QCD dynamics from the forward hadrons and jets measurements

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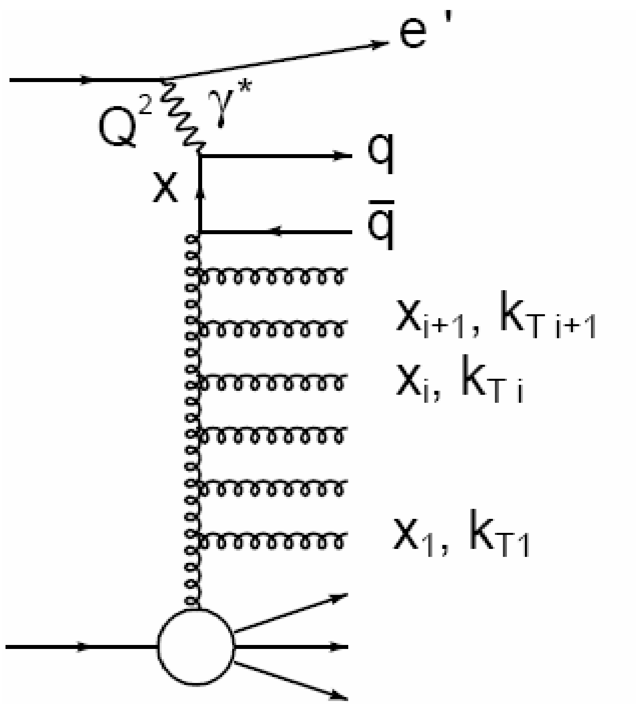
- QCD dynamics at low Bjorken-x
- Monte Carlo models with different QCD dynamics
- NLO DGLAP calculations
- Forward jet and forward π^0 measurements
- Conclusions and outlook

QCD dynamics at low Bjorken-x

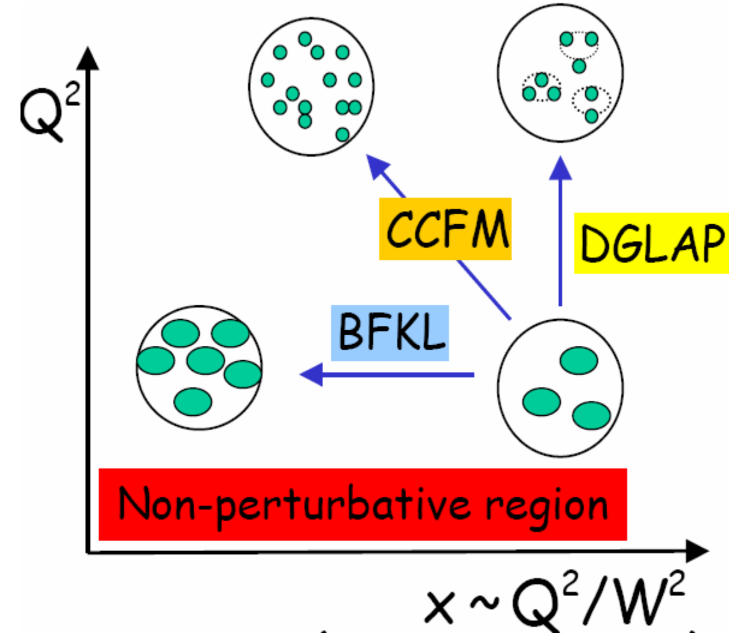
HERA : DIS at low Bjorken-x down to 10^{-5} ⟶ large γ^*p centre of mass energy

- enhanced phase space for gluon cascades exchanged between the proton and the photon (large parton densities, saturation ??)
- multiparton emissions described only in approximations



- standard DGLAP approximation, large Q^2 :
  sums terms $\sim\alpha_s \log Q^2$
  strong ordering of parton k_T
- BFKL evolution equation, low x :
  sums terms $\sim\alpha_s \log(1/x)$
  strong ordering in x_i / no ordering in k_T
- CCFM equation applicable at all x and Q^2:
  implements angular ordering resulting from QCD interference effects

- search for effects of parton dynamics beyond DGLAP
- define observables/phase space regions sensitive to low x effects
- importance of higher order terms in perturbative expansion

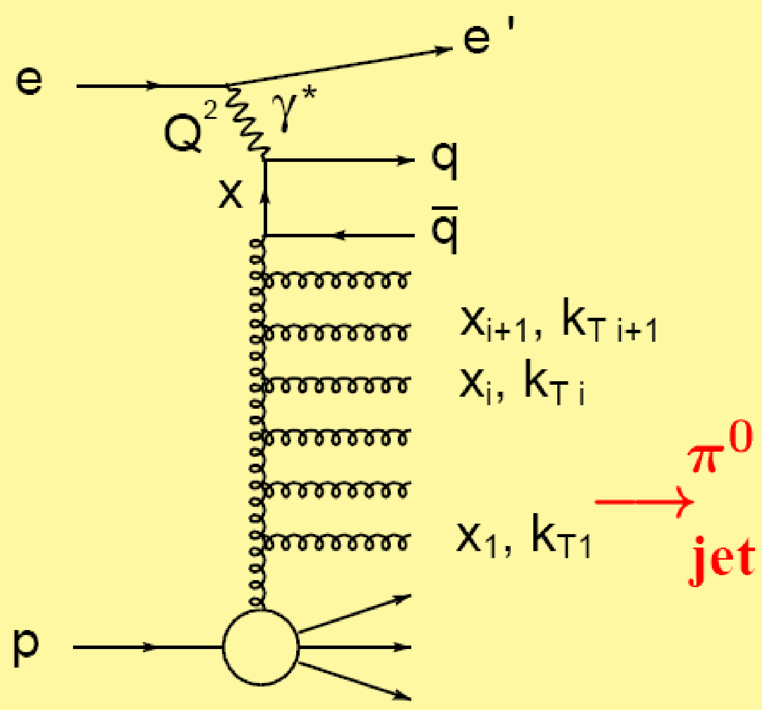


- Strong rise of $F_2(x,Q^2)$ with decreasing x – well described by NLO DGLAP over a large Q^2 range

interplay of perturbative and non-perturbative effects (input distributions)
inclusive F_2 measurement not able to discriminate between different QCD approaches

- Study of hadronic final states ⟶ reflection of the kinematic structure of gluon emissions (forward jets/particles, inclusive jets, dijets ⟶ azimuthal jet separation, multijet production, hadrons at large p_T, transverse energy flow)

QCD dynamics at low Bjorken-x



BFKL – more hard partons emitted close to the proton

Mueller-Navelet jets in DIS (1990):

high transverse momentum and high energy jets in p-remnant direction (forward region in LAB)

Suppress DGLAP evolution in Q^2 :

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

Enhance BFKL evolution in x :

$$x_{jet} >> x_B$$

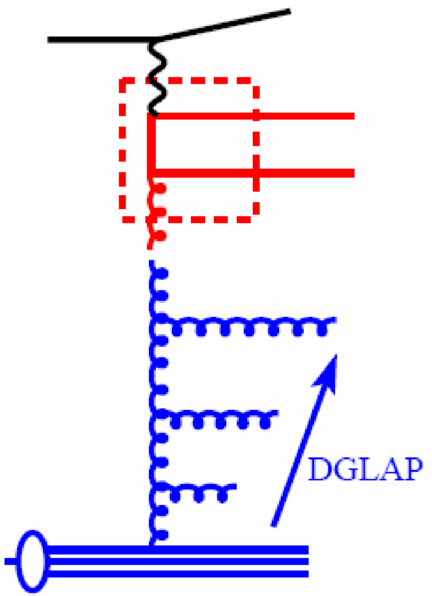
$$x_{jet} = \frac{E_{jet}}{E_p}$$

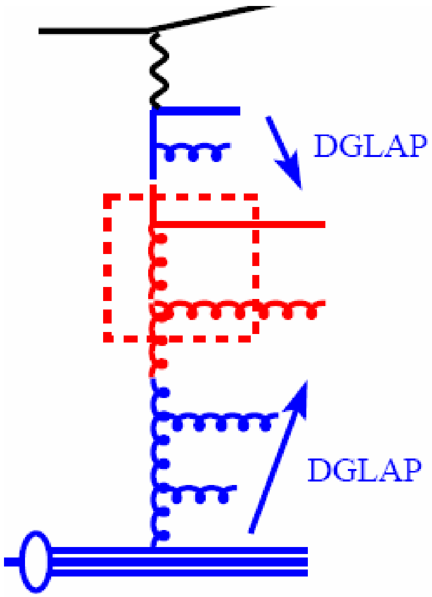
Forward jets ➡ forward particles complementary mesurements

Monte Carlo models with different QCD dynamics

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

Inclusion of resolved photon processes





important for

$E_T^2 > Q^2$

single DGLAP ladder with strong k_T ordering

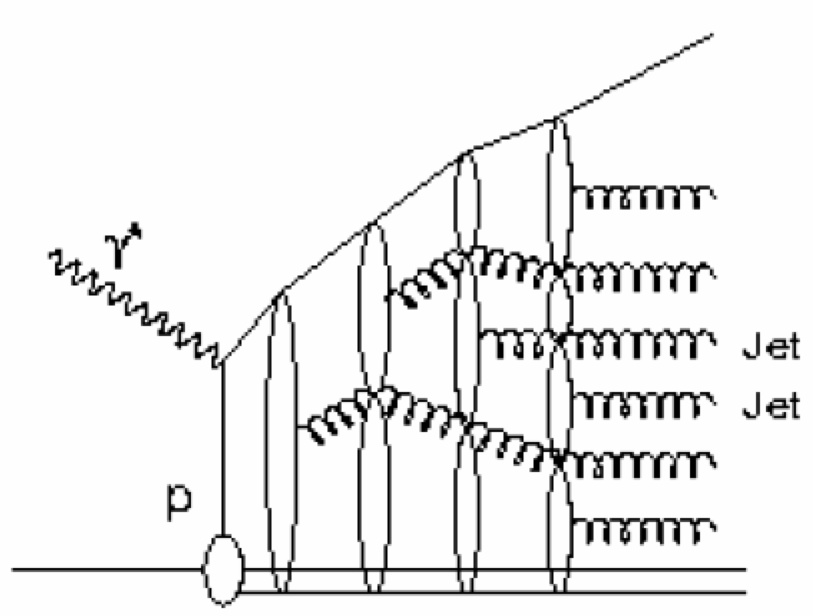
LEPTO, RAPGAP - direct

two k_T ordered DGLAP cascades initiated from the proton and the photon

RAPGAP - resolved

Monte Carlo models with different QCD dynamics

Colour Dipole Model (CDM) – implemenation in Monte Carlo ARIADNE



QCD radiation from the dipole formed by the struck q and the 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

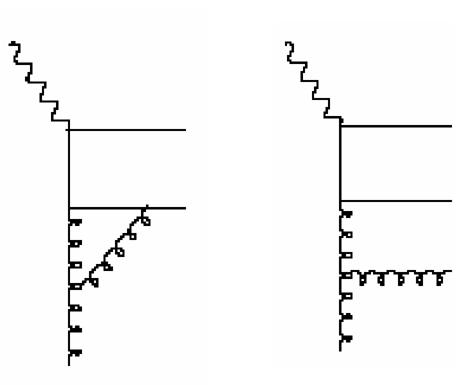
+ parton emissions based on the CCFM equation

input: unintegrated gluon densities (fitted using CCFM evolution to describe the inclusive DIS cross sections), different sets of uPDF including singular or full gluon splitting functions

NLO parton level MC programs

Forward jet cross sections – comparison with the predictions of pQCD at

LO(α_S) and NLO(α_S^2) accuracy

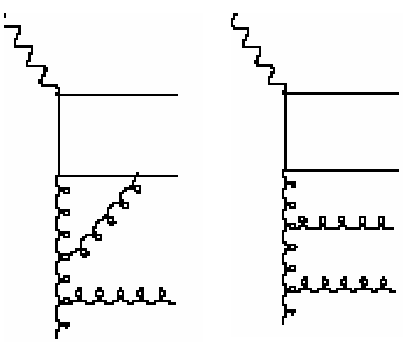


DISENT (*Catani, Seymour* , 1996-1997)

NLO(α_S^2) diagrams for a dijet configuration

JetVip (*Pötter*, 1999-2000) – includes NLO corrections to resolved photon processes (approximation of NNLO effects) but has problems with stability of NLO-res, disagrees with other MC in NLO-dir, will be modified ?

Cross section calculations for the production of ‘forward jet + 2 additional jets’



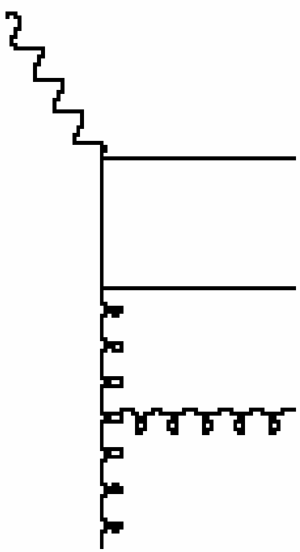
NLOJET++ (*Nagy, Trocsanyi*, 2001) – **the only NLO generator for 3-jet configuration**

NLO(α_S^3) diagrams for three –jet production

NLO calculations of high p_T hadron production

Three independent analyses :

Aurenche, Basu, Fontannaz, Godbole	hep-ph/0504008 , hep-ph/0312359
Daleo, De Florian, Sassot	hep-ph/0411212
Kniehl, Kramer, Maniatis	hep-ph/0411300



BFKL Born term

HO corrections of order α_s^2 to QCD Compton and boson gluon fusion processes

convolution with NLO parton distributions and fragmentation functions

test of the sensivity to the renormalisation, factorisation and fragmnetation scales

Aurenche et al. - also NLO corrections to the resolved photon processes (common scale twice bigger than in Daleo et al. and Kniehl et al. – NLO dir substantially smaller)

Modified LO BFKL calculation (Kwiecinski, Martin, Outhwaite hep-ph/9903439) major part of non-leading correct. included by consistency constraint

Production of forward jets and particles – experimental aspects

Studies for the last 10 years – challenge to the experiment

Region of high energy and particle densities close to the proton remnant

Jet reconstruction:

Inclusive k_T algorithm on calorimeter cells or combined track-calo cluster objects (cells + tracks $\longrightarrow$ improved resolution), in Breit frame or in LAB + phase space constraints

Data correction using LO MC models (acceptance, efficiency, hadronization, QED)

Parton level QCD calcul. corrected for hadronization effects using LO MC models

Main exp. uncertainty : hadronic energy scale (1-4% $\longrightarrow$ effect on measur.5-10%)
model dependence of detector corrections

Reconstruction of forward π^0:

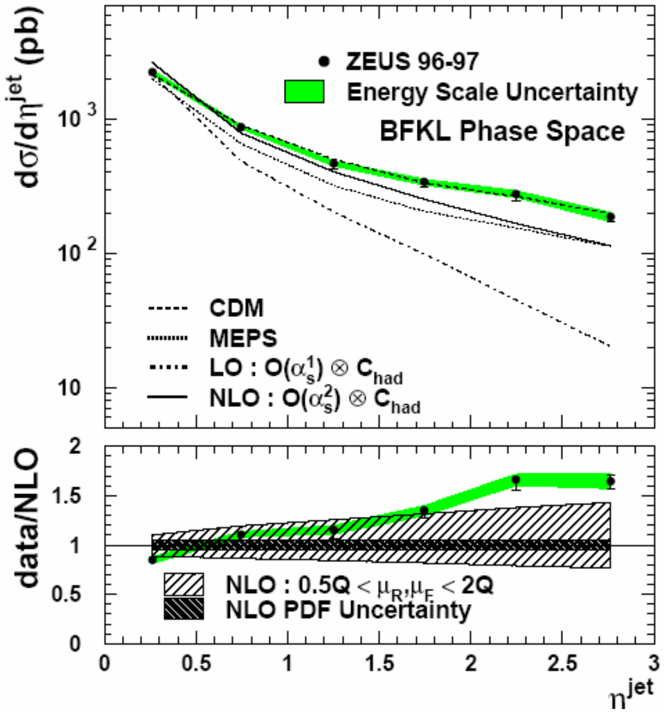
high energy $\pi^0 \longrightarrow 2\gamma$ reconstructed as one electromagnetic cluster in the H1 calorimeter

Identification possible in more forward region than for forward jets, no ambiguities of the jet algoritm

Lower rates and fragmentation effects more significant

ZEUS inclusive forward jet measurements

DESY-05-017



Data 96-97, 38 pb^{-1}

Q^2 > 25 GeV^2, y > 0.04

Jet reconstruction in LAB

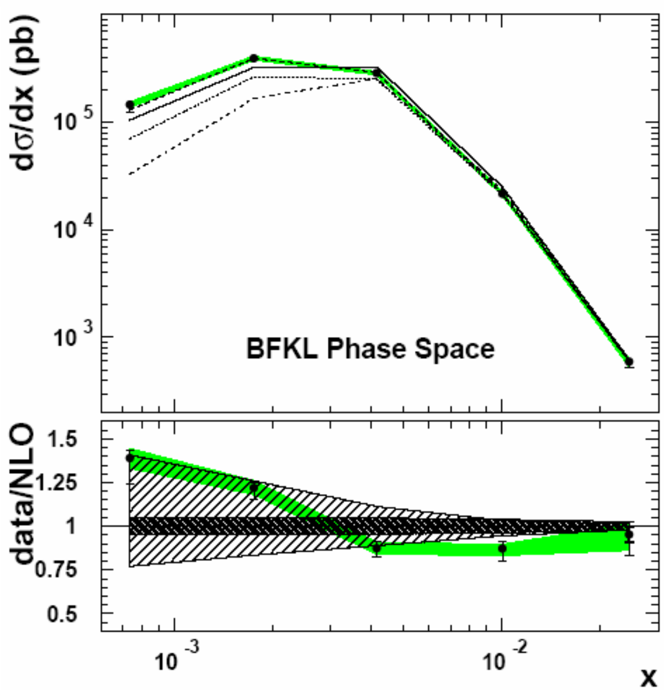
$0.5 < E_T^2/Q^2 < 2$

$0 < \eta_{jet} < 3$

$\gamma_h > 90^0$

Suppresses QPM

DISENT predictions :



NLO (α_S^2) , μ_R = Q : reasonable description except forward region (η_{jet} >1) and low x

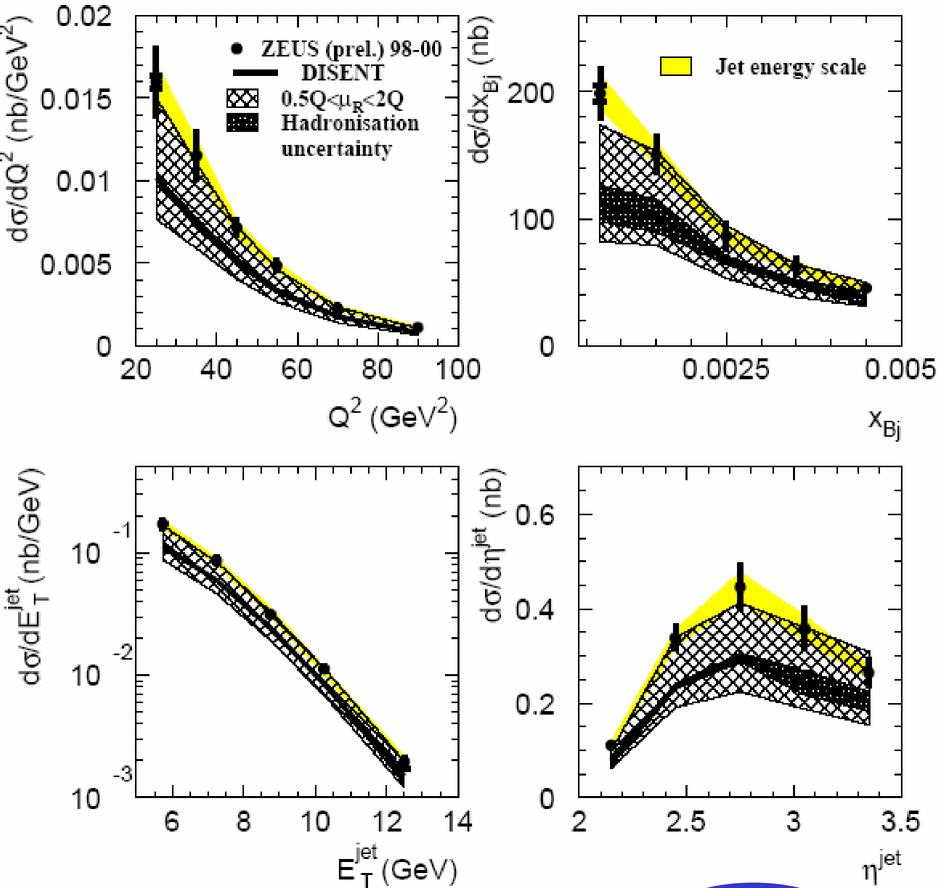
Large η, low x

large NLO corrections related with t channel g exchange (NLO/LO ~ 5 at η_{jet} ~ 3)

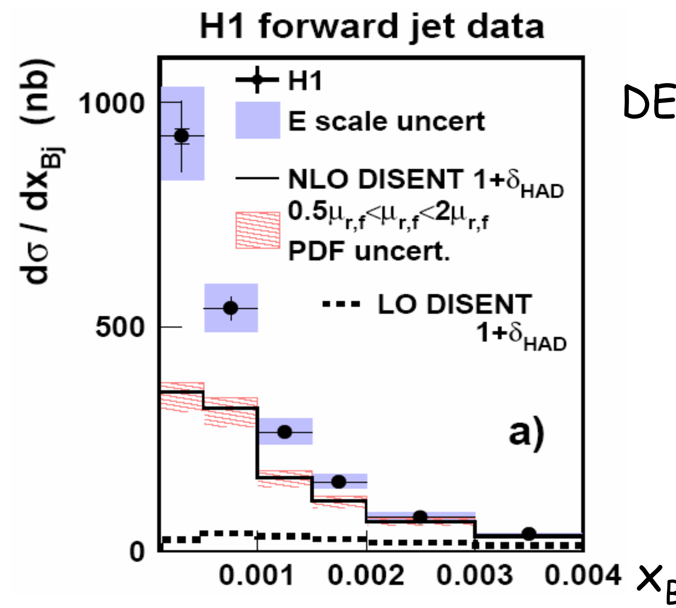
large scale variation uncertainties → higher oder terms needed

CDM good description

ZEUS – jets in very forward region



cut	H1 13.7 pb^{-1}	ZEUS 82 pb^{-1}
Q^2 [GeV^2]	5 - 85	20 - 100
x	0.0001 - 0.004	0.0004 - 0.005
E_T^2 / Q^2	0.5 - 5	0.5 - 2
η_{jet}	1.7 - 2.8	2 - 3.5



DESY -05-135

ZEUS DISENT NLO(α_S^2) $\mu_R^2 = Q^2$

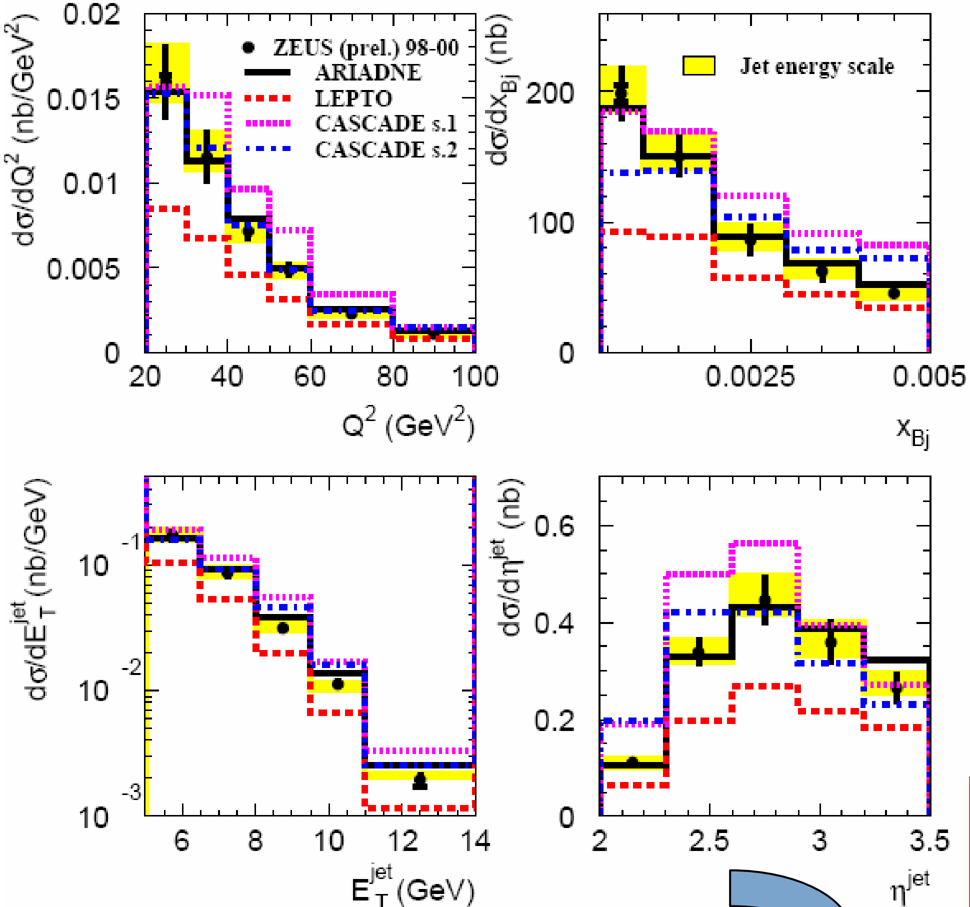
H1 DISENT NLO(α_S^2) $\mu_R^2 = \langle p^2_{T,dijets} \rangle$

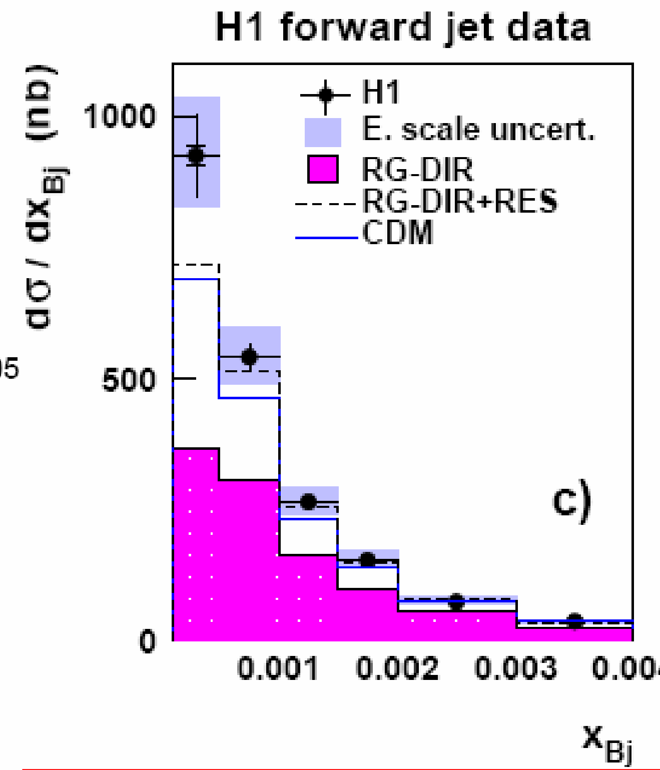
NLO predictions below the data but within theoretical uncertainties

Low x ⟶ NLO prediction order of magnitude larger than LO
below the data at low x (factor 2)

Large renormalisation scale uncertainty

Comparison of H1 and ZEUS forward jets with Monte Carlo models





DGLAP- direct below the data

CDM (k_T not ordered) good

CCFM fails to describe shapes

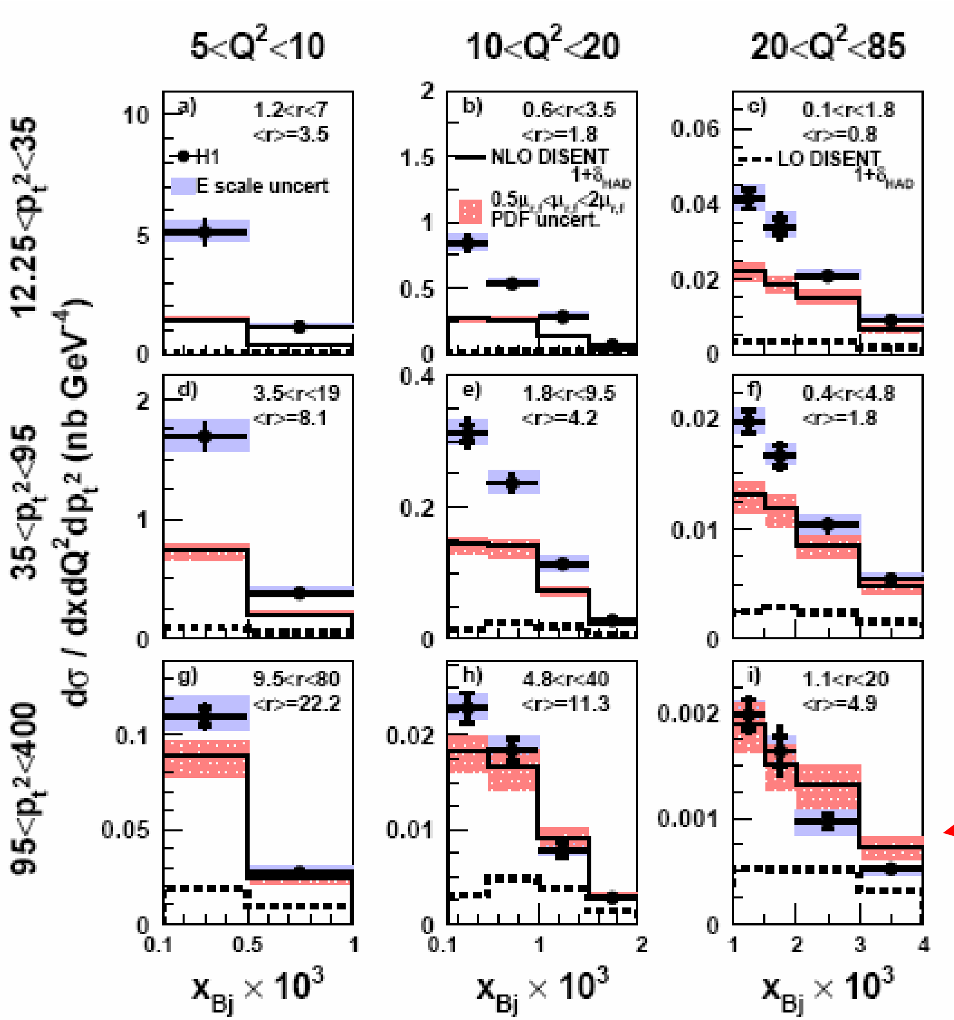
(parametr. of uPDF, missing g-> qq terms ?)

DGLAP -direct below the data
resolved photon processes better
CDM similar to DGLAP(dir+res)

but

CDM and DGLAP(dir + res) below data at low x

H1 forward jets: triple differential cross section



Cross section as a function of x_B in bins of Q^2 and p_T^2 of the forward jet

No p_T^2/Q^2 cut

DISENT NLO(α_S^2) :

NLO dijet calculations closer to the data than LO predictions

NLO agrees better at large x_B, Q^2 and p_T^2

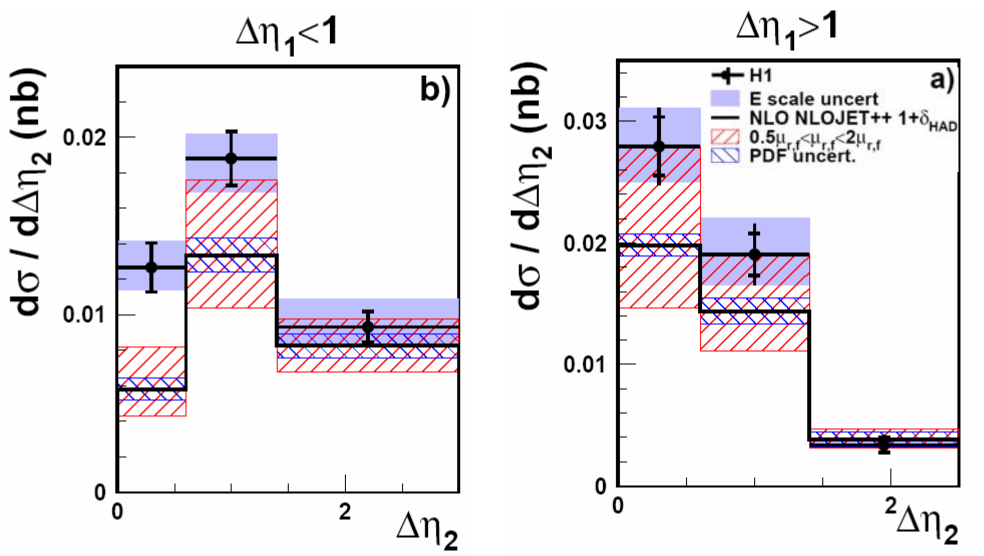
$$\mu_r^2 = < p_{t,dijet}^2 > \qquad \mu_f^2 = < p_{t,fwdjet}^2 >$$

H1 : dijet + forward jet

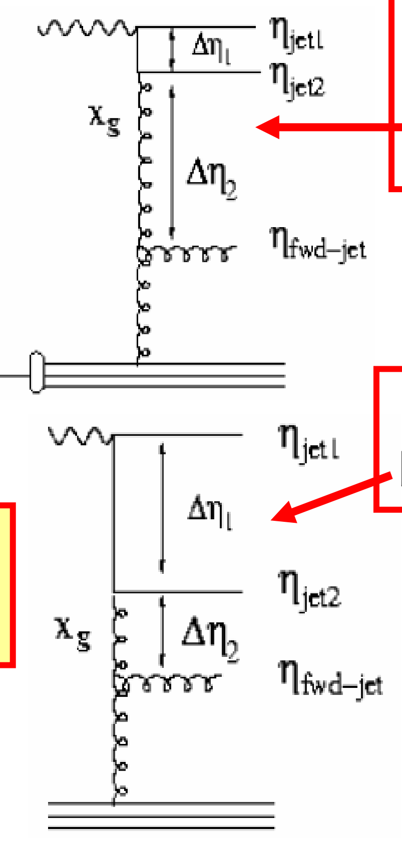
Comparison with NLOJET ++ (NLO-3jet)

Forward jet + 2 hardest jets
all jets with $p_T > 6$ GeV

$\eta_e < \eta_{jet1} < \eta_{jet2} < \eta_{fwdjet}$



Choice of $\Delta\eta_1$ and $\Delta\eta_2$ selects different radiation pattern:



Large PS for radiation between forw. jet and dijet

Large $\Delta\eta_2$

Large PS for radiation between jet_1 and jet_2

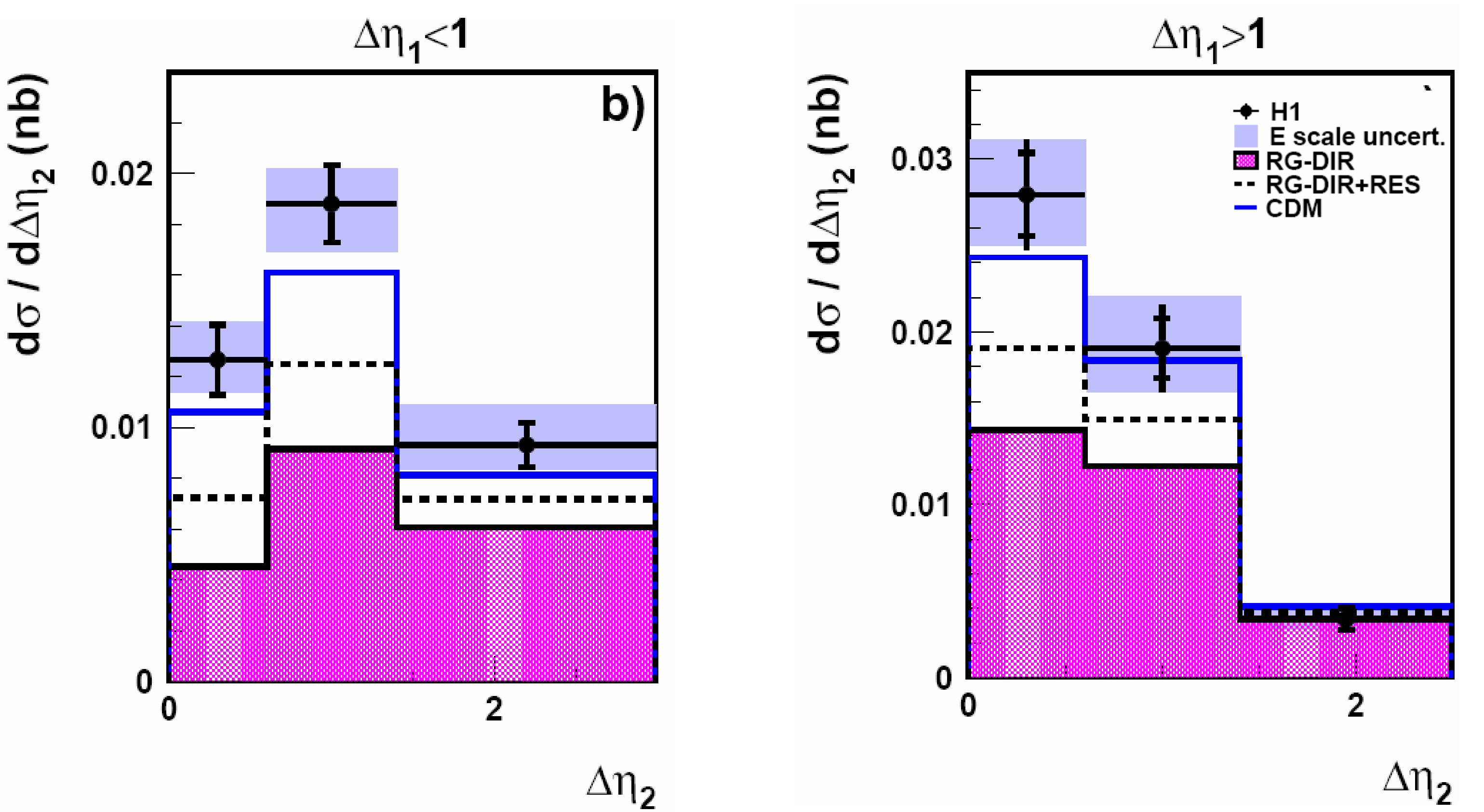
Large $\Delta\eta_1$

good description by NLO (α_s^3)
topology forw. jet + central dijet

small $\Delta\eta_1$ and $\Delta\eta_2$ → 3 forward jets → configuration supressed in NLO 3-jet

H1 : dijet + forward jet

Forward jet + 2 hardest jets
all jets with $p_T > 6$ GeV



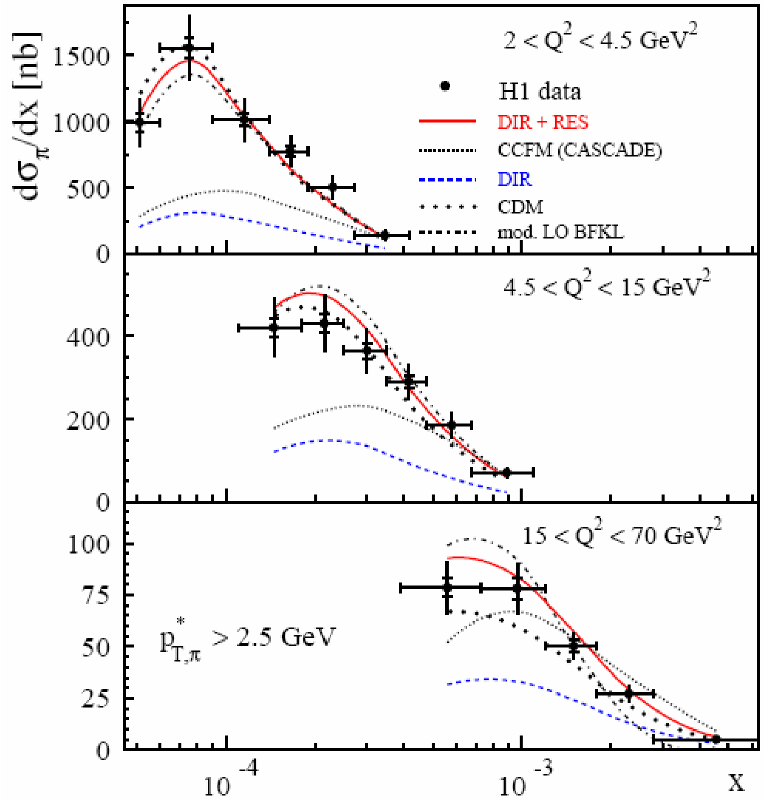
DGLAP (dir + res) fails

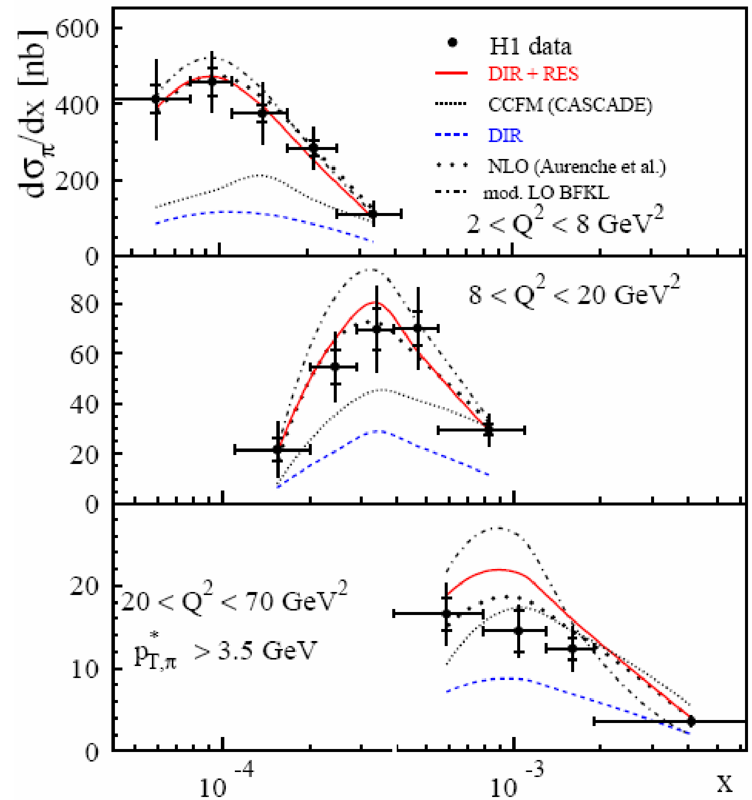
CDM (BFKL-like) close to data

→ Need for different type of kt-order breaking than in resolved γ^* model

(CCFM does not describe shapes)

Forward π^0-meson production





DGLAP - dir below the data

Resolved γ^* component improves the description

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

CDM OK

CCFM fails

(quark initiated cascades, g->qq ?)

NLO(α_s^2) calculation (Aurenche et al.) describes the data well !!

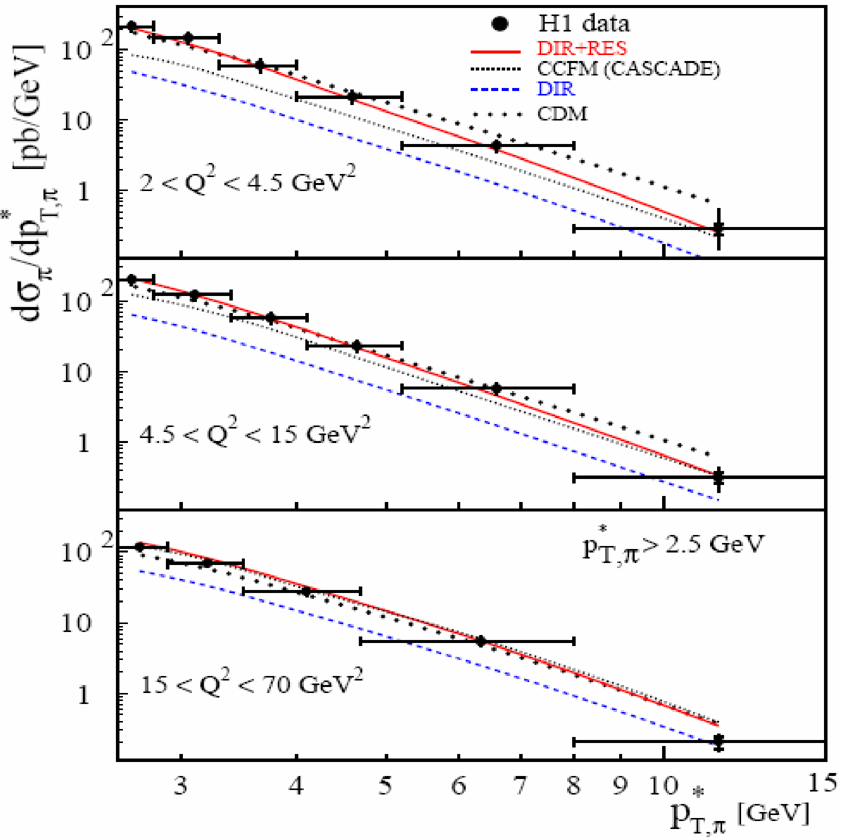
$$\mu^2 = (Q^2 + p_T^2)/2$$

BFKL-like diagrams important

Mod.LO BFKL reasonable

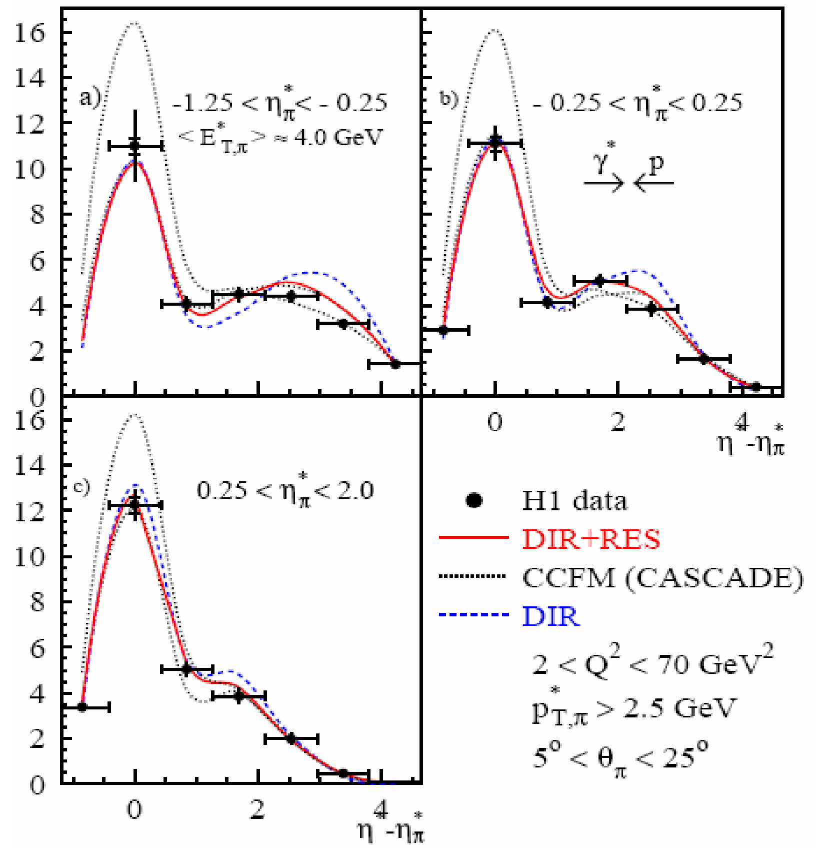
but too high at higher Q^2

π^0 transverse momentum in hCMS



E_T flow around π^0

$$\frac{1}{N}\frac{dE_T^*}{d(\eta^* - \eta_\pi^*)}$$



p_T dependence well described by MC models

only

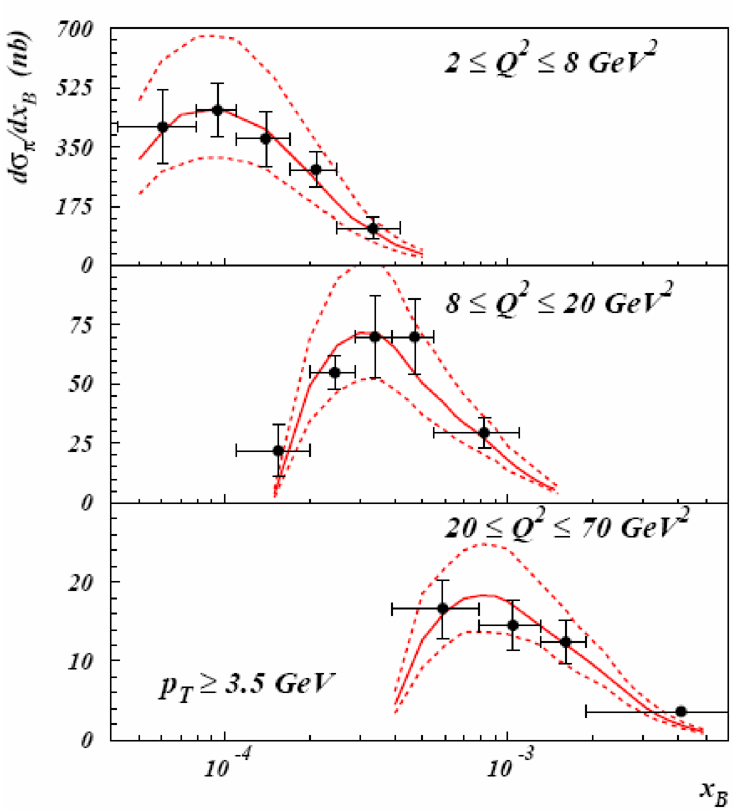
E_T flow around π^0 → transv. momentum compensation along the parton ladder

Resolved γ^*, CCFM - good

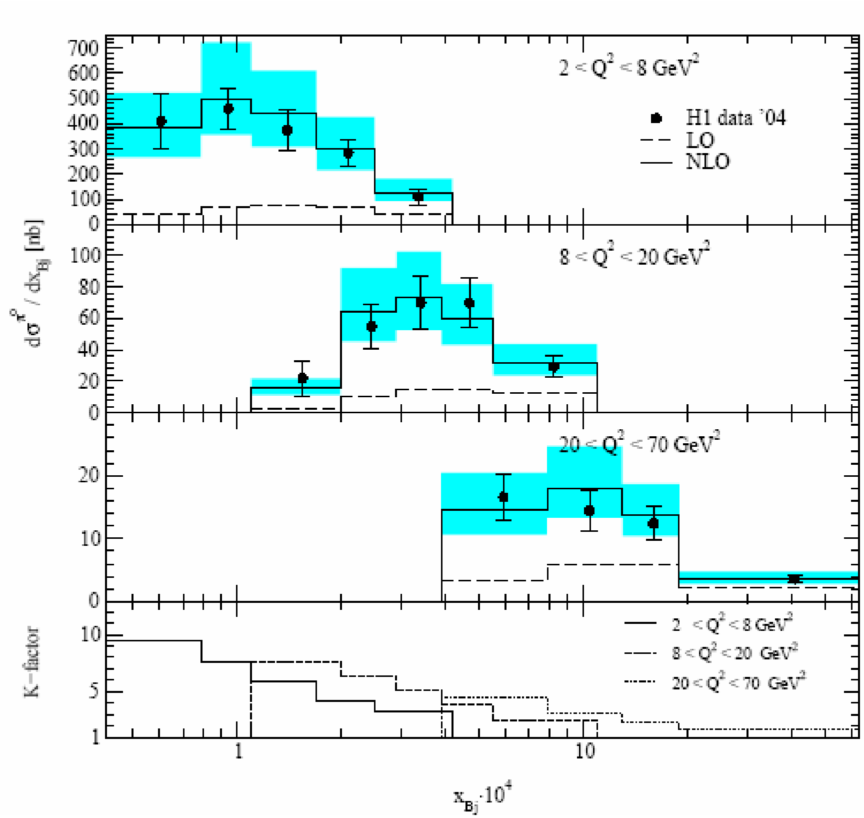
CDM too hard tr. momentum spectrum → too much E_T in the vicinity of π^0

Forward π^0 production at NLO (α_s^2)

Daleo et al.



Kniehl et al.



NLO predictions in good agreement with the H1 data

Large K factors and theoretical uncertainties

Need for NNLO analysis

Talk of B.Kniehl

Future studies of forward jet and particle production at low x

HERA lumi goal until July 2007 : 700 pb^{-1} , 5 x HERA I statistics !

- Improve the precision of the measurements (higher p_T and jet energy x_{jet})
- Investigate the dependence on p_T^2/Q^2 , x_B/x_{jet}, $\cos\gamma_h$ ...
- Importance of resolved γ^* processes → contrib. of multiple interactions ?
- Jet shape analysis of forward jets (quark/gluon jets ?)
- Azimuthal correlation between the scattered electron and the forward jet
- Multijet production with different forward jet configurations
- Forward photon as a probe of small x dynamics (difficult experimentally)
- Comparison with NLO predictions - how to estimate theoretical uncertainty ?

Limitations of HERA measurements :

Available center-of-mass energy → sufficient PS to differentiate
'not asymptotic energy' between DGLAP-BFKL-CCFM ??

Geometrical acceptance of detectors for forw. jet/particle reconstruction
(η up to ~3.5)

Summary and outlook

- Forward jet and particle production in DIS at HERA
  → ten years of precise measurements by H1 and ZEUS

- Cross sections much larger than lowest order DGLAP predictions
- Inclusion of resolved photon component – considerable improvement of the data description

- NLO predictions give reasonable description but higher order calculations needed to improve agreement/reduce theoretical uncertainties

- CCFM (CASCADE) model (k_T not ordered) does not describe the data
- CDM (ARIADNE) model (k_T not ordered) describes the data in most phase space region

Understanding high energy QCD parton dynamics is challenge

More precise mesurements and improvements in theory needed