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Diffraction in High Energy ep Collisions

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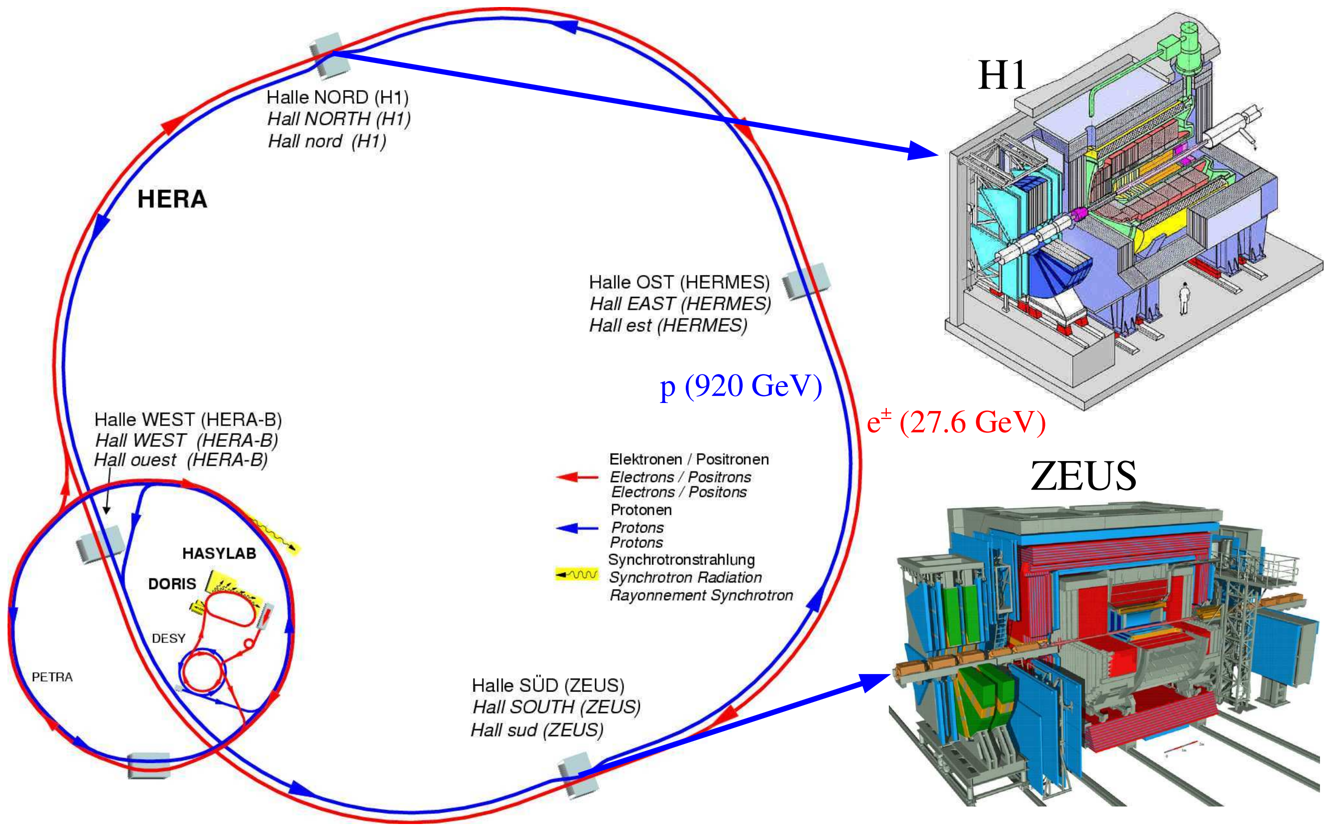
On behalf of the H1 and ZEUS Collaborations

Outline:

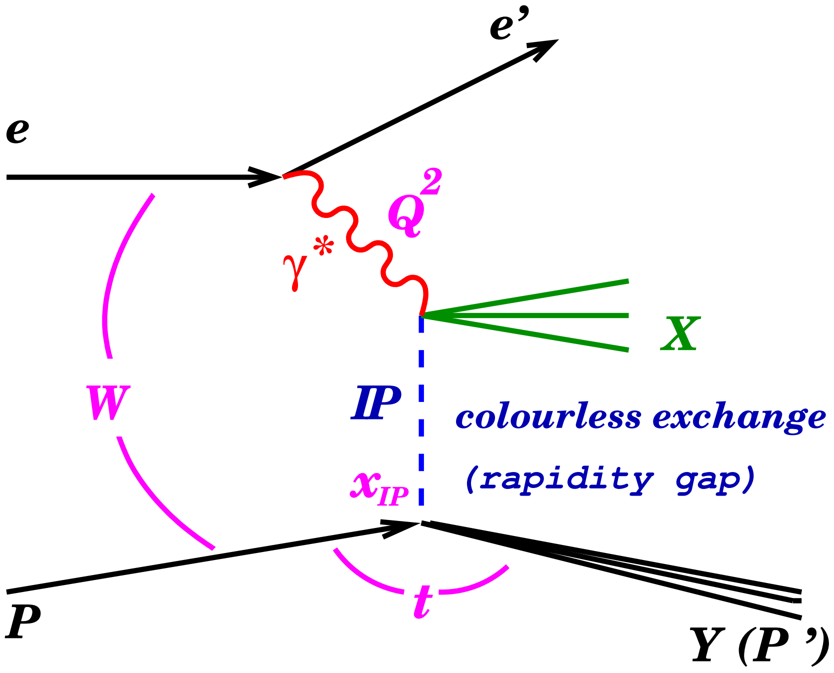
- Introduction
- Vector Meson Production and DVCS
- Inclusive Diffraction in DIS
- F_2^D QCD fits
- Dijets and Open Charm in Diffraction
- Dijets and Open Charm with Leading Neutrons
- Conclusions and Outlook

HERA– the world's only $e^{\pm}p$ collider



$\sqrt{s} = \sqrt{4E_eE_p} \approx 320\ GeV$ **equivalent to 50 TeV fixed target !**

HERA-I (1993-2000): integrated luminosity– more than 100 pb^{-1} per experiment



$Q^2 = -q^2$	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

Diffraction– t-channel exchange of the vacuum quantum numbers

- Colourless exchange
- Large Rapidity Gap
- small momentum transfer t
- $x_{I\!P} \lesssim 0.05$
- $M_X \ll W$
- $M_Y \simeq m_p$

If no hard scale– $Q^2,\ |t| \approx 0$: similar to soft hadron-hadron interactions

$\longrightarrow$ weak energy dependence

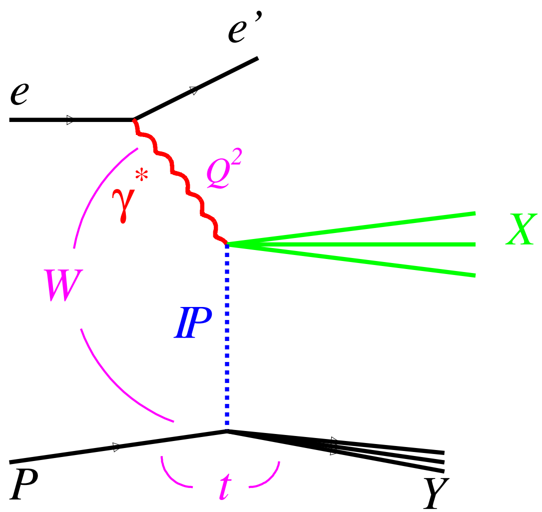
– Regge theory: diffraction is *exchange of Pomeron*

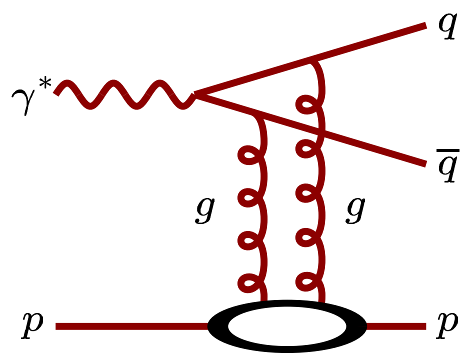
If large $Q^2,\ |t|,\ p_T^{jet},\ m_q$: pQCD at $\gamma^* I\!P$ vertex

$\longrightarrow$ steep energy dependence

– Resolved Pomeron: γ^* probes $I\!P$ structure

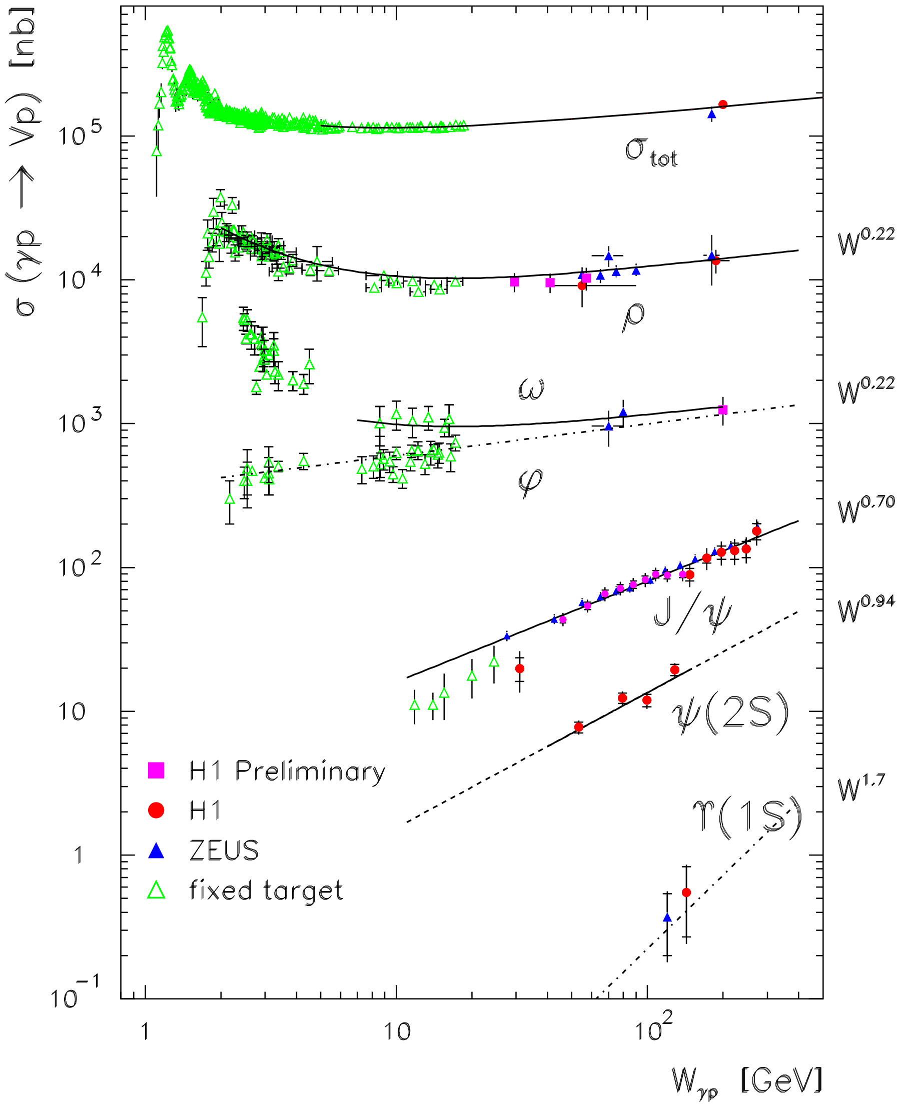
– Colour dipole: diffraction is *exchange of colour singlet gluon ladder* between ($\gamma^* \to q\bar{q}, q\bar{q}g$) and the proton



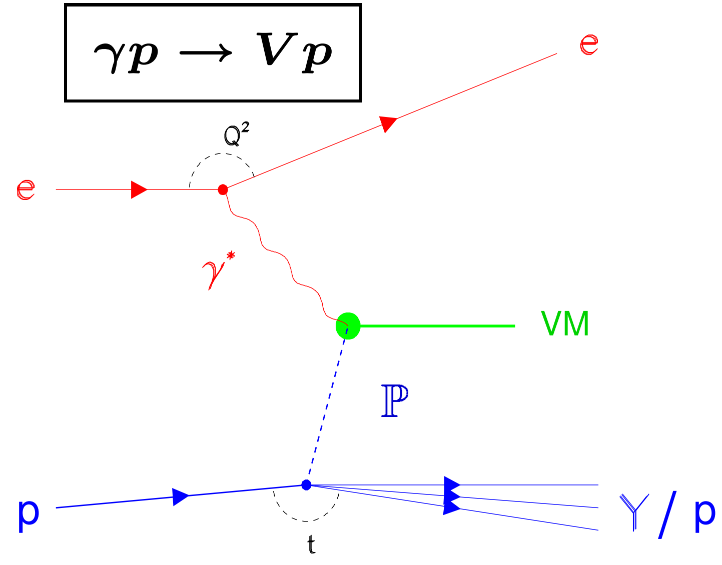


HERA– unique facility
to study transition from soft to hard regime and
to probe partonic content of diffractive exchange .

Photoproduction of Vector Mesons



$\gamma p \rightarrow V p$

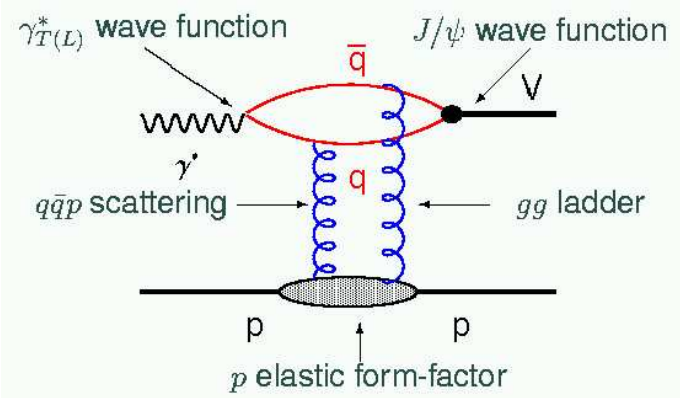


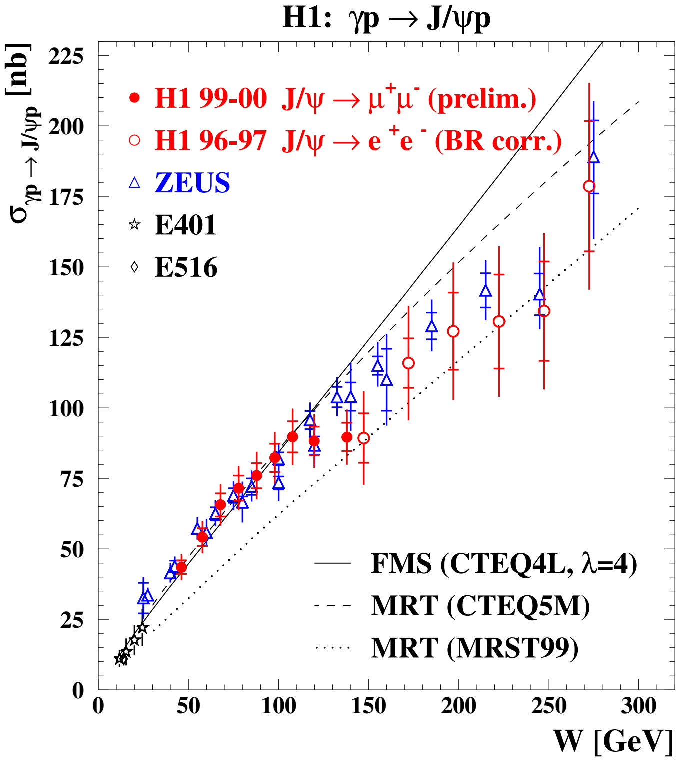
- The cross sections of VM photoproduction (and $\sigma_{tot}^{\gamma p}$) indicate a power law behaviour $\sigma \sim W^{\delta}$ for $W > 10\ GeV$
- For ρ, ω, ϕ: $\delta \approx 0.2$, compatible with $\sigma_{tot}^{\gamma p}$
- For J/Ψ: $\delta \approx 0.7$

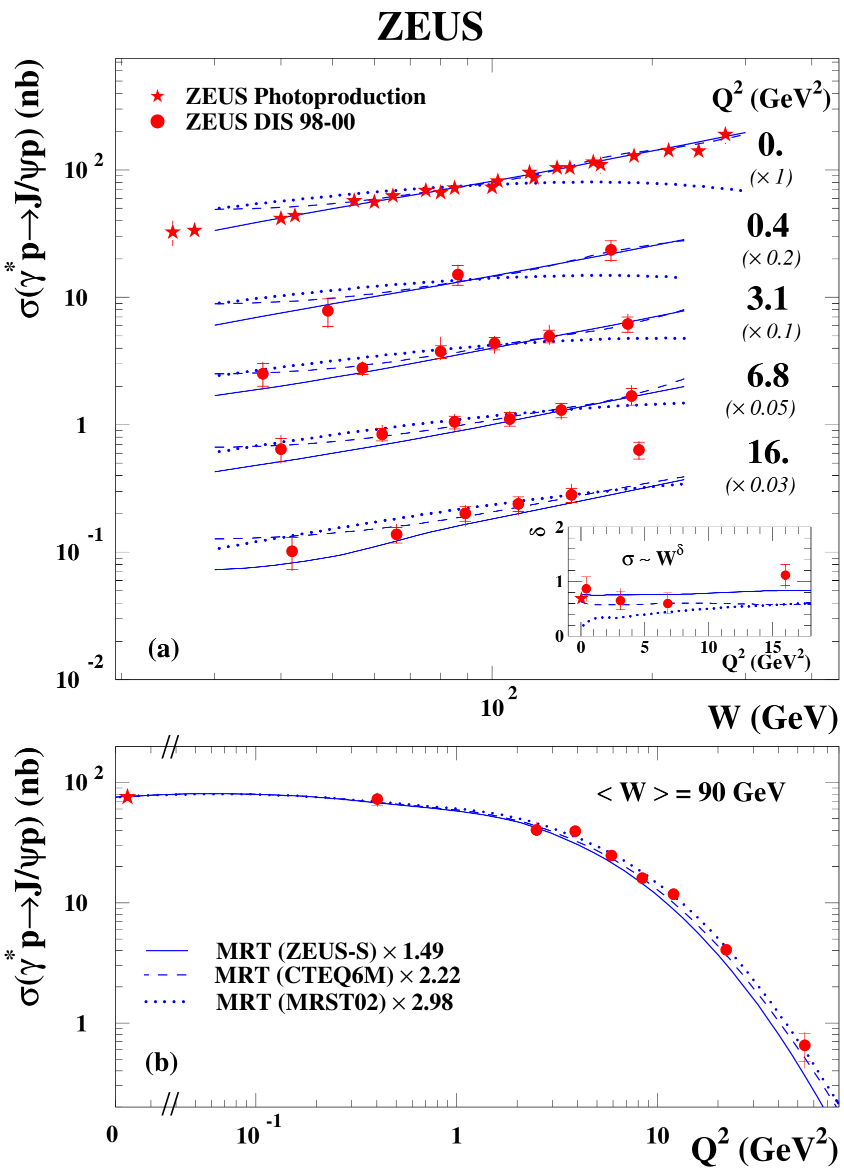
  $\Longrightarrow$ Steeper W dependence for heavy Vector Mesons

  $M_{J/\Psi}$ sets a hard scale for pQCD calculation !

Exclusive Production of J/Ψ



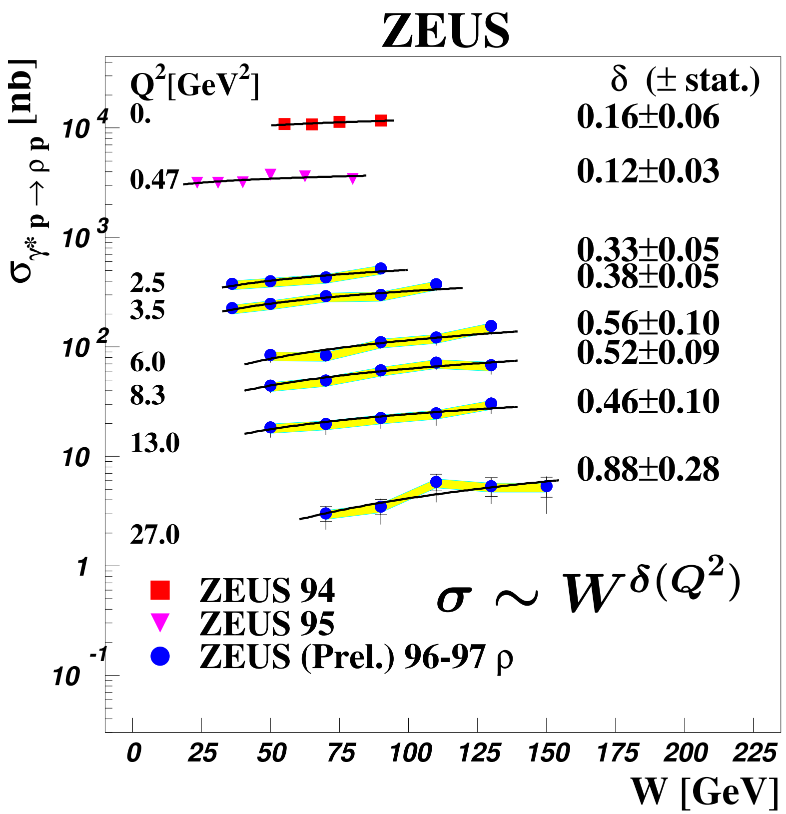


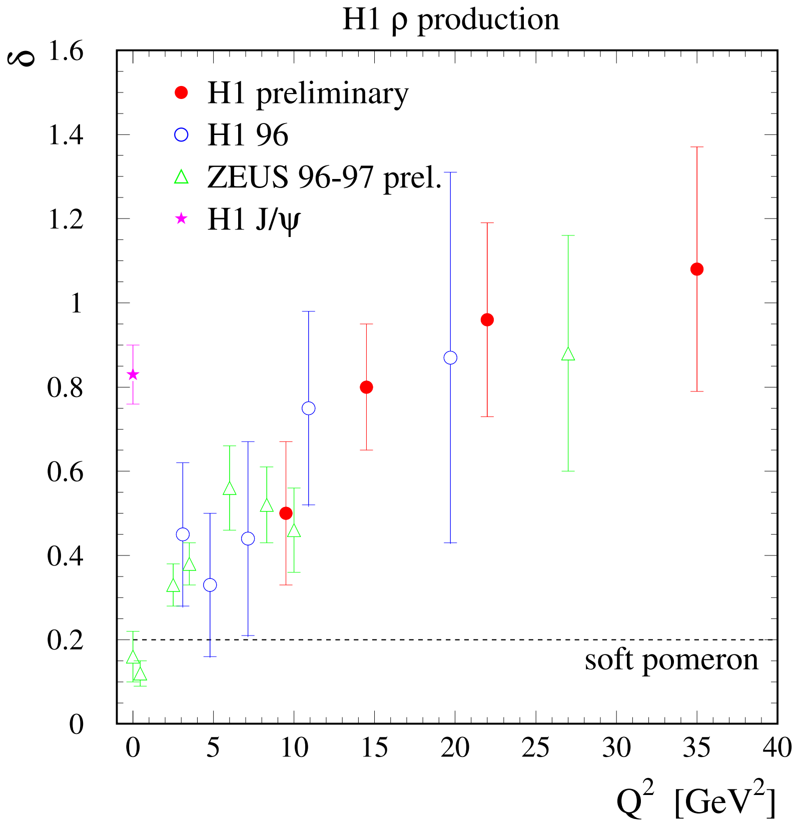


– The pQCD calculations describe the energy dependence for J/Ψ

– Comparison to different PDFs– strong sensitivity to (generalized) gluon distribution

VM-meson Production in DIS





W dependence steeper for ρ with increasing Q^2

$\Rightarrow$ Transition from soft to hard physics as Q^2 increases

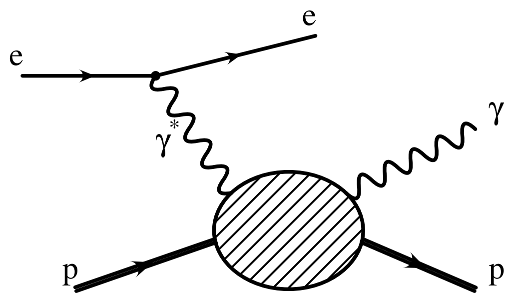
Recent development in theory: the NLO calculations for Vector Mesons !
(D.Ivanov, A.Schäfer, L.Szymanovksi, G.Krasnikov - *presented at DIS-2004)*

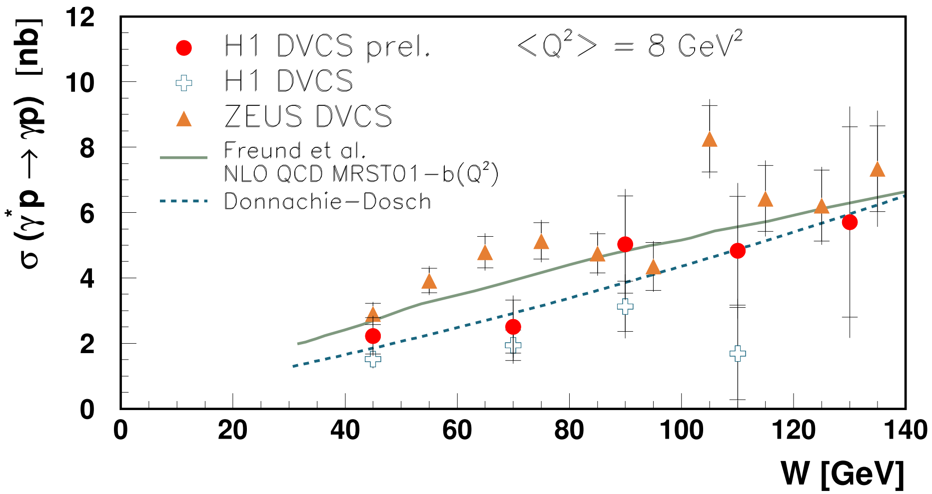
Deeply Virtual Compton Scattering (DVCS)

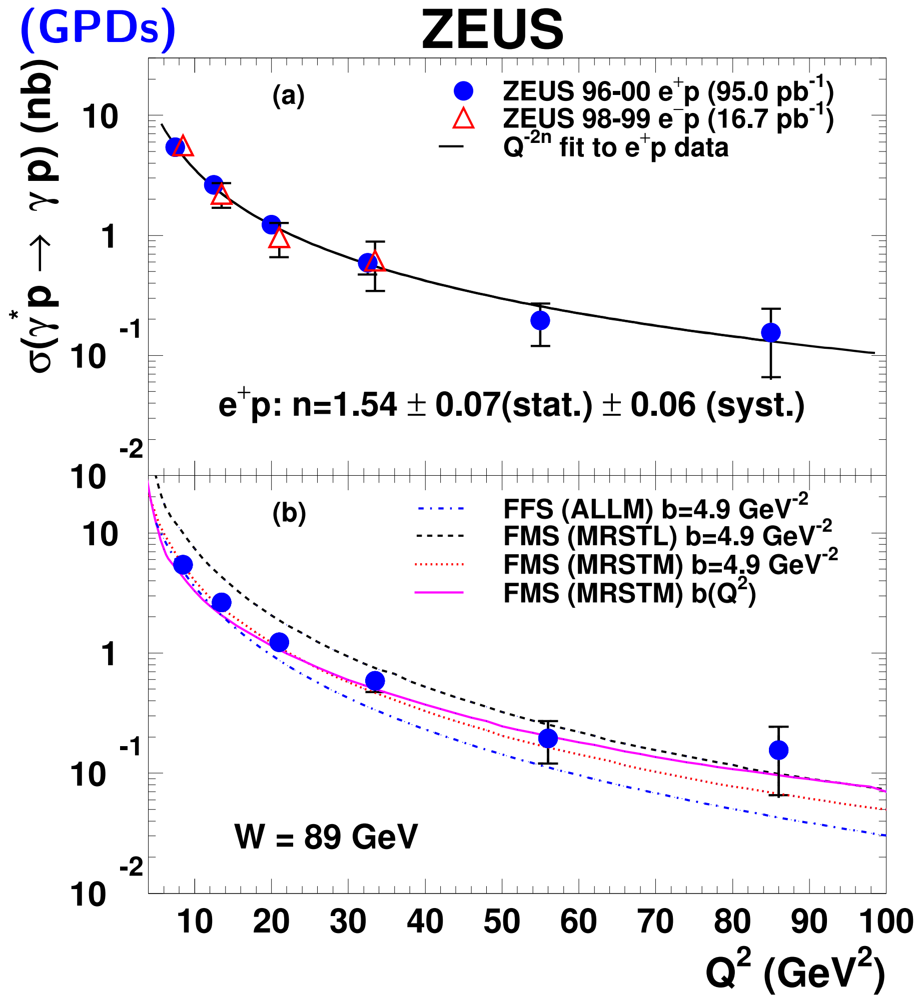
–Elastic scattering of a virtual photon off a proton.

–Very clean picture (no VM wave function), fully calculable in QCD

–Sensitivity to Generalized Parton Distributions (GPDs)

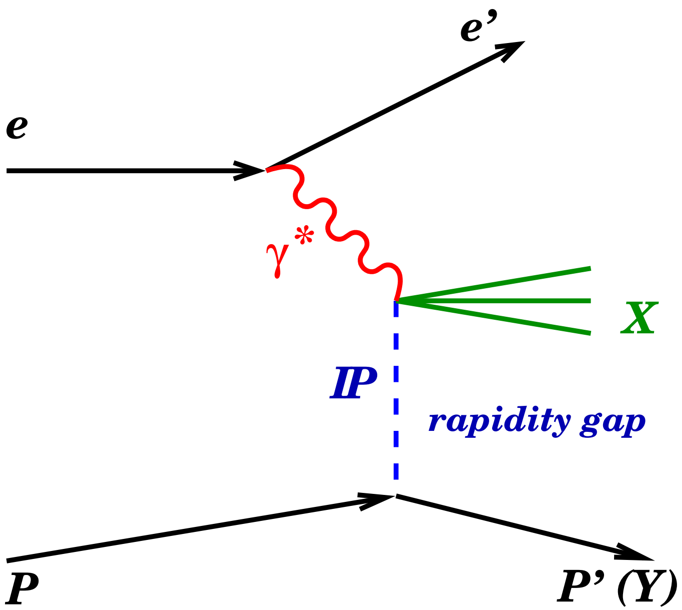


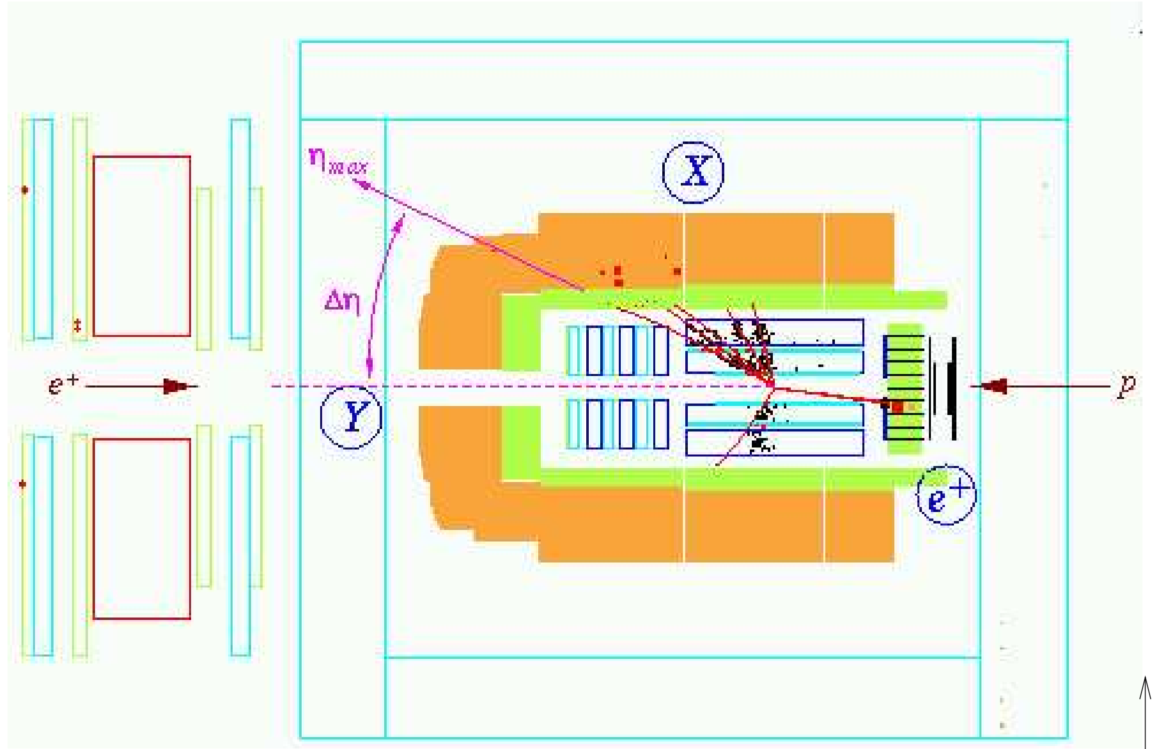


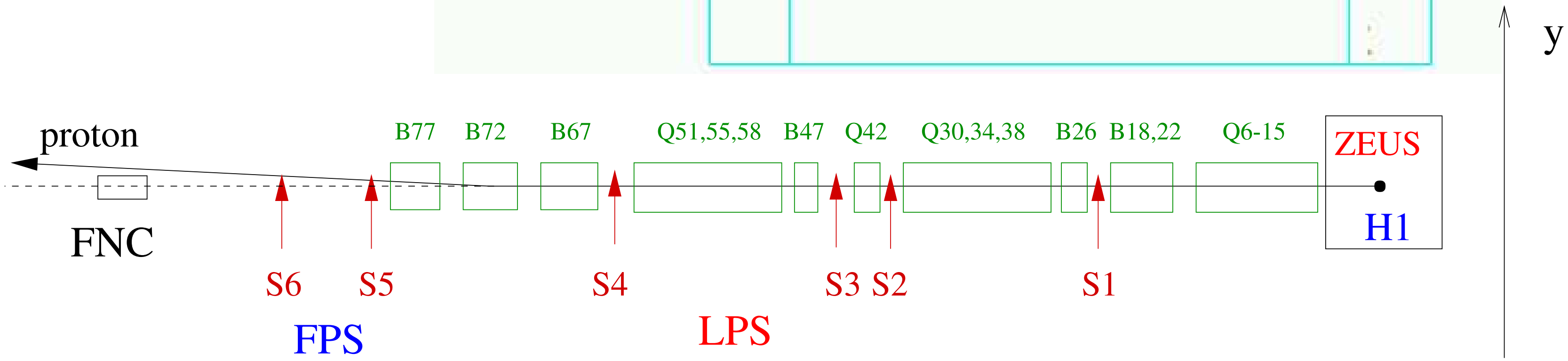


New HERA measurements are well reproduced by QCD calculations based on GPDs.

Selection of diffractive DIS events

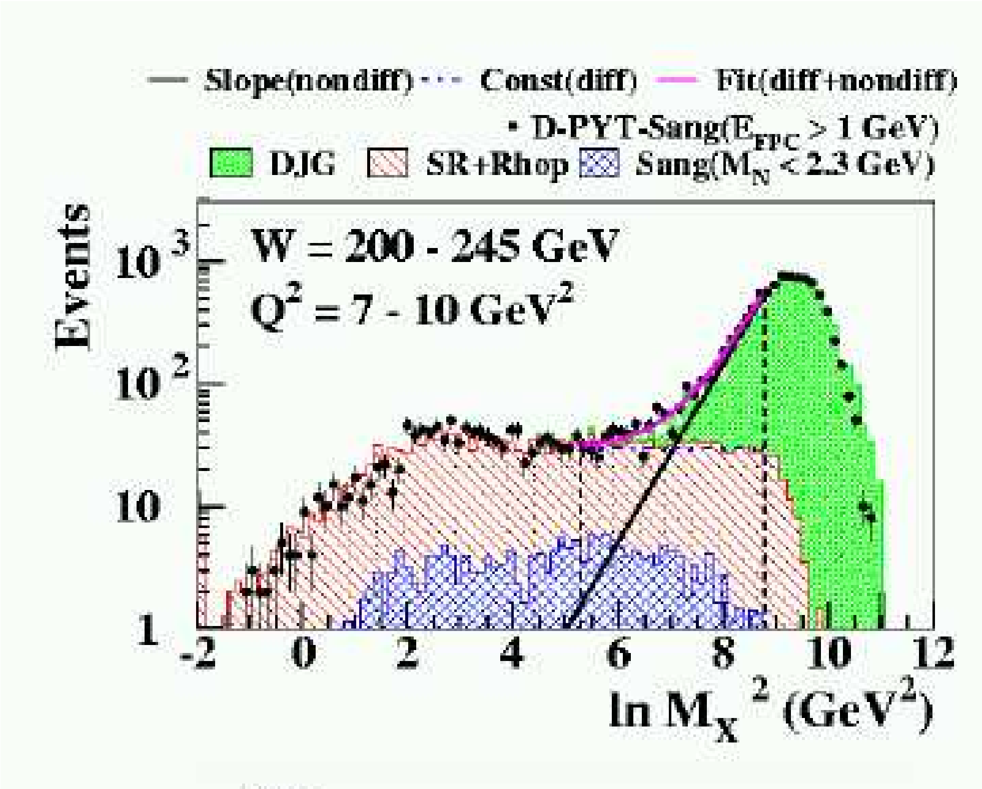






- 'Leading proton' method (scattered proton detected in 'Roman Pot' detectors)
- 'Rapidity gap' method
- 'M_X' method (non-diffractive contribution subtracted from fit to M_X distribution)

Selection of diffractive events- M_X method

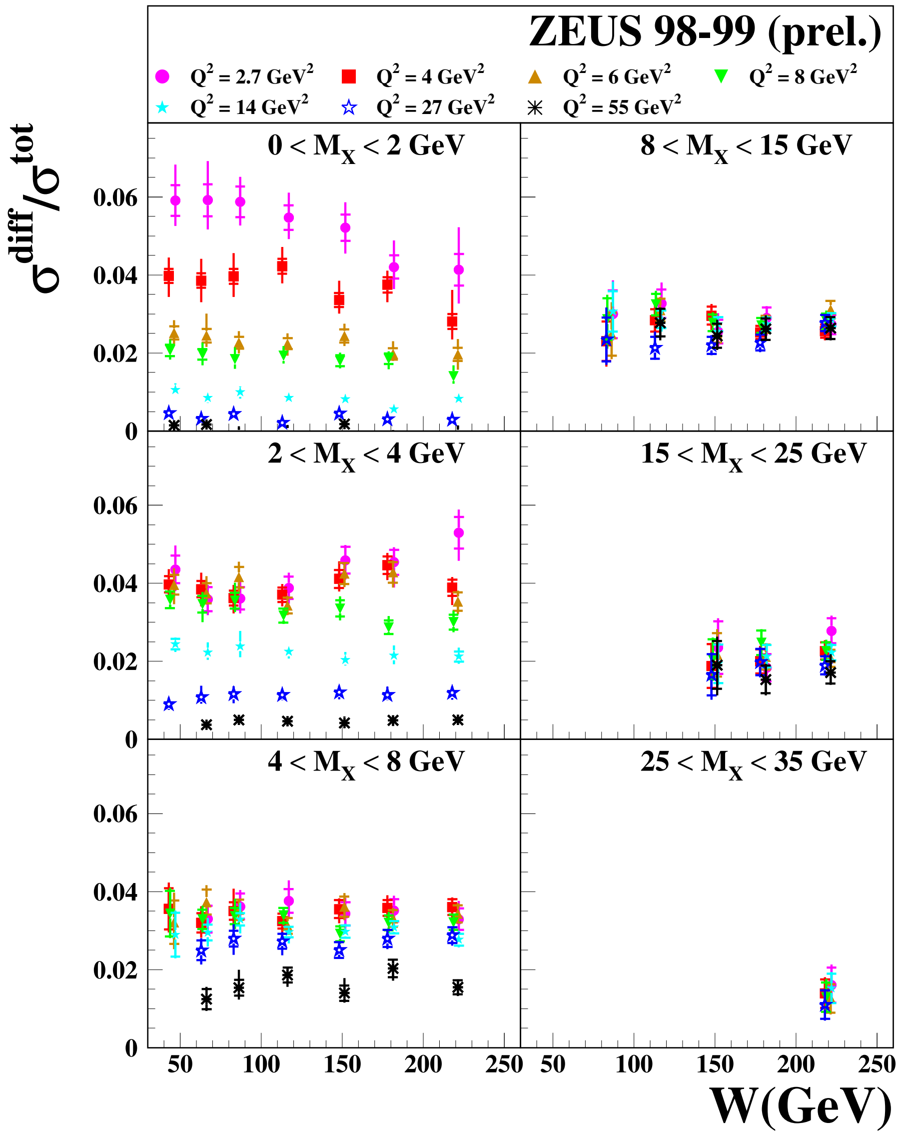


$$\frac{dN}{d\ lnM_X^2} = D + c \cdot exp(b \cdot lnM_X^2)$$

Properties of M_X distribution:

- ◇ exponential rise with M_X for non-diffractive events
- ◇ flat behaviour vs lnM_X^2 for diffractive events
- ◇ $\Longrightarrow$ non-diffractive events can be subtracted from fit to M_X

Energy dependence of σ_{diff} in DIS



for $M_X \gtrsim 2\ GeV$, $\frac{\sigma_{diff}}{\sigma_{tot}}$ is flat in W !

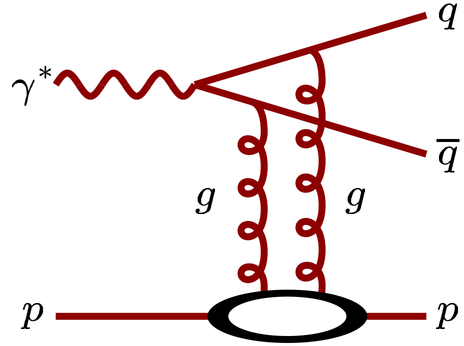
$\Longrightarrow$

Same energy behaviour in diffractive and inclusive DIS !

Energy dependence of σ_{diff} in DIS

In pQCD diffraction– exchange of colour singlet gluon ladder between $(\gamma^* \to q\bar{q}, q\bar{q}g)$ and the proton.

Expectations: different approaches



- Two perturbative (hard) gluons

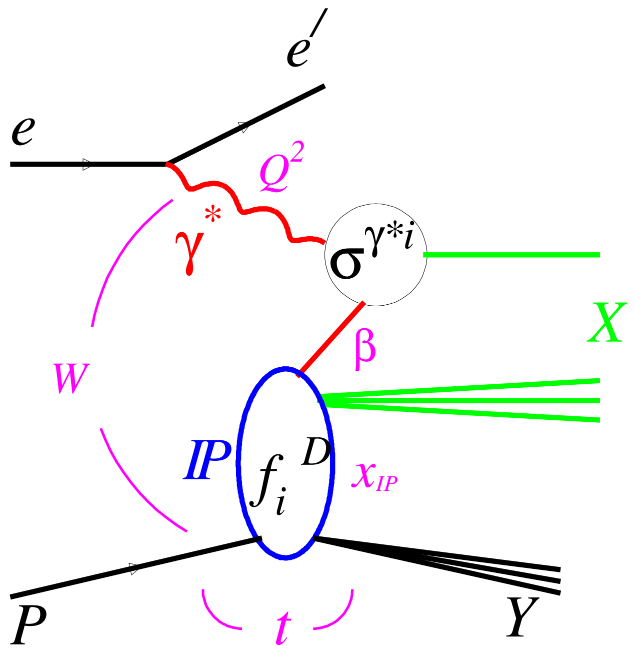
  $\sigma_{diff} \propto |xg(x)|^2$,
  $\longrightarrow \sigma_{diff}/\sigma_{tot} \propto xg(x) \propto W^a$
  (since $\sigma_{tot} \propto xg(x)$ and $W^2 \sim Q^2/x$ for $x \ll 1$)

- Softer gluons are exchanged (Soft Colour Interaction model, Saturation model,...)
  $\longrightarrow \sigma_{diff}/\sigma_{tot}$ rises less steep than $g(x)$ or W^a

◇ Measurements: Same energy behaviour in diffractive and inclusive DIS.

Softer than "two hard gluon" exchange !

Cross-section of Inclusive Diffractive DIS



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

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

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

Cross Section:

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

$(\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{1+(1-y)^2} F_L^{D(4)}$ – *reduced diffractive cross section)*

Factorization Properties of Diffractive Cross-Section:

QCD factorization -proven in diffractive ep (Collins 1997)

$$\boldsymbol{\sigma^D(\gamma^* p \to X p) \sim \sum_i f^D_{i/p}(x_{I\!P}, t, x, Q^2) \otimes \hat{\sigma}_{\gamma^* i}(x, Q^2)}$$

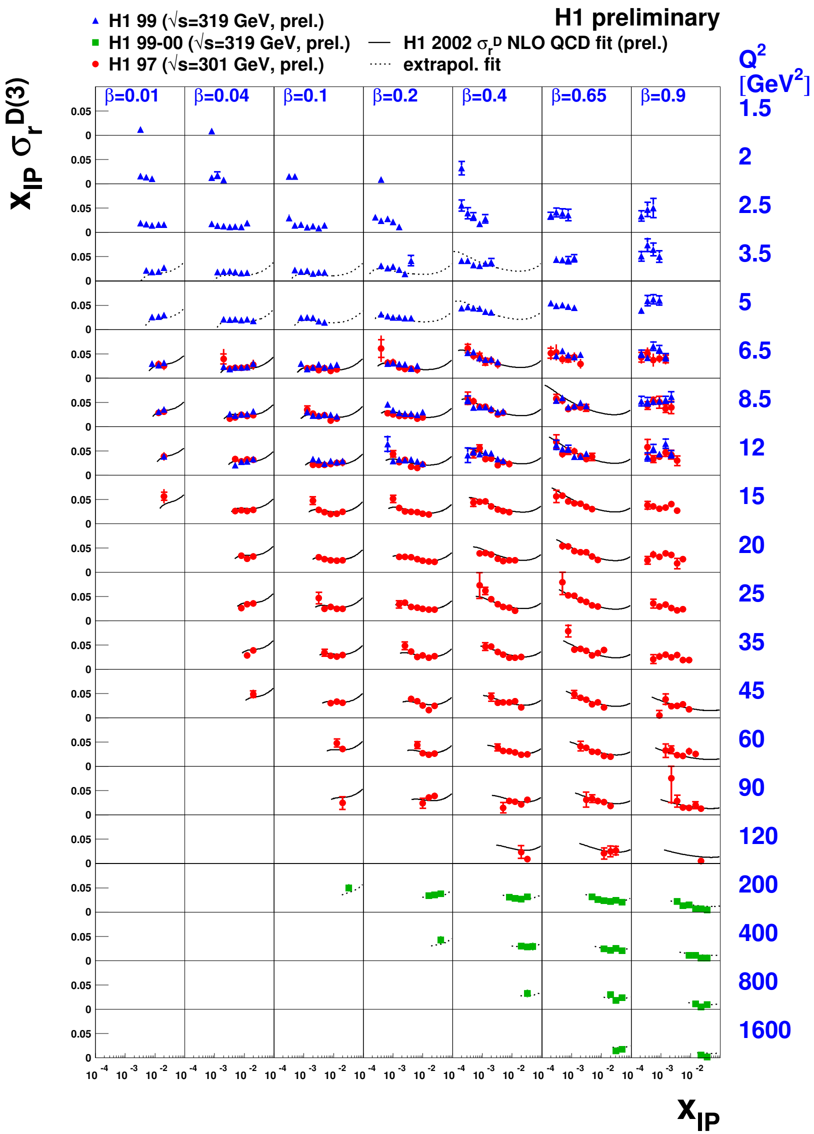
Diffractive parton densities: $f^D_{i/p}(x_{I\!P}, t, x, Q^2)$:

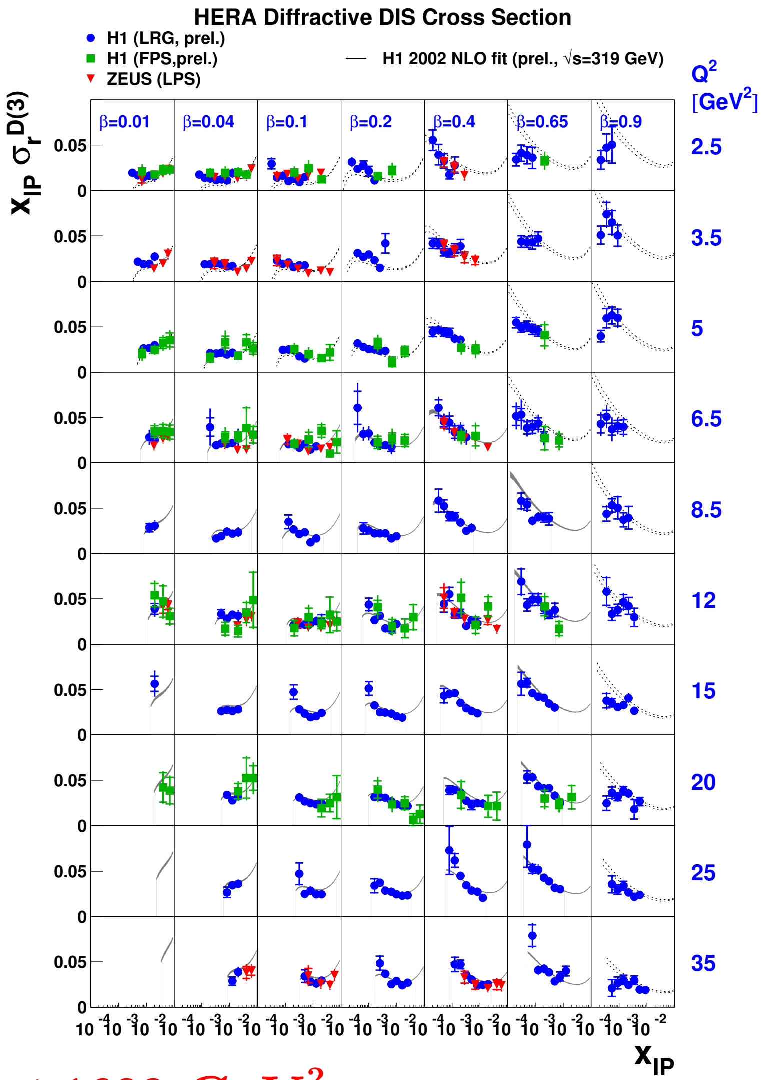
- ◇ *conditional proton parton probability* distributions with final state proton at fixed $x_{I\!P}$, t
- ◇ evolve with x and Q^2 according to QCD evolution

Are they *universal* for diffractive DIS (!?)

$\Longrightarrow$ Apply NLO QCD DGLAP technique to Q^2 and β dependences as for inclusive DIS. Extract diffractive parton densities from F_2^D and use to predict the diffractive final states.

$x_{I\!P}, \beta, Q^2$ dependence of $F_2^{D(3)}$



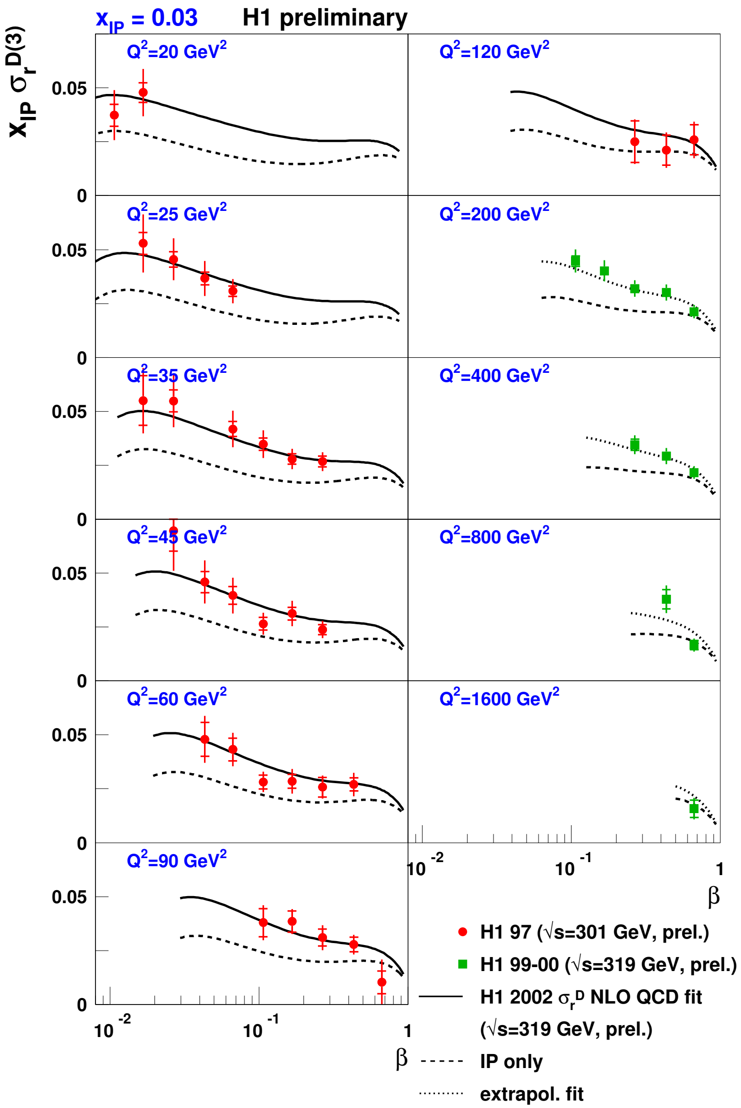


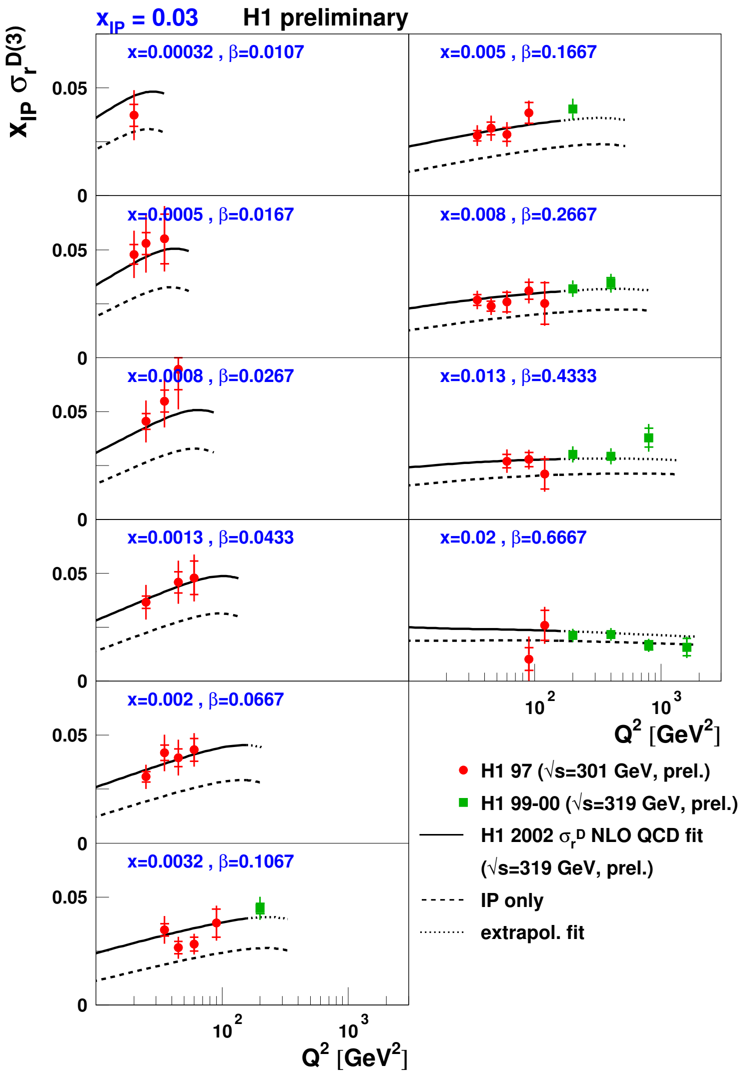
Large kinematic range covered $1.5 < Q^2 < 1600\ GeV^2$

Large statistical precision

Excellent agreements between two methods and two experiments

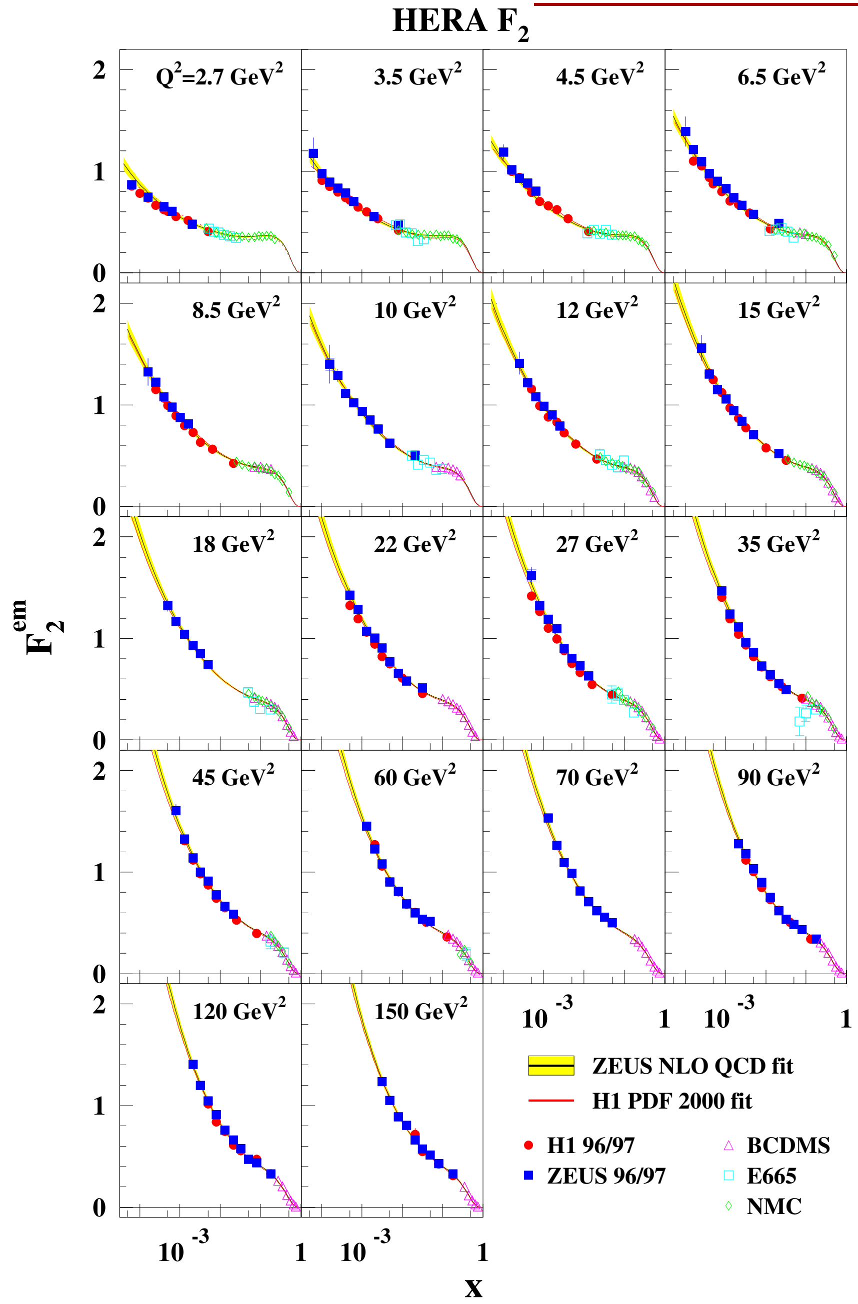
Q^2 and β dependence of $F_2^{D(3)}$



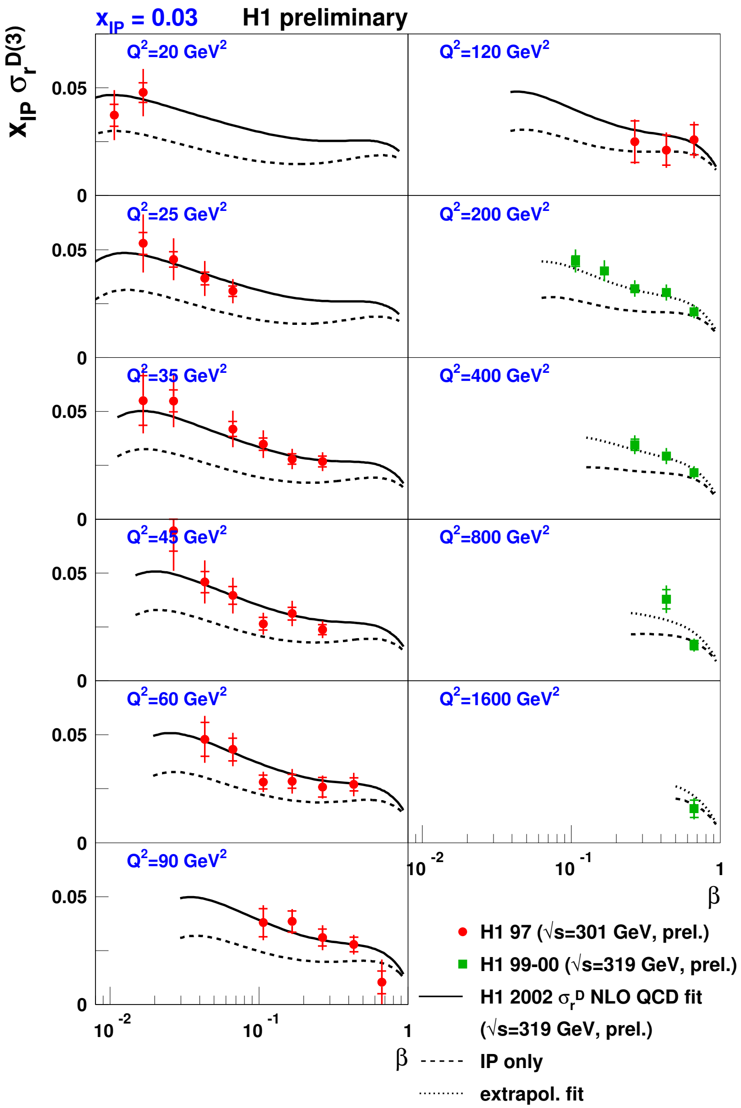


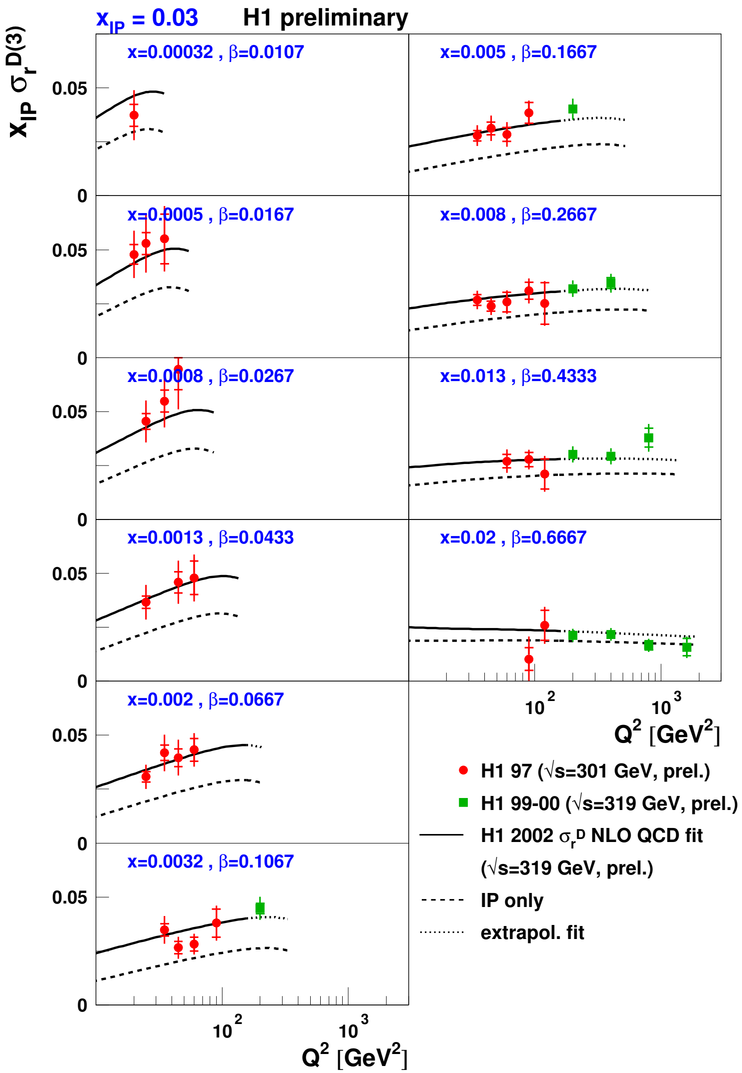
– β dependence relatively flat (different from F_2^p)

Q^2 and x dependence of F_2^p



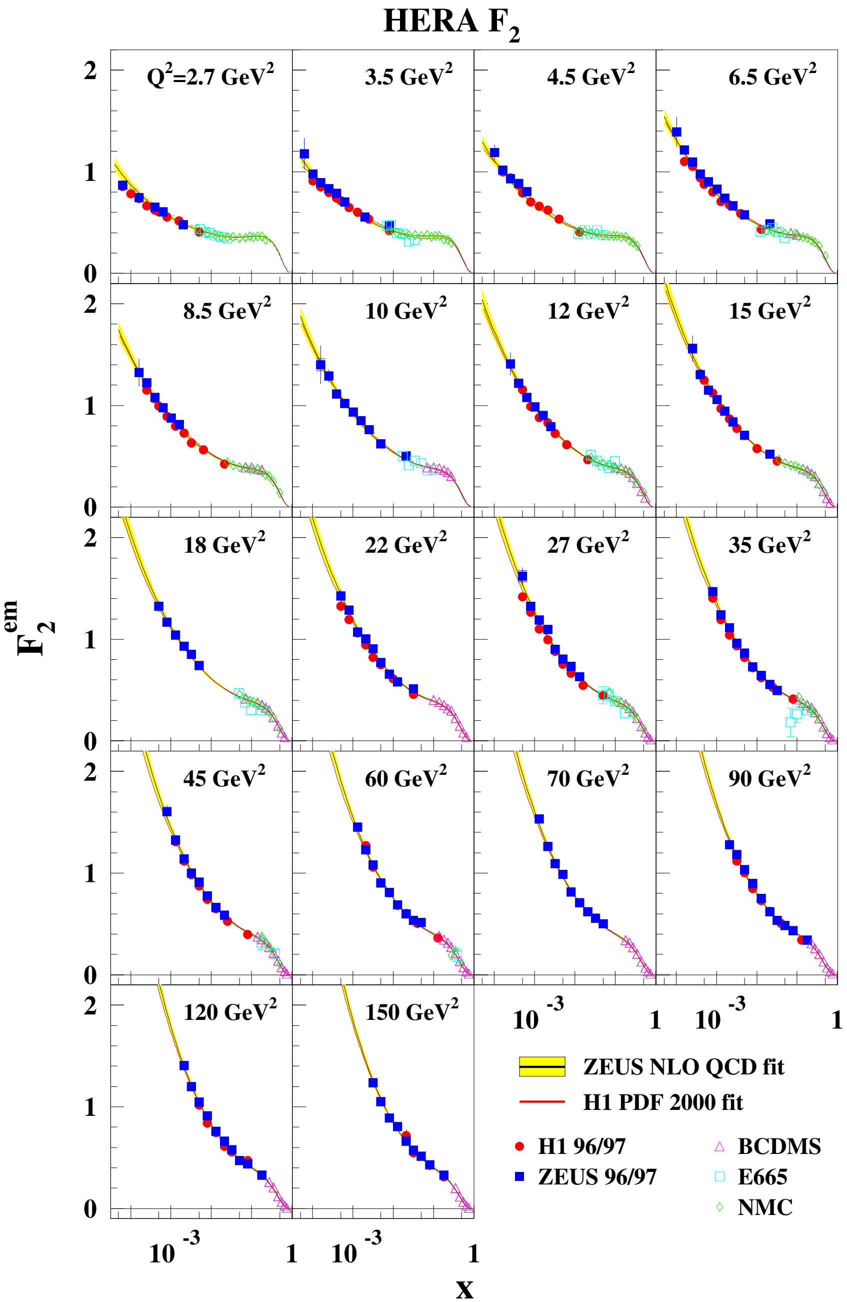
Q^2 and β dependence of $F_2^{D(3)}$

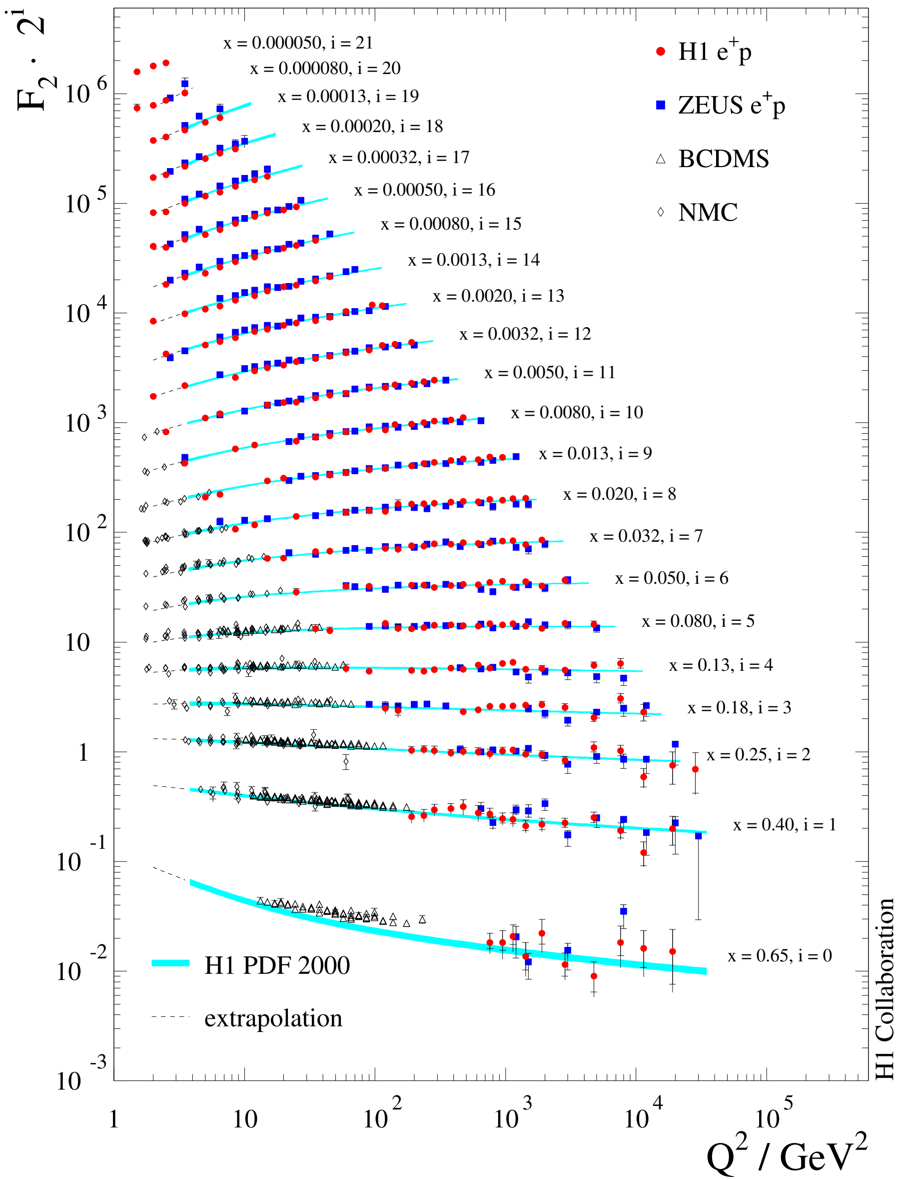




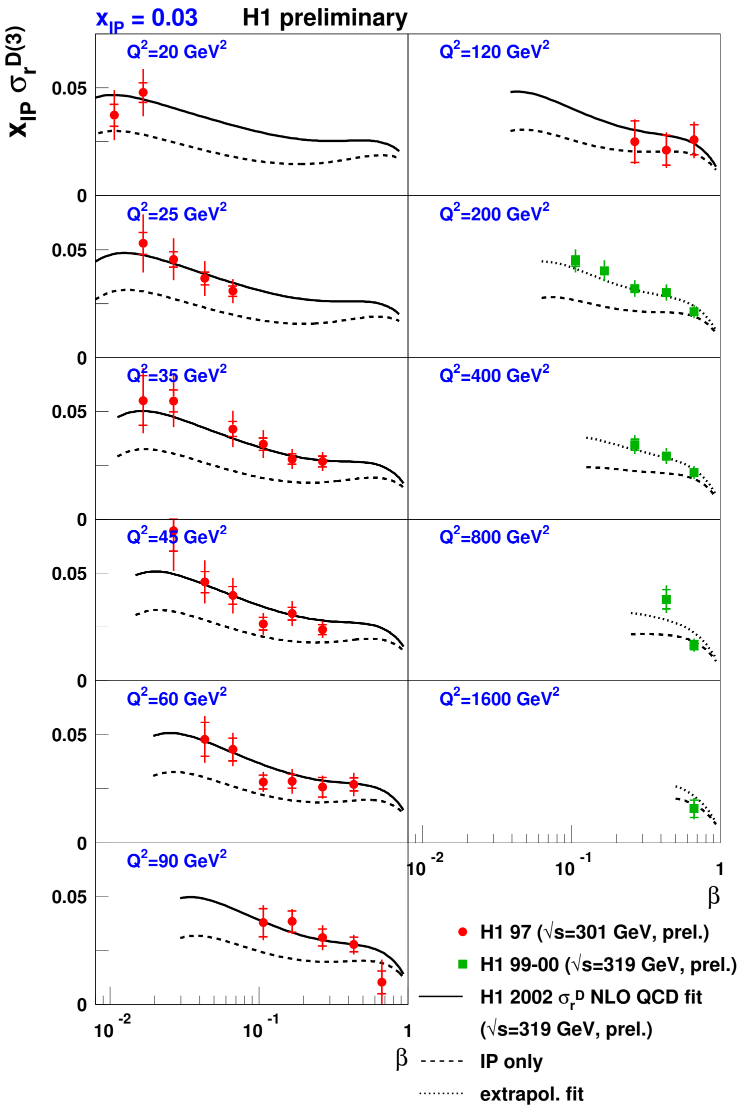
- β dependence relatively flat (different from F_2^p)
- scaling violation rising with lnQ^2 up to large β

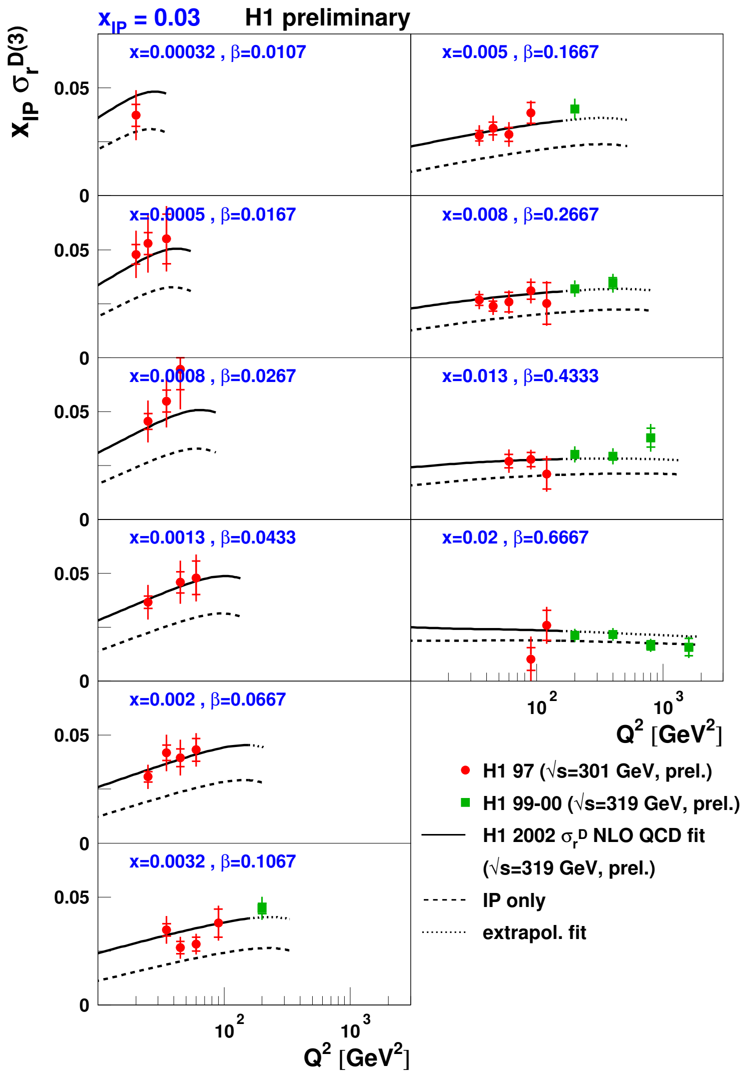
Q^2 and x dependence of F_2^p





Q^2 and β dependence of $F_2^{D(3)}$





– β dependence relatively flat (different from F_2^p)

– scaling violation rising with lnQ^2 up to large β

$\longrightarrow$ large gluon contribution for F_2^D !

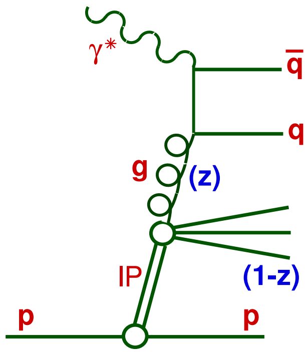
Diffractive Parton Densities from QCD Fit to $F_2^{D(3)}$

Apply same NLO QCD DGLAP technique to Q^2 and β dependences as for inclusive DIS

▷ singlet quark density $\Sigma(z, Q^2)$– directly from F_2^D

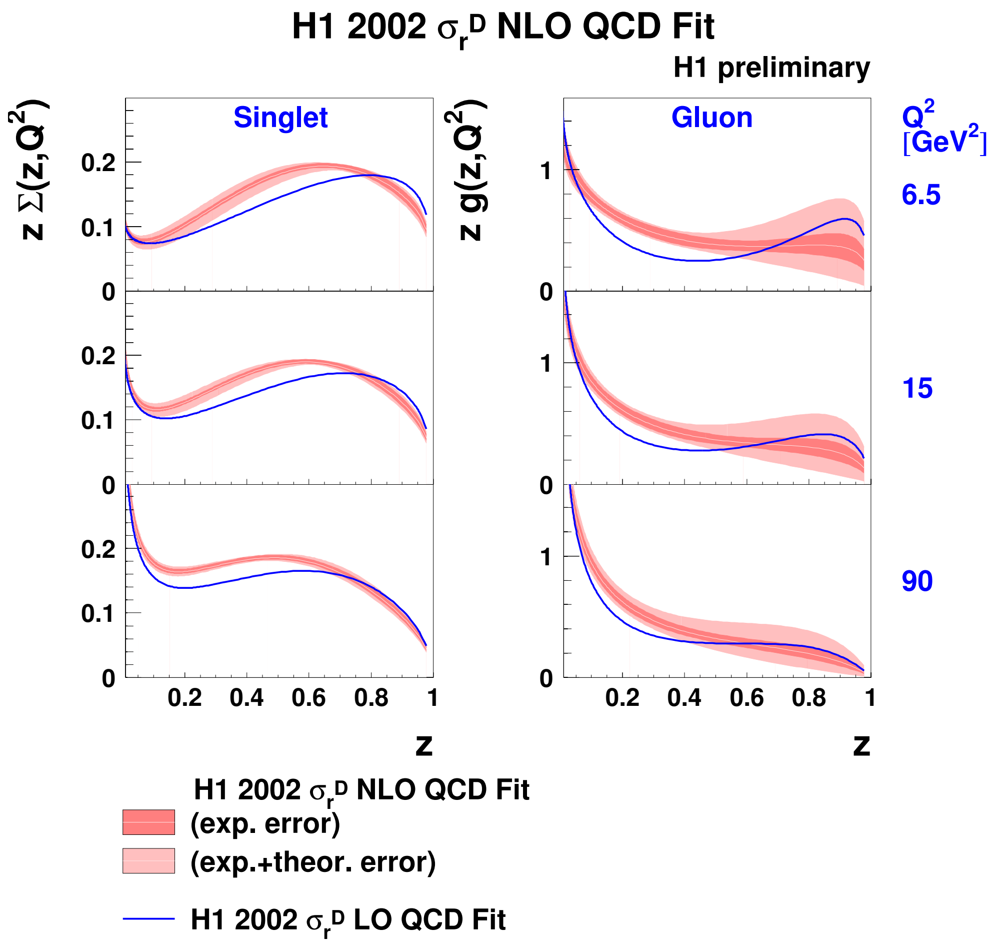
$(\Sigma = 6u, u = d = s = \bar{u} = \bar{d} = \bar{s})$

▷ gluon density $g(z, Q^2)$– from scaling violation

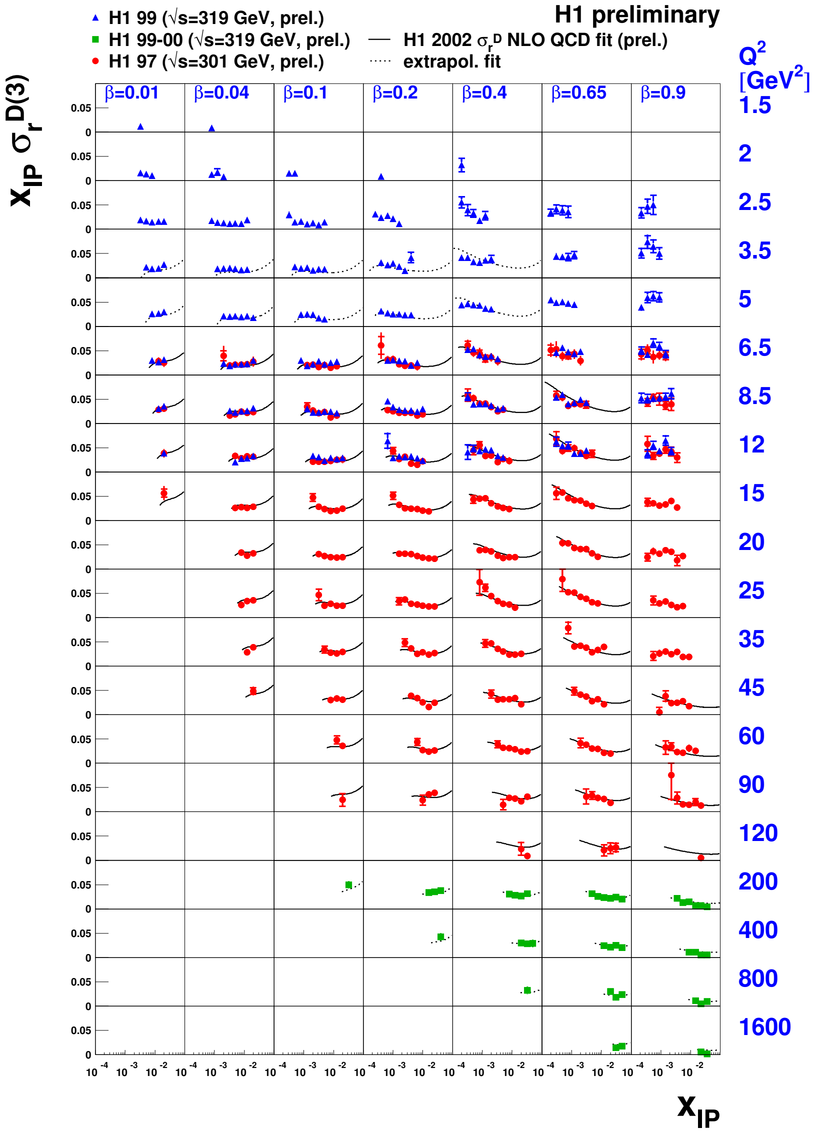


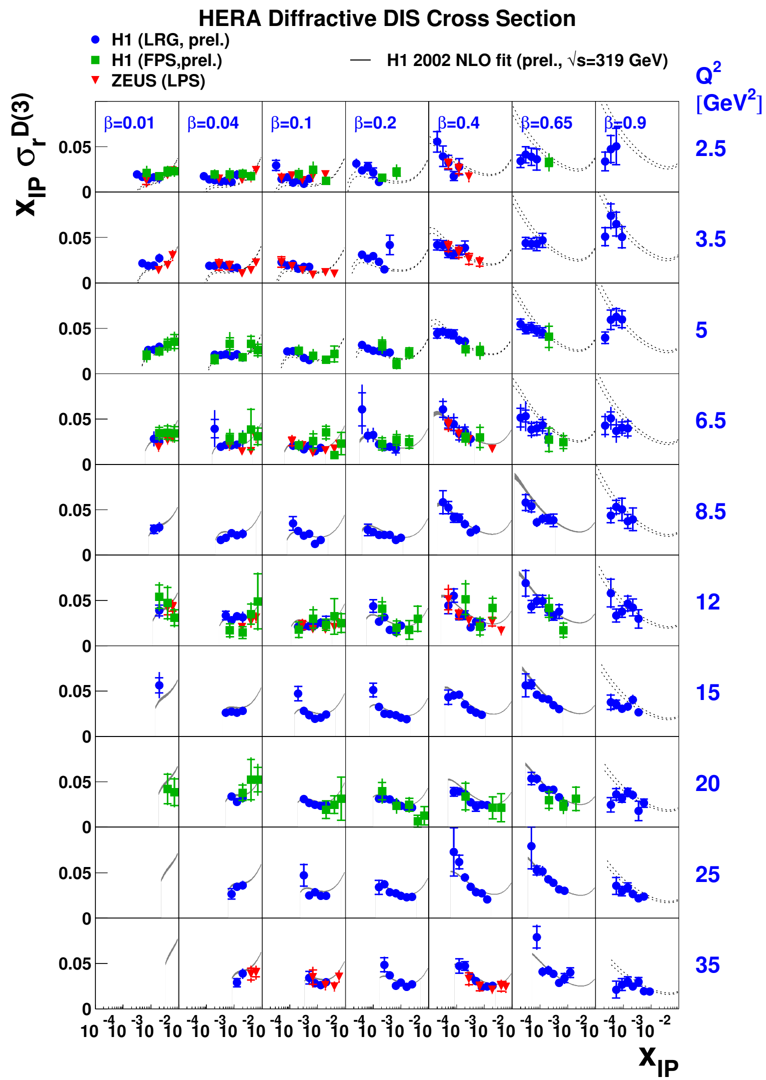
z- long.momentum fraction of the exchange

- low z behaviour similar to F_2^p
- hard gluon distribution extending to high z
- momentum fraction of colour singlet exchange carried by gluons $75 \pm 15\%$ for $Q^2 \propto 6.5 \ldots 800\ GeV^2$
- large uncertainty for $g(z, Q^2)$ at $z > 0.6$



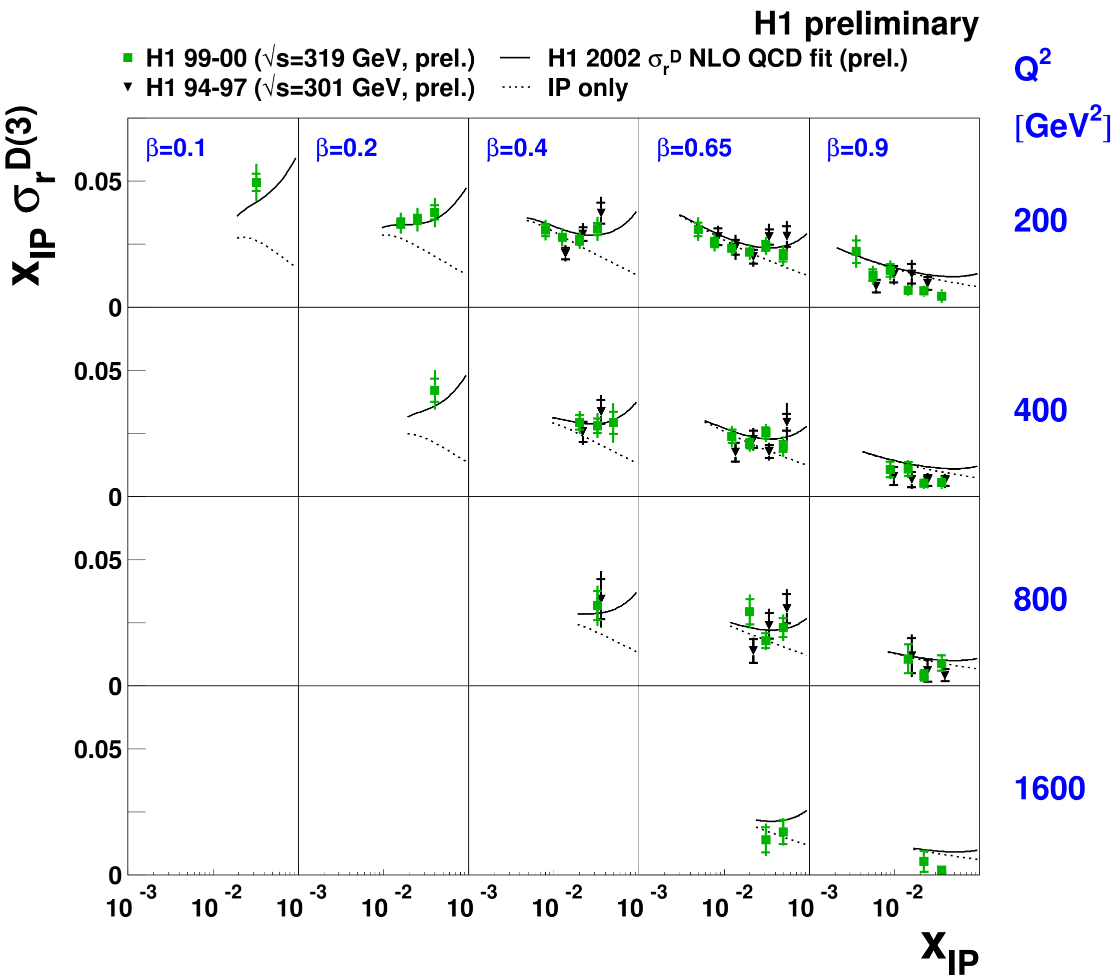
$x_{I\!P}, \beta, Q^2$ dependence of $F_2^{D(3)}$





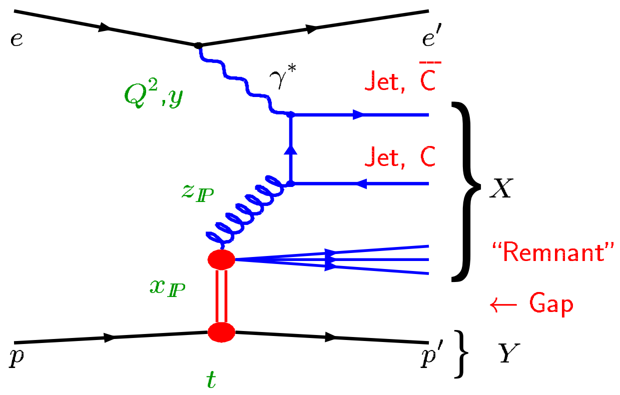
- DGLAP evolution based fit describes the data over full kinematic range
- Predictions of NLO fit based on medium Q^2 describe low Q^2 and high Q^2 data

Measurements at high Q^2 vs Predictions of QCD fit



- Improved statistics and kinematical range of new measurement compared to previous measurements
- Predictions of NLO fit based on medium Q^2 describe high Q^2 data
- Sub-leading trajectory needed at high $x_{I\!P}$ and low β

Diffractive Dijets and Open Charm production



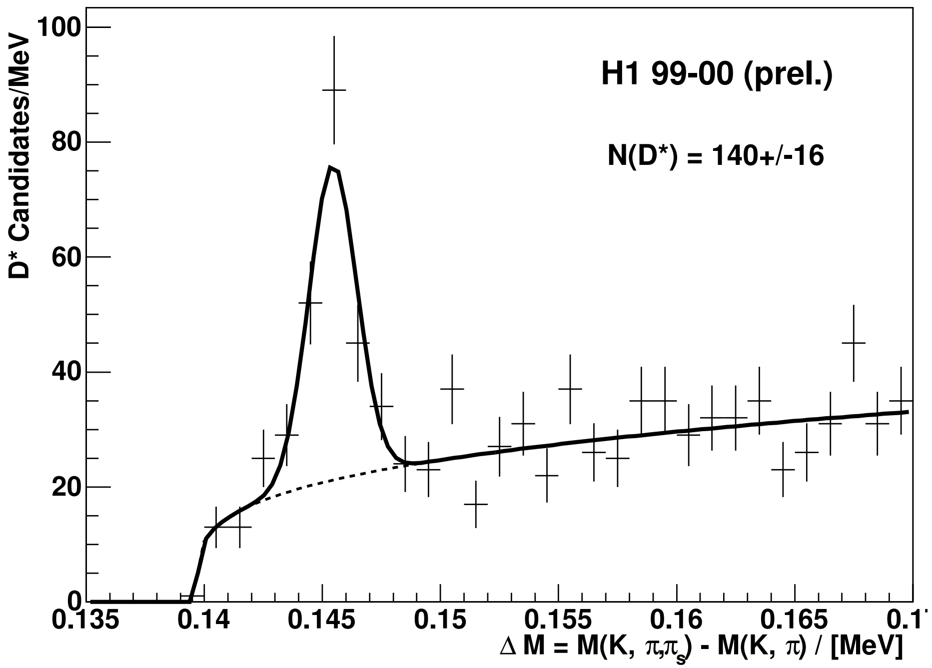
Ideal test of underlying dynamics of diffraction:

- **Test universality of parton distributions (extracted from F_2^D)**
- **Production mechanism is directly sensitive to the gluon content of colour singlet exchange $\longrightarrow$ give constrain of shape and normalization of gluon density in diffractive exchange**
- **Presence of two hard scales (Q^2 and p_T^{jet}, m_Q)**

Open Charm (D^*) in Diffractive DIS

- **Test of factorization in heavy flavour production in diffractive DIS**

New H1 measurement:



- *Diffractive selections*
  $x_{I\!P} < 0.04$,
  $M_Y < 1.6\ GeV$, $|t| < 1\ GeV^2$

- *DIS kinematic range*
  – $2 < Q^2 < 100\ GeV^2$
  – $0.05 < y < 0.7$

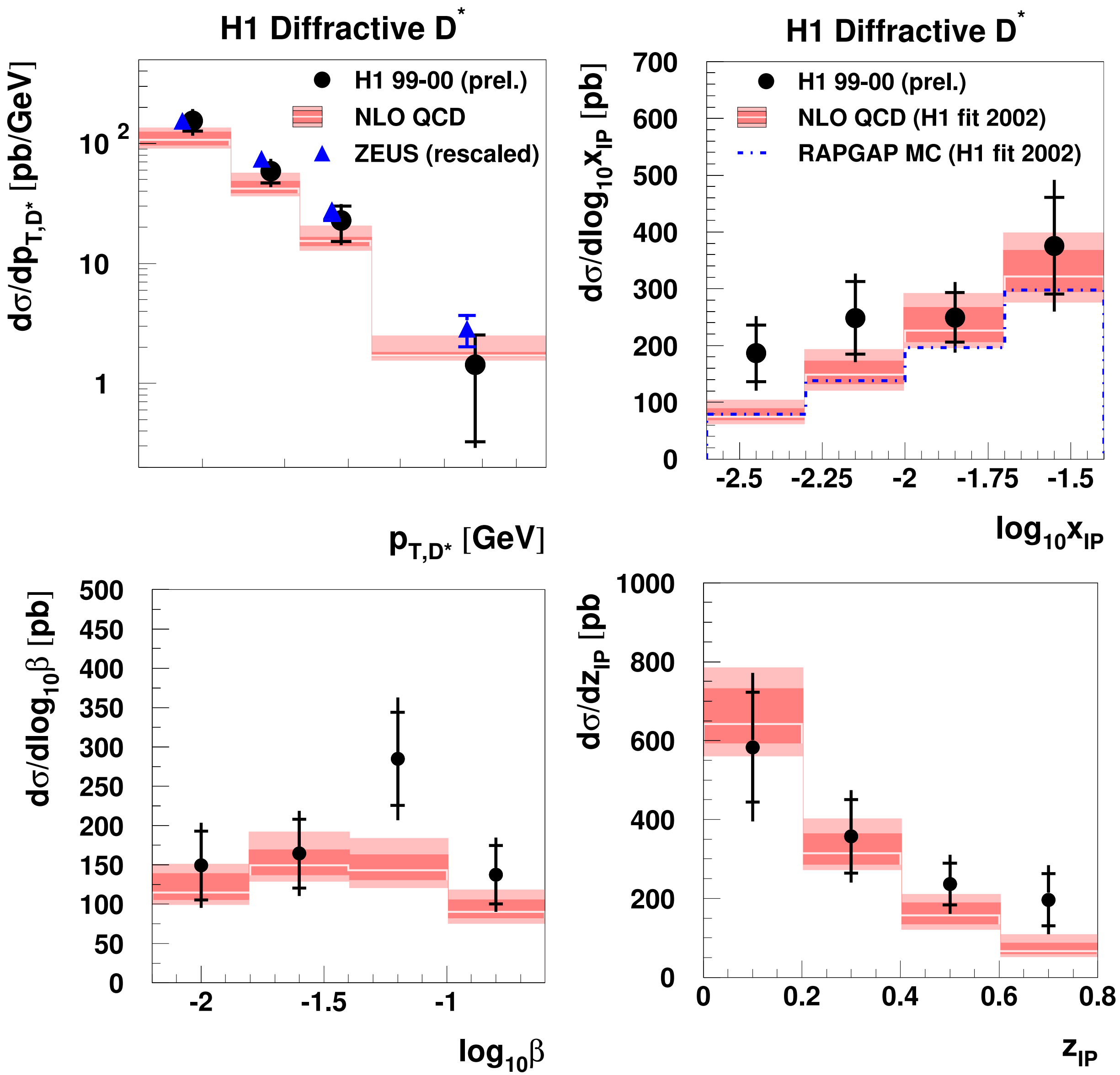
- *D^* selection*
  $p_{T,D*} > 2\ GeV$, $|\eta_{D^*}| < 1.5$

Number of selected events: 140 $\pm$ 16

total diffractive $D^{*\pm}$ cross-section

H1 data	358 $\pm$ 41 (stat.) $\pm$ 61 (syst.) pb
ZEUS data (extrapolated from different phase space)	305 $\pm$ 25 (stat.) $^{+20}_{-34}$ (syst.) pb
H1 NLO	242 $^{+66}_{-39}$ pb

Differential $D^{*\pm}$ cross sections in Diffractive DIS

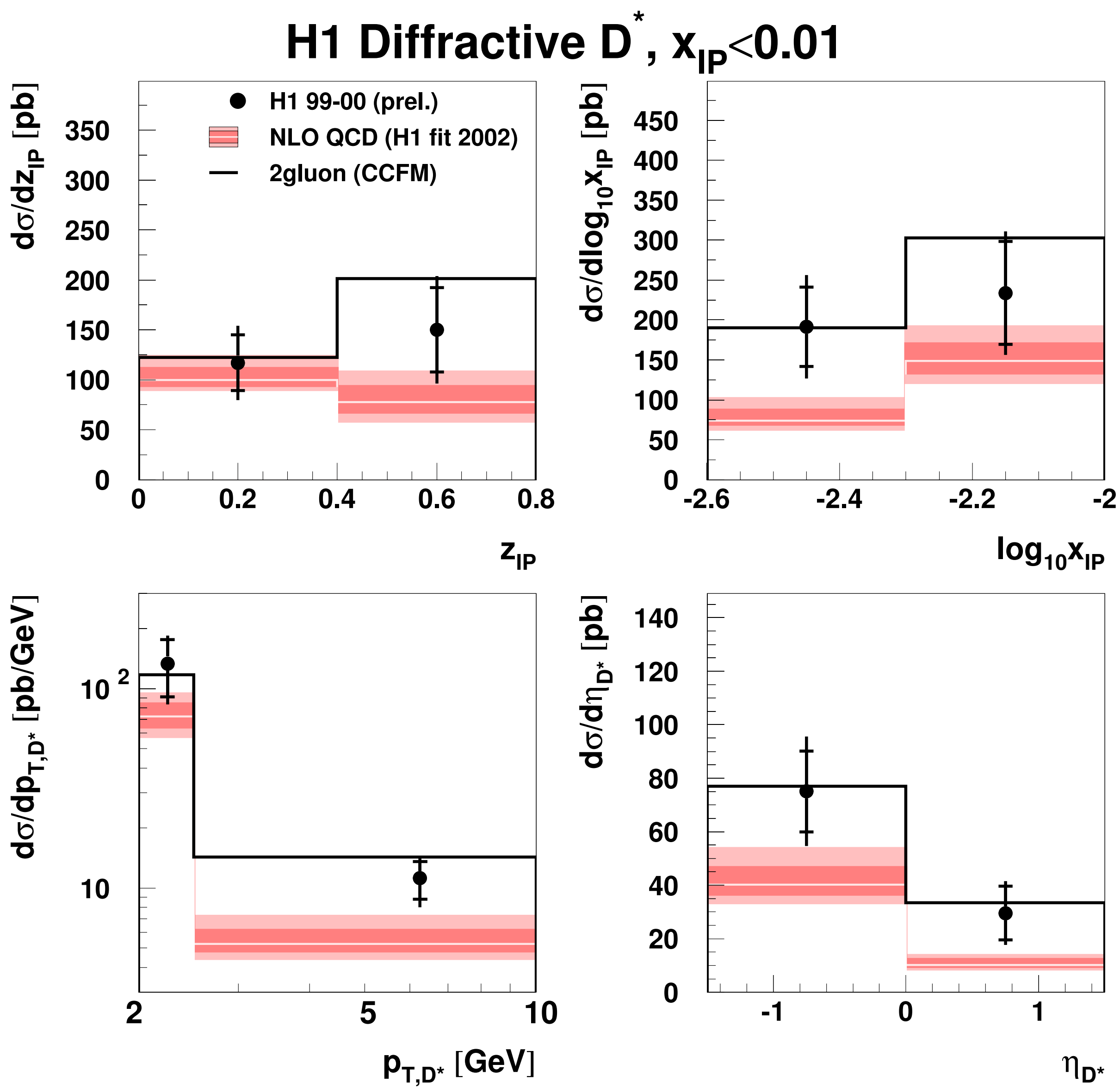


- agreement between H1 and ZEUS measurements
- NLO predictions below the data but agreement within errors
- also RAPGAP Monte Carlo agrees with data

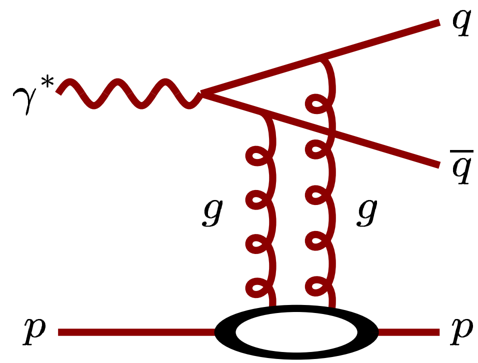
$\Longrightarrow$

- support for the validity of QCD factorization in diffractive DIS

Open Charm– comparison with 2-gluon exchange models

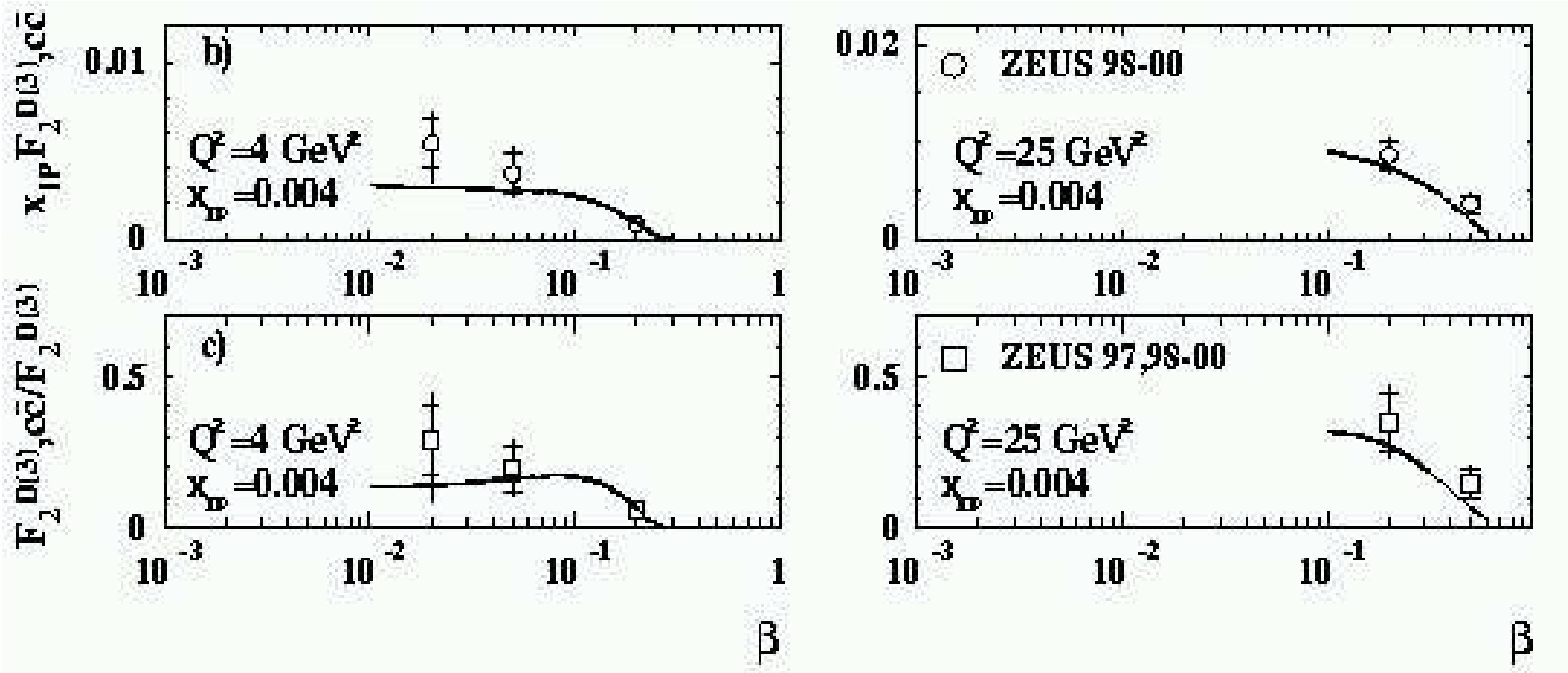


Perturbative '2-gluon' approach: use of unintegrated gluon density obtained from CCFM evolution to the inclusive F_2 data



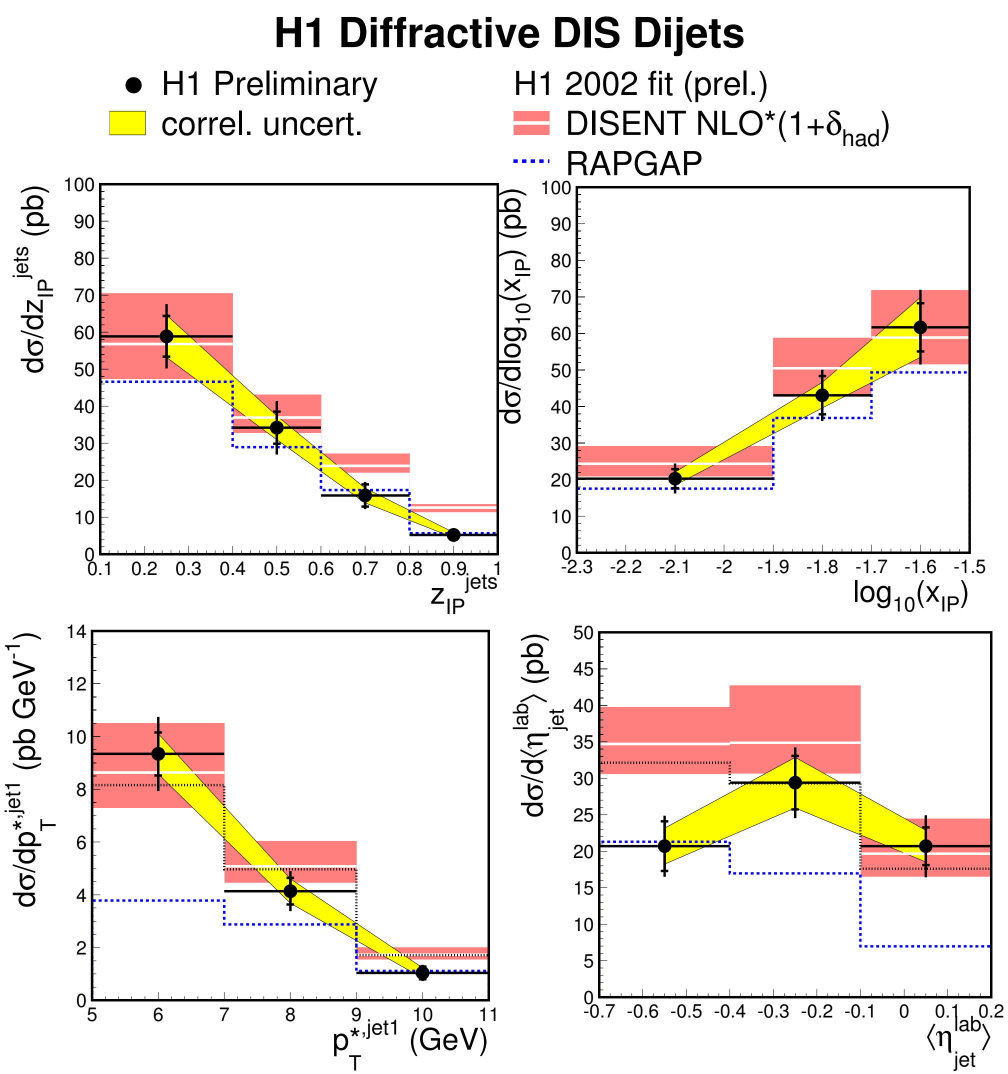
Good agreement with data in all distributions

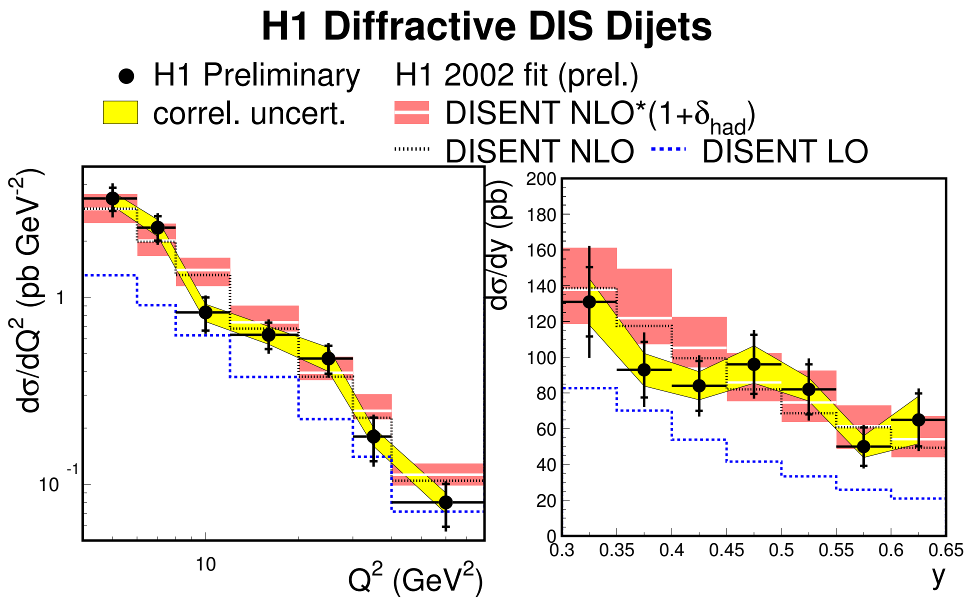
Charm Contribution to Diffractive Structure Function



Well described by NLO QCD fit (ZEUS)

Diffractive dijets in DIS

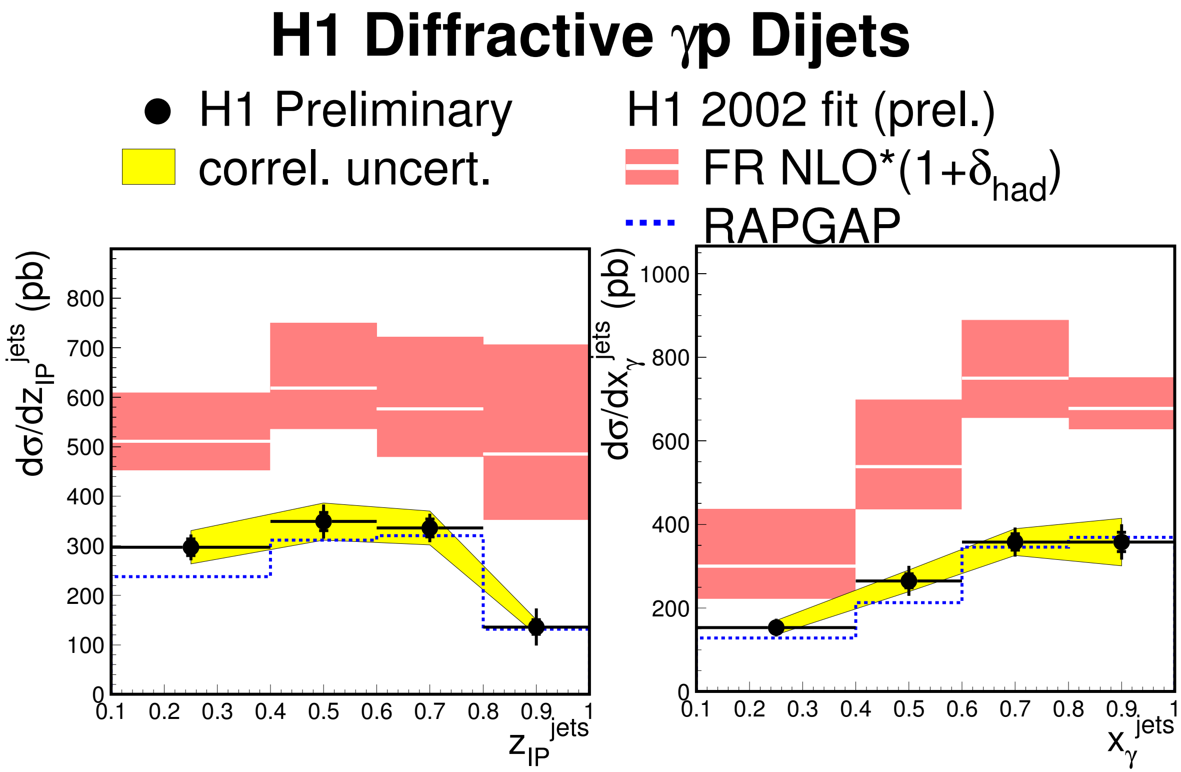


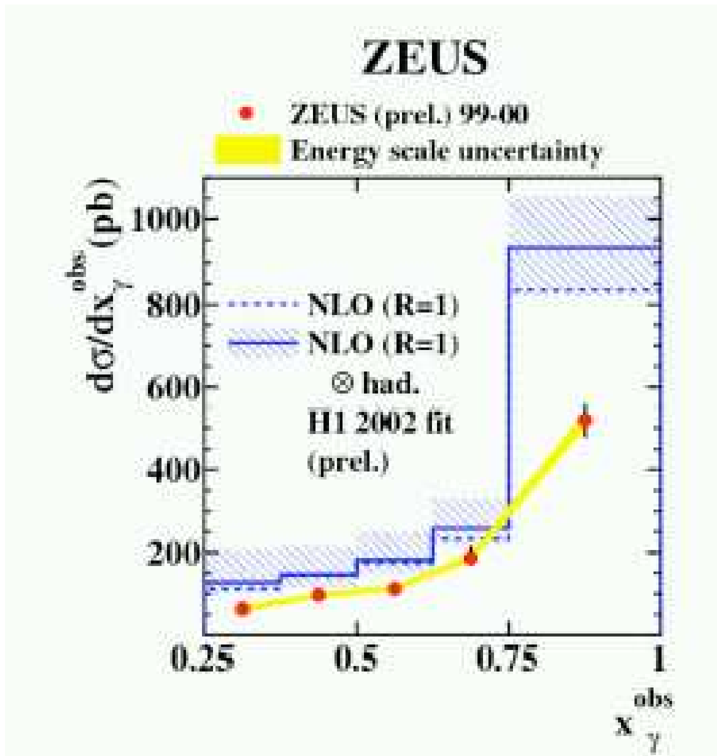


NLO predictions with QCD fits to inclusive diffractive DIS are in agreement with measurements

$\Longrightarrow$ **Support for QCD factorization in diffractive DIS**

Diffractive dijets in Photoproduction

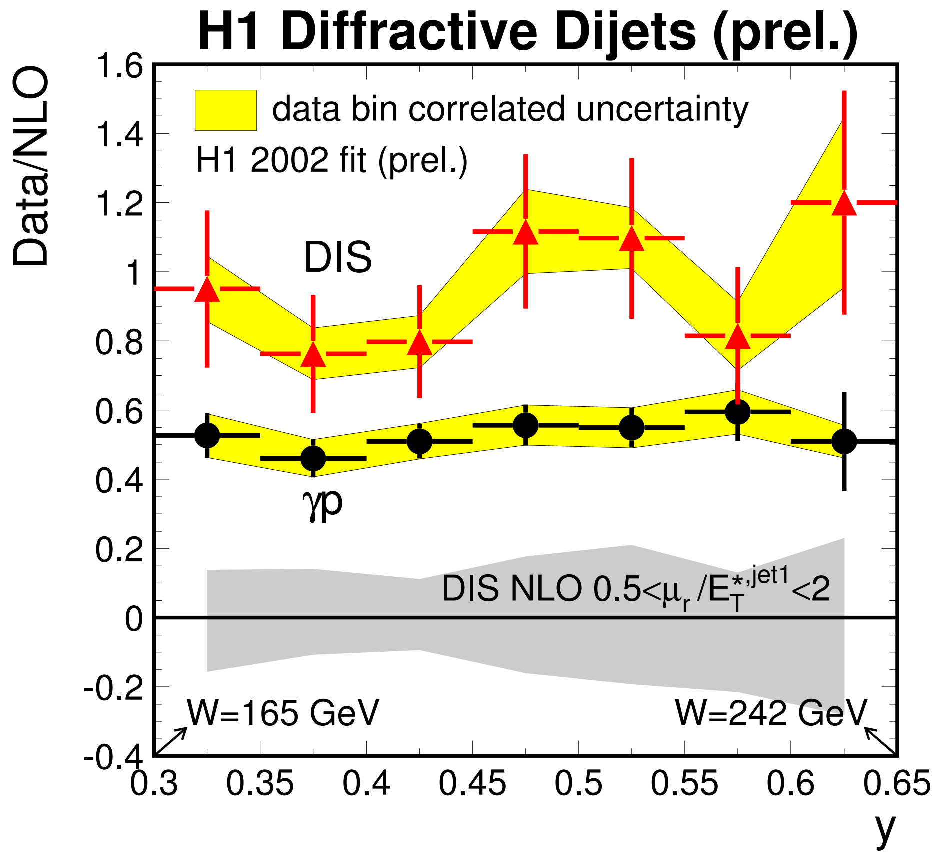


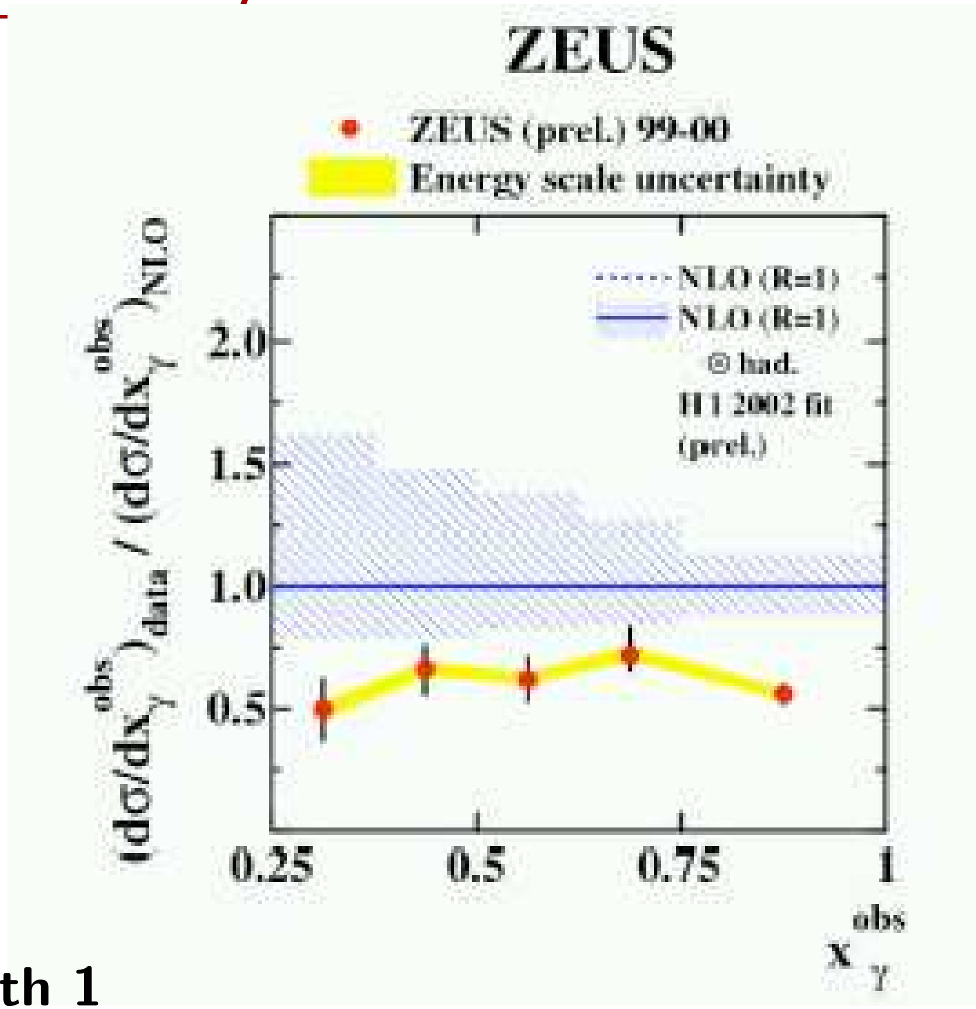


NLO predictions are too high by $\sim$ factor 2

$\Longrightarrow$ **Breaking of QCD factorization in diffractive dijet photoproduction**

Diffractive Dijets: ratios Data/NLO





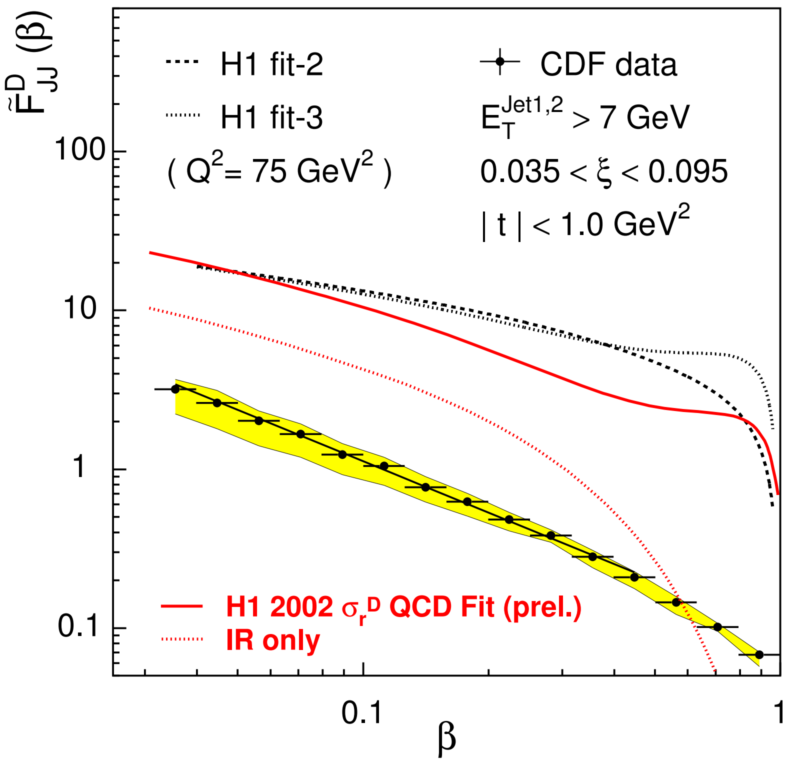
▷ **DIS:** **ratio 'Data/NLO' is compatible with 1**

▷ **photoproduction:** **ratio 'Data/NLO' is around 0.5**

but ... at TeVatron the factor is ∼ 0.2–0.1 !

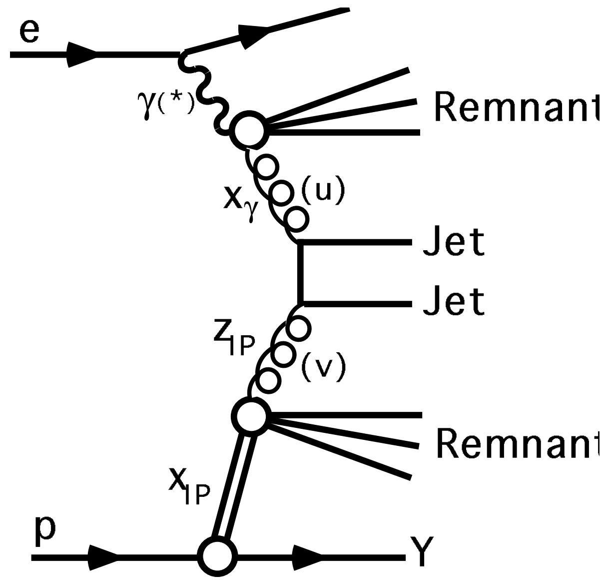
Breakdown of QCD factorization at TeVatron

Tevatron ($p\bar{p}$)



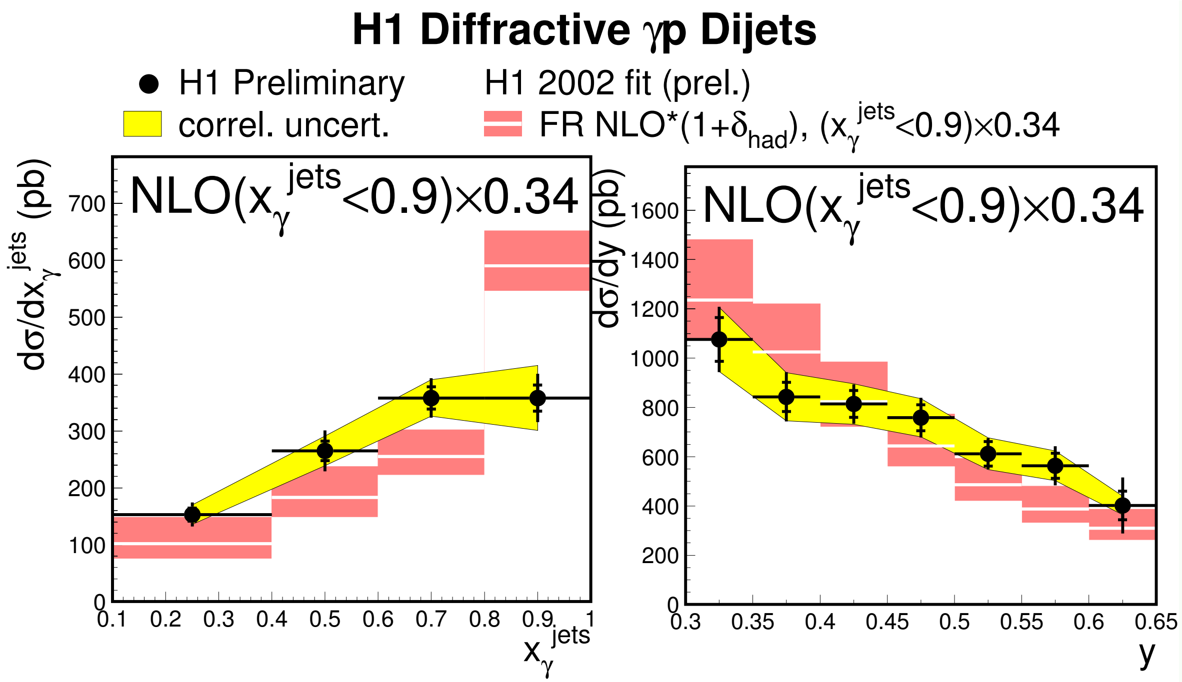
Hard diffraction in pp is suppressed by factor 5-10 w.r.t. predictions using diffractive PDFs from HERA
$\longrightarrow$ reduction of 'gap survival probability'

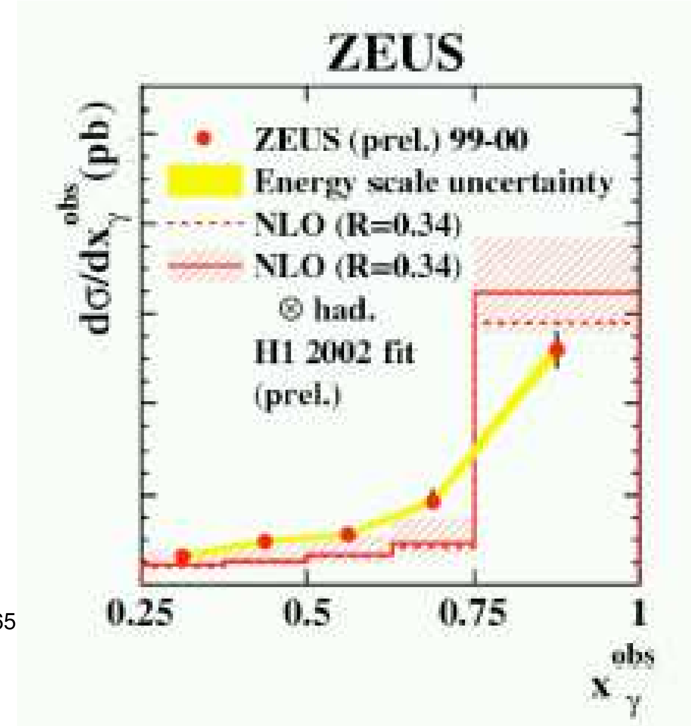
Expect similar suppression effect in resolved photoproduction at HERA
(resolved photon interacts hadronically)



Kaidalov,Khoze,Martin and Ryskin:
In Real Photoproduction the resolved contribution suppressed by 0.34
(Phys.Lett.B567 (2003) 61)

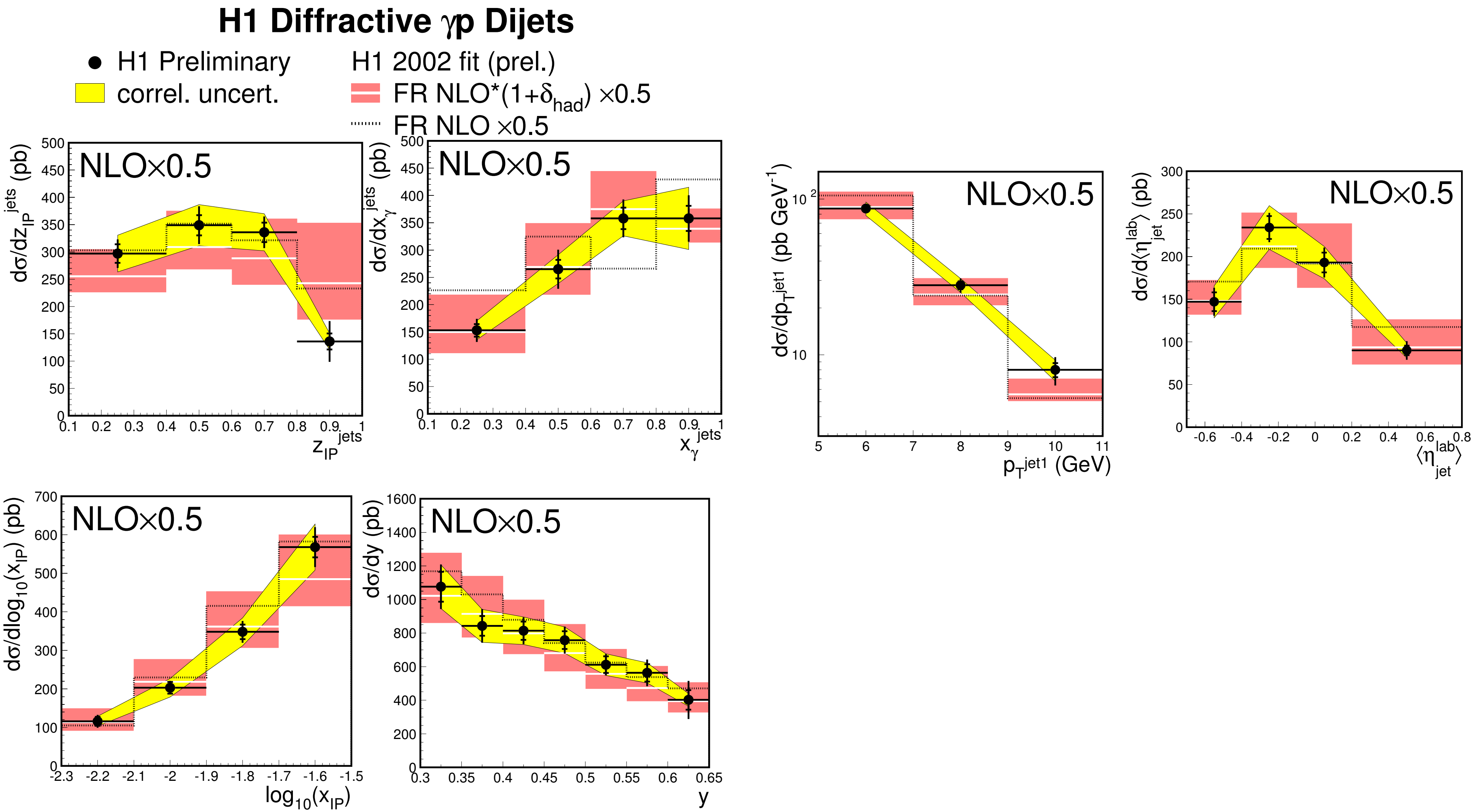
Diffractive dijets in Photoproduction





Suppression of only resolved component by factor 0.34 (predicted by Kaidalov et al.) is not favored by these measurements

Diffractive dijets in Photoproduction

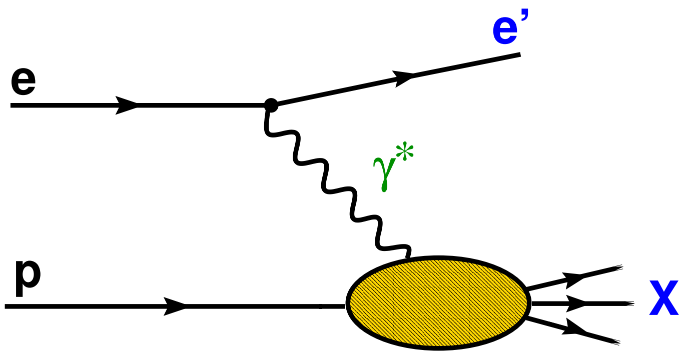


Good agreement with NLO predictions using diffractive PDFs globally suppressed by ~ 0.5

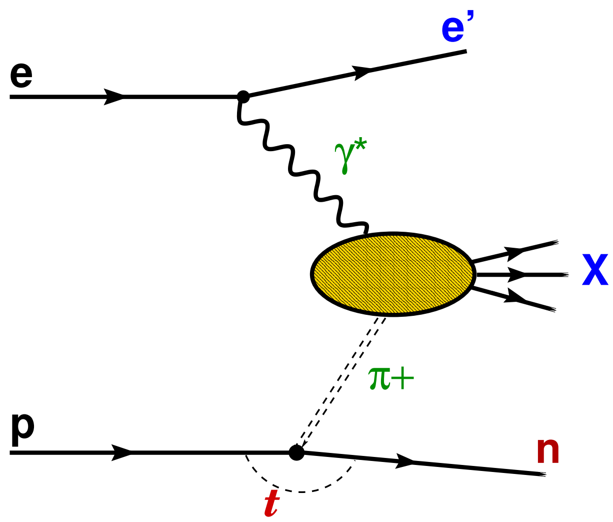
Charm and Dijets with Leading Neutrons

Possible mechanisms for production of highly energetic proton/neutron in forward direction:

– Fragmentation of proton remnant



– Exchange processes



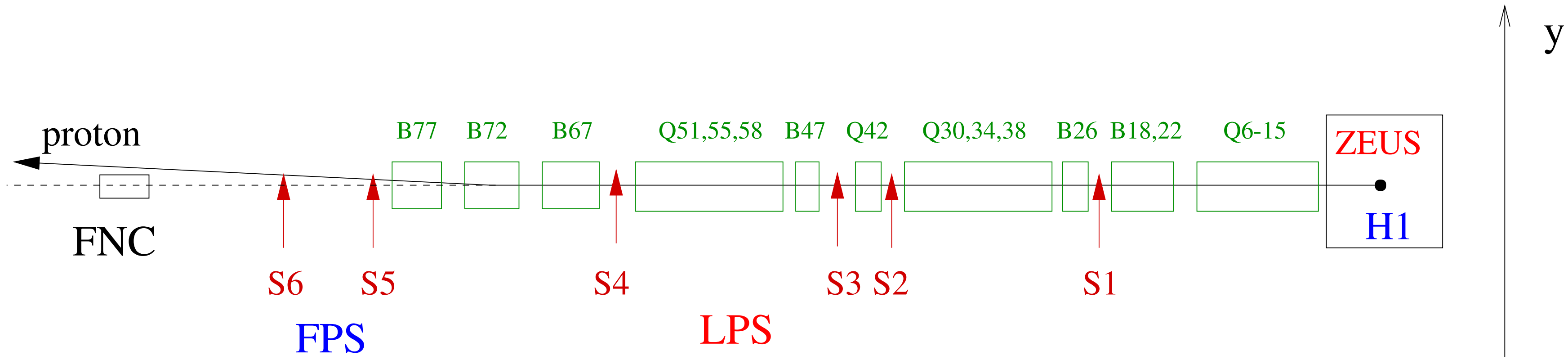
$$\sigma(ep \to e'nX) = f_{\pi/p}(x_L, t) \times \sigma(e\pi \to e'X)$$

– Study the mechanism of leading neutron production

– Factorization hypothesis $\longrightarrow$ leading neutron (LN) production rate is independent from kinematical variables

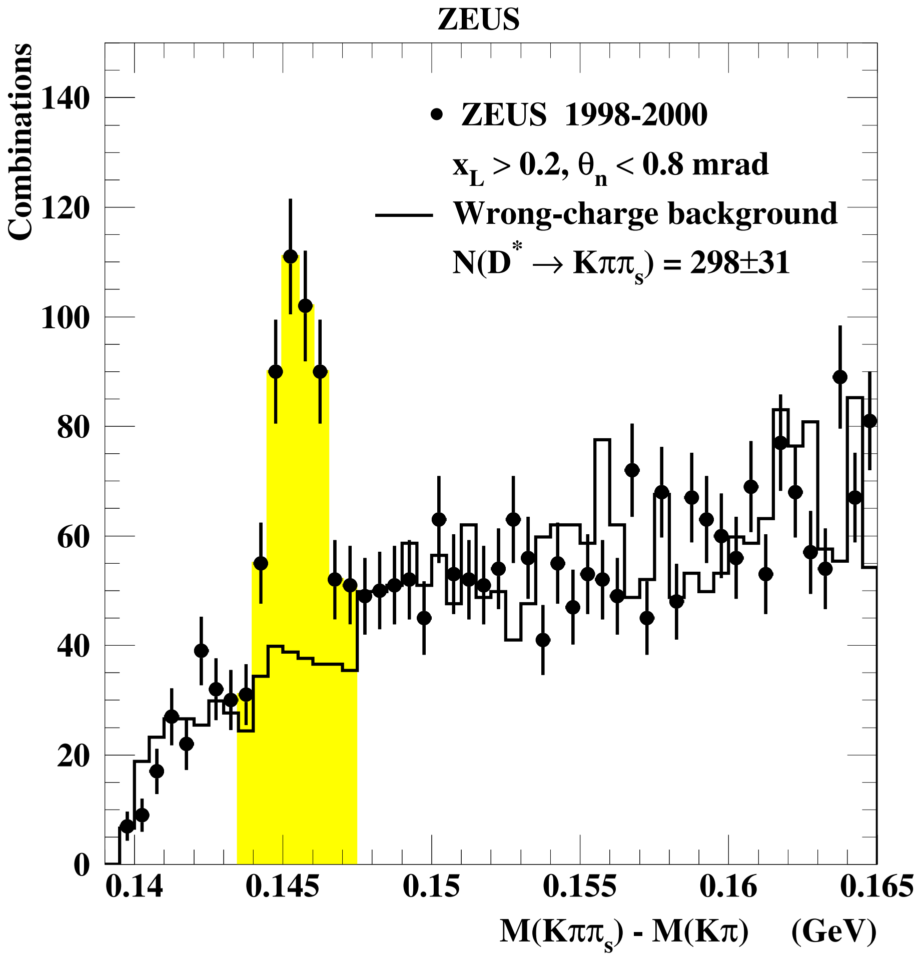
– Rescattering hypothesis (I.D.'Alesio and H.J.Pirner, 2000) $\longrightarrow$ neutron rescatters on the hadronic component of the photon $\longrightarrow$ LN rate depends on the transverse size of virtual photon

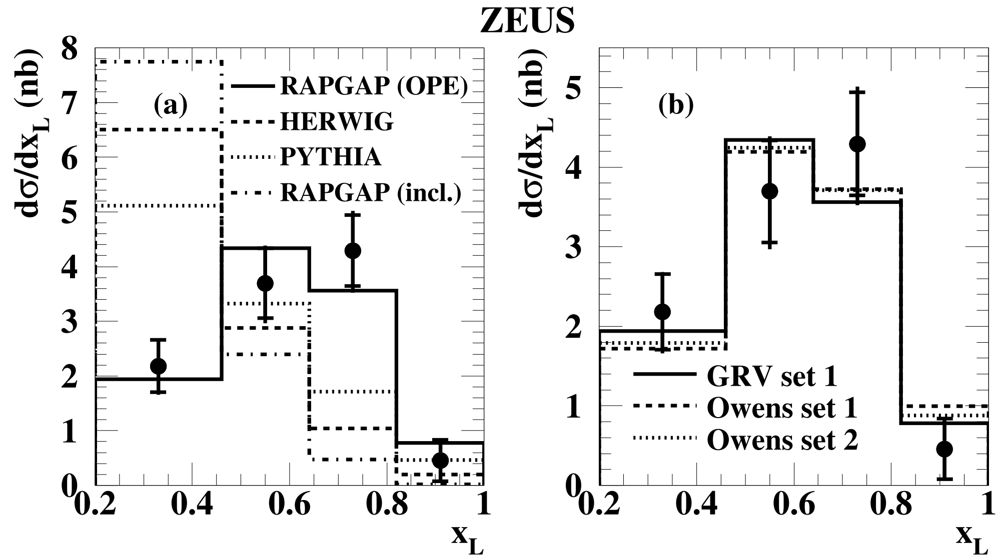
Forward Neutron Calorimeters at HERA



- **Dedicated detectors installed 107 m downstream in proton direction from HERA-interaction point.**
- **Acceptance limited by magnet apertures**
  H1 and ZEUS FNC: $\theta_n \lesssim 0.8\ mrad,\ p_t < 0.66\ x_L$

D^* with a leading neutrons



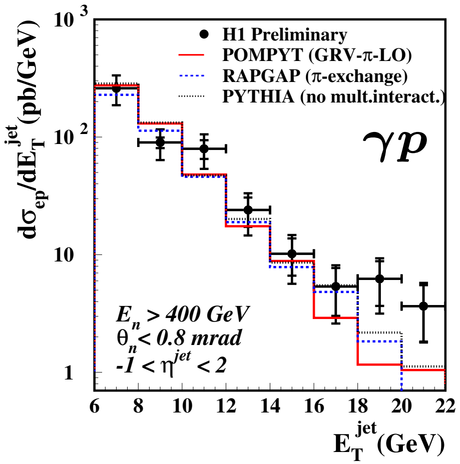


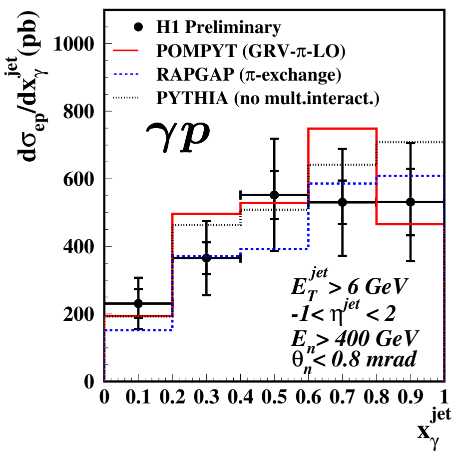
$$x_L = E_n/E_p$$

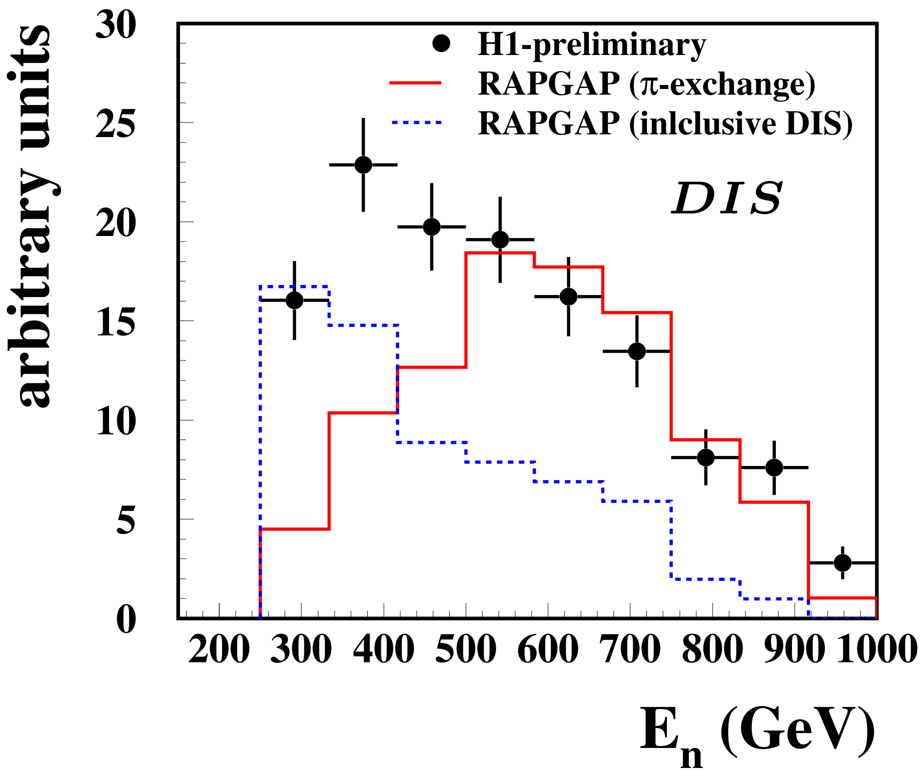
- ZEUS 1998-2000
  $x_L > 0.2$, $\theta_n < 0.8$ mrad

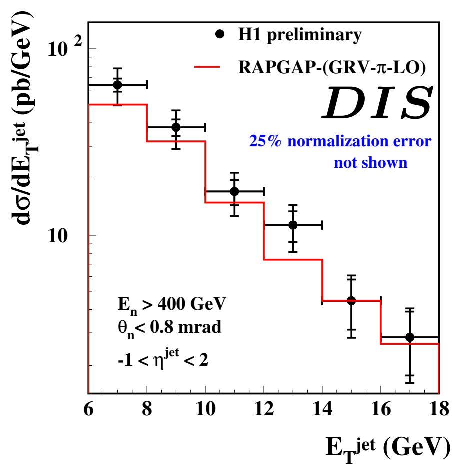
- Standard fragmentation models (HERWIG, PYTHIA,..) describe well cross sections in p_T, η and W $(not\ shown)$, but don't describe x_L distribution.
  Only pion exchange model (RAPGAP) describes x_L.
- Measurement is not sensitive to the different parameterizations of the pion PDF

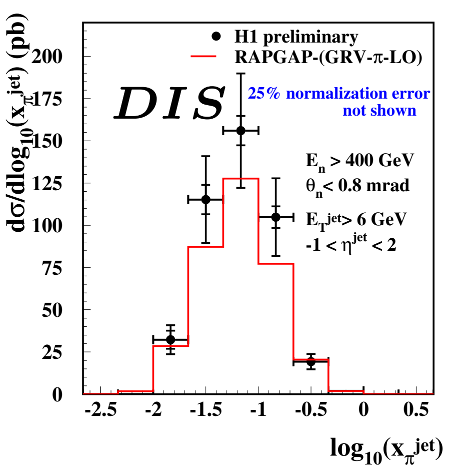
Dijet events with a leading neutrons







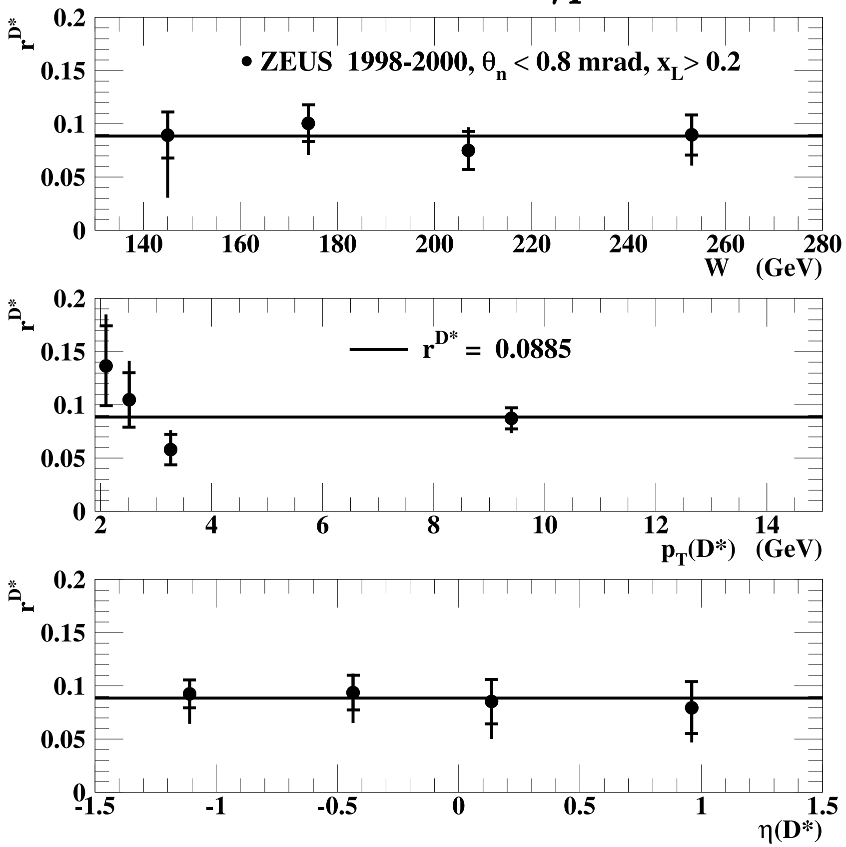




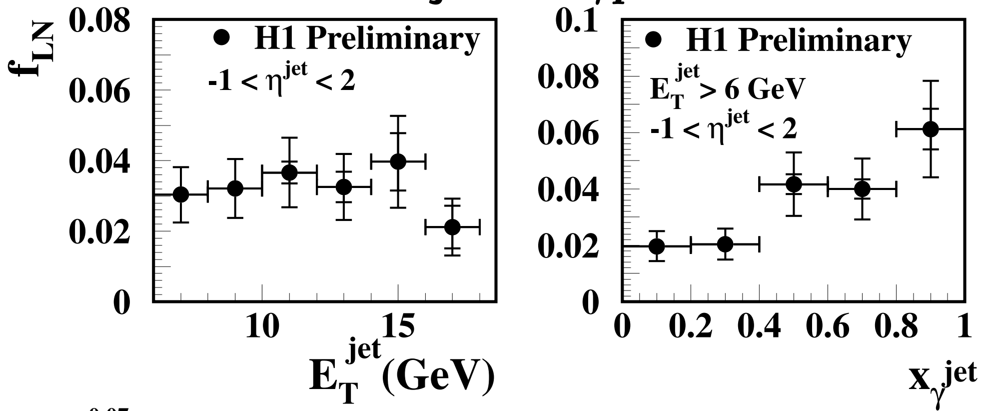
Well described by a pion exchange models both in γp and in DIS (RAPGAP, POMPYT).

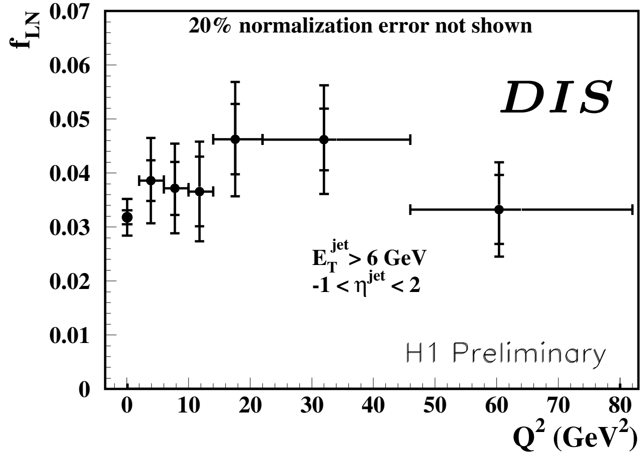
Yield of D^* and Dijet events with a Leading Neutron

D^* in γp



Dijets in γp





– Ratio $\frac{\sigma_{LN}}{\sigma_{incl}}$ for D^* is flat w.r.t. W, p_T and η $\rightarrow$ factorization holds.

– Ratio for Dijets is flat with E_T^{jet}, Q^2 but increase with x_γ^{jet}

– In ZEUS, for $x_L > 0.49$, $r^{JJ} = 4.9 \pm 0.4\%$,

$$r^{D^*} = 6.55 \pm 0.76^{+0.35}_{-0.45}\%$$

$r^{D^*} > r^{JJ}$ $\rightarrow$ rescattering ?

Conclusions

- HERA is an ideal facility to investigate the diffractive exchange in terms of pQCD and to study transition from soft to hard diffraction, explored using different hard scales ($Q^2, M_q, p_T^{jet}, \ldots$)
- Measurements of inclusive diffraction and the hadronic final states in diffractive DIS can be described within a consistent picture:
  - QCD factorization
  - NLO DGLAP evolution
  - Diffractive PDFs dominated by gluon contribution ($> 75\%$)
- Open questions (e.g. breakdown of factorization at TeVatron, flat dependence $\sigma_{diff}/\sigma_{tot}$,...)

Outlook

- Still more results to come from HERA-I data
- HERA-II – new quality of diffractive measurements
  - $\times 5$ increase of statistics
  - new detectors- H1 VFPS – large acceptance for low $x_{I\!P}$ and $|t| \lesssim 0.5$ GeV^2.