

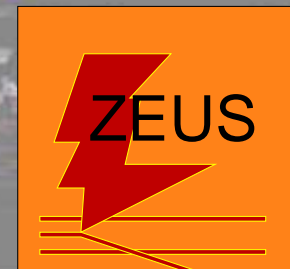
*XXXV International Symposium on Multiparticle Dynamics*

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## **Factorization and factorization breaking in diffraction at HERA**

S. Levonian, DESY

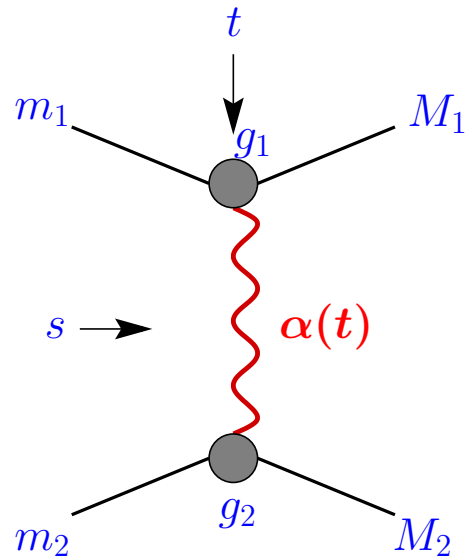
*representing*



- Introduction
- Testing Regge factorisation in inclusive diffraction
- Testing QCD factorisation in diffractive final states
- Summary

# Two approaches to Strong Interactions

## 1. Regge Pole Model $\Rightarrow$ RFT

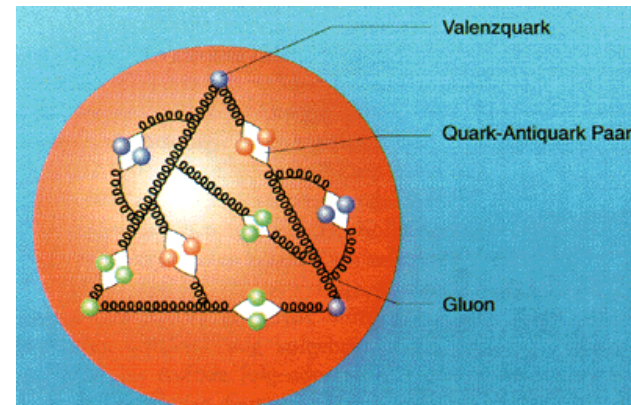


$$A(s, t) =$$

$$g_1(m_1, M_1, t) g_2(m_2, M_2, t) \frac{s^{\alpha(t)} \pm (-s)^{\alpha(t)}}{\sin(\pi\alpha(t))}$$

hadronic language

## 2. Quark-Parton Model $\Rightarrow$ QCD



$$\sigma_{ab} =$$

$$\int f_{i/a}(x_i, \mu^2) \cdot f_{j/b}(x_j, \mu^2) \cdot \hat{\sigma}_{ij}(x_i, x_j, \mu^2)$$

sub-hadronic language

**Ultimate goal: derive (1) from (2)**

RFT: soft  $hh$  scattering

vs

QCD: deep inelastic  $ep$  scattering

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• **Hadronic** degrees of freedom

• Validity: large  $s \gg t$

•  $\mathbb{P}$  dominates:  $\alpha_{\mathbb{P}}(0) > \alpha_{\mathbb{R}}(0)$   
 $\rightarrow \sigma_{\text{tot}} \propto s^{\alpha_{\mathbb{P}}(0)-1}$

• Unitarity corrections unavoidable  
( $\sigma_{\text{tot}} \leq \ln^2(s/s_0)$  at  $s \rightarrow \infty$ )

• When?  $s_{\text{sat}} = ?$

• First to be seen in diffraction:  $\sigma_D \propto s^{2(\alpha-1)}$

• **Partonic** degrees of freedom

• Low  $x$ :  $W^2 \gg Q^2, t$  ( $Q^2/W^2 \simeq x \ll 1$ )

• gluons dominate:  $xg(x) \gg xq_{\text{val}}(x)$   
 $F_2(x, Q^2) \propto xg(x) \sim x^{-\lambda}$

• Saturation of the  $xg(x)$   
(non-linear effects, shadowing, ...)

•  $x_{\text{sat}}(Q_{\text{sat}}) = ?$

• First to be seen in diffraction:  $\sigma_D \propto |xg(x)|^2$

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$\Rightarrow$  Diffraction  $\equiv$  Physics of the Pomeron,  
the essence of strong interactions

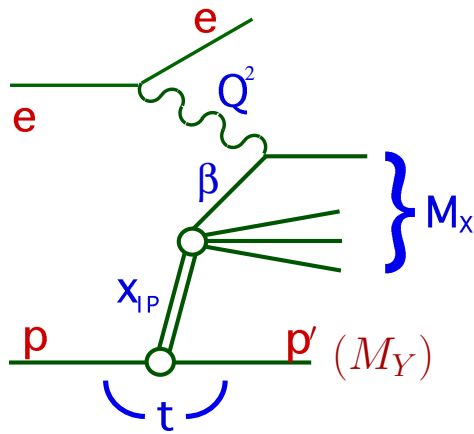
(in high energy limit)

$\Rightarrow$  Diffraction  $\equiv$  Gluodynamics,  
the essence of QCD

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# Diffraction at HERA

- Fundamental aim: understand high energy limit of QCD (gluodynamics; CGC ?)
- Novelty: for the first time probe partonic structure of diffractive exchange
- Practical motivations: study factorisation properties of diffraction; try to transport to  $hh$  scattering (e.g. predict diffractive Higgs production at LHC)



$$x_{\mathcal{P}} = \xi = \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

(momentum fraction of colour singlet exchange)

$$\beta = \frac{Q^2}{Q^2 + M_X^2} = x_{q/\mathcal{P}} = \frac{x}{x_{\mathcal{P}}}$$

(fraction of exchange momentum, coupling to  $\gamma^*$ )

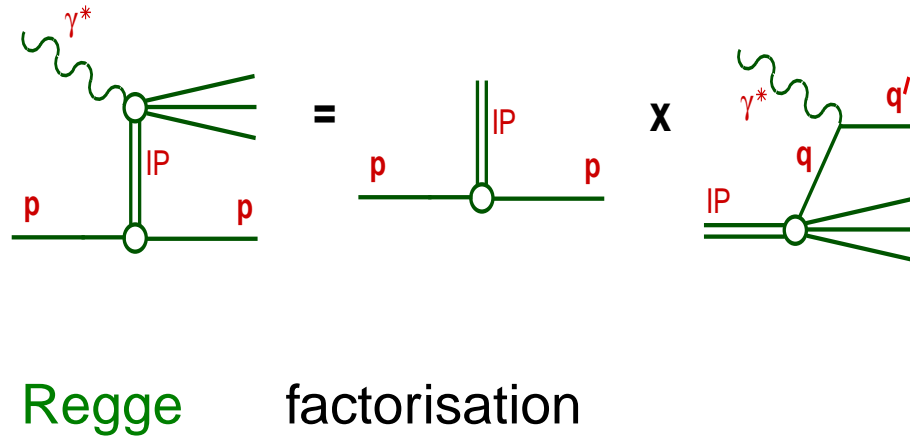
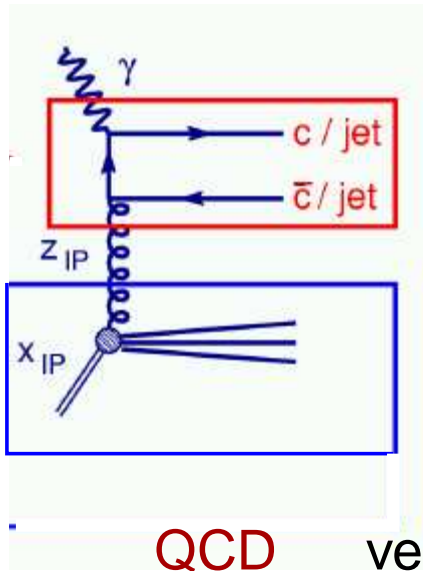
$$t = (p - p')^2$$

(4-momentum transfer squared)

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

$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{2(1 - y + y^2/2)} F_L^{D(4)} \Rightarrow F_2^{D(3)} = \int dt F_2^{D(4)}$$

# Factorisation properties in diffraction



## QCD factorisation

(rigorously proven for DDIS by Collins et al.):

## Regge factorisation

(conjecture, e.g. RPM by Ingelman, Schlein):

$$\sigma_r^{D(4)} \propto \sum_i \hat{\sigma}^{\gamma^* i}(x, Q^2) \otimes f_i^D(x, Q^2; x_{\mathbb{P}}, t)$$

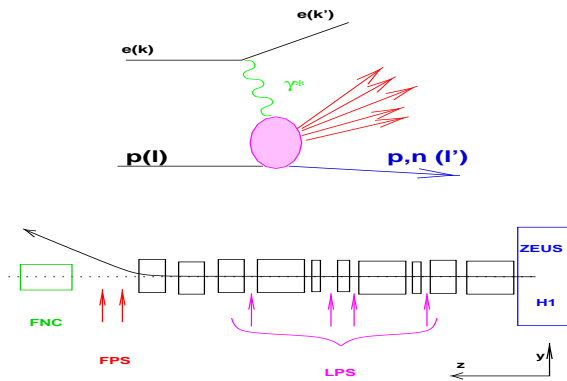
- $\hat{\sigma}^{\gamma^* i}$  – hard scattering part, same as in inclusive DIS
- $f_i^D$  – diffractive PDF's, valid at fixed  $x_{\mathbb{P}}, t$  which obey (NLO) DGLAP

$$F_2^{D(4)}(x_{\mathbb{P}}, t, \beta, Q^2) = \Phi(x_{\mathbb{P}}, t) \cdot F_2^{\mathbb{P}}(\beta, Q^2)$$

- In this case shape of diffractive PDF's is independent of  $x_{\mathbb{P}}, t$  while normalization is controlled by Regge flux  $\Phi(x_{\mathbb{P}}, t)$

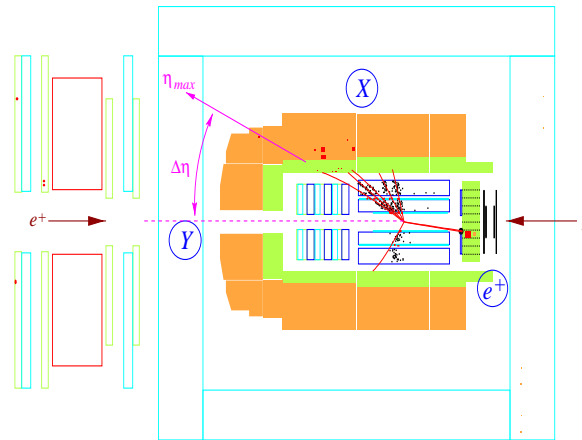
# Selecting Diffractive Events at HERA

## LPS (H1, ZEUS)



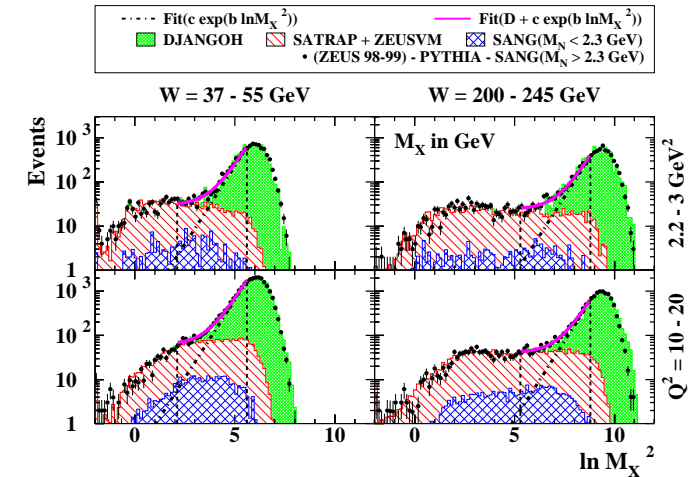
- clean sample, free of p-dissociative bgr
- provides  $t$  measurement
- limited statistics (beam cond.,  $x_P$ ,  $t$  acceptance)

## LRG (H1)



- large statistics, bigger phase space coverage:  
 $3.2 < \eta_{\text{gap}} < 7.5$  (tag)  $\eta_{\text{max}} < 5.0$  (meas)
- integrate over  $t > -1 \text{ GeV}^2$
- some dissociative admixture remains in sample:  
 $M_Y < 1.6 \text{ GeV}$   $M_Y < 2.3 \text{ GeV}$

## $M_X$ (ZEUS)



## Strategy

- obtain NLO DPDFs from inclusive DDIS (and test Regge factorisation)
- predict final states to NLO, or model them using MC technique (charm, jets)
- confront to the data (test QCD factorisation)

### NLO QCD:

DIS: HQVDIS, DDISENT

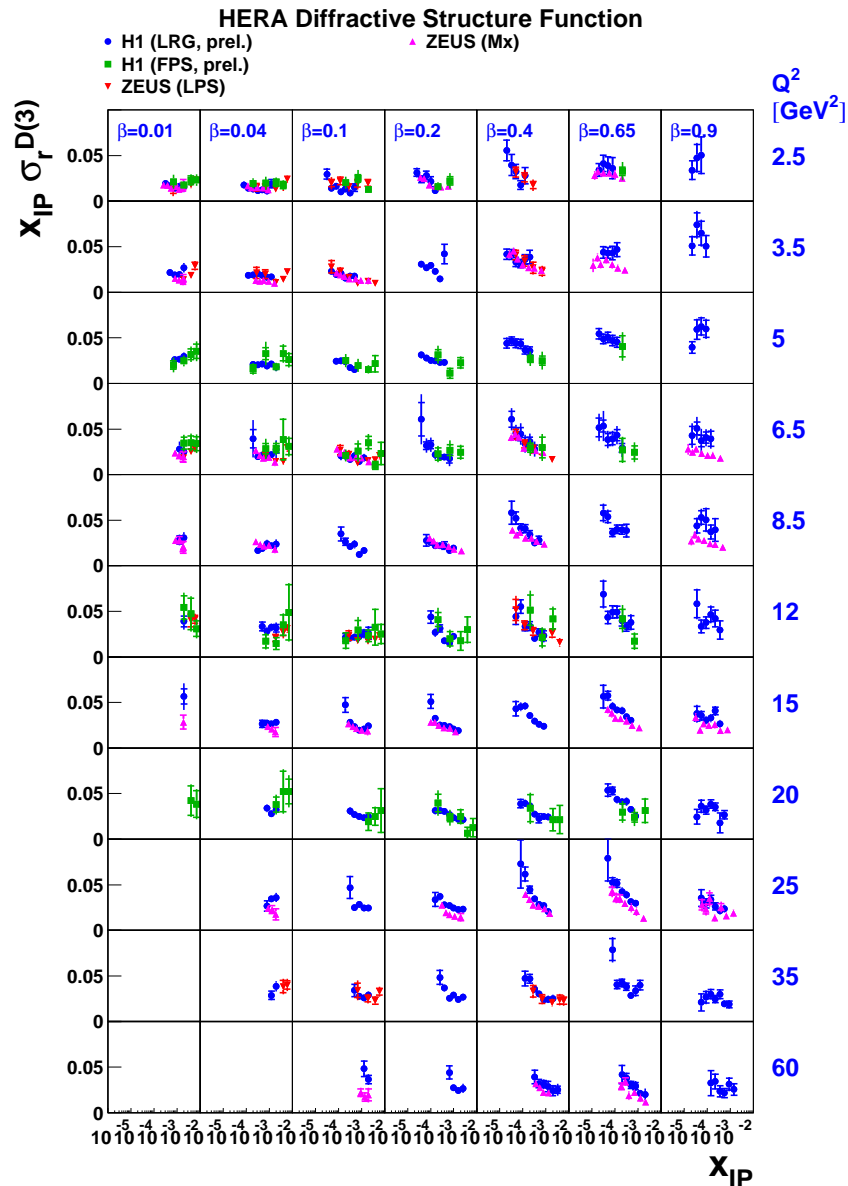
$\gamma p$ : Frixione, KK

## Data Samples

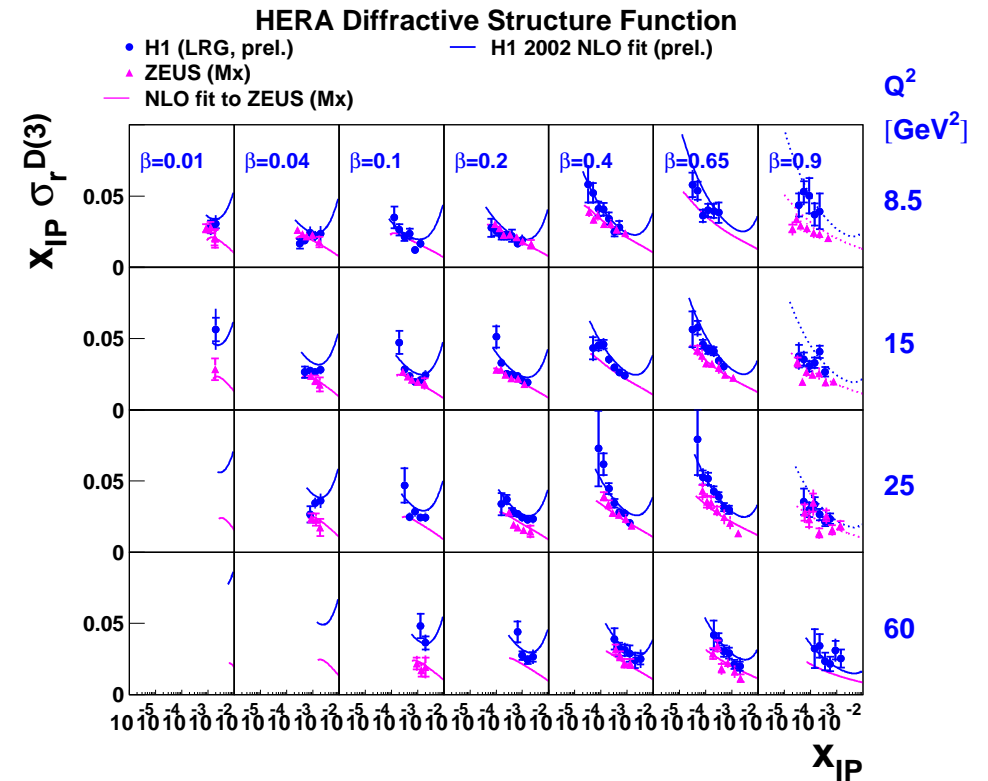
Sample	$Q^2$ range	$\mathcal{L}$
LPS (ZEUS)	$0.03 < Q^2 < 0.6 \text{ GeV}^2$	$3.6 \text{ pb}^{-1}$
	$2 < Q^2 < 100 \text{ GeV}^2$	$12.8 \text{ pb}^{-1}$
FPS (H1)	$2 < Q^2 < 50 \text{ GeV}^2$	$28.8 \text{ pb}^{-1}$
$M_X$	$2.2 < Q^2 < 80 \text{ GeV}^2$	$4.2 \text{ pb}^{-1}$
LRG	$1.5 < Q^2 < 12 \text{ GeV}^2$	$3.4 \text{ pb}^{-1}$
	$6.5 < Q^2 < 120 \text{ GeV}^2$	$10.6 \text{ pb}^{-1}$
	$200 < Q^2 < 1600 \text{ GeV}^2$	$63 \text{ pb}^{-1}$

All data analysed so far  
are from HERA-1 run

# Inclusive diffraction: H1 vs ZEUS



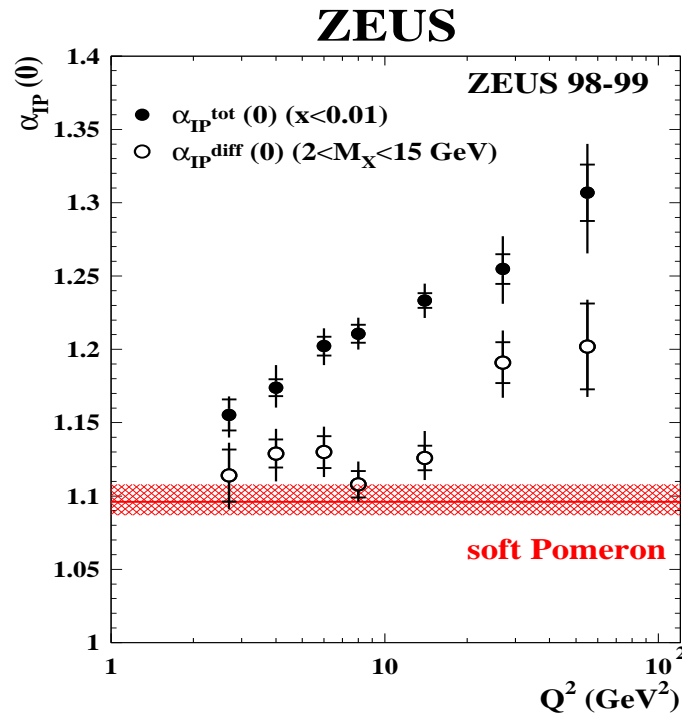
- All data are scaled to  $M_Y < 1.6$  GeV
- All data are transported to H1 LRG bin centers



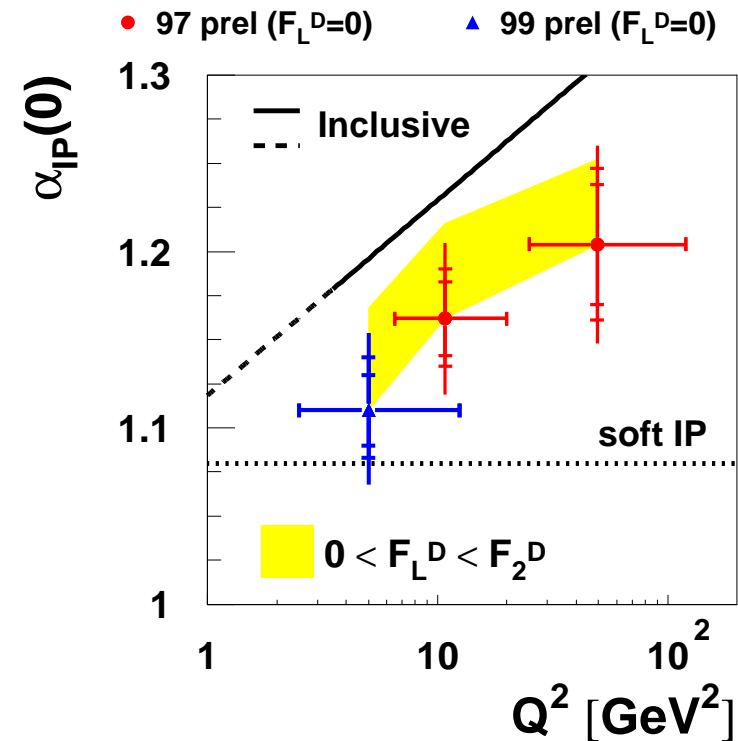
- Reasonable agreement between data sets
- Differences: (a) at low  $M_X$ , (b)  $Q^2$  dependence

# $\alpha_{\mathbb{P}}(0)$ in total vs diffractive DIS

Related via Optical theorem:  $\sigma^{tot} \sim W^2(\alpha_{\mathbb{P}}(0)-1)$      $\sigma^{el/diff} \sim W^4(\alpha_{\mathbb{P}}(0)-1)$



## H1 Diffractive Effective $\alpha_{\mathbb{P}}(0)$



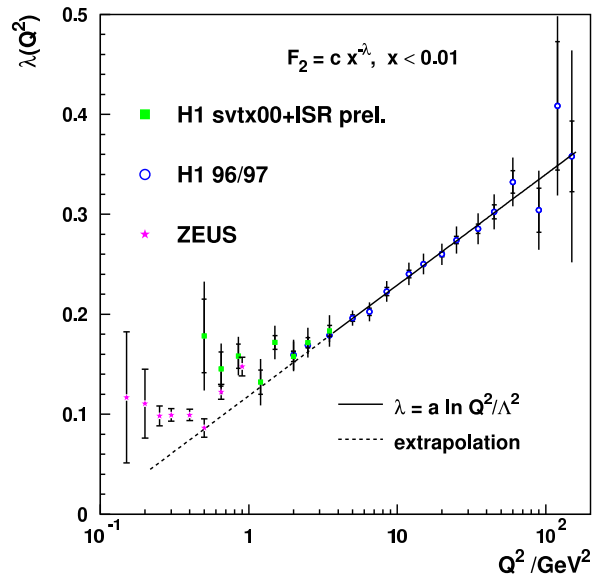
⇒ in DIS region  $\alpha_{\mathbb{P}}(0)$  is incompatible with soft  $\mathbb{P}$

⇒ indication for Regge factorisation breaking

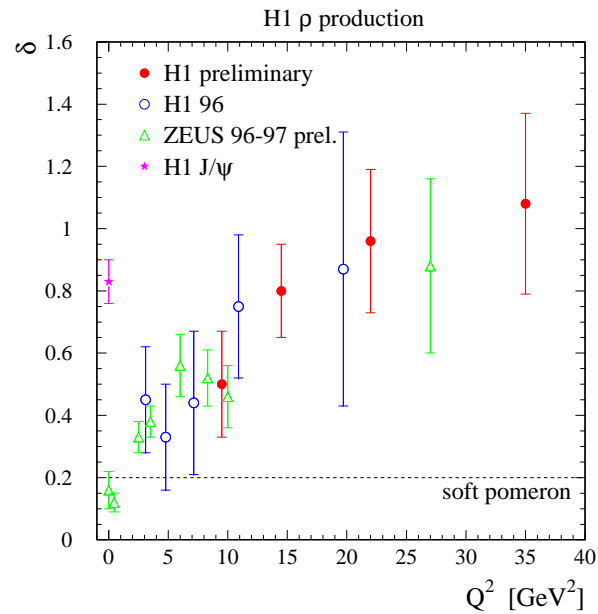
⇒  $\alpha_{\mathbb{P}}^{diff}(0) - 1 \simeq \frac{1}{2}(\alpha_{\mathbb{P}}^{tot}(0) - 1) \rightarrow$  UC ??

# Pomeron intercept in inclusive, elastic and diffractive DIS

Optical theorem

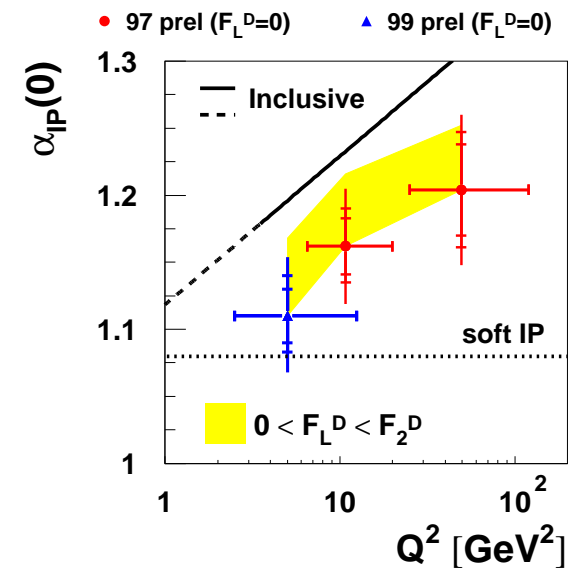


$$\lambda = (\alpha_P(0) - 1)$$



$$\delta = 4(\overline{\alpha_P(0)} - 1)$$

H1 Diffractive Effective  $\alpha_{IP}(0)$

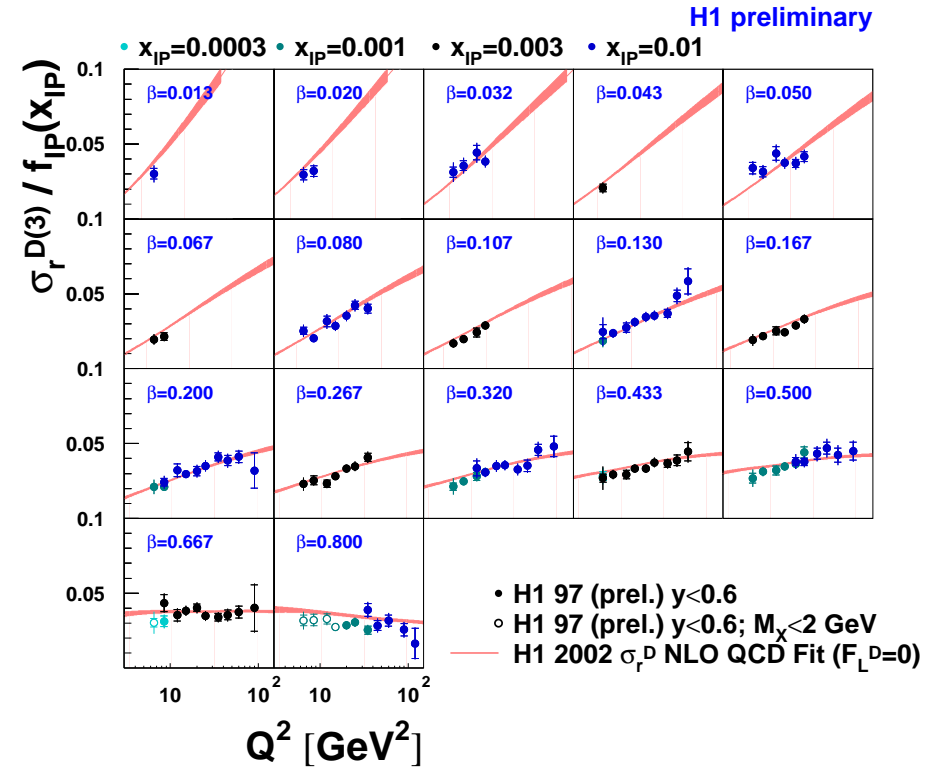
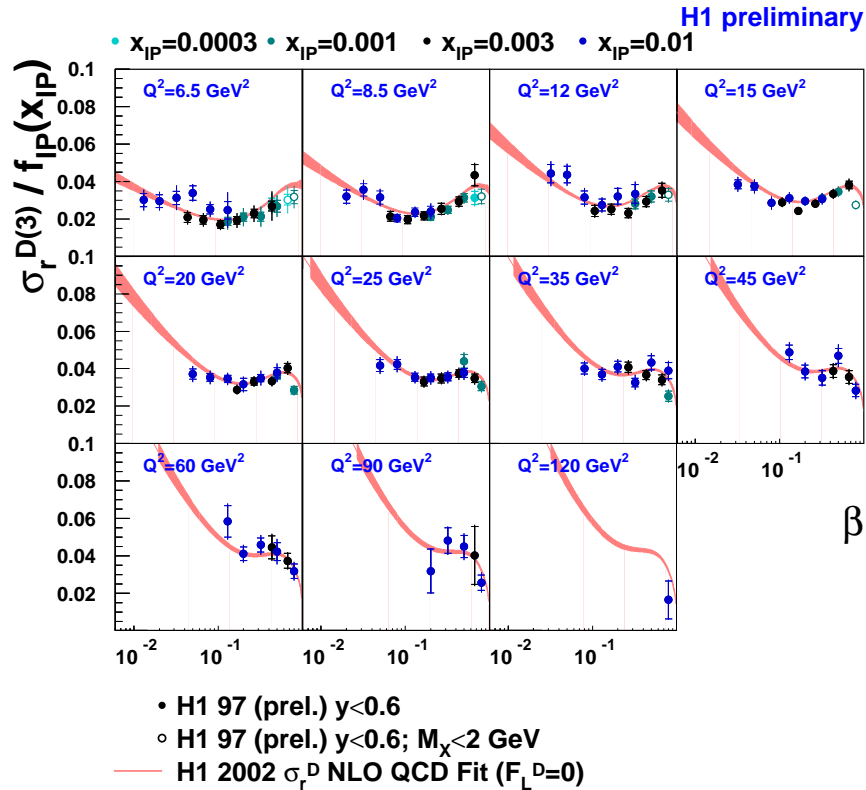


Unitarity corrections?

Understanding of colour singlet exchange remains a major challenge in QCD:

It is a complicated interplay between soft and hard phenomena

# H1 $F_2^D(\beta, Q^2)$



- Regge factorisation approx. holds for  $x_{IP} < 0.01 \rightarrow$  simplifies QCD fit
- positive scaling violation except largest  $\beta \rightarrow$  gluon dominance

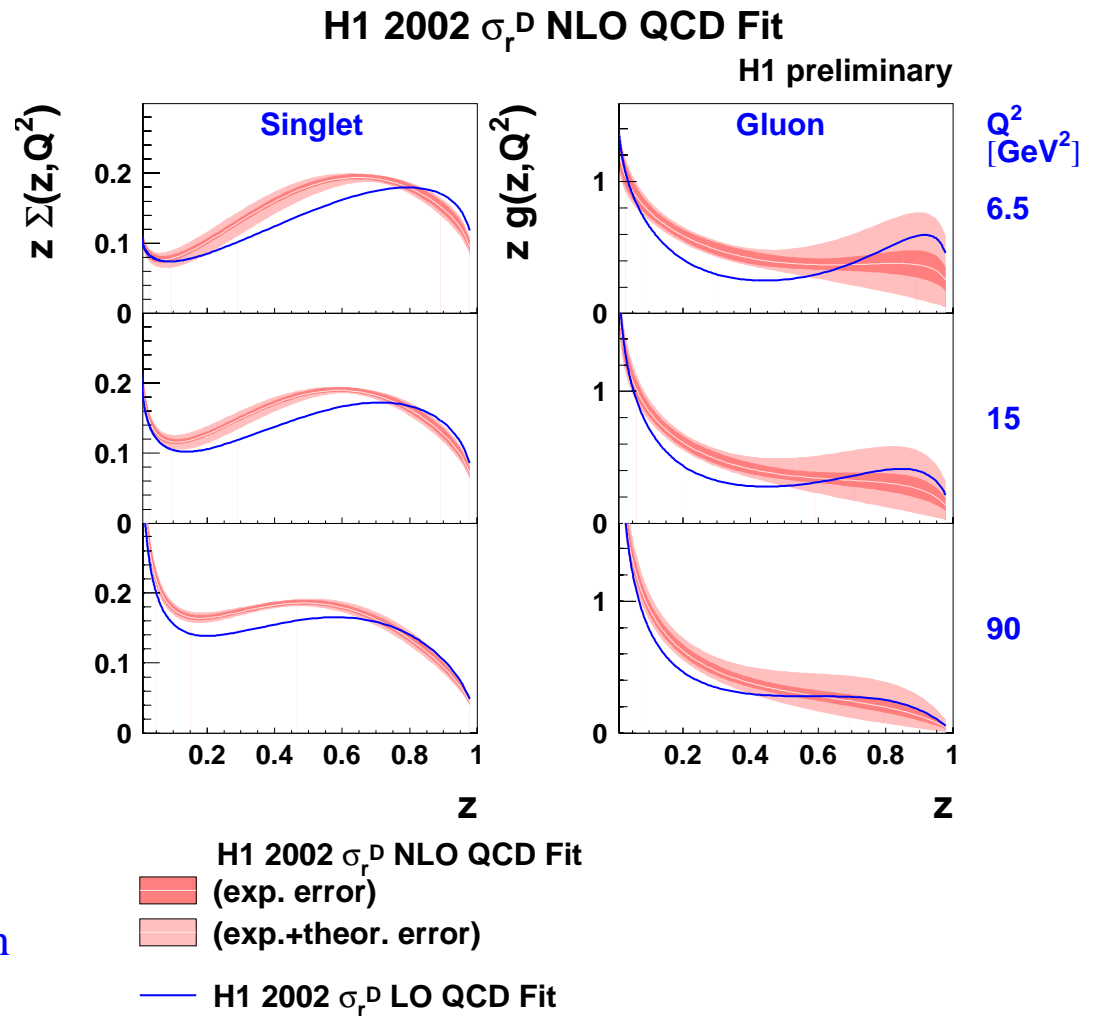
# NLO DGLAP QCD fit and Diffractive PDF's

## QCD fit technique

- Regge factorisation with  $\mathbb{P}$ ,  $\mathbb{R}$  terms (pion PDF (Owens) are used for  $\mathbb{R}$ )
- Singlet  $\Sigma$  and gluon  $g$  in  $\mathbb{P}$  parametrized at  $Q_0^2 = 3 \text{ GeV}^2$
- NLO DGLAP evolution for  $Q > Q_0$
- Fit 313 data points for  $Q^2 > 6.5 \text{ GeV}^2$  and  $M_X > 2 \text{ GeV}$  (7 free par.)
- Propagate exp. and theor. uncertainties to obtain PDF's with error band

## Resulting diffractive PDF's

- Gluon dominated
- Singlet part is well constrained
- Substantial (theor.) uncertainty for gluon at highest fractional momenta  $z$



# NLO QCD fit to ZEUS $M_X$ data

## NLO QCD fits to H1 and ZEUS data

Similar fit as for H1. Differences:

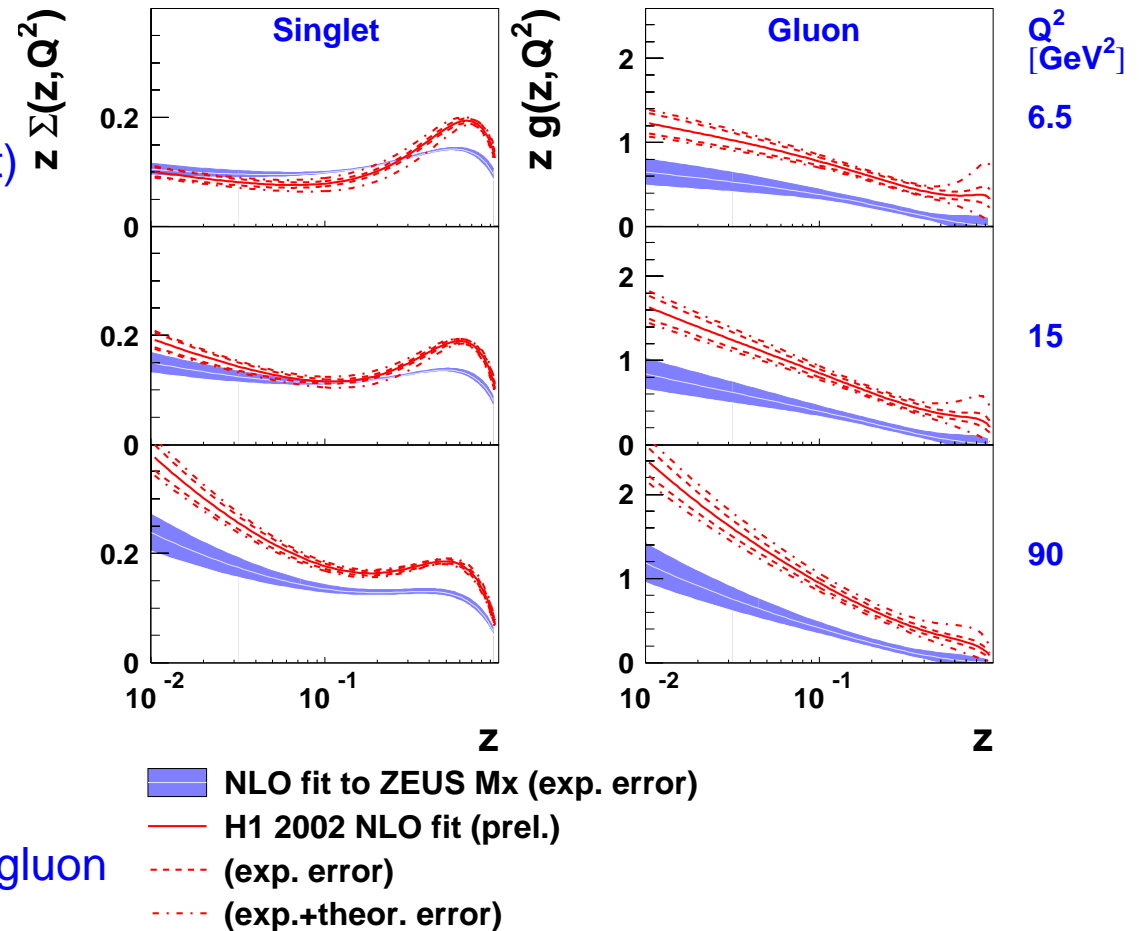
- Only  $\mathbb{P}$  term, no meson component (including one does not improve the fit)
- Fit 138 data points for  $Q^2 > 4 \text{ GeV}^2$
- Common Pomeron intercept fitted together with pdf's

$$\chi^2/ndf = 90/131$$

$$\alpha_{\mathbb{P}}(0) = 1.132 \pm 0.006(\text{exp.})$$

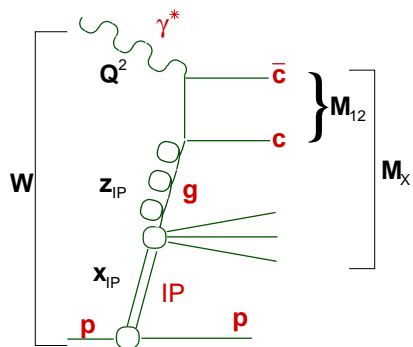
Resulting diffractive PDF's

- Singlet: similar at low  $Q^2$
- Gluon: factor of  $\sim 2$  smaller than H1 gluon

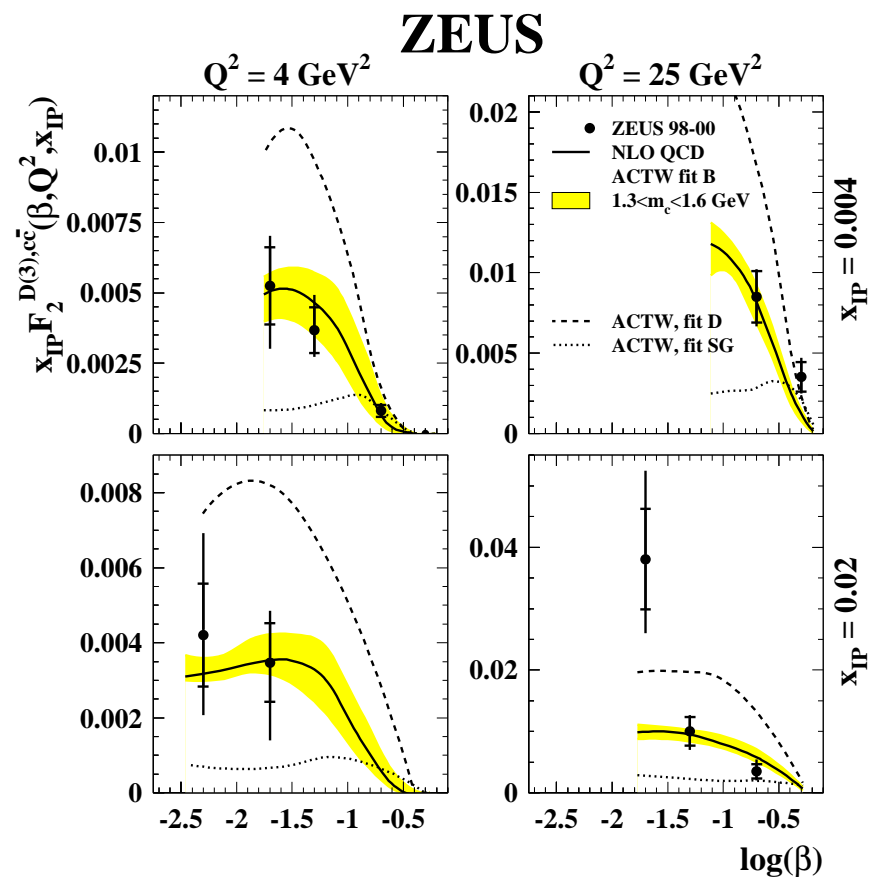
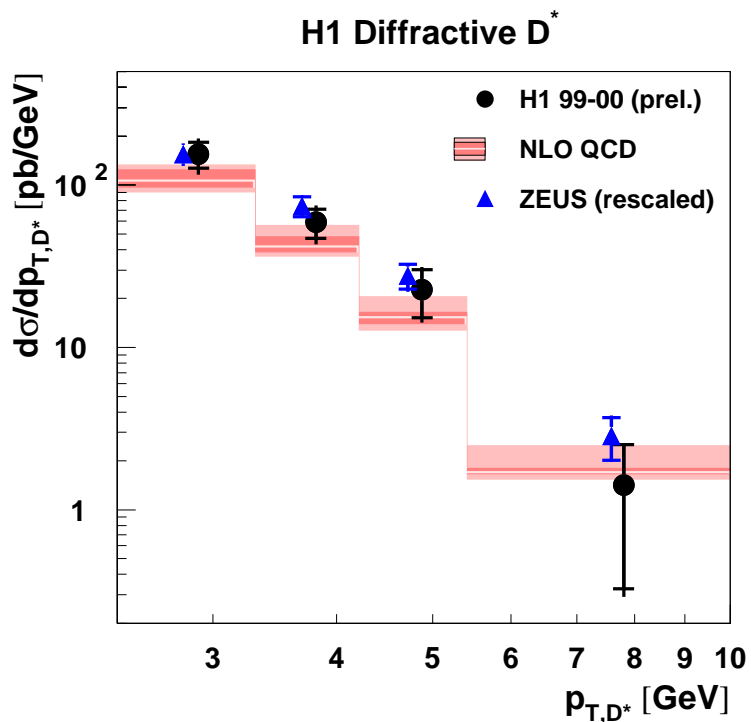


⇒ Need more direct access to diffractive gluons

# Diffraction $D^*$ in DIS regime



- H1 and ZEUS data are in agreement
- Consistent with QCD factorisation and H1 gluon
- Provides extra constraints to DPDFs



# Diffraction dijets in DIS regime

Old H1 measurement (cone jets)

$$4 < Q^2 < 80 \text{ GeV}^2; \quad E_{T1} > 5 \text{ GeV}, \quad E_{T2} > 4 \text{ GeV}; \quad -3 < \eta_{jet}^* < 0$$

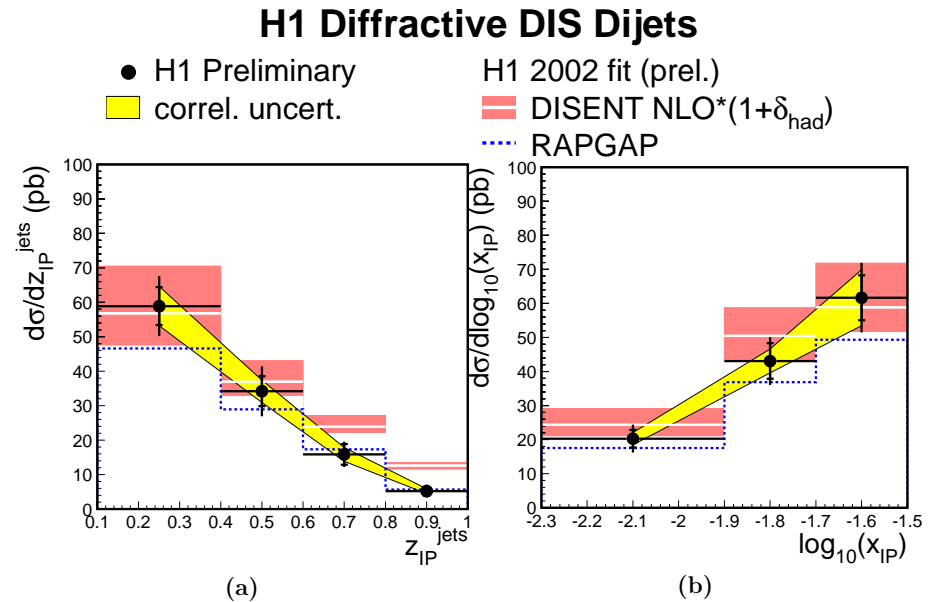
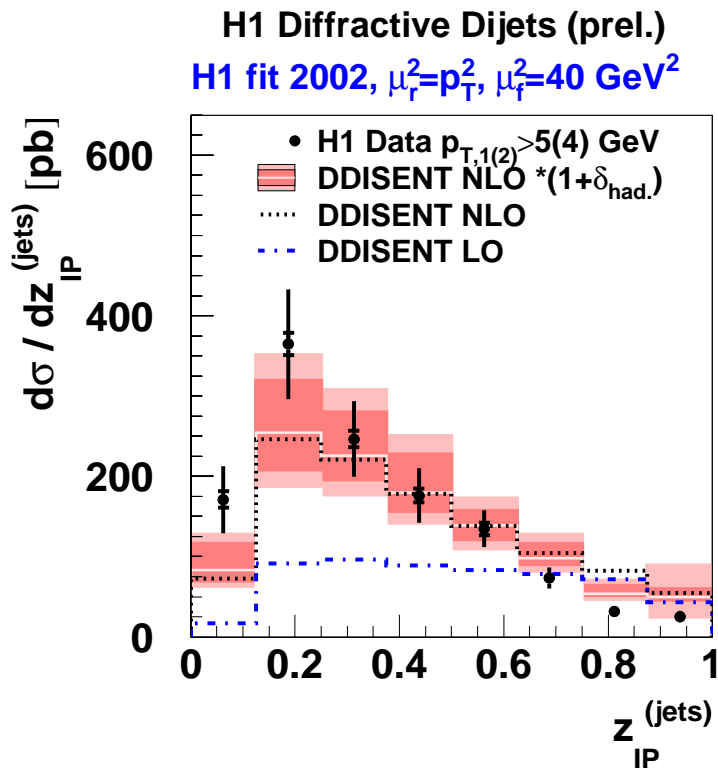
$$0.1 < y < 0.7$$

$$x_{\mathbb{P}} < 0.05$$

New H1 measurement ( $k_T$  jets)

$$0.3 < y < 0.65$$

$$x_{\mathbb{P}} < 0.03$$

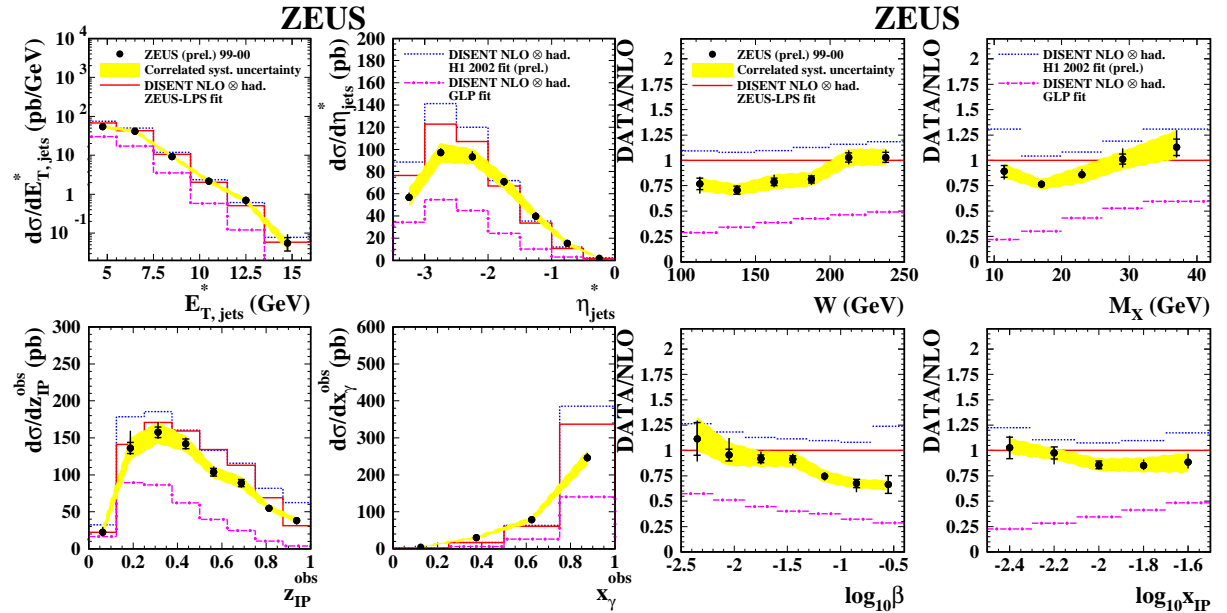
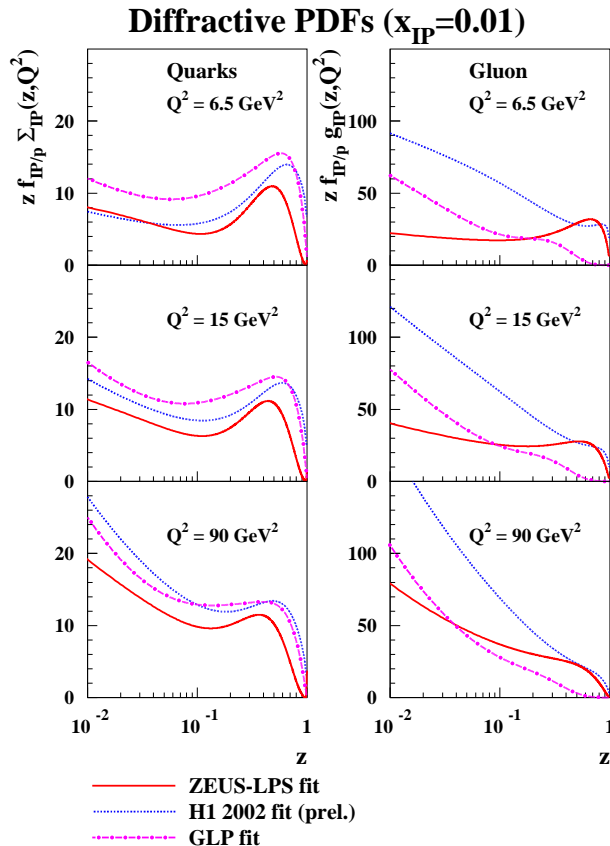


**H1: Consistent picture of diffractive DIS  
to NLO QCD!**

# Diffractive dijets in DIS: sensitivity to DPDFs

New ZEUS NLO analysis  
using different DPDF sets:

GLP: fit to ZEUS  $M_X$  data  
ZEUS-LPS: fit to LPS data  
and charm fraction in  $F_2^{D(3)}$

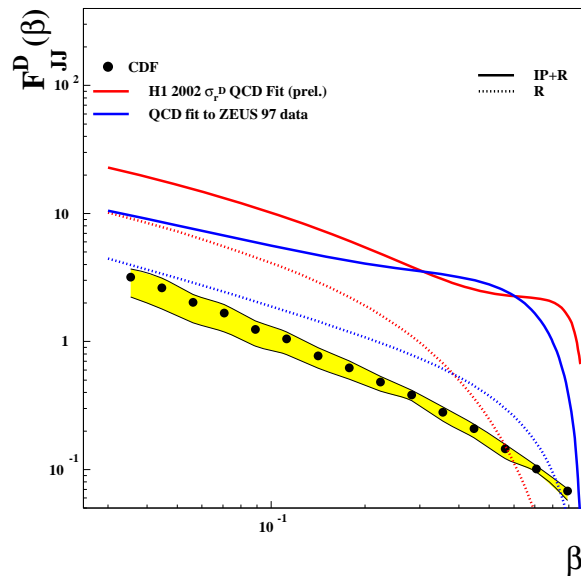


⇒ low GLP prediction due to small gluon at large  $z$

ZEUS: "Better understanding of DPDFs and their uncertainties is required before a firm statement about validity of QCD factorisation can be made"

# More factorisation tests: from DIS via $\gamma p$ to Tevatron

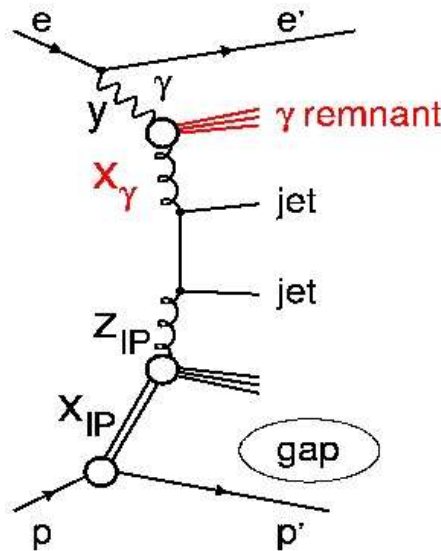
Tevatron vs HERA



Factorisation breakdown  
by factor of  $\sim 7$

(Gap survival probability;  
soft physics, hence hard  
to calculate precisely)

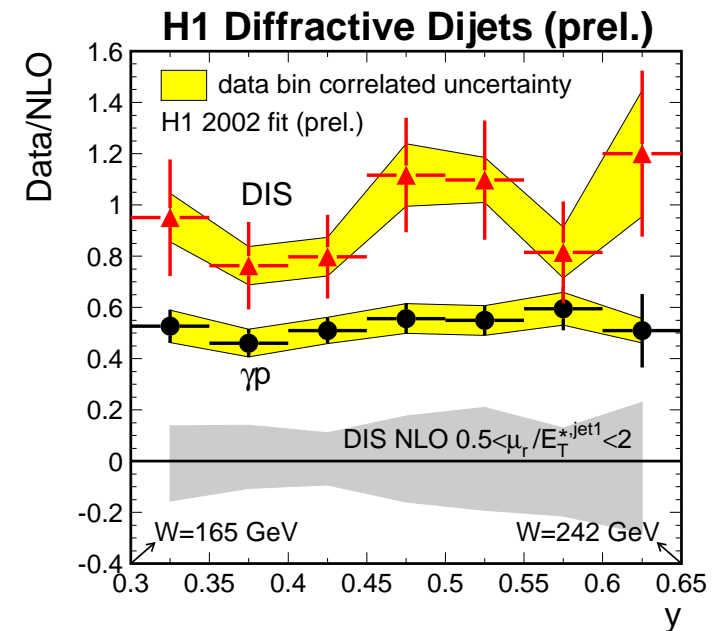
$Q^2 \approx 0$ :  
can secondary interactions  
fill the gap?



$x_\gamma = 1$  – direct photon coupling,  
DIS-like

$x_\gamma < 1$  – “resolved” photon,  
hadron-like

Compare  $\gamma p$  with DIS via the ratio  
data/NLO using the same DPDFs:

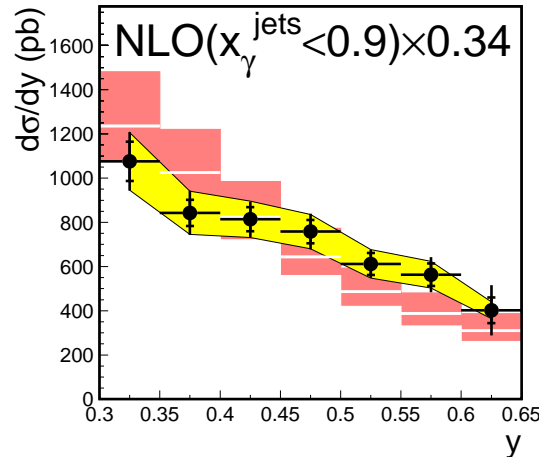
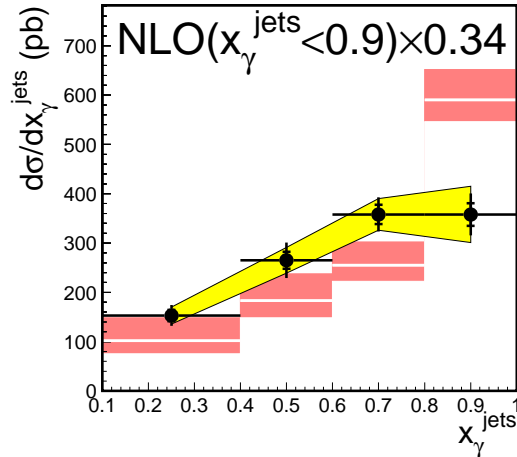


$\gamma p$  suppressed by factor  $\sim 2$  wrt DIS  
 $\Rightarrow$  look in more detail...

# Suppression of H1 $\gamma p$ dijets

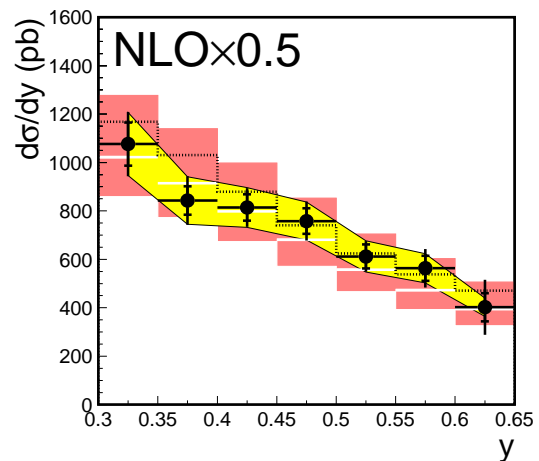
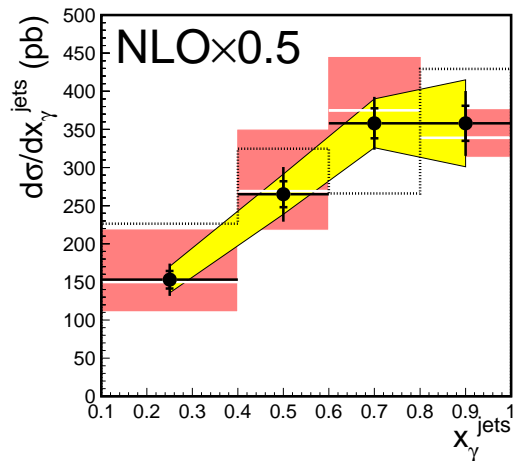
## H1 Diffractive $\gamma p$ Dijets

- H1 Preliminary
- correl. uncert.
- H1 2002 fit (prel.)
- FR NLO\*(1+ $\delta_{had}$ ), ( $x_\gamma^{jets} < 0.9$ ) $\times 0.34$



## H1 Diffractive $\gamma p$ Dijets

- H1 Preliminary
- correl. uncert.
- H1 2002 fit (prel.)
- FR NLO\*(1+ $\delta_{had}$ ) $\times 0.5$
- ⋯ FR NLO  $\times 0.5$



## Data:

$k_T$  jets with  $E_{T1} > 5$ ,  $E_{T2} > 4$  GeV

$Q^2 < 0.01$  GeV<sup>2</sup>,  $0.3 < y < 0.65$

$x_P < 0.03$

$$x_\gamma = \frac{\sum_{jets} (E - p_z)}{2yE_e}$$

## Results:

- "direct" unsuppressed  
does not describe  $x_\gamma$  shape
- global suppression  
describes data within  
uncertainties

# Suppression of ZEUS $\gamma p$ dijets

## Data:

$k_T$  jets with  $E_{T1} > 7.5$ ,  $E_{T2} > 6.5$  GeV

$Q^2 < 1 \text{ GeV}^2$ ,  $0.2 < y < 0.85$

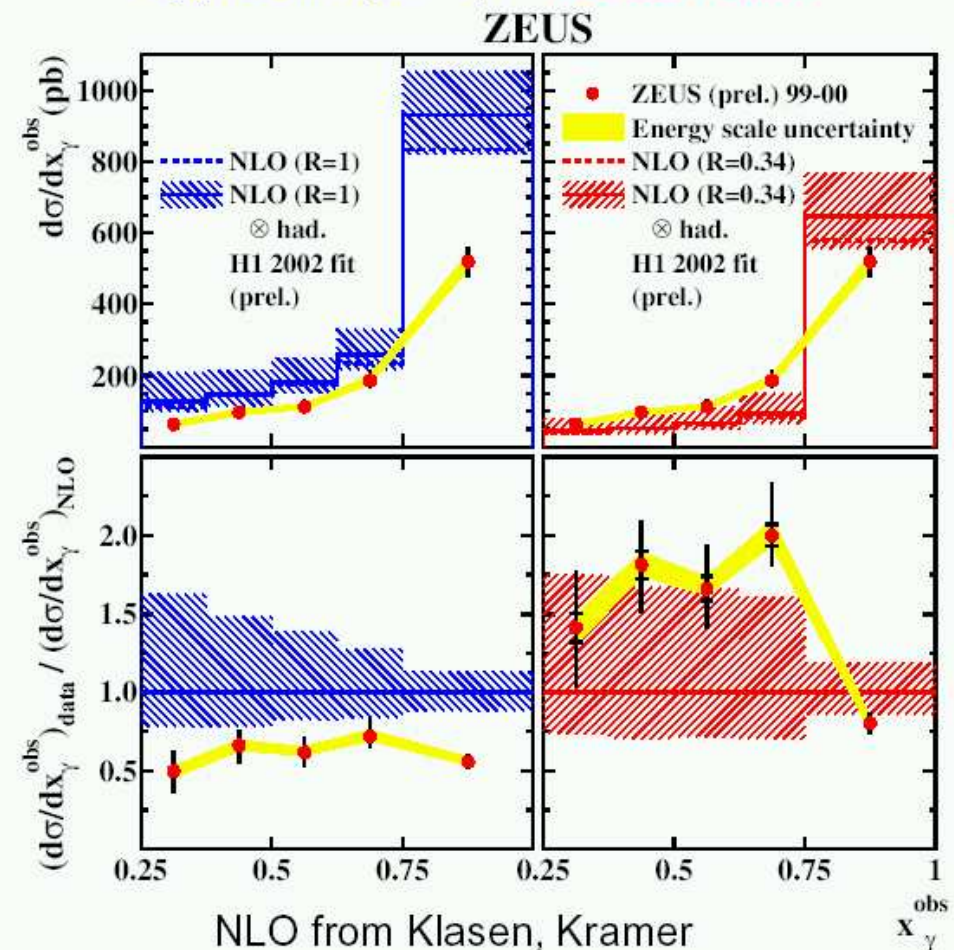
$x_P < 0.025$

## Results:

- data/NLO is flat in  $x_\gamma$
- global suppression by  $\sim 0.6$  is clearly preferred over "resolved"-only suppression

NLO, no resolved suppression ( $R = 1$ )

NLO, resolved suppressed  
Factor calculated from the CDF-H1 and fit 2002 comparison:  $R = 0.34$  by Kaidalov et al.



# Summary

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## ■ Inclusive diffraction

- ▷  $Q^2$  dependence of  $\alpha_{\mathbb{P}}(0)$  suggests Regge factorisation breaking in DIS regime
- ▷ Energy dependence:  $\alpha_{\mathbb{P}}^{diff}(0) - 1 \simeq 0.5 \cdot (\alpha_{\mathbb{P}}^{tot}(0) - 1)$  implies either severe failure of Regge picture in  $\gamma^*p$ , or unitarity corrections at work
- ▷ H1 vs ZEUS: despite measured  $F_2^D$  are in fair agreement remaining differences lead to approximately 2 times **different gluon** in diffractive PDFs  $\Rightarrow$  to be clarified with new data

## ■ Diffractive final states

- ▷ NLO predictions strongly depend upon specific choice of DPDFs
- ▷ When using H1 DPDFs both diffractive charm and dijets in DIS regime support QCD factorisation
- ▷ In diffractive photoproduction QCD factorisation is broken, showing at the moment global  $x_\gamma$  independent suppression factor of  $\sim 2$ , contrary to (naive) theoretical expectation

- Although an important progress is made recently, understanding of colour singlet exchange remains a major challenge in QCD