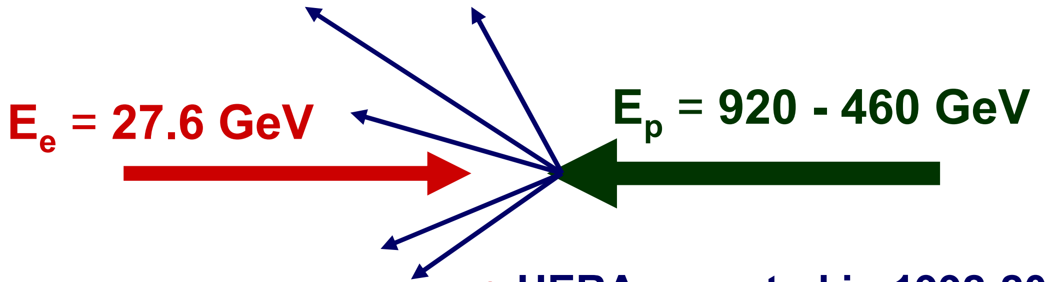
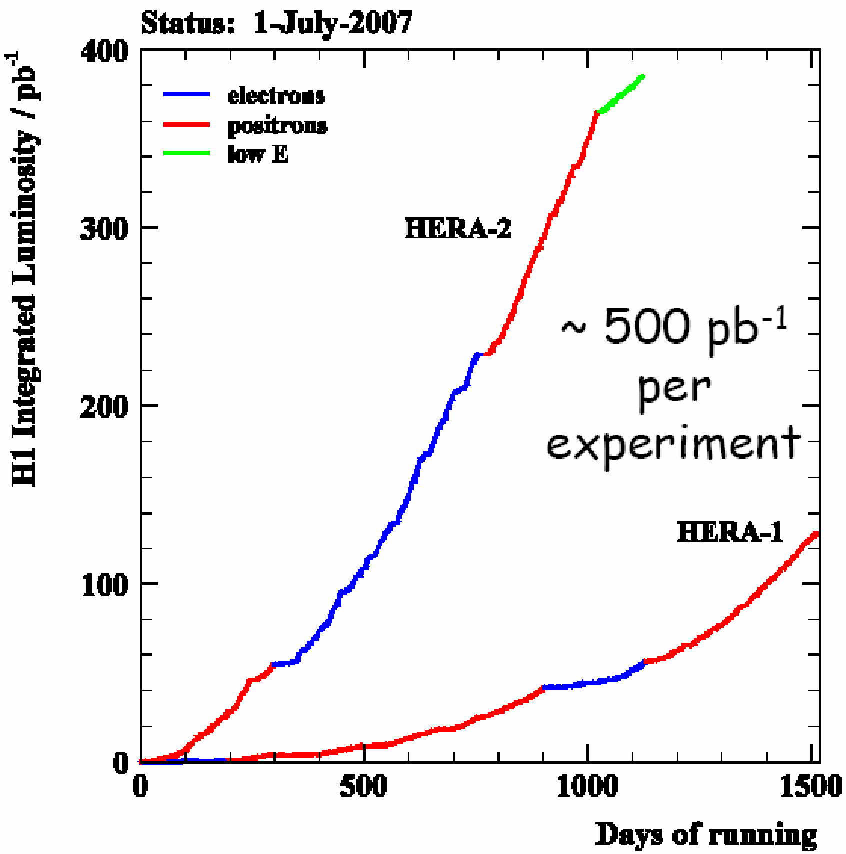
Inclusive diffraction at HERA

- 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 operated in 1992-2007, colliding electrons or positrons at 27.5 GeV with protons

- Nominal proton beam energy :

  E_p = 820 / 920 GeV
  √S = 300 / 318 GeV, (HERA- I phase)

  E_p = 920 GeV
  √S = 318 GeV, (HERA- II phase)

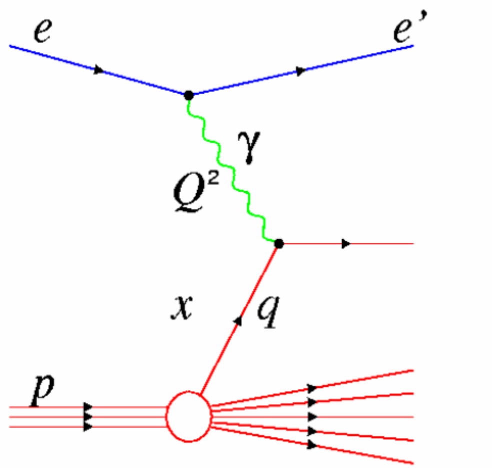
- Reduced proton beam energy :

  E_p = 460 GeV, √S = 225 GeV

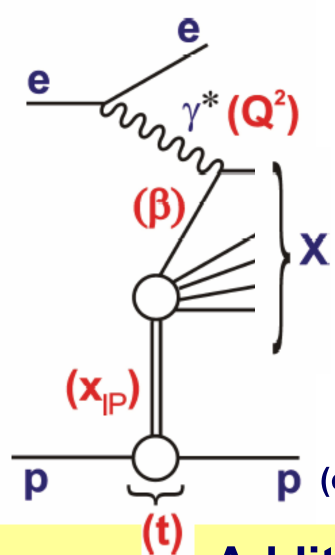
  E_p = 575 GeV, √S = 250 GeV

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

Deep inelastic ep scattering



Diffractive DIS



(or low mass excitation)

Surprise of HERA

expectation before HERA ~ 0.01%

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

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

Standard DIS variables :

Q^2 virtuality of the exchanged boson

x in QPM fraction of proton momentum carried by struck quark

$y = Q^2 / xs$ inelasticity

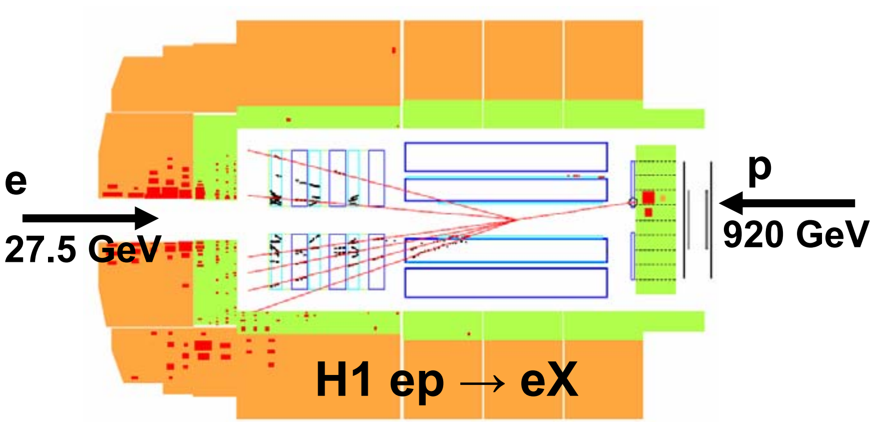
Additional variables for DDIS :

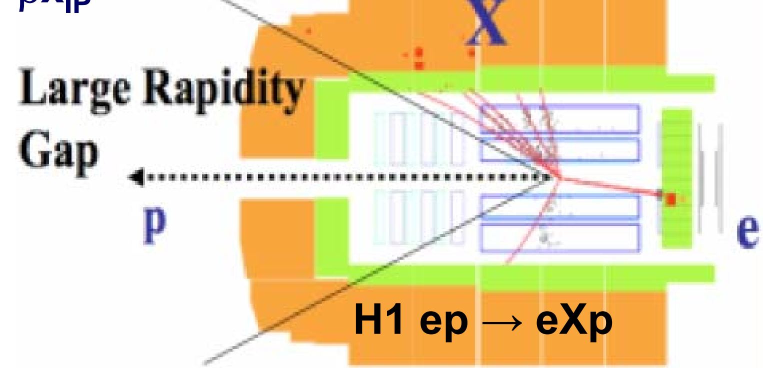
x_{IP} p-momentum fraction carried by IP

β IP-momentum fraction carried by struck quark

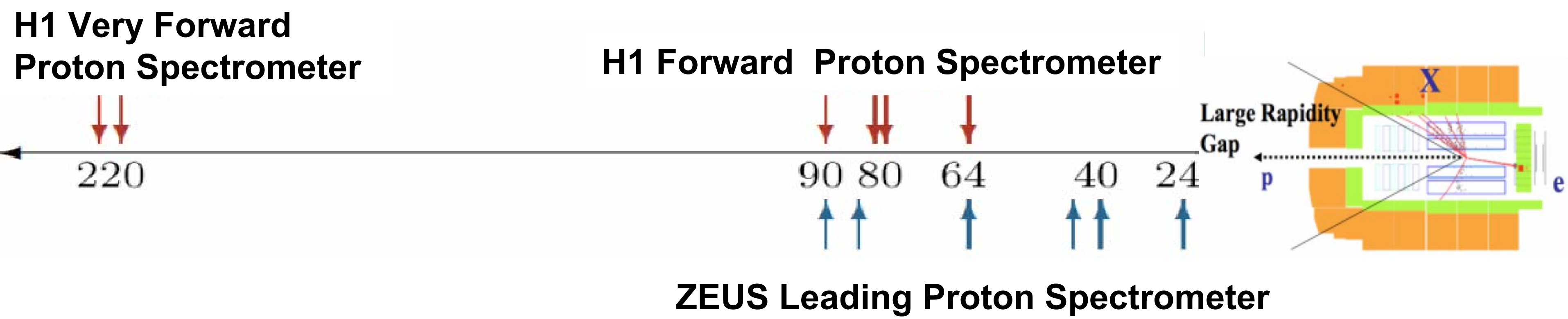
t squared 4-momentum transfer at proton vertex

$x = \beta x_{IP}$



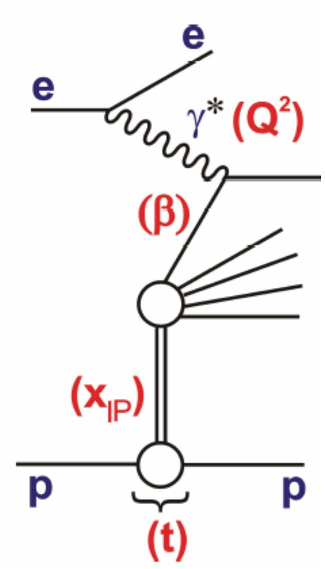


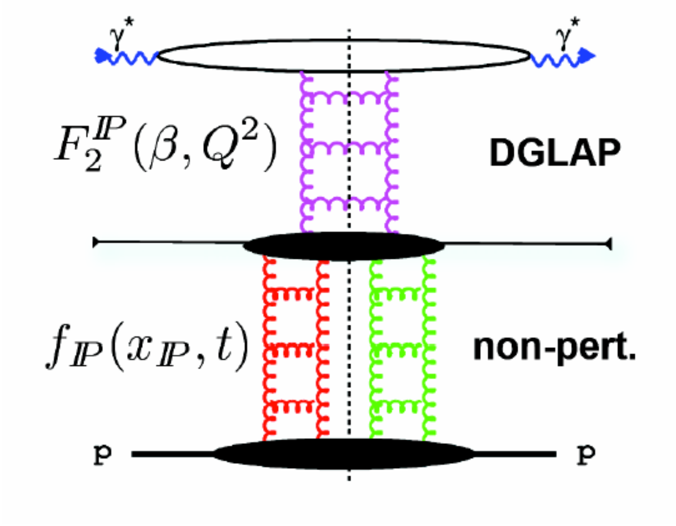
Selection of diffractive events



- **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:**
  - high acceptance → more statistics
  - integration over $|t| < 1$ GeV^2
  - background from proton dissociation into low mass N^*
- **The 2 methods have different kinematical coverage, very different systematics**

Infinite momentum frame : diffractive structure function approach





QCD hard scattering collinear factorisation at fixed x_{IP} and t (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 PDFs (DPDFs), DGLAP evolution in Q^2

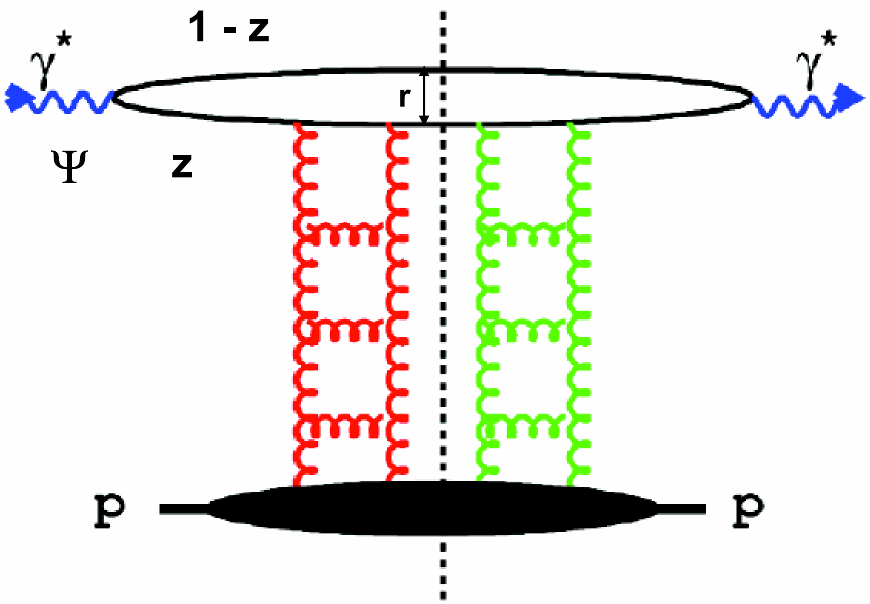
Proton vertex factorisation: separate (x_{IP}, t) from (β, Q^2) dependences

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

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

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

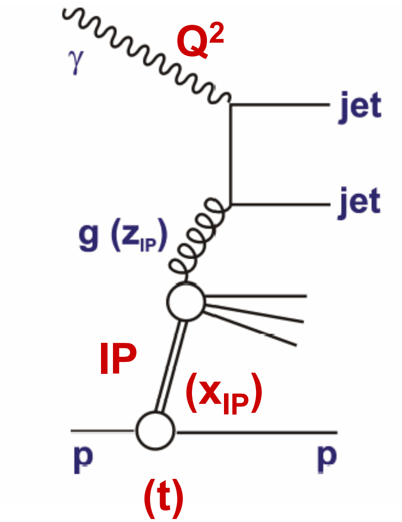
Ψ : $\gamma^* \rightarrow q\bar{q}$ wavefunction

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)

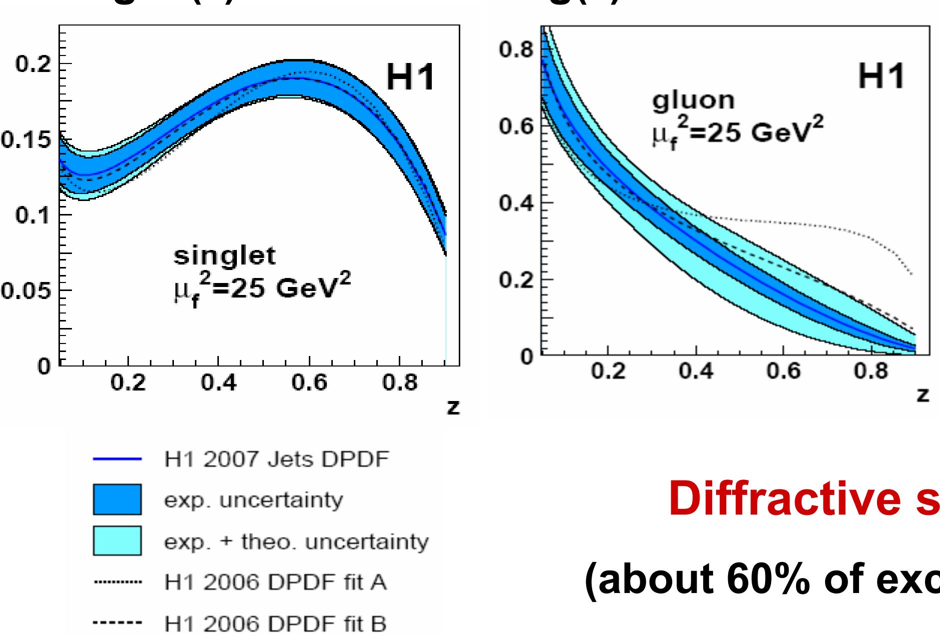
Diffractive parton densities (DPDFs)

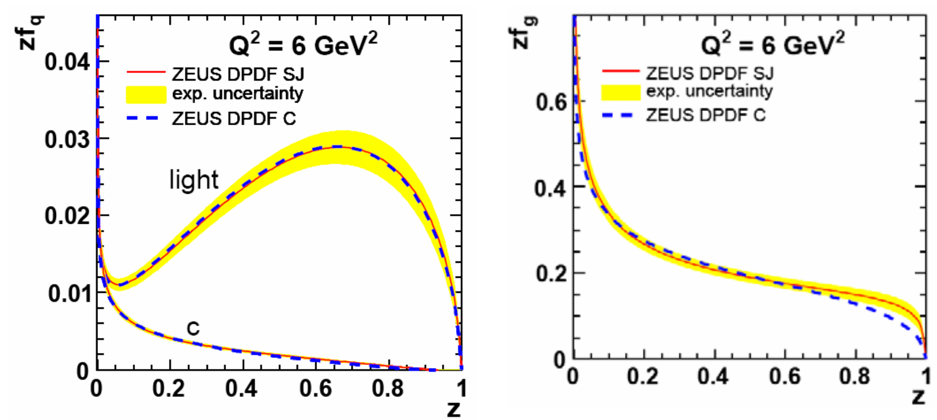


- Diffractive PDFs obtained through NLO DGLAP QCD fit to data
  - inclusive DDIS cross section → diffractive gluon density weakly constrained at high z_{IP}
  - combined fit to diffractive inclusive and dijet cross sections → comparable precision of quark and gluon densities for all z_{IP}

z_{IP}= momentum fraction parton / IP

z·singlet(z) **z·g(z)**

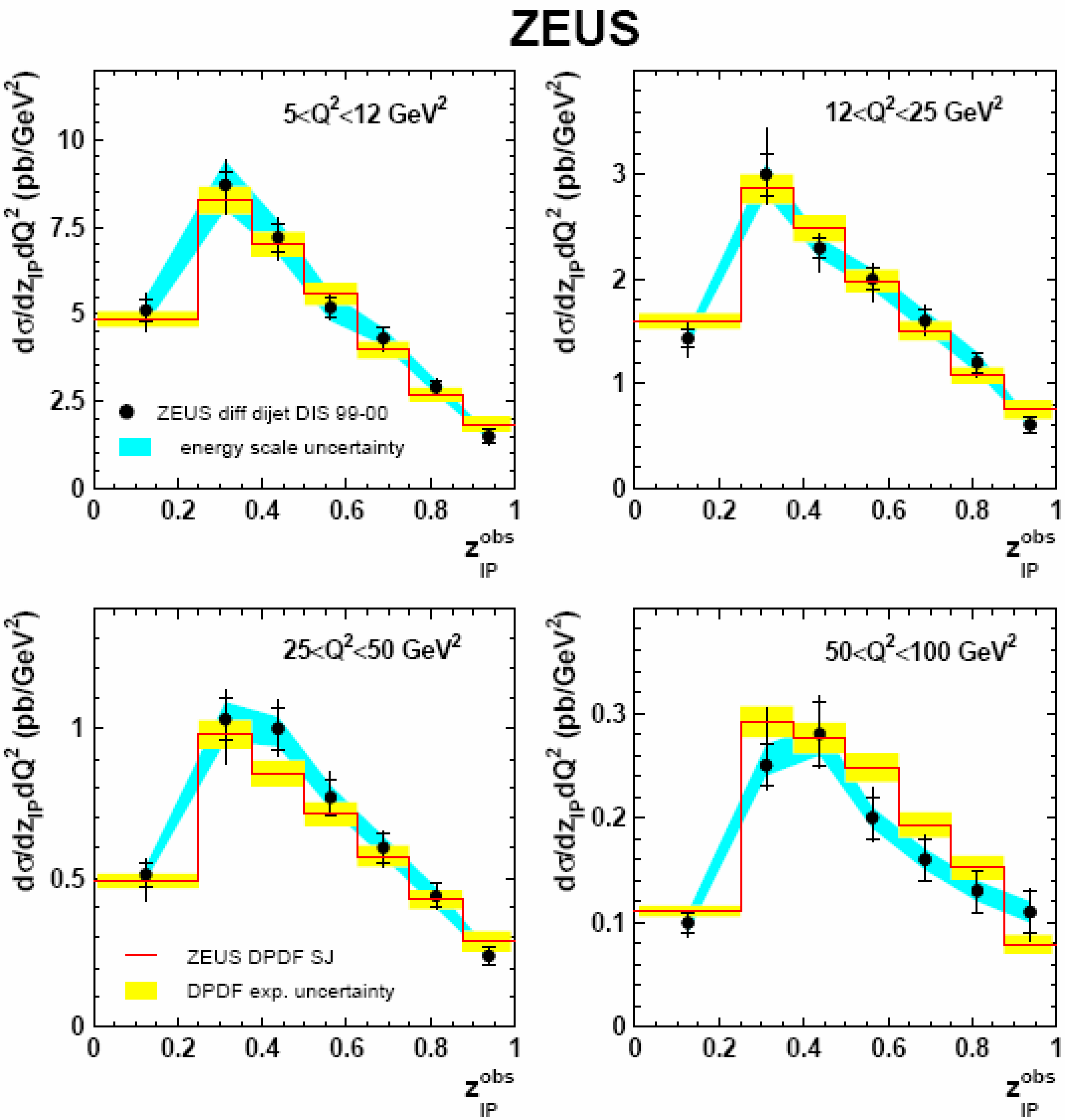




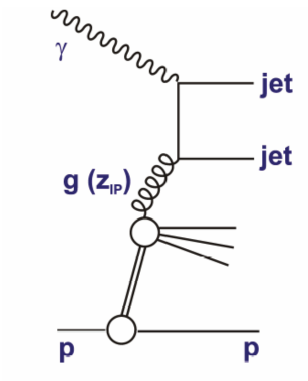
Diffractive scattering is dominated by gluons

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

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

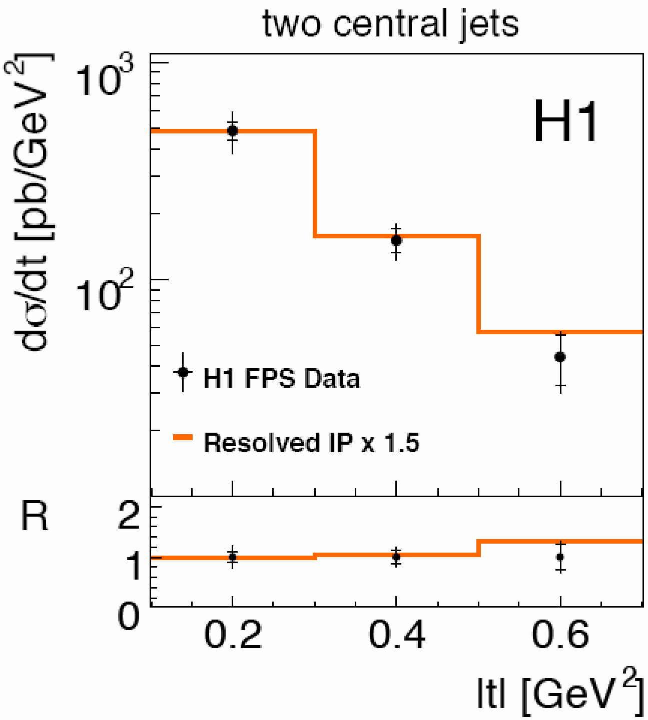
Nucl. Phys. B831 (2010) 1

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

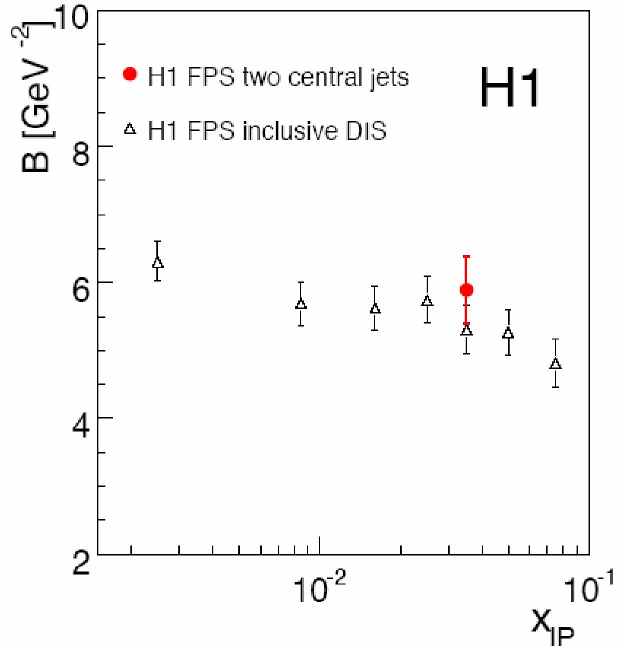
pt of jets in hcms **$p_{T,1}^* > 5$ GeV, $p_{T,2}^* > 4$ GeV, $-1 < \eta_{1,2} < 2.5$**

Eur. Phys. J. C72 (2012) 1970



Regge motivated fit exp(Bt)

$\rightarrow$ 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

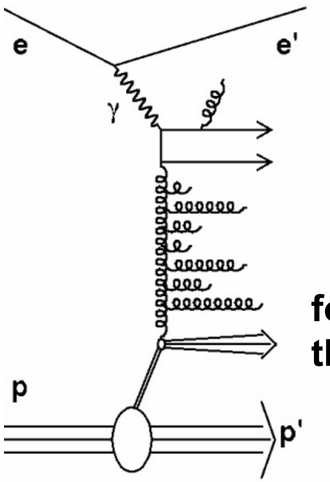
Dijets in diffractive DIS with a leading proton

one central + one forward jet

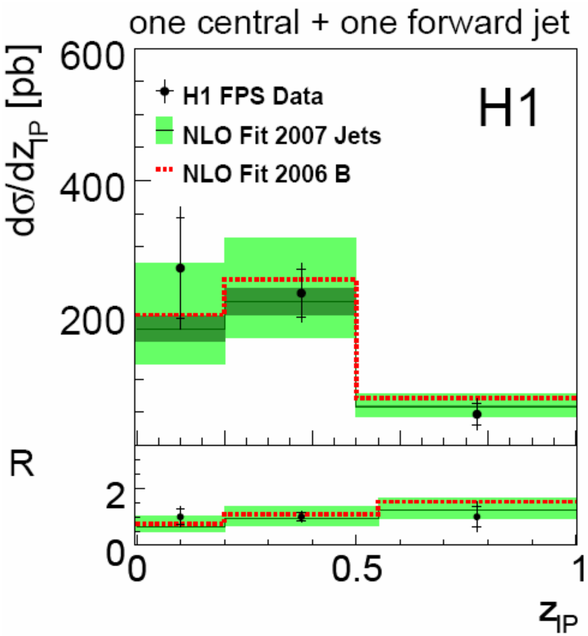
$4 < Q^2 < 110\ GeV^2$, $0.05 < y < 0.7$, $x_{IP} < 0.1$, $|t| < 1\ GeV^2$

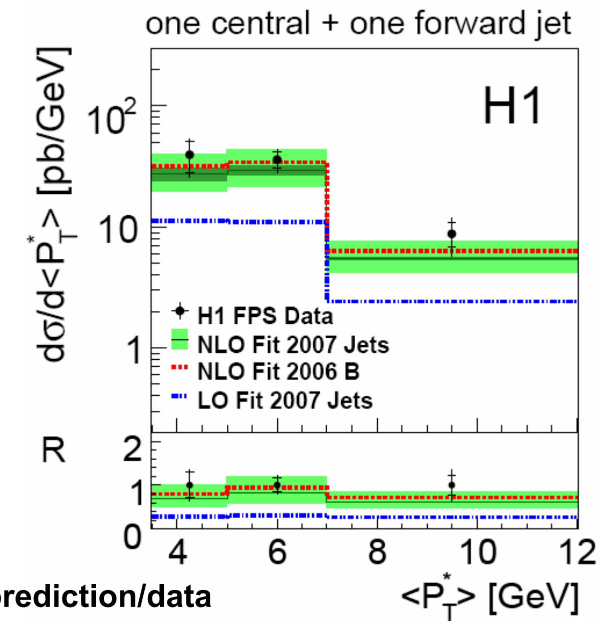
$p_{T,c}^*, p_{T,f}^* > 3.5$ GeV, $M_{jj} > 12$ GeV, $-1 < \eta_c < 2.5$, $1 < \eta_f < 2.8$, $\eta_f > \eta_c$

search for physics beyond DGLAP



forward jet close to the proton





R = prediction/data

DPDF + NLO QCD works well

No sign for deviations from DGLAP

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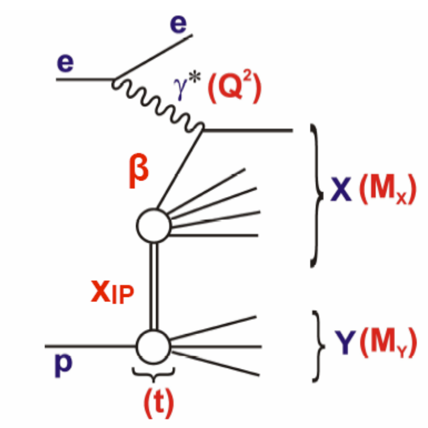
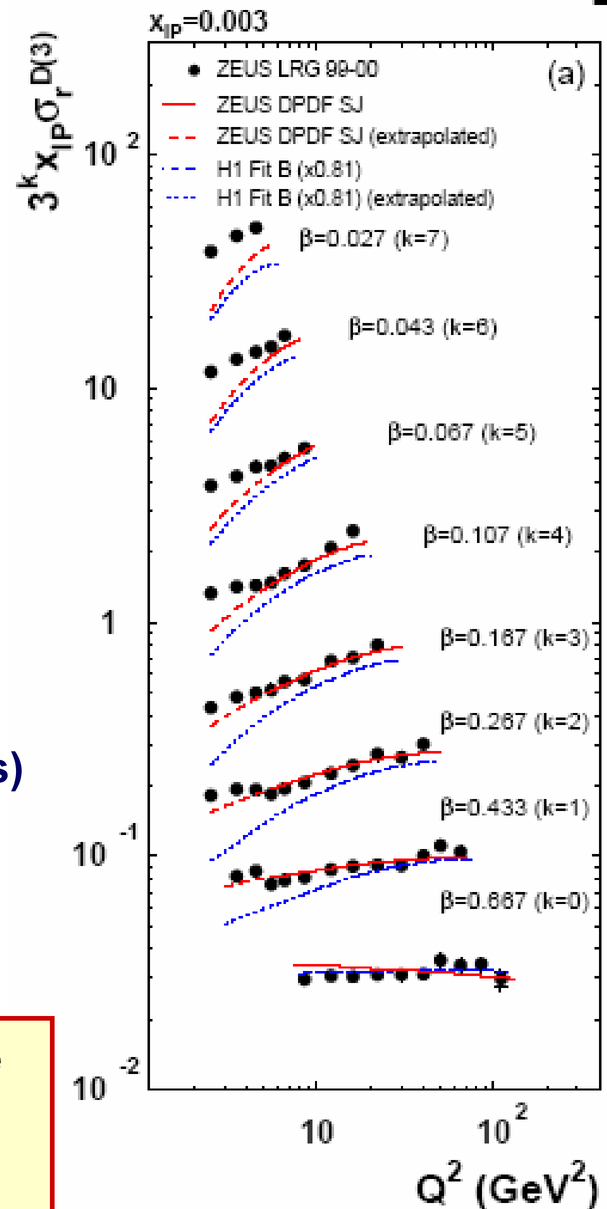


Comparison of the fit

ZEUS DPDF SJ and H1 2006 DPDF Fit B to the ZEUS LRG data



Nucl. Phys. B831 (2010) 1

- **Differential cross section :**

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

- **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 agreement worsens.

Combination of proton tagged data

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

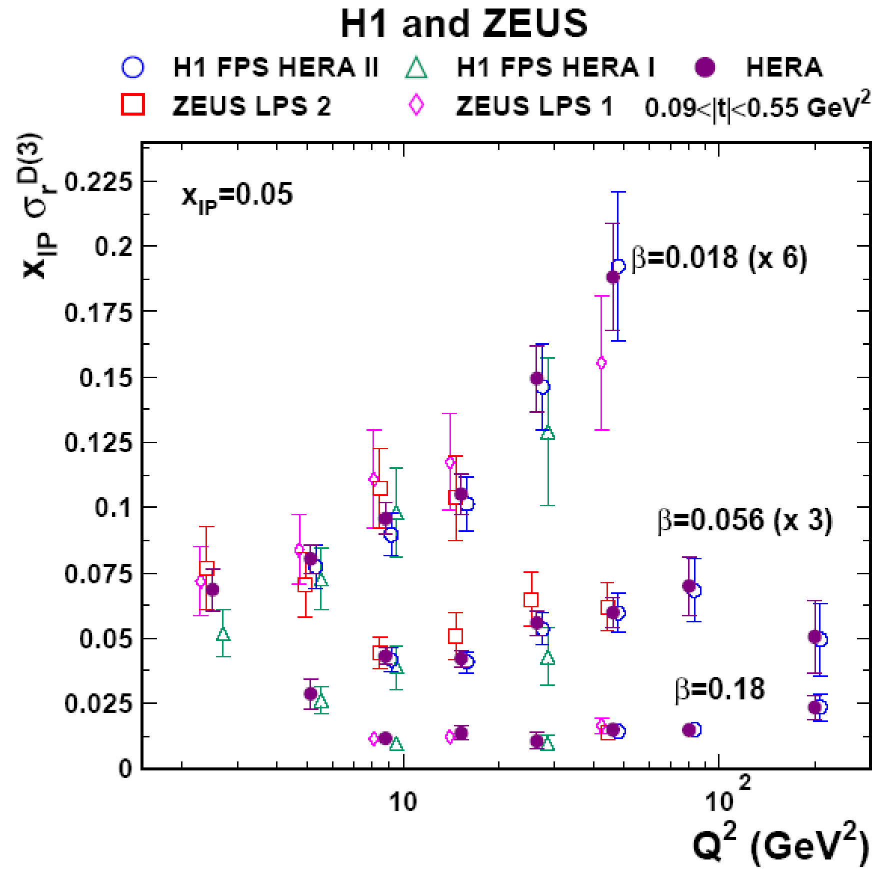
$2.5 < Q^2 < 200$ GeV^2, $0.00035 < x_{IP} < 0.09$,

$0.09 < |t| < 0.55$ 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:**

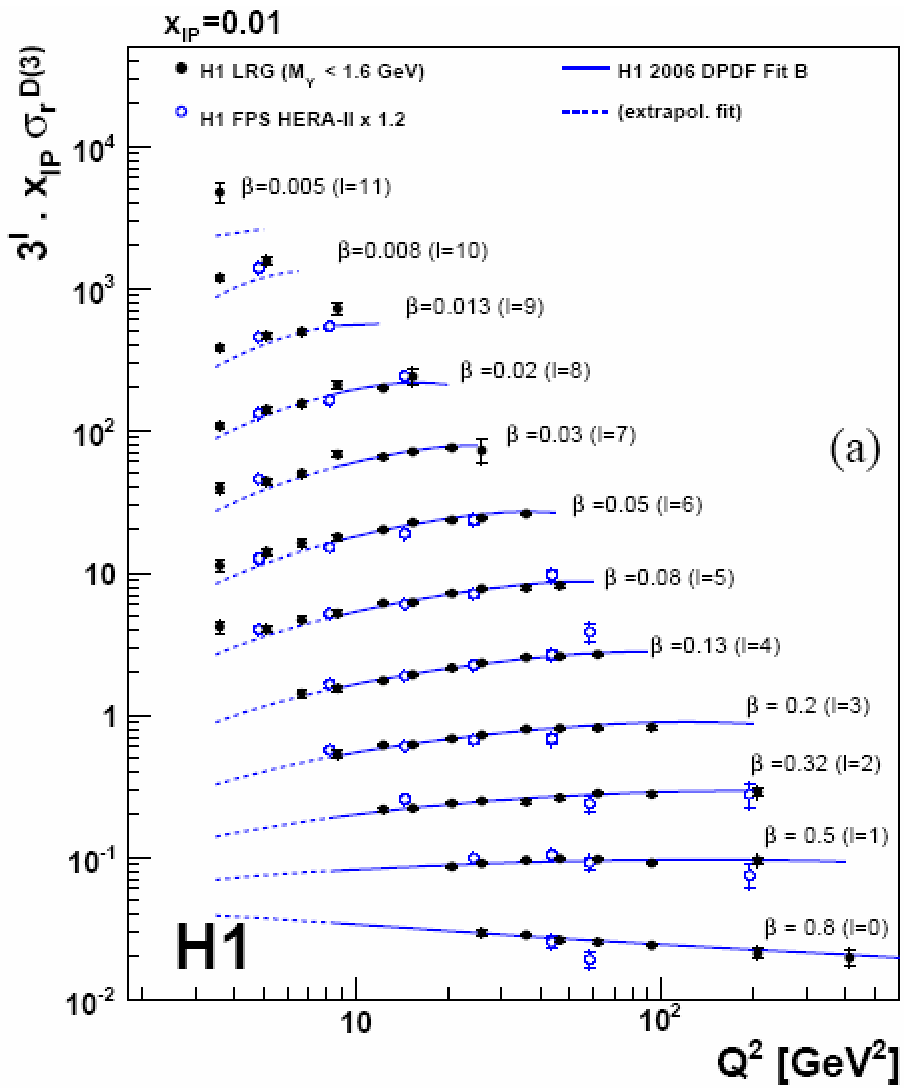
  $3.5 < Q^2 < 1600$ GeV^2
  $0.0017 < \beta < 0.8$
  0.0003 , $x_{IP} < 0.03$

- **Ratio of the LRG and the proton spectrometer 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

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



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

NLO QCD + DPDF:

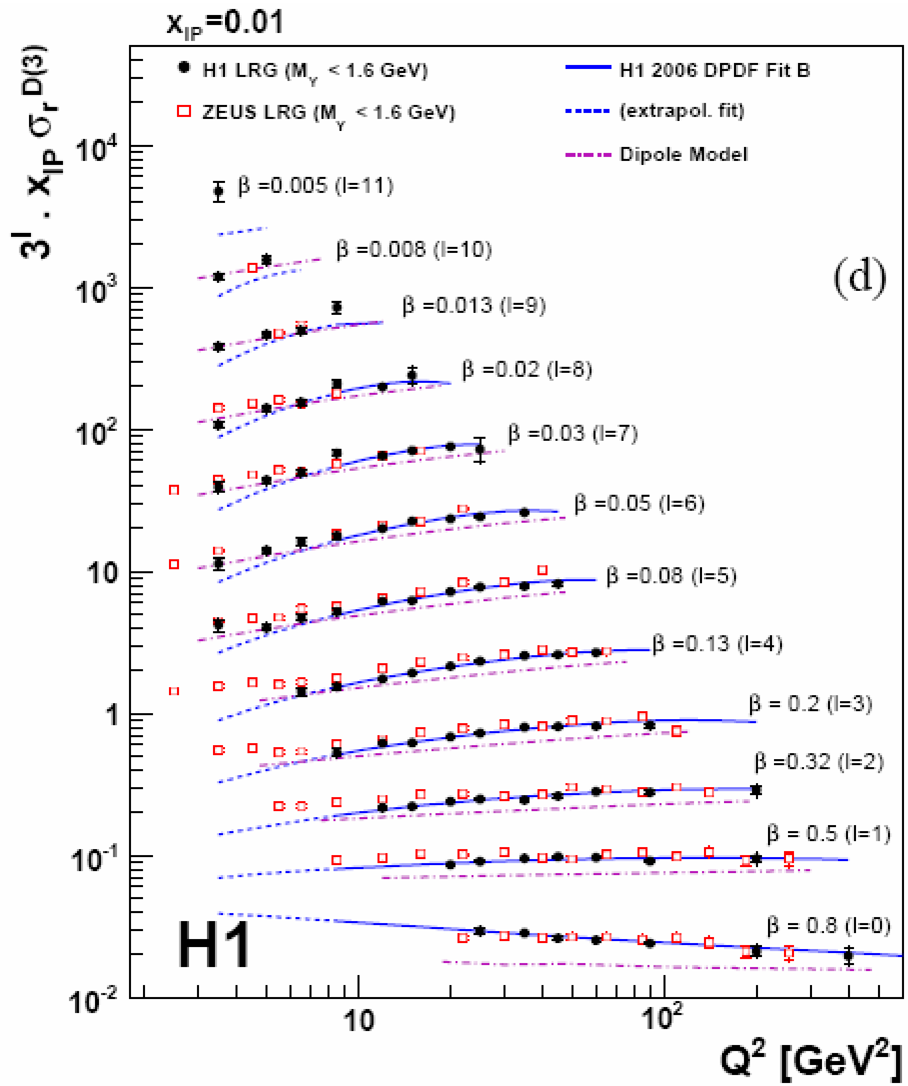
– problems at low Q^2
– good for $Q^2 > 10$ GeV^2

Dipole model with saturation:

– good at low Q^2

– too low at high Q^2 and β

Eur. Phys. J. C72 (2012) 2074

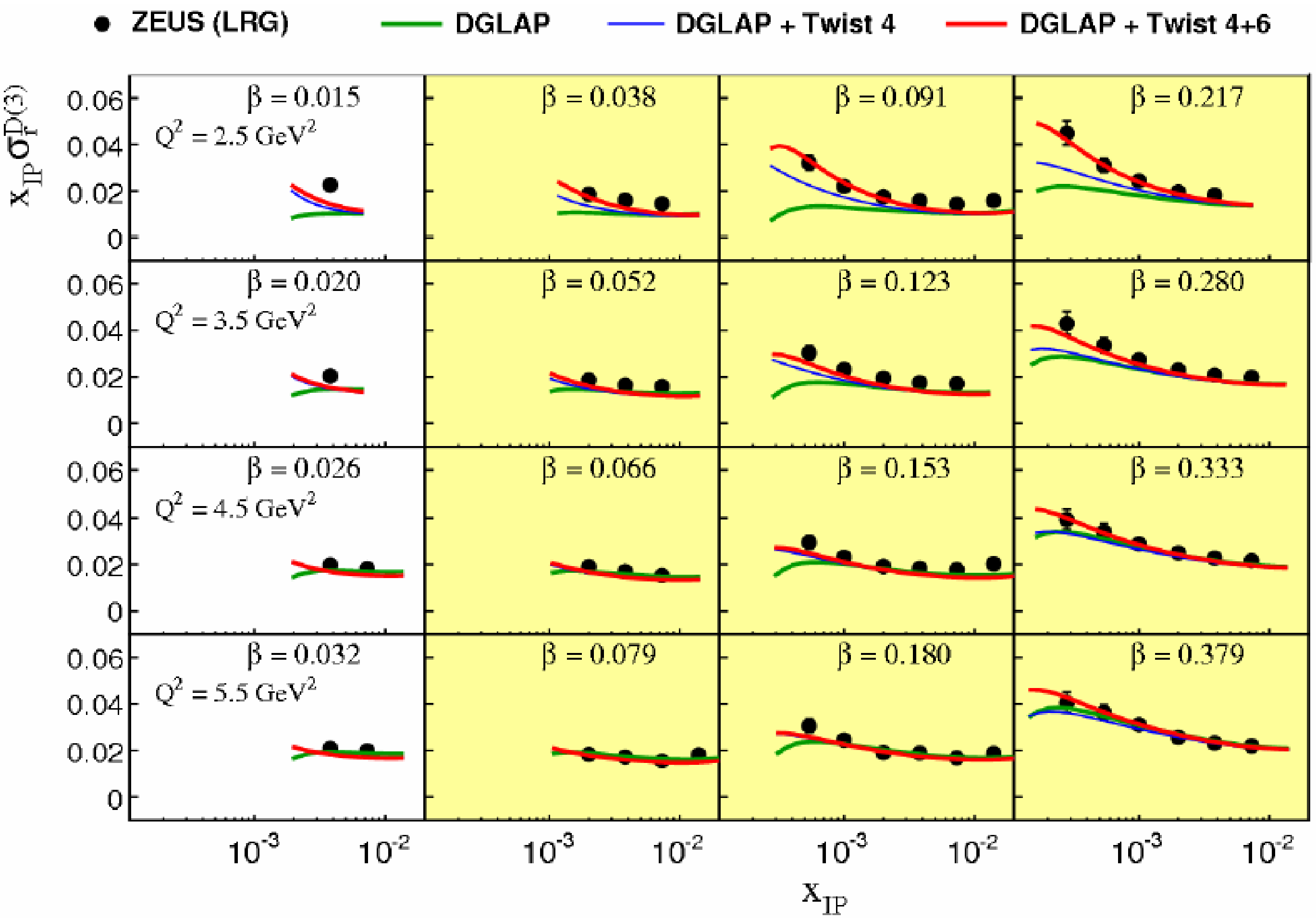


Dipole model :
C. Marquet, arXiv:0706.2682

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

Pomeron trajectory

- **Regge fit to LRG cross section**

contributions from Pomeron + Reggeon

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

$$f_{I\!P/p,I\!R/p}(x_{I\!P}) = \int_{t_{cut}}^{t_{min}} \frac{e^{B_{I\!P,I\!R}t}}{x_{I\!P}^{2\alpha_{I\!P,I\!R}(t)-1}} \mathrm{d}t$$

$$\alpha_{I\!P,I\!R}(t) = \alpha_{I\!P,I\!R}(0) + \alpha'_{I\!P,I\!R}t$$

Mean value of the Pomeron intercept :

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

Pomeron intercept :

- **Independent of Q^2**

(within the statistical uncertainties)

In agreement with the dominance of non-perturbative effects in the IP structure function

- **Supports the proton vertex factorisation**

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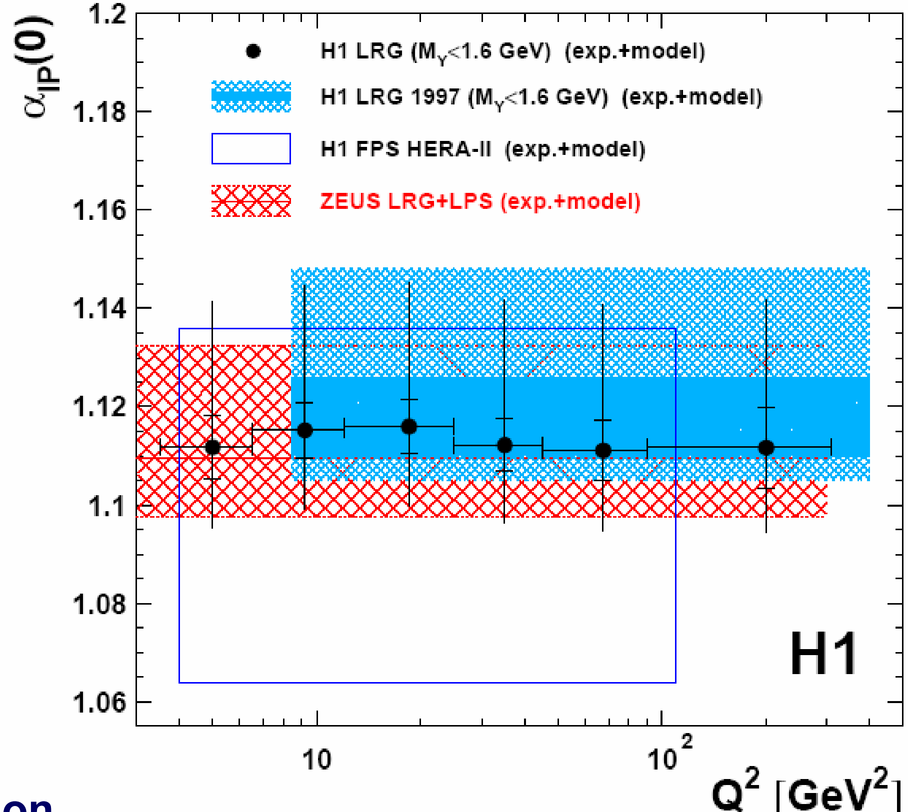


Good agreement of all HERA measurements

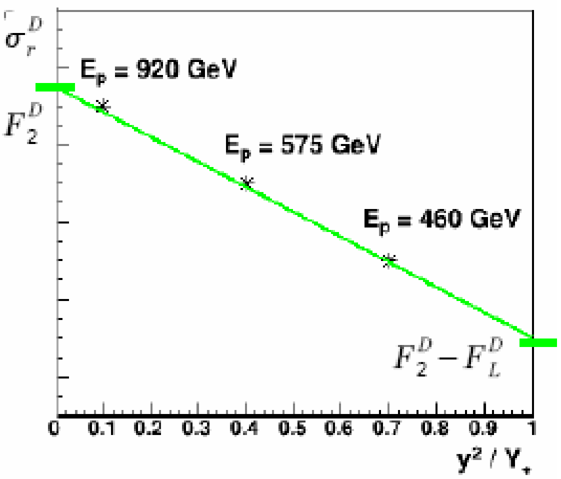
Diffractive longitudinal structure function F_L^D

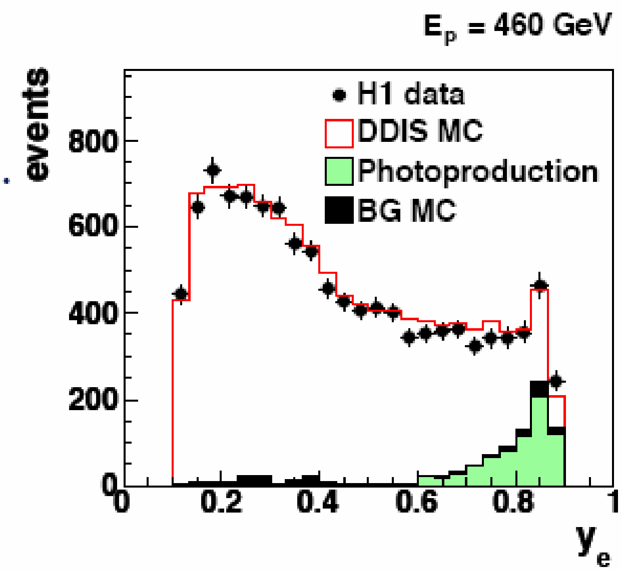
- FLD is sensitive to gluons and provides an independent test of QCD factorization.
- The FLD and F2D structure functions can be separated only by combining measurements at different y (for fixed x_{IP}, β, Q^2).

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

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

- Data at different centre-of-mass energy are needed.
- Highest sensitivity to FLD is at high y (low β).
- Challenging measurement due to high level of photoproduction background.

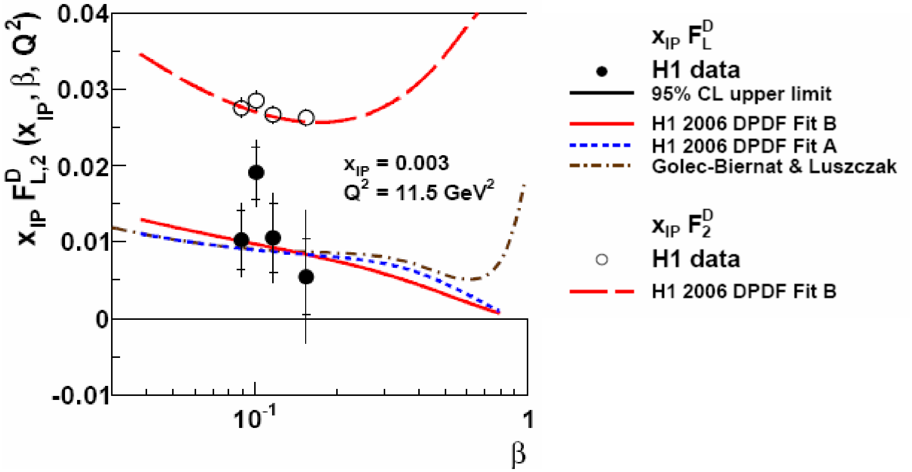




F_L in diffraction

Eur. Phys. J. C72 (2012) 1836

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

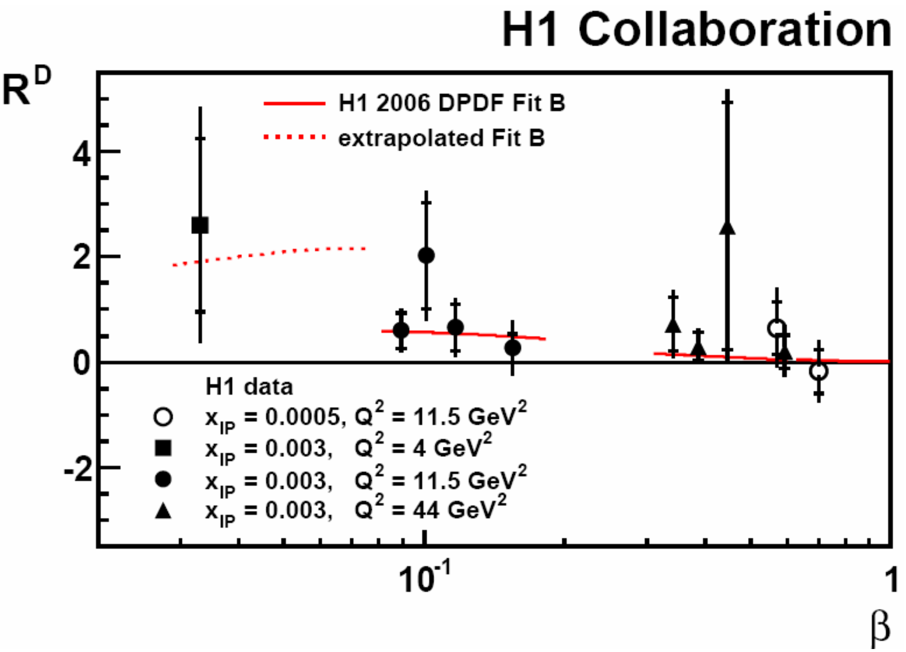


F_L^D measurements compared with leading twist predictions (NLO QCD + H1 DPDF) and with the model including a higher twist contribution derived from a colour dipole approach (Golec-Biernat & Luszczak)

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 ~1 and F_2^D ~2F_L^D)

Summary

- HERA observed hard diffraction in ep DIS
- First combination of the H1 and ZEUS diffractive data (proton- tag results)
- H1 precision LRG measurement using the full dataset
- The first direct measurement of F_L^D
- HERA measurements support the proton vertex and QCD factorisation

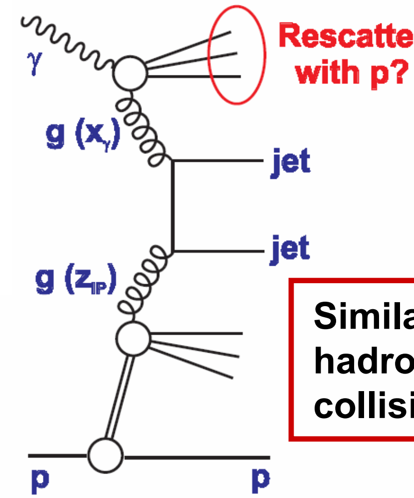
backup

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 ($x_\gamma < 0.2$)

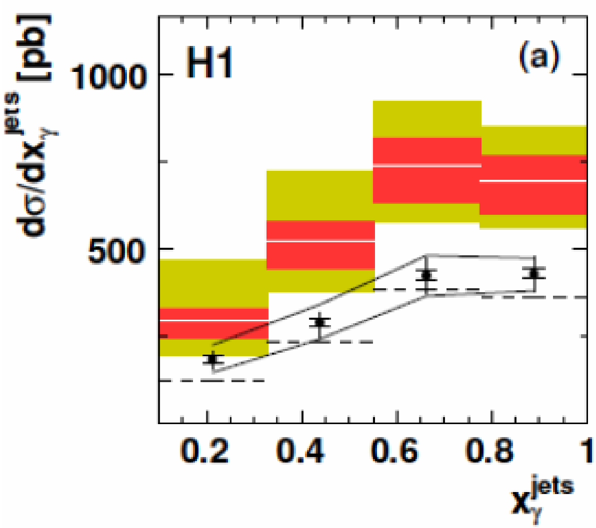
X_γ – fraction of photon's momentum in hard subprocess

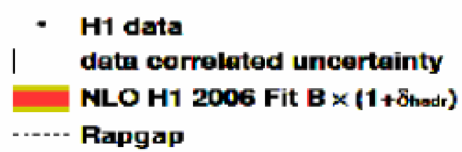


Similarity with hadron-hadron collisions

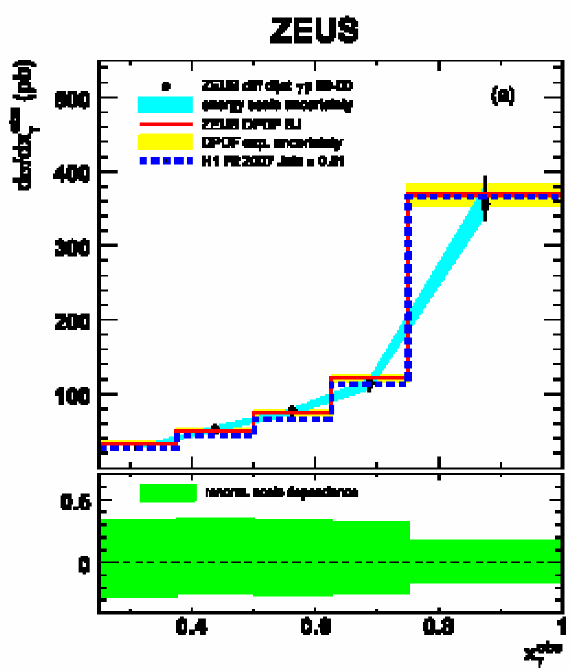
Factorisation breaking observed by H1, two analyses,
EPJC C51 (2007),549, - suppression ~ 0.5
EPJ C68 (2010),381 - suppression ~ 0.6

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



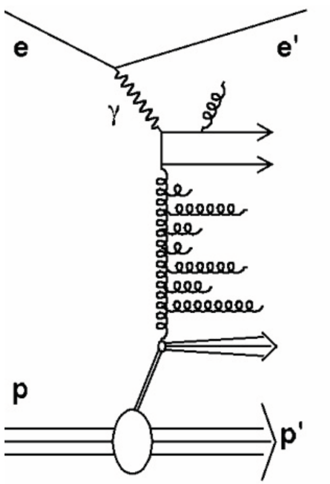


The difference not fully understood



Diffractive forward jets

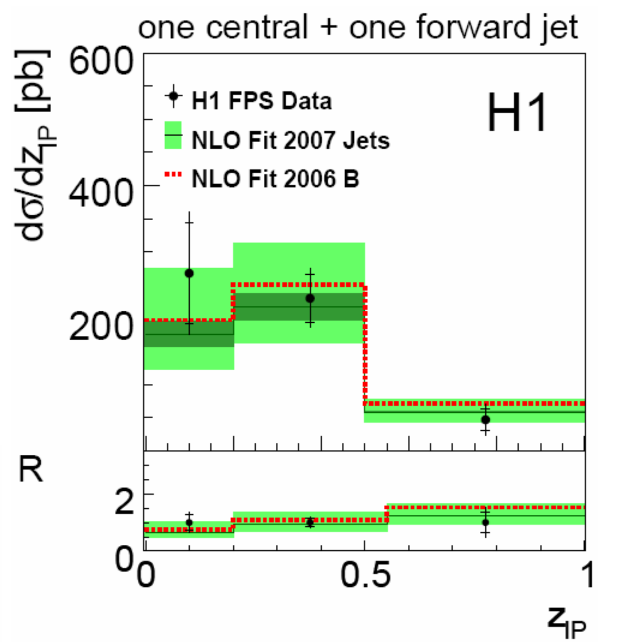
search for physics beyond DGLAP

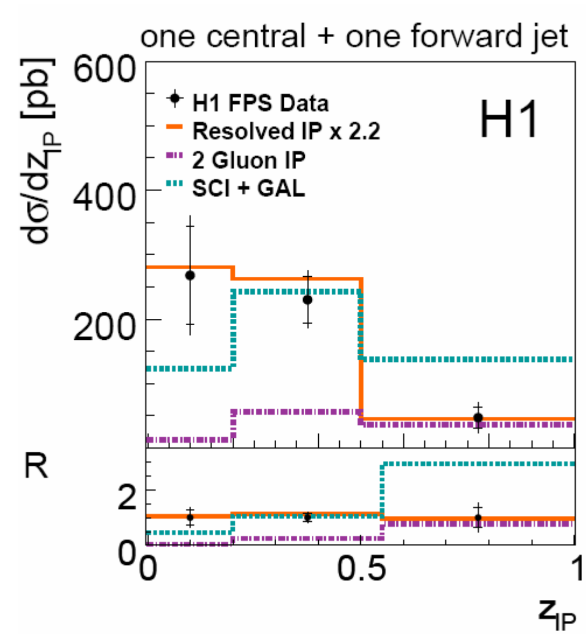


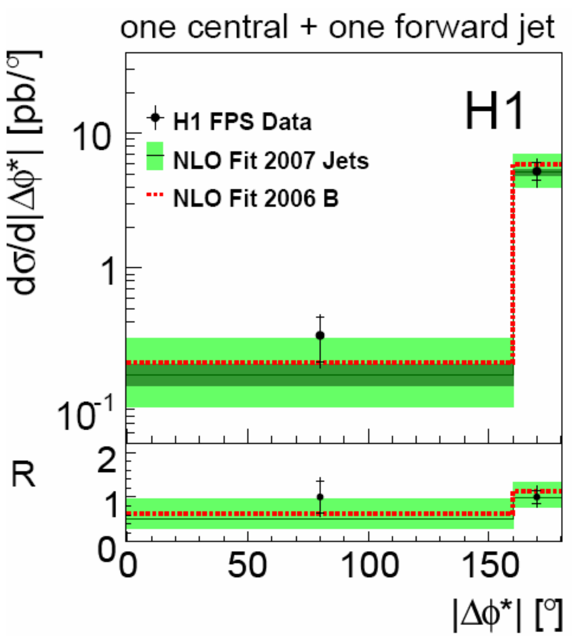
one central + one forward jet

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

$p_{T,c}^*, p_{T,f}^* > 3.5\ GeV$, $M_{jj} > 12\ GeV$, $-1 < \eta_c < 2.5$, $1 < \eta_f < 2.8$, $\eta_f > \eta_c$



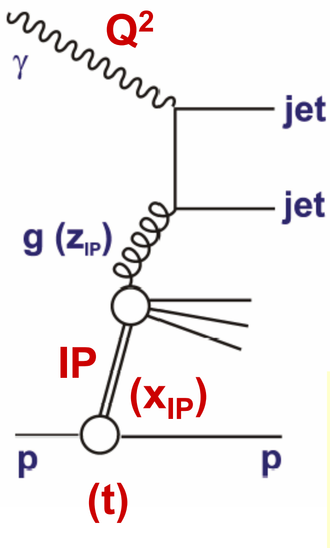




No sign for deviations from DGLAP.

The shapes of measured distributions well described only by the Resolved IP model.
(too low in normalisation)

Diffractive final states



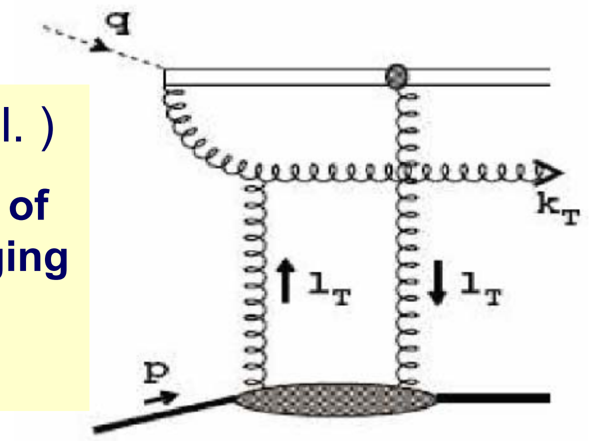
Resolved Pomeron model (Ingelman & Schlein)
based on QCD and proton vertex factorisation.

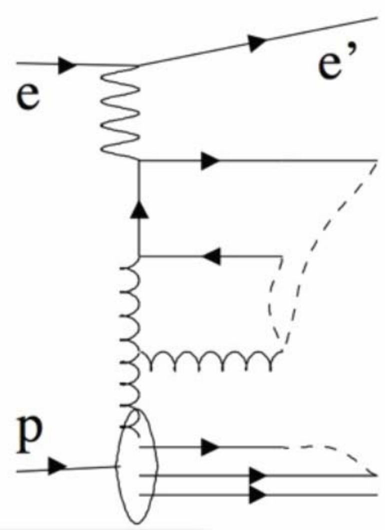
(RAPGAP generator, IP + Reggeon trajectories, DPDF H1 2006 Fit B)

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.

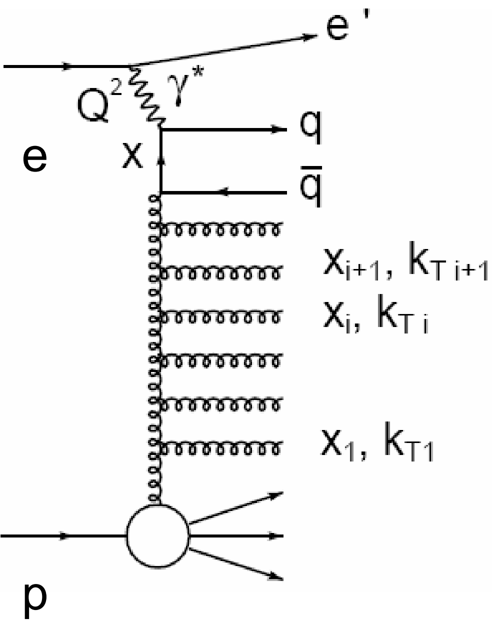
Suppression of long strings (SCI + GAL)

(LEPTO generator, PDF CTEQ6L)

QCD dynamics at low Bjorken-x

HERA : DIS at low Bjorken-x down to 10^{-5} $\rightarrow$ energy in γ^*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 $\rightarrow$ 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**