Dijet production at HERA and tests of QCD factorisation

Lidia Goerlich

Institute of Nuclear Physics PAN, Cracow

on behalf of the H1 and ZEUS collaborations

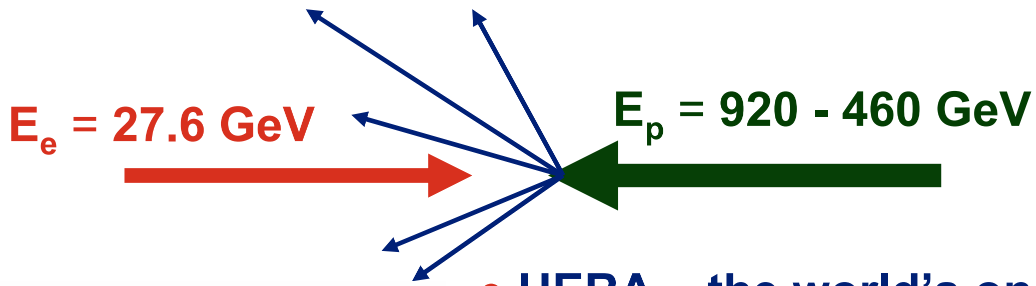
- Diffraction in ep collisions
- Selection of diffractive events
- Diffractive parton distribution functions
- Exclusive dijet production in diffractive DIS
- Tests of QCD factorisation
- Summary

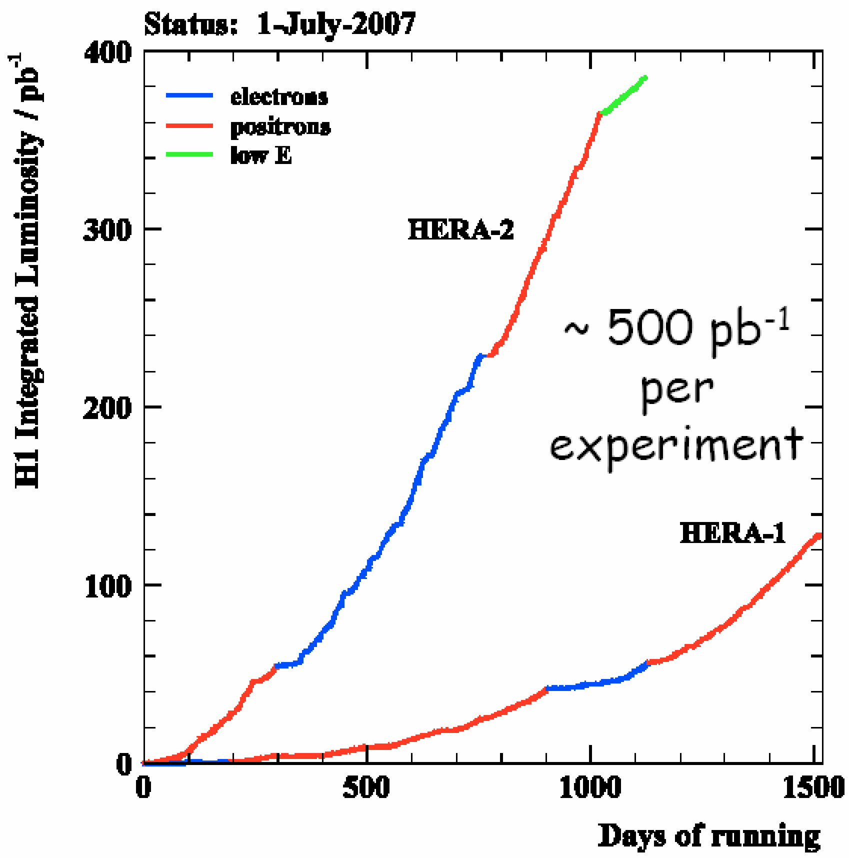
MPI @ LHC 2014

3-7 November, 2014

Kraków, Poland

HERA





- HERA – the world's only ep collider

  operated in 1992-2007 colliding
  electrons or positrons with protons

- two colliding beam experiments: H1 and ZEUS

- Nominal proton beam energy :

  E_p = 820 / 920 GeV
  $\sqrt{S}$ = 300 / 318 GeV, (HERA- I phase)

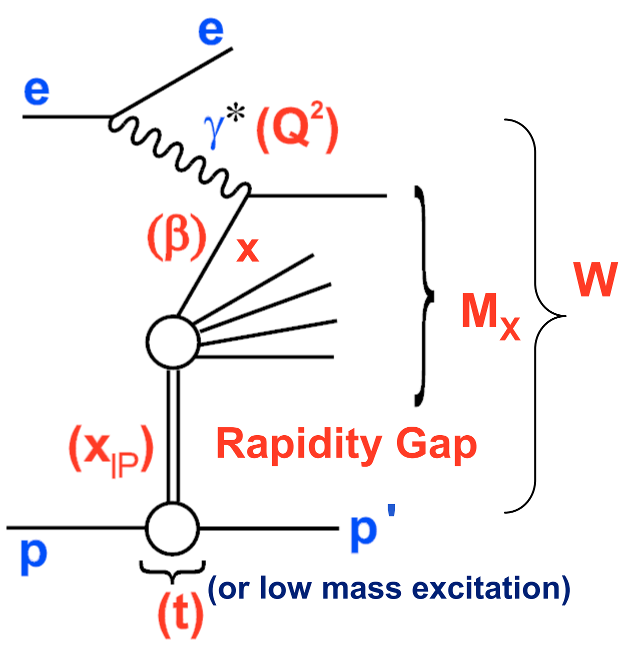
  E_p = 920 GeV
  $\sqrt{S}$ = 318 GeV, (HERA- II phase)

- Reduced proton beam energy :

  E_p = 460 GeV, $\sqrt{S}$ = 225 GeV, L_{int} = 12.4 pb^{-1}

  E_p = 575 GeV, $\sqrt{S}$ = 250 GeV, L_{int} = 6.2 pb^{-1}

Diffraction in ep collisions



Standard DIS variables :

- Q^2 |virtuality| of the exchanged boson
- x fraction of proton momentum carried by struck quark in Quark Parton Model
- y inelasticity, fraction of lepton energy transfered in the proton rest frame

$Q^2 >> 1\ GeV^2$ deep inelastic scattering (DIS)

$Q^2 \sim 0\ GeV^2$ photoproduction

Surprise of HERA : ~10% of DIS events have no activity in the forward direction (Large Rapidity Gap)
→ exchange of a colourless object (Pomeron, IP)

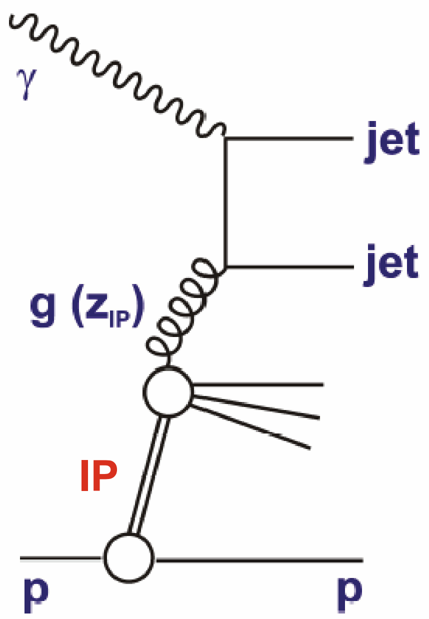
diffractive variables :

$$x_{I\!P} = \xi = \frac{Q^2+M_X^2}{Q^2+W^2}$$ p-momentum fraction carried by IP

$$\beta = \frac{Q^2}{Q^2+M_X^2} = \frac{x}{x_{I\!P}}$$ IP-momentum fraction carried by struck quark

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

Diffractive dijet production



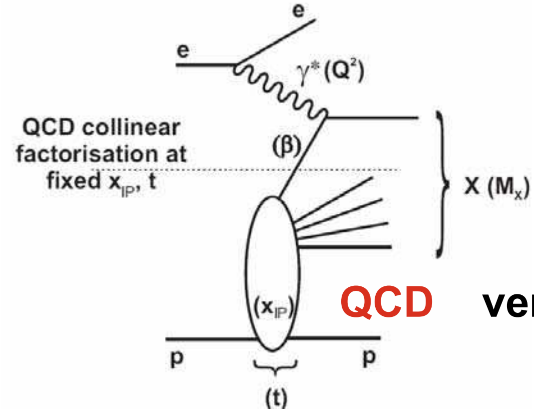
- Tests of QCD (inspired) models of diffraction
- Study factorisation properties of diffractive processes
- Probe partonic structure of diffractive exchange

  Diffractive dijets - direct sensitivity to the gluon component of the Pomeron
- Search for physics beyond DGLAP parton evolution

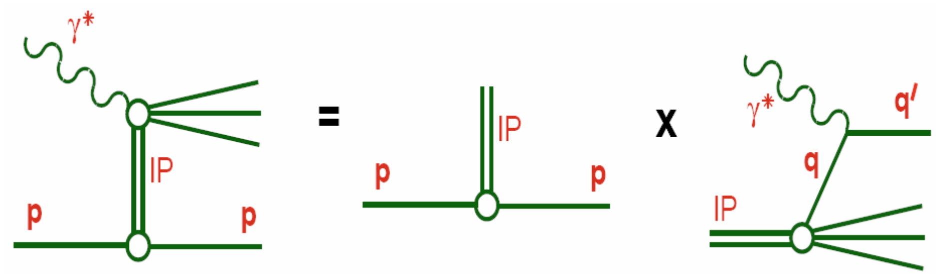
  Diffraction at HERA – low Bjorken-x phenomenon

  …

Factorisation in hard diffraction



QCD **versus**



Regge factorisation

QCD hard scattering collinear factorisation (proven by Collins 1998) :

$$d\sigma^{ep\to eXp}(\beta, Q^2, x_{IP}, t) = \Sigma f_i^D(\beta, Q^2, x_{IP}, t) \otimes d\sigma^{ei}(\beta, Q^2)$$

f_i^D – diffractive parton density functions (DPDFs), DGLAP evolution in Q^2
σ^{ei} – partonic cross sections, same as in inclusive DIS

Proton vertex factorisation : separate (x_{IP}, t) from (β, Q^2) dependences (Ingelman & Schlein, 1985)

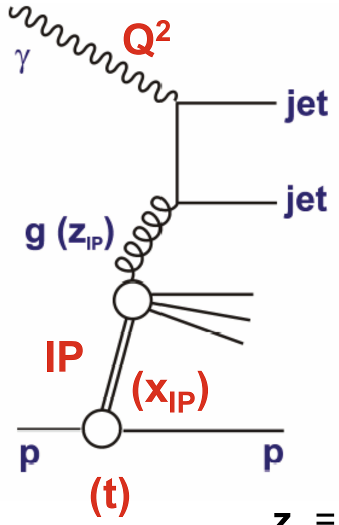
$$f_i^D(\beta, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot F_i^{IP}(\beta, Q^2)$$

No QCD basis, consistent with experimental data

Pomeron flux (Regge form)	Pomeron structure function

Diffractive exchange as the Pomeron with a partonic structure

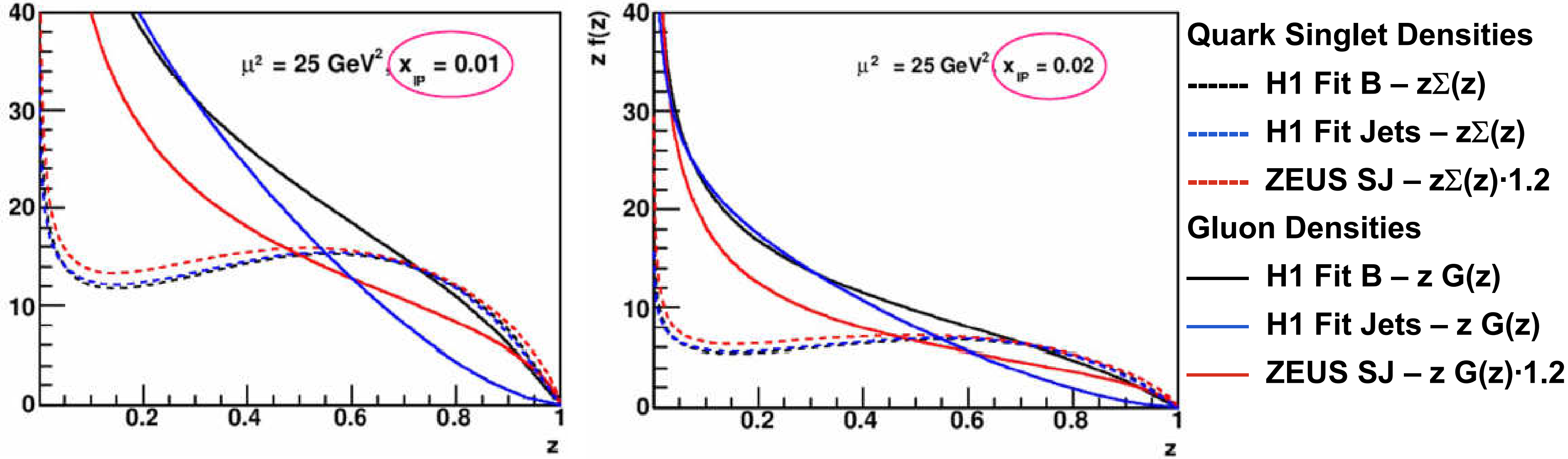
Diffractive parton density functions



- Diffractive PDFs obtained through NLO DGLAP QCD fit to data
  - inclusive DDIS cross section → diffractive gluon density weakly constrained at high z_{IP} → 2 solutions **H1 2006 Fit A and Fit B**
  - combined fit to diffractive inclusive and dijet cross sections → comparable precision of quark and gluon densities for all z_{IP}

    (H1 2007 Jets DPDF, ZEUS DPDF SJ)

z_{IP}= momentum fraction parton / IP

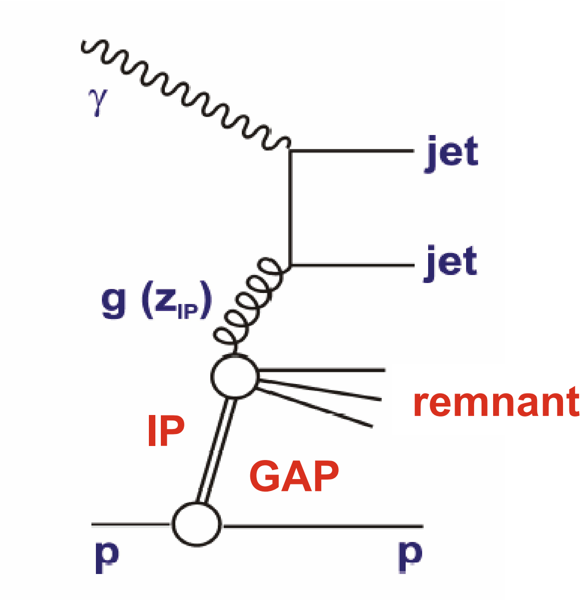


Diffractive scattering is dominated by gluons

(about 60-70 % of exchanged momentum, extending to large z)

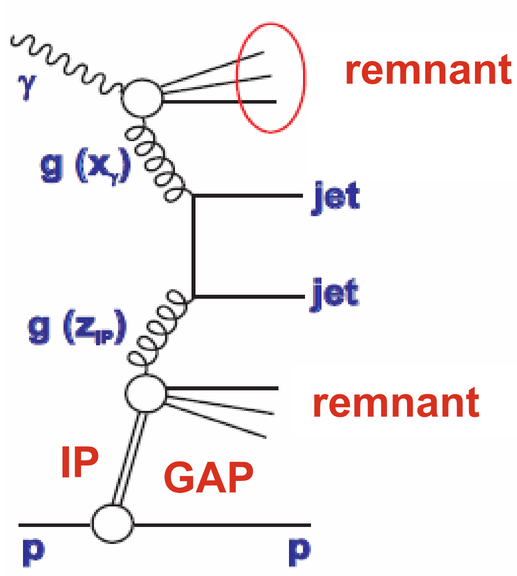
Diffractive dijet production

dominant LO QCD diagram
in diffractive DIS / direct photoproduction



$x_\gamma = 1$

LO QCD diagram
in resolved photoproduction
(γ interacts through its partonic structure)

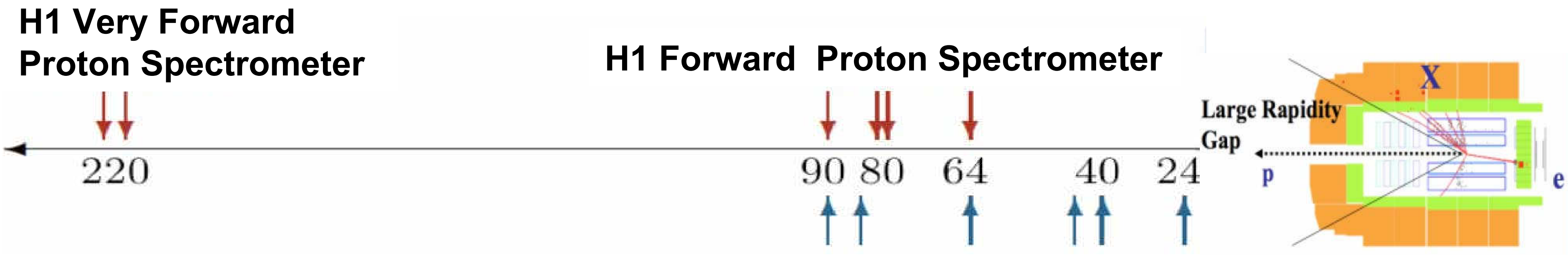


$x_\gamma < \sim 0.8$

x_γ – fraction of γ momentum in hard subprocess

Diffractive dijet photoproduction at HERA → **sensitive to multi-parton interactions which might occur in resolved photon processes in the presence of photon and Pomeron remnants** → **breaking of QCD factorisation ?**

Selection of diffractive events



- **Proton spectrometers:**
  - detection of elastically scattered protons → free of proton dissociation background
  - low geometrical acceptance → low statistics
  - direct measurement of t, x_{IP}
  - high x_{IP} accessible
- **Large Rapidity Gap:**
  - selection of LRG adjacent to outgoing (untagged) proton
  - high acceptance → more statistics
  - integration over $|t| < 1$ GeV^2
  - background from proton dissociation into low mass resonances N^*
- **The 2 methods have different kinematical coverage, very different systematics**

Exclusive dijet production in diffractive DIS

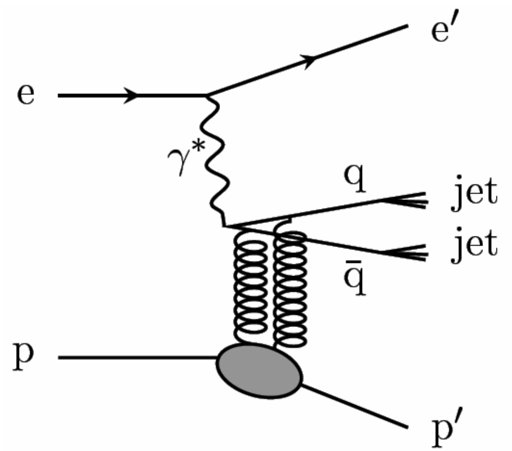
New ZEUS analysis of high statistics HERA - II data based on Large Rapidity Gap method

- e + p → e + p + jet + jet
- **study of the nature of diffractive exchange**

  → investigation of azimuthal angular distribution

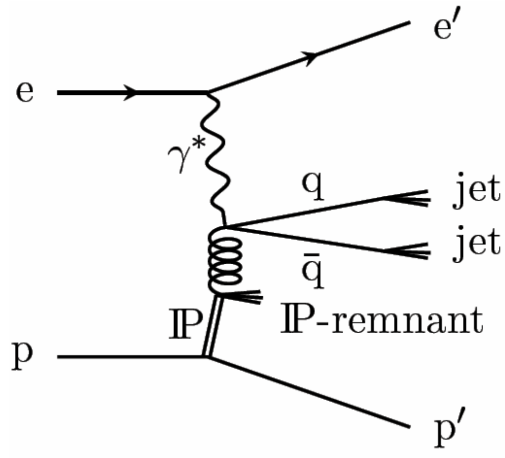
  (J. Bartels et al., Phys. Lett. B386 (1996) 389)

2 gluon exchange



Fully perturbative calculations based on proton PDF (J. Bartels et al.)

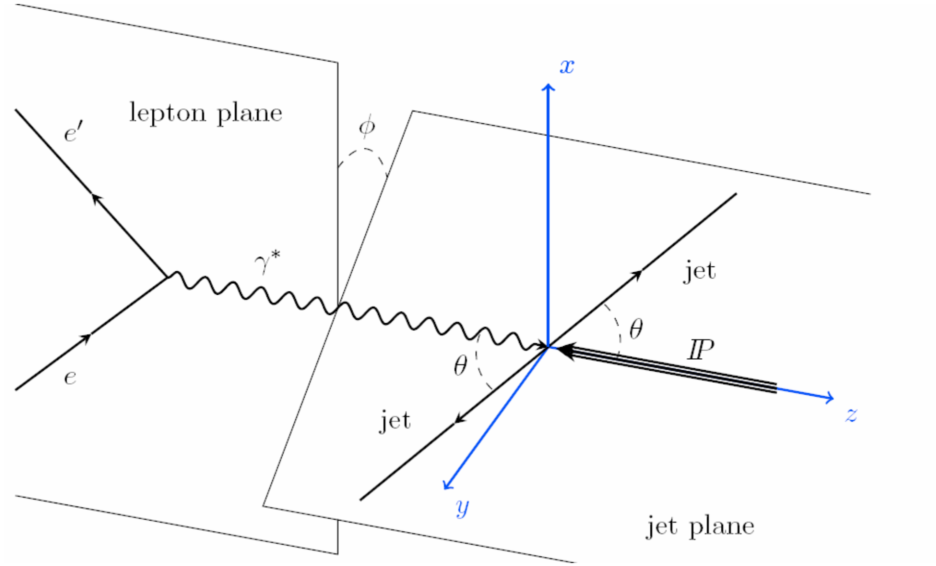
boson-gluon fusion



Resolved Pomeron model (Ingelman & Schlein)

Diffractive dijet production in γ^* - IP CMS

Dijet azimuthal angle ϕ – angle between the lepton plane and the γ^*- dijet plane in the γ^* - IP rest frame

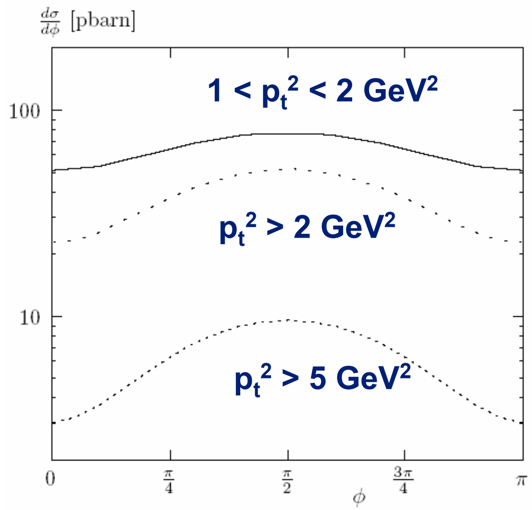


$$d\sigma/d\phi \propto 1 + A\cos(2\phi)$$

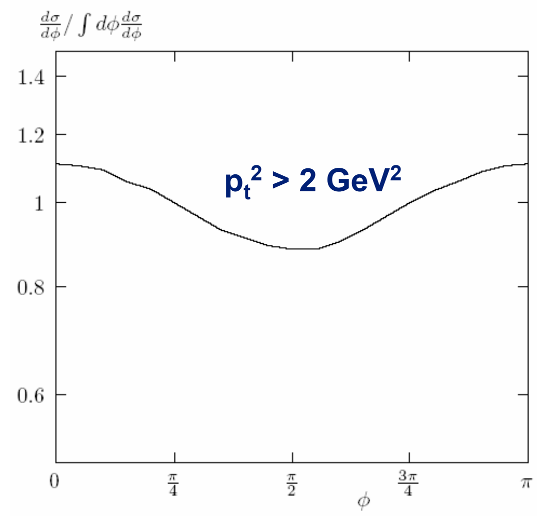
- **models predict different shapes for dijet azimuthal angular distribution**
- **2g exchange : negative A, maximum of $d\sigma/d\phi$ at $\phi = \pi/2$**
- **boson gluon fusion : positive A, maximum of $d\sigma/d\phi$ at $\phi = 0, \pi$**

Parton level predictions

2 gluon exchange



boson-gluon fusion



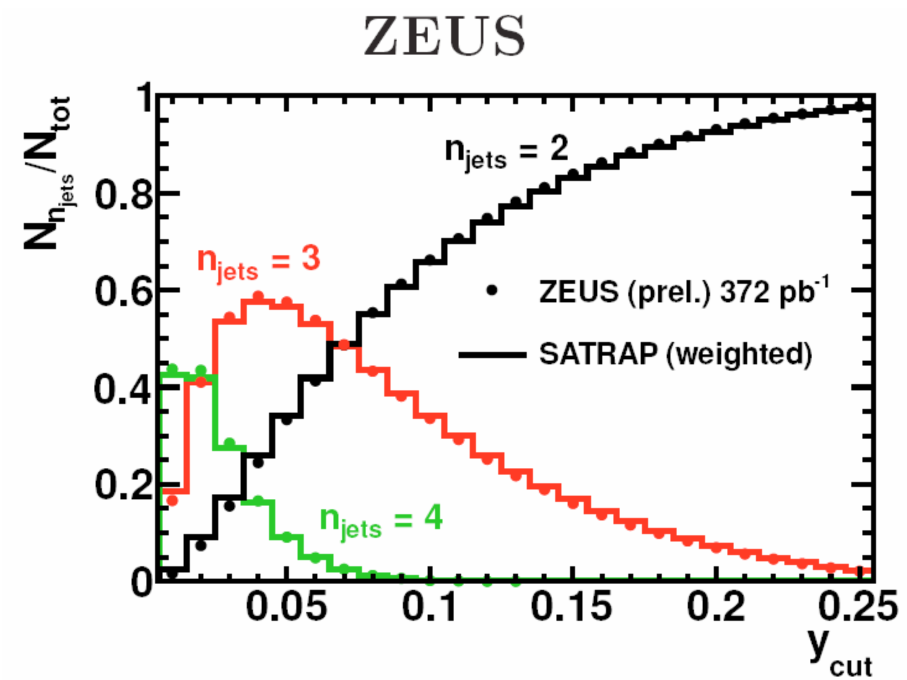
Exclusive dijet production in diffractive DIS

New ZEUS analysis of HERA - II data ($L_{int} \approx 370\ pb^{-1}$) based on Large Rapidity Gap method

- $Q^2 > 25\ GeV^2$, $90 < W < 250\ GeV$
  $x_{IP} < 0.01$, $0.5 < \beta < 0.7$
  $p_{T\ jet} > 2\ GeV$ (γ^*- IP CMS)

- Durham exclusive k_t jet algorithm :
  final state objects are merged as long as
  $k_T^2 < y_{cut} \cdot M_X^2$,
  every object must be clustered into a jet

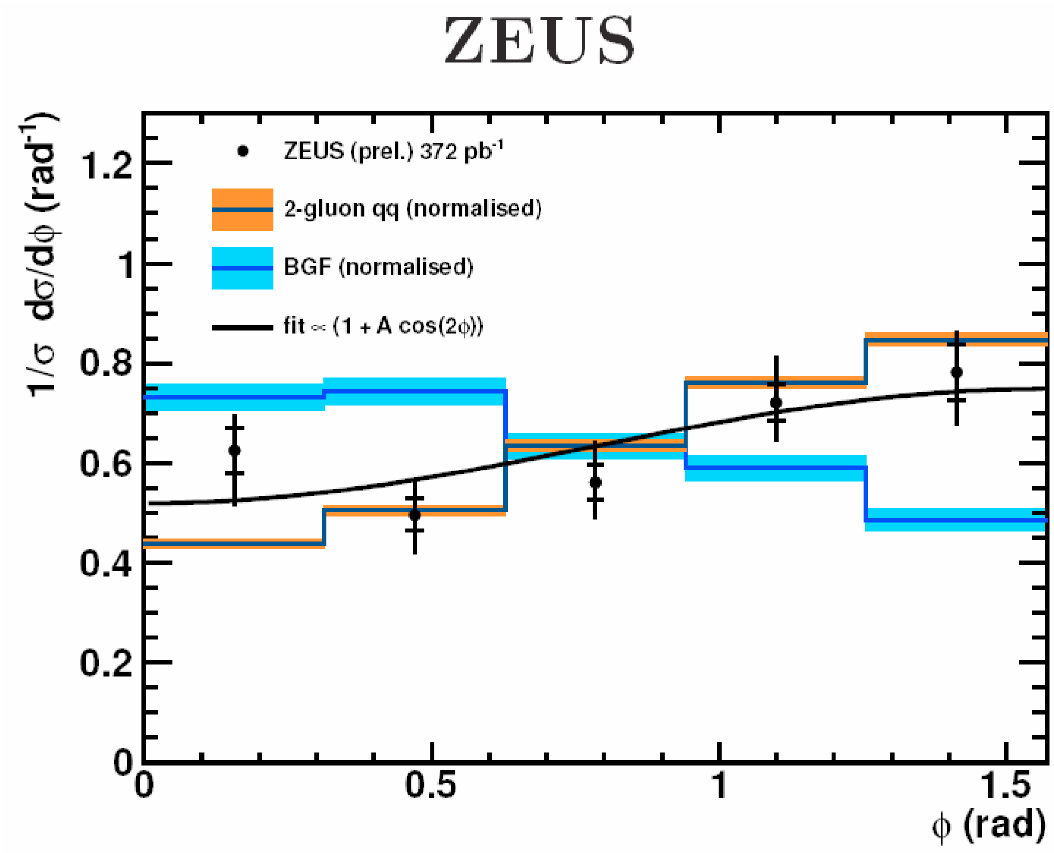
- Jet resolution parameter $y_{cut} = 0.15$
  optimizes efficiency vs. purity of dijet
  sample



SATRAP:

- color dipole model with saturation
- $q\bar{q}$ and $q\bar{q}g$ in a final state
- good agreement with data
- used in unfolding procedure

Exclusive dijet production in diffractive DIS



- First measurement of the shape of the azimuthal angular distribution of exclusive dijets in DDIS
- The data favour two gluon exchange model of quark anti-quark production over boson-gluon fusion model

$$d\sigma \propto 1 + A\cos(2\phi), \quad A = -0.18 \pm 0.06(\text{stat.})^{+0.06}_{-0.09}(\text{sys.})$$

Test of QCD factorisation

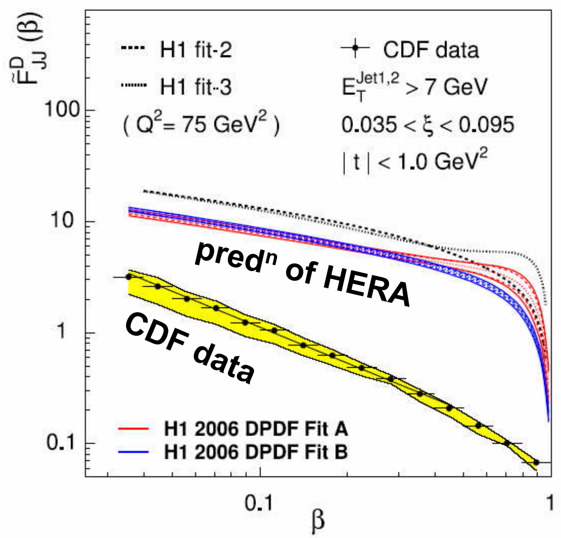
Use HERA DPDFs and NLO QCD calculations to predict diffractive dijet production

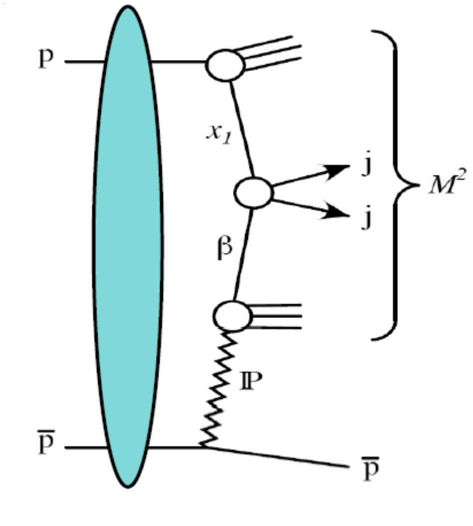
Suppression factor $S^2 = \sigma(\text{data}) / \sigma(\text{theory}_{\text{NLO QCD}})$

- **DIS : several measurements of H1 and ZEUS → QCD factorisation works within hard diffraction in DIS**

- **Factorisation breaking at the Tevatron (factor 10)**

Phys. Rev. Lett. 84 (2000) 5043





Similar effect also observed at the LHC

CMS : Phys. Rev. D87 (2013) 012006

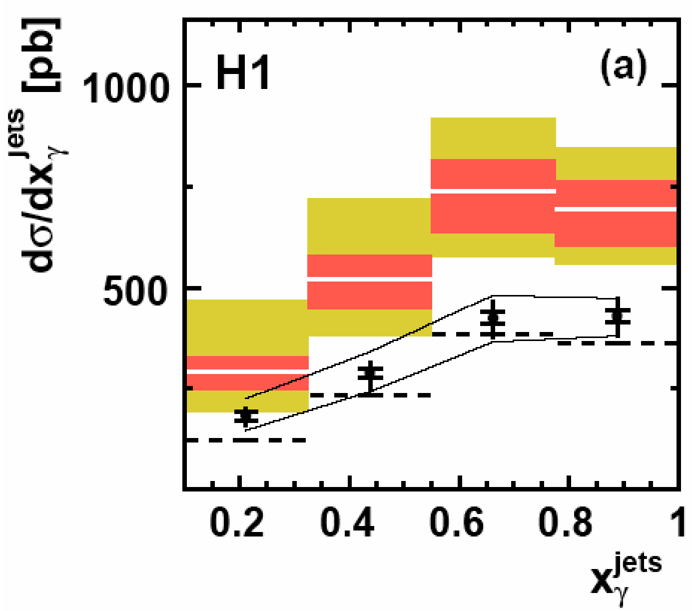
- **Photoproduction :**

H1 : breaking of QCD factorisation ($S^2 \sim 0.5 - 0.6$)
ZEUS: no factorisation breaking ($S^2 \sim 1$)

Diffractive dijet in photoproduction at HERA

Eur. Phys. J. C70 (2010) 15

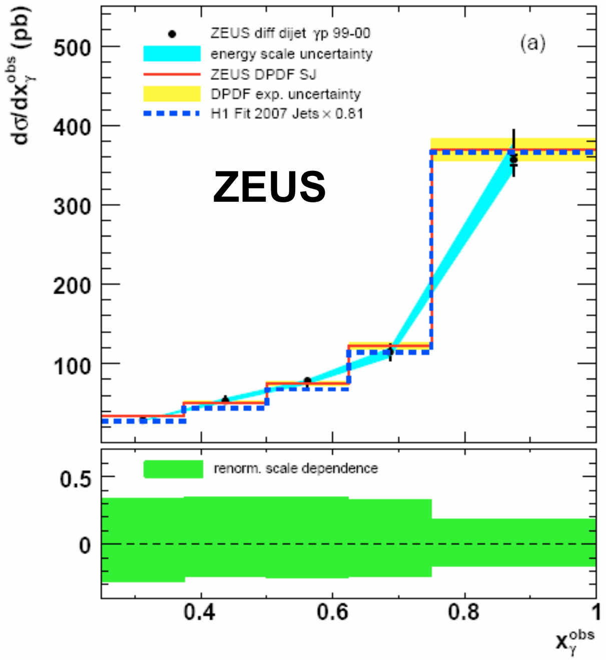
$E_T^{jet1(2)} > 5(4)$ GeV



$\sigma_{DATA}/\sigma_{NLO} \approx 0.6$

Nucl. Phys. B381 (2010) 1

$E_T^{jet1(2)} > 7.5(6.5)$ GeV

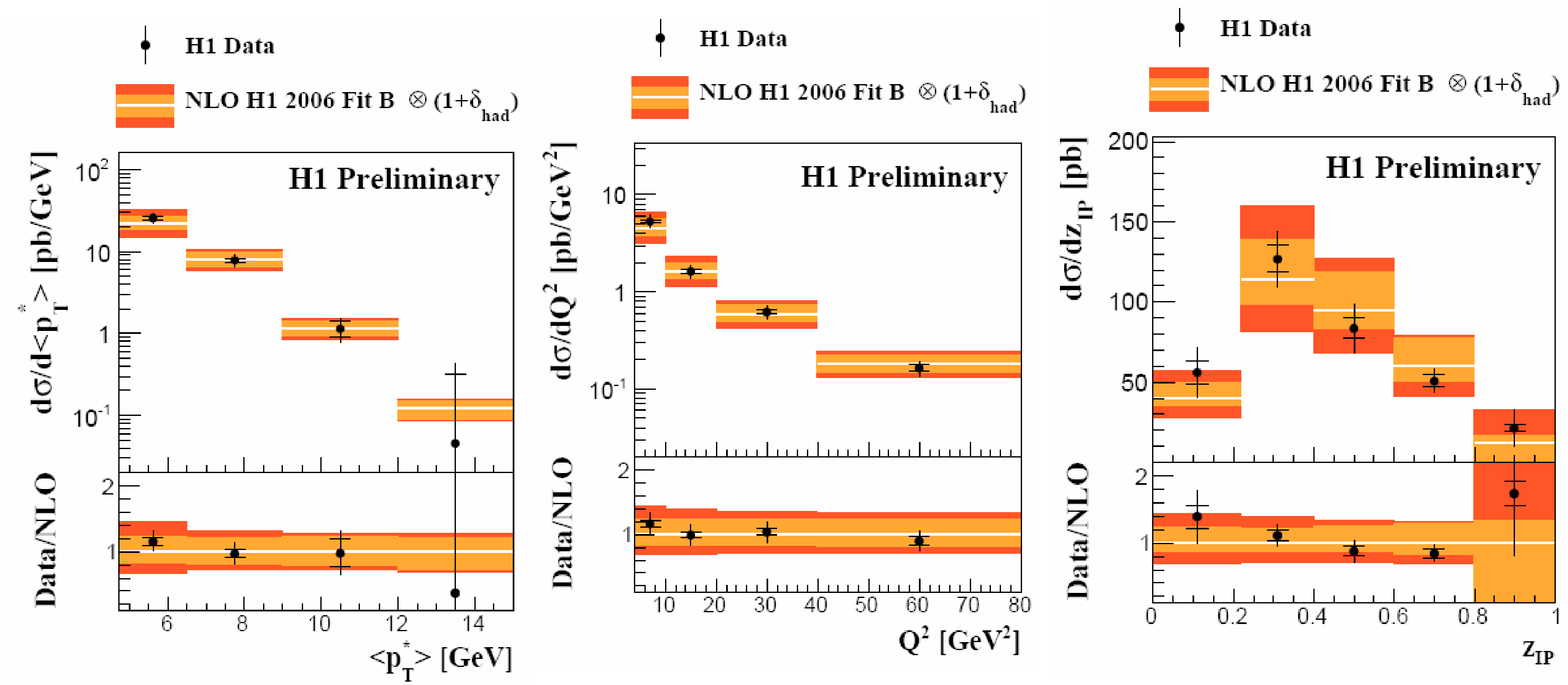


$\sigma_{DATA}/\sigma_{NLO} \approx 1.0$

- The suppression is expected to be stronger at low scales and low x_γ
- … but no evidence for the expected x_γ dependence of the suppression factor
- Factorisation breaking observed by H1 but not observed by ZEUS in slightly different phase space

Diffractive dijet production in DIS

- **New H1 analysis of high statistics HERA - II data based on Large Rapidity Gap selection**
- $4 < Q^2 < 80$ GeV^2, $0.1 < y < 0.7$, $E_T^{*}{}_{jet1(2)} > 5.5(4)$ GeV, regularised unfolding procedure



- **Data in agreement with the NLO QCD calculations (NLOJET++) using DPDF H1 2006 Fit B**

  → confirmation of QCD factorisation

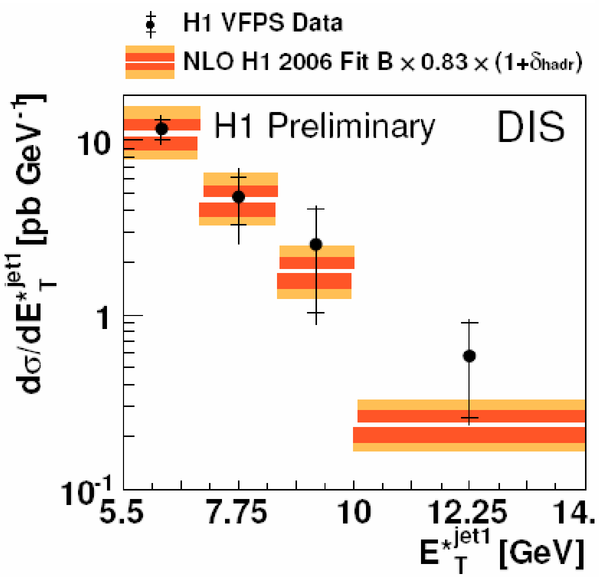
- **Data are more precise than theory predictions**

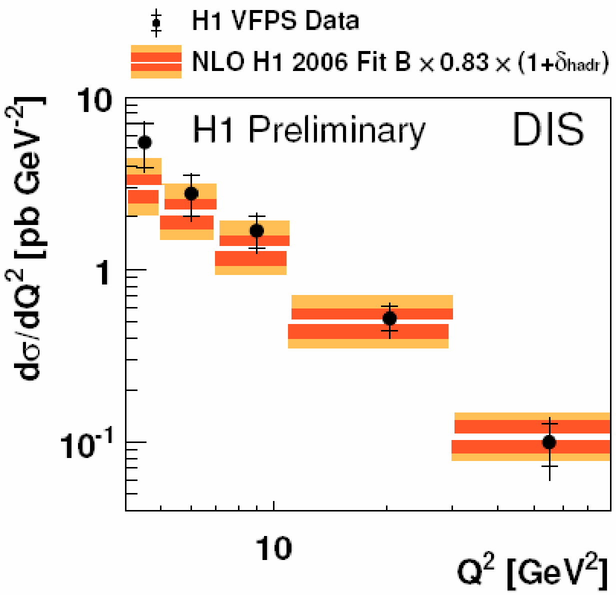
  → possible improvement of DPDF fits

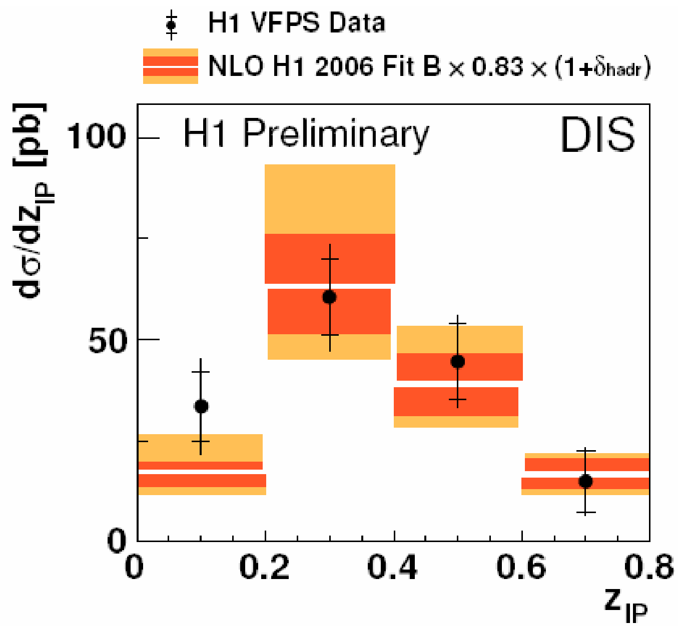
  → possiblity of determination of the strong coupling constant α_S

Diffractive dijet production in DIS

New H1 analysis with proton measured in Very Forward Proton Spectrometer







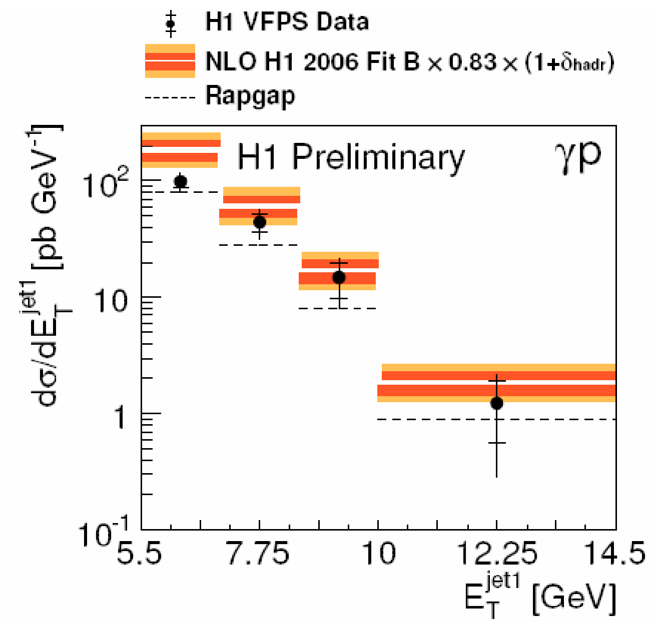
- **Data in agreement with NLO QCD calculations (NLOJET++) using DPDF H1 2006 Fit B $\rightarrow$**

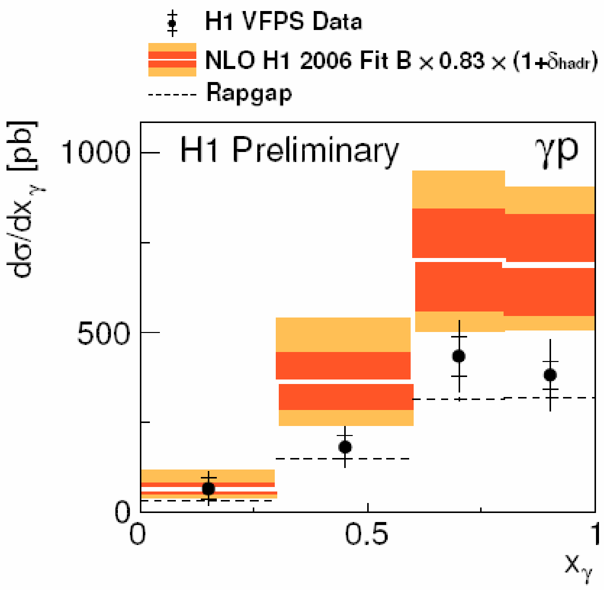
  confirmation of QCD factorisation in DDIS
- **Photoproduction events selected with same condition except for Q^2**

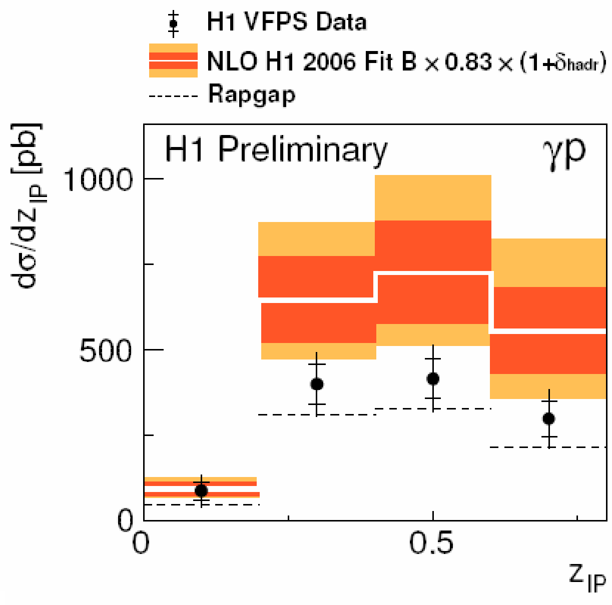
γp	DIS
$Q^2 < 2\,\mathrm{GeV}^2$	$4\,\mathrm{GeV}^2 < Q^2 < 80\,\mathrm{GeV}^2$
Common Cuts	
$0.2 < y < 0.7$ $E_T^{*\mathrm{jet1}} > 5.5\,\mathrm{GeV}$ $E_T^{*\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $-1 < \eta^{\mathrm{jet1,2}} < 2.5$	
$0.010 < x_{I\!P} < 0.024$ $\lvert t\rvert < 0.6\,\mathrm{GeV}^2$ $z_{I\!P} < 0.8$	

Diffractive dijet in photoproduction

New H1 analysis with proton measured in Very Forward Proton Spectrometer



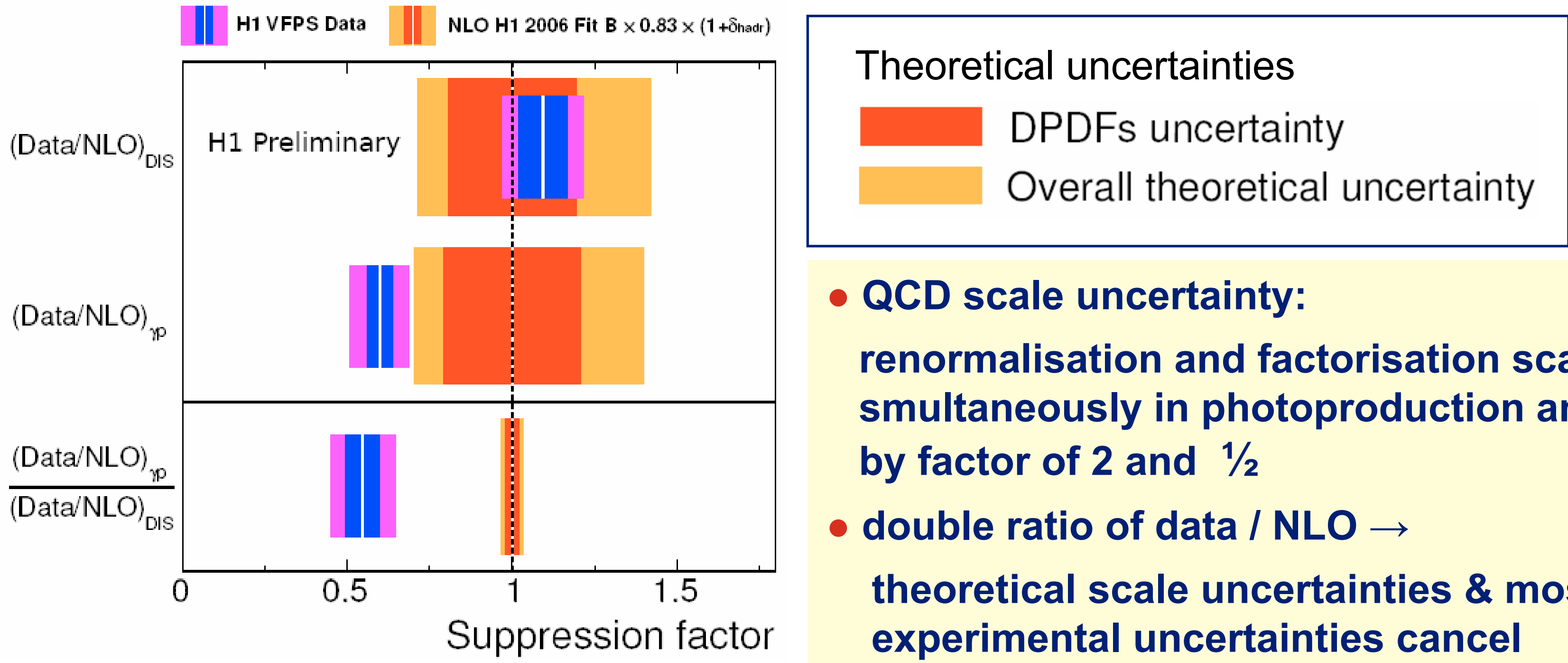




- The NLO QCD predictions (Frixione et. al) using DPDF H1 2006 Fit B overestimate the measured cross sections
- No indication of the higher supression factor at low x_γ , supression is almost independent on x_γ
- Hints for a higher supression at low E_T^{jet1}
- Problem of large theoretical uncertainties $\rightarrow$ use cross section double ratio of data to NLO prediction for photoproduction and DIS

Proton-tagged diffractive dijets in photoproduction and DIS

The cross section double ratio of data to NLO prediction for photoproduction and DIS



- **QCD scale uncertainty:**
  renormalisation and factorisation scales varied smultaneously in photoproduction and DIS by factor of 2 and ½
- **double ratio of data / NLO →**
  theoretical scale uncertainties & most of experimental uncertainties cancel

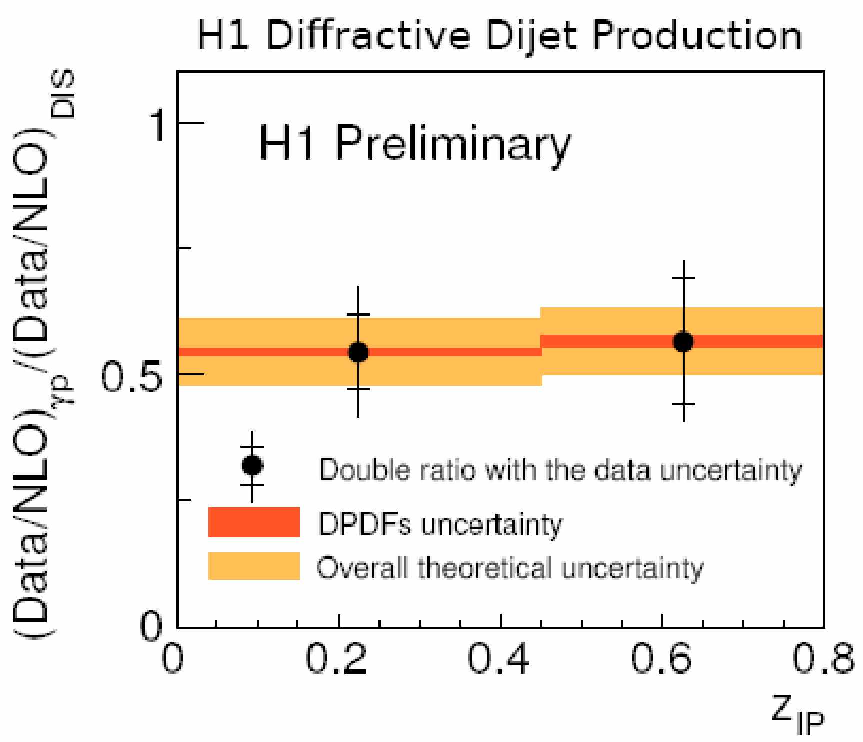
$$\frac{(\mathrm{DATA/NLO})_{\gamma p}}{(\mathrm{DATA/NLO})_{\mathrm{DIS}}} = 0.55 \pm 0.10\,(\mathrm{data}) \pm 0.02\,(\mathrm{theor.})$$

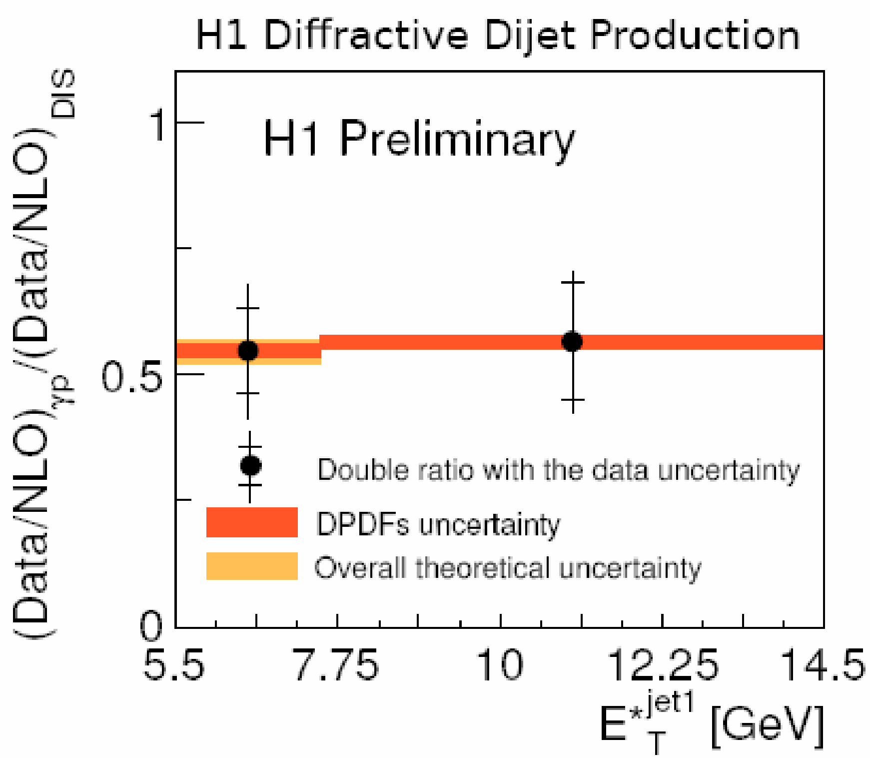
Confirmation of QCD factorisation breaking in diffractive dijet photoproduction

(suppression not due to proton dissociation)

Proton-tagged diffractive dijets in photoproduction and DIS

The cross section double ratio of data to NLO prediction for photoproduction and DIS





No dependence of the suppression on z_{IP} and E_T of the leading jet

Summary

- New precise results on diffractive dijets from the H1 and ZEUS Collaborations
- The shape of the azimuthal angular distribution of exclusive dijets in diffractive DIS has been measured by ZEUS for the first time

  → the data favour 2-gluon exchange model of $q\bar{q}$ production over boson gluon fusion model

- Dijet production with Large Rapidity Gap in diffractive DIS confirms QCD factorisation
- New H1 measurements of diffractive dijets in photoproduction and DIS with leading proton :

  – suppression factor of 0.55 in photoproduction independent of kinematics is consistent with breaking of QCD factorisation

  – the origin of different conclusions of H1 and ZEUS on factorisation breaking in photoproduction not explained