Low-x physics results from HERA

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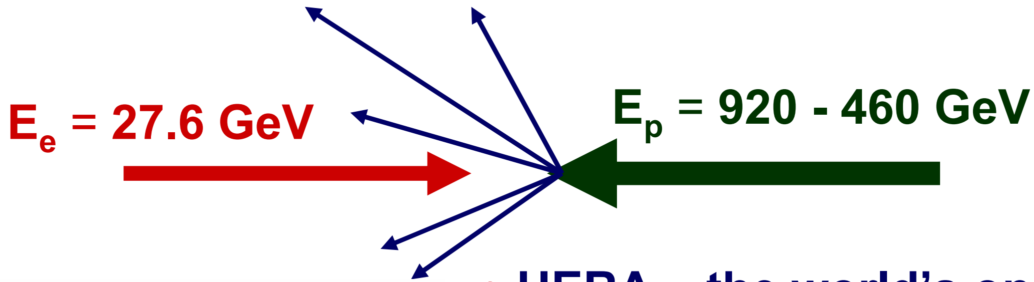
- Electron-proton collider HERA at DESY / Hamburg
- QCD dynamics at low Bjorken-x
- QCD tests with the Hadronic Final State
- Forward jet production
- Diffractive dijets and QCD factorisation
- Summary

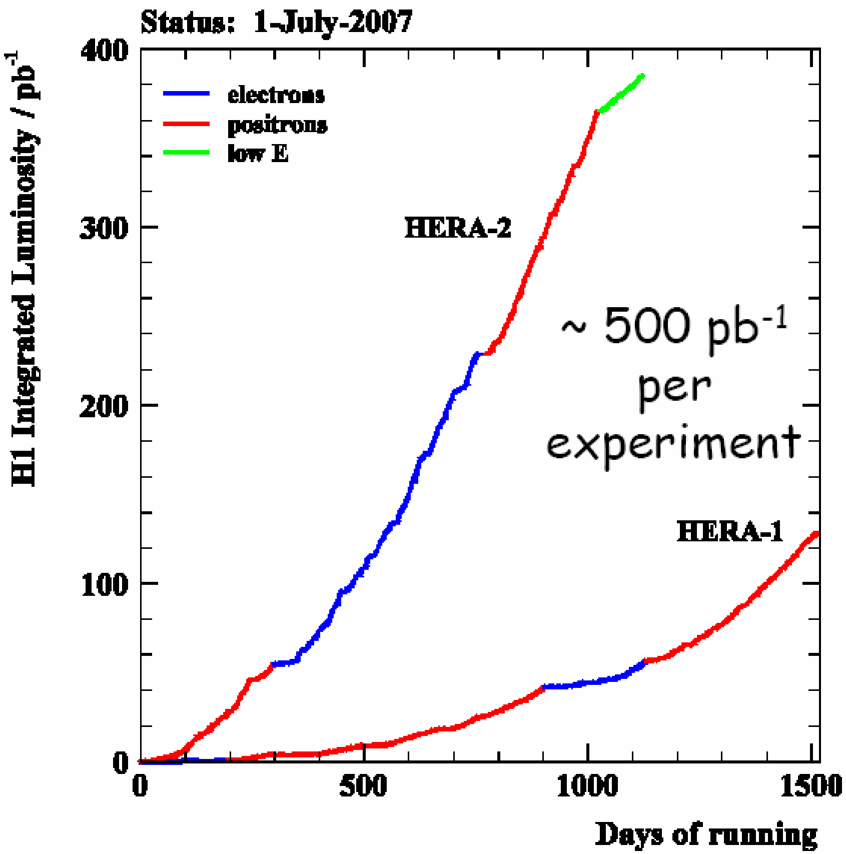
1st Symposium
of the Division for Physics of Fundamental Interactions
of the Polish Physical Society

Various Faces of QCD

Jan Kochanowski University, Kielce, Poland, May 10-11, 2014

HERA





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

  operated in 1992-2007 colliding electrons or positrons with protons

- **two colliding beam experiments: H1 and ZEUS**

- **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)

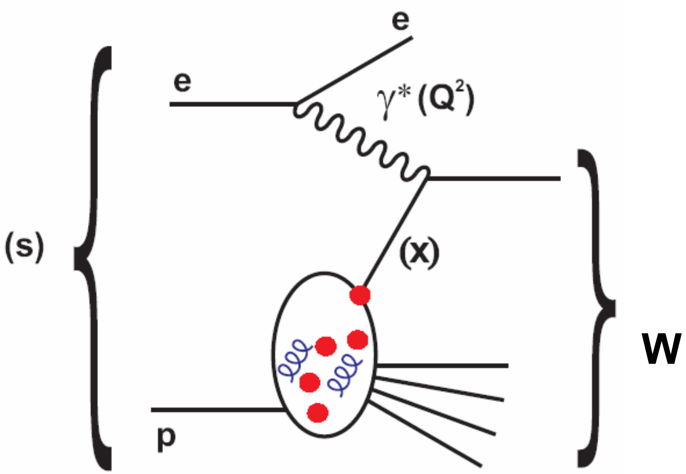
- **Reduced proton beam energy :**

  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

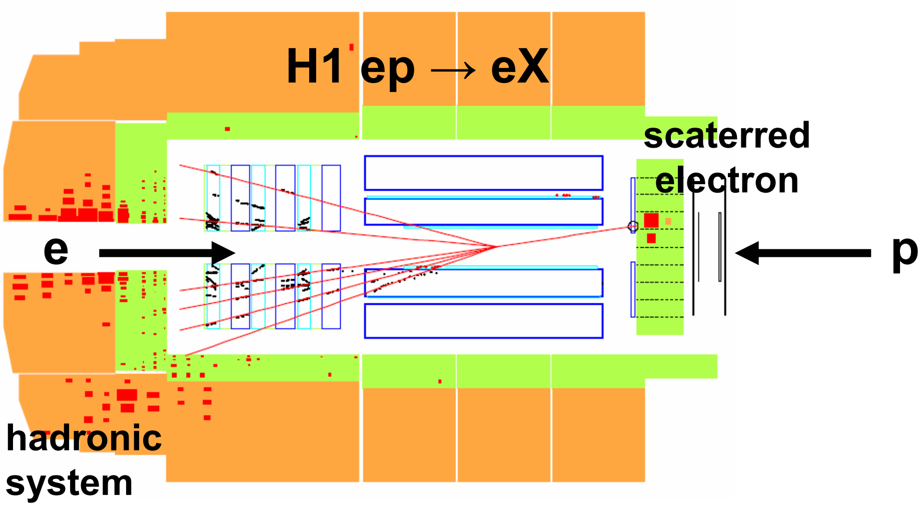
x the Bjorken variable, fraction of the proton momentum carried by the struck quark in the Quark Parton Model

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

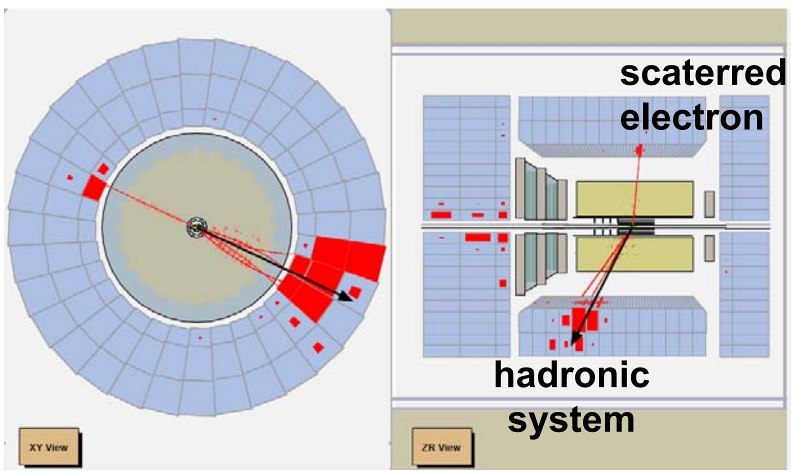
$Q^2 \approx xys$

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

W : invariant mass of the hadronic final state (HFS)



ZEUS ep → eX

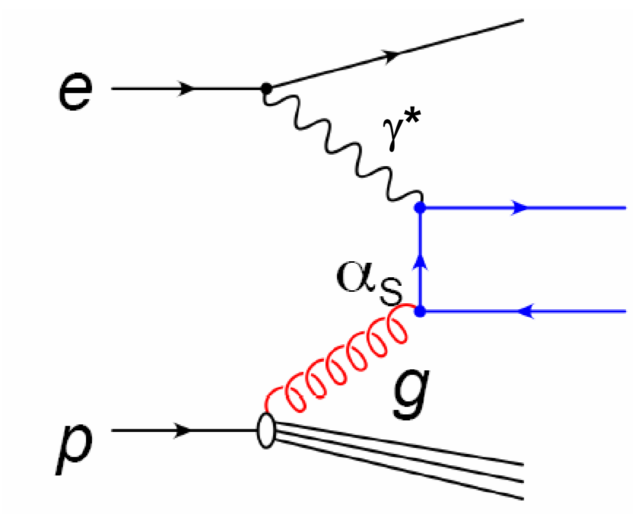


Precise measurement of the scattered electron (E_e scale at 1%) and the HFS (E_h scale at 1- 4%)

Measurements of the Hadronic Final State

Measurements of the Hadronic Final State in DIS are complementary to inclusive studies
(structure of the proton, parton distribution functions PDF …)

HFS : the full final state after removal of the scattered beam lepton
(and any electroweak radiation associated with it)



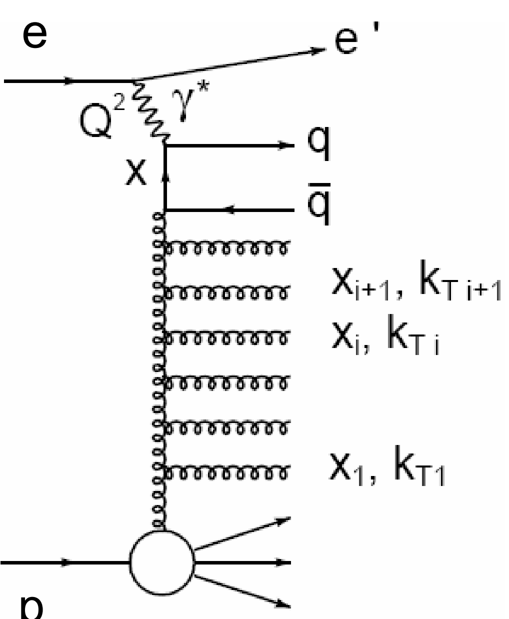
boson-gluon fusion

- **Information on the gluon density in the proton**
- **Determination of α_s**
- **Mechanisms of hadroproduction**
- **Search for effects of parton dynamics beyond the standard DGLAP parton evolution**
  …

QCD dynamics at low Bjorken-x

HERA : DIS at low Bjorken-x down to 10^{-5} $\rightarrow$ large γ^*p centre-of-mass-energy
($W_{\gamma^* p} \approx Q^2 / x$)

- **enhanced phase space for gluon cascades exchanged between the proton and the photon**
- **pQCD – multiparton emissions described only with approximations :**



- **DGLAP**

  Dokshitzer-Gribov-Lipatov-Altarelli-Parisi evolution

  Assumes strong ordering of parton k_T

  Resums terms ~ $(\alpha_S \ln Q^2)^n$

- **BFKL**

  Balitsky-Fadin-Kuraev-Lipatov evolution

  No ordering in k_T, strong ordering in x_i

  Transition from DGLAP to BFKL scheme expected at low x

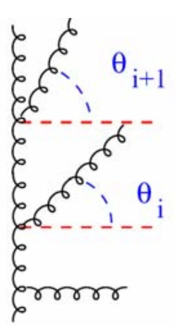
  Resums terms ~ $(\alpha_S \ln(1/x))^n$

- **CCFM**

  Ciafaloni-Catani-Fiorani-Marchesini evolution

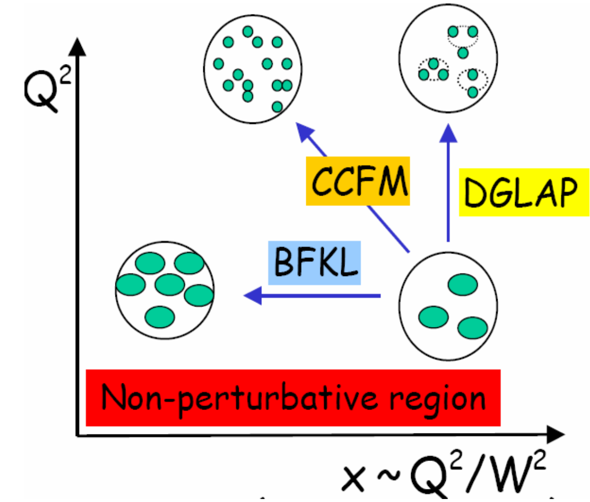
  Emitted partons are ordered in angles

  Reproduces DGLAP at large x and BFKL at x $\rightarrow$ 0



QCD dynamics at low Bjorken-x

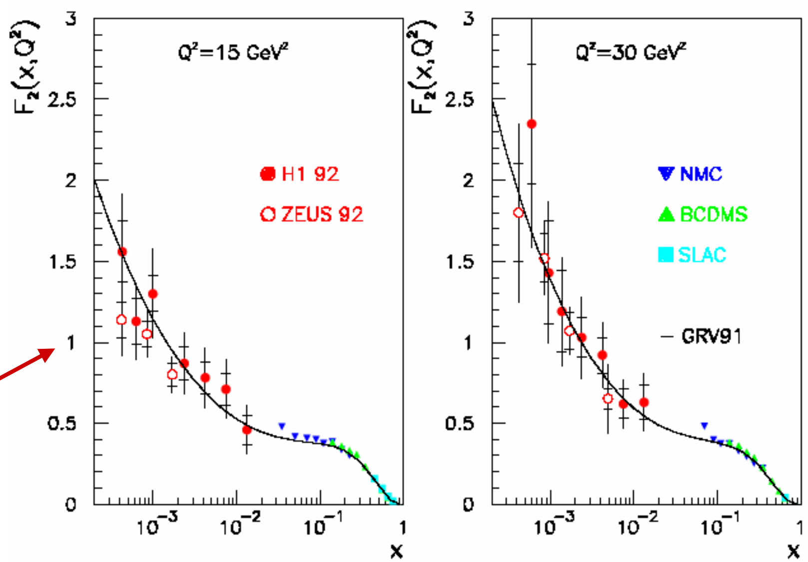
- Search at HERA for effects of parton dynamics beyond the standard DGLAP approach
- Define observables / phase space regions sensitive to low x effects
- Large parton densities at low x → phenomena of parton saturation and non-linear evolution may become important



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 is too inclusive to discriminate between different QCD evolution schemes

The first F_2 measurements from HERA in 1992



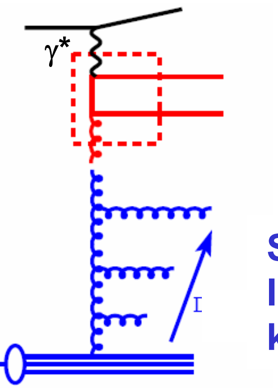
Hadronic final states – reflect kinematics, structure of gluon emissions

(forward jets / particles, inclusive jets, multijet production, azimuthal correlation in dijet events, tranverse energy flow, p_T distribution of hadrons)

Low x phenomenology : Monte Carlo models with different QCD dynamics

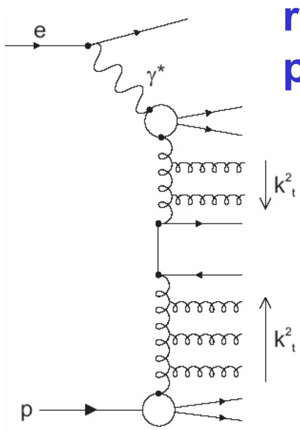
RAPGAP - DGLAP

LO QCD matrix elements
+ HO modelled by leading log parton showers



direct photon

Single DGLAP ladder with strong k_T ordering



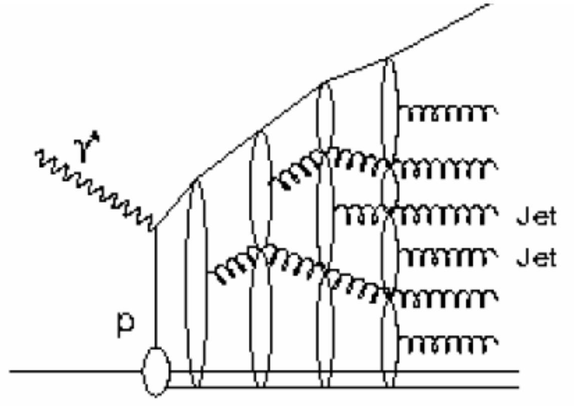
resolved photon

2 k_T - ordered cascades initiated from the proton and the photon

DJANGOH
Colour Dipole Model

CDM: QCD radiation from the colour dipole formed by the struck quark and the proton remnant.

Chain of independently radiating dipoles formed by the emitted gluons.

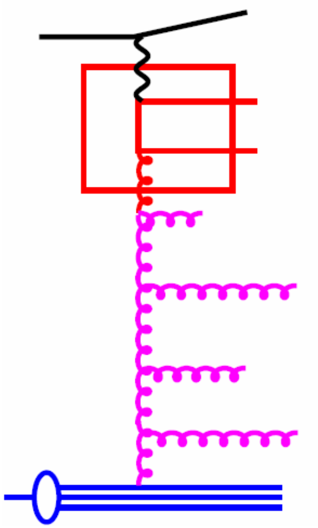


BFKL- like Monte Carlo : random walk in k_T

CASCADE - CCFM

Off-shell QCD ME
+ parton emissions based on the CCFM equation

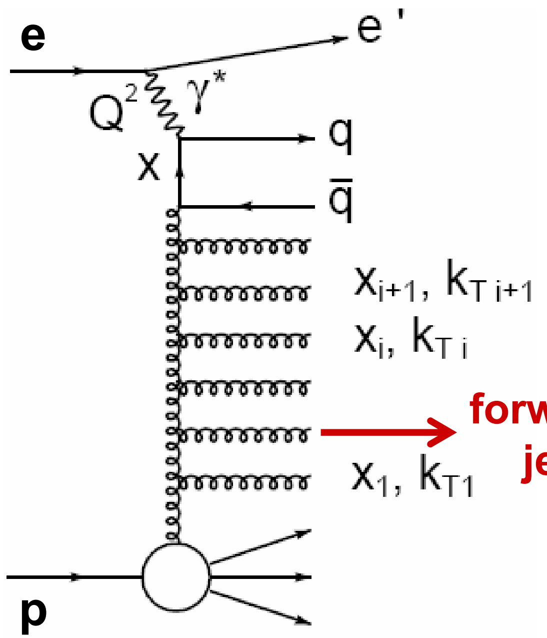
k_t – factorisation



Angular ordering of parton emissions

Input : unintegrated gluon densities (uPDF)

Forward jets in DIS



BFKL - more hard partons emitted close to the proton

Studies of forward jets are an experimental challenge :

region of high particle densities close to the proton remnant

Mueller – Navelet jets in DIS (1990) :

High transverse momentum and high energy jets produced close to the proton remnant direction

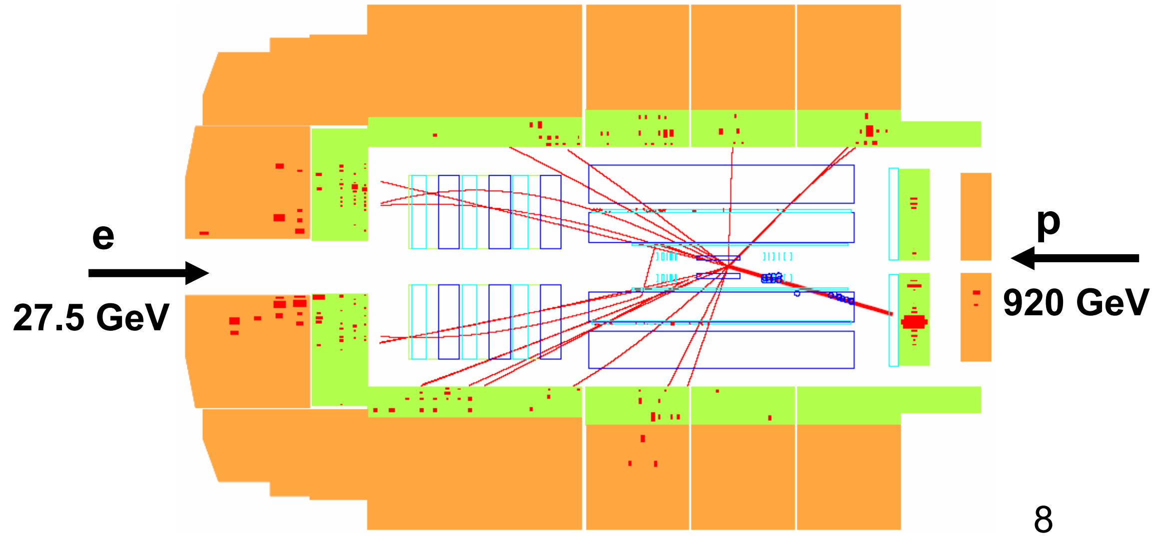
(forward region in LAB)

Suppress standard DGLAP evolution in Q^2 :

$$p^2_{T,jet} \approx Q^2$$

Enhance BFKL evolution in x :

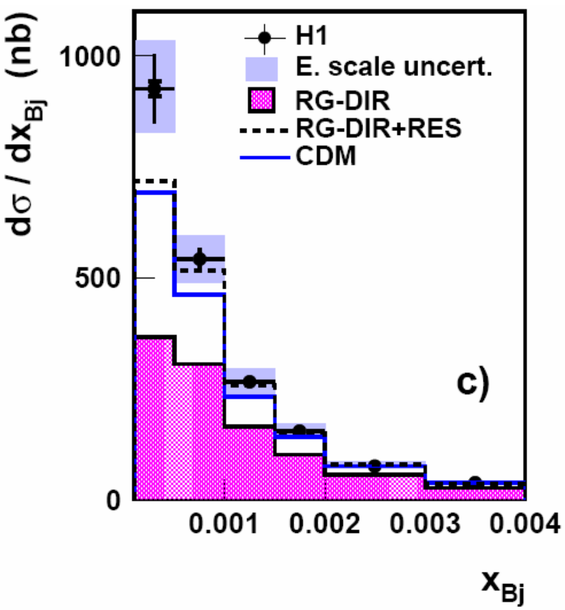
$$x_{fwdjet} = E_{fwdjet} / E_p >> x_{Bj}$$

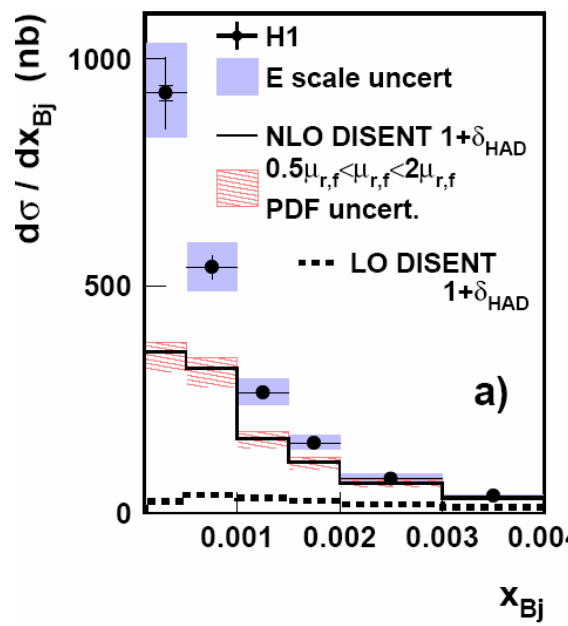


DIS event at low Q^2

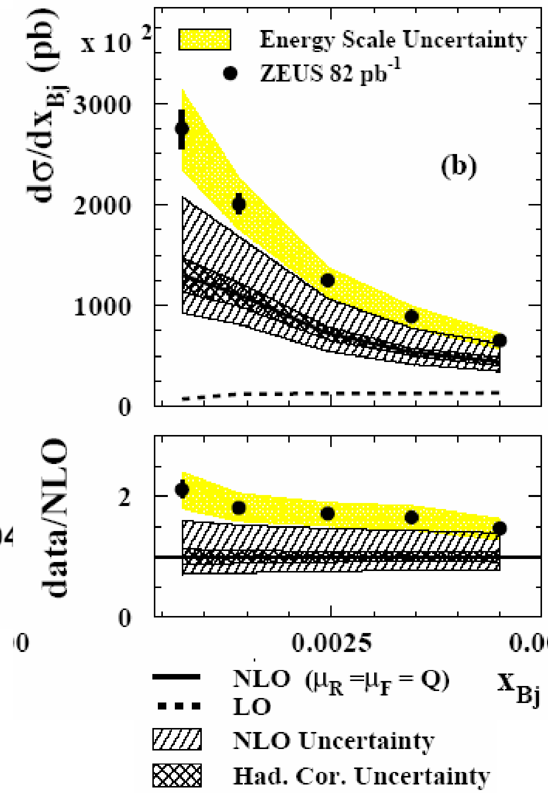
Forward jet production at low x-Bjorken in DIS

$5 < Q^2 < 85$ GeV2
$0.0001 < x_{Bj} < 0.004$
$E_T^{\ jet} > 3.5$ Ge, $x_{jet} > 0.035$,
$7^0 < \theta_{jet} < 20^0$, $0.5 < E_{T,jet}^2 / Q^2 < 5$





EPJ C46 (2006) 27



EPJ C52 (2007) 515

LO DGLAP (RG-DIR) **below the data**

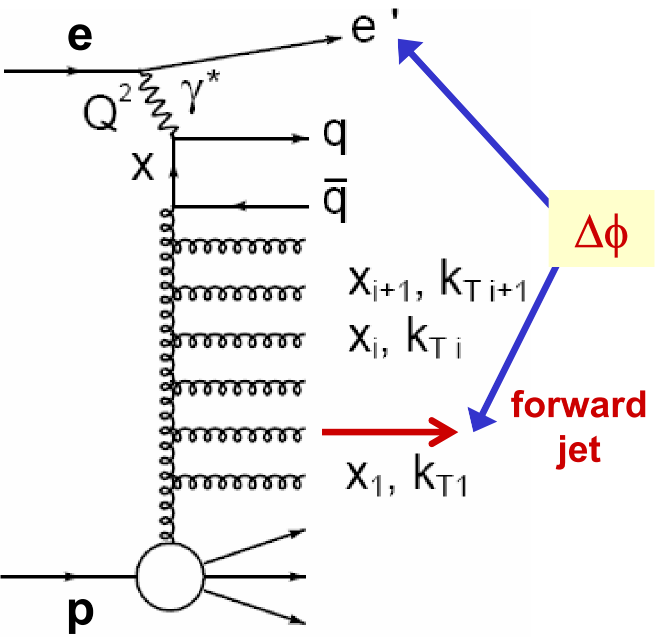
CDM and DGLAP resolved photon model (RG-DIR+RES) **closest to the data, but still below the data at low x**

CCFM **(not shown) fails to describe shapes (parameteris. of uPDF, missing g→qq terms ?)**

low x : NLO QCD prediction

order of magnitude larger than LO, but still below the data (factor 2 at low x)
→ missing higher orders

Forward jet azimuthal correlations



Azimuthal angle difference $\Delta\Phi$ between the scattered positron and the forward jet may be sensitive to BFKL dynamics

- **Quark Parton Model**

  $e + q \rightarrow e + q$

  simple two-body kinematics $\Delta\phi = \phi_{el} - \phi_{fwdjet} = \pi$

- **Inclusion of higher order processes decorrelates the jet from the positron**

H1 experiment, Eur. Phys. J. C72 (2012) 1910

DIS selection

$0.1 < y < 0.75$,

$5 < Q^2 < 85\ \mathrm{GeV}^2$

$0.0001 < x < 0.004$

Jets reconstructed in the Breit frame and boosted to LAB, all cuts in LAB

$p_{T,\,fwdjet} > 6$ GeV, $1.73 < \eta_{fwdjet} < 2.79$

$x_{fwdjet} = E_{fwdjet} / E_p > 0.035$, $0.5 < p_{T,fwdjet}^2 / Q^2 < 6.0$

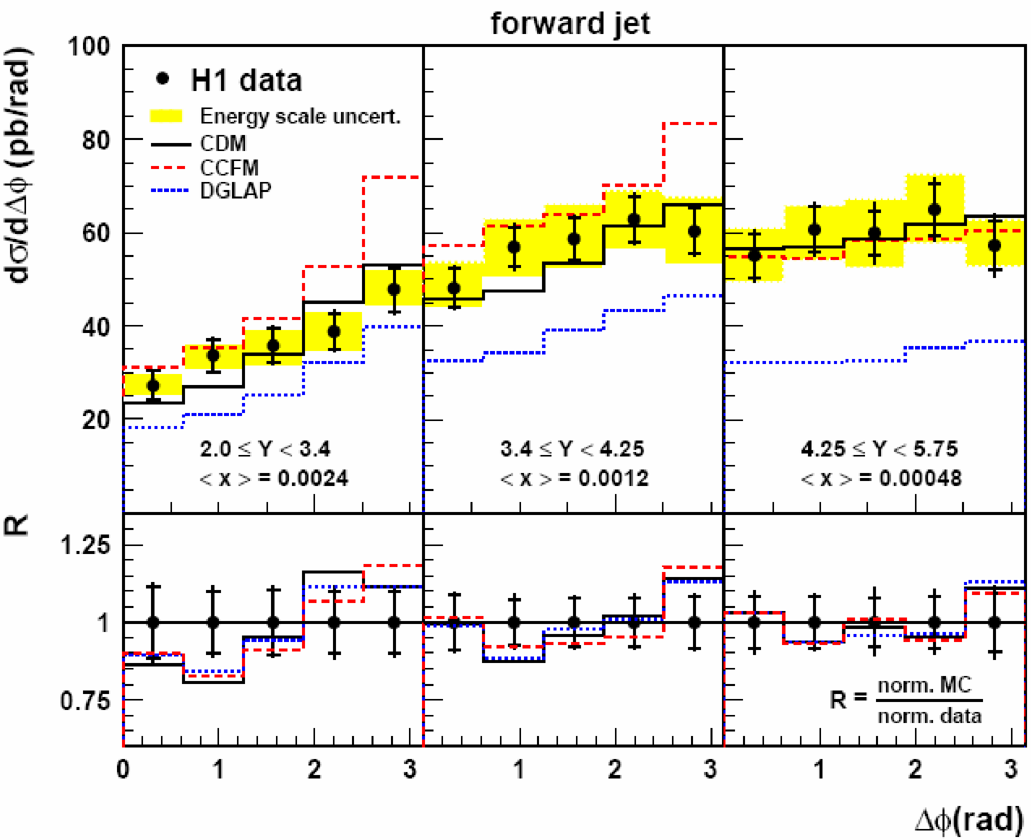
$\eta = -\ln\tan(\theta/2)$

θ with respect to proton beam direction

Forward jet azimuthal correlations

$Y = \ln(x_{fwdjet} / x)$ rapidity distance between the most forward jet and the scattered positron

Eur. Phys. J. C72 (2012) 1910



Cross sections best described by BFKL-like model CDM

- DGLAP predictions below the data
- CCFM (uPDF set A0) as good description as CDM at large Y
- CCFM predictions depend on the choice of uPDF

The shapes of the Δϕ distributions are described equally well by all MC models

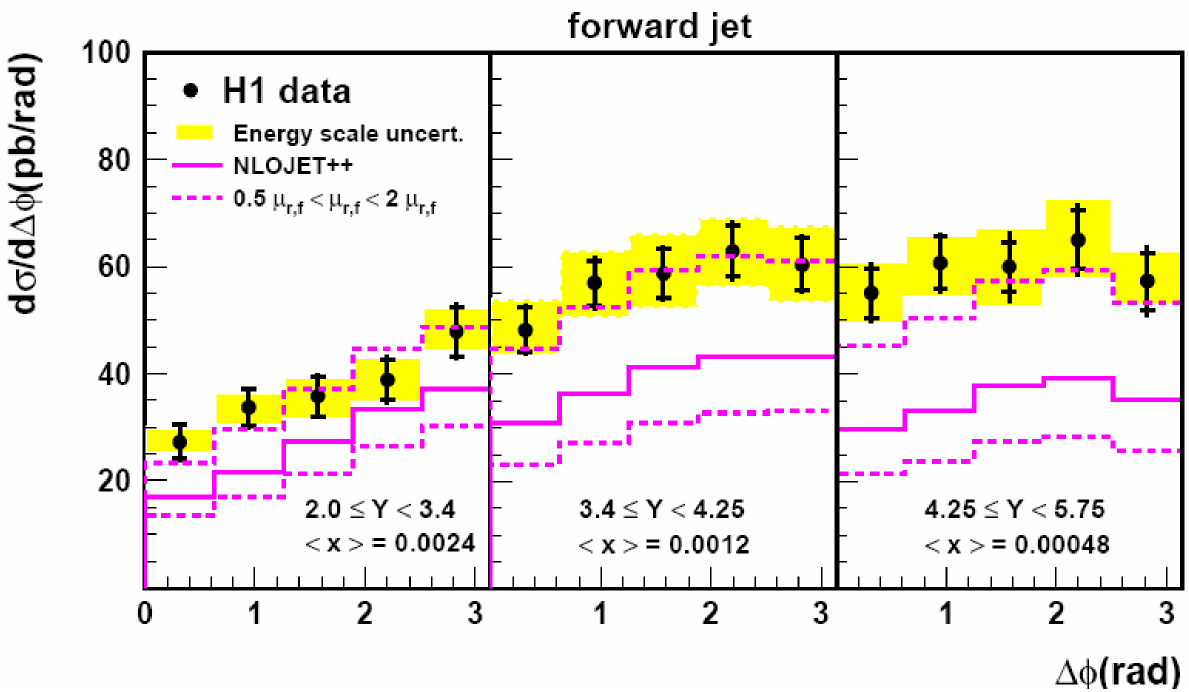
At higher Y correspondig to lower x the forward jet is more decorrelated from the scattered positron

$$R = \left(\frac{1}{\sigma^{\mathrm{MC}}}\frac{d\sigma^{\mathrm{MC}}}{d\Delta\phi}\right) \Big/ \left(\frac{1}{\sigma^{\mathrm{data}}}\frac{d\sigma^{\mathrm{data}}}{d\Delta\phi}\right)$$

Forward jet azimuthal correlations

Comparison to NLO ($O(\alpha_s^2)$) predictions

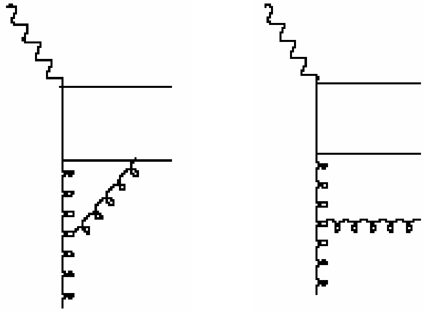
EPJ C72 (2012) 1910



NLOJET++ (Nagy & Trocsanyi, 2001)

NLO predictions

- shape of $\Delta\phi$ distributions described, but central value too low
- large scale uncertainty (of up to 50%) indicates importance of higher orders



Dijet production at parton level in DIS at NLO(α_s^2)

Forward jets at HERA :

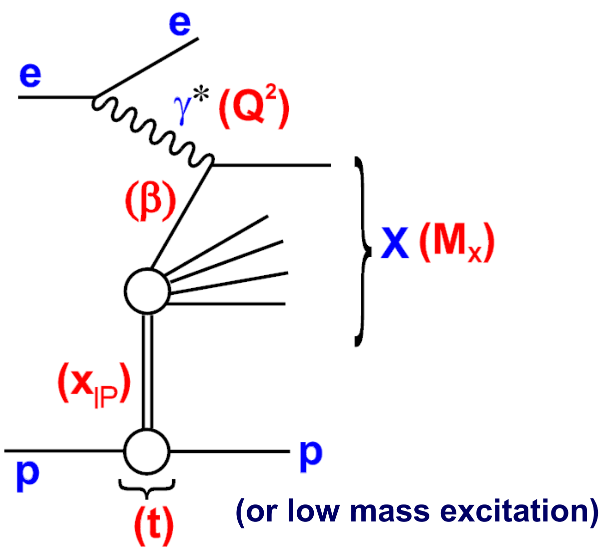
- evidence for novel (BFKL-like) parton cascade dynamics
- not yet clear to which extent these low-x effects can be explained through higher order DGLAP calculations

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 with vacuum quantum numbers, called Pomeron (IP)

Diffraction at HERA – low Bjorken-x phenomenon



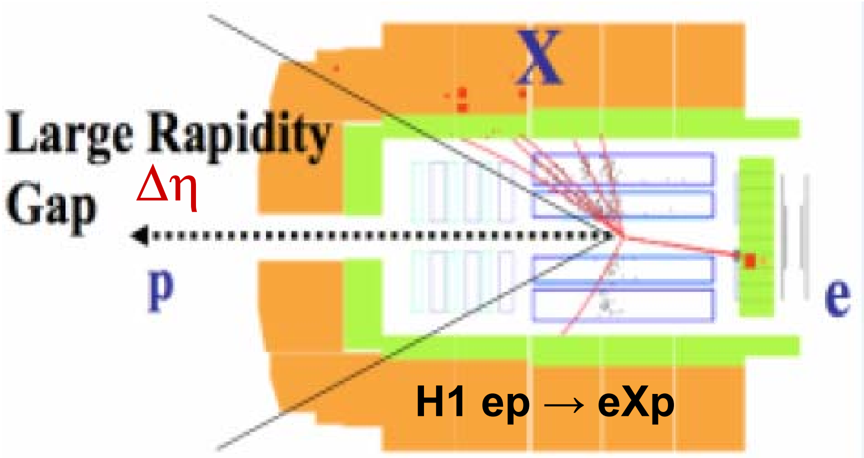
Additional variables for DDIS :

x_{IP} proton momentum fraction carried by IP

β IP-momentum fraction carried by struck quark

$x = x_{IP}\,\beta$

t squared 4-momentum transfer at proton vertex

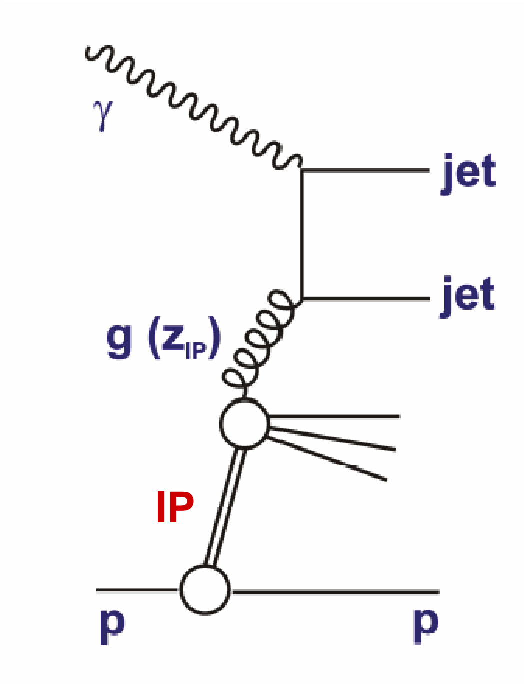


$\Delta\eta \sim \ln(W^2 / M_X^2)$

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

Measurements of the hadronic final states

Measurements of the HFS in diffractive DIS are complementary to inclusive studies

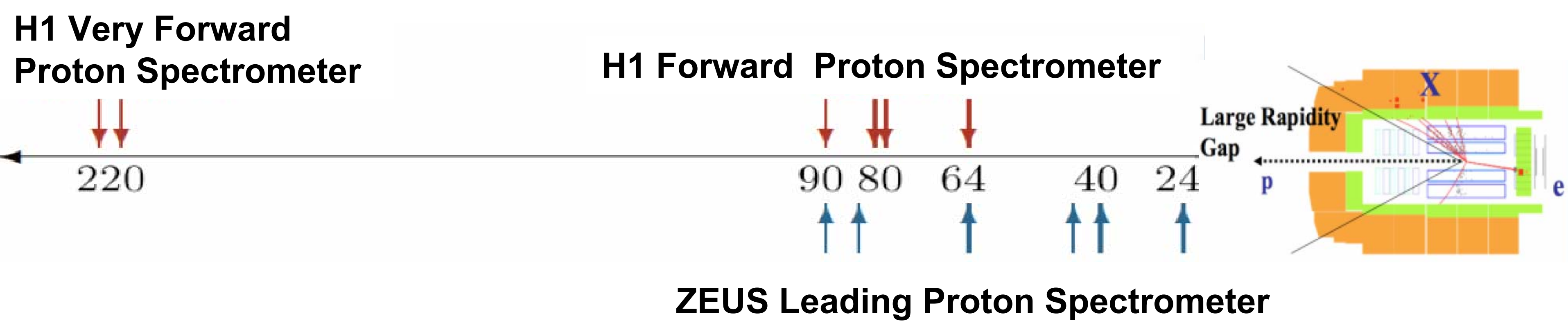


- **Tests of QCD (inspired) models of diffraction**
- **Probe partonic structure of diffractive exchange**

  Diffractive dijets - direct sensitivity to the gluon component of the Pomeron
- **Search for physics beyond DGLAP parton evolution**

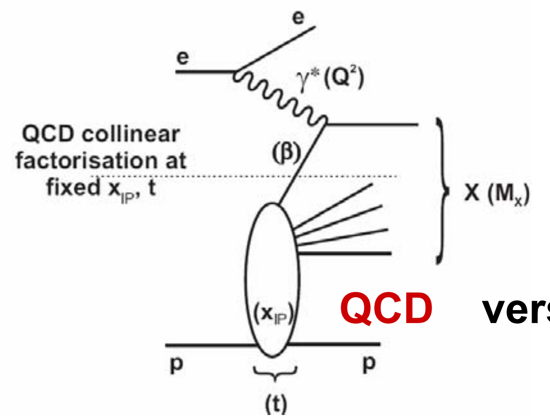
  …

Selection of diffractive events

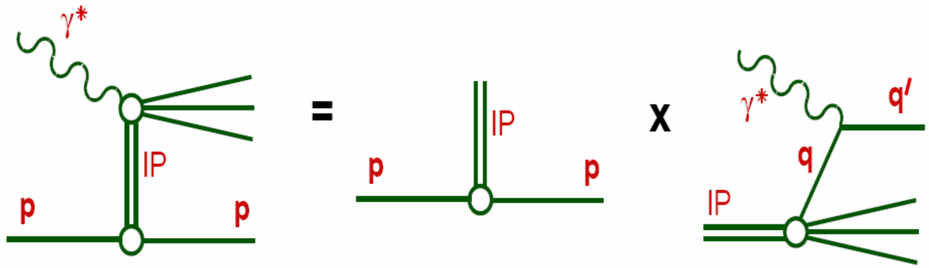


- **Proton spectrometers:**
  - detection of elastically scattered protons
  - low geometrical acceptance → less statistics
  - direct measurement of t, x_{IP}
  - high x_{IP} accessible
- **Large Rapidity Gap:**
  - selection of LRG adjacent to outgoing (untagged) proton
  - high acceptance → more statistics
  - 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 versus



Regge factorisation

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

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

f_i^D – diffractive parton density functions (DPDFs), DGLAP evolution in Q^2
σ^{ei} – partonic cross sections, same as in inclusive DIS

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

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

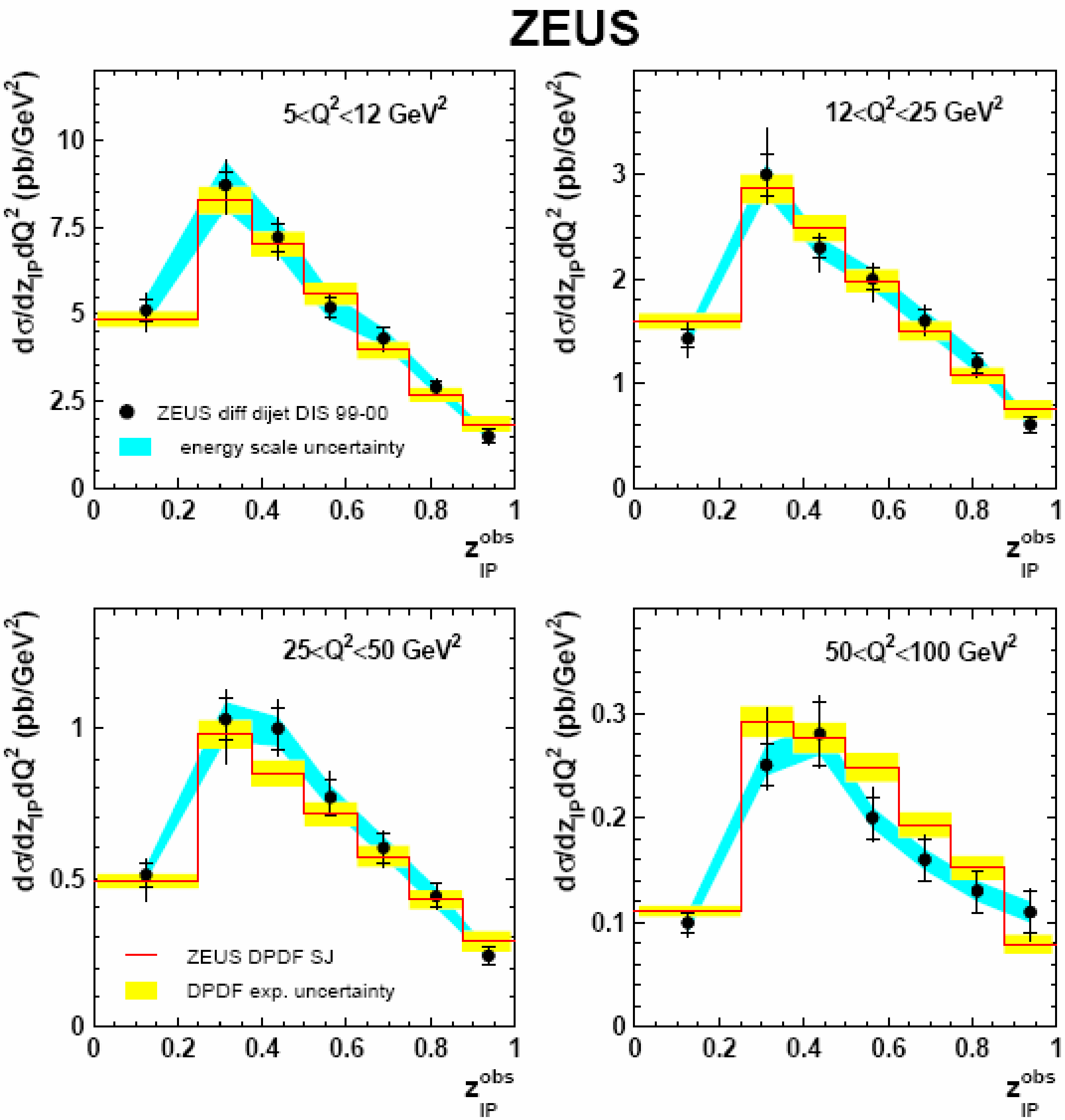
No QCD basis, consistent with experimental data

Pomeron flux

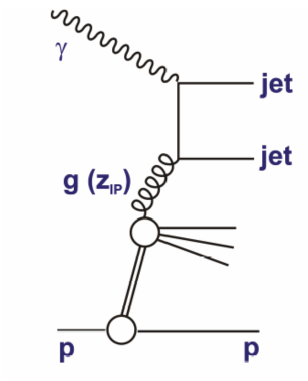
IP structure function

Diffractive exchange as the Pomeron with a partonic structure

Test of QCD factorisation in diffractive DIS



- 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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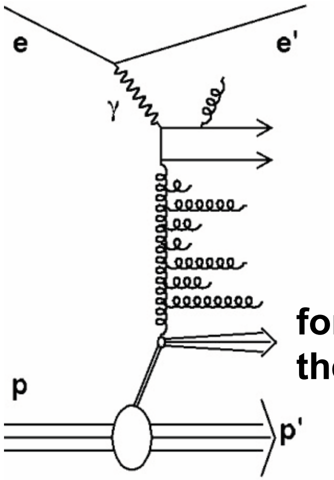
Dijets in diffractive DIS with a leading proton

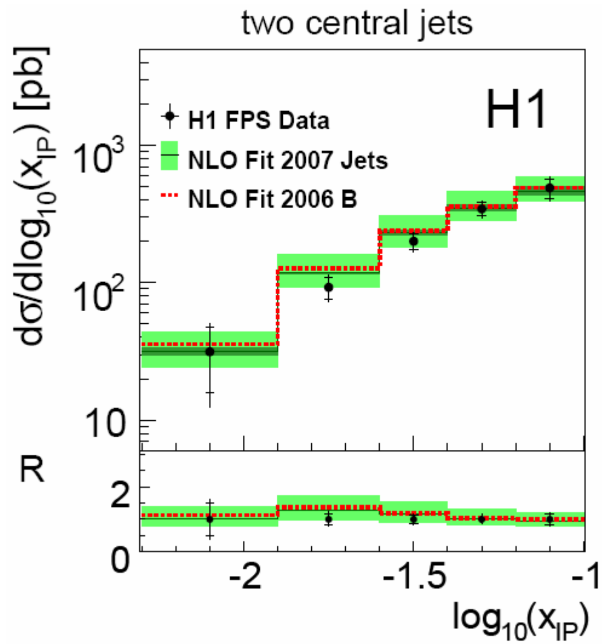
2 topologies:

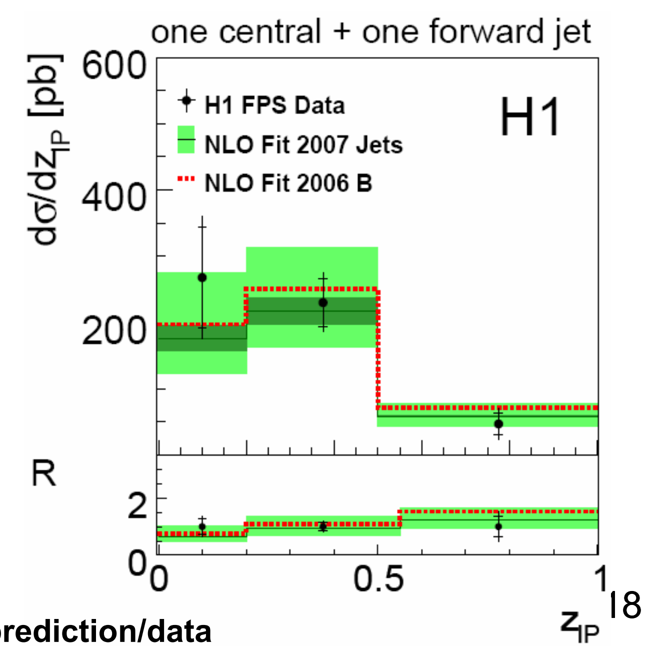
- **two central jets**
- **one central + one forward jet**

search for physics beyond DGLAP



forward jet close to the proton





DPDF + NLO QCD works well :

QCD factorisation holds in DIS regime

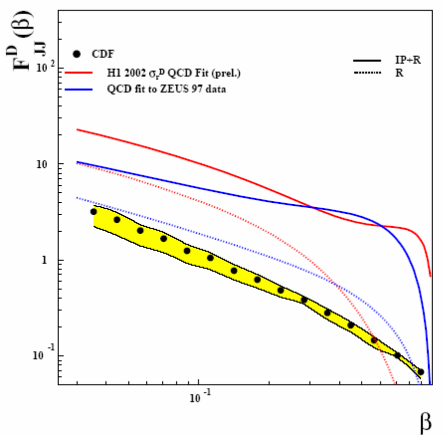
No sign for deviations from DGLAP

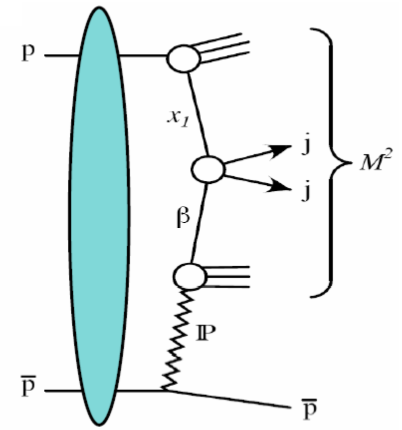
Eur. Phys. J. C72 (2012) 1970

R = prediction/data

Test of QCD factorisation in diffractive photoproduction

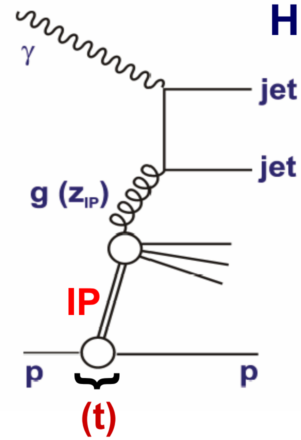
Tevatron vs HERA



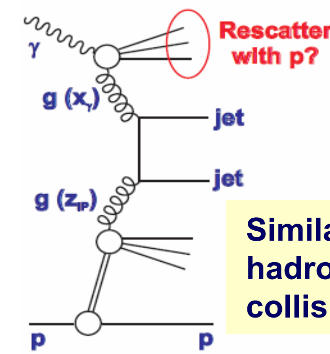


direct photoproduction

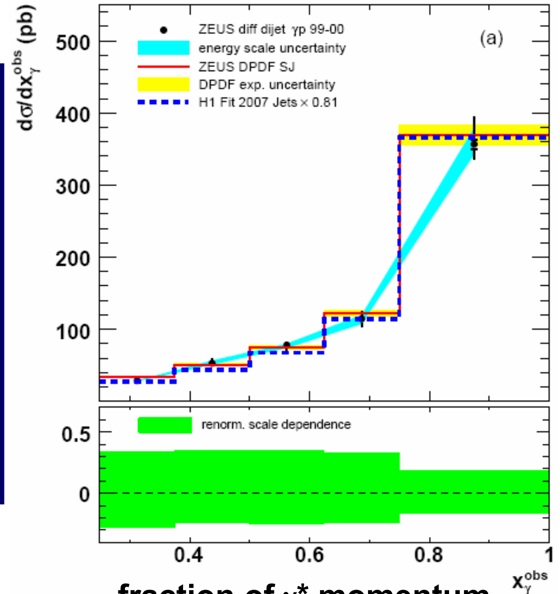
HERA



resolved photoproduction



Similarity with hadron-hadron collisions



fraction of γ^* momentum in hard subprocess

DPDFs from HERA applied to diffractive pp̄ scattering at the Tevatron

- **predictions for diffractive dijets exceed the data by a factor ~10**
- **breaking of QCD factorisation due to multiple scaterring in the presence of beam remnants → test of QCD factorisation in diffractive dijet photoproduction at HERA**

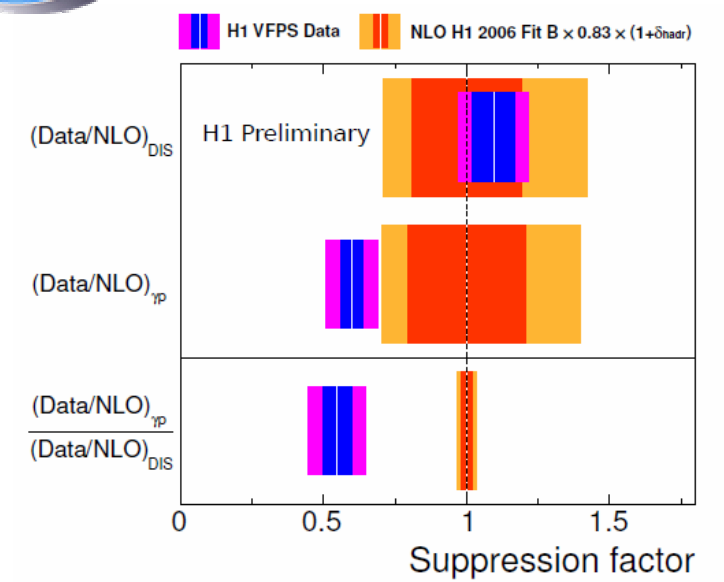
ZEUS data on diffractive dijet photoproduction consistent with no suppression (Nucl. Phys. B831 (2010) 1)

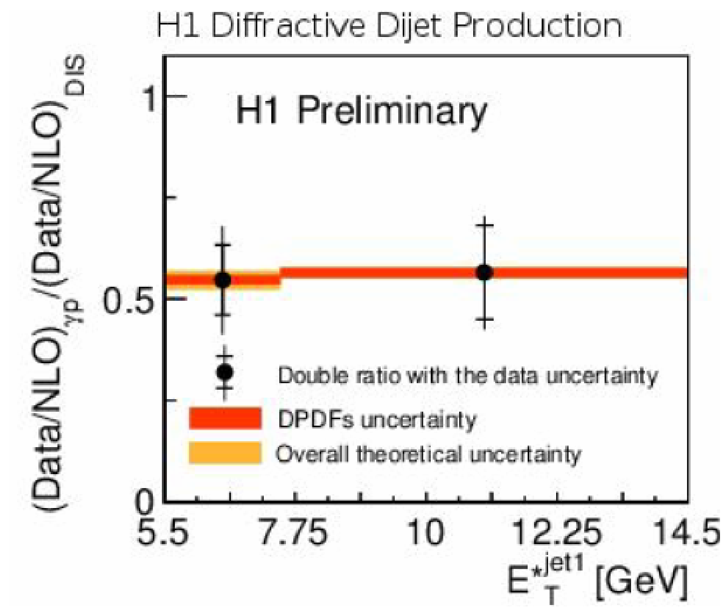
Diffractive dijets in DIS and photoproduction at HERA

Measurement of proton-tagged diffractive dijets in DIS and photoproduction

Test of QCD collinear factorisation

H1@DIS2014





The cross section double ratio of data to NLO prediction for photoproduction and DIS :

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

- **Confirmation of the previous H1 measurement based on large rapidity gap method**
- **Suppression factor in photoproduction ~0.55**
- **No dependence of supression factor on E_T of the leading jet**

Summary

- **Search for effects beyond the standard DGLAP approximation in low-x hadronic final state at HERA**

  Forward jet / particle production in DIS and diffractive DIS
  → 17 years of precise measurements by H1 and ZEUS

- **Measured cross sections much larger than lowest order DGLAP predictions**

- **Preference for models with QCD evolution non-ordered in transverse momentum observed, however no unequivocal evidence for non-DGLAP dynamics has been found**

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► **The data are in general more precise than NLO QCD predictions → challenge for QCD**

► **MC models matching NLO QCD calculations to parton showers would help to interpret measurements of the HFS at HERA**

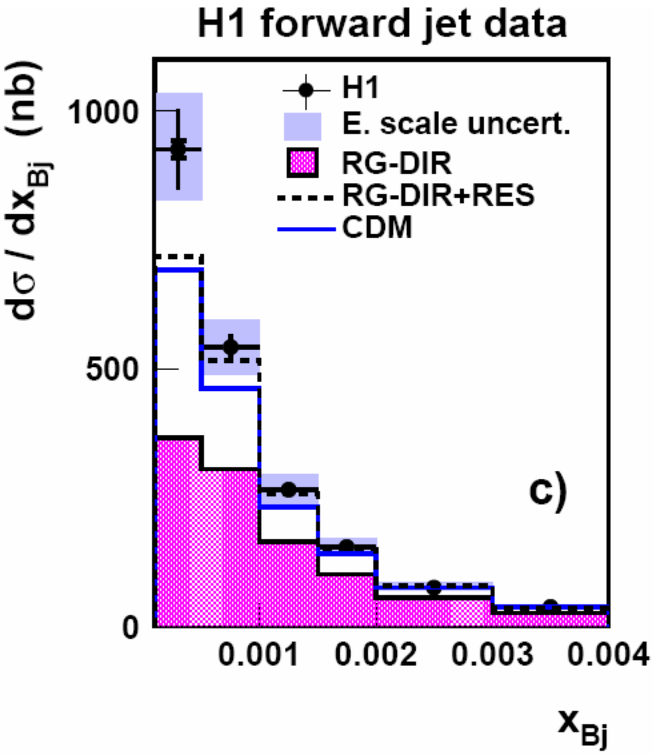
► **NLL BFKL (NLL BFKL kernel & NLO impact factors) calculation with Brodsky-Lepage-Mackenzie renormalisation scale fixing describes nicely Mueller-Navelet dijet decorrelation at LHC**

No such calculations for azimuthal decorrelation of forward jets in DIS

backup

Forward jet cross section dσ/dx

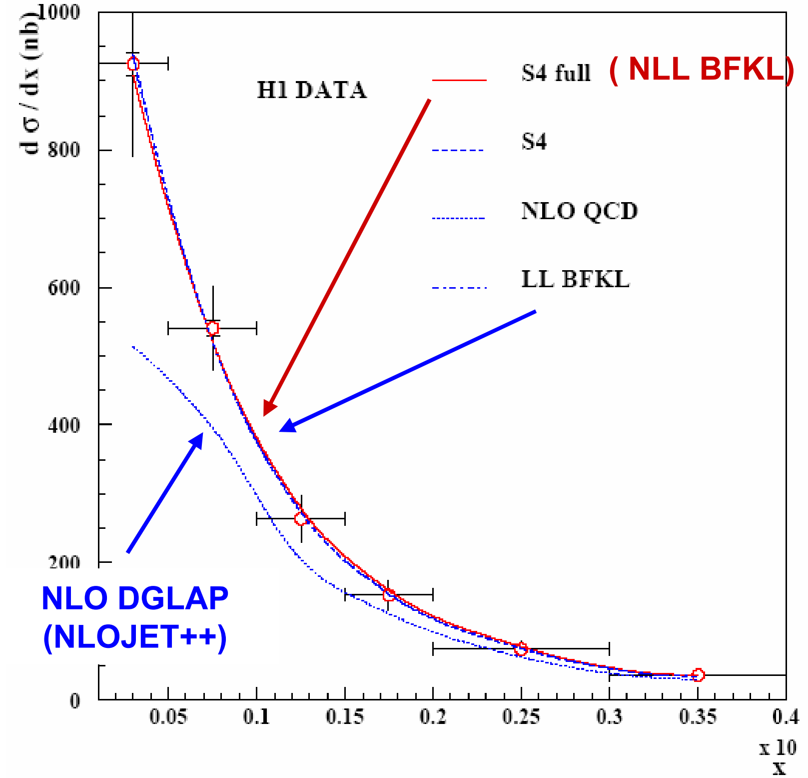
H1 data : Eur. Phys. J. C46 (2006)27



LO DGLAP (RG-DIR) below the data

CDM model and DGLAP resolved photon model (RG-DIR+RES) closest to the data, however the data are still below predictions at low x

BFKL calulations
Kepka, Royon, Marquet & Peschanski
Phys. Lett. B665 (2007) 236



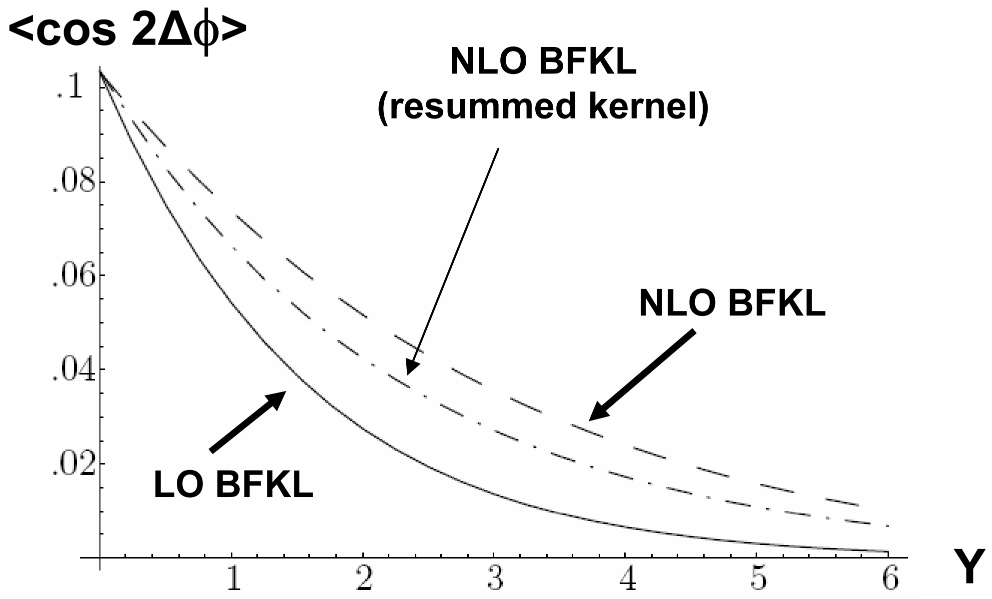
NLO DGLAP below the data at low x

Difference between LL-BFKL and NLL-BFKL (NLL BFKL kernel + free normalisation parameter) is very small

Forward jet production at NLO BFKL

S. Vera and F. Schwennsen, Phys. Rev. D77 (2008) 014001

BFKL kernel at NLO accuracy, jet vertex & photon impact factor using LO approximation



Results
for forward jets with ZEUS cuts

$20 < Q^2 < 100\ \text{GeV}^2$

$0.05 < y < 0.7$

$4 \cdot 10^{-4} < x_{Bj} < 5 \cdot 10^{-3}$

$0.5 < p_t^2 / Q^2 < 2.0$

$\Delta\phi = \phi_{el} - \phi_{fwdjet}$

$Y = \ln(x_{jet} / x_{BJ})$ – evolution length in BFKL formalism

- The forward jet is more decorrelated from the scattered lepton for larger rapidity difference Y (center of mass energy)
- The azimuthal angle correlations increase when HO corrections are included for a fixed value of Y

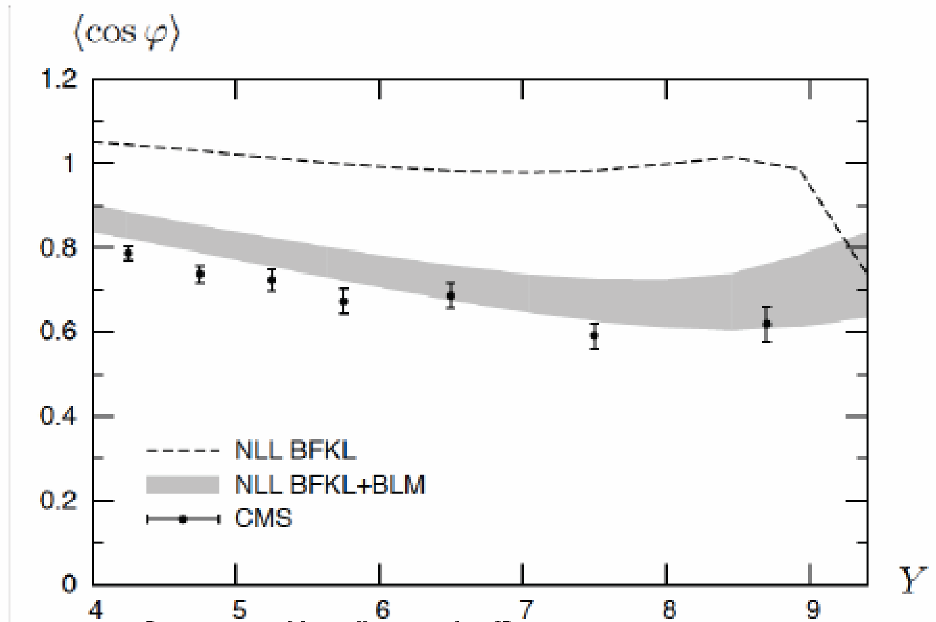
Mueller- Navelet dijet decorrelation

Preliminary CMS data at √s = 7 TeV

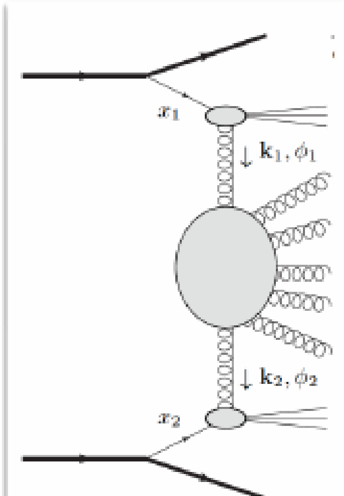
P. Van Mechelen @ DIS2014 Conference in Warsaw

NLL calculation by Szymanowski, Wallon, Ducloué

- NLL BFKL kernel
- NLO impact factors
- Brodsky-Lepage-Mackenzie procedure to fix scale for α_s



[Szymanowski, Wallon, Ducloué]

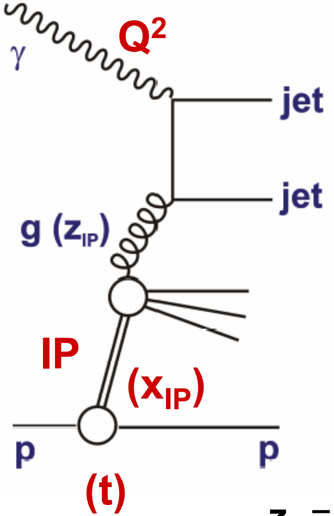


[Szymanowski, Wallon, Ducloué]

See talk by
- B. Ducloué (WG2+4, Wed. a.m.)

▸ **this implementation of BFKL describes data nicely!**

Diffractive parton density functions



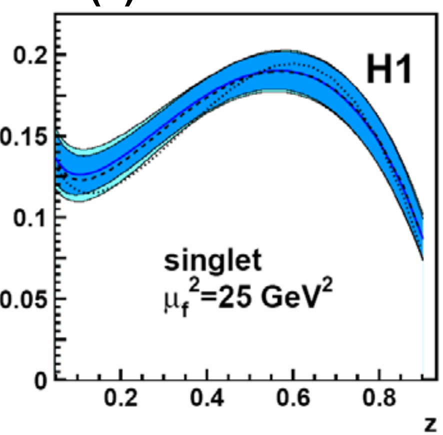
- Diffractive PDFs obtained through NLO DGLAP QCD fit to data
  - inclusive DDIS cross section → diffractive gluon density weakly constrained at high z_{IP}
  - combined fit to diffractive inclusive and dijet cross sections → comparable precision of quark and gluon densities for all z_{IP}

(H1 2007 Jets DPDF, ZEUS DPDF SJ)

z_{IP}= momentum fraction parton / IP

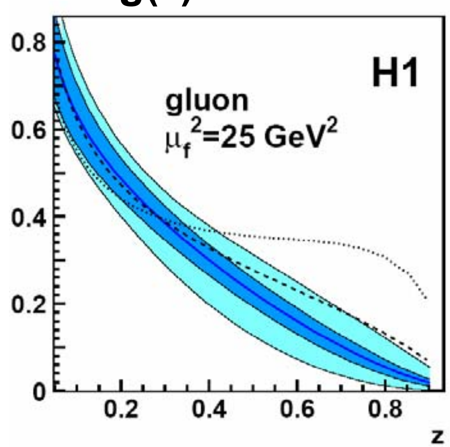
singlet quark density

$z \cdot \Sigma(z)$

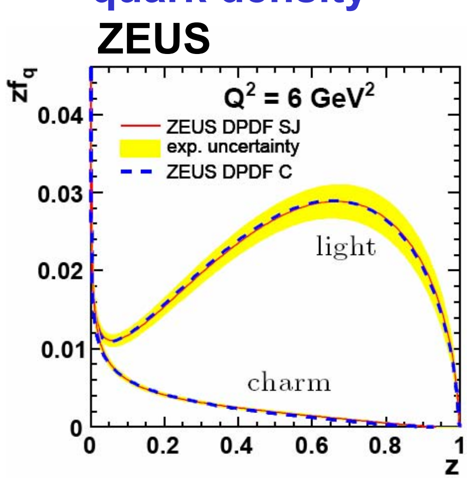


gluon density

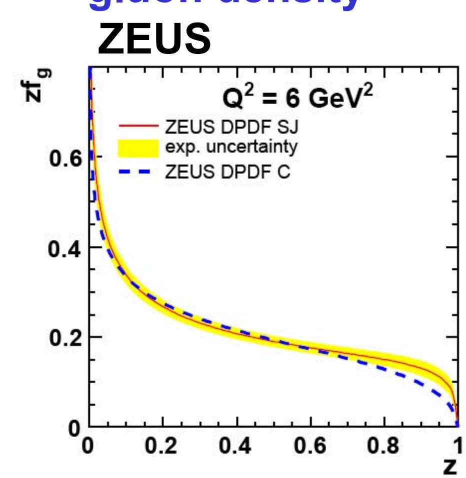
$z \cdot g(z)$

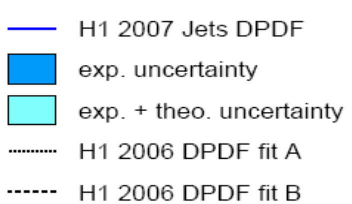


quark density



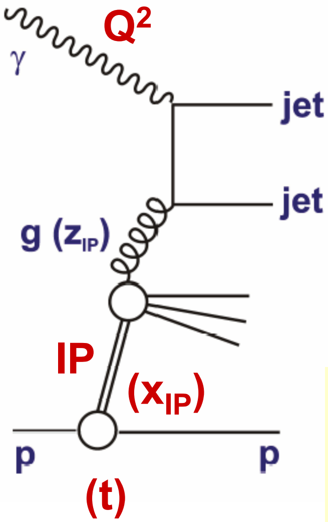
gluon density





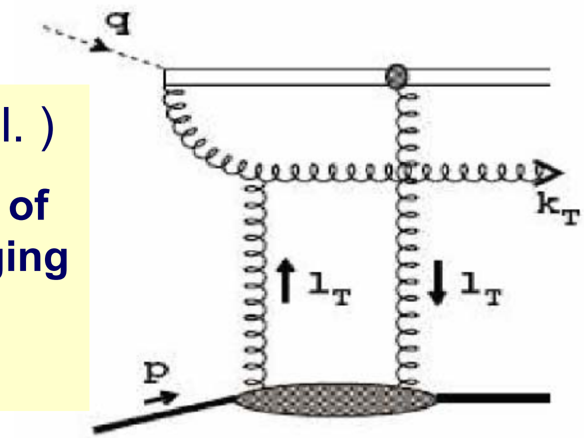
Diffractive scattering is dominated by gluons

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



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

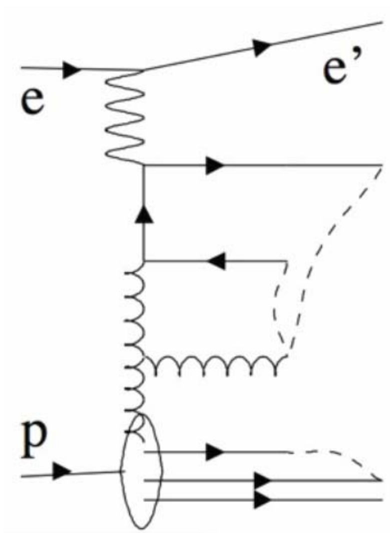
(RAPGAP generator, IP + Reggeon trajectories, DPDF H1 2006 Fit B)



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)