Lowx Workshop, Nafplion 2003

Forward jet and π^0 production in deep-inelastic scattering at HERA

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on behalf of the H1 and ZEUS collaborations

- Introduction
- Inclusive Jet Measurements
- Forward Jet Measurements
- Forward π^0 Measurements
- Conclusions

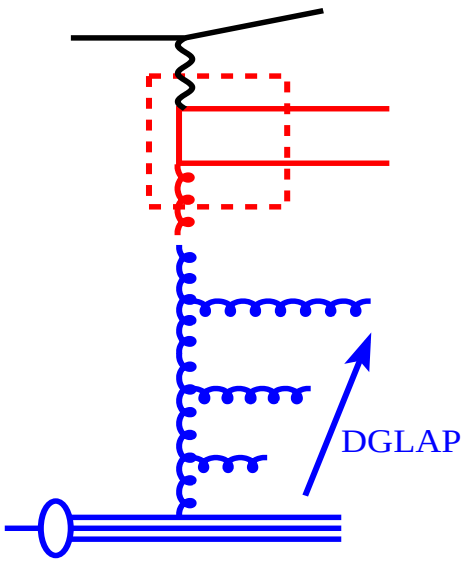
Prescriptions of the QCD dynamics at small x

DGLAP BFKL CCFM

MC models:

RAPGAP DIR

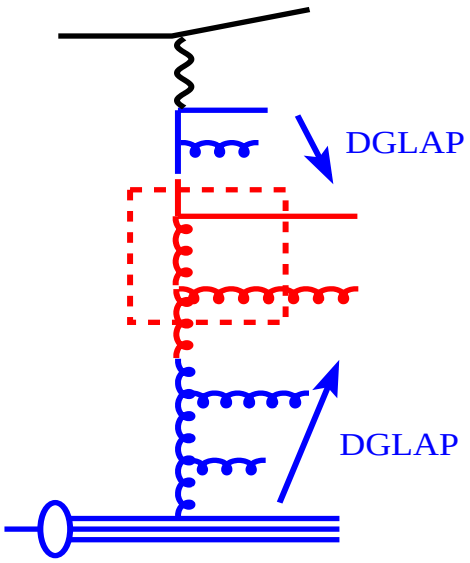
LO



ordered in k_T

RAPGAP RES

resolved photon



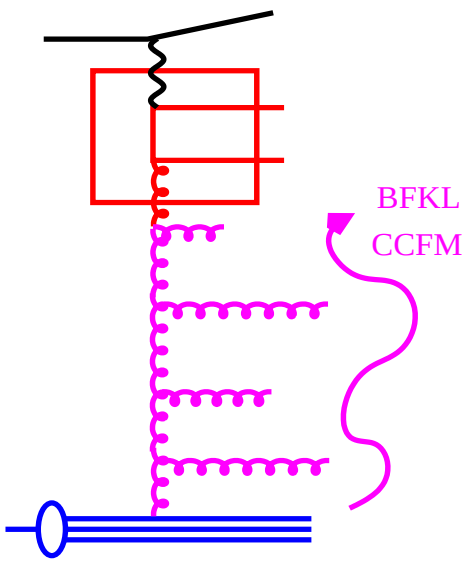
each ladder ordered in k_T

scale $Q^2 + p_T^2$ for jets

scale $Q^2 + 4p_T^2$ for π^0

CASCADE

k_t – factorization



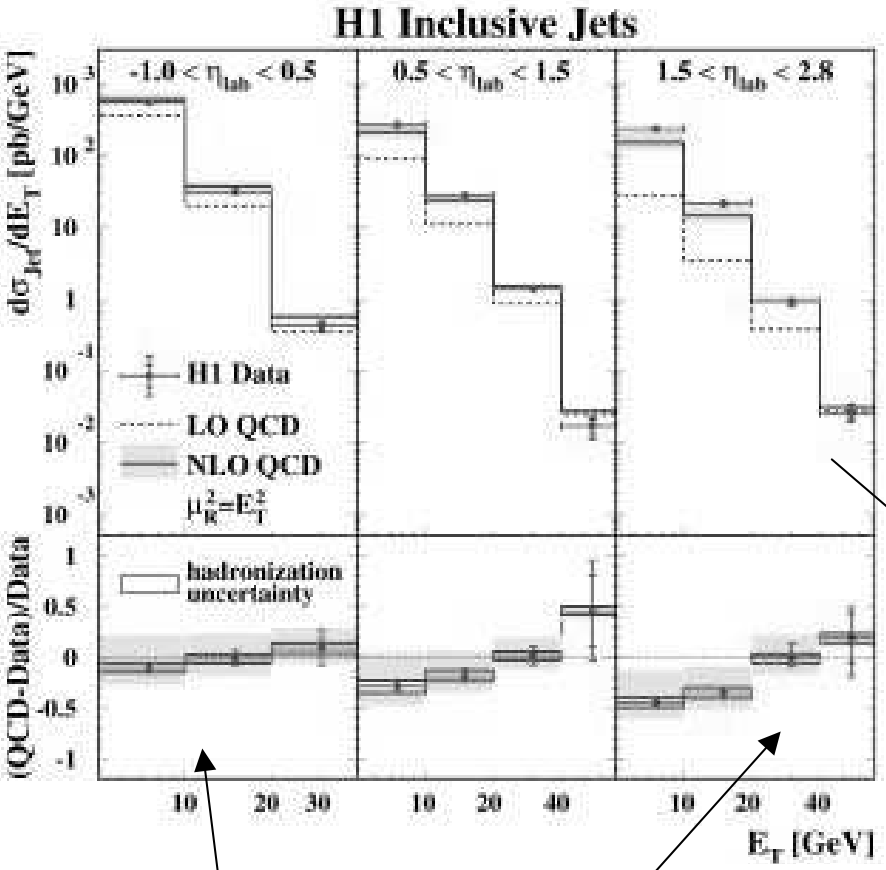
ordered in energy in angle

using concept

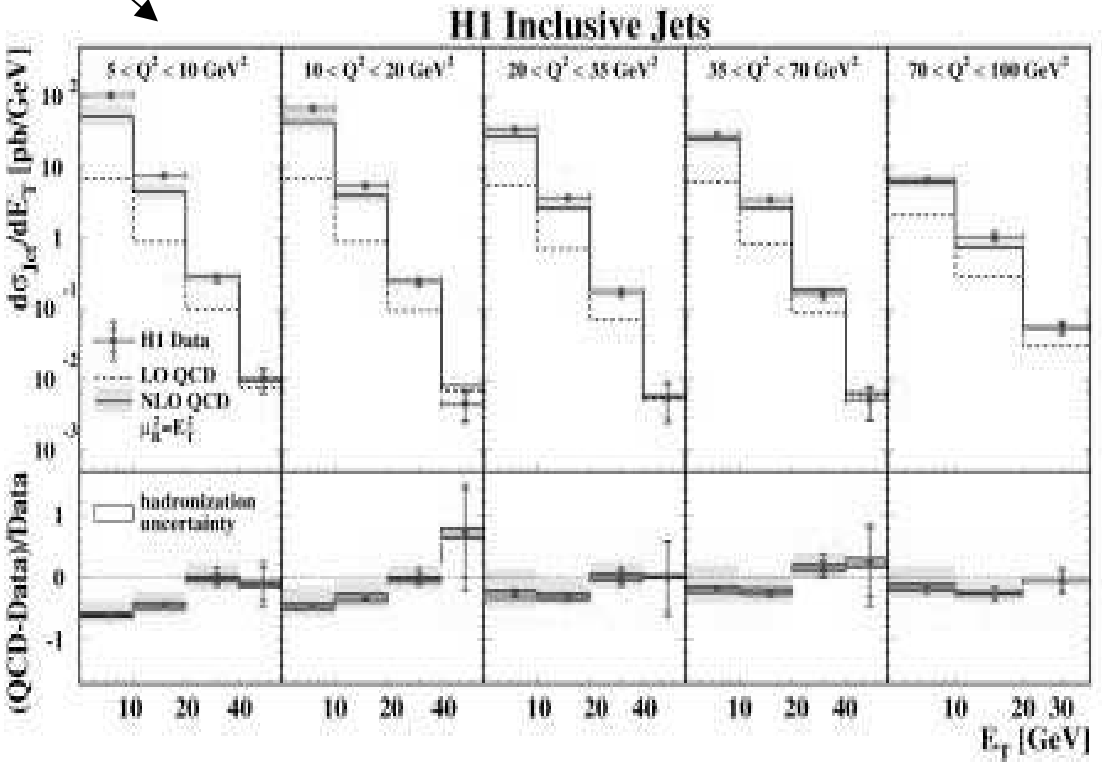
of colour coherence

Inclusive Jets in DIS

$5 < Q^2 < 100$ GeV^2, $0.2 < y < 0.6$
incl. k_T algorithm in Breit frame



DGLAP description gradually deteriorates when going from backward to forward direction



Forward region:

- huge NLO correction
- large deviations at small Q^2 & E_T

Moral: NNLO may be important in forward region

Event Selection

Data Set: ZEUS 96/97 (~38.6 pb^{-1})

Monte Carlo: Detector acceptance estimated with LO Color Dipole Model (CDM) implemented with Ariadne, using CTEQ4M PDFs

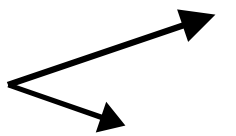
Phase space selection:

- $Q^2 > 25$ GeV
- $y > 0.04$
- $E_{T,jet} > 6$ GeV
- $-1 < \eta_{jet} < 3$ $\quad \eta = -\ln(\tan\frac{\theta}{2})$

DIS selection made by requesting high-energy positron in the final state with additional cuts applied to reject background.

Jets are selected in the lab frame using the longitudinally invariant k_T-cluster algorithm:

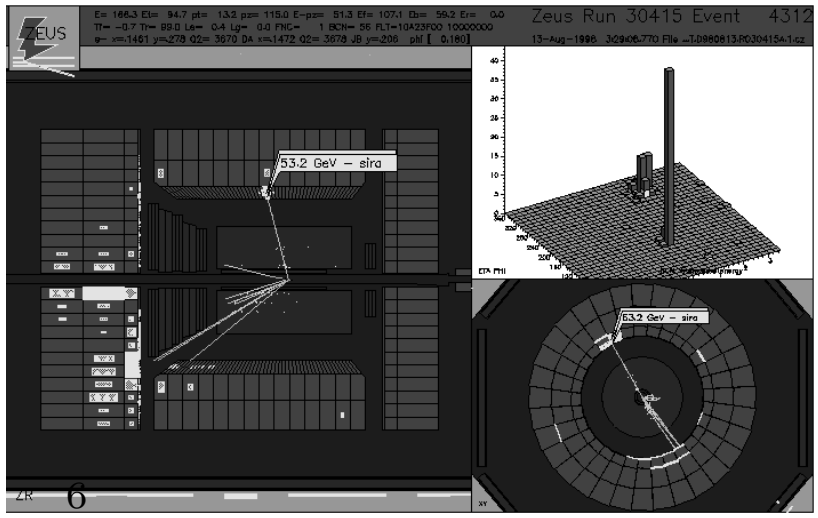
Catani et.al.; Ellis & Soper



$$d_i = E_{T,i}^2$$

$$d_{i,j} = min(E_{T,i}^{2,} E_{T,j}^2)[\Delta\eta^2 + \Delta\phi^2]$$

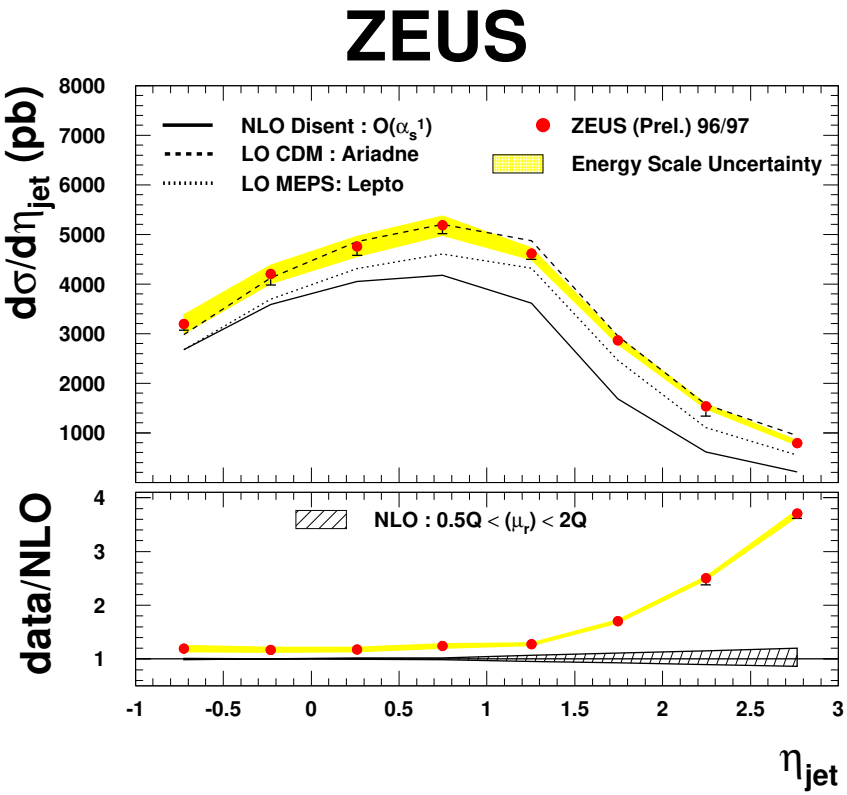
Combine particles i and j into a jet if $d_{i,j}$ is smaller of $\{d_i, d_{i,j}\}$.

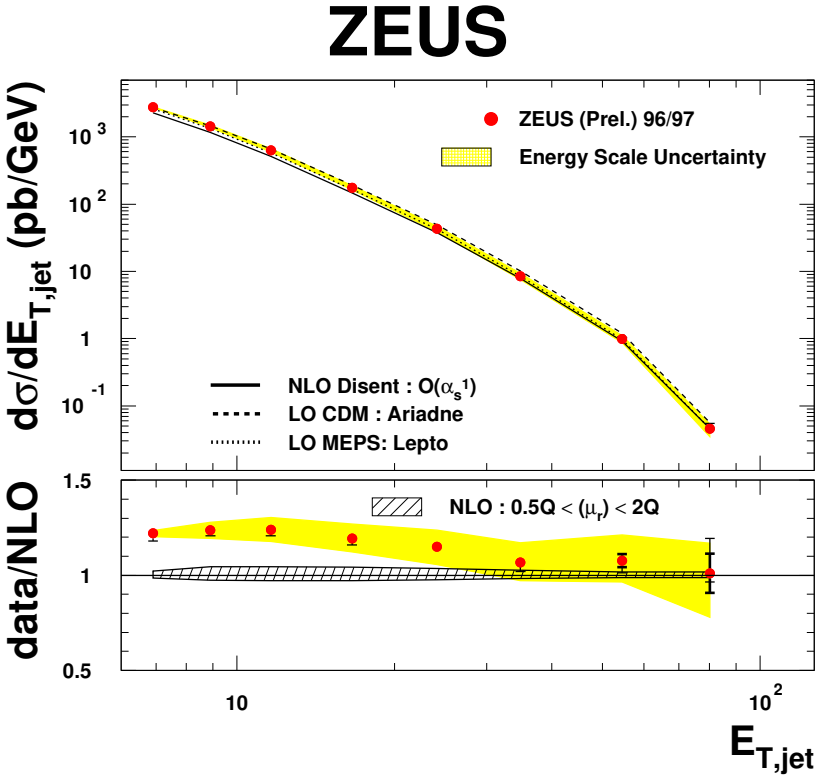


Measurement of hadronic cross sections for **inclusive** jet production: $d\sigma/d\eta_{jet}$, $d\sigma/dE_{T,jet}$

DISENT implementation of NLO calculation
LO = $O(\alpha_s^0)$; NLO = $O(\alpha_s^1)$
MRST99 PDF's

Data corrected for ISR/FSR effects



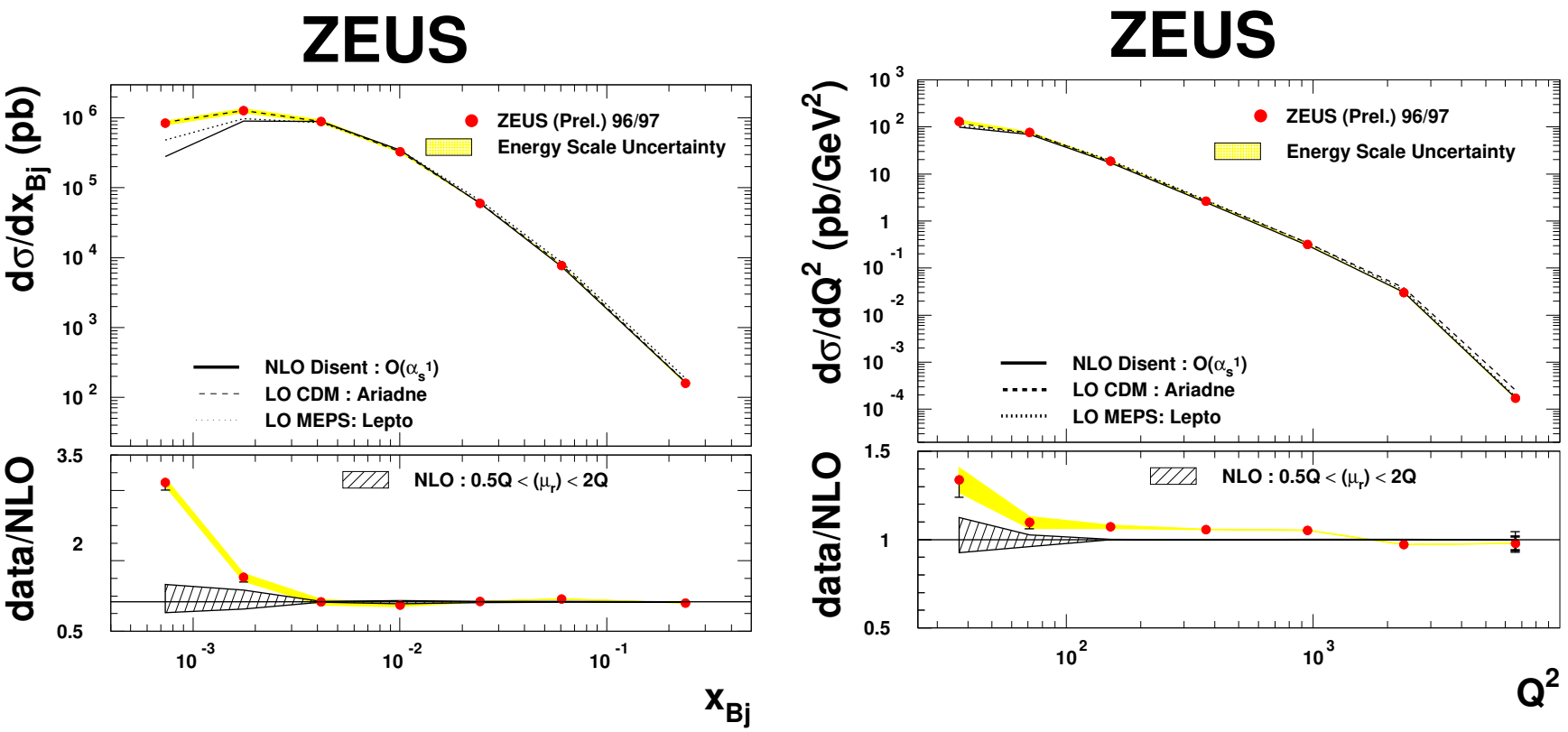


Cross sections dominated by Quark Parton Model (QPM) events

Differential cross sections in kinematic quantities:

$$d\sigma / d\,x_{Bj} \quad , \quad d\sigma / dQ^2$$

Large discrepancy in the forward and central regions of the detector are localized in the smallest x_{Bj} values.



Redefinition of phase space

Inclusive Jet Phase Space

- $Q^2 > 25$ GeV
- $y > 0.04$
- $E_{T,jet} > 6$ GeV
- $-1 < \eta_{jet} < 3$

to suppress QPM →

" Dijet" Phase Space

- $Q^2 > 25$ GeV
- $y > 0.04$
- $E_{T,jet} > 6$ GeV
- $0 < \eta_{jet} < 3$
- $\cos(\gamma_{had}) < 0.0$

Disent Calculations:

LO = $O(\alpha_s^0)$ = QPM → QPM = 0 for $\eta > 0$ → LO = $O(\alpha_s^1)$ = BGF + QCDC

NLO = QPM + corrections → BGF + QCDC for $\eta > 0$ → NLO = $O(\alpha_s^2)$ = BGF + QCDC + corrections

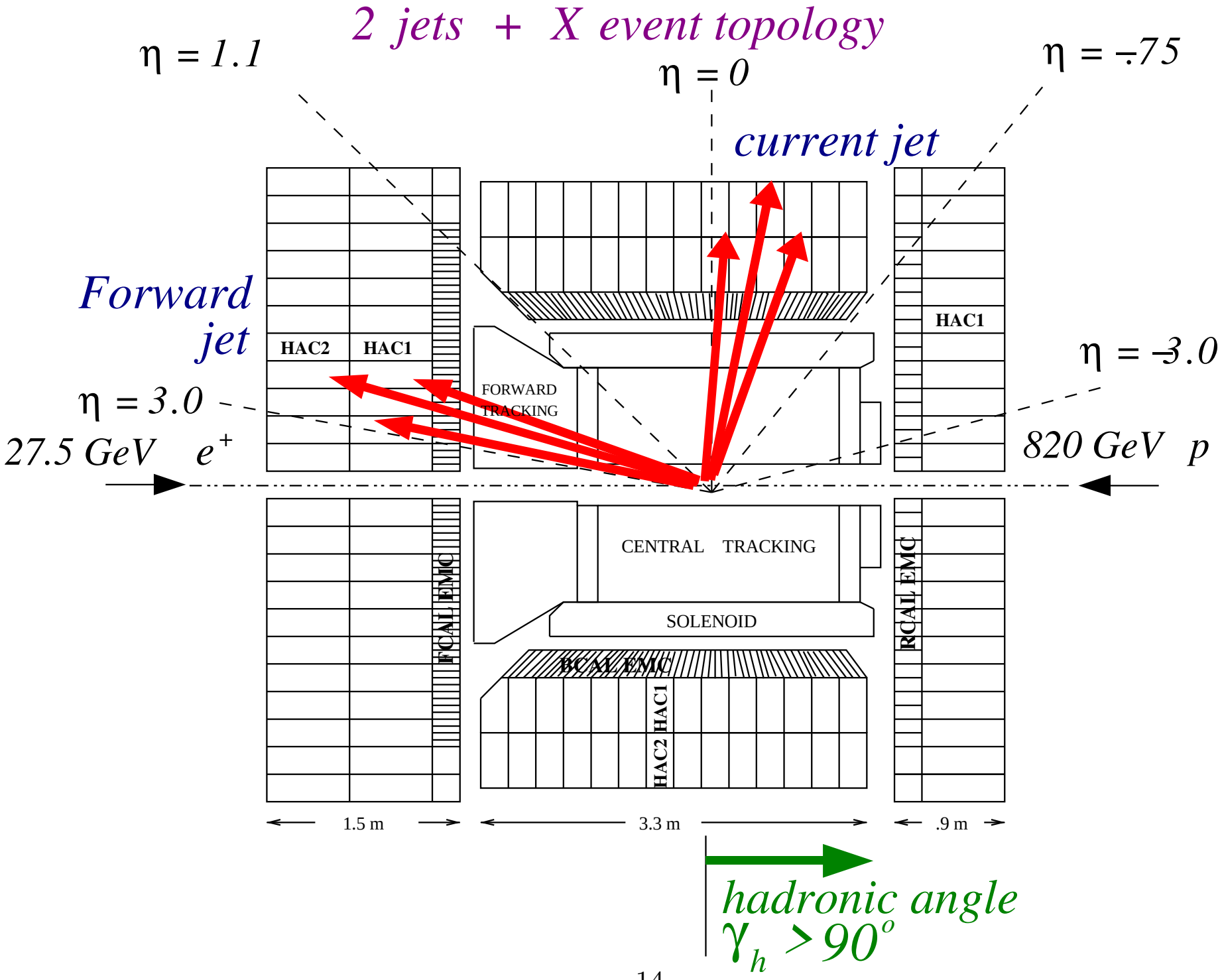
with hadronic angle requirement

Just 1 order in the series of α_s

Disent Calculations:

2 orders in the series of α_s

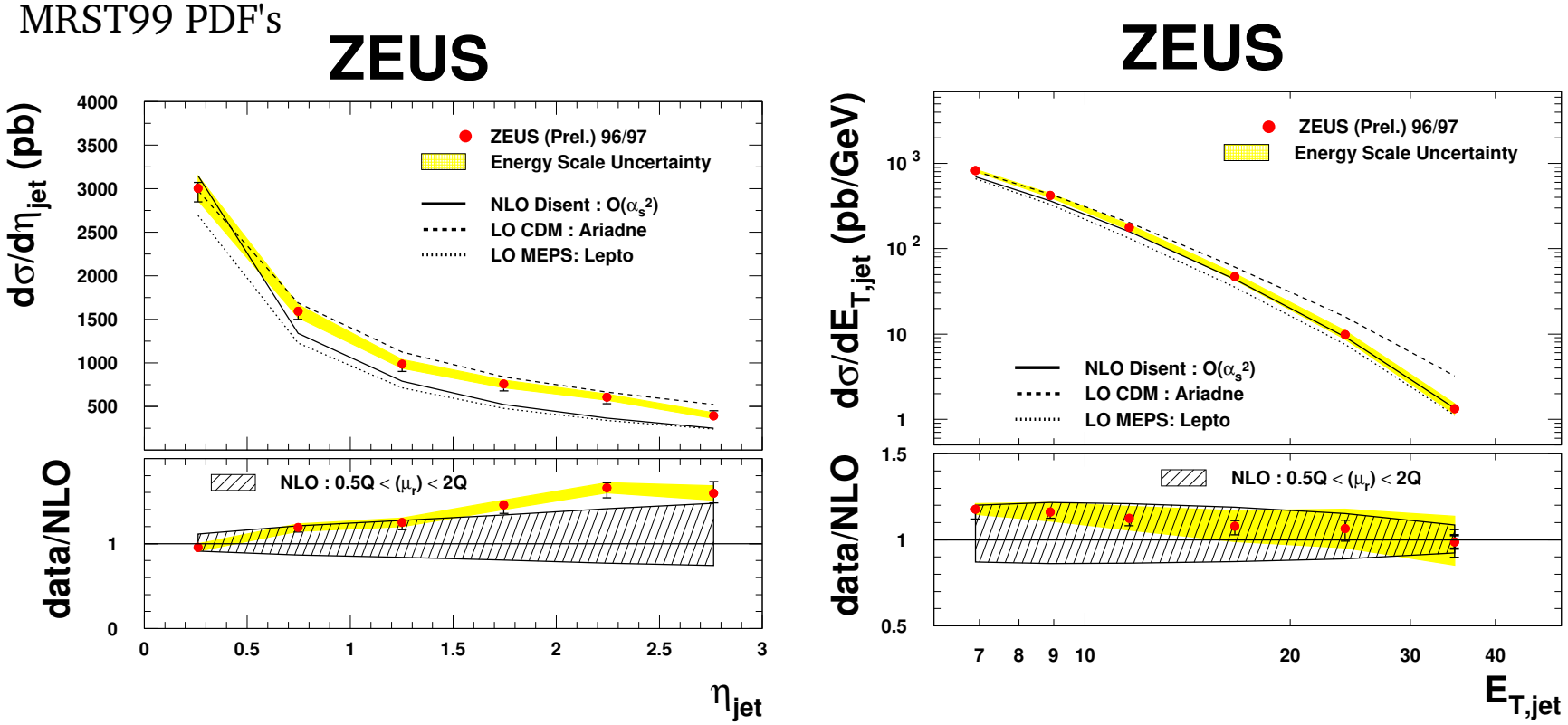
2 orders in the series of α_s


2 jets + X event topology
η = 1.1
η = 0
η = -.75
current jet
Forward jet
η = 3.0
27.5 GeV e+
η = -3.0
820 GeV p
HAC2
HAC1
FORWARD TRACKING
HAC1
CENTRAL TRACKING
SOLENOID
FCAL EMC
BCAL EMC
HAC2 HAC1
RCAL EMC
1.5 m
3.3 m
.9 m
hadronic angle
γh > 90°

Measurement of $d\sigma/d\eta_{jet}$, $d\sigma/dE_{T,jet}$ for inclusive jets with $\cos\gamma_h < 0$

DISENT implementation of NLO calculation
LO = $O(\alpha_s^1)$; NLO = $O(\alpha_s^2)$
MRST99 PDF's

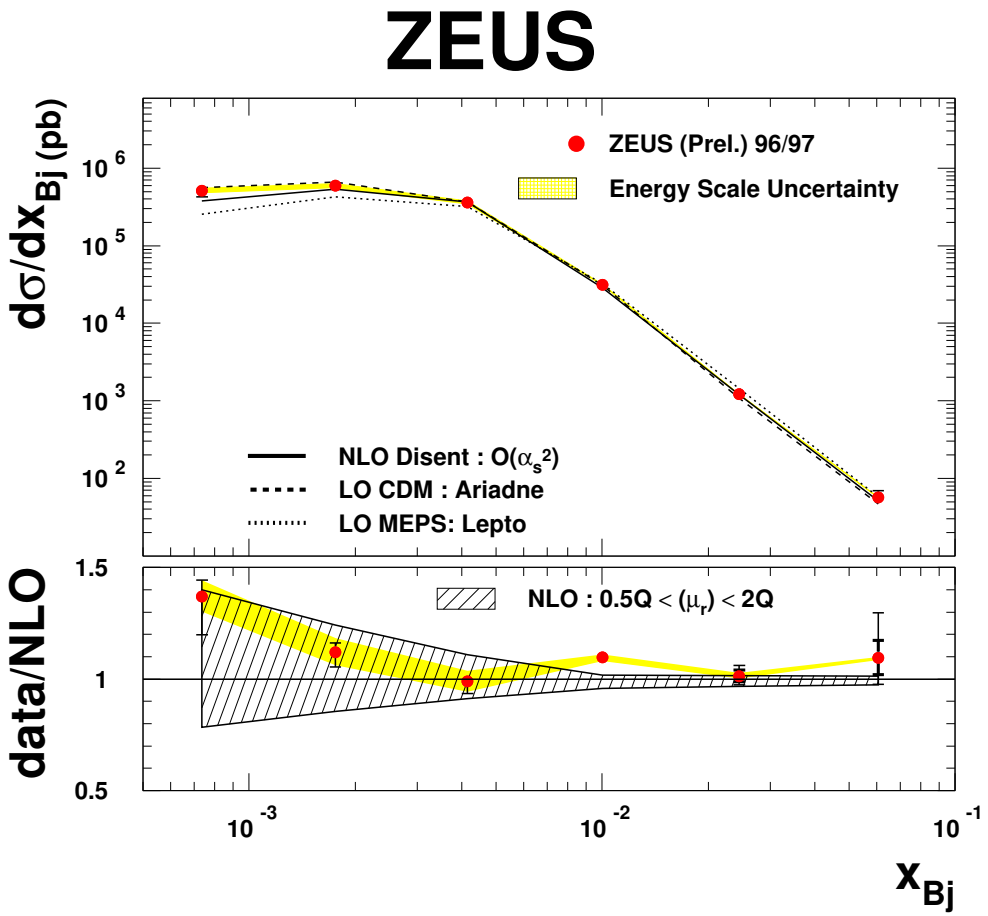
"Dijet" Phase Space

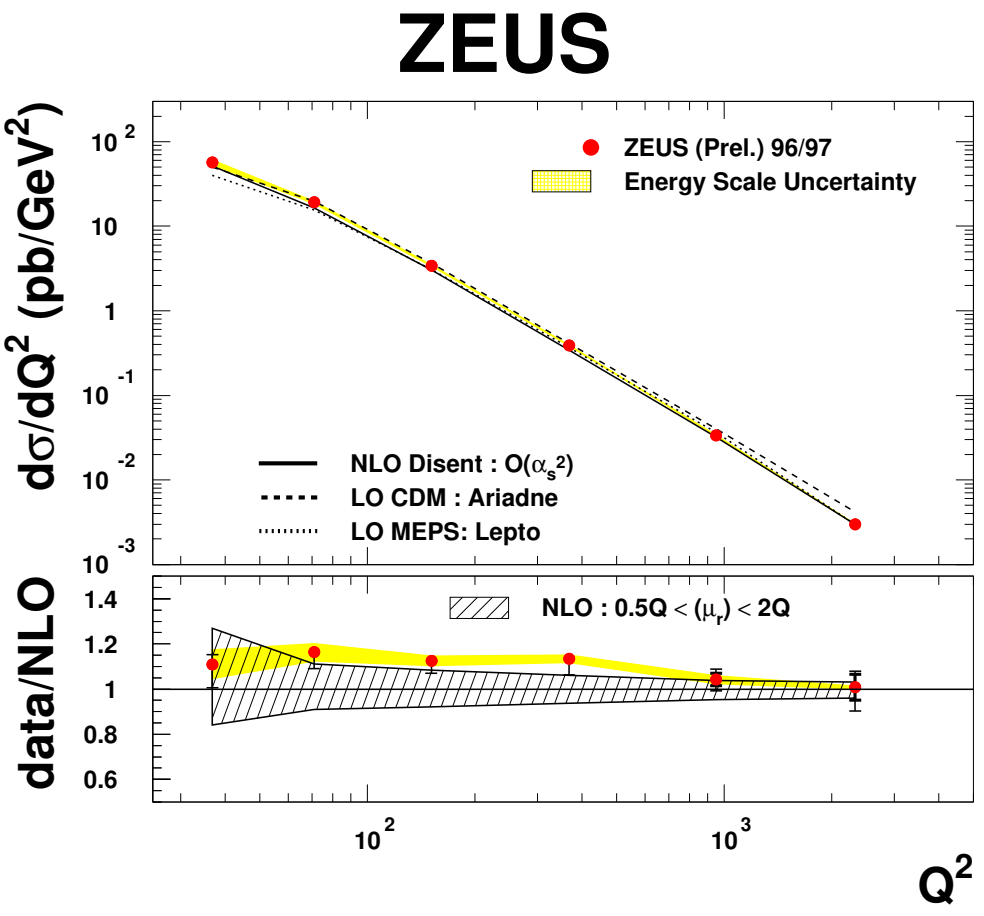


NLO agrees with data within
larger renormalization scale uncertainty

Measurement of $d\sigma/dx_{Bj}$, $d\sigma/dQ^2$ with $\cos\gamma_h < 0$

" Dijet" Phase Space





NLO agrees with data

Large renormalization scale dependence => higher orders contribute!

Prescription of the QCD dynamics at small x

- Colour Dipole Model (CDM) as implemented in ARIADNE:
  - ✓ gluon radiation comes from the dipole formed between the struck quark and the remnant and subsequently from the dipoles formed by the radiated gluons
  - ✓ random walk in k_t BFKL-like

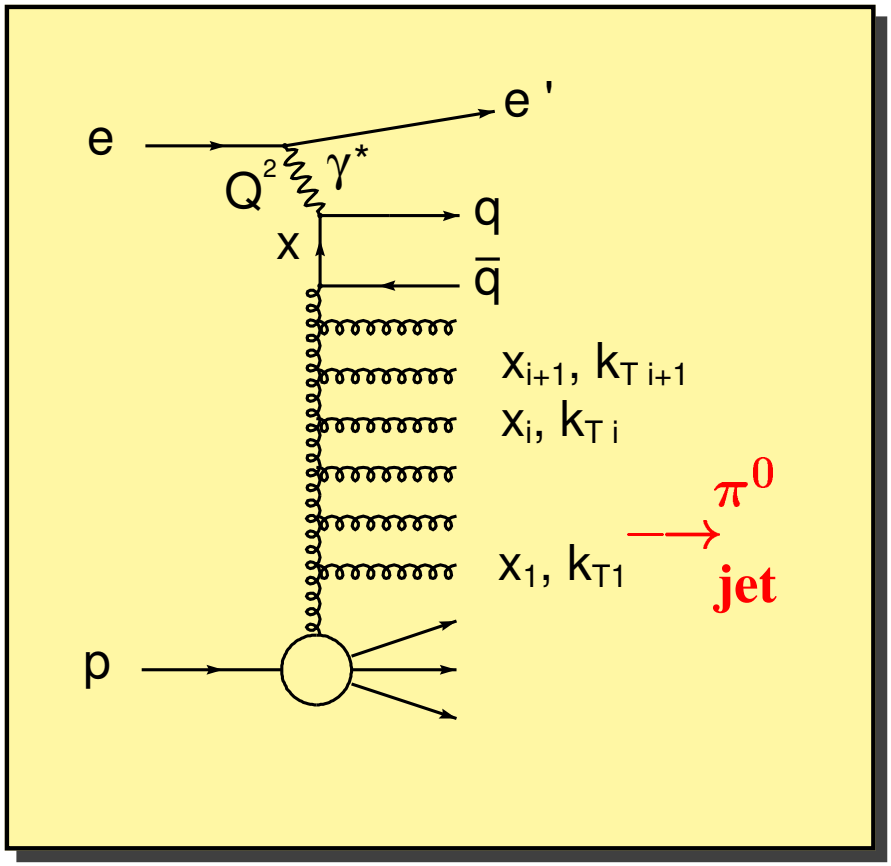
- Modified LO BFKL calculation (Kwiecinski, Martin, Outhwaite hep-ph/9903439)
  - ✓ inclusion of a kinematical "consistency constraint" on the emitted gluons
  - ✓ dominant part of all higher order effects included
  - ✓ normalization very sensitive to infrared cut-off and scale of α_S

- for π^0 analysis:

$$\sigma(\pi^0) = \sigma(jet) \times (\text{ convolution with FF })$$

  - ✓ fragmentation functions of Kniehl,Kramer and Pőtter (2000)
  - ✓ Mod. LO BFKL calculations tuned to H1 1997 forward jet data

Parton dynamics at small x : forward jets and forward π^0



Mueller - Navelet jets in DIS :
jet/π^0 in p - direction
(forward region in LAB) with

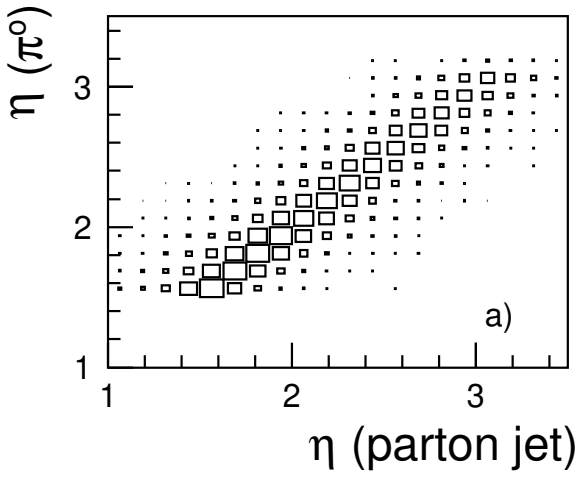
$\boldsymbol{p^2_{t\ jet/\pi^0} \approx Q^2}$,
$\boldsymbol{x_{jet/\pi^0}}$ large
but
small $\boldsymbol{x_{bj}}$

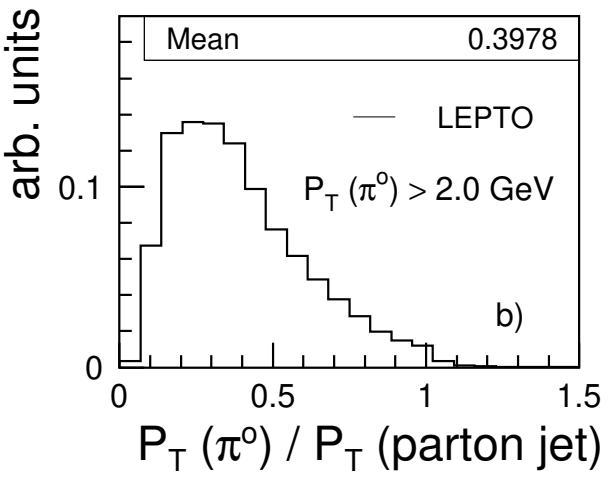
suppress DGLAP($\boldsymbol{Q^2}$) evolution

allow evolution in $\boldsymbol{x}$ (BFKL)

Forward jet/particle production in DIS

high p_t forward jet/particle sensitive to underlying parton dynamics

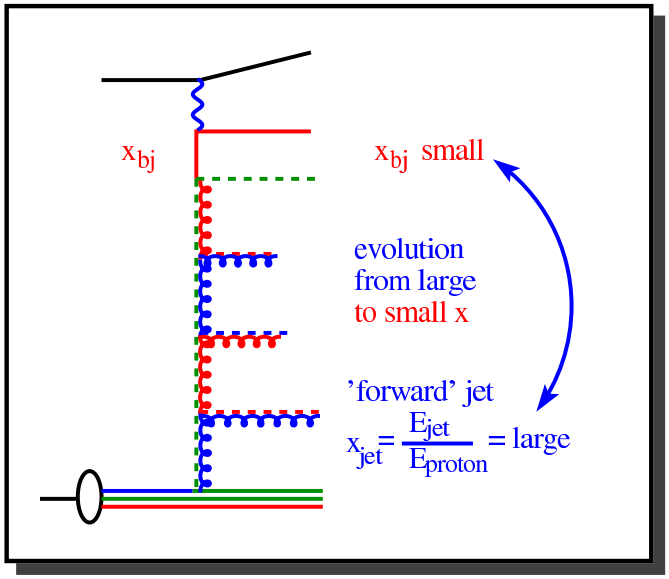




	forward jet mesurements
+	better parton correlation
+	higher rates
−	ambiguities of jet algorithm
−	exp. difficult in very forward (p) region

	forward particle measurement
−	fragmentation effects more significant
−	smaller rate
+	identification possible in more forward region

Selection of DIS forward jets and π^0



similar event selection for forward jets and π^0

DIS kinematics from the scattered electron

forward jets

$5 < Q^2 < 75$ **GeV**^{2}

$0.1 < y < 0.7$

$7 < \theta_{jet} < 20^\circ$

$p_{t\ jet} > 3.5(5.0)$ **GeV (LAB)**

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

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

inclusive k_t algorithm

Breit frame

forward π^0 detection

$2 < Q^2 < 70$ **GeV**^{2}

$0.1 < y < 0.6$

$5 < \theta_{\pi^0} < 25^\circ$

$p_{\pi^0} > 2.5(3.5)$ **GeV (hCMS)**

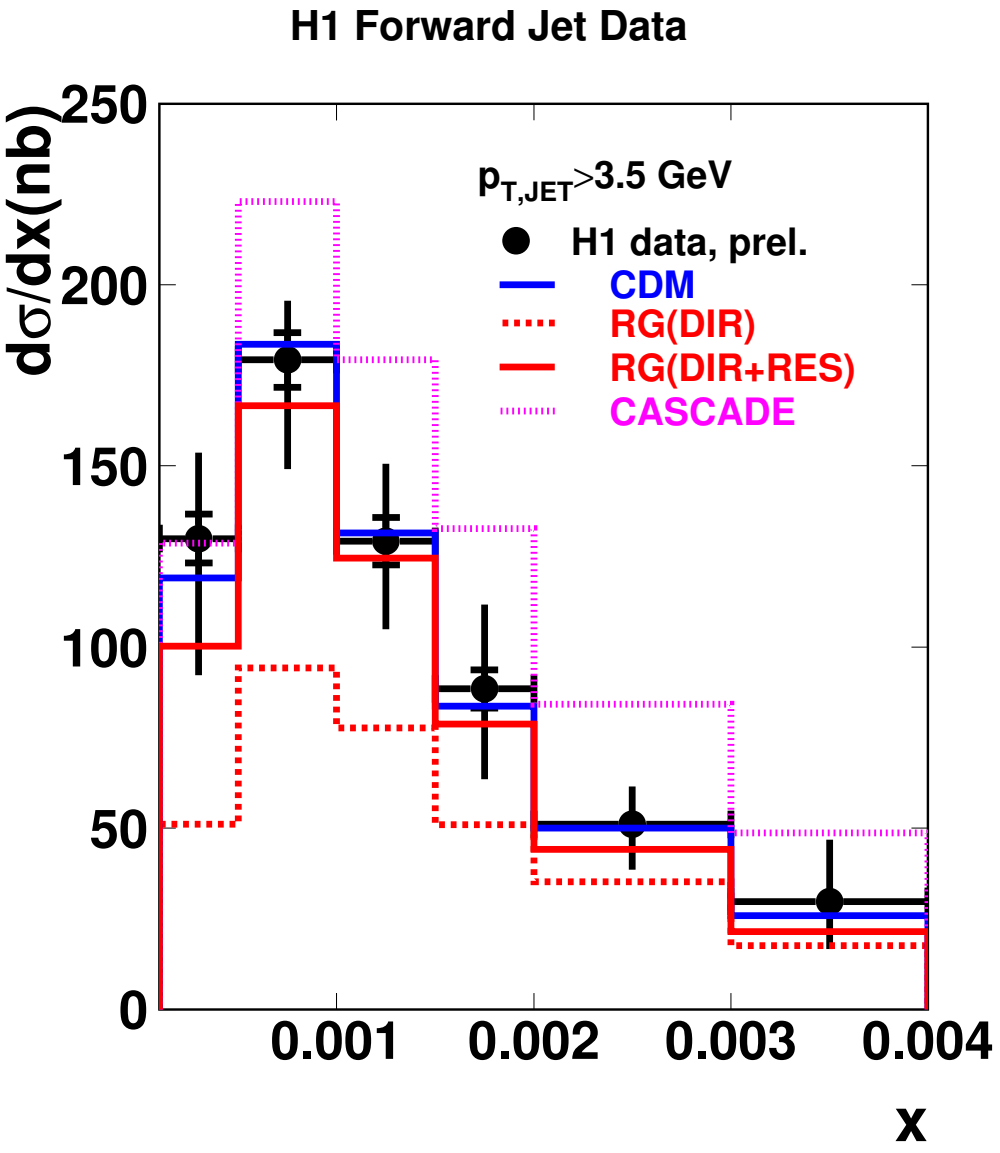
$x_{\pi^0} = E_{\pi^0}/E_p > 0.01$

$\rightarrow E_{\pi^0} > 8.2GeV$

$\pi^0 \rightarrow 2\gamma$ **reconstructed**

as one em cluster in H1 calo

Forward jets : $d\sigma/dx$



CDM :

very good description of data

DGLAP RG(DIR)

well below data

DGLAP RG(DIR+RES)

addition of resolved γ^* $\longrightarrow$ improvement

CCFM (CASCADE) :

above the data $\longrightarrow$ improve

Hannes Jung's talk at DIS2003

Forward jets: $d\sigma/dx$

(published '94 H1 data) cone jet algorithm ↘

predictions too low

orig. CCFM

new fits of unintegrated gluon density,
new treat. of soft region →

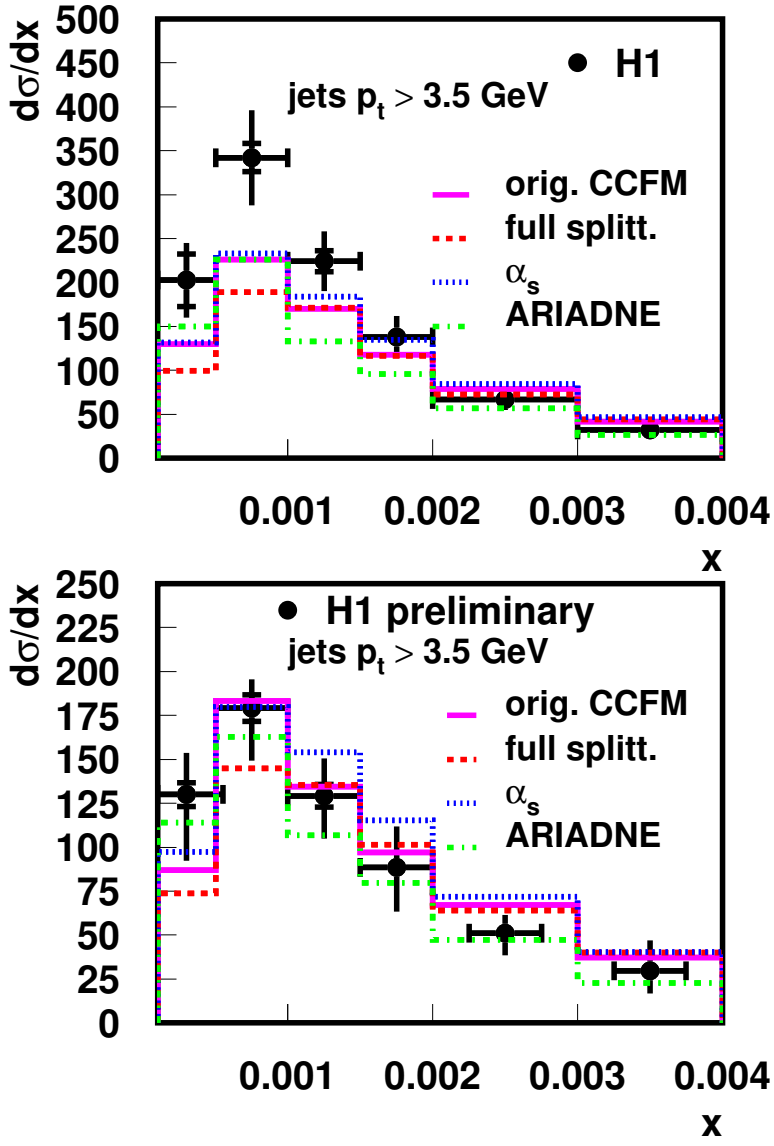
smaller x-sect. for forward jets

(prel. '97 H1 data) incl. kt algorithm ↘

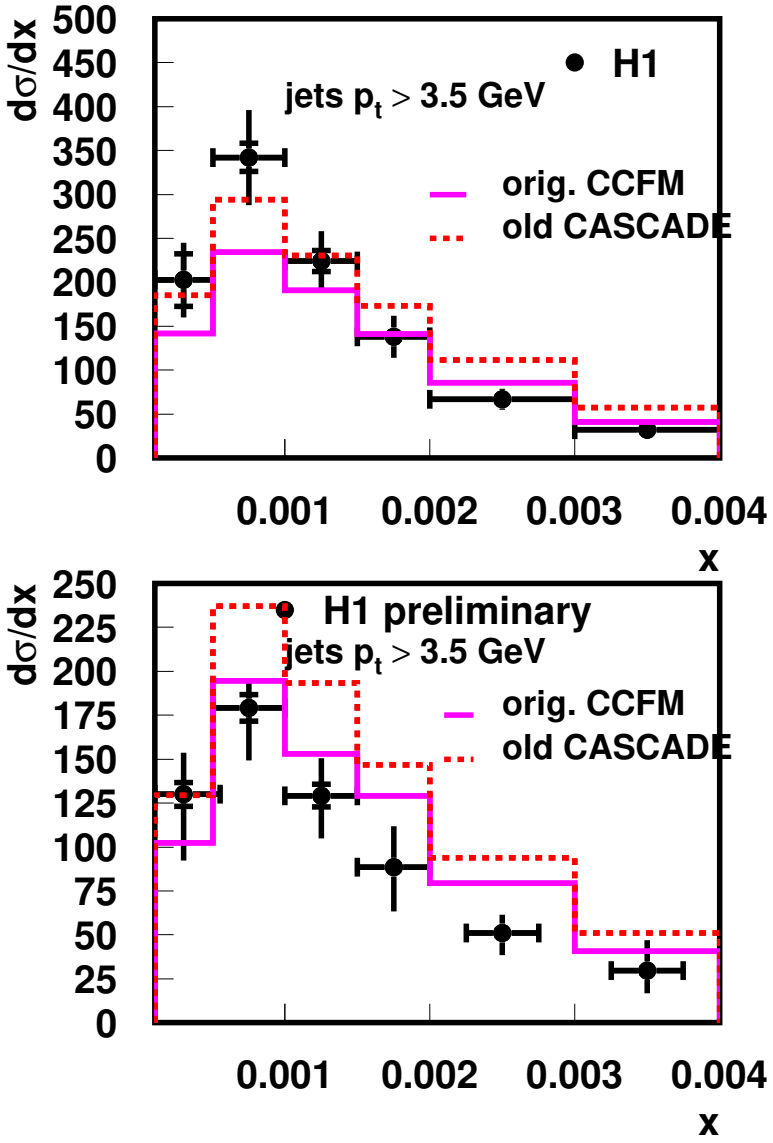
o.k.

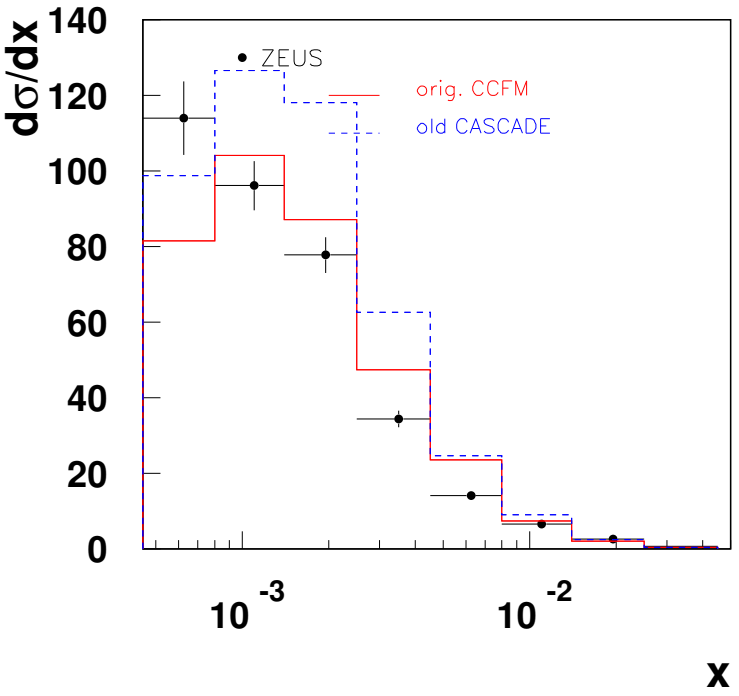
- agrees better with new data
- similar to ARIADNE

  new → full splitting function
  new → change of scale in α_s



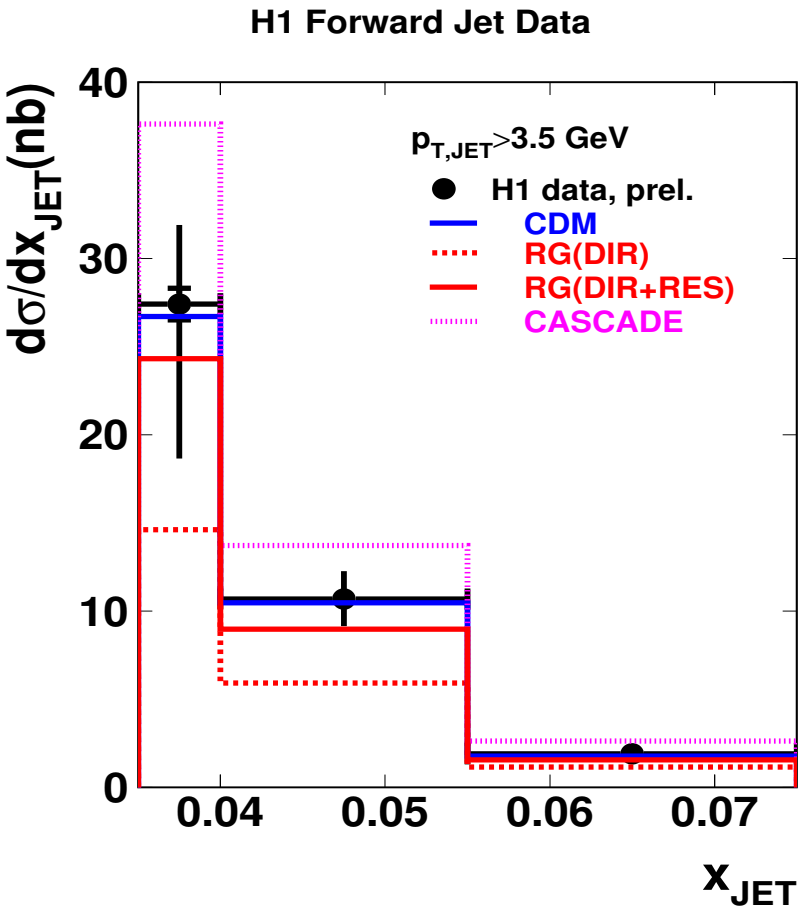
H1/ZEUS Forward jets: new/old CASCADE

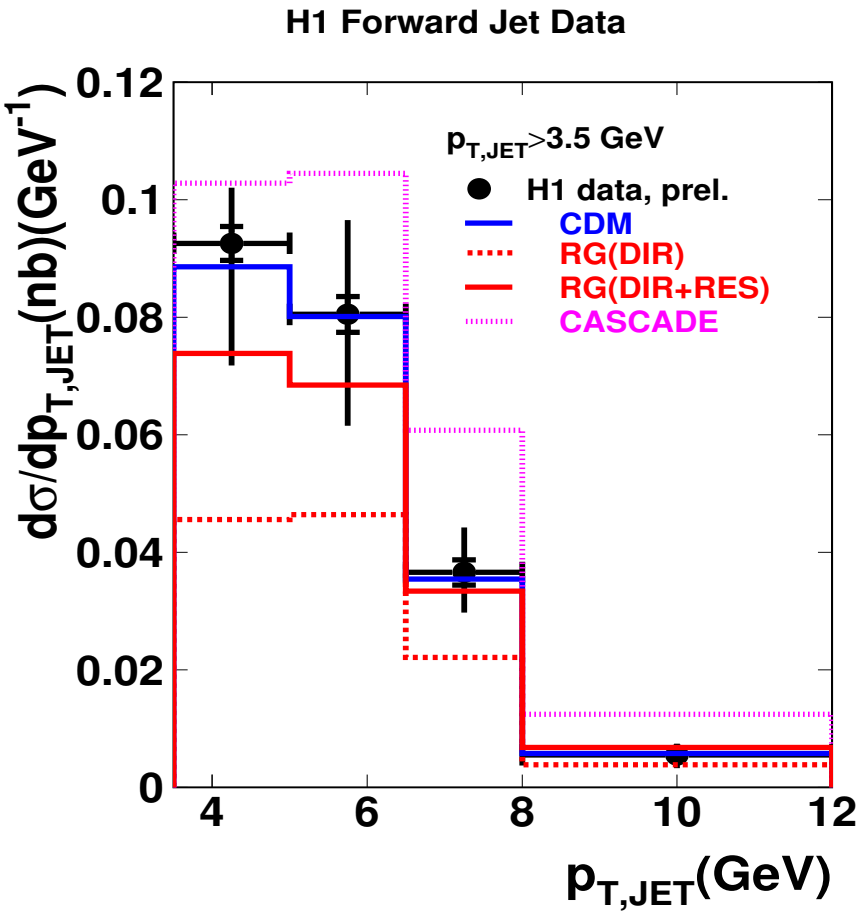




better agreement with ZEUS data

Forward jets: $d\sigma/dp_t$ and $d\sigma/dx_{jet}$





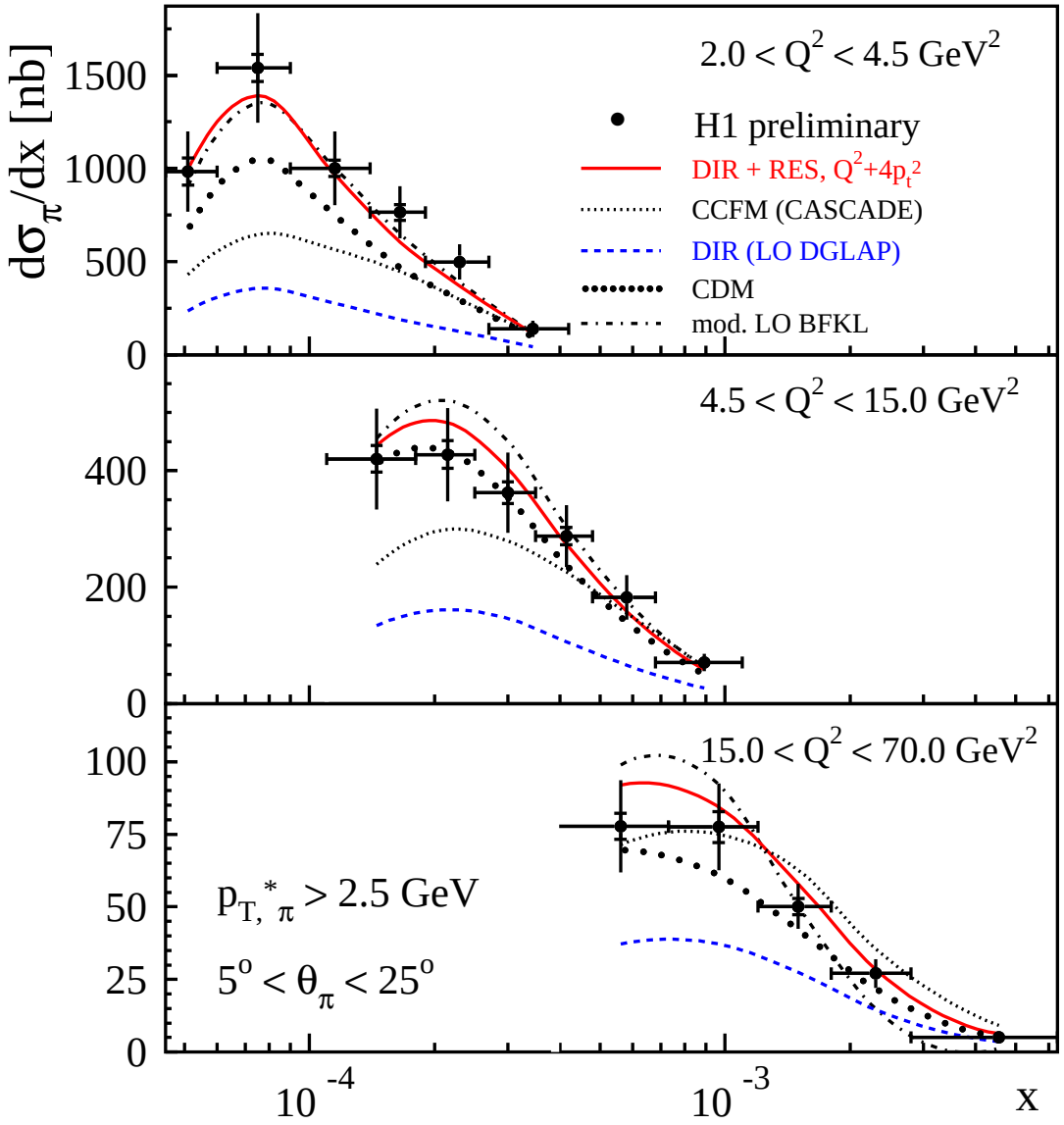
patterns of agreement/disagreement similar as for $d\sigma/dx$

CDM and DGLAP(RG(DIR+RES)) including resolved γ^* o.k.

DGLAP(RG(DIR)) below the data

CCFM(CASCADE) overestimates the data

Forward π^0 : $d\sigma/dx$, $p^*_{t\,\pi} > 2.5\ GeV$



DGLAP : below data

resolved γ^* component improves the description

$\rightarrow \mu^2 = Q^2 + 4p_T^2$

CDM:

reasonable description of data

CCFM(CASCADE):

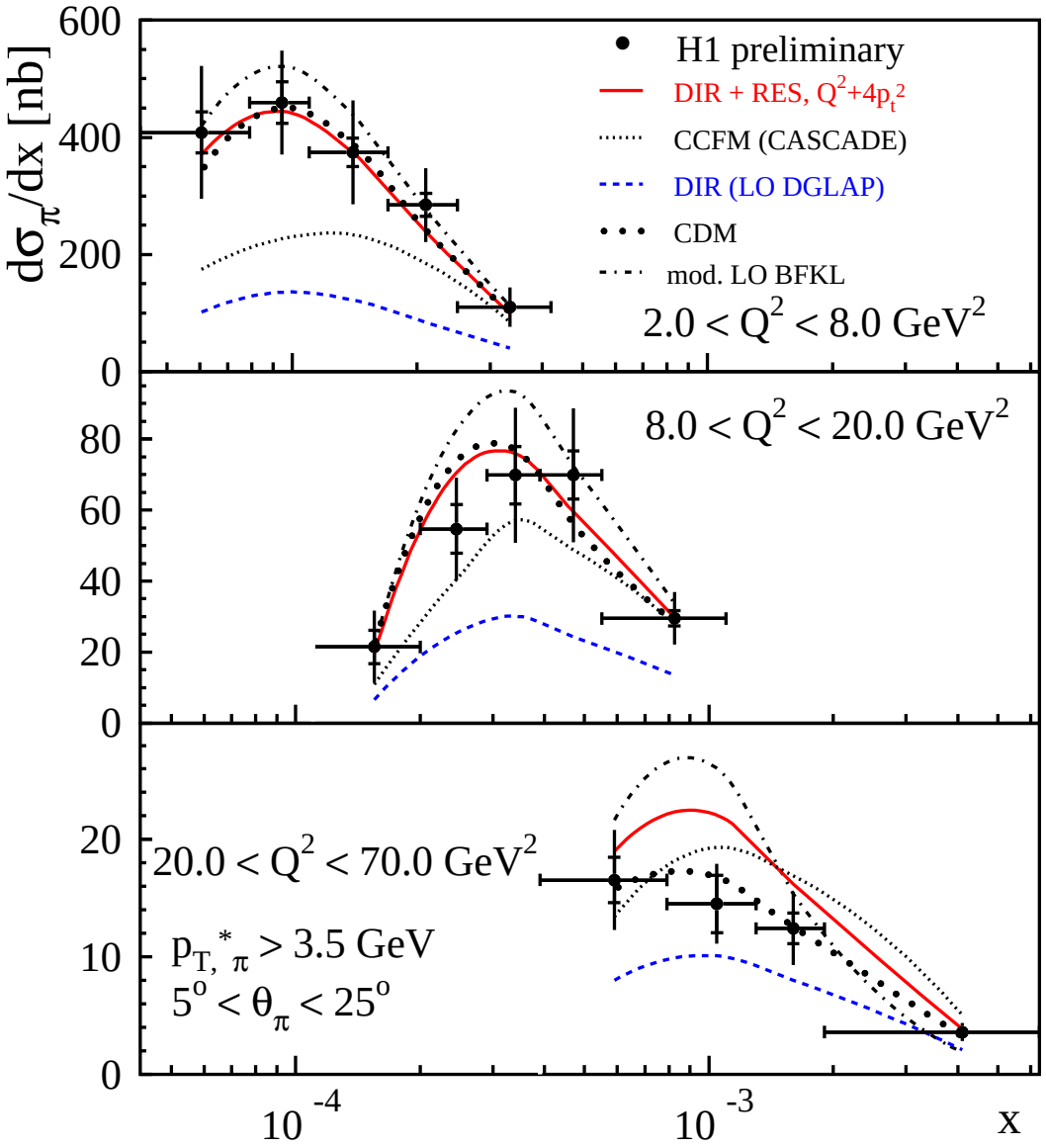
below the data at low x and Q^2

$\rightarrow$ the region not covered by forward jets ($x < 0.001$)

mod. LO BFKL

reasonable description of data

Forward π^0 : $d\sigma/dx$, $p^*_{t\,\pi} > 3.5\ GeV$



DGLAP (DIR)

below the data everywhere

DGLAP (DIR + RES $\gamma^\star$)

o.k.

the best description of the data by CDM

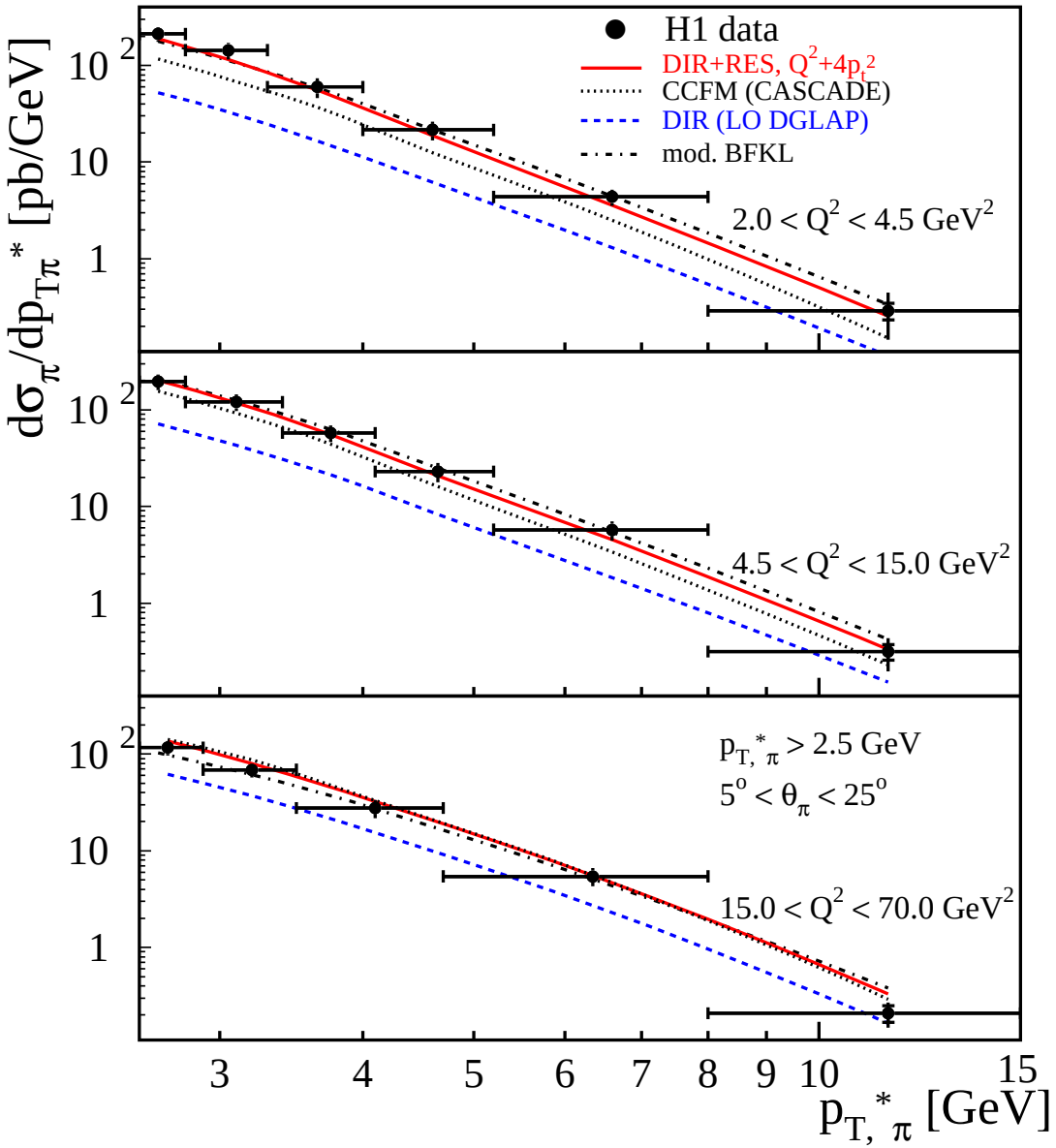
CCFM (CASCADE) :

low at small x and Q^2,

mod. LO BFKL

too high at higher Q^2

Forward π^0 : $d\sigma/p_T$ in 3 ranges of Q^2



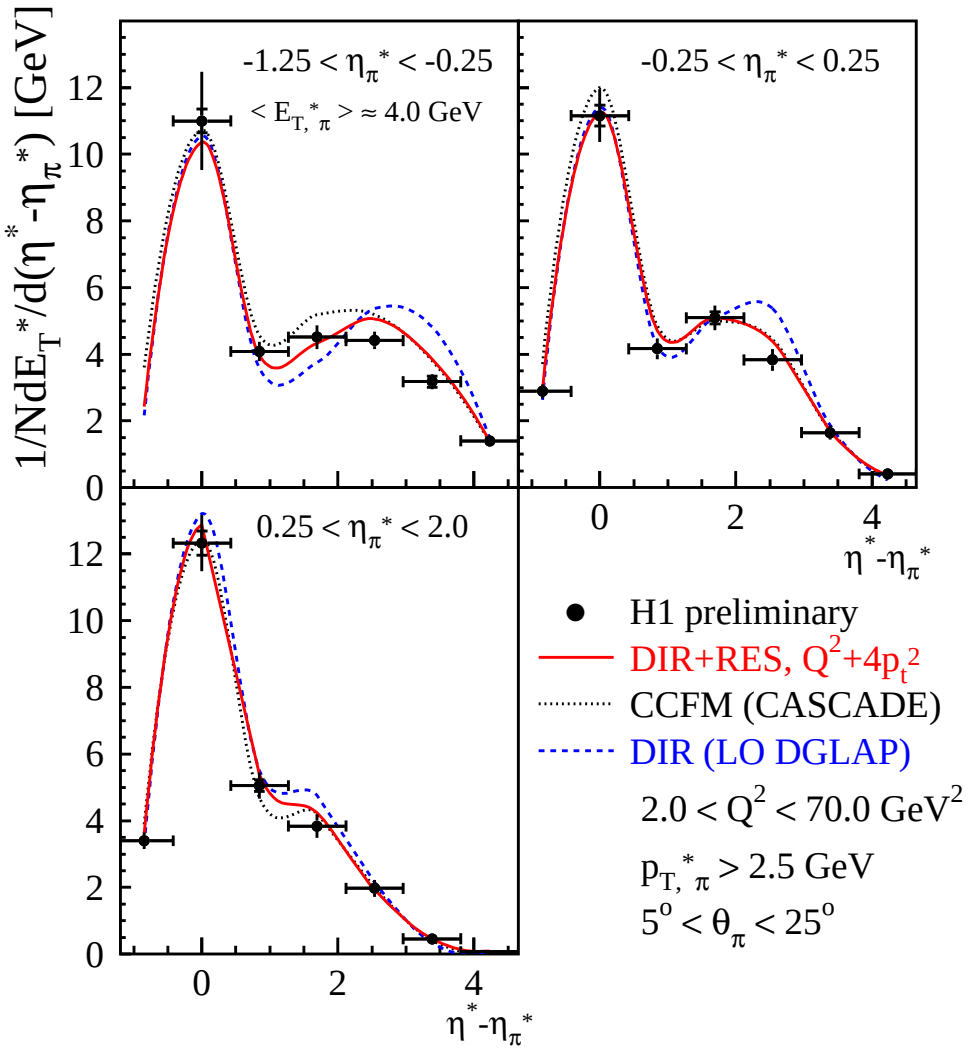
$p^{\star}_{T\pi}$: in hadronic CMS

p_T dependence well described everywhere by MC models only

CDM (not shown) gives harder spectrum

E_T flow around π^0 in 3 ranges of $\eta^\star_\pi$

π^0 close to proton $\searrow$ γ^* p $\longrightarrow$ $\longleftarrow$



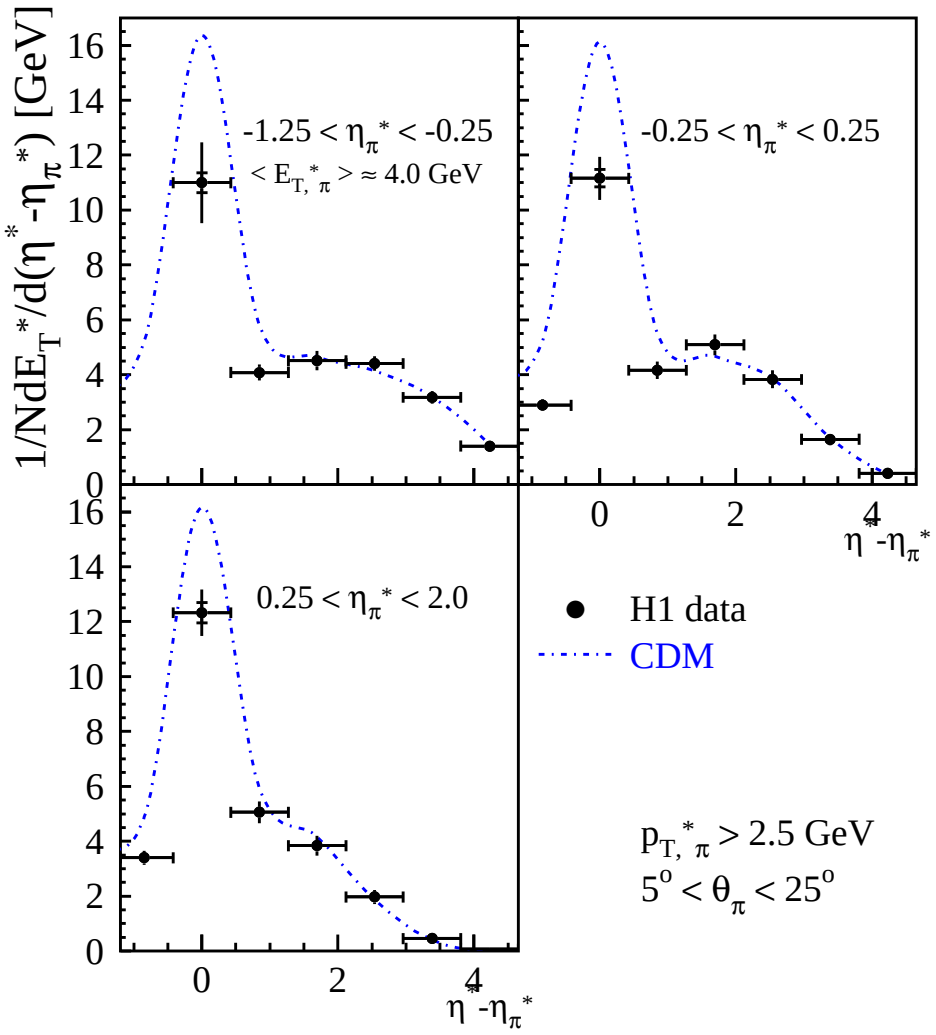
$\boldsymbol{E_T}$ flow as a function of distance, $\boldsymbol{\eta^* - \eta^*_\pi}$ to $\boldsymbol{\pi^0}$ in 3 regions of $\boldsymbol{\eta^*_\pi}$

contribution from $\boldsymbol{E_T}$ of $\boldsymbol{\pi^0}$ included

$\boldsymbol{E_T}$ flow around $\boldsymbol{\pi^0}$ $\rightarrow$ transverse momentum compensation along the ladder

E_T flow around π^0 in 3 ranges of η^*_π

π^0 close to proton ↘ γ^* p ⟶ ⟵



η^*_π rapidity in had CMS

CDM :

too hard transverse momentum spectrum of the forward π^0

⟶ too much E_T in the vicinity of π^0

Conclusions

Inclusive Jet Measurements

- NLO QCD fails to describe the inclusive jet rate in central and forward (proton direction) regions
- huge NLO corrections

➜ discrepancy between data and theory is localized in low x_{Bj} region

Measurements in the limited phase space: cos $\gamma_h < 0$
to suppress the contribution from the QPM process in the forward region;

- NLO QCD calculations consistent with the data within sizeable theoretical uncertainties
- a much better agreement between data and the calculations at low x_{Bj} is obtained

➜ **Large renormalization scale uncertainty swamps any possible signal for BFKL in this region**

Conclusions *cont.*

Forward Jet/π^0 Measurements

- DGLAP (RAPGAP DIR) with direct γ^* interactions below the data
- DGLAP (RAPGAP DIR+RES) with direct + resolved γ^* interactions describes the forward jet/π^0 data but
  ➜ different renormalization and factorization scale
- CDM (ARIADNE) describes the cross sections very well,
  ➜ too much transverse energy around forward π^0
- CCFM (CASCADE) improvement: fwd jet $d\sigma/dx$ well described
- mod. LO BFKL tuned to H1 '97 fwd jet data describes fwd π^0 cross-sections