Hard diffraction at HERA:
Recent Results and QCD Interpretation

Workshop on Diffraction and Glueballs at RHIC
May 2002, BNL / Upton (New York)

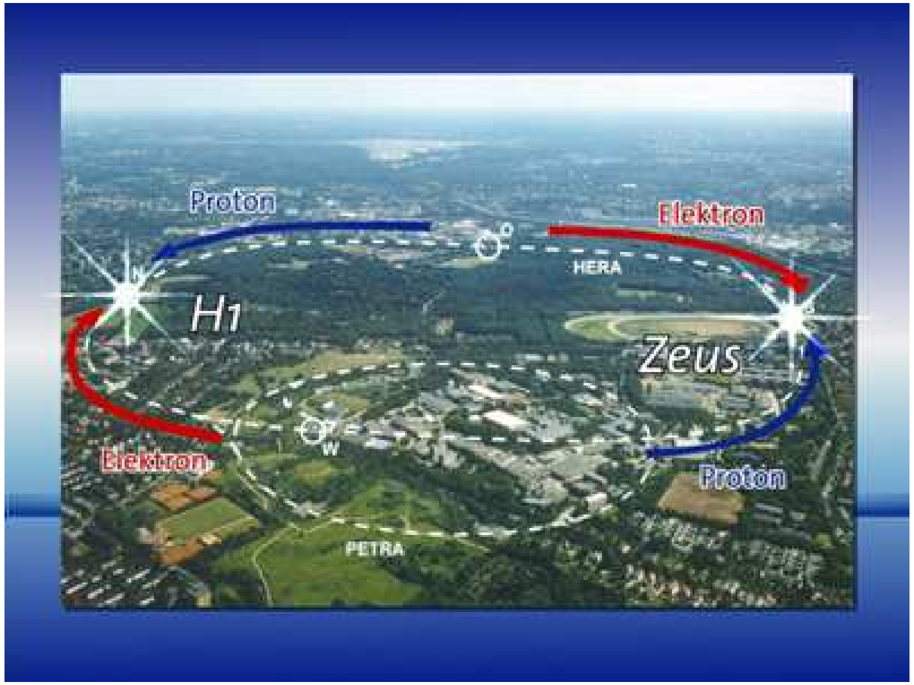
Frank-Peter Schilling (DESY)

H1 Collaboration

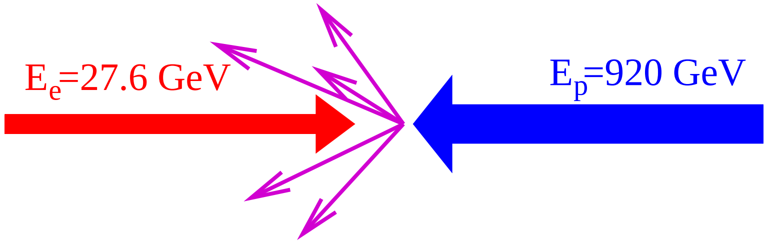
- Introduction
- New results in inclusive diffraction (F_2^D)
- New NLO DGLAP QCD fit and diffractive pdf's
- Diffractive final states (jets and charm)
- Dipole Models
- Summary and conclusions

HERA and the H1 Detector

The HERA ep Collider at DESY / Hamburg:



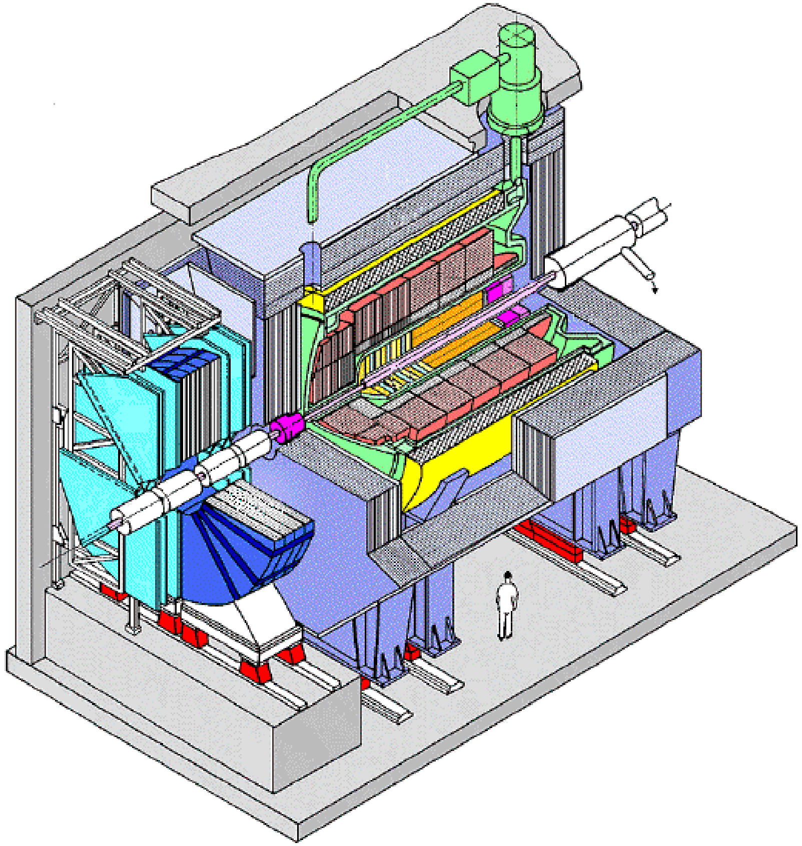
- **HERA I: until 09/2000: $\mathcal{L} \sim 120\ \mathrm{pb}^{-1}$**
- **Upgrade (lumi and dets.) just completed**
- **HERA II: $\mathcal{L} \sim 1\ \mathrm{fb}^{-1}$ until 2006**



H1 and ZEUS:

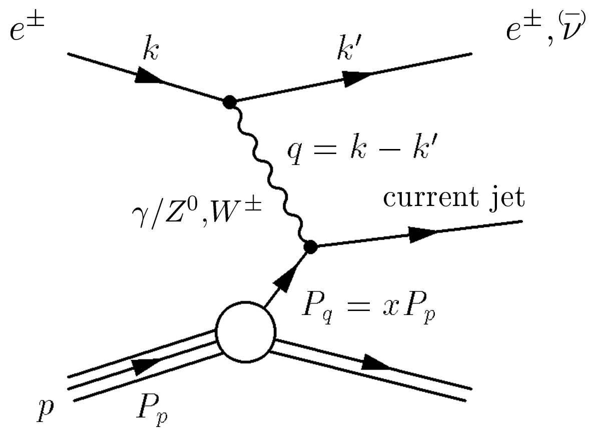
ep collisions at $\sqrt{s} = 320$ GeV

The H1 Experiment:



$\sim$ 400 physicists

Preface: Deep-Inelastic Scattering (DIS) at HERA

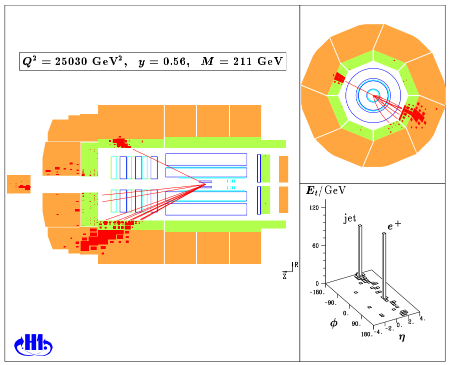


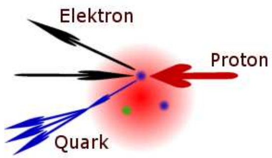
$$Q^2 = -q^2 = (k - k')^2$$

Photon virtuality

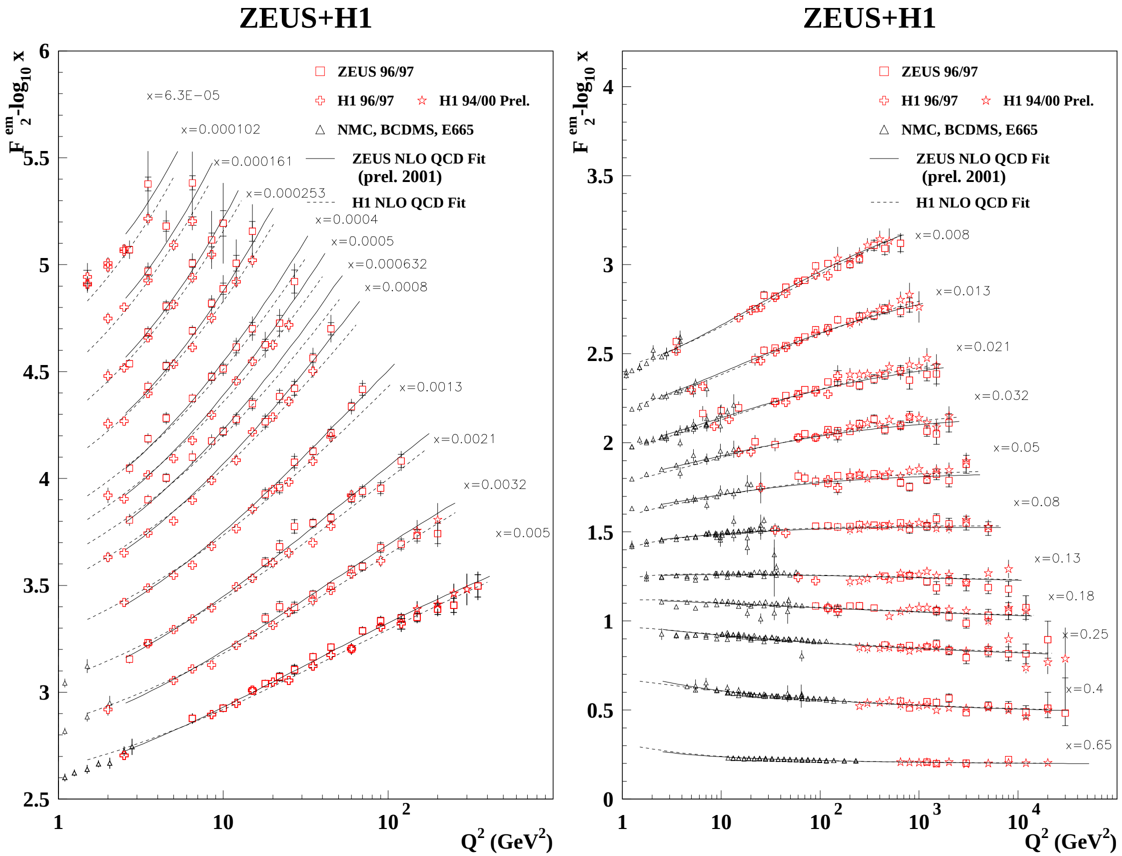
$$x = \frac{-q^2}{2P \cdot q} \quad (0 < x < 1)$$

Parton momentum frac. Bjorken-x





Precise measurements of $F_2(x, Q^2)$: Scaling violations

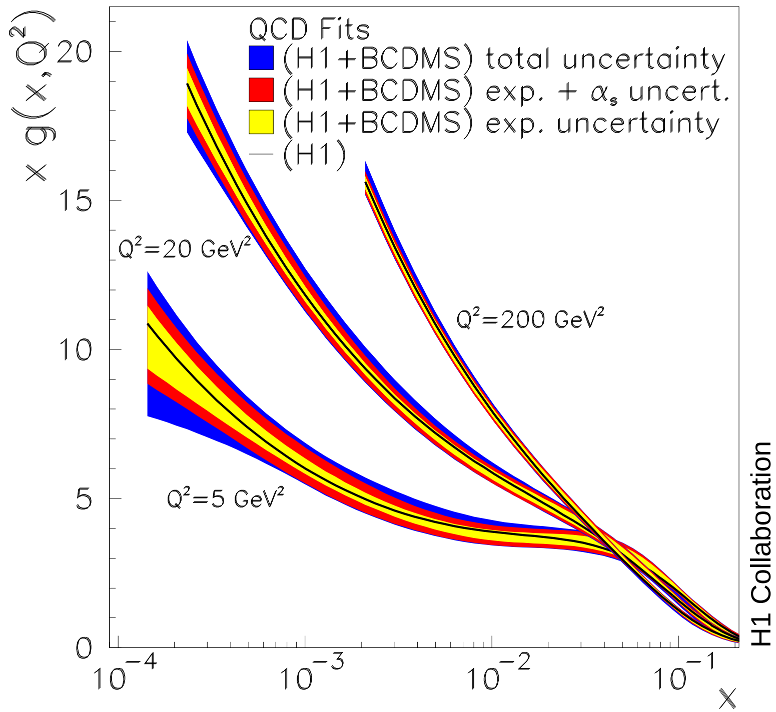


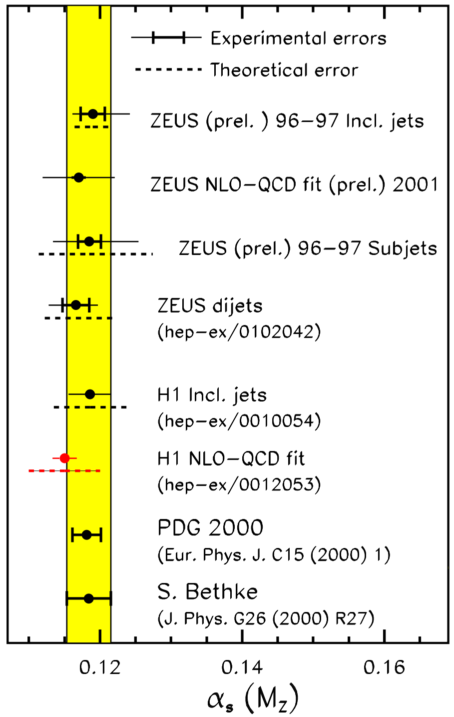
strong scaling violations at low x: $g \longrightarrow q\bar{q}$

Preface: DIS at low x, gluons and α_s

QCD analysis of F_2 in framework of DGLAP:

$$\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\left[\sum_i q_i(z,Q^2)P_{gq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{gg}\left(\frac{x}{z}\right)\right]$$





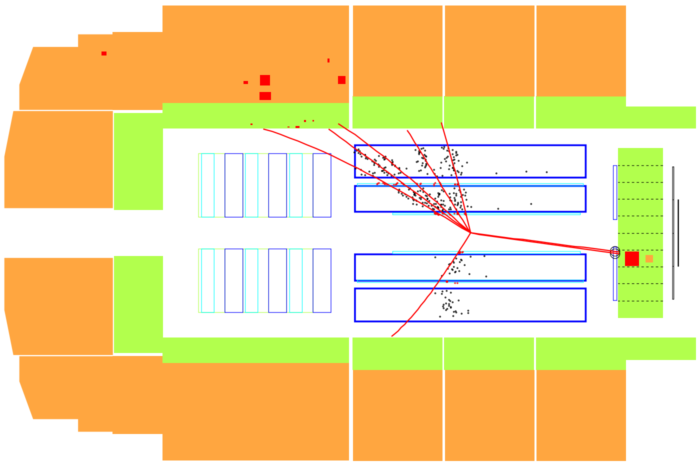
⇒ Precise determinations of the gluon distribution and α_s

Diffraction in DIS at HERA

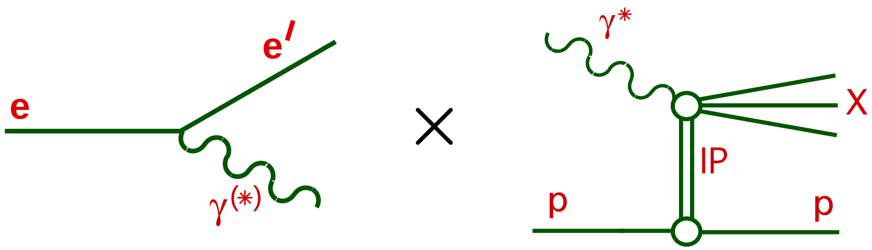
Early Observation at HERA:

10% of low-x DIS events are diffactive

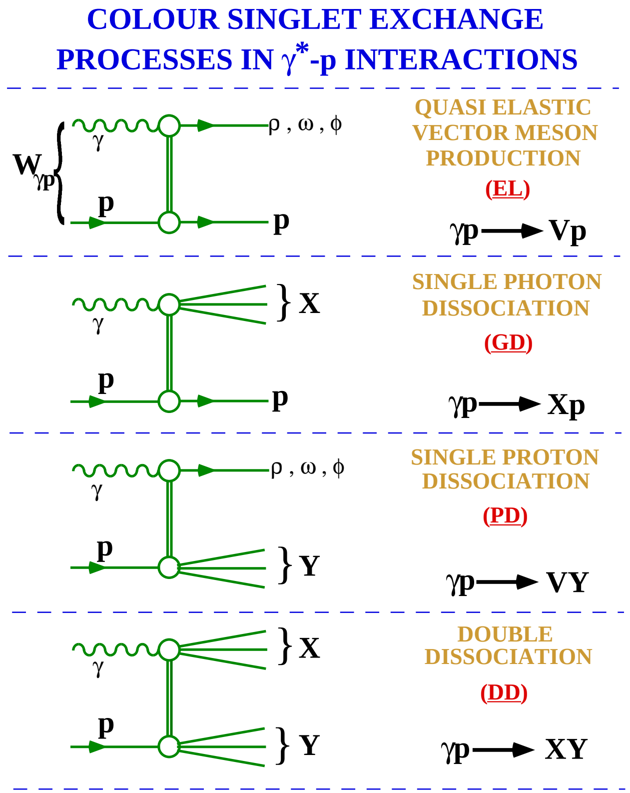
$ep \rightarrow e'p'X$



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



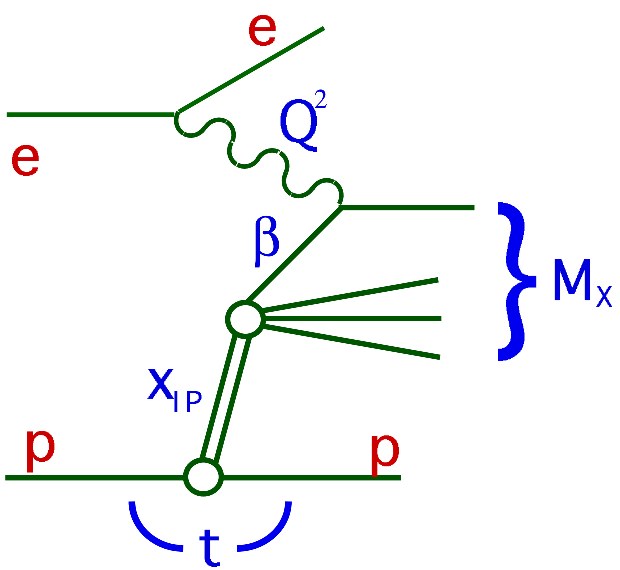
More generally: $\gamma^{(*)}p \rightarrow XY$



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:

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

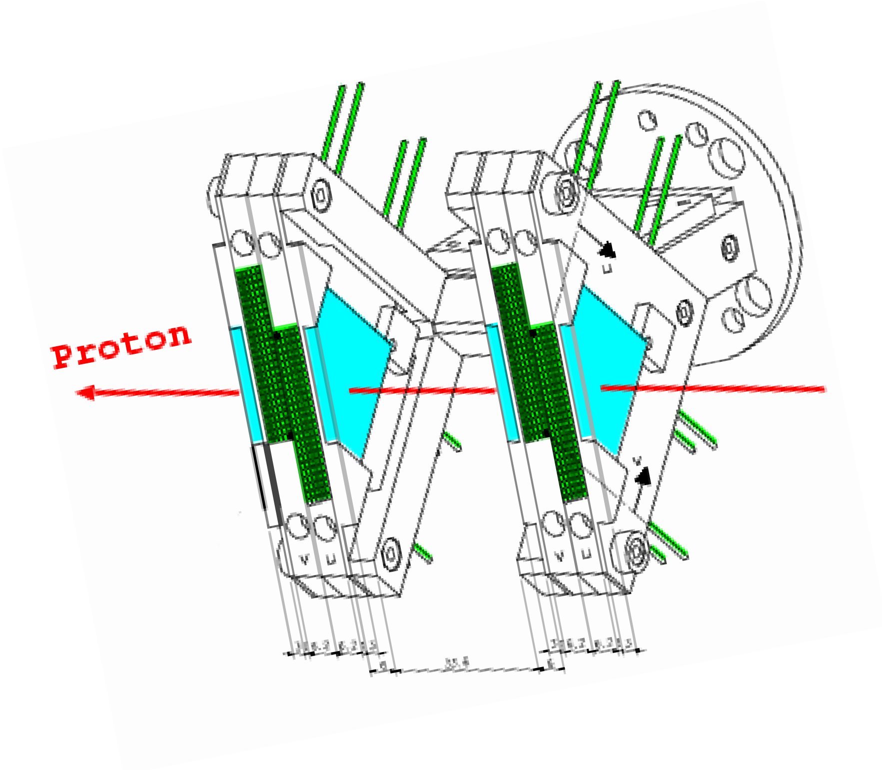
Structure functions F_2^D and F_L^D:

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

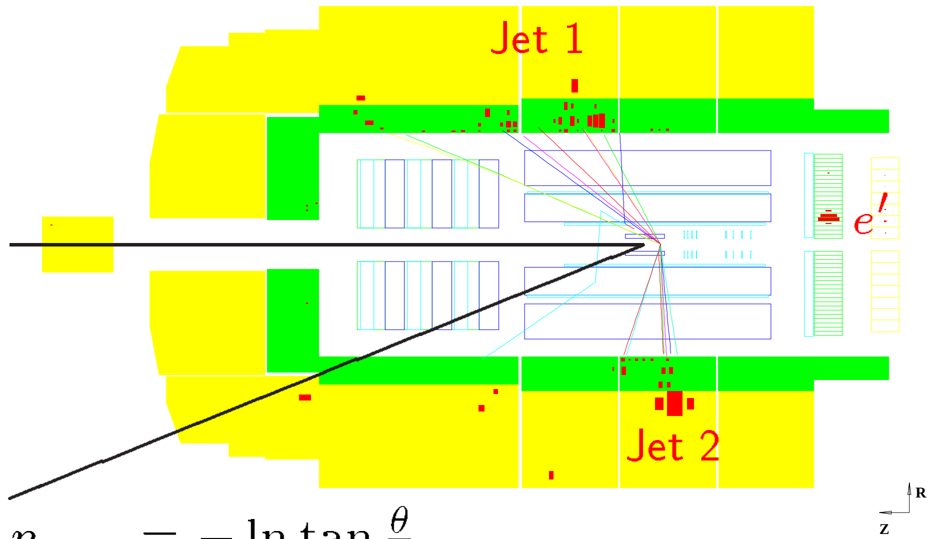
Integrated over t: $F_2^{D(3)} = \int dt\ F_2^{D(4)}$

Experimental Techniques

Forward Proton Spectrometer at $z = 65 \ldots 90$ 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:

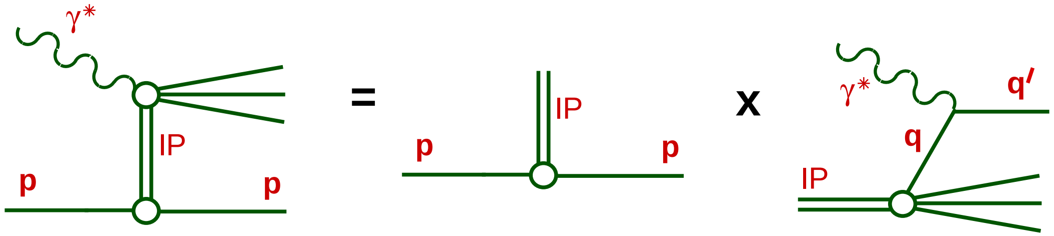
- **Diffractive parton distributions (Trentadue, Venezianio, Berera, Soper, Collins, ...):**

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

- $\hat{\sigma}^{\gamma^* i}$ 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, ...)

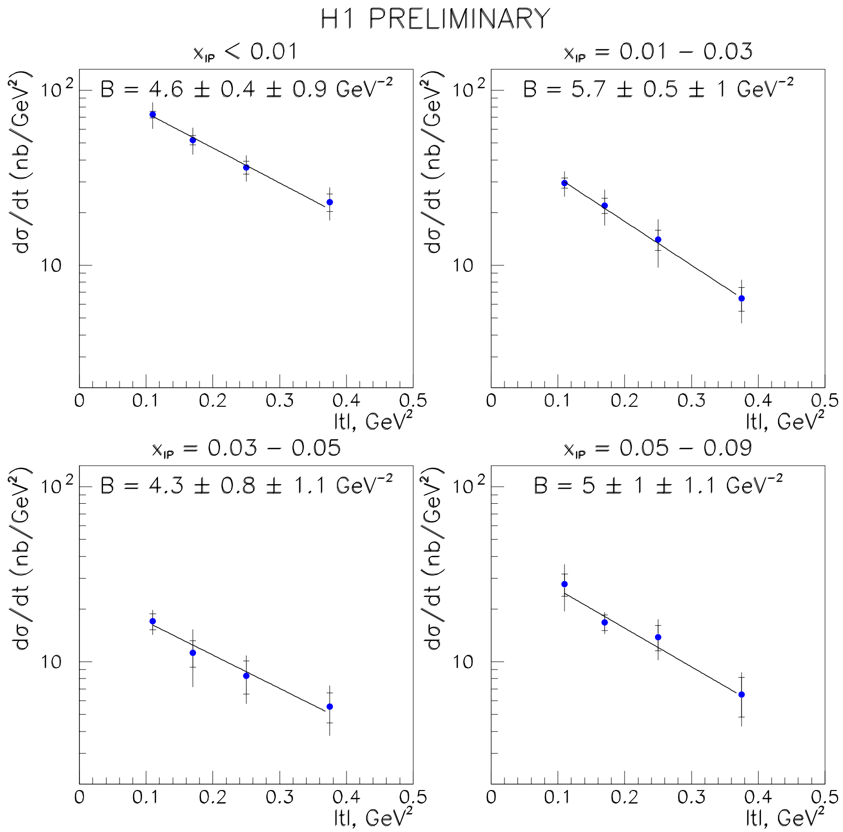


$$F_2^D(x_{I\!P}, t, \beta, Q^2) = f_{I\!P/p}(x_{I\!P}, t)\ F_2^{I\!P}(\beta, Q^2)$$

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

New measurement of $F_2^{D(4)}$ using Roman Pots

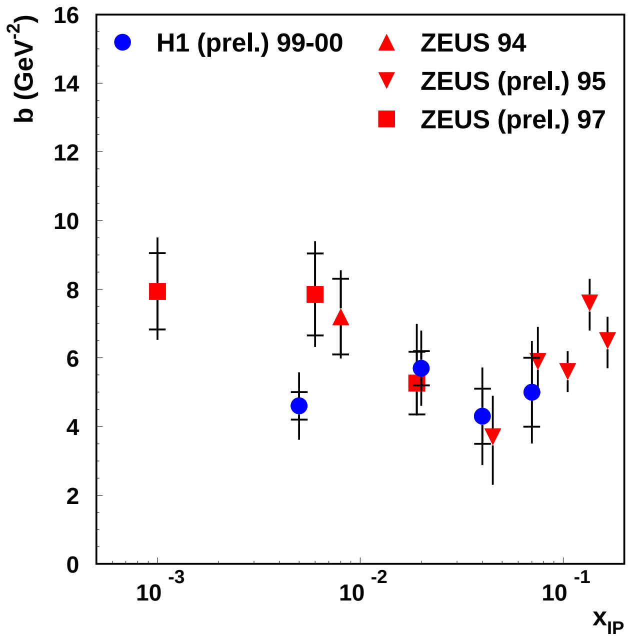
Cross section differential in t at different $x_{I\!P}$:



t dependence: $\frac{d\sigma}{dt} \sim e^{Bt}$

In Regge theory expect shrinkage:

$$B = B_0 + 2\alpha' \ln \frac{1}{x_{I\!P}}$$



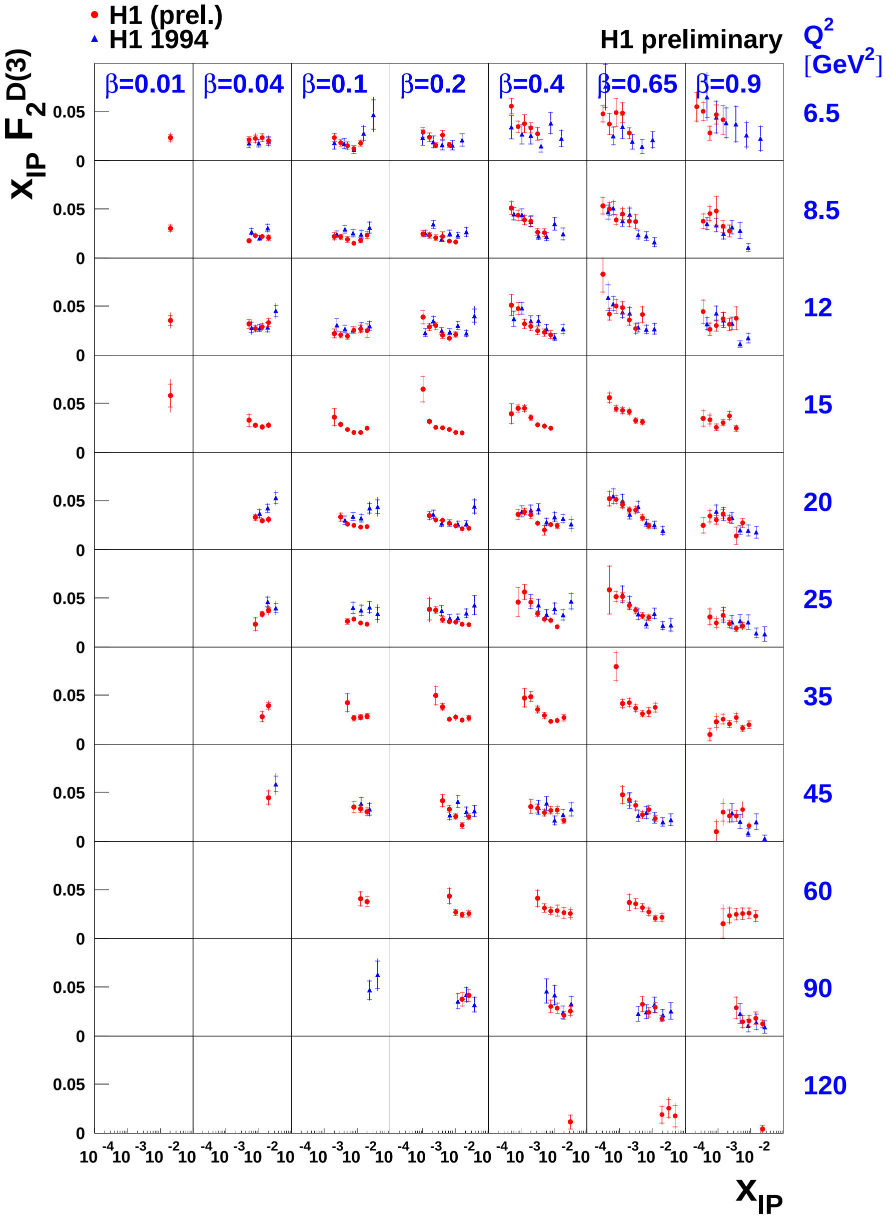
Kinematic range:

$$2 < Q^2 < 50 \text{ GeV}^2,\ 0.005 < \beta < 1$$
$$x_{I\!P} < 0.09,\ -0.45 < t < -0.08 \text{ GeV}^2$$

... data inconclusive so far

$$B = (5.0 \pm 0.3 \pm 0.8) \text{ GeV}^{-2}$$

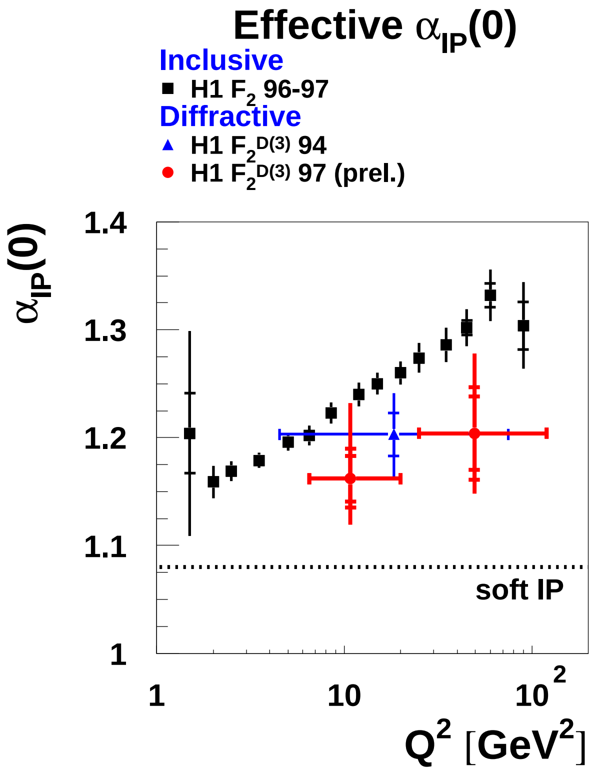
New $F_2^{D(3)}$ measurement (Rapidity gap)



5 times more statistics than previous data

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

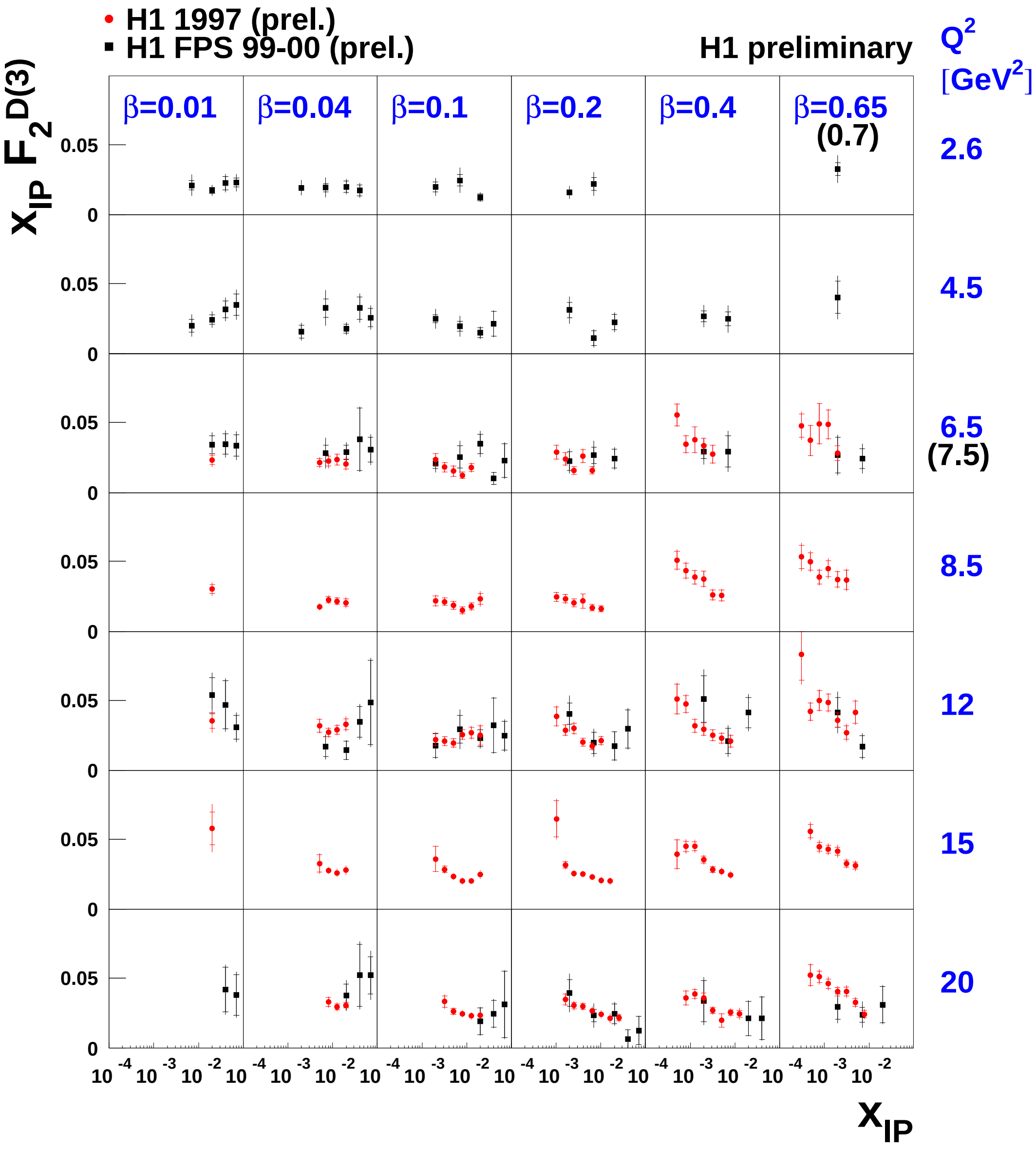
$$F_2^D(x_{I\!P},\beta,Q^2) \sim B(\beta,Q^2)\left(\frac{1}{x_{I\!P}}\right)^{2\alpha_{I\!P}-1}$$



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

Growth with Q^2 slower in diffractive case?

Comparison Leading proton / rapidity gap data



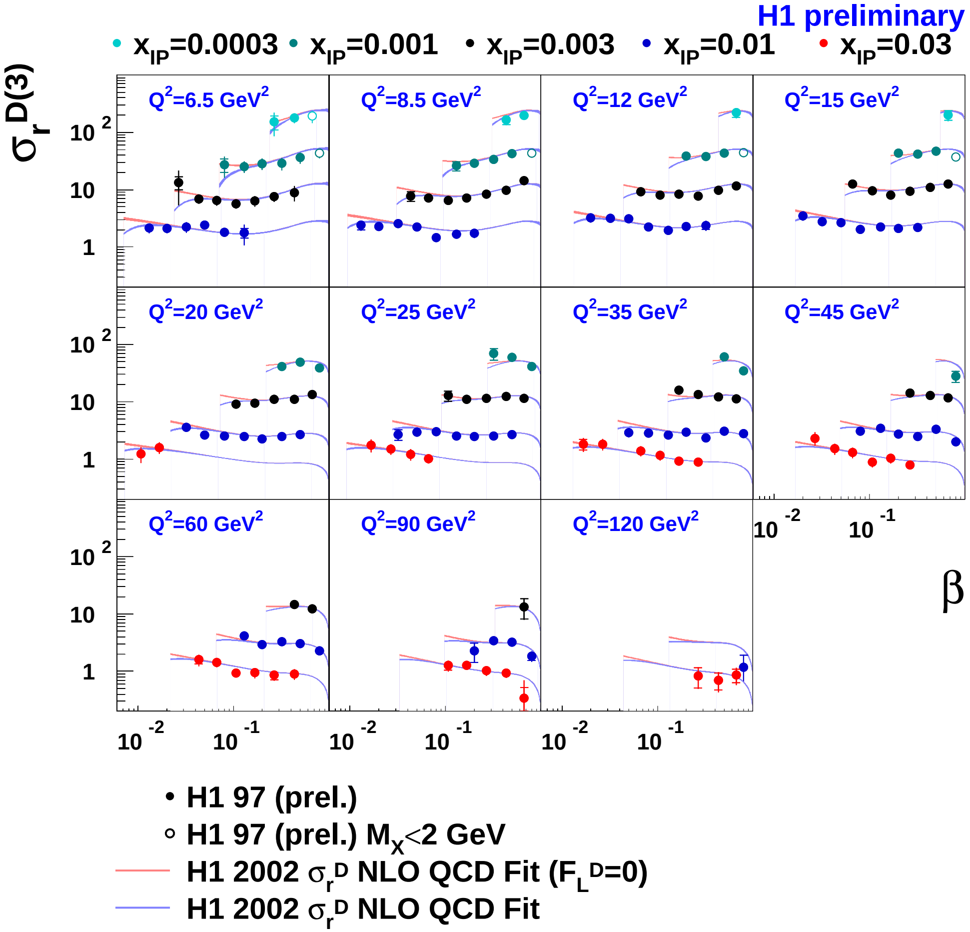
$$F_2^{D(3)} = \int \mathrm{d}t\ F_2^{D(4)}$$

good agreement between methods

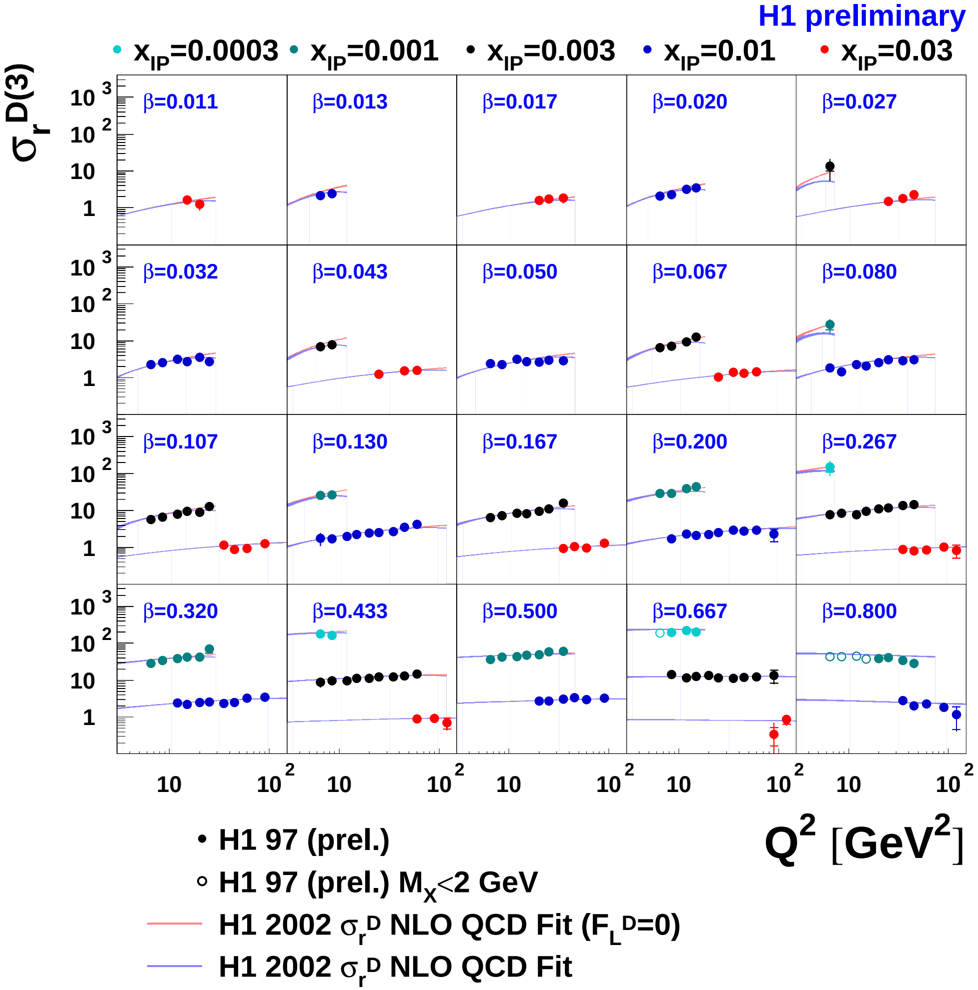
justifies rapidity gap method!

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

β dependence at fixed Q^2:



Q^2 dependence at fixed β:



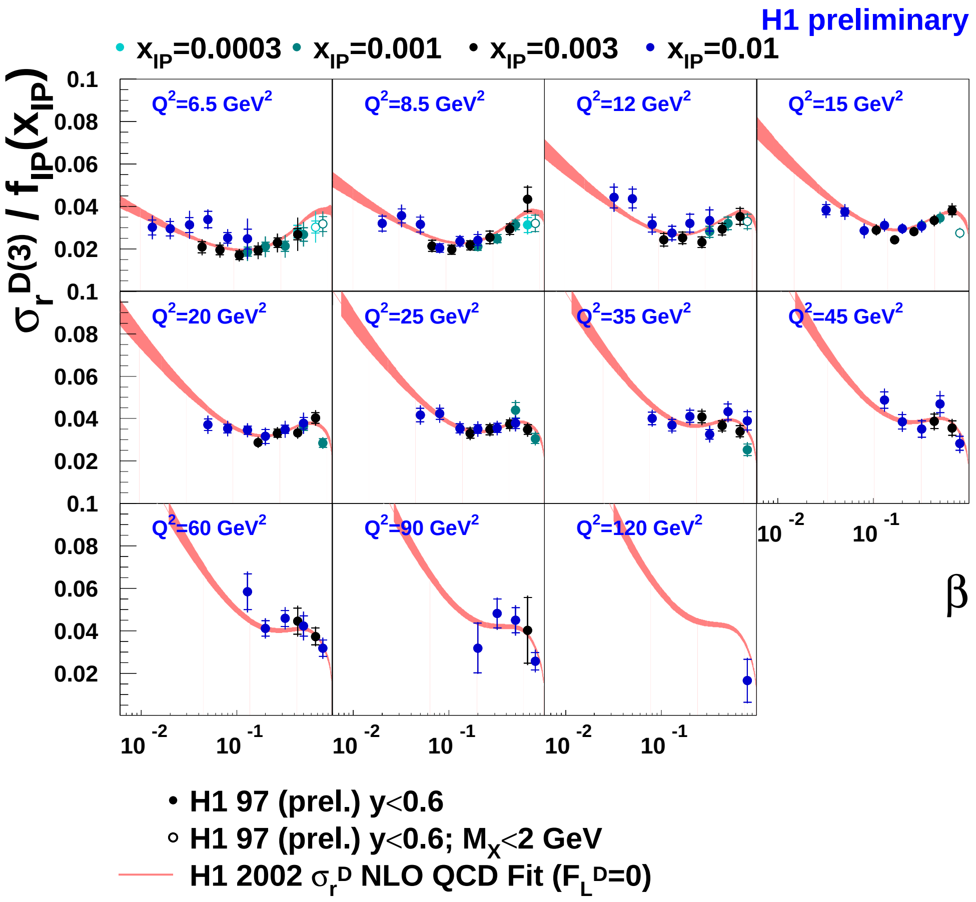
sensitive to diffr. pdf's integrated over t

Different behaviour than for proton !

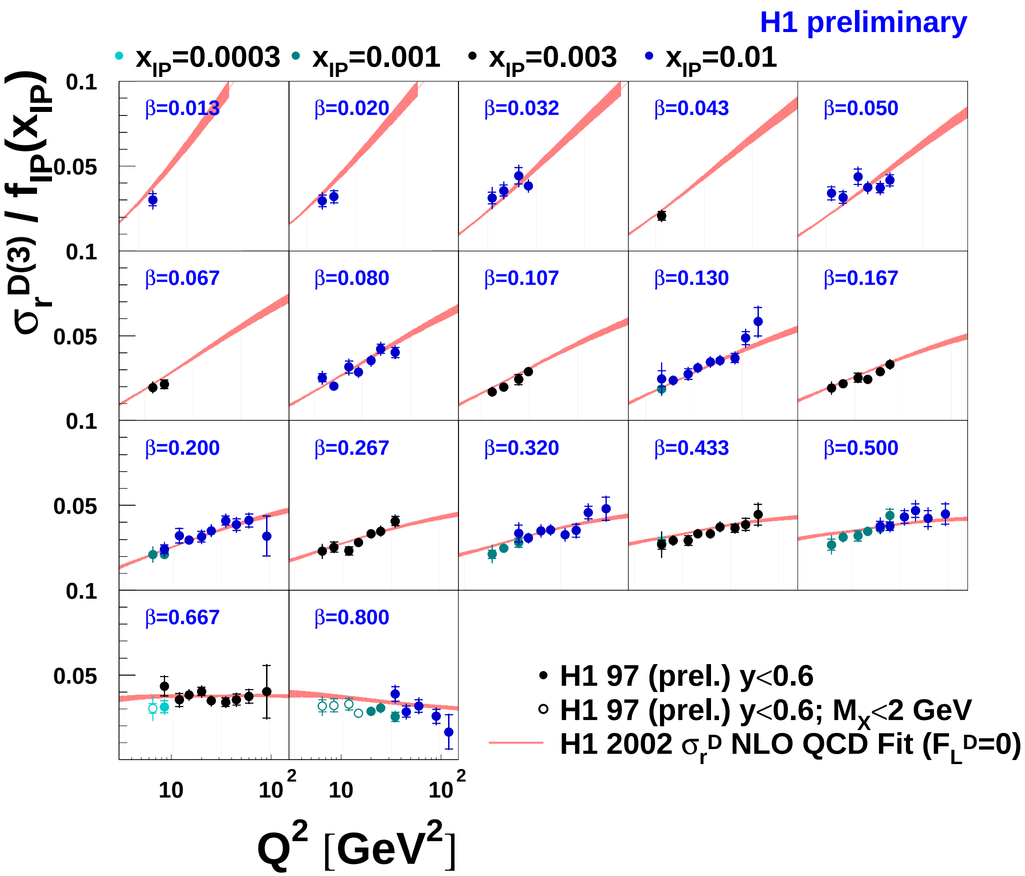
Taking out the $x_{I\!P}$ dependence ...

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

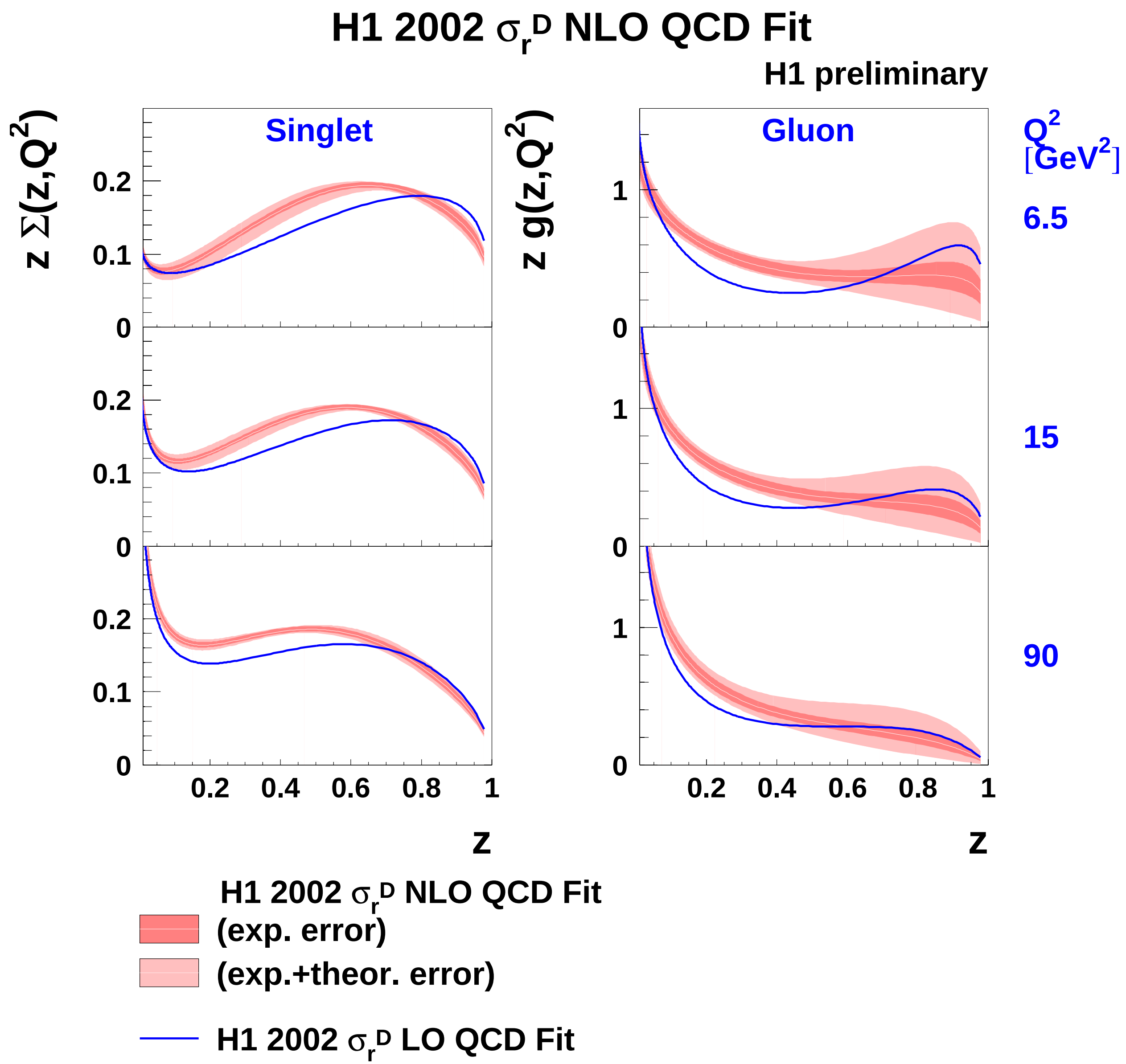
PDF parameterization:

- 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:

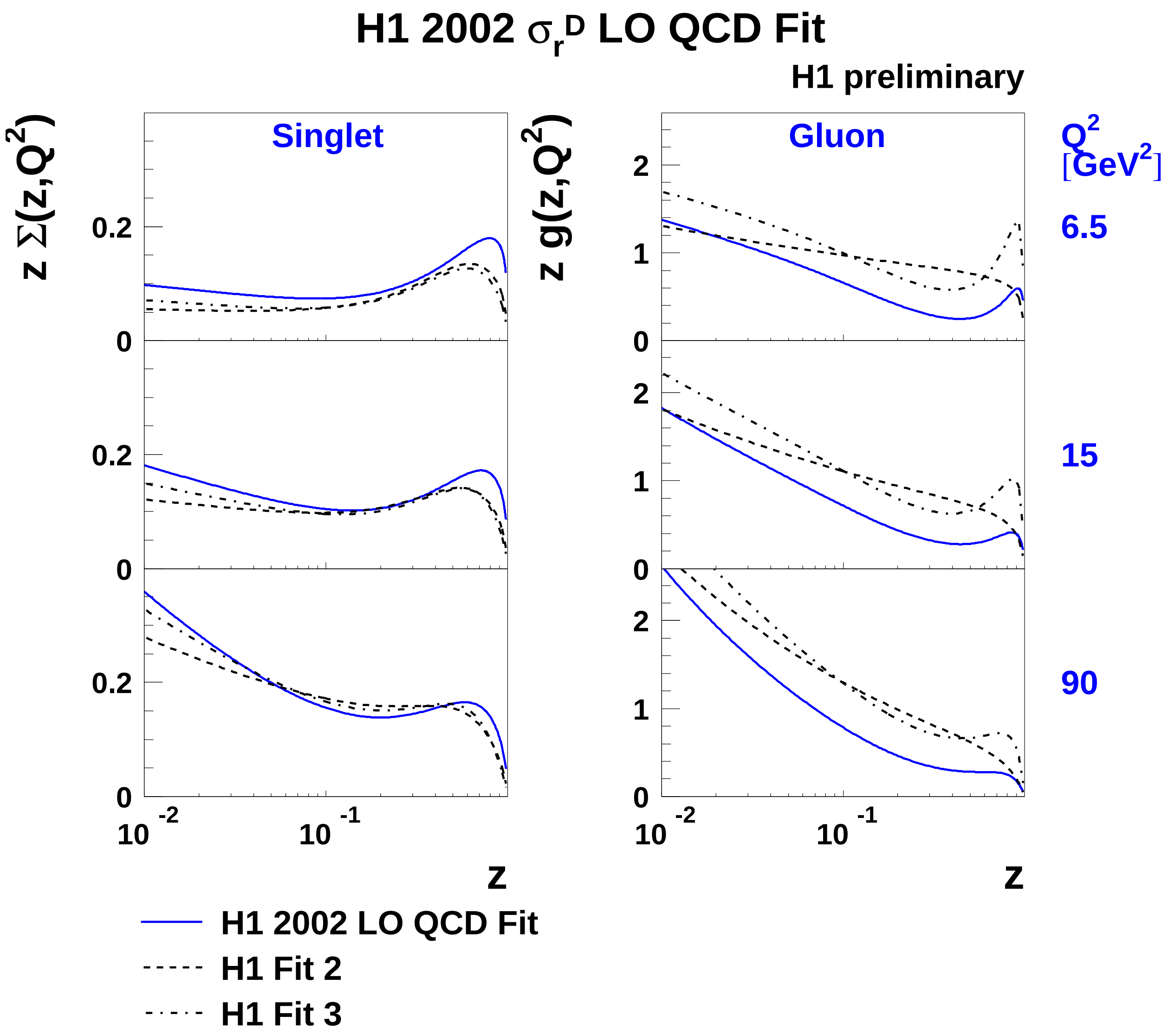
- Charm treatment in massive approach (BGF)
- Cut $M_X > 2\ \mathrm{GeV}$ justifies leading twist analysis
- Full propagation of exp. and model systematic uncertainties !

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)

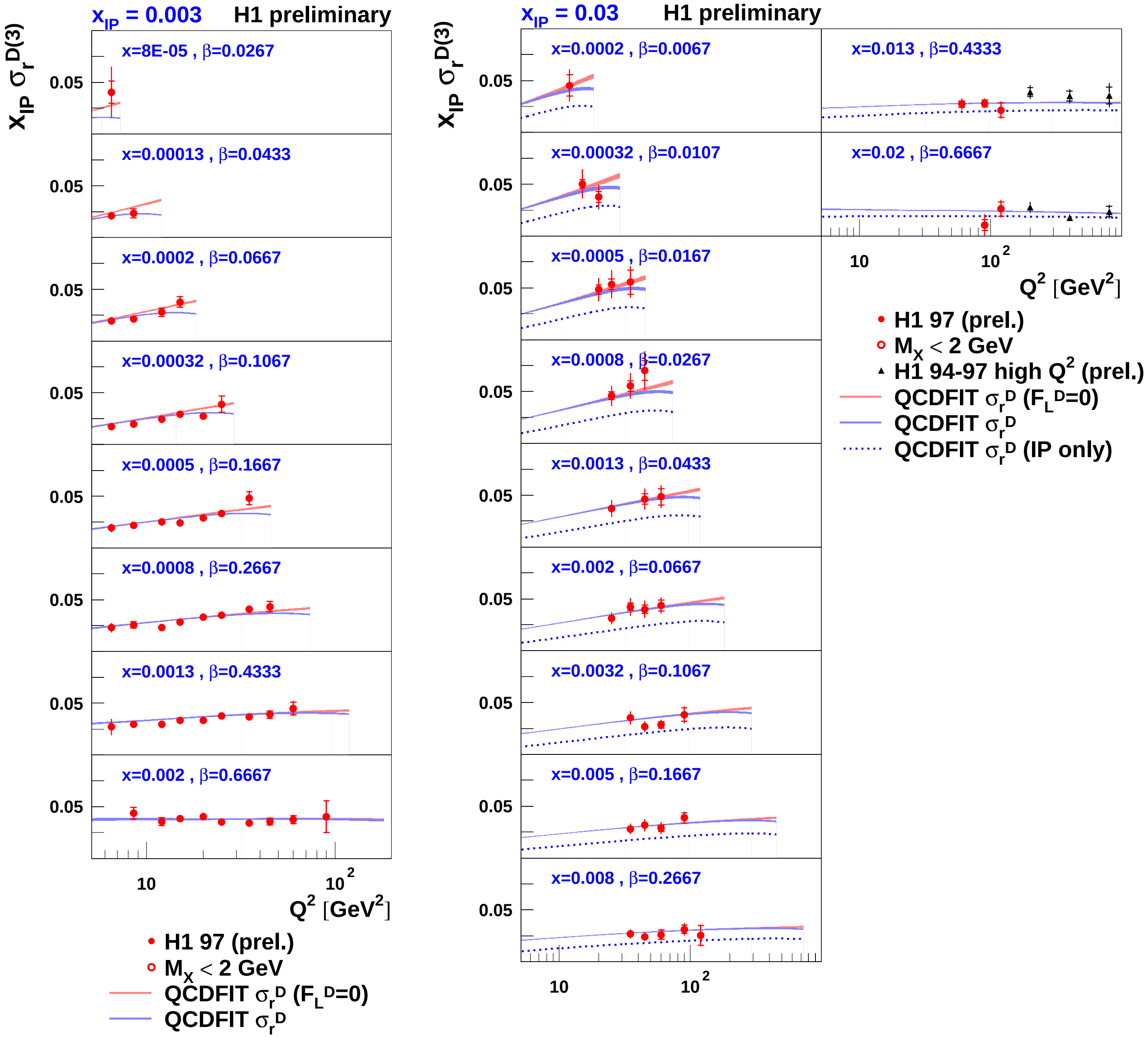
Leading order Fit and Comparison with previous H1 fits



- Comparisons with previous LO fits to 1994 data:
  - H1 Fit 2 (“flat gluon”)
  - H1 Fit 3 (“peaked gluon”)
- Reasonable agreement of $\Sigma(z, Q^2)$ for $z < 0.65$ (common fit range)
- Gluon normalization smaller by $20 - 30\%$ at low z, 50% at high z

Agreement reasonable , taking errors of old and new fits into account

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



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

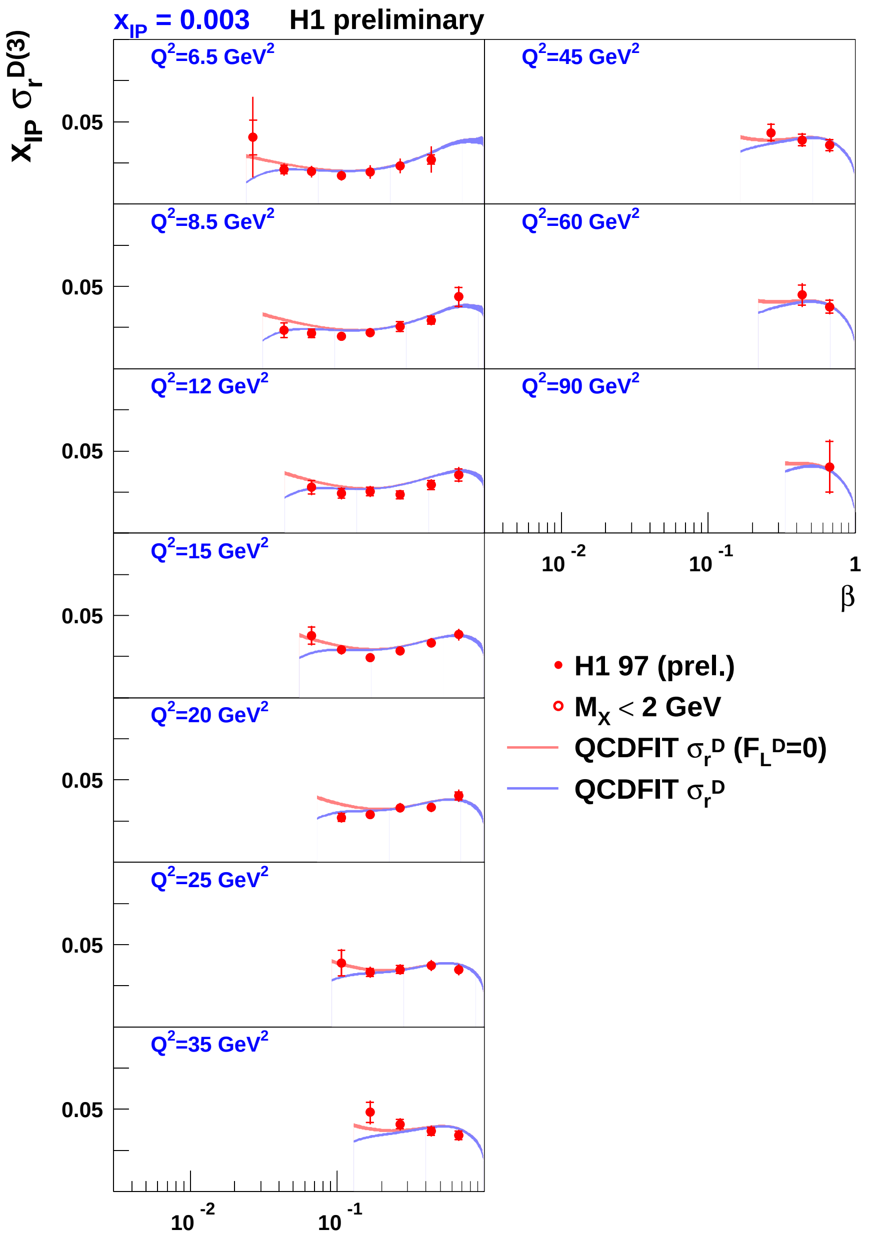
Q^2 scaling violations well constrained by data

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 $\beta \to 1$, low Q^2 reflected by $\Sigma(z, Q^2)$

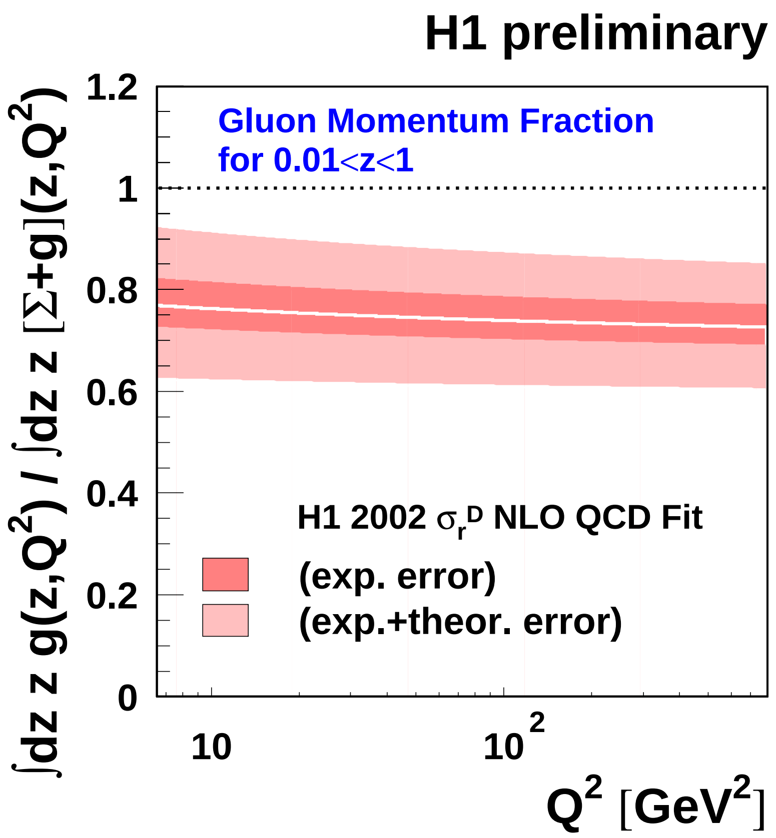
β dependence independent of $x_{I\!P}$

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:

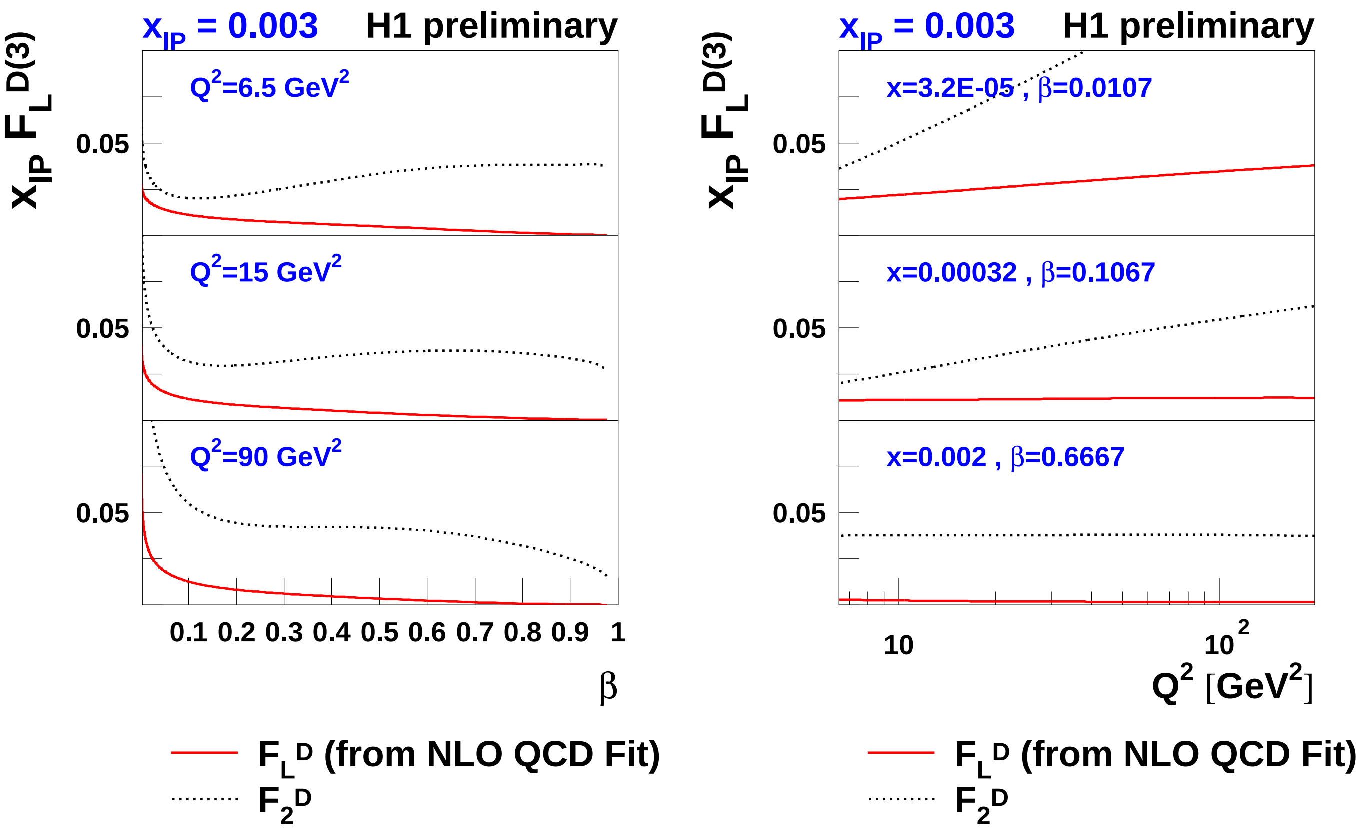


- **Integration of pdf's in measured range** $0.01 < z < 1$
- **Momentum fraction of colour singlet exchange carried by gluons** 75% **for** $6.5 < Q^2 < 800\ \mathrm{GeV}^2$
- **Fully consistent with results from previous H1 data**

Longitudinal Structure Fraction F_L^D

At NLO QCD, the leading twist longitudinal structure function F_L^D is predicted:

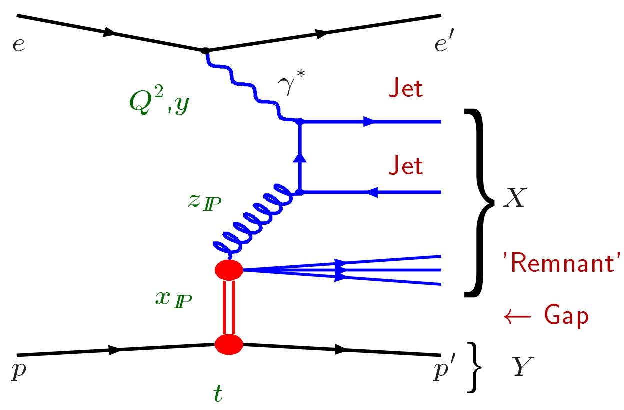
$$F_L^D \sim \frac{\alpha_s}{2\pi}\left[C_q^L \otimes F_2^D + C_g^L \otimes \sum_i e_i^2 \, zg^D(z, Q^2)\right]$$



$\longrightarrow$ **pert. F_L^D rel. large, in particular at low Q^2, low β (due to large $g(z, Q^2)$)**

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:

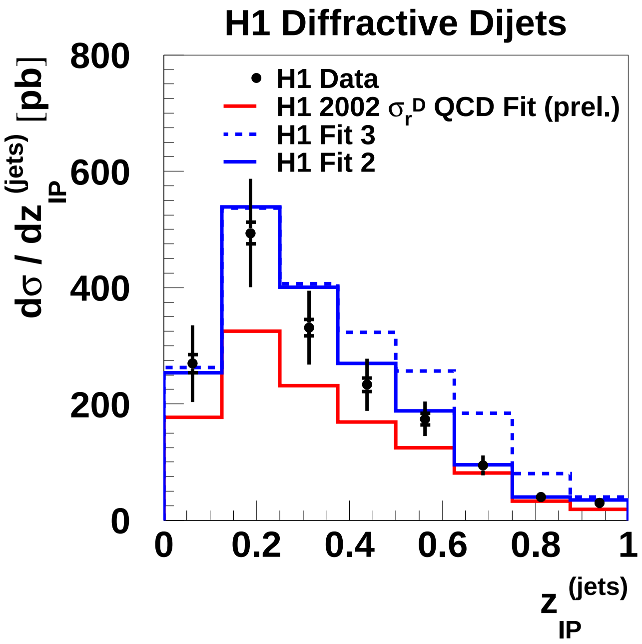


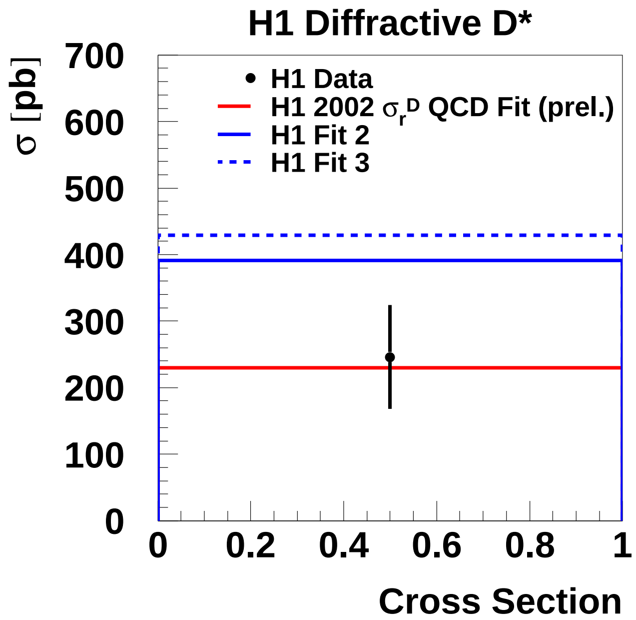
Comparison based on MC model (RAPGAP)

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

Diffferential distributions remain well described

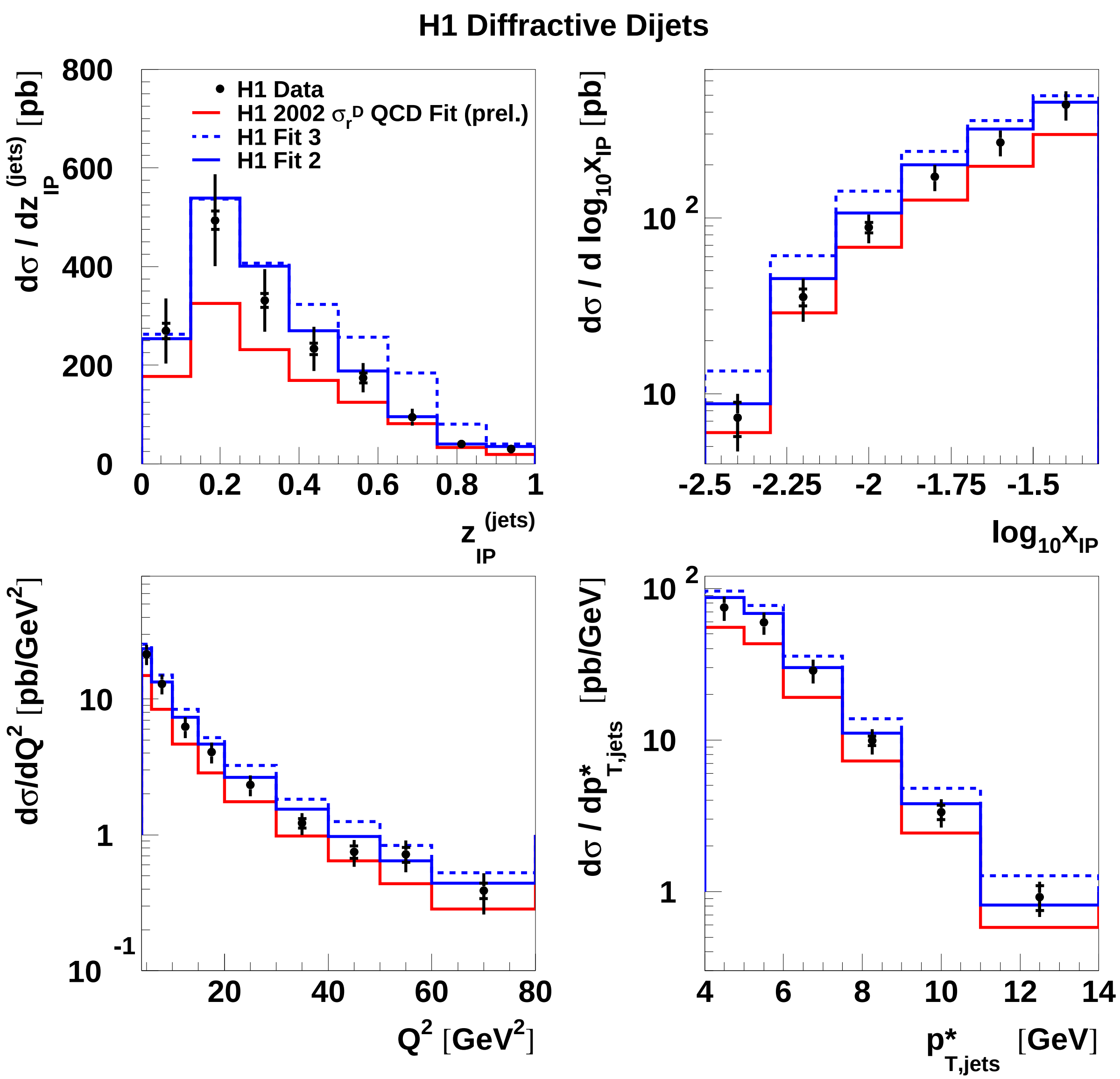
Normalization: pdf/NLO/scale uncertainty





⇒ Consistent with QCD factorization !

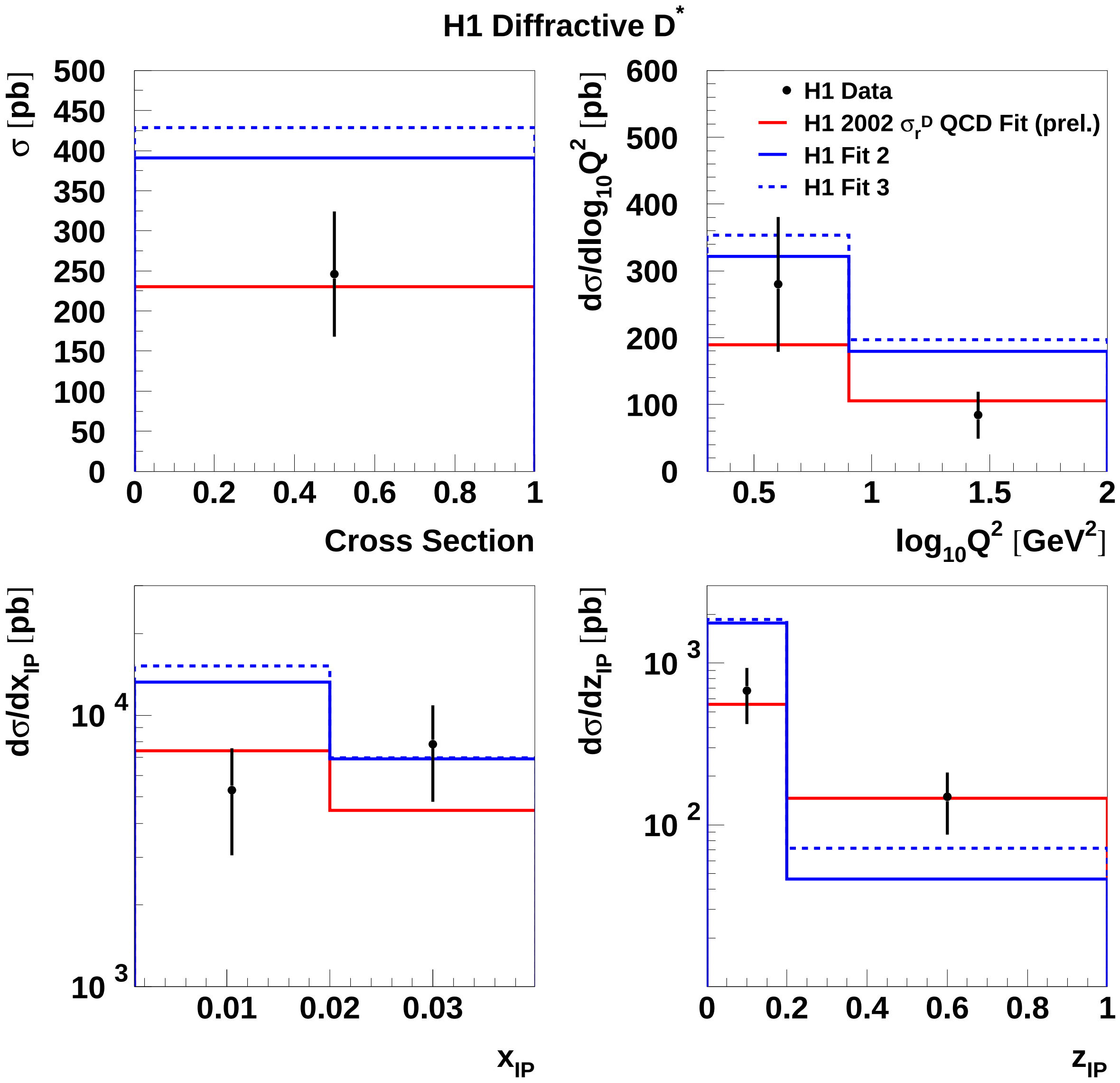
Diffractive Dijets



Good agreement, taking NLO/pdf/scale uncertainties into account

Consistent with QCD factorization

Diffractive Charm



Good agreement within errors

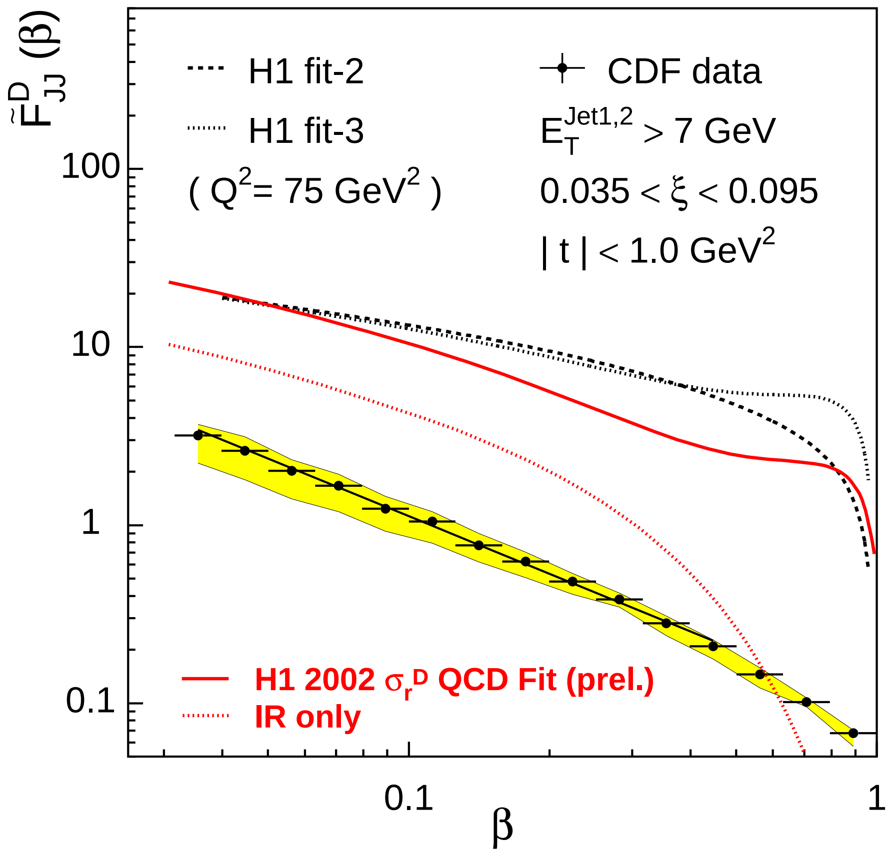
Consistent with QCD factorization

Comparison with CDF diffractive Dijet cross sections

Dijet production with tagged leading anti-proton at TEVATRON:

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

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

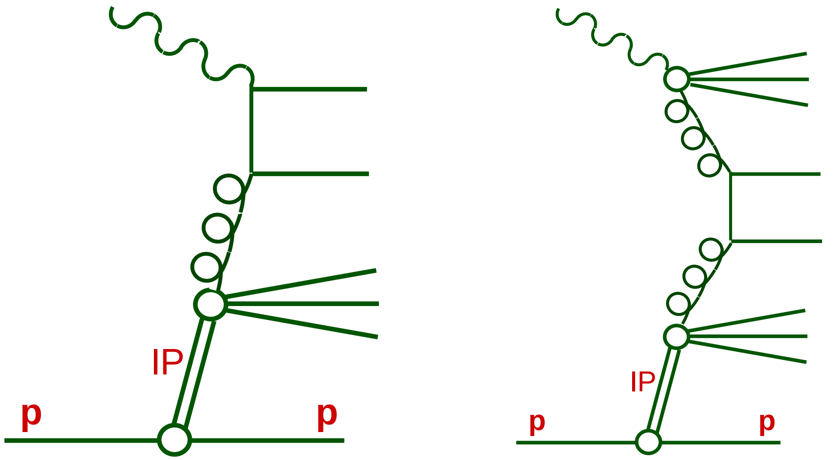


- **New fit confirms serious breakdown of factorization (gap survival, absorptive corrections)**
- **β dependence similar (except highest β)**
- **NOTE $x_{I\!P}$ domain: 50% contribution from sub-leading exchange in this kinematic regime**

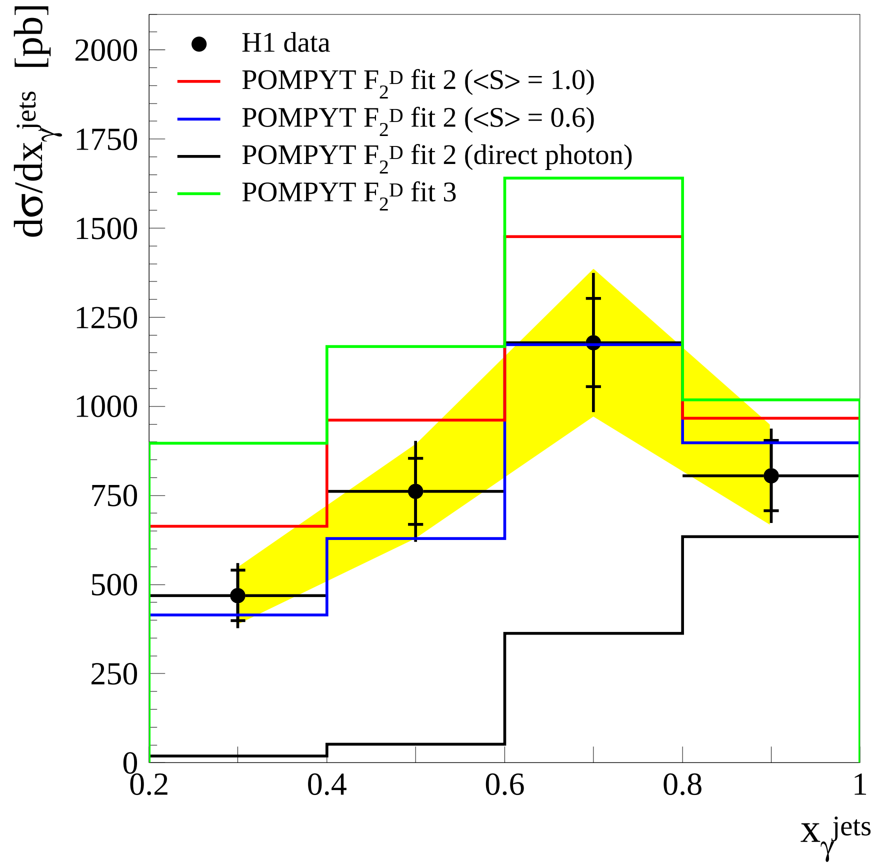
Control Experiment: Dijets in Photoproduction

Hard diffractive photoproduction:
With and w/o remnants ...

x_γ: fraction of γ momentum entering hard scatter



direct: $x_\gamma = 1$ **resolved: $x_\gamma < 1$**



Resolved γp resembles hadron-hadron!

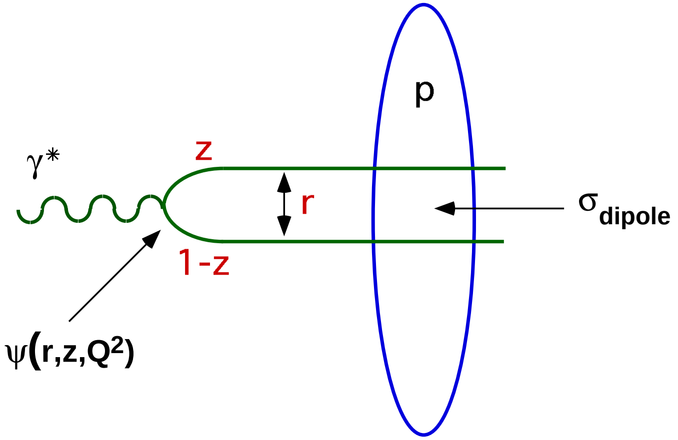
$\longrightarrow$ Description based on diffractive partons from F_2^D improved by suppressing resolved interactions by 'gap survival probability' of $< S >= 0.6$

More data needed for firm conclusions ...

Colour Dipole and 2-gluon Exchange models

Consider low x in p rest frame:

$\gamma^* \longrightarrow q\bar{q}$ well in advance of target
Interaction between photon and $q\bar{q}$ dipole



Diffractive if dipoles scatter elastically

Inclusive:
$$\sigma \sim |\Psi_{T,L}(r,z,Q^2)|^2 \otimes \sigma_{\rm dipole}(x,r)$$

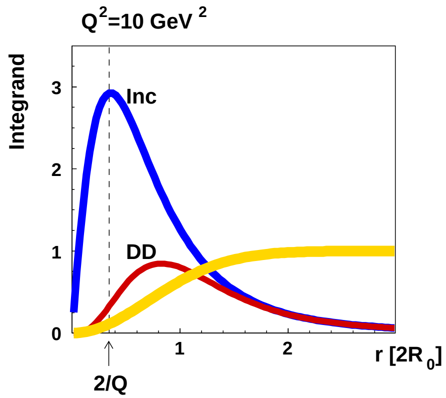
Diffractive:
$$\sigma^D \sim |\Psi_{T,L}(r,z,Q^2)|^2 \otimes \sigma^2_{\rm dipole}(x,r)$$

$\Psi_{T,L}(r,z,Q^2)$: Light cone wave functions

$\gamma^*_T \longrightarrow q\bar{q}$
$\gamma^*_L \longrightarrow q\bar{q}$ (high β)
$\gamma^*_T \longrightarrow q\bar{q}g$ (low β)

Dipole cross section $\sigma_{\rm dipole}$:

Model dependent, e.g. Golec-Biernat:



$\sim r^2$ as $r \longrightarrow 0$
$\longrightarrow$ const as $r \longrightarrow \infty$

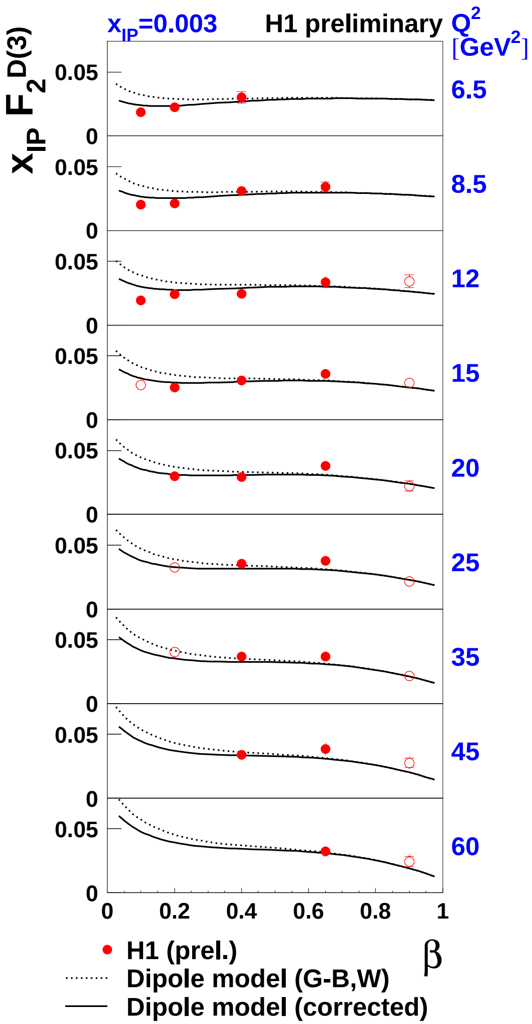
Sat. radius $R_0(x)$

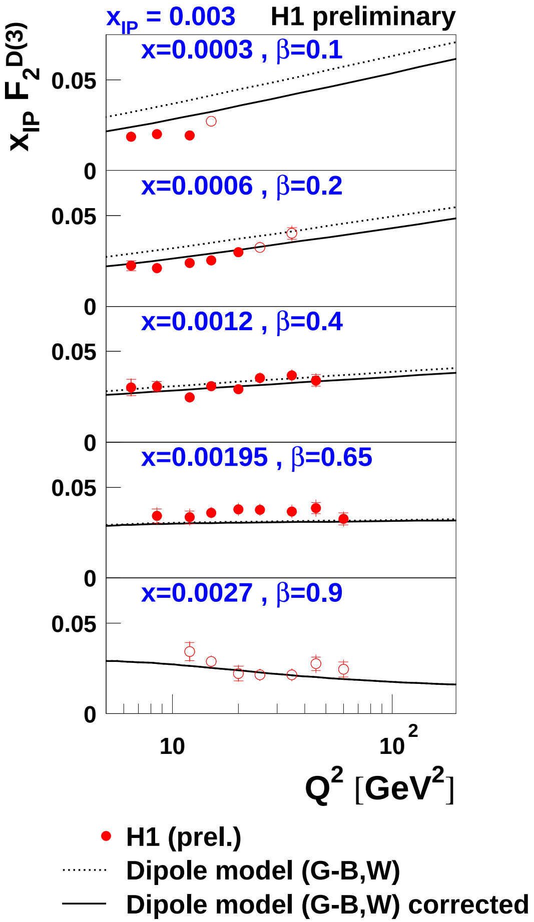
Fix parameters by fit to inclusive $F_2(x,Q^2)$

Predict F_2^D at $t=0$
Need t slope as input

Dipole models: Comparison with Data

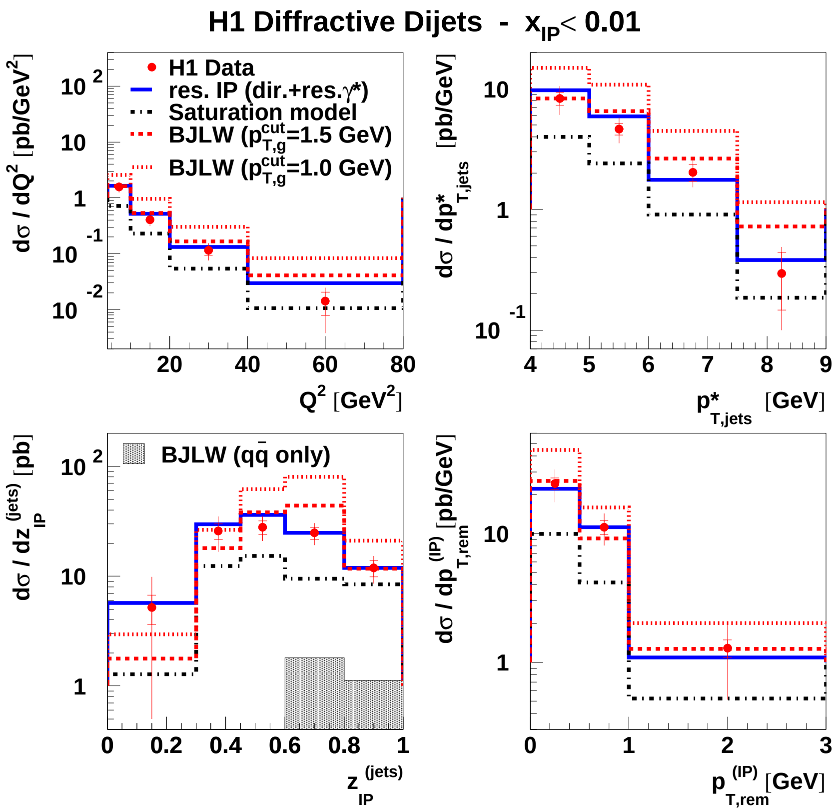
Inclusive: F_2^D





Agreement reasonable, except low Q^2,β

Diffr. Dijets



Saturation model underestimates normalization by factor 2

BJLW: Bartels et al. pQCD calculation for hard jets can describe data

Summary and Conclusions

Disclaimer:

- **Impossible to cover everything in one talk. Here, the focus was on new results on inclusive hard diffraction (F_2^D) and QCD interpretation**
- **Many other interesting results (Vector mesons, DVCS, ...) could not be shown**

Conclusions:

- **Data on diffraction at HERA has reached high precision !**
- **Virtual photon in diffractive DIS enables to study quark/gluon (QCD) structure of diffraction**
- **New DGLAP NLO QCD fit to determine diffractive parton distributions (as for F_2) (justified by semi-inclusive QCD factorization proof)**
- **Large diffractive gluon distribution extending to large β**
- **Diffractive final states (Jets, charm): QCD factorization works in ep, failure in pp confirmed!**
- **Real photoproduction: Bridge HERA - TEVATRON to understand factorization breaking ep vs pp ?**