Measurement of the Azimuthal Correlation between the most Forward Jet and the Scattered Positron in Deep Inelastic Scattering at HERA

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(on behalf of the H1 Collaboration)

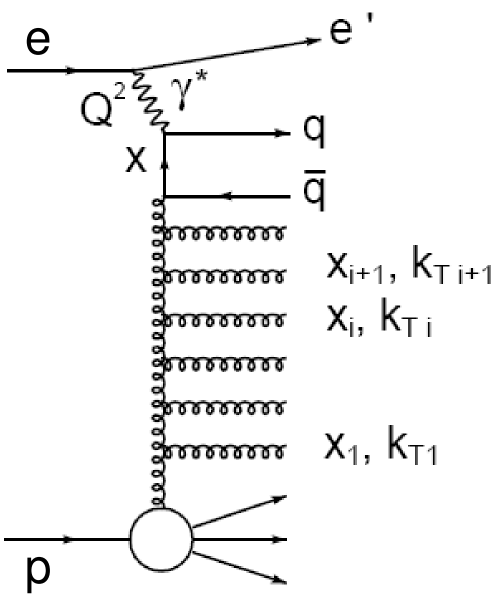
- **QCD dynamics at low Bjorken-x**
- **QCD models**
- **Experimental Method**
- **Results**
- **Conclusions**

QCD dynamics at low Bjorken-x

HERA : DIS at low Bjorken-x down to 10^{-5} $\rightarrow$ large γ^*p centre-of-mass-energy

($W_{\gamma^* p} \approx Q^2 / x$)

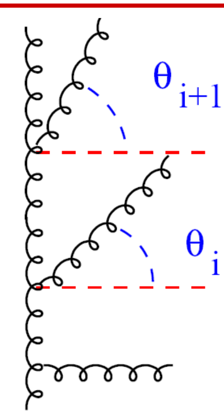
- enhanced phase space for gluon cascades exchanged between the proton and the photon
- pQCD – multiparton emissions described only with approximations :



- **DGLAP : Dokshitzer-Gribov-Lipatov-Altarelli-Parisi evolution**
  applicable at large Q^2
  Assumes strong ordering of parton k_T
  Resums terms $\sim (\alpha_S \ln Q^2)^n$

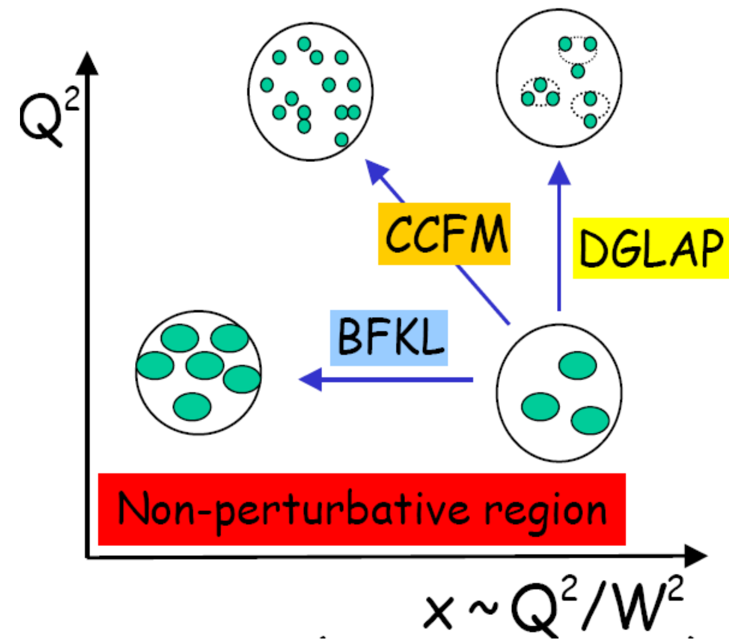
- **BFKL : Balitsky-Fadin-Kuraev-Lipatov evolution**
  Transition from DGLAP to BFKL scheme expected at low x
  No ordering in k_T, strong ordering in x_i
  Resums terms $\sim (\alpha_S \ln(1/x))^n$

- **CCFM : Ciafaloni-Catani-Fiorani-Marchesini equation**
  applicable at all x and Q^2
  Unification of DGLAP and BFKL approaches
  Emitted partons are ordered in angles



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



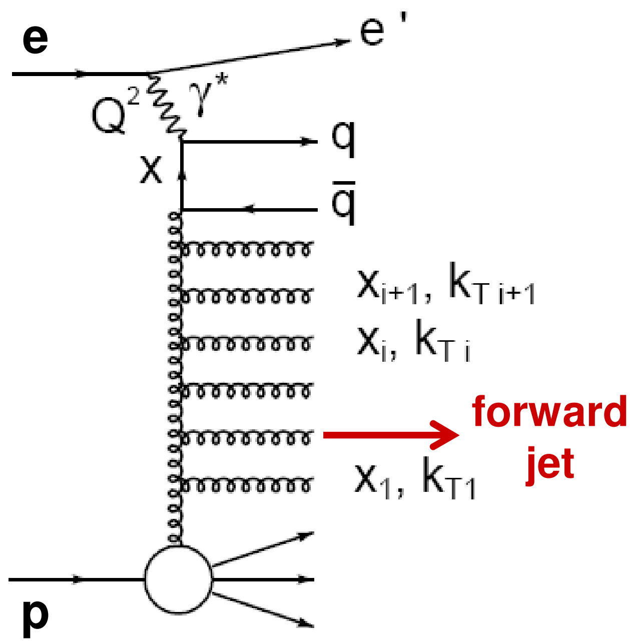
- **Strong rise of the proton structure function $F_2(x, Q^2)$ with decreasing x**
  - well described by NLO DGLAP over a large range of Q^2

F_2 measurement is too inclusive to discriminate between different QCD evolution schemes

Hadronic final states – reflect kinematics, structure of gluon emissions

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

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

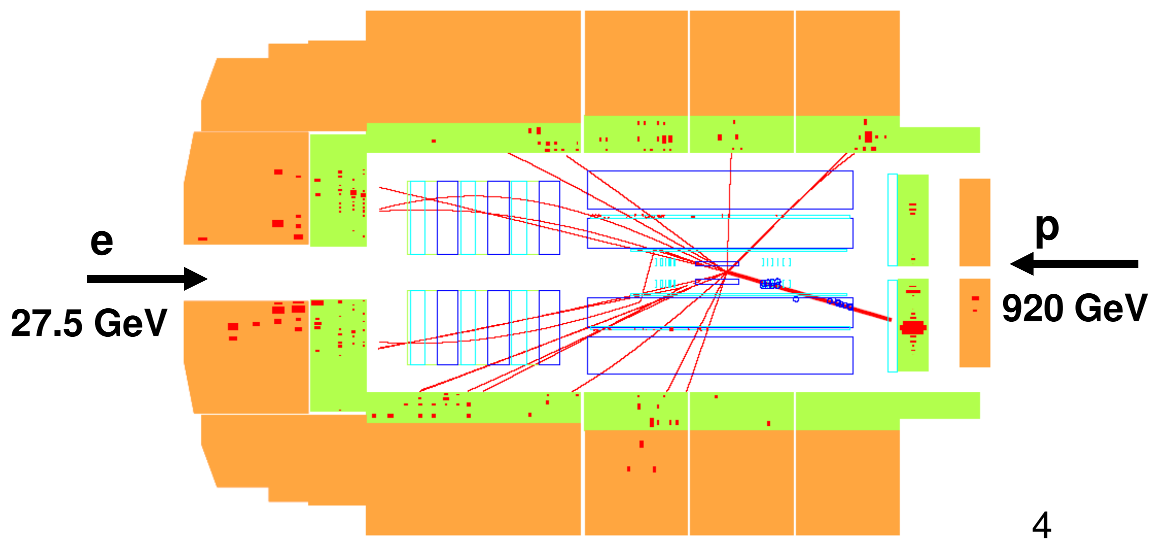
(forward region in LAB)

Suppress standard DGLAP evolution in Q^2 :

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

Enhance BFKL evolution in x :

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

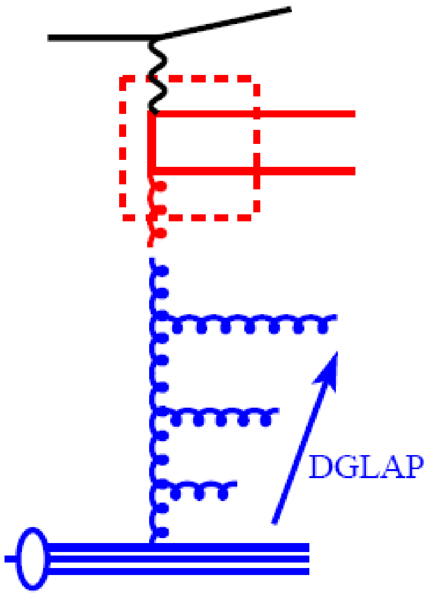


DIS event at low Q^2

Monte Carlo models with different QCD dynamics

RAPGAP - DGLAP

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

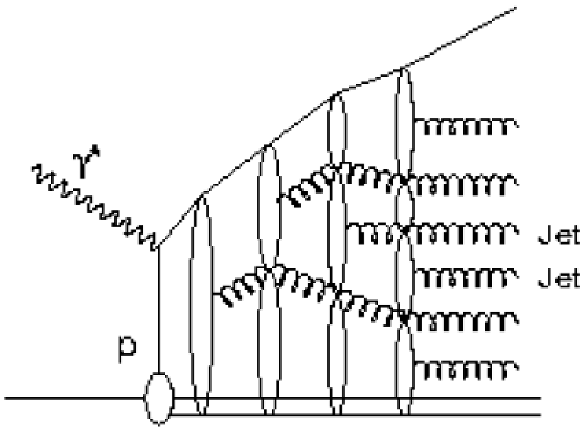


Single DGLAP ladder with strong ordering in k_T

ARIADNE Colour Dipole Model

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

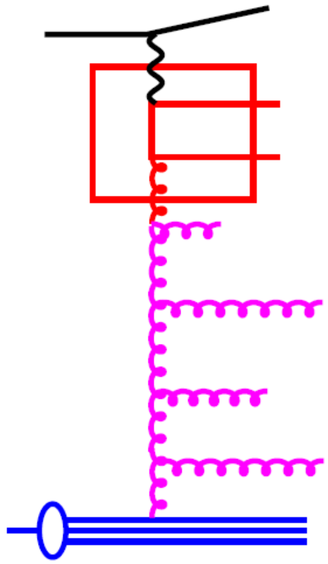
Chain of independently radiating dipoles formed by the emitted gluons.



BFKL- like Monte Carlo : random walk in k_T

CASCADE - CCFM

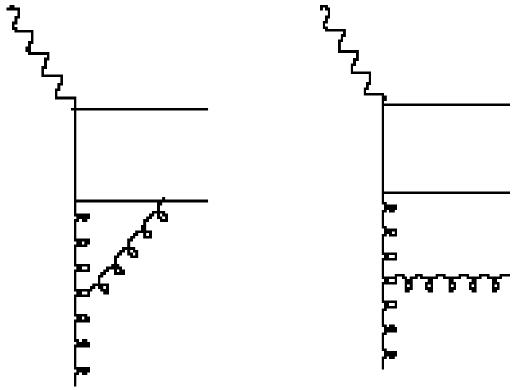
Off-shell QCD ME + parton emissions based on the CCFM equation



Input : unintegrated gluon density function, different uPDF sets include singular or full terms of the gluon splitting function

Fixed order NLO DGLAP predictions

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

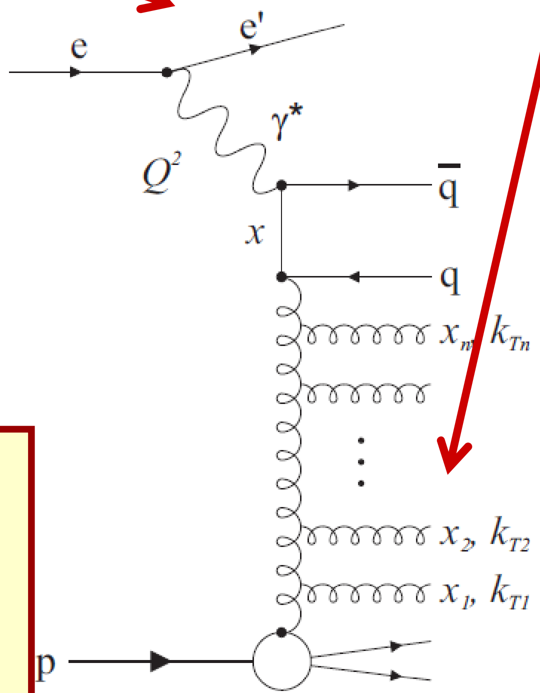


- **Forward jet analysis – reconstruction of jets in the Breit frame $\rightarrow$ at least dijet topology**

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**

Azimuthal angle difference $\Delta\Phi$ between the scattered positron and the forward jet may offer a signature of BFKL dynamics



- **Quark Parton Model e + q → e + q**

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

- **Inclusion of higher order processes $O(\alpha_S^n)$ decorrelates the jet from the positron**

As the rapidity distance approximated by $Y = \ln(x_{fwdjet}/x_{Bj})$ between the scattered positron and the forward jet grows the probability of multi-gluon emissions is increased

- **J. Bartels et al., Phys. Lett. B384(1996)300**

  calculated $\Delta\phi$ in LO BFKL, resumming the dominant terms $\sim (\alpha_S Y)^n$

- **S. Vera & F. Schwennsen, Phys. Rev. D77(2008)014001**

  calculated $\Delta\phi$ in NLO BFKL, resumming the dominant terms $\sim \alpha_S (\alpha_S Y)^n$

Data selection

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

DIS selection

$0.1 < y < 0.7$

$5 < Q^2 < 85\ GeV^2$

$0.0001 < x < 0.004$

Forward jets (inclusive k_T algorithm)

Jets reconstructed in the Breit frame
from combined track-calorimeter cluster objects
and then boosted to LAB, all cuts in LAB

$p_{T,\,fwdjet} > 6\ GeV$

$1.73 < \eta_{fwdjet} < 2.79$

$x_{fwdjet} = E_{fwdjet} / E_p > 0.035$

$0.5 < p_{T,fwdjet}^2 / Q^2 < 6.0$

- suppress k_T ordered evolution by cut on p_T^2 / Q^2
- enhance phase space for BFKL evolution without k_T ordering by cut on x_{fwdjet}

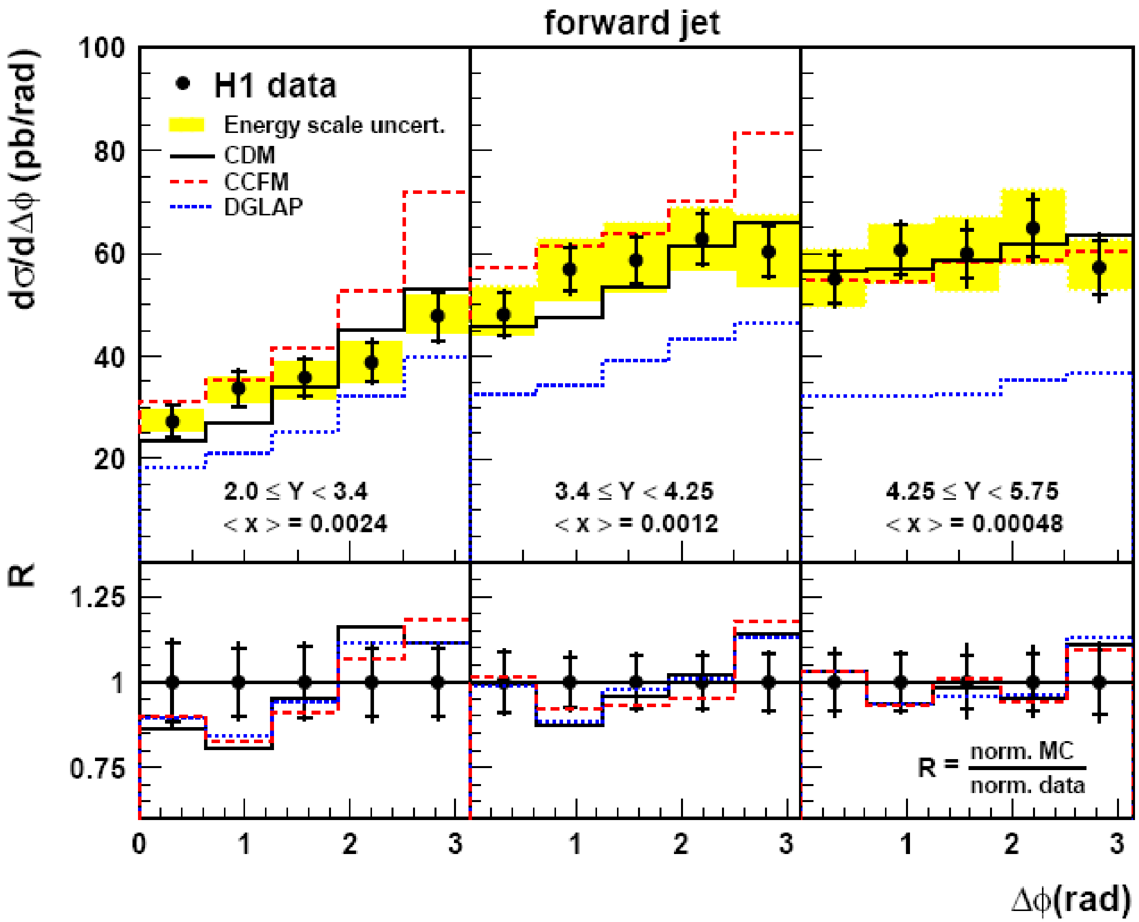
~ 14000 DIS events with at least one forward jet

if more than one forward jet is found, the jet with the largest η_{fwdjet} is chosen
$\eta = -\ln(\tan\theta/2)$, θ defined with respect to the initial proton direction

Forward jet azimuthal correlations

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

Positron – fwd jet rapidity distance Y = ln(x_{fwdjet} / x)



Cross sections :

- **well described by BFKL-like model CDM**
- **DGLAP predictions below the data**
- **CCFM (set A0) as good description as CDM at large Y**

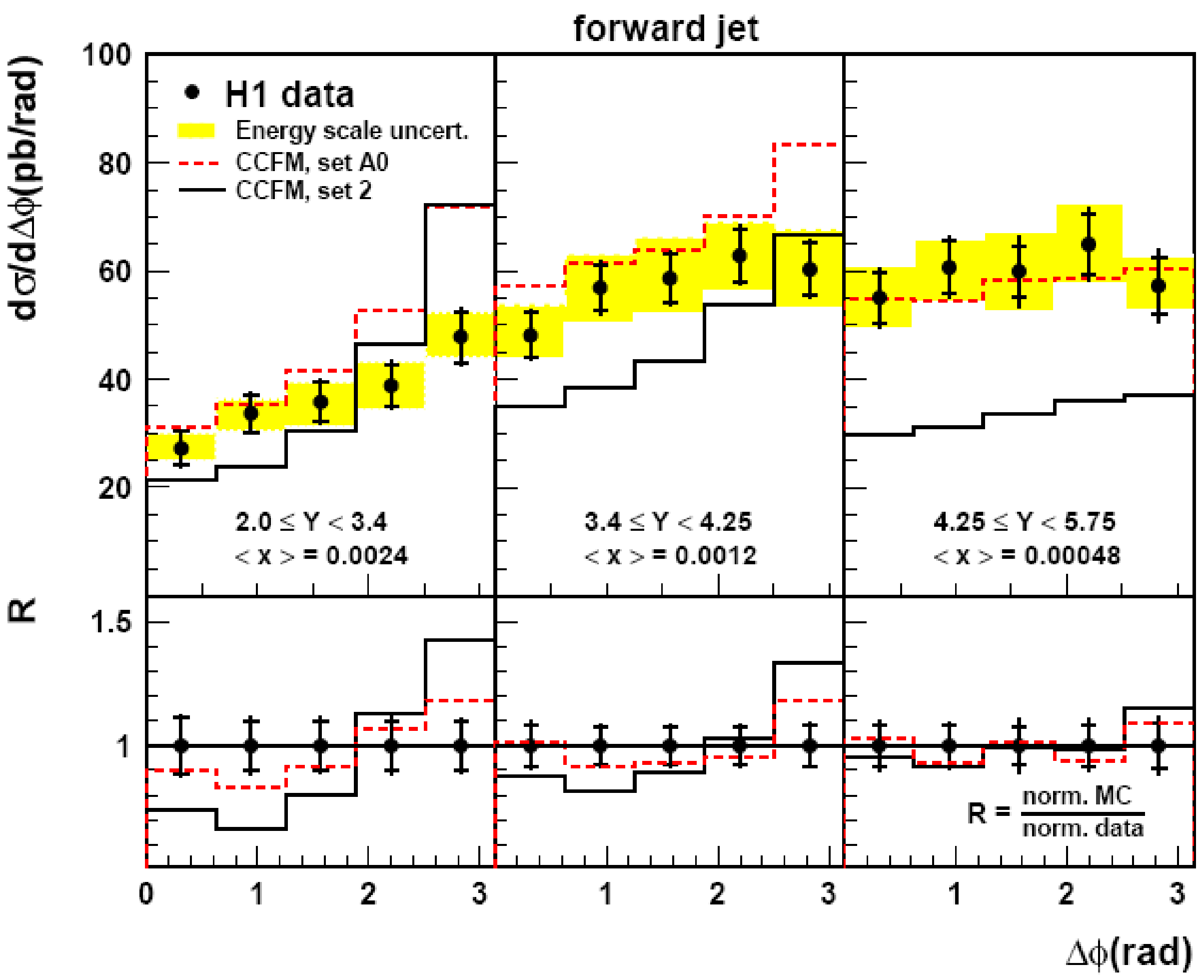
Ratio R of MC to data for normalised cross-section

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

The shape of Δϕ distributions is well described by all MC models

Forward jet azimuthal correlations

Predictions of the CCFM model depend on the choice of uPDF



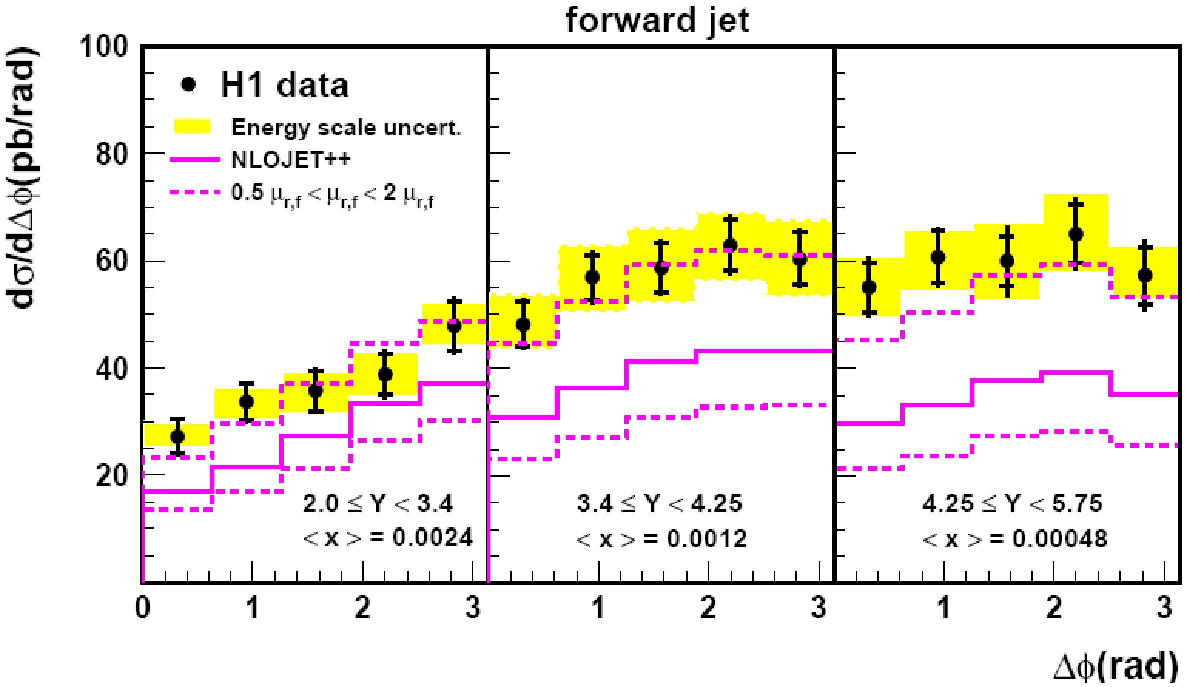
- **Cross sections**
  strongly depend on uPDF
- **Shape of Δφ distributions**
  - at low Y shows sensitivity to uPDF
  - well described by the set A0

Different splitting functions used in uPDF :

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

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

$\Delta\phi$ decorrelation: no discrimination between different evolution schemes

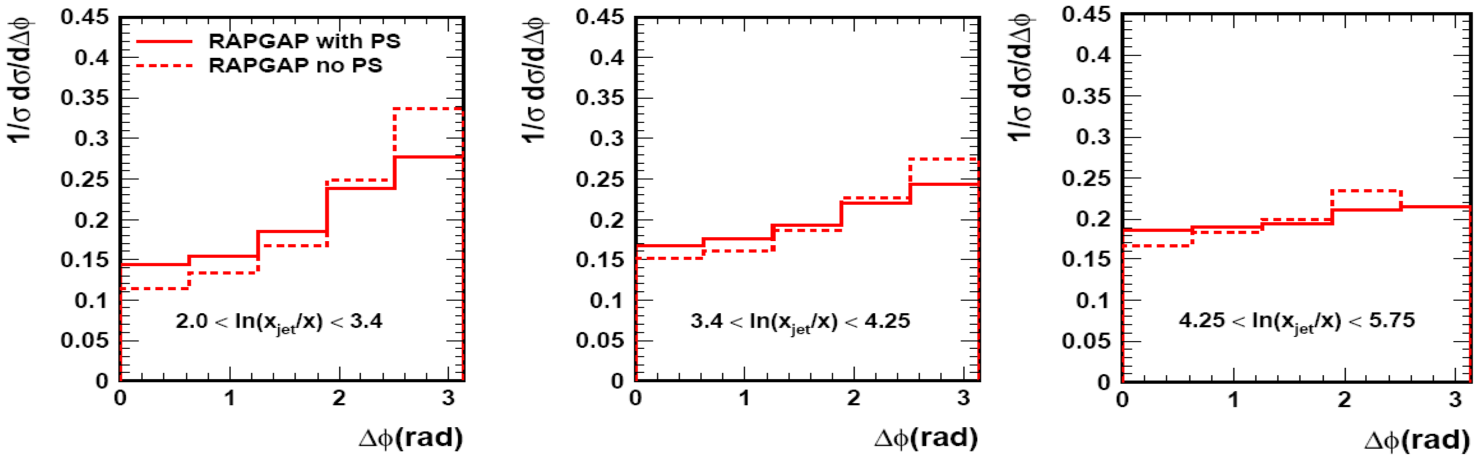
- **Does forward jet originate from the hard matrix elements ?   No !**

Studies of parton to hadron correlation with the DGLAP-based RAPGAP model

→ ~ 80% of forward jets produced by parton showers

- **Why no dependence of $\Delta\phi$ shape on parton shower ?**

RAPGAP parton showers switched on / off

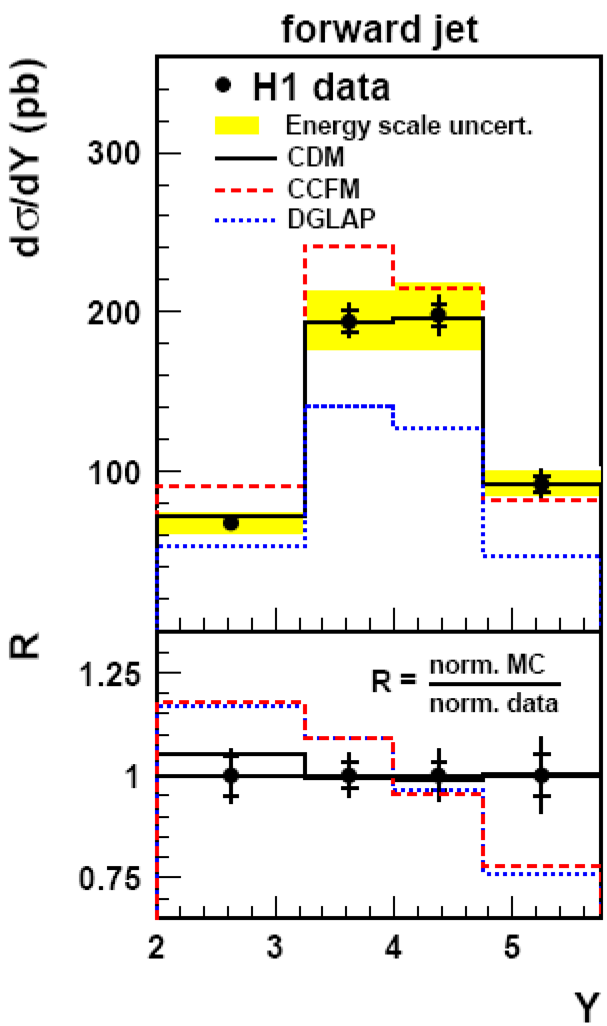


- **The shape of $\Delta\phi$ only slightly changed when the initial state parton shower is switched off**

Decorrelation in $\Delta\phi$ is governed by the phase space requirements
(mainly by rapidity separation Y)

Normalisation of the cross sections depends on the evolution scheme

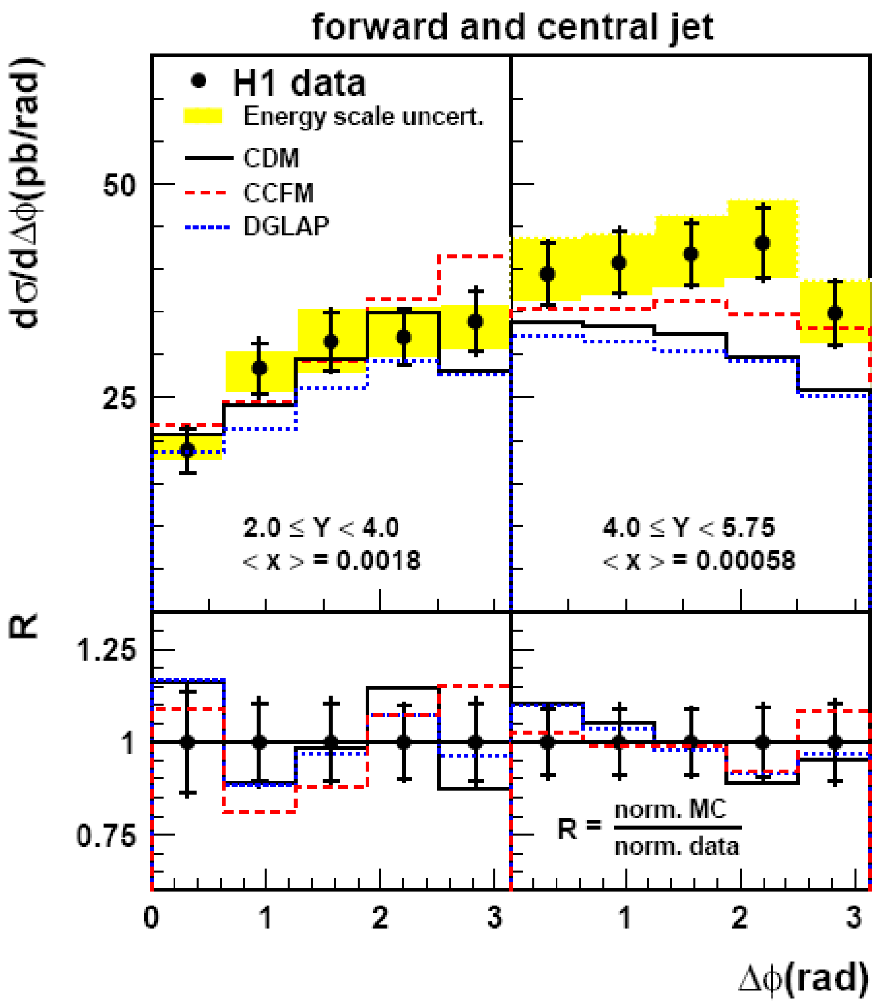
Forward jet cross section dσ / dY



- BFKL–like model CDM describes the data best
- DGLAP too low, especially at large Y
- CCFM (set A0) 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 and central jet cross sections $d\sigma / d\Delta\phi$



- Subsample of events with

  forward jet + additional central jet

  (~8900 events)

  $p_{T,cenjet} > 4$ GeV

  $-1 < \eta_{cenjet} < 1$

  $\Delta\eta = \eta_{fwdjet} - \eta_{cenjet} > 2$

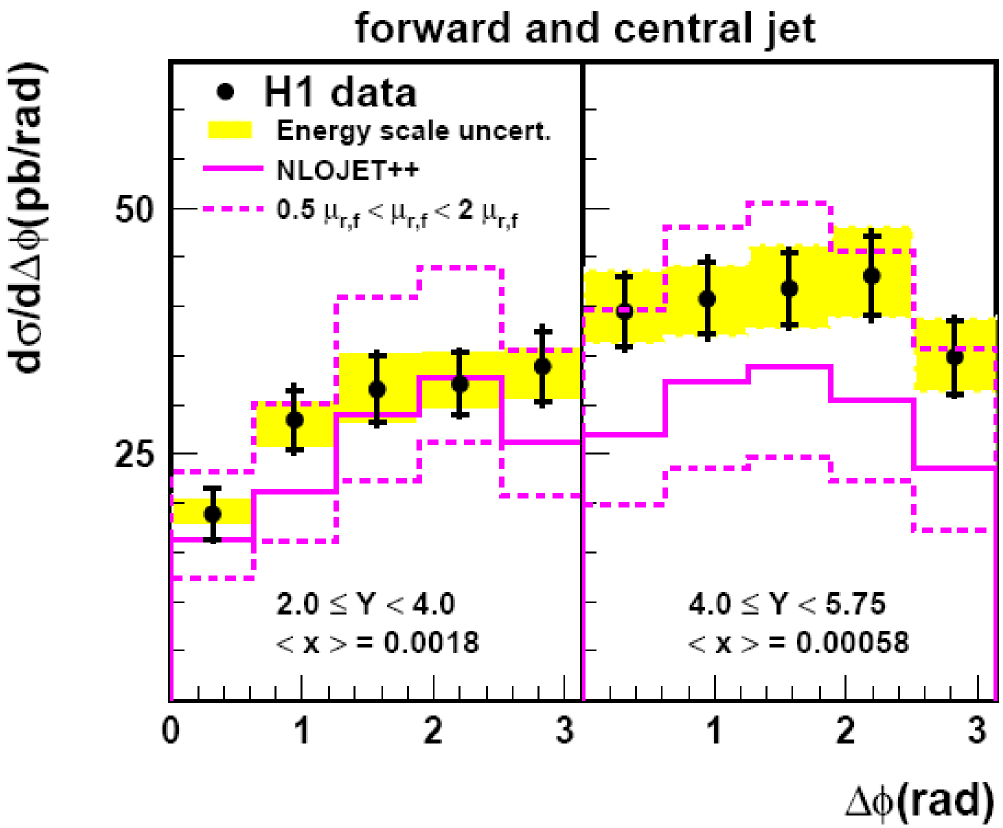
  (enhance radiation between the forward and central jet)

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

- at low Y all models describe the data reasonably well
- at high Y all models are below the measurements
  - ► with CCFM (set A0) closest to the data

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

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



NLO predictions

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

NLOJET++

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

$$\mu_r^2 = \mu_f^2 = (0.5\,(p_{T,\,fwdjet} + p_{T,\,cenjet})^2 + Q^2)\,/\,2$$

Conclusions

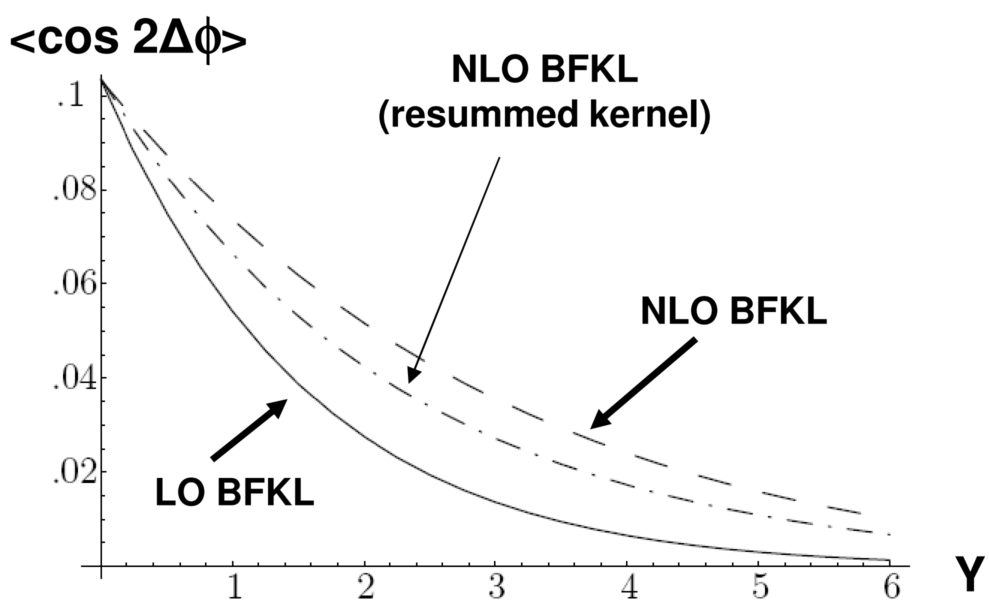
- Differential cross sections & normalised distributions have been measured as a function of $\Delta\phi$ and the rapidity separation Y, between the forward jet and the scattered positron
- Cross sections are best described by the BFKL-like model CDM
- DGLAP-based RAPGAP model is substantially below the data
- The CCFM model gives a reasonable description of the data but shows sizeable sensitivity to uPDF
- The shape of $\Delta\phi$ distributions is well described by MC models based on different QCD evolution schemes
- NLO DGLAP predictions are in general below the data, but still in agreement with the large theoretical uncertainties

backup

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

Systematic uncertainties

	$d\sigma/d\Delta\phi$ fj	$d\sigma/d\Delta\phi$ fj + cj	$d\sigma/dY$
Model dependence (CDM,Rapgap)	2 – 6%		
LAr hadronic en. scale (±4%)	7 – 12%		
Spacal em en. scale (±1%)	below 3%		
Angle of scattered electron (± 1 mrad)	negligible effect		
Trigger	2 – 4%		
Luminosity	1.5%		
Total	11 – 12%		

$\Delta\phi$ decorrelation :

no discrimination between different evolution schemes

- **forward jet originates from the hard matrix elements ?**

  (similar in used MC models)

Studies of parton to hadron correlation with the DGLAP-based RAPGAP model :

► **define "distance measure" ΔR between parton jet and hadron jet**

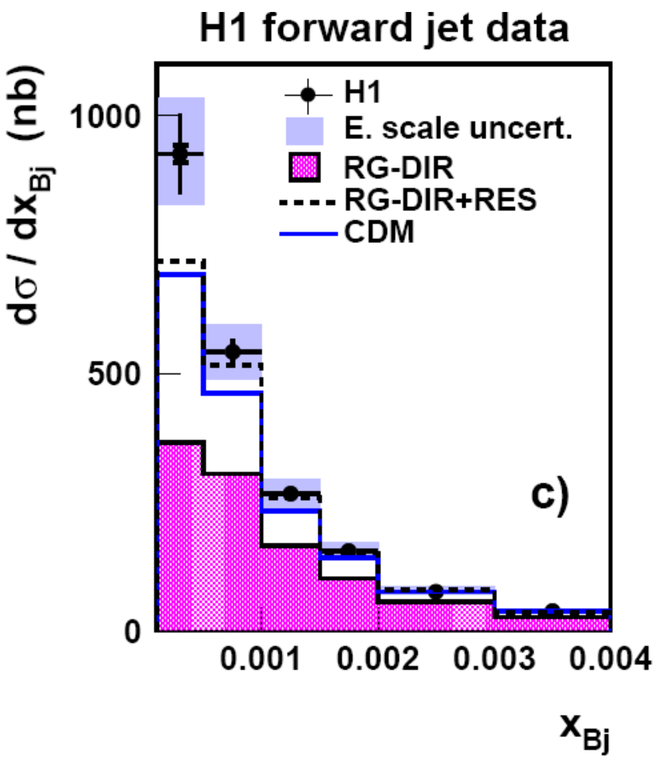
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\Phi)^2}$$

$\Delta R < 0.5$ hadron jet is correlated to parton from ME / from parton shower

► **Y bin**	**forward jet originated from PS**
bin no. 1 ($2 < Y < 3.4$)	51.9%
bin no. 2 ($3.4 < Y < 4.25$)	67.5%
bin no. 3 ($4.25 < Y < 5.75$)	79.0%

Forward jet cross section dσ/dx

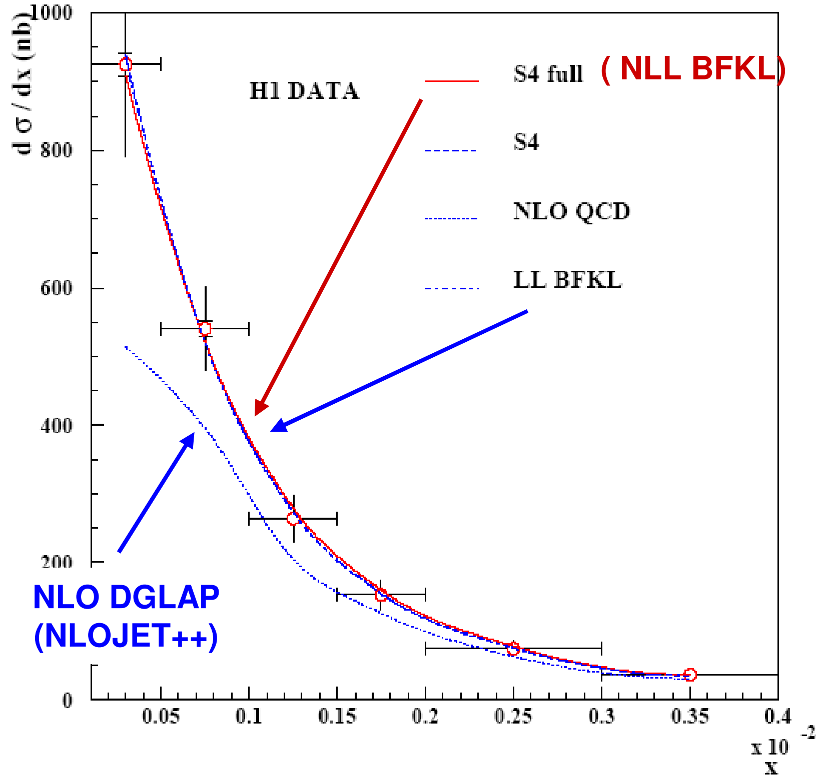
H1 data : Eur. Phys. J. C46 (2006)27



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

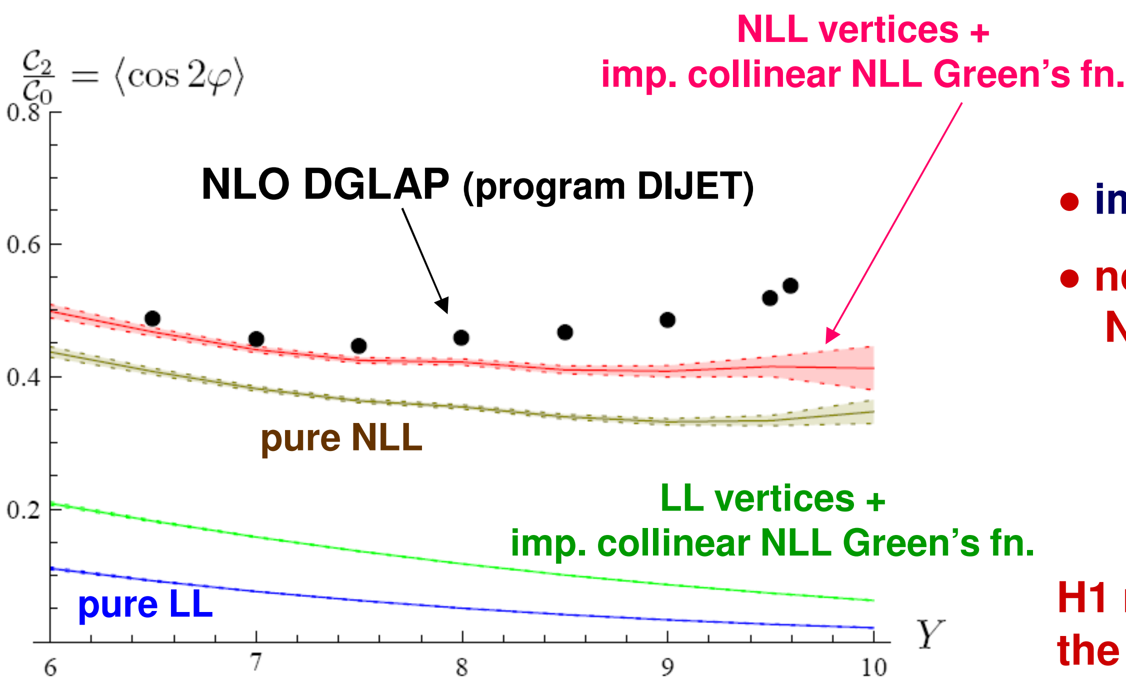
Difference between LL-BFKL and NLL-BFKL (NLL BFKL kernel + free normalisation parameter) is very small

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



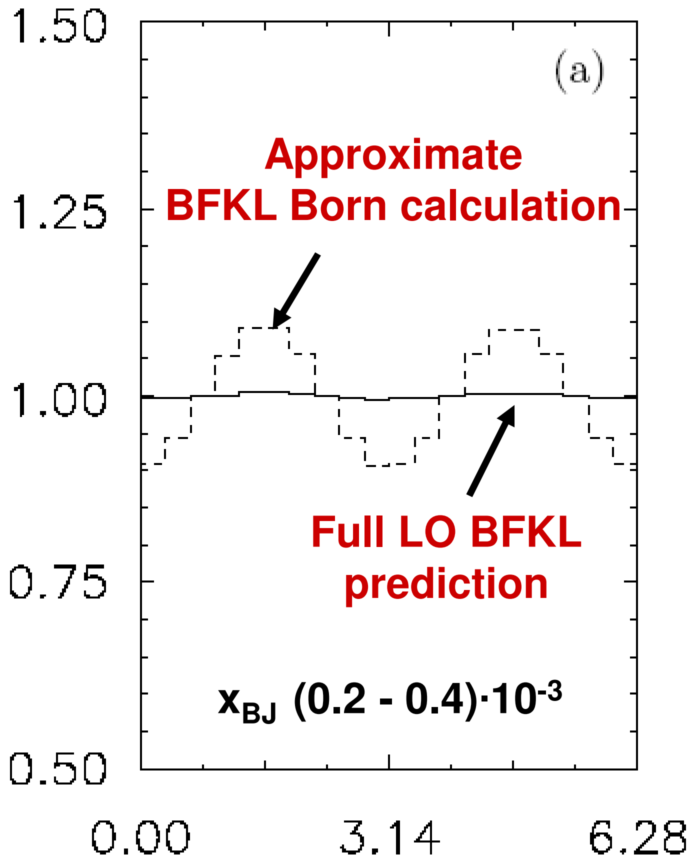
- importance of NLL vertex corrections
- no significant difference between NLL BFKL and NLO DGLAP

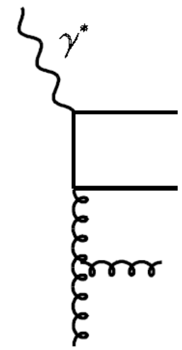
H1 measurements →
the electron-forward jet decorrelation in DIS does not discriminate between different evolution schemes

Forward jets in DIS, Bartels et al., 1996, $\Delta\Phi = \Phi_{el} - \Phi_{jet}$ in the LAB frame

normalised cross section

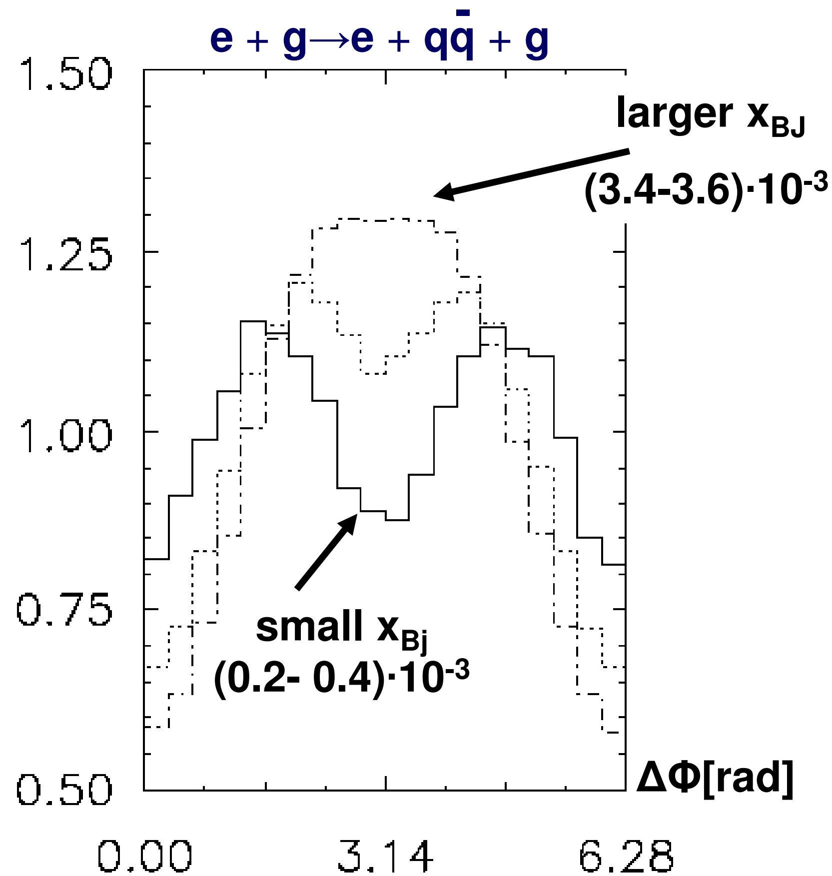
LO BFKL





BFKL Born term

Fixed order $O(\alpha_S^2)$ predictions



BFKL Born - clear maximum at $\Delta\Phi = \pi/2$
Full LO BFKL – no Φ dependence

small x_{BJ} – fixed order $O(\alpha_S^2)$ and BFKL Born predictions are similar (max. at $\Delta\Phi \sim \pi/2$)