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Inclusive Diffraction at HERA

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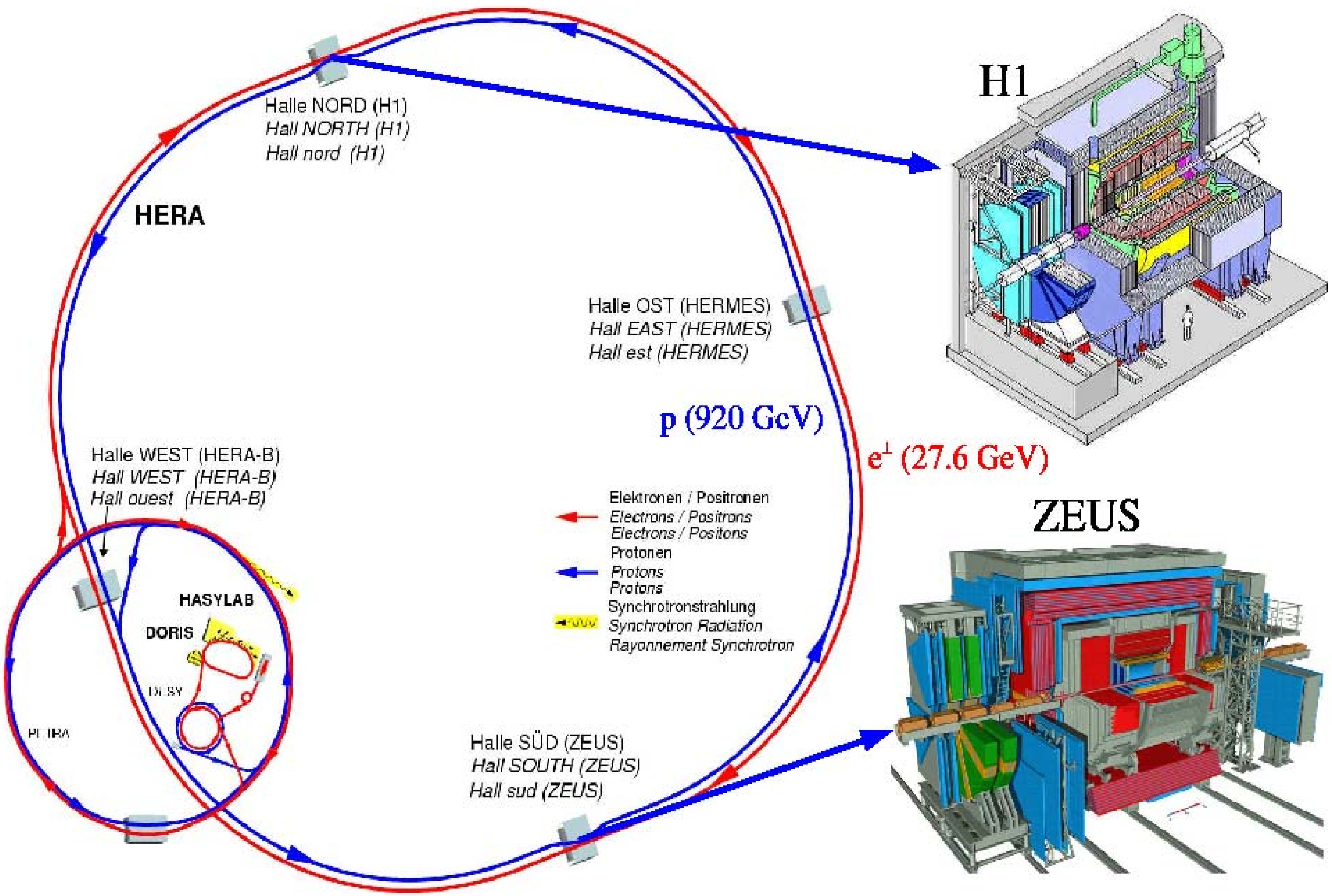
On behalf of the H1 and ZEUS Collaborations

- **Diffractive DIS at HERA**
- **Measurements of diffractive structure function**
- **QCD fits**
- **Comparison with hadronic final states**
- **Conclusions**

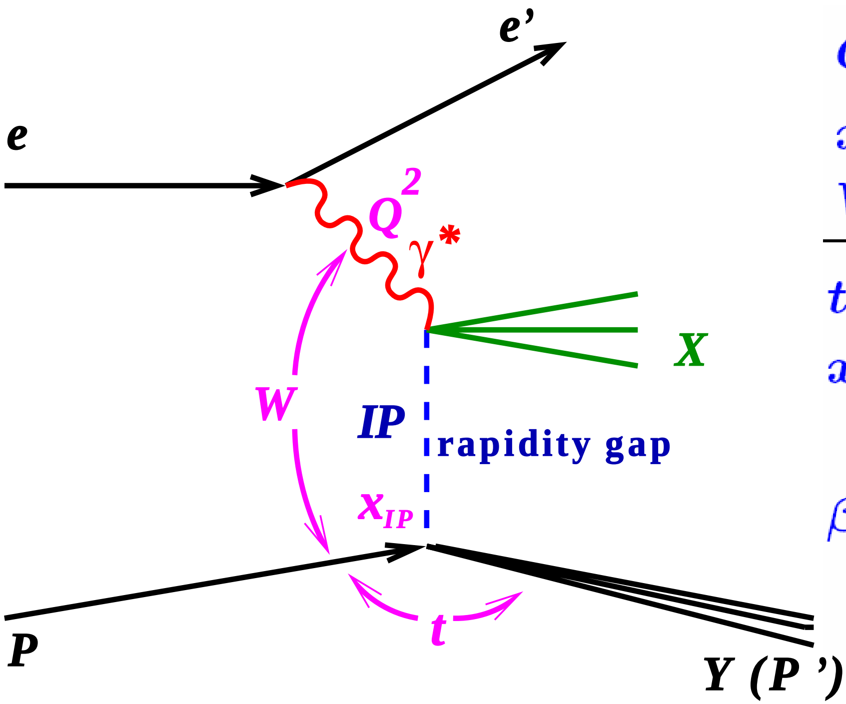
HERA

The world's only electron/positron-proton collider. E_e = 27.6 GeV E_p = 920 GeV
Two colliding experiments: H1 and ZEUS ($\sqrt{s} \approx 320$ GeV),
fixed target experiment: HERMES



The results presented in this talk are based on HERA-I data

Definition of kinematic variables



$Q^2 = -q^2$ photon virtuality

$x = \frac{Q^2}{2q \cdot p}$ Bjorken scaling variable

$W^2 = (p+q)^2$ $\gamma^* p$ CM energy squared

$t = (p - p_Y)^2$ 4-momentum transfer squared

$x_{I\!P} = \frac{q \cdot (p-Y)}{q \cdot p}$ fraction of p momentum transferred to $I\!P$ ($x_{I\!P} \simeq 1 - E_Y / E_p$)

$\beta = \frac{Q^2}{2q \cdot (p-Y)}$ fraction of $I\!P$ momentum carried by struck quark ($x_{I\!P}\beta = x$)

M_X Inv. mass of system X

- t-channel exchange of vacuum quantum numbers
- proton survives the collision intact or dissociates to low mass state, $M_Y \sim O(m_p)$
- large rapidity gap
- small t (four-momentum transfer) and x_{IP} (fraction of proton momentum)
- $M_X \ll W$

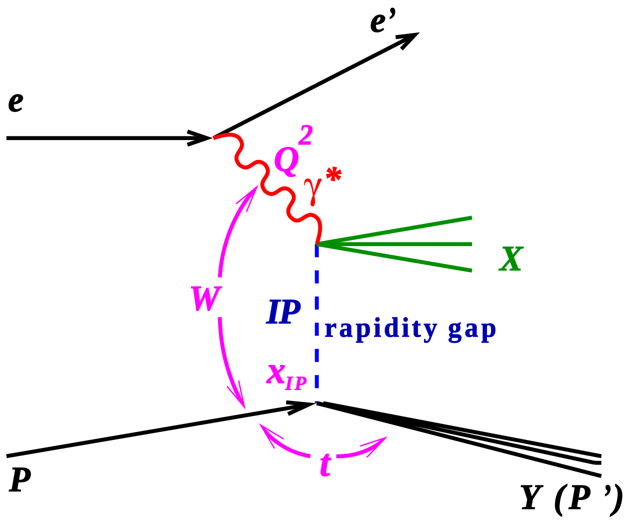
Diffraction at HERA

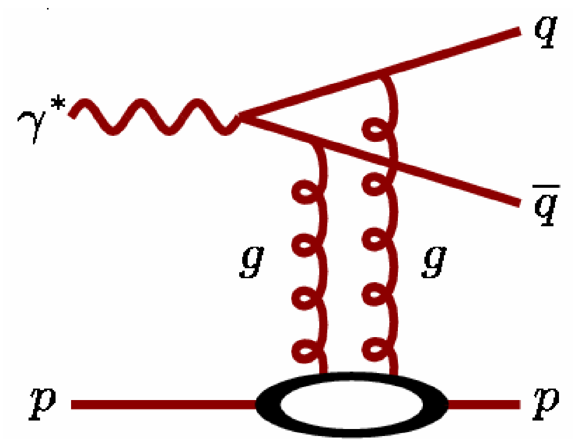
If no hard scale – Q^2, $|t|\approx 0$: similar to soft hadron-hadron interactions
- Regge theory: diffraction is *exchange of Pomeron*

→ **Weak energy dependence**

If hard scale (large Q^2, $|t|$, p_T^{jet}, m_Q) present: study diffractive phenomena in terms of QCD
- Resolved Pomeron: probe the structure of exchanged object
- Colour dipole: diffraction is *exchange of colour singlet gluon ladder* between ($\gamma^* \to q\bar{q}$, $q\bar{q}g$) and the proton

→ **Steep energy dependence**

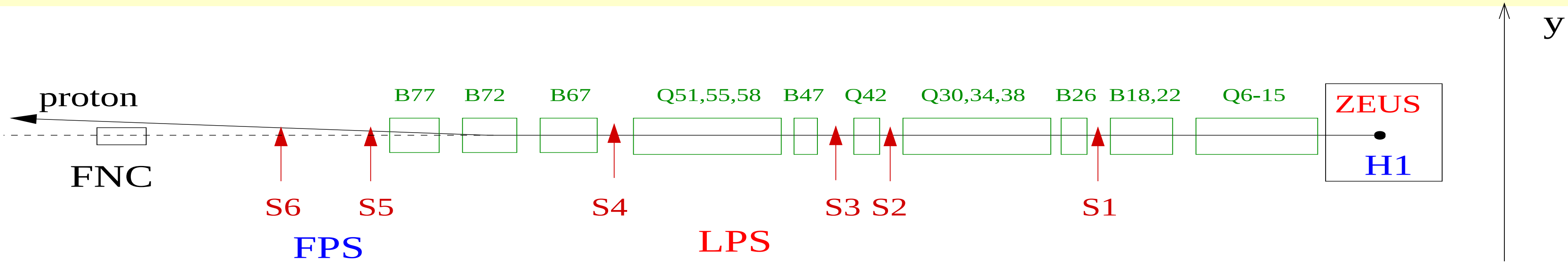




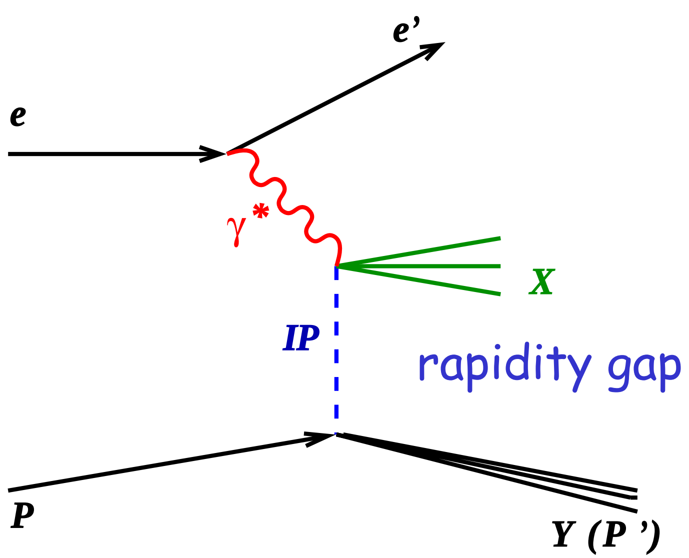
HERA- unique facility to study transition from soft to hard regime and to probe partonic content of diffractive exchange.

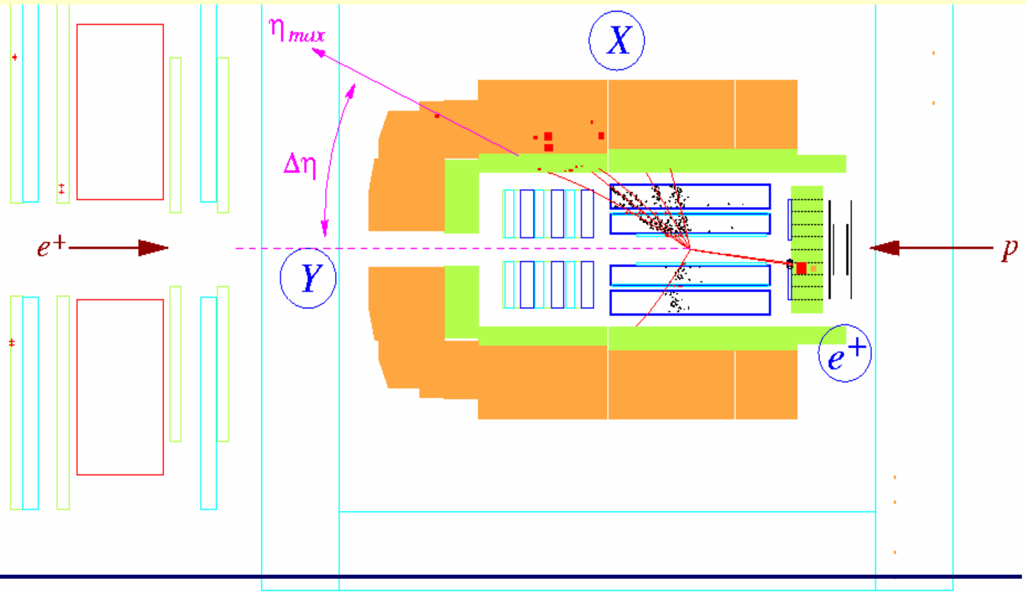
~10% of DIS events at HERA are diffractive

➢ **'Leading proton' method (LPS)– scattered proton detected in 'Roman Pots' (LPS,FPS)**
free of p-diss.background, *t* and x_{IP} measurement, but low acceptance/statistics

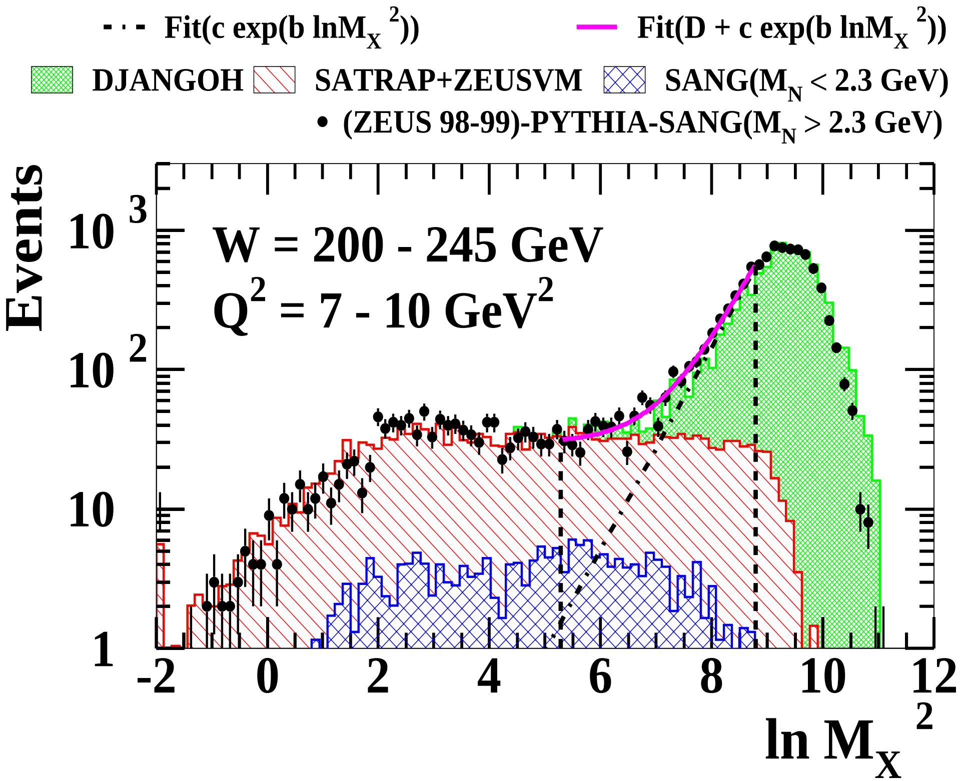


➢ **Large Rapidity Gap' method (LRG)**
t is not measured, some p-diss. background (for H1 measurements M_Y<1.6 GeV)





➢ **'M_X' method- non-diffractive contribution subtracted from fit to M_X distribution**



$\ln M_X^2$ distribution

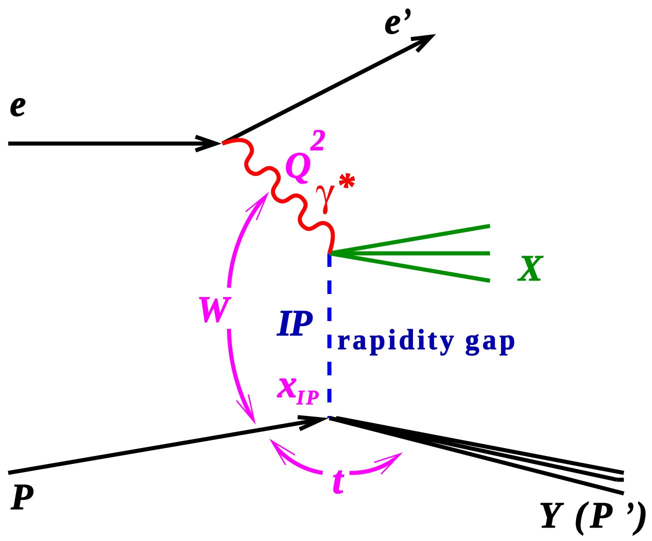
$$\frac{dN}{d\ lnM_X^2} = D + c \cdot exp(b \cdot lnM_X^2)$$

- exponential rise with M_X for non-diffractive events
- flat behavior vs $\ln M_X^2$ for diffractive events

➔ Non-diffractive events can be subtracted from fit to M_X

- some p-diss. background (M_Y<2.3 GeV)
- t is not measured

Cross-section of inclusive diffractive DIS



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

$x_{I\!P} = \frac{q\cdot(p-p')}{q\cdot p}$ fraction of p momentum transferred to $I\!P$

$\beta = \frac{Q^2}{2q\cdot(p-p')}$ fraction of $I\!P$ momentum carried by struck quark

Diffractive DIS cross-section:

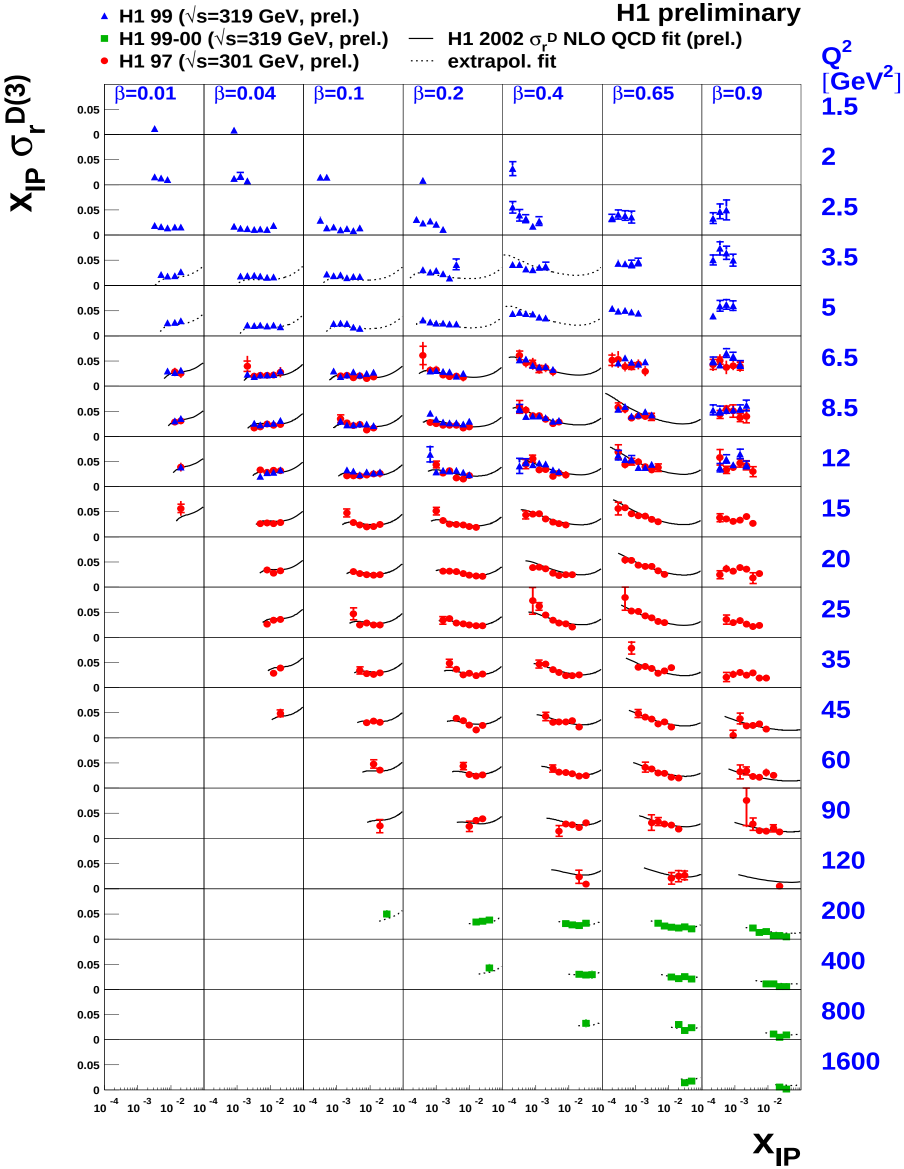
$$\frac{d\sigma^D}{d\beta dQ^2 dx_{I\!P} dt} = \frac{2\pi\alpha}{\beta Q^4}(1 - y + y^2/2)\cdot \sigma_R^{D(4)}(\beta, Q^2, x_{I\!P}, t)$$

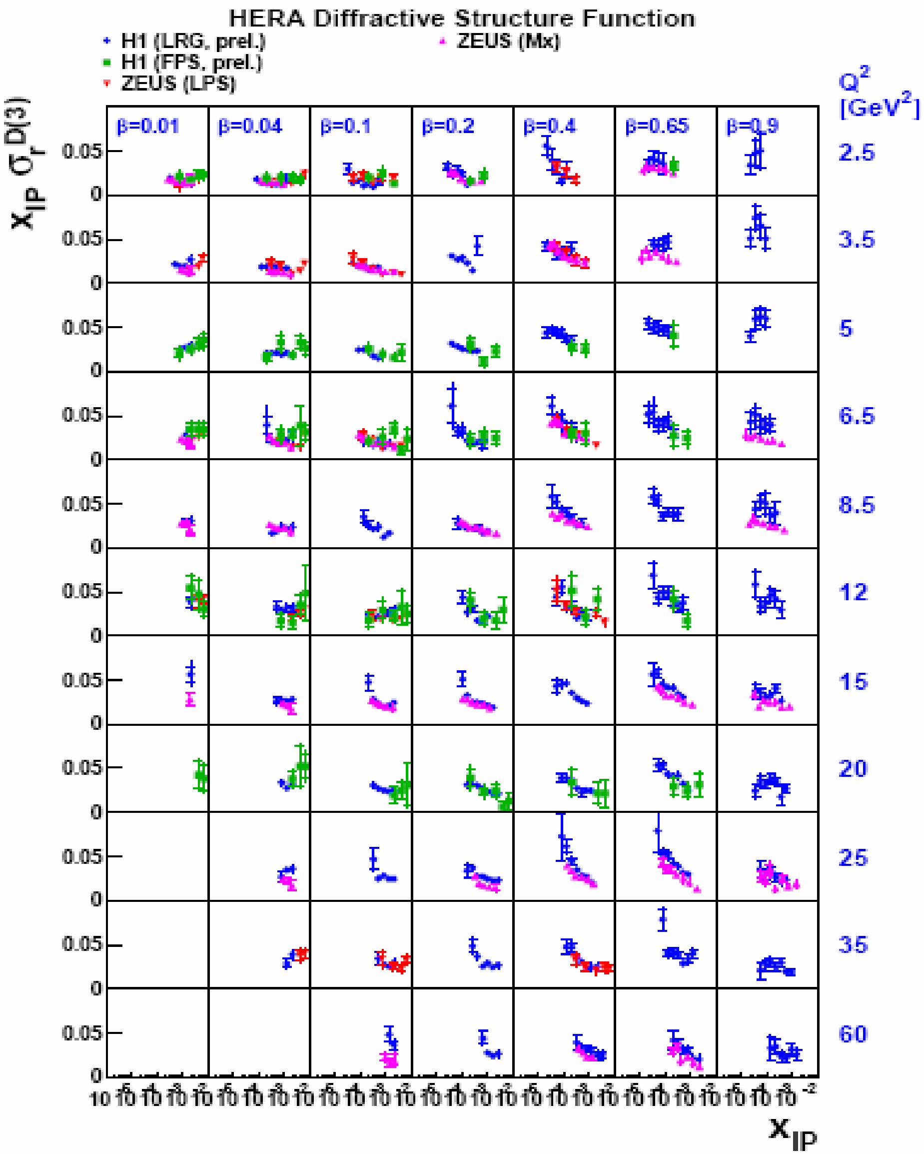
$$\sigma_R^{D(3)}(\beta, Q^2, x_{I\!P}) = \int \sigma_R^{D(4)}(\beta, Q^2, x_{I\!P}, t)\cdot dt$$

Reduced cross-section:

$$\sigma_R^D = F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D \qquad (\sigma_R^D = F_2^D \text{ if } F_L^D = 0)$$

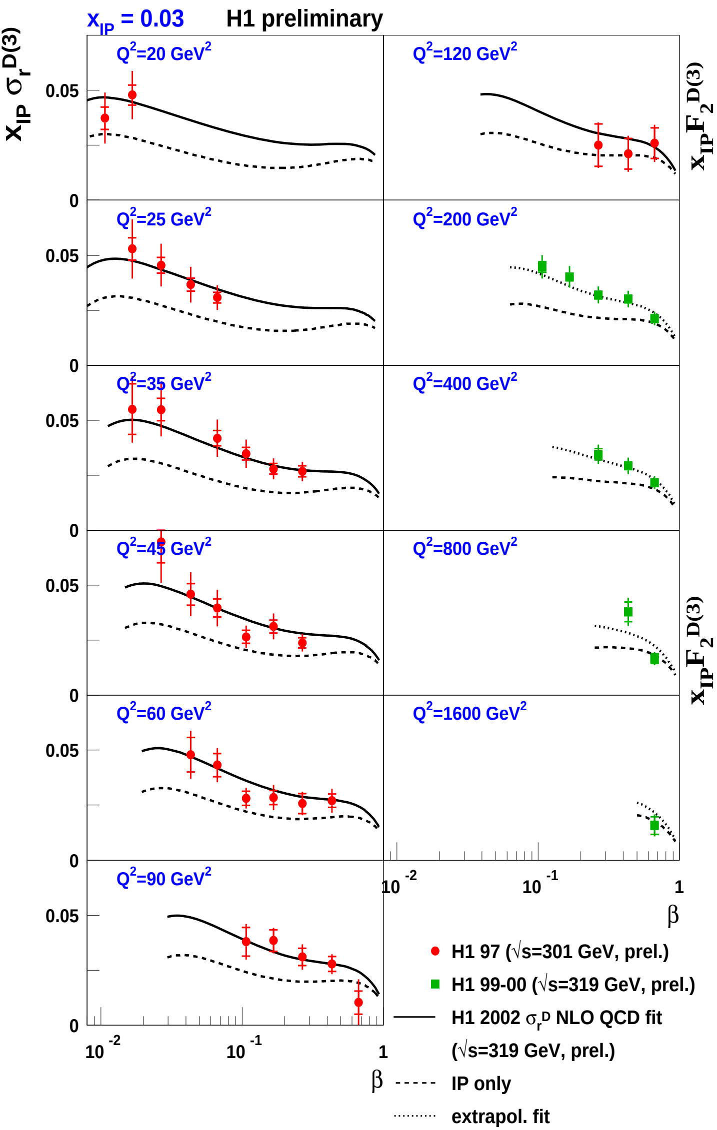
Diffractive structure functions $F_2^{D(3)}$, $\sigma_r^{D(3)}$ - x_{IP}, β and Q^2 dependence

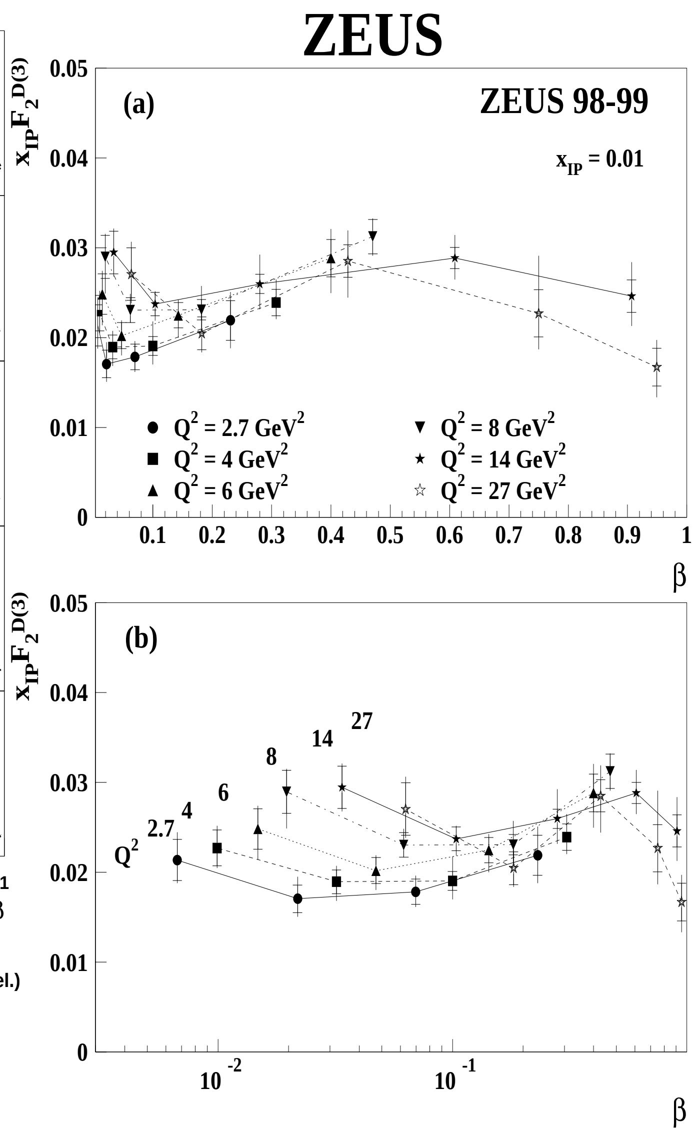




- large kinematic region covered $1.5 < Q^2 < 1600$ GeV^2
- large statistical precision
- good agreement between two experiments and different methods

β- dependence of F_2^D

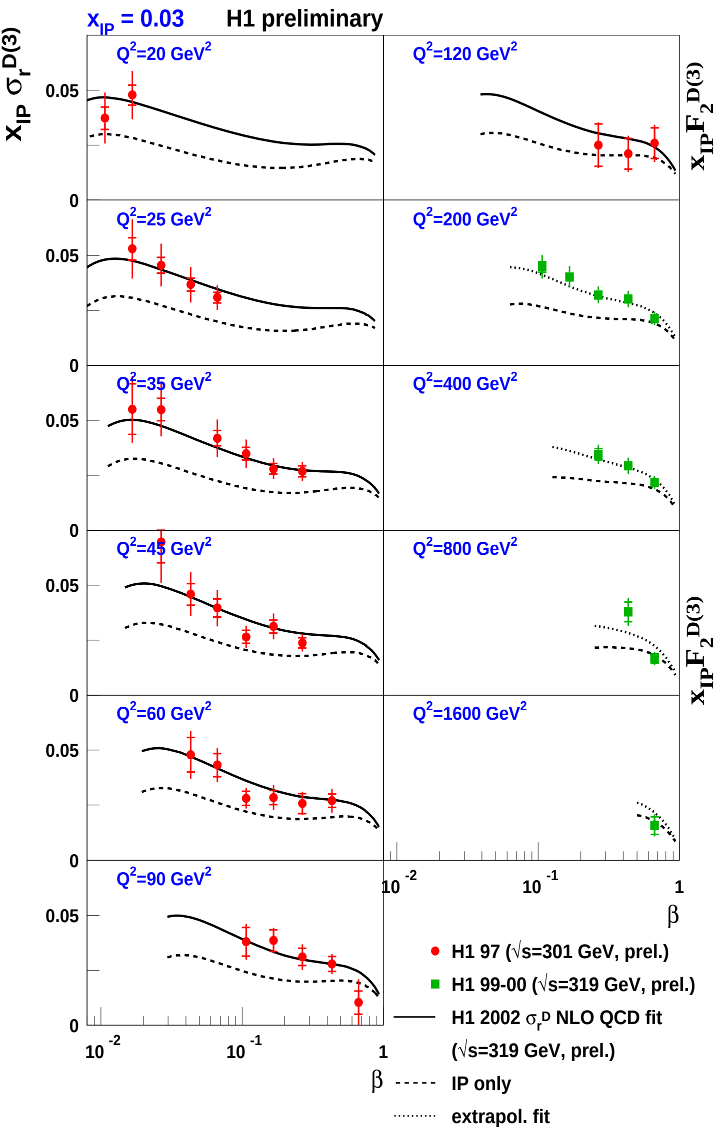


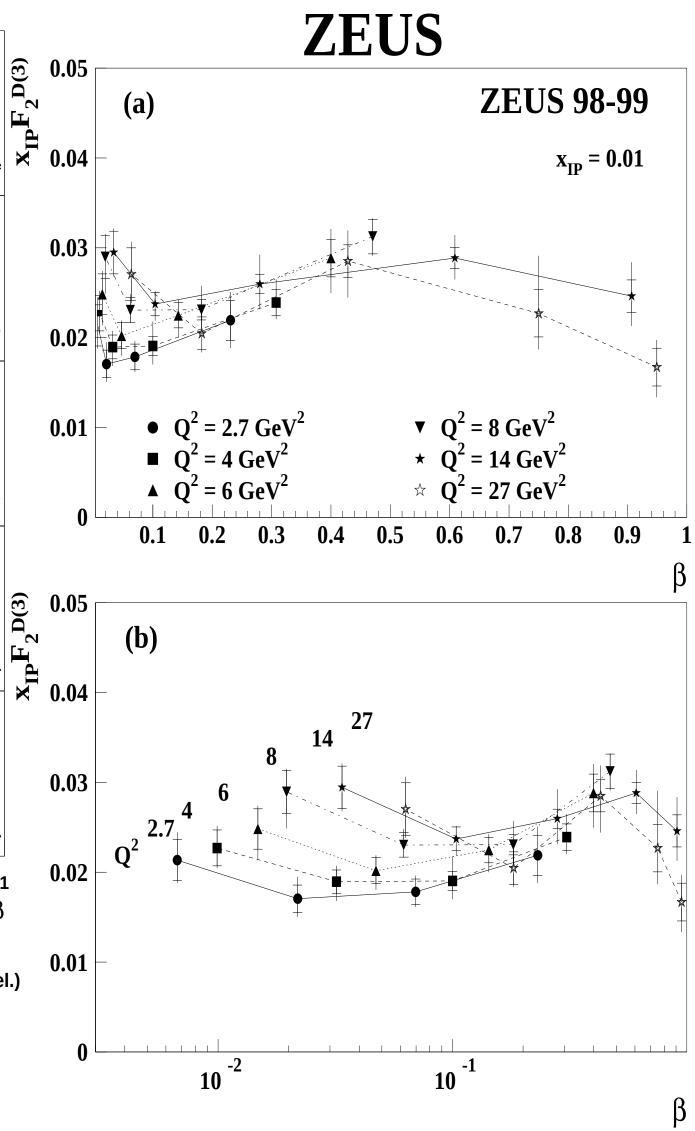


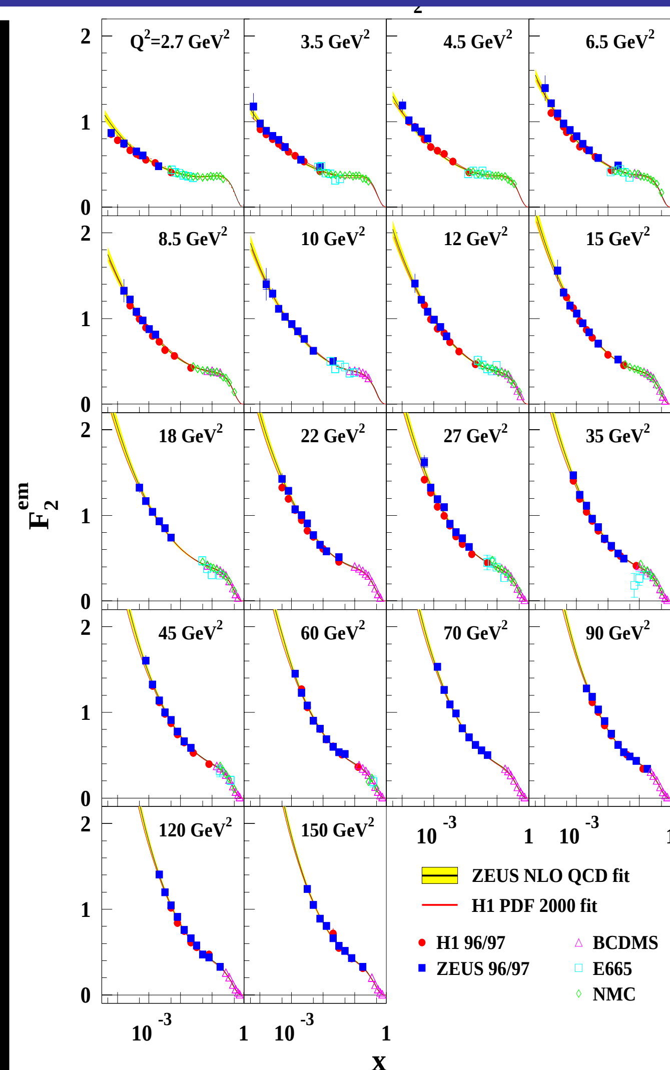
$F_2^D(\beta,Q^2)$ vs β

β-dependence relatively flat

β- dependence of F_2^D





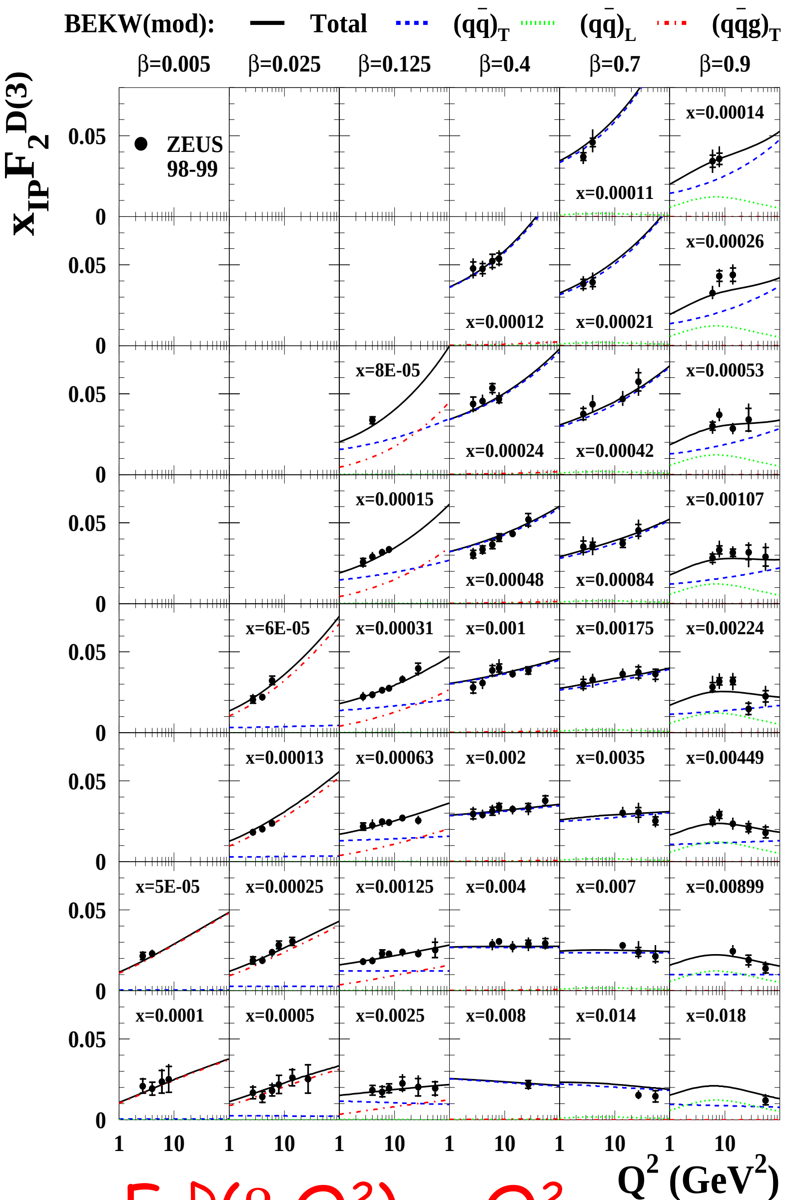


$F_2^D(\beta,Q^2)$ vs β

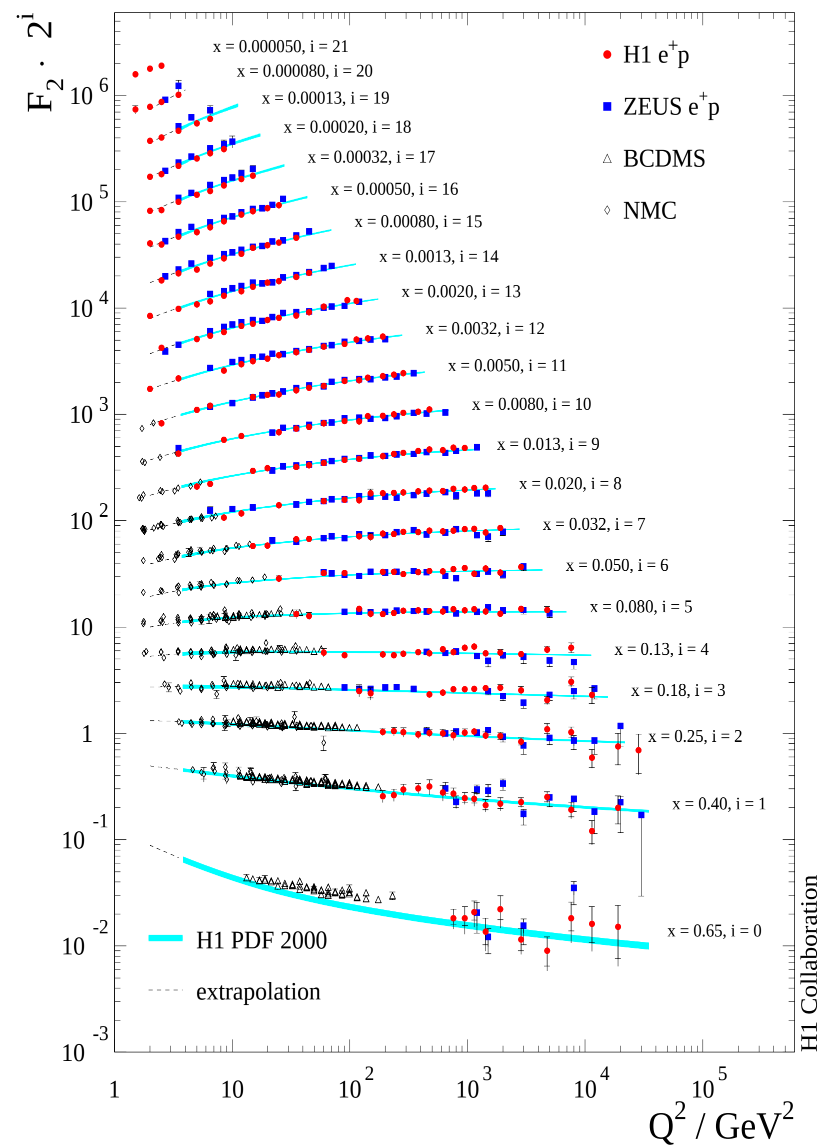
$F_2^P(x,Q^2)$ vs x

β-dependence relatively flat – different from F_2 (recall $x=x_{IP}\cdot\beta$)

Q^2 dependence of F_2^D



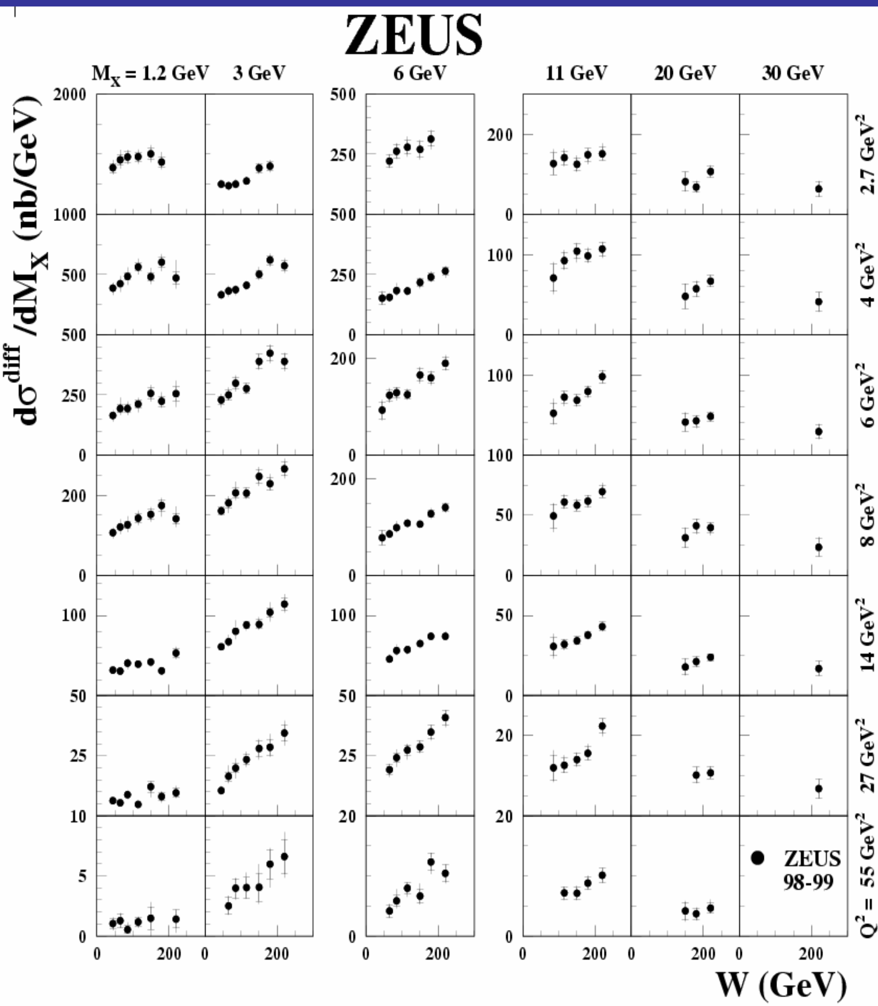
$F_2^D(\beta,Q^2)$ vs Q^2



$F_2^p(x,Q^2)$ vs Q^2

F_2^D increases with Q^2 → **positive scaling violation up to large β** → different from F_2

Diffractive cross section: W dependence of σ^{diff}

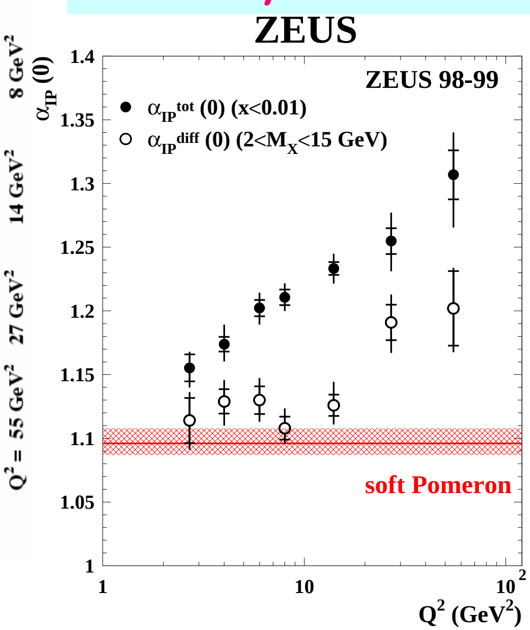


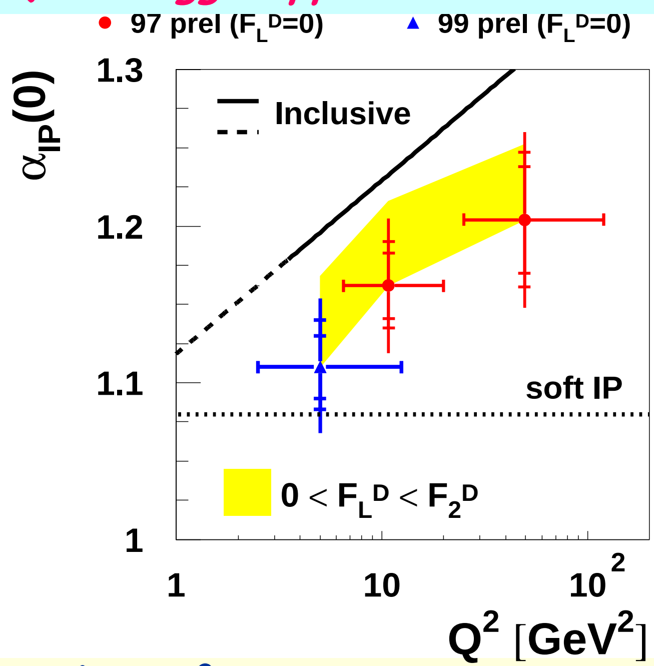
Quantify W dependence as

$$d\sigma^{diff}/dM_X \propto W^{\alpha^{diff}} \approx W^{4\left(\alpha_{IP}^{diff}(0)-1.03\right)}$$

In Regge approach relation between α^{diff} and pomeron trajectory α_{IP}^{diff}, averaged over t

Effective pomeron trajectory $\alpha_{IP}(0)$ should be independent of Q^2 in Regge approach





M_X< 2 GeV: weak rise with W
M_X> 2 GeV: strong rise with W at Q^2 > 4 GeV²

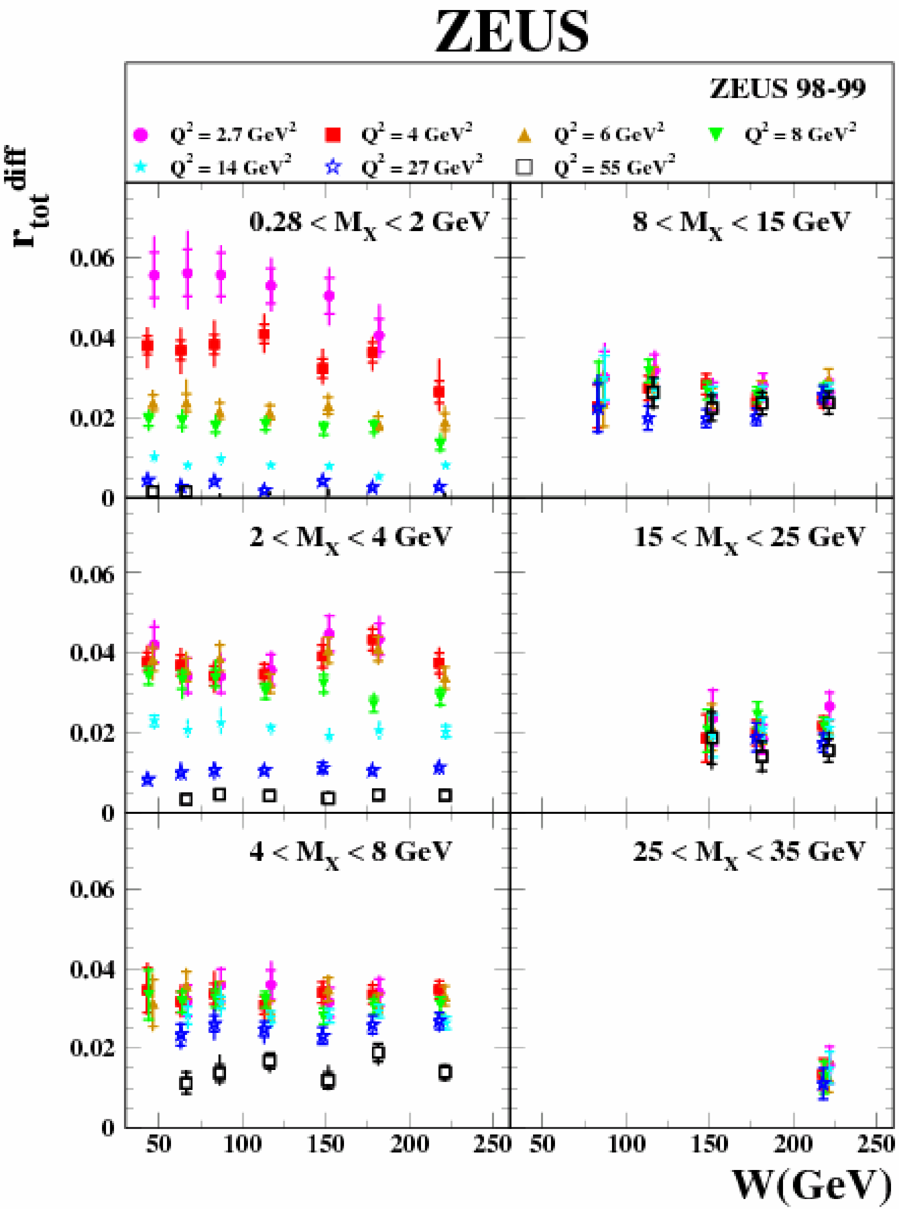
consistent with soft Pomeron at low Q^2,

increase with Q^2 → not consistent with **Regge factorization**

(H1 data consistent within the errors)

lower than for inclusive DIS cross section $F_2 \propto (W^2)^{\alpha_{IP}^{tot}(0)-1}$

W and Q² dependence of $\sigma^{diff}/\sigma^{tot}$



- for M_x >2 GeV ratio is independent of W
  → same energy behavior in diffr. and incl. DIS
  → not consistent with naïve picture

$$r = \frac{|\,xg(x,Q^2)\,|^2}{xg(x,Q^2)} = xg(x,Q^2)$$

expect rise with W

- for M_x <2 GeV (high β) ratio decreases with increasing W : contribution of vector mesons

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- high M_x >8 GeV– no Q² dependence
  → same DGLAP evolution
- low M_x<2 GeV (high β)-strong decrease with Q²

- diffractive contribution to σ^{tot}
  (200<W<245GeV, 0.28< M_x<25 GeV,M_N<2.3GeV)

$r_{tot}^{diff} = 15.8^{+1.2}_{-1.0}\%$ at Q²=4 GeV² $r_{tot}^{diff} = 9.6^{+0.7}_{-0.7}\%$ at Q²=27 GeV²

NLO QCD fits to F_2^D

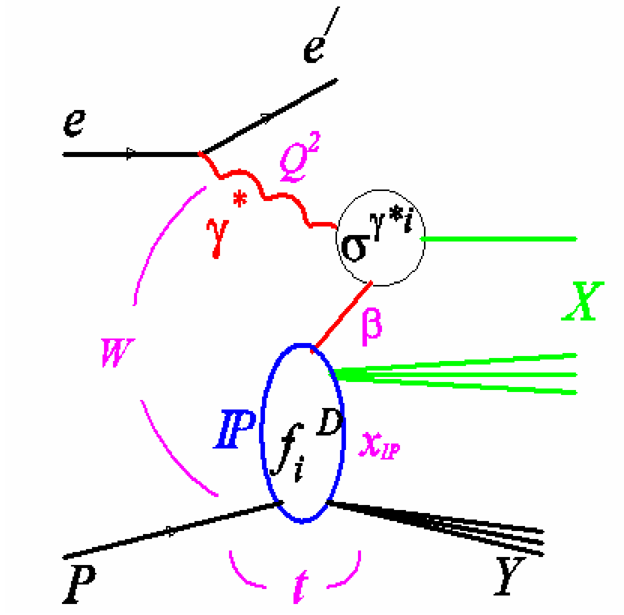
Extract diffractive parton densities from F_2^D data and use to predict the diffractive final states ➔

are these PDFs universal ?

Make use of different data sets, theoretical models and approaches

Diffractive PDFs from HERA are essential ingredients for the prediction of diffractive cross sections at the LHC, e.g. diffractive Higgs production.
Along with understanding of factorization breaking mechanism in the diffractive $p\bar{p}$ interactions, the precise measurements and understanding of diffractive PDFs are needed for reliable predictions.

Factorization properties of diffractive cross sections

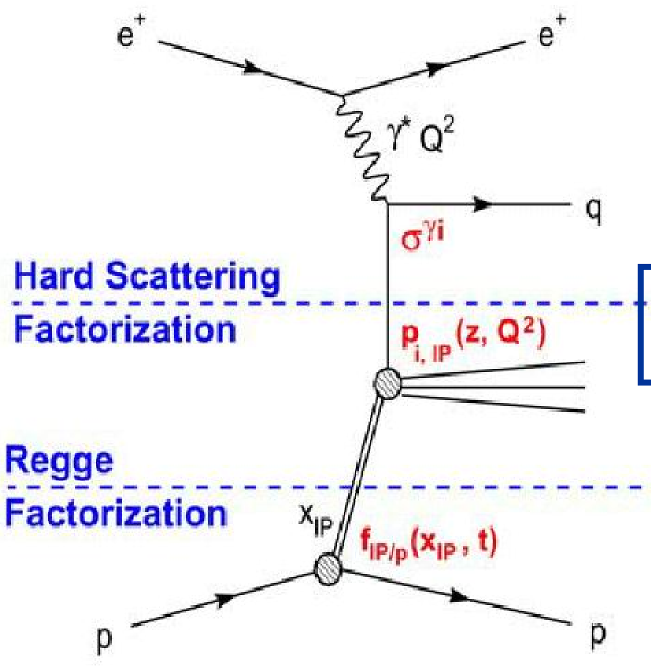


QCD factorization in diffractive DIS (Collins 1997)

$$\sigma^D\left(\gamma^* p \to Xp\right) \propto \sum_i f_{i,p}^D(x_{IP}, t, x, Q^2) \otimes \sigma^{\gamma^*,i}\left(x, Q^2\right)$$

$f_{i,IP}^D$ -diffractive parton distribution function – conditional proton parton probability distributions with final state proton at fixed x_{IP}, t

$\sigma^{\gamma^*,i}$ -universal hard scattering cross section



Regge factorization (assumption- no firm basis in QCD):

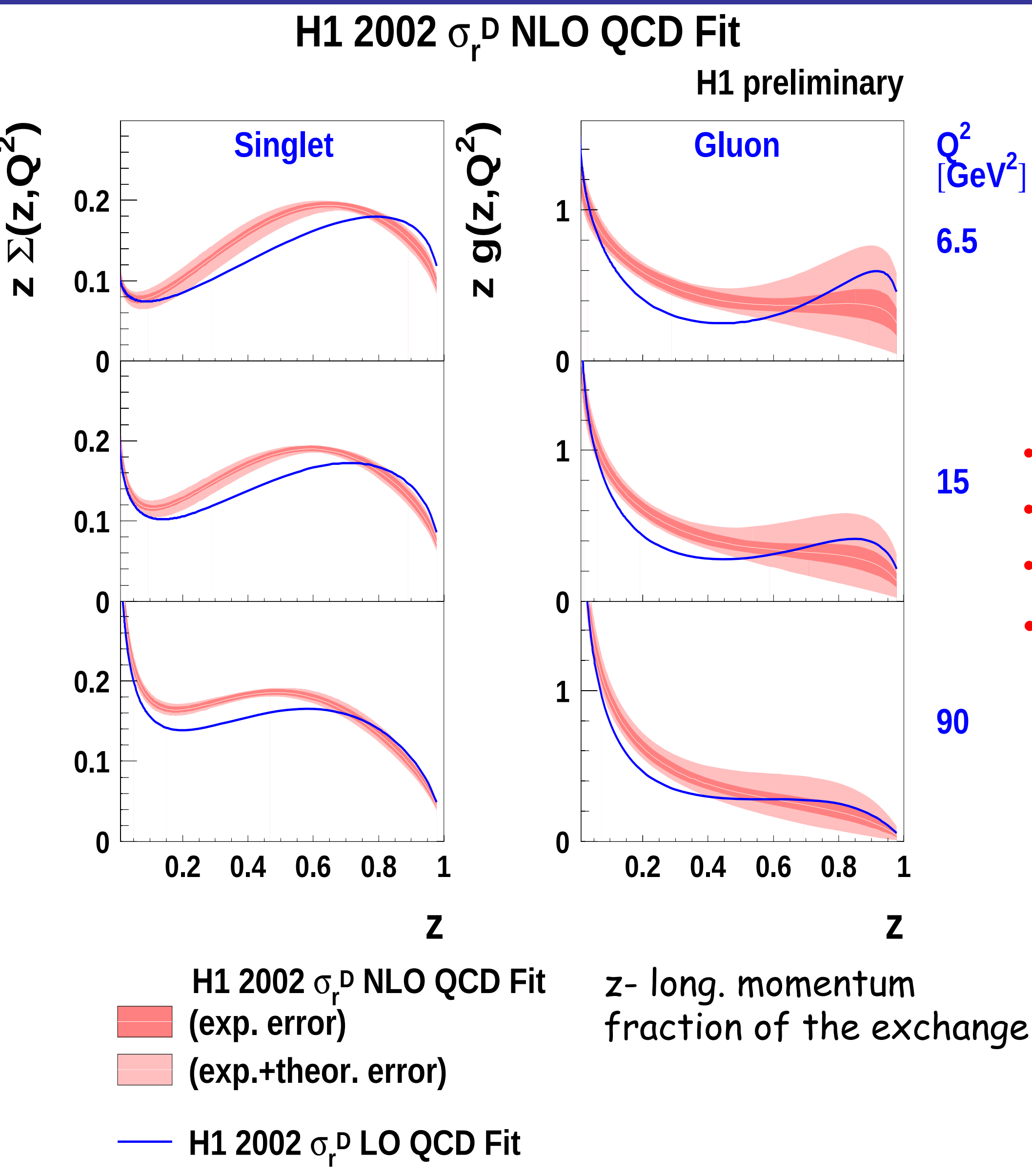
PDF = Pomeron-flux × Pomeron-PDF

$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \times f_i^{IP}(\beta = x / x_{IP}, Q^2)$$

where **Pomeron flux**

$$f_{IP/p}(x_{IP}, t) = \frac{e^{Bt}}{x_{IP}^{2\alpha(t)-1}}, \alpha(t) = \alpha(0) + \alpha'(t)$$

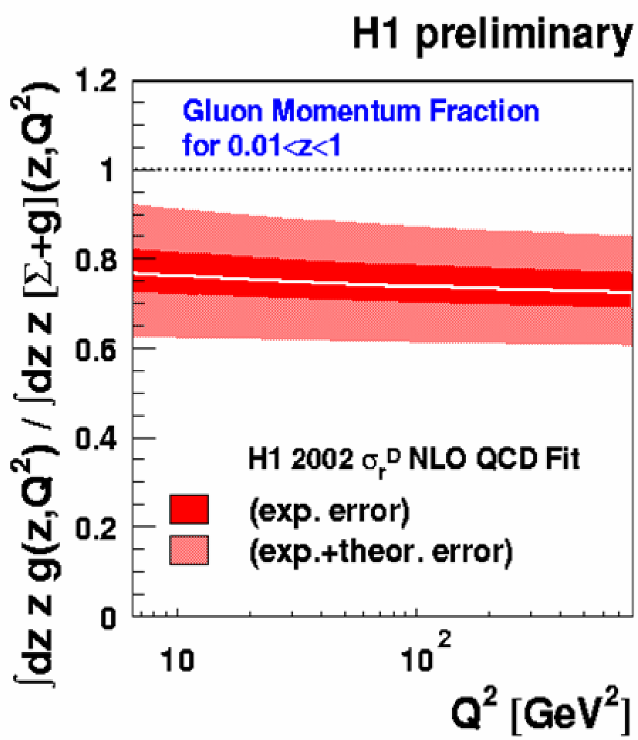
Diffractive PDFs: H1 NLO QCD fit (H1 LRG data)



z- long. momentum fraction of the exchange

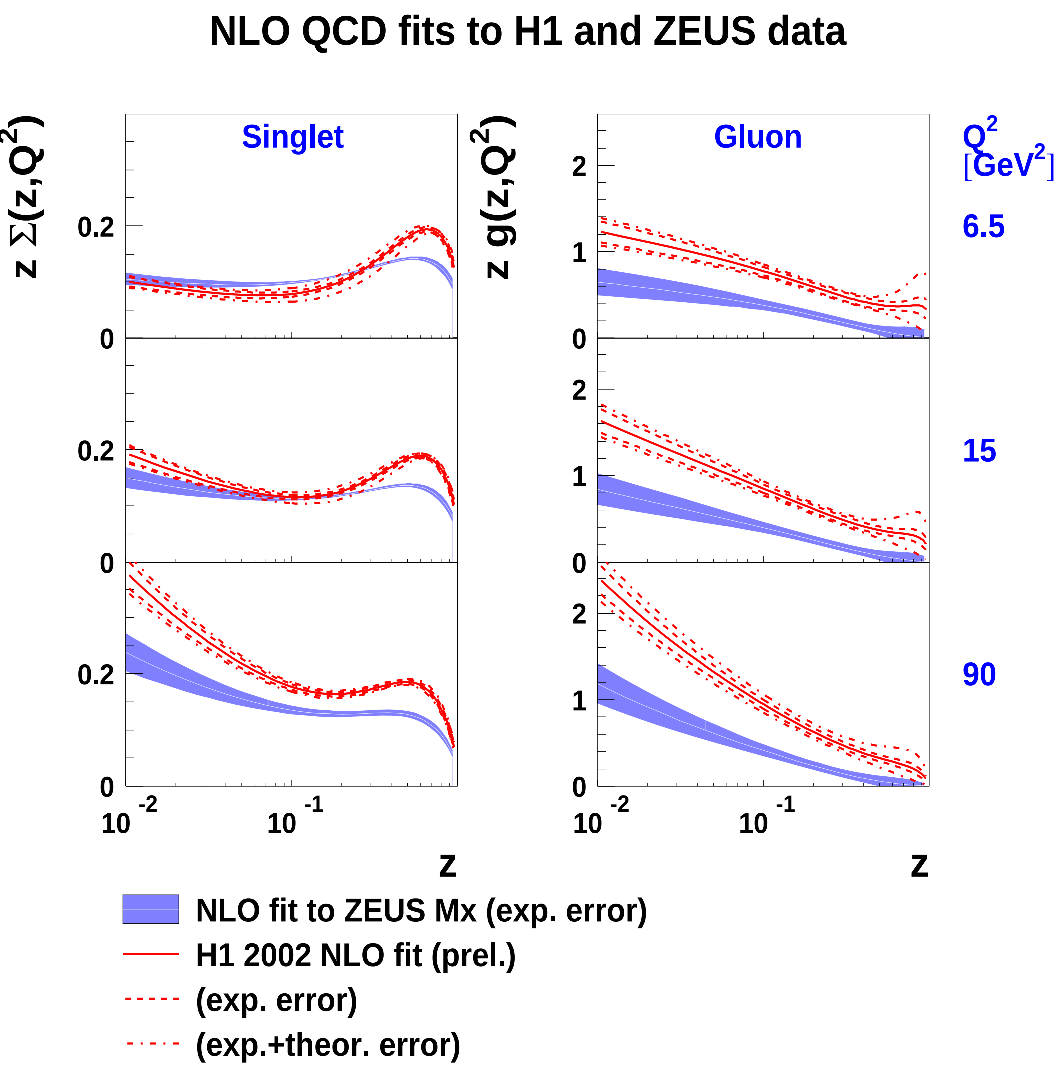
- assume Regge factorization
- apply NLO QCD DGLAP analysis technique to Q^2 and β dependencies of diffractive structure function as for inclusive DIS
  - quark density directly from F_2^D
  - gluon density from scaling violation

- low z behavior similar to F_2
- hard gluon distribution extended to high z
- gluon carries 75%±15% of $I\!P$ momentum
- $\alpha_{I\!P}(0)=1.173$



Diffractive PDFs: more QCD NLO fits (ZEUS-M_X data)

Several analyses done in the framework of HERA-LHC workshop



NLO-QCD fit to ZEUS-M_X data:
(Laycock, Newman and Schilling)

similar procedure as for H1-2002-NLO fit to H1-LRG data

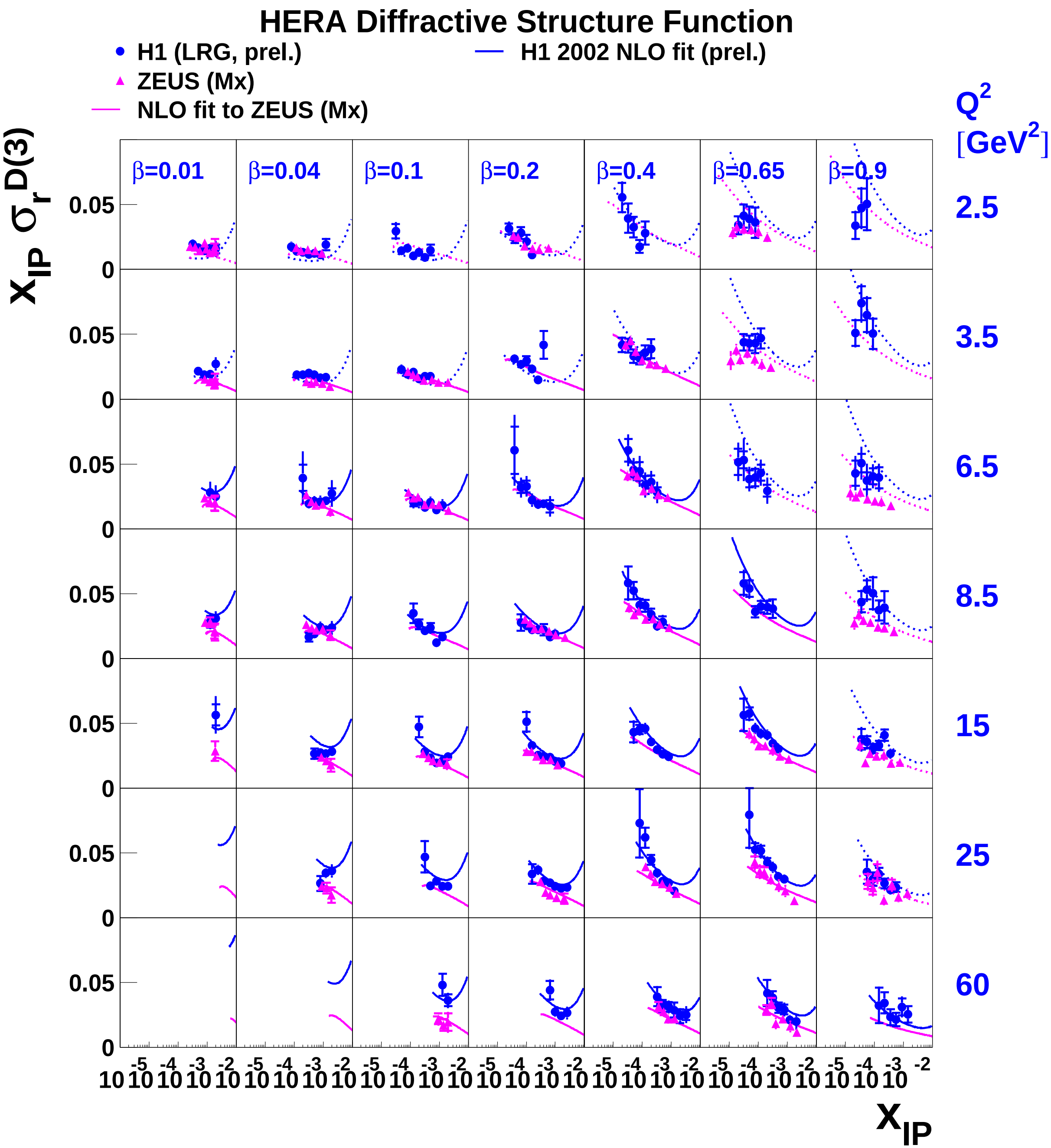
-Significant difference between diffractive gluon densities from H1-LRG and ZEUS-M_x data

- Singlet similar at low Q^2, evolving differently to higher Q^2

- Fraction of gluon momentum: 55%
- α_{IP} (0)=1.132

Differences in the fits to the H1-LRG and ZEUS-M_X data are due to the difference in Q^2 dependence in the measurements

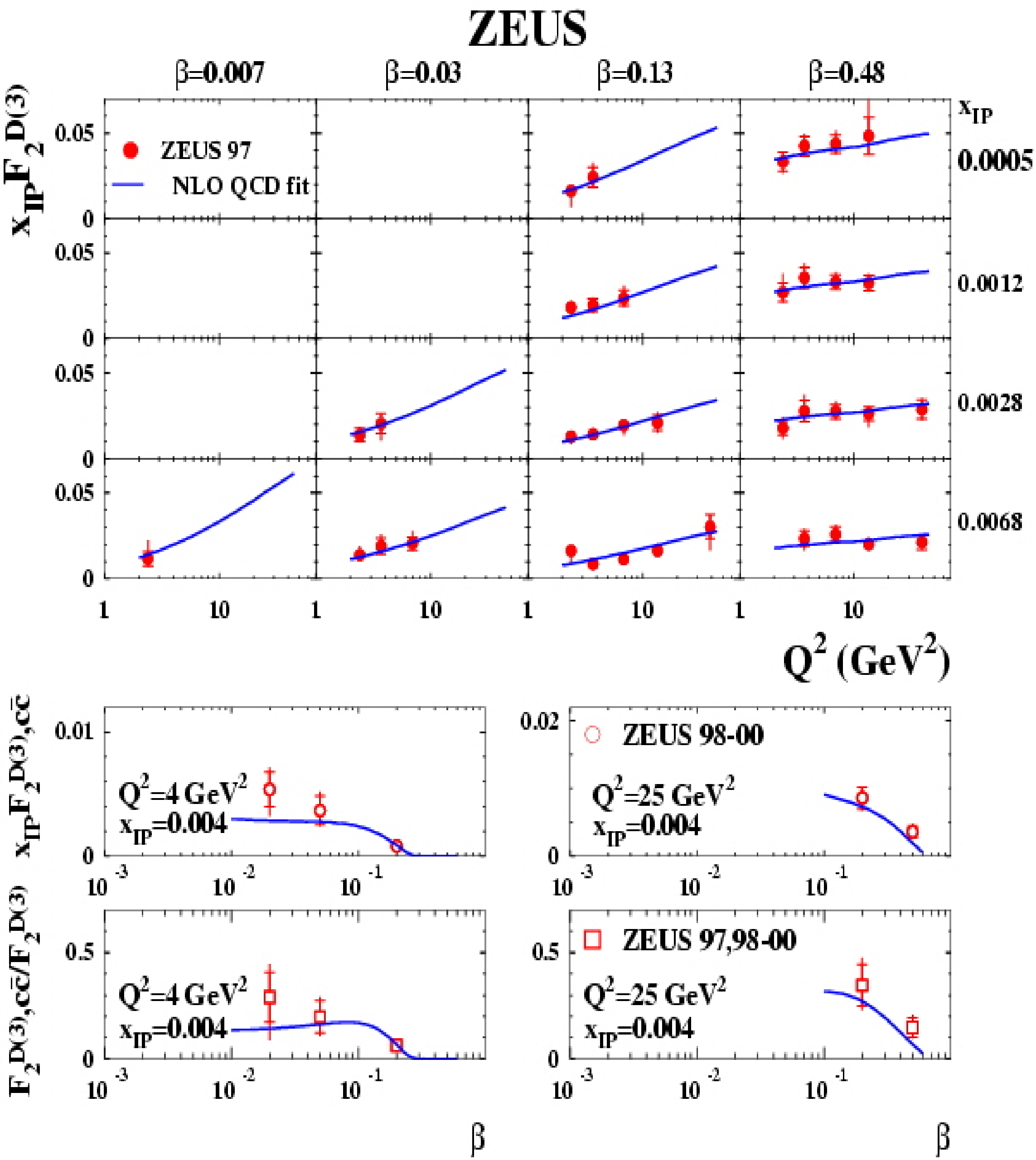
H1-LRG vs ZEUS-M_X data



- At closer look there is a difference between the two measurements at high β (low M_x) region, and smaller positive scaling violations in ZEUS-M_x data, e.g. less gluons

the differences between the measurements are not yet understood

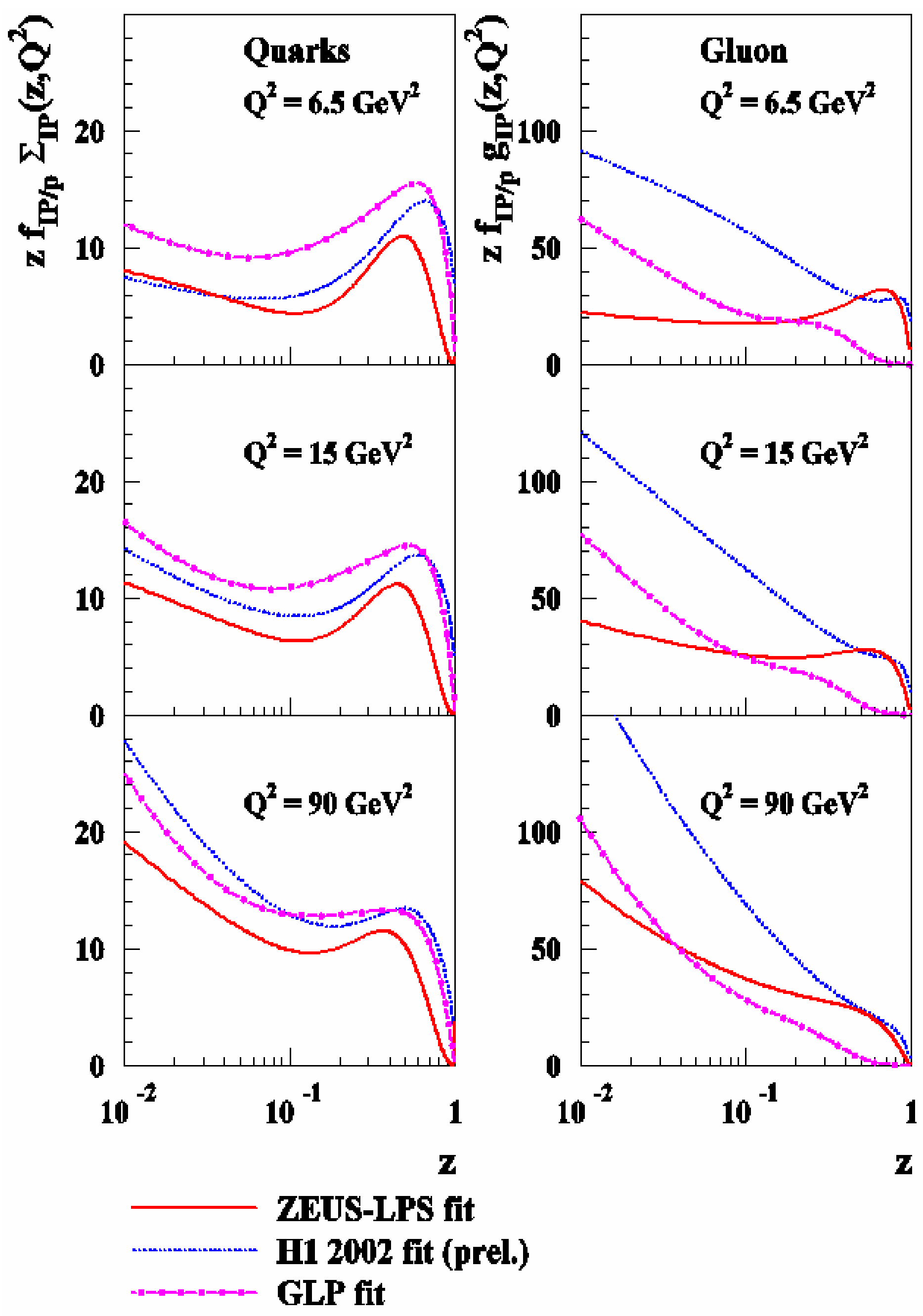
ZEUS NLO QCD fit to F_2^D (ZEUS-LPS) and $F_2^{D,\,charm}$



- Regge factorization, $x_{IP}<0.01$
 include diffractive charm data
 $\alpha_{IP}(0)=1.16\pm0.02\pm0.02$

fractional gluon momentum at initial scale of $Q^2=2$ GeV^2
82±8(stat) ±9(sys) %
→ consistent with H1-LRG data

More NLO QCD fits



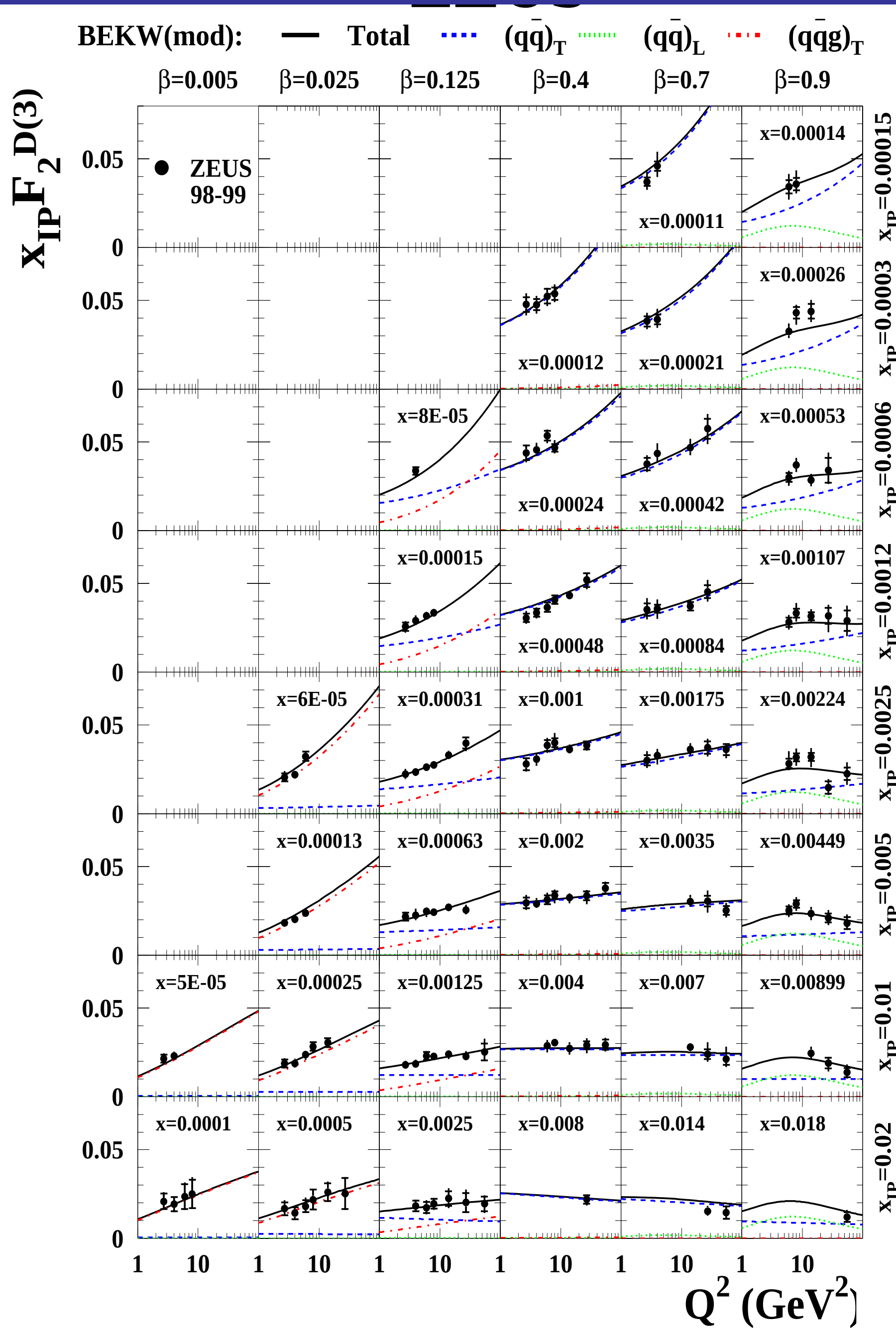
Groys, Levy, Proskuryakov (GLP)

(Fits to H1-LRG, ZEUS-LPS and ZEUS-Mx data)

Evident discrepancies between the different fits and approaches

Need more work for precise and consistent determination of diffractive PDFs

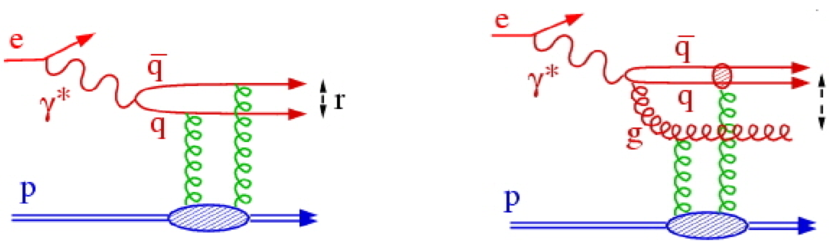
Comparison with theoretical models



Bartels, Ellis, Kowalski, Wüsthoff (**BEKW**)

Colour Dipole model

γ^* fluctuates into $(q\bar{q})_T$, $(q\bar{q})_L$ or $(q\bar{q}g)_T$ before interaction with the proton



$$x_{IP}F_2^{D(3)} = c_T F_{q\bar{q}}^T + c_L F_{q\bar{q}}^L + c_g F_{q\bar{q}g}^T$$

$F_{q\bar{q}g}^T \propto (1-\beta)^\gamma$ -at low β (high M_x)

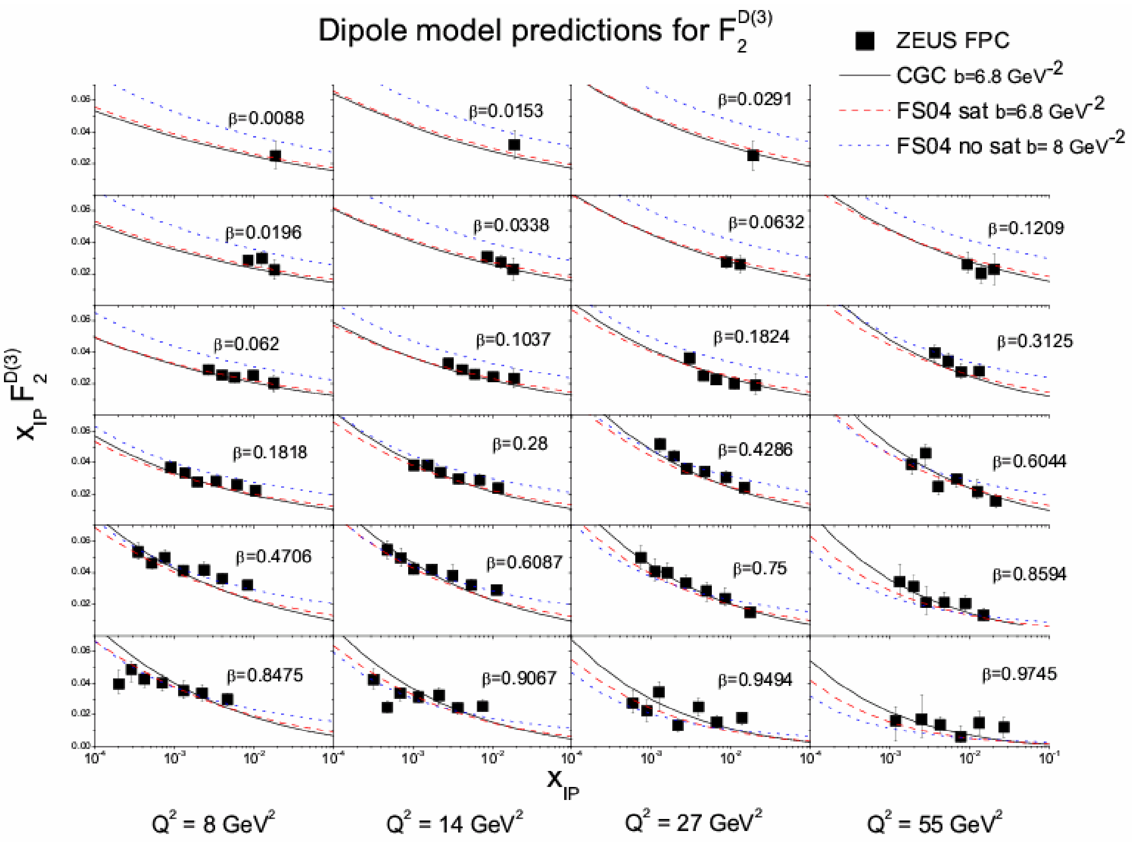
$F_{q\bar{q}}^T \propto \beta(1-\beta)$ -at medium β

$F_{q\bar{q}}^L \propto \beta^3(1-2\beta)^2$ -at high β (low M_x)

5 free model parameters

Model reasonably describes data

Comparison with theoretical models



Forshaw, Shaw → hep-ph/0411337

❑Diffraction is color singlet exchange between dipole and proton

➔fit F_2 data and predict $F_2^{D(3)}$

➔need gluon saturation at low x to describe data

Iancu, Itakura, Munier → hep/0310338

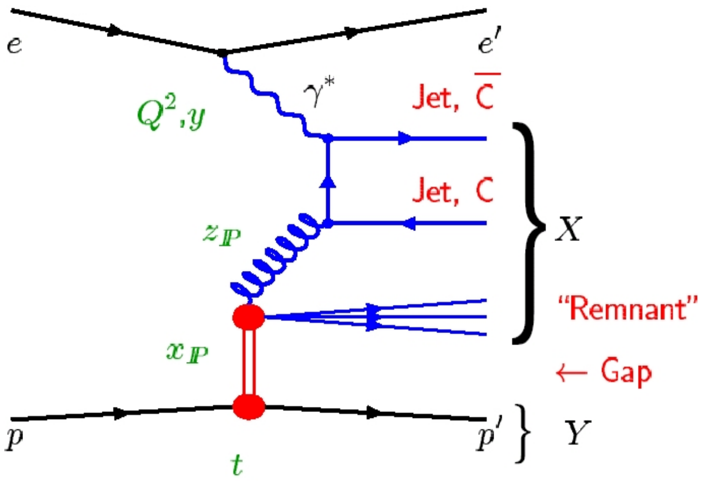
❑ Color glass condensate model:

➔non-linear saturation effects at high gluon densities

➔prediction consistent with data

Considerable theoretical interest to HERA diffractive data

Application of diffractive PDFs to hadronic final states

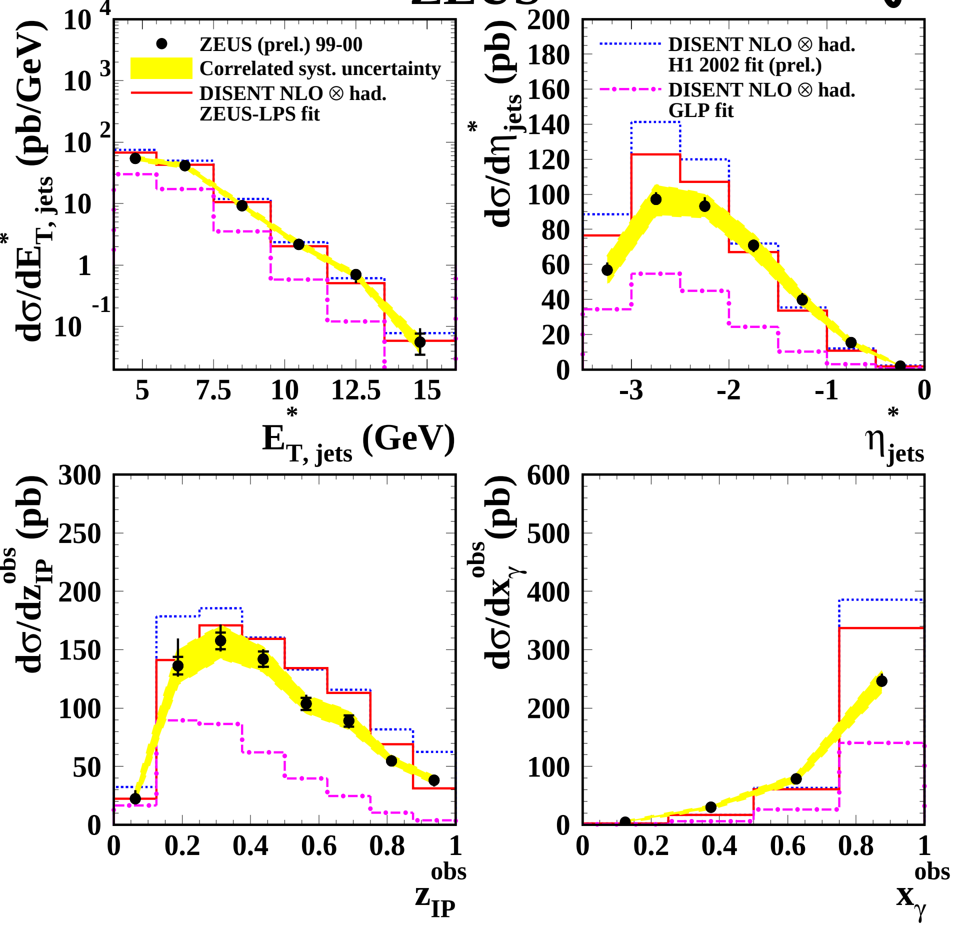


Test the universality of parton distributions extracted from the fits to F^D_2 - use the PDFs in the QCD calculations for other diffractive processes, e.g. diffractive jet and D* production

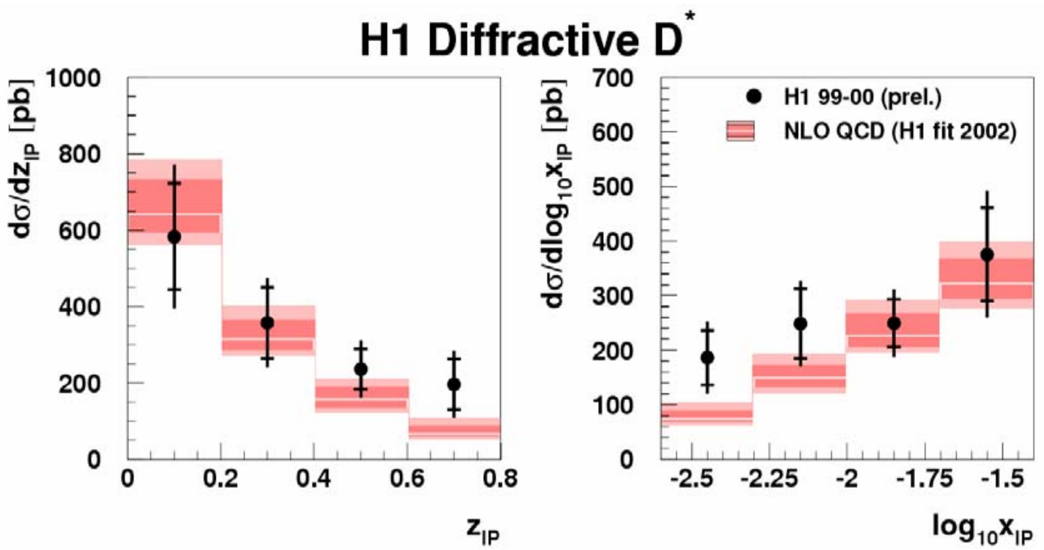
- cross sections are calculable in pQCD
- production mechanisms are directly sensitive to the gluon content of colour singlet exchange → give constrain of shape and normalization of gluon density in diffractive exchange
- can be compared to theoretical models and approaches

Comparison of NLO with diffractive jets and D* in DIS

ZEUS-diffractive dijets



H1 Diffractive D*



$$z_{I\!P} = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$

- NLO calculations with diffractive PDFs from the fits to F_2^D measurements provide in general a reasonable description of diffractive jets and D* in DIS

➔ suggest validity of QCD factorization in diffractive DIS

- However results depend on the choice of diffractive PDFs
- Situation is more complicated in photoproduction regime and in $p\bar{p}$:
  rescattering corrections, survival probability,… (see talk of Alessia Bruni)

Conclusions

- The partonic structure of diffraction is measured by H1 and ZEUS with improved precision and extended kinematical range
- Diffractive PDFs extracted from the NLO fits to the data:

  QCD factorization, NLO DGLAP evolution, dominated by gluons

  Differences between the measurements to be understood

- Considerable theoretical interest to HERA diffractive data
- Understanding of factorization breaking mechanism ep vs $p\bar{p}$ is needed to make predictions for the LHC (e.g. diffractive Higgs production)

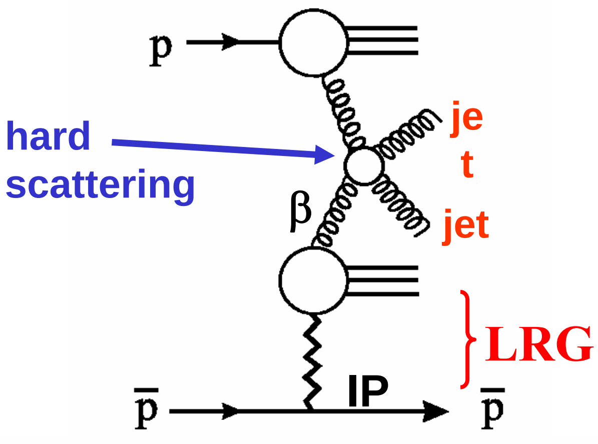
o Need better measurements and understanding of diffractive PDFs

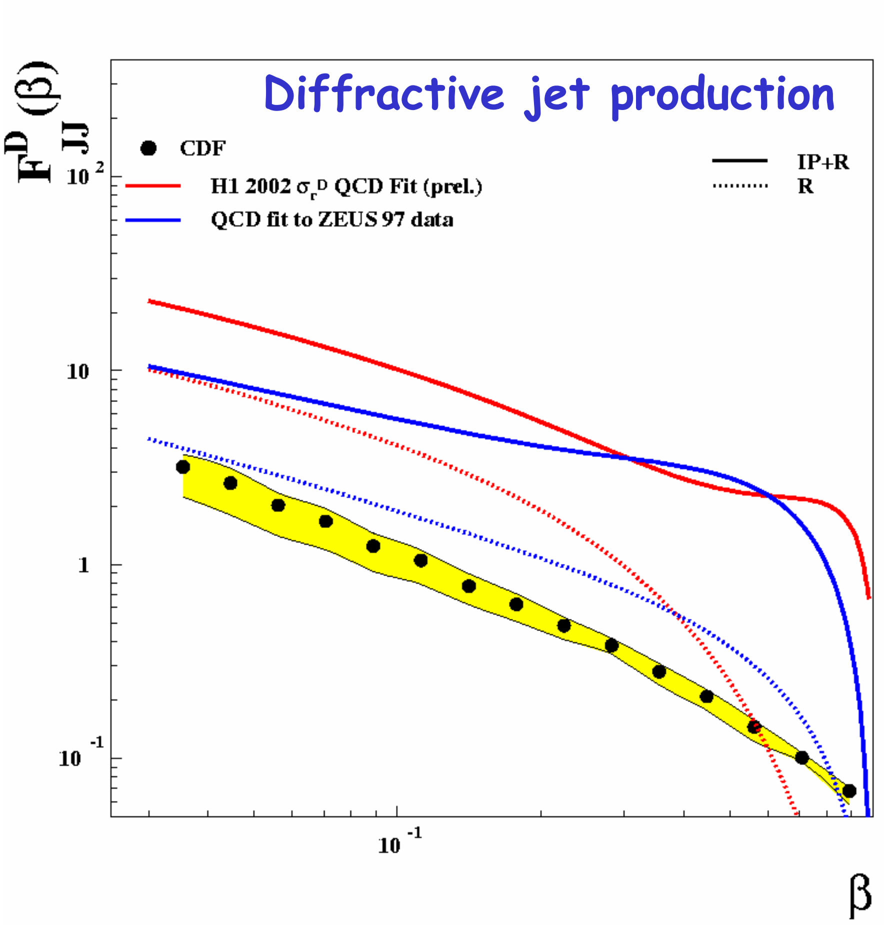
o Need diffractive PDFs in kinematic range relevant for LHC

- Outlook: presented results are based on HERA-1 data. More exciting results to come in HERA-2 - (x5 increase of integrated luminosity, new H1-VFPS detector with high acceptance for low x_{IP})

The End

$p\bar{p}$ (CDF) data vs H1/ZEUS PDF fits

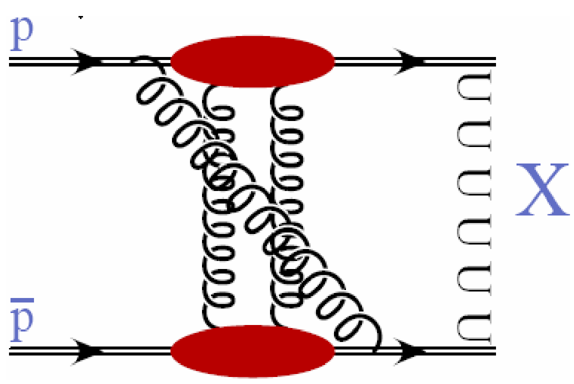




Use diffractive PDFs from HERA to predict cross sections at $p\bar{p}$

→ QCD factorization breaks in $p\bar{p}$ hard scattering

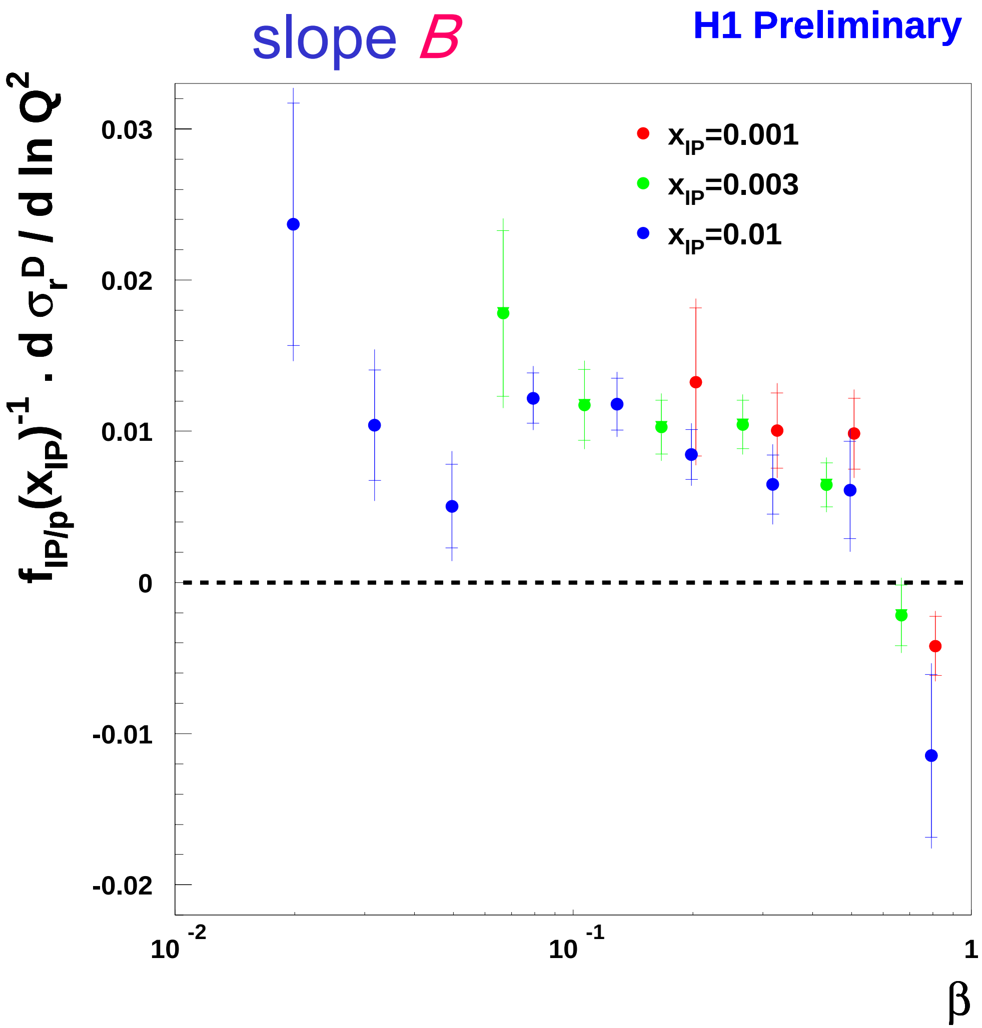
Factorization not expected to hold in $p\bar{p}$ due to soft rescattering of spectator partons.



Rapidity gap 'survival probability' due to multi-Pomeron exchange in $p\bar{p}$
But other approaches exist

(Kaidalov, Khoze, Martin, Ryskin; Goulianos; Gotsman, Levin, Maor,…)

Q^2 dependence of F_2^D → Scaling violations



Diffractive reduced cross section

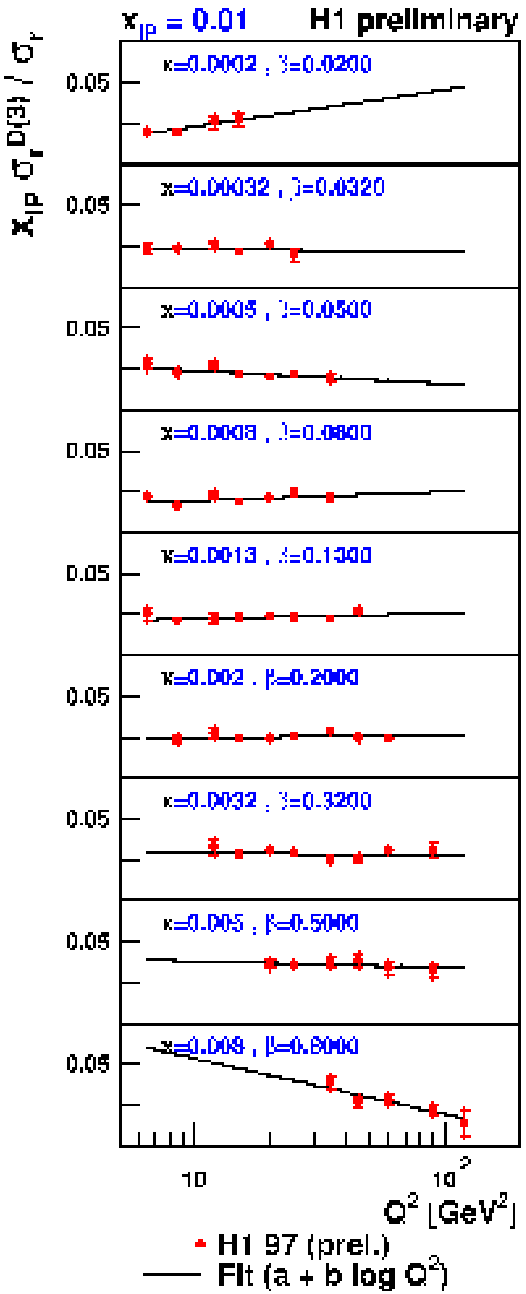
- quantify scaling violations at fixed x_{IP} and β:

$$\sigma_r^D = A + B \ln Q^2$$

$$B = d\,\sigma_r^D / d \ln Q^2$$

- large positive scaling violations up to β~0.6
  - ➔ large gluon contribution

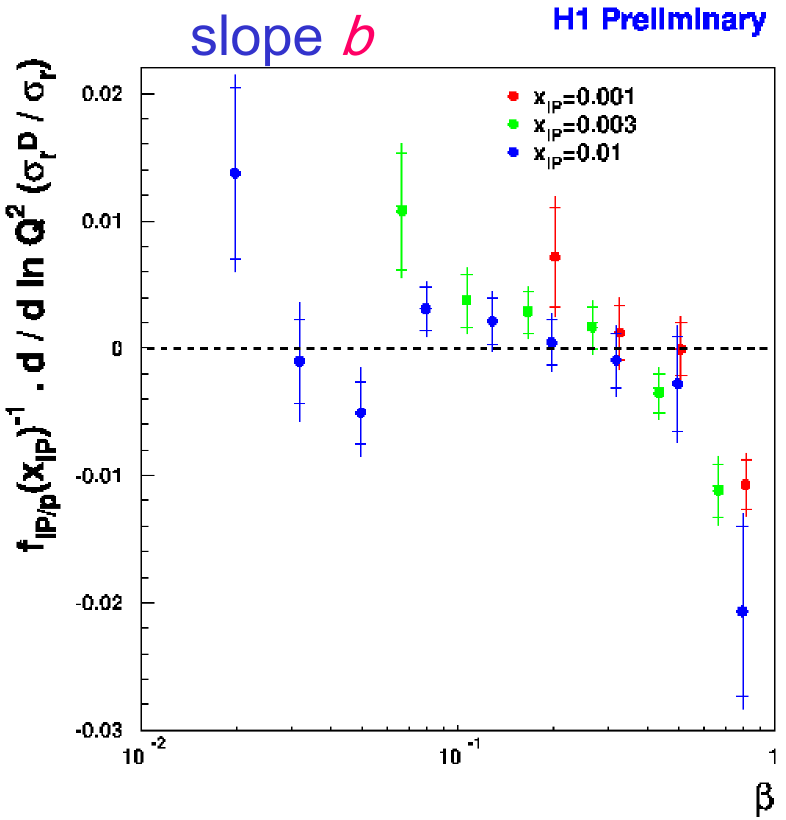
Ratio of diffractive to inclusive DIS cross sections



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

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

-reduced diffractive cross section



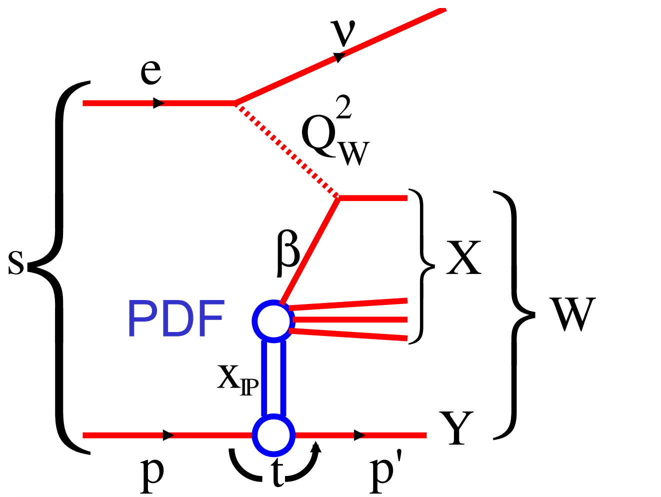
Fit Q^2 dependence at fixed x_{IP} and β:

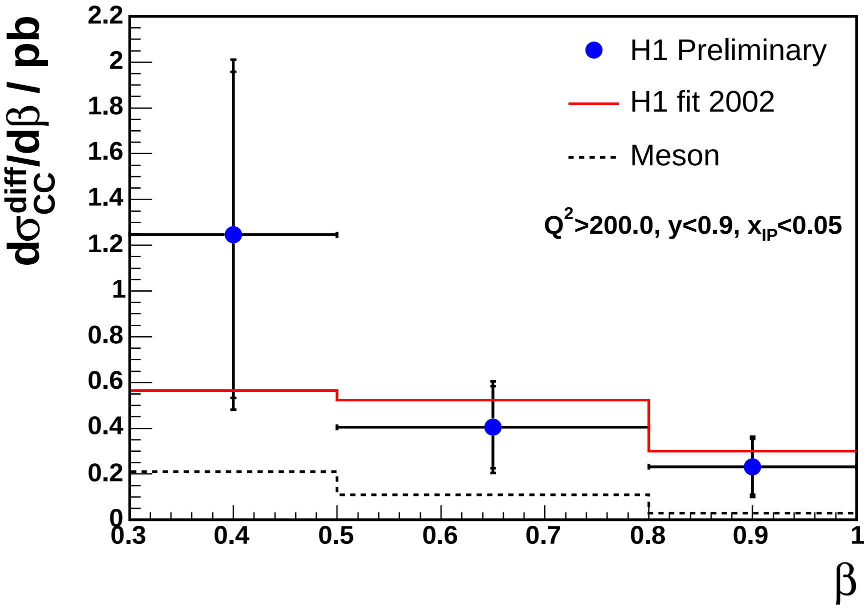
$R = a + b \ln Q^2$

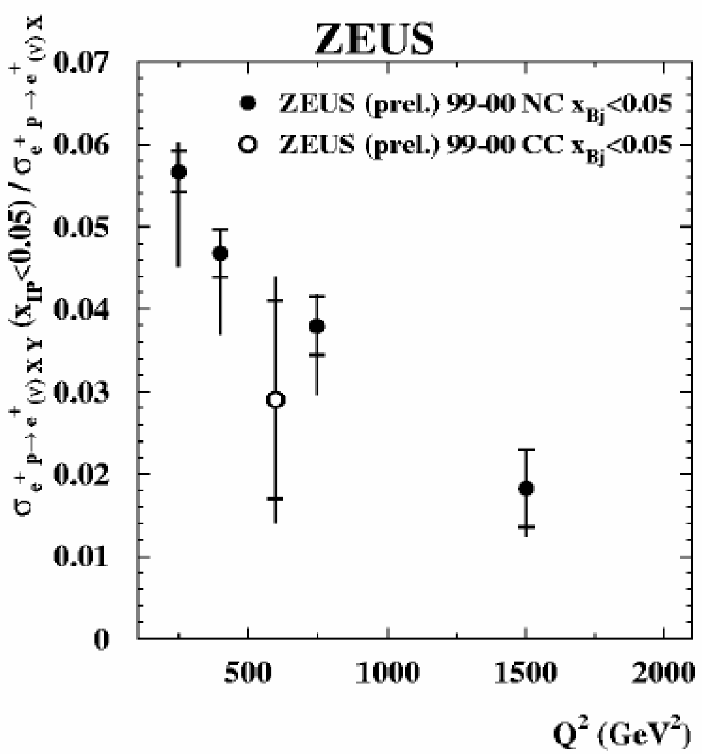
- ratio is flat vs Q^2 up to β~0.6
- similar Q^2 dynamics in diffractive and inclusive DIS
- consistent with ZEUS Q^2 dependence at low M_X

High Q^2 diffractive charged current events

Probe diffractive processes via weak interactions: $e^+p \rightarrow \nu W^+ p \rightarrow \nu XY$







Ratio of LRG to inclusive CC cross section:

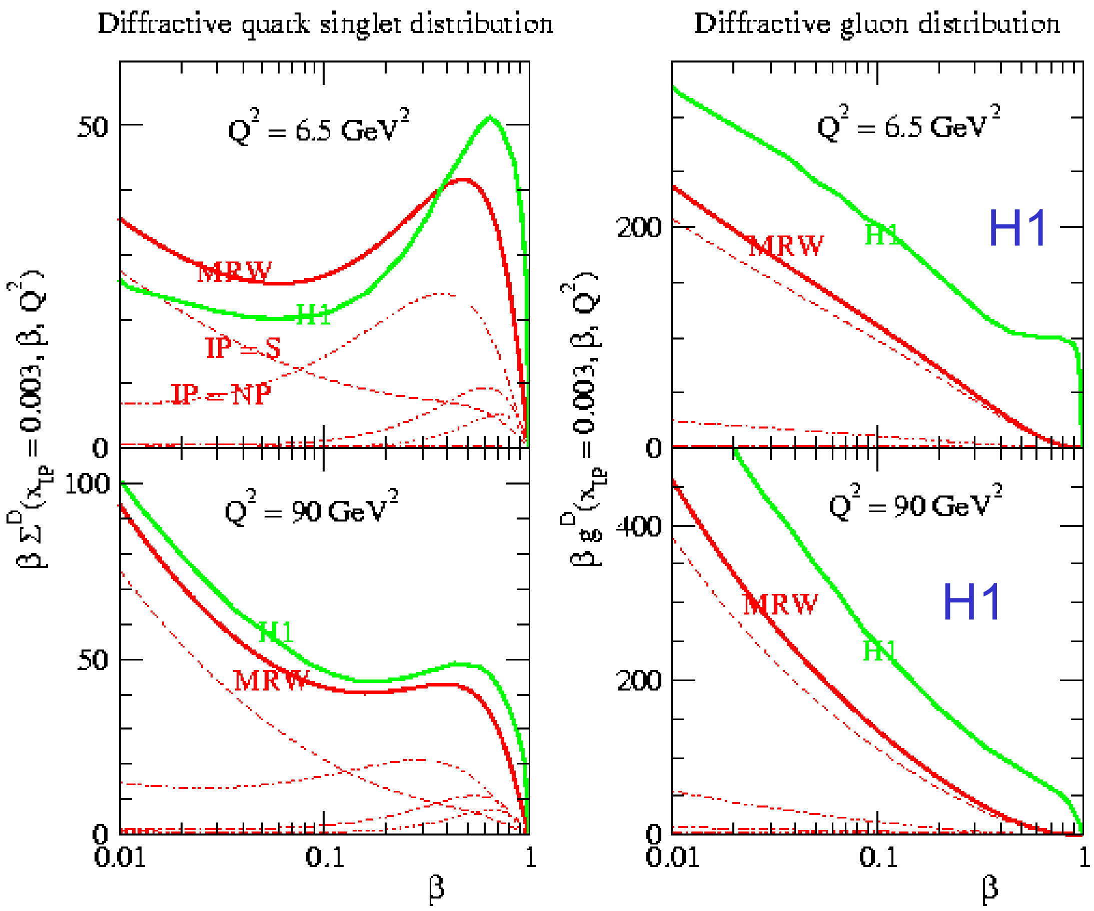
ZEUS: $\sigma^{CC}_{LRG} / \sigma^{CC}_{Incl}$= 2.9 ±1.2(st.)±0.8(sys)%
H1: $\sigma^{CC}_{LRG} / \sigma^{CC}_{Incl}$= 2.5 ±0.8(st.)±0.6(sys)%

➔good agreement between measurements

➔**Diffractive PDFs from QCD fits describe LRG CC cross sections**

More QCD NLO fits (MRW)

Martin, Ryskin, Watt → hep-ph/0412212



- Combined MRW analysis of F_2 and F_2^D
- Combined H1+ZEUS $F_2^{D(3)}$ data

$$F_2^{D(3)} = F_{2,P}^{D(3)} + F_{2,NP}^{D(3)} + F_{L,IP}^{D(3)} + F_{2,IR}^{D(3)}$$

$$F_2(x,Q^2) = F_2^{DGLAP}(x,Q^2) + \Delta F_2^{abs}(x,Q^2)$$

- No Regge factorization assumption
- Input quark singlet and gluon from LO QCD diagrams
- Non-linear power corrections slow down DGLAP evolution

→ smaller gluon than H1-2002 fit