Inclusive diffraction at HERA

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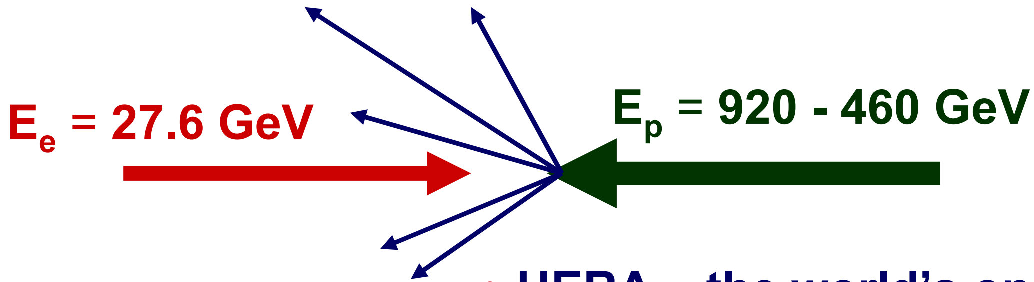
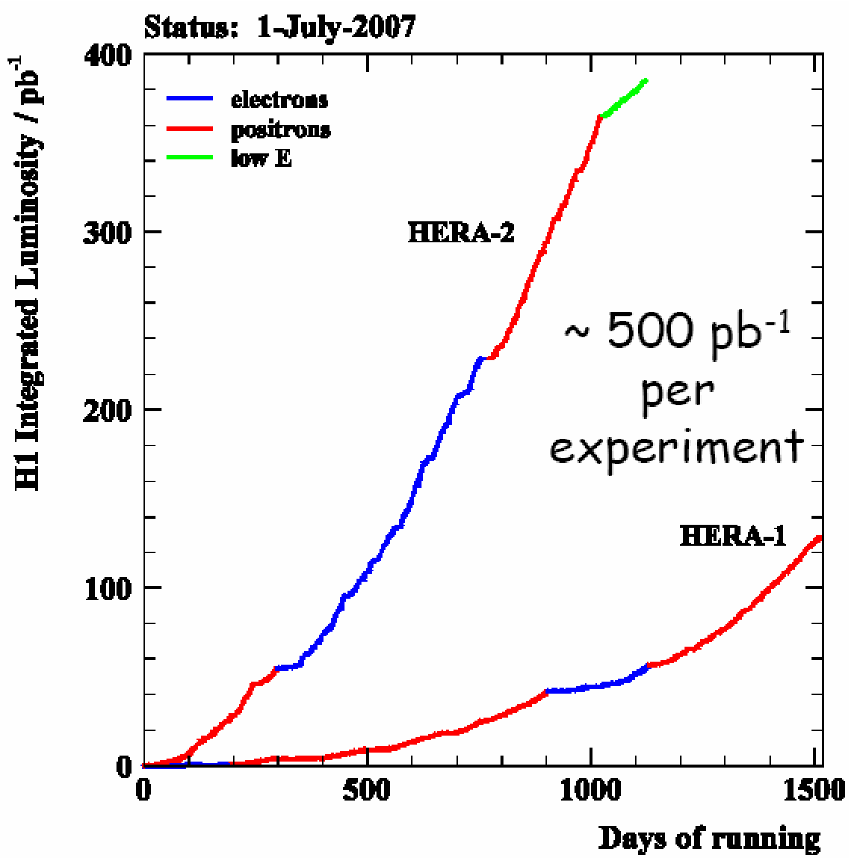
on behalf of the H1 and ZEUS collaborations

- **Selection of diffractive events**
- **Diffractive parton distribution functions**
- **Tests of QCD factorisation**
- **First combination of the H1 and ZEUS diffractive data** (proton tag)
- **Precision Large Rapidity Gap cross sections**
- **Pomeron trajectory**
- **F_L^D measurement**
- **Conclusions**

HERA





- **HERA – the world's only ep collider**

  operated in 1992-2007 colliding electrons or positrons with protons

- **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)

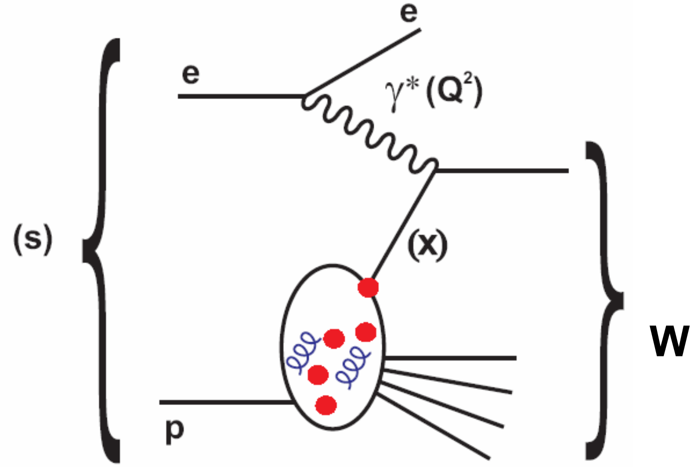
- **Reduced proton beam energy :**

  E_p = 460 GeV, $\sqrt{S}$ = 225 GeV

  E_p = 575 GeV, $\sqrt{S}$ = 250 GeV

  Low energy data → measurements of the longitudinal proton structure functions F_L and F_L^D

Deep inelastic scattering at HERA



Standard DIS variables :

Q^2 |virtuality| of the exchanged boson

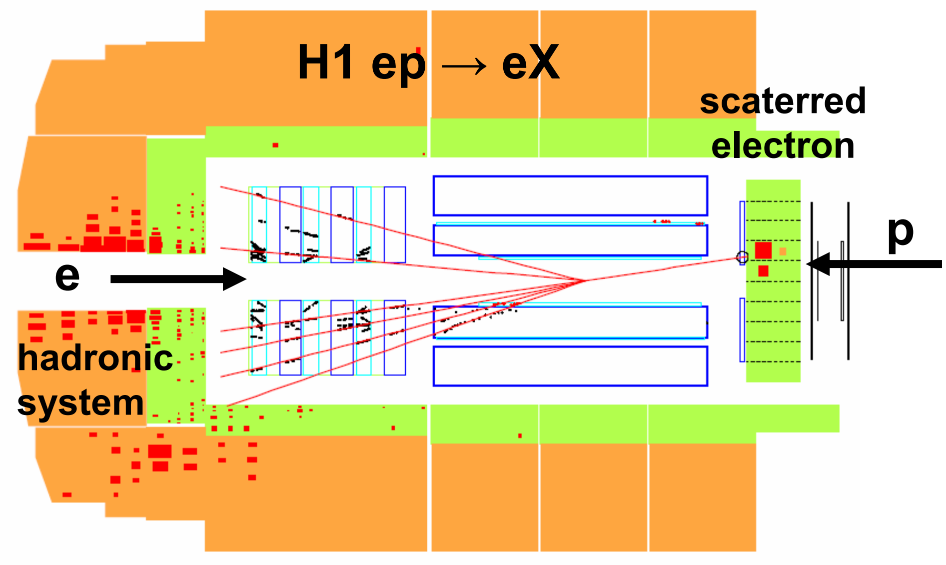
x fraction of proton momentum carried by struck quark in Quark Parton Model

y inelasticity, fraction of lepton energy transfered in the proton rest frame

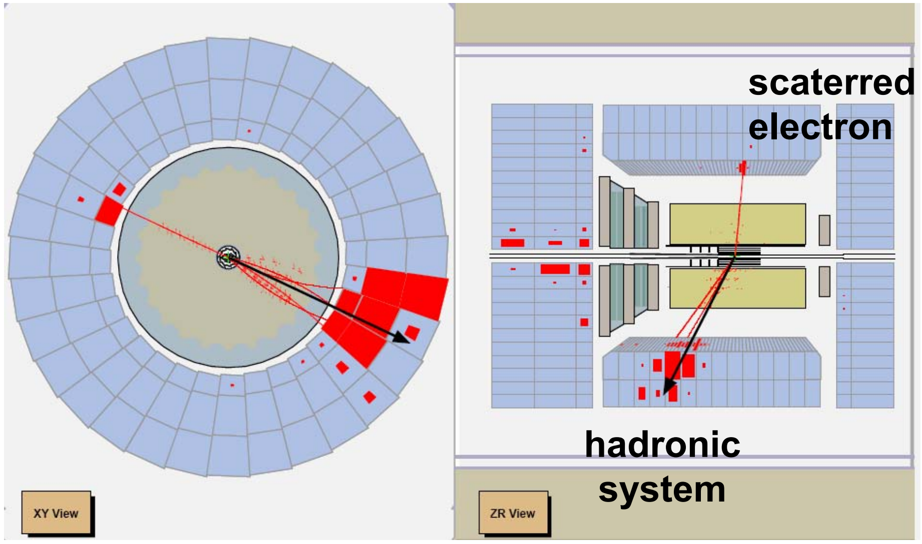
$Q^2 \approx xys$

$\sqrt{s}$: e-p centre-of mass energy

W : invariant mass of hadronic final state



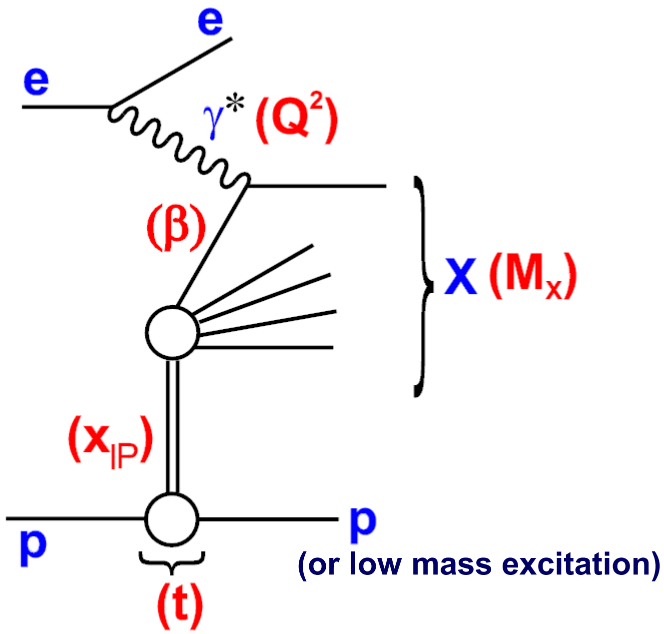
ZEUS ep → eX



Diffractive deep inelastic scattering at HERA

Surprise of HERA : ~10% of DIS events at HERA have no activity in the forward direction (Large Rapidity Gap events)

→ exchange of a colourless object, called Pomeron (IP)



Additional variables for DDIS :

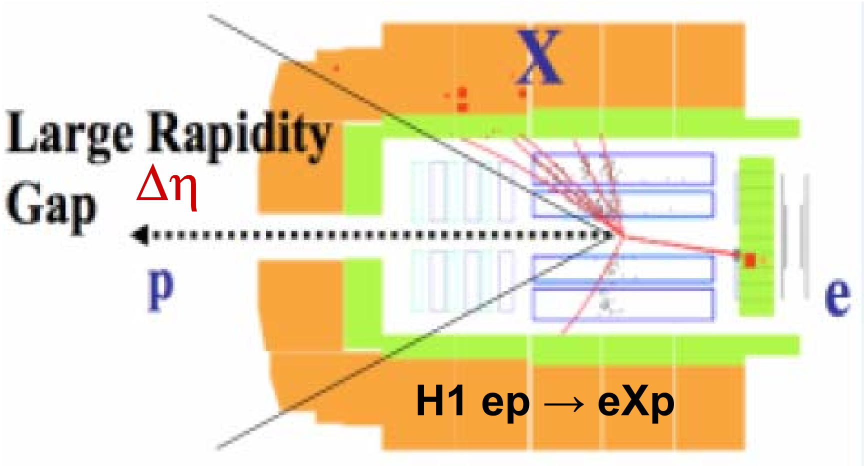
$$x_{I\!P} = \xi = \frac{Q^2+M_X^2}{Q^2+W^2}$$

p-momentum fraction carried by IP

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

IP-momentum fraction carried by struck quark

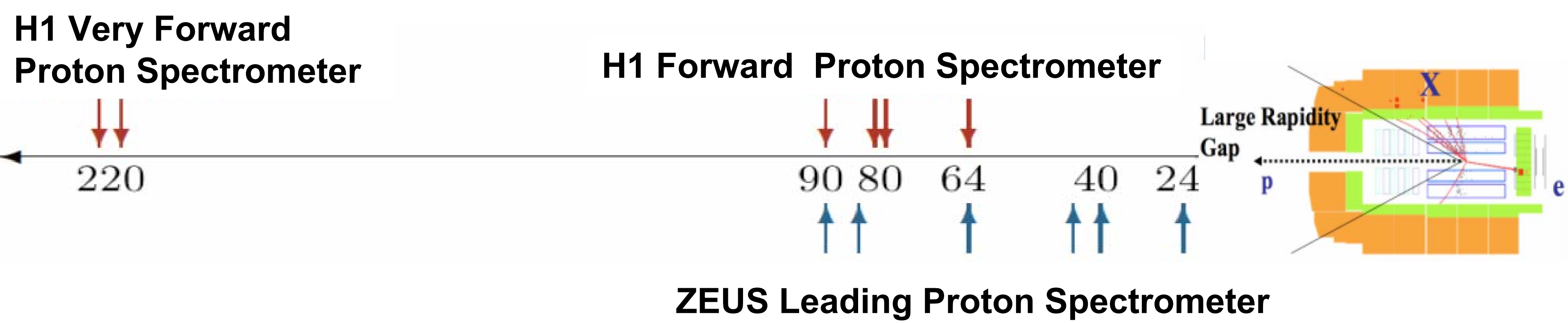
t squared 4-momentum transfer at proton vertex



$\Delta\eta \sim \ln(W^2 / M_X^2)$

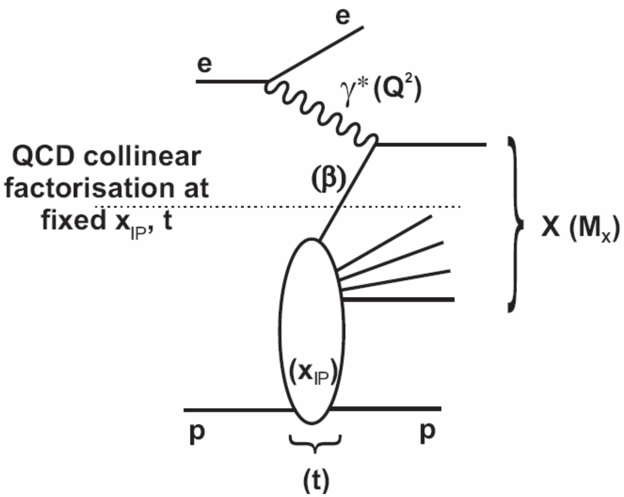
$\eta = -\ln [\tan (\theta/2)]$

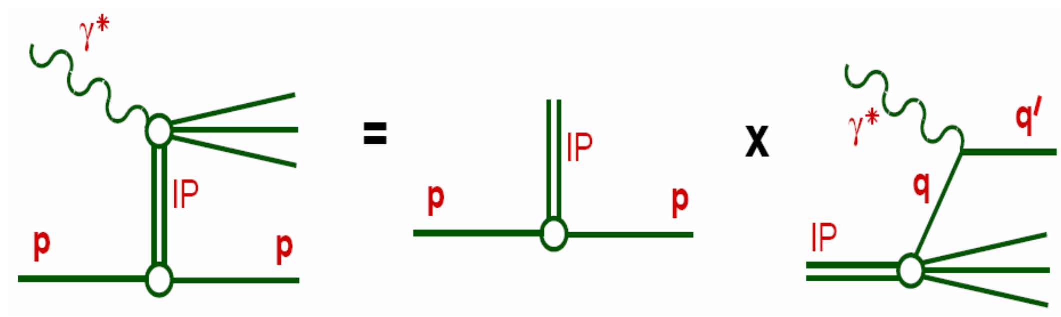
Selection of diffractive events



- **Proton spectrometers:**
  - detection of elastically scattered protons
  - low geometrical acceptance → less 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**

Infinite proton momentum frame : diffractive structure function approach





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

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

f_i^D – diffractive parton density functions (DPDFs), DGLAP evolution in Q^2

σ^{ei} – partonic cross sections, same as in inclusive DIS

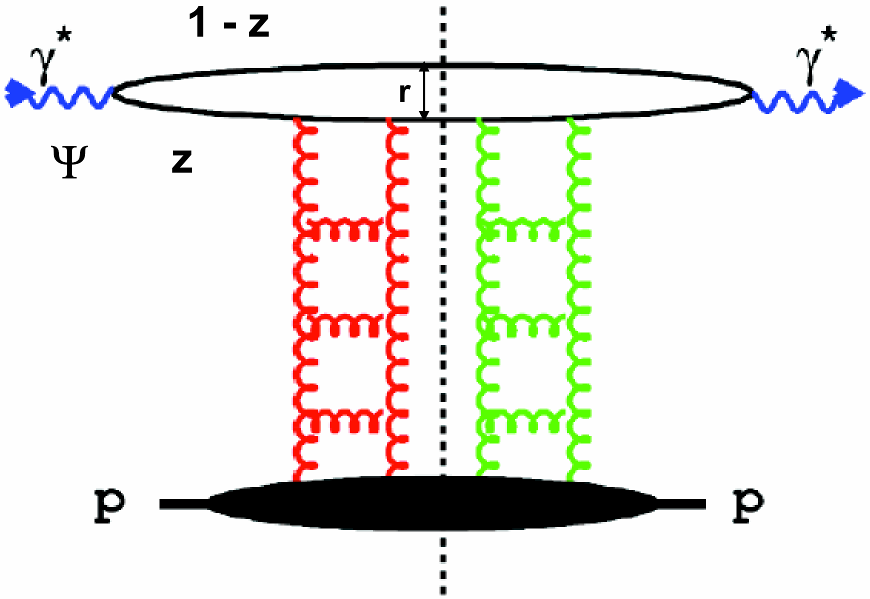
Proton vertex factorisation (Ingelman&Schlein, 1985):
separate (x_{IP}, t) from (β, Q^2) dependences

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

No QCD basis,
consistent with experimental data

Pomeron flux (Regge form)	Pomeron structure function

Proton rest frame : dipole approach



- The virtual photon fluctuates into a colour singlet $q\bar{q}$ pair (called dipole)
  - transverse size of the dipole r ~ 1/Q
  - contribution of $q\bar{q}$- g dipoles at low β
- The long living dipole interacts with the gluons from the proton

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

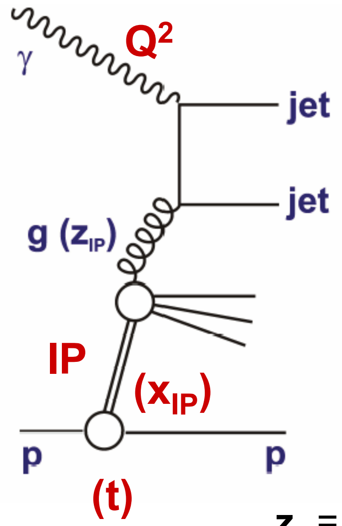
Ψ : $\gamma^* \rightarrow q\bar{q}$ wavefunction

σ_{qq} : dipole-proton cross section

- Direct relation to inclusive DIS
  (the same dipole scattering amplitudes applied for inclusive and diffractive cross sections)

- Dipole approach incorporates saturation dynamics
  pioneering work of K. Golec-Biernat & M. Wüsthoff, 1999
  hep-ph / 9807513, hep-ph / 9903358

Diffractive parton density functions

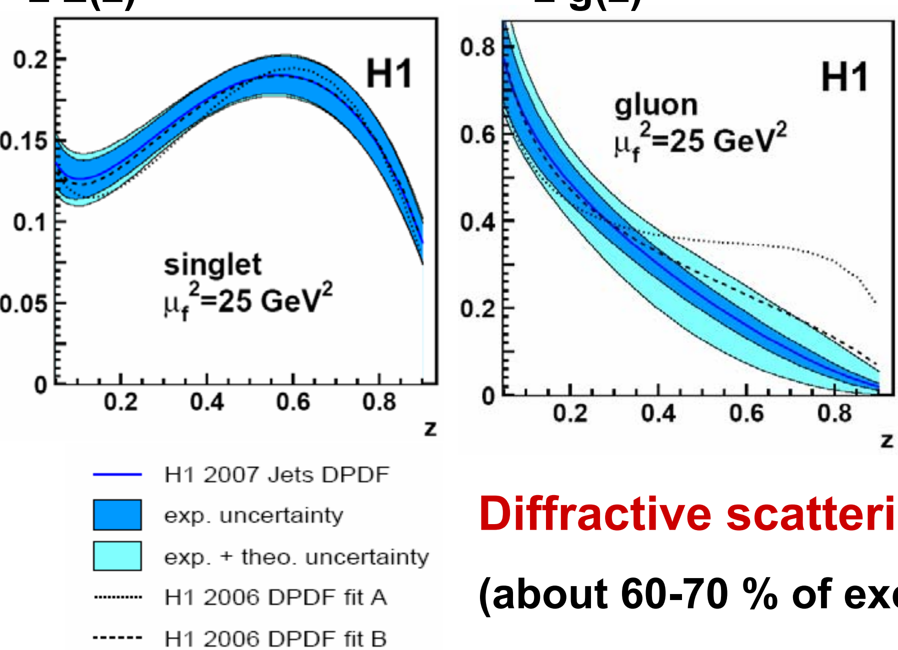


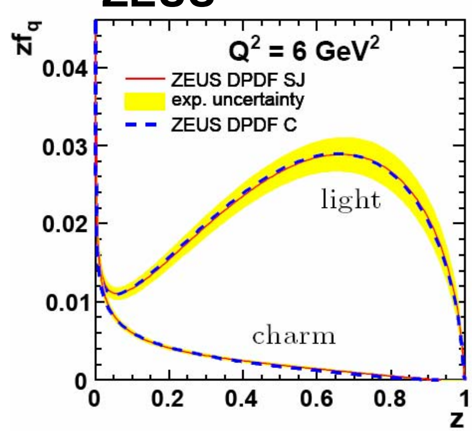
- Diffractive PDFs obtained through NLO DGLAP QCD fit to data
  - inclusive DDIS cross section → diffractive gluon density weakly constrained at high z_{IP}
  - combined fit to diffractive inclusive and dijet cross sections → comparable precision of quark and gluon densities for all z_{IP}

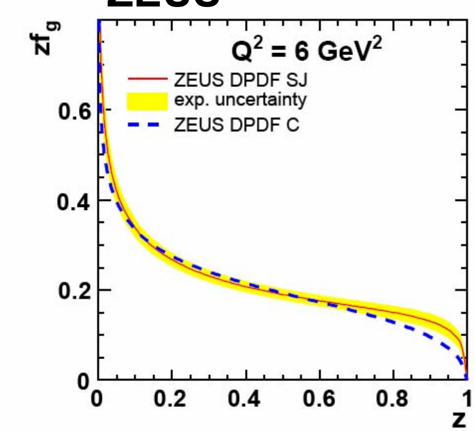
    (H1 2007 Jets DPDF, ZEUS DPDF SJ)

z_{IP}= momentum fraction parton / IP

singlet quark density $z\cdot\Sigma(z)$ | **gluon density** $z\cdot g(z)$ | **quark density** ZEUS | **gluon density** ZEUS

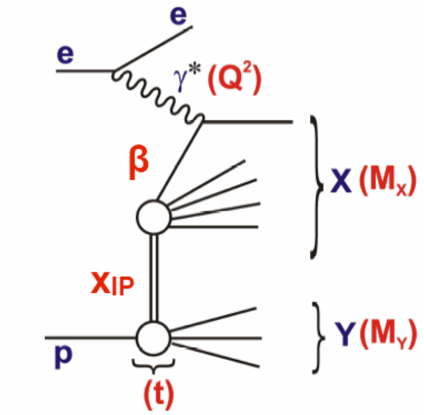






Diffractive scattering is dominated by gluons

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



Fits ZEUS DPDF SJ and H1 2006 DPDF Fit B

compared to

the ZEUS LRG data

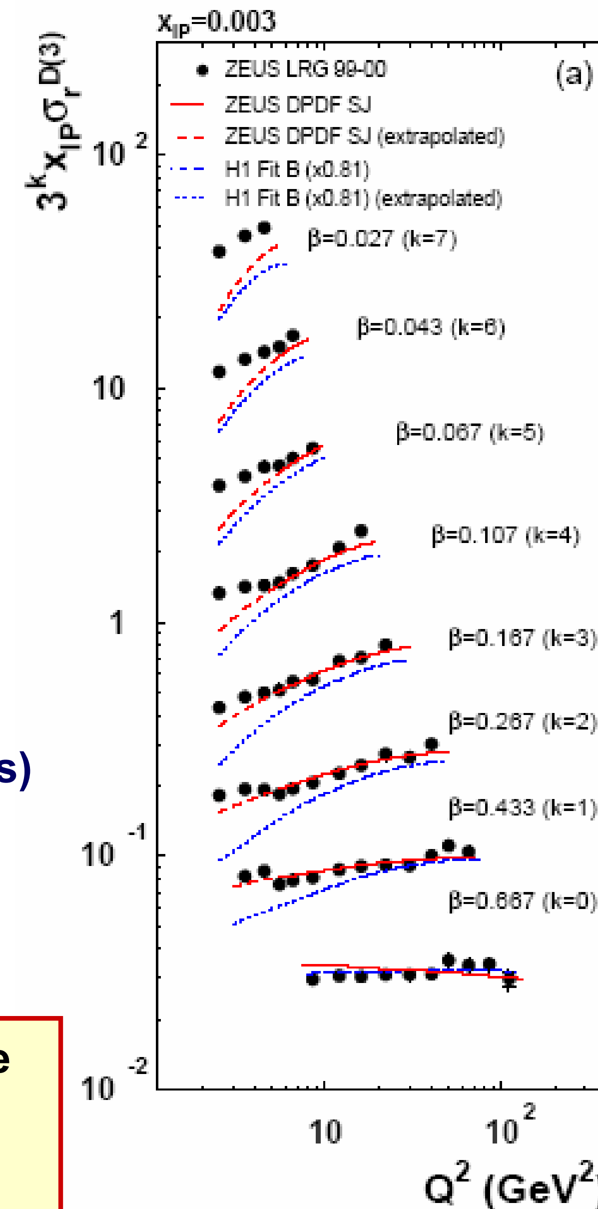
- **Differential cross section :**

$$\frac{d\sigma^{ep\to eXp}}{d\beta dQ^2 dx_{I\!P}} = \frac{2\pi\alpha^2}{\beta Q^4}\left[1+(1-y)^2\right]\sigma_r^{D(3)}(\beta, Q^2, x_{I\!P})$$

- **Diffr. reduced cross section (related to structure functions)**

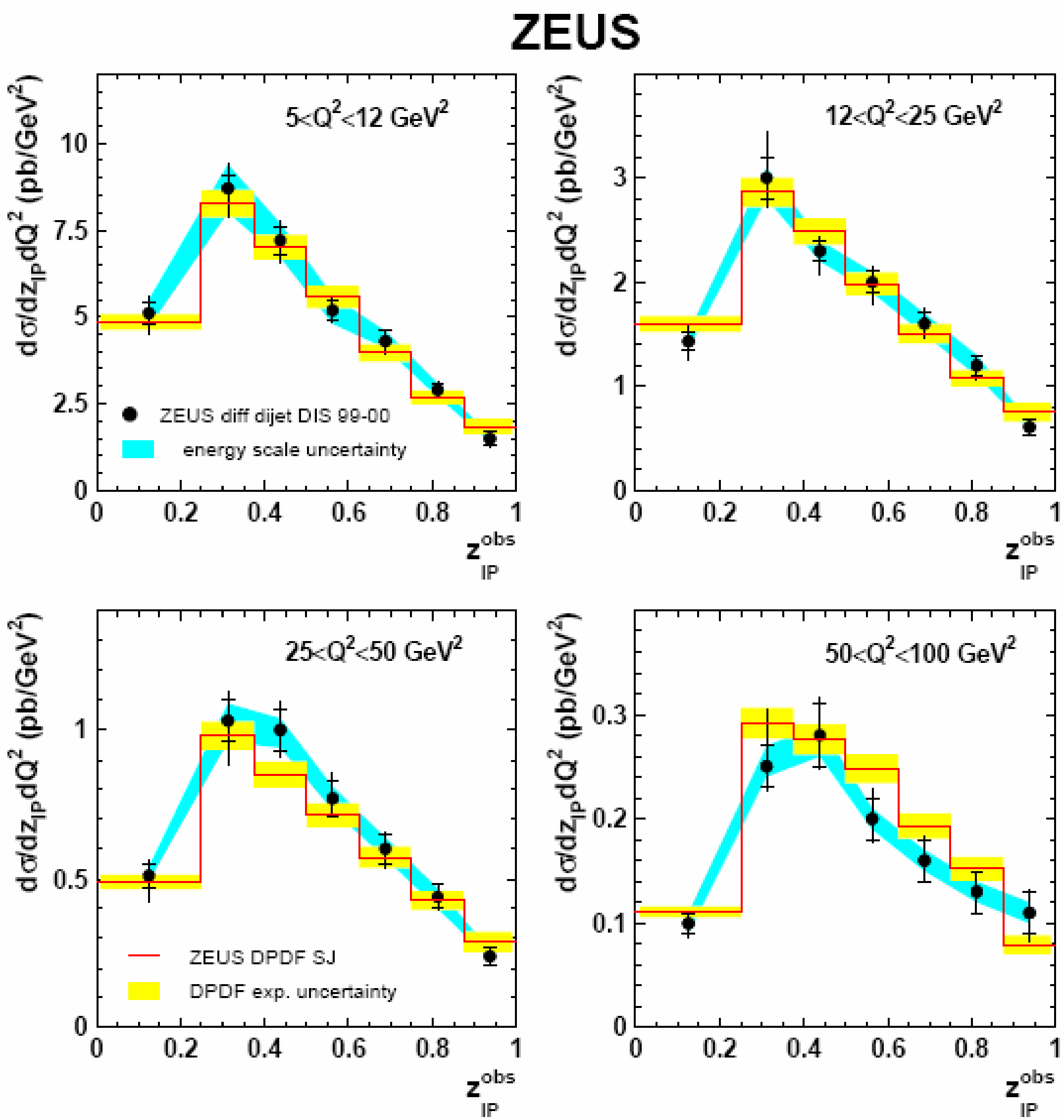
$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{1+(1-y)^2}F_L^{D(3)}$$

For β < 0.2, ZEUS and H1 fits agree in shape, but show some difference in the normalisation.
At higher β and where the predictions are extrapolated the disagreement becomes larger.

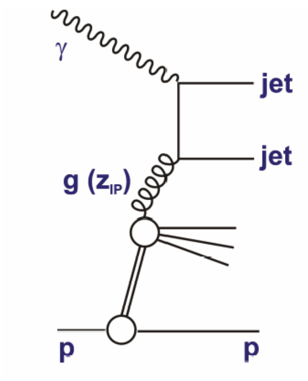


Nucl. Phys. B831 (2010) 1

Test of QCD factorisation



- Diffractive dijets in DIS



- NLO QCD + ZEUS DPDF SJ remarkably good description of the dijet data
- QCD factorisation holds
- precision limited by theory scale uncertainty

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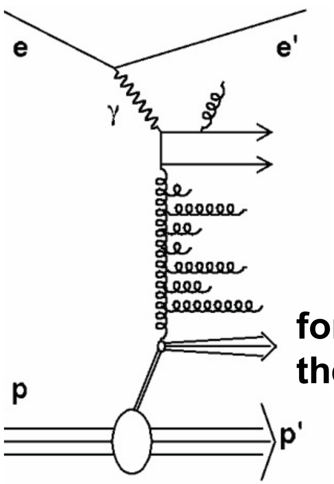
Dijets in diffractive DIS with a leading proton

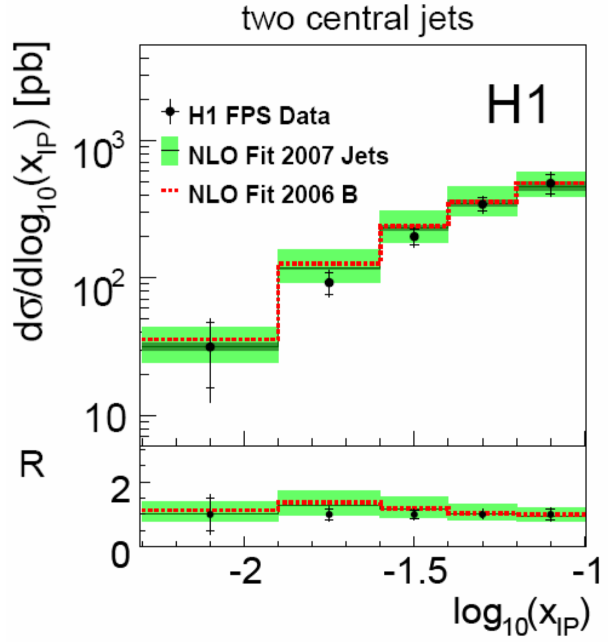
2 topologies:

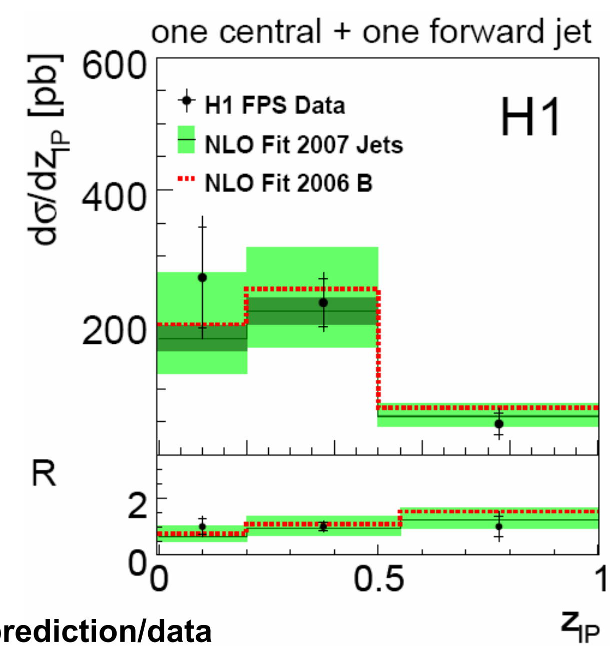
- **two central jets**
- **one central + one forward jet**

search for physics beyond DGLAP



forward jet close to the proton





R = prediction/data

DPDF + NLO QCD works well :

QCD factorisation holds in DIS regime

No sign for deviations from DGLAP

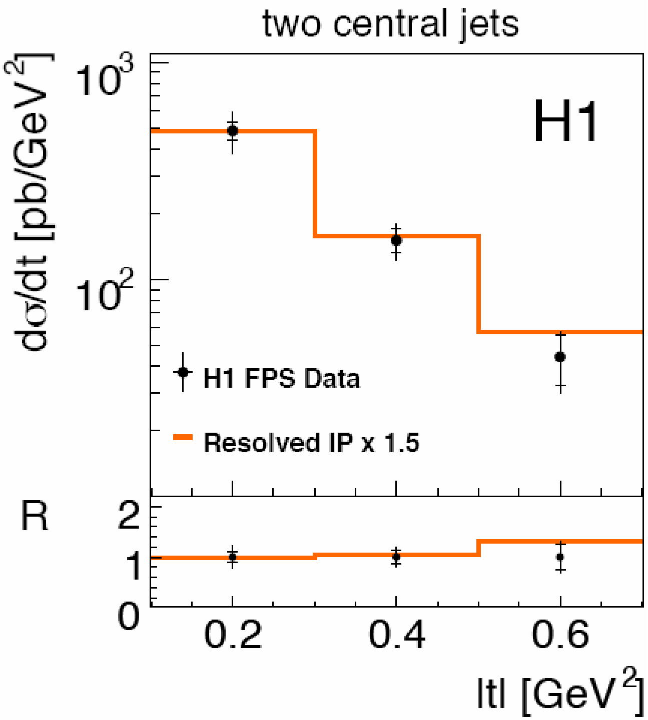
Eur. Phys. J. C72 (2012) 1970

Dijets in DDIS with a leading proton - proton vertex factorisation

$4 < Q^2 < 110$ GeV^2, $0.05 < y < 0.7$, $x_{IP} < 0.1$, $|t| < 1$ GeV^2

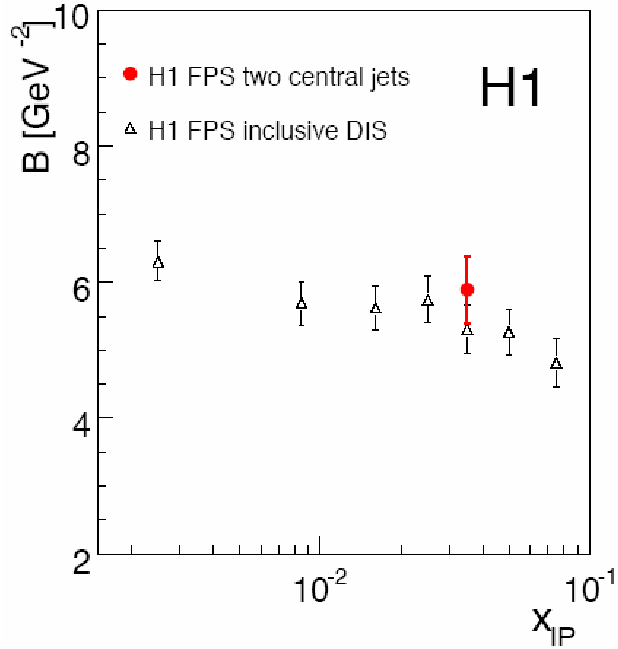
pt of jets in hcms **$p_{T,1}^* > 5$ GeV, $p_{T,2}^* > 4$ GeV, $-1 < \eta_{1,2} < 2.5$**

Eur. Phys. J. C72 (2012) 1970



Regge motivated fit exp(Bt)

→ B = 5.89 ± 0.50 GeV^{-2}



t slope consistent with the value measured in inclusive diffractive DIS with a leading proton in the final state

Confirmation of the proton vertex factorisation hypothesis for diffractive dijet production

Combination of proton tagged data

First combined H1 (FPS & VFPS) and ZEUS (LPS) data

$2.5 < Q^2 < 200$ GeV^2, $0.00035 < x_{IP} < 0.09$,

$0.09 < |t| < 0.55$ GeV^2, $0.0018 < \beta < 0.816$

Combination includes correlations of systematic uncertainties

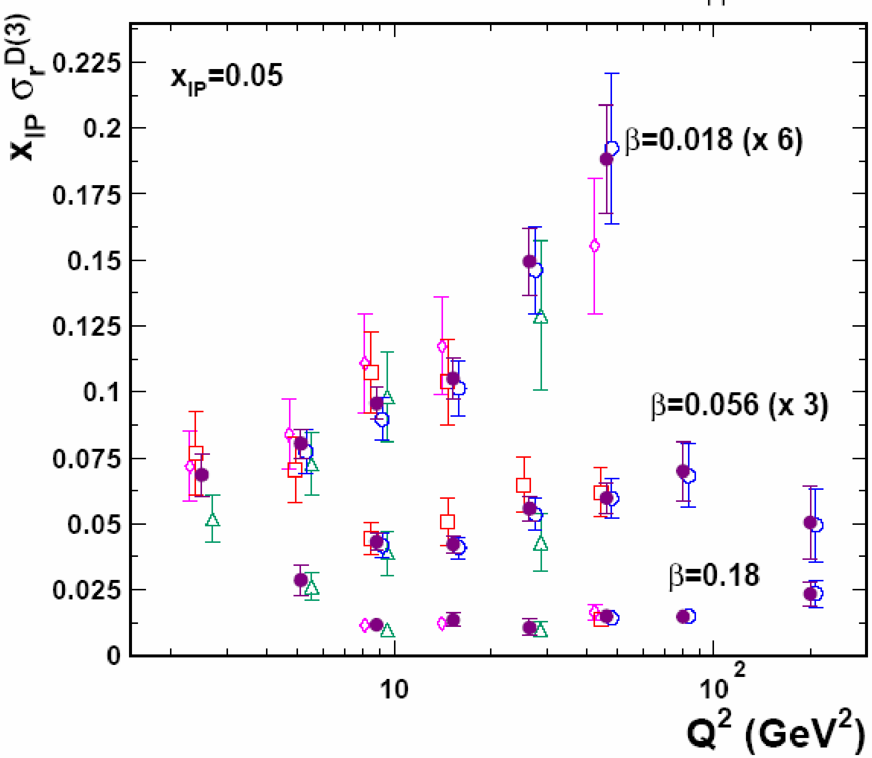
profits from different detectors (systematics)

cross calibration reduces uncertainties significantly (total uncertainty on the x-sec is 6% for the most precise points)

Scaling violation clearly visible

Most precise determination of the absolute normalisation of the ep → eXp cross section

Eur. Phys. J. C72 (2012) 2175



Diffraction with Large Rapidity Gap

- **New H1 data sets combined with previously published data**
  35 x more data @ medium Q^2
  [Eur. Phys. J. C72 (2012) 2074]

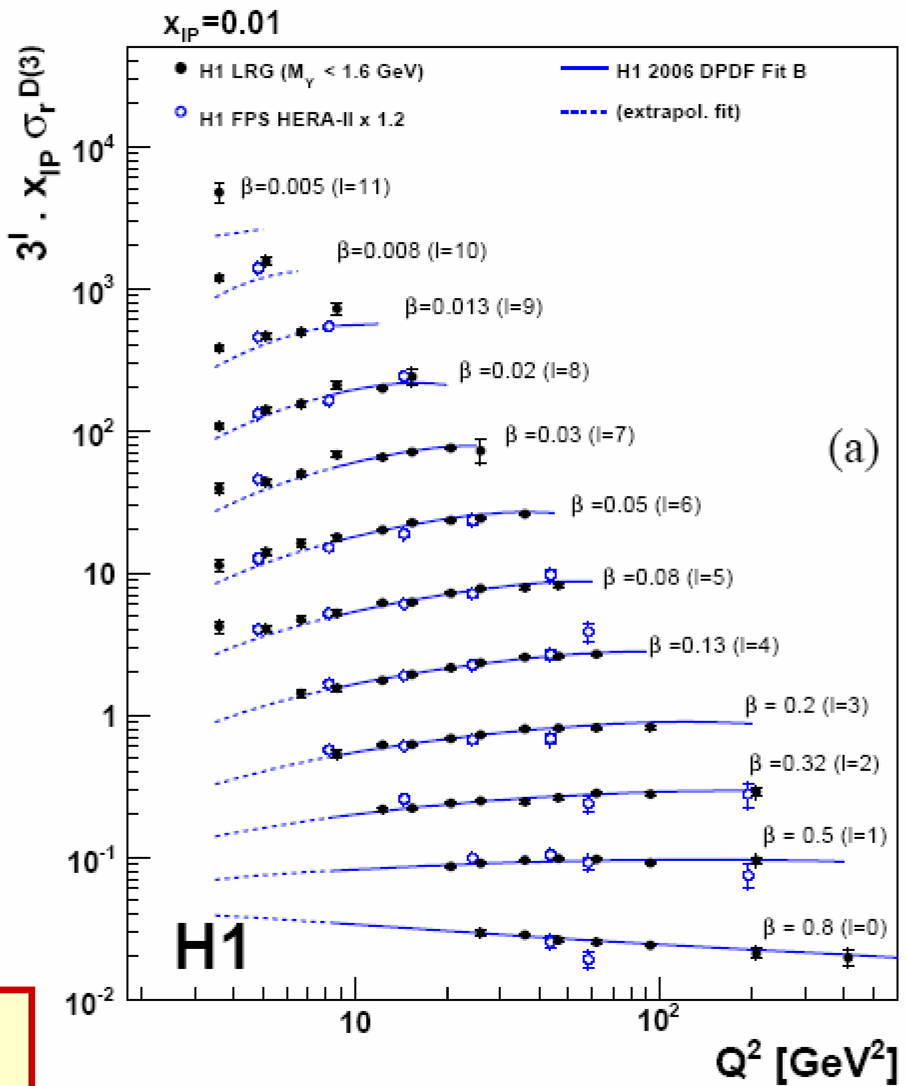
- **Kinematical coverage:**
  $3.5 < Q^2 < 1600$ GeV^2
  $0.0017 < \beta < 0.8$
  $0.0003 < x_{IP} < 0.03$

- **Ratio of the LRG and the proton spectrometer FPS results quantifies the contribution of the proton dissociation in LRG**

$$\frac{\text{LRG}}{\text{FPS}} = 1.203 \pm 0.019(\text{exp}) \pm 0.087(\text{norm})$$

LRG and FPS data agree well,
no Q^2 and β differences observed

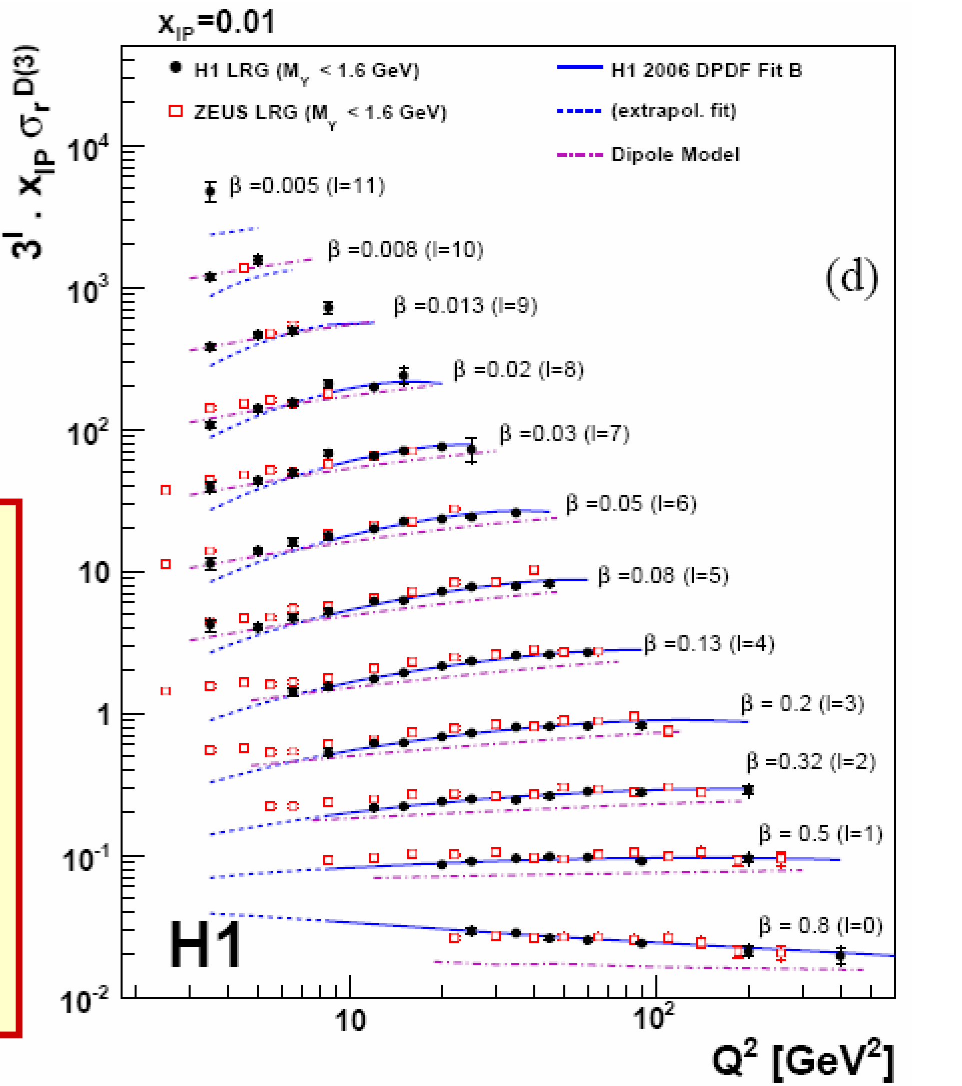
NLO QCD (DPDF) does well for $Q^2 > 10$ GeV^2



Diffraction with Large Rapidity Gap

Eur. Phys. J. C72 (2012) 2074

- Good agreement between H1 and ZEUS data in general
- ~10% normalisation difference (within the uncertainties)



NLO QCD + DPDF:

– problems at low Q^2
– good for Q^2 > 10 GeV^2

Dipole model with saturation:

– good at low Q^2

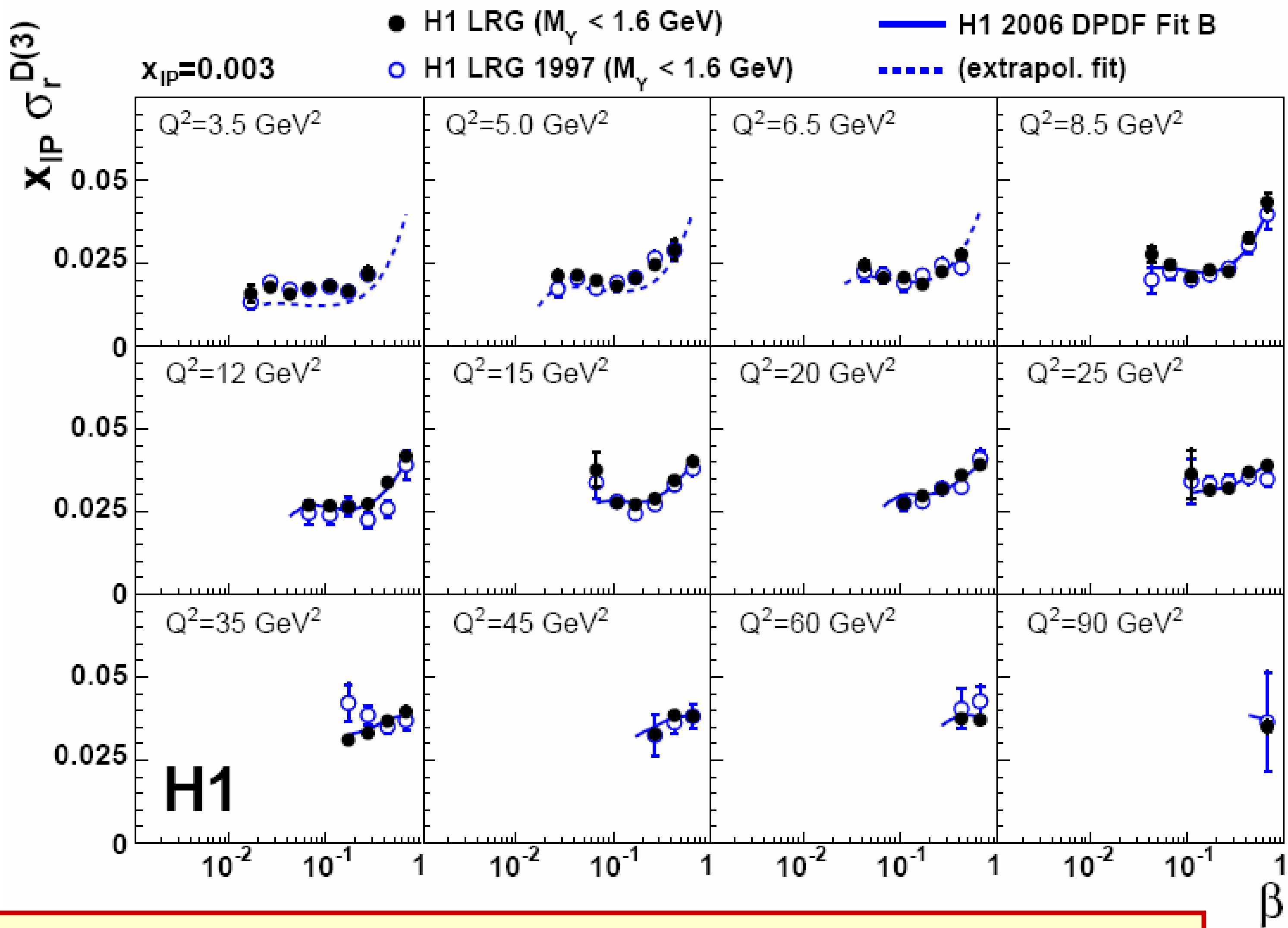
– too low at high Q^2 and β

New precise data challenge models

Dipole model :
C. Marquet, arXiv:0706.2682

Diffraction with Large Rapidity Gap

Eur. Phys. J. C72 (2012) 2074



β dependence of the combined reduced cross section (H1 LRG) multiplied by x_{IP}

Good agreement with NLO QCD predictions based on DPDFs (H1 2006 DPDF Fit B)

Pomeron trajectory

- **Regge fit to LRG cross section (contributions of Pomeron and reggeon trajectories)**

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

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

Mean value of the Pomeron intercept :

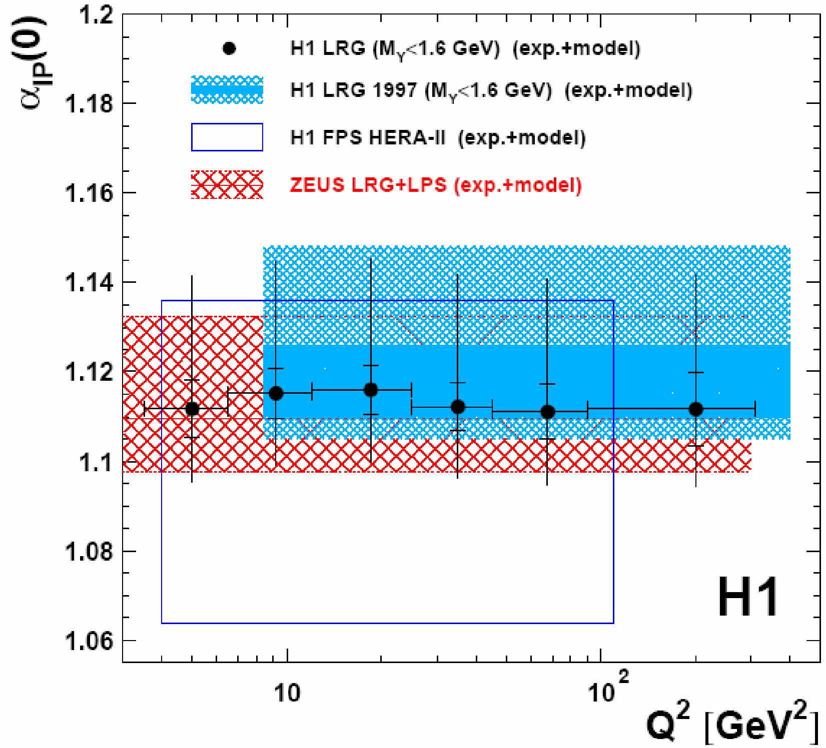
$$\alpha_{I\!P}(0) = 1.113 \pm 0.002\ (\mathrm{exp.})\ ^{+0.029}_{-0.015}\ (\mathrm{model})$$

- **Independent of Q^2**
- **Good agreement of all HERA measurements**
- **Supports the proton vertex factorisation**

$\alpha_{IP}(0)$ – consistent with 'soft IP'

$\alpha'_{IP} \leq 0.1$ – typical for 'hard IP'

Eur. Phys. J. C72 (2012) 2074



→ **complicated interplay of hard and soft phenomena**

Diffractive longitudinal structure function F_L^D

- F_L^D is sensitive to gluons and provides an independent test of QCD factorisation

- The F_L^D and F_2^D structure functions can be only separated by combining measurements at different y (for fixed x_{IP}, β, Q^2)

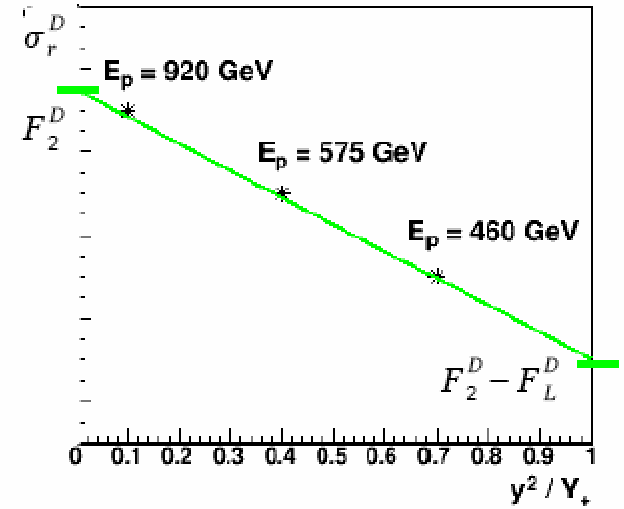
$$\sigma_r^D = F_2^D - \frac{y^2}{Y_+} F_L^D \qquad Y_+ = 1 + (1-y)^2$$

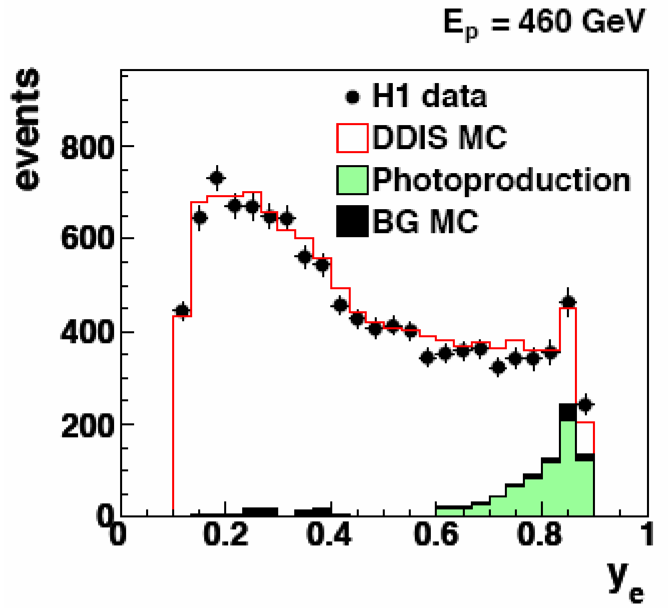
$$Q^2 = x_{IP}\, \beta\, y\, s$$

- Data at different centre-of-mass energy are needed

- Highest sensitivity to F_L^D at high y (low β)

- Challenging measurement due to high level of photoproduction background

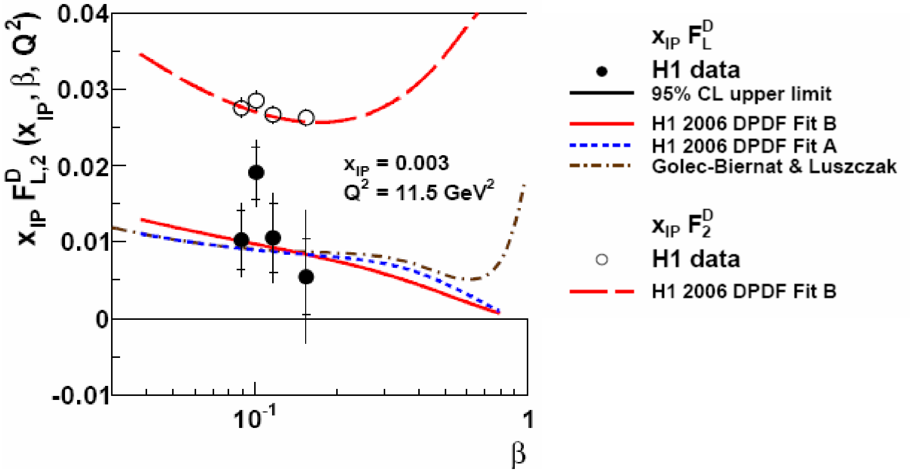




F_L in diffraction

Eur. Phys. J. C72 (2012) 1836

Direct mesurement of F_2^D and F_L^D (no assumptions)

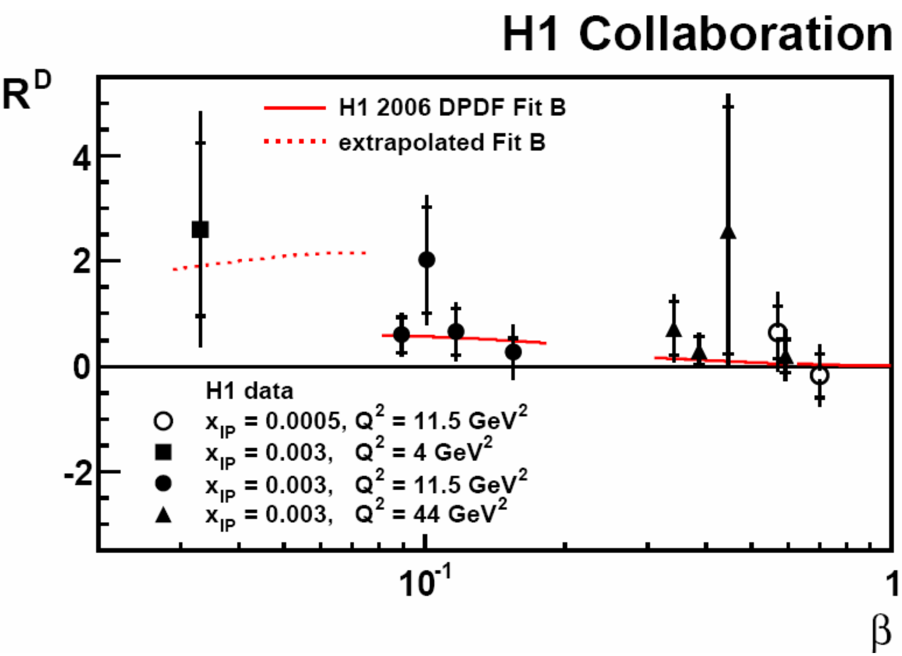


F_L^D measurements compared with leading twist predictions (NLO QCD + H1 DPDF) and with the model including a higher twist contribution derived from a colour dipole approach (Golec-Biernat & Luszczak)

Clearly non-zero F_L^D

$0 < F_L^D < F_2^D$

Predictions agree (no distinction possible)



Ratio R^D of cross sections for longitudinally to transversly polarised photons :

$R^D = F_L^D / (F_2^D - F_L^D)$

At $Q^2 = 11.5$ GeV^2 longitudinally and transversly polarized photon cross-sections are of the same magnitude ($R_D \sim 1$ and $F_2^D \sim 2F_L^D$)

Summary

20 years of diffraction measurements at HERA

- First combination of the H1 and ZEUS diffractive data (proton- tag results)
- H1 precision LRG measurement using the full dataset
  Overall good agreement between H1 and ZEUS results
- The first direct measurement of F_L^D
- HERA measurements support the proton vertex and QCD factorisation hypothesis
- Precise HERA data provide new constraints to QCD based models

Interplay between soft and hard phenomena still represent a challenge for theoretical models of ep diffraction

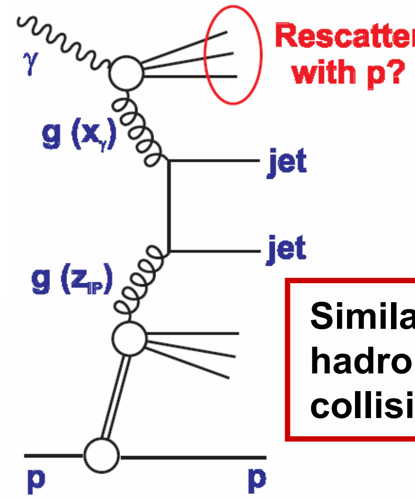
backup

Dijets in photoproduction – breaking of QCD factoristaion ?

γ^*p, $Q^2 \to 0$, direct and resolved photoproduction

hadron-like component in resolved γ^*p : photon fluctuates into hadronic system taking part in hard scattering ($x_\gamma < 0.2$)

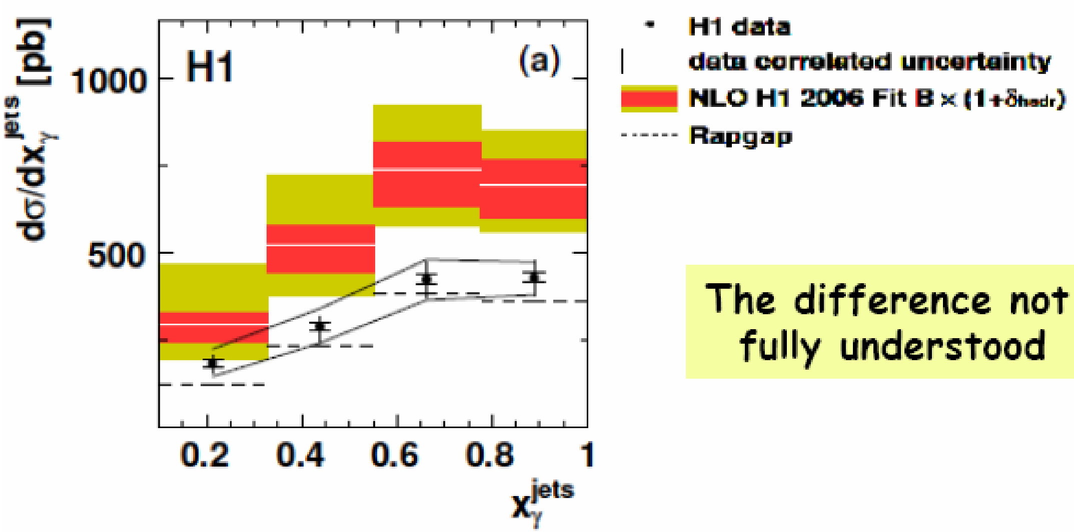
X_γ – fraction of photon's momentum in hard subprocess



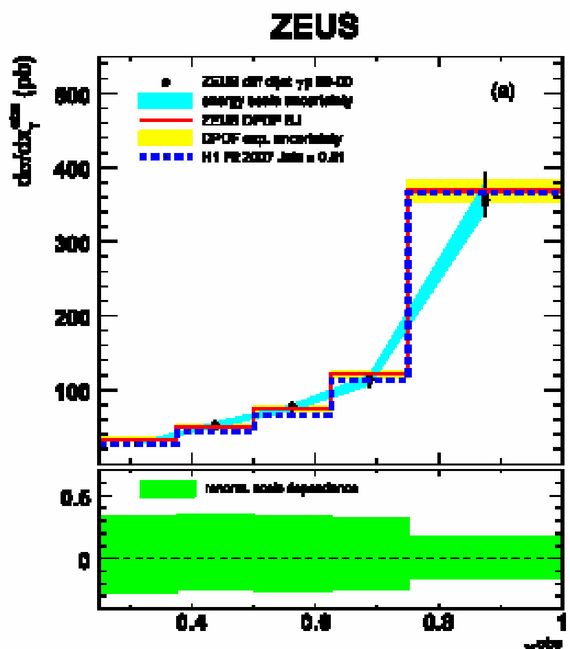
Similarity with hadron-hadron collisions

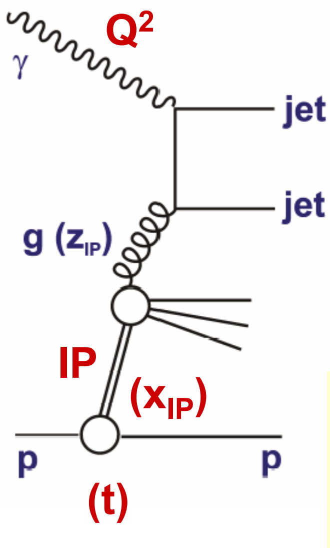
Factorisation breaking observed by H1, two analyses,
EPJC C51 (2007),549, - suppression ~ 0.5
EPJ C68 (2010),381 - suppression ~ 0.6

not observed by ZEUS, Nucl.Phys. B381 (2010) - no suppression ~ 1.



The difference not fully understood





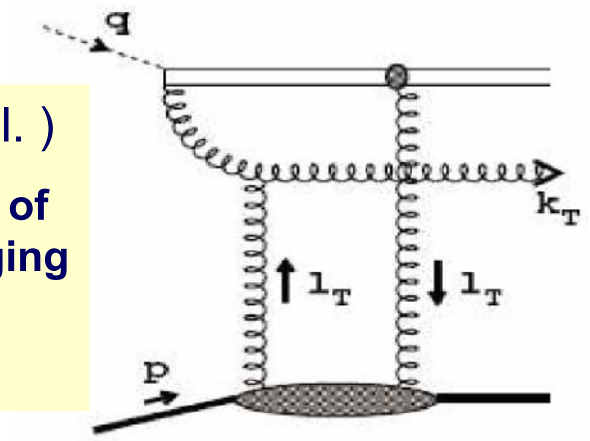
Resolved Pomeron model (Ingelman & Schlein)
based on QCD and proton vertex factorisation.

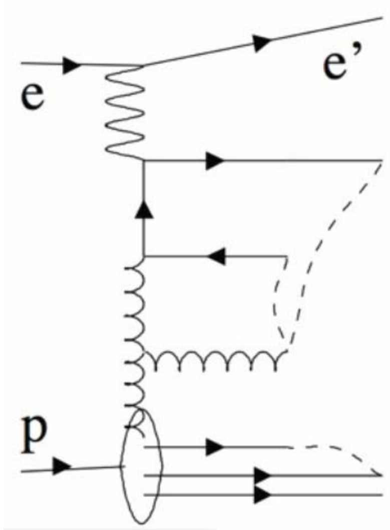
(RAPGAP generator, IP + Reggeon trajectories, DPDF H1 2006 Fit B)

2 Gluon Pomeron model (J. Bartels et al.)

Interaction of IP modeled as colourless pair of gluons with $q\bar{q}$ or $q\bar{q}g$ configurations emerging from the photon.

(RAPGAP, unintegrated PDF – set A0)





Soft Colour Interaction (SCI)
(Edin, Ingelman & Rathsman)

Non-diffractive DIS with subsequent colour rearrangement between the partons in the final state.

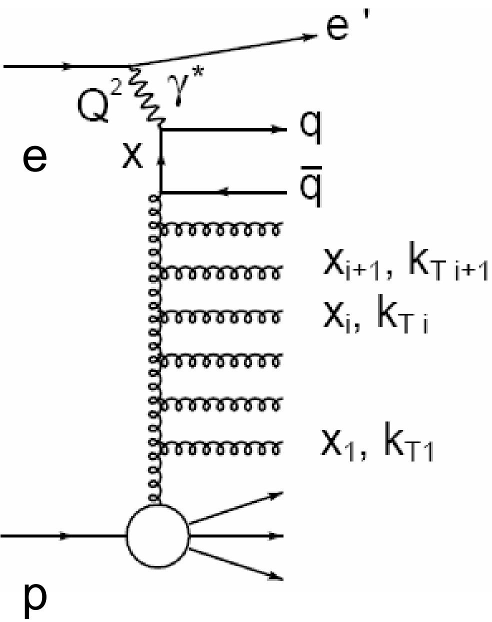
Suppression of long strings (SCI + GAL)

(LEPTO generator, PDF CTEQ6L)

QCD dynamics at low Bjorken-x

HERA : DIS at low Bjorken-x down to 10^{-5} → energy in $\gamma^* p$ cms is large ($W_{\gamma^* p} \approx Q^2 / x$)

- long gluon cascades exchanged between the proton and the photon
- pQCD – multiparton emissions described only with approximations :



- **DGLAP** evolution: resums terms ~ ($\alpha_s \ln Q^2$)^n
  Assumes strong ordering of parton k_T
- **BFKL** evolution: resums terms ~ ($\alpha_s \ln(1/x)$)^n
  No ordering in k_T, strong ordering in x_i
  Transition from DGLAP to BFKL scheme expected at low x
- **CCFM** evolution: emitted partons are ordered in angles
  reproduces DGLAP at large x and BFKL at x → 0

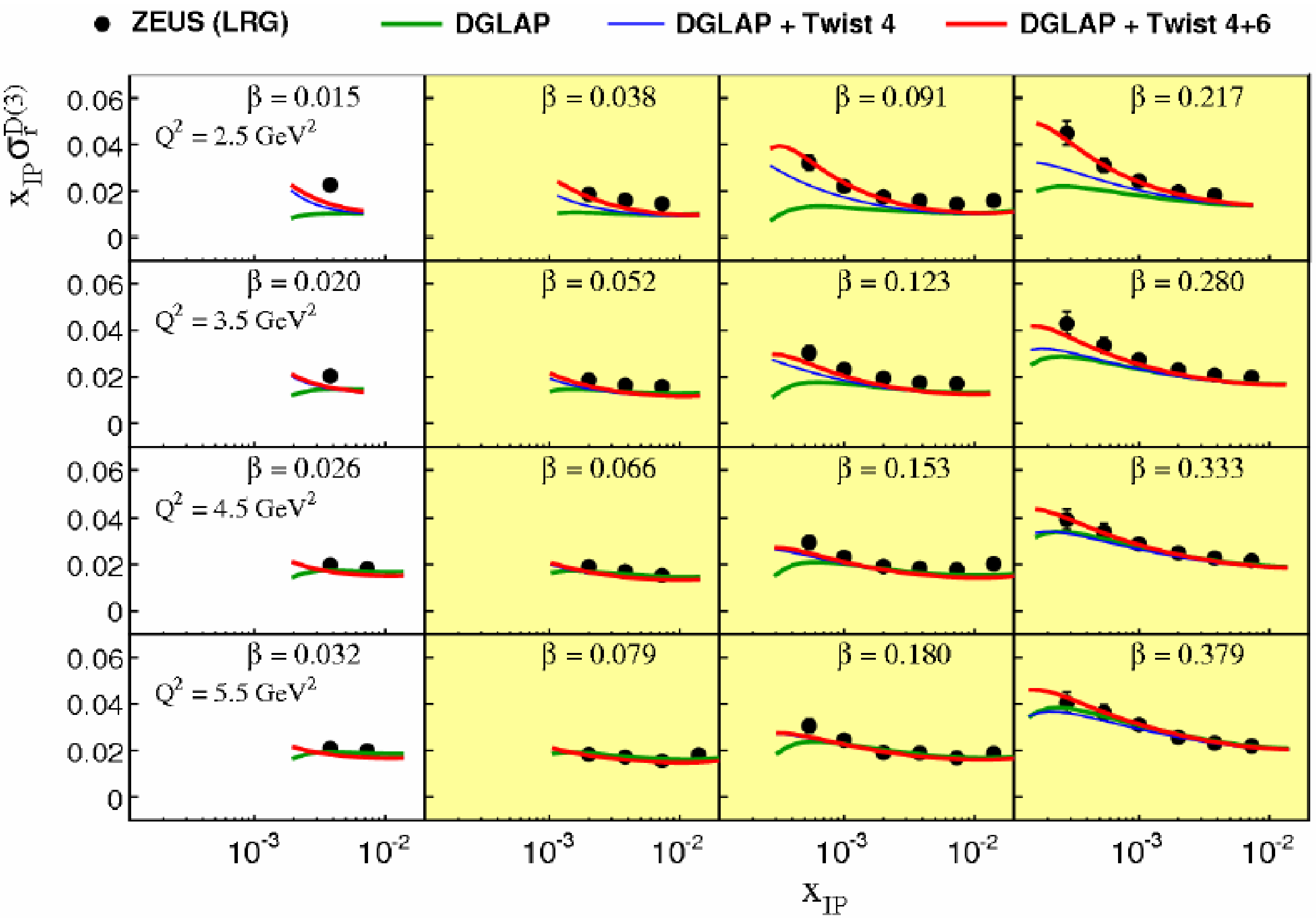
Search at HERA for effects of parton dynamics beyond the standard DGLAP approach

- Strong rise of the proton structure function $F_2(x, Q^2)$ with decreasing x
  – well described by NLO DGLAP over a large range of Q^2
  F_2 measurement too inclusive to discriminate between different QCD evolution schemes
- Look at **hadronic final states** – reflecting kinematics, structure of gluon emissions

Evidence of higher twist effects in DDIS

L. Motyka, L. Sadzikowski, W. Slominski, arXiv: 1203.5461

Standard twist-2 DGLAP description of the DDIS cross section fails below $Q^2 < 5$ GeV^2



ZEUS LRG data :

Nucl. Phys. B816 (2009) 1

HT contributions from Marquer -Munier & Shoshi saturation model

Inclusion of twist 4 and 6 to the DGLAP fit – good description of the data at low Q^2