Low x & diffraction at HERA

Alice Valkárová
Charles University, Prague

on behalf of H1 and ZEUS Collaborations

HERA collider experiments

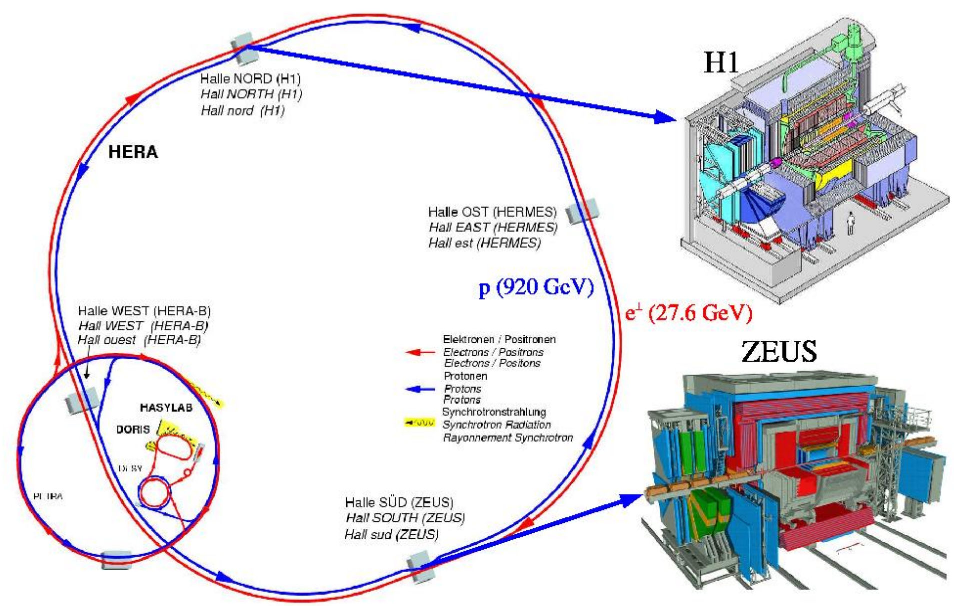
- 27.5 GeV electrons/positrons on 920 GeV protons →$\sqrt{s}$=318 GeV
- data taken in 1992-2007
- HERA I,II: ~ 500 pb^{-1} per experimen
- H 1 & ZEUS - 4π detectors

Why to study diffraction?

Fundamental aim:
understand high energy limit of QCD

Novelty:
probe partonic structure of diffractive exchange

Applications: study factorisation properties, transport PDFs to pp scattering (Tevatron, LHC).



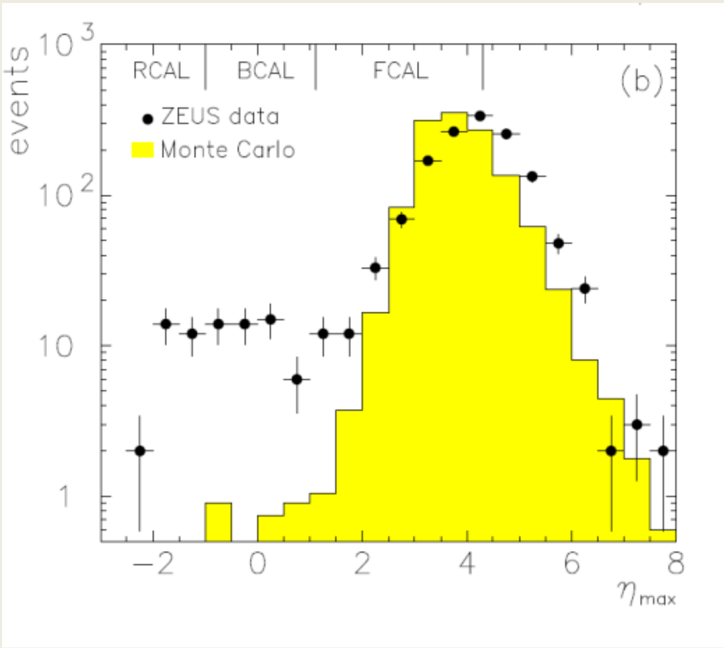
Historical reminder

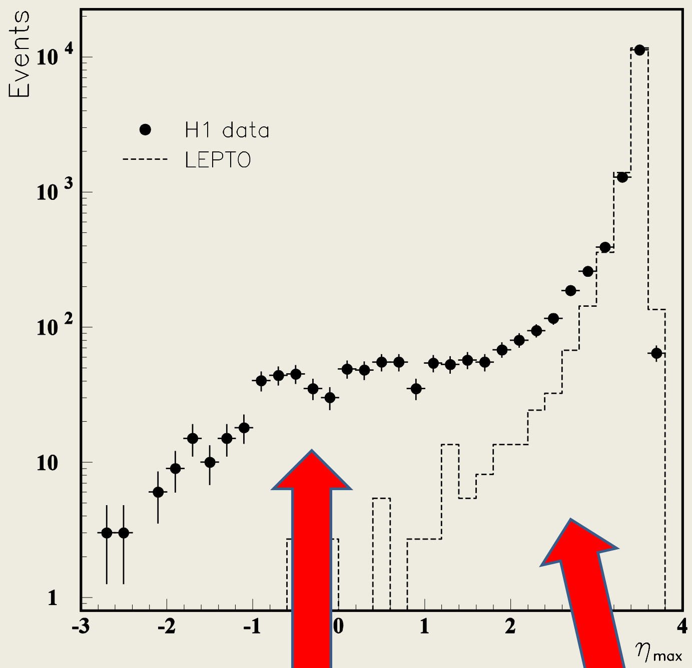
- **21 years** after the observation of diffractive DIS events at HERA!
- HERA opened **new era of diffraction studies**

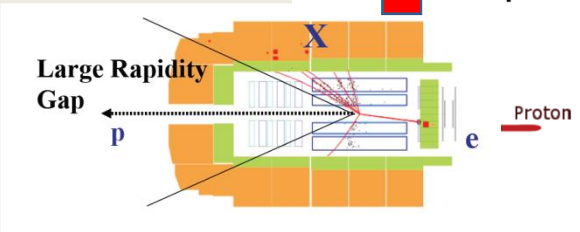
ZEUS Collab.,Physics Letters B 315 (1993) 481-493

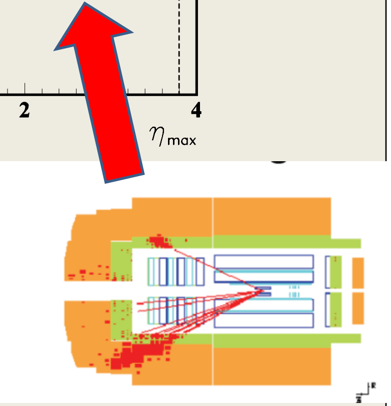
1993-1994

H1 Collab., Nucl. Phys. B429 (1994) 477

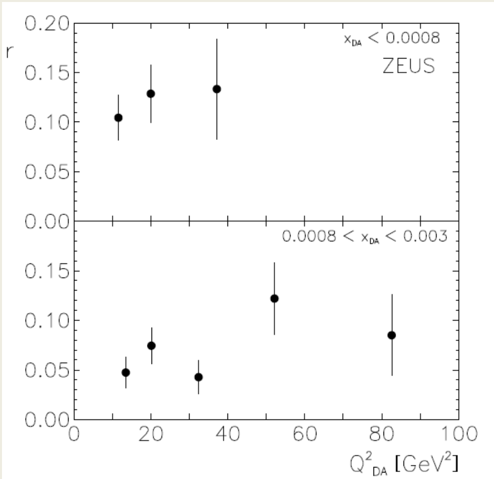






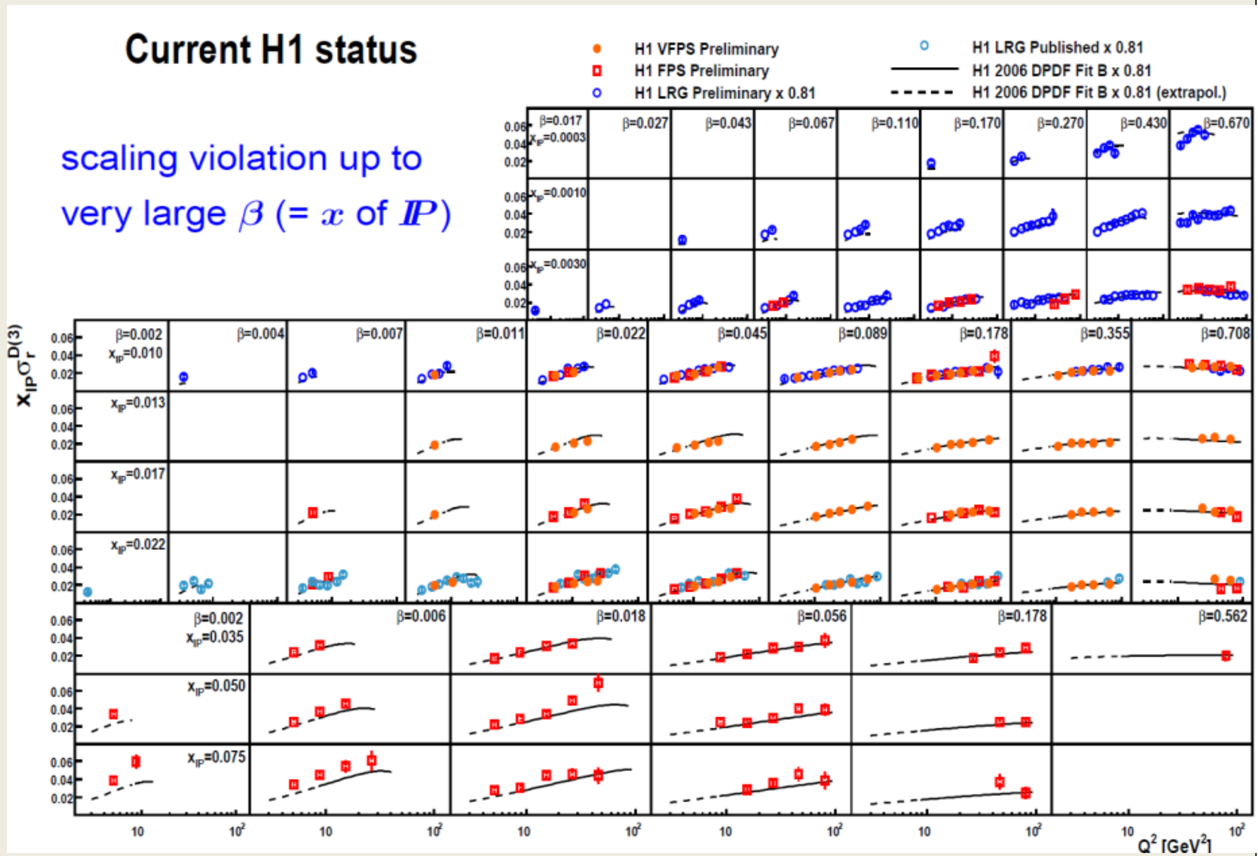


Historical reminder



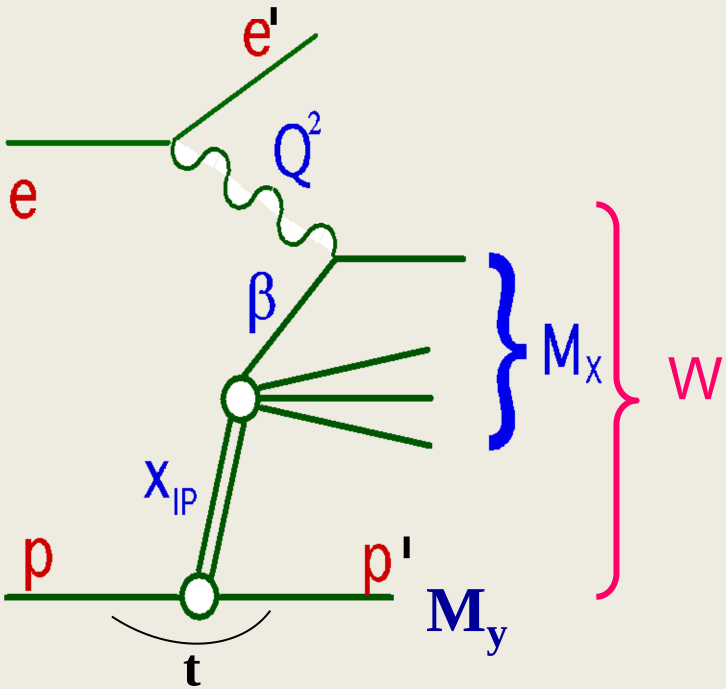
ZEUS Collab.,Physics Letters B 315 (1993) 481-493

1993



2014

Diffractive kinematics



Q^2~0 GeV^2→ photoproduction
Q^2>>0 GeV^2→ deep inelastic scattering (DIS)

HERA: ~10% of events diffractive

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

momentum fraction of color singlet exchange

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

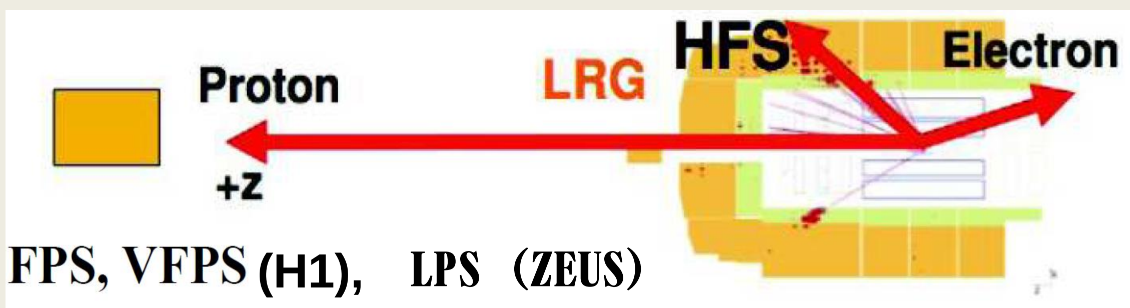
fraction of exchange momentum, coupling to γ

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

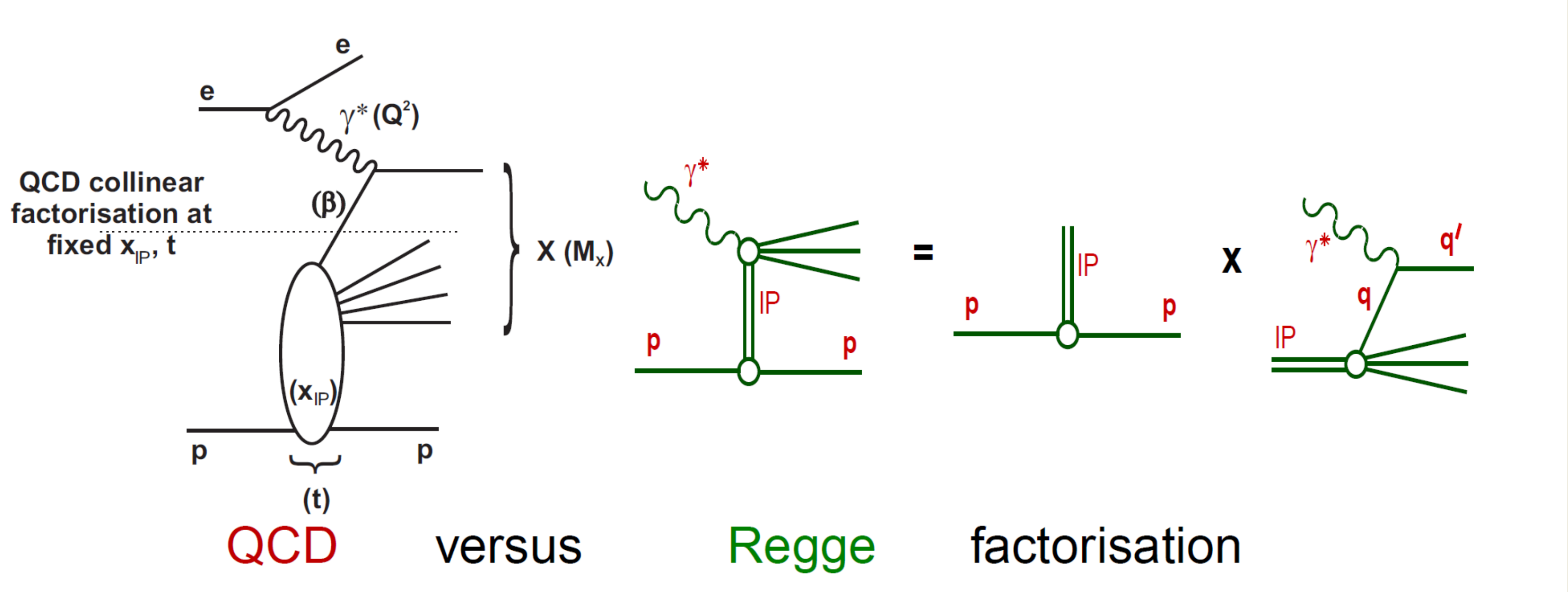
$M_y = m_p$ proton stays intact, needs detector setup to detect protons
$M_y > m_p$ proton dissociates, contribution should be understood

Experimental methods:

- selecting LRG events
- measuring p in Roman pots (60-220m from Int.Point)



Factorisation properties of diffraction



QCD factorisation
(rigorously proven for DDIS by Collins et al.)

$$\sigma^D(\gamma^* p \to Xp) = \sum_{parton\_i} f_i^D(x, Q^2, x_{IP}, t) \cdot \sigma^{\gamma^* i}(x, Q^2)$$

f_i^D - DPDFs – obey DGLAP, universal for diff. ep DIS (inclusive,dijet..)

$\sigma^{\gamma^* i}$ - hard scattering cross section (same as in non-diffractive DIS)

Regge factorisation
(conjecture, e.g. Resolved Pomeron Model by Ingelman&Schlein)

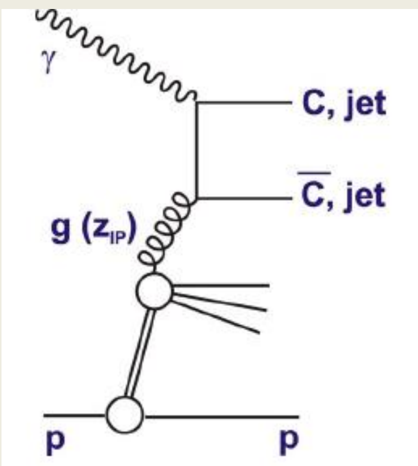
$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_i^{IP}(\beta = x/x_{IP}, Q^2)$$

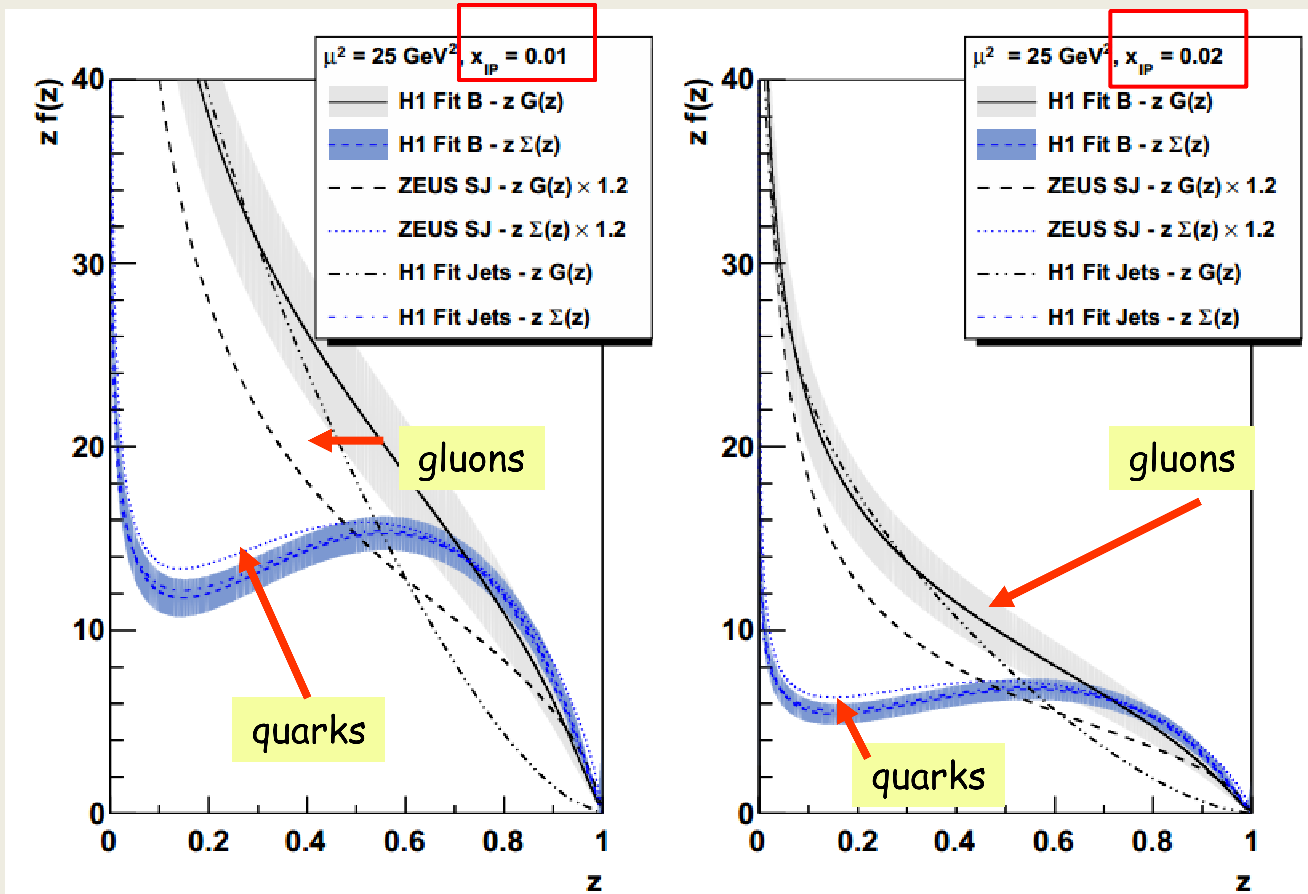
pomeron flux factor   pomeron PDF

DPDFs in DIS

DPDFs obtained by H1 and ZEUS from inclusive, dijet (and D* measurements….)
DPDFs used in HERA analyses – H1 fit B, H1 fit Jets, ZEUS fit SJ
Main differences are in gluonic part.

$$z = z_{IP} = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$





Diffractive reduced cross section

- select diffractive events
- correct for detector effects
- derive cross sections -> F_2^D

$$\frac{d^4\sigma(ep \to eXp)}{d\beta\, dQ^2 dx_P dt} = \frac{4\pi\alpha_{em}^2}{\beta Q^4}(1 - y + \frac{y^2}{2})\ \sigma_R^{D(4)}(\beta, Q^2, x_P, t)$$

y - inelasticity → 1-(E'_e/E_e)

$\sigma_R^{D(4)}$ → **diffractive reduced cross section**

$$\sigma_R^{D(4)} \approx F_2^{D(4)}$$

at low and medium *y*

$$\sigma_R^{D(4)} = F_2^{D(4)} - \frac{y^2}{2(1 - y - \frac{y^2}{2})} F_L^{D(4)}$$

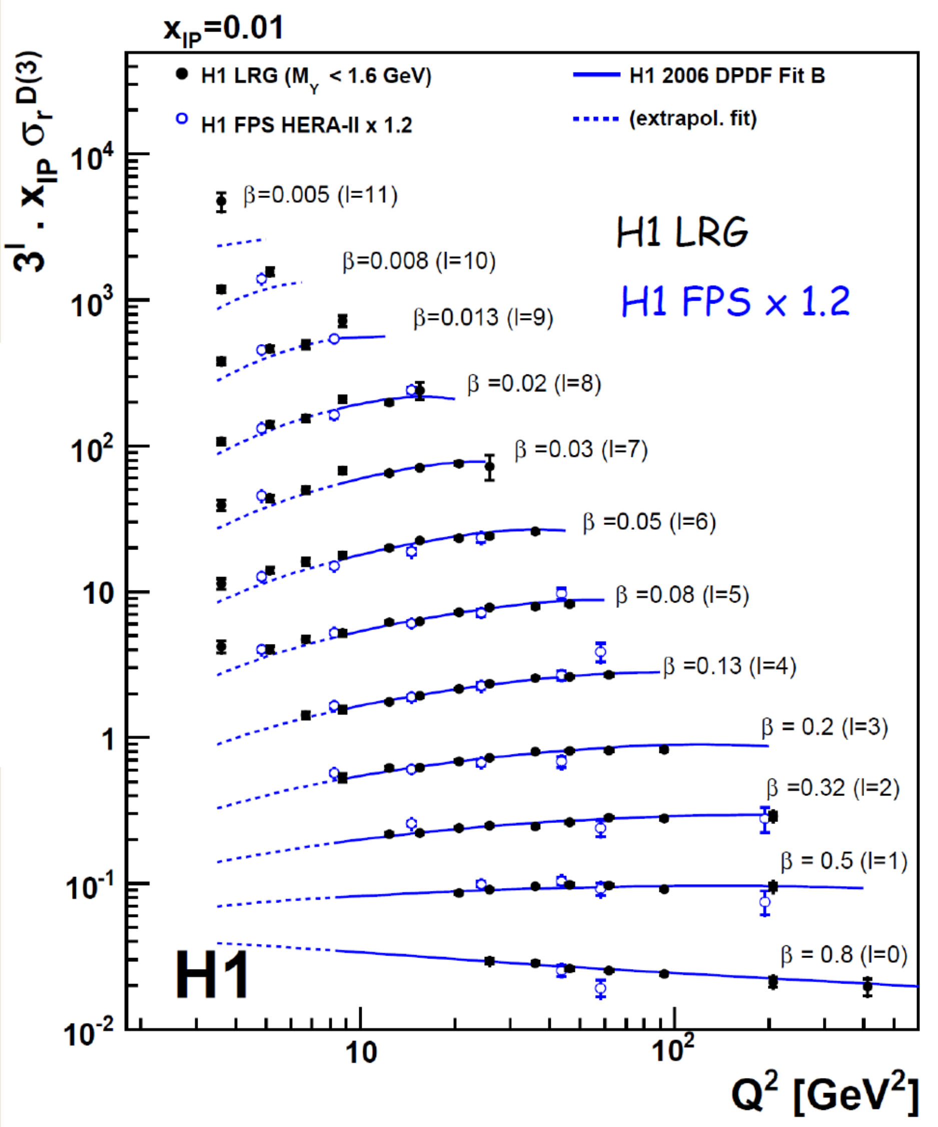
$$\sigma_R^{D(4)} = F_2^{D(4)} \quad \text{if}$$

$$F_L^{D(4)} = 0$$

Integrate over *t* when proton is not tagged

$$\rightarrow \sigma_R^{D(3)}(\beta, Q^2, x_P)$$

Combined H1 LRG & FPS



EPJC 72, (2012),2074.

The ratio LRG/FPS :

$$\frac{\sigma\,(M_Y < 1.6\,\mathrm{GeV})}{\sigma\,(Y = p)} = 1.203 \pm 0.019(\mathrm{exp.}) \pm 0.087(\mathrm{norm.})$$

(1.6%) (7.2%)

FPS cross sections are multiplied by factor 1.2 to take into account the dissociation admixture in LRG sample

Agreement with previous results, no Q^2 or β dependence for the factor observed !

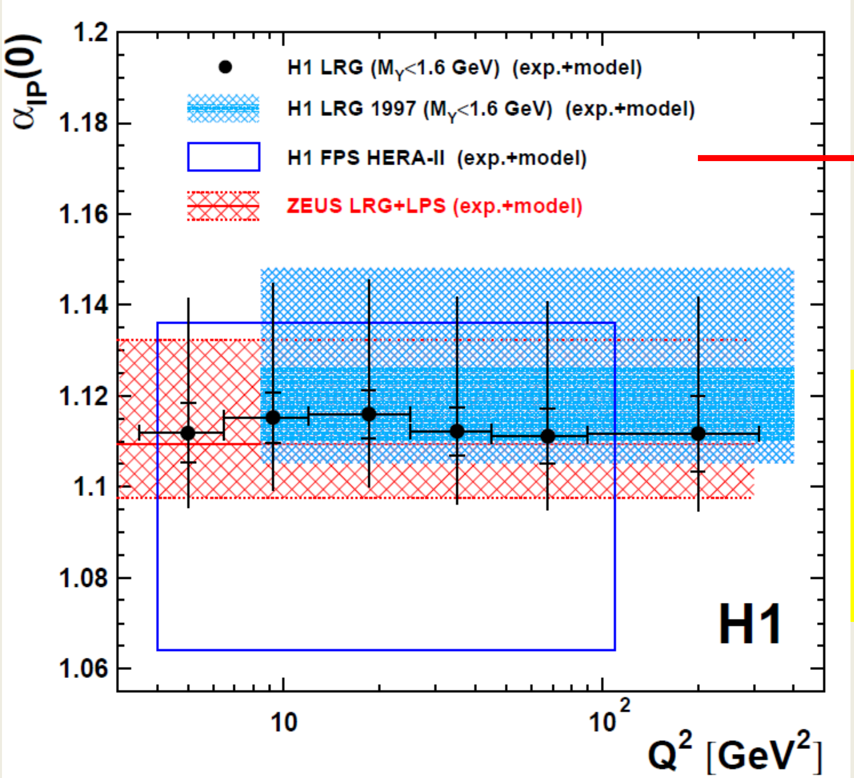
LPS/LRG=0.76 ± 0.01(st) ± $^{0.03}_{0.02}$(sy)±$^{0.08}_{0.05}$(norm)

Extraction of the pomeron trajectory

Regge fit to LRG cross sections:

$$F_2^{D(3)}(Q^2,\beta,x_{I\!P}) = f_{I\!P/p}(x_{I\!P})\ F_2^{I\!P}(Q^2,\beta) + n_{I\!R}\ f_{I\!R/p}(x_{I\!P})\ F_2^{I\!R}(Q^2,\beta)$$

$$f_{I\!P/p,I\!R/p}(x_{I\!P}) = \int_{t_{cut}}^{t_{min}} \frac{e^{B_{I\!P,I\!R}t}}{x_{I\!P}^{2\alpha_{I\!P,I\!R}(t)-1}}\mathrm{d}t \qquad \alpha_{I\!P,I\!R}(t) = \alpha_{I\!P,I\!R}(0) + \alpha'_{I\!P,I\!R}t$$



The mean value of pomeron intercept

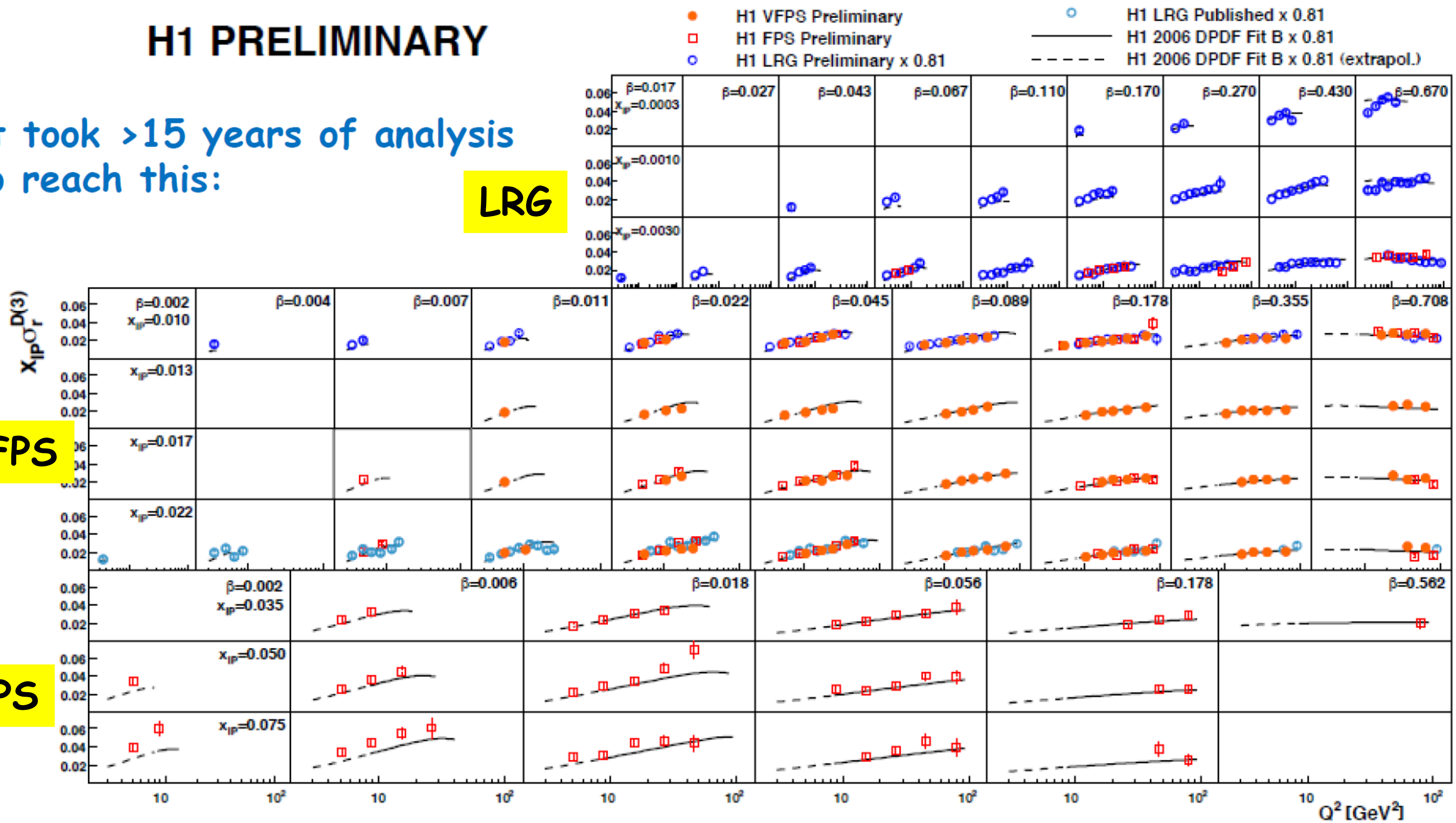
$$\alpha_{I\!P}(0) = 1.113\ \pm 0.002\ (\mathrm{exp.})\ {}^{+0.029}_{-0.015}\ (\mathrm{model})$$

- no Q^2 dependence observed
- consistent with other measurements
- supports the hypothesis of the proton vertex factorization

$\alpha_{I\!P}(0)$ – consistent with 'soft $I\!P$'

Experimental summary for H1 F_2^D

It took >15 years of analysis to reach this:



HERA combined $\sigma_r^{D(3)}$ - proton spectrometers

H1 FPS

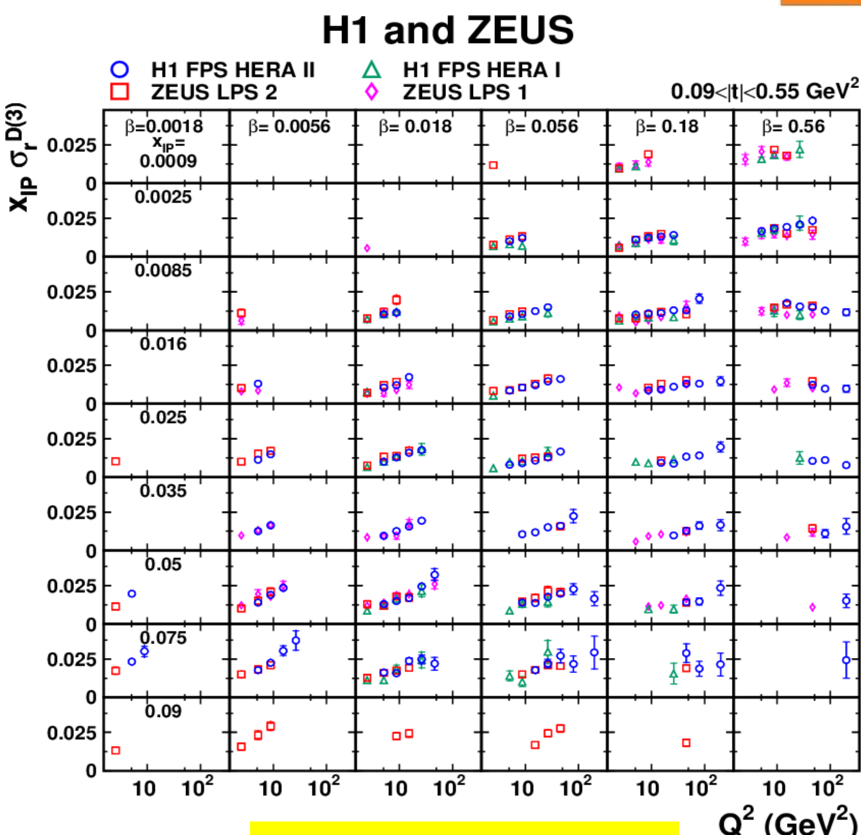
H1 Collab., Eur. Phys. J. C71 (2011) 1578
H1 Collab., Eur. Phys. J. C48 (2006) 749

ZEUS LPS

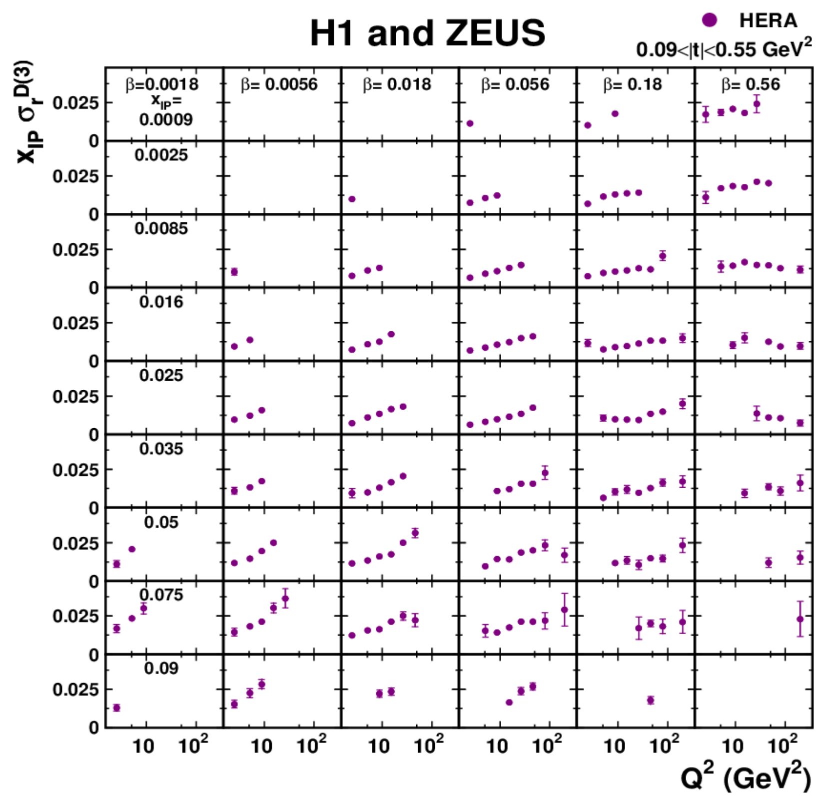
ZEUS Collab., Nucl. Phys. B816 (2009) 1
ZEUS Collab., Eur. Phys. J. C38 (2004) 43

Kinematic range

$Q^2 = 2.5 - 200\ GeV^2$
$\beta = 0.0018 - 0.816$
$x_{IP} = 0.00035 - 0.09$
$|t| = 0.09 - 0.55$



$\sigma_r^{D(3)}$ for combination



EPJC C72 (2012),2175

Factorisation tests in diffractive dijet production

Measurements compared to NLO QCD predictions, (using HERA DPDFs).

suppression factor

$$S^2 = \frac{\sigma\,(\text{data})}{\sigma\,(\text{theory}_{(\text{NLO QCD})})}$$

DIS – several measurements

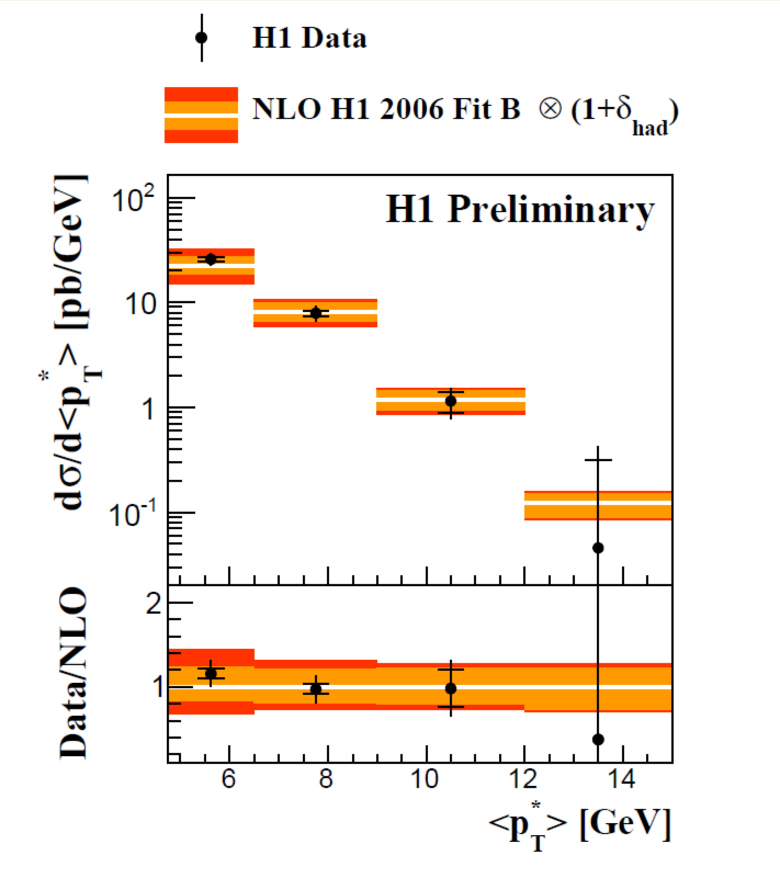
Factorisation **confirmed** by H1 and ZEUS measurements for dijets in DIS

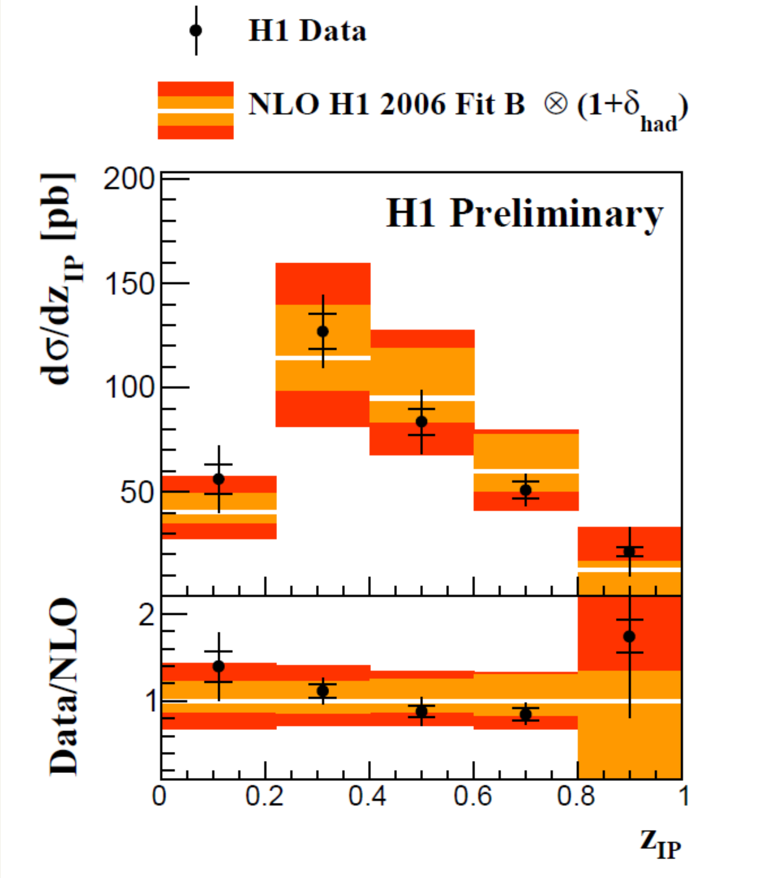
Photoproduction -three independent measurements

- **H1** – LRG method, tagged photoproduction, $E_T^{jet1(2)}$>5(4) GeV,
  S^2 = 0.5 ± 0.1 EPJC C51 (2007),549
- **H1** – LRG method, tagged photoproduction , $E_T^{jet1(2)}$>5(4) GeV,
  S^2 = 0.58 ±0.01±0.12(exp) ±0.14±0.09(th) EPJ C68 (2010),381
- **ZEUS** – LRG method, untagged photoproduction $E_T^{jet1(2)}$>7.5(6.5) GeV
  S^2 ~ 1 Nucl.Phys. B381 (2010)

Diffractive dijet production in DIS

New measurement with 6x larger statistics than previous measurements, LRG method, $E_T^*{}_{jet1(2)}$>5.5(4) GeV, sophisticated unfolding procedure

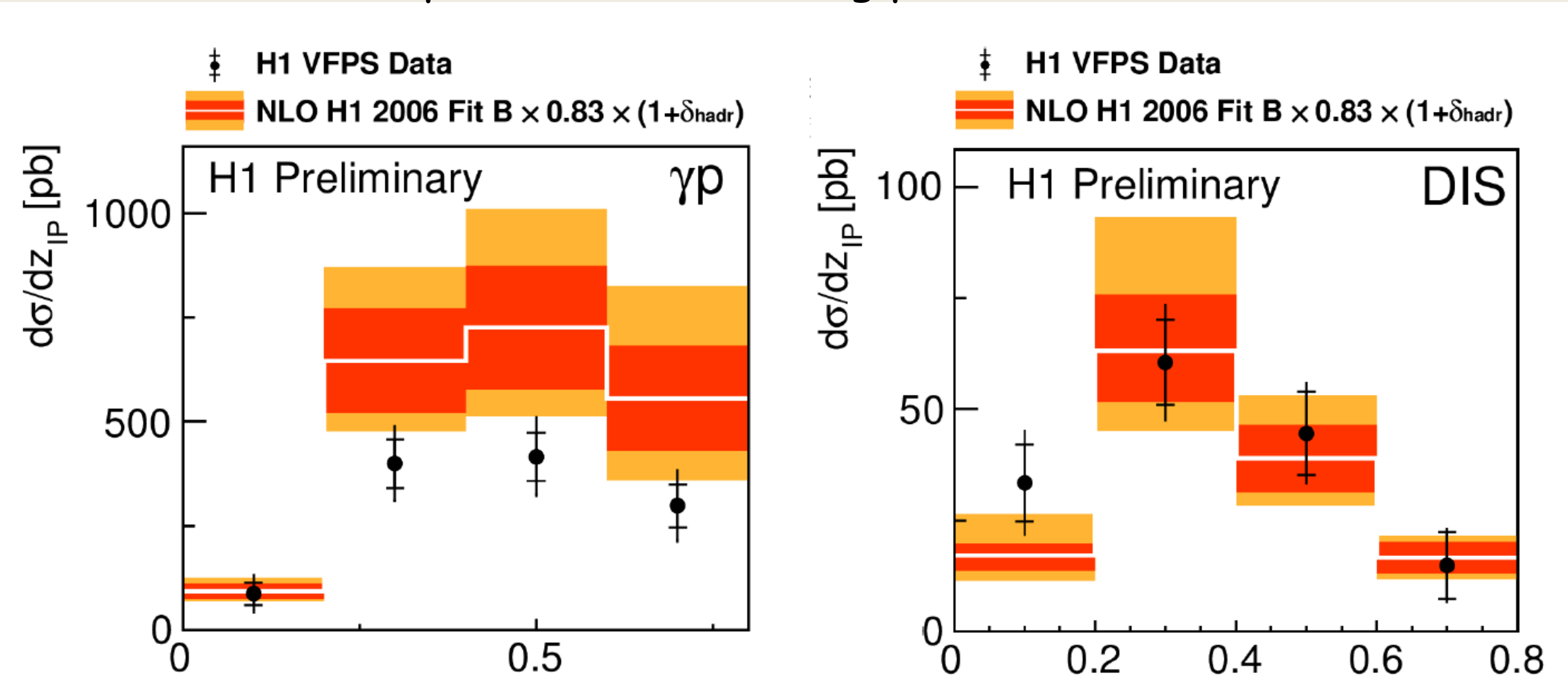




Measurements in agreement with NLO QCD calculations, factorisation confirmed.

Diffractive dijet photoproduction & DIS

New measurement – proton measured in Very Forward Proton Spectrometer
$E_T^{jet1(2)}$>5.5(4) GeV, sophisticated unfolding procedure

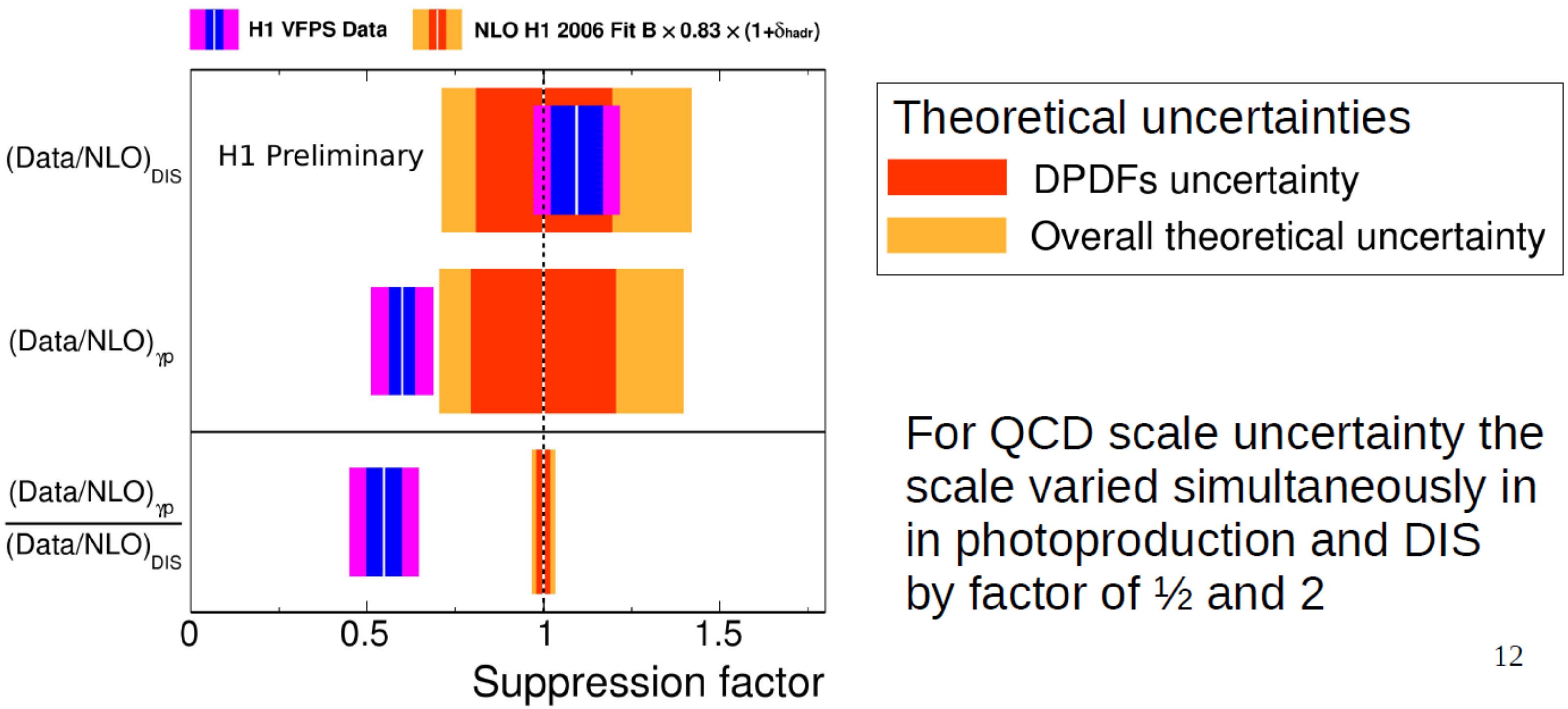


Photoproduction DIS

DIS – measurements described by NLO QCD calculations
Photoproduction – data suppressed in comparison with NLO QCD

Diffractive dijet production - double ratio

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

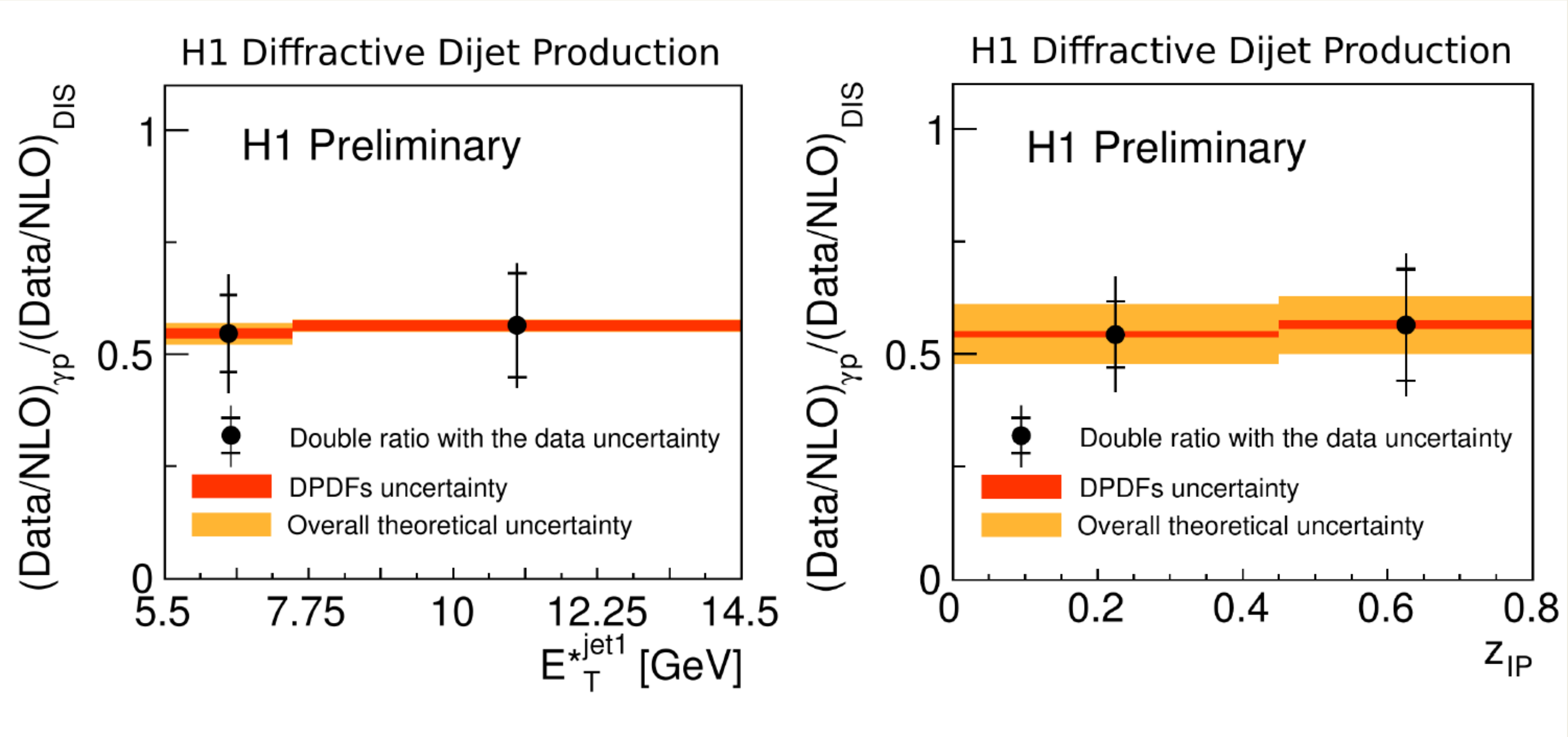


For QCD scale uncertainty the scale varied simultaneously in in photoproduction and DIS by factor of ½ and 2

12

Previous H1 measurements confirmed, factorisation breaking in diffractive dijet photoproduction established

Diffractive dijet production - double ratio



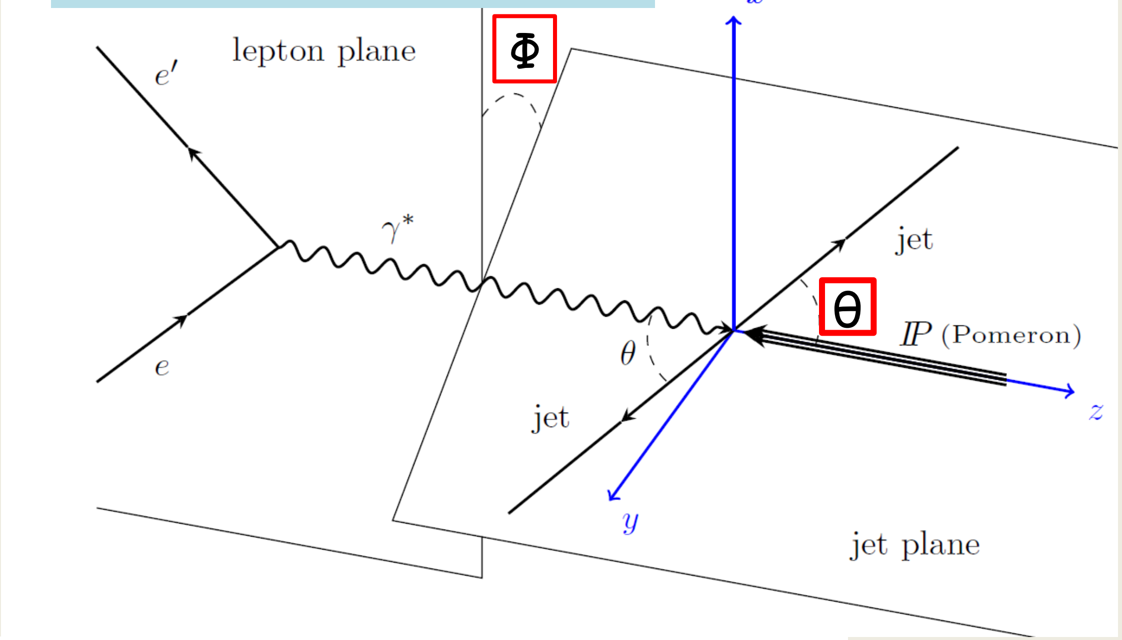
Double ratio photoproduction/DIS

Dependence of the suppression on E_T of the leading jet and z_{IP} not observed!

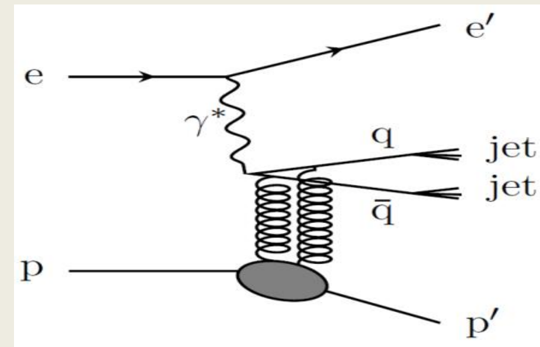
Diffractive dijet production in γ*IP CMS

How to distinguish between diffractive models???

$e + p \rightarrow e' + p' + jet + jet$



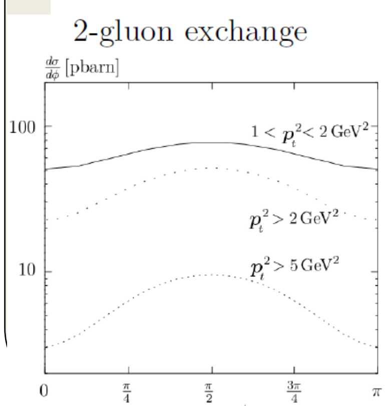
Two gluon exchange model

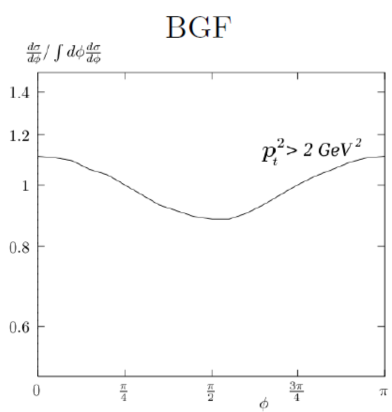


J.Bartels et al.,Phys.Lett.B386,389

Φ – angle between lepton and jet planes

Θ – polar angle of jet





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

- Two gluon exchange – negative A
- Boson-gluon fusion - positive A

Diffractive dijet production in γ^*IP CMS

Kinematic region

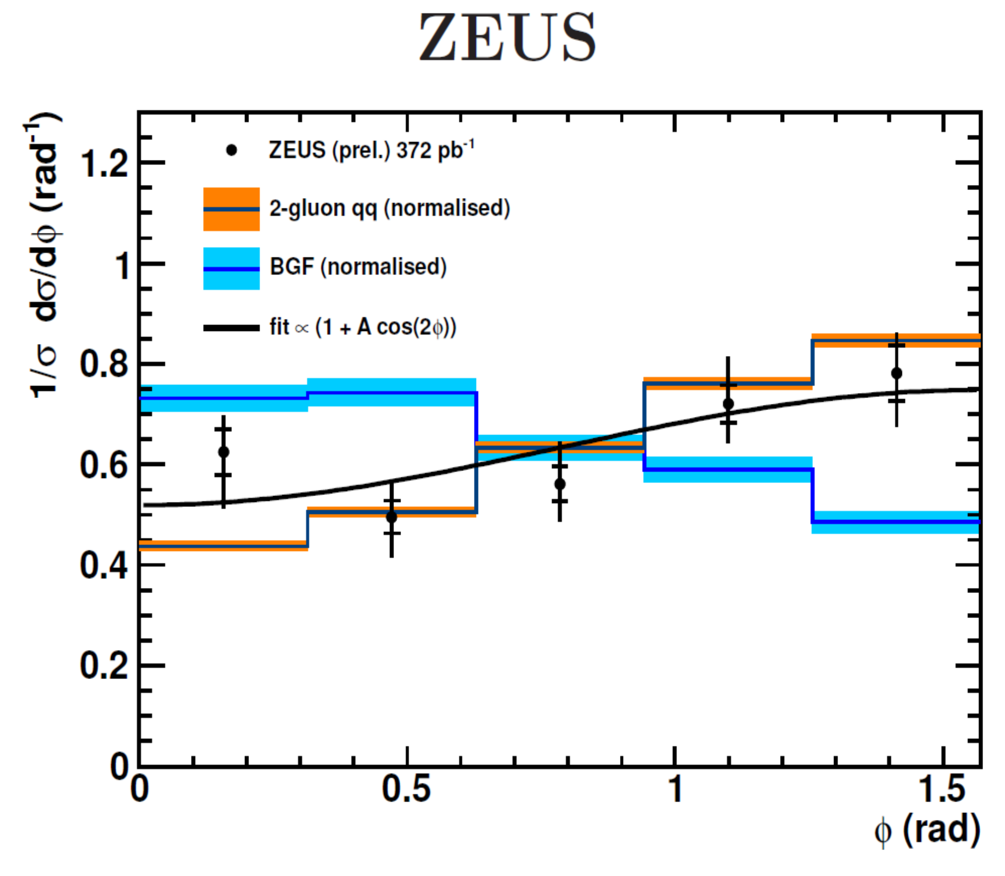
$$
\begin{aligned}
90\ \mathrm{GeV} < & \ W & < 250\ \mathrm{GeV} \\
25\ \mathrm{GeV}^2 < & \ Q^2 & \\
& \ x_{IP} & < 0.01 \\
0.5 < & \ \beta & < 0.7 \\
& \ n_{jets} & = 2 \\
2\ \mathrm{GeV} < & \ p_{T\ jet} &
\end{aligned}
$$

LRG selection of diffraction

- Jet finder – exclusive k_t jet algorithm
- For corrections model SATRAP used (method of singular value decomposition with regularisation – NIM, A372 (1996),469)
- Unfolded data compared to :

2-gluon exchange model – RAPGAP 3.01/26
Boson-Gluon-Fusion model (resolved pomeron) - RAPGAP 3.01/26

Diffractive dijet production in γ*IP CMS



Fit

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

	A
fit	$-0.18 \pm 0.06(\text{stat.})^{+0.06}_{-0.09}(\text{sys.})$
2-gluon(qq) MC	$-0.34 \pm 0.01(\text{stat.})$
BGF MC	$0.21 \pm 0.02(\text{stat.})$

- Negative A favours two gluon exchange model
- None of the models are able to describe the normalisation of x-section

Conclusions

- H1 and ZEUS combined inclusive cross section measured with forward proton spectrometers in DIS published ➔ EPJC C72 (2012),2175
- **HERA data available for comparison with models**
- New H1 measurement of diffractive dijet production in DIS → **measurements described by NLO QCD predictions using H1 DPDF**
- New H1 measurement of diffractive photoproduction and DIS dijets with VFPS proton spectrometer → **suppression factor 0.55 ± 0.1 in photoproduction observed, consistent with factorisation breaking!**
- The shape of the azimuthal angular distributions of exclusive dijets in diffractive DIS has been measured by ZEUS for the first time → **the data prefer 2-gluon exchange model of $q\bar{q}$ production over Boson Gluon Fusion model.**