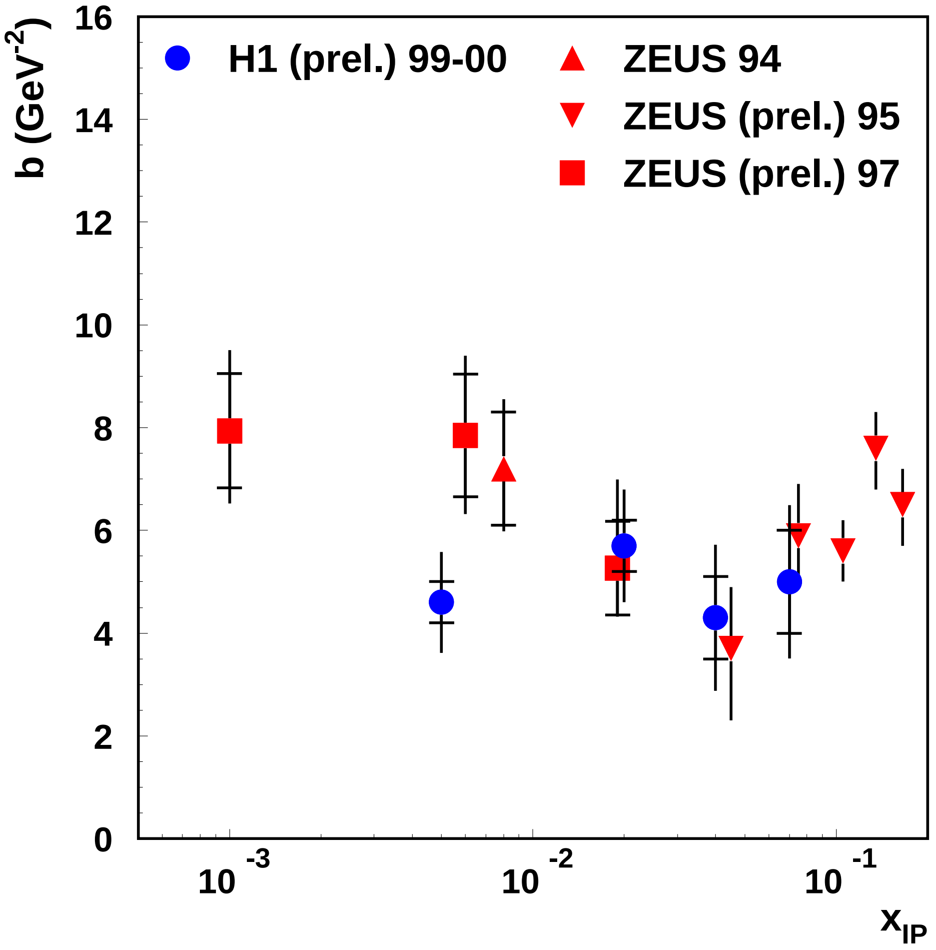


H1 Measurements



- good agreement between different samples and methods
- rise at high $x_{I\!P}$ – evidence for $I\!R$ contribution

Measurement of the t-dependence



acceptance range: $t > -0.4$ GeV^2

(for H1 FPS: $t < -0.08$ GeV^2)

$$d\sigma/dt \propto e^{bt}$$

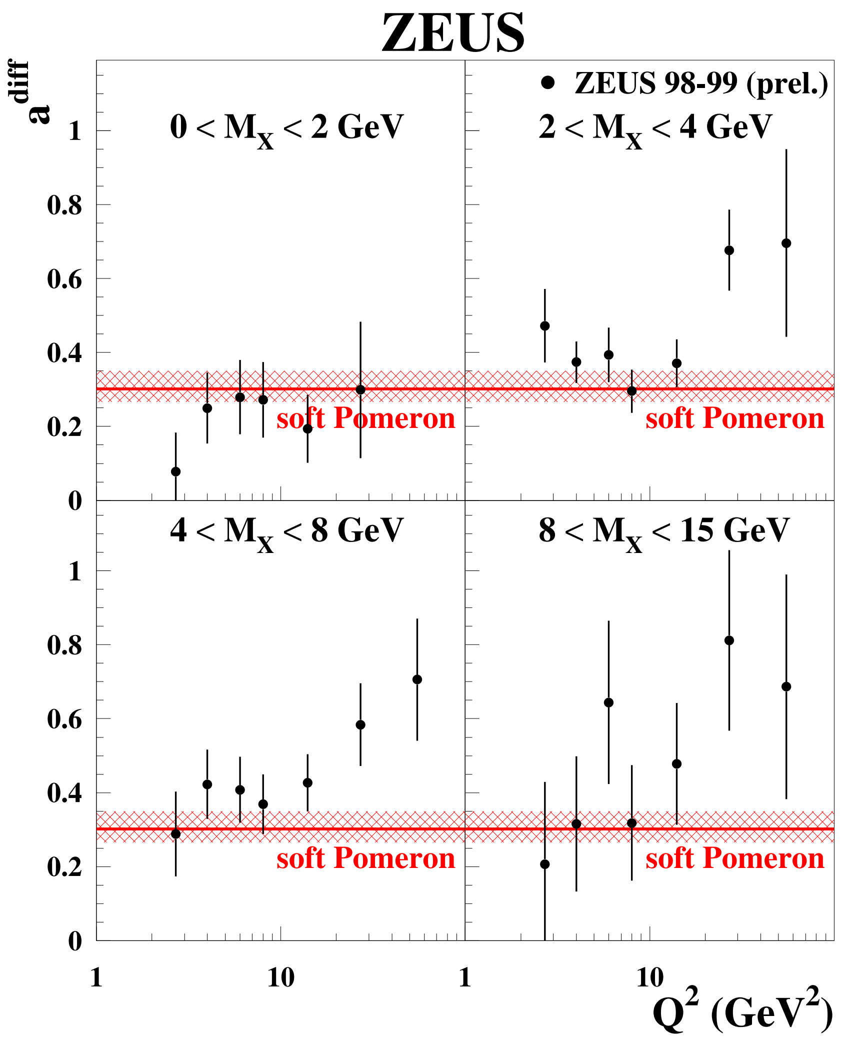
Regge expectation: shrinkage with W

$$b = b_0 + 2\alpha'_{I\!P} \ln(1/x_{I\!P})$$

$\Rightarrow$ so far inconclusive

good prospects at HERA-2 with H1 VFPS

Energy dependence



Regge motivated fits:

$$\frac{d\sigma^{diff}}{dM_X} = c \cdot W^{a^{diff}} \qquad \overline{\alpha_{I\!P}} = 1 + a^{diff}/4$$

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

Compare with soft $I\!P$ from hh scattering:

$\alpha_{I\!P}(0) = 1.096 \quad \rightarrow \quad a^{sof} = 0.302$

(corrected by $\delta\alpha_t = 0.02$ for $t \neq 0$)

For $M_X > 2$ GeV and $Q^2 > 10$ GeV^2

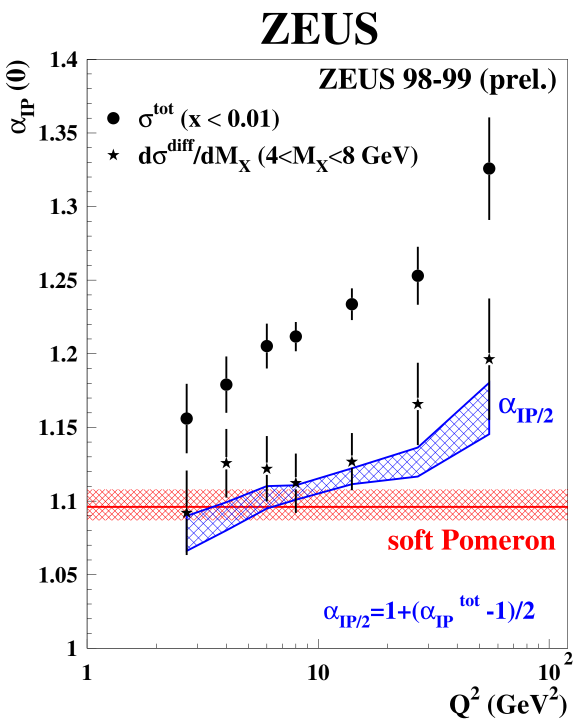
diffractive slope is incompartible with soft $I\!P$

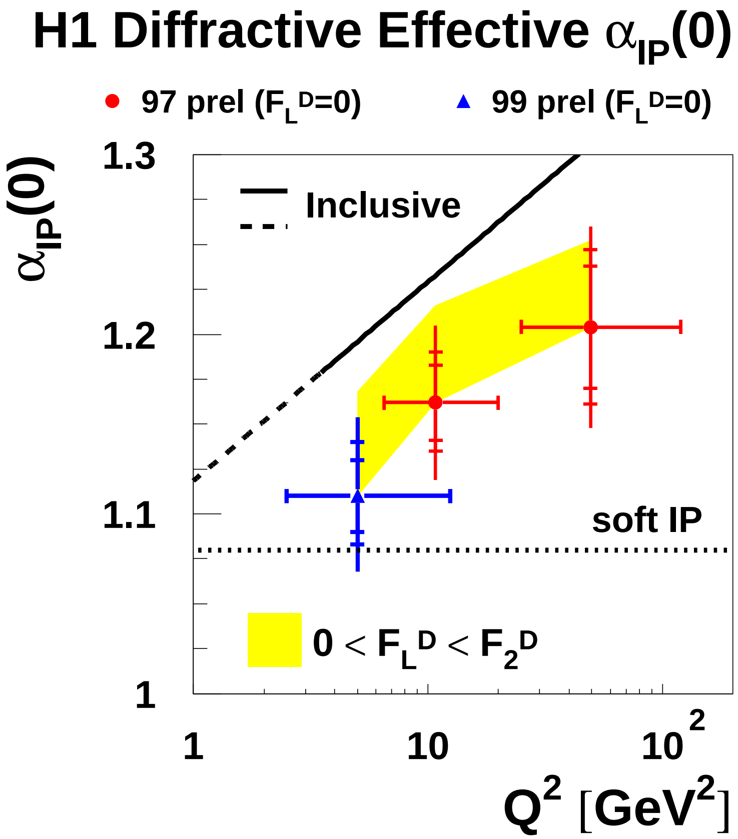
$\alpha_{I\!P}(0)$ in total vs diffractive DIS

Related via Optical theorem: $\sigma^{tot} \sim W^{2(\alpha_{I\!P}(0)-1)}$ $\sigma^{el/diff} \sim W^{4(\alpha_{I\!P}(0)-1)}$

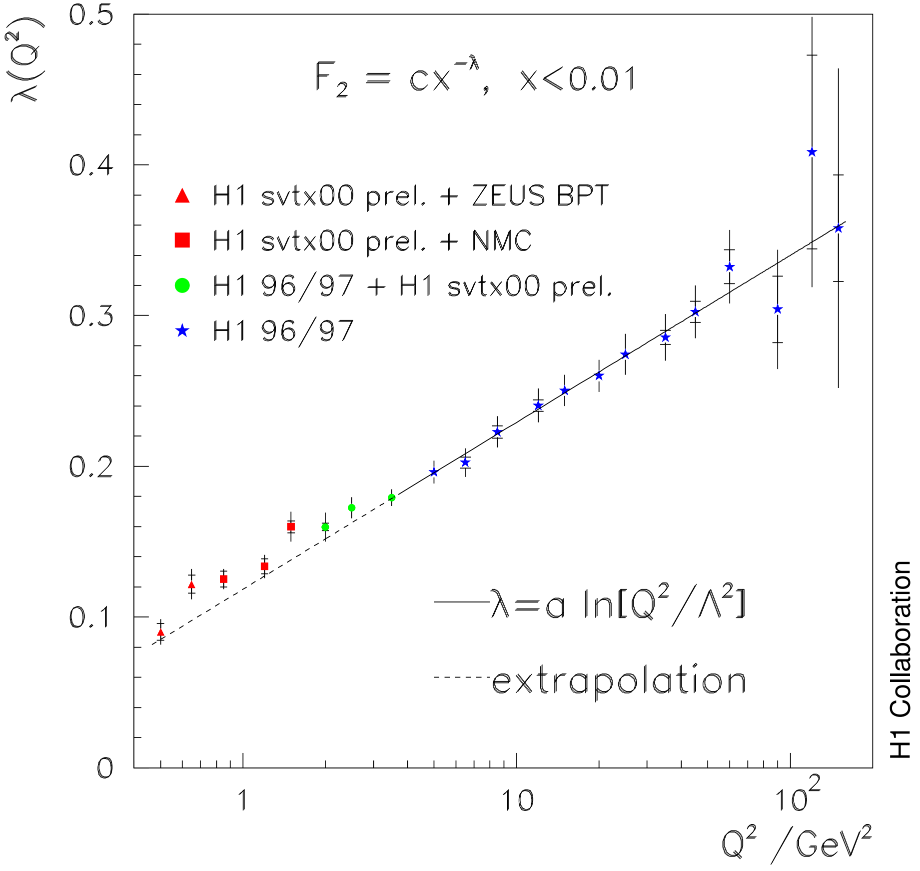
$\Rightarrow$ qualitatively OK for $\sigma^{el}(\gamma^* p \to \rho p)$ and for σ^{diff} at $Q^2 \approx 0$, but different in diffractive DIS:

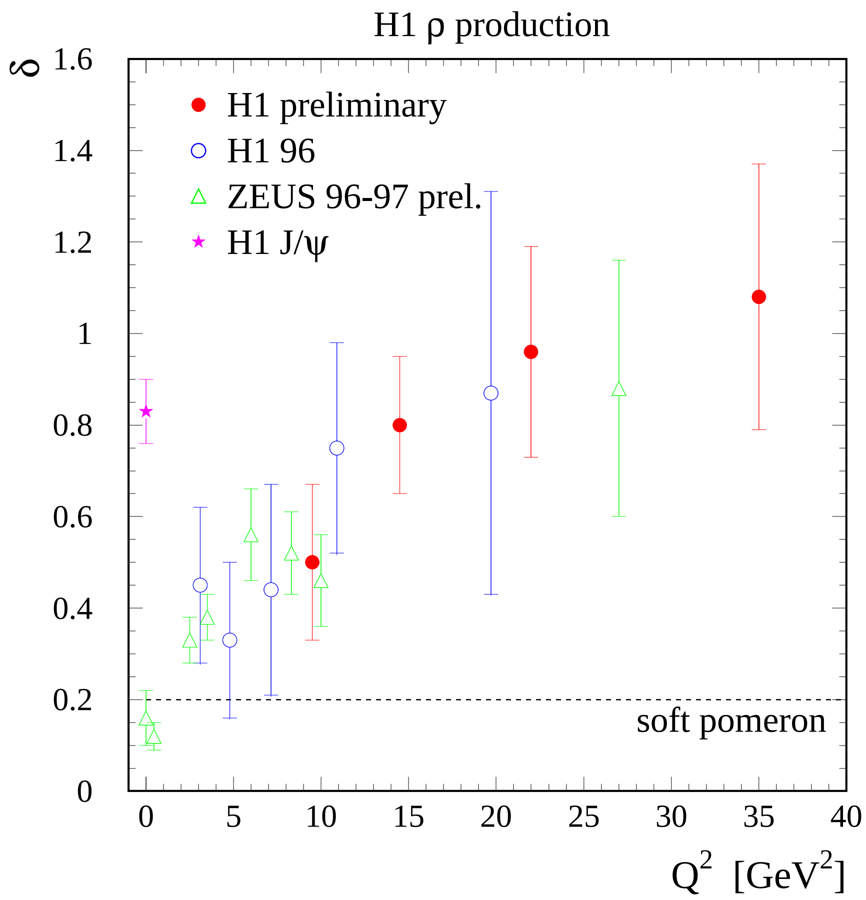
$\Rightarrow$ in DIS region $\alpha_{I\!P}(0)$ is incompartible with soft $I\!P$





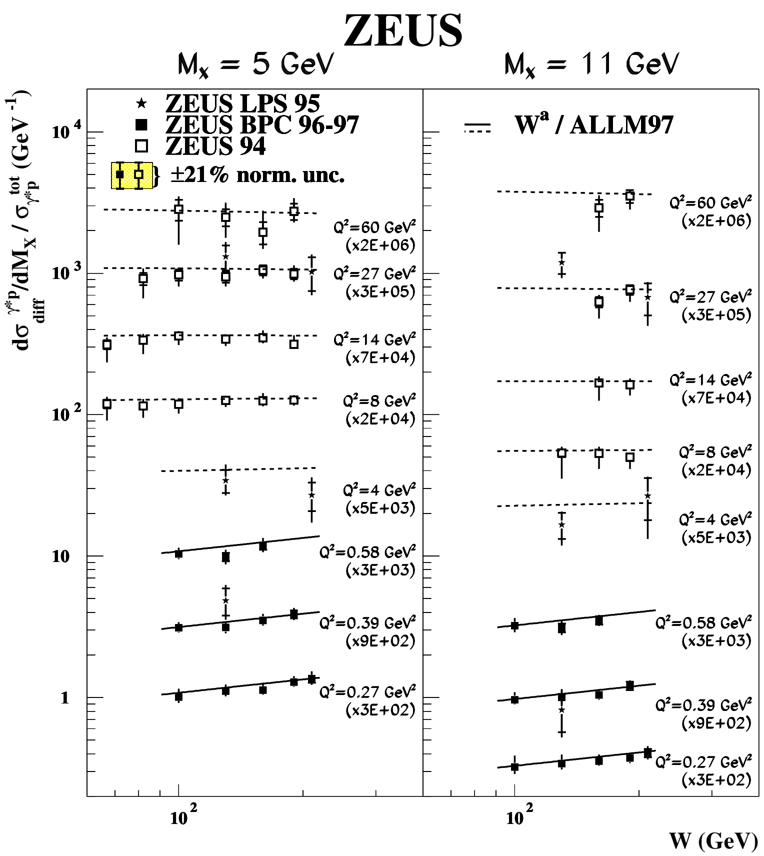
Pomeron intercept in inclusive and elastic DIS

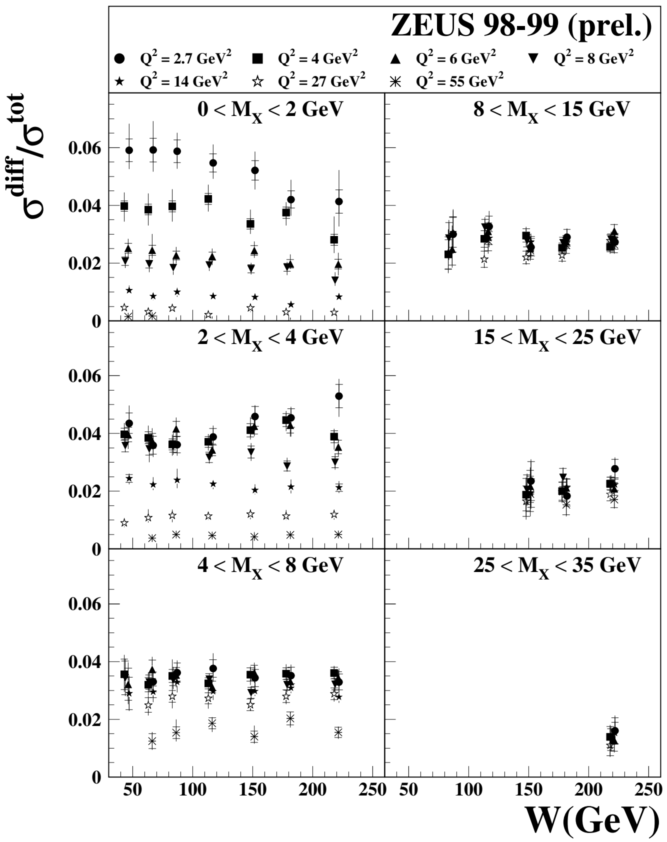




$$\lambda = (\alpha_{I\!P}(0) - 1) \qquad \delta = 4(\overline{\alpha_{I\!P}(0)} - 1)$$

Ratio diffractive/inclusive: Energy dependence





$$r = \int dt (d\sigma^D/dM_X)/\sigma^{tot} \sim W^\rho$$

low Q^2 : $\rho = 0.24 \pm 0.07$ $\rightarrow$ Regge-like

in DIS: $\rho = 0.00 \pm 0.03$ $\rightarrow$ not Regge-like

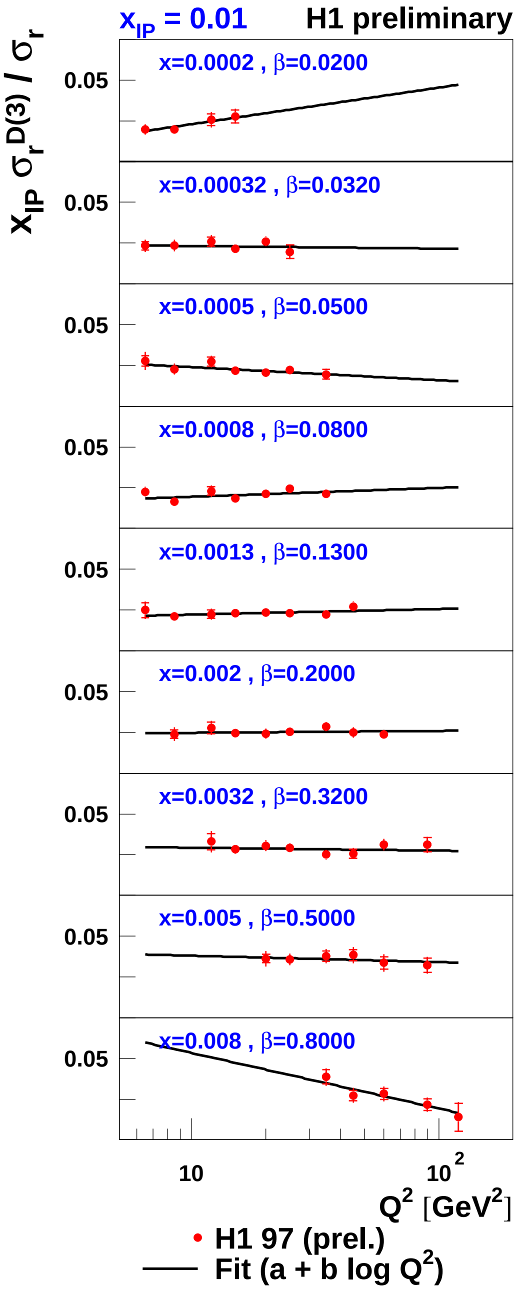
New data: at low M_X r even drops with W

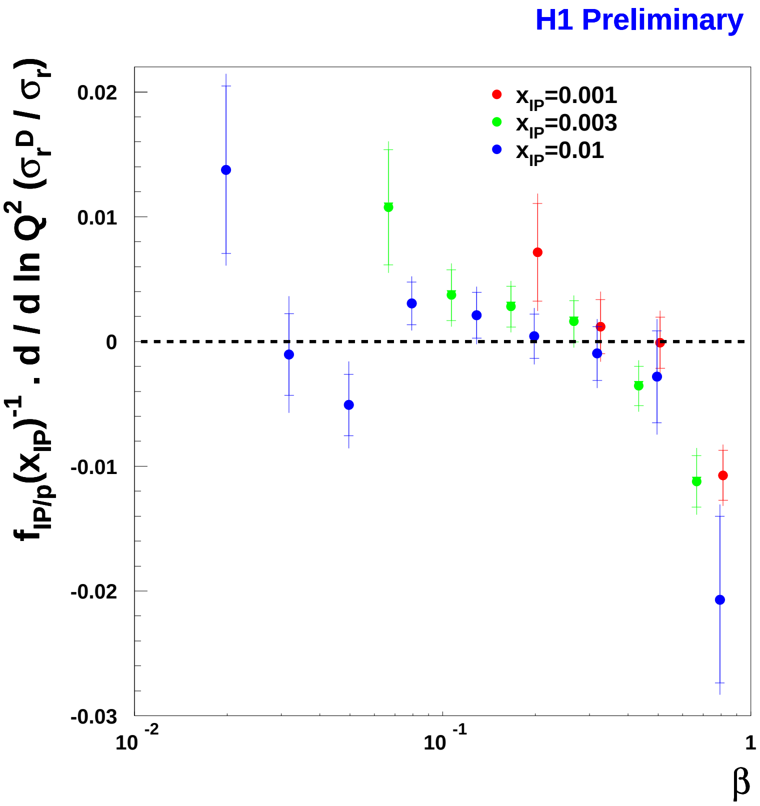
little Q^2-dependence at high M_X (low β)

strong decrease with Q^2 at low M_X (high β)

Ratio diffractive/inclusive: Q^2 dependence

$$\frac{\sigma_r^{D(3)}(x, Q^2, x_{I\!P})}{\sigma_r(x, Q^2)}\Big|_{x, x_{I\!P}} \sim A + B \ln Q^2$$

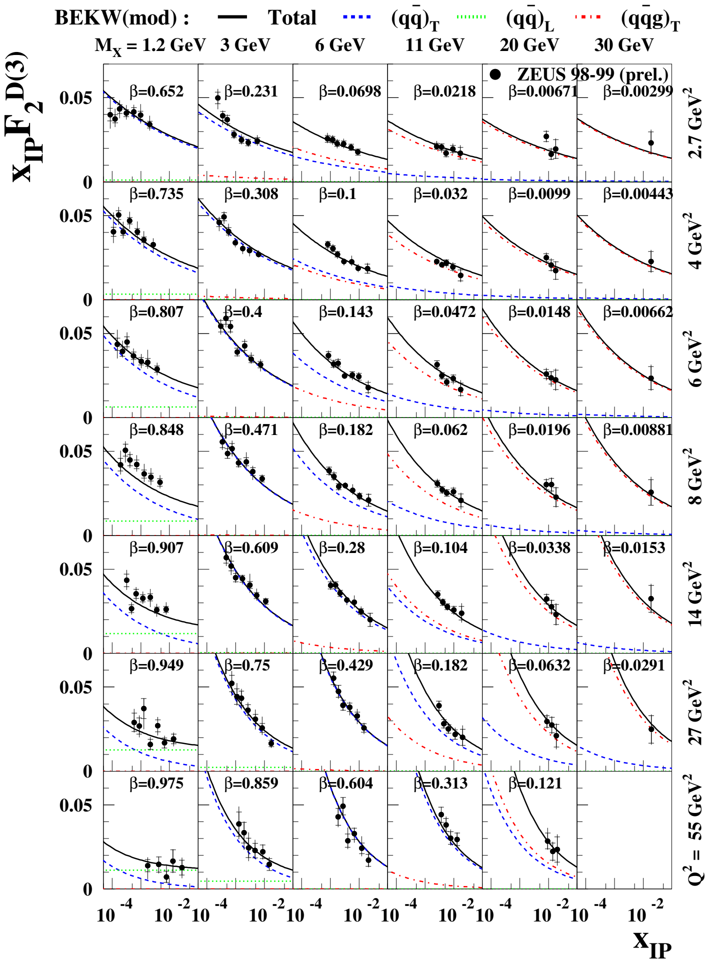


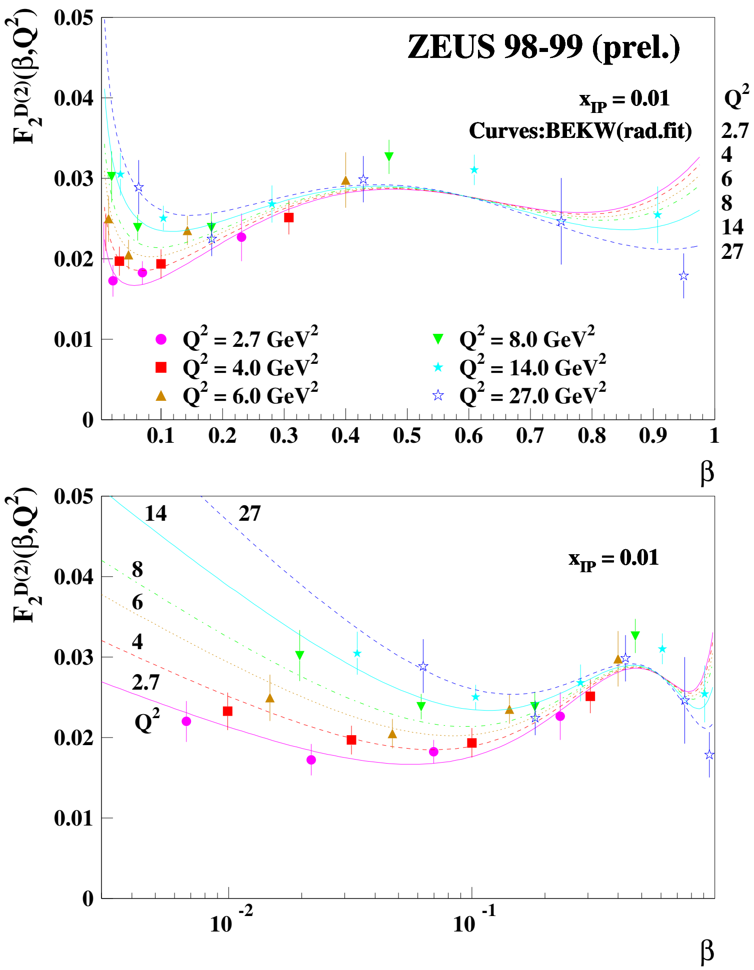


Also flat in Q^2

(Drop at the high edge of β could be simple kinematics, or higher twist effect)

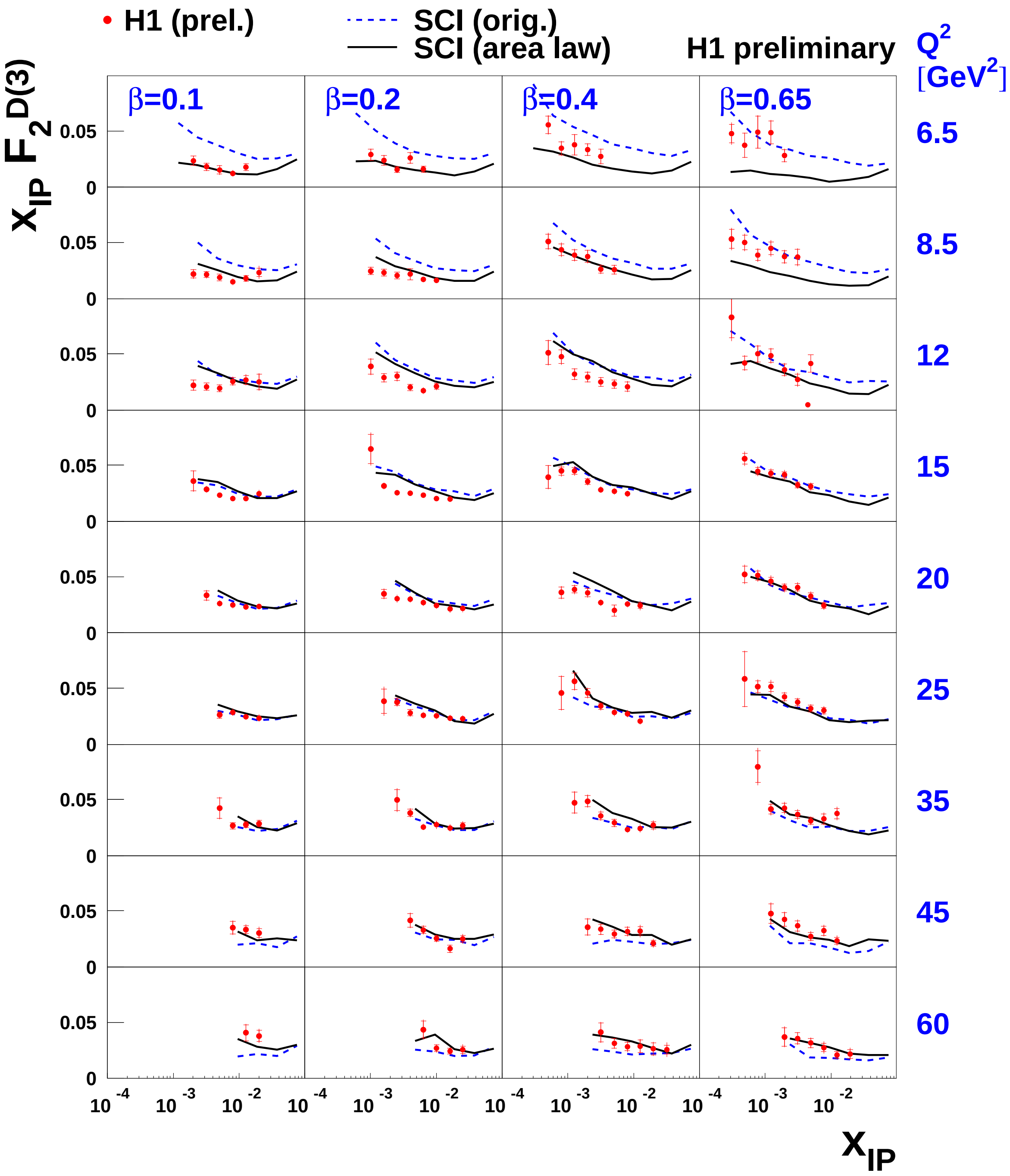
ZEUS F_2^D vs Colour Dipole model





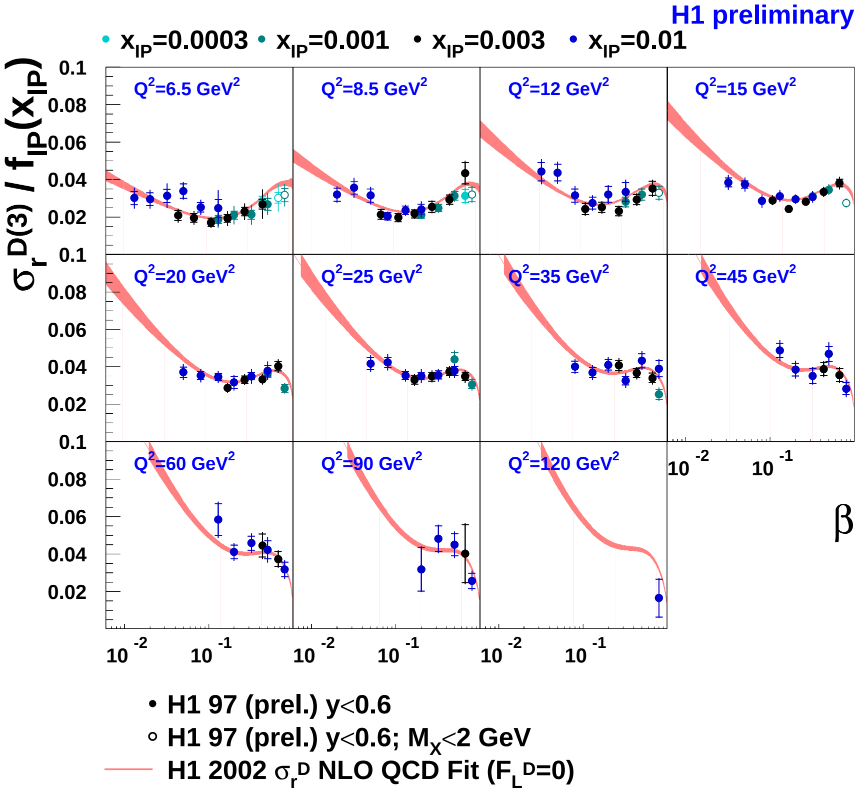
In valence region $\beta > 0.1$ $q\bar{q}$ dominate, while at low β main contribution is due to $q\bar{q}g$

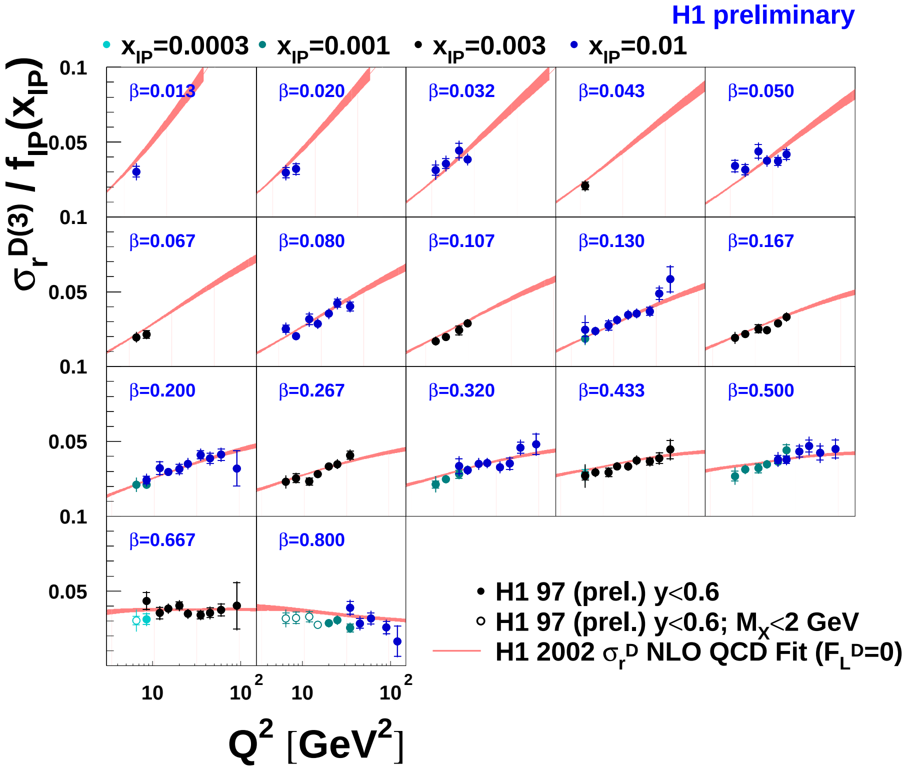
H1 F_2^D vs Soft Colour Interaction model



⇒ Fair description. Refined version is in a better agreement with the data than the original one

H1 $F_2^D(\beta, Q^2)$





- Regge factorization holds for $x_{I\!P} < 0.01$ $\rightarrow$ simplifies QCD fit
- positive scaling violation except largest β $\rightarrow$ gluon dominance

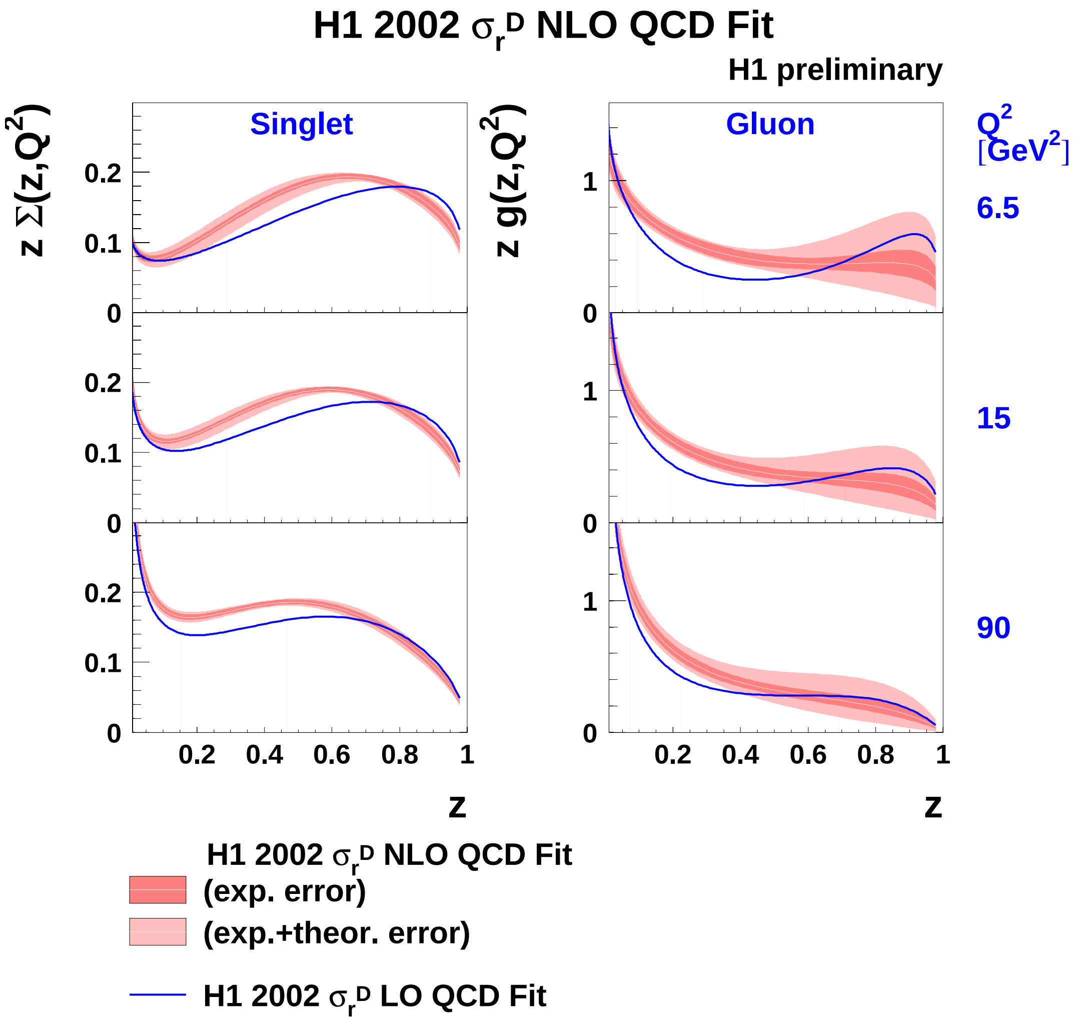
NLO DGLAP QCD fit and Diffractive PDF's

QCD fit technique

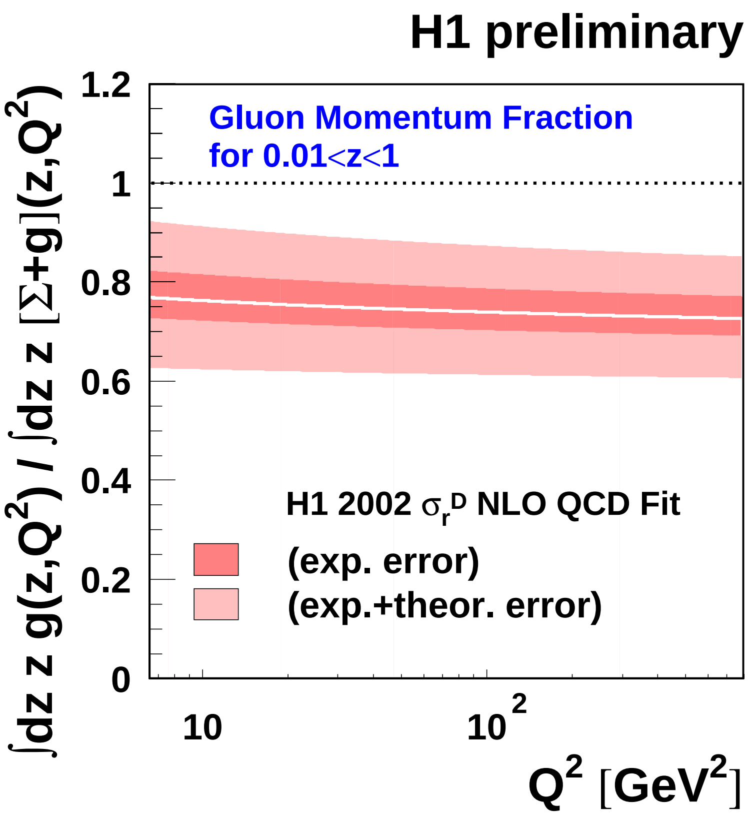
- Regge factorization with $I\!P$, $I\!R$ terms (pion PDF (Owens) are used for $I\!R$)
- Singlet Σ and gluon g in $I\!P$ parametrized at $Q_0^2 = 3$ GeV^2
- NLO DGLAP evolution for $Q > Q_0$
- Fit 313 data points for $Q^2 > 6.5$ GeV^2 and $M_X > 2$ GeV (7 free par.)
- Propagate exp. and theor. uncertainties to obtain PDF's with error band

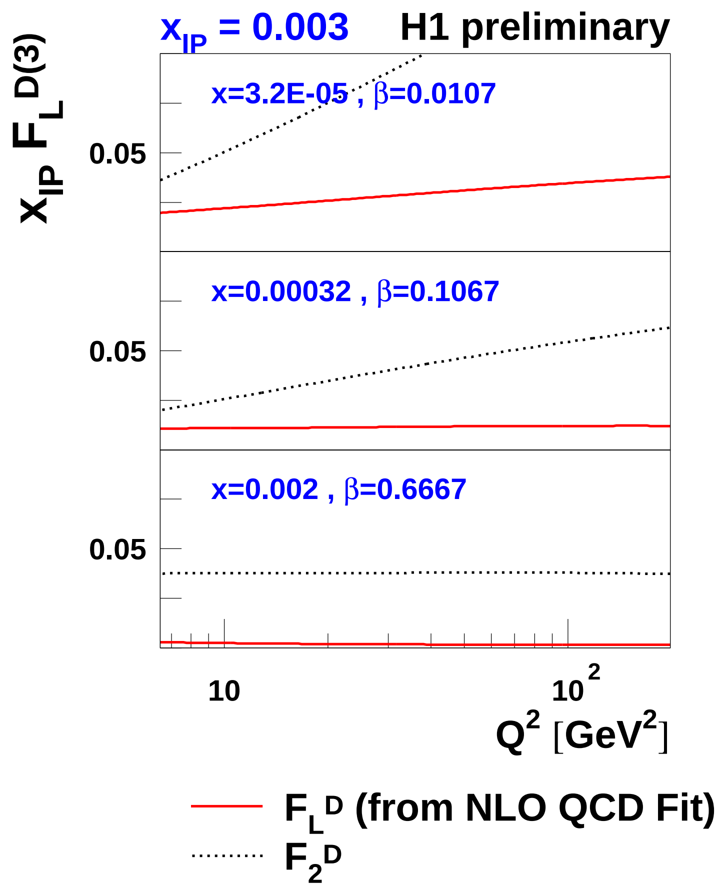
Resulting diffractive PDF's

- Gluon dominated
- Singlet part is well constrained
- Substantial (theor.) uncertainty for gluon at higest fractional momenta z



H1 NLO QCD fit: Gluon dominance of diffractive exchange

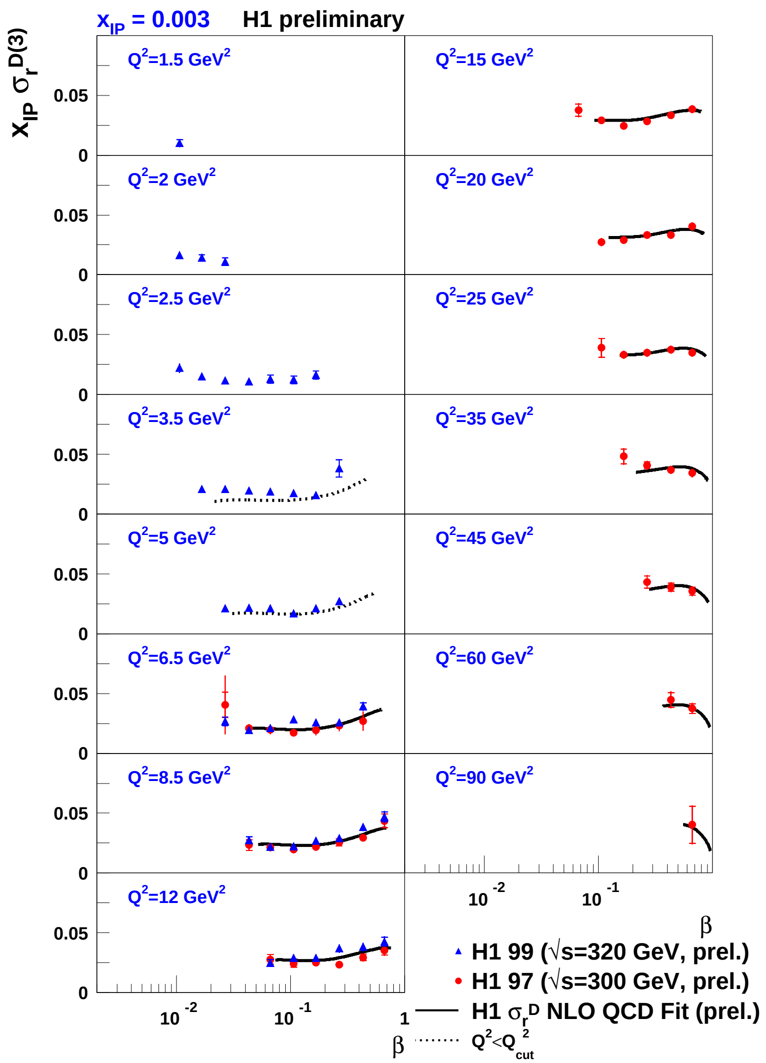


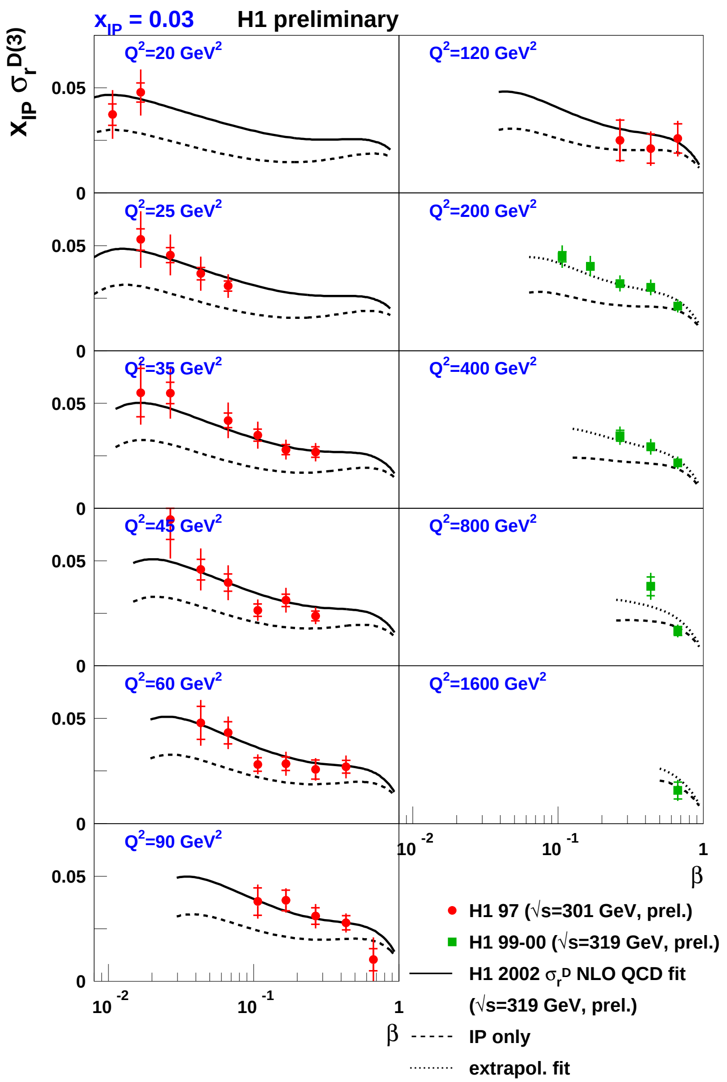


Large momentum fraction of diffractive exchange is carried by gluons: $75 \pm 15\%$

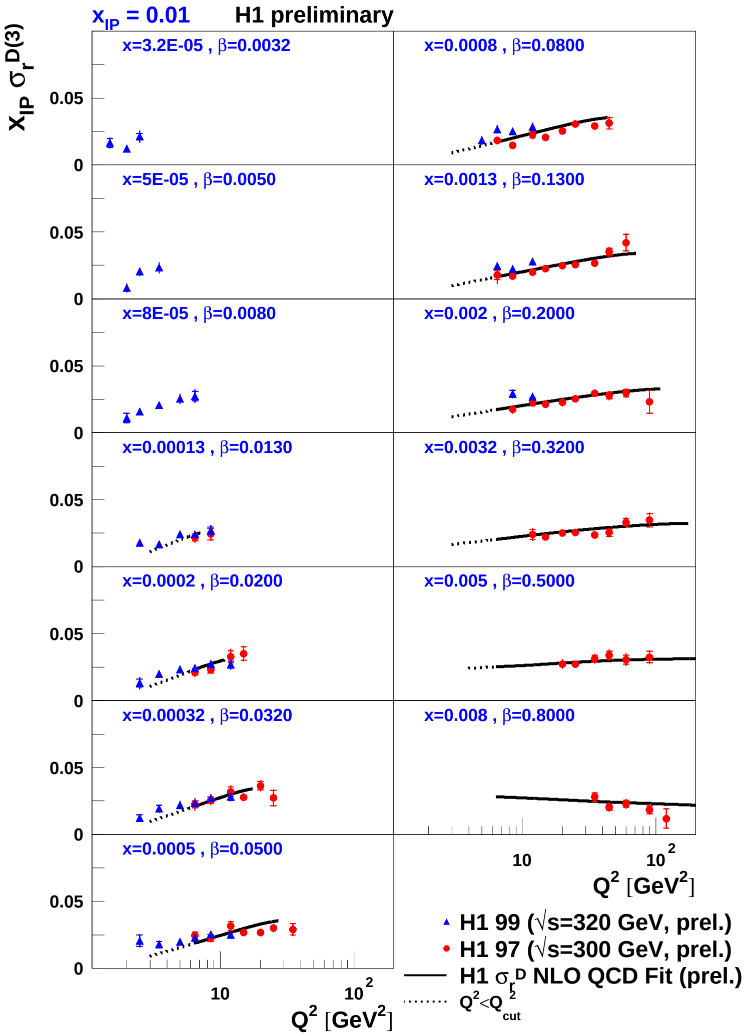
$\Rightarrow$ F_L^D is important at low Q^2, low β

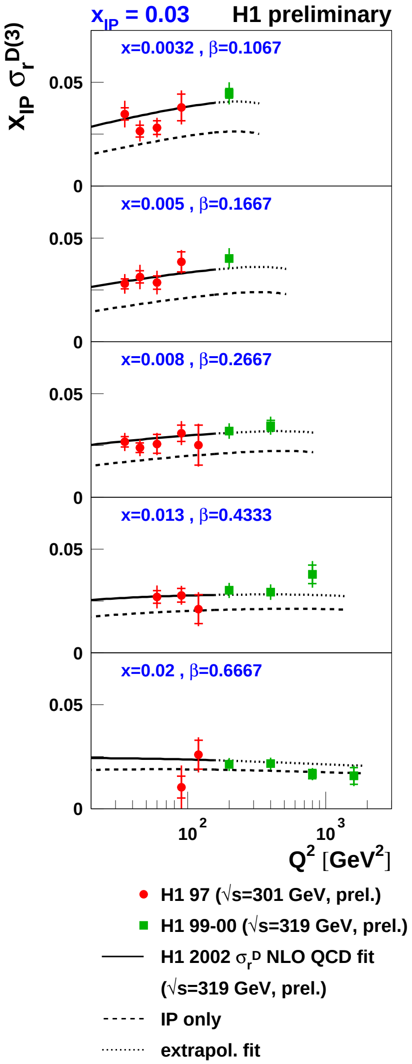
H1 NLO QCD fit: β dependence

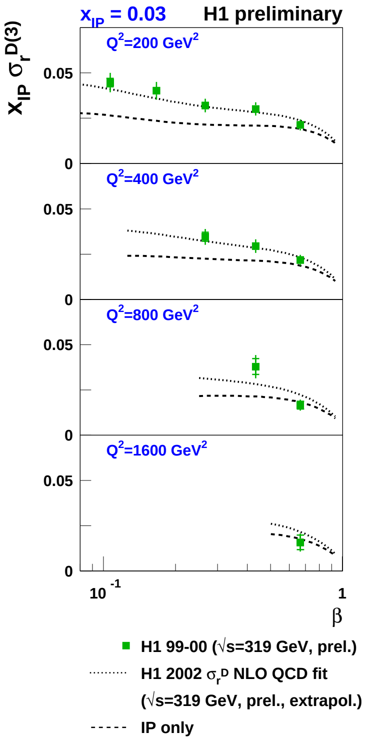




H1 NLO QCD fit: Q^2 dependence







Summary

- New precision measurements of inclusive diffraction over extended kinematical range are now available from HERA experiments

- Energy dependence and $\alpha_{I\!P}(0)$ – no simple explanation at the moment

- Ratio diffractive to inclusive cross section in DIS regime is remarkably flat, except compicated structure at high β region

- Despite Regge picture fails in DIS in several respects at present level of precision Regge factorization still holds in ep diffraction

- Colour dipole models in a broad agreement with diffractive SF

- NLO DGLAP QCD fit of H1 data provides:
  - ▷ diffractive parton distributions including error band
  - ▷ gluon distribution dominates diffractive scattering
  - ▷ can be used to test (QCD and Regge) factorization in ep and hh collisions

- Although an important progress is made recently, understanding of color singlet exchange remains a major challenge in QCD