Inclusive Diffraction at HERA: Diffractive pdf's and QCD factorization tests

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[DESY]

Contents:

- QCD factorization in diffraction
- Inclusive Diffractive DIS
- Determination of diffractive pdf's
- Factorization tests with jets and charm (HERA, Tevatron)

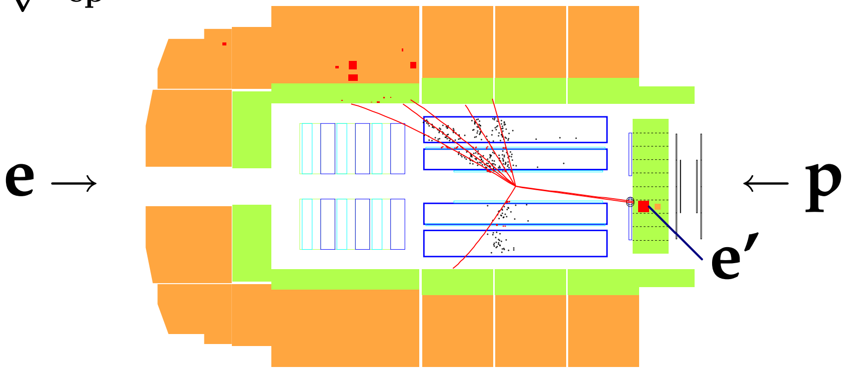
Diffraction at the LHC

Rio de Janeiro, April 2004

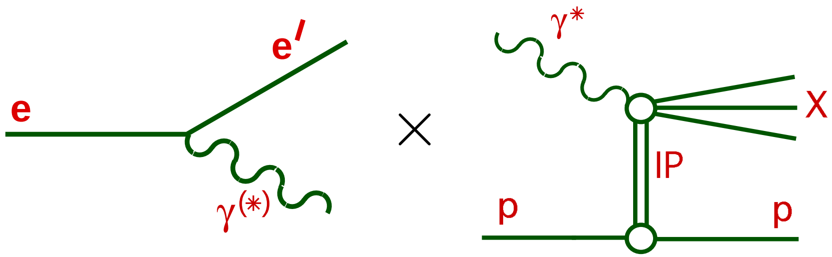
Diffraction at HERA

- HERA: An ideal laboratory to study **hard diffraction**:
- 10% of low-x DIS events are diffractive

$\sqrt{s_{ep}} = 320$ **GeV**



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



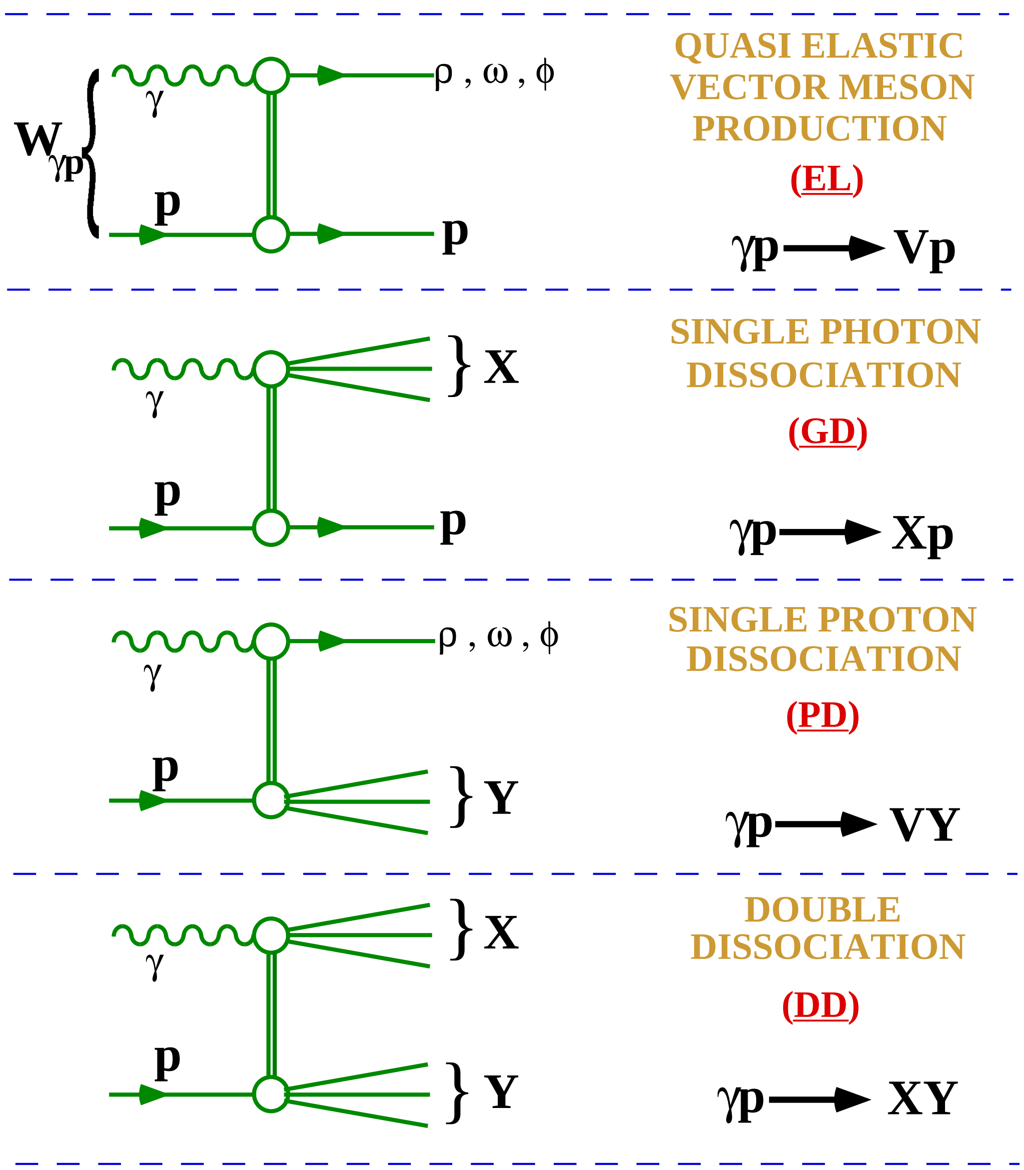
Virtual photon γ^* as a probe

- Inclusive DIS:
  Probe proton structure ($F_2(x, Q^2)$)
- Diffractive DIS:
  Probe structure of
  colour singlet exchange!

Why diffraction?

- Diffraction is significant part of σ_{tot}
- Novel tool to study **soft-hard transition in QCD**
- **Low-x structure of the proton**
  (e.g. saturation)

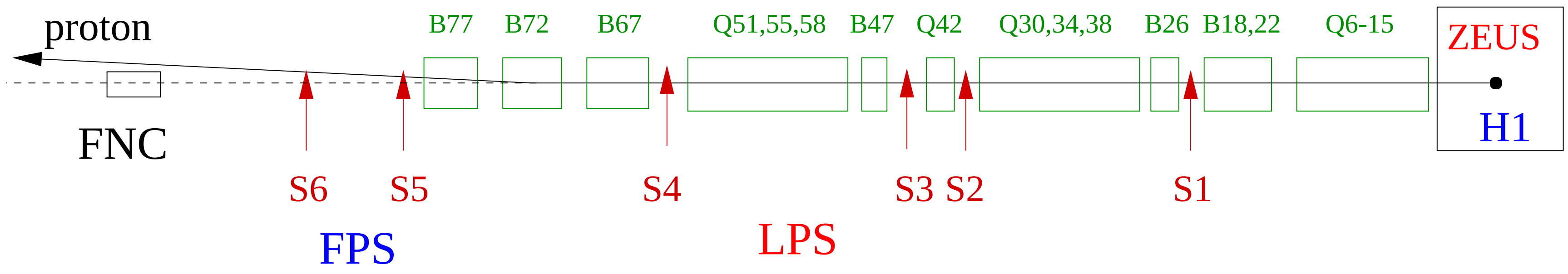
Diffractive Processes in γp Interactions



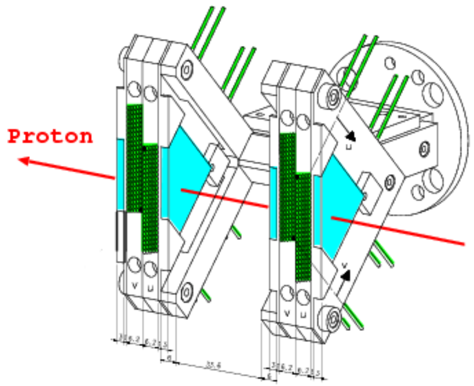
- All 4 processes can be measured with varying Q^2, W, t, M_X, M_Y
- large Q^2:
  γ^* probes diffractive exchange
  This talk!
- large $|t|$: perturbative QCD applicable to $I\!P$ (BFKL)?
- $Q^2 \sim 0$, $|t| \sim 0$:
  similar to soft hadronic diffraction

Exclusive diffraction (VM, DVCS, ...): see talk by Mara Soares!

Experimental Techniques



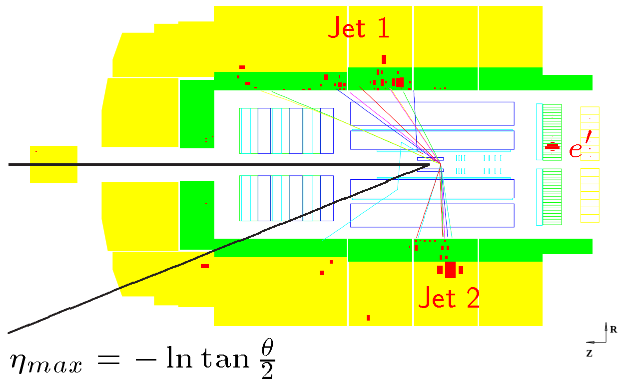
Forward Proton Spectrometers at $z = 24 \ldots 90$ m



Measure leading proton

- Free of dissociation bkgd.
- Measure p 4-momentum
- low statistics (acceptance)

Rapidity Gap Selection in central detector

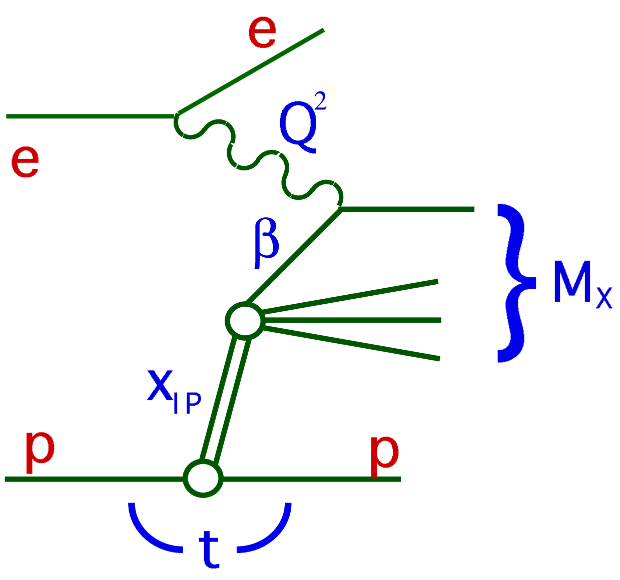


Require large rapidity gap

- $\Delta\eta$ large when $M_{\rm central} \ll W_{\gamma p}$
- integrate over outgoing p system
- high statistics (similar: M_X method)

Diffractive Cross section and Structure Functions

In a frame where the proton is moving fast:



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

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

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

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

– Longitudinal F_L^D: affects σ_r^D at high y

[γ inelasticity $y = Q^2/sx$]

– If $F_L^D = 0$: $\sigma_r^D = F_2^D$

Factorization in Diffraction

Diffractive pdf's / proof of QCD Factorization for diffractive DIS:

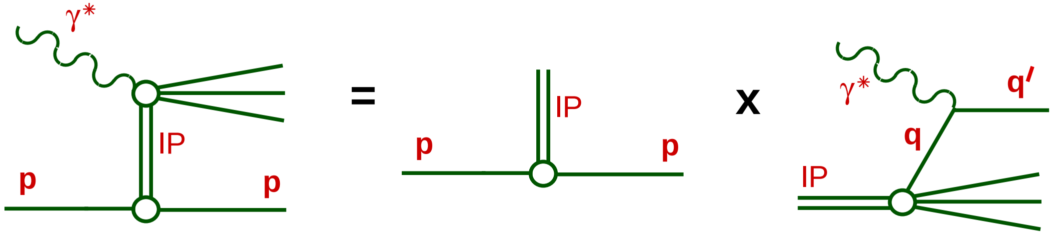
- Diffractive parton distributions (Trentadue, Veneziano, Berera, Soper, Collins, ...):

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

- $\hat{\sigma}^{\gamma^* i}$ hard scattering coeff. functions, as in incl. DIS
- p_i^D diffractive PDF's in proton, conditional probabilities, valid at fixed $x_{I\!P}$, t, obey (NLO) DGLAP

Ingelman-Schlein Model ('Resolved Pomeron' model):

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

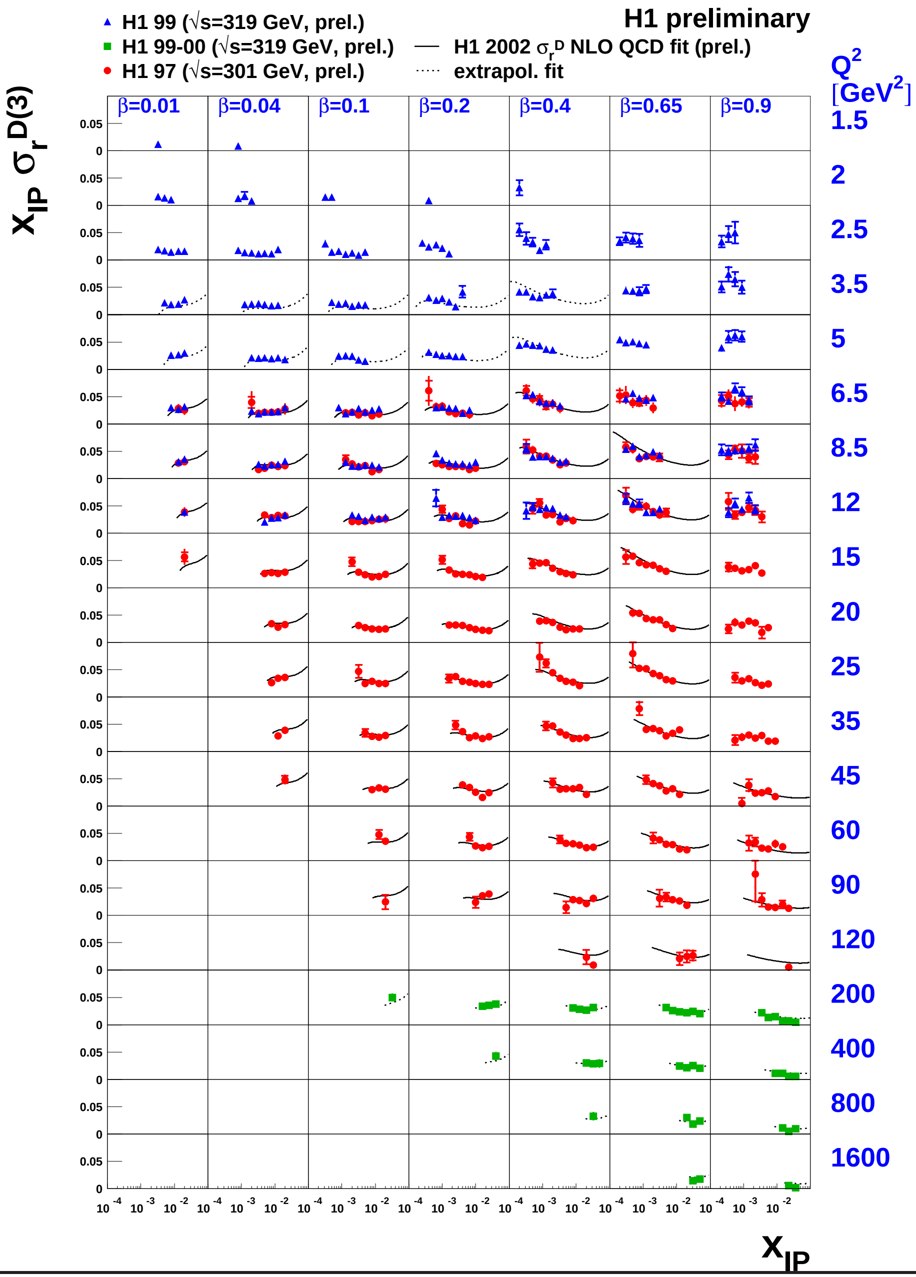


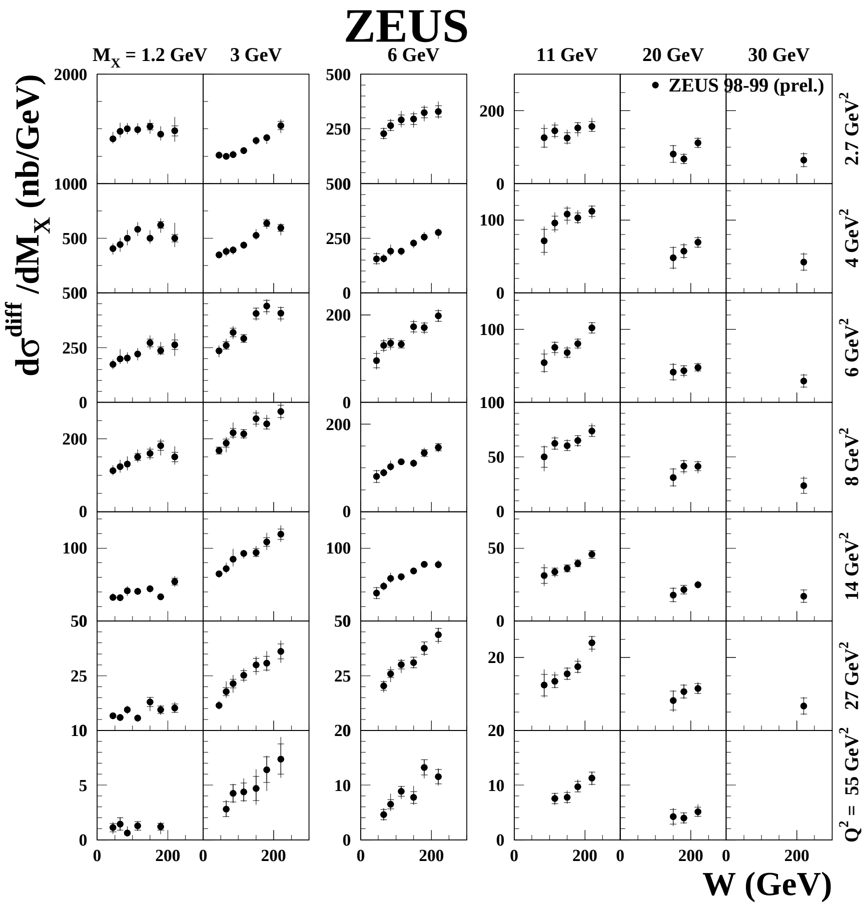
- additional assumption, no proof !
- consistent with present data if sub-leading $I\!R$ included

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

Shape of diffr. PDF's indep. of $x_{I\!P}$, t, normalization controlled by Regge flux $f_{I\!P/p}$

Recent Diffractive DIS cross section data





- Large kinematic range covered
- $1.5 < Q^2 < 1600\ \mathrm{GeV}^2$
- large stat. precision
- At low Q^2 limited by syst. err. from diffractive selection

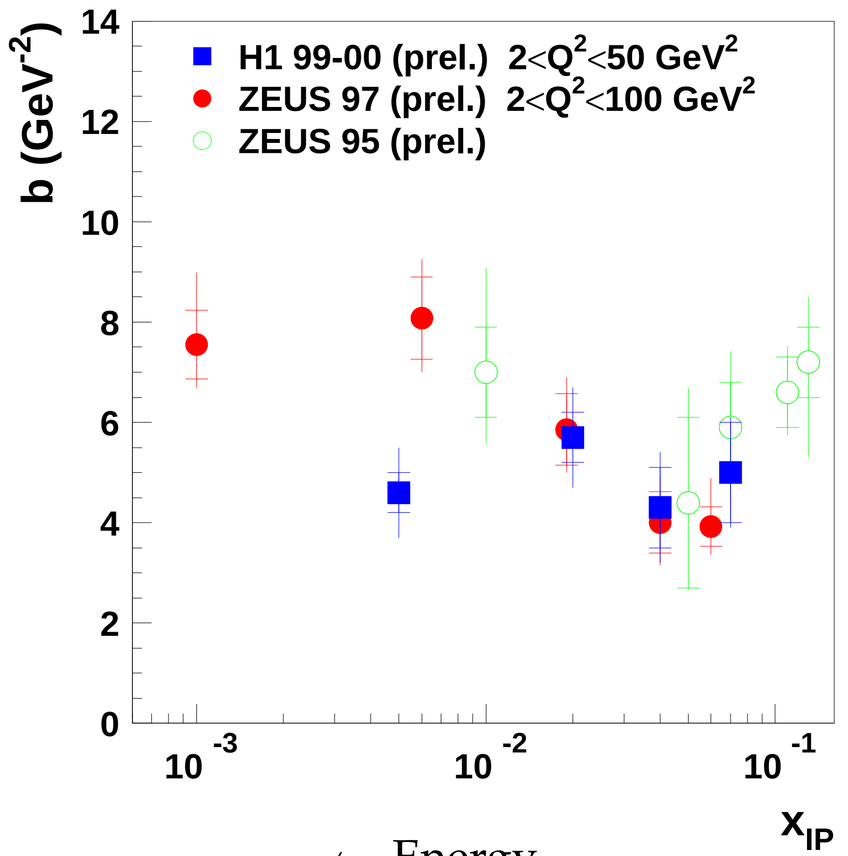
Forward Proton Detectors: t Measurement

$\frac{d\sigma}{d|t|}$ measured for $-0.4 \lesssim t < |t|_{\min}$

Exponential fit to t distribution:

$$\frac{d\sigma}{d|t|} \sim e^{-b|t|}$$

b is related to
the interaction radius: $b = R^2/4$



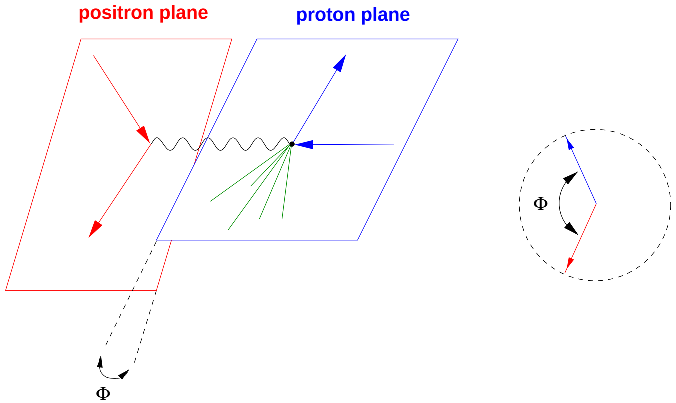
$\leftarrow$ Energy

In Regge phenomenology expect 'shrinkage':
(proton gets 'bigger' with increasing energy)

$$b = b_0 + 2\alpha' \log \frac{1}{x_{I\!P}} \qquad x_{I\!P} \sim M_X^2/W_{\gamma p}^2$$

So far inconclusive ...

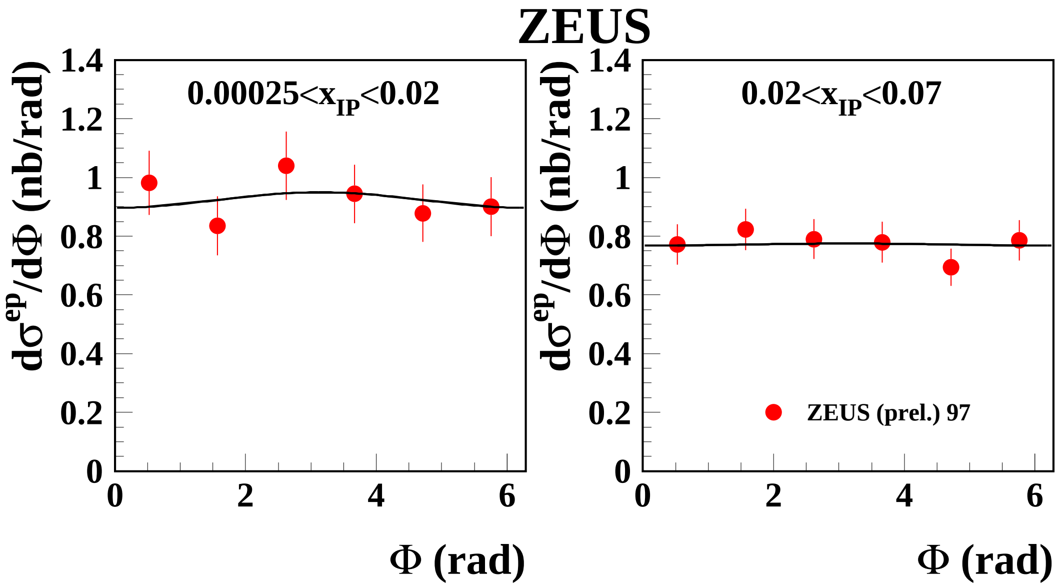
Forward Proton Detectors: ϕ Measurement



Φ: Azimuthal angle between electron and proton scattering planes

$\frac{d\sigma^D}{d\Phi}$ sensitive to σ_L^D through interf. term:

$$\frac{d\sigma^D}{d\Phi} \sim \sigma_T^D + \epsilon\sigma_L^D - 2\sqrt{\epsilon(1+\epsilon)}\sigma_{LT}^D \cos\Phi - \epsilon\sigma_{TT}^D \cos 2\Phi$$



Measured asymmetries from fit $\frac{d\sigma}{d\Phi} \sim 1 + A_{LT}\cos\Phi$:

$A_{LT} = -0.029 \pm 0.066^{+0.026}_{-0.047}$
$(0 \lesssim x_{I\!P} < 0.02\,;\ \beta \approx 0.32)$

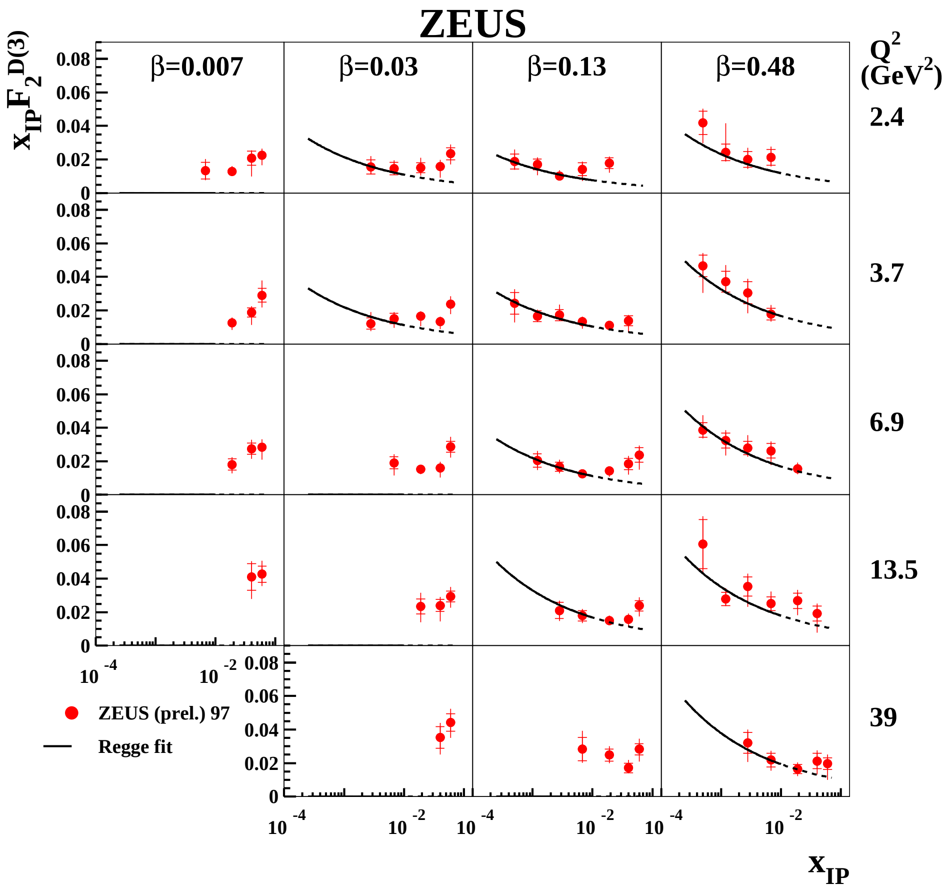
$A_{LT} = -0.005 \pm 0.052^{+0.048}_{-0.047}$
$(0.02 < x_{I\!P} < 0.07\,;\ \beta \approx 0.1)$

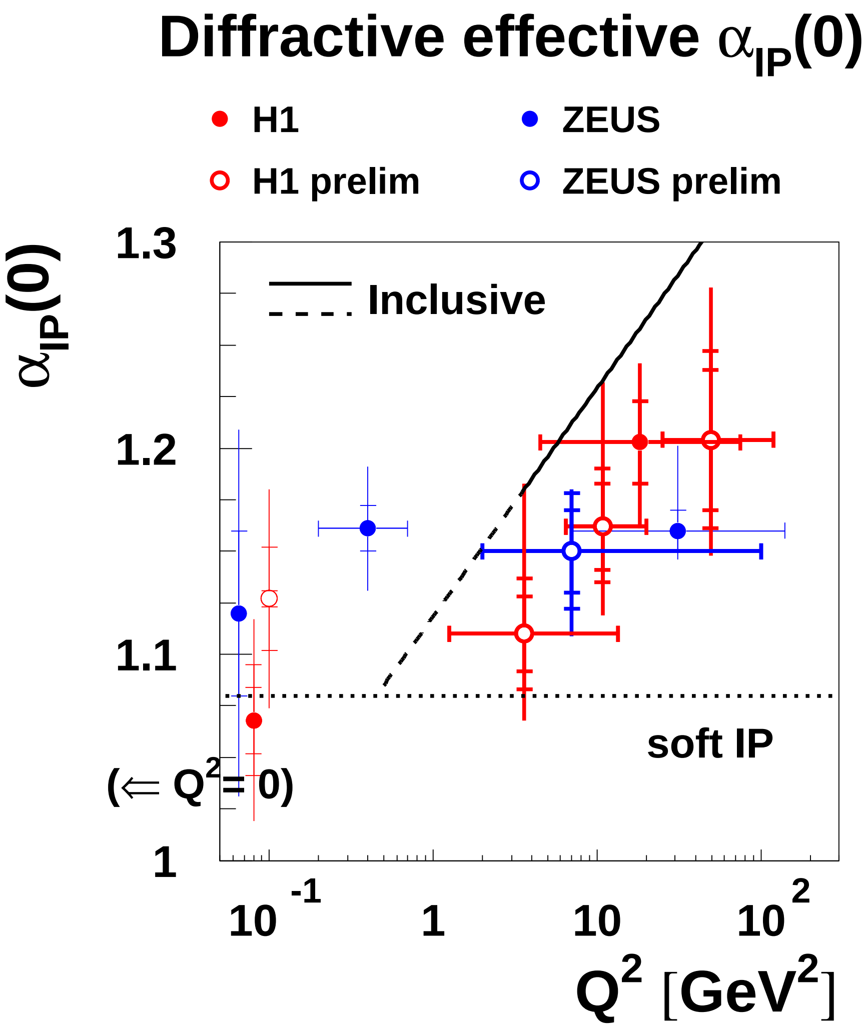
⇒ Interference term small in measured region

[Interesting high β region (pert. 2-gluon exch. predicts large asymmetry) not yet explored]

Energy dependence and $\alpha_{I\!P}(0)$

Example: ZEUS LPS data





Fit to $x_{I\!P}$ dependence:

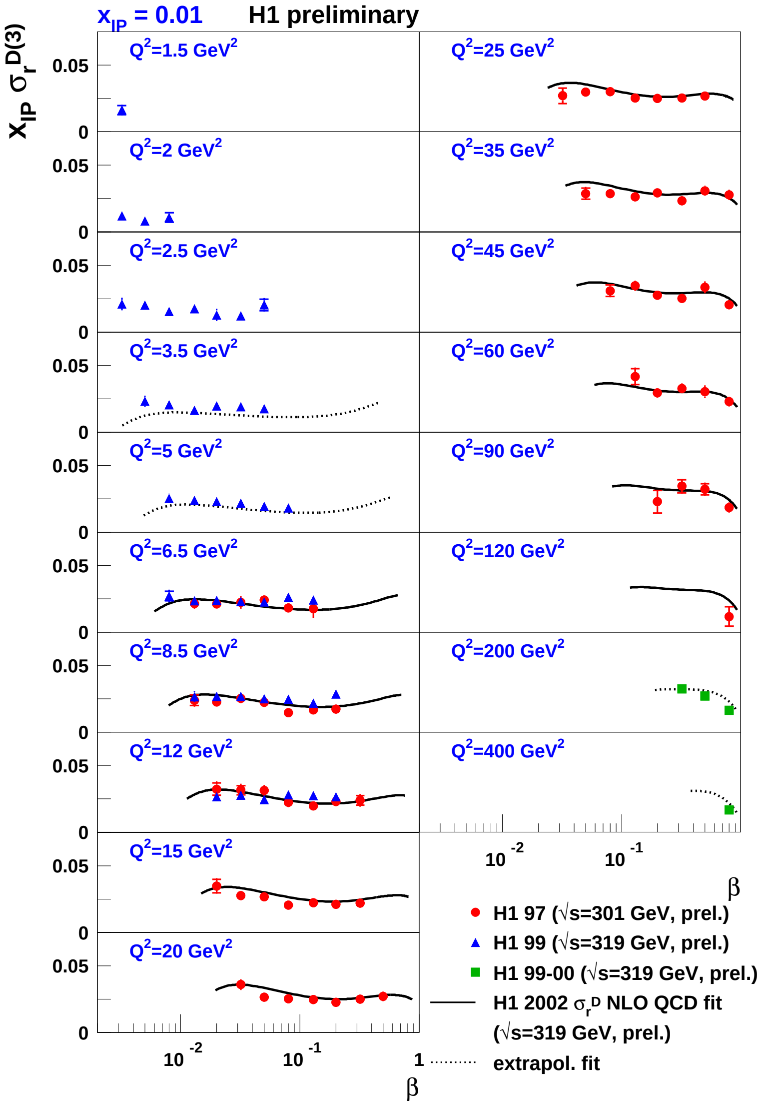
$$F_2^D(x_{I\!P}, \beta, Q^2) = \left(\frac{1}{x_{I\!P}}\right)^{2\overline{\alpha_{I\!P}}-1} \cdot A(\beta, Q^2)$$

Indications for increase with Q^2 ?

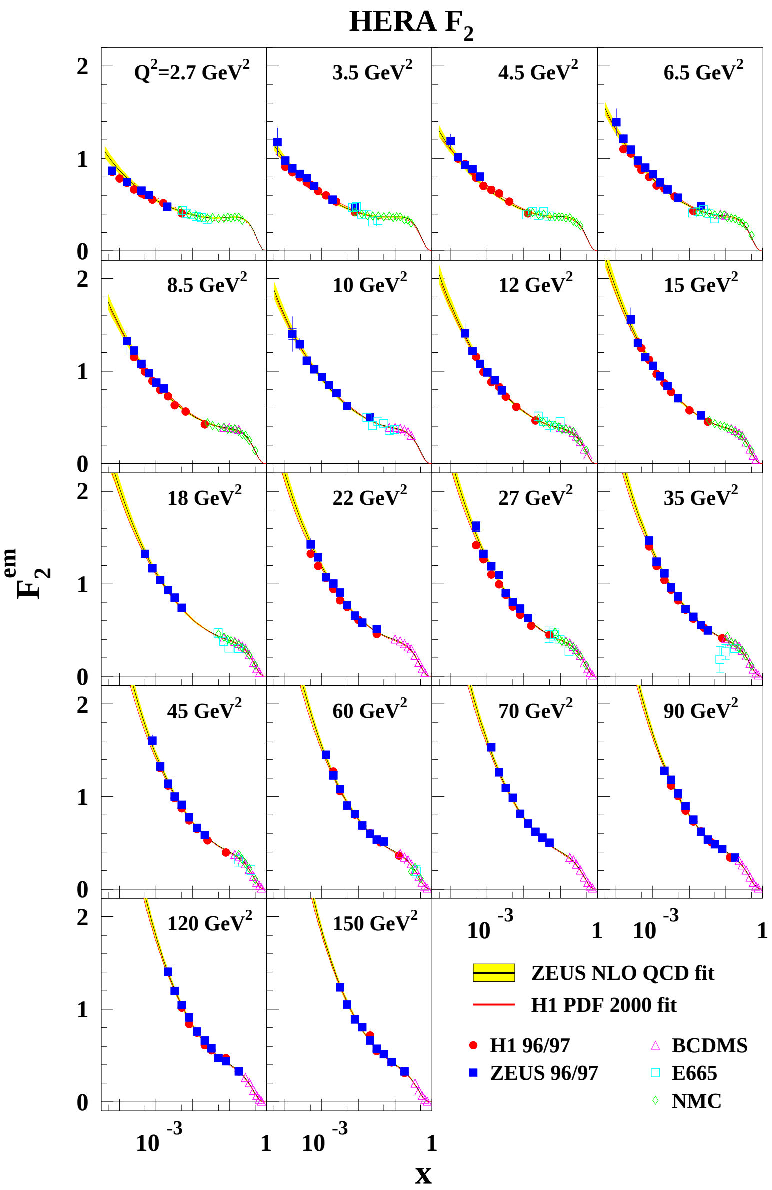
Naive expectation $\alpha_{I\!P}^{\text{diff.}}(0) = 2\ \alpha_{I\!P}^{\text{inc}}(0)$ fails in DIS region?

Comparision diffractive vs inclusive: β or x dependence

Diffractive:



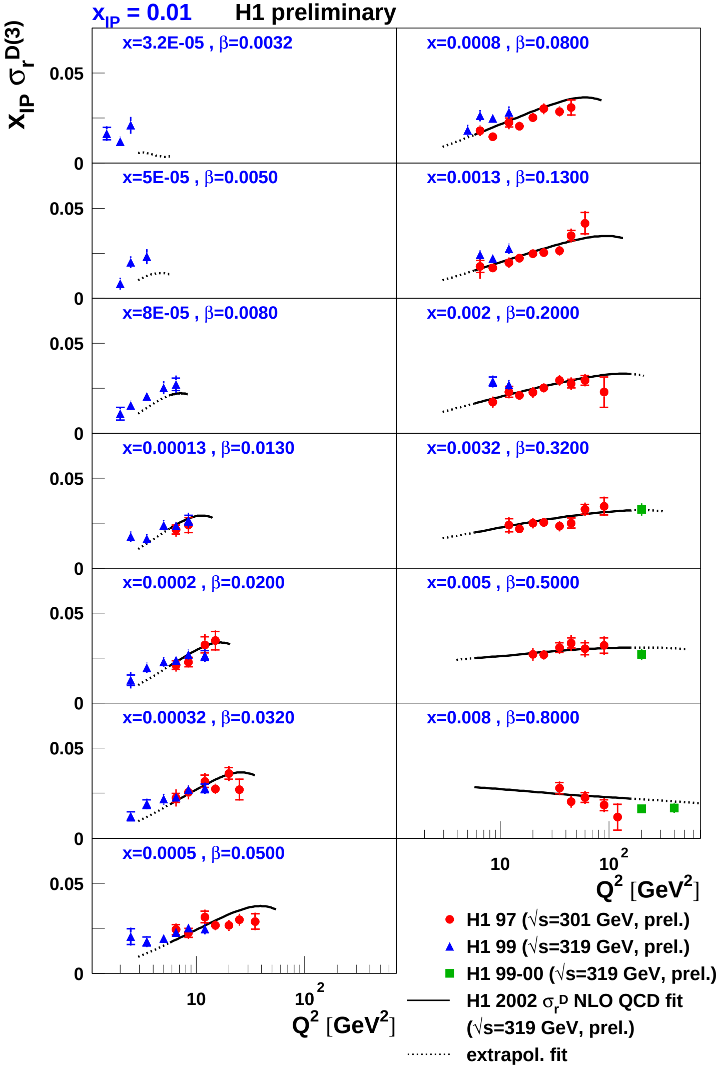
Proton:



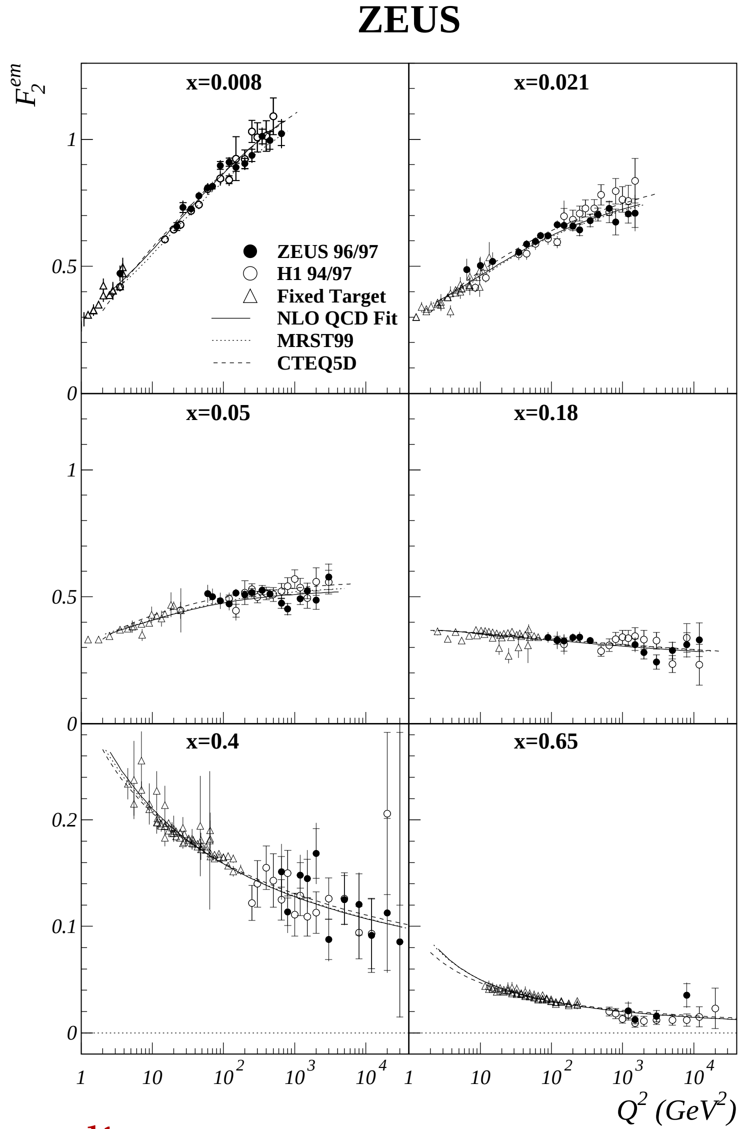
⇒ Only weak β dependence! Similar to photon ...

Comparision diffractive vs inclusive: Q^2 dependence

Diffractive:



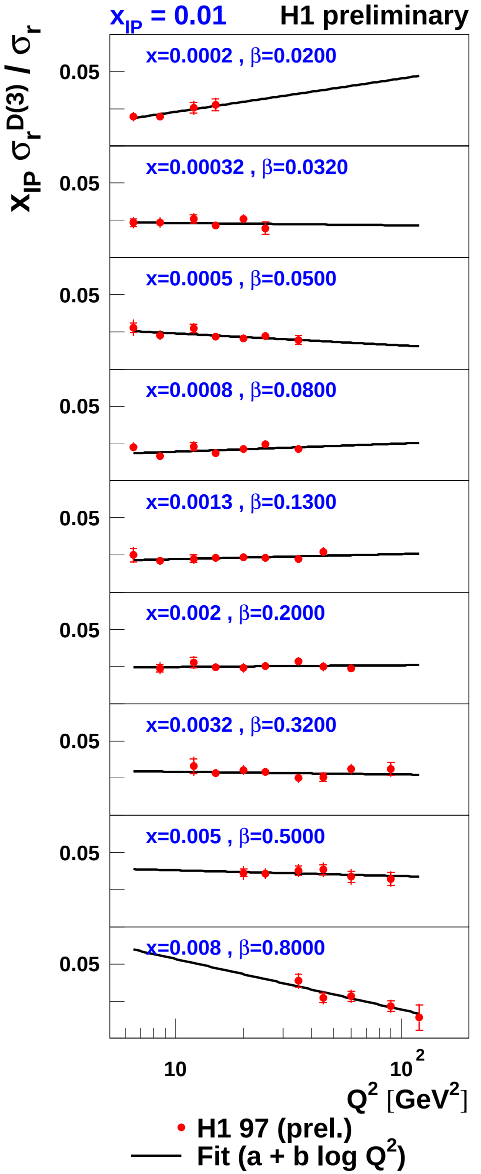
Proton:

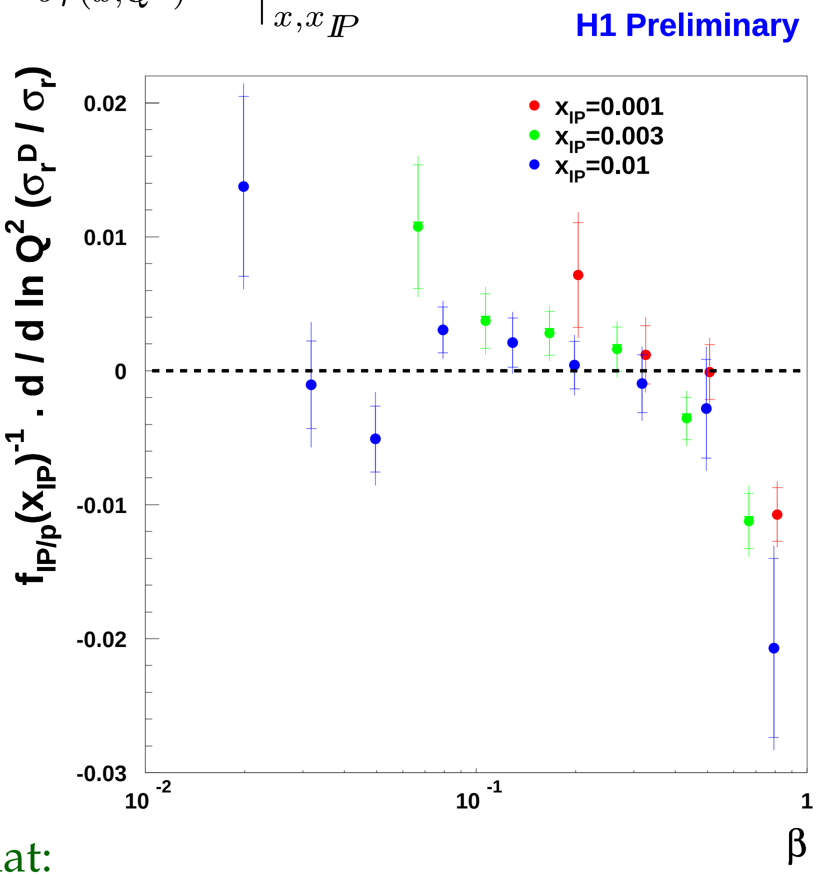


⇒ +ve scaling violations to highest β: Gluon dominated!

Ratio Diffractive / Inclusive: Q2 dependence (H1)

Logarithmic Q^2 dependence of the ratio $\left.\frac{\sigma_r^{D(3)}(x,Q^2,x_{I\!P})}{\sigma_r(x,Q^2)}\right|_{x,x_{I\!P}} \sim A_R + B_R \log Q^2$





Low β: rel. flat:

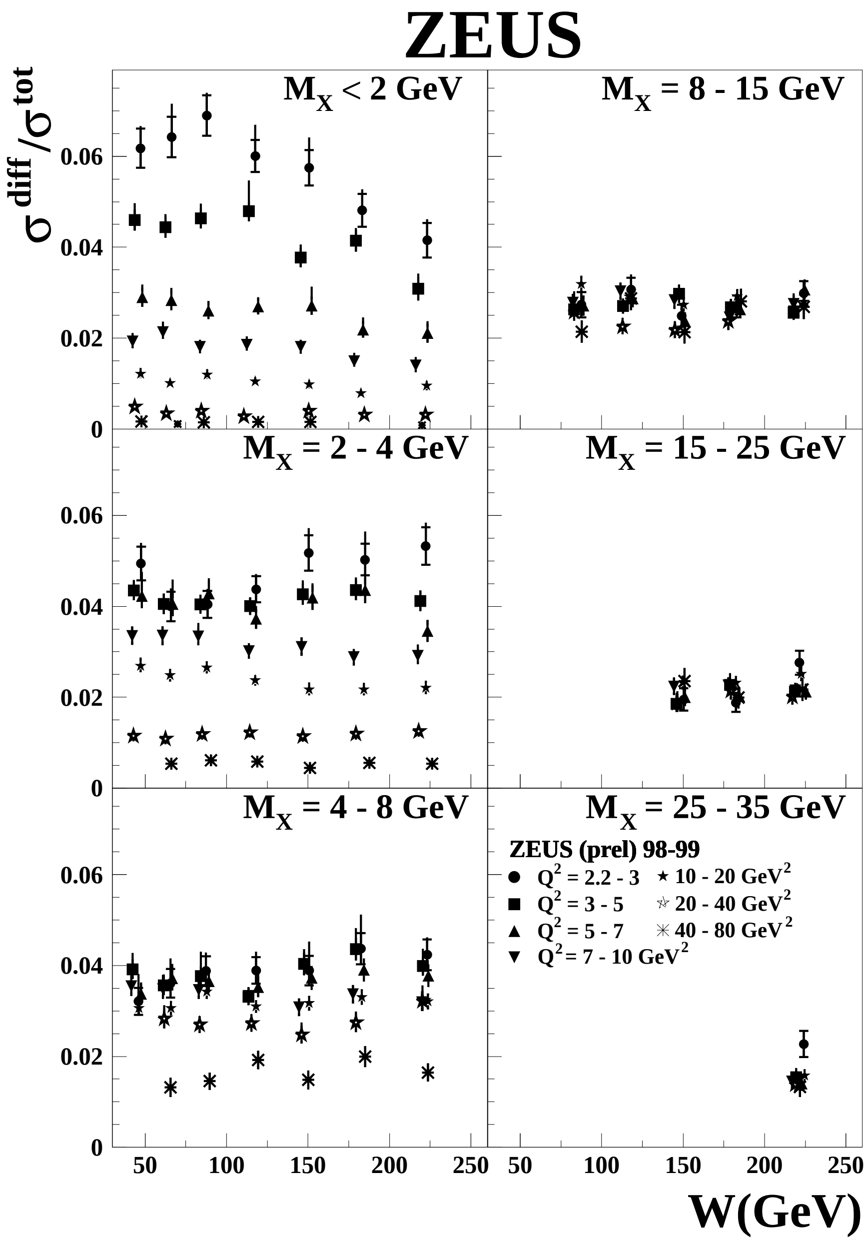
– ratio of diffr. to incl. $g(x, Q^2)$ constant

– diple models (IF $\sigma_{dipole} \propto R$)

As $\beta = 1$: falling:

– Q^2-suppressed higher twist (pert. 2-gluon exchange)

– DGLAP evolution (gluon radiation)



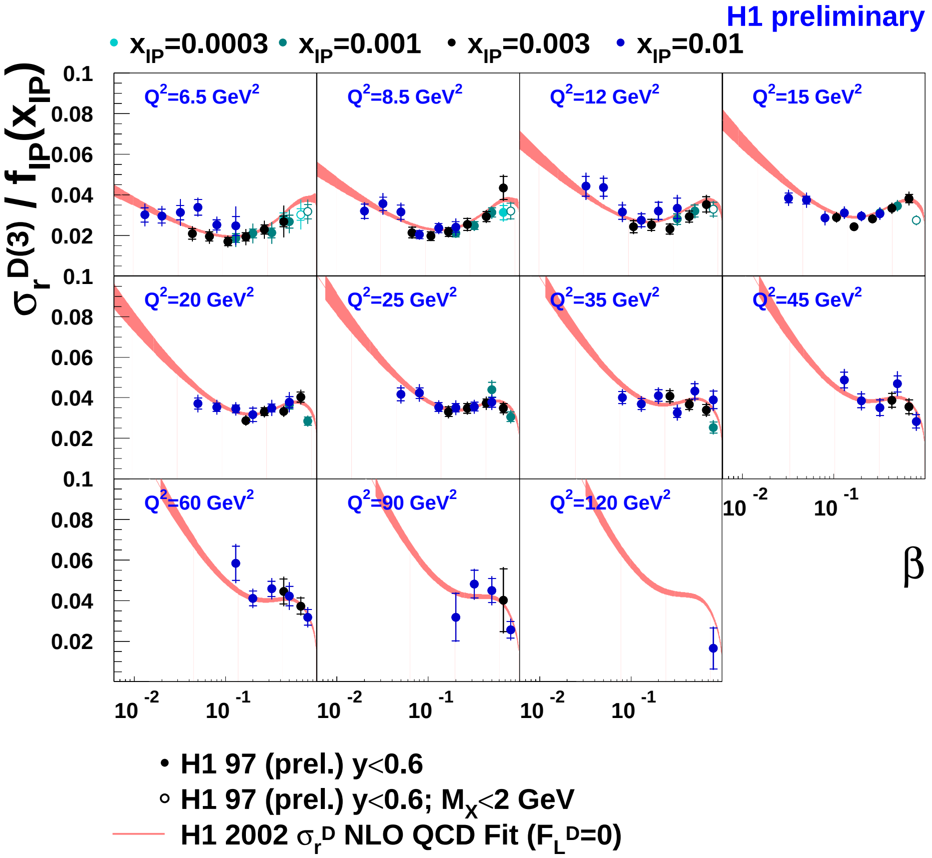
Diffractive / Inclusive: Ratio from ZEUS

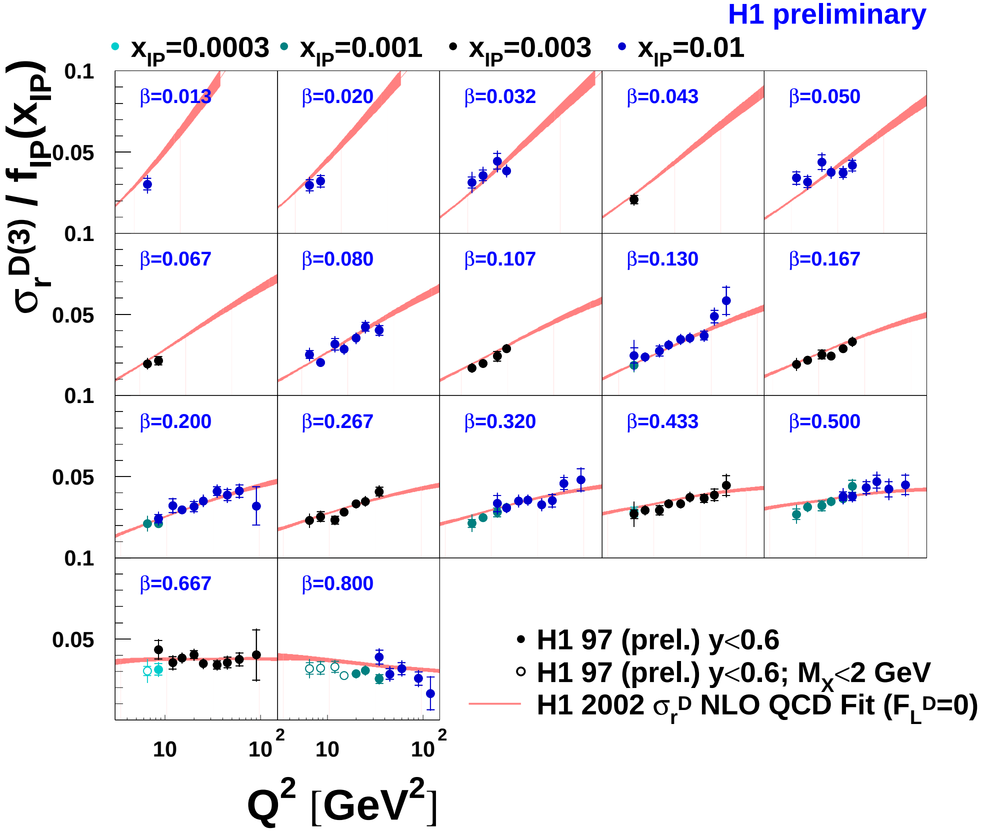
Similar features observed:

- little Q^2 dependence at high M_X ($\sim$ low β)
- strong (negative) Q^2 dependence at small M_X ($\sim$ high β)

Precise H1 Measurement of β, Q^2 dependences

Prerequisite for NLO DGLAP QCD fit:





β dep.: $\sim \sum_i e_i^2 (q_i^D + \bar{q}_i^D)$ $d\sigma / d \ln Q^2$: $\sim \alpha_s \otimes g^D(\beta, Q^2)$

– $x_{I\!P}$ dep. taken out: factorization holds for $x_{I\!P} < 0.01$
– rising for $\beta \to 1$ at low Q^2
– positive scaling violations expect for largest β (gluon dominance)

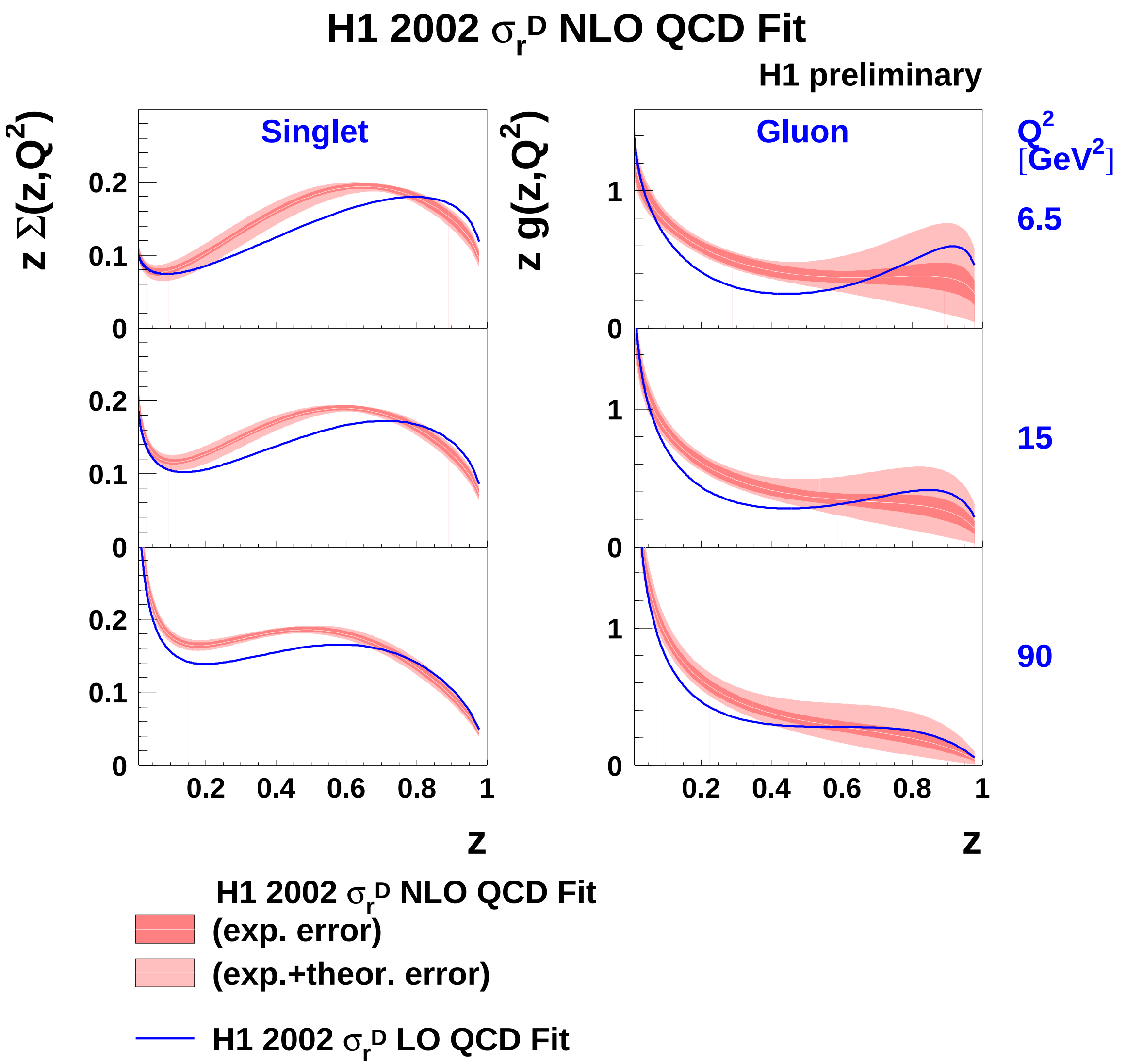
NLO DGLAP QCD Fit (H1)

QCD Fit Technique:

- factorize $f(x_{I\!P})f(z,Q^2)$
- Singlet Σ and gluon g parameterized at $Q_0^2 = 3\ \mathrm{GeV}^2$
- NLO DGLAP evolution
- Fit data for $Q^2 > 6.5\ \mathrm{GeV}^2$, $M_X > 2\ \mathrm{GeV}$
- For first time propagate exp. and theor. uncertainties !

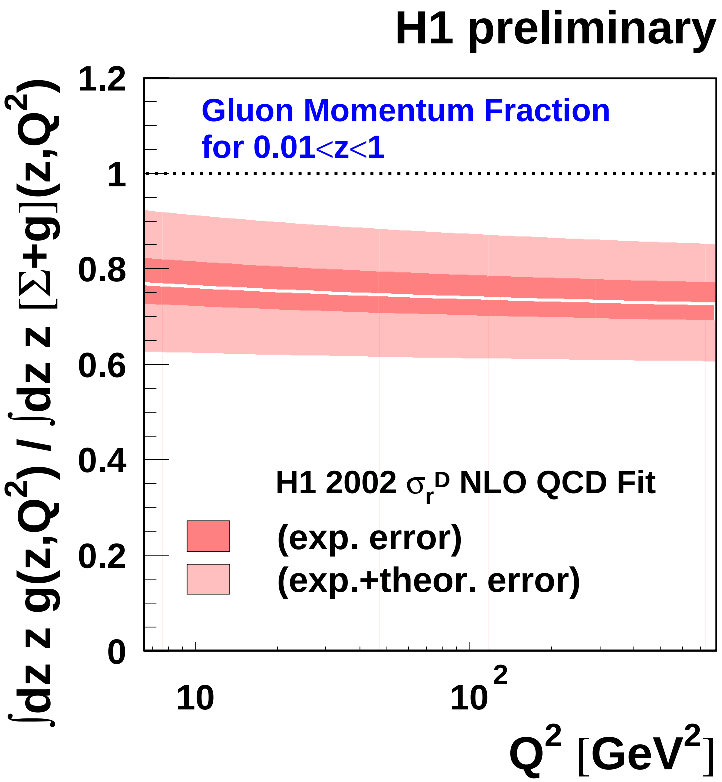
PDF's of diffractive exchange:

- Extending to large fractional momenta z
- Gluon dominated
- Σ well constrained
- substantial uncertainty for gluon at highest z
- Similar to previous fits



H1 NLO QCD Fit: Gluon fraction and F_L^D

Integrate PDF's over measured range:

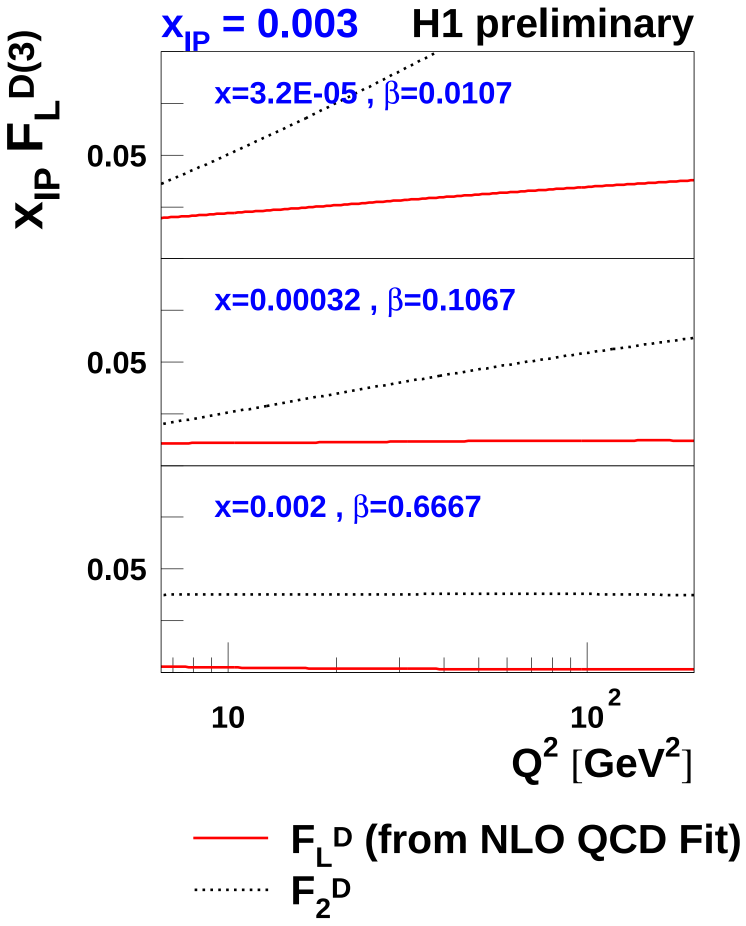


Momentum fraction of diffractive exchange carried by gluons:

$$75 \pm 15\%$$

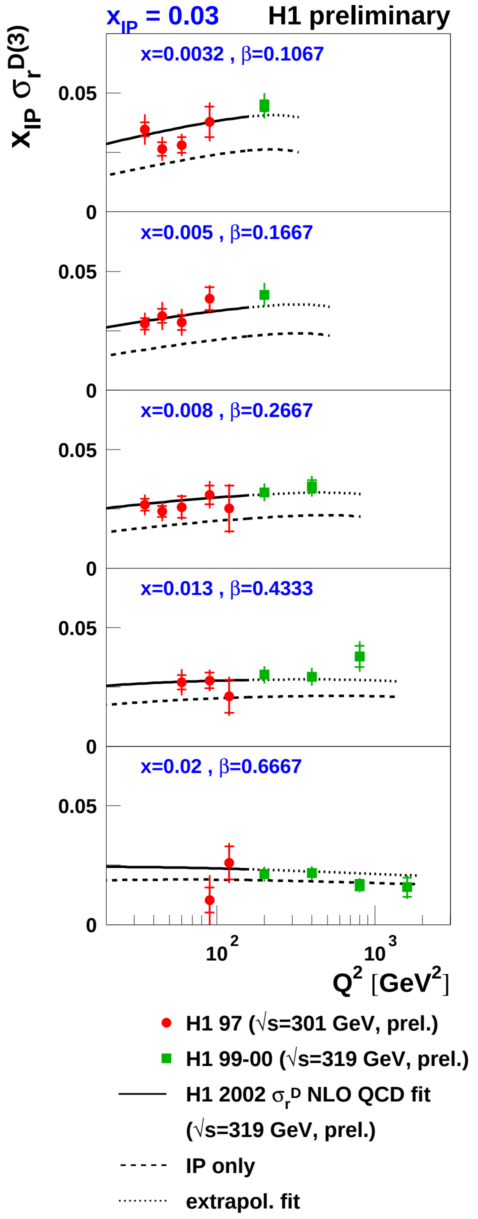
Longitudinal F_L^D:

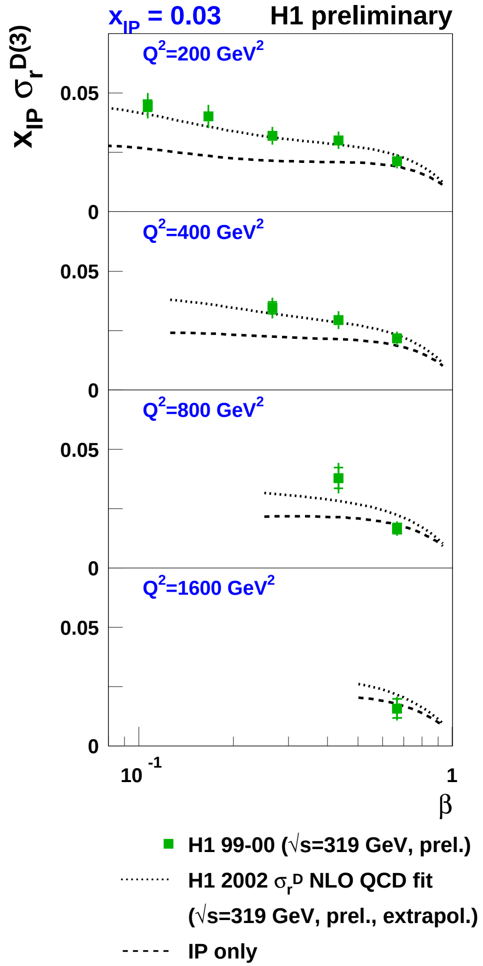
$$F_L^D \sim \frac{\alpha_S}{2\pi}\left[C_q^L \otimes F_2^D + C_g^L \otimes \sum_i e_i^2\, zg^D(z,Q^2)\right]$$



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

Extrapolation of QCD fit to high Q^2

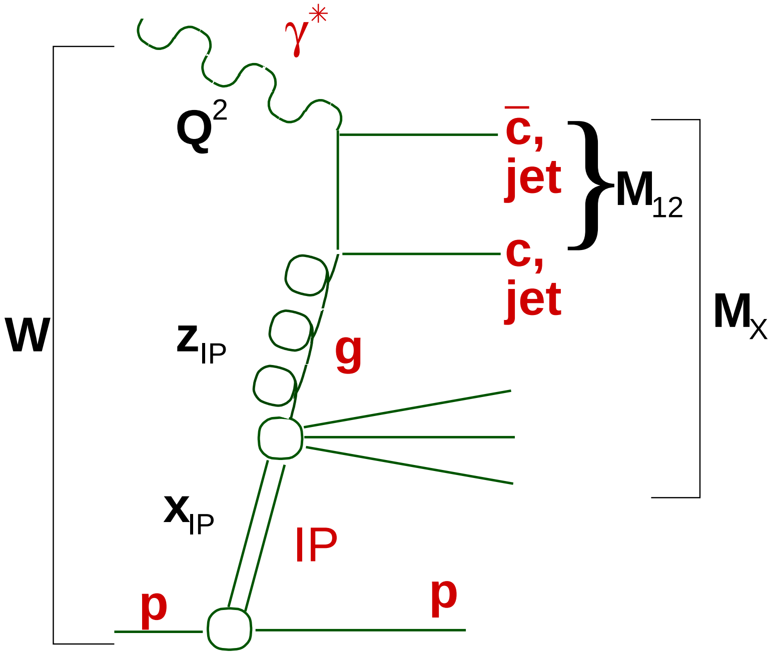




- New diffractive cross section data for $200 < Q^2 < 1600 \text{ GeV}^2$
- Well described by evolved pdfs extracted from lower Q^2 data

Jet and Open Charm Production in Diffractive DIS

Test QCD factorization by applying dpdf's to final state cross sections ...



Q^2: Photon virtuality
W: $\gamma^* p$ CMS energy

M_X: mass of diffractively produced system

$M_{12} = \sqrt{\hat{s}}$: mass of two jets / $c\bar{c}$ pair

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

momentum fraction of diffractive exchange w.r.t. proton

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

momentum fraction of diffractive exchange entering hard process

$\longrightarrow$ High sensitivity to diffractive gluon distribution!

- high p_T jet production
- $c \longrightarrow D^*$ Meson production

NLO Calculations for Diffractive Final States

- So far mostly LO Monte Carlo programs with parton showers used
- QCD factorization: Hard scattering cross section same as for normal DIS
- NLO important to describe non-diffractive Jet production

$\rightarrow$ use standard NLO programs for jets and heavy quarks in DIS ($\mathcal{O}(\alpha_s^2)$)

Diffractive DIS Jets:

Use DISENT (Seymour)
c.f. Hautmann [JHEP 0210 (2002) 025]

Calculate NLO cross section at fixed $x_{I\!P}$ by running with reduced $E_p = x_{I\!P} E_{p,nom.}$

Use diffractive pdf $p_{i/I\!P}(z, \mu^2)$

Mul. w/ flux $f_{I\!P}(x_{I\!P}) = \int \mathrm{d}t f_{I\!P}(x_{I\!P}, t)$

Data integrated over $x_{I\!P}$:
"$x_{I\!P}$ slicing"

Diffractive DIS D^*:

Diffractive version of HVQDIS (Harris, Smith) by Alvero, Collins, Whitmore [hep-ph/9806340]

$x_{I\!P}$, t integration numerically

NLO Calculation in massive scheme

Peterson fragmentation

Both Interfaced to H1 diffractive pdf's

NLO Comparisons with Diffractive DIS Jets

Data:

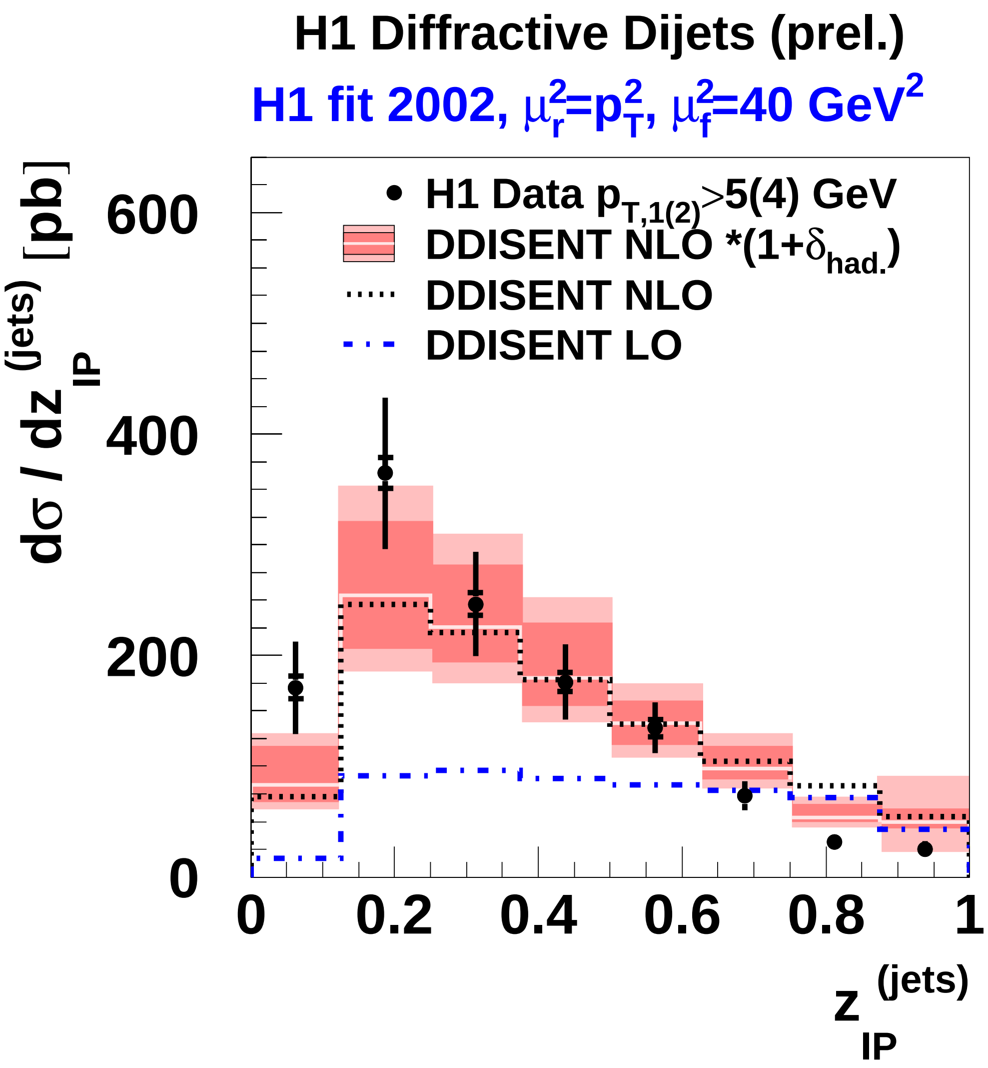
Published H1 data:
[Eur. Phys. J. **C20** (2001) 29]
$4 < Q^2 < 80\ \mathrm{GeV}^2, 0.1 < y < 0.7,$
$x_{I\!P} < 0.05$
Jets: CDF cone, $p_{T,jet} > 4$ GeV

But: NLO unstable if $p_{T,1} \sim p_{T,2}$
$\rightarrow$ Data corrected to $p_{T,1(2)} > 5(4)$ GeV

NLO Calculations with DISENT:

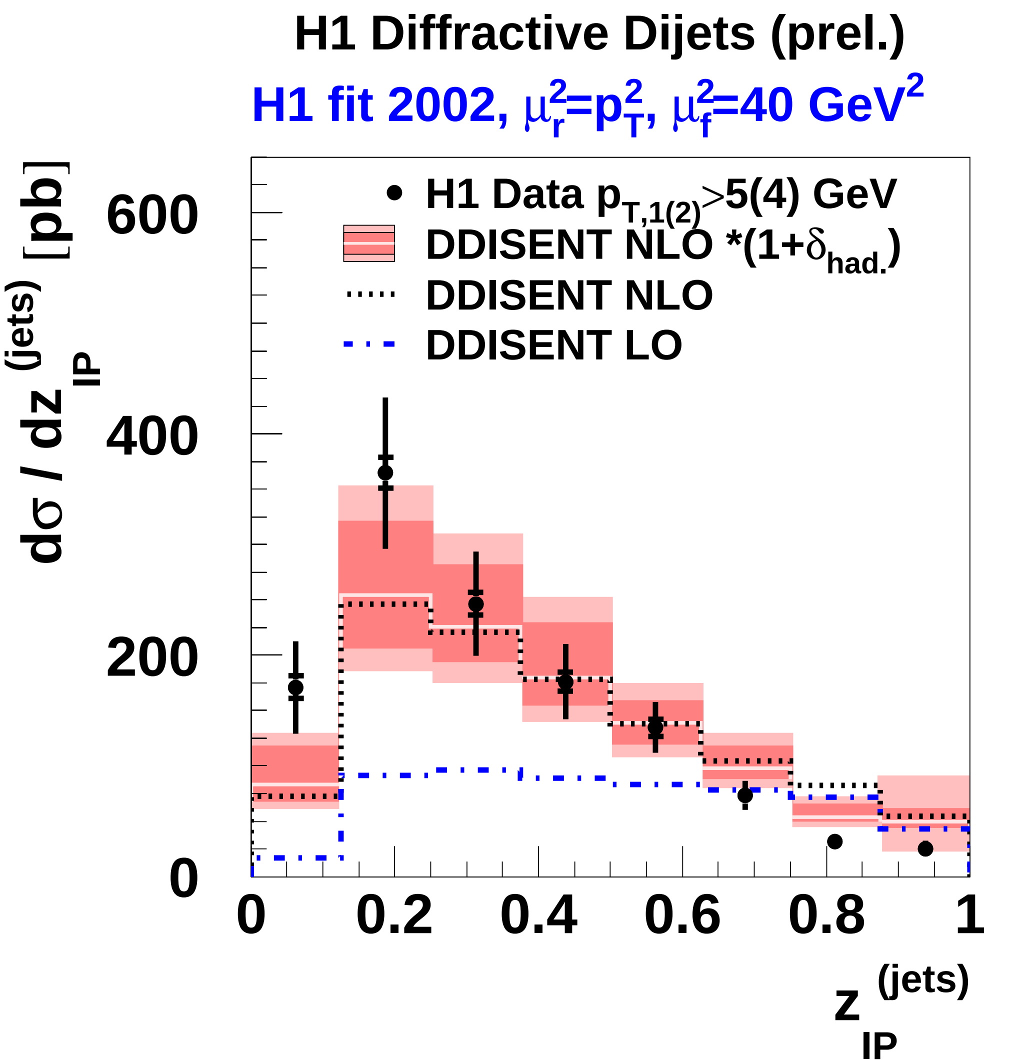
$\mu_r^2 = p_T^2, \mu_f^2 = 40\ \mathrm{GeV}^2$
$\Lambda^4_{QCD} = 0.2$ GeV (as in QCD fit)
Hadronization corrections applied

Inner band: $0.25\mu_r^2 \ldots 4\mu_r^2$
Outer band includes unc. in hadr. corr.



NLO Comparisons with Diffractive DIS Jets (cont.)

- Cross section differential in $z_{I\!P}$
- LO Calculation too low, shape of data not reproduced (note: w/o parton showers!)
- Size of NLO correction on average factor ~ 2 (due to low jet p_T)
- NLO, corrected for hadronization: reasonable description in shape and normalization
- Renormalization scale unc. $\sim 20\%$
- Not shown: pdf uncertainty (gluon at high $z_{I\!P}$)

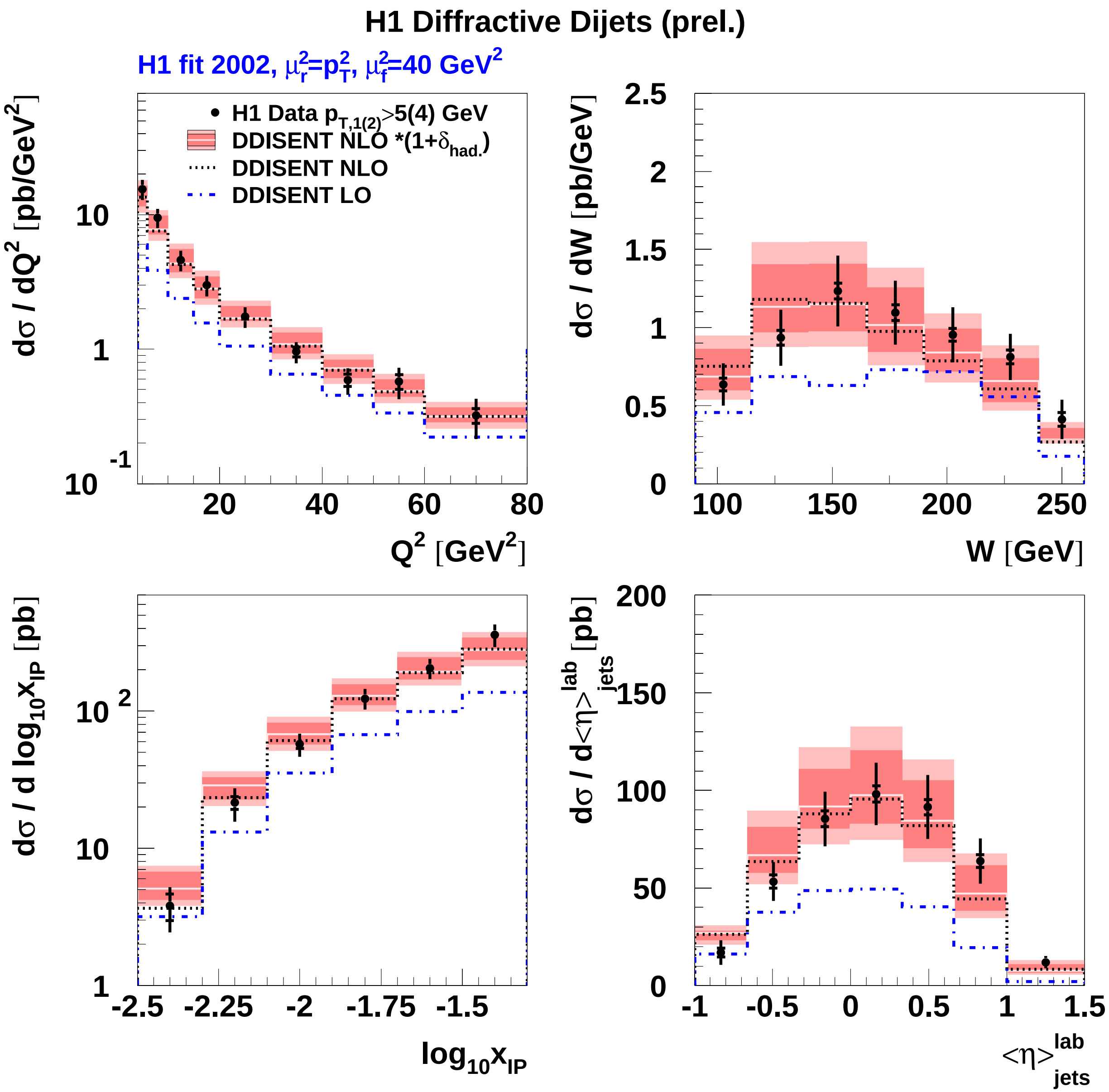


NLO Comparisons with Diffractive DIS Jets (cont.)

- Further Cross sections:

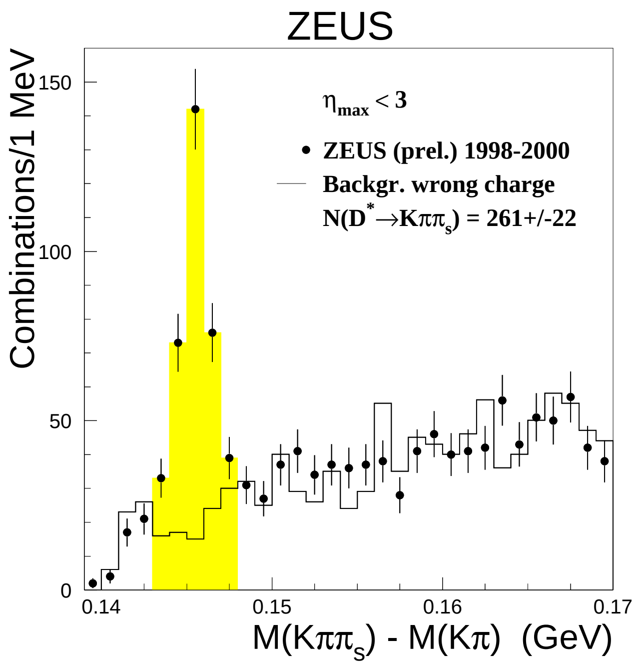
- Size of NLO Corrections decreasing with Q^2 (and p_T ,not shown)

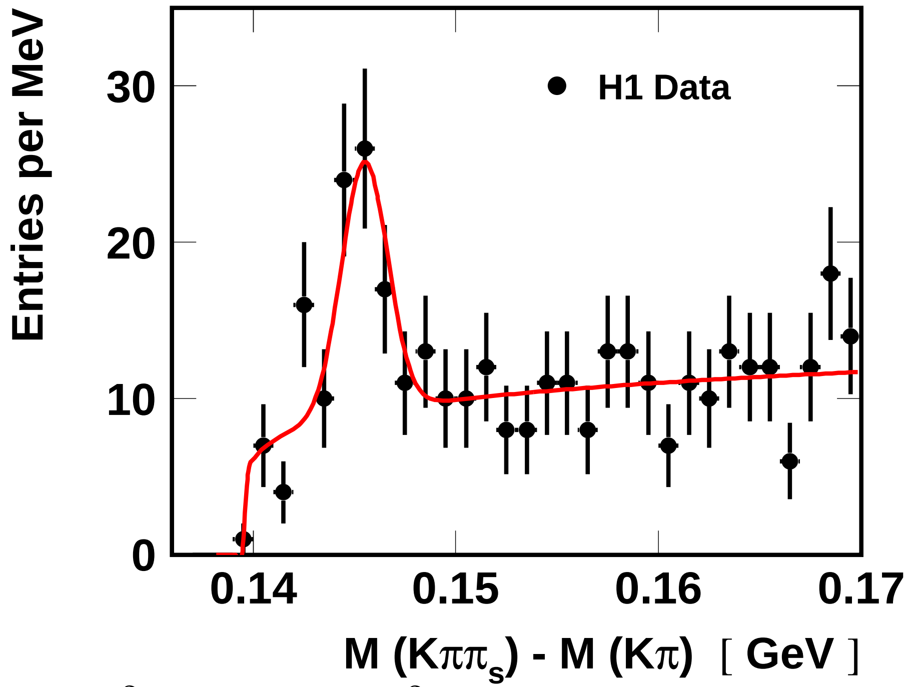
- Reasonable agreement with NLO calculation



Diffractive Open Charm in DIS

Use $D^* \longrightarrow D_0 \pi_s \longrightarrow K \pi \pi_s$





$1.5 < Q^2 < 200 \text{ GeV}^2$
$x_{I\!P} < 0.035$
$p_{T,D^*} > 1.5 \text{ GeV}, |\eta_{D^*}| < 1.5$

$2 < Q^2 < 100 \text{ GeV}^2$
$x_{I\!P} < 0.04$
$p^*_{T,D^*} > 2 \text{ GeV}, |\eta_{D^*}| < 1.5$

So far measurements statistics limited

NLO Comparisons with Diffractive DIS D^* (H1)

NLO Calculations with diffr. HVQDIS:

$\mu_r^2 = \mu_f^2 = Q^2 + 4m_c^2$
$\Lambda^4_{QCD} = 0.2$ GeV (as in QCD fit)

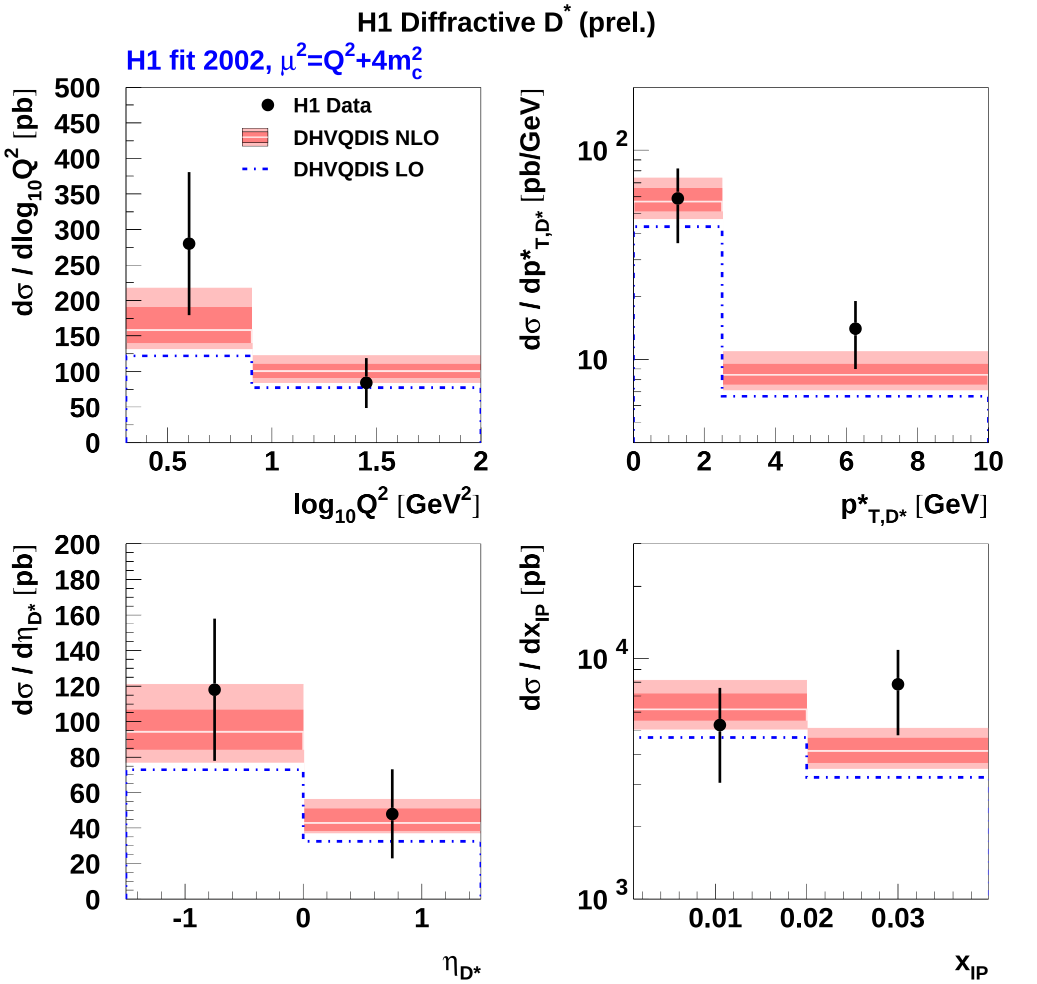
Peterson Fragmentation: $\epsilon = 0.078$

$m_c = 1.5$ GeV, $f(c \rightarrow D^*) = 0.233$

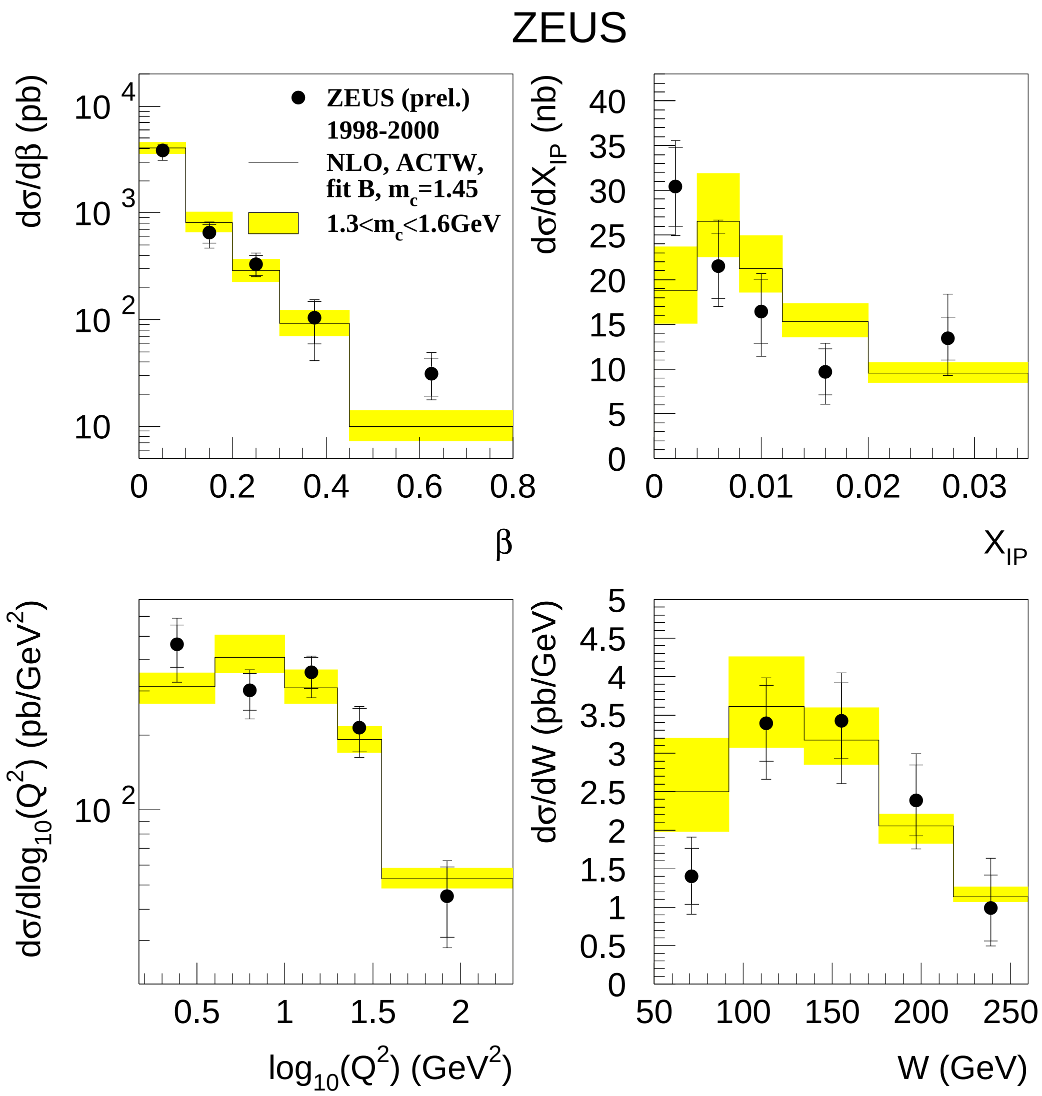
Inner NLO error band: $0.25\mu_r^2 \ldots 4\mu_r^2$
Outer band also includes
– $1.35 < m_c < 1.65$ GeV ($\pm 12\%$)
– $0.035 < \epsilon < 0.100$ ($+21/-7\%$)

Good agreement in shape and normalization within uncertainties

Size of NLO correction smaller than for dijets



Diffractive D^* in DIS (ZEUS)

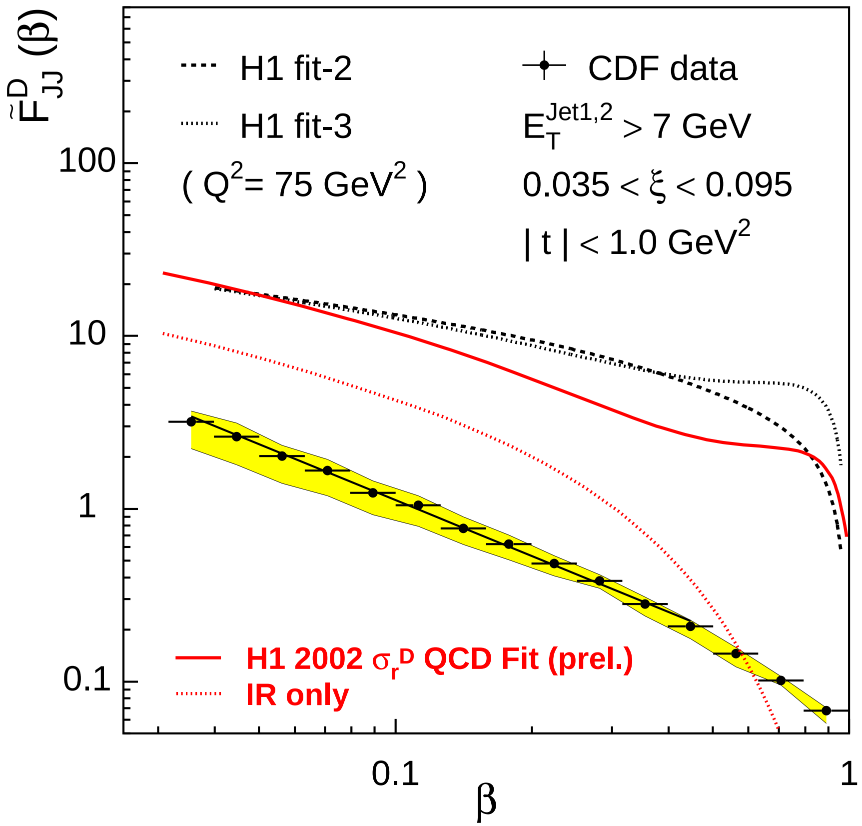


- Theory: gluon dominated pdf's from inclusive fits (ACTW), interfaced to NLO matrix elements
- Differential cross sections well described by calculation!

⇒ Support for QCD factorization in diffractive DIS!

Diffractive Dijets at the Tevatron (CDF)

Use pdf's to predict hard diffraction in pp:



- Serious breakdown of factorization observed if HERA pdf's transported to TEVATRON:
- Prediction based on H1 pdf's one order of magnitude above CDF data
- Also observed for other processes:
  Relative rate of diffractive processes $\sim 1\%$

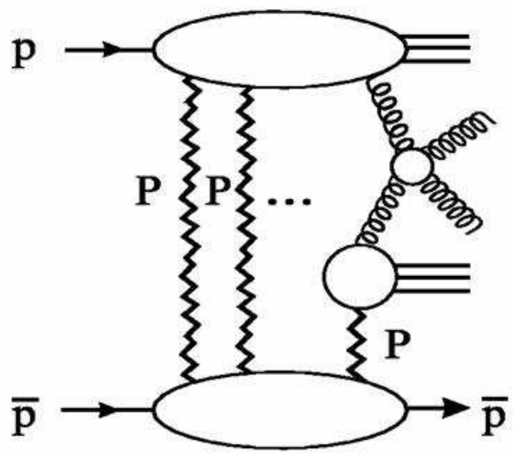
Due to presence of second hadron in initial state?
Spectator interactions/rescattering effects break up $\overline{p}$, "rapidity gap survival probability"

Understanding Factorization Breaking at the Tevatron

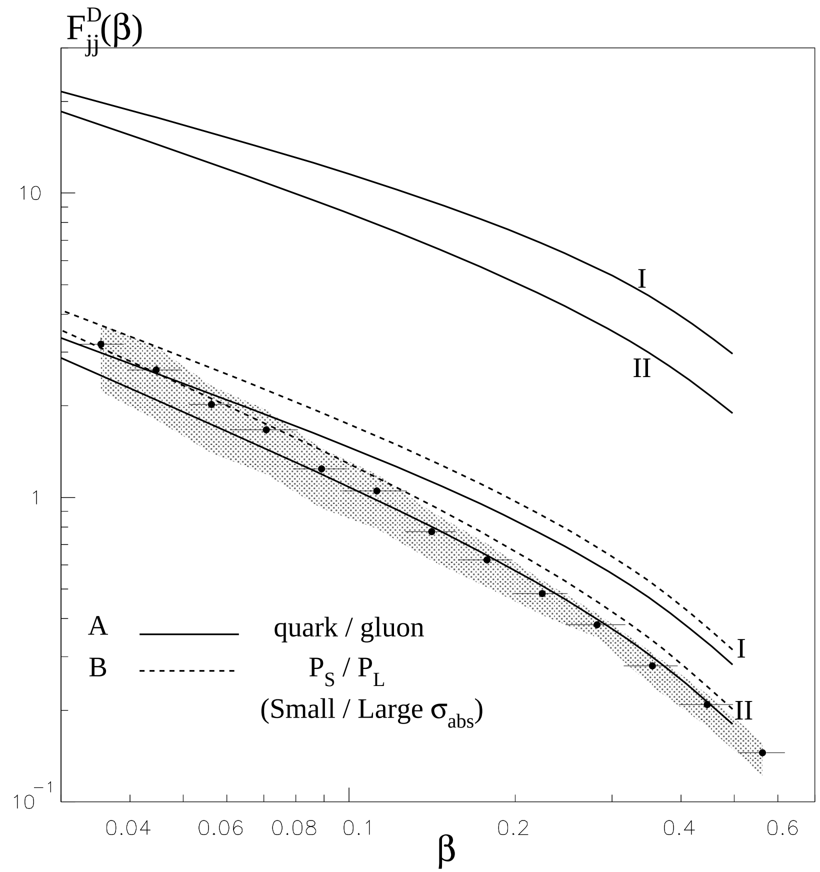
For Example:

Model by Kaidalov, Khoze, Martin, Ryskin (KKMR)

Soft rescattering corrections of spectator partons



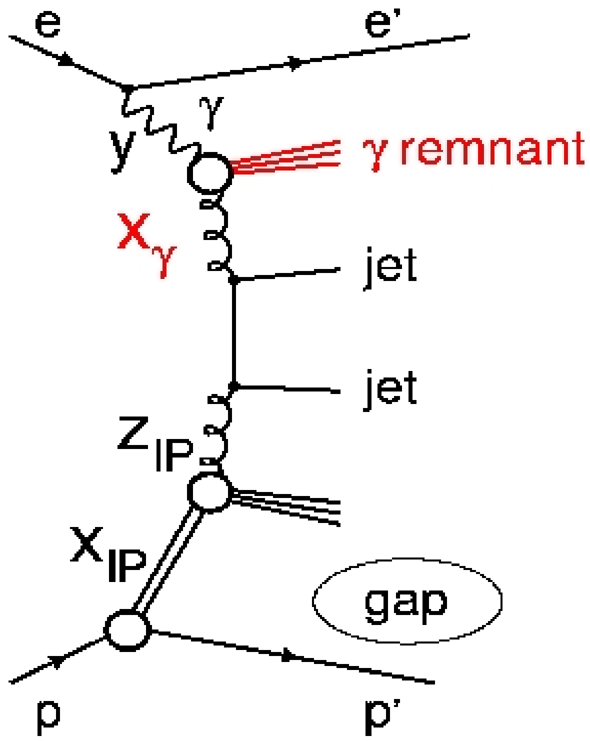
[Two-component eikonal model]



Reasonable description using HERA pdf's + rescattering corrections

Dijets in Diffractive Photoproduction ($Q^2 \sim 0$)

Real photon $\sim$ hadron: Look at HERA in photoproduction ...



Real photon may develop hadronic structure
$\rightarrow$ similar to hadron-hadron interactions

x_γ: Momentum fraction of photon entering the hard process

- $x_\gamma = 1$: Direct interaction, similar to DIS
- $x_\gamma < 1$: Resolved interaction, similar to hadron-hadron scattering

- Does QCD factorization also work in diffractive photoproduction (although not proven)?
- Is there a dependence on x_γ?
- Can factorization breaking w.r.t. Tevatron be understood?

Dijets in Diffractive Photoproduction

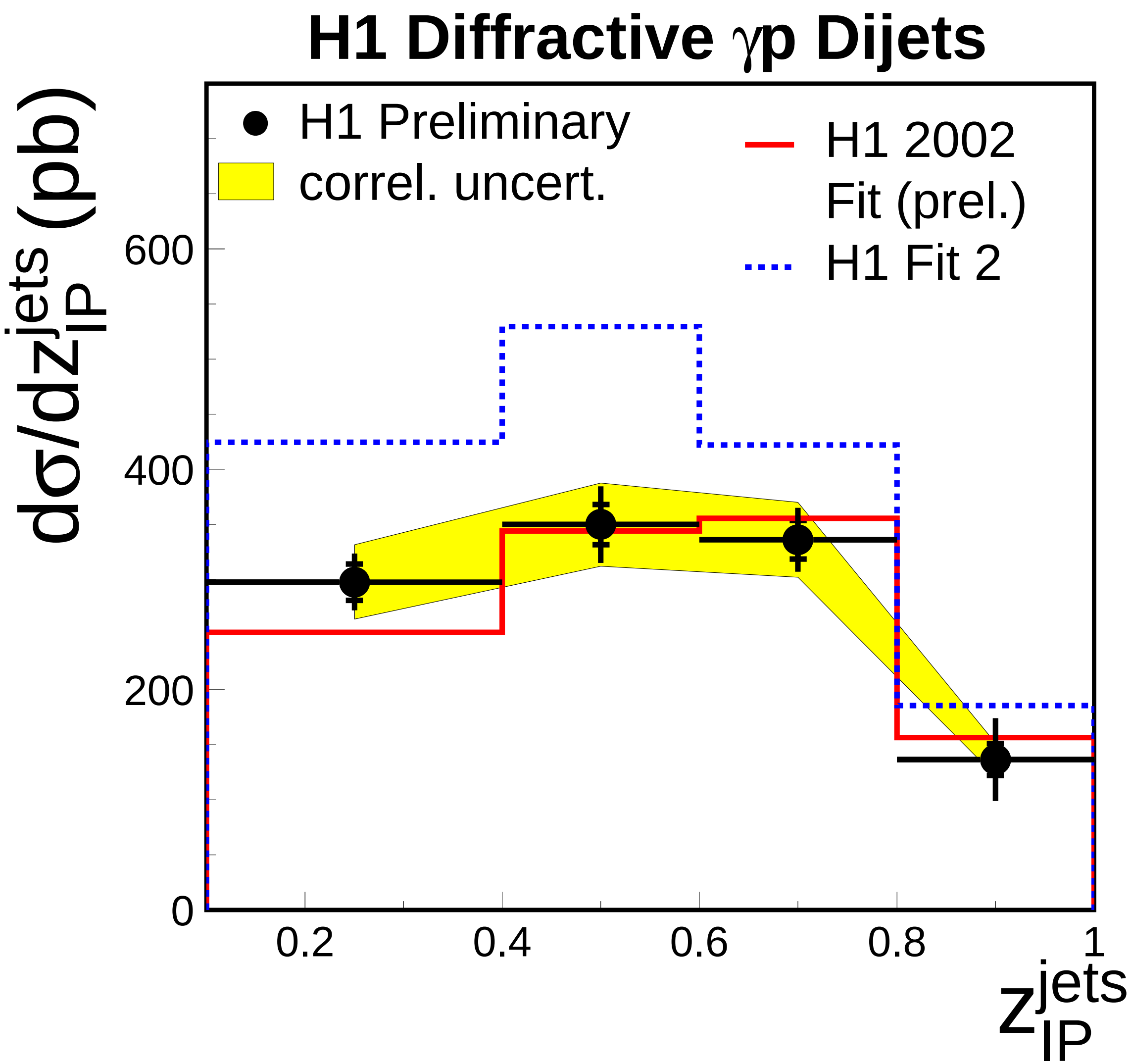
H1 data:

$Q^2 < 0.01\ \mathrm{GeV}^2, 0.3 < y < 0.65$
$x_{I\!P} < 0.03$
Jets: incl. k_T algo.
$p_{T,1(2)} > 5(4)\ \mathrm{GeV}$

Monte Carlo comparisons:
LO ME + parton showers: RAPGAP

$\mu_r^2 = p_T^2$

- New 2002 LO fit describes data very well
- Old "H1 fit 2" too high, but large uncertainties



Dijets in Diffractive Photoproduction

- Cross section as a function of x_γ
- New 2002 fit describes direct and resolved contribution

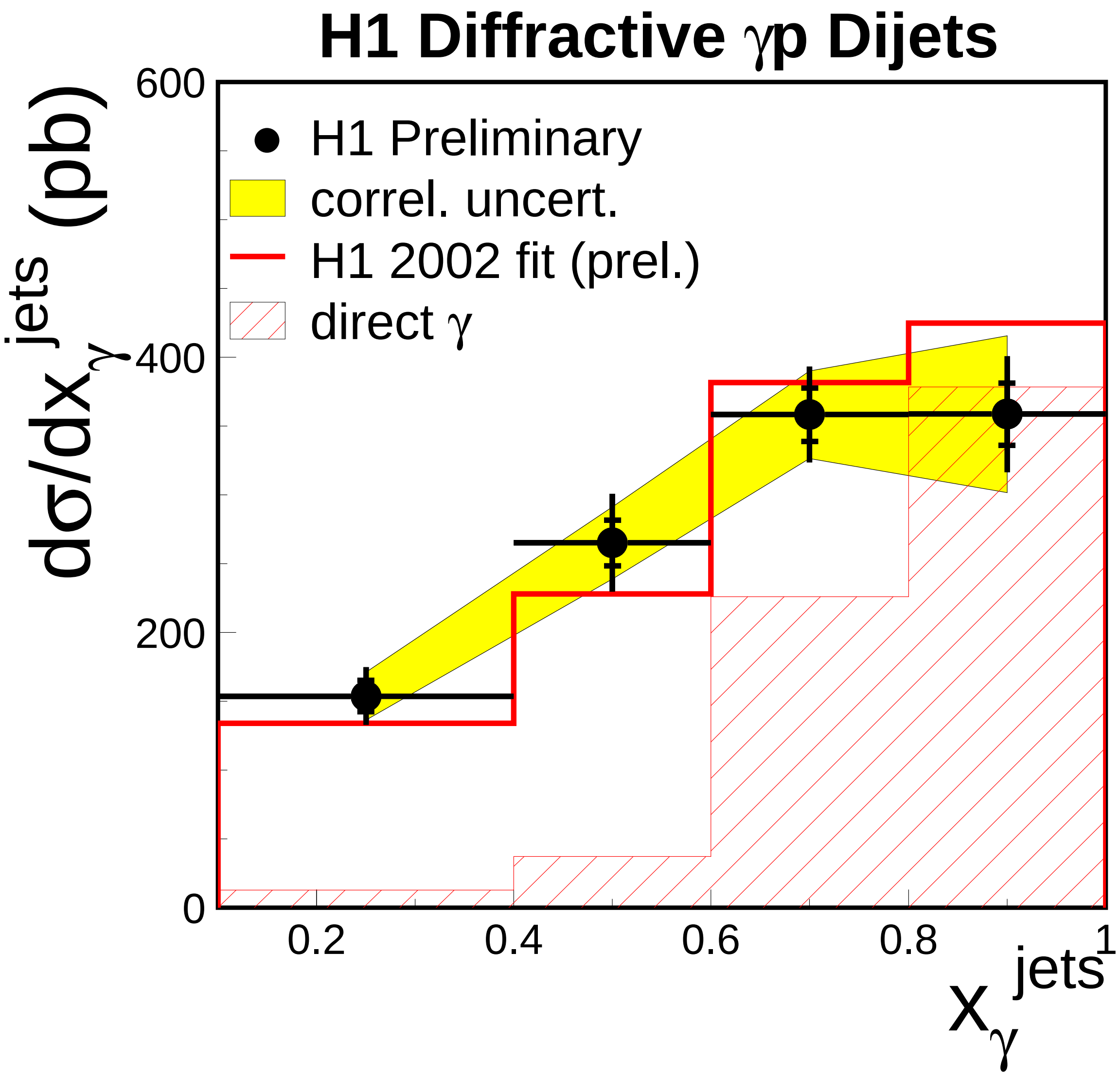
Direct comparison DIS vs γp:

$$\frac{\left(\frac{Model}{Data}\right)_{\gamma p}}{\left(\frac{Model}{Data}\right)_{DIS}} = 1.25 \pm 0.30(\text{exp.})$$

Within uncertainties no suppression of γp w.r.t. DIS diffractive jets

Independent of fit

(NLO Calculations being worked on...)



Conclusions

HERA-I has told us:

- Diffractive DIS at HERA: Investiage **quark/gluon structure of diffraction**
- **High precision HERA data** in large kinematic range available
- **Diffractive pdf's of proton** have been determined at NLO
- Comparison with jets/charm: **Self-consistent QCD picture of diffractive DIS to NLO**
- Does factorization also hold in diffractive photoproduction? (Need NLO calc.)

From HERA to the LHC (via TEVATRON):

- HERA-II to provide a lot **more data**
  (in particular using the H1 **VFPS**)
- Understanding of **factorization breaking mechanism** ep vs pp needed
- Need diffr. pdf's in **kinematic range relevant for LHC!**
- Can **diffractive pdf's + non-factorizing mechanism be combined** in a sensible way to obtain predictions for the LHC (e.g. diffractive Higgs)?