Low-x Dynamics through Jet Studies

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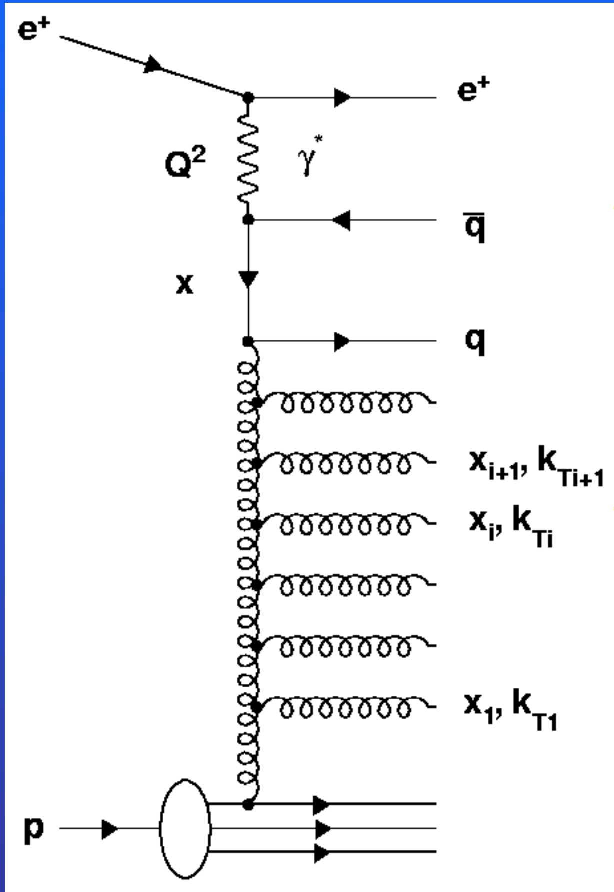
On behalf of the
H1 and ZEUS collaborations

Outline:
- Introduction
- Multijet production at low-x in DIS
- Angular correlation between jets
- Forward jets
- Summary

Parton Dynamics at low x in $e^{\pm}p$ collisions

Different approximations to the summation of the perturbative expansion of parton evolution:



2 Jets from the hard subprocess

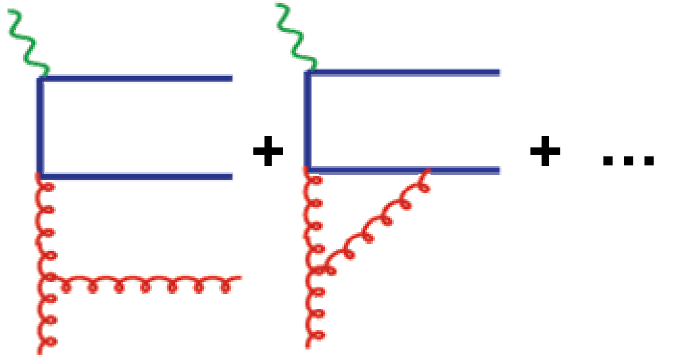
Jets initiated by radiated gluons

- DGLAP $\sum(\alpha_s \ln Q^2)^n$
  - strong ordering in virtuality, i.e. $k_{T1}^2 \ll k_{T2}^2 \ll \ldots \ll Q^2$
  - weak ordering in x, i.e. $x_1 > x_2 > \ldots > x_{Bj}$
  - works very well at large Q2
  - expected to fail at low Q2 and x
- BFKL $\sum(\alpha_s \ln 1/x)^n$
  - no k_T ordering
  - strong ordering in x, i.e. $x_1 \gg x_2 \gg \ldots \gg x_{Bj}$
  - should be applicable at low x
- CCFM $\alpha_s \ln Q^2$ & $\alpha_s \ln 1/x$
  - angular ordering, $\Theta_n \gg \Theta_{n-1} \gg \ldots \gg \Theta_1$
  - expected to be valid in whole x, Q^2 range

DGLAP well established at HERA (PDFs, QCD fits, F_2) -> look into measurements with better sensitivity to BFKL effects. Important for LHC: at large Q^2 and x HERA PDFs can be evolved using DGLAP, but are HERA data described by DGLAP down to low x ?

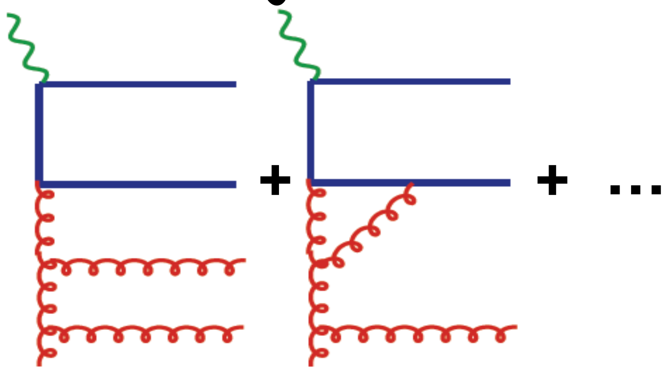
NLO QCD Calculations and Monte Carlo Models

Disent, NLOjet++



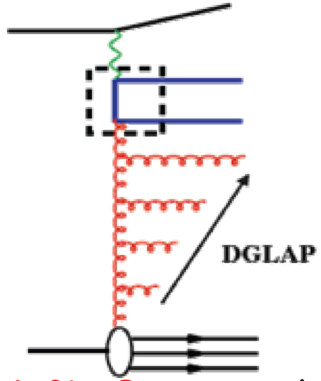
NLO Dijet (α_S^2)

NLOjet++



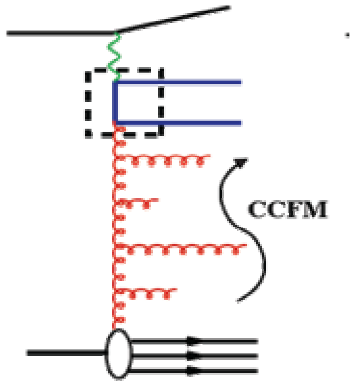
NLO Trijet (α_S^3)

Lepto/Rapgap



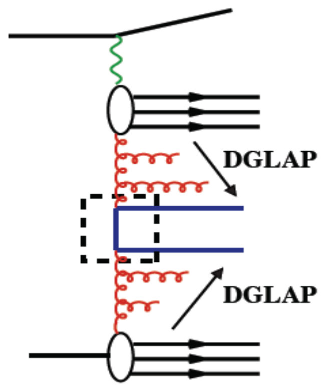
DGLAP approach, direct photon

Cascade



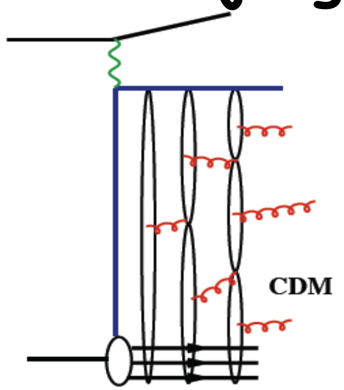
CCFM, angular ordering, unintegrated $g(x,k_T,\mu)$

Rapgap



DGLAP approach, direct + resolved photon

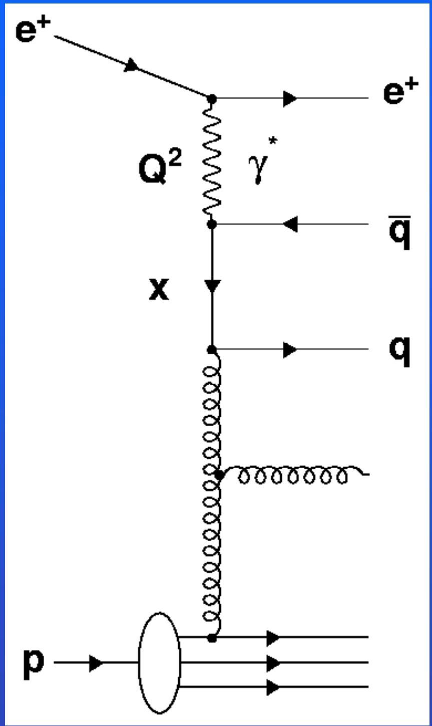
Ariadne/DjangoH

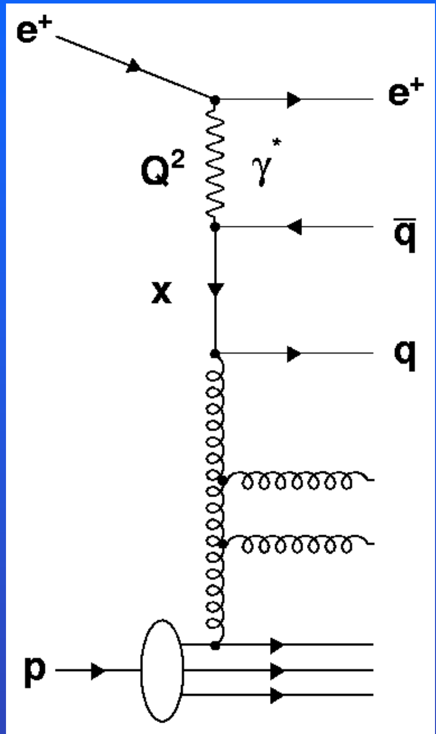


Color dipoles spanned between partons, radiate in all directions, no k_T ordering.

Multijet (dijets, trijets) Production at Low x

$O(\alpha_S^2)$ $O(\alpha_S^3)$





Kinematic selection to enhance (unordered) gluon radiation and to study parton dynamics (at low-x):

- select phase space for evolution in x (BFKL):

$$x_{Bj} \ll x_{jet} = E_{jet}/E_p$$

- suppress phase space for evolution in Q^2 (DGLAP):

$$p_{T,fwd\ jet}^2 \sim Q^2$$

Hadronic Center-of-Mass

Comparison with NLO at order $O(\alpha_S^2)$ and $O(\alpha_S^3)$ -> NLOJET, DISENT
Comparison with Monte Carlo's LO-PS with/out γ_{res} -> CDM-DjangoH, RAPGAP

H1 compares at parton level, ZEUS compares at hadron level

Multijet Production at Low x

H1-prelim-06-034

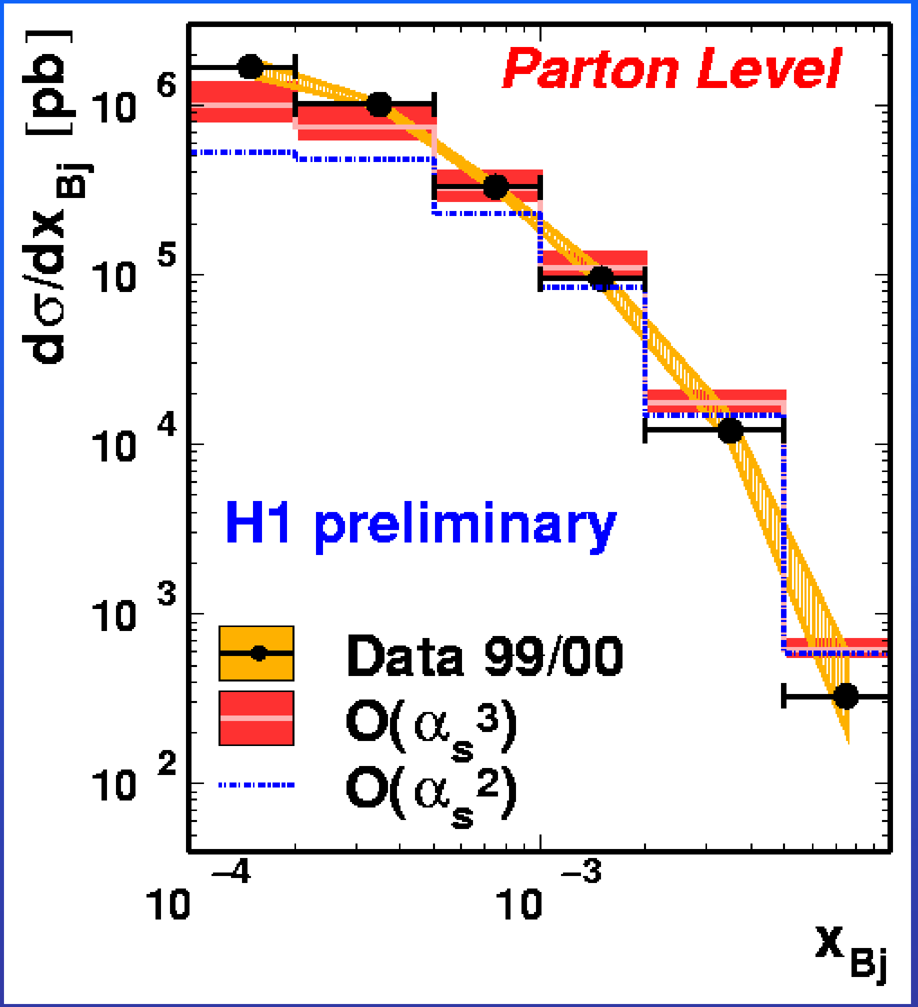
$\int Ldt$ = 44.2 pb^{-1} (99-00 data)
$10^{-4} < x_{Bj} < 10^{-2}$, $5 < Q^2 < 80\ GeV^2$

At least 3 jets with: $E_{Tjet1} > 4$ GeV
$E_{Tjet2}+E_{Tjet3} > 9$ GeV
$-1 < \eta_{lab} < 2.5$
one jet $-1 < \eta_{lab} < 1.3$

Jet reconstruction: inclusive k_T algorithm in γ^*p CMS

NLO predictions error band: varying renormalisation scale and factorisation scale simultaneously by a factor 2 and 0.5, resp. ($\mu_r=\mu_f=(\sum p^*_{Ti})/m$, $i=1,N_{jet}$, m=3 or 4)

- NLOjet++ $O(\alpha_S^3)$ – describes x_{Bj} dependence with possible exception of very low x bin



Multijet Production at Low x

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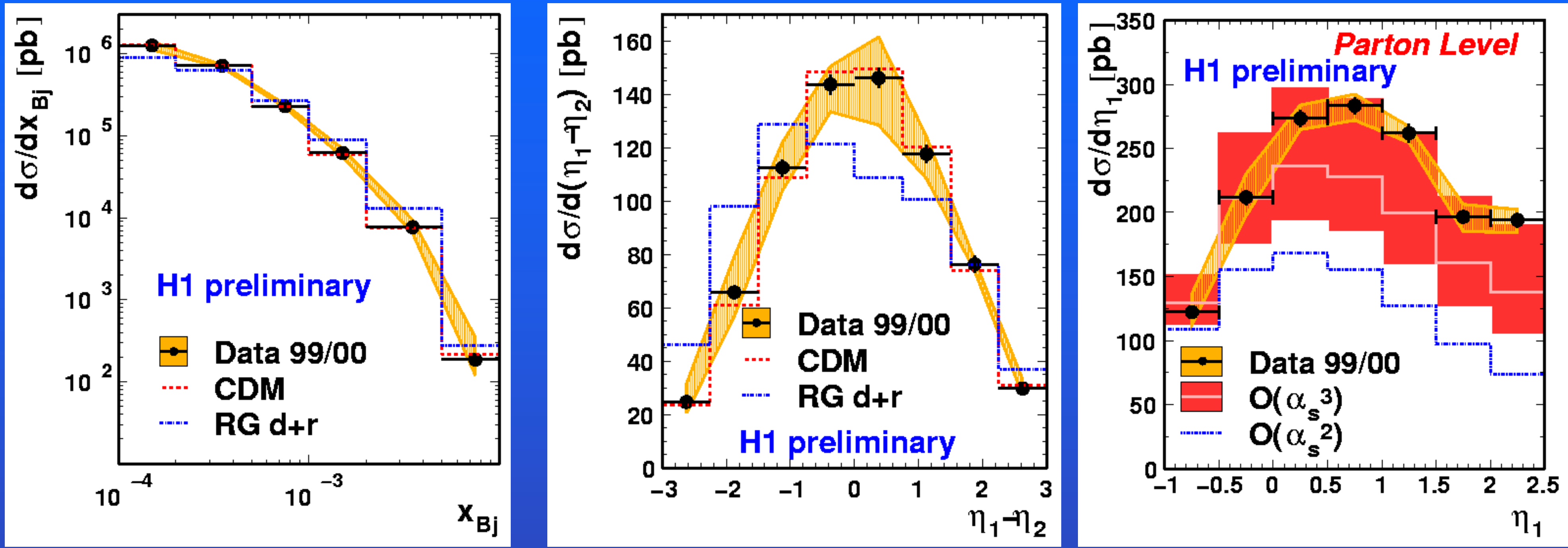
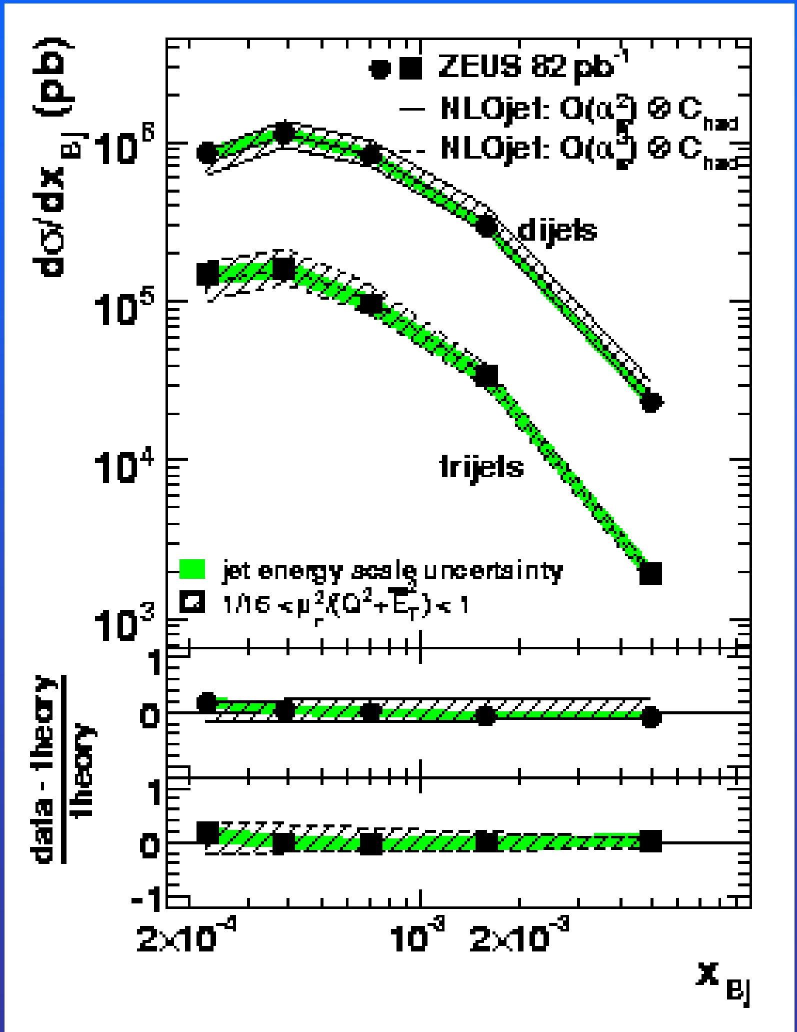


- CDM (DjangoH) – good description
- Rapgap (Dir+Res) – too low for η_1-η_2
- $O(\alpha_S^2)$ – prediction too low. $O(\alpha_S^3)$ – significant improvement, but for forward rapidities still low

Multijet Production at Low x

C_{had} = hadronisation corr. factors



ZEUS: DESY-07-062

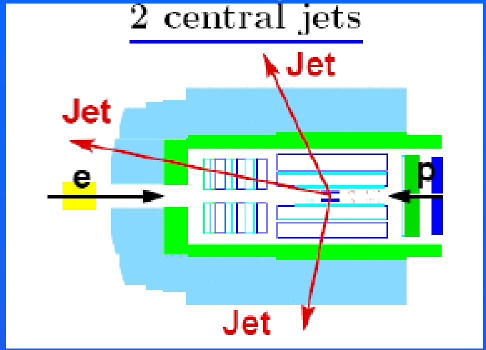
$\int Ldt$ = 82.2 pb^{-1} (98-00 data)
$10^{-4} < x_{Bj} < 10^{-2}$,
$10 < Q^2 < 100$ GeV^2

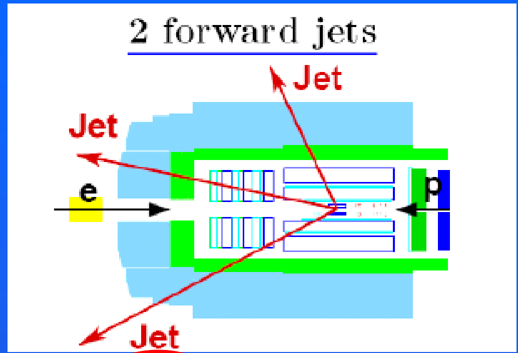
2 or 3 jets with:
$E_{Tjet1} > 7$ GeV
$E_{Tjet2(3)} > 5$ GeV
$-1 < \eta_{lab} < 2.5$

Renormalisation and factorisation scales:
$\mu_r^2 = \mu_f^2 = (\langle E^2_{T,HCM} \rangle + Q^2)/4$
$\langle E_{T,HCM} \rangle$= average E_T of two (three) highest jets.

NLOjet++ $O(\alpha_s^3)$: good description of the data (lowest Q^2=10 GeV^2 instead of 5 GeV^2 for H1)

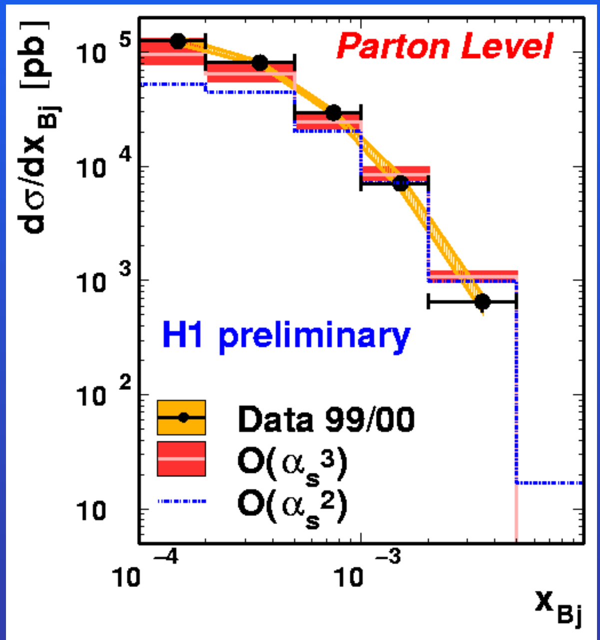
Three-jet Cross-section – Forward jet selection



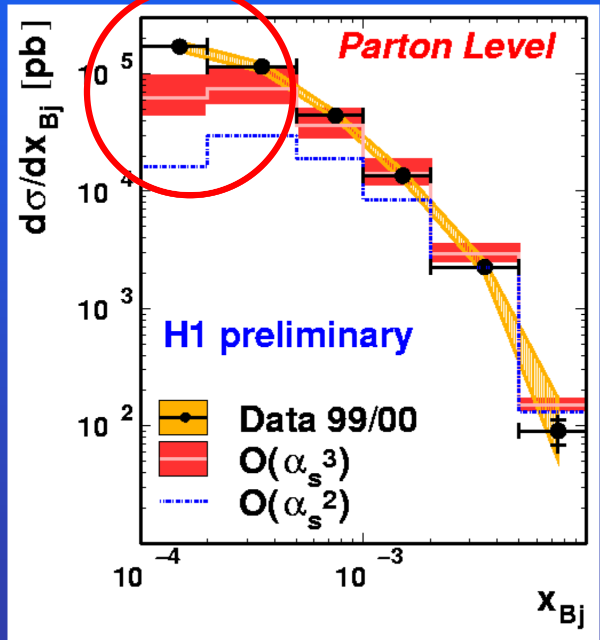


H1-prelim-06-034

- central jet : $-1 < \eta_{jet} < 1$
- forward jet: $\eta_{jet} > 1.73$
- $x_{jet} = E^*_{jet}/E_{p,beam} > 0.035$



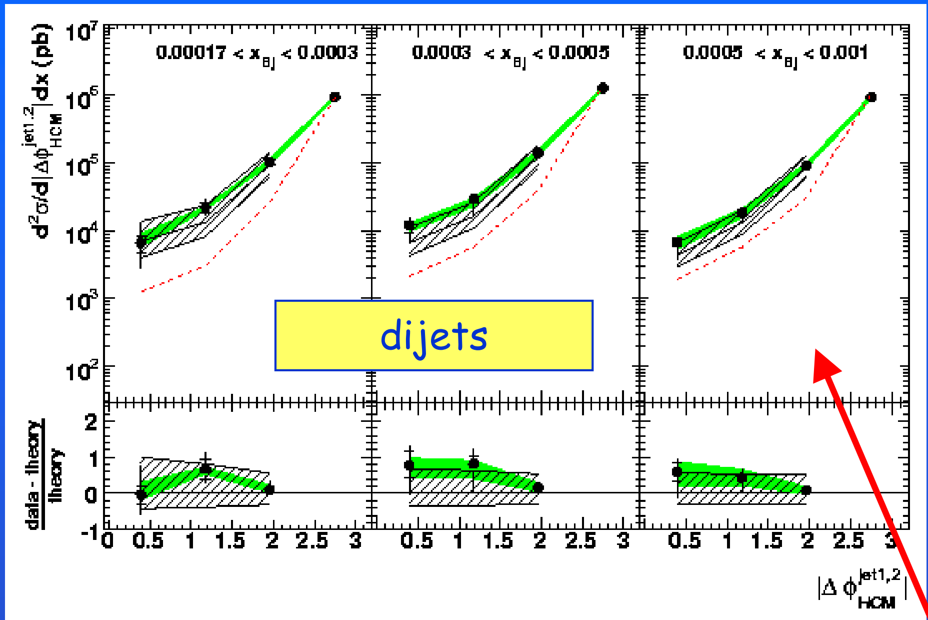
From LO to NLO factor of 2 at low x. NLO in agreement with data.

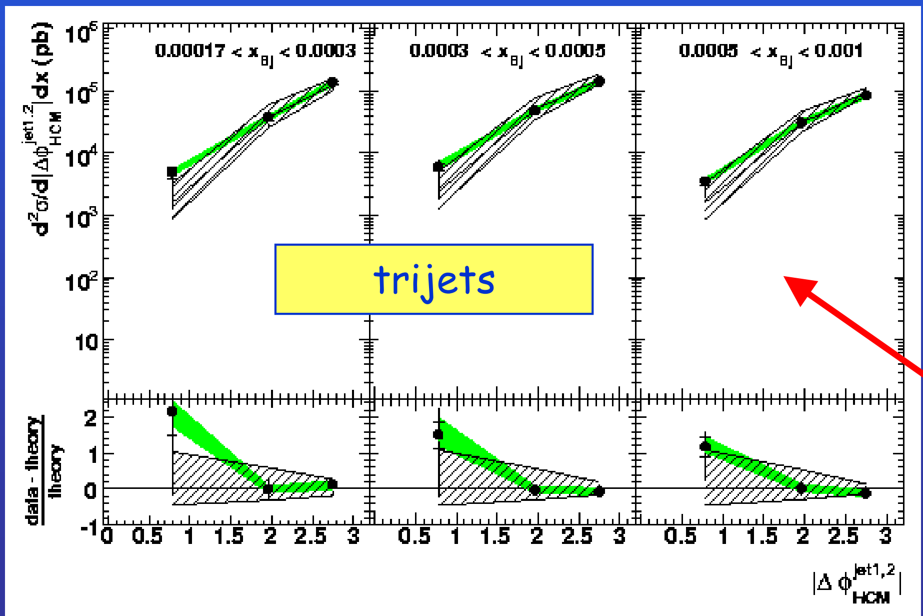


From LO to NLO a factor of 3.5 at low x, but NLO still factor of 3 below data.

- improvement going from α_S^2 (1 gluon) to α_S^3 (2 gluons)
- discrepancy at lowest x_{Bj} and forward rapidities is in a region where unordered gluon emissions are expected to be important !
- need NNLO or unordered gluon radiation ?

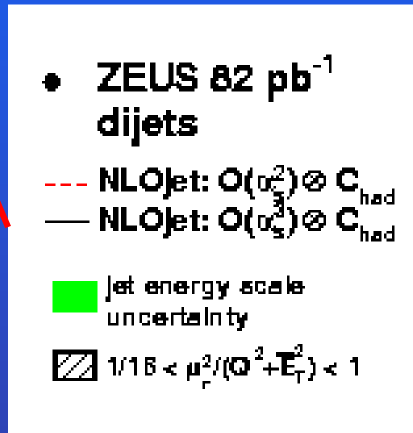
Multijet Production at Low x





Azimuthal separation between two jets with the highest hadronic center of mass E_T

- $\Delta\,\Phi^*$ sensitive to parton evolution scheme, gluon radiation (jets are back-to-back without gluon emissions)



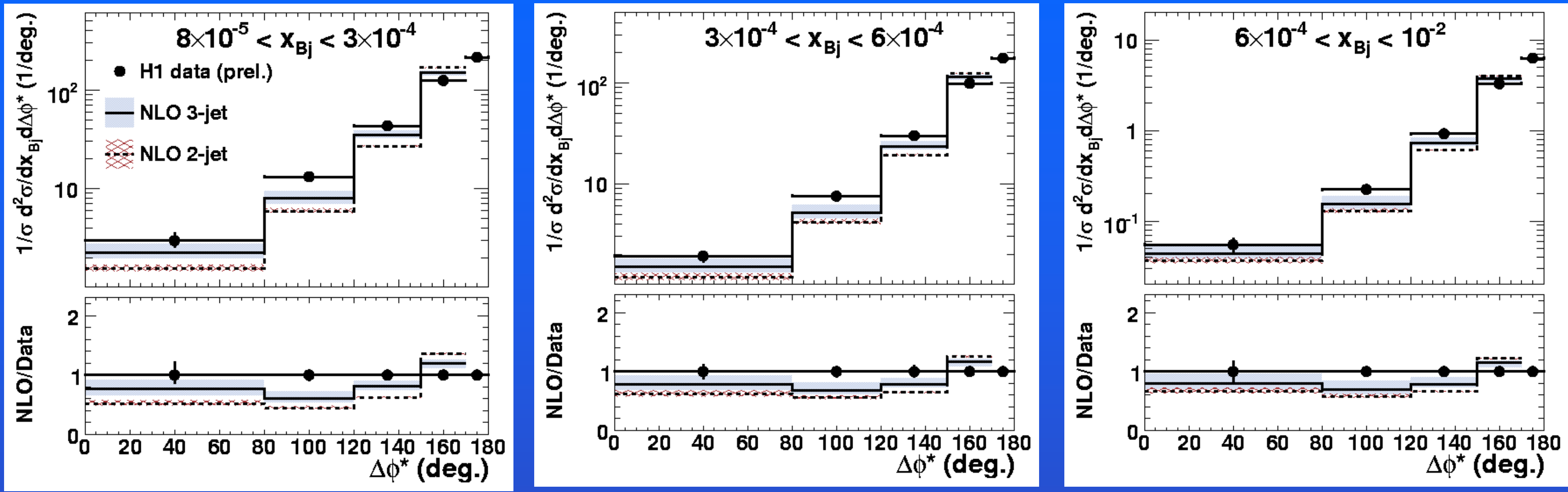
ZEUS: DESY-07-062

trijets
NLOjet: $O(\alpha_S{}^3)\otimes C_{had}$

<u>dijets:</u>
description improved going from $O(\alpha_S{}^2)$ to $O(\alpha_S{}^3)$

<u>trijets:</u>
good description by pQCD, but rather large scale uncertainities indicating the need for higher orders

Azimuthal Correlations in Dijets



H1-prelim-06-032

$\Delta \Phi^* = | \Phi_{jet1} - \Phi_{jet2} |$
in HCM

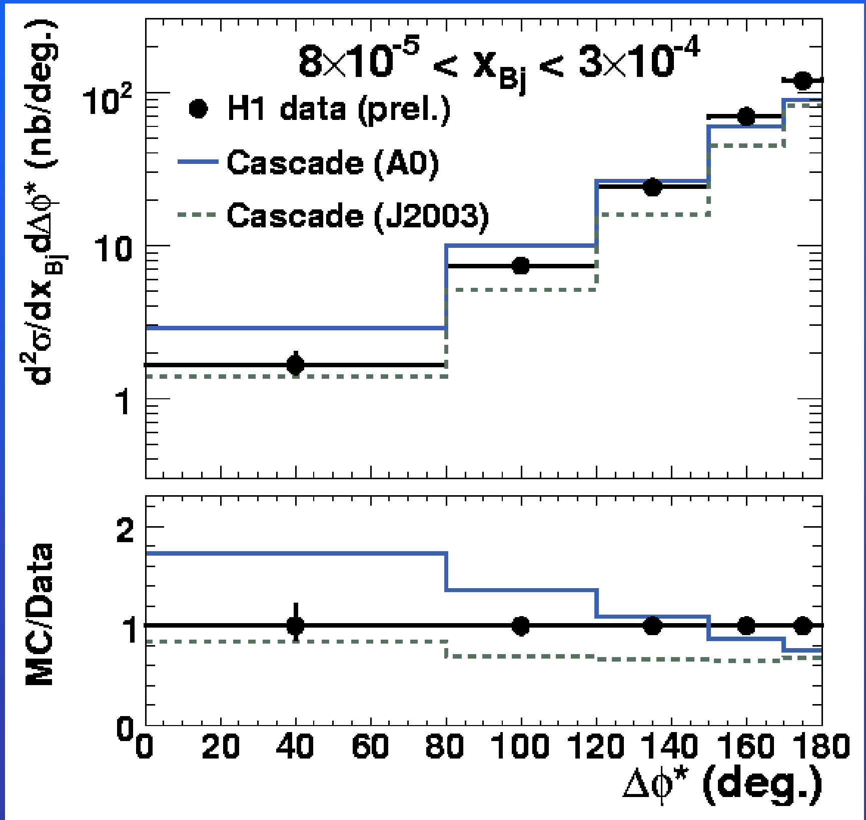
H1 99-00 data (64 pb^{-1}):
DIS: $5 < Q^2 < 100$ GeV^2

2 jets with:
$-1 < \eta_{jet} < 2.5$ (LAB)
$E^*_{Tj} > 5$ GeV (HCM)

- one parton radiation (NLO 2-jet) not enough to describe the data
- two parton radiation (NLO 3-jet) still systematically low at low x_{Bj}, low $\Delta \Phi^*$

Azimuthal Correlations in Dijets

H1-prelim-06-032



Comparison with Monte Carlo models (broader $\Delta\ \Phi^*$ spectrum expected from BFKL, CCFM):

- Cascade with J2003 pdf describes data except in lowest x_{Bj} bin
- Cascade with A0 pdf fails in all x_{Bj} bins
- CASCADE predictions depend on unintegrated gluon density -> could be determined

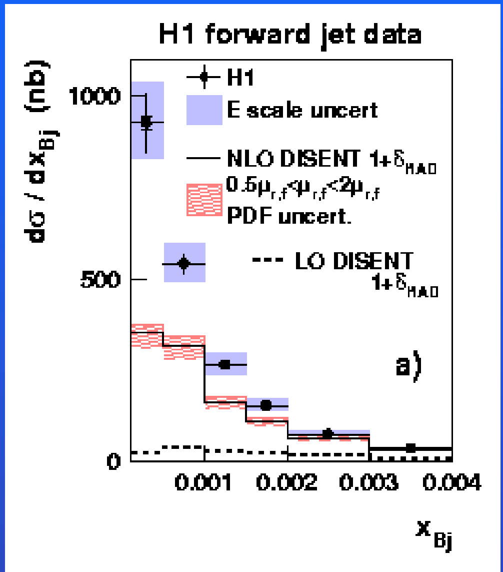
Forward Jets

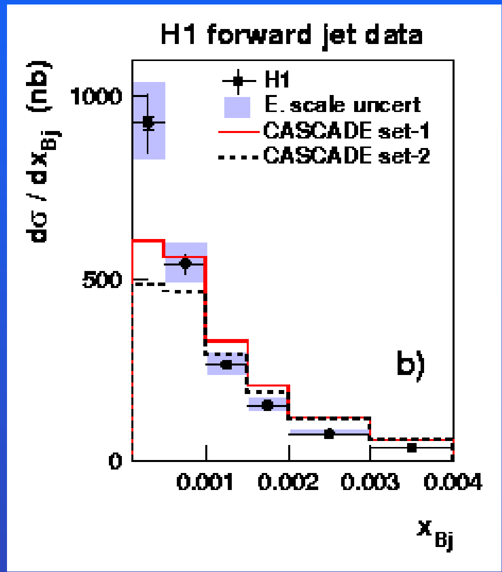
H1 data in the kinematic region: $10^{-4} < x < 4 \times 10^{-3}$, $5 < Q^2 < 85\ GeV^2$, $p_{T,jet} > 3{,}5\ GeV$, $7^o < \Theta_{jet} < 20^o$

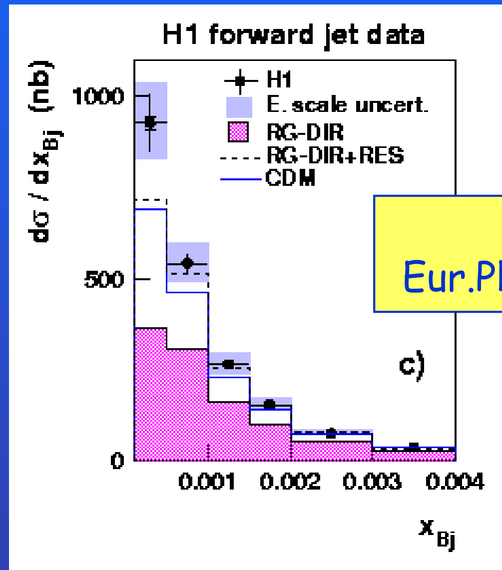
$x_{jet} = E_{jet}/E_p > 0.035$

$0.5 < (p_{T,jet})^2/Q^2 < 2$
to suppress DGLAP and enhance BFKL behaviour

$L = 13.7\ pb^{-1}$



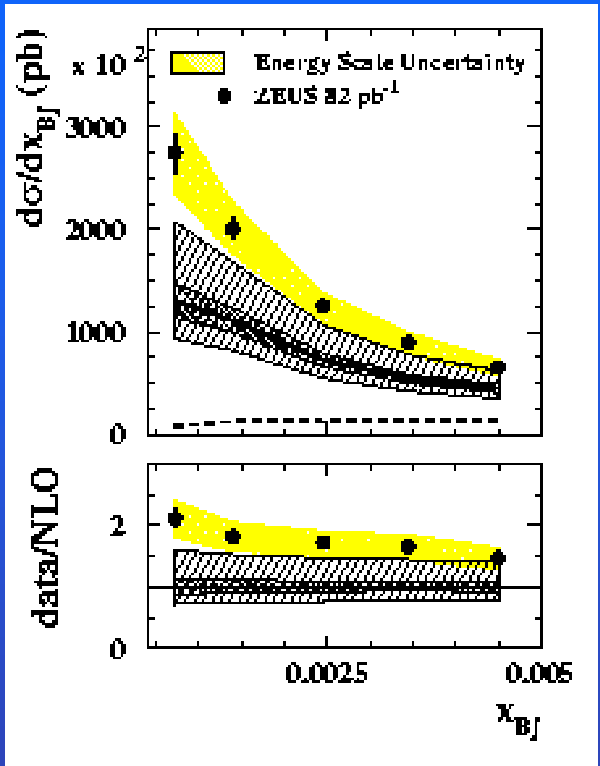


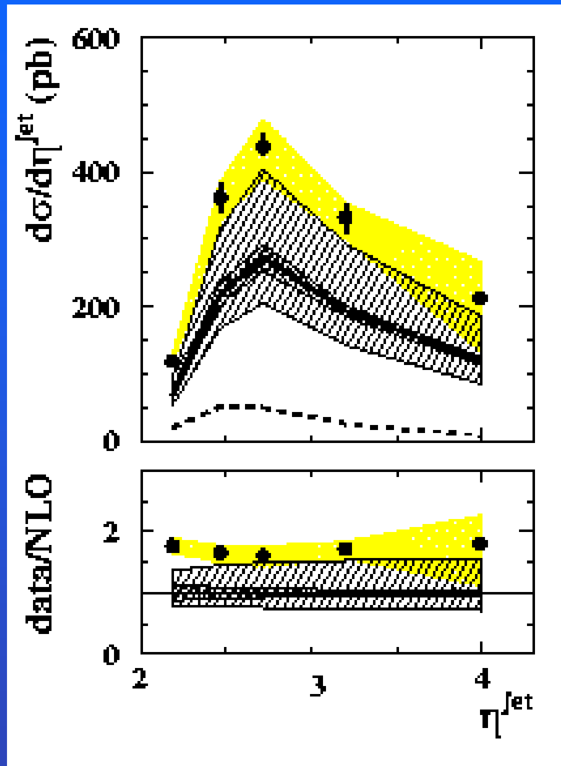


H1:
Eur.Phys.J.C46(2006)27

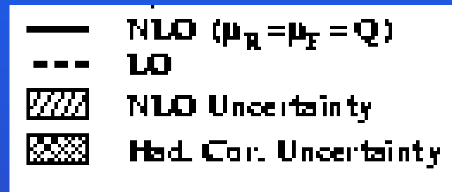
- LO-DGLAP fails
- NLO-DGLAP is a factor 2 too low
- Monte Carlo models with extra parton radiation provide an improved description of the data
- improved description in case of inclusion of a resolved-photon component (-> RAPGAP: DIR+RES)

Forward Jets





ZEUS: DESY-07-100



- LO-DGLAP fails completely
- NLO-DGLAP well below data at low x (as seen by H1)

Forward Jet and Dijet

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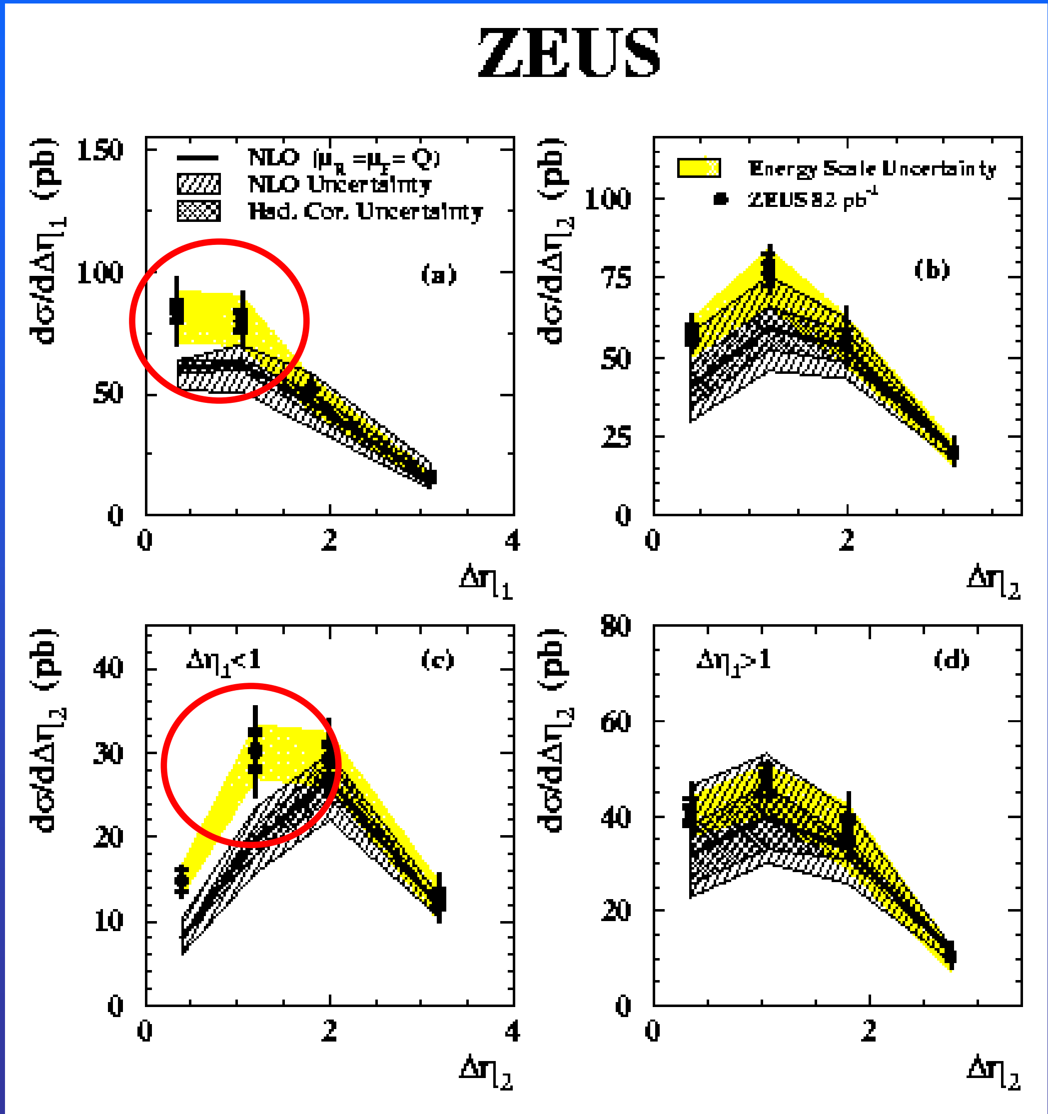


New measurement 98-00 data:

$2 < \eta_{jet} < 4.3$ (Fwd Plug Calorimeter)

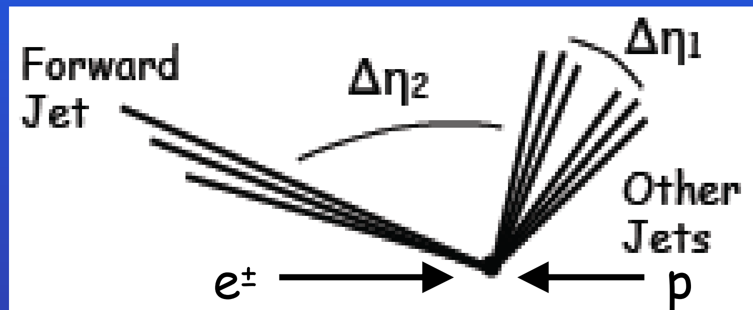
$20 < Q^2 < 100$ GeV^2

$10^{-4} < x_{Bj} < 5\times10^{-2}$

$x_{jet} > 0.036$ -> enhance BFKL expected behaviour

$\Delta\eta_1 = \eta_2 - \eta_1$

$\Delta\eta_2 = \eta_{fwd} - \eta_2$

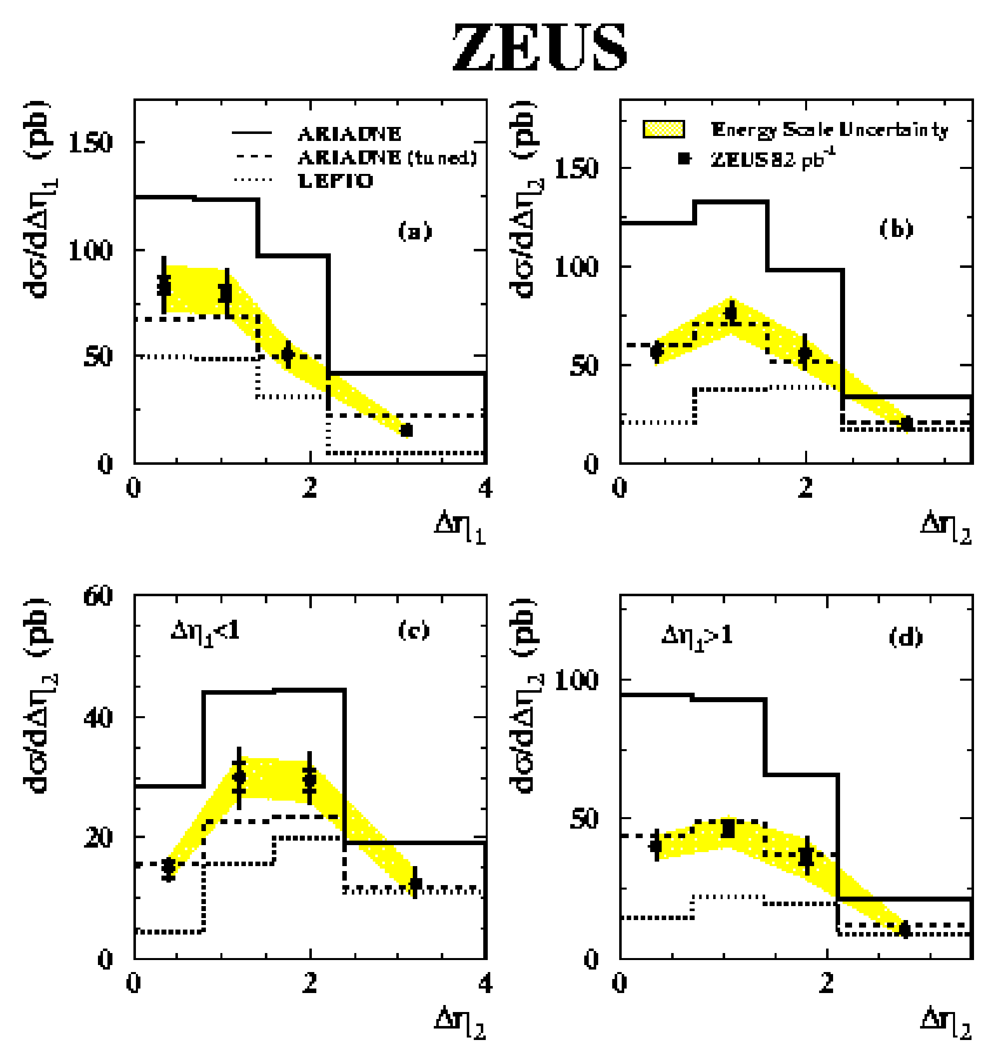


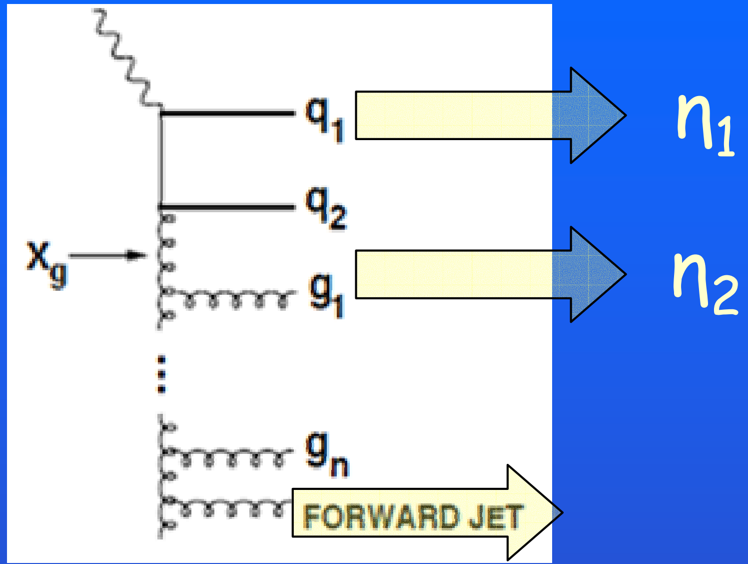
- discrepancy at low $\Delta\eta_1$ and $\Delta\eta_2$, when all 3 jets tend to go forward
- need for additional higher orders or BFKL resummation

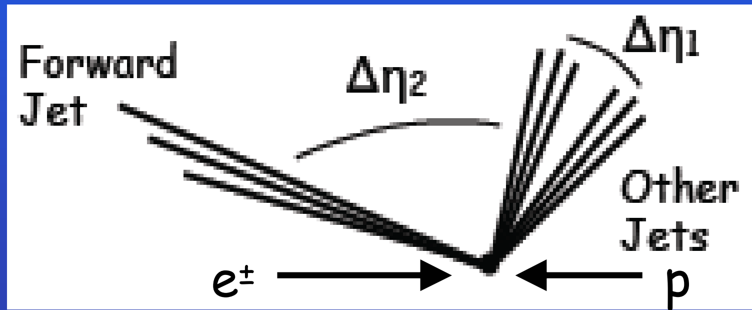
Forward Jet and Dijet

ZEUS: DESY-07-100

$\Delta\eta_1 = \eta_2 - \eta_1$
$\Delta\eta_2 = \eta_{fwd} - \eta_2$







- CDM (Ariadne tuned) describes data reasonably well
- breaking of k_T ordering best modeled by CDM

Summary

- Multi- and forward- jets production has been measured in the region x_{BJ}~10^{-4} and low Q^2 where NLO DGLAP pQCD is expected to fail
- Agreement between data and DGLAP NLO QCD calculations significantly improved going from $O(\alpha_S{}^2)$ to $O(\alpha_S{}^3)$. Nevertheless BFKL enhanced forward jet data at low x_{Bj} are not described even by $O(\alpha_S{}^3)$
- DGLAP based models fail to describe inclusive forward jet measurements, dijet and trijet correlations
- CASCADE (CCFM) depends on unintegrated PDF. Fails to describe inclusive forward jet cross sections
- CDM as implemented in Ariadne (tuned) provides a good description of most datasets

Backup Slides

Kinematic Coverage of Colliders