# Review of H1 results on the hadronic final state 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
- Hadroproduction in DIS
- Summary

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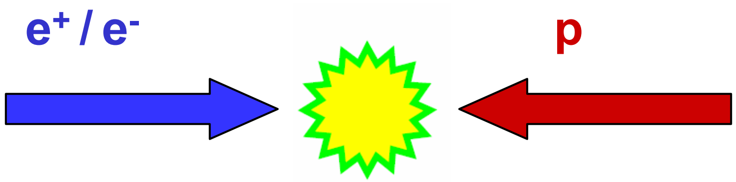
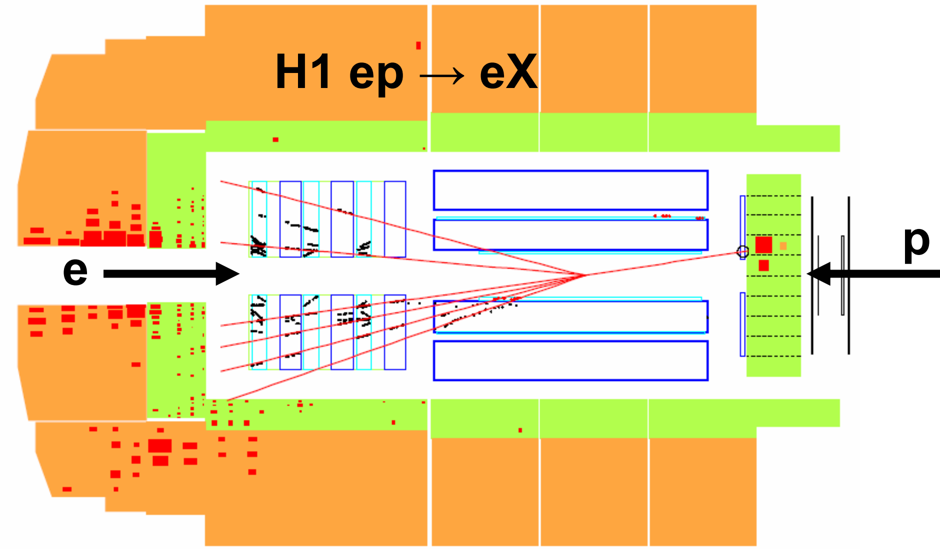
# Deep inelastic scattering at HERA

**HERA (1992 – 2007): electron (positron) – proton collider at DESY, Hamburg**



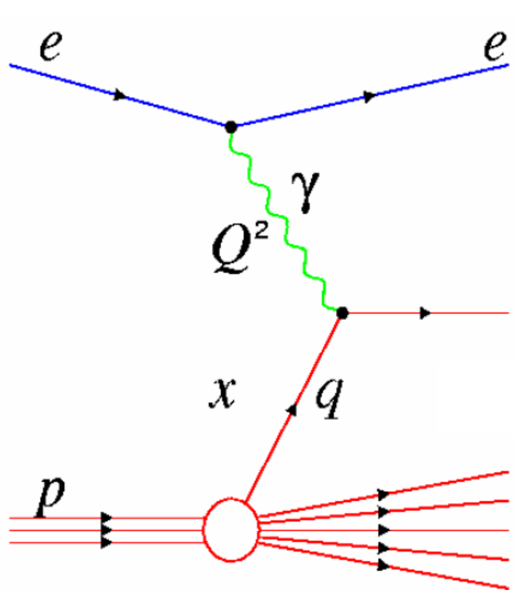

$E_e$ = 27.6 GeV

$E_p$ = 920, 820, 575, 460 GeV




**Centre-of-mass energy up to √s ~ 320 GeV**

**Total lumi: ~ 0.5 fb$^{-1}$ per H1 and ZEUS experiment**



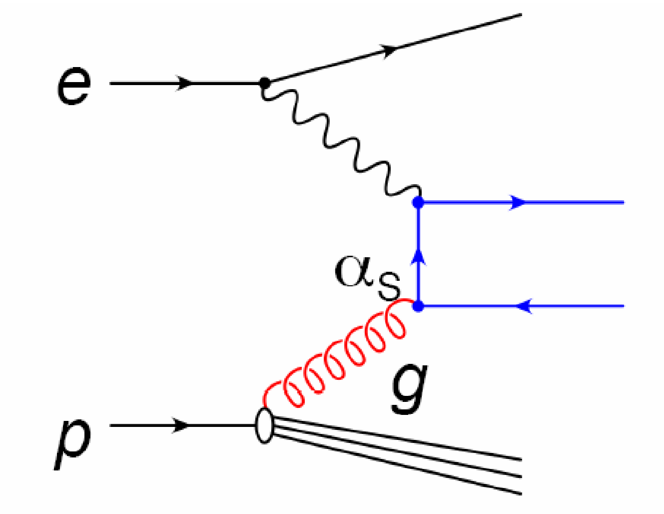

**Standard DIS variables :**

- **$Q^2$** |virtuality| of the exchanged boson
- **x** fraction of proton momentum carried by struck quark in Quark Parton Model
- **$y = Q^2 / xs$** inelasticity, fraction of lepton energy transfered in the proton rest frame

# Measurements of the hadronic final states

**Measurements of the HFS in DIS are complementary to inclusive measurements**

**(structure of the proton, parton distribution functions PDF …)**



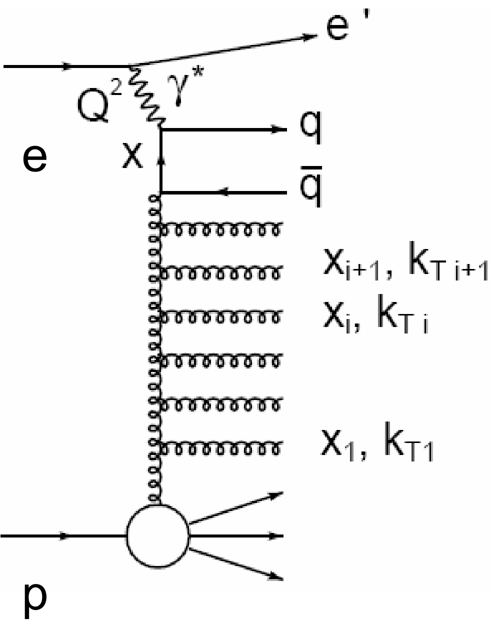

- **Information on the gluon density in the proton**
- **Determination of $\alpha_s$**
- **Search for effects of parton dynamics beyond the standard DGLAP approach**
- **Mechanisms of hadroproduction**

…

# QCD dynamics at low Bjorken-x

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



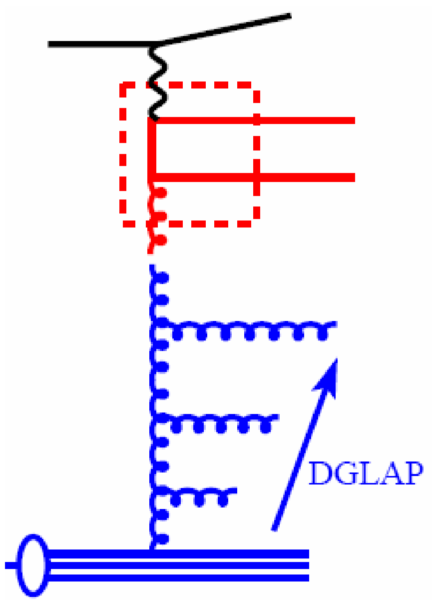

- **DGLAP evolution: resums terms ~ ( $\alpha_s \ln Q^2$ )$^n$**
  **Assumes strong ordering of parton $k_T$**
- **BFKL evolution: resums terms ~ ($\alpha_s \ln(1/x)$ )$^n$**
  **No ordering in $k_T$, strong ordering in $x_i$**
  **Transition from DGLAP to BFKL scheme expected at low x**
- **CCFM evolution: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

**RAPGAP, Herwig++**
**DGLAP**

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

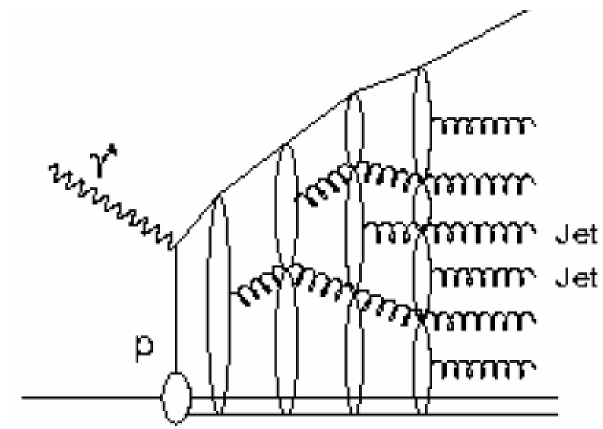



Single DGLAP ladder with strong ordering in $k_T$

**DJANGOH**
**Colour Dipole Model**

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

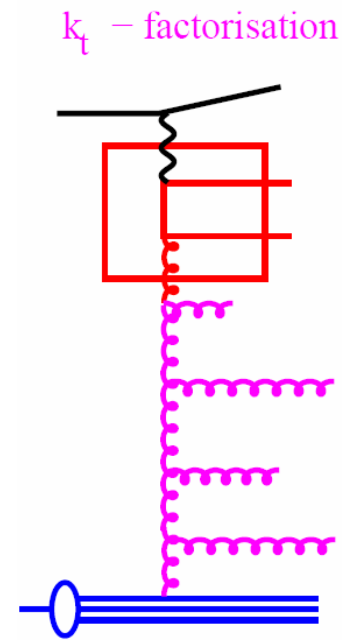
Chain of independently radiating dipoles formed by the emitted gluons.




BFKL- like Monte Carlo : random walk in $k_T$

**CASCADE - CCFM**

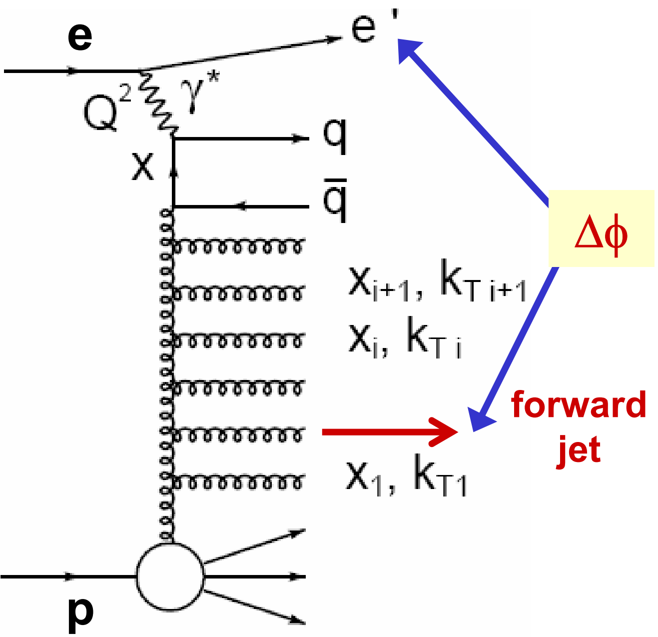
Off-shell QCD ME + parton emissions based on the CCFM equation




Angular ordering of parton emissions

**Hadronisation parameters tuned to $e^+e^-$ data ( ALEPH tune )**

# 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 :**

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

## H1 experiment, L = 38.2 $pb^{-1}$

**DIS selection**

$0.1 < y < 0.75,$

$5 < Q^2 < 85$ 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, $1.73 < \eta_{fwdjet} < 2.79$

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

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

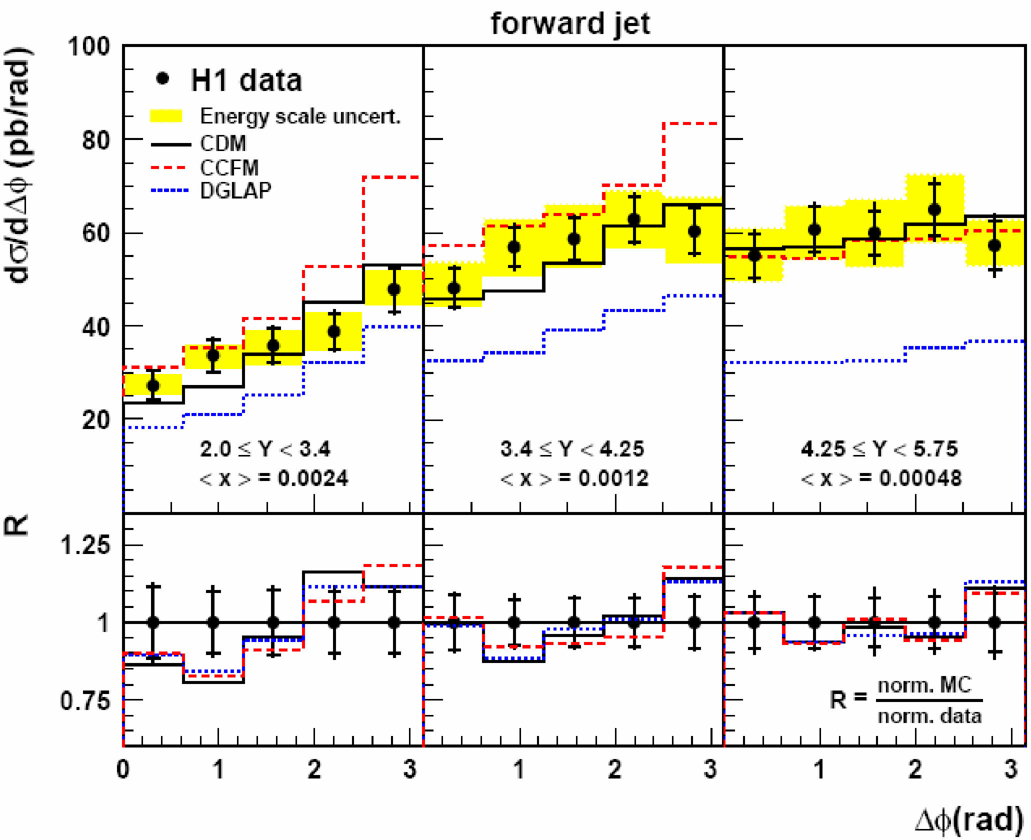
$\theta$ with respect to proton beam direction

**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.**

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

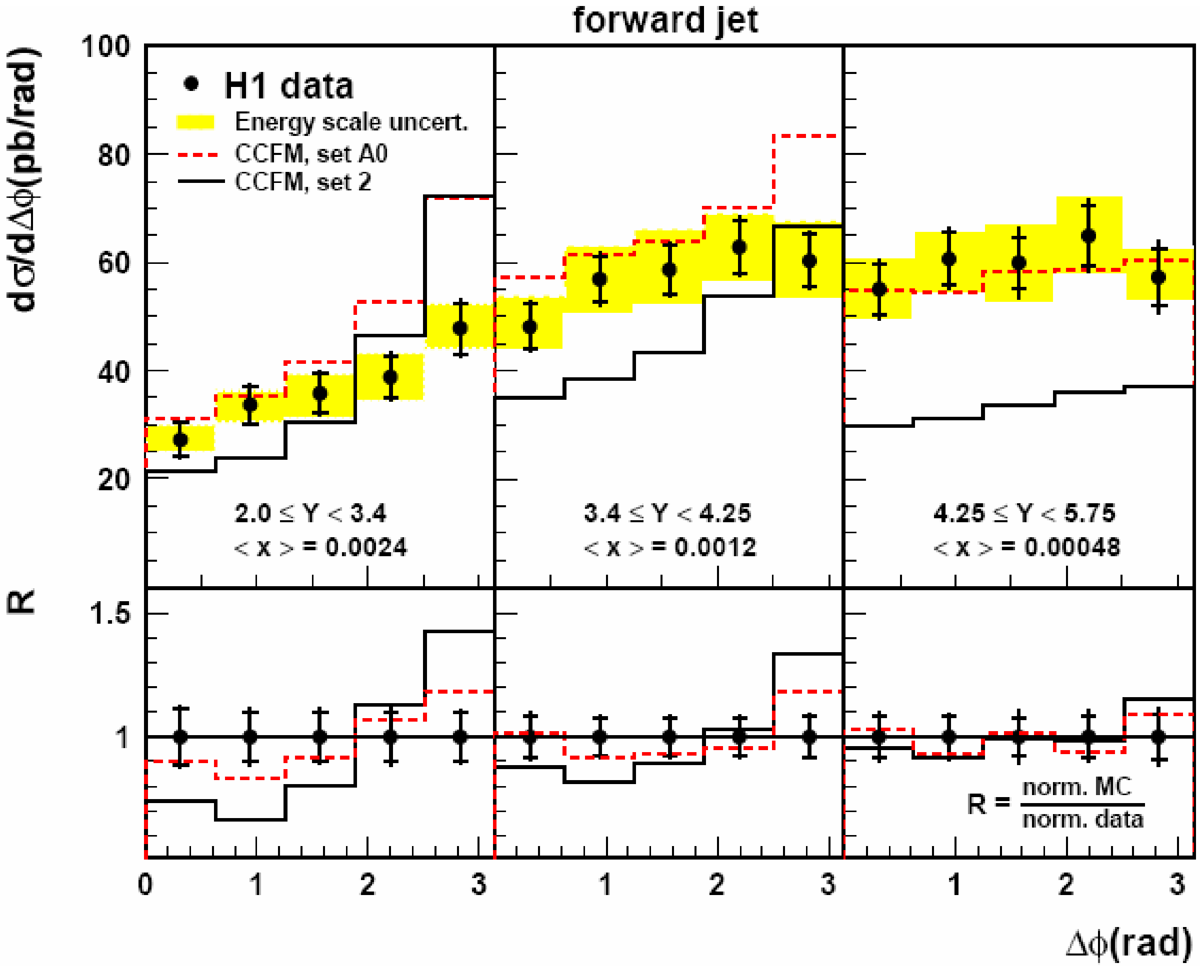
**Y = ln($x_{fwdjet}$ / x) rapidity distance between the most forward jet and the scattered positron**

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

# 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**



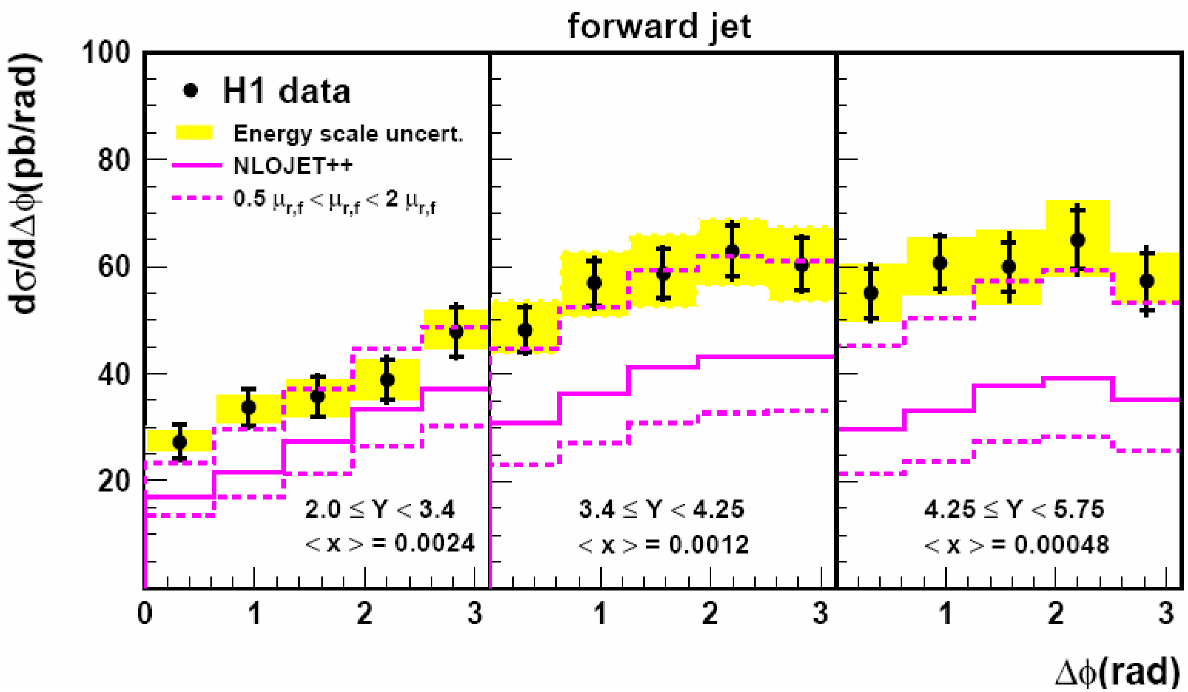

- **Cross sections** strongly depend on uPDF
- **Shape of $\Delta\phi$ distributions**
  - at low Y shows sensitivity to uPDF
  - well described by the set A0

**EPJ C72 (2012) 1910**

**Predictions of the CCFM model depend on the choice of uPDF**

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

EPJ C72 (2012) 1910




**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

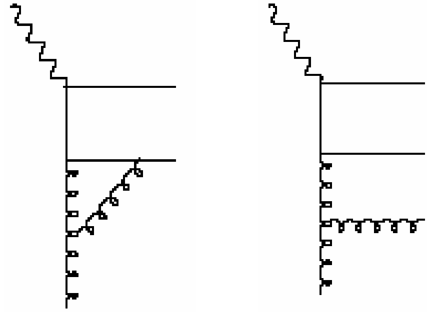
**NLOJET++ ( Nagy & Trocsanyi, 2001)**

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

renormalisation and factorisation scales :

$$\mu_r = \mu_f = \sqrt{\frac{p^2_{T,\,fwdjet} + Q^2}{2}}$$

theoretical uncertainty :
factor 2 or ½ applied to $\mu_r$ and $\mu_f$ scales simultaneously

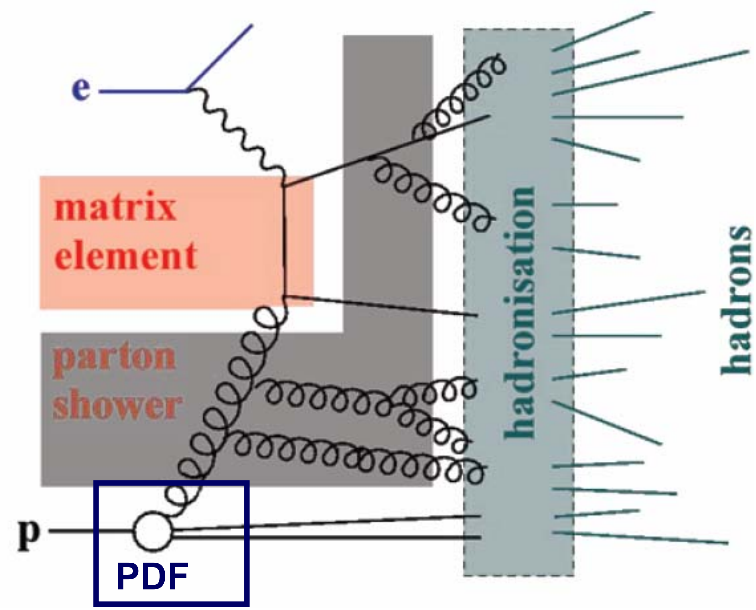


Dijet production at parton level in DIS at NLO($\alpha_S^2$)

# Charged particle densities in DIS

**The underlying dynamics of hadron production in high energy particle interaction is still not fully understood.**

**PDF ⊗ parton dynamics ⊗ hadronisation → hadronic final state**




**Different kinematic regions sensitive to different effects:**

- **low $p_T$ region**
  → **hadronisation effects dominate**
- **high $p_T$ region**
  → **sensitivity to parton evolution effects**

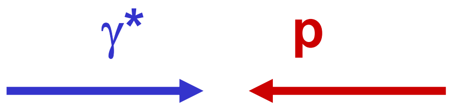
## Recent H1 results on charged particle spectra:

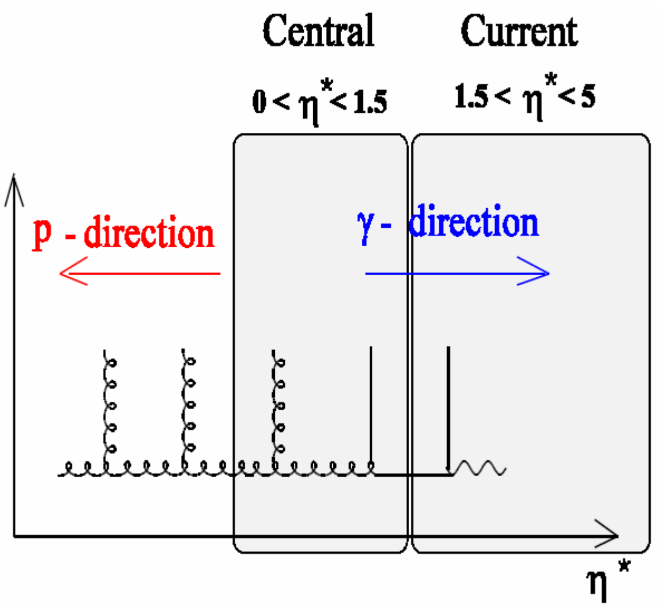
- **proton energy $E_p$= 920 GeV ($\sqrt{s}$ = 319 GeV), L= 88.6 $pb^{-1}$ , Eur. Phys. J. C73 (2013) 2406**

# Charged particle density: test of QCD dynamics at low x

**Eur. Phys. J. C73 (2013) 2406**

Analysis in the virtual photon – proton ( $\gamma^*$p) rest frame




**Observables : charged particle densities vs. pseudorapidity $\eta^*$ and transverse momentum $p_T^*$**

$$\frac{1}{N}\frac{dn}{d\eta^*} \qquad \frac{1}{N}\frac{dn}{dp_T^*}$$

**$p_T^*$ dependence studied in two $\eta^*$ intervals :**

**$0 < \eta^* < 1.5$ central region → test of parton shower models**

**$1.5 < \eta^* < 5$ current region → large sensitivity to the hard scatter**

**target region $\eta^* < 0$ not accessible**

**DIS selection**

$0.05 < y < 0.6$,

$5 < Q^2 < 100$ GeV$^2$

$0.0001 < x < 0.01$

**Charged particles**

LAB frame : $-2 < \eta < 2.5$

$p_T > 150$ MeV

$\gamma^*$p frame : $0 < \eta^* < 5$

$0 < p_T^* < 10$ GeV

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

$\theta^*$ with respect to virtual photon direction

# Charged particle density as a function of pseudorapidity

Eur. Phys. J. C73 (2013) 2406

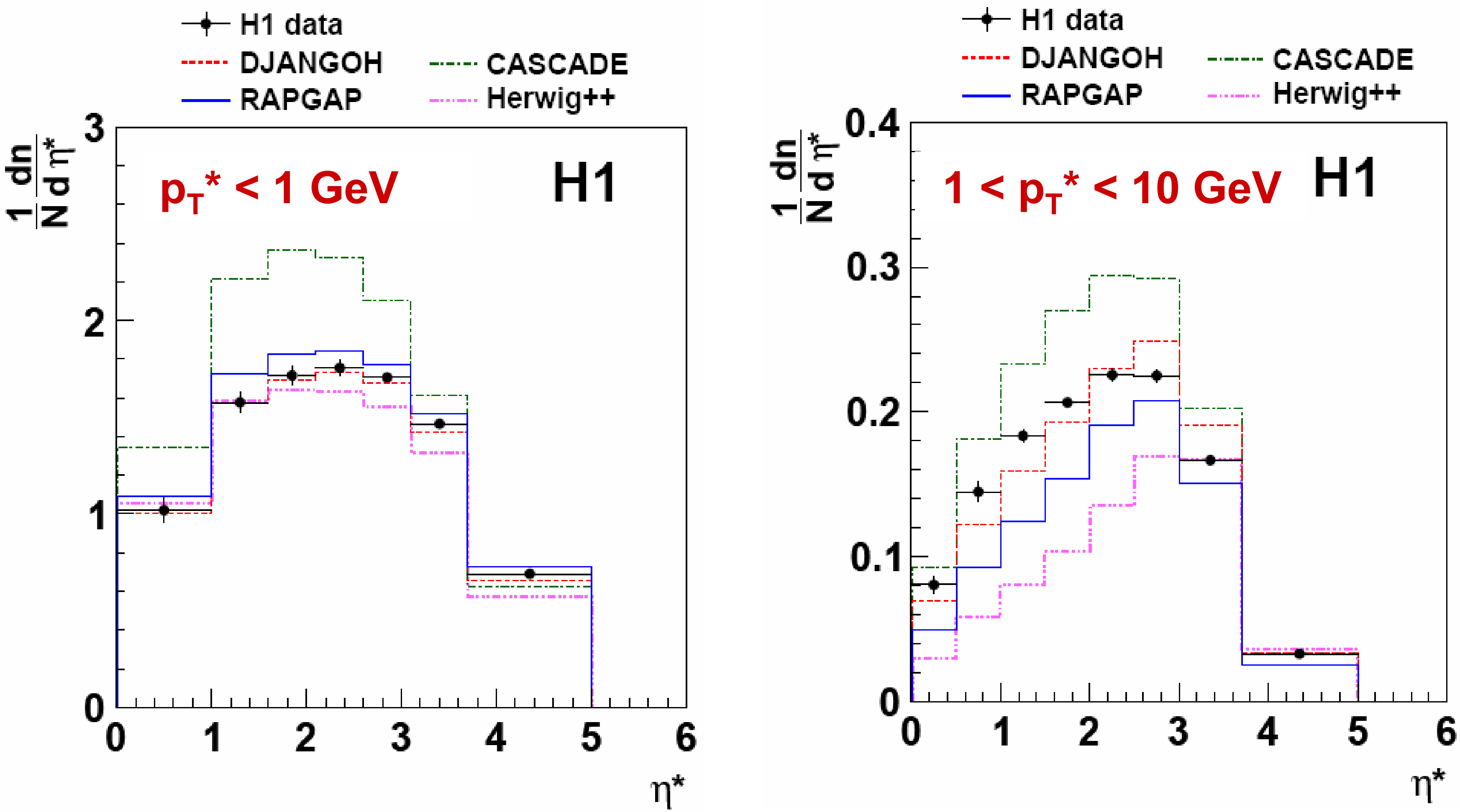
$$\frac{1}{N}\frac{dn}{d\eta^*} \quad \text{vs.} \quad \eta^*$$

**measurements for two $p_T^*$ regions:**

- $p_T^* < 1$ GeV
- $1 < p_T^* < 10$ GeV

**First focus on the low and high $p_T$ regions for understanding the influence of hadronisation and parton evolution effects** →

# Charged particle density : sensitivity to QCD dynamics




All models, except CASCADE (CCFM), describe the data within PDF uncertainties

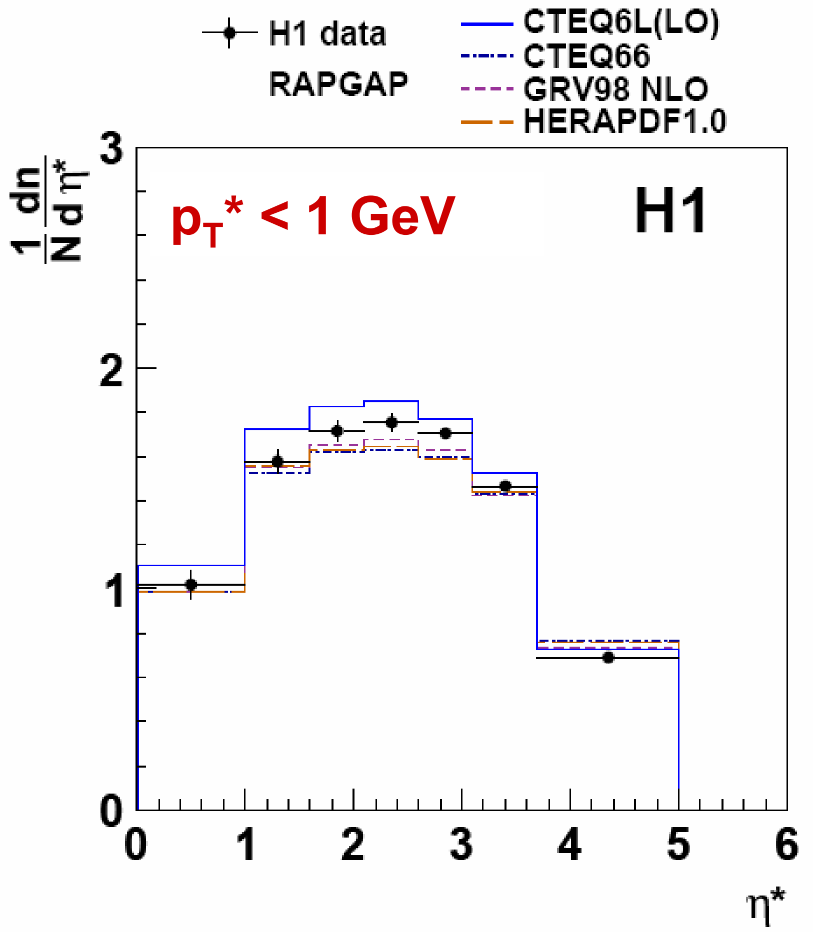
DJANGOH (CDM) provides the best description of the data

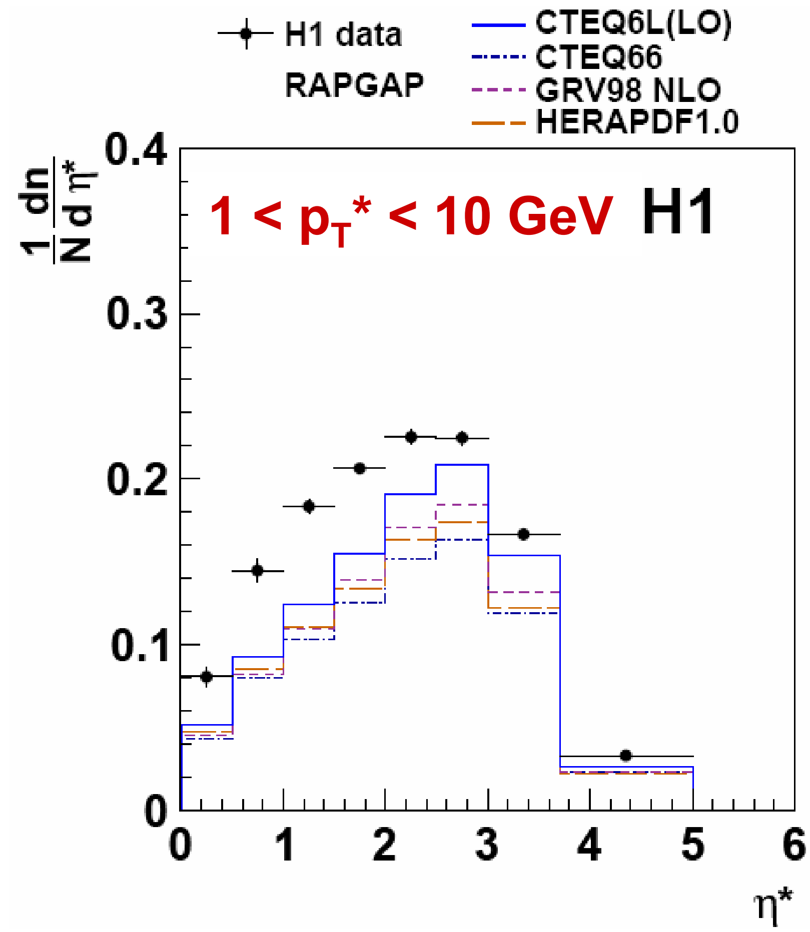
**Strong sensitivity to QCD dynamics at high transverse momentum $p_T^*$**



EPJ C73 (2013) 2406

## Charged particle density : DGLAP predictions for different PDFs




- All predictions are close to the data
- RAPGAP (LO ME + LL parton shower) with different NLO PDFs predicts similar results

- None of the predictions describe the data
- CTEQ6L(LO) is closest to the data

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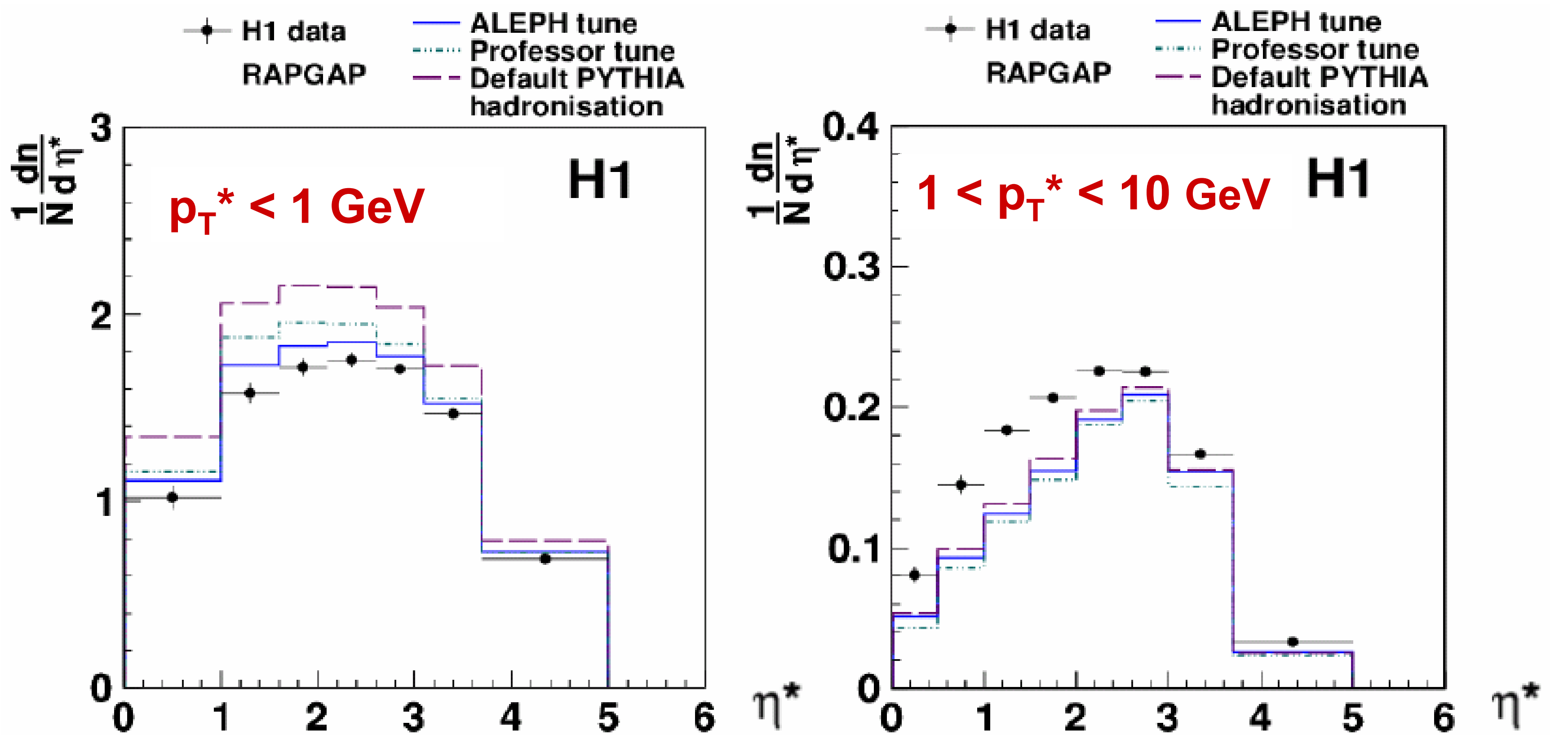
# Charged particle density : sensitivity to hadronisation schemes

## RAPGAP ( DGLAP – based model ) + 3 sets of fragmentation parameters




- Sensitivity to the tunning of hadronisation parameters
- Data are best described by the ALEPH tune ( $e^+e^-$ )

- Little sensitivity to hadronisation
- None of the tunes describe the data

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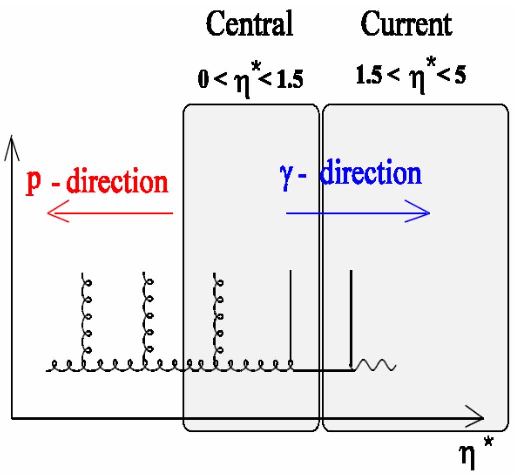
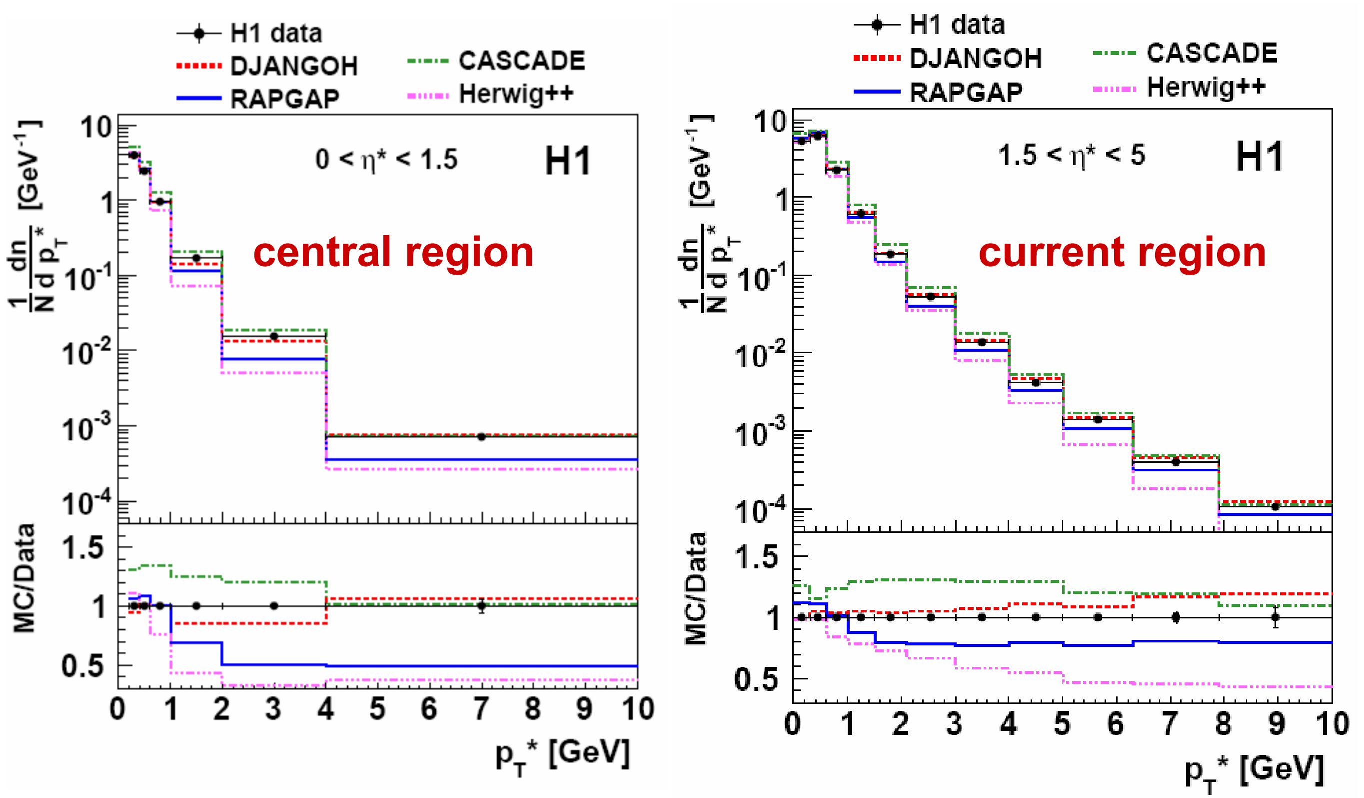
# Transverse momentum distribution



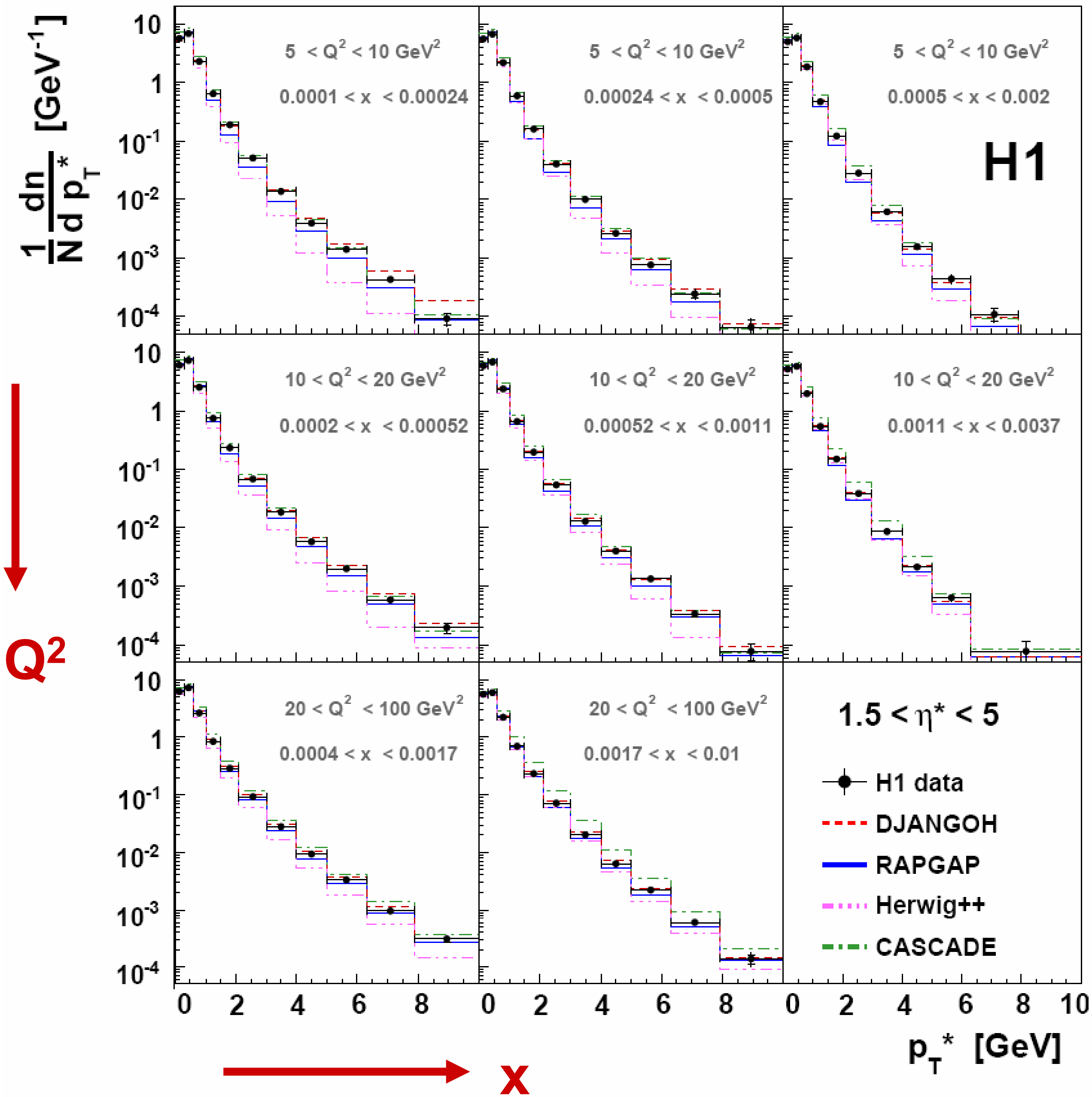

**EPJ C73 (2013) 2406**

**Study the effect from parton showers (central region)**
**and from the hard scatter (current region)**




- Predictions are sensitive to different parton shower dynamics at high $p_T^*$
- DJANGOH ( CDM ) provides a reasonable description of the data, other models fail → deviations are strongest in the central region

# Charged particle $p_T^*$ spectra in bins of $Q^2$ and x




**current region**

**1.5 < $\eta^*$ < 5**

**at high $Q^2$ RAPGAP**
( based on DGLAP )
**is almost as good as**
**DJANGOH** ( CDM )
**at large $p_T^*$**

**the region most sensitive to the hard scatter**

# Summary

## Azimuthal correlation of forward jets in DIS at HERA

- 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 shapes of the $\Delta\phi$ distributions are equally well described by LO MC models with different QCD evolution schemes
- NLO DGLAP predictions are in general below the data, but still in agreement within the large theoretical uncertainties

## Measurements of charged particle spectra in DIS at HERA

- Transverse momentum and pseudorapidity distributions in the hadronic centre-of-mass system were measured in *ep* collisions at low $Q^2$ for $\sqrt{s}$ = 319 GeV
- The data are compared to QCD models with different parton evolution dynamics (DGLAP, CDM, CCFM) and with different hadronisation schemes
- DGLAP- based models are below the data especially at high $p_T^*$ and low $\eta^*$
- CDM provides a reasonable description of the data

**backup**

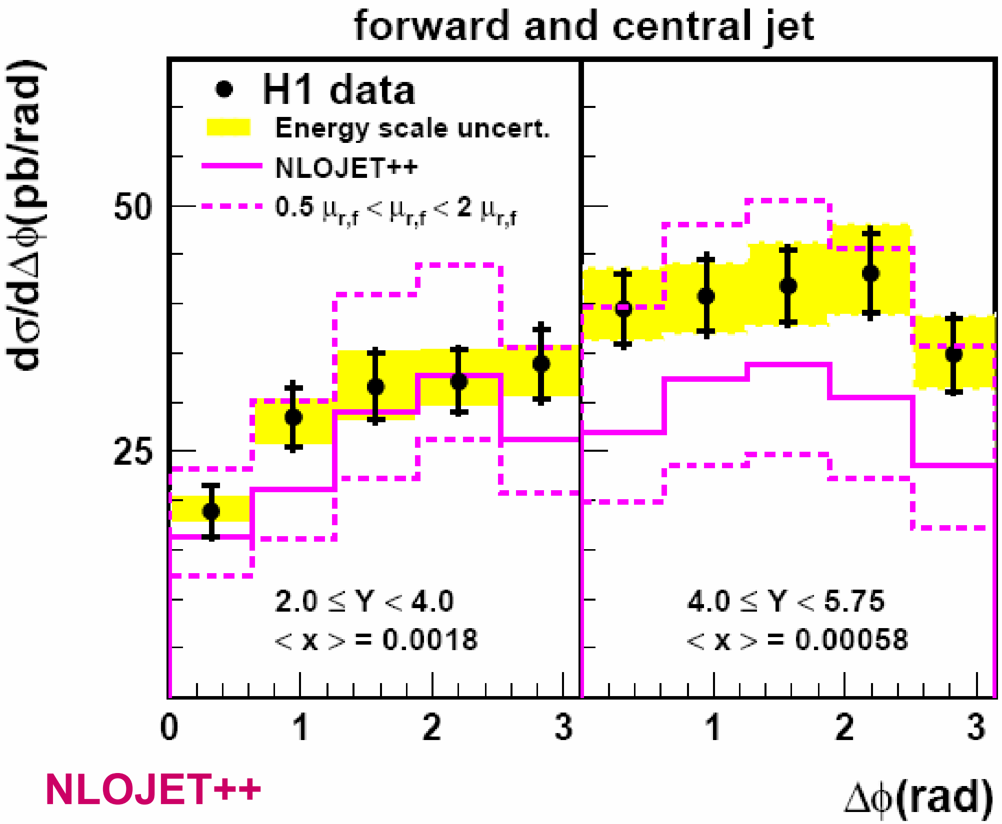
# Forward and central jet cross sections $d\sigma / d\Delta\phi$

- 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, $\alpha_S(M_Z)=0.118$

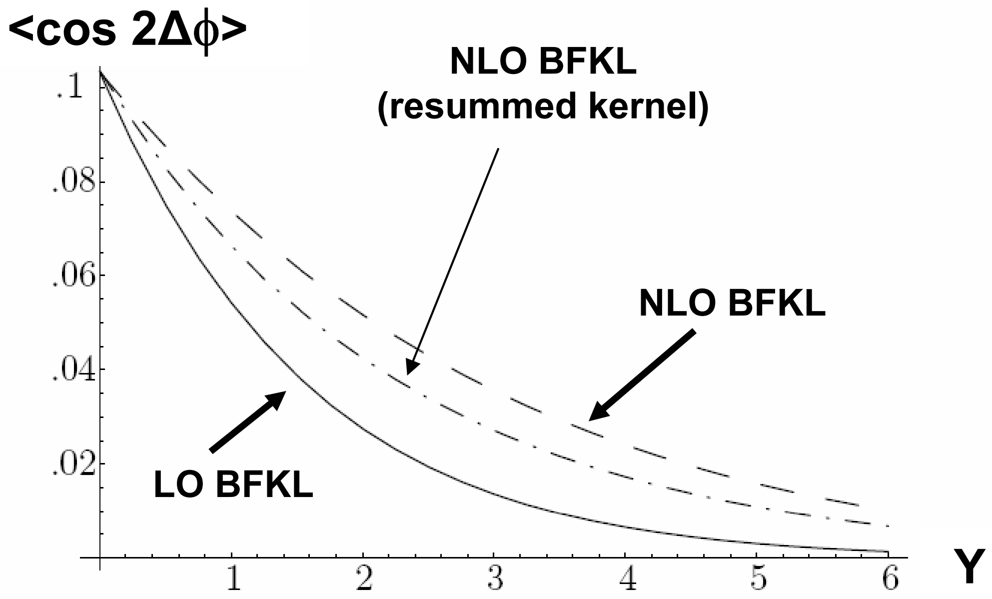
$\mu_r^2 = \mu_f^2 = (\langle p_T\rangle^2 + Q^2) / 2$

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

# 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**

$20 < Q^2 < 100\ \mathrm{GeV}^2$
$0.05 < y < 0.7$
$4\cdot10^{-4} < x_{Bj} < 5\cdot10^{-3}$
$0.5 < p_t^2 / Q^2 < 2.0$

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

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

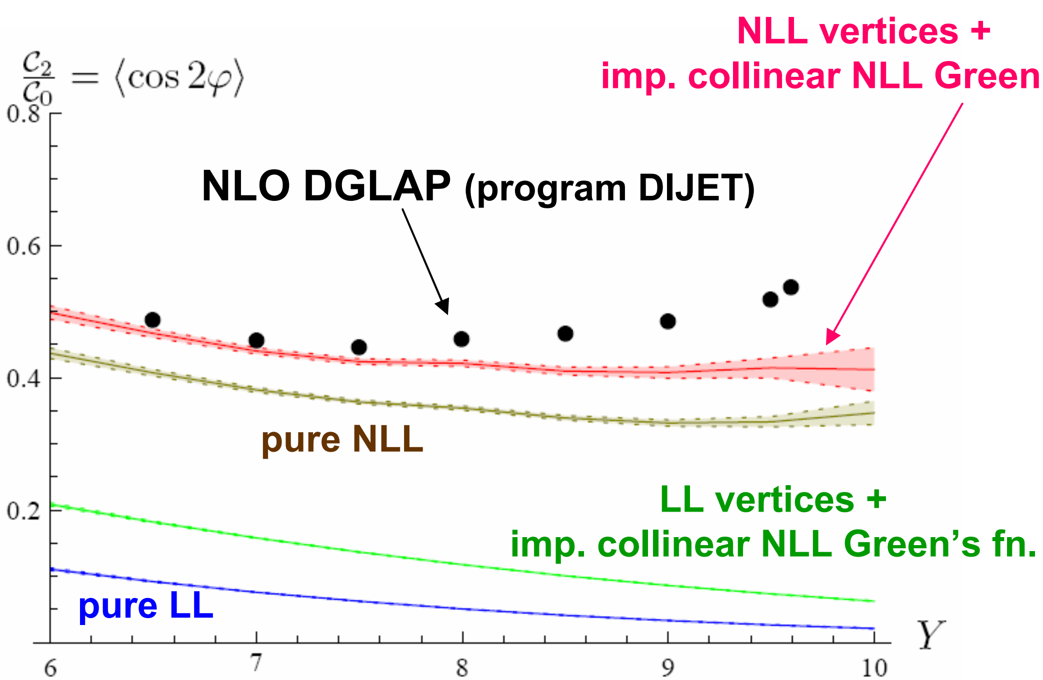
- The forward jet is more decorrelated from the scattered lepton for larger rapidity difference Y ( center of mass energy)
- The azimuthal angle correlations increase when HO corrections are included for a fixed value of Y

# 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 <cos2ϕ> = <cos(2 · ($\phi_{jet1} - \phi_{jet2} - \pi$))>**




- **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**