

Workshop on high-energy photon collisions at LHC, 2008  
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# Factorisation breaking in diffraction

Alessia Bruni, INFN Bologna  
on behalf of the H1 and ZEUS collaborations

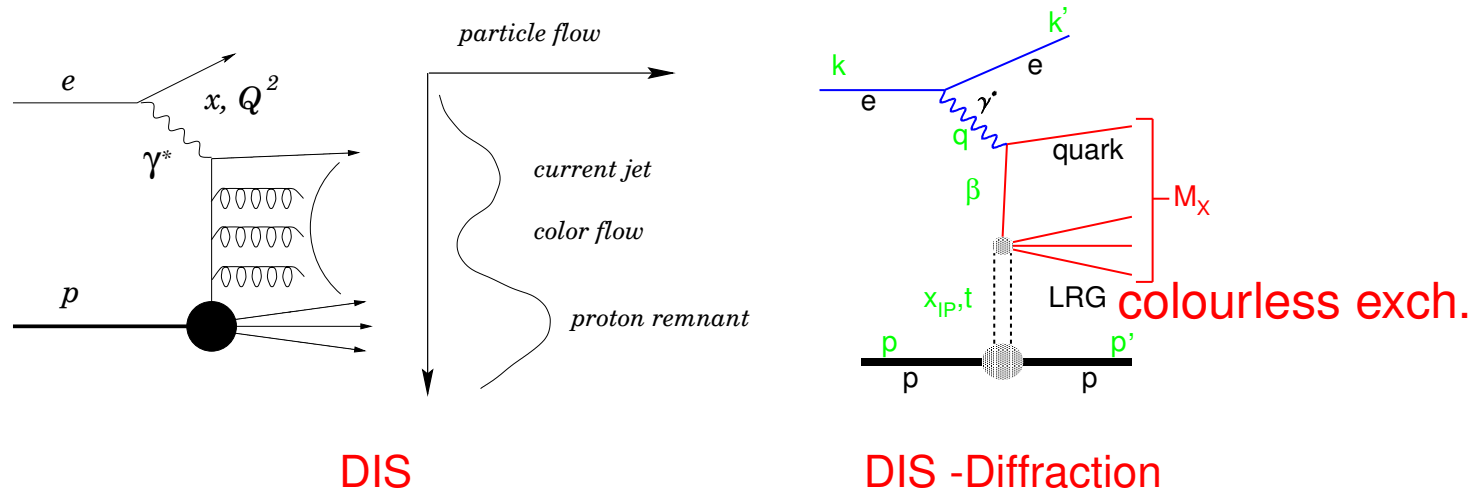
## OUTLINE

- **Diffraction hard selection**
- **Hard diffraction in QCD**
- **Diffraction Parton Density Functions**
- **Diffraction final states (open charm, jets)**
- **Events with leading neutrons**

# Diffractive event selection

HERA: 27.5 GeV  $e$  + 920 GeV  $p$ ,  $\sqrt{s} = 318$  GeV

A large fraction (10% - 20%) of DIS events is diffractive

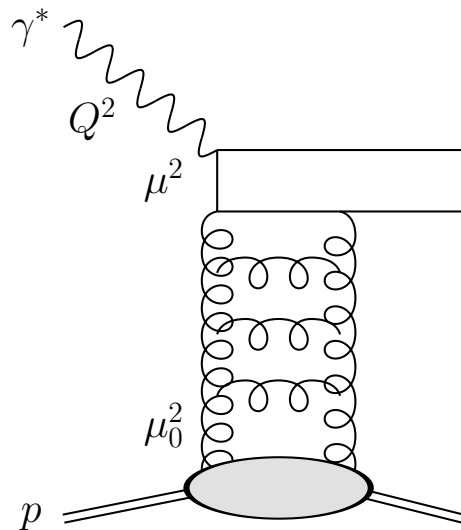


- Beam particles emerge intact or dissociated into low-mass states; energy  $\simeq$  beam energy (within a few %)
- Final-state particles separated by Large Rapidity Gap (LRG)
- Interaction mediated by  $t$ -channel exchange of object with vacuum quantum numbers: colour singlet exchange or Pomeron

# Hard diffraction in QCD

Diffractive processes with one or several large scales are called hard  
Hard diffraction is the interplay of systems with small size configurations (quark and gluon) and large size configurations (set by the size of the protons)

Application of pQCD relies on the ability to separate small (hard) from large configurations (soft)



2-gluon diagram

Hard diffraction is a laboratory for QCD studies:

- scale transition soft-hard
- factorisation tests
- dynamics of hard processes

# Kinematic variables

## DIS

$Q^2 = -q^2$ , virtuality of exchanged boson

$x_B = Q^2 / 2p \cdot q$ , Bjorken variable

fraction of proton's momentum carried by struck quark

$y = Q^2 / sx$ ,  $\gamma$  inelasticity

$W$  photon-proton centre of mass energy

## Diffractive DIS

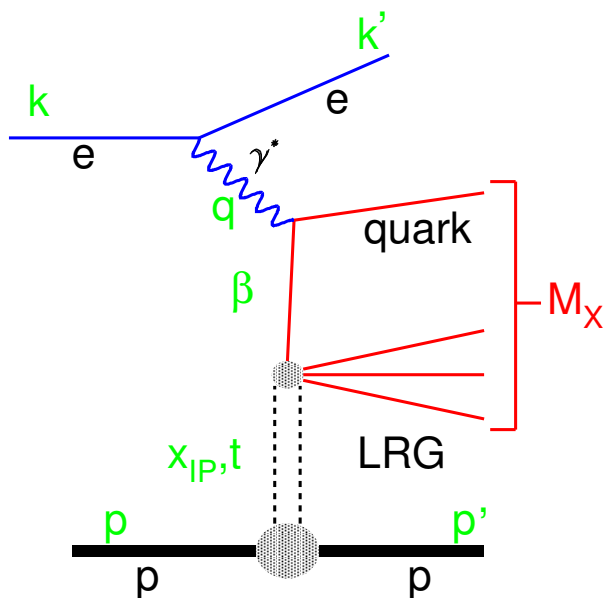
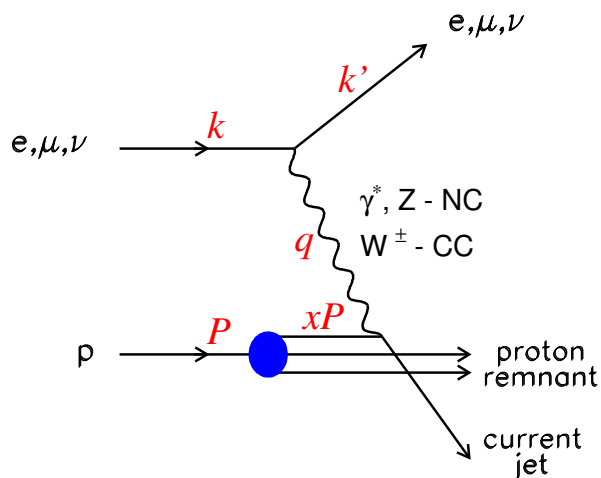
$x_P$  fraction of proton's momentum of colour singlet

$$\text{exchange} = \frac{q \cdot (p - p')}{q \cdot p} \simeq \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

$\beta$  fraction of Pomeron's momentum carried by quark

$$\text{coupling to } \gamma^* = \frac{Q^2}{2q \cdot (p - p')} \simeq \frac{Q^2}{Q^2 + M_X^2} = x_B / x_P$$

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



# QCD factorisation theorem

Breit rest frame (fast proton)

## DIS

$$F_2(x, Q^2) = \sum_{i=q,g} \int dz \quad f_i(z, Q^2) \quad C_i(x, Q^2)$$

structure

parton distribution function

hard scattering coefficients

functions

(universal, dglap)

(pqcd)

at LO, coefficients  $C_q(x) = e_q^2 \delta(1-x)$ ,  $C_g(x) = 0$

## Diffraction DIS

$$F_2^{D(4)} = \frac{d^2 F_2^D(x_{\mathbb{P}}, t, x, Q^2)}{dx_{\mathbb{P}} dt} = \sum_{i=q,g} \int dz \quad \frac{d^2 f_{i/p}^D(x_{\mathbb{P}}, t, z, \mu_F^2)}{dx_{\mathbb{P}} dt} \quad C_i\left(\frac{x}{z}, \frac{Q^2}{\mu_F^2}\right)$$

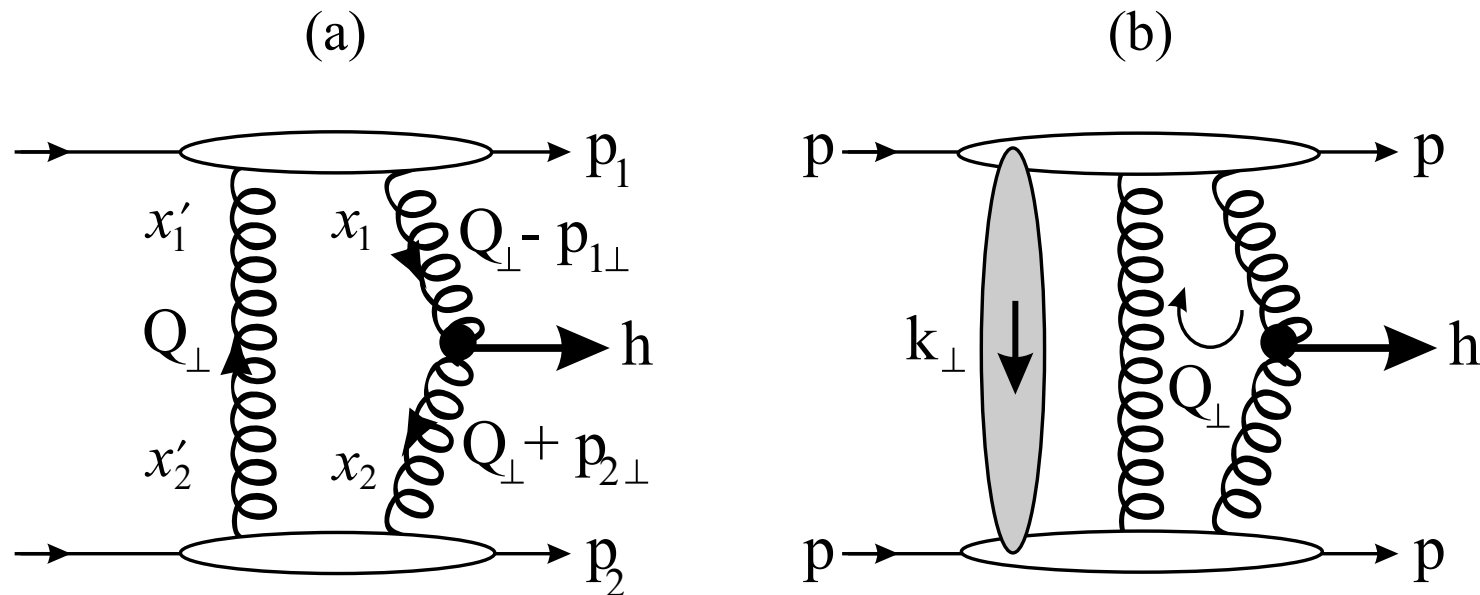
Diffraction PDF

same as  $F_2$

- Factorisation proved for DDIS and exclusive hard diffraction for large  $\mu_F$  (Collins, Berera & Soper, Trentadue & Veneziano)
- Not true for diffr. hadron-hadron collisions

# Factorisation not expected to hold for $pp$

- Violation of factorization understood in terms of (soft) rescattering between the 2 hadrons and their remnants, in initial and final state, suppressing the large rapidity gap



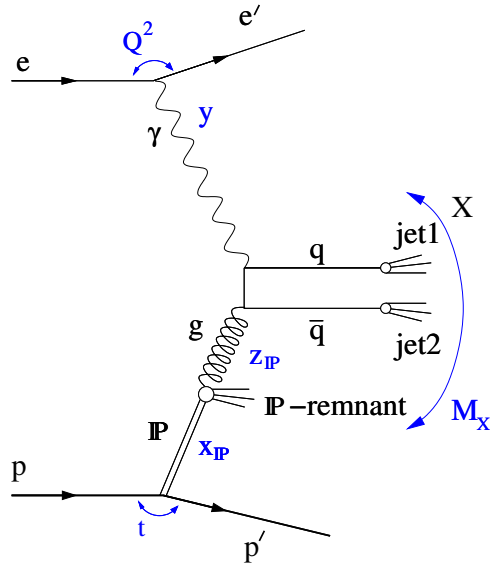
- Suppression observed for diffractive dijet production at Tevatron
- Interest for LHC diffractive production

# Factorisation tests in $\gamma^*p$ and $\gamma p$

Real photon ( $Q^2 \simeq 0$ ) can develop hadronic structure

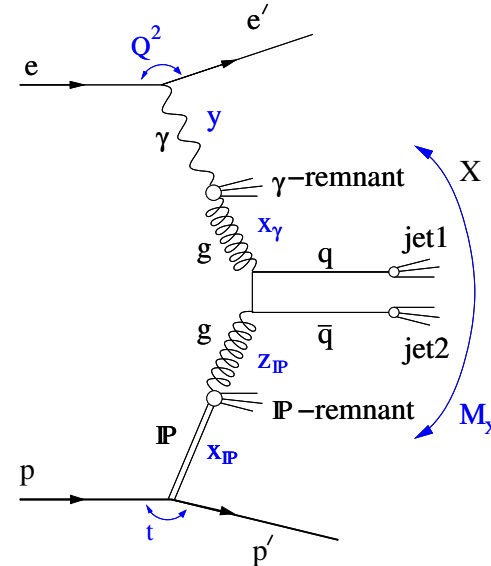
⇒ study fact. breaking at HERA

- direct  $\gamma$  ( $x_\gamma \simeq 1$ )



small  $\gamma$  couples directly to parton,  
dominant contribution in DIS  
and for high  $E_T$  jets

- resolved  $\gamma$  (hadron like, at low  $x_\gamma$ )



large  $\gamma$ , soft rescattering expected,  
dominant contribution for low  $E_T$  jets

- Theory: direct and resolved processes well separated only at LO

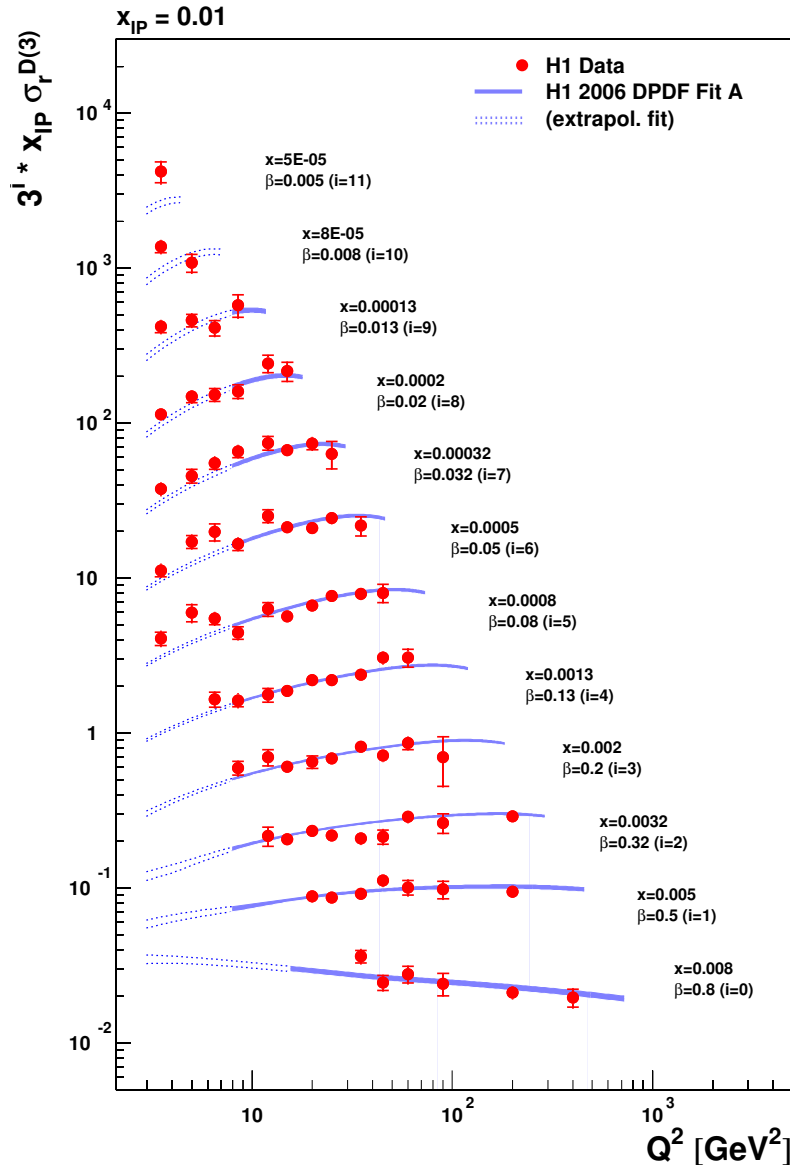
- Experimentally:  $x_\gamma$  reconstructed by jets,  $x_\gamma = x_\gamma^{OBS} = \frac{\sum (E-p_z)_{jets}}{\sum (E-p_z)_{hadrons}}$

# Diffraction final states, factorisation tests

- Basic strategy
  - measure  $F_2^D$  from inclusive measurement,
  - extract diffractive PDFs from NLO DGLAP fit
  - measure an exclusive diffractive final state, open charm and dijets, in DIS and PHP
  - compare the measurement to NLO calculation



# Diffractive structure functions, inclusive data



$$\frac{d^3 \sigma_{ep \rightarrow eXp}}{d\beta dQ^2 dx_{IP}} = \frac{4\pi\alpha_{em}^2}{\beta Q^4} Y^+ \sigma_r^{D(3)}(\beta, Q^2, x_{IP})$$

$$Y^+ = 1 + (1 - y)^2$$

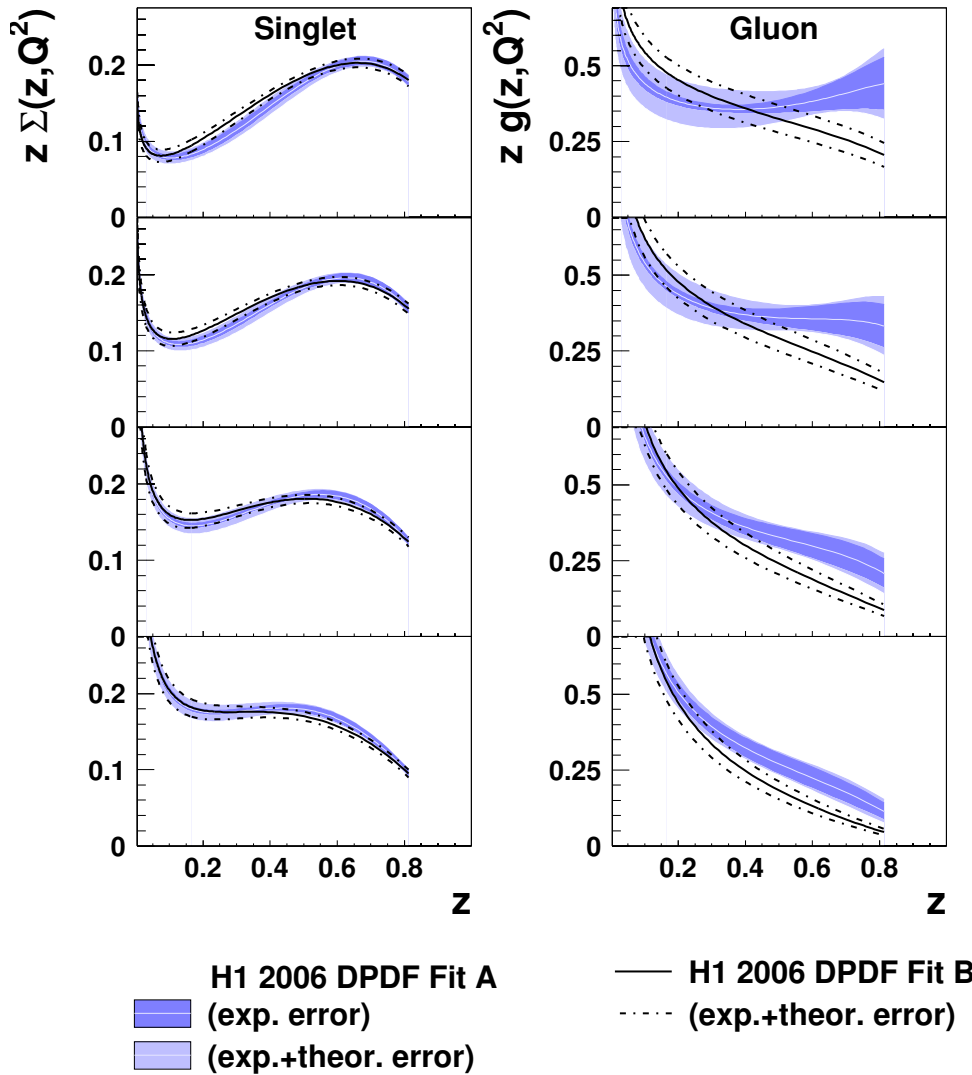
$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{Y^+} F_L^{D(3)}$$

$$F_L^{D(3)} = 0 \text{ at LO}$$

Reduced cross section constrains quark density  
 gluon density from  $\log Q^2$  dependence

- Positive scaling violations up to high  $\beta$
- ⇒ lot of gluons in diffractive exchange

# Diffractive PDFs from inclusive data



- Additional assumption: proton vertex factorisation

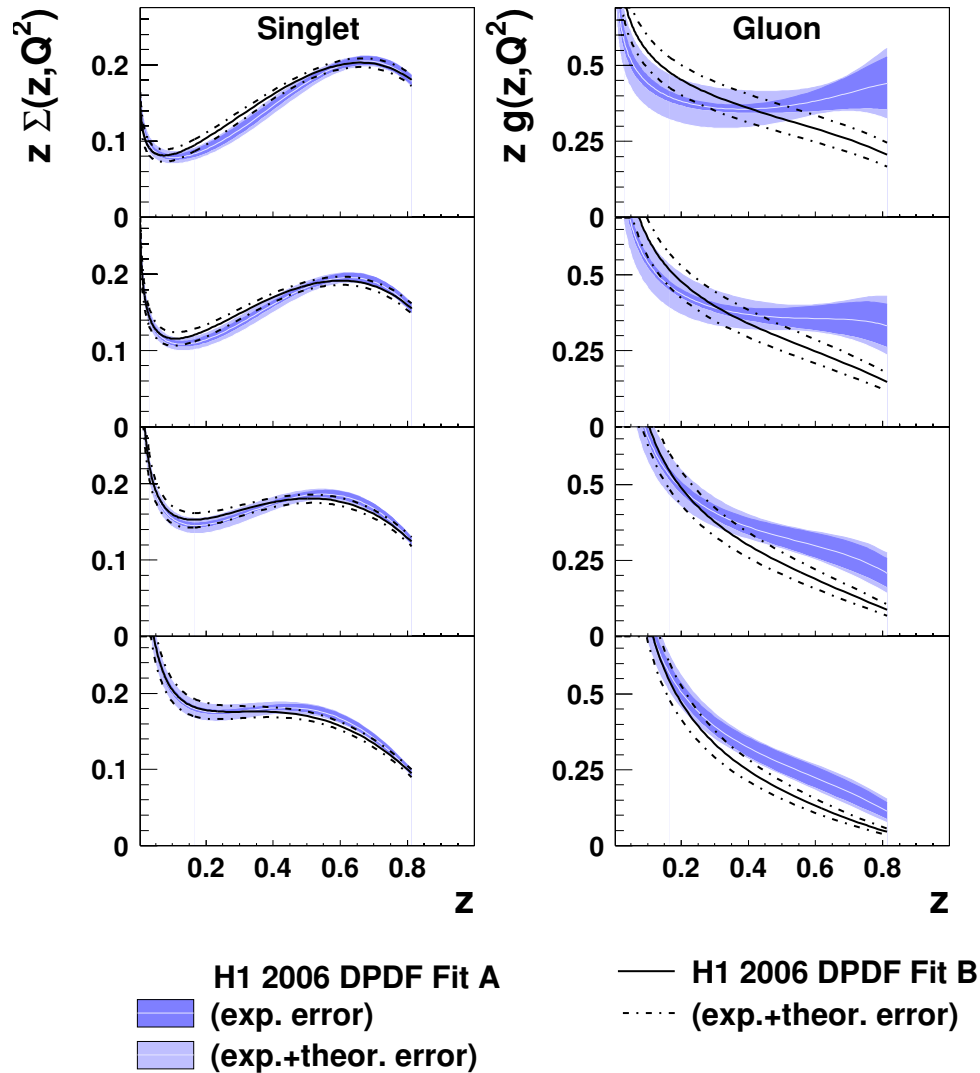
$$\frac{d^2 F_2^D(x_P, t, x, Q^2)}{dx_P dt} = f_{IP/p}(x_P, t) F_2^{IP}(\beta, Q^2)$$

- NLO DGLAP fits:
  - parametrise Flavour Singlet ( $q, \bar{q}$ ) and Gluons at  $Q^2 \simeq 3 \text{ GeV}^2$
  - evolve with NLO DGLAP and fit

- Different parametrisations:
  - H1 2006 fit A:  $zg(z, Q_0^2) = A(1 - z)^B$
  - H1 2006 fit B:  $zg(z, Q_0^2) = A(1 - z)$
  - but also Martin Ryskin Watt, ZEUS fit LPS + charm ...

$z$  = fractional momentum of parton participating in hard scattering

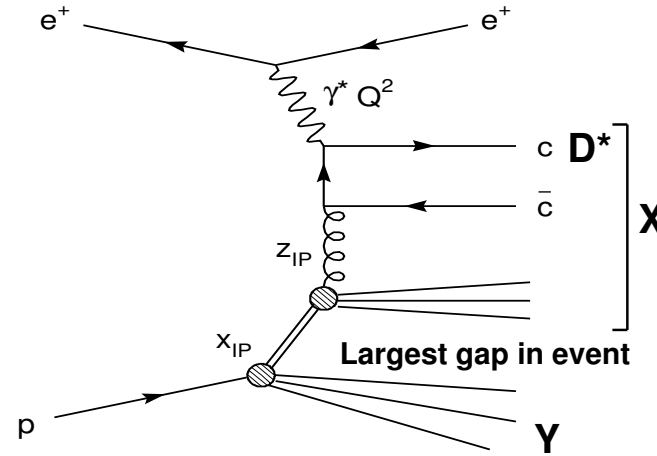
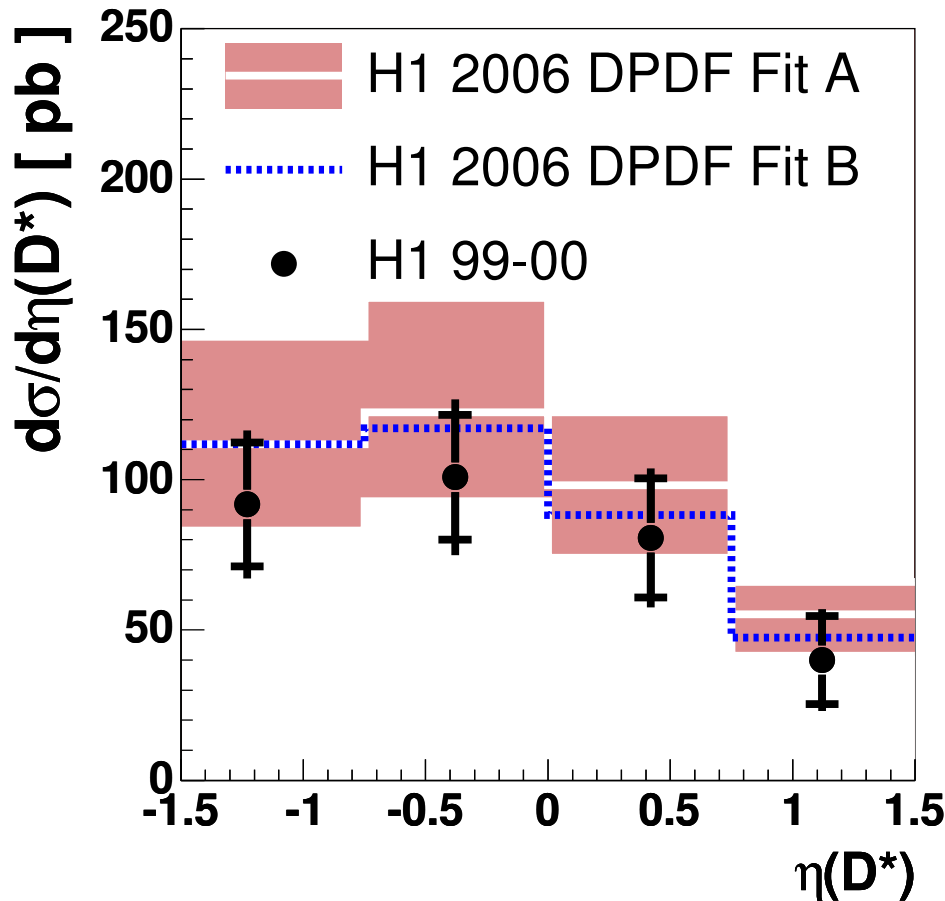
# Diffractive PDFs from inclusive data



- Well constrained singlet
- Gluon dominated, 75% of exchanged momentum carried by gluons. Gluons weakly constrained, exp. at high values of  $z$  = fractional momentum of parton participating in hard scattering
- Low  $z$ : evolution driven by  $g \rightarrow q\bar{q}$  strong sensitivity to gluons
- High  $z$ :  $q \rightarrow qg$  contribution to evolution dominant, relative error on derivative grows

# Factorisation tests: $D^*$ in DIS

- Use **diffractive PDFs** from NLO DGLAP fits of  $F_2^D$  to predict rate of charm production



Kinematic range:

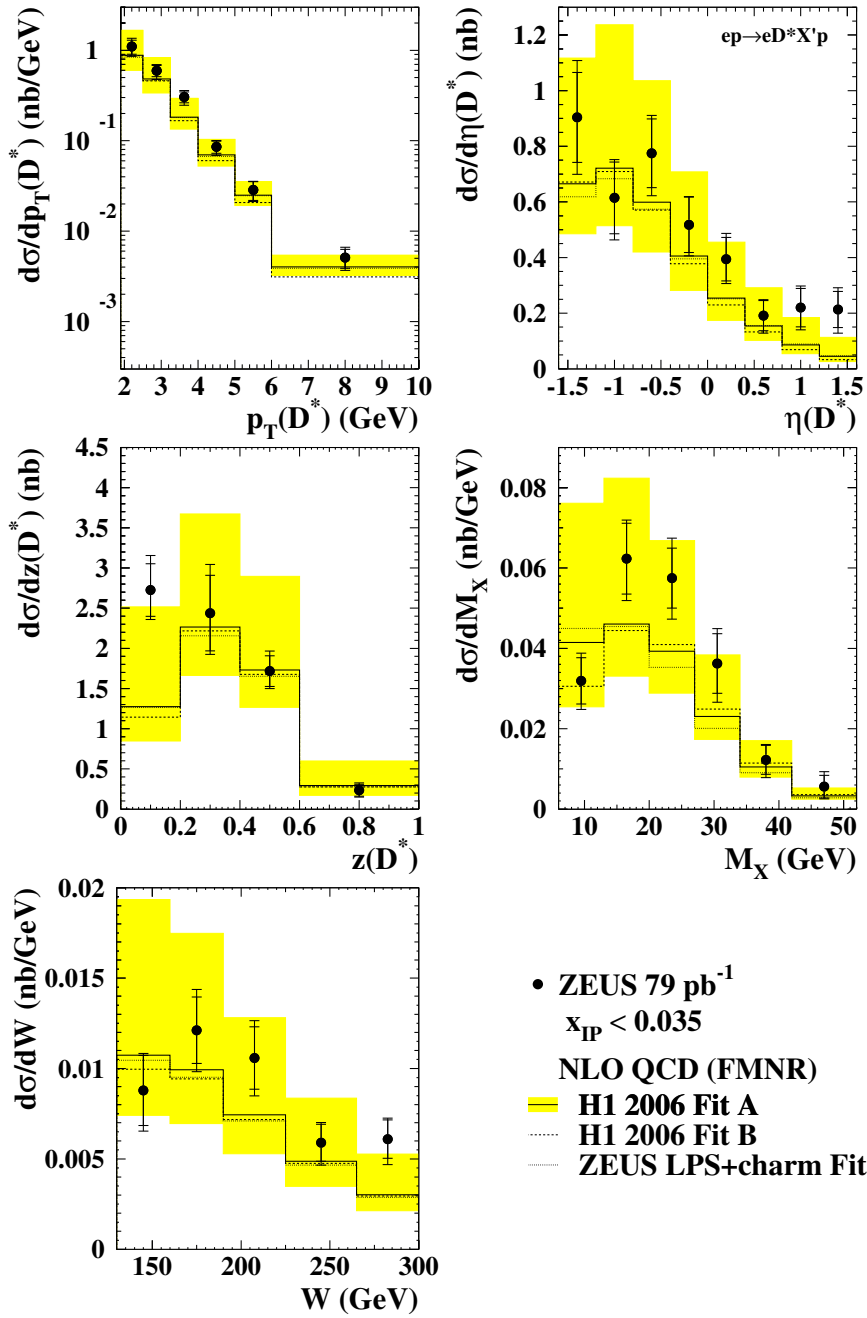
$$2 < Q^2 < 100 \text{ GeV}^2, p_T(D^*) > 2 \text{ GeV},$$

$$|\eta(D^*)| < 1.5, 0.05 < y < 0.7,$$

150 diffractive  $D^*$

- NLO calc. + diffractive PDFs describe data
- ⇒ Within uncertainties, QCD factorisation works

# ZEUS



## Factorisation tests: D\* in $\gamma p$

Kinematic range:

$130 < W < 300 \text{ GeV}$ ,  $p_T(D^*) > 1.9 \text{ GeV}$ ,

$|\eta(D^*)| < 1.6$

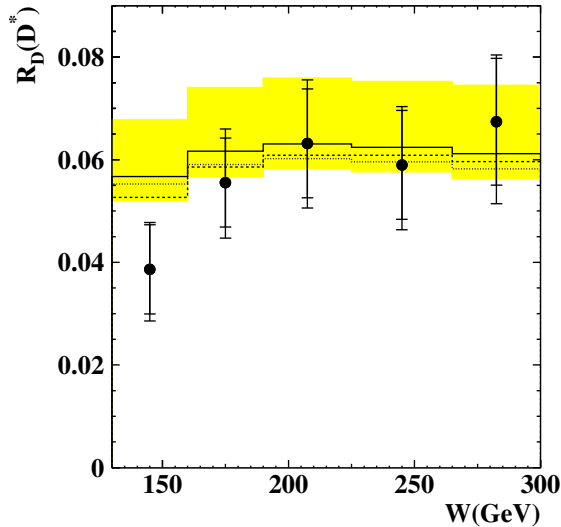
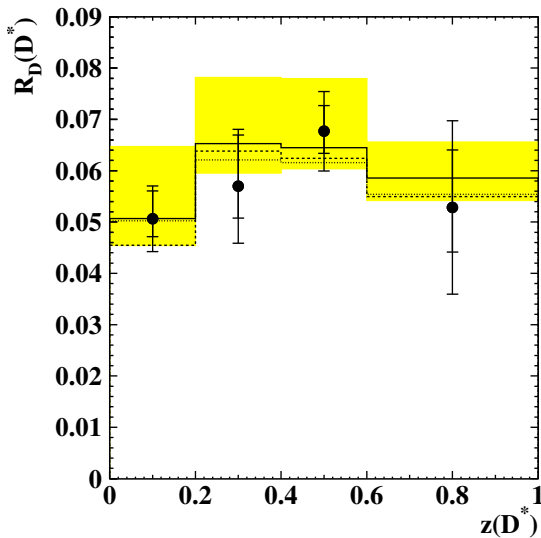
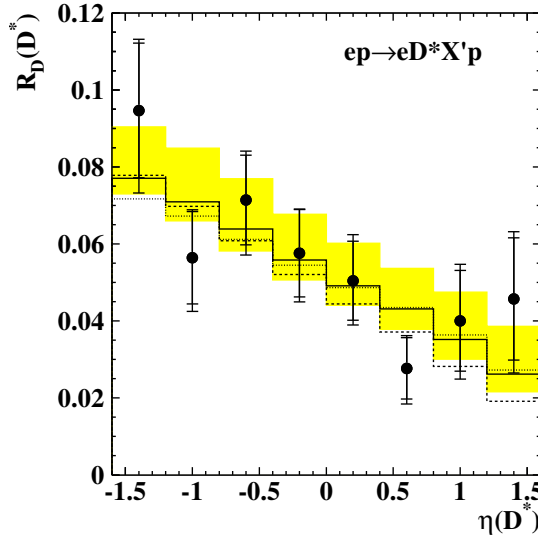
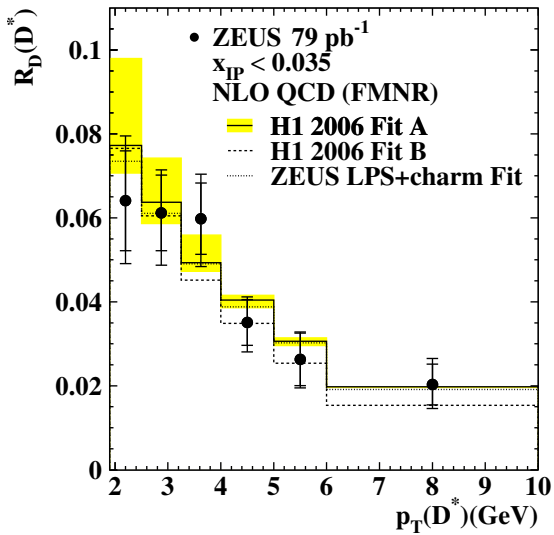
12500 D\*, 200 diffractive D\*

In the kin. region of the measurement, D\* production mainly produced in direct photon processes → no suppression expected

• NLO calc. + diffractive PDFs describe data

⇒ No evidence of factorisation breaking

# ZEUS



## Factorisation tests: D\* in $\gamma p$

- Ratio diffractive/inclusive

$$R_D = 5.7 \pm 0.5\%$$

- Ratio from NLO calculations:

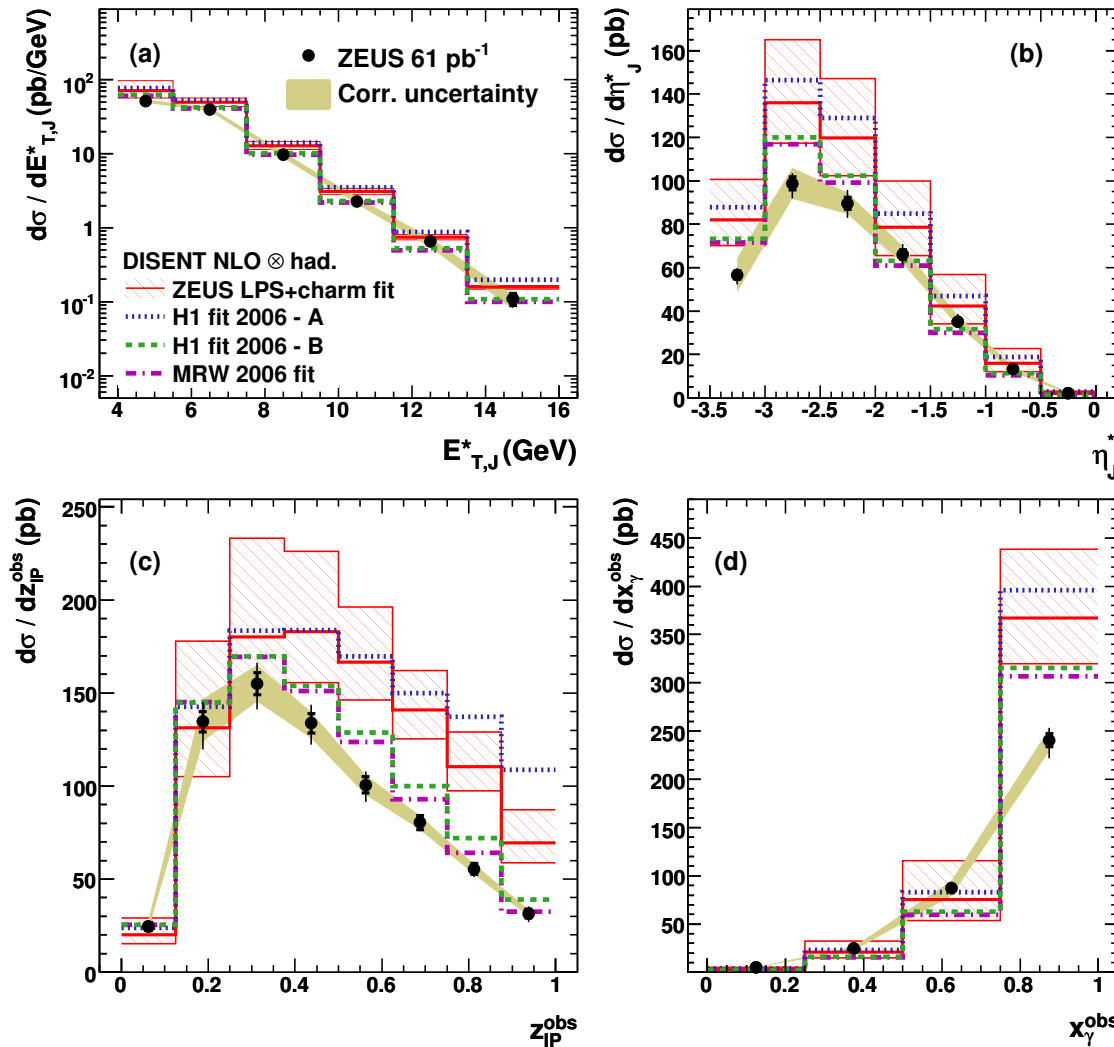
H1 fit 2006 B ⇒ 5.7%

ZEUS fit LPS + charm: ⇒ 5.8%

⇒ No evidence of factorisation breaking

# Factorisation tests: dijet in DIS

## ZEUS



Kinematic range:

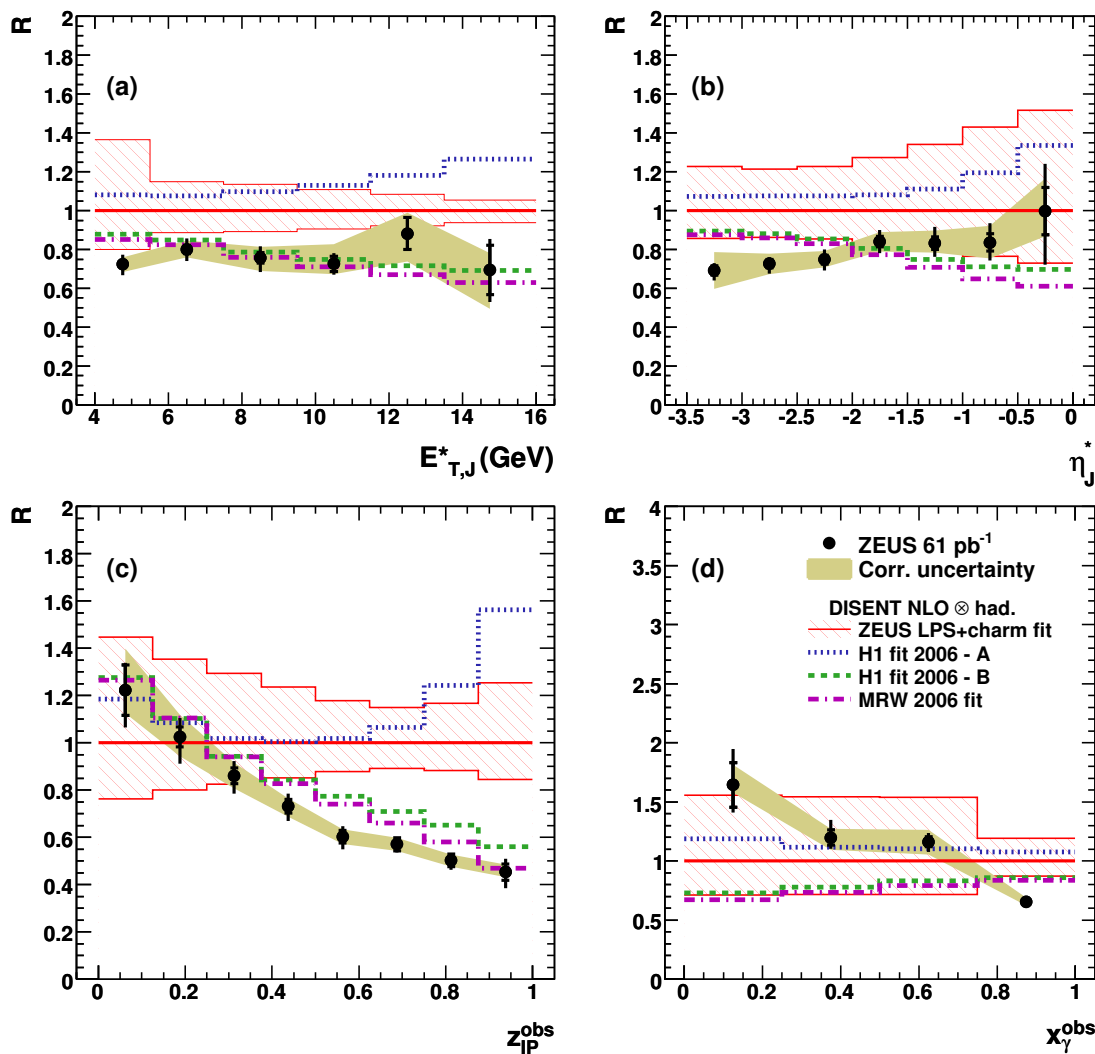
$$5 < Q^2 < 100 \text{ GeV}^2,$$

$$E_{Tjet1(jet2)} > 4.(5.) \text{ GeV}$$

- NLO predictions using diffractive PDFs describes data within theoretical uncertainties
- Agreement depends on kinematic region (0 – 25%)
- Large discrepancy between different diffractive PDFs, best agreement for **H1 2006 fit B** and **Martin Ryskin Watt**

# Factorisation tests: dijet in DIS

## ZEUS



●  $R = \text{data/NLO (LPS + charm)}$

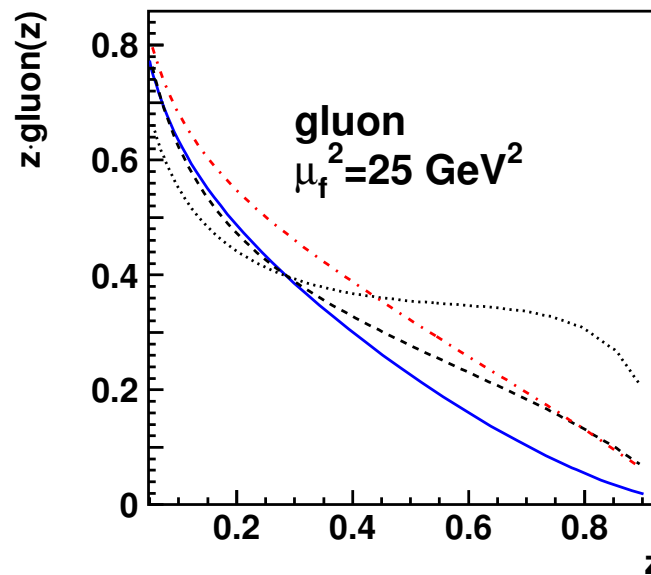
● Discrepancy at large  $z$ , new fits:

— H1 2007 Jets DPDF

--- H1 2006 DPDF fit B

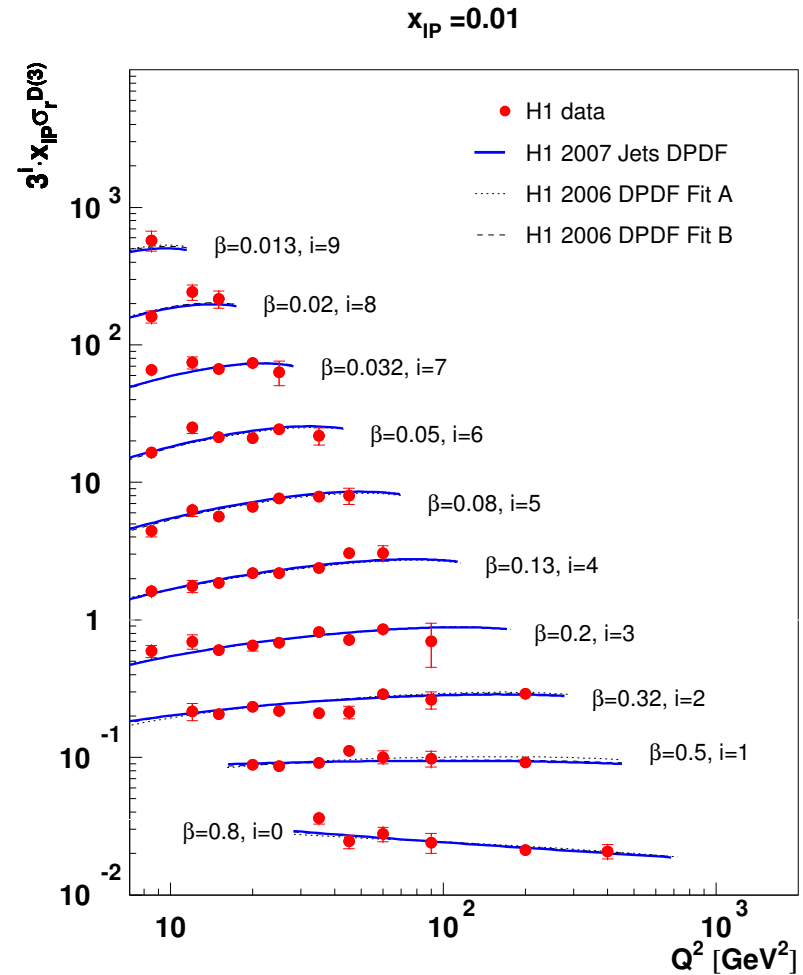
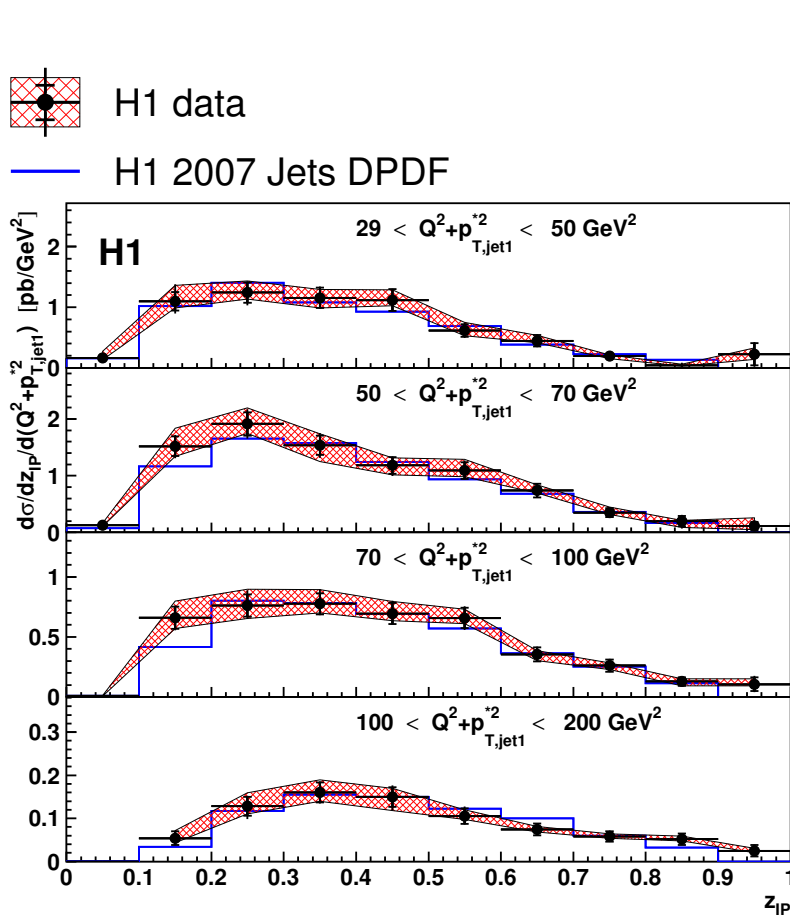
--- H1 2006 DPDF fit A

--- Martin, Ryskin, Watt 2006





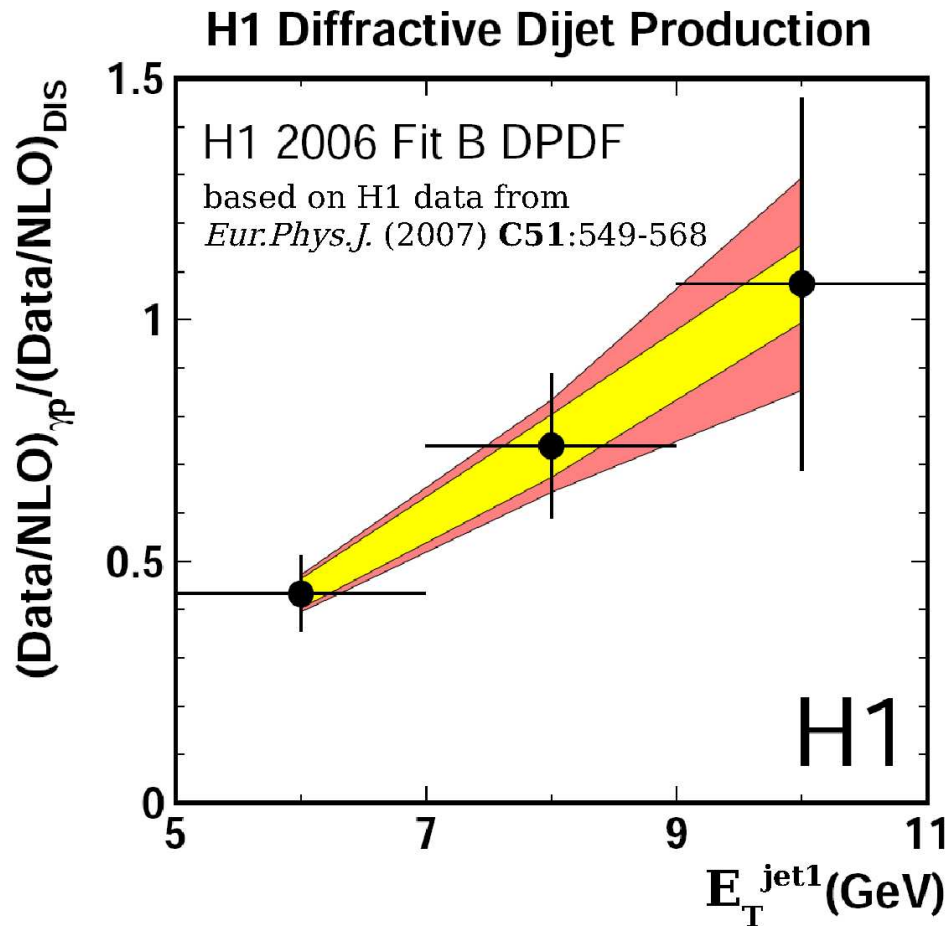
# Combined fit to inclusive and dijet DIS data



- Combined fit constrains quark and gluon densities over a wide range  $0.05 < z < 0.9$
- ⇒ Uncertainty on gluon density reduced

# Factorisation tests in $\gamma p$

Double ratio of  $(\text{data/NLO})^{\gamma p} / (\text{data/NLO})^{DIS}$ , to cancel diffractive PDF uncertainty



Factorisation breaking expected vs  $x_\gamma$

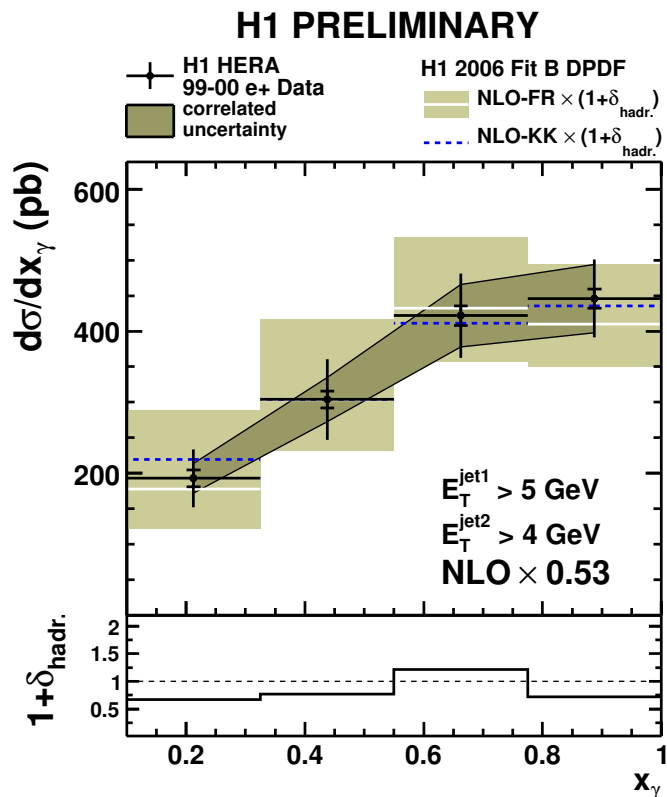
HERA data:

global suppression vs  $x_\gamma$

possible dependence of gap survival on  $E_T$  range

⇒ Measurement investigated vs  $x_\gamma$   
in different  $E_T$  region

# Factorisation tests in $\gamma p$



- Low  $E_T$

$$E_{T \text{jet1}(\text{jet2})} > 5.(4.) \text{ GeV}$$

$$-1. < \eta^{\text{jet}} < 2$$

$$0.3 < y < 0.65$$

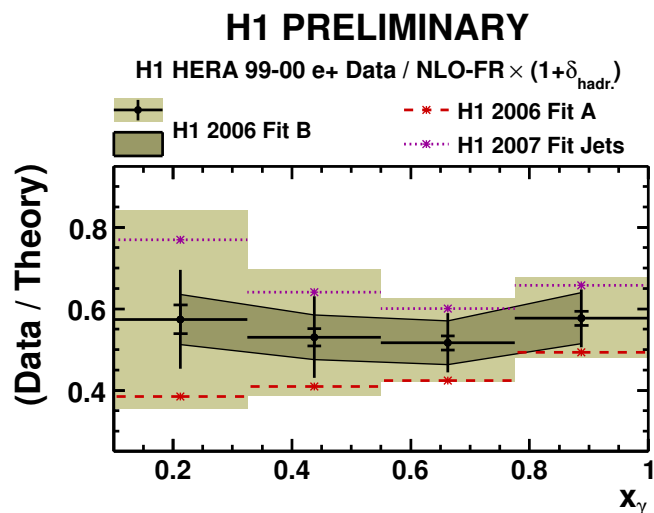
- Prediction extrapolated at high  $z$ , beyond the range of the diffractive PDF

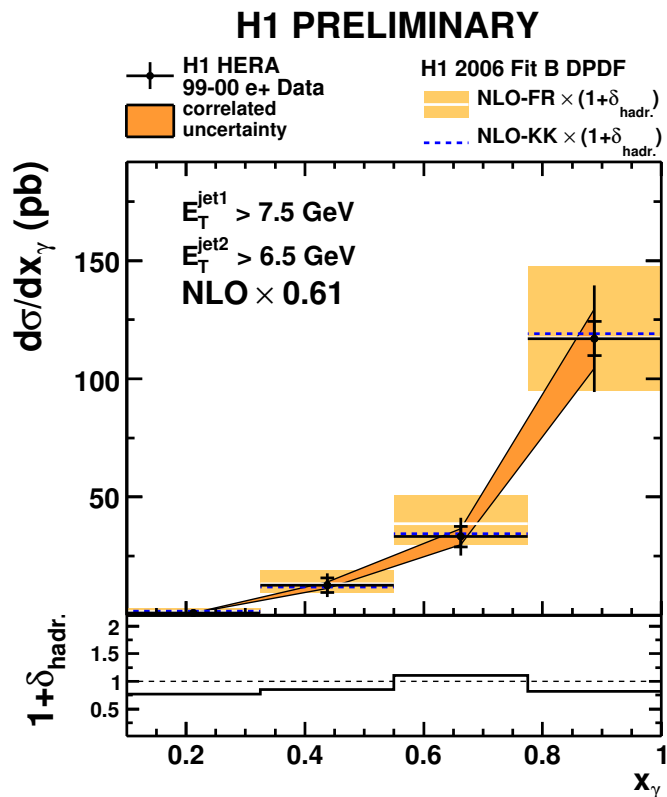
⇒ No evidence of suppression of resolved contribution only

⇒ Global suppression

$$\text{data} / \text{NLO}(\text{H1 fit B}) = 0.54 \pm 0.10(\text{sys}) \pm 0.14(\text{scale})$$

$$\text{data} / \text{NLO}(\text{H1 fit jets}) = 0.65 \pm 0.11(\text{sys})$$





## Factorisation tests in $\gamma p$

- High  $E_T$

$$E_{Tjet1(jet2)} > 7.5(6.5) \text{ GeV}$$

$$-1.5 < \eta^{jet} < 1.5$$

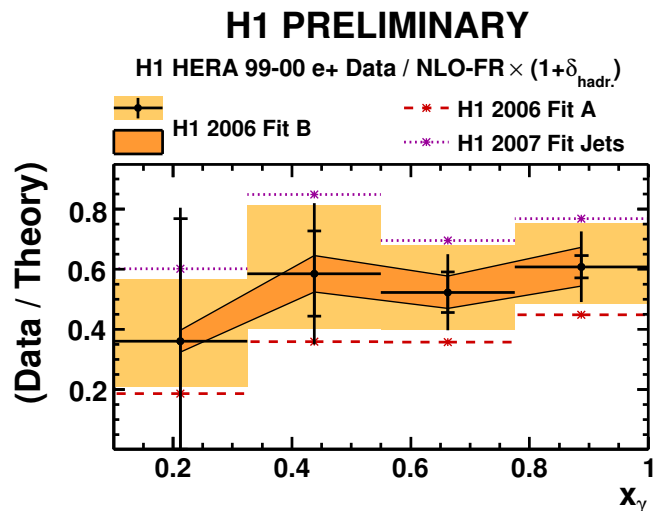
$$0.3 < y < 0.65$$

⇒ No evidence of suppression of resolved contribution only

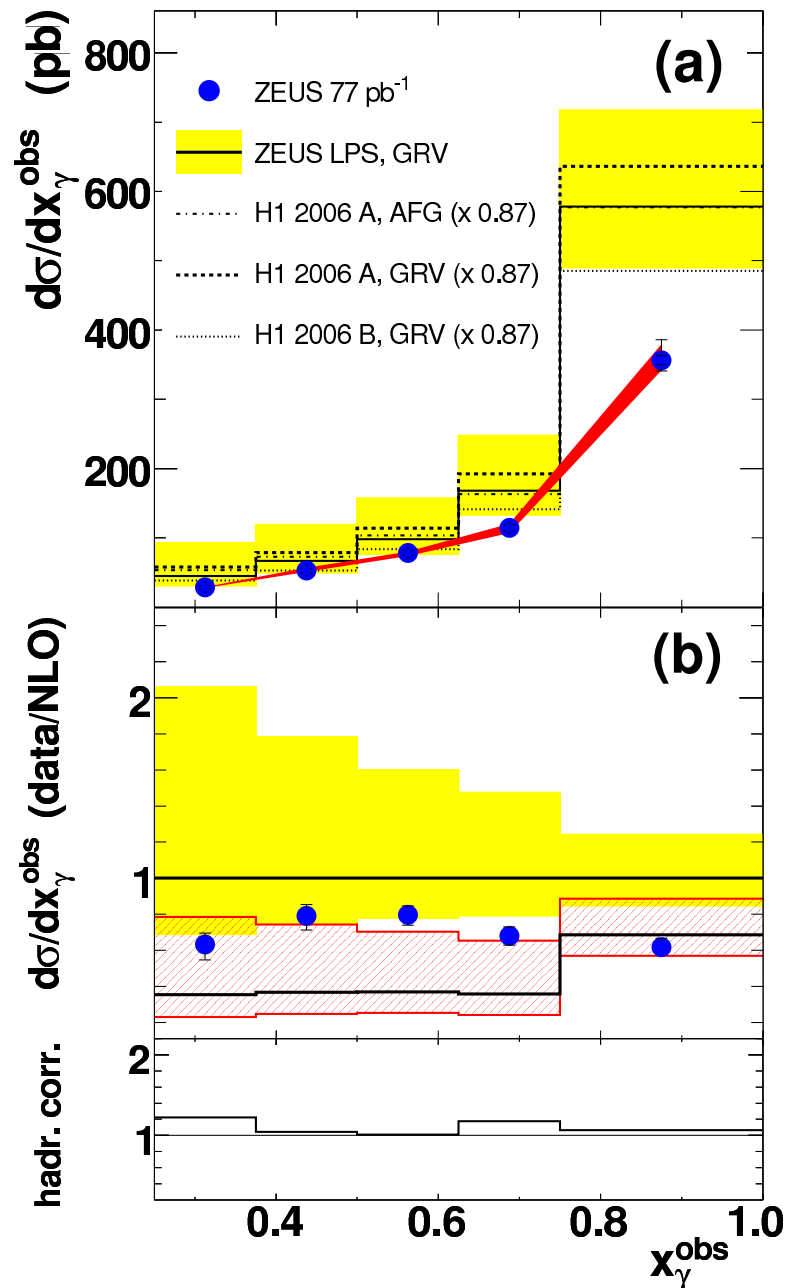
⇒ Global suppression

$$\text{data} / \text{NLO}(\text{H1 fit B}) = 0.61 \pm 0.13(\text{syst}) \pm 0.15(\text{scale})$$

$$\text{data} / \text{NLO}(\text{H1 fit jets}) = 0.79 \pm 0.16(\text{syst})$$



# Factorisation tests in $\gamma p$



• High  $E_T$

$$E_{Tjet1(jet2)} > 7.5(6.5) \text{ GeV}$$

$$-1.5 < \eta^{jet} < 1.5$$

$$0.2 < y < 0.85$$

⇒ Large theoretical uncertainty

⇒ No suppression of resolved contribution only

⇒ Global suppression

$$\text{data} / \text{NLO}(\text{ZEUS LPS} + \text{charm}) \simeq 0.6$$

$$\text{data} / \text{NLO}(\text{H1 fit B}) \simeq 0.9$$

→ data compatible with no or small suppression, depending on diffractive PDFs

→ Indication of possible suppression at small  $E_T$

# Uncertainties for predictions

DIS, PHP

- Large scale dependence
  - higher QCD order important
- Flavour scheme dependence
  - dPDF fitted using 3-flavour FFNS + massive c,b
  - dijets calculated with all flavours massless ZM-VFNS
- Gluon content of the Pomeron
  - poorly constrained at high z
- Proton dissociation correction factor
  - 10% uncertainty when using H1 dPDF to ZEUS

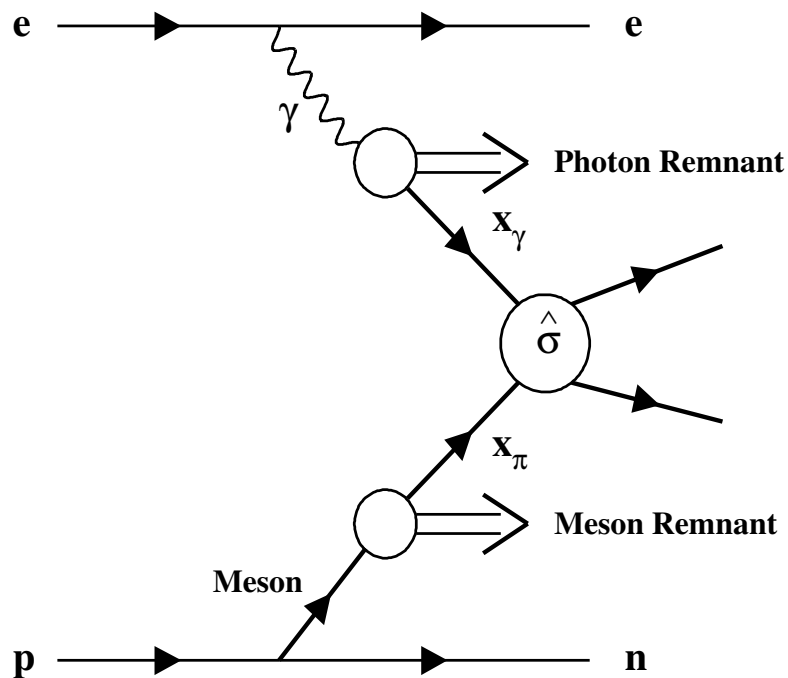
PHP

- Factorisation scheme dependence for the photon
- quark/gluon content of the photon

⇒ up to  $\sim 30\%$  uncertainty

Another test of factorisation breaking:  
Dijet photoproduction with a leading neutron

## Dijet photoproduction with a leading neutron



- Factorisation breaking expected in dijet photoproduction with a leading neutron  $\gamma p \rightarrow jjnX$ ; • events with a non-diffractive exchange (pion exchange)
- Soft rescattering expected between  $\gamma$  remnant and  $n$
- NLO predictions (non-perturbative pion flux factor) normalised to DIS  $ep \rightarrow ejjXn$  data and compared to photoproduction data, looking for suppression



# Dijet photoproduction with a leading neutron

**ZEUS**

kinematic range:

$$E_{Tjet1(jet2)} > 7.5(6.5) \text{ GeV}$$

$$-1.5 < \eta^{jet} < 2.5$$

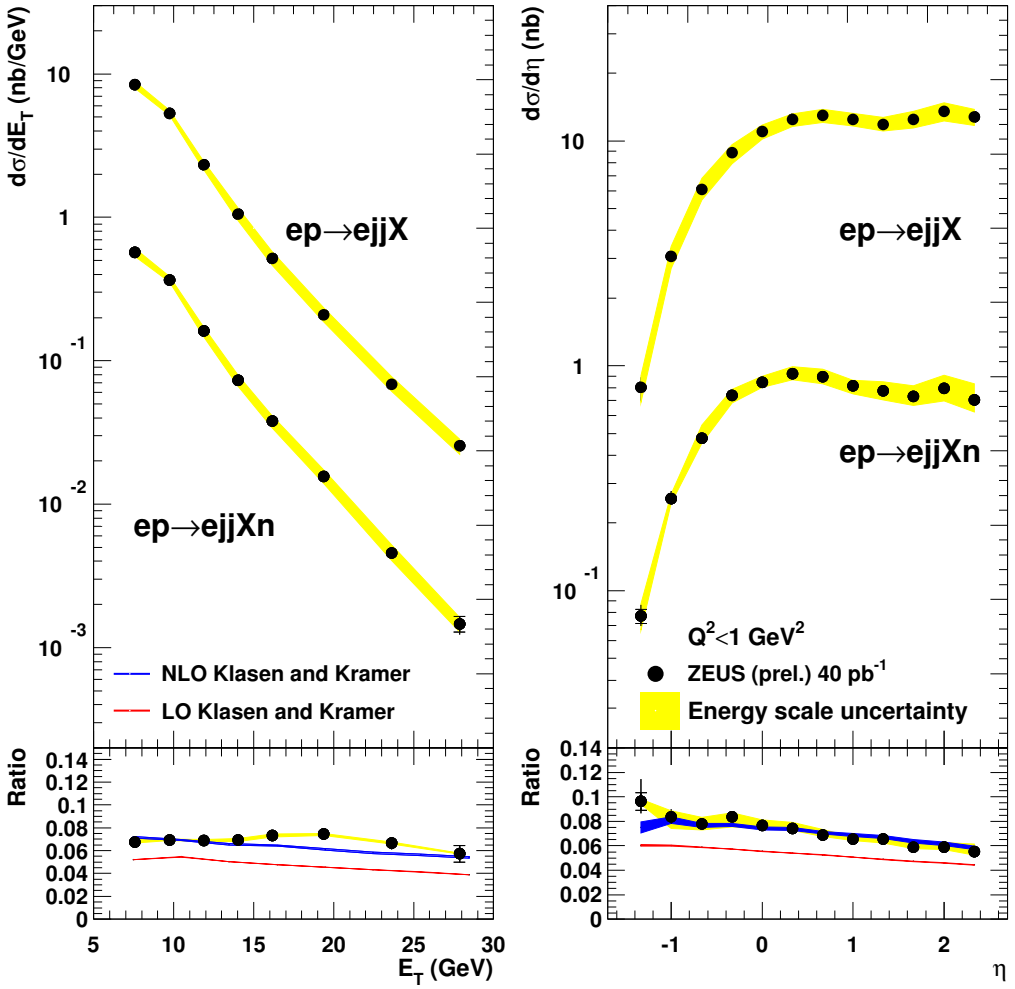
$$130 < W < 280 \text{ GeV}$$

$$E_n > 184 \text{ GeV}$$

- Ratio ( $ep \rightarrow ejjXn$ )/( $ep \rightarrow ejjX$ ) compared to NLO (hadronisation corr. cancel in ratio)  
 $\Rightarrow$  NLO predictions describe data

- data consistent with factorisation of lepton and hadron vertices and one-pion-exchange model

$\Rightarrow$  no sign of factorisation breaking



# QCD factorisation tests summary

Factorisation studied within QCD framework:

- New diffractive PDFs available:
- inclusion of dijet data in the fits provides a better constraint on gluon density

Diffractive charm in PHP and DIS:

- within low statistics and large NLO uncertainties **no hint of factorisation breaking observed**

Diffractive dijets:

- diffractive dijet production measured in wide range of photon virtualities (0-100 GeV<sup>2</sup>)
- experimental errors much smaller than theoretical uncertainties
- NLO predictions based on dPDFs from inclusive data describes data in shape
- in PHP, data favor a global suppression of NLO QCD rather than a suppression of only the resolved component

**Factorisation breaking observed at low  $E_T$**

# Conclusions

- QCD factorisation investigated at HERA in many final states and over a wide kinematic range
- Indications of factorisation breaking observed in dijets photoproduction at low  $E_T$  (where resolved processes dominate), but not clearly vs  $x_\gamma$
- Exp: cross-section ratios can be useful, i.e. ratio diffractive/inclusive production vs  $E_T, x_\gamma$
- Better QCD prediction needed (consistent flavours/masses treatment, showering ...) to quantify the suppression