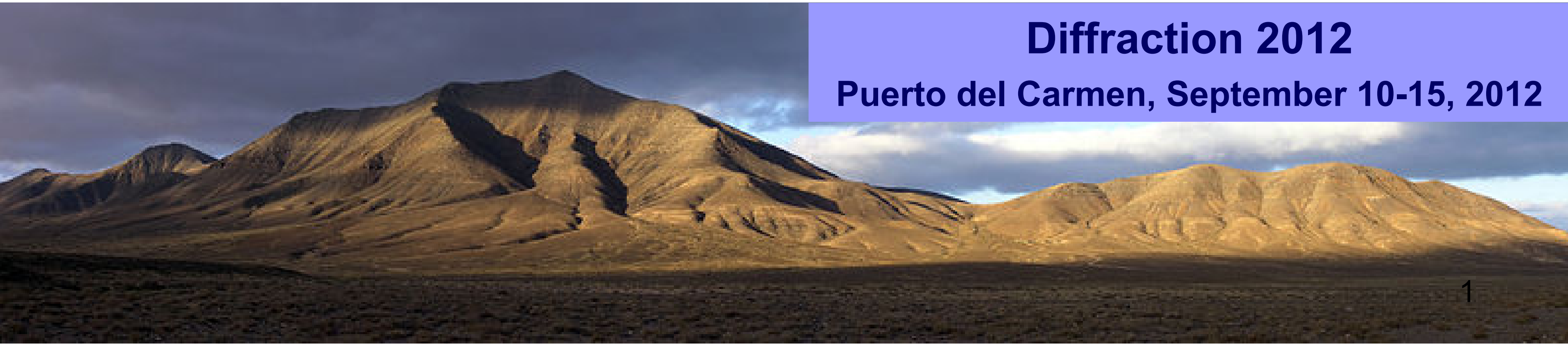
Recent results from low-x and forward physics at HERA

Lidia Goerlich
Institute of Nuclear Physics PAN, Cracow
(on behalf of the H1 Collaboration)

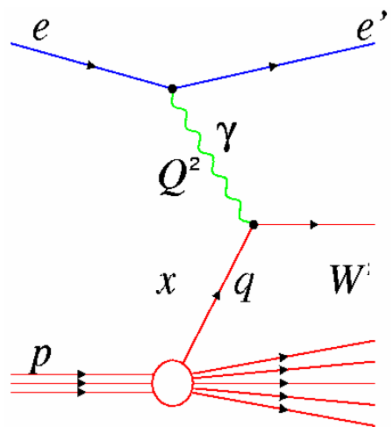
- QCD tests with the hadronic final states
- Azimuthal correlation of forward jets in DIS
- Dijet production in diffractive DIS with a leading proton
- Summary



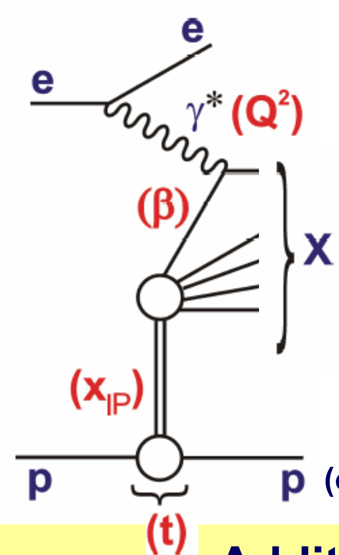
Diffraction 2012

Puerto del Carmen, September 10-15, 2012

Deep inelastic ep scattering



Diffractive DIS



(or low mass excitation)

~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

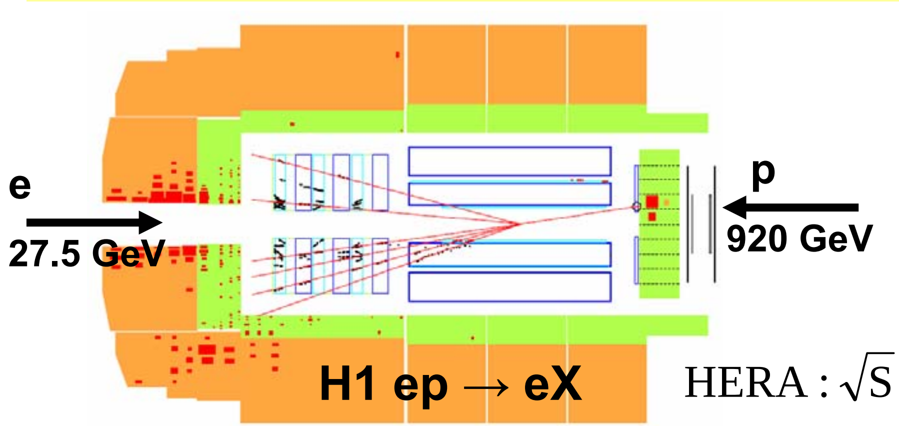
$y = Q^2 / xs$ inelasticity

Additional variables for DDIS :

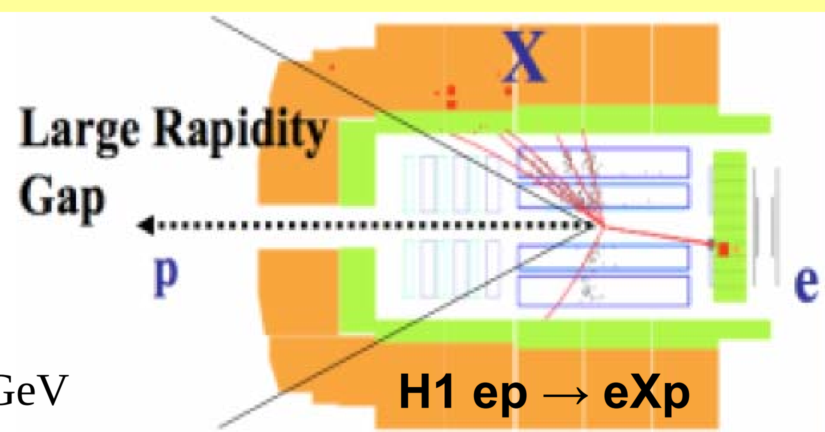
x_{IP} p-momentum fraction carried by IP

β IP-momentum fraction carried by struck quark

t 4-momentum transfer at proton vertex

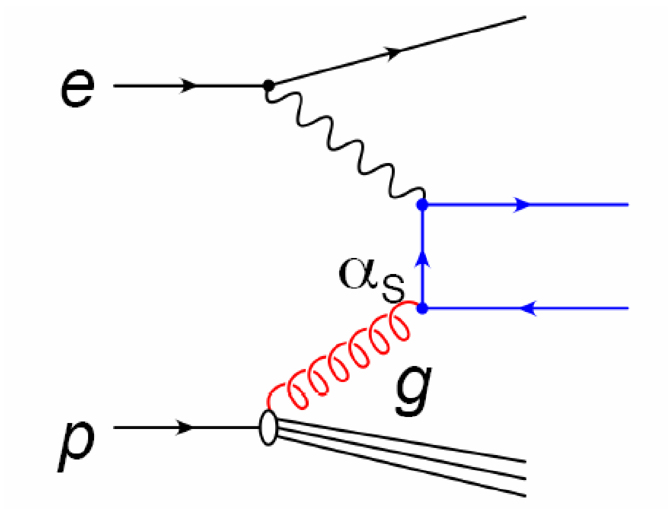


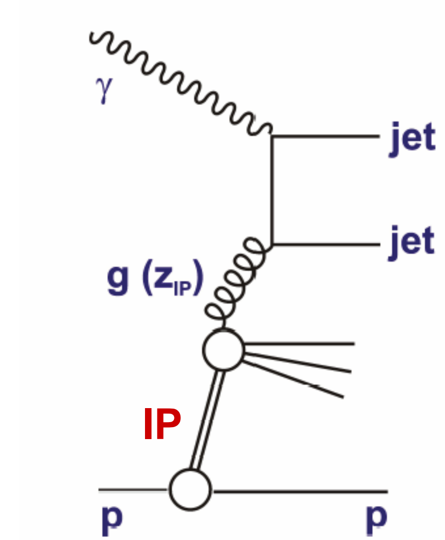
HERA : $\sqrt{S} \approx 300$ GeV



Measurements of the hadronic final states

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





- Information on the gluon density in the proton
- Determination of α_S
- Search for effects of parton dynamics beyond the standard DGLAP approach

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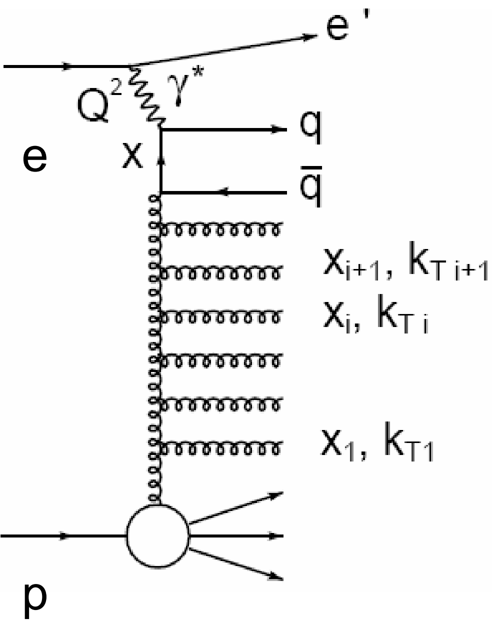
- Tests of QCD (inspired) models of diffraction
- Diffractive dijets - direct sensitivity to the gluon component of the Pomeron
- Search for physics beyond DGLAP parton evolution

…

QCD dynamics at low Bjorken-x

HERA : DIS at low Bjorken-x down to 10^{-5} → 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 :

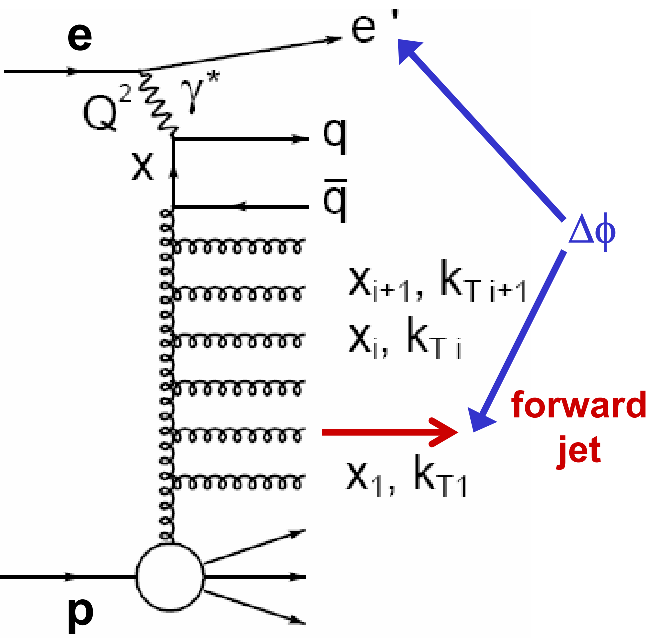


- **DGLAP** evolution: resums terms ~ ($\alpha_s \ln Q^2$)^n
  Assumes strong ordering of parton k_T
- **BFKL** evolution: resums terms ~ ($\alpha_s \ln(1/x)$)^n
  No ordering in k_T, strong ordering in x_i
  Transition from DGLAP to BFKL scheme expected at low x
- **CCFM** evolution: emitted partons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

Forward jets in DIS



Mueller – Navelet jets in DIS (1990) :

BFKL – more hard partons emitted close to the proton

Study high transverse momentum and high energy jets produced close to the proton (forward region in LAB)

Suppress standard DGLAP evolution in Q^2 :

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

Enhance BFKL evolution in x :

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

Data selection

~14000 forward jet events

H1 experiment, HERA data (2000) with 38.2 pb^{-1}

$0.1 < y < 0.75, < Q^2 < 85\ GeV^2, 0.0001 < x < 0.004$

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

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

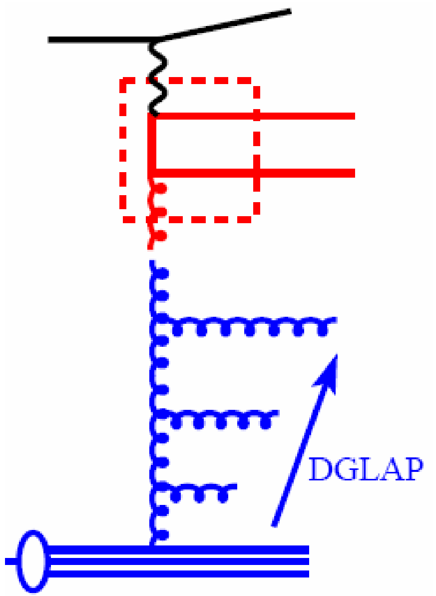
$x_{fwdjet} = E_{fwdjet} / E_p > 0.035,\ 0.5 < p_{T,fwdjet}^2 / Q^2 < 6.0$

Measurement of the azimuthal angle difference $\Delta\phi$ between the scattered positron and the forward jet as a function of the rapidity distance Y between them.

Low x phenomenology : Monte Carlo models with different QCD dynamics

RAPGAP - DGLAP

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

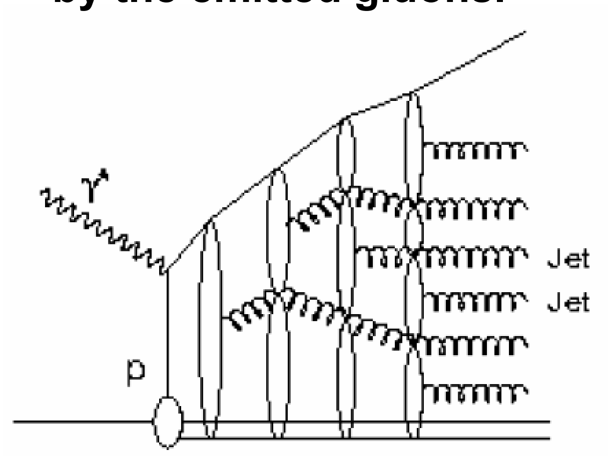


Single DGLAP ladder with strong ordering in k_T

ARIADNE Colour Dipole Model

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

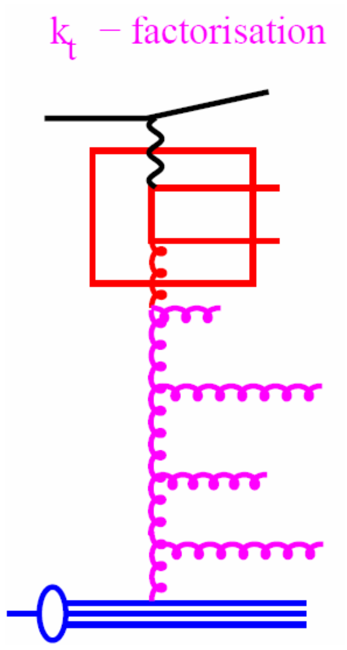
Chain of independently radiating dipoles formed by the emitted gluons.



BFKL- like Monte Carlo : random walk in k_T

CASCADE - CCFM

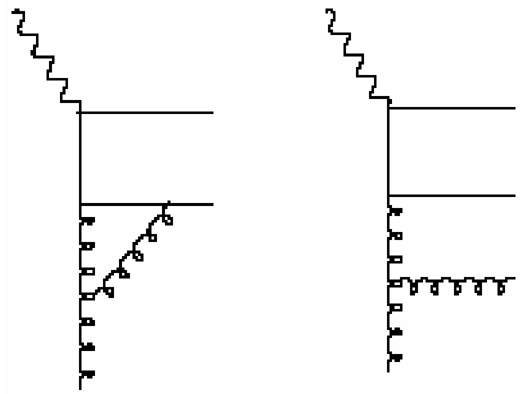
Off-shell QCD ME
+ parton emissions based on the CCFM equation



Angular ordering of parton emissions

Low x phenomenology : fixed order NLO DGLAP calculations

Forward jet cross sections – comparison with the predictions of pQCD at NLO (α_s^2) accuracy



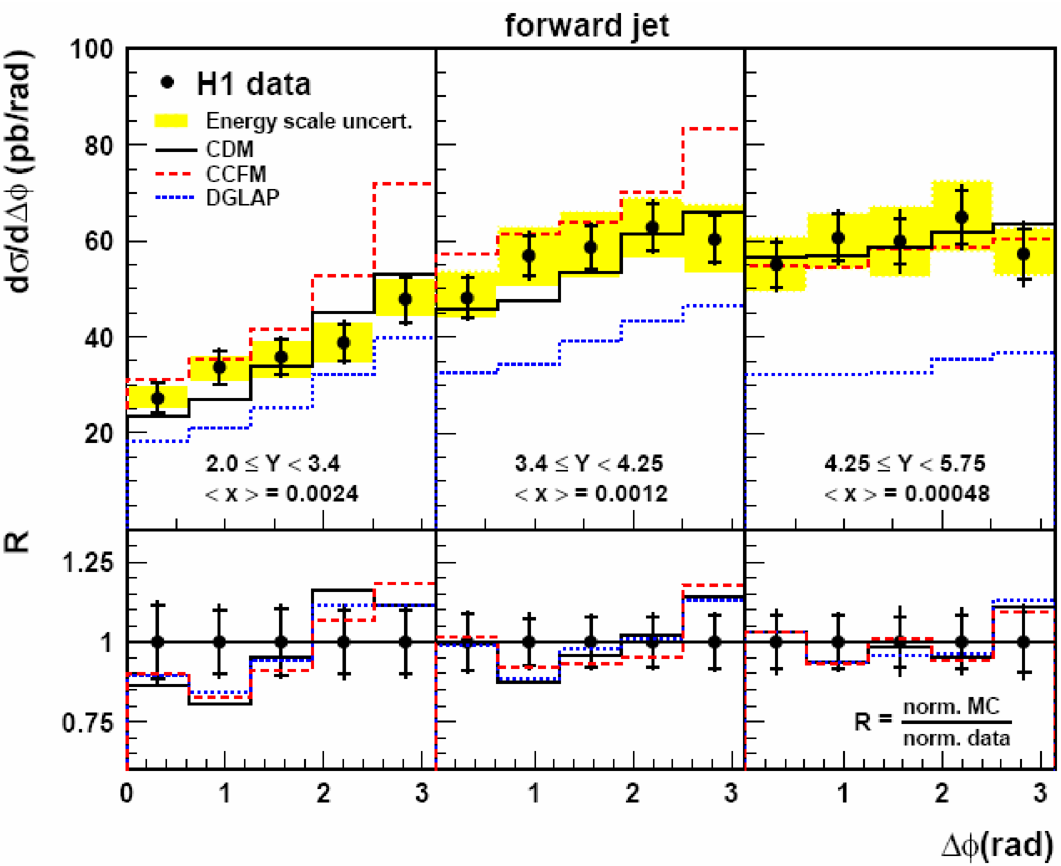
- **Forward jet analysis – reconstruction of jets in the Breit frame $\rightarrow$ at least dijet topology**

NLOJET ++ program (Nagy & Trocsanyi, 2001) :
dijet production at parton level in DIS at NLO (α_s^2)

- **PDF : CTEQ6.6, $\alpha_s(M_Z) = 0.118$**
- **parton level cross sections corrected for hadronistaion effects using the RAPGAP model**

Forward jet azimuthal correlations

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



Eur. Phys. J. C72 (2012) 1910

Cross sections best described by BFKL-like model CDM

- **DGLAP predictions below the data**
- **CCFM (set A0) as good description as CDM at large Y**

The shape of Δφ distributions well described by all MC models

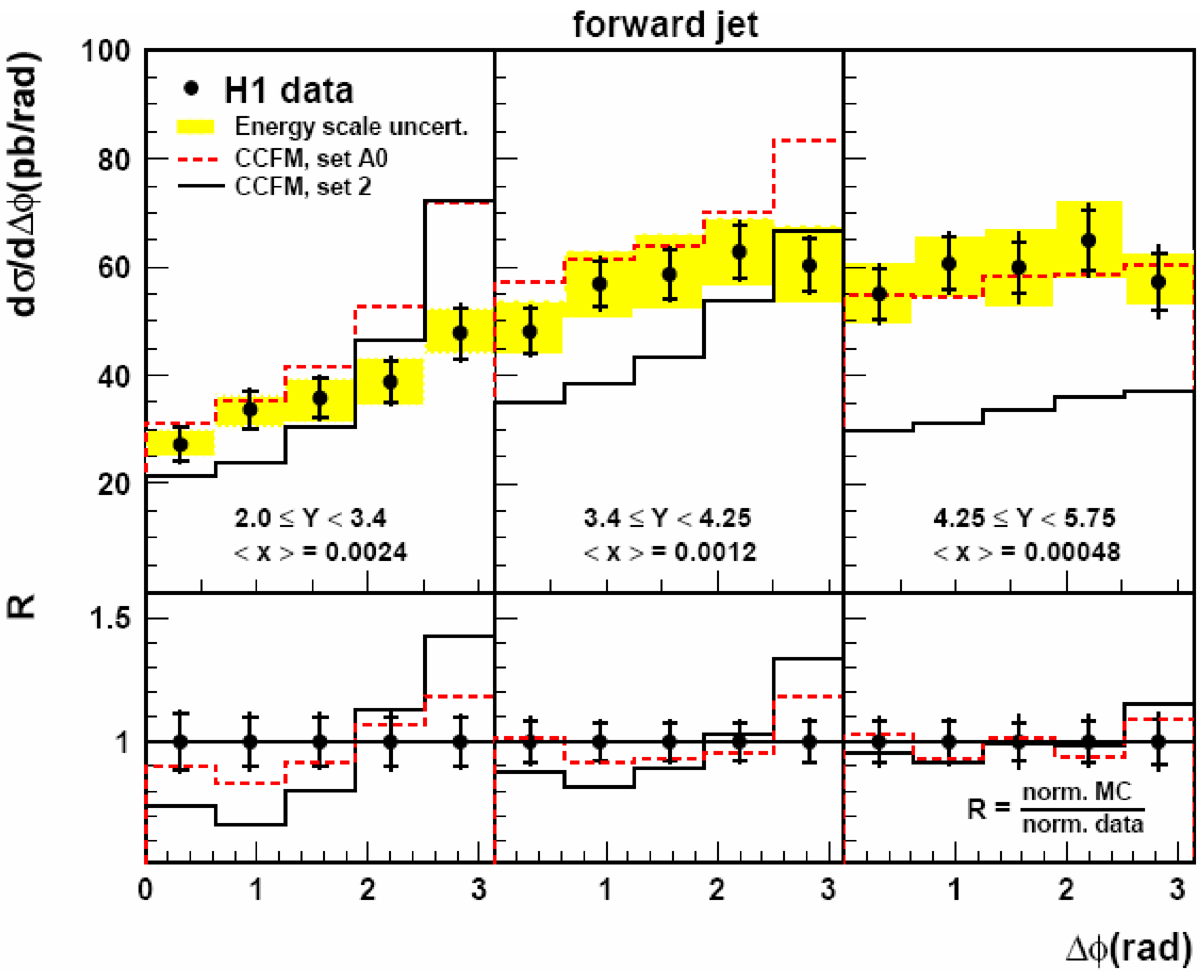
Y = ln(x_{fwdjet} / x) rapidity distance between the most forward jet and the scattered positron

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

Forward jet azimuthal correlations

Different splitting functions used in unintegrated gluon density function (uPDF):

set A0 – only singular terms of the gluon splitting function
set 2 – includes also non-singular terms

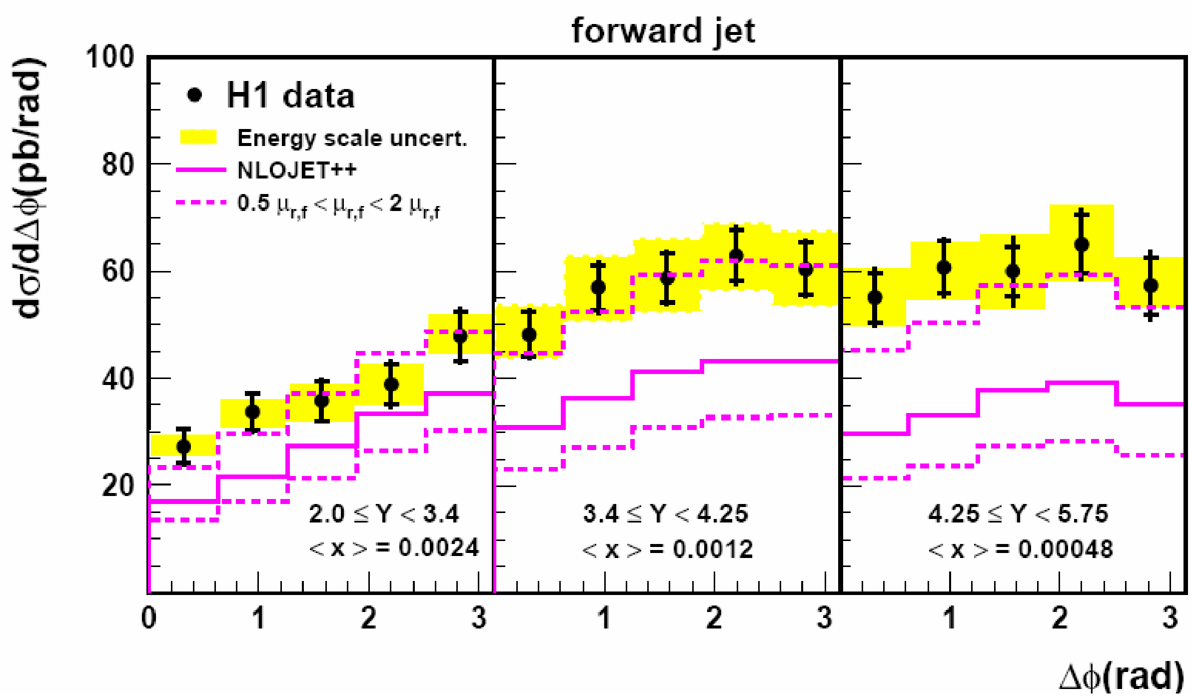


- **Cross sections**
  strongly depend on uPDF
- **Shape of Δϕ distributions**
  - **at low Y shows sensitivity to uPDF**
  - **well described by the set A0**

Predictions of the CCFM model depend on the choice of uPDF

Forward jet azimuthal correlations

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



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

NLOJET++

PDF : CTEQ6.6, $\alpha_S(M_Z)=0.118$

renormalisation and factorisation scales :

$\mu_r^2 = \mu_f^2 = (p^2_{T,\,fwdjet} + Q^2) / 2$

theoretical uncertainty : factor 2 or ½ applied to μ_r and μ_f scales simultaneously

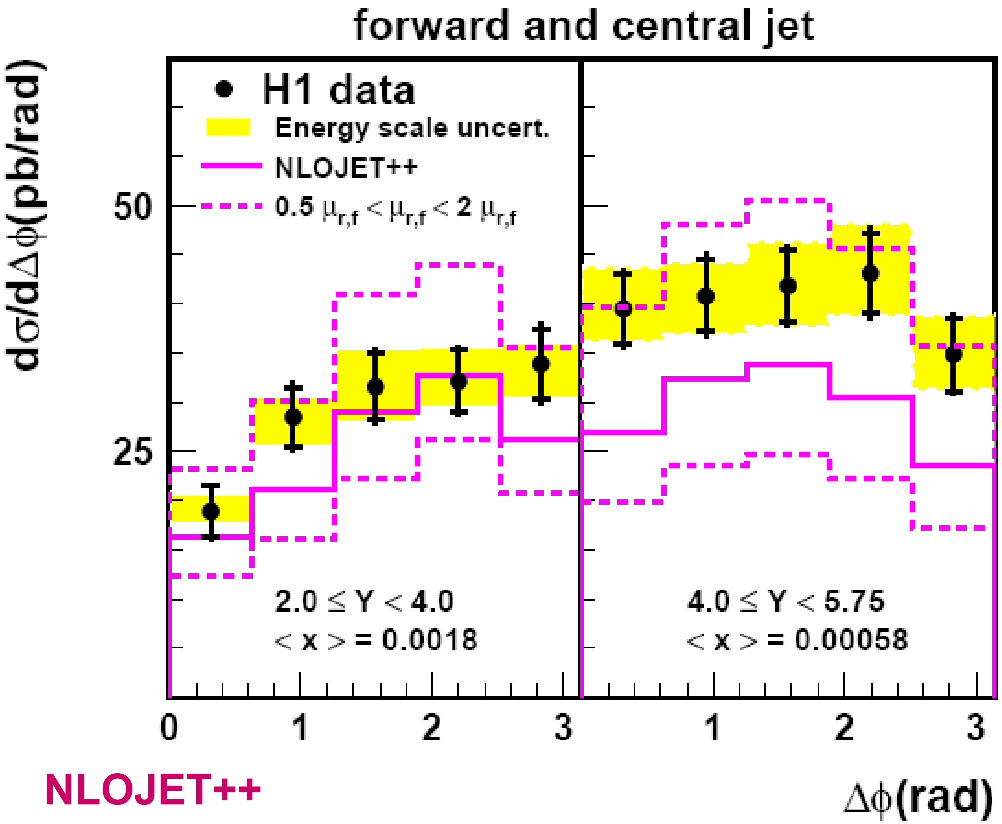
Forward and central jet cross sections $d\sigma / d\Delta\phi$

- **Subsample of events with forward jet + additional central jet**

  $p_{T,cenjet} > 4$ GeV, $-1 < \eta_{cenjet} < 1$

  $\Delta\eta = \eta_{fwdjet} - \eta_{cenjet} > 2$ (enhance radiation between the forward and central jet)

- **$\Delta\phi$ still between the forward jet and the scattered positron**



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

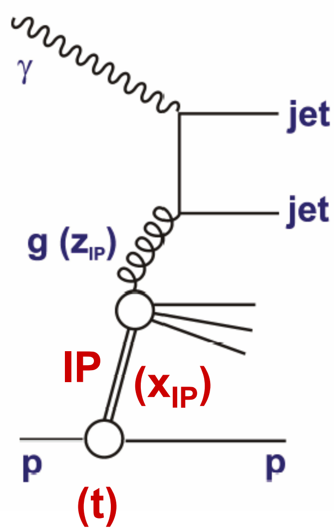
- at low Y reasonable description of the data
- at high Y, central value to small but still within theory uncertainty
- large scale uncertainty (of up to 40%) indicates importance of higher order contributions

NLOJET++

PDF : CTEQ6.6, $\alpha_S(M_Z)=0.118$

$\mu_r^2 = \mu_f^2 = (\langle p_T \rangle^2 + Q^2) / 2$

$\langle p_T \rangle = 0.5 (p_{T,\,fwdjet} + p_{T,\,cenjet})$



$e\,p \rightarrow e\,jj\,X'\,p$

at least 2 jets + outgoing proton measured in the H1 Forward Proton Spectrometer

(no background from proton dissociation)

FPS @ H1

- 2 horizontal Roman Pot stations at 61m and 80 m
- Scintillating fibres with PMTs + trigger tiles
- Acceptance :

$x_{IP} = 1 - E_{p'}/E_p$ up to 0.1

$0.1\ GeV^2 < |t| < 0.7\ GeV^2$

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

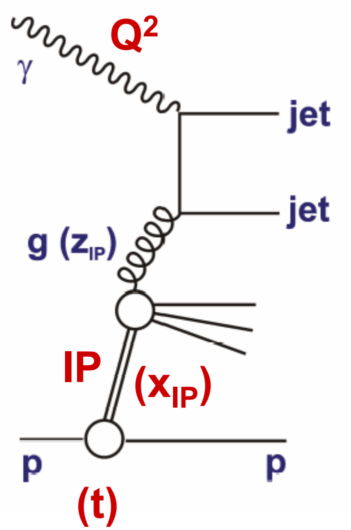
Proton vertex factorisation: separate (x_{IP}, t) from (β, Q^2) dependences

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

No QCD basis, consistent with experimental data

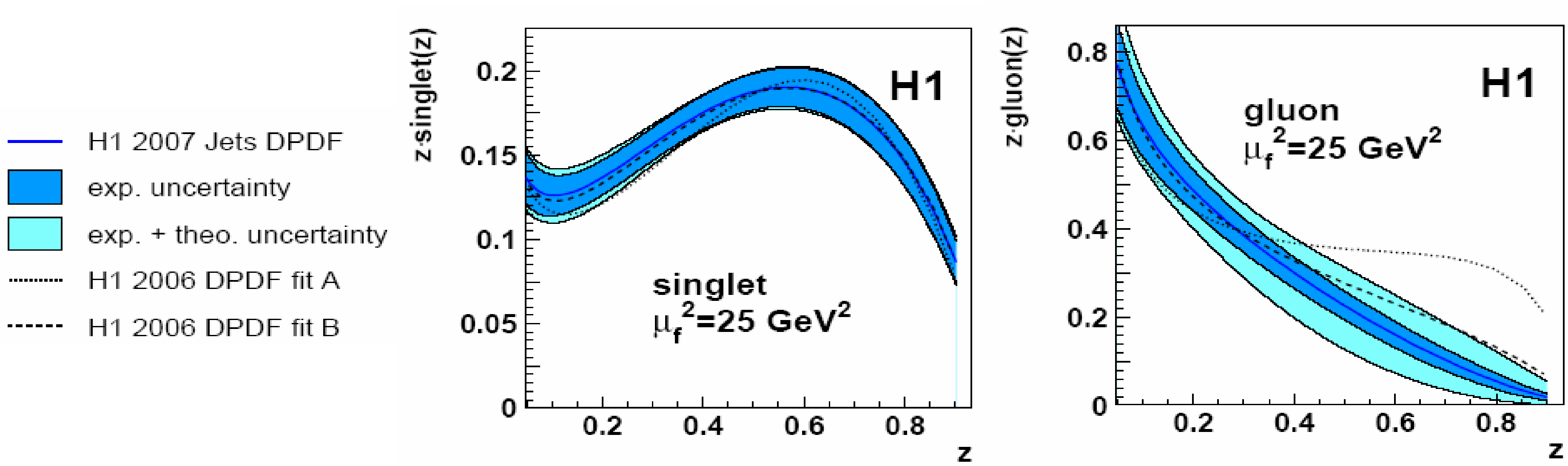
Pomeron flux (Regge form)	Pomeron structure function

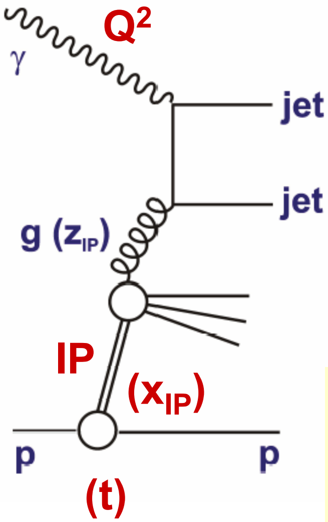
Diffractive PDFs



z_{IP}= momentum fraction parton / IP

- Diffractive PDFs extracted from
  - measurements of inclusive DDIS → H1 2006 DPDF Fit B (diffractive gluon density weakly constrained at high z_{IP})
  - combined fit to diffractive inclusive and dijet cross sections → H1 2007 Jets DPDF (diffractive dijets constrain g(z_{IP}) at high z_{IP})
- The photon virtuality Q^2 and the high transverse momentum of jets provide a hard scale for pQCD calculations (program NLOJET++ modified for diffraction)

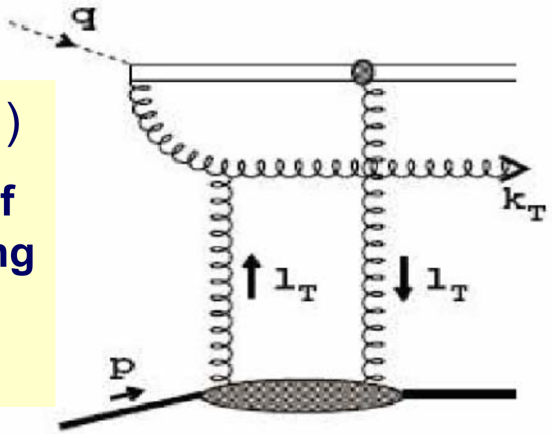




Resolved Pomeron model (Ingelman & Schlein)

based on QCD and proton vertex factorisation.

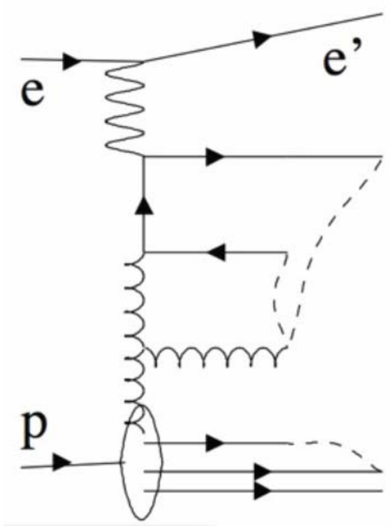
(RAPGAP generator, IP + Reggeon trajectories, DPDF H1 2006 Fit B)



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)

H1 FPS – 2 central jets in diffractive DIS

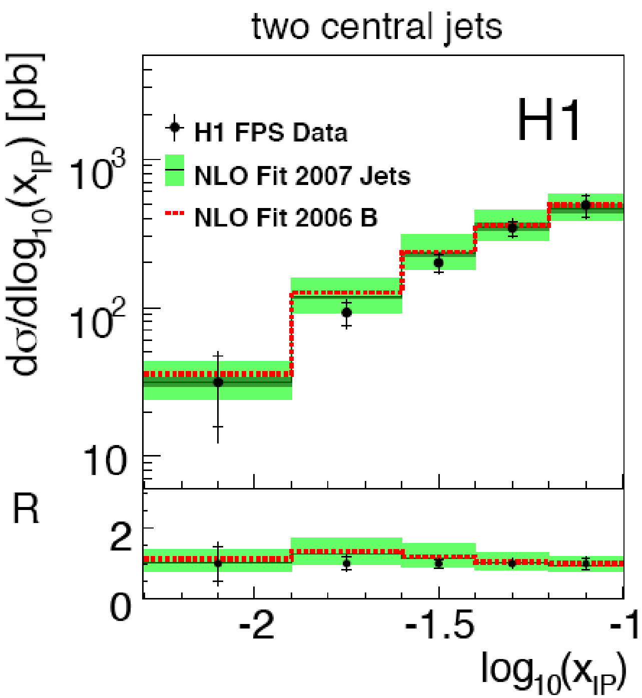
Eur. Phys. J. C72 (2012) 1970

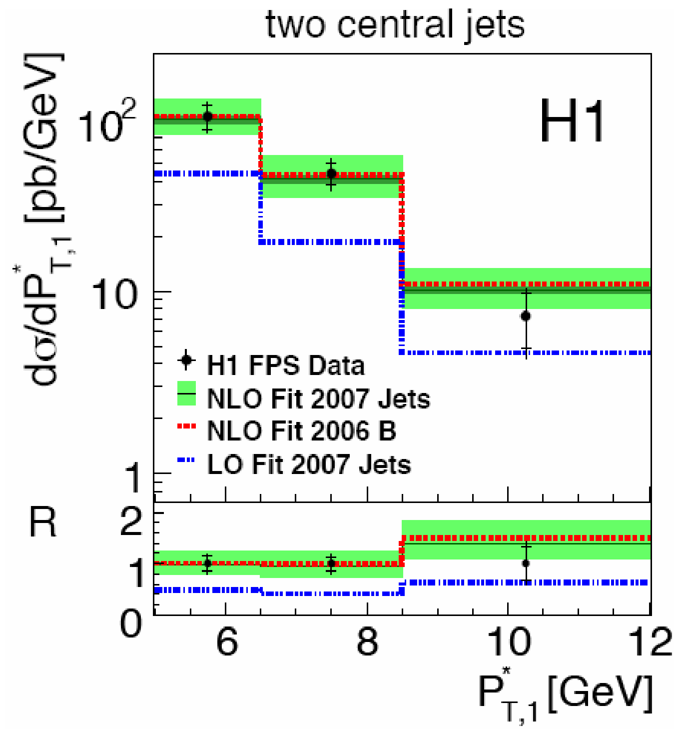
HERA data (2005-2007) 156.6 pb^{-1}

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

$p_{T,1}^* > 5$ GeV, $p_{T,2}^* > 4$ GeV, $-1 < \eta_{1,2} < 2.5$

transverse momenta of jets in hcms



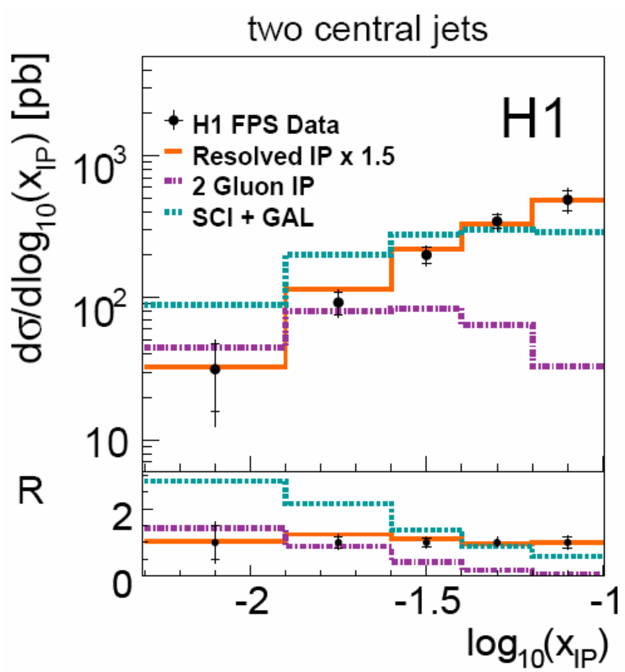


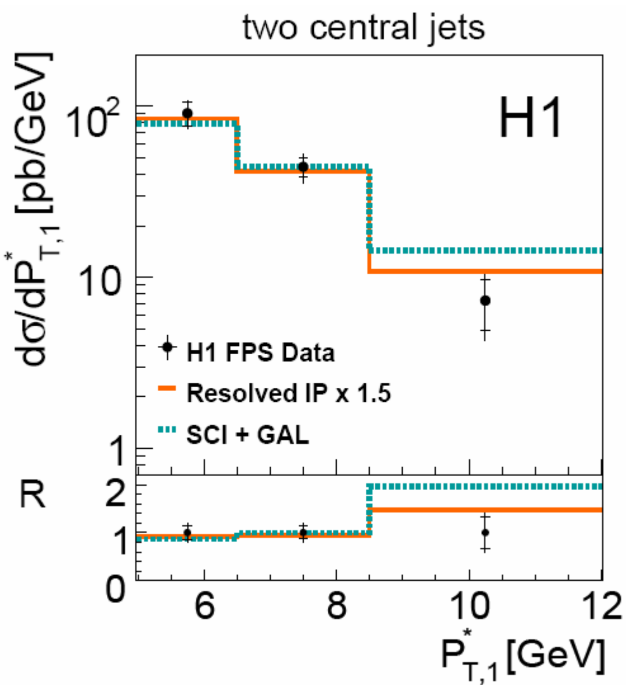
$$R = \frac{\text{prediction}}{\text{data}}$$

NLO QCD predictions based on the DGLAP approach with DPDF sets H1 2006 Fit B and H1 2007 Jets describe the dijet cross sections within errors.

Diffractive dijets – comparison with MC models

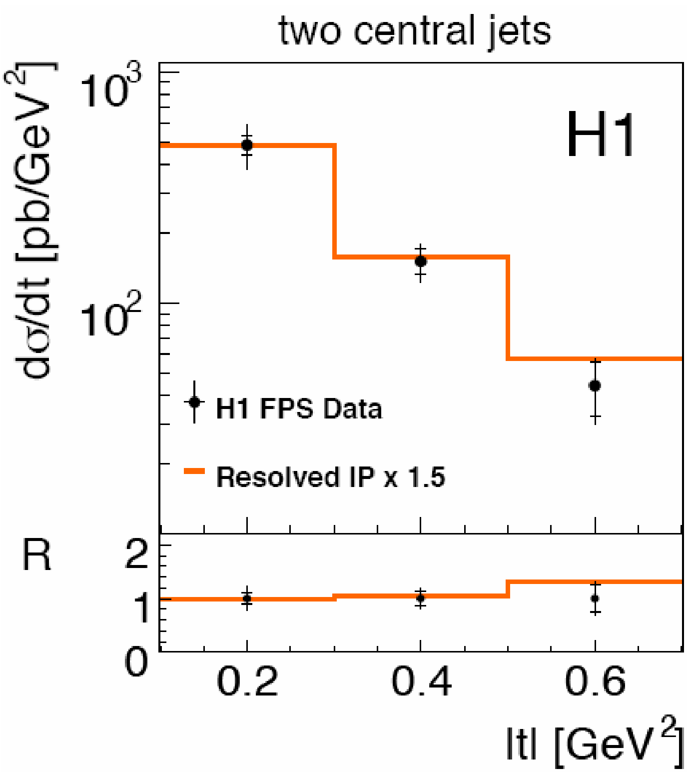
MC models based on leading order matrix elements and parton showers

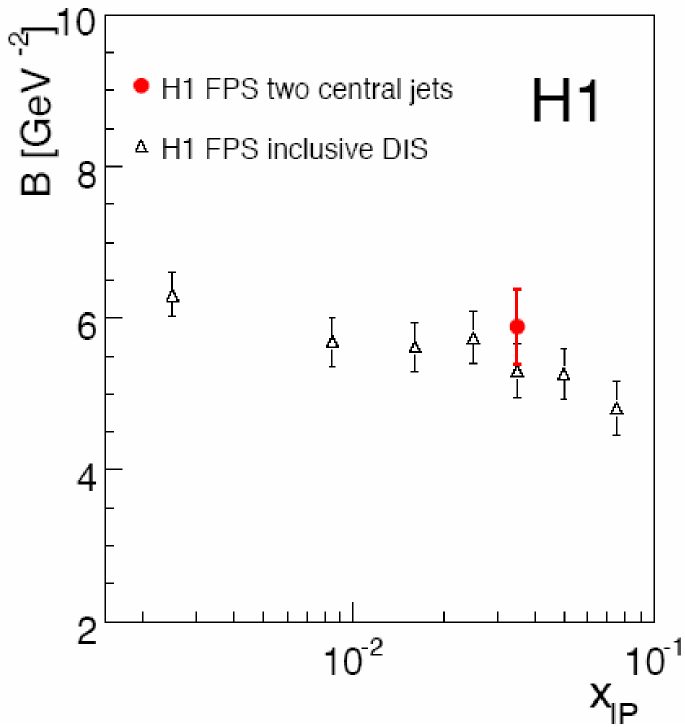




- **Resolved IP model describes the shapes but underestimate the dijet cross section (factor 1.5).**
- **SCI + GAL and 2 Gluon IP models fail to describe the shape of the distributions of the diffractive variables.**
- **SCI + GAL describes reasonably well the cross section as a function of the jet variables.**

Proton vertex factorisation





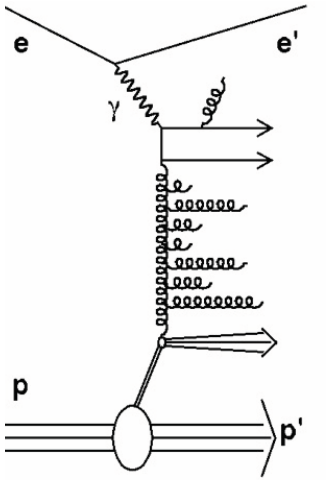
Regge motivated fit exp(Bt)

$\rightarrow$ B = 5.89 $\pm$ 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

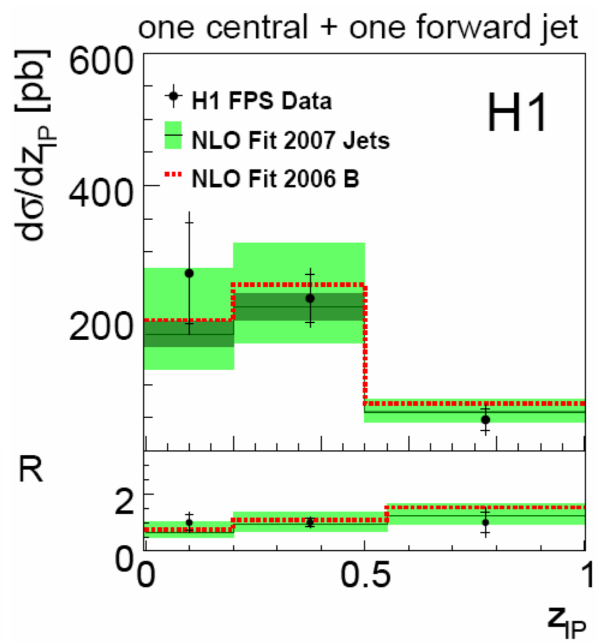
search for physics beyond DGLAP

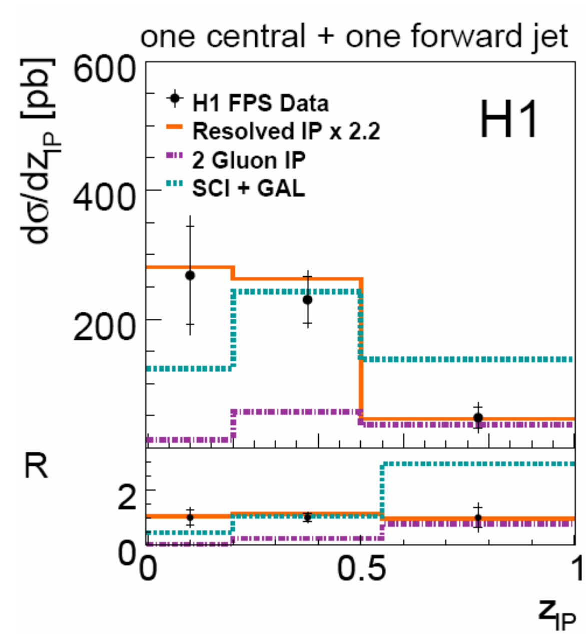


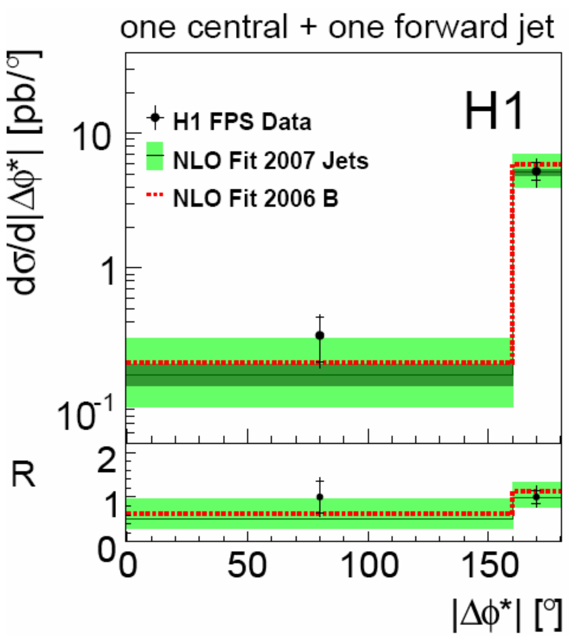
one central + one forward jet

$4 < Q^2 < 110$ 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)

Summary

Azimuthal correlation of forward jets in DIS

- Cross sections as a function of $\Delta\phi$ and rapidity separation between the forward jet and the scattered positron are best described by the BFKL – like model CDM
- The shape of $\Delta\phi$ distributions is well described by LO MC models with different QCD evolution schemes
- NLO DGLAP predictions are in general below the data, but still in agreement with the large theoretical uncertainties

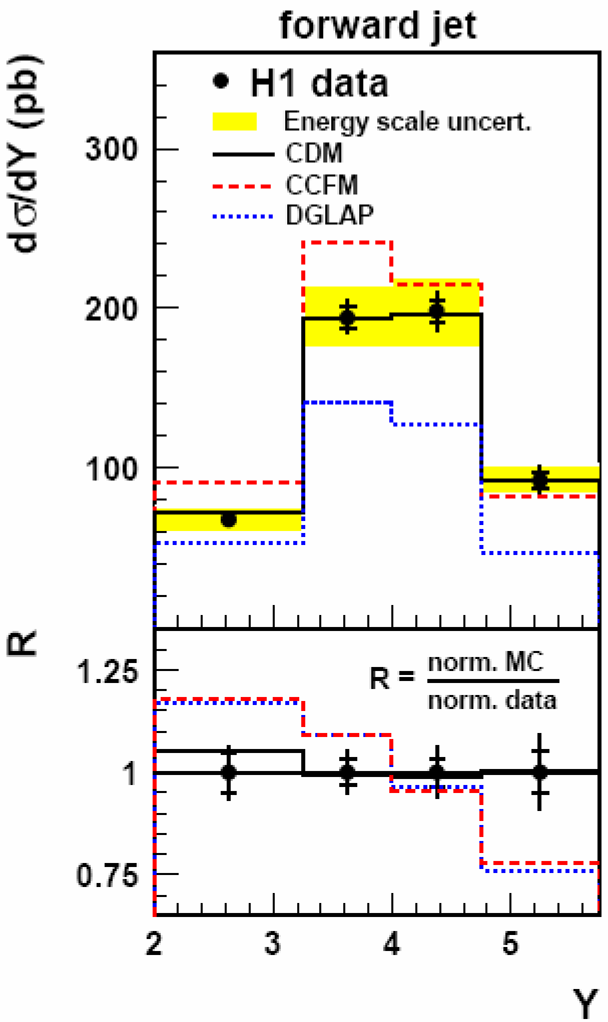
Diffractive dijet measurement with a leading proton in the H1 FPS

- NLO DGLAP predictions using DPDFs describe the data within errors
- No deviation from DGLAP in the accessible phase space
- Confirmation of the proton vertex factorisation hypothesis
- LO MC models do not describe the data satisfactorily

The data are in general more precise than NLO QCD predictions $\rightarrow$ challenge for QCD

backup

Forward jet cross section $d\sigma / dY$



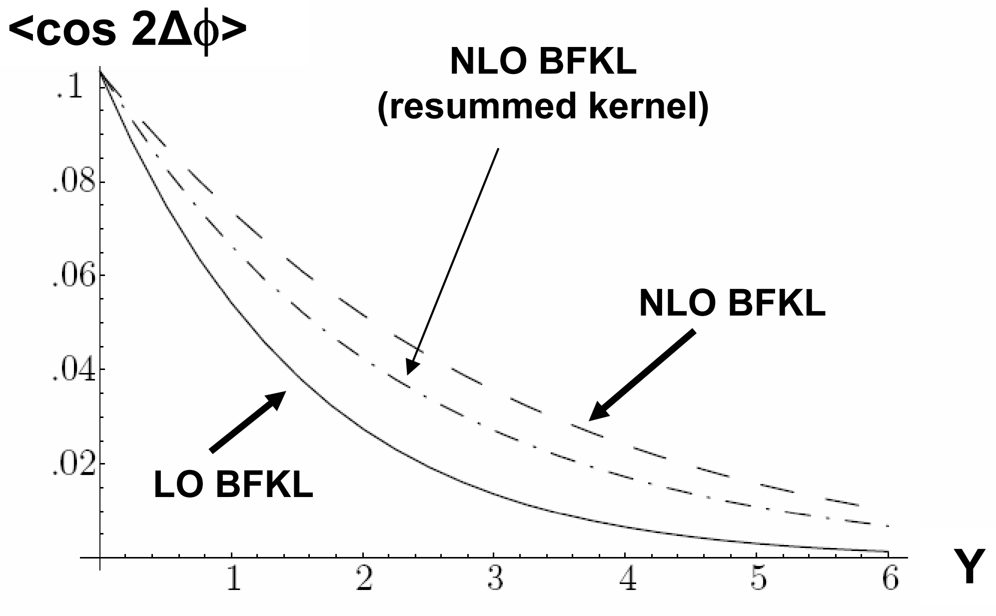
- BFKL–like model CDM describes the data best
- DGLAP too low, especially at large Y
- CCFM predictions to high at low x, but describe the data at large Y

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

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

$$20 < Q^2 < 100\ \mathrm{GeV}^2$$
$$0.05 < y < 0.7$$
$$4\cdot 10^{-4} < x_{Bj} < 5\cdot 10^{-3}$$
$$0.5 < p_t^2 / Q^2 < 2.0$$

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

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

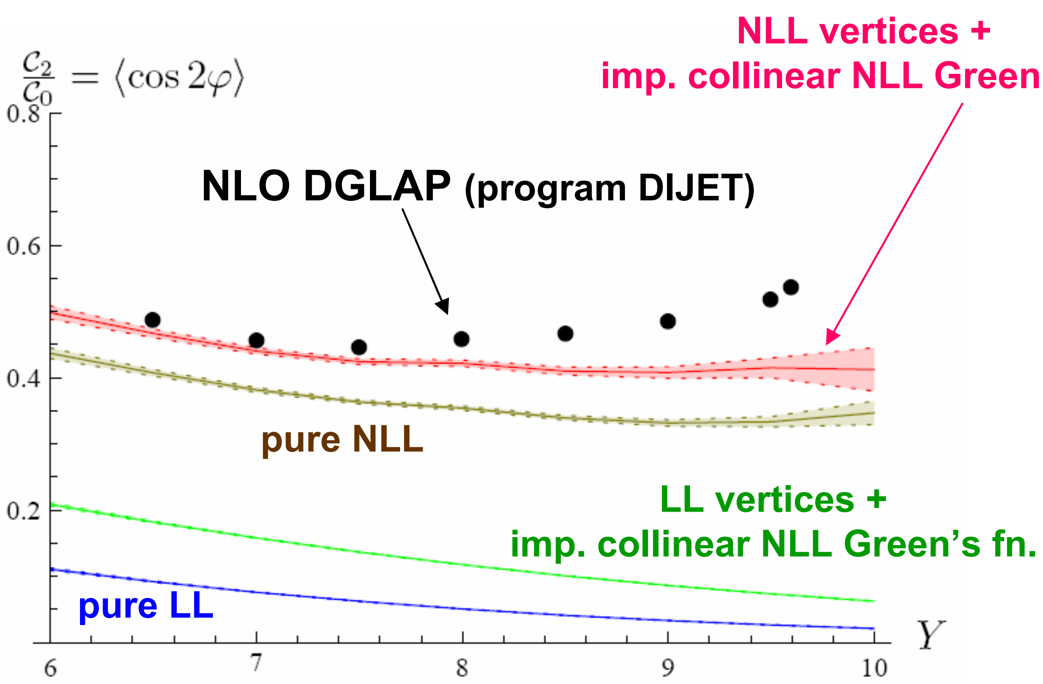
- The forward jet is more decorrelated from the scattered lepton for larger rapidity difference Y (center of mass energy)
- The azimuthal angle correlations increase when HO corrections are included for a fixed value of Y

Mueller- Navelet jets at LHC – complete NLL BFKL calculations

Colferai, Schwennsen, Szymanowski & Wallon,
JHEP 12(2010)026
next-to-leading corrections to the Green's function and to the Mueller-Navelet vertices

LHC $\sqrt{S}$ = 14 TeV, $p_{T,jet1}$ = 35 GeV, $p_{T,jet2}$ = 50 GeV

Azimuthal correlation $\langle\cos 2\phi\rangle = \langle\cos(2 \cdot (\phi_{jet1} - \phi_{jet2} - \pi))\rangle$

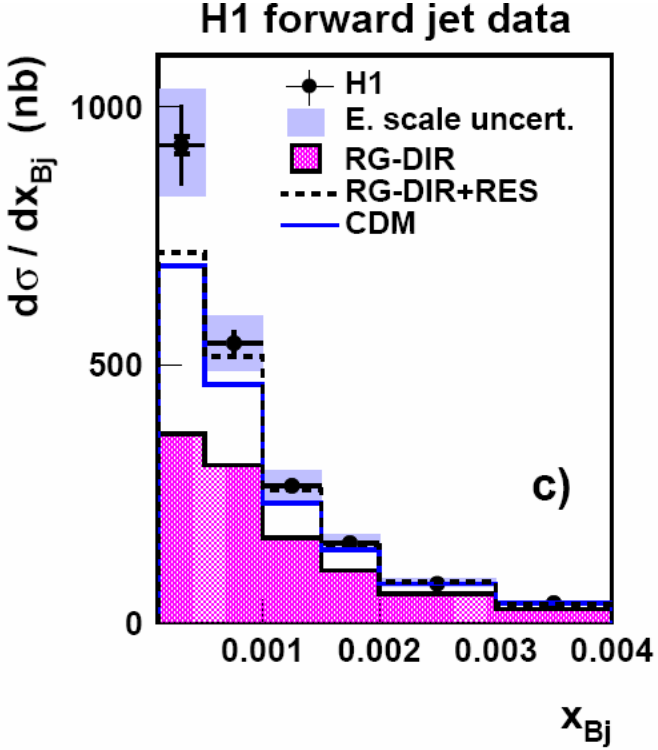


- **importance of NLL vertex corrections**
- **no significant difference between NLL BFKL and NLO DGLAP**

H1 measurements →
the electron-forward jet decorrelation in DIS does not discriminate between different evolution schemes

Forward jet cross section dσ/dx

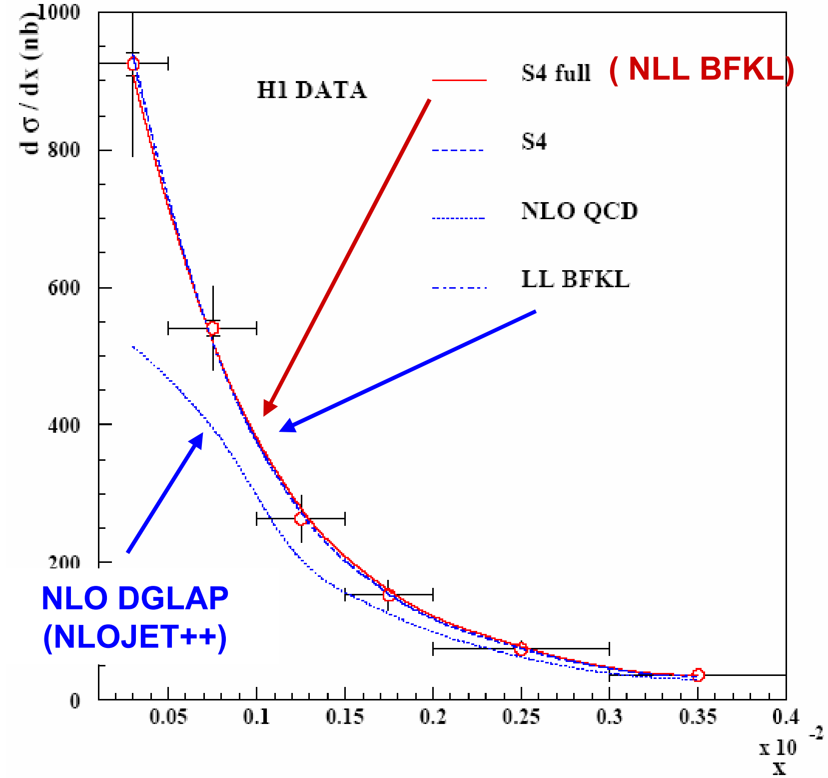
H1 data : Eur. Phys. J. C46 (2006)27



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