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

Izabela Milcewicz-Mika

Institute of Nuclear Physics PAN, Cracow

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QCD dynamics at low x-Bjorken

Monte Carlo models

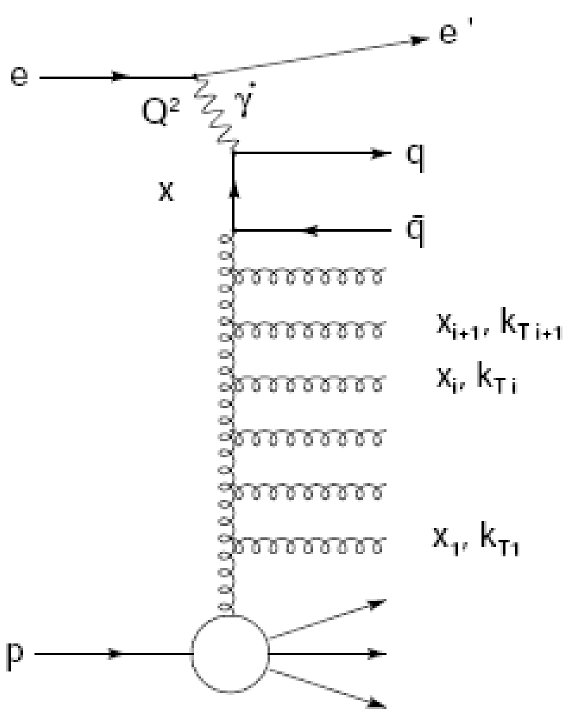
Forward jet selection

Results

Conlusions

QCD dynamics at low x-Bjorken

- In DIS at low x-Bjorken the quark struck by a virtual photon originates from a QCD cascade initiated by a parton from the proton
- At HERA x-Bjorken values accessible down to 10^{-5}
  - Enhanced phace space for long gluon cascades
  - pQCD- multiparton emissions described only with approximations :



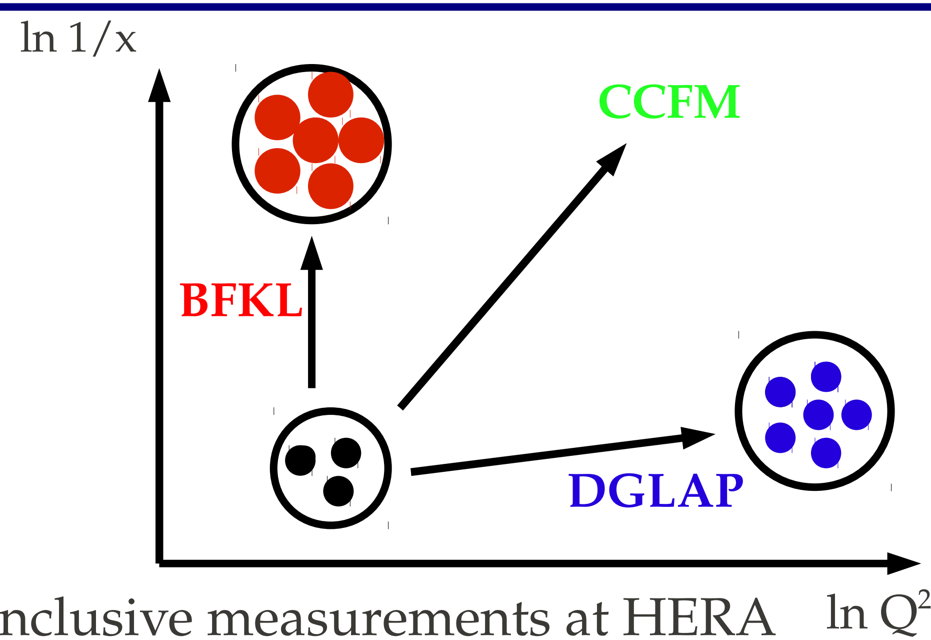
- **DGLAP** - Dokshitzer, Gribov, Lipatov, Altarelli, Parisi evolution scheme:
  Applicable at large x
  Emitted partons are ordered in k_T: $k_{T,i}^2 \ll k_{T,i+1}^2 \ll \ldots \ll Q^2$
  Sums leading $(\alpha_s \ln Q^2)^n$ terms

- **BFKL** - Balitsky, Fadin, Kuraev, Lipatov evolution scheme:
  Applicable at small x
  Emitted partons are strongly ordered in x: $x_i \gg x_{i+1} \gg \ldots \gg x$
  Sums leading $(\alpha_s \ln(1/x))^n$ terms

- **CCFM** - Catani, Ciafaloni, Fiorani, Marchesini evolution equation:
  Applicable at small and at large x
  Emitted partons are ordered in angles
  At large x DGLAP-like, at small x BFKL-like behaviour

QCD dynamics at low x-Bjorken

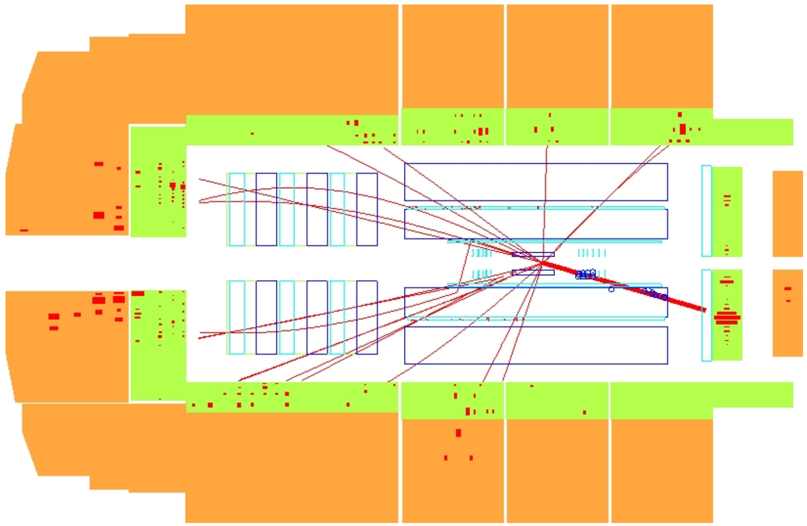
- ✗ Can we see effects of BFKL dynamics ?
- ✗ Look for observables that would be sensitive to underlying parton dynamics

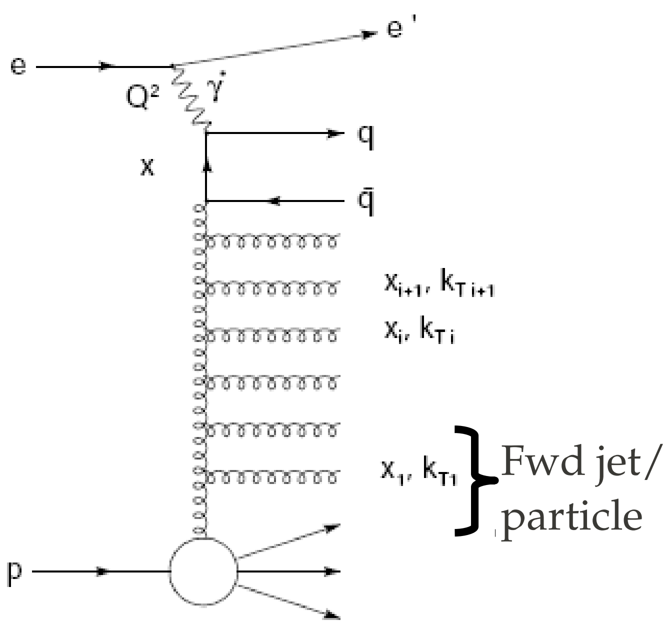


- ✗ DGLAP proved to be very successful in inclusive measurements at HERA
- ✗ F_2 measurements are in a very good agreement with NLO DGLAP calculations
- ✗ F_2 measurement is too inclusive to discriminate between different QCD evolution schemes
- ✗ One has to perform more exclusive measurements than F_2

Hadronic final states – reflect kinematics, structure of gluon emissions
forward jets/particles, diffractive jets, inclusive jets, multijets

Forward jets





Forward jets :

high transverse momentum and high energy jets produced in the direction of the proton remnant (forward region in LAB)

Suppress DGLAP phase space by :

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

Enhance BFKL phase space :

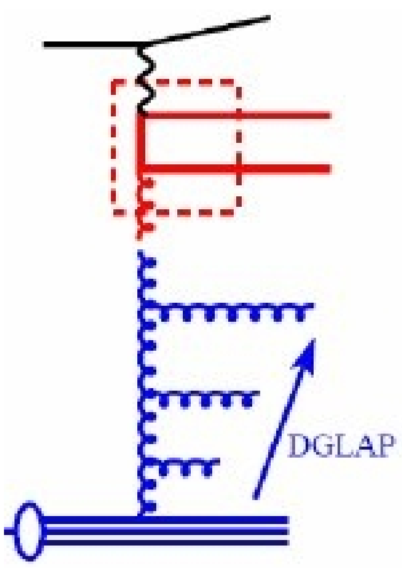
$$x_{jet} = E_{jet}/E_p >> x_{Bj}$$

- ✗ **Studies of fwd jets are an experimental challenge**
- ✗ Region of high particle densities close to the proton remnant
- ✗ Reconstruction using inclusive k_T algorithm on combined objects (tracks+clusters in calorimeter)
- ✗ Data corrected using LO MC models : acceptance, efficiency, QED effects

Monte Carlo models

RAPGAP DIR

DGLAP : LO QCD ME + HO modelled by leading log parton showers

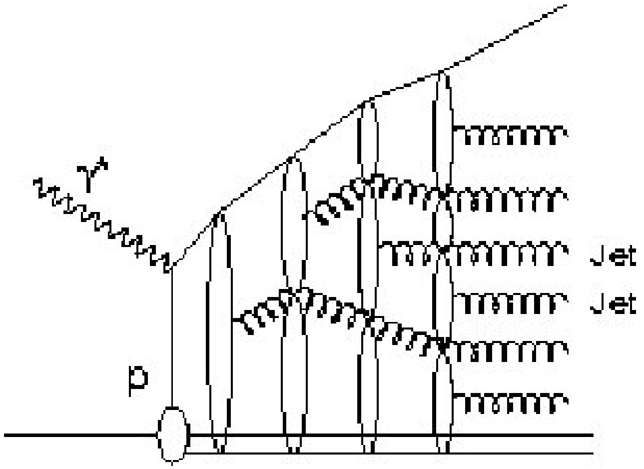


single DGLAP ladder with strong ordering in k_T

ARIADNE

CDM : QCD radiation comes from the dipole created by struck q and p remnant . Chain of independently radiated dipoles formed by emitted gluons

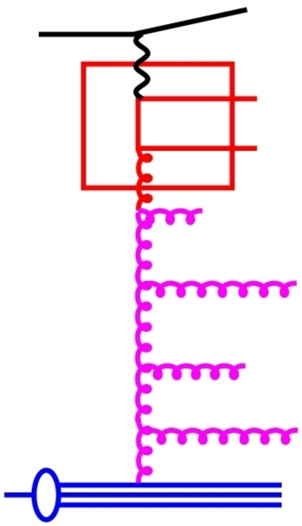
BFKL-like Monte Carlo : random walk in k_T



CASCADE

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

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



Azimuthal (de)correlations of forward jets

The correlation in the azimuthal angle between scattered electron and the forward jet in DIS may be another signature of the BFKL dynamics

- **Quark Parton Model** $e + q \rightarrow e + q$
  simple two body kinematics $\Delta\phi = \phi_{el} - \phi_{fj} = \pi$
- $O(\alpha_s^{\ n})$ **processess lead to decorrelation effects**

- As the rapidity distance measured as **$Y = \ln(x_{jet}/x_{Bj})$** between the scattered electron and the forward jet grows the probability of multi-gluon emissions is increased (**$Y = \ln(x_{jet}/x_{Bj})$ – evolution length in BFKL formalism**)
- J. Bartels *at al.*, Phys. Lett. B384(1996) 300 → **calculation of** $\Delta\phi$ distribution **in LO BFKL**
- S. Vera & F. Schwennsen, Phys. Rev. D77(2008) 014001 → **calculation of azimuthal correlation in NLO BFKL**

Forward jet selection

H1 2000 data, 51.5 pb^{-1}

DIS cuts:

$5 < Q^2 < 85$ GeV^2
$0.1 < y < 0.7$
$0.0001 < x_{Bj} < 0.004$

~14000 forward jet events

Forward jets:

Inclusive k_t algorithm – p_t weighting scheme
jets reconstructed in Breit frame
→ boosted back to LAB
Selection of high energy and high p_t jets
close to the proton, all cuts in LAB

$7° < \theta_{jet} < 20°$

$p_{t,jet} > 6$ GeV

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

enhancing phase space for BFKL

$0.5 < p_{t,jet}^2/Q^2 < 6.0$

suppressing phase space for DGLAP evolution

Forward jet + central jet selection

- ✗ Study more exclusive topology: foward jet + jet in the central region
- ✗ At least two hard jets – reduce effects of soft parton radiation, no contribution from QPM-like events
- ✗ Jet in the central region - good trigger efficiency

Select forward jet

$1.73 < \eta_{jet} < 2.79$

$p_{t,jet} > 6$ GeV

$x_{jet} > 0.035$

$0.5 < p^2_{t,jet}/Q^2 < 6.0$

Select central jet

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

$p_{t,jet} > 4$ GeV

Large rapidity distance between the most forward jet and the most backward central jet :

$$\Delta\eta = \eta(\text{fwd.jet}) - \eta(\text{central jet}) > 2.0$$

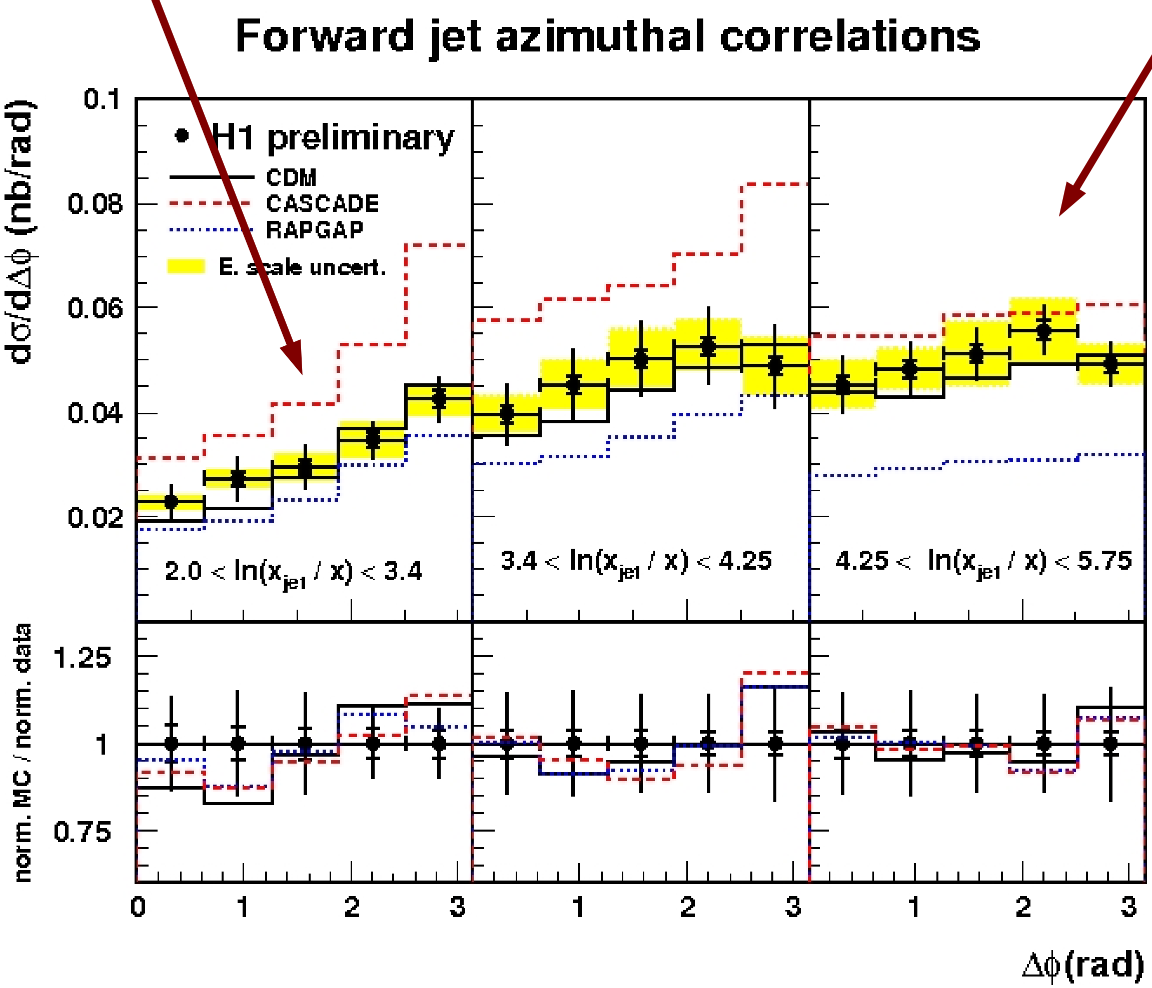
Phase space for additional parton emisssions

Inclusive forward jet cross-section $d\sigma/d\Delta\phi$

in three intervals of rapidity distance $Y = \ln(x_{jet}/x)$

large x

small x



At lower x the forward jet is more decorrelated from the scattered electron

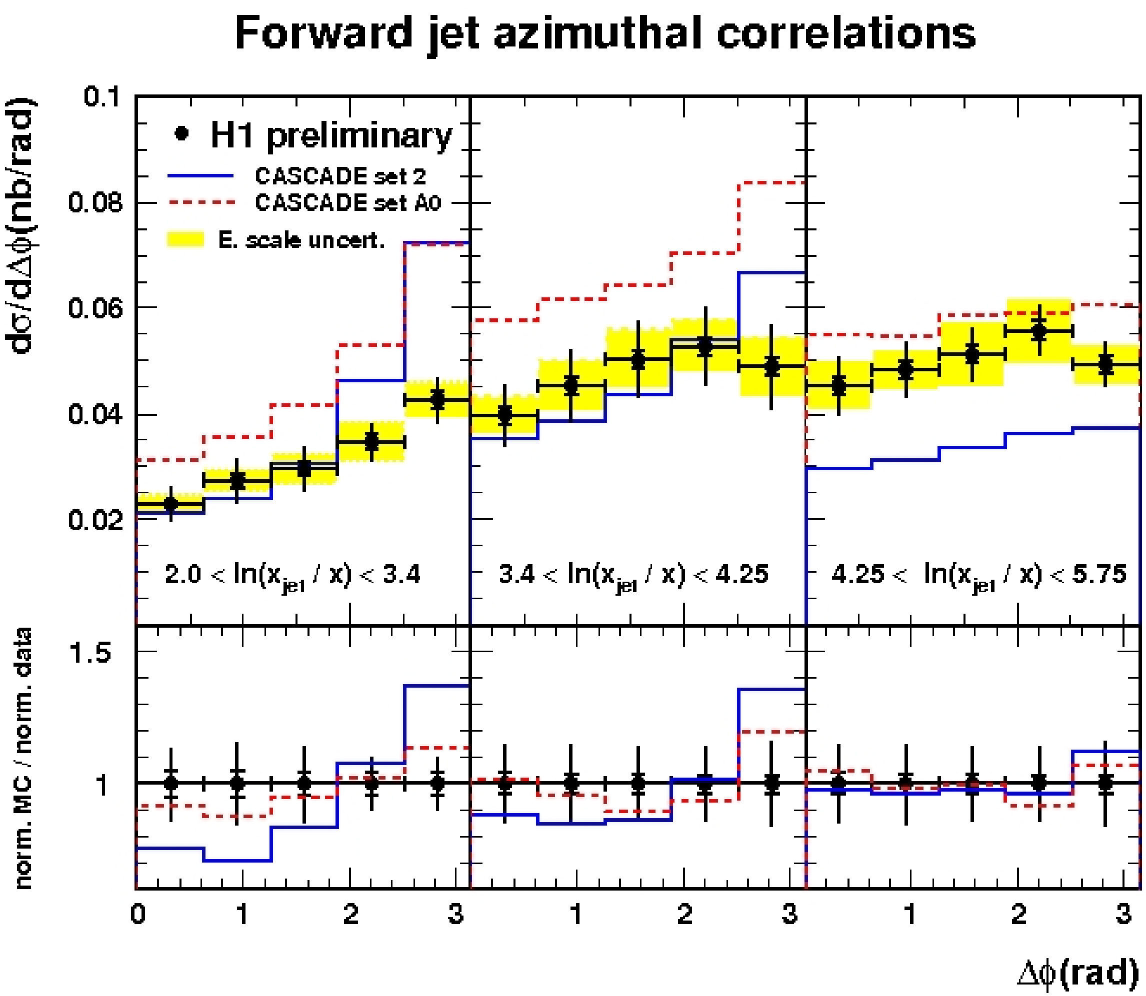
- ✗ Cross-section described best by BFKL-like model (CDM)
- ✗ Ratio R of MC to data for normalised cross-section

$$R = \frac{\frac{1}{\sigma^{MC}} \cdot \frac{d\sigma^{MC}}{d\Delta\phi}}{\frac{1}{\sigma^{data}} \cdot \frac{d\sigma^{data}}{d\Delta\phi}}$$

The shape of $\Delta\phi$ distributions do not discriminate between different models

Inclusive forward jet cross-section $d\sigma/d\Delta\phi$

Predictions of the CCFM model (CASCADE)



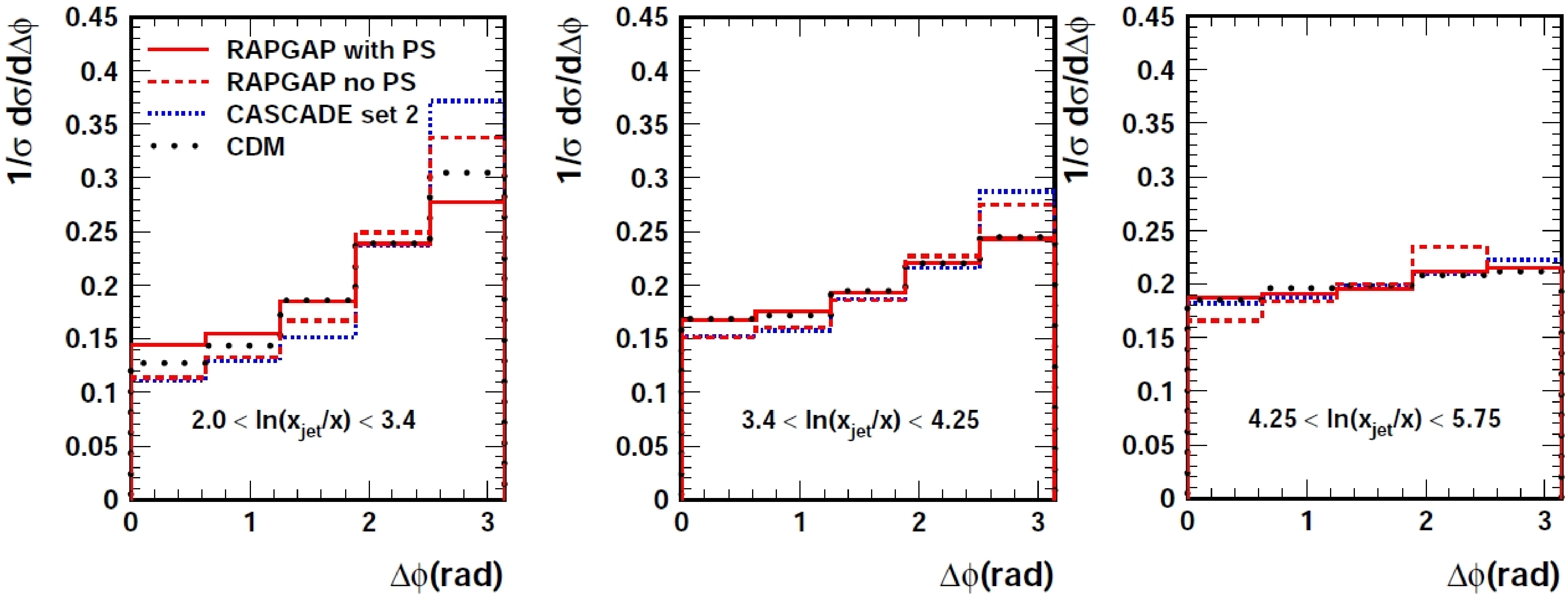
- ✗ **Set A0** – uPDF with only singular terms of the gluon splitting function
- ✗ **Set 2** – includes also non singular terms

Predictions of CCFM depend on the choice of uPDF

Measurements of cross-sections and shape distributions in $\Delta\phi$ may help to determine uPDF

Contribution of parton shower to shape distribution in $\Delta\phi$

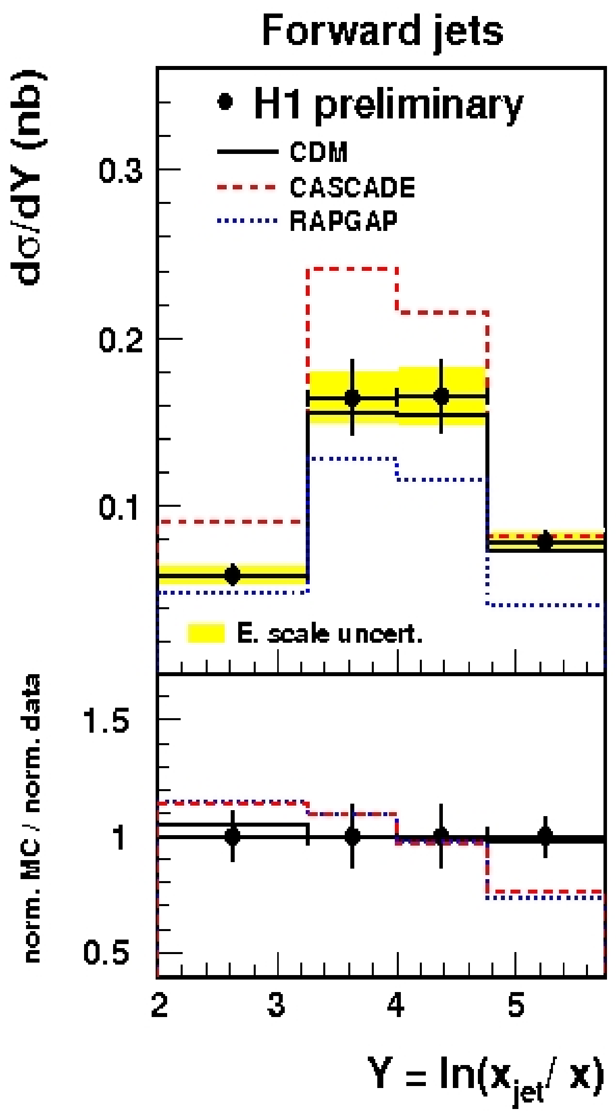
RAPGAP parton showers switched on/off



At higher x there is slight influence of parton shower on the shape distributions of $\Delta\phi$ for RAPGAP

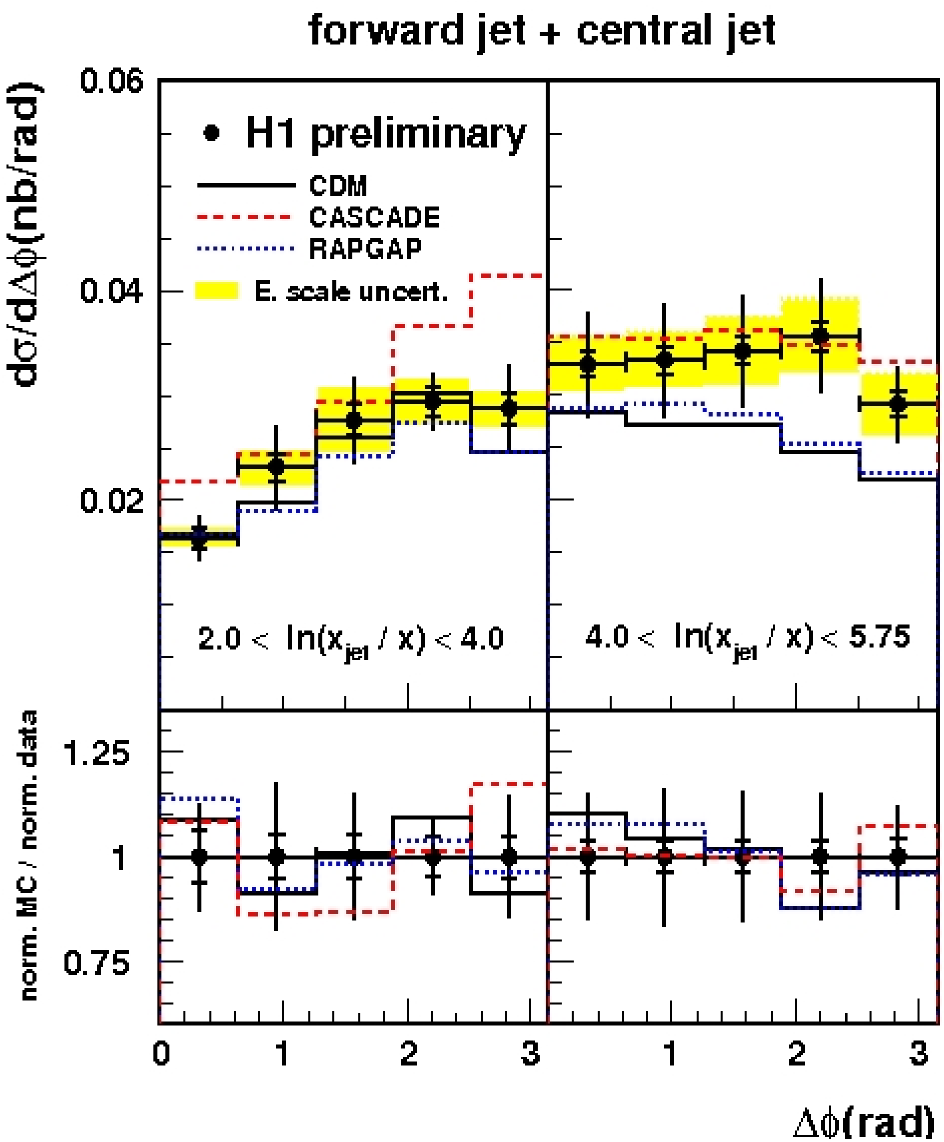
At low x values the shape distribution in $\Delta\phi$ for RAPGAP is fully determined by matrix elements

Inclusive forward jet cross-section dσ/dY



- ✗ **Very good description of the data by the CDM model.**
- ✗ Rapgap (LO DGLAP) falls below the data
- ✗ Cascade (CCFM) is above.

Forward jet + central jet cross-section $d\sigma/d\Delta\phi$



- ✗ Low Y (large x) – data best described by the CDM model
- ✗ Large Y (small x) :

  → CASCADE (set A0) – agreement with the data

  → CDM, RAPGAP – below the data within 2 standard deviations

Conclusions

- ✗ Forward jet cross-sections as a function of $\Delta\phi$ and Y = ln(xjet/x) have been measured.
- ✗ Azimuthal correlations can help to determine uPDFs in the CCFM formalism.
- ✗ At large Y(small x) parton emissions non-ordered in p_t become important – CCFM and CDM models better describe the data
- ✗ Standard LO DGLAP fails to describe the data.
- ✗ Normalised shape distributions in $\Delta\phi$ don't discriminate between different QCD evolution schemes.

Backup

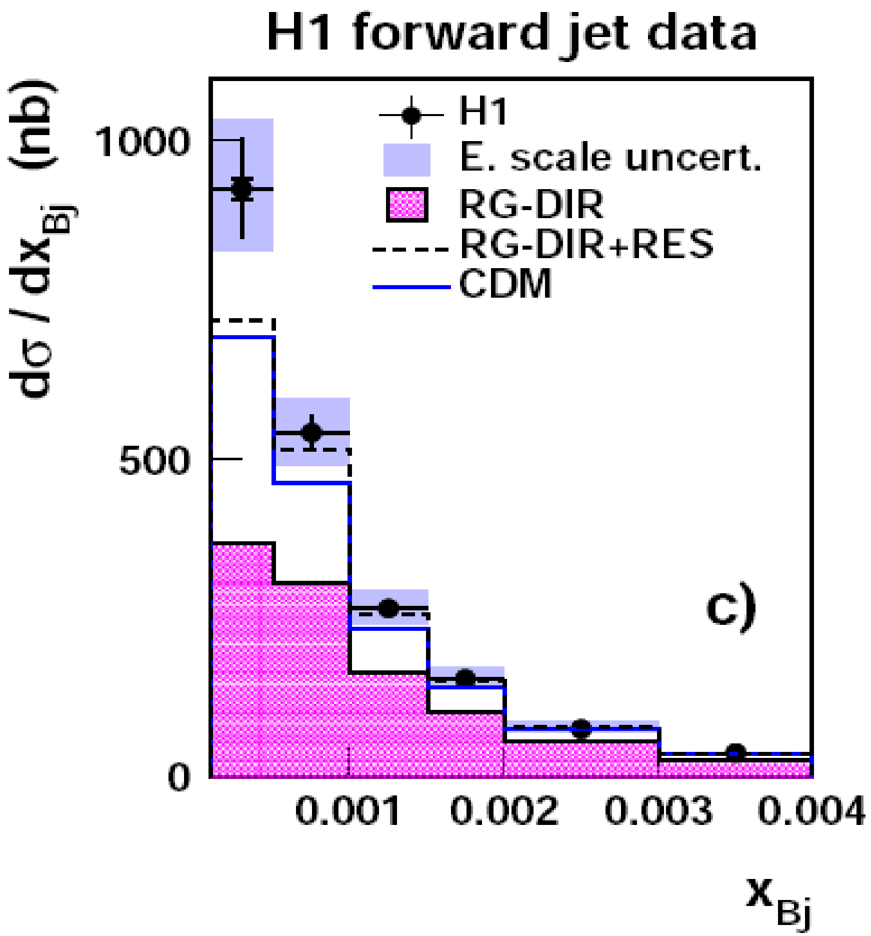
Systematic uncertainties

	$d\sigma/d\Delta\phi$ fj	$d\sigma/d\Delta\phi$ fj+cj	$d\sigma/dY$
Model dependence (CDM,RAPGAP)	2-10 %	2-15 %	4-10 %
LAr hadronic en. Scale (±4%)	8-12 %	6-11 %	8-10 %
Spacal em en. Scale (±1%)	1-2 %	1-2 %	1-2 %
Angle of scattered electron (±1 mrad)	~0.5 %	~0.5 %	~0.5 %
Trigger		3-5 %	
Luminosity		1.5 %	
Total	8-15 %	5-15 %	8-13 %

Main experimental uncertainty comes from hadronic energy scale and model dependence of correction factors (detector & QED)

Previous forward jets results

Eur.Phys.J.C46 (2006)27-42

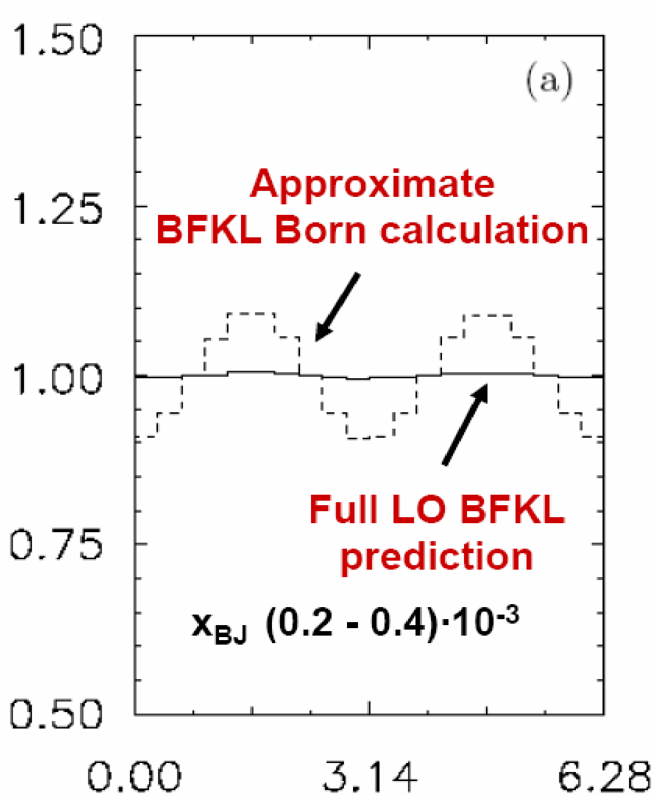


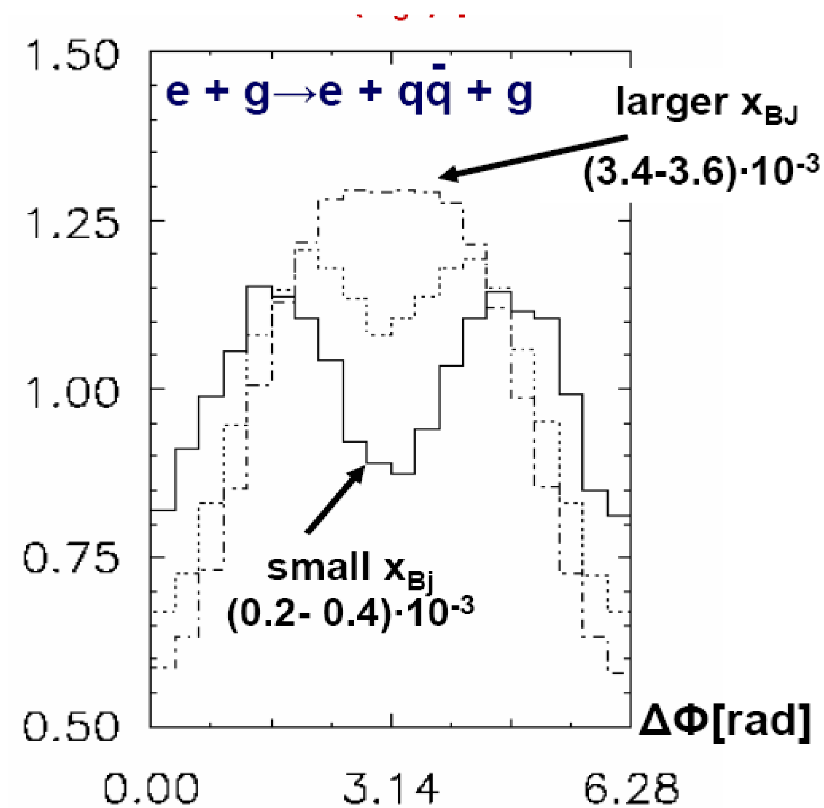
- ✗ Xsec as a function of x-Bjorken – LO DGLAP (RG direct) fails to describe the data, best description by the CDM model
- ✗ Similar conclusions for triple differential xsec (not presented here) and some more exclusive topologies
- ✗ **Studies of additional observables needed.**

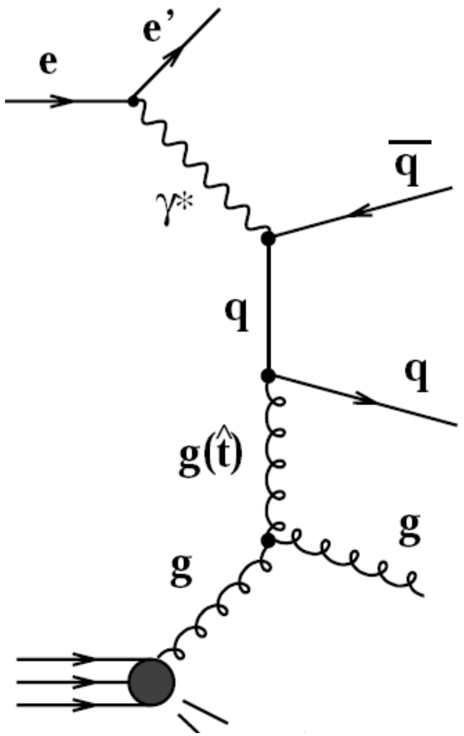
Azimuthal (de)correlations

BFKL – with increasing rapidity distance between forward jet and current jet, the forward jet „forgets" about the azimuthal direction defined by outgoing lepton.

Cross section becomes $\Delta\phi$ independent

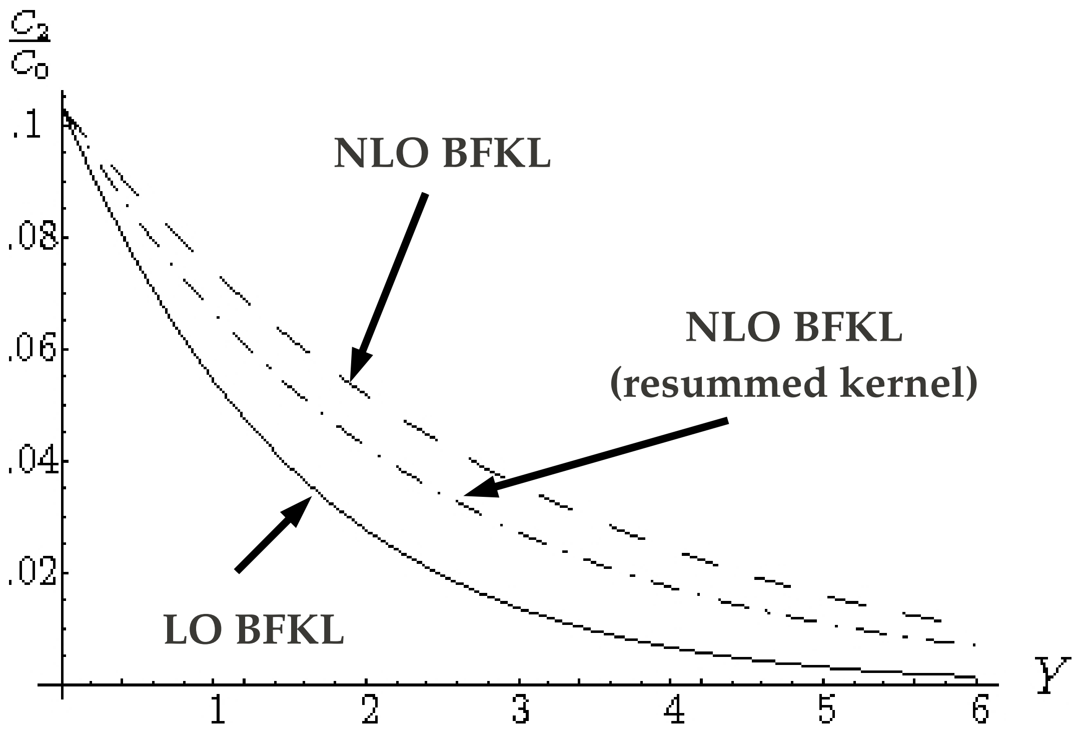






$O(\alpha_s^2)$ process

Forward jet production at NLO BFKL



The evolution in rapidity driven by the NLO BFKL kernel

Results for forward jets with ZEUS cuts

- ✗ **The fwd jet is more decorrelated from the scattered electron for larger rapidity distance**
- ✗ **The azimuthal angle correlations increase when HO corrections are included for fixed values of x_{Bj}**
- ✗ **Some angular decorrelation exist even for small values of Y**