Hard diffraction at HERA

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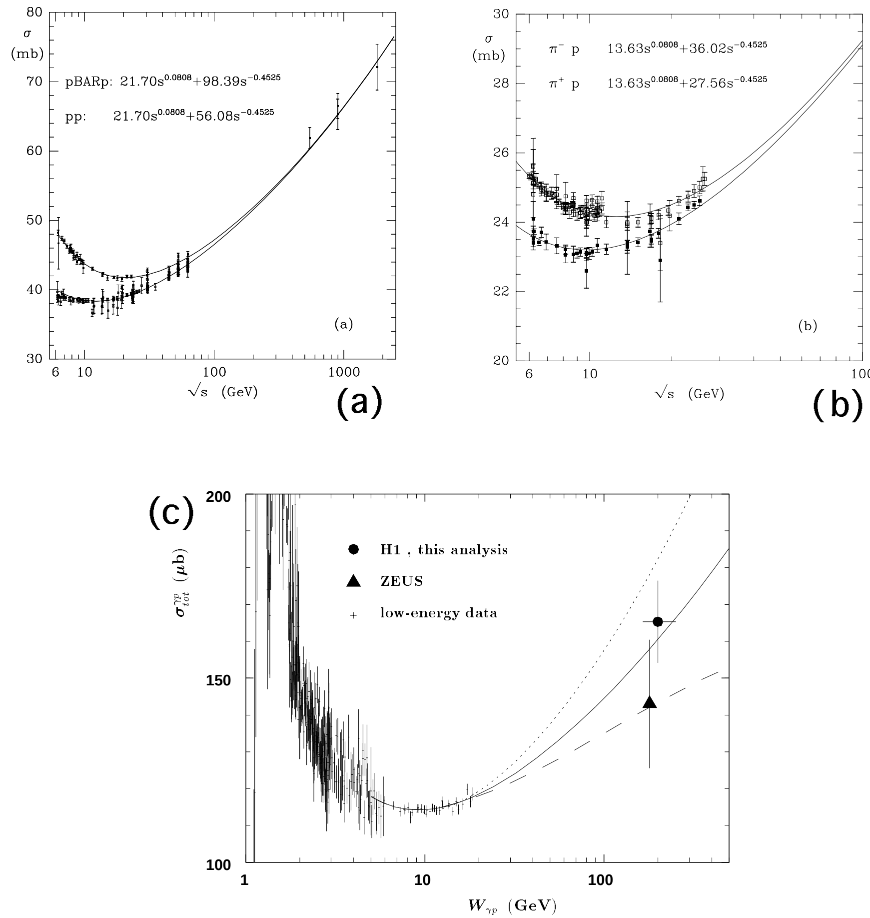
H1 Collaboration

- Introduction
- Diffractive Structure Function F_2^D
- NLO QCD fit and diffractive pdf's
- Diffractive final states
- Summary

Preface: Why is diffraction (still) interesting ?

- Early observation:
  total hadronic cross sections rise at high s
- $\sigma_{\rm tot}$ dominated by soft processes, where pQCD does not apply
  large fraction of elastic / diffractive processes
- Parameterized in terms of
  Regge phenomenology:
  $$\frac{d\sigma}{dt} \sim \frac{1}{s^2}|T(s,t)|^2 = f(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$$
  $$\sigma_{tot} \sim \frac{1}{s}\mathrm{Im}(T(s,t))|_{(t=0)} = s^{\alpha(0)-1}$$
- At high s: the pomeron trajectory
  (vacuum quantum numbers, elastic scattering)
  $$\alpha(t) = \alpha(0) + \alpha' t = 1.08 + 0.25\ t$$
- Diffraction exists also in hard processes

Total cross sections at high energy:

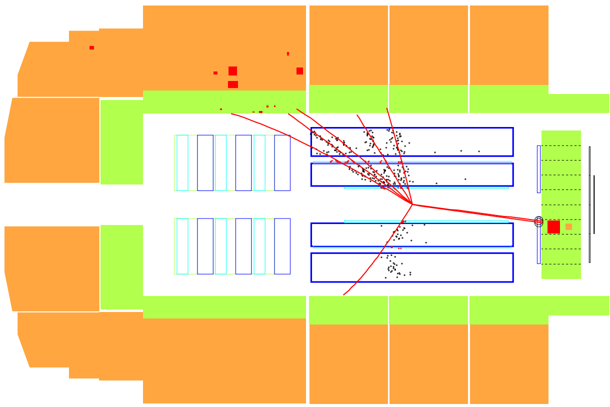


→ QCD (quark-gluon) structure of diffraction !

Diffraction in DIS at HERA

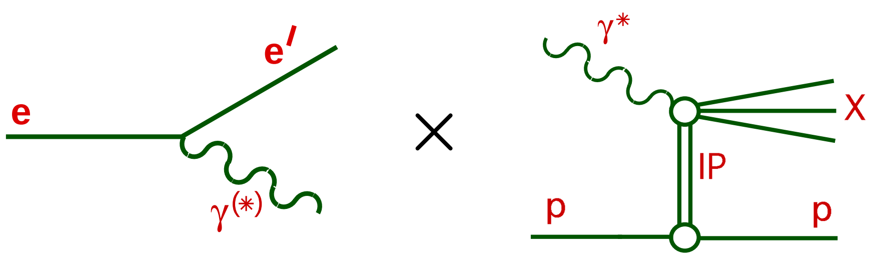
Early Observation at HERA:

10% of low-x DIS events are diffactive
$ep \rightarrow e'p'X$

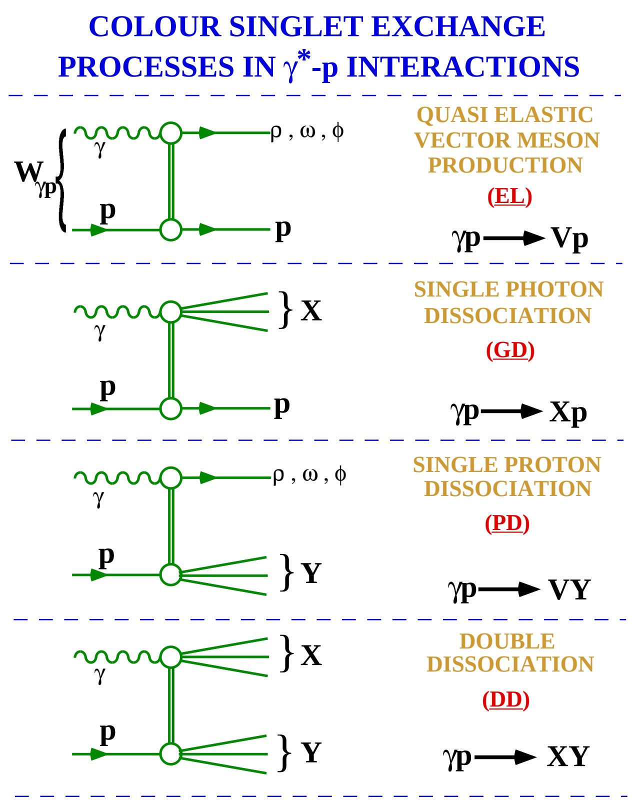


Colour-singlet or "pomeron" exchange

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



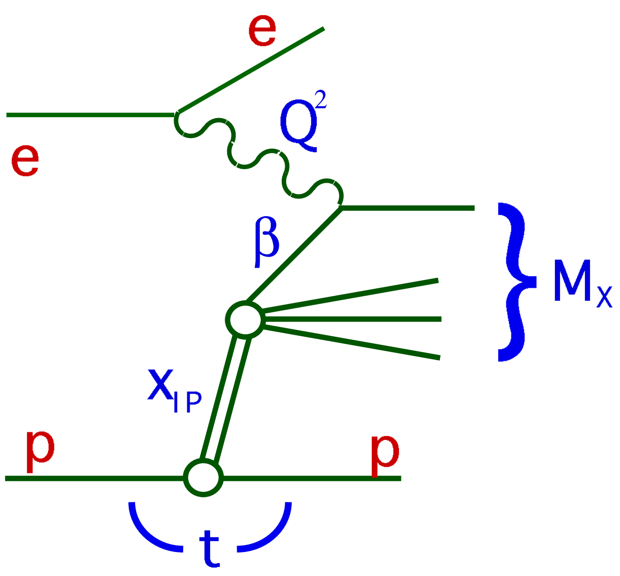
More generally: $\gamma^{(*)} p \rightarrow XY$



All can be measured by varying
Q^2, W, t, M_X, M_Y

This talk mostly $\gamma^* p \rightarrow Xp$
(large Q^2, small $|t|$)

Diffractive DIS



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

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

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

Diffractive reduced cross section σ_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:

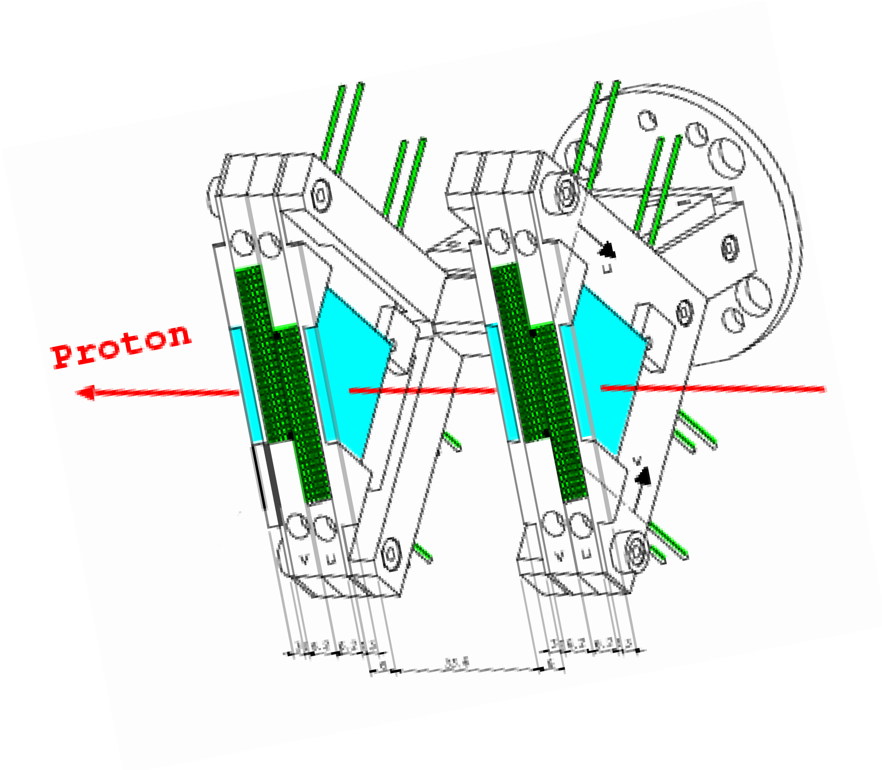
$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{2(1-y+y^2/2)}\,F_L^{D(4)}$$

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

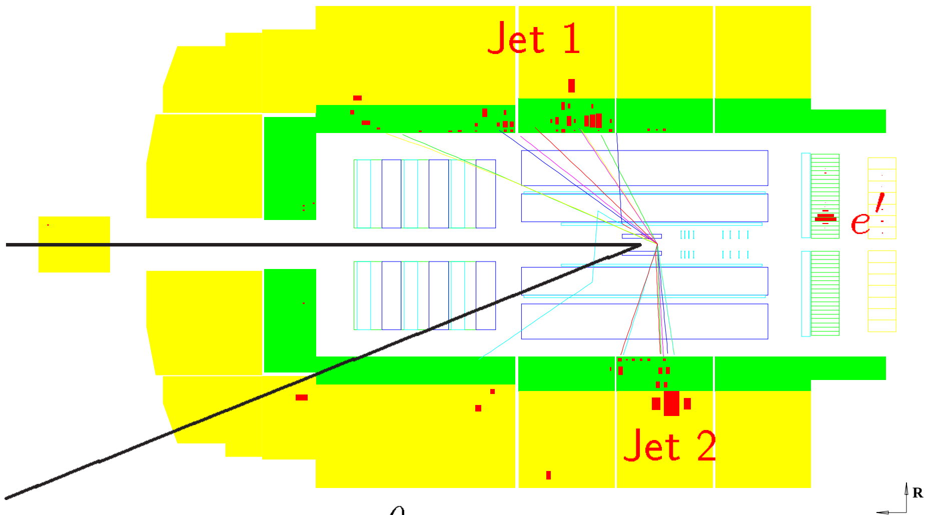
Probe QCD (quark-gluon) structure of diffraction (Pomeron exchange) !

Experimental Techniques

Forward Proton Spectrometer
at $z = 65\ldots90$ m



Rapidity Gap Selection
in central detector



$$\eta_{max} = -\ln\tan\frac{\theta}{2}$$

Measure leading proton

- Free of p dissociation bkgd.
- Measure t distribution
- low statistics (acceptance)

Require large rapidity gap

- $\Delta\eta$ large when $M_X \ll W$
- integrate over M_Y,t
- high statistics

Factorization Properties of F_2^D

QCD Factorization for diffractive DIS:

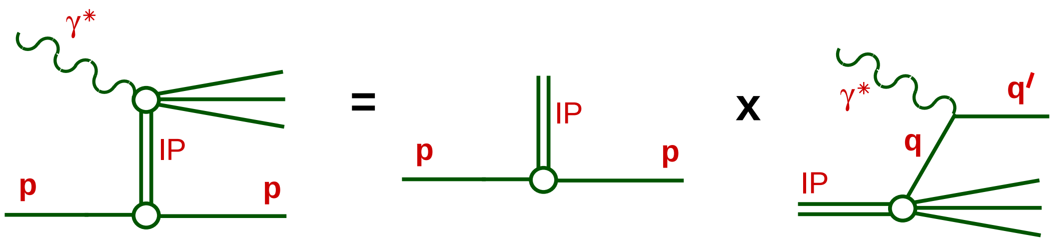
- Diffractive parton distributions (Trentadue, Venezianio, Berera, Soper, Collins, ...):

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

- $\hat{\sigma}^{\gamma^* i}$ 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 DGLAP
- not proven for diffractive hadron-hadron scattering

Regge Factorization / resolved Pomeron model:

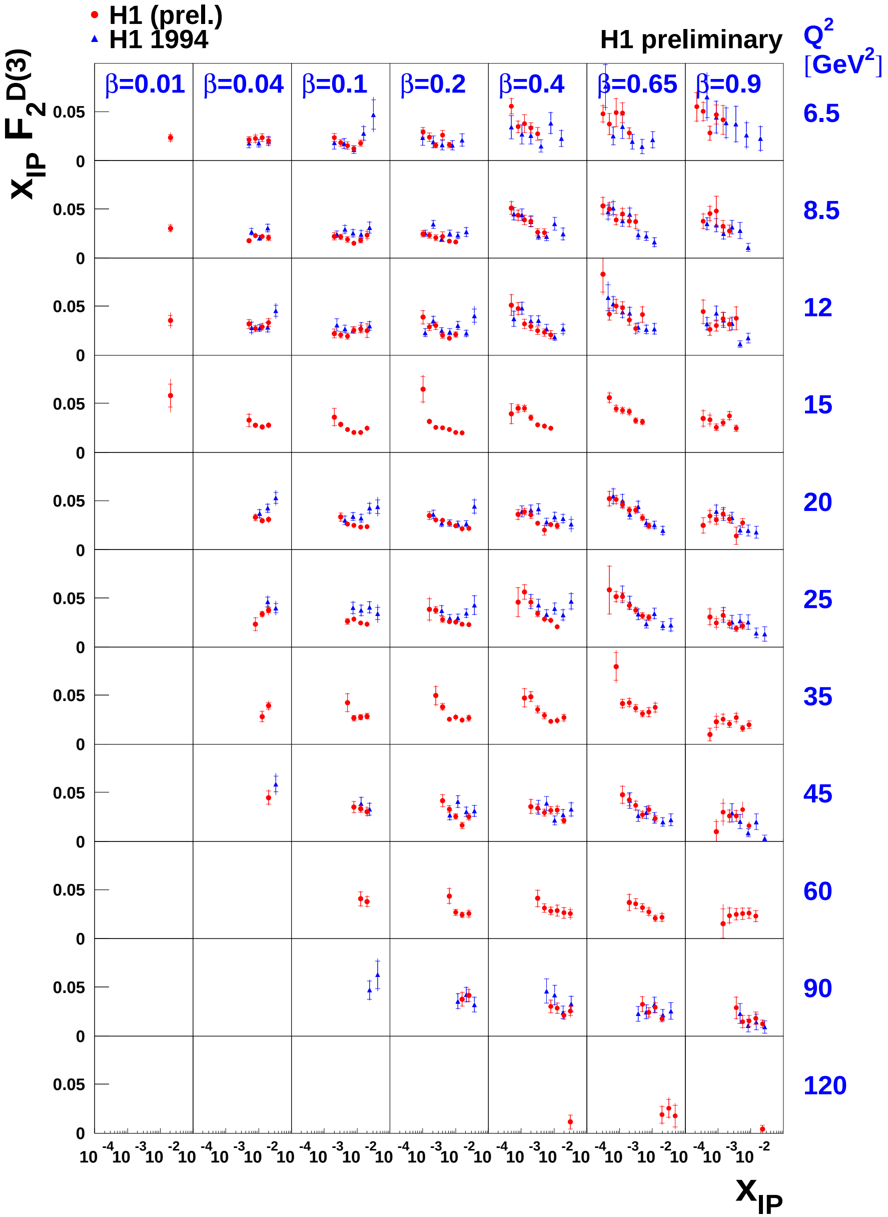
$x_{I\!P}, t$ dependence factorizes out: Donnachie, Landshoff, Ingelman, Schlein, ...)



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

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

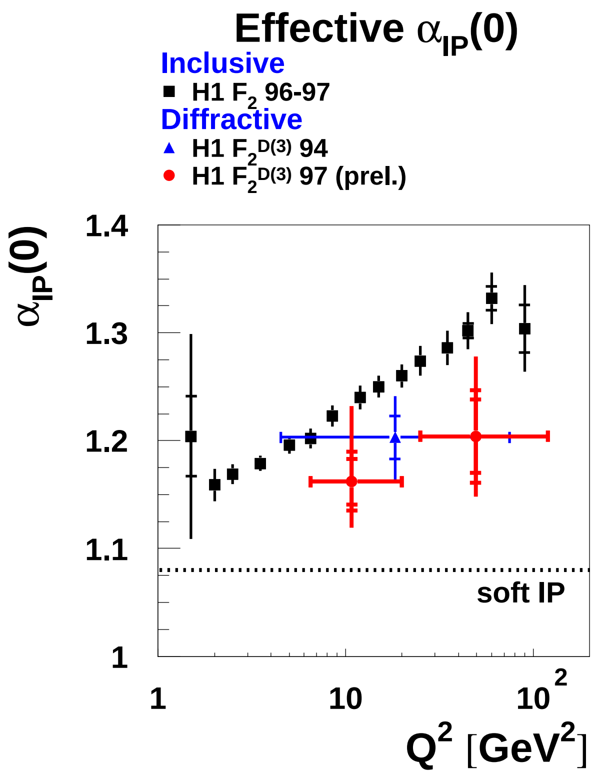
New $F_2^{D(3)}$ measurement (Rapidity gap)



5 times more statistics than previous data

Fit to $x_{\mathbb{P}}$ dependence: effective $\alpha_{\mathbb{P}}(0)$

$$F_2^D(x_{\mathbb{P}}, \beta, Q^2) \sim B(\beta, Q^2) \left(\frac{1}{x_{\mathbb{P}}}\right)^{2\alpha_{\mathbb{P}}-1}$$

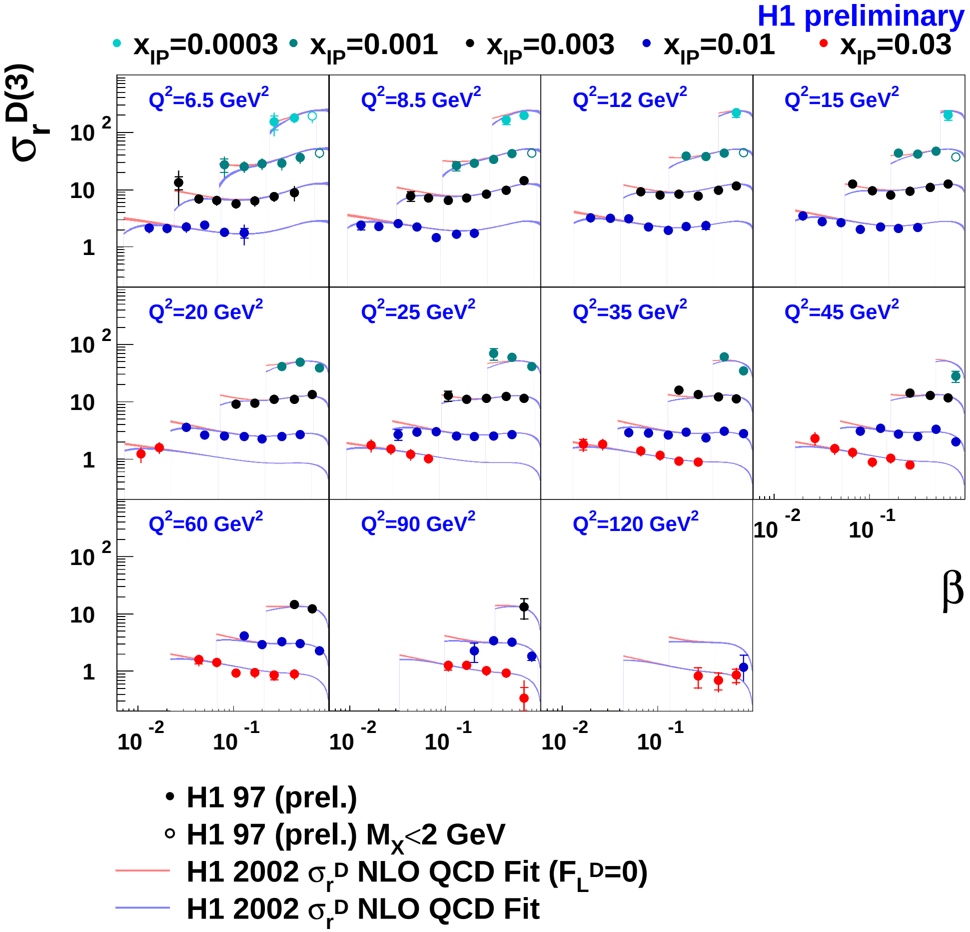


$$\alpha_{\mathbb{P}}(0) = 1.173 \pm 0.02 \pm 0.02^{+0.06}_{-0.03}$$

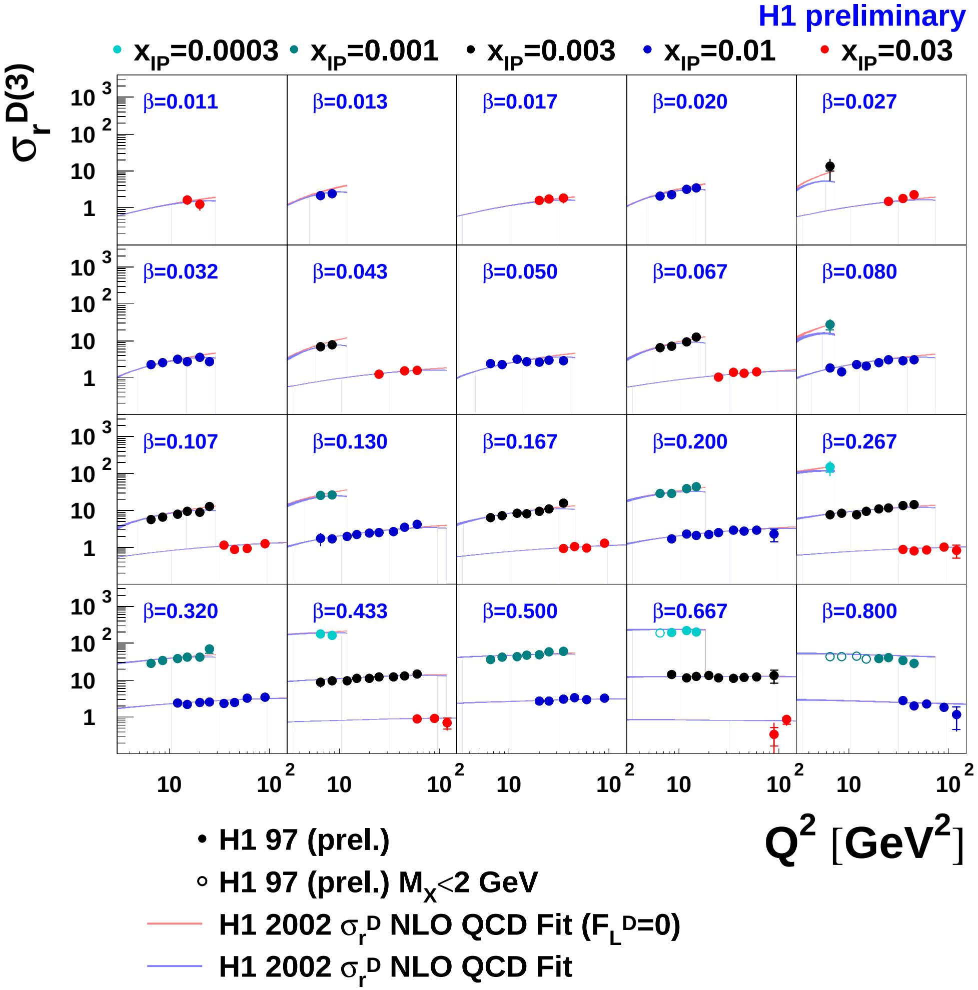
Growth with Q^2 slower in diffractive case?

$F_2^{D(3)}$: β and Q^2 dependence overview

β dependence at fixed Q^2:



Q^2 dependence at fixed β:



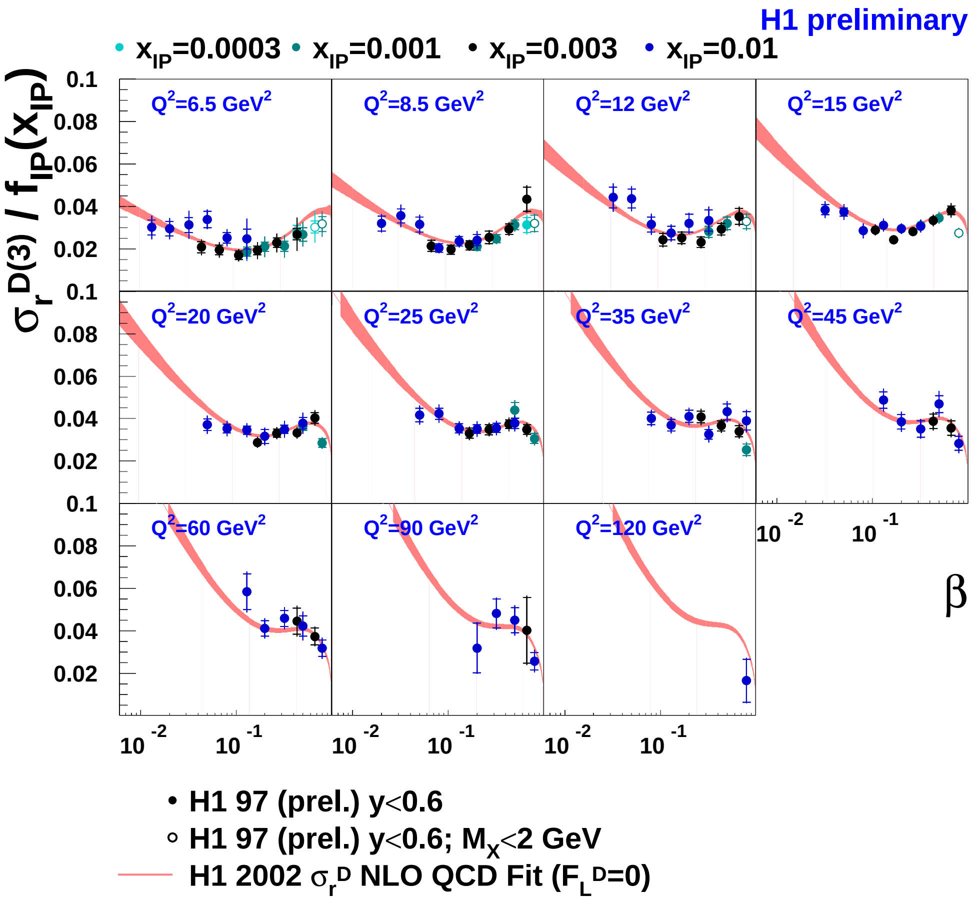
sensitive to diffr. pdf's integrated over t

Different behaviour than for proton !

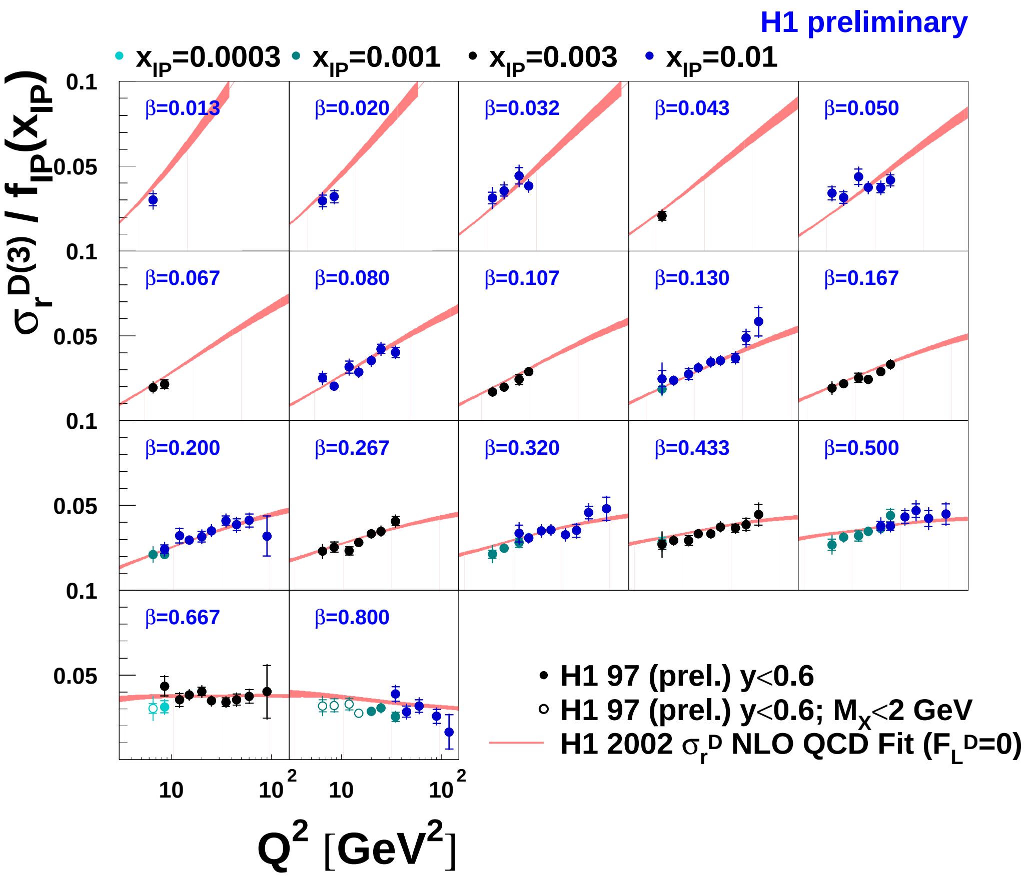
Taking out the $x_{I\!P}$ dependence ...

Data divided by flux factor $f_{I\!P}(x_{I\!P})$

β dependence at fixed Q^2:



Q^2 dependence at fixed β:



β dep.: $F_2^D = \sum e_i^2(q_i + \bar{q}_i)$

Scaling violations: gluon

Data consistent with Regge factorization

NLO DGLAP QCD Fit

Modelling of $\sigma_r^{D(3)}$:

- Shape of Q^2,β dep. of σ_r^D observed to be largely independent of $x_{I\!P}$:

$$\sigma_r^{D(4)}(x_{I\!P}, t, \beta, Q^2) = f_{I\!P}(x_{I\!P}, t) * \sigma_r^{D(2)}(\beta, Q^2)$$

- $x_{I\!P}$ dependence conveniently parameterized as

$$f_{I\!P}(x_{I\!P}) = \int dt\ x_{I\!P}^{1-2\alpha_{I\!P}(t)} e^B t$$

  using $\alpha_{I\!P}(0) = 1.173 \pm 0.018$ (determined from data)
- Small contribution from sub-leading exchange at large $x_{I\!P} > 0.01$ required

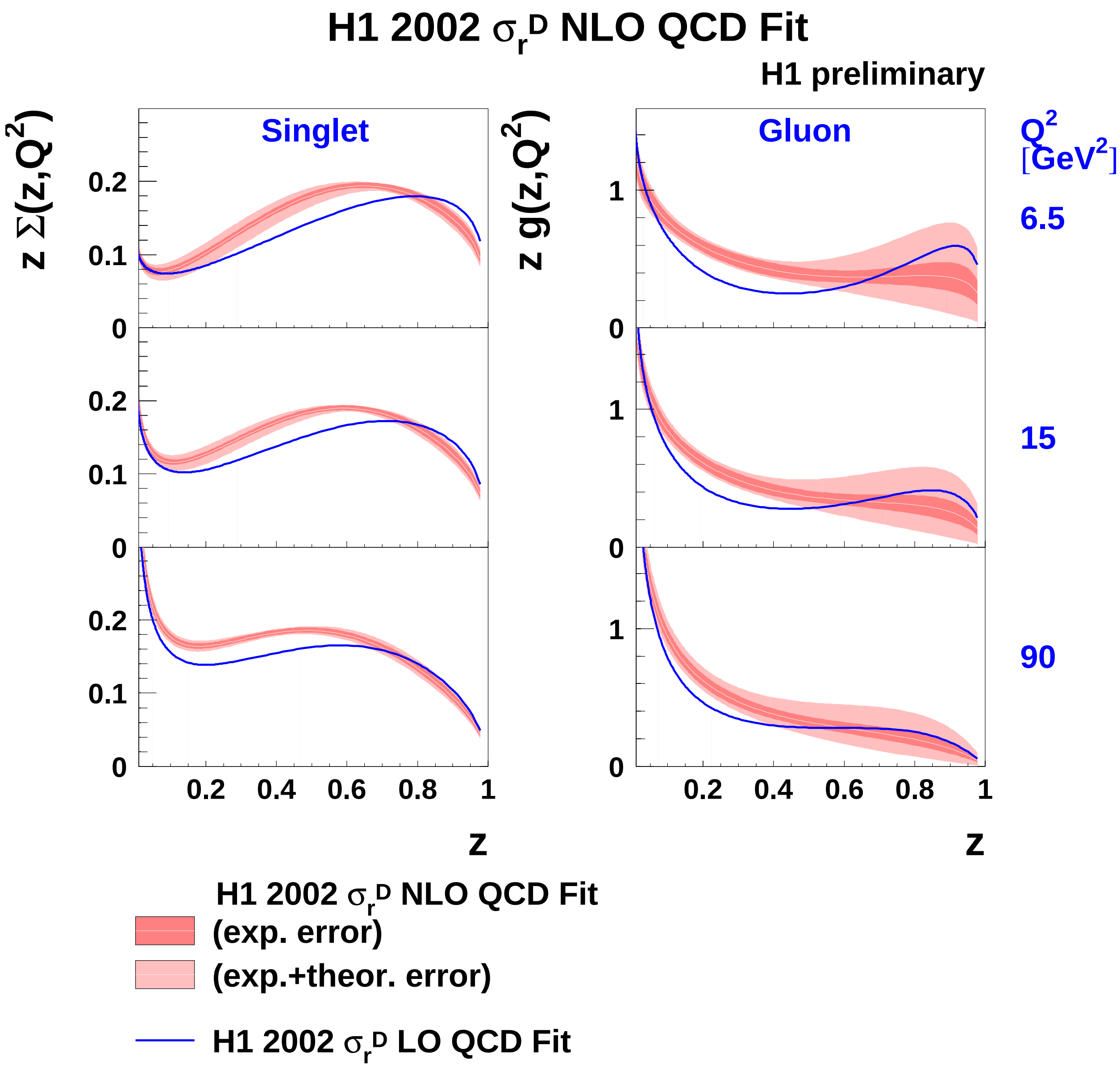
PDF parameterization:

- At starting scale $Q_0^2 = 3\ \mathrm{GeV}^2$:
  – Singlet distribution $\Sigma(z, Q_0^2)$ ($\Sigma = 6u$, $u = d = s = \bar{u} = \bar{d} = \bar{s}$)
  – Gluon distribution $g(z, Q_0^2)$
- Parameterization using unbiased, flexible functional form: Chebychev polynomials

Technique:

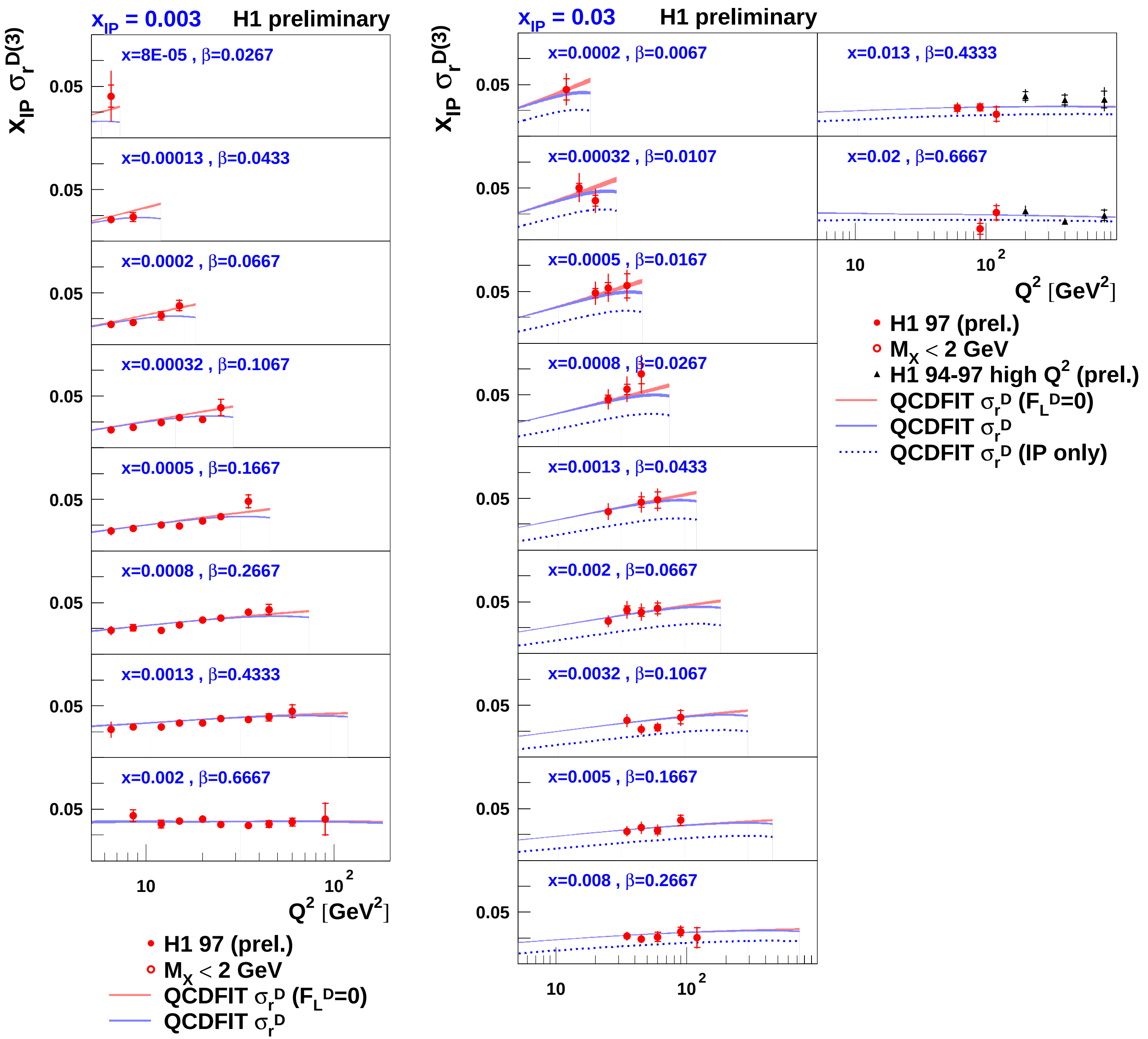
- Charm treatment in massive approach (BGF)
- Cut $M_X > 2$ GeV justifies leading twist analysis
- Full propagation of exp. and model systematic uncertainties !

Result of NLO fit



- pdfs extending to large fractional momenta z
- precise measurement of singlet distribution $\Sigma(z, Q^2)$
- hard gluon distribution, flat or rising towards $z \longrightarrow 1$ (LO fit more peaked than central NLO fit)
- large uncertainty for $g(z, Q^2)$ at $z > 0.6$ (mainly related to model)

Comparison of NLO QCD fit with Data: Q^2 dep.



Two example $x_{I\!P}$ bins

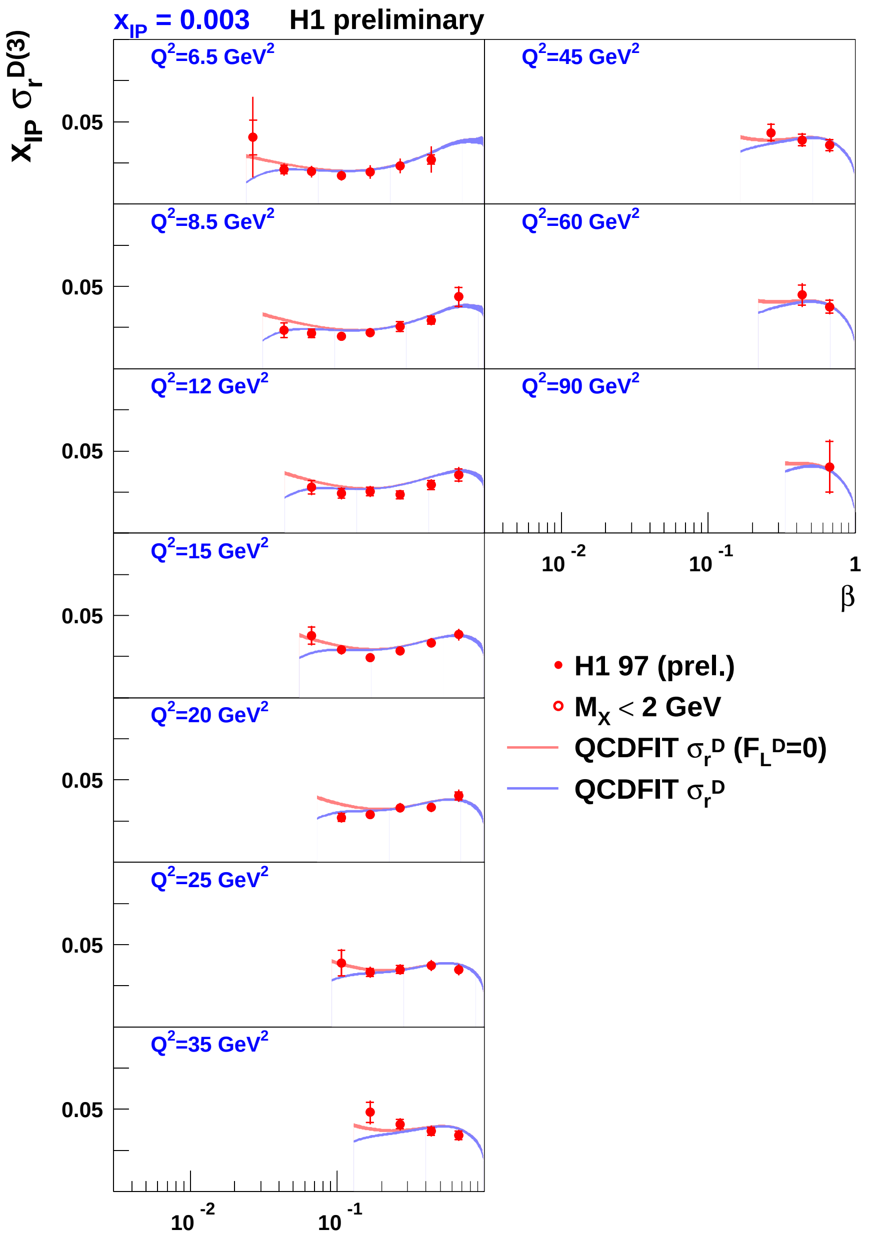
Q^2 scaling violations well constrained by data

Rising except at highest β

Well reproduced by QCD fit up to $Q^2 = 800\ \mathrm{GeV}^2$

Sub-leading contribution at $x_{I\!P} = 0.03$, smaller than for previous data

Comparison of NLO QCD fit with Data: β,x dep.



Example $x_{I\!P}$ bin at 0.003:

Rising behaviour at $\beta \longrightarrow 1$, low Q^2 reflected by $\Sigma(z, Q^2)$

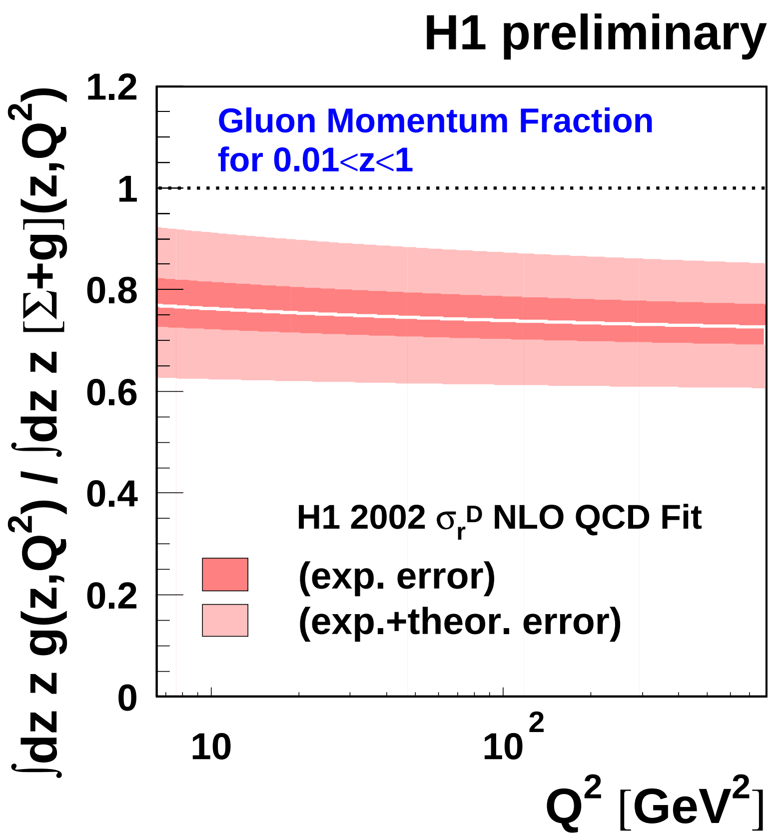
β dependence independent of $x_{I\!P}$

high $y \leftrightarrow$ low x or β at fixed $x_{I\!P}$: Effect of F_L^D

presently no direct handle on F_L^D from data

Gluon Momentum Fraction

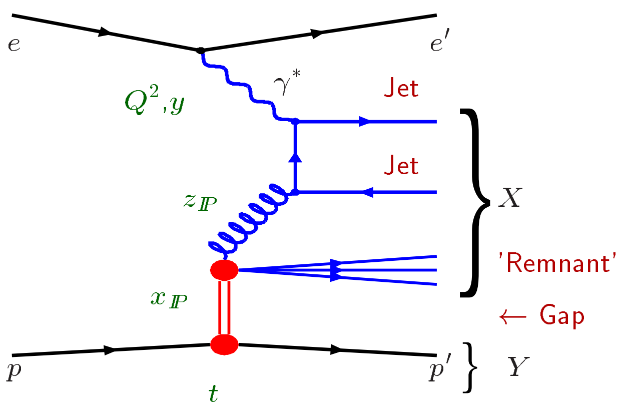
From NLO Fit:



- Integration of pdf's in measured range $0.01 < z < 1$
- Momentum fraction of colour singlet exchange carried by gluons **75%** for $6.5 < Q^2 < 800\ \mathrm{GeV}^2$
- Fully consistent with results from previous H1 data

Comparison with H1 diffractive DIS final states

Use pdf's from LO fit to predict dijets / D^* cross sections in diffractive DIS as measured by H1:

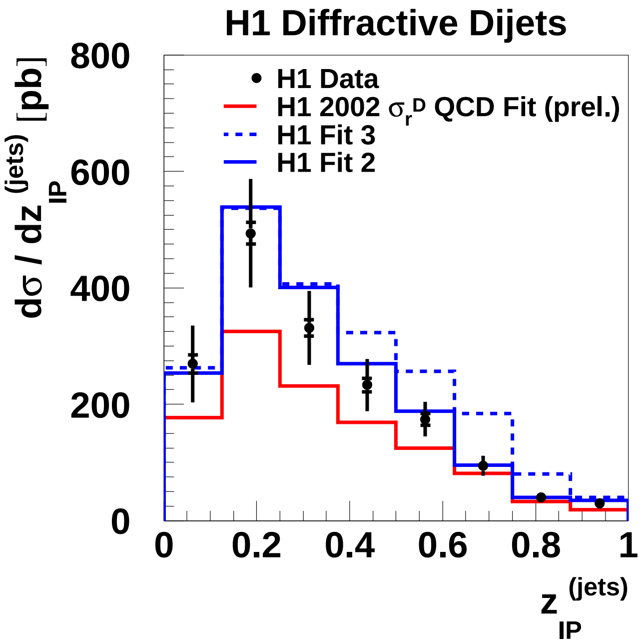


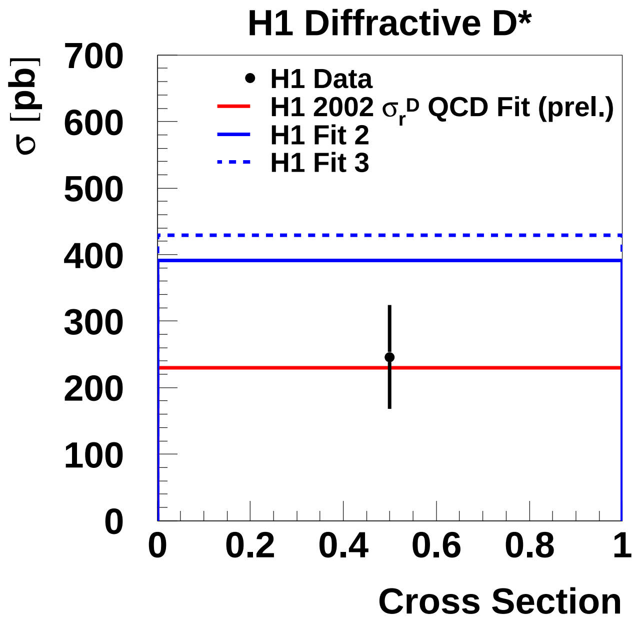
Comparison based on MC model (RAPGAP)

$$\mu^2 = Q^2 + p_T^2 + m^2$$

Diffferential distributions remain well described

Normalization: pdf/NLO/scale uncertainty





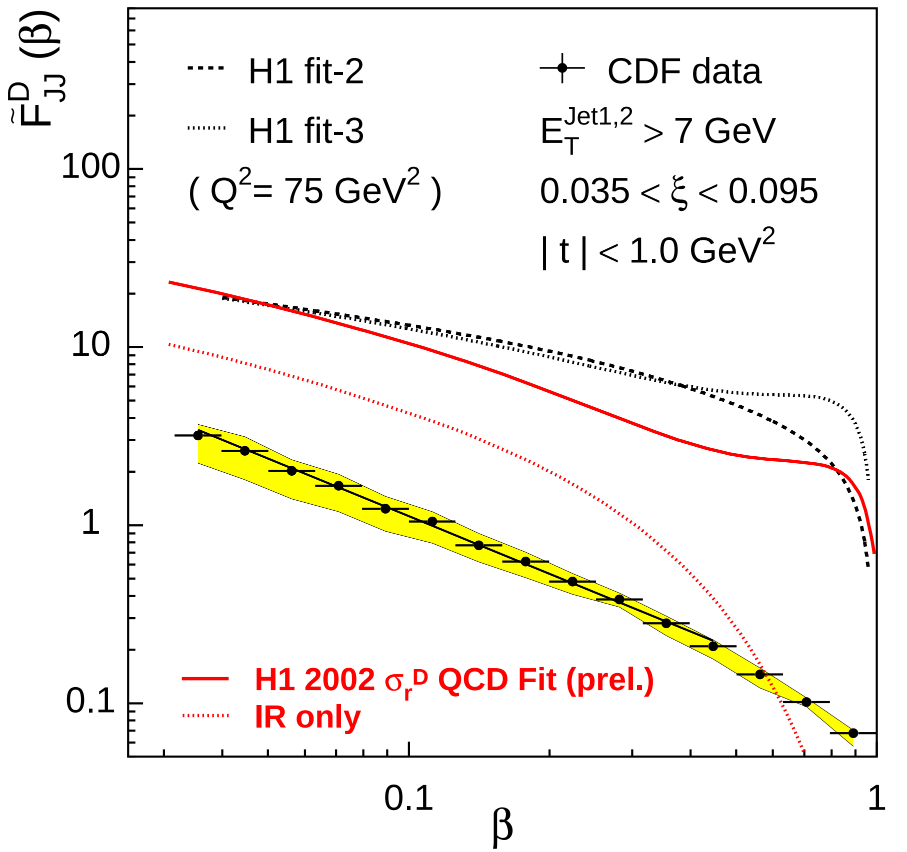
⇒ Consistent with QCD factorization !

Comparison with CDF diffractive Dijet cross sections

Dijet production with tagged leading anti-proton at TEVATRON:

Effective diffractive structure function $\tilde{F}^D_{jj}$:

$$\tilde{F}^D_{jj}(\beta) = \int dx_{I\!P} dt f(x_{I\!P}, t)\ \beta \left[g(\beta, Q^2) + \tfrac{4}{9}\Sigma(\beta, Q^2)\right] \qquad (Q^2 = 75\ GeV^2)$$



- New fit confirms serious breakdown of factorization (gap survival, absorptive corrections)
- β dependence similar (except highest β)
- NOTE $x_{I\!P}$ domain: 50% contribution from sub-leading exchange in this kinematic regime

Conclusions

- In diffractive DIS at HERA, the QCD structure of diffractive interactions (pomeron) can be probed using a virtual photon
- Experimental data have reached high precision
- Proof of QCD factorization in diffractive DIS provides firm theoretical basis
- Diffractive pdf's determined from F_2^D are dominated by large gluon contribution (75%) extending to large fractional momenta
- Comparisons with diffractive final states (dijets, charm): Consistent with QCD factorization
- Diffractive jets in $p\bar{p}$: Breakdown of factorization (gap survival, absorptive corrections)

Precision QCD in hard diffraction !