Forward Jet/π^0 Production in DIS at HERA

On behalf of the
H1 and ZEUS Collaborations
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Didar Dobur, University of Freiburg

Outline

- QCD Dynamics at low x
- MC Models
- Inclusive Forward Jet Measurements from ZEUS and H1
- Forward π^0 Measurements from H1
- Di-Jet Measurement from H1
- Conclusions

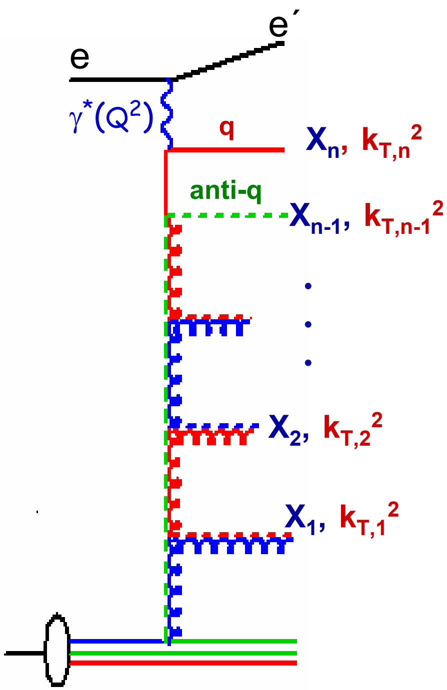
QCD Dynamics at low x

Jet/particle production have been successfully described by DGLAP at high scales (Q^2)

- **DGLAP**(Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) only terms proportional to $(\ln Q^2)^n$ are kept and summed.

$$\alpha_s(Q^2)\ln(Q^2),\ \alpha_s(Q^2)\ln\frac{1}{x}\approx 1$$

strong k_T ordering



→ DGLAP is expected to break down at low scales and low x

→ This break down might be observed in forward jet/particle production at HERA

Alternative approaches to explain parton dynamics at low x ;

- **BFKL**(Balitsky-Fadin-Kuraev-Lipatov) provides an evolution in x at fixed Q^2 by ignoring terms which includes Q^2

$$\alpha_s(Q^2)\ln(Q^2)\approx 1\ ,\ \alpha_s(Q^2)\ln\frac{1}{x}$$

no k_T ordering, but x

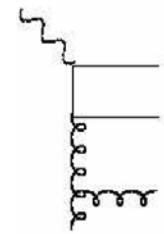
Applicable at very low-x

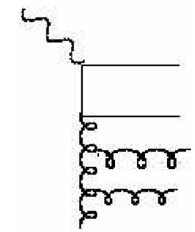
- **CCFM**(Ciafaloni-Catani-Fiorani-Marchesini) gives an evolution in both Q^2 and and approches BFKL at low x and DGLAP at high Q^2 , angular ordering

- DGLAP+Resolved Photon; parton cascade from γ side

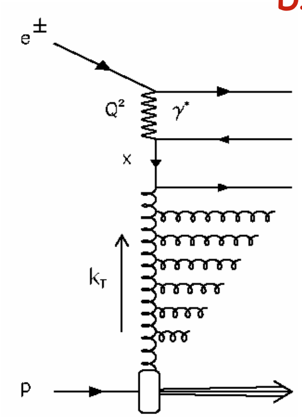
QCD Calculations and MC Models

DISENT/NLOJET: Fixed order QCD partonic cross section, on mass shell ME + DGLAP


DISENT


NLOJET

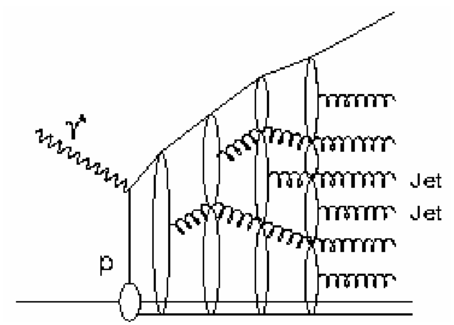
RAPGAP/LEPTO: LO ME+PS , (DGLAP)



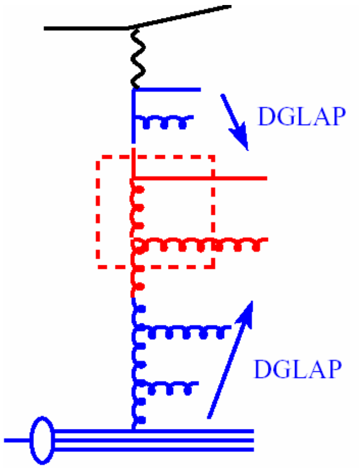
- Strong ordering in k_T

ARIADNE: LO, an implementation of Color Dipole Model (CDM)

- Independently radiating dipoles formed by emitted gluons
- Random walk in k_T
- BFKL-like



MC Models



RAPGAP Res-γ: LO, RAPGAP with an additional DGLAP evolution starting from γ

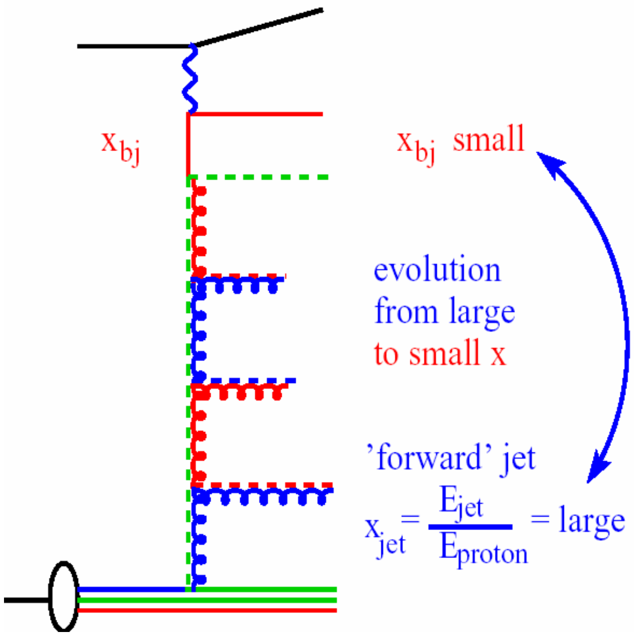
→ Contributes when $E_T^2 > Q^2$

CASCADE: LO off mass shell ME + PS based on k_T factorized CCFM evolution model

→ angular ordering in parton emission

All MC models described here use LUND string fragmentation scheme for hadronization !

Inclusive Fwrd Jet measurements from ZEUS

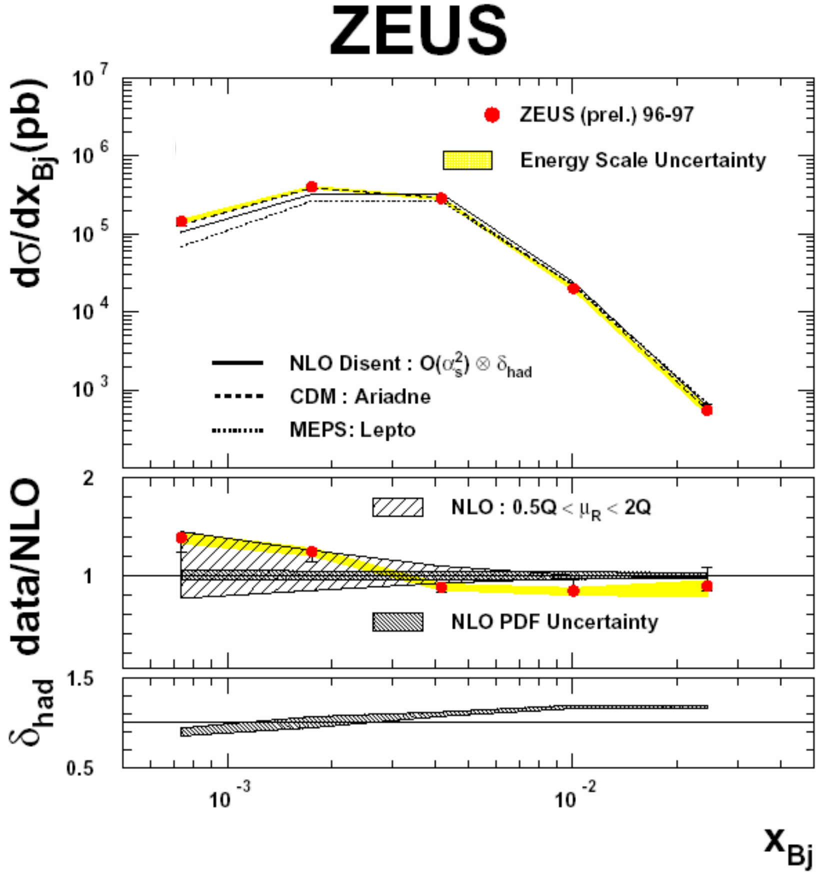


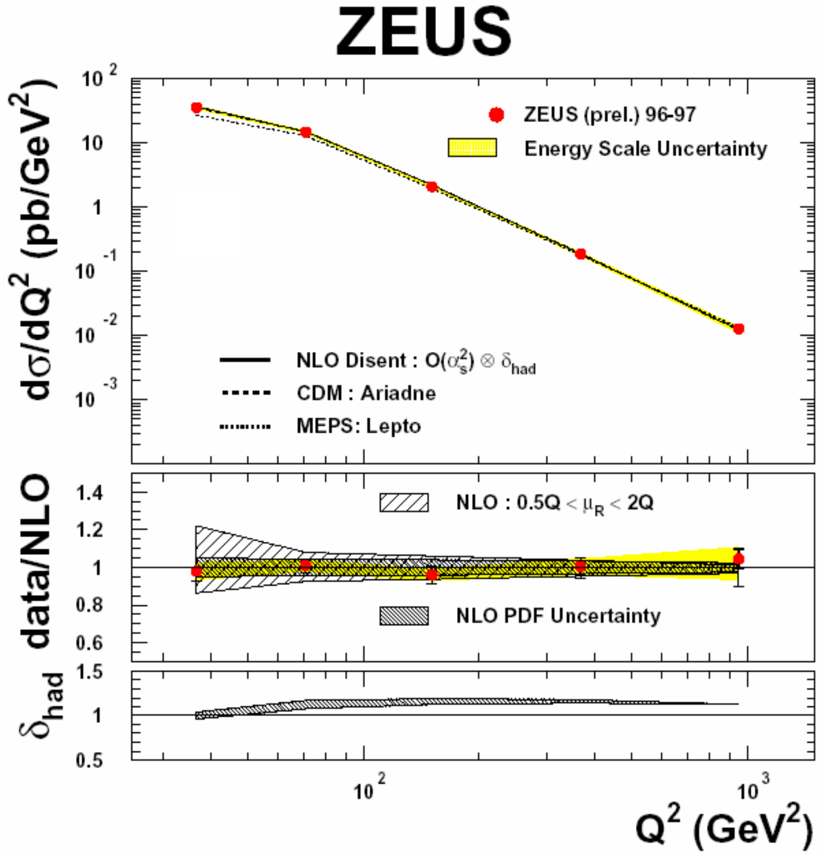
Measurement-1	Measurement-2
Kinematical range	
95-97 Data, L≅38 pb^{-1}	98-00 Data, L≅ 82 pb^{-1}
$Q^2 > 25 GeV^2$	$20 < Q^2 < 100$ GeV^2
No restriction	$0.0004 < x_{Bj} < 0.005$
$y > 0.04$	$0.04 < y < 0.7$
Forward Jet selection	
Jet Finding with Inclusive K_T Algorithm in Lab Frame	Jet Finding with Inclusive K_T Algorithm in Breit Frame
$E_{T,jet} > 6$ GeV	$E_{T,jet} > 5$ GeV
No restriction	$x_{jet} > 0.036$
$0.5 < E^2_{T,jet}/Q^2 < 2$	$0.5 < E^2_{T,jet}/Q^2 < 2$
$0 < \eta^{jet} < 3$	$2 < \eta^{jet} < 3.5$
$\cos\gamma_{had} < 0$ Suppresses QPM	

$x_{jet} = E_{jet}/E_{proton} >> x_{Bj}$ enhances BFKL effe

$E^2_{T,jet} \sim Q^2$ suppress DGLAP evolution

Forward Jet (event) Cross Sections (ZEUS-1)

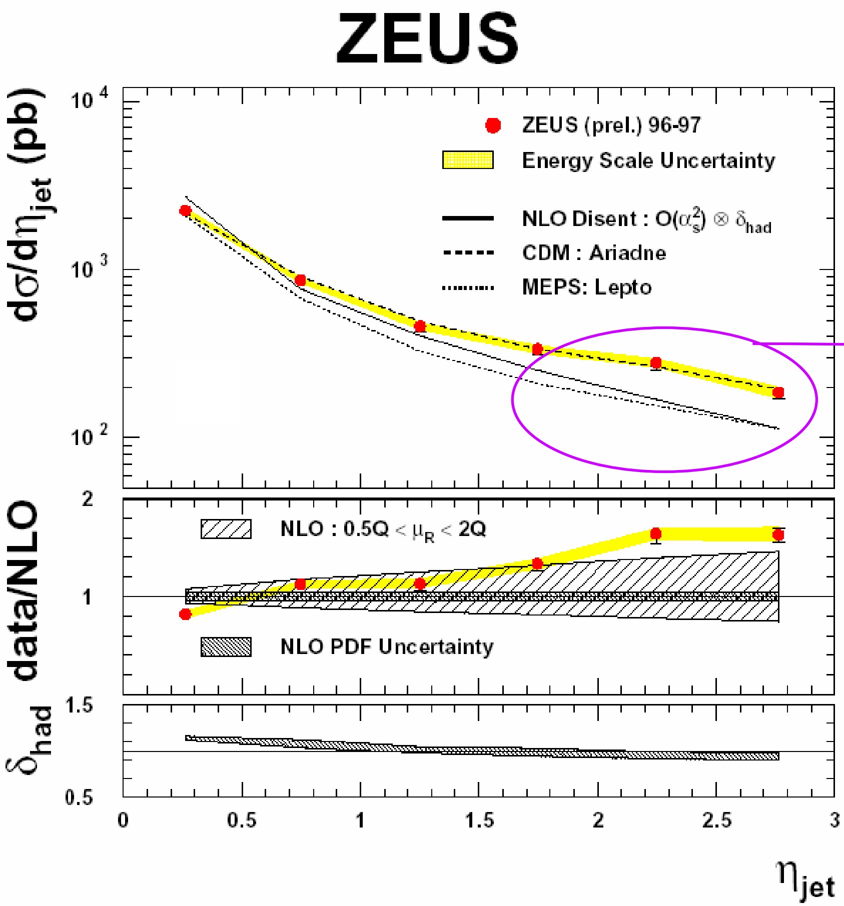


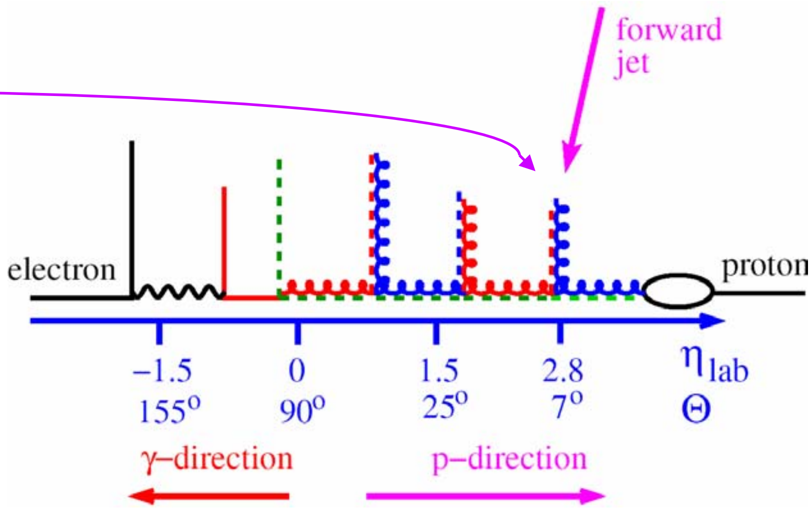


NLO calculations with $\mu_r^2 = Q^2$, corrected to hadron level

- NLO predictions lower than data at low x_{Bj} but still within the theoretical uncertainties
Gives a good description of Q^2 dependence
- CDM describes both measured cross sections
- ME+PS:LEPTO (DGLAP) fails for low x_{Bj} and Q^2

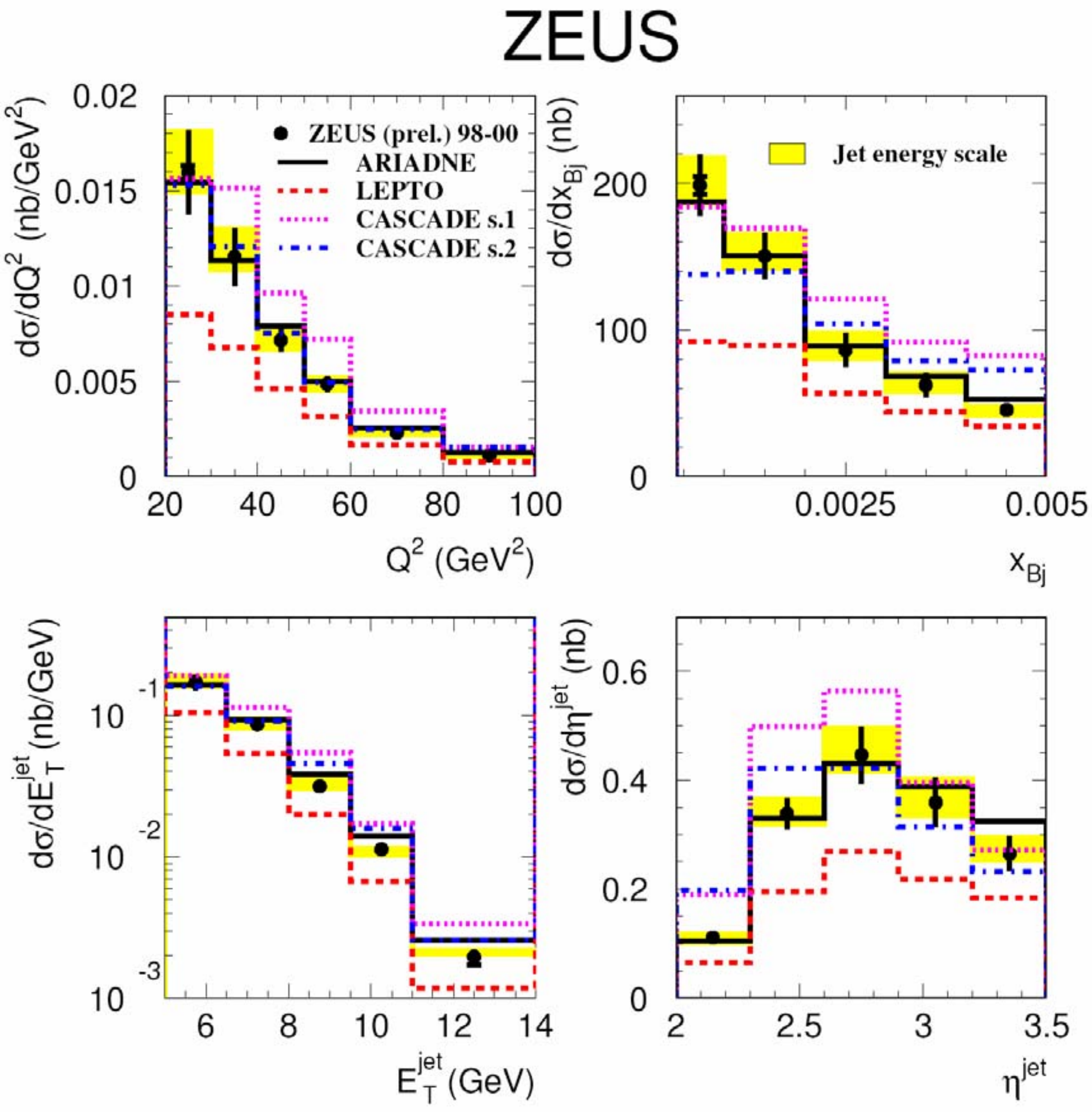
Inclusive Forward Jet Cross Sections (ZEUS-1)





- Discrepancy between data and NLO in the forward region $\eta^{jet}>1.5$, this region is more sensitive to higher order radiations (estimation of uncertainty from higher orders is large)
- CDM describes well measured cross section
- ME+PS:LEPTO (DGLAP) fails in all η^{jet} range

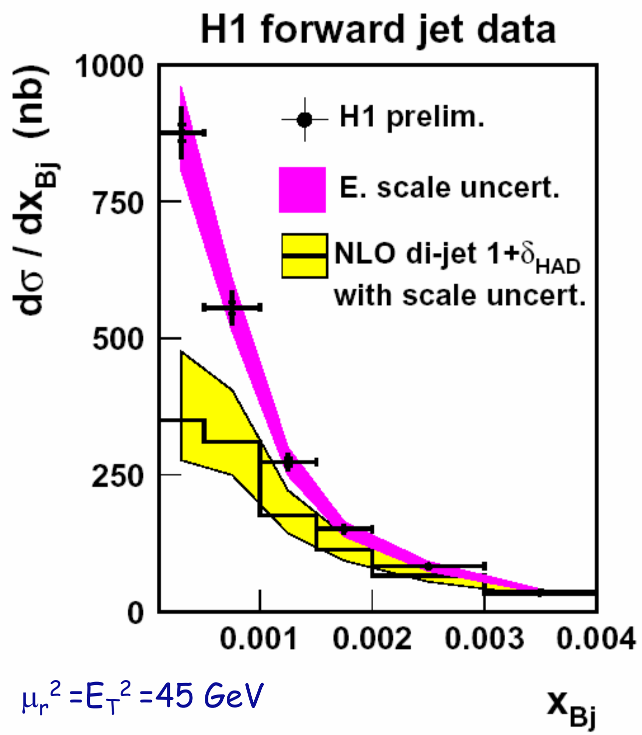
Inclusive Forward Jet Cross Sections (ZEUS-2)



Look more forward region
$2 < \eta^{jet} < 3.5$

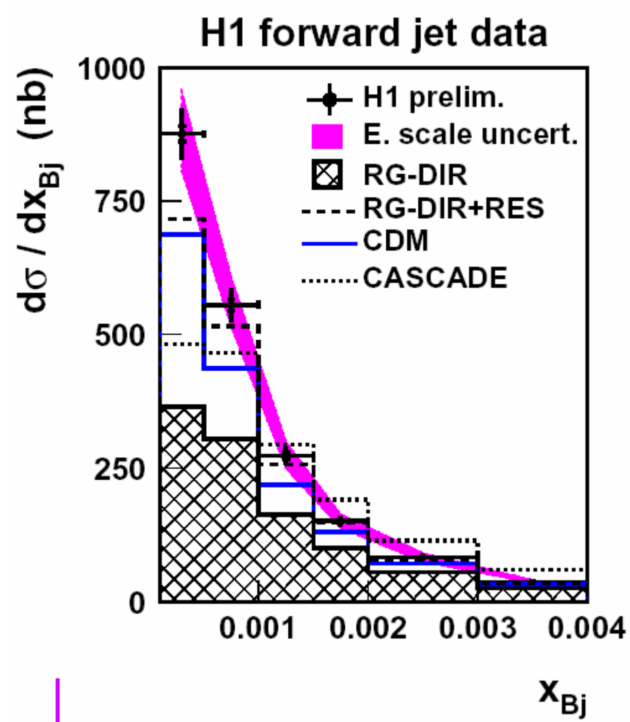
- DGLAP underestimates data by a factor of 2
- CCFM set1 disagrees with all cross sections
- CCFM set2 in a good agreement with data in Q^2 and E_T but fails to reproduce the shapes of x_{Bj} and η^{jet}
- CDM gives a good description of data in all measured cross sections

} BFKL-l



$\mu_r^2 = E_T^2 = 45$ GeV

CTEQ6M



97 Data , L= 13.72 pb^{-1}

Kinematical range

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

$10^{-4} < x_{Bj} < 4.10^{-3}$

$0.1 < y < 0.7$

Jet selection

Inclusive K_T Algorithm i

Breit Frame

$x_{jet} > 0.035$

$0.5 < E^2_{T,jet}/Q^2 < 5$

$P_{T,jet} > 3.5$ GeV

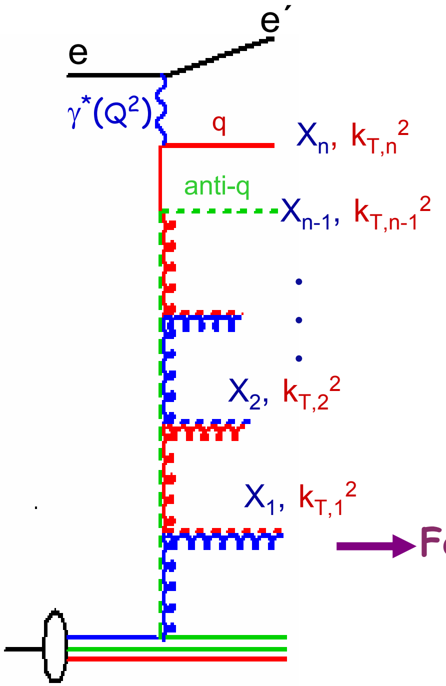
$7° < \theta_{jet} < 20°$

- Strong increasing of data as x_{Bj} decreases
- NLO calculations fail at low-x_{Bj} region (as ZEUS)

- DGLAP is similar to NLO
- DGLAP with res-γ is closest to data
- CDM gives a reasonable description for higher x
- CCFM does not describe the shape of x dependenc

More high E_T QCD radiation is needed in the low-x region

Forward π^0 Measurement from H1 Experiment



$$e + P \rightarrow e + \pi^0 + X$$

Data 96-97 , L~21.2 pb^{-1}

Kinematical range

$2 < Q^2 < 70$ GeV^2

x_{Bj} down to 10^{-5}

$0.1 < y < 0.6$

π^0 candidates are identified via the (dominant decay)
$\pi^0 \longrightarrow 2\gamma$ using CAL information

$x_\pi = E_\pi / E_p > 0.01$

$P^*_{T,\pi} > 2.5$ GeV

$5° < \theta_\pi < 25°$

γs are merged into a single EM cluster in hadronic-CMS

\+ No ambiguity of jet algorithms

\+ Identification of π^0s is easier in the very forward region than reconstructing jets

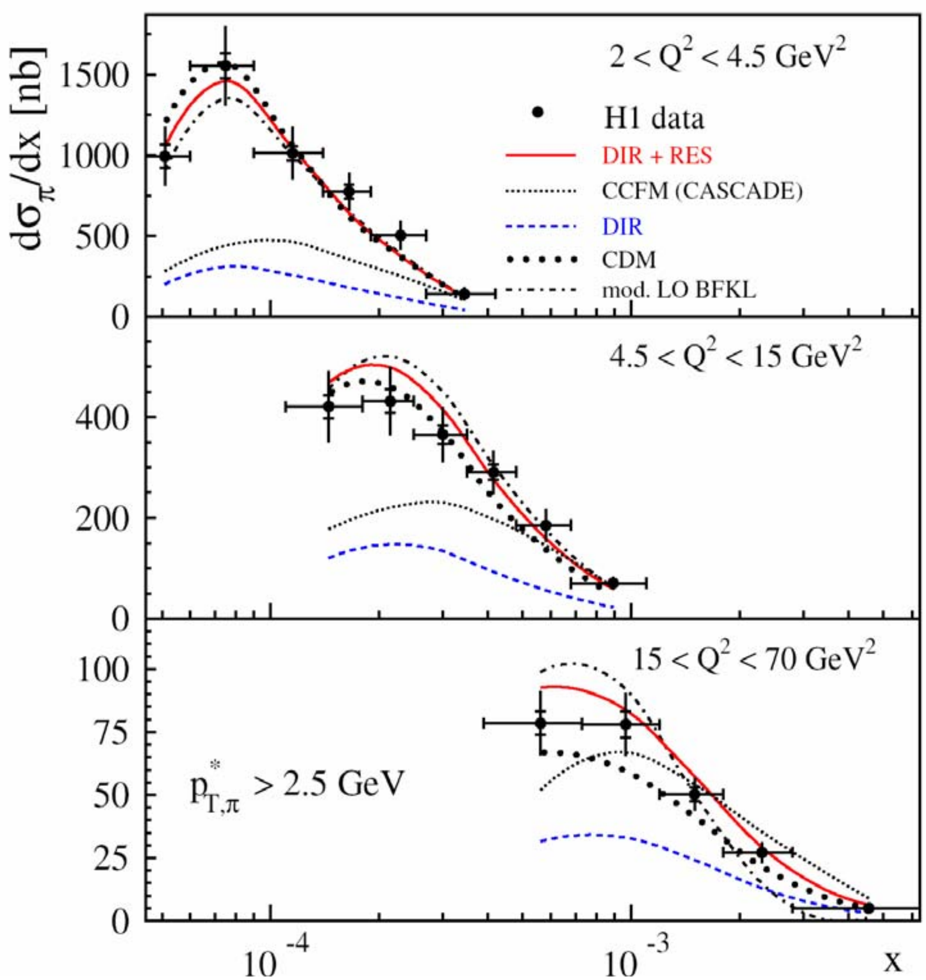
\+ More forward is possible with π^0s

\- Hadronization effects are more pronounced than for jet production

\- lower rate than jet production

Forward π^0 Cross Sections

Measured π^0 cross sections versus x_{Bj} in different Q^2 intervals

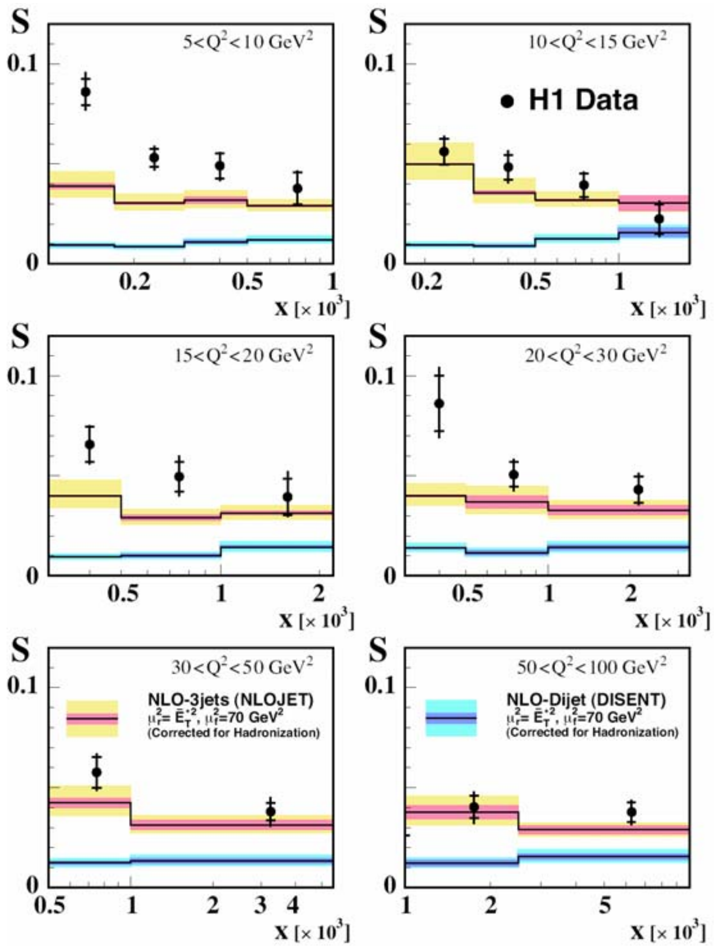


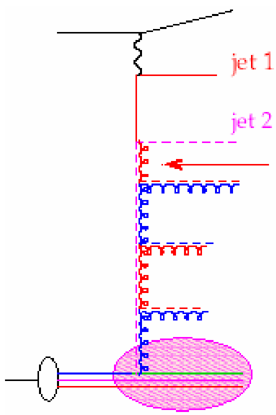
- DGLAP-DIR falls substantially below data, disagreement more pronounced at low x
- DGLAP DIR+RES describes the data well, large μ_r and μ_f $(4p_T^2+Q^2)$ needed to get enough resolved photon contribution
- CCFM falls below data at low x and low Q^2
- CDM gives good description of data
- Analytical calculations Mod-BFKL (momentum conservation in parton emissions is taken into account) describe the data well in low Q^2 regions

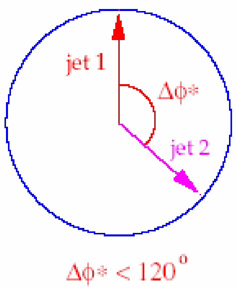
CTEQ6M , SAS-1D parton and virtual γ densities

Results from Di-jet Measurement H1

Parton dynamics beyond DGLAP apprx. studied looking at azimuthal correlation in di-jet events







$$S = \frac{\int_0^{120} N_{dijet}\, d\Delta\phi^*}{\int_0^{180^\circ} N_{dijet}\, d\Delta\phi^*}$$

Fraction of events with $\Delta\phi > 120$

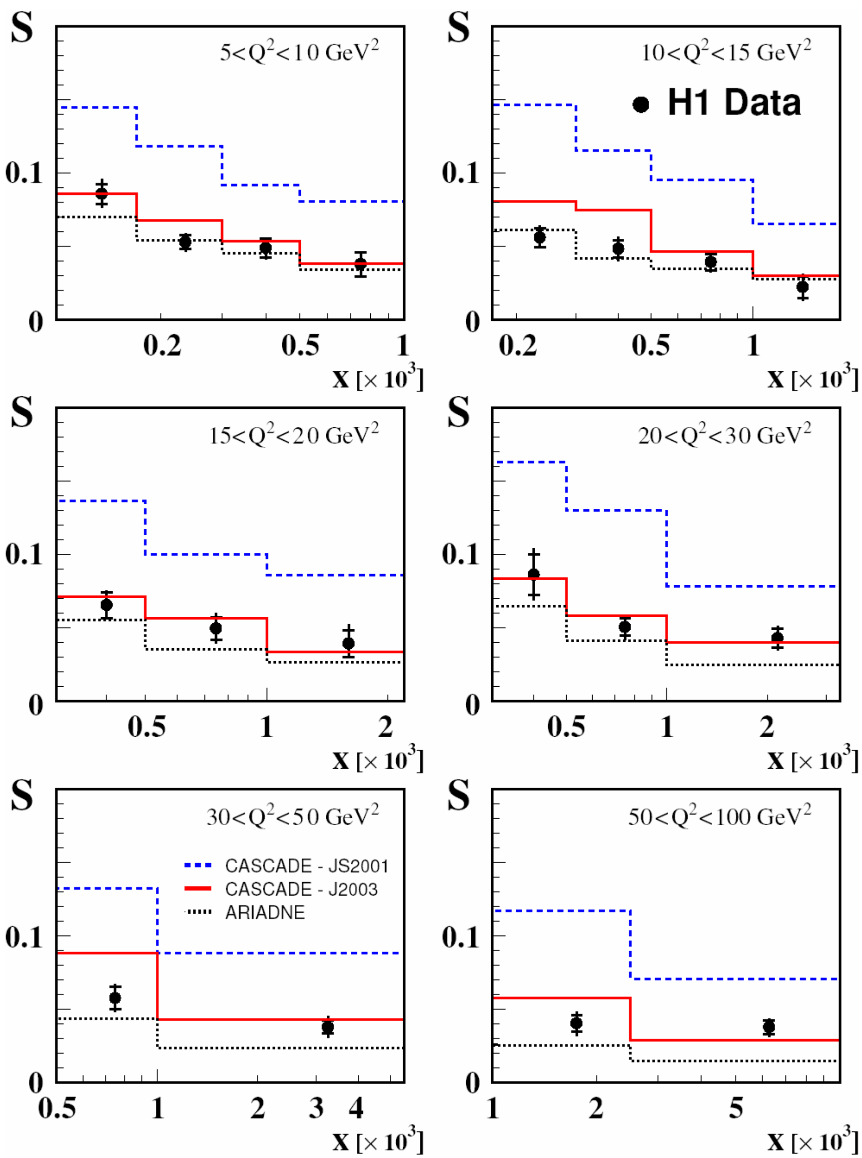
—low K_T partons entering hard scattering process produce di-jets with $\Delta\phi^* \sim 180$ as assumed in DGLAP

—large K_T partons entering HS process (CCFM and BFKL) small $\Delta\phi^*$

Kinematical range	Jet selection
$5 < Q^2 < 100$ GeV^2	Inclusive K_T Algorithm
$10^{-4} < x_{Bj} < 10^{-2}$	in HCMS
$0.1 < y < 0.7$	$P_{T,jet} > 5$ GeV
	$-1 < \eta^{jet} < 2.5$

- Measured S values ~ 5% and increase with decreasing x_{Bj}
- DISENT (lowest order) calculations predict S ~ 1% and show no x_{Bj} dependence
- NLOJET (NLO) calculations give a good description at high Q^2 and x_{Bj} but fail at low x and Q^2

Results from Di-jet Measurement H1



- Comparison with the models beyond DGLA
- Higher orders simulated by PS

- CDM gives a reasonable description of dat
- CCFM with JS2001 PDF lies above the dat
- With J2003 (also non-singlr. terms included in gluon splitting function) better description

- S measurements are sensitive to different un-integrated PDFs
- Significant constraint on the unintegrated gluon density

Conclusions

- Parton dynamics at low-x studied in forward jet/π^0 and di-jet production in DIS by ZEUS and H1
- Lowest-order DGLAP calculations fail to describe forward jet/π^0 cross sections but including res-γ a better description of data obtained
- NLO calculations fail at low Bjorken-x and for very forward jets, higher order corrections needed
- Models beyond DGLAP evolution (CCFM, BFKL) look promising in describing parton dynamics at low x