

Low x & diffraction at HERA



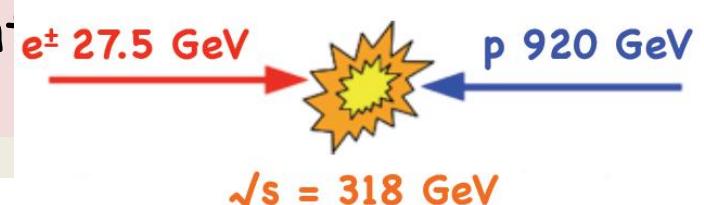
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Charles University, Prague



on behalf of H1 and ZEUS Collaborations

HERA collider experiments

- 27.5 GeV electrons/positrons on 920 GeV protons $\rightarrow \sqrt{s} = 318$ GeV
- data taken in 1992-2007
- HERA I,II: ~ 500 pb $^{-1}$ per experiment
- H1 & ZEUS - 4π detectors



Why to study diffraction?

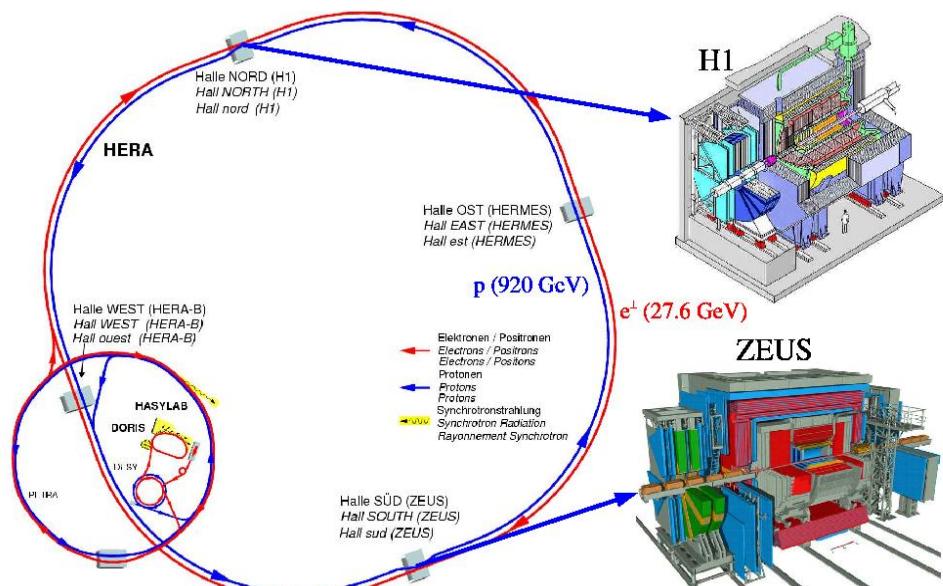
Fundamental aim:

understand high energy limit of QCD

Novelty:

probe partonic structure of diffractive exchange

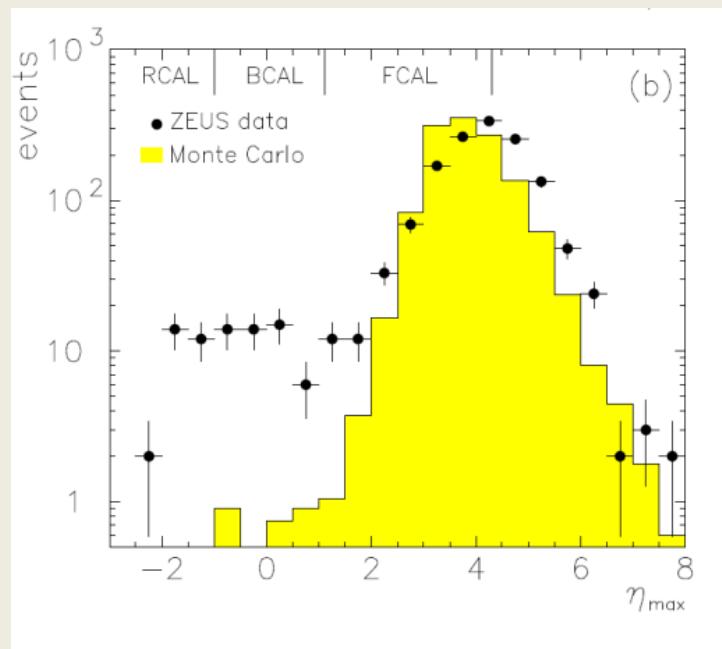
Applications: study factorisation properties, transport PDFs to pp scattering (Tevatron, LHC).



Historical reminder

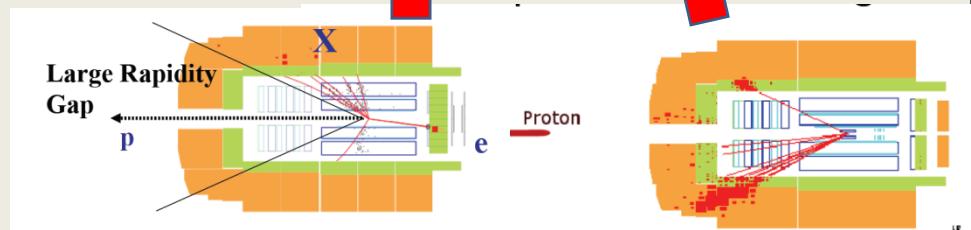
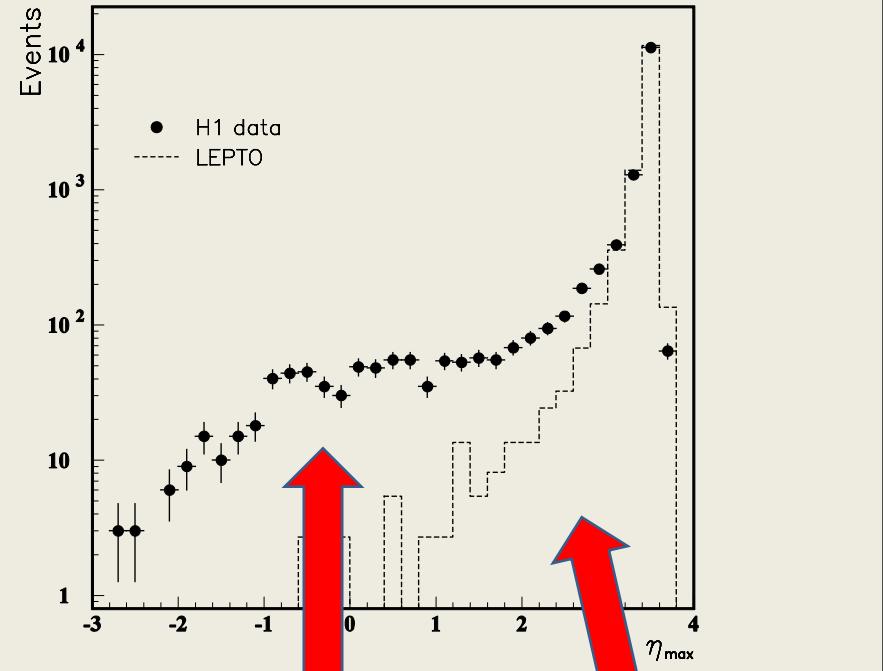
- **21 years** after the observation of diffractive DIS events at HERA!
- **HERA opened new era of diffraction studies**

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



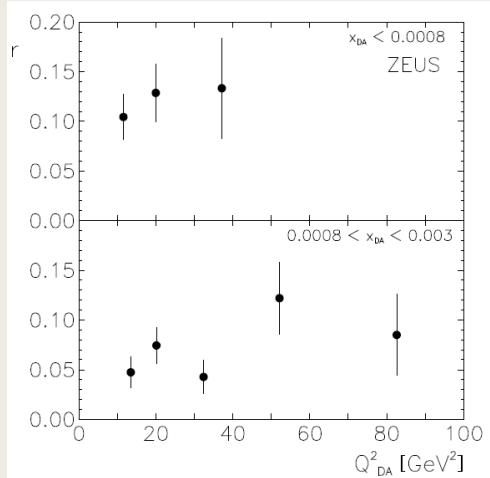
1993-1994

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



24.6.2014

Historical reminder



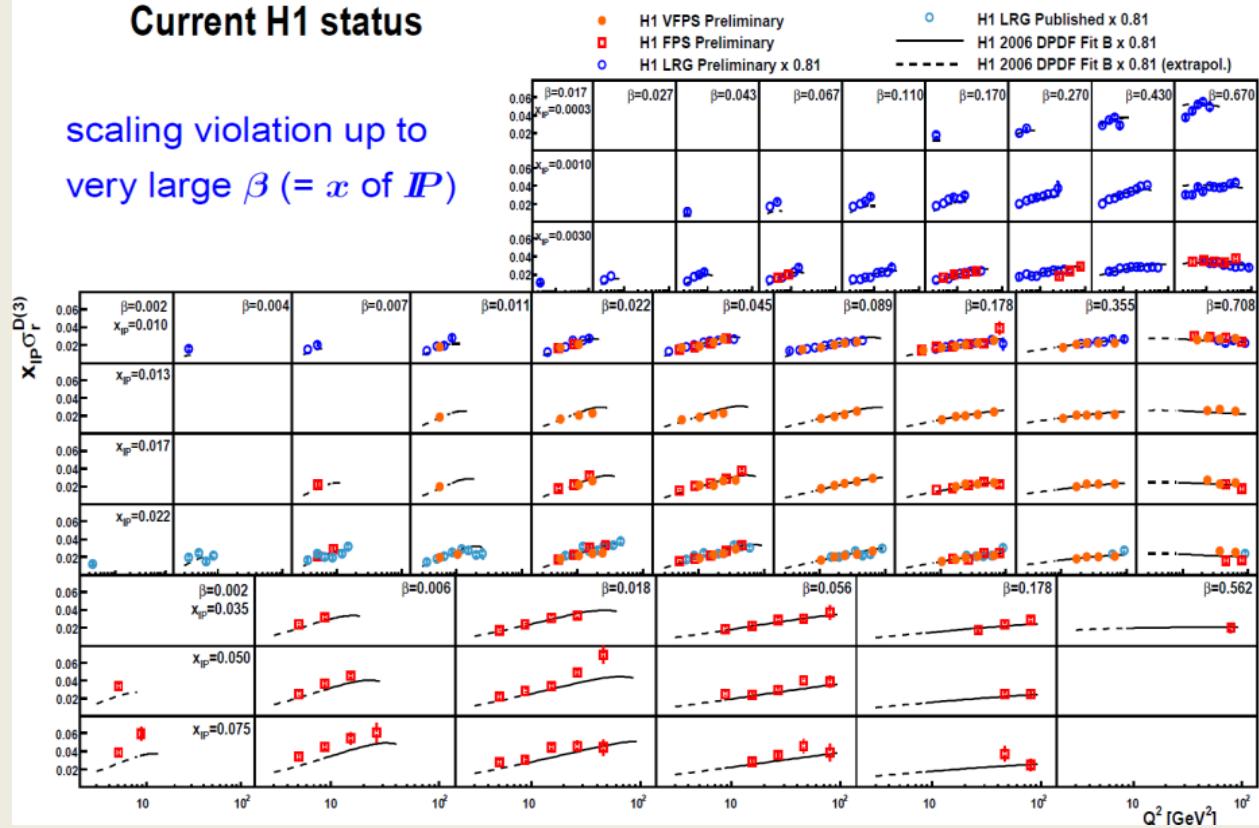
2014

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

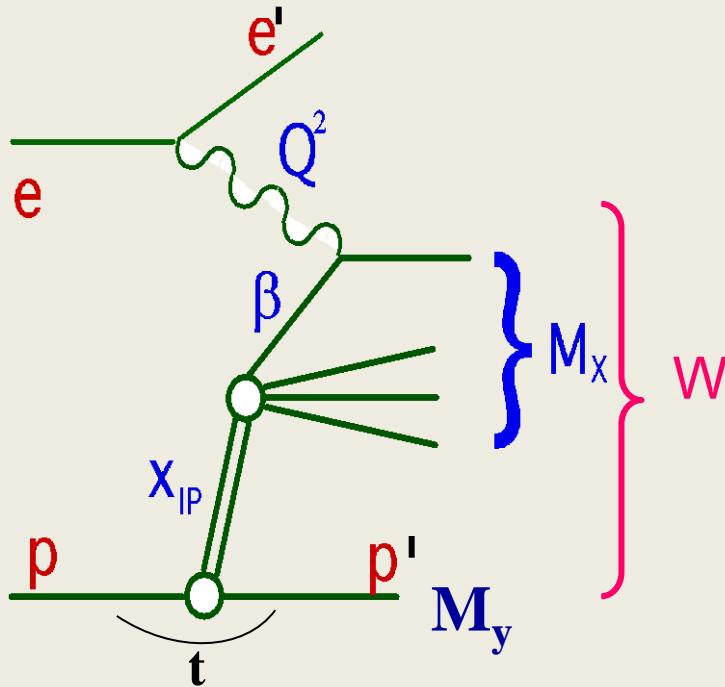
1993

Current H1 status

scaling violation up to
very large β (= x of IP)



Diffractive kinematics



$M_y = m_p$ 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)

$Q^2 \sim 0 \text{ GeV}^2 \rightarrow$ photoproduction
 $Q^2 \gg 0 \text{ GeV}^2 \rightarrow$ deep inelastic scattering (DIS)

HERA: $\sim 10\%$ of events diffractive

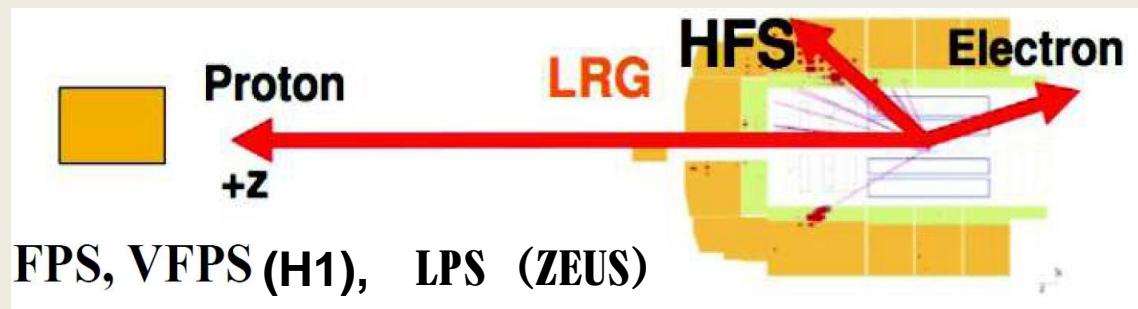
$$x_{IP} = \xi = \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

momentum fraction of color singlet exchange

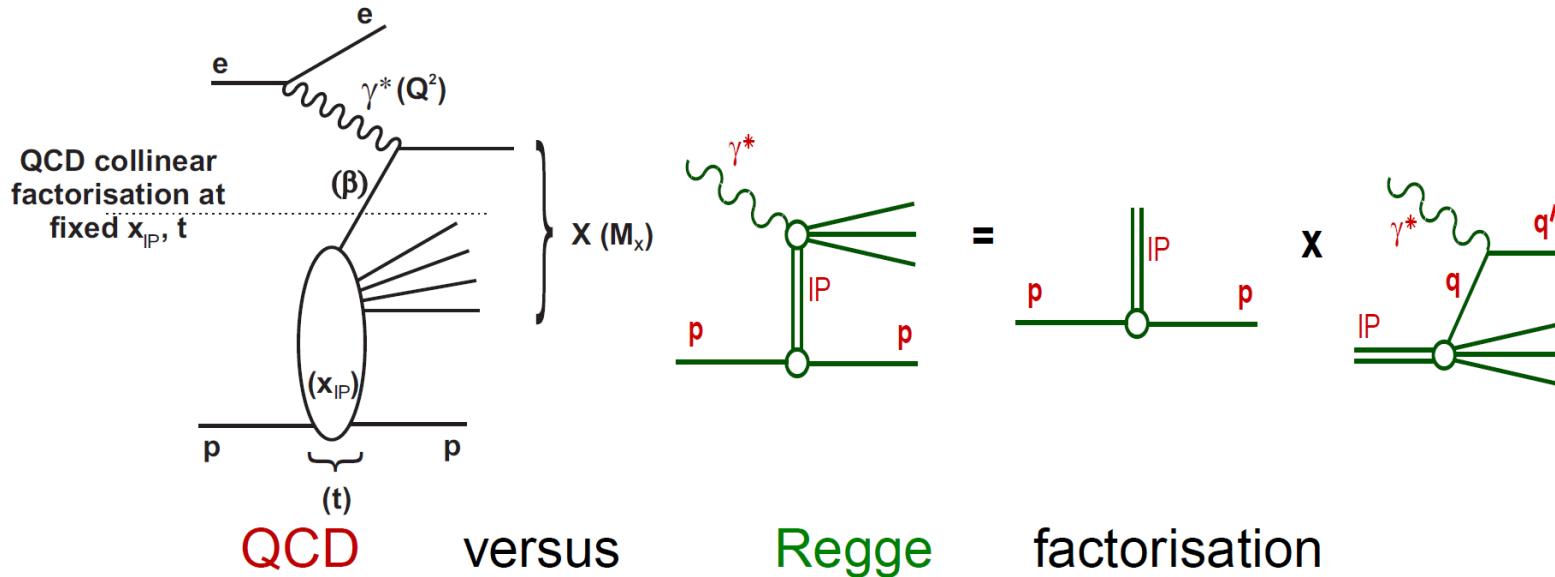
$$\beta = \frac{Q^2}{Q^2 + M_X^2} = x_{q/IP} = \frac{x}{x_{IP}}$$

fraction of exchange momentum, coupling to γ

$$t = (p - p')^2 \quad \longrightarrow \quad \text{4-momentum transfer squared}$$



Factorisation properties of diffraction



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

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

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

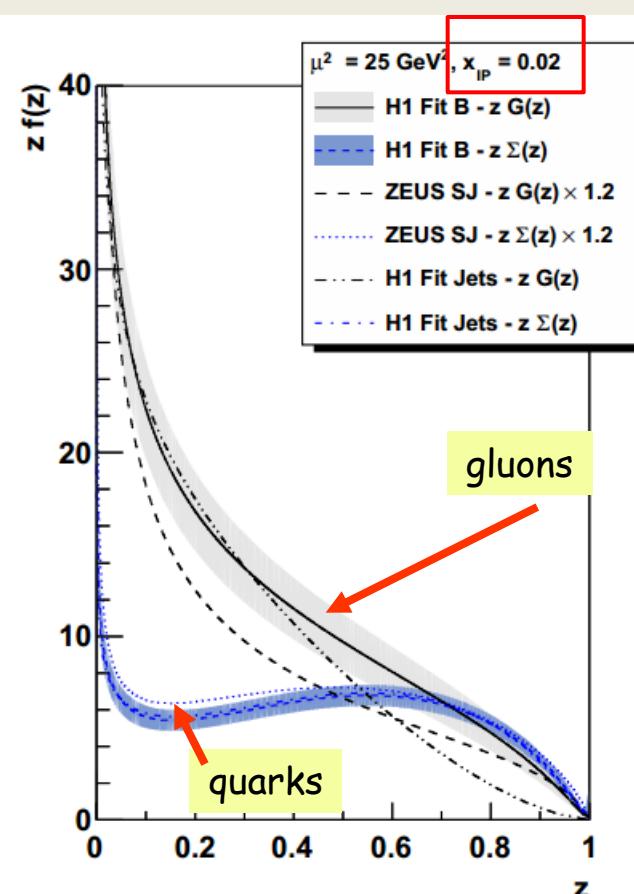
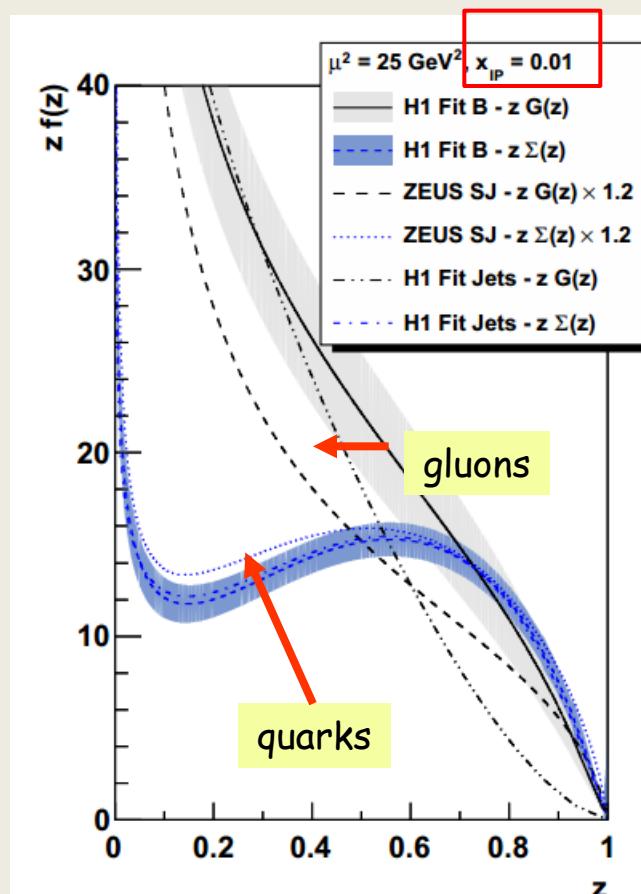
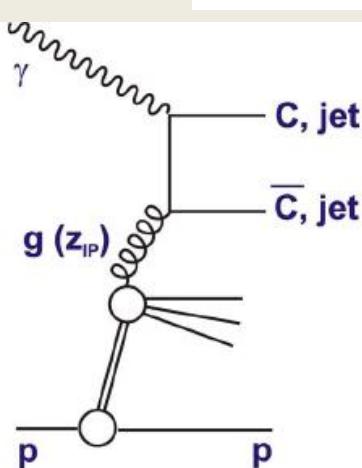
DPDFs in DIS

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 $\rightarrow F_2^D$

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

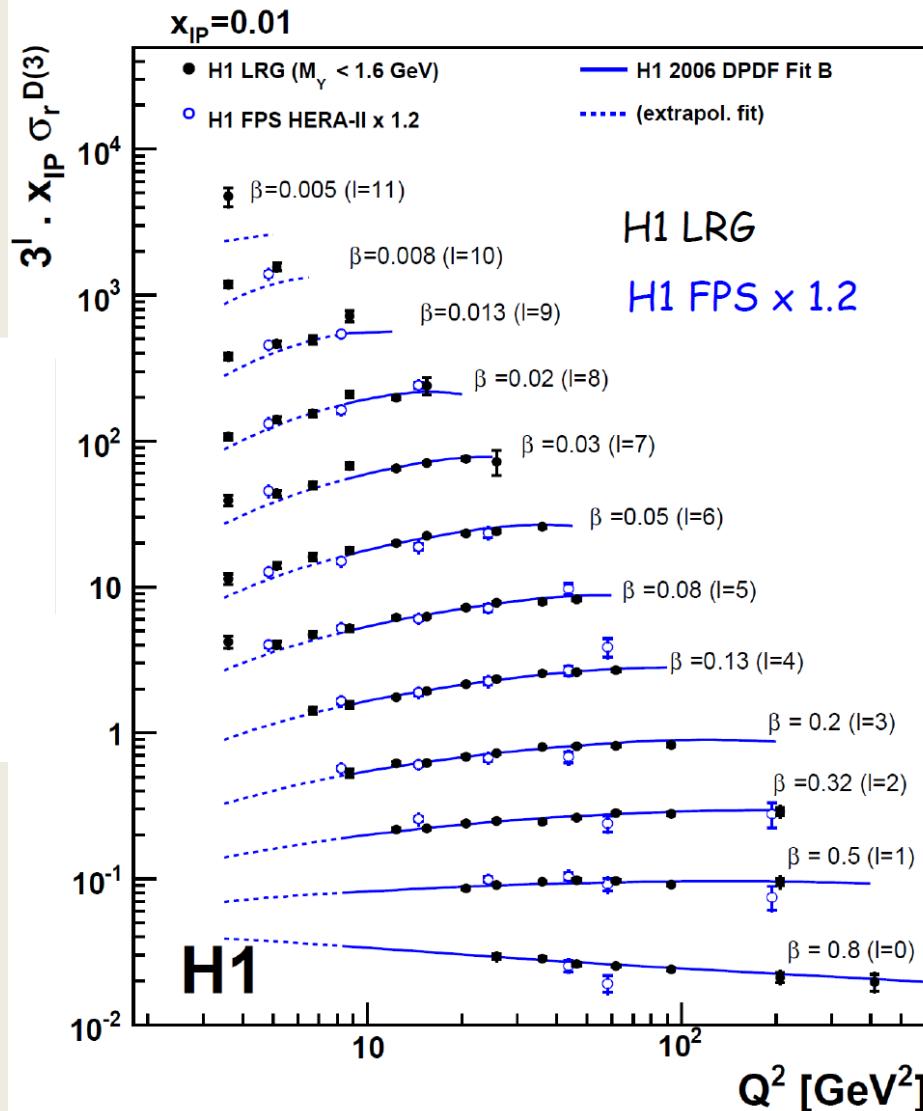
$\sigma_R^{D(4)}$ \rightarrow diffractive reduced cross section γ - inelasticity $\rightarrow 1 - (E'_e/E_e)$ $\sigma_R^{D(4)} \approx F_2^{D(4)}$ at low and medium y

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

$$\sigma_R^{D(4)} = F_2^{D(4)} \quad \text{if} \\ F_L^{D(4)} = 0$$

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 :

$$\frac{\sigma(M_Y < 1.6 \text{ GeV})}{\sigma(Y = p)} =$$

$$\frac{1.203 \pm 0.019(\text{exp.}) \pm 0.087(\text{norm.})}{(1.6\%) \quad (7.2\%)}$$

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!



$$LPS/LRG = 0.76 \pm 0.01(\text{st}) \pm {}^{+0.03}_{-0.02}(\text{sy}) \pm {}^{+0.08}_{-0.05}(\text{norm})$$

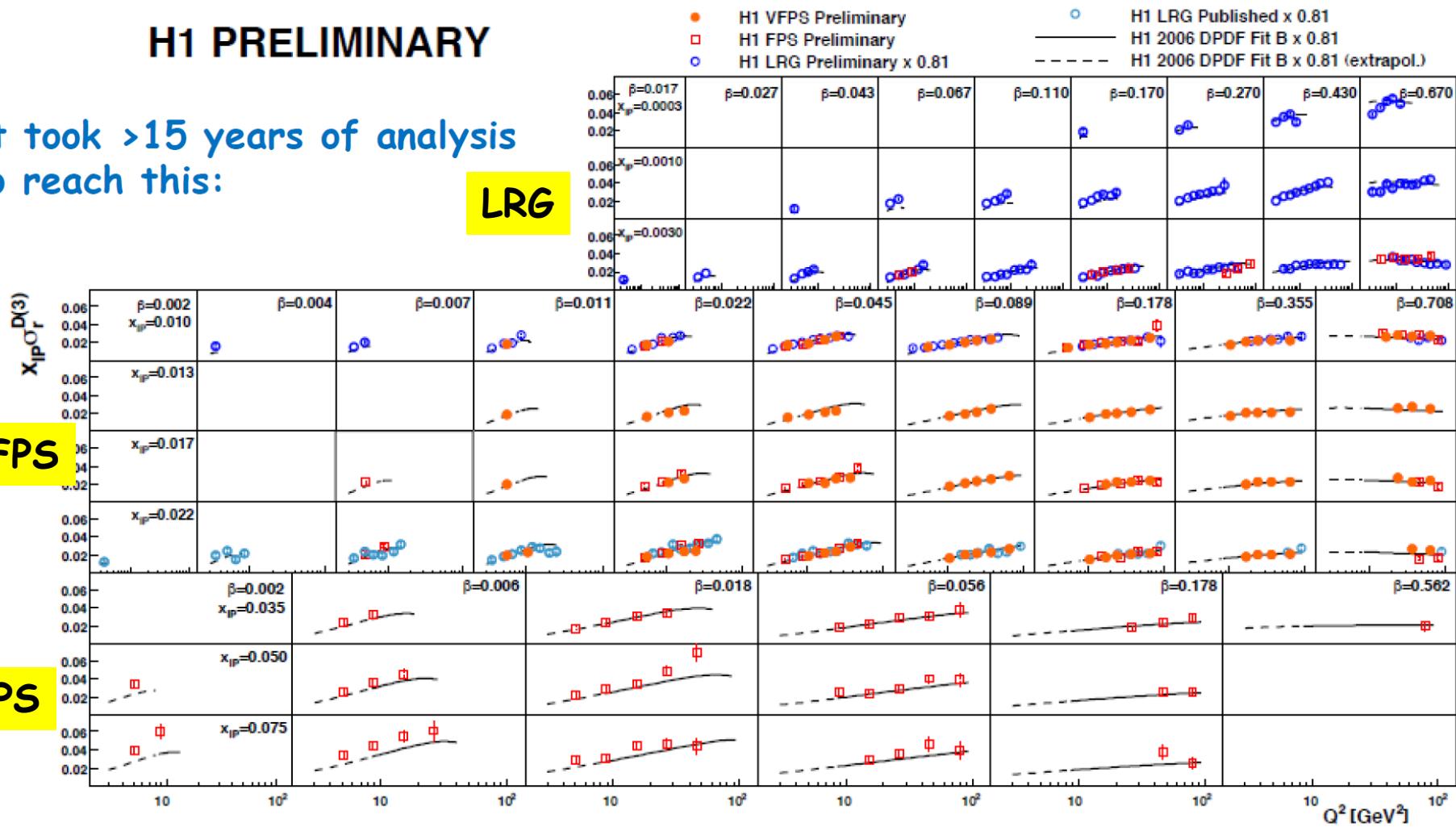
Experimental summary for H1 F_2^D



H1 PRELIMINARY

It took >15 years of analysis
to reach this:

LRG



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

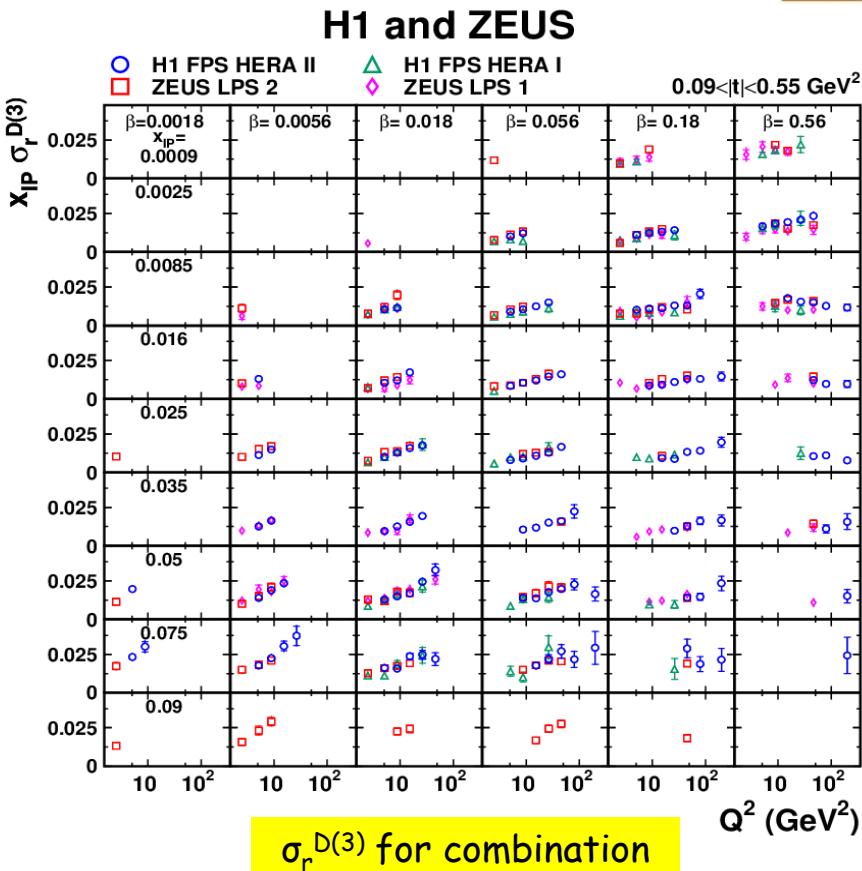
H1 FPS

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



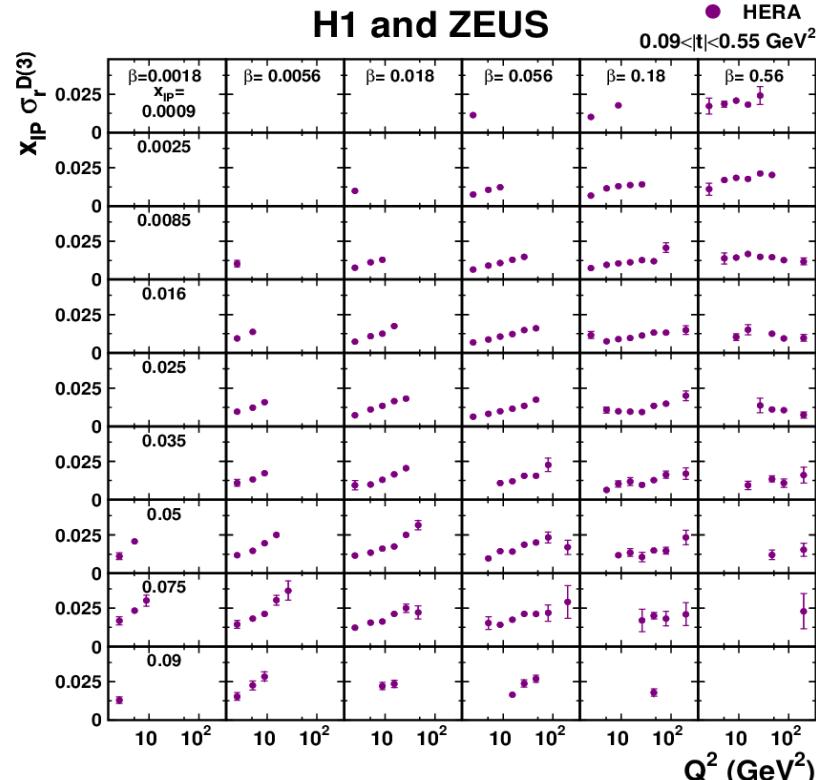
Kinematic range

$$Q^2 = 2.5 - 200 \text{ GeV}^2$$

$$\beta = 0.0018 - 0.816$$

$$x_{IP} = 0.00035 - 0.09$$

$$|t| = 0.09 - 0.55$$



Factorisation tests in diffractive dijet production

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

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

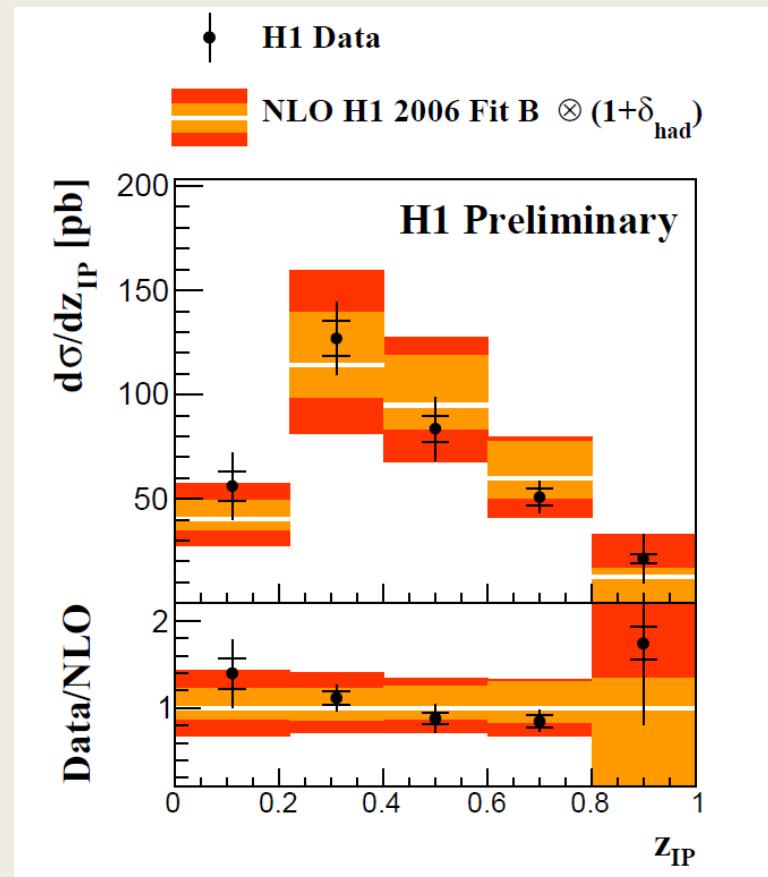
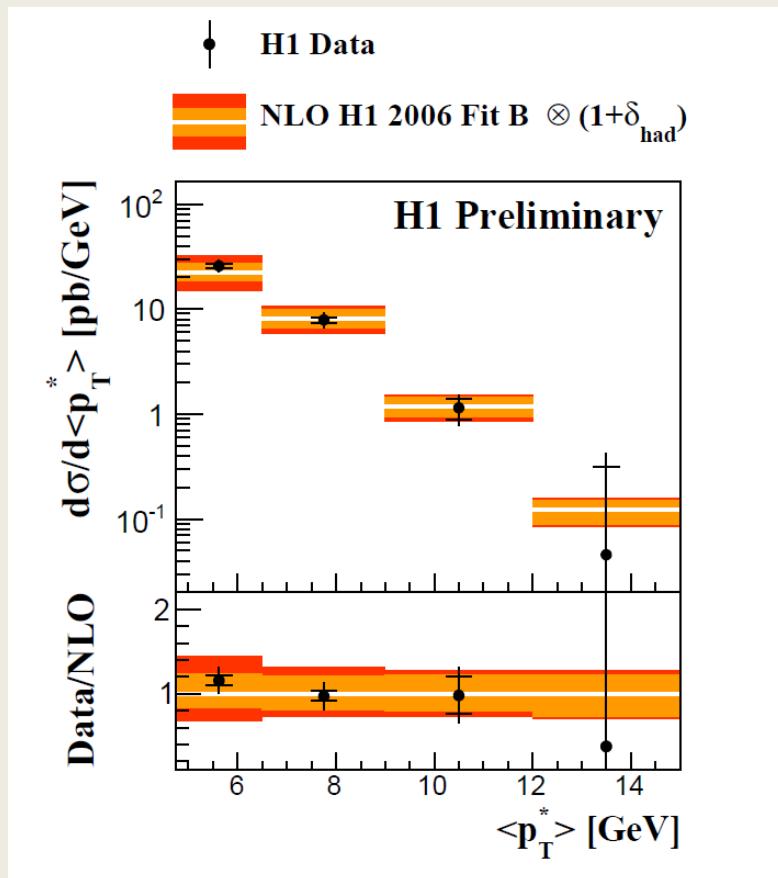
- **H1** - LRG method, tagged photoproduction, $E_T^{\text{jet}1(2)} > 5(4)$ GeV,
 $S^2 = 0.5 \pm 0.1$ EPJC C51 (2007), 549
- **H1** - LRG method, tagged photoproduction , $E_T^{\text{jet}1(2)} > 5(4)$ GeV,
 $S^2 = 0.58 \pm 0.01 \pm 0.12(\text{exp}) \pm 0.14 \pm 0.09(\text{th})$ EPJ C68 (2010), 381
- **ZEUS** - LRG method, untagged photoproduction $E_T^{\text{jet}1(2)} > 7.5(6.5)$ GeV
 $S^2 \sim 1$ 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

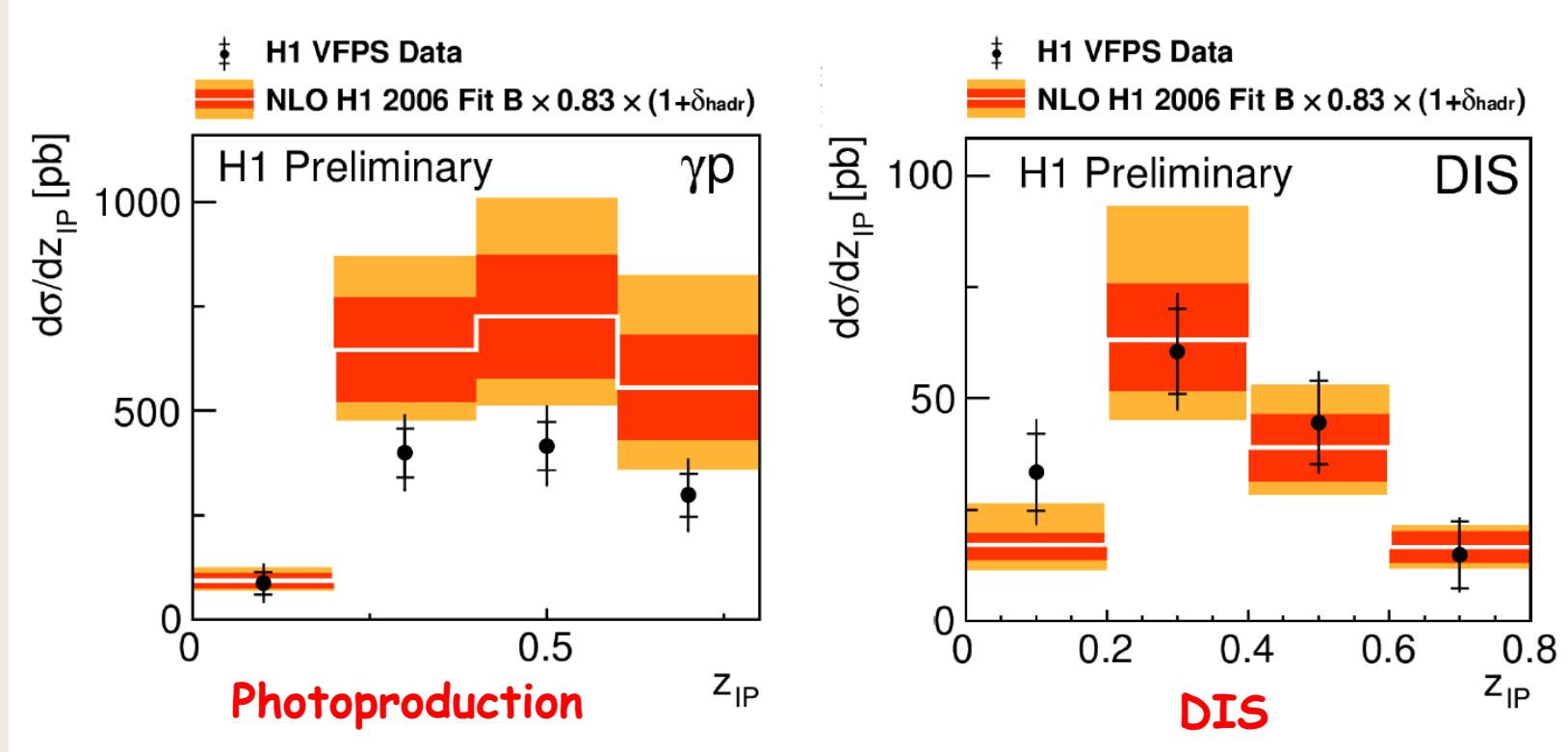


Measurements in agreement with NLO QCD calculations, factorisation confirmed.

Diffractive dijet photoproduction & DIS



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



DIS -

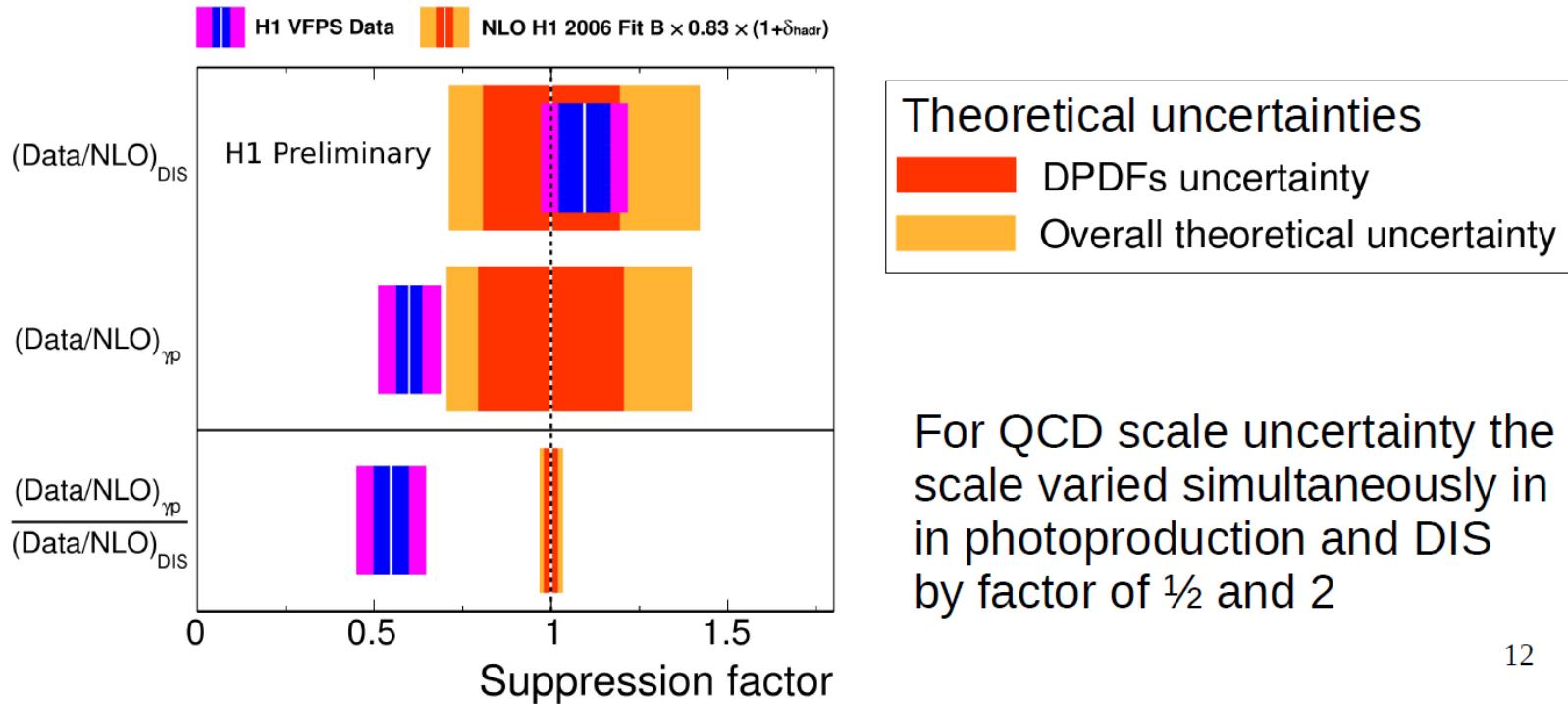
measurements described by NLO QCD calculations

Photoproduction - data suppressed in comparison with NLO QCD

Diffractive dijet production - double ratio



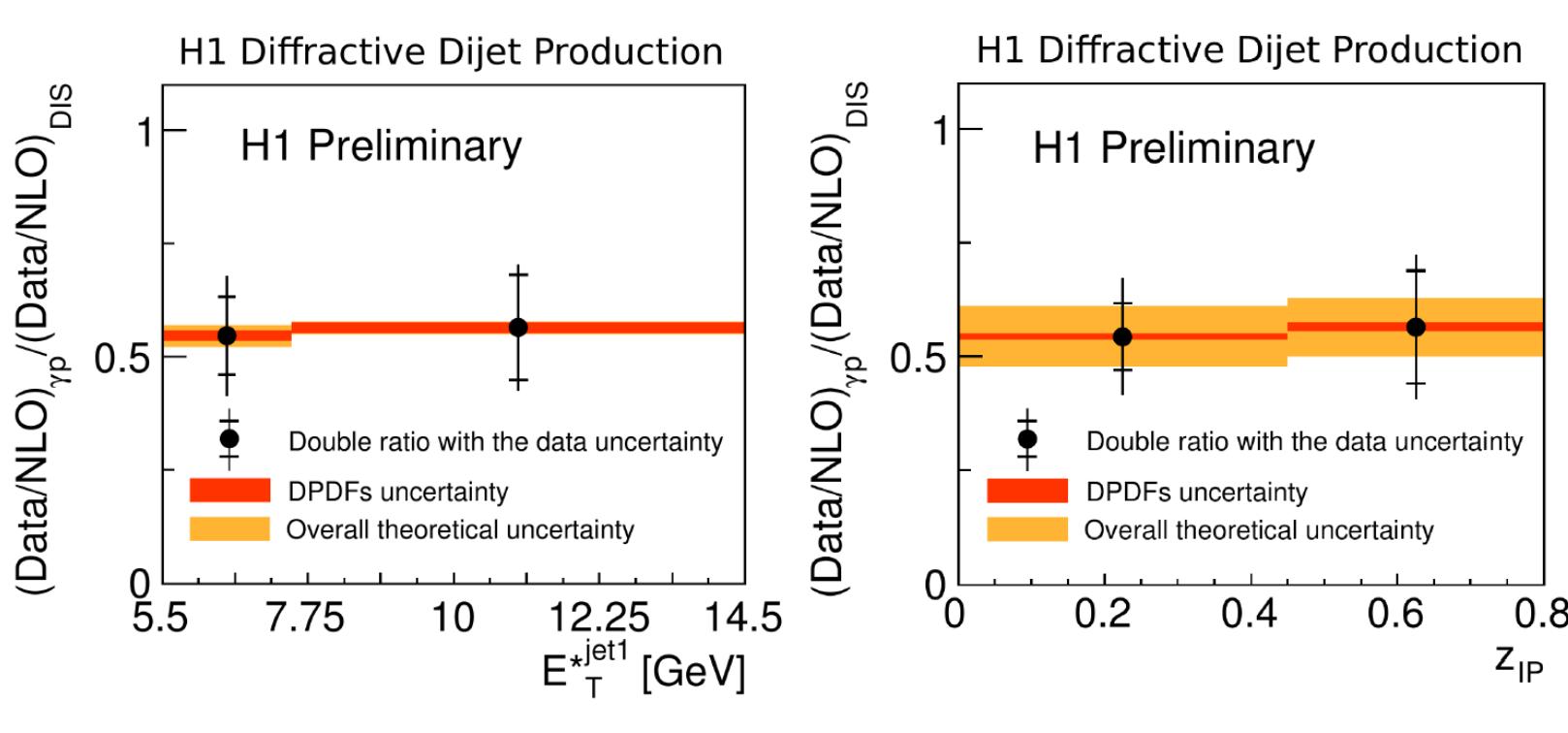
$$\frac{(\text{DATA/NLO})_{\gamma p}}{(\text{DATA/NLO})_{\text{DIS}}} = 0.55 \pm 0.10 \text{ (data)} \pm 0.02 \text{ (theor.)}$$



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

Diffractive dijet production - double ratio



Double ratio photoproduction/DIS

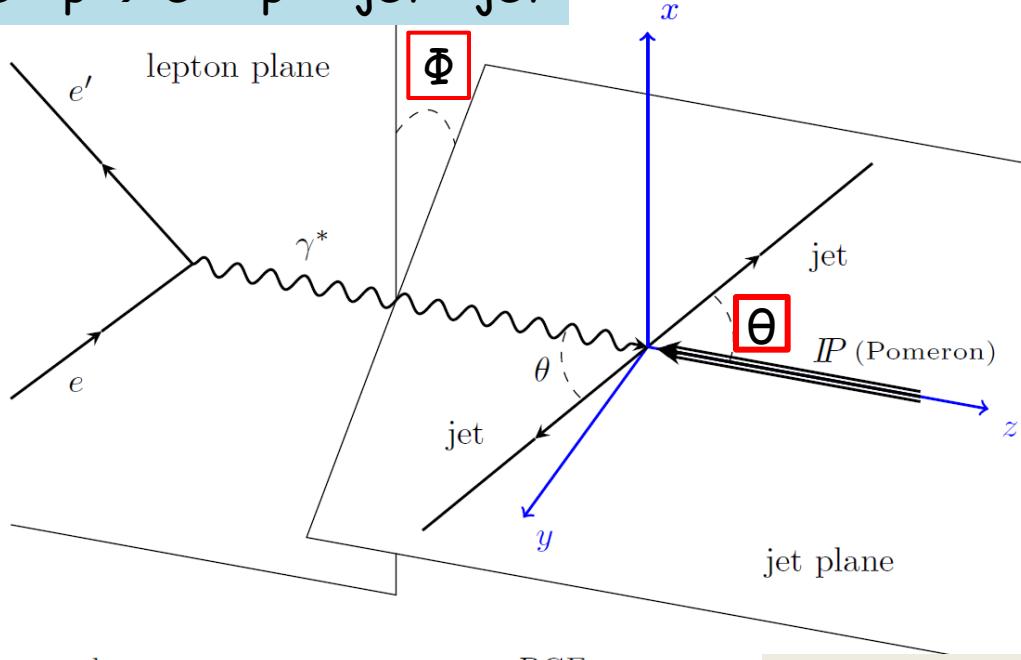
Dependence of the suppression on E_T of the leading jet and z_{IP} not observed!

Diffractive dijet production in $\gamma^* p$ CMS

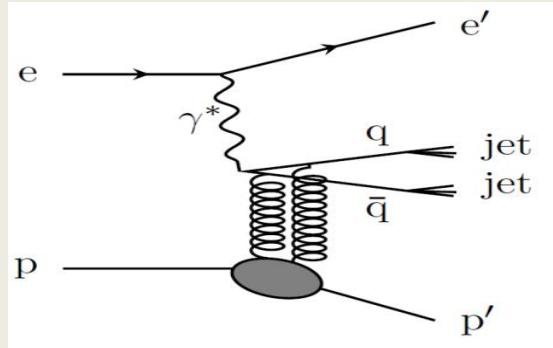


How to distinguish between diffractive models???

$$e + p \rightarrow e' + p' + \text{jet} + \text{jet}$$



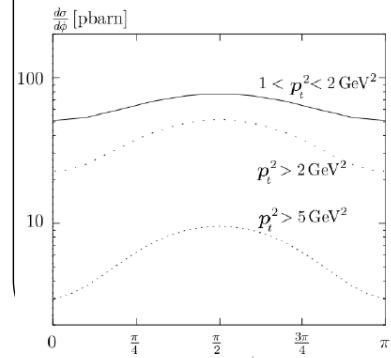
Two gluon exchange model



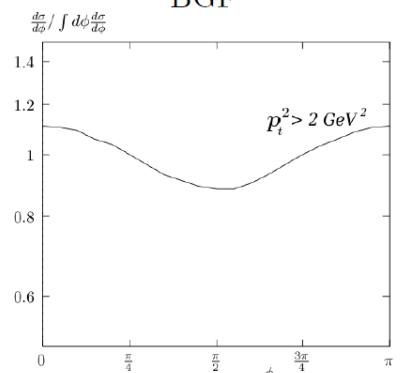
J.Bartels et al., Phys.Lett.B386,389

Φ - angle between lepton and jet planes
 Θ - polar angle of jet

2-gluon exchange



BGF



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

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

24.6.2014

Kinematic region

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

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 :

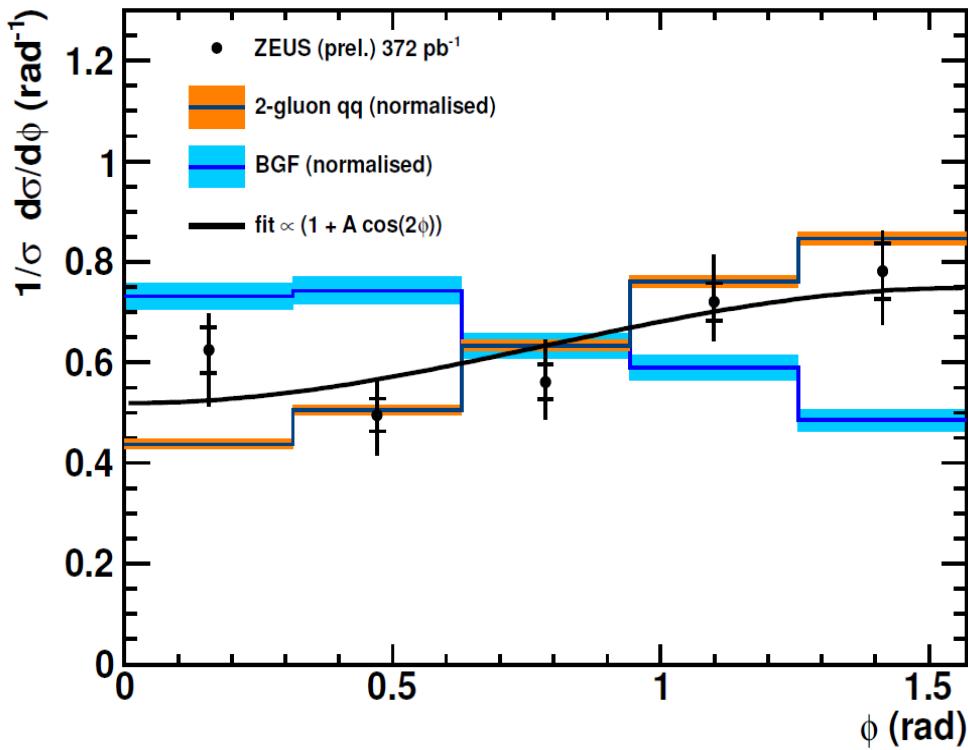
2-gluon exchange model - RAPGAP 3.01/26

Boson-Gluon-Fusion model (resolved pomeron) - RAPGAP 3.01/26

Diffractive dijet production in $\gamma^* p\bar{p}$ CMS



ZEUS



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	$0.21 \pm 0.02(\text{stat.})$

2-gluon(qq) MC

BGF MC

fit

- 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.