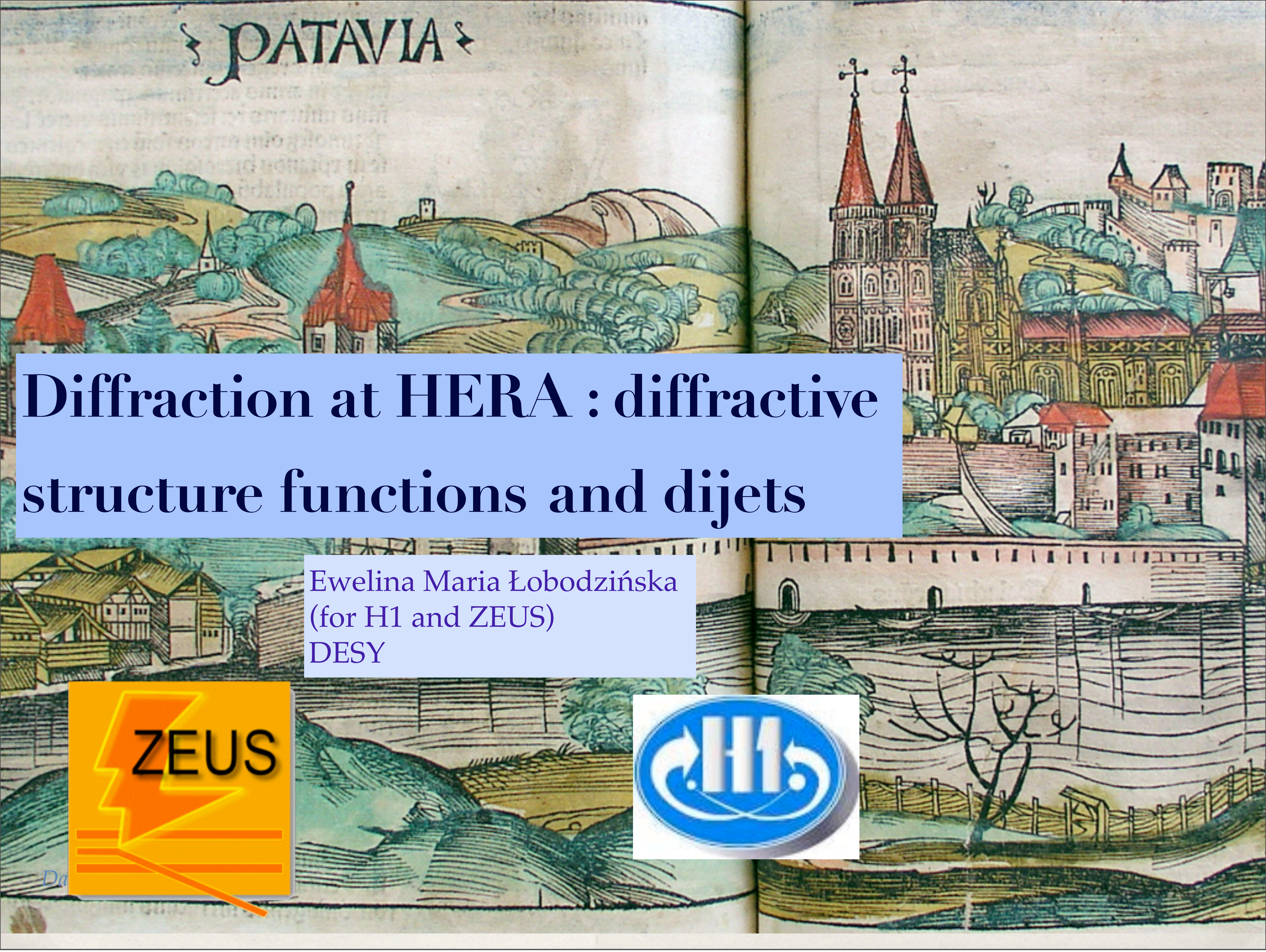
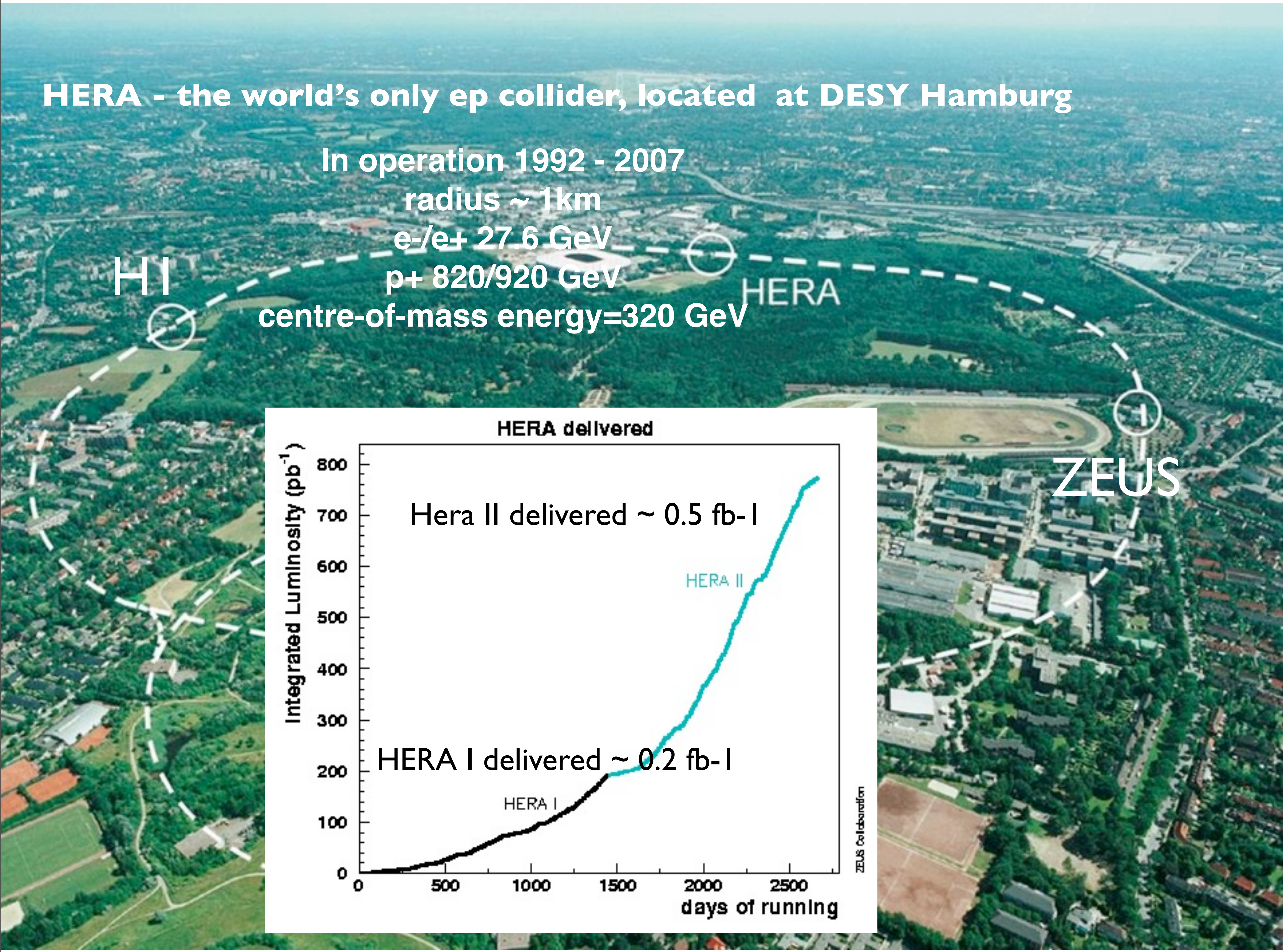


Diffraction at HERA : diffractive structure functions and dijets

Ewelina Maria Łobodzińska
(for H1 and ZEUS)
DESY

HERA - the world's only ep collider, located at DESY Hamburg

In operation 1992 - 2007
radius ~ 1km
e-/e+ 27.6 GeV
p+ 820/920 GeV
centre-of-mass energy=320 GeV



Hera II delivered ~ 0.5 fb-1

HERA I delivered ~ 0.2 fb-1

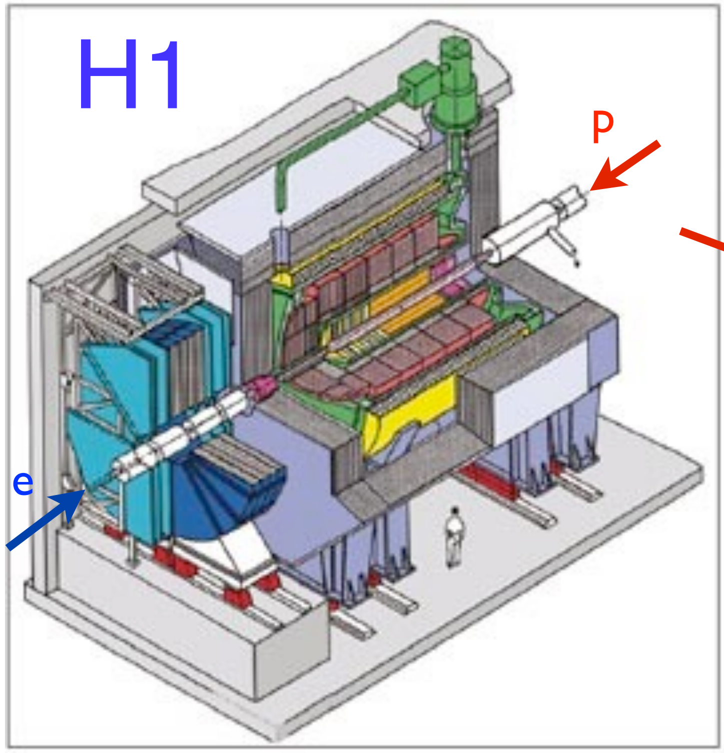
H1 and ZEUS experiments

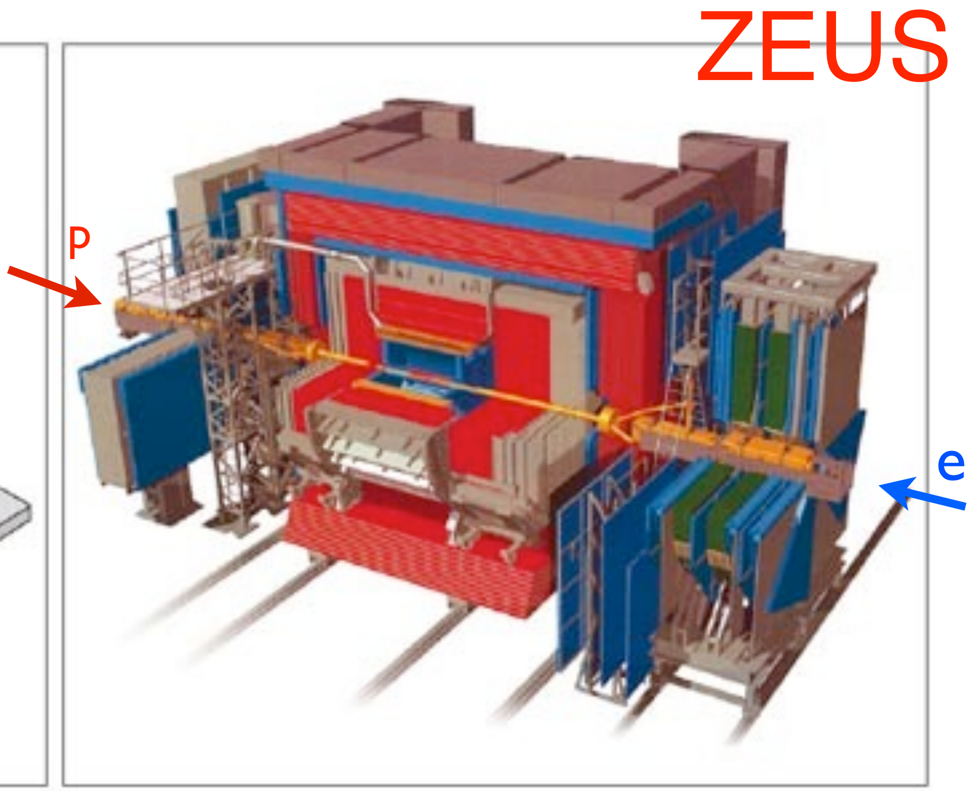
Each experiment collected lumi ~ 0.5 fb-1
10% of events are diffractive

asymmetric detectors, prepared to see more activity in the forward region

cylindrical around the beam axis

4π hermetic





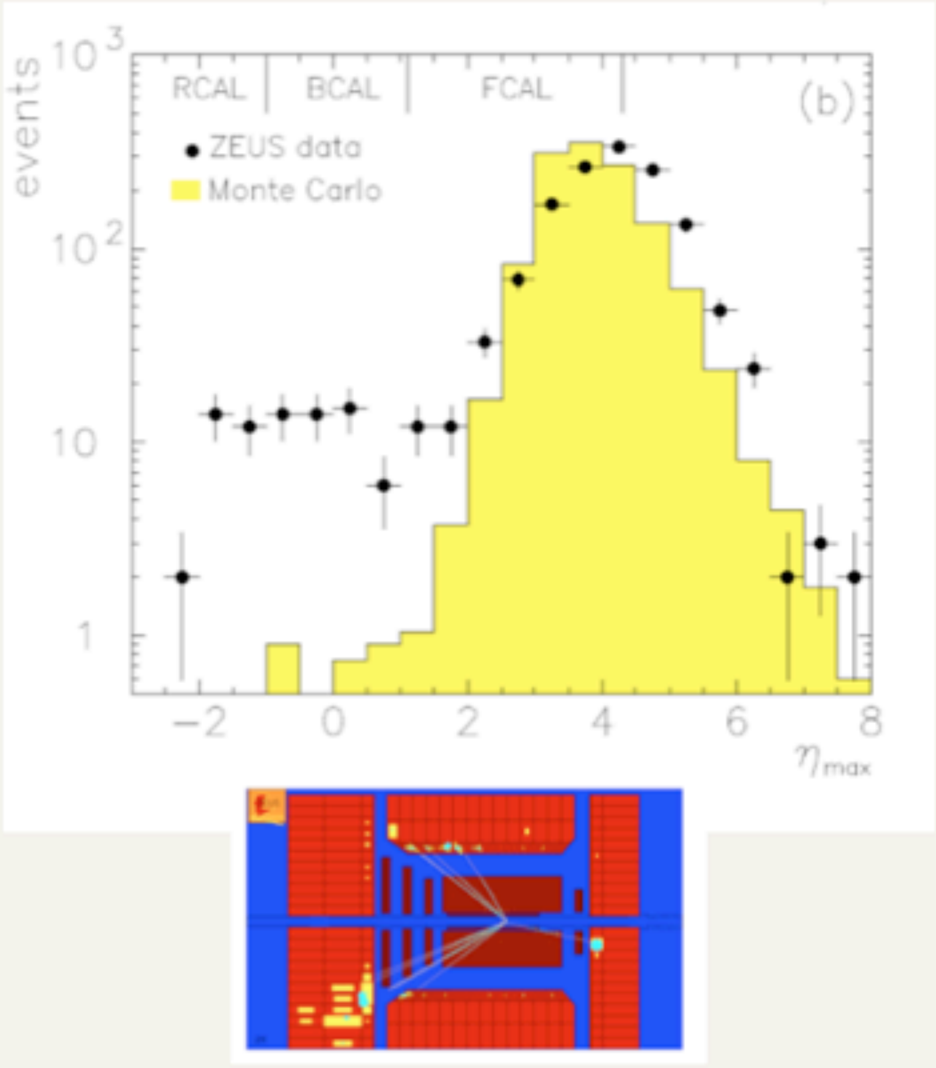
Diffraction at HERA - history

For the first time the diffraction was observed at HERA in 1993

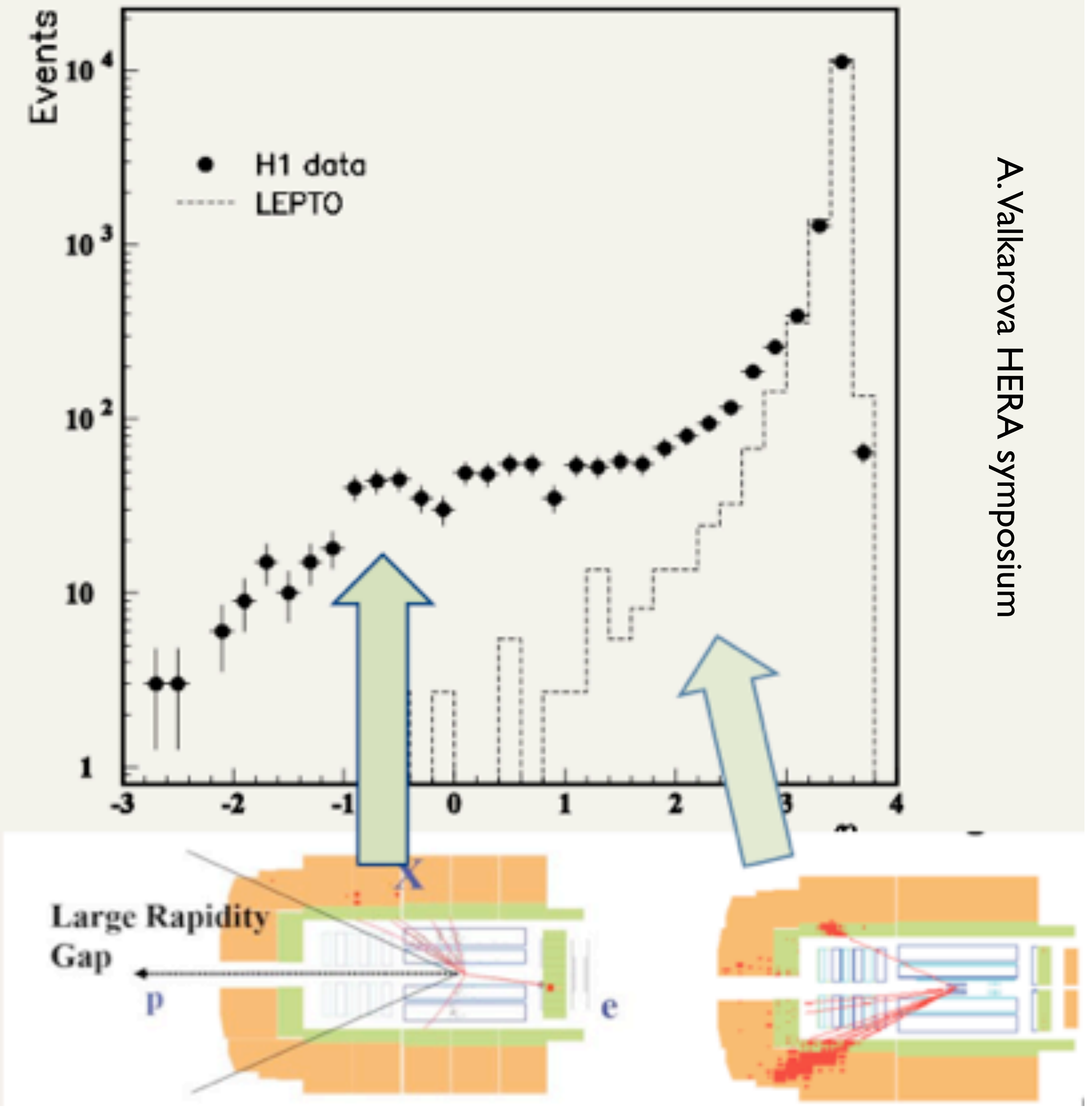
21 years studies of diffraction at HERA !

1993-1994

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



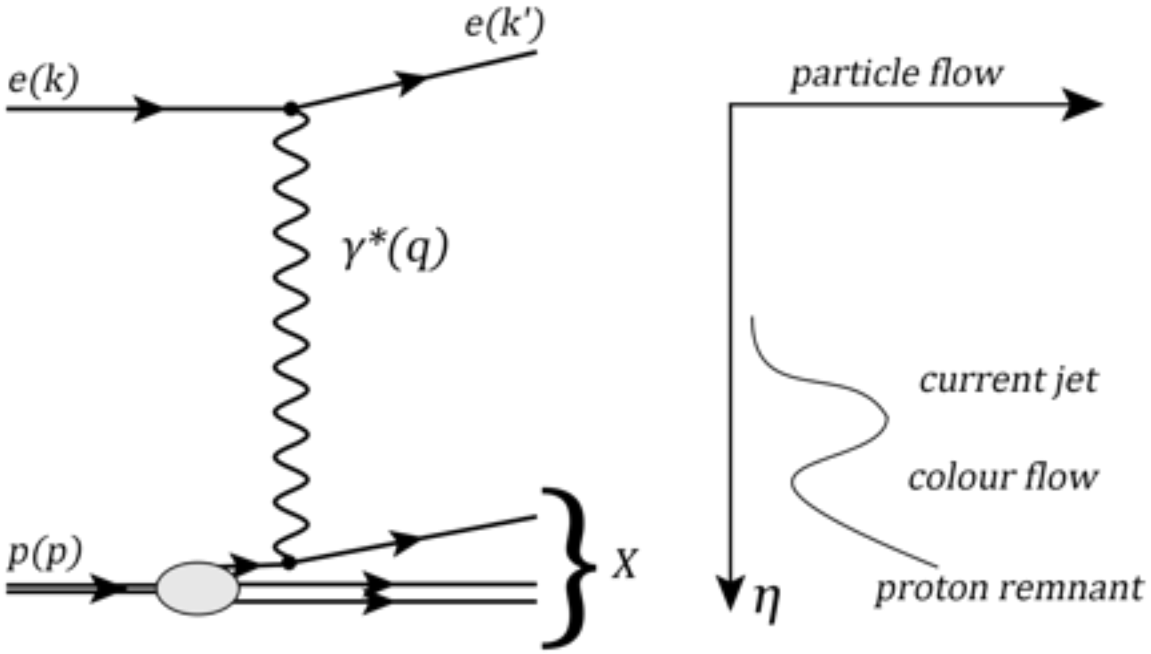
H1 Collab., Nucl. Phys. B429 (1994) 477



A.Valkarova HERA symposium

(D)DIS kinematics

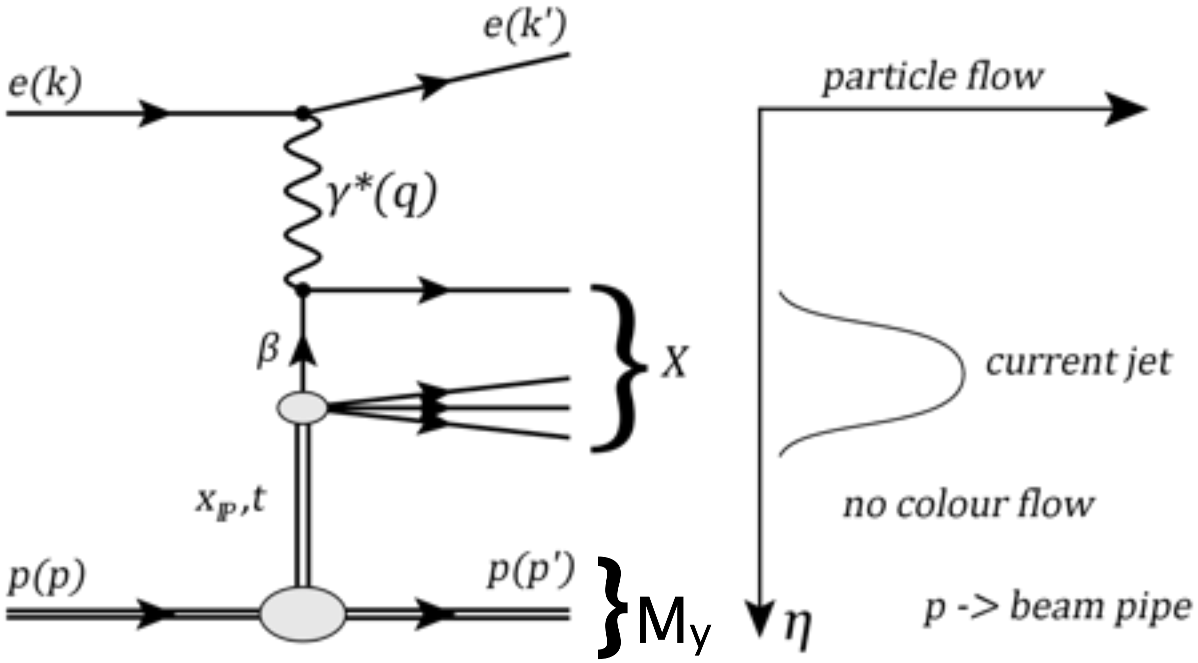
Deep inelastic scattering (DIS)



$Q^2 = -q^2$ virtuality of the photon
$Q^2 \sim 0$ photoproduction $Q^2 >> 0$ DIS
$\sqrt{s}$ centre-of-mass energy
W photon-proton CME
x Bjorken-x: fraction of proton's momentum carried by struck quark
y = Pq/Pk inelasticity

$s = Q^2 xy$

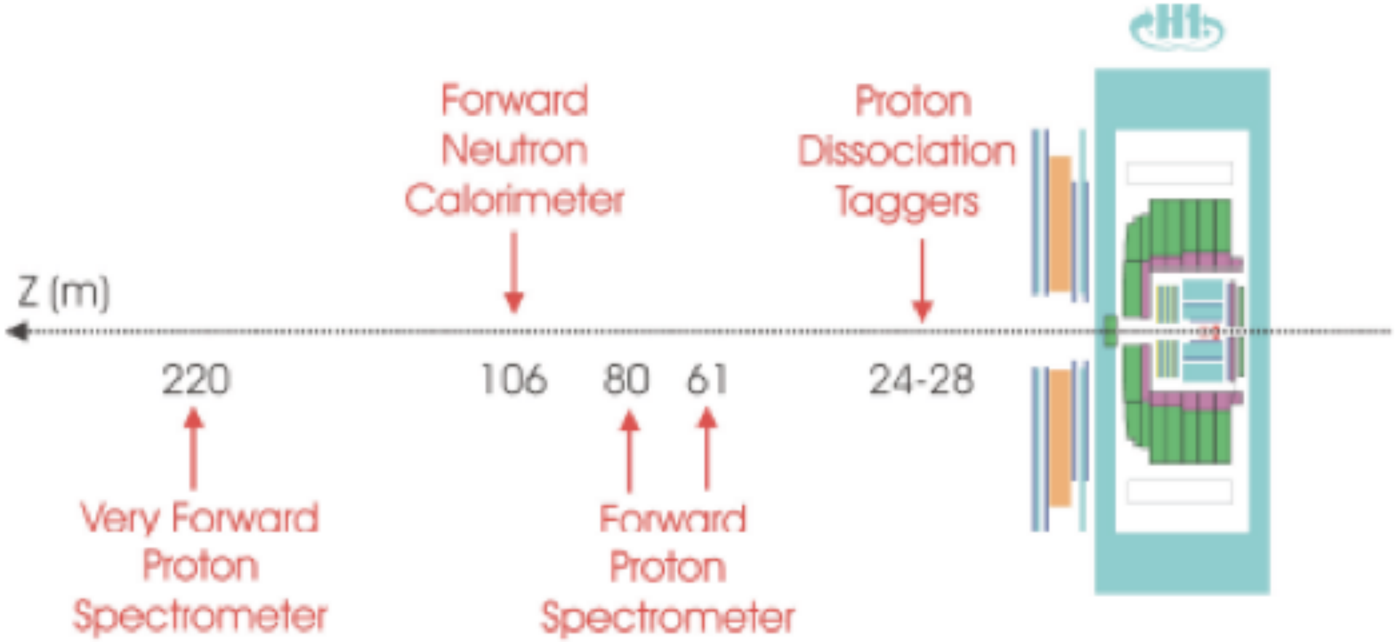
Diffractive DIS (DDIS)



x_{IP} fractional longitudinal proton's momentum loss
β fraction of x_{IP} taking part in the interaction with the photon
$x = \beta\, x_{IP}$
$t = (p-p')^2$ 4-mom. transfer squared at proton vtx
My = m_p proton stays intact (elastic case)
My > m_p proton dissociates

Experimental methods

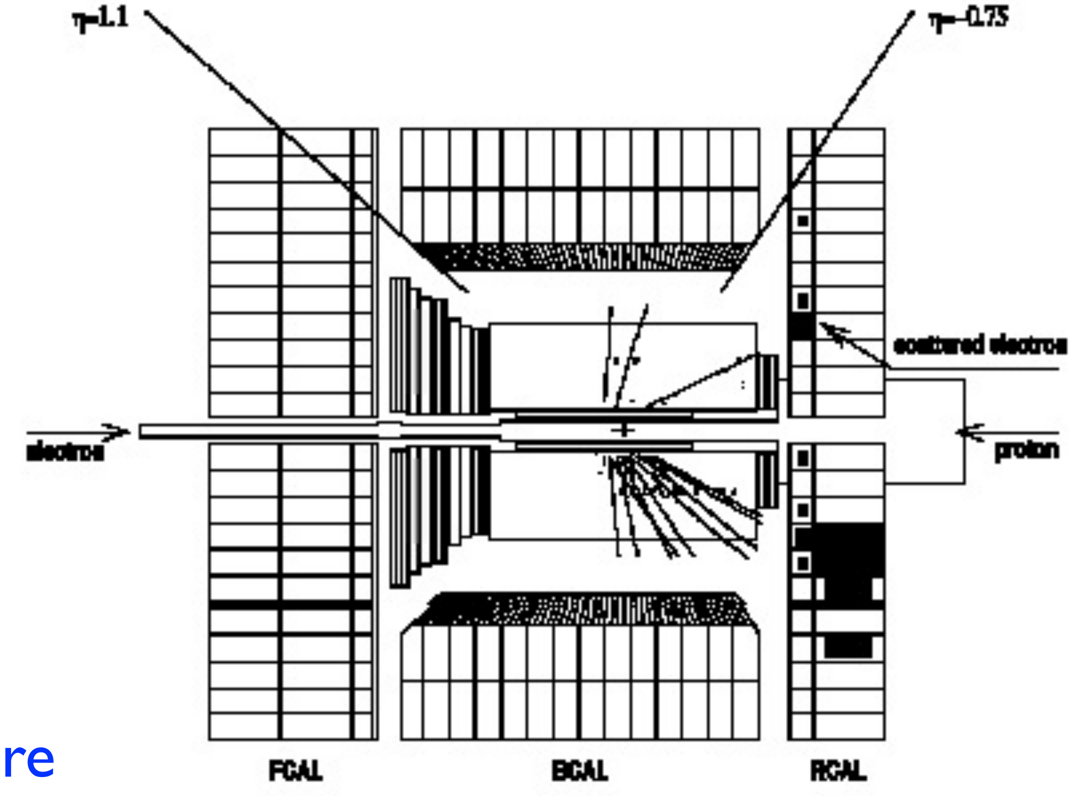
10% of events at HERA - diffraction



Methods of measurement:

Proton Spectrometer:

+ clean measurement p-tagging
+ free of p-dissociation background
+ x_{IP} and t can be measured
+ access to high x_{IP} range
- small acceptance



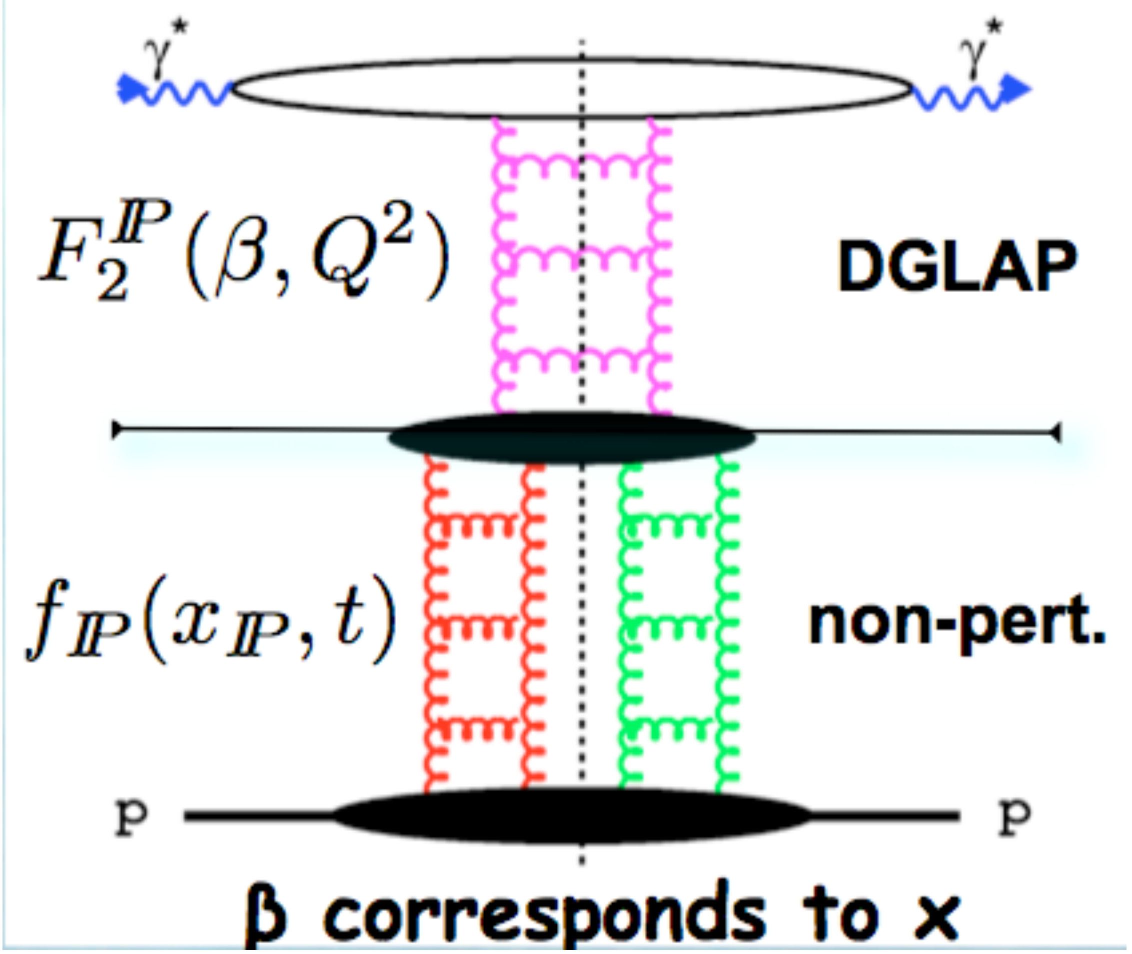
Large Rapidity Gap:

+ very good acceptance at low x_{IP} => high statistics
- t not measured, integrated over |t|<1GeV2
- p dissociative background ~ 20%

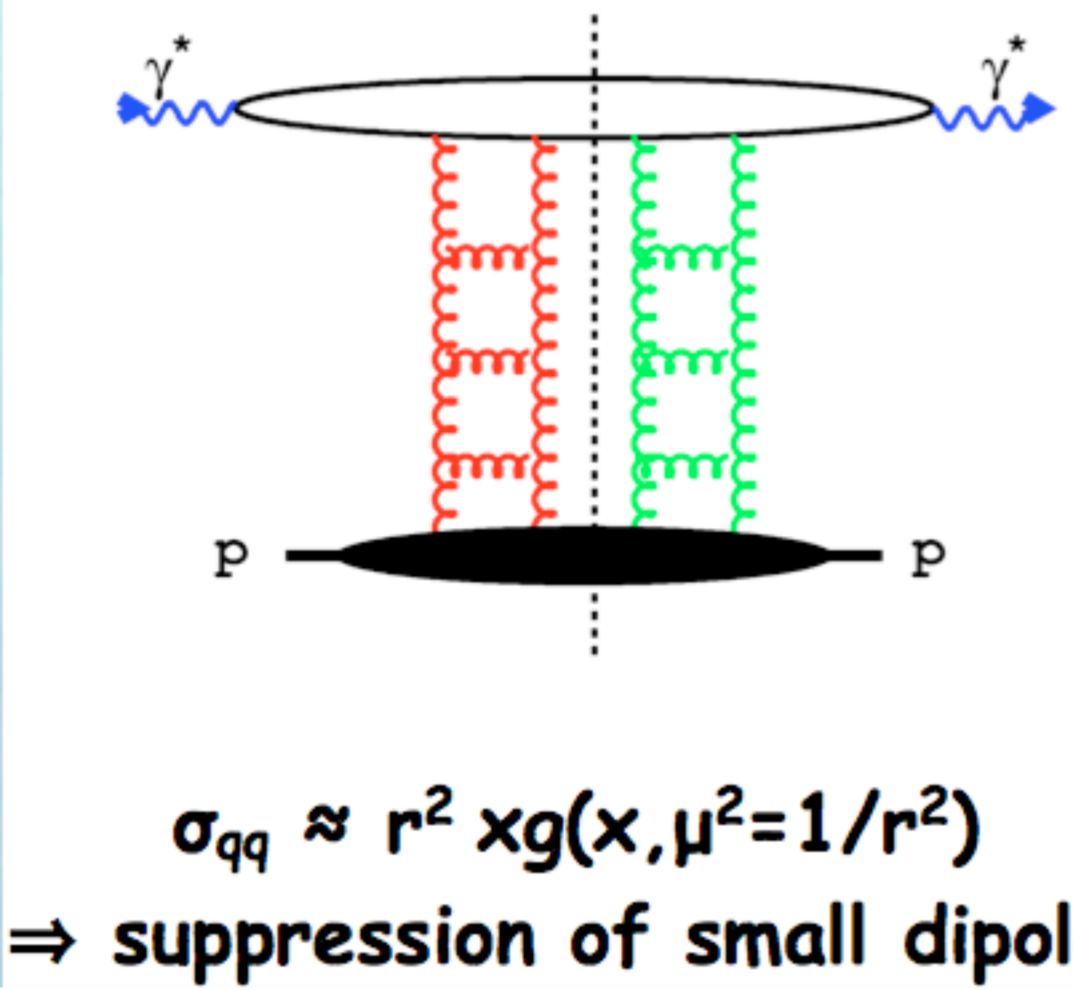
Different phase space and systematics - not easy to compare

Modeling of diffraction

Diffractive structure function approach



Dipole approach



H. Kowalski Ringberg Proceedings (2006)

$\sigma_{qq} \approx r^2\, xg(x, \mu^2 = 1/r^2)$

⇒ suppression of small dipoles

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

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

Pomeron flux factor

pomeron PDF

e.g. Resolved Pomeron Model by Ingelman & Schlein

$d\sigma^{\gamma^* p}{}_{diff}/dt \propto \int dz dr^2 \Psi^* \sigma^2{}_{qq}(x, r^2, t) \Psi$

Long living quark pairs interact
with gluons of the proton

e.g. two gluon exchange model by Bartels et al.

Diffractive cross-section and factorisation

Reduced diffractive cross section (in analogy to the inclusive DIS):

$$\sigma_r^{D(4)}(\beta,Q^2,x_{IP},t) = F_2^{D(4)}(\beta,Q^2,x_{IP},t) - \frac{2y^2}{2-2y+y^2} F_L^{D(4)}(\beta,Q^2,x_{IP},t)$$

when proton is not tagged - integrate over t => $\sigma_r^{D(3)}(\beta,Q^2,x_{IP})$
$\sigma_r^{D(4)} \approx F_2^{D(4)}$ at low and medium y

QCD factorisation:

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

DPDFs - obey DGLAP
universal for diff. ep DIS

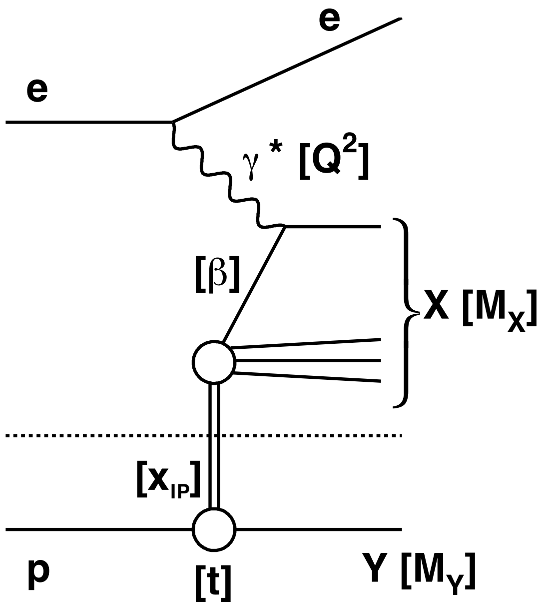
hard scattering cross section

proton vertex factorisation:

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

pomeron flux factor

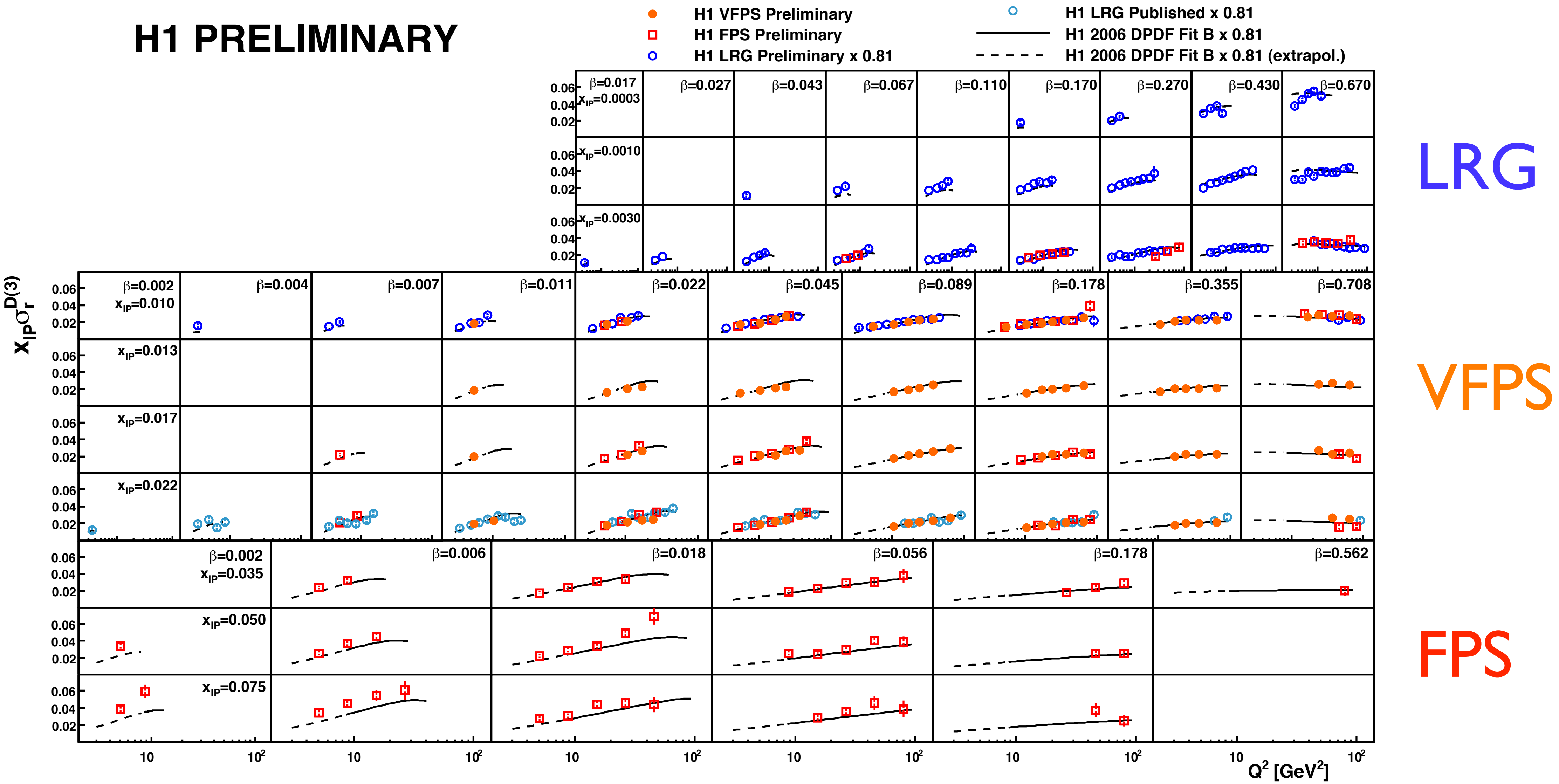
pomeron PDF



The DPDFs extracted from the inclusive diffr. data can be used with NLO calculations to predict diffractive jet production → factorisation test.

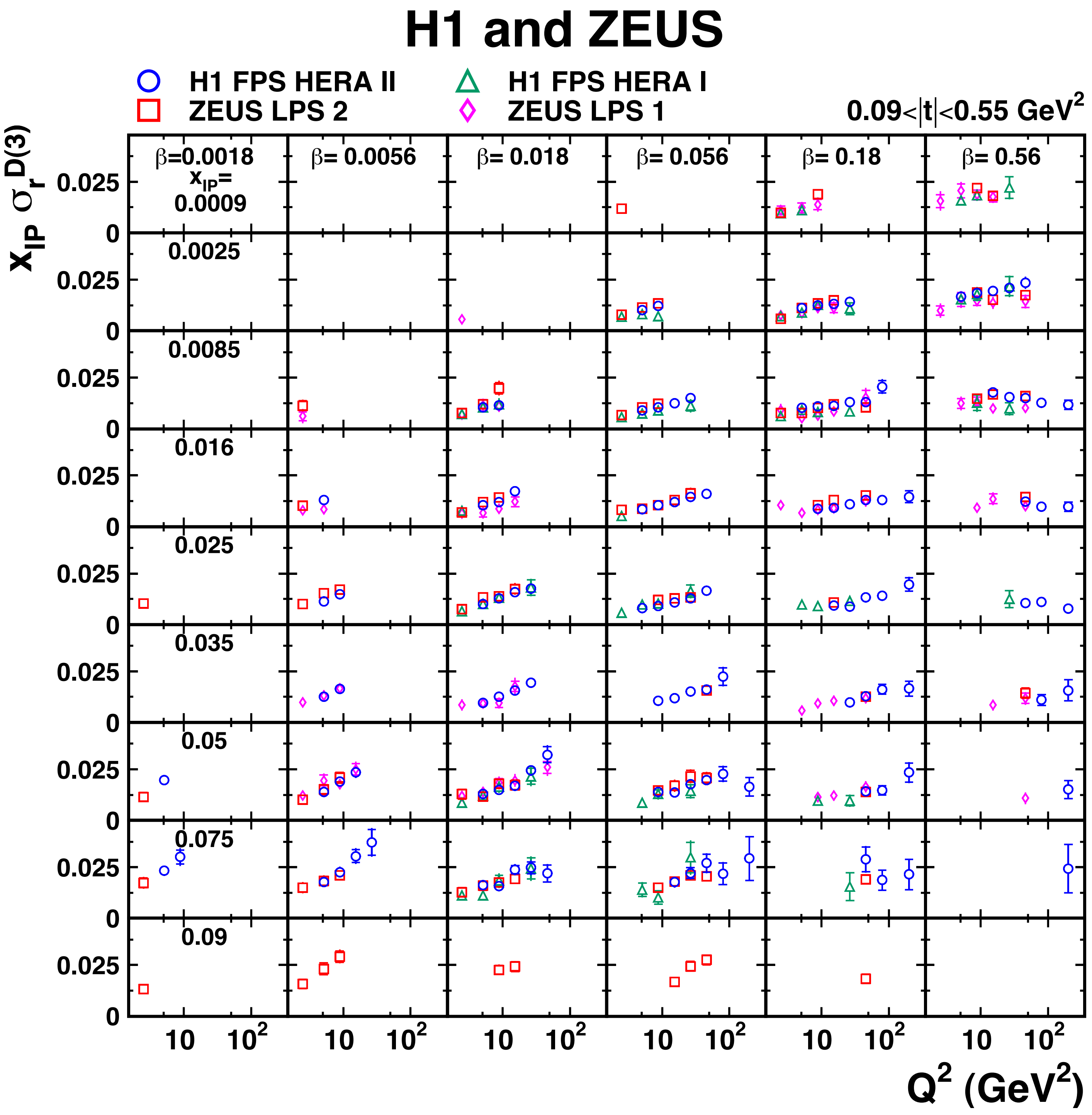
Diffractive cross section measurement

Overview of H1 $\sigma_r^{D(3)}$ measurements using different techniques



In the region of overlap of kin. area available for different techniques - data consistent.
Good agreement with the DPDF fits

$\sigma_r^{D(3)}$ in H1 and ZEUS using proton spectrometers



used proton spectrometers LPS(ZEUS) and FPS (H1) to detect leading protons

data extrapolated to a common (Q^2, x_{IP}, β) grid using NLO DPDF 'ZEUS SJ' parametrisation and checked with NLO DPDF H1 Fit B, corrections mostly < 10%

shown data published in:
H1: EPJ C71 (2011) 1578
H1: EPJ C48 (2006) 749
ZEUS: Nucl. Phys. B816 (2009) 1
ZEUS: EPJ C38 (2004) 43

data collected by different experiments and in different running periods show good agreement

Combined inclusive diffractive cross section

LPS and FPS data combined using χ^2 minimisation method

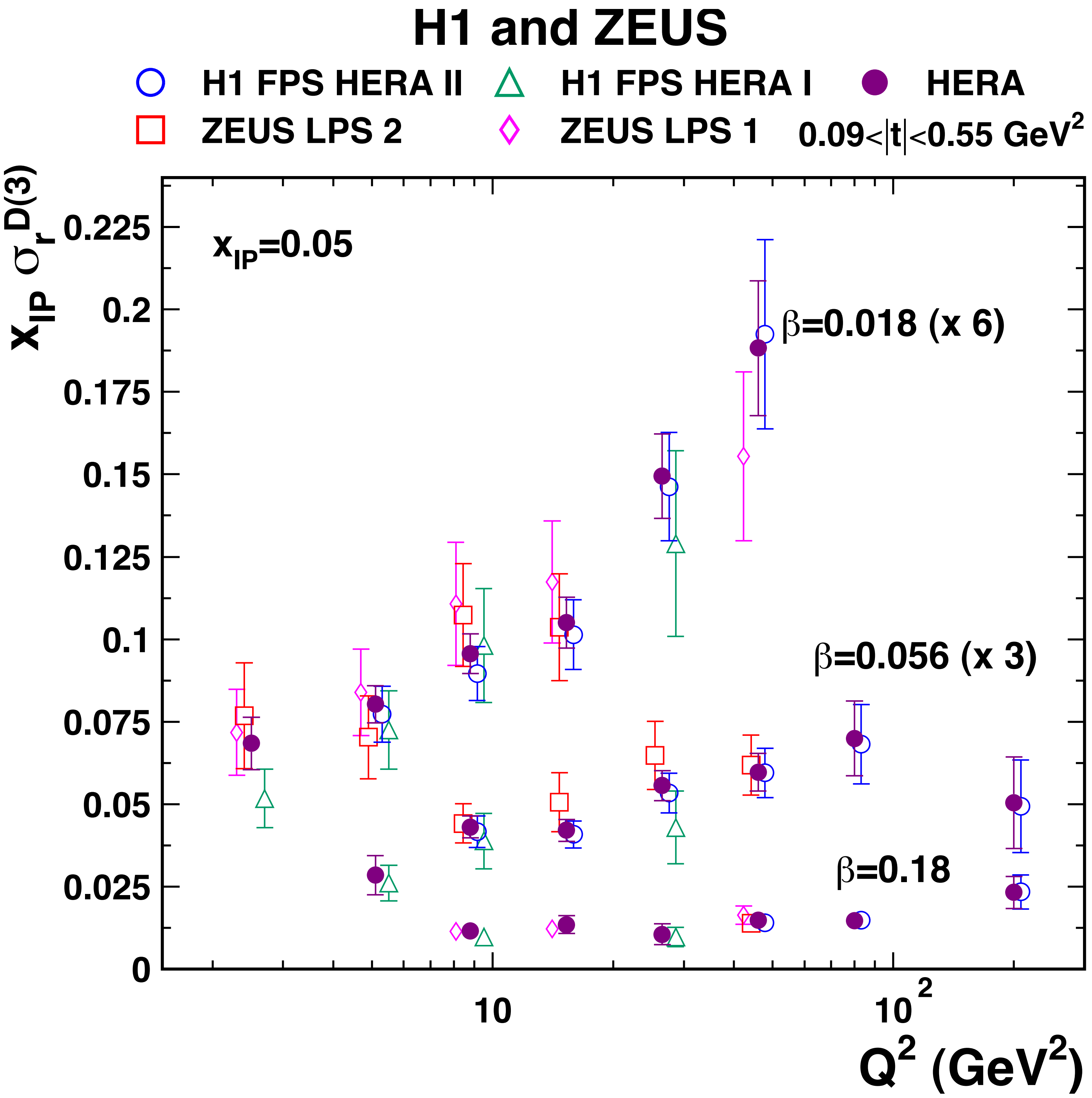
Input data are consistent :
$\chi^2_{min}/n_{dof}=133/161$
n_{dof} = total number of measurements - number of data points

correlation of systematic uncertainties taken into account

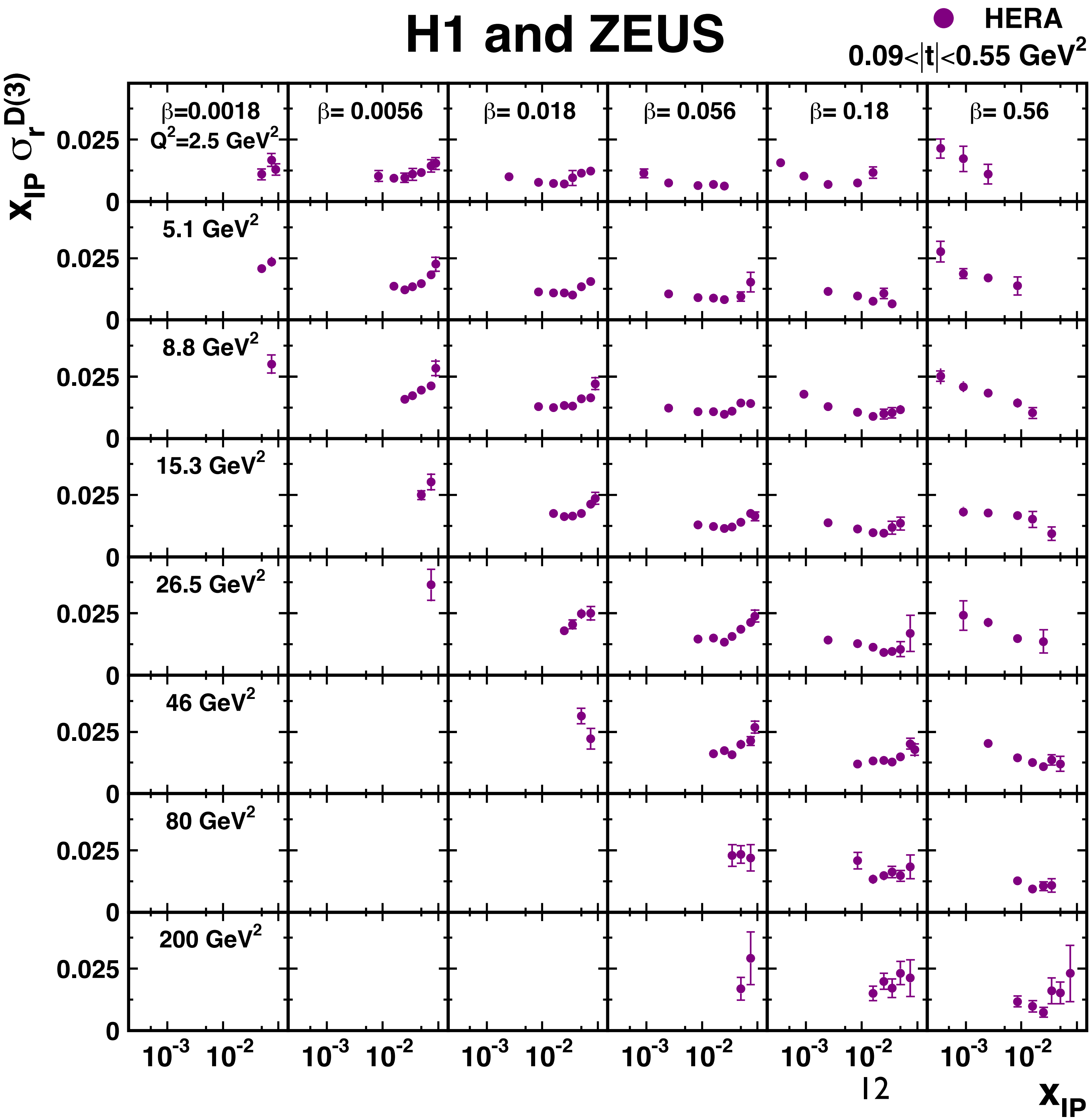
H1 and ZEUS use different reconstruction methods → the two experiments calibrate each other

reduction of experimental errors by ~27%

precision of the cross section measurement after combination of data ~14% in the average, ~ 6% for the most precise points



Combined inclusive diffractive cross section

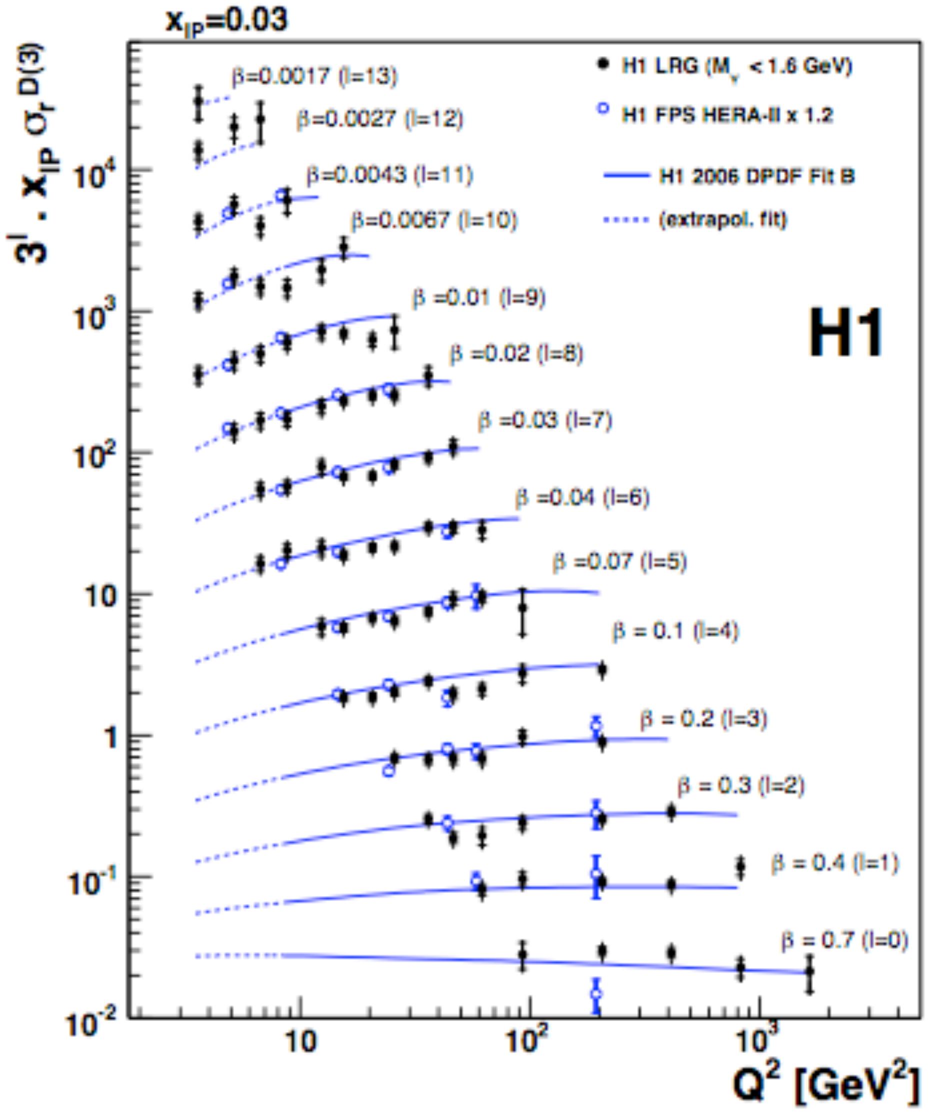


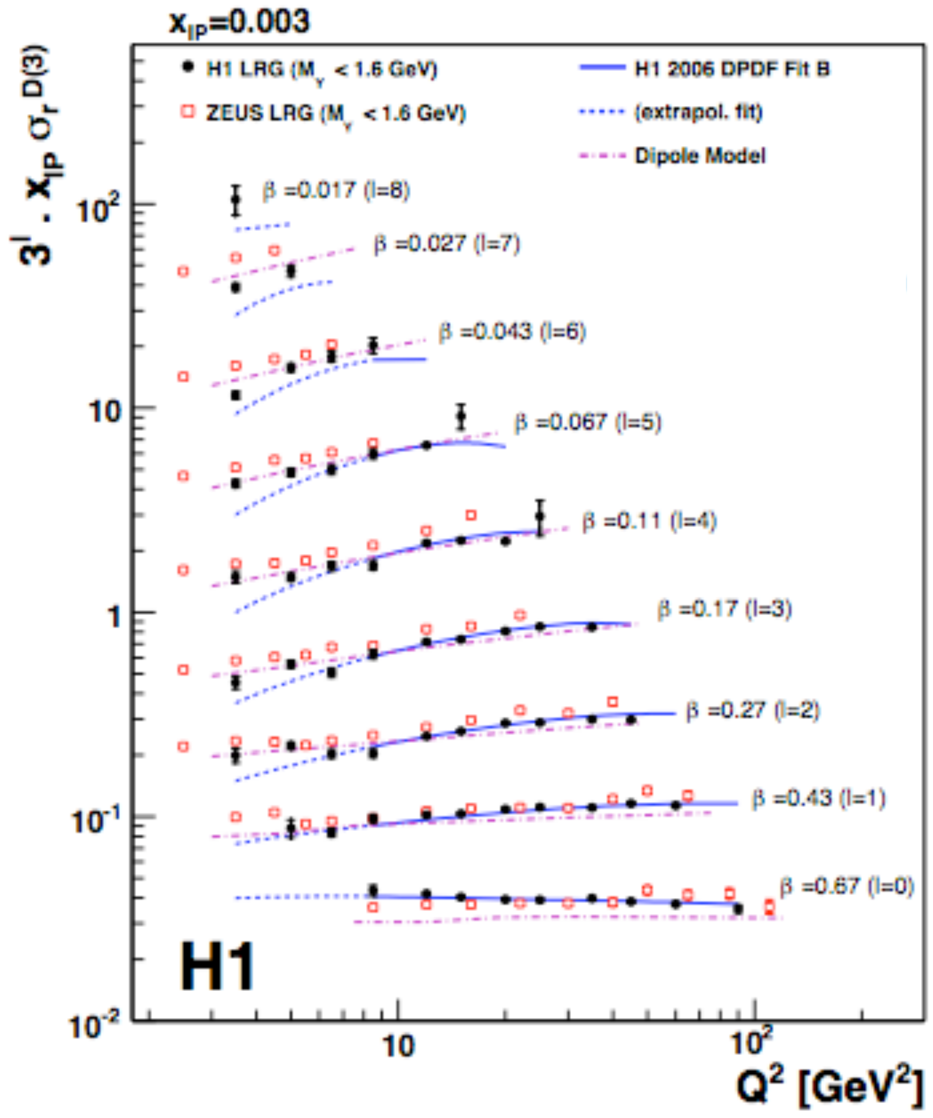
Combined data cover the range:
$2.5 < Q^2 < 200$ GeV^2
$0.00035 < x_{IP} < 0.09$
$0.09 < |t| < 0.55$ GeV^2
$0.0018 < \beta < 0.816$

The combined data provide the most precise determination of the absolute normalisation of the ep→eXp cross section.

Inclusive measurement of diffractive DIS

Combined H1 measurements for LRG method





EPJ C72 (2012) 2074

Increase in statistics
Reduction of uncertainties
stat error (for Q^2>12 GeV^2) ~ 1%
systematic error (for Q^2 >12 GeV^2) ~ 5%

LRG data (after subtraction of 20% of dissociative events) in agreement with FPS

Dipol model (including saturation) describes the low Q^2 kinematic domain well.

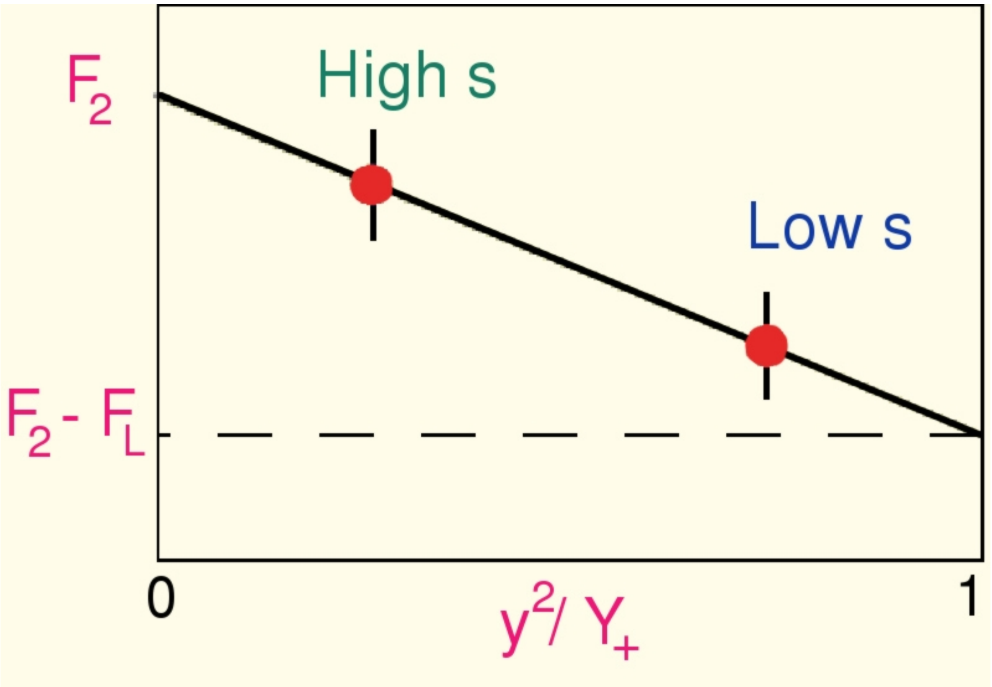
DPDF fits more successful in the high Q^2 region.

Measurement of the F_L^D

F_L^D measurement

- a tool to verify our understanding of underlying dynamics of diffraction in QCD
- a test of the DPDFs.

Particularly important at lowest z (direct information on the gluon density cannot be obtained from dijets due to kinematic limitations.)

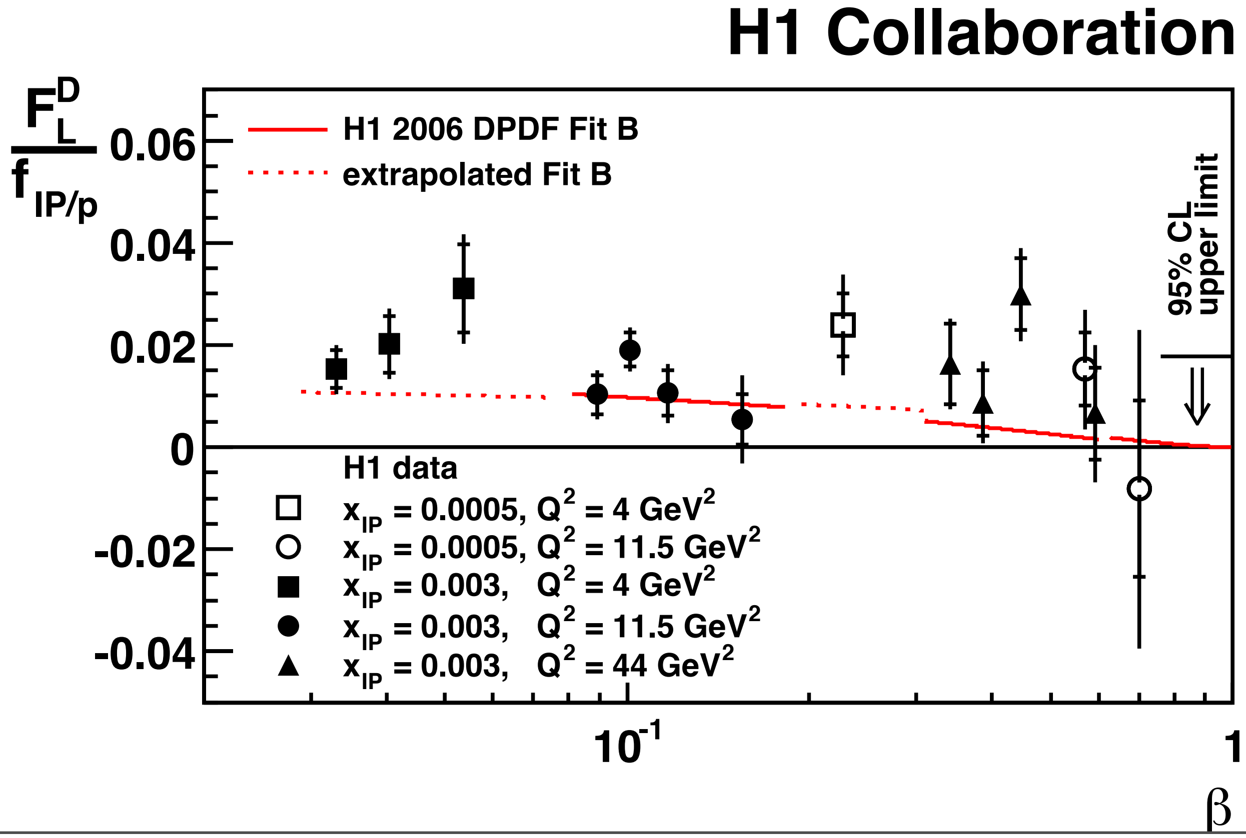


$$\sigma_r^D = F_2^D - (y^2/Y_+)F_L^D$$

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

σ_R^D measured at different y
(but fixed x_{IP},β,Q^2)

Data collected with :
Ep = 820 GeV
Ep = 920 GeV
Ep = 460 GeV
Ep = 575 GeV

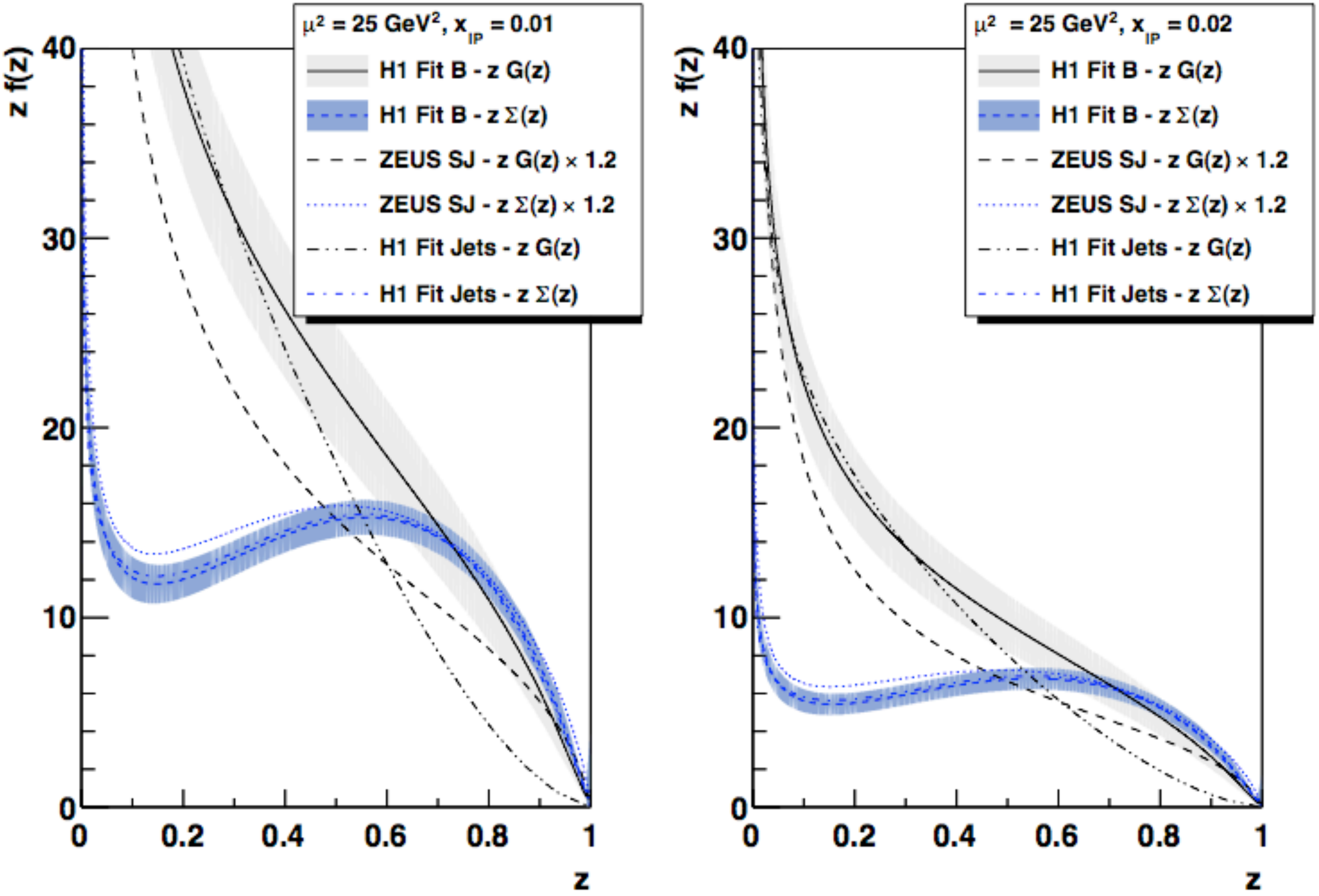


The data are compatible with H1 2006 DPDF fit A and Fit B.

$F_L^D > 0$

Diffractive PDFs

DPDFs obtained by H1 and ZEUS from inclusive measurements and dijets



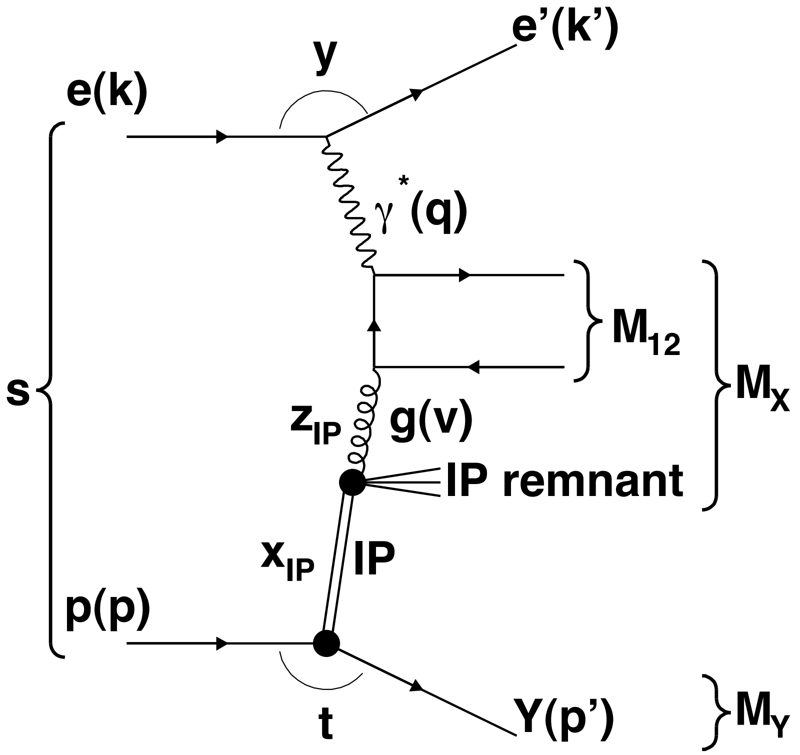
z - the longitudinal 4-momentum fraction of the hadron entering the hard subprocess with respect to the pomeron

$M_Y < 1.6$ GeV,
$|t| < 1$ GeV^2

In blue quark singlet density distributions in black gluons density.

Diffractive dijets in DIS

Two hard scales in the process:
the virtuality of the photon
the transverse energy of the jets



Sensitivity to the gluon given by the
production mechanism of the dijets:
Boson-Gluon Fusion

Dijets in DDIS as a benchmark for the DPDF and factorisation theorem

Supports the universality of DPDFs

The dijets data can be used to constrain the DPDFs in a combination with the inclusive data

Diffractive dijets in DIS

Most important HERA results on diffractive dijets:
H1, LRG measurement, JHEP 0710:042 (2007)
ZEUS, LRG measurement, EPJC 52 (2007) 813
H1, proton tagging - FPS, EPJC 72 (2012) 1970
H1, proton tagging - VFPS, H1 preliminary (2014)

H1, LRG measurement, H1 preliminary (2014)

highest luminosity compared to former HERA data
used ~290 pb-1 data collected in years 2005-2007

cross-sections determined using regularised unfolding procedure, which takes into account efficiencies, migrations and correlations between measurements

measured cross sections compared to next-to-leading order QCD predictions evaluated with input DPDFs determined in previous inclusive diffractive measurements

All HERA results - within errors - in agreement with NLO QCD calculations

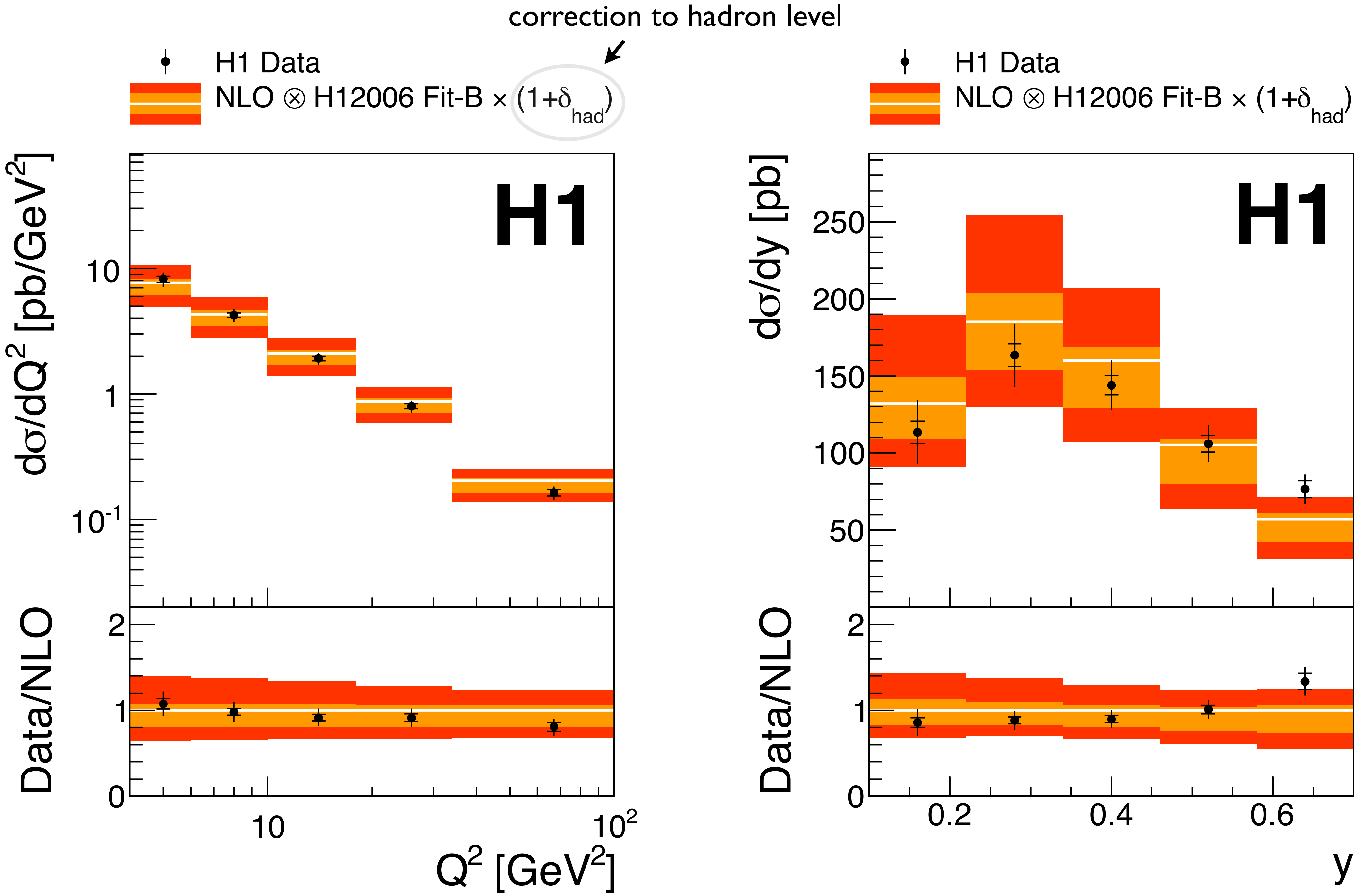
DDIS dijet selection:
$4 < Q^2 < 80$ GeV^2
$0.1 < y < 0.7$

$P^*_{T,1} > 5.5$ GeV
$p^*_{T,2} > 4.0$ GeV
$-1 < \eta < 2$

$x_{IP} < 0.03$
$|t| < 1$ GeV^2
$M_Y < 1.6$ GeV

~14000 events accepted

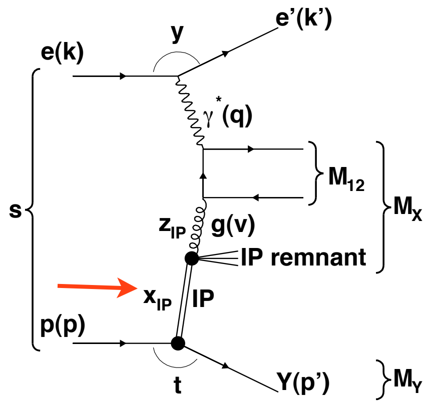
Diffractive dijets in DIS



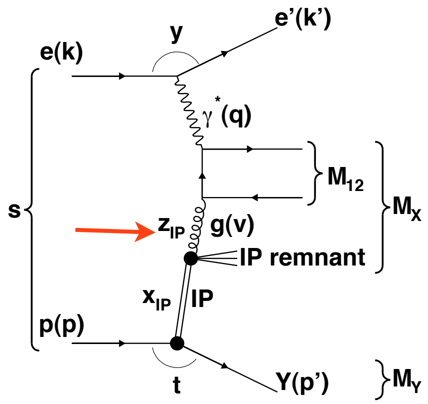
Inner error bars - statistical uncert.
outer error bars - systematic uncert.
added in quadrature

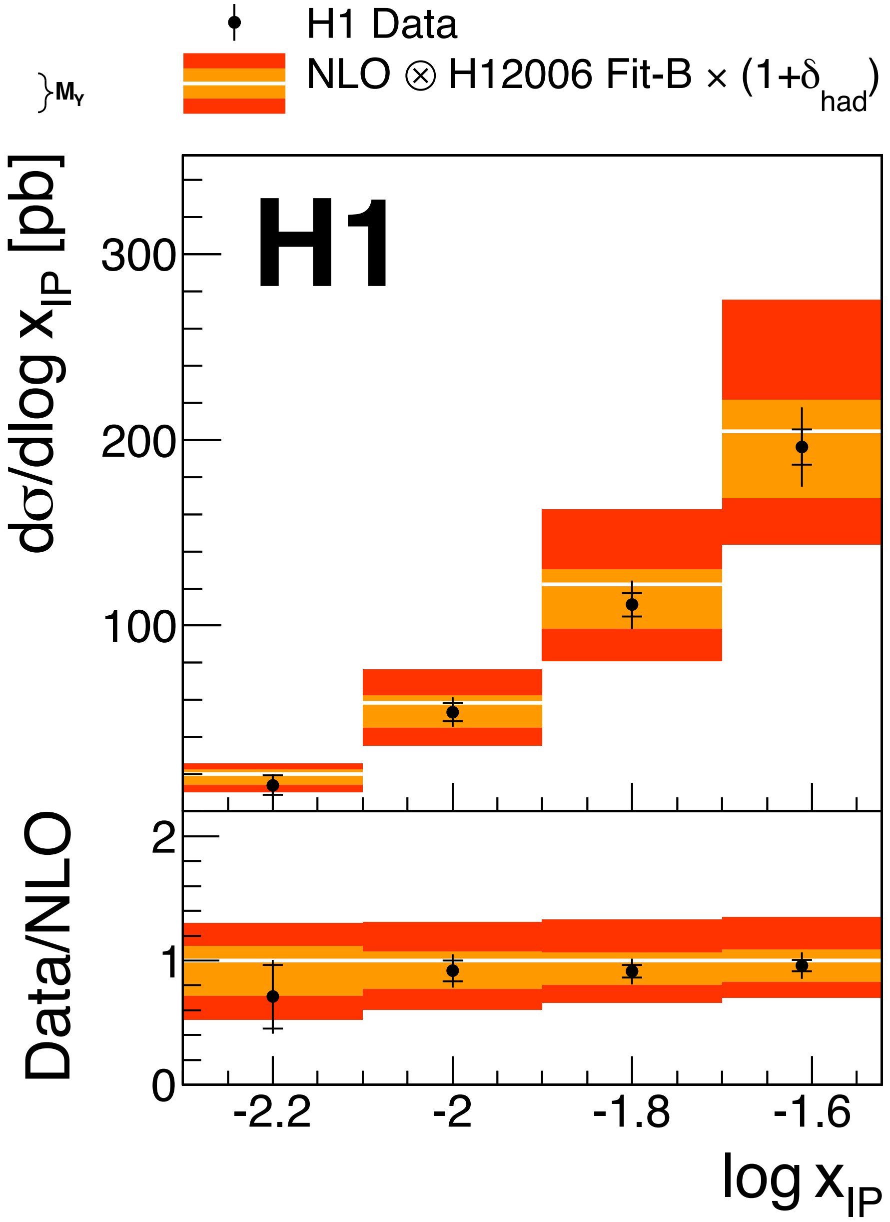
NLO QCD
inner band - uncertainty of hadronisation and DPDF fit added in quadrature,
outer band - total uncertainty (incl. QCD scale uncert.)

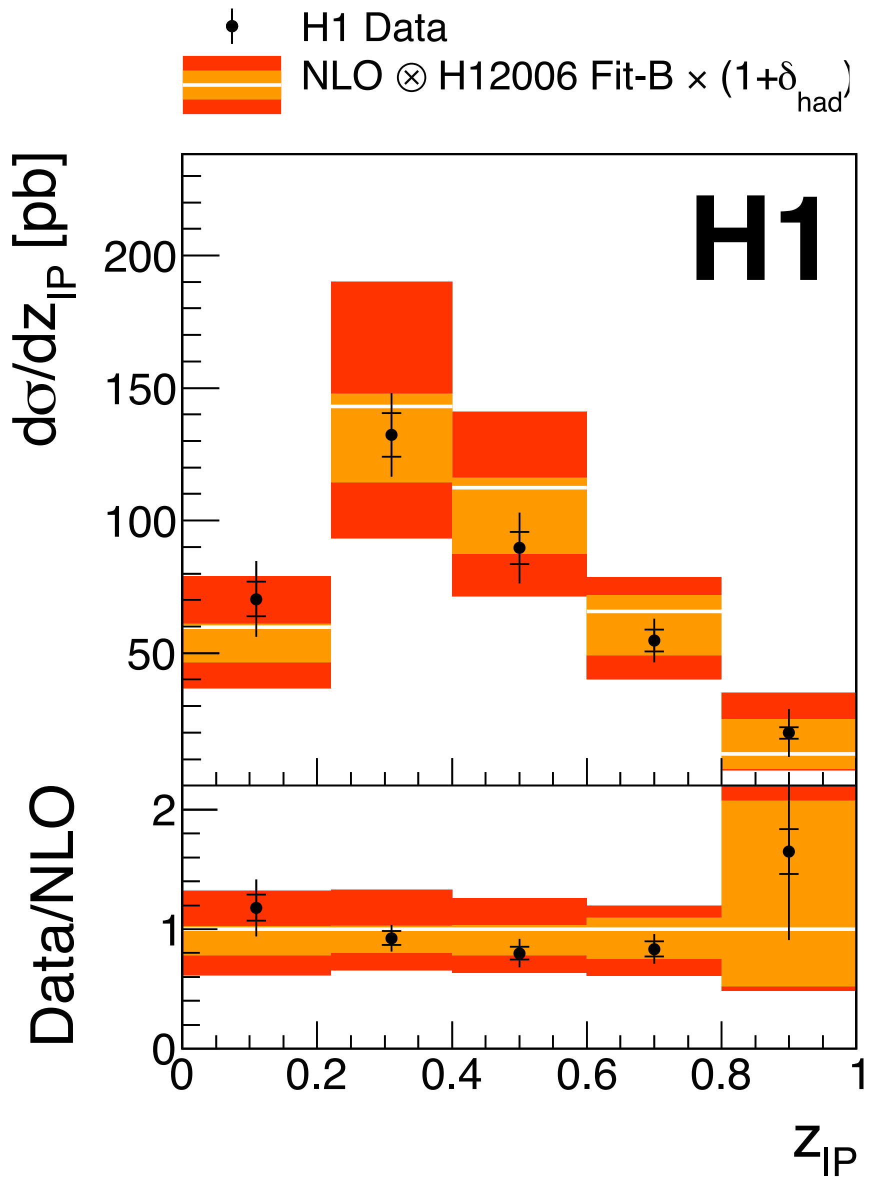
Data well described (in shape and normalisation) by the QCD prediction within experimental and theoretical uncertainties



Diffractive dijet in DIS



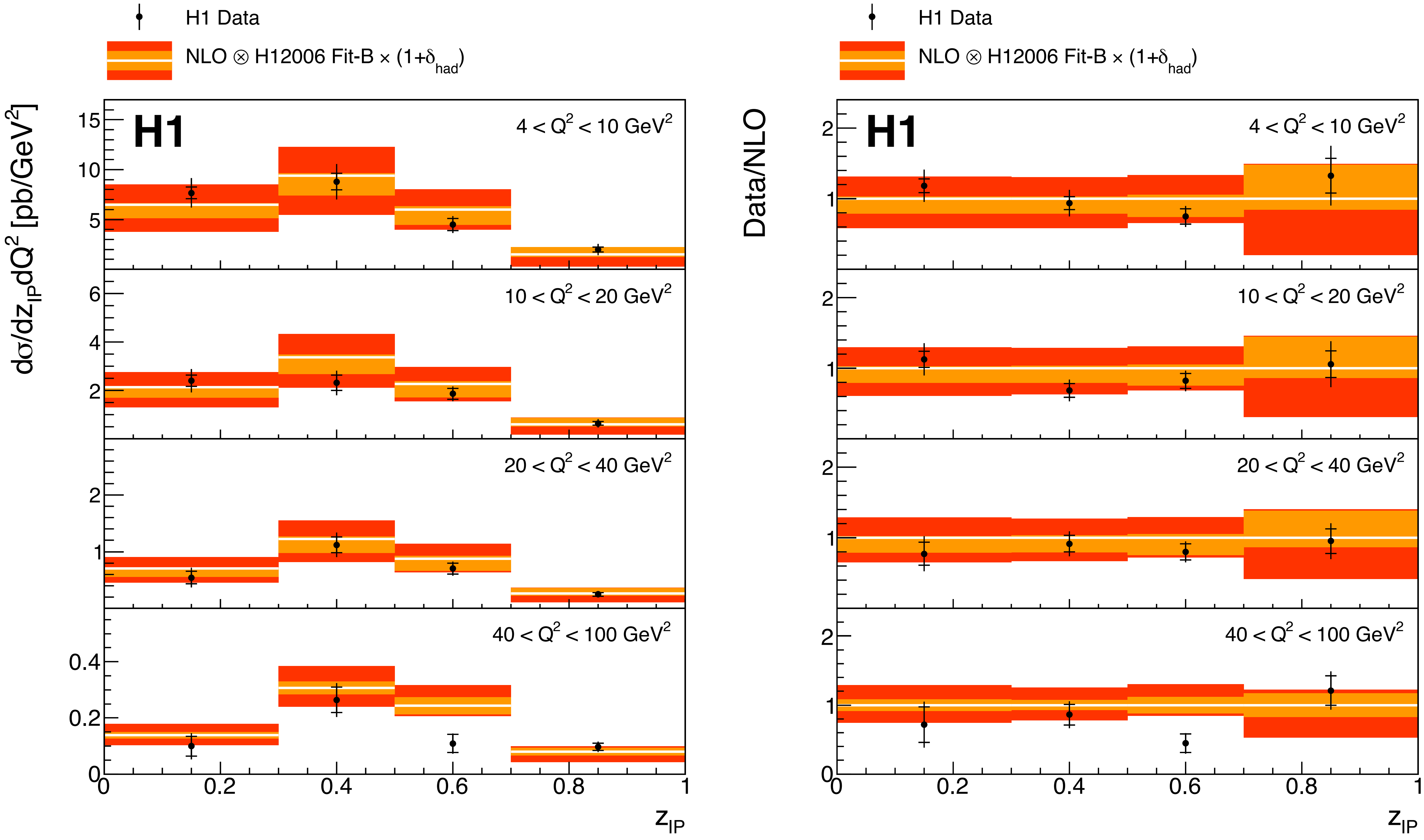




Experimental uncertainty of measurement in z_{IP} smaller than DPDF fit uncertainty ⇒ gluon DPDF may be further constrained

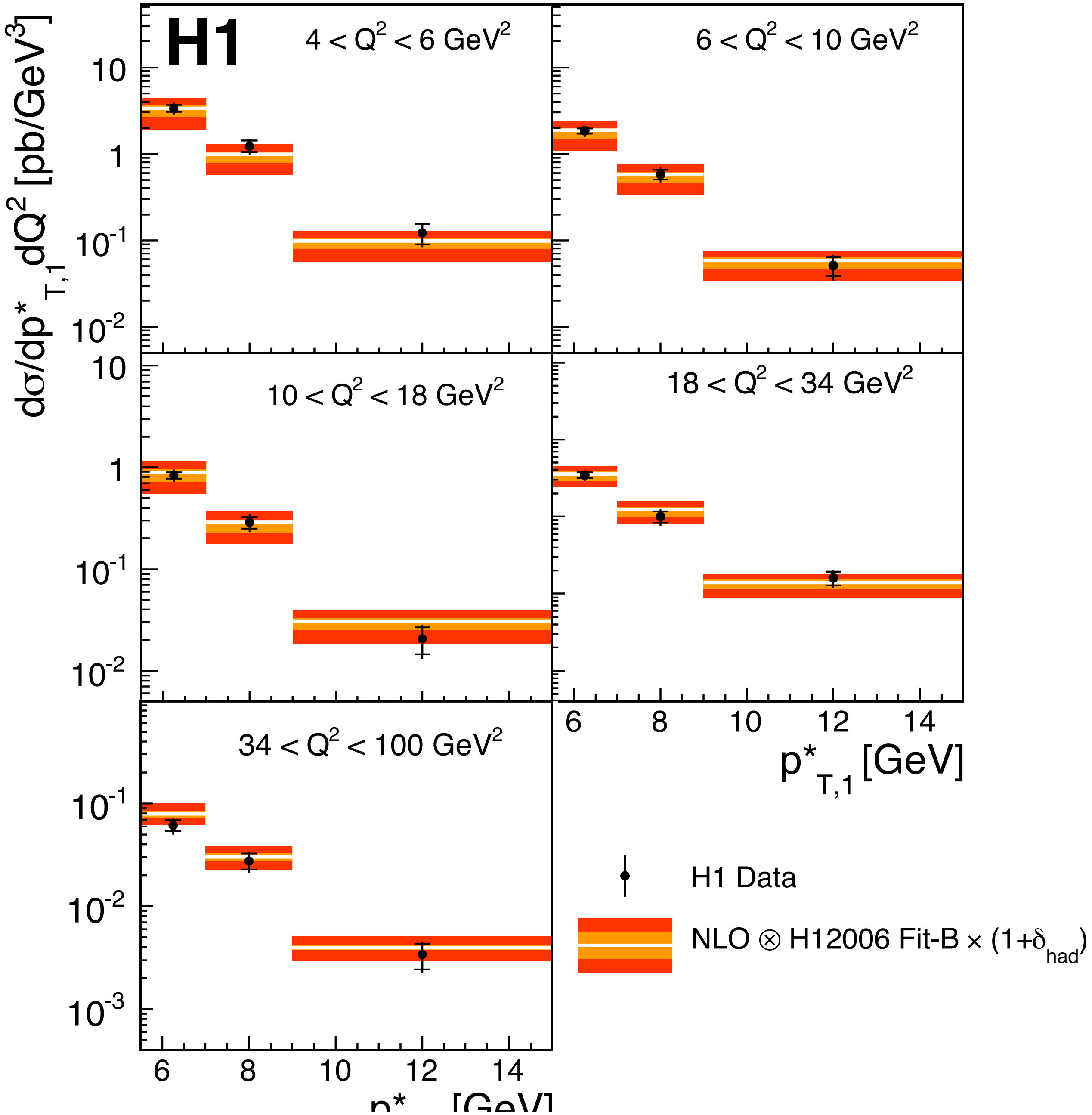
Agreement with NLO QCD calculations, factorisation confirmed

Diffractive dijet in DIS



Good agreement with NLO QCD, the last bin in z_{IP} where DPDF is only extrapolated can be used to improve further DPDF fits.

Diffractive DIS dijet - α_s



A fit to double differential cross section as a function of p^*_{T1} and Q^2 used to determine the value of strong coupling constant at the scale of Z boson mass.

$\alpha_S(M_Z)$ = 0.119±0.004(exp)±0.0(had)±0.005 (DPDF)±0.01(μ_r)±0.004(μ_f)
= 0.119±0.004(exp)±0.012(DPDF, theo)

in agreement with world average:
$\alpha_S(M_Z)$ = 0.1185±0.0006

Diffraction DIS can consistently be described by NLO QCD using DPDF and factorisation.

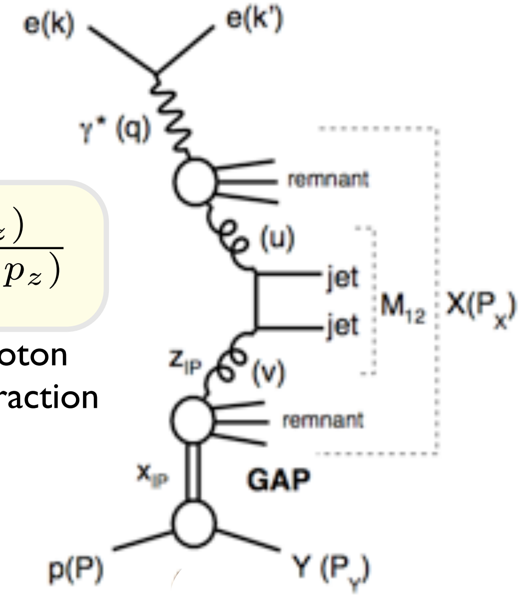
Diffractive dijet in photoproduction

Test of QCD factorisation in diffractive photoproduction

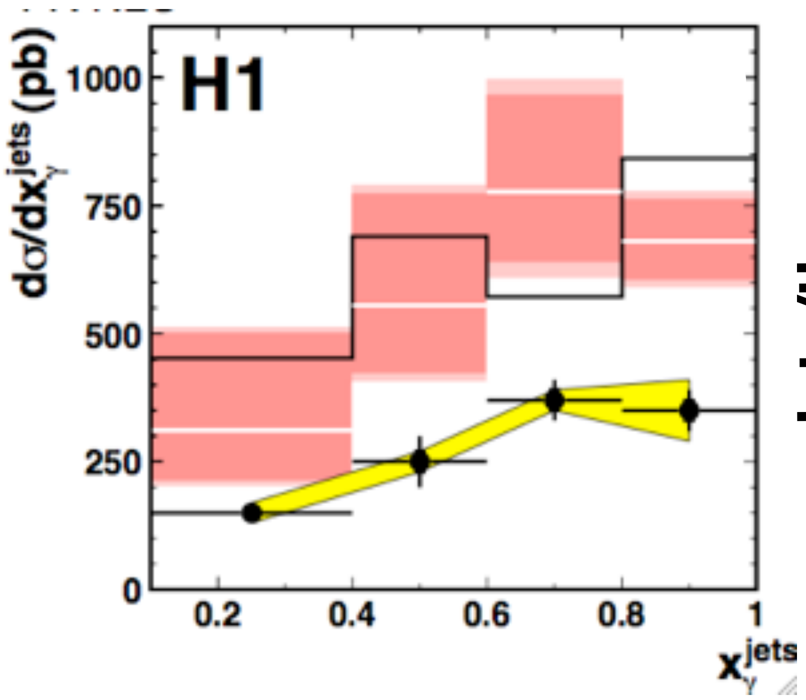
suppression $s^2 = \sigma(\text{data}) / \sigma(\text{theory(NLO QCD)})$

$$x_\gamma = \frac{\Sigma_{jets}(E-p_z)}{\Sigma_{hadrons}(E-p_z)}$$

4-mom. fraction of the photon taking part in the hard interaction

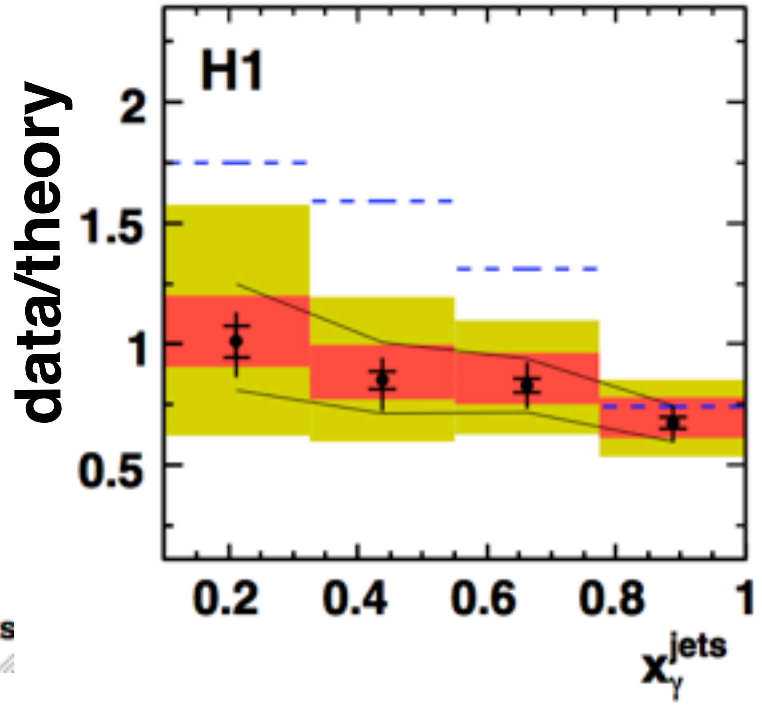


EPJC C51 (2007),549

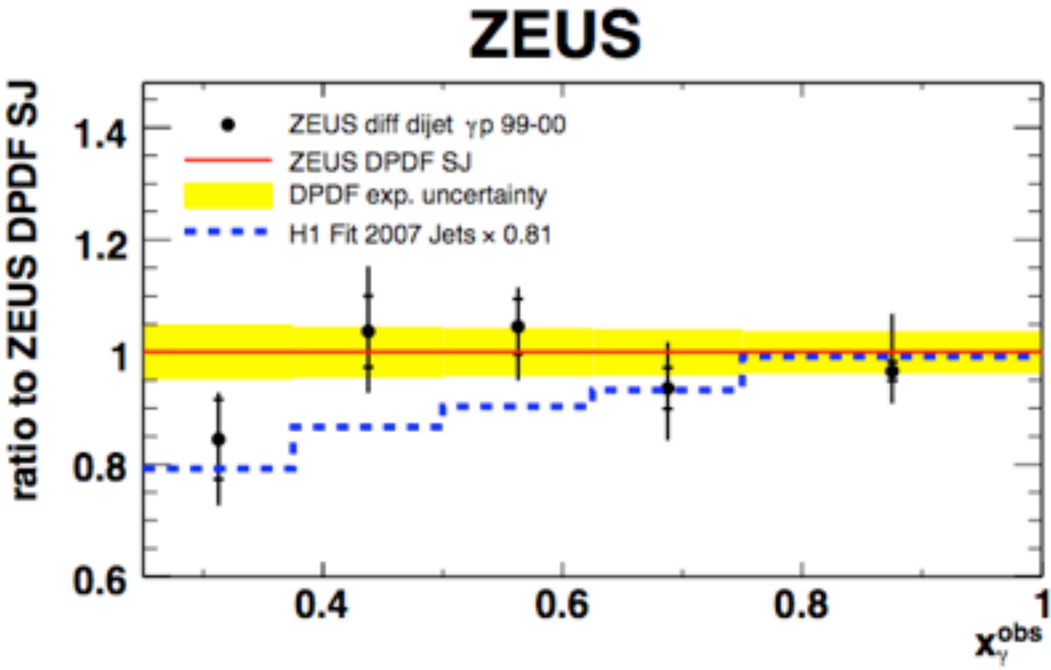


$s^2 \sim 0.5$

EPJ C68 (2010), 381



$s^2 \sim 0.58 \pm 21$



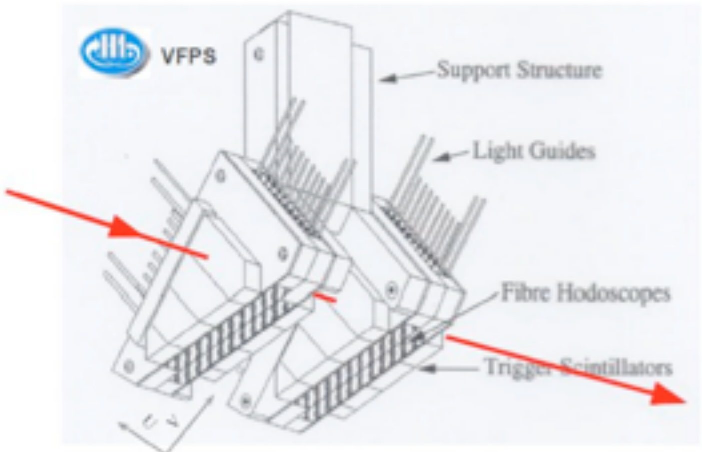
Nucl. Phys. B831 (2010) 1

$s^2 \sim 1$

No dependence of s^2 on x_γ,
(shape described OK)

- ☛ Different phase space in H1 and ZEUS analyses
- ☛ H1 tagged photoproduction, ZEUS untagged
- ☛ ZEUS larger E_T of jets

Diffractive dijet photoproduction



located 220 m in proton beam direction

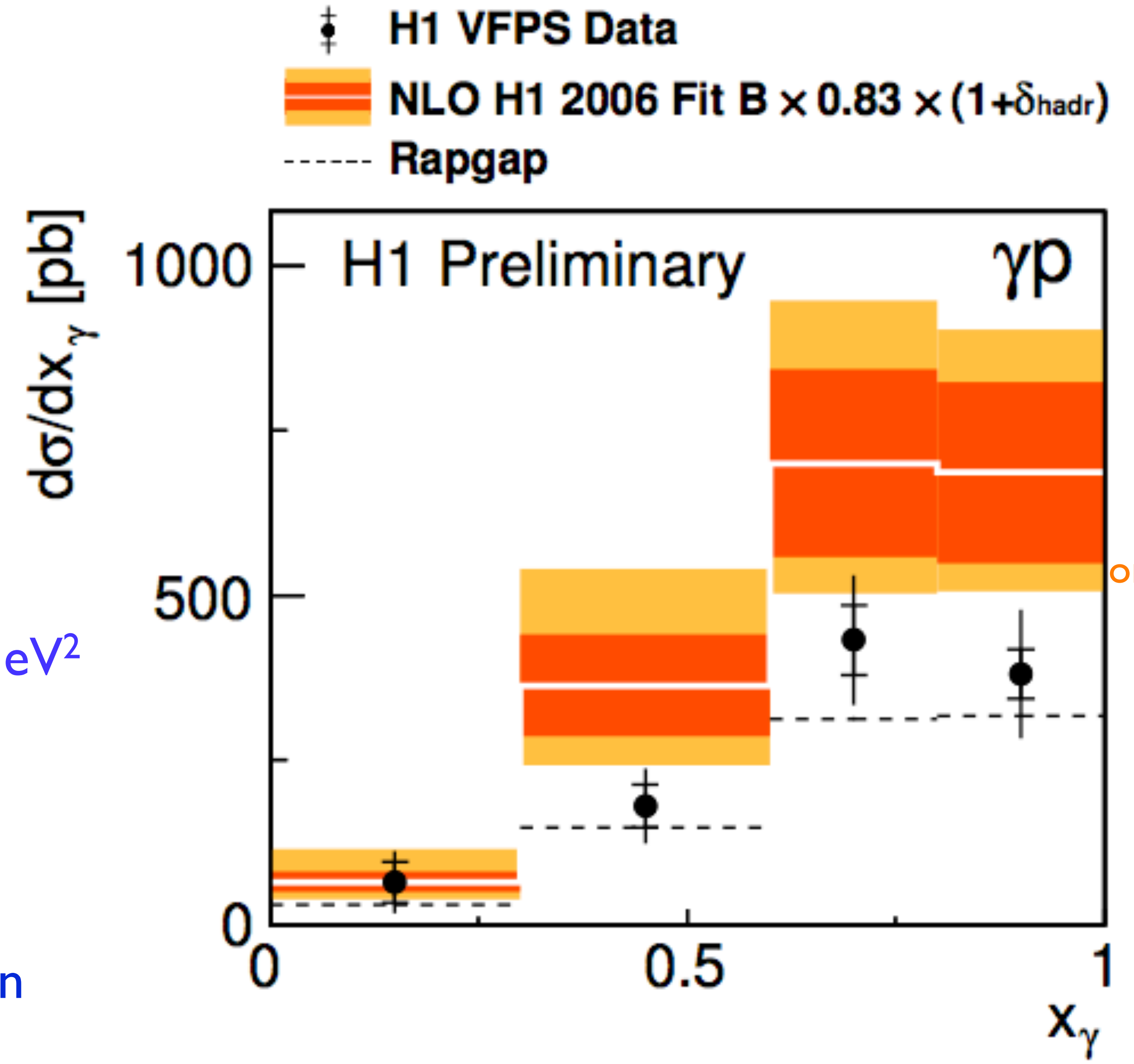
New analysis with leading protons detected in Very Forward Proton Spectrometer

Selection of photoproduction :

$E_T^{jet1} > 5.5$ GeV
$E_T^{jet2} > 4$GeV
$-1 < \eta^{jet1(2)} < 2.5$
$Q^2 < 2$ GeV^2
$0.2 < y < 0.7$
$|t| < 0.6$ GeV^2

DIS:
$4 < Q^2 < 80$ GeV^2

$x_\gamma = 1$ - direct photoproduction
$x_\gamma < 1$ - resolved photoproduction



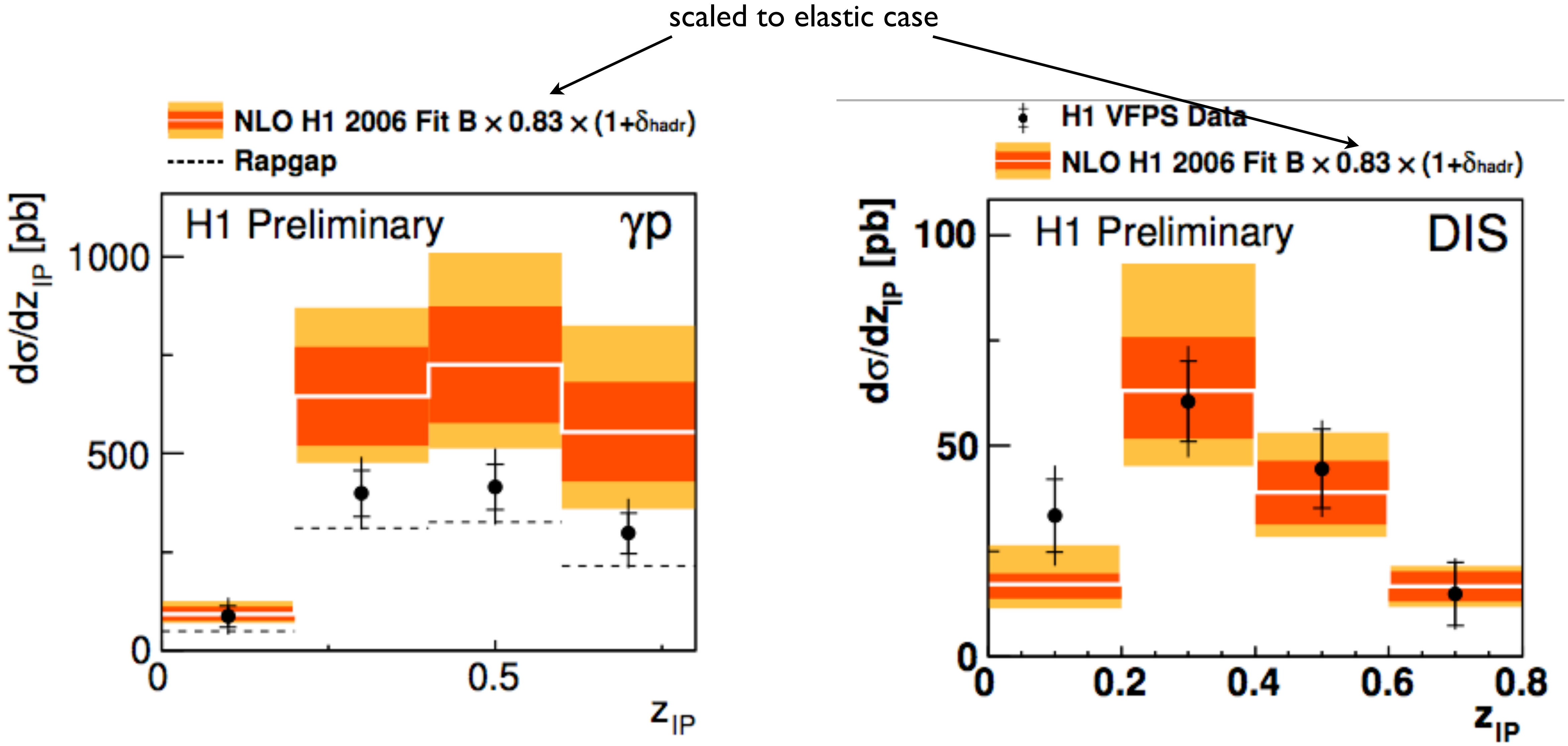
red - DPDFs uncertainty

orange - overall theoretical uncertainty

No hint that for $x_\gamma < 1$ suppression higher.

s2 = Data/NLO = 0.60 ± 0.08 (data) ± 0.21 (theor.)

Diffractive dijet photoproduction & DIS



scaled to elastic case

Photoproduction - data suppressed in comparison with NLO QCD by ~ 0.6
DIS - data satisfactorily described by NLO QCD calculations

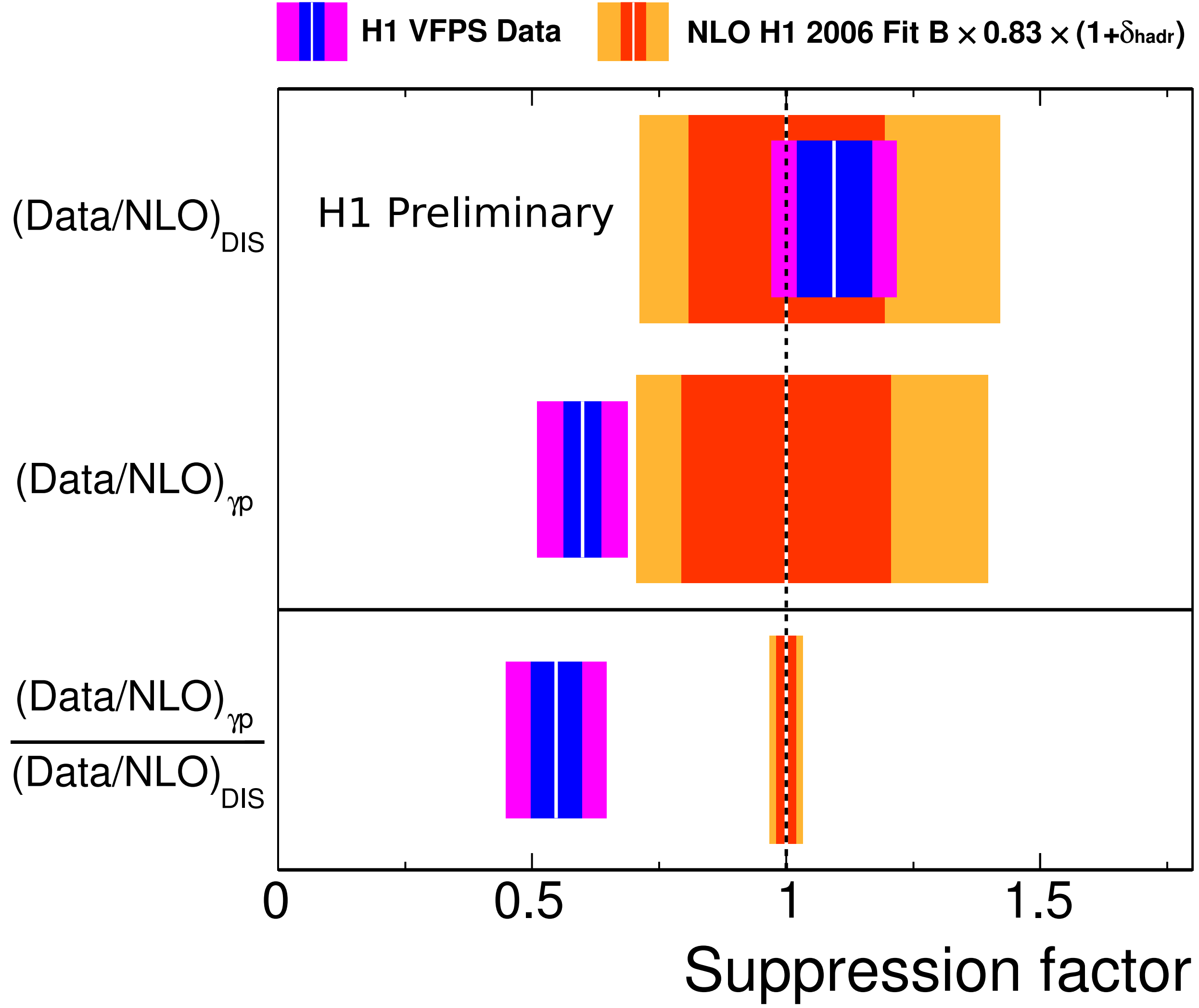
Diffractive dijet production - double ratio

statistical and systematic errors added in quadrature

overall theoretical uncertainty

statistical errors

DPDFs uncertainties

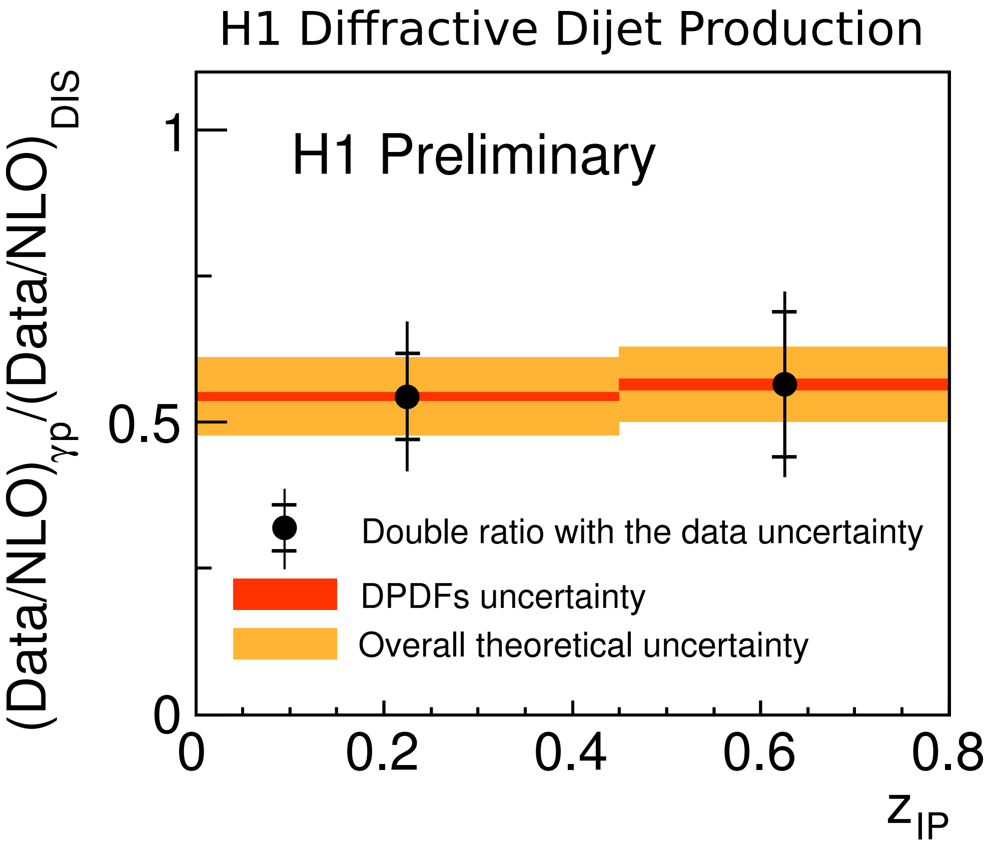


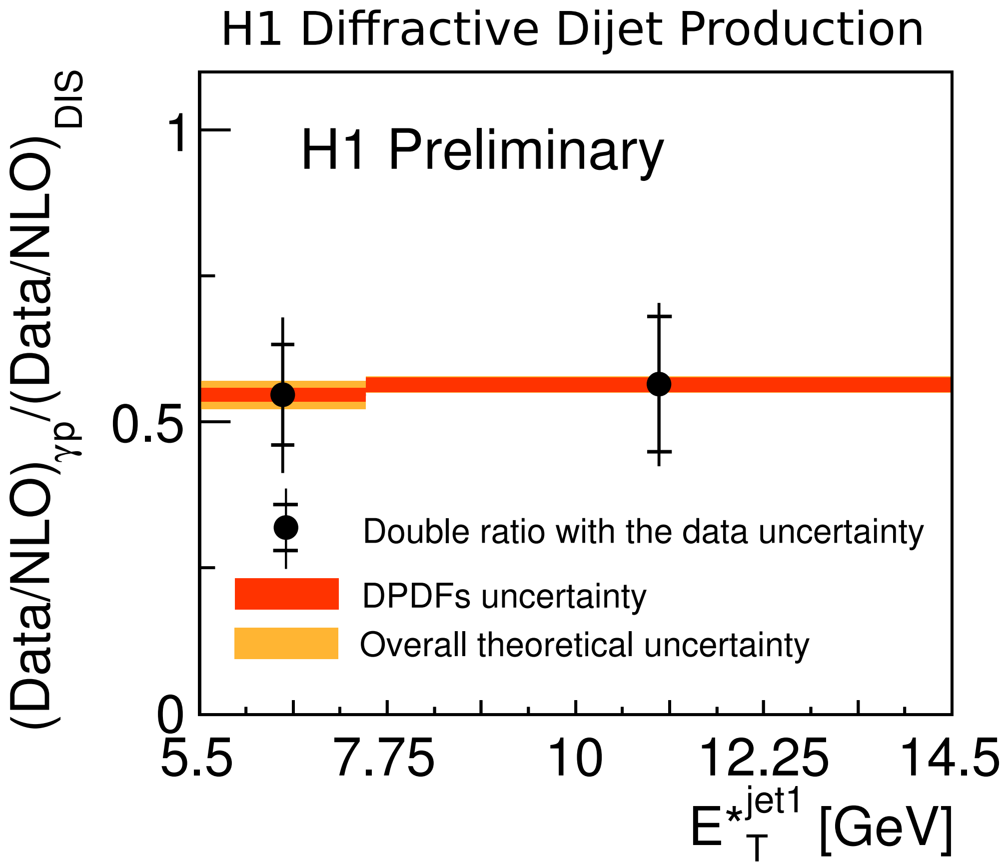
Double ratio of data to NLO QCD predictions for photoproduction and DIS reduce data systematic and theoretical uncertainties

$$\frac{(DATA/NLO)_{\gamma p}}{(DATA/NLO)_{DIS}} = 0.55 \pm 0.1(data) \pm 0.02(theor.)$$

Previous H1 results confirmed - factorisation breaking in diffractive photoproduction.

Diffractive dijet production - double ratio

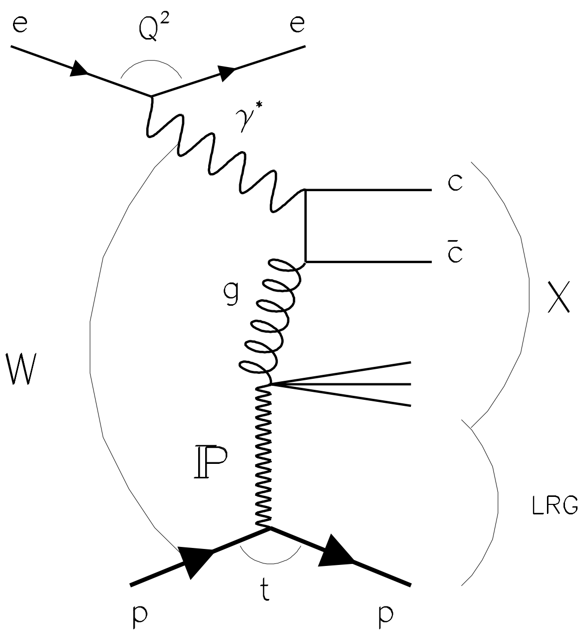




Double ratio photoproduction/DIS - uncertainties reduced

No dependence on z_{IP} or E_T of the leading jet observed

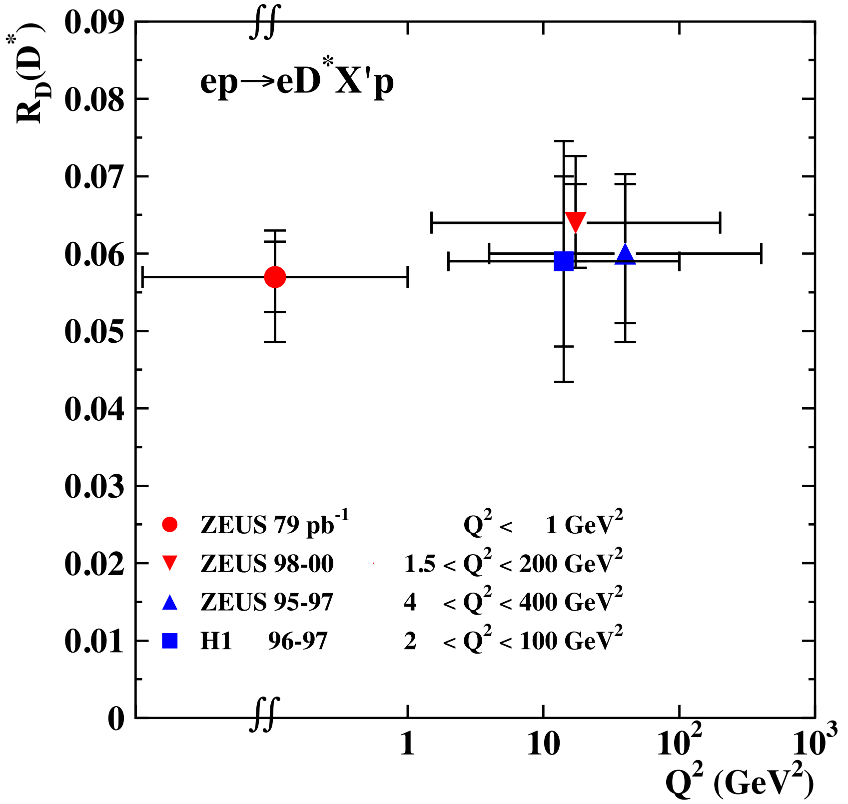
Diffractive photoproduction of D*±(2010)

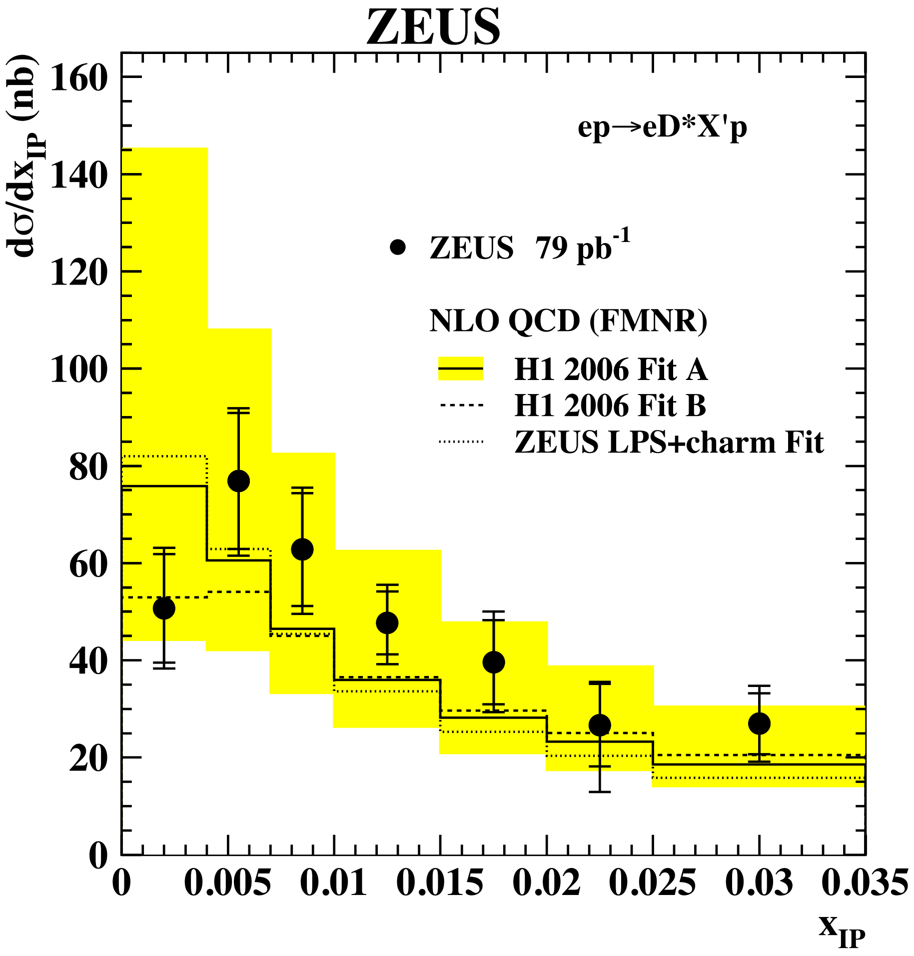


Charm provides a hard scale, ensuring the applicability of pQCD even for low Q^2

is sensitive to the gluon content of the diffractive exchange

RD - fraction of charm production diffractive/inclusive is approximately independent of Q^2





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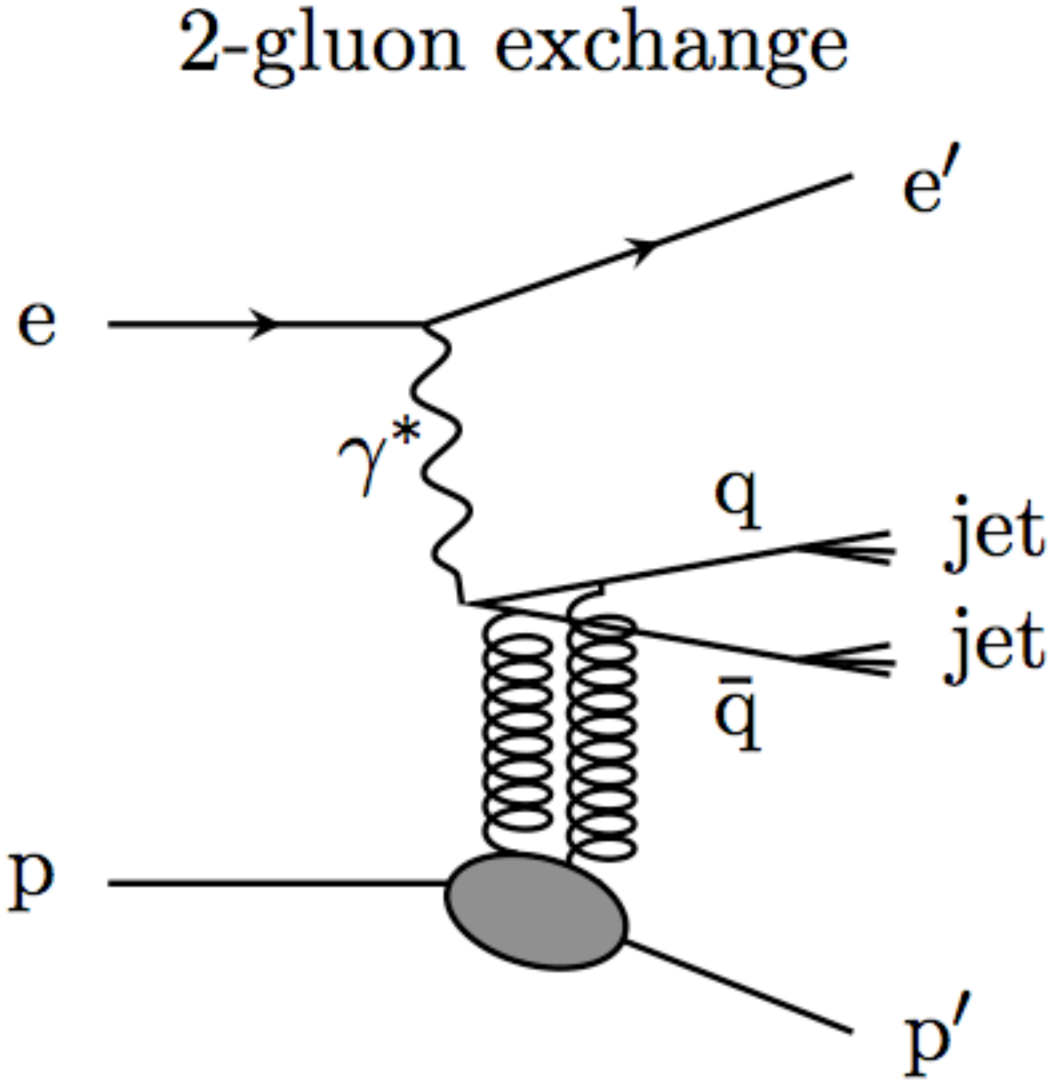
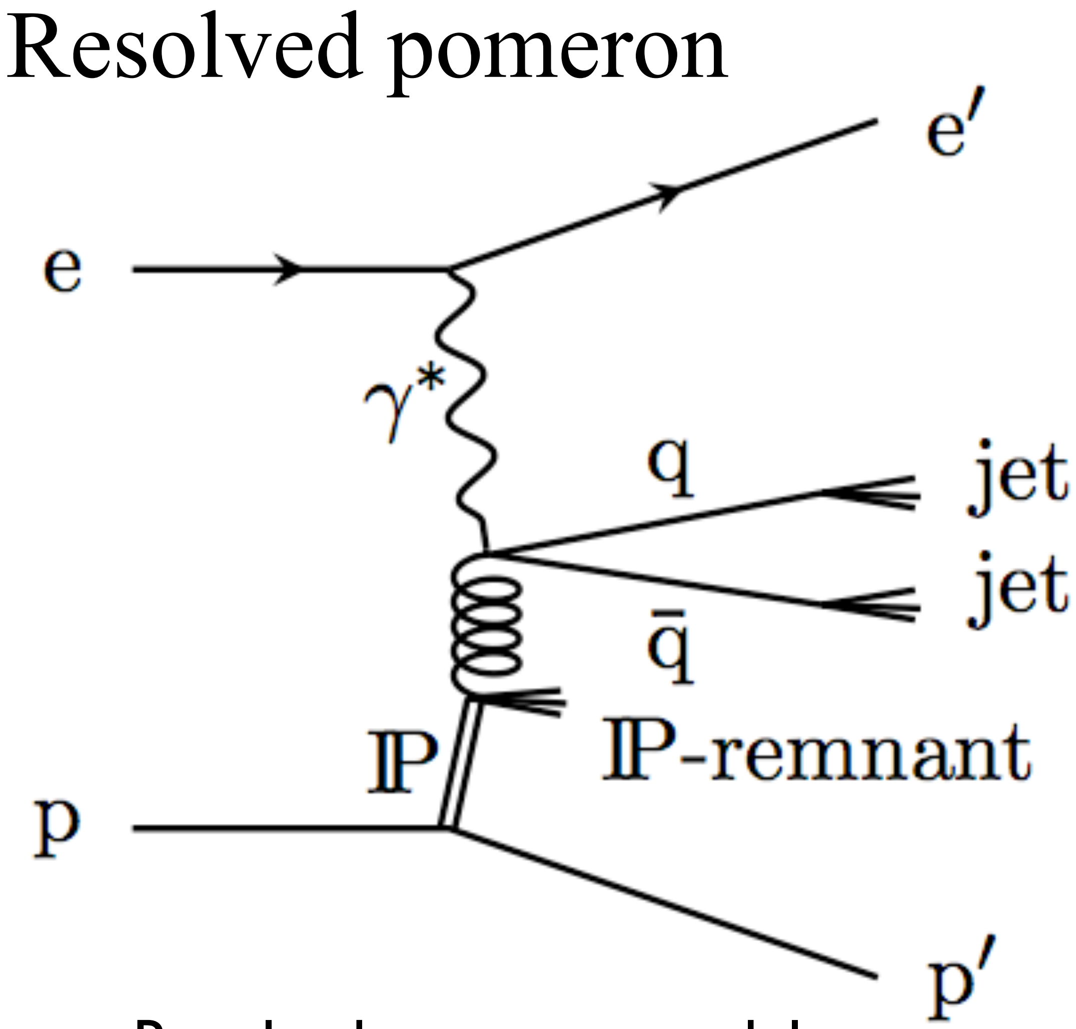
The NLO QCD calculations reproduce the x_{IP} differencial cross section in both shape and normalisation

Supports the QCD factorisation theorem in diffraction, implying the universality of diffractive PDFs

Exclusive dijet production in diffractive DIS


2-gluon exchange

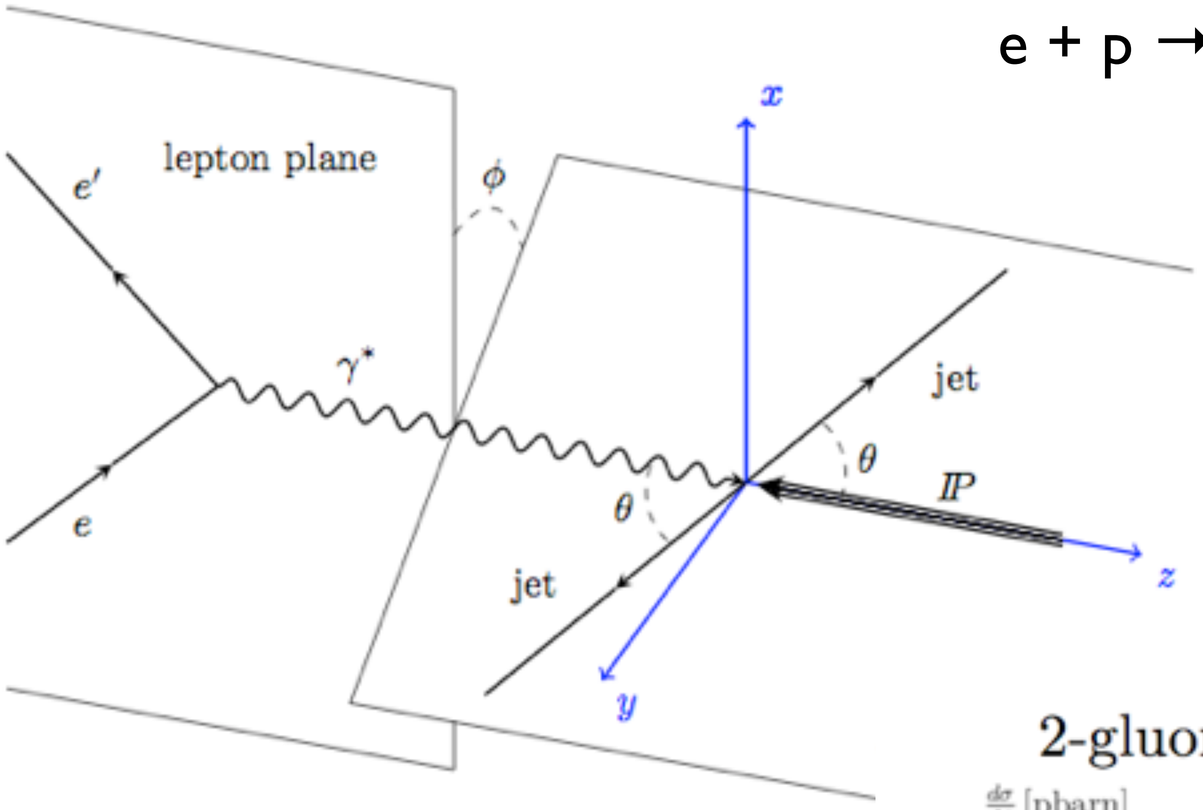
(J. Bartels, H. Jung et al.)
fully perturbative calculations
based on proton PDF -
no extra parameters needed


Resolved pomeron

Resolved pomeron model
(G. Ingelman, P. Schlein et al.)
calculations based on
pomeron structure functions

Models predict different shape for dijet azimuthal angular distribution

Exclusive dijet production in diffractive DIS

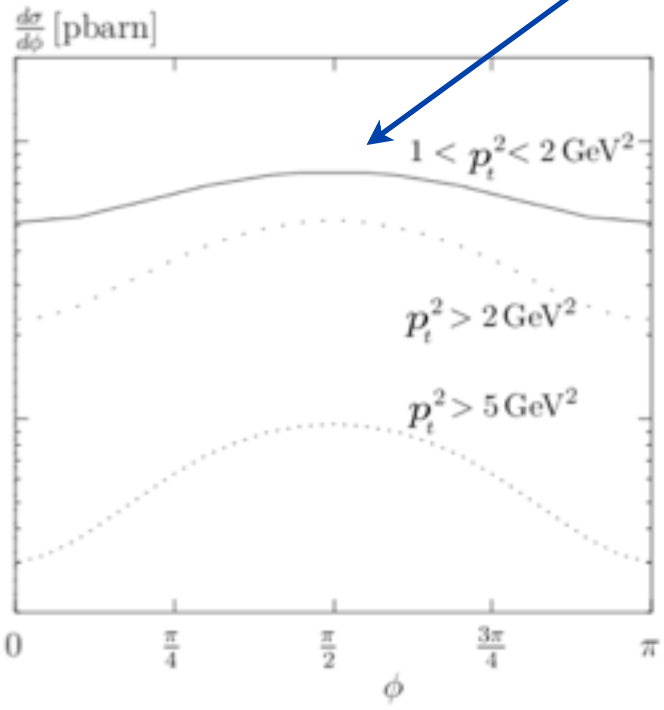


e + p → e’ + p’ + jet + jet

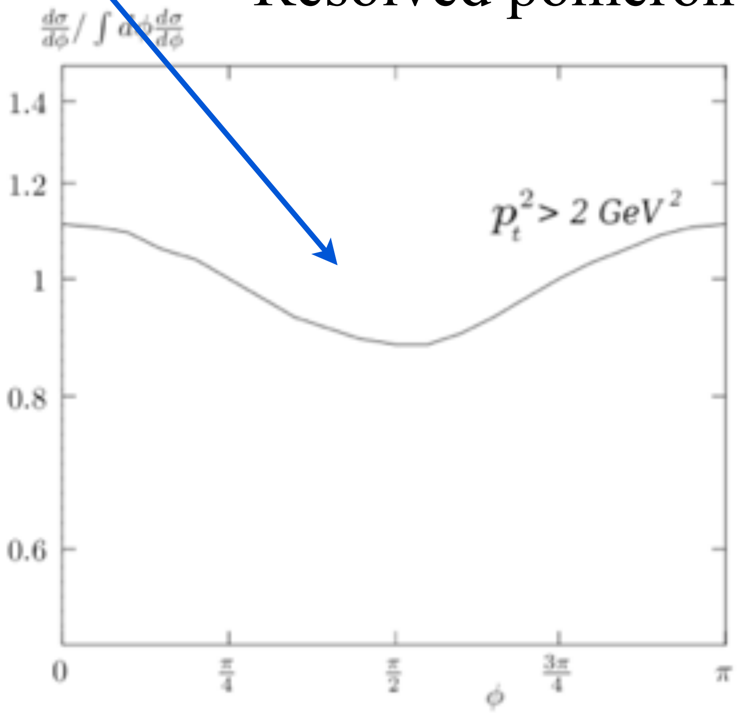
ϕ- angle lepton and jets plane
θ - polar angle of a jet

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

2-gluon exchange

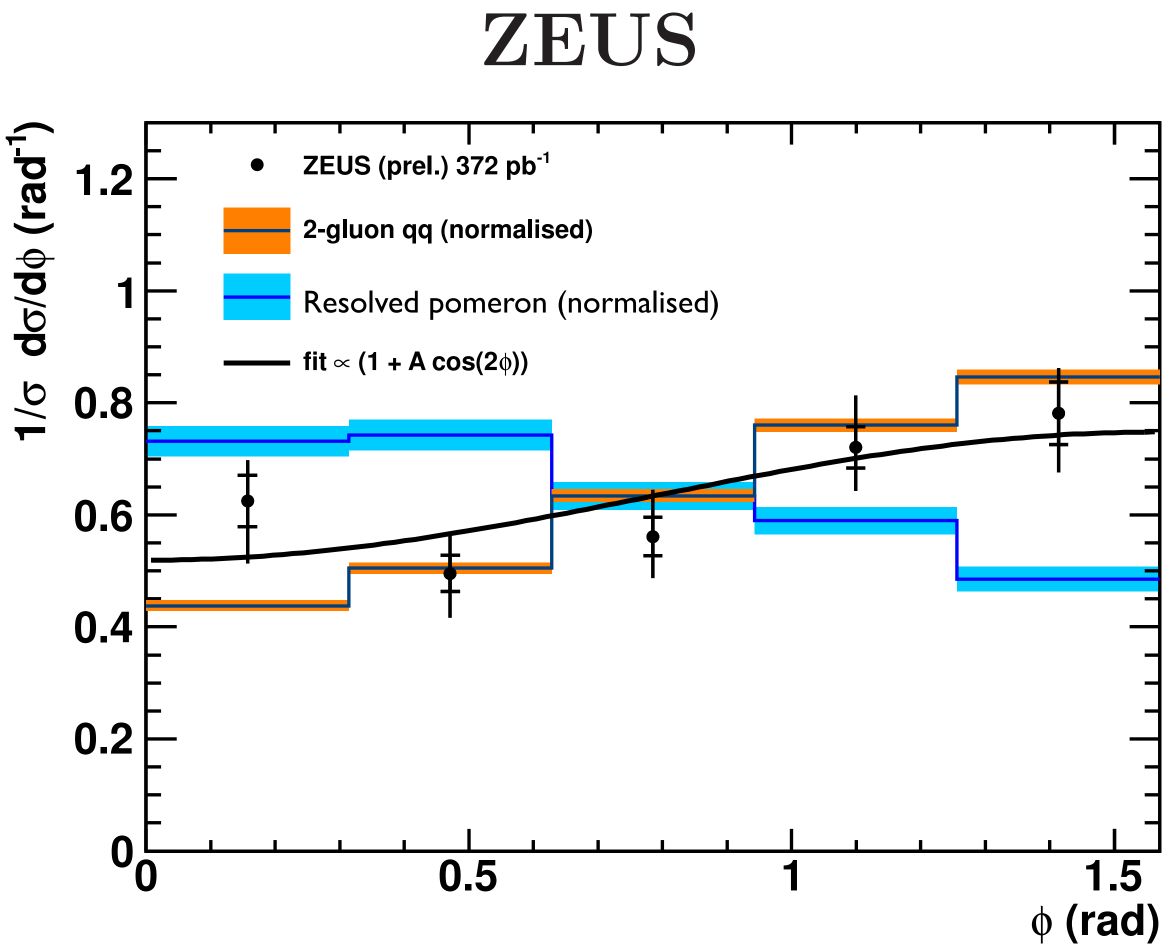


Resolved pomeron



the same function describes dσ/dϕ
for both models
2-gluon exchange - negative A
Resolved pomeron - positive A

Exclusive dijet production in diffractive DIS



Data collected in 2003-7
Analysis method: LRG

Kinematic range to which data are unfolded:
$90 \text{ GeV} < W < 250 \text{ GeV}$
$25 \text{ GeV}^2 < Q^2$
$x_{IP} < 0.01$
$0.5 < \beta < 0.7$
$n_{jets} = 2$
$2 \text{ GeV} < p_{Tjet}$

Hadron level predictions: 2-gluon exchange model and Resolved pomeron model as implemented in RAPGAP 3.01/26

Negative A favours 2-gluon exchange model
None of the models is able to describe the normalisation of the data

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

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

Summary

- Diffractive events observed at HERA since 1993
- Diffraction studies by means of LRG and proton spectrometer
- Diffractive structure function F_2D and F_LD measured at HERA
- Diffractive cross section measurement results from H1 and ZEUS unified → increase in statistics and reduction of systematics
- Diffractive DIS dijet cross section agrees well with NLO QCD calculations → QCD factorisation confirmed
- Diffractive dijet DIS and photoproduction with leading proton compared to NLO QCD calculations. Factorisation breaking of ~ 0.5 observed in photoproduction by H1. Result not confirmed by ZEUS, which sees good agreement between data and NLO QCD also for photoproduction.
- Measurement of the shape of the azimuthal angle distributions of exclusive dijets in diffractive DIS prefers 2-gluon exchange model over Resolved Pomeron model.