Multijet Production at Low X_{Bj} and Forward Jet Production in DIS

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Parton dynamics

Perturbative expansion of parton evolution equations $\sim \Sigma_{mn} A_{mn} \ln(Q^2)^m \ln(1/x)^n$

Cannot be explicitly calculated to all orders

1. Fixed order calculations

2. Approximations ⇨ resumming certain infinit subsets of terms according to the phase space region

- **DGLAP, collinear factorisation:** $\sum (\alpha_s \ln Q^2)^n$

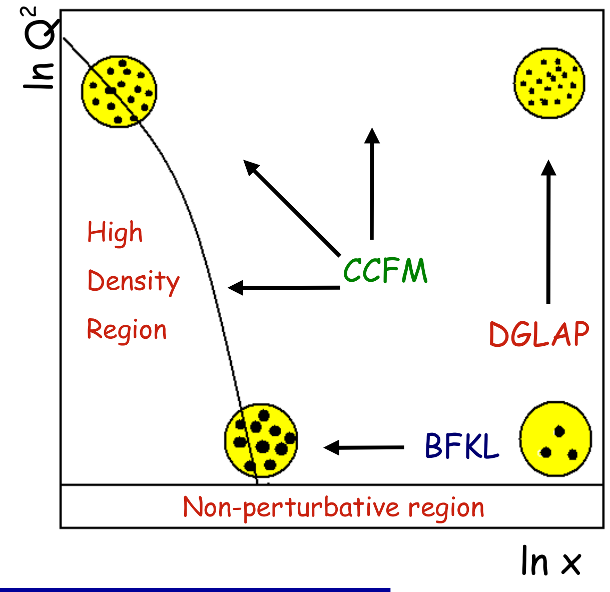
  Ordering in x, ***strong ordering in k_T***

- **BFKL, k_T factorisation :** $\sum (\alpha_s \ln (1/x))^n$

  Strong ordering in x, ***no k_T ordering***

- **CCFM, k_T factorisation:** resum $\ln Q^2$ and $\ln (1/x)$

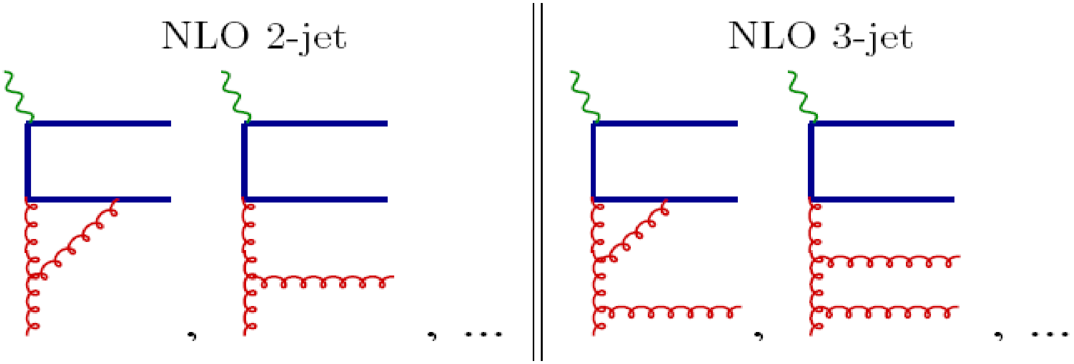
  Angular ordering ⇨ ***k_T non-ordered at small x_{Bj}***



If HERA's x_{BJ} are small enough to reveal deficiency of DGLAP?

QCD Calculations

NLOJET++: Fixed order QCD partonic cross section, on mass shell ME + DGLAP , (collinear factorisation)

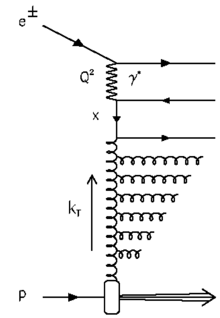


- Terms of up to O(α^2_s) (O(α^3_s)) for dijet (trijet) calculations
- One-loop corrections for virtual particles
- Correction for 3rd (4th) parton in final state (soft/collinear gluon emissions)
- O(α^3_s) calculations possible for dijets for certain jet phase space region
- No fragmentation, hadronization corrections from MC

MC Models

LEPTO: **LO ME on mass shell + PS in DGLAP**

➡ ***Strong ordering in k_T***



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

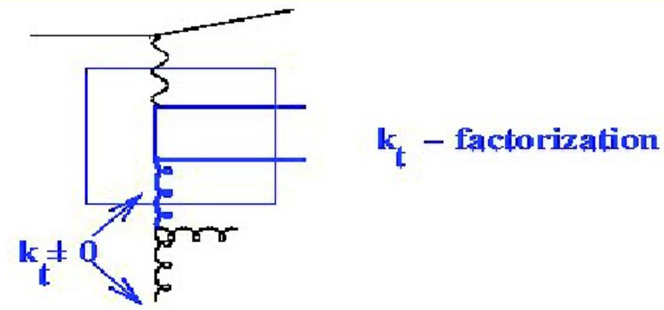
transverse momentum of emitted gluon $k_\perp > k_\perp^{cut}$

<u>uPDF set1</u> : $k_\perp^{cut}$ = 1.33 GeV

<u>uPDF set2</u> : $k_\perp^{cut}$ = 1.18 GeV

non-singular term in splitting function

At small x_{Bj} ***no ordering in k_T***

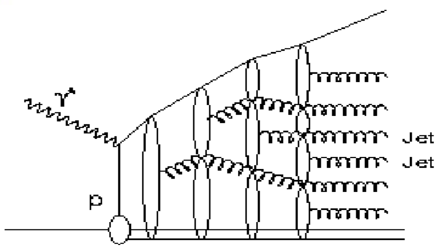


ARIADNE: **implementation of Color Dipole Model (CDM)**

➡ **Independently radiating dipoles formed by emitted gluons**

➡

➡ ***Random walk in k_T*** **<u>like in BFKL</u>**



Dijets&trijets without forward jet

Event & Jet selection

1998 – 2000 ZEUS $e^{\pm}p$ data, 82 pb^{-1}

Low – x_{Bj} DIS selection

$$10^{-4} < x_{Bj} < 10^{-2}$$

$$10 < Q^2 < 100\ GeV^2$$

$$0.1 < y < 0.6$$

Dijet/trijet selection

$$E_{T,HCM}^{jet1} > 7\ GeV$$

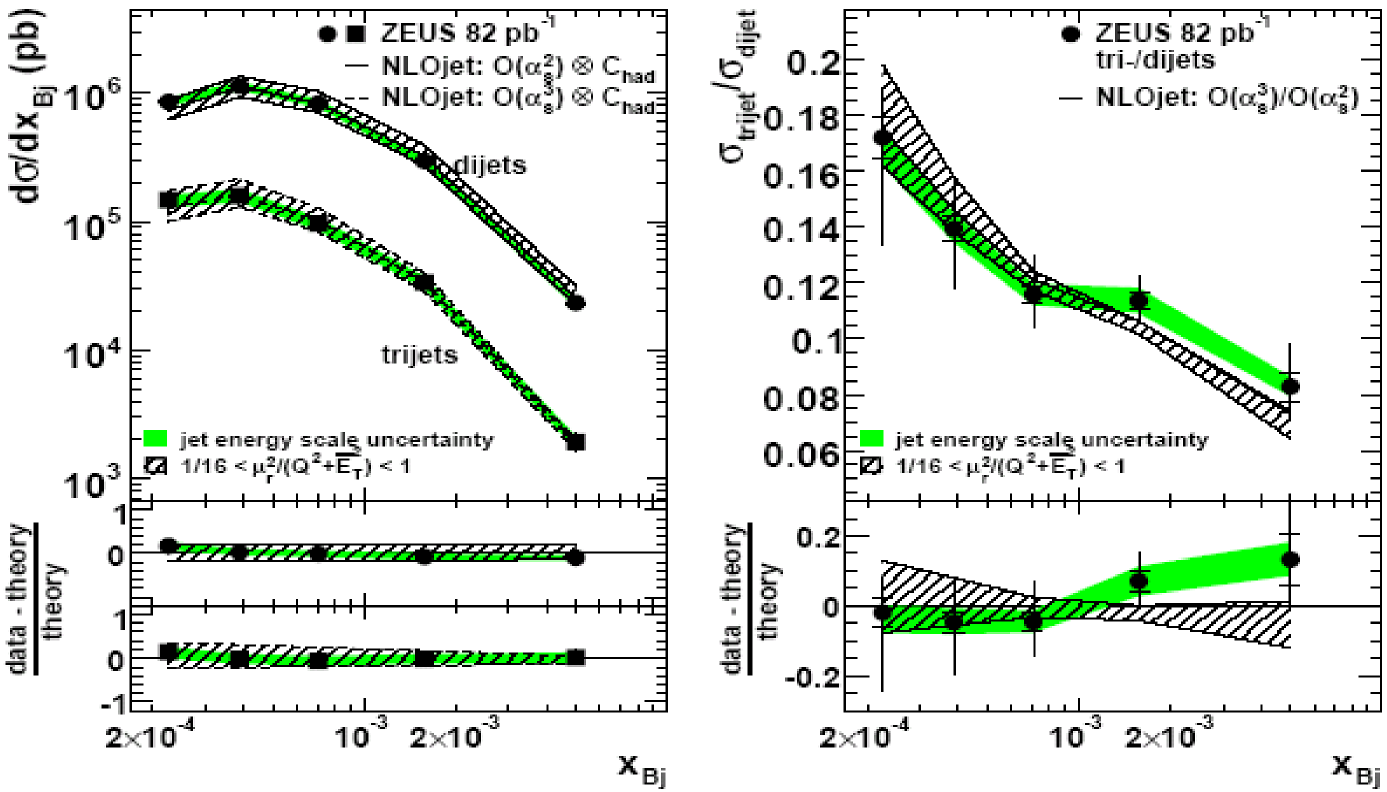
$$E_{T,HCM}^{jet2(,3)} > 5\ GeV$$

$$-1 < \eta_{LAB}^{jet1,2(,3)} < 2.5$$

Jets reconstructed with K_T algorithm in inclusive mode

Dijets & trijets vs. x_{Bj}

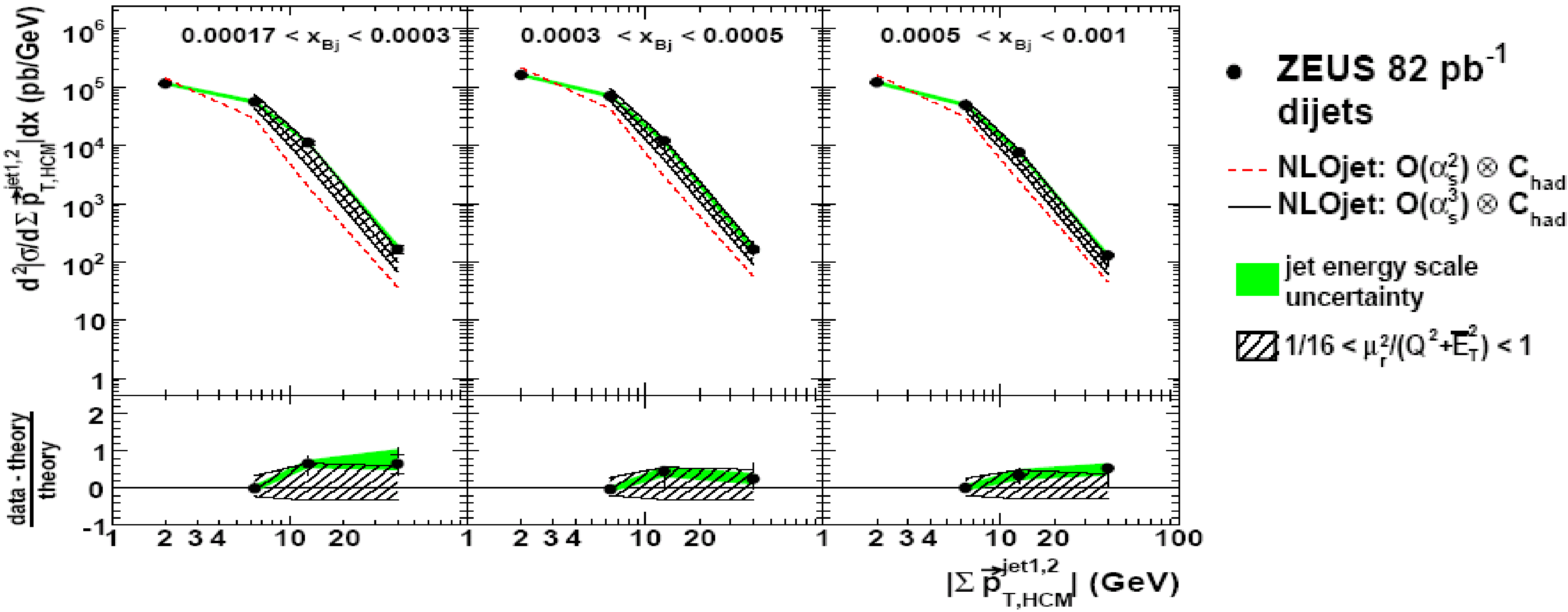
NLOjet++ compared with data on inclusive cross-sections (left) and ratios of trijet to dijet cross-sections (right)



- **Dijets and trijets are described by NLO.**
- **For cross section ratios theoretical uncertainties mainly canceled, within these smaller uncertainties agreement is again satisfactory**

P_T correlations for dijets

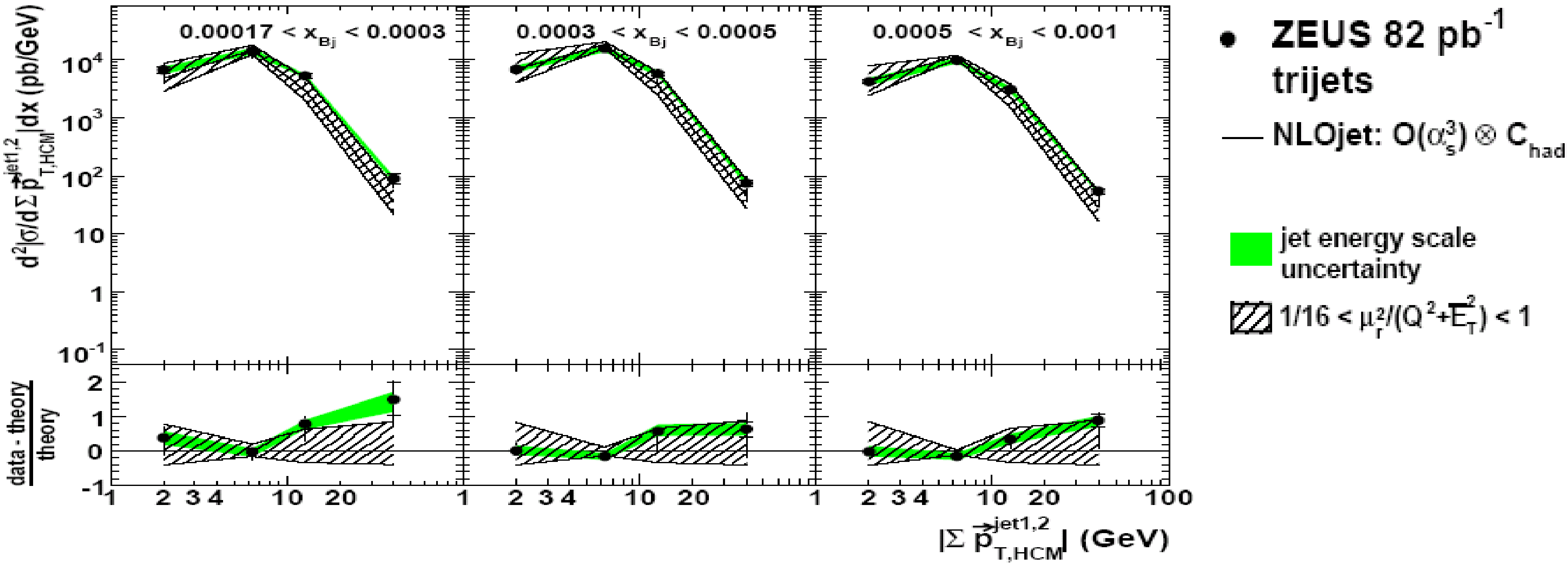
Inclusive distributions are of insufficient resolving power, try correlations.
First, abs. value of vector sum of p_T of two jets, NLOjet vs data
Without gluon radiation two jets are correlated, back to back in HCMS: $|\Sigma p_T| = 0$



- **Calculations at $O(\alpha_s^2)$ are much below data**
- **Difference is largest for smallest x_{BJ}**
- **Addition of $O(\alpha_s^3)$ leads to agreement with data (within theoretical uncertainty, which is large)**

P_T correlations for trijets

Abs. value of vector sum of p_T of two highest E_T jets, NLOjet vs data

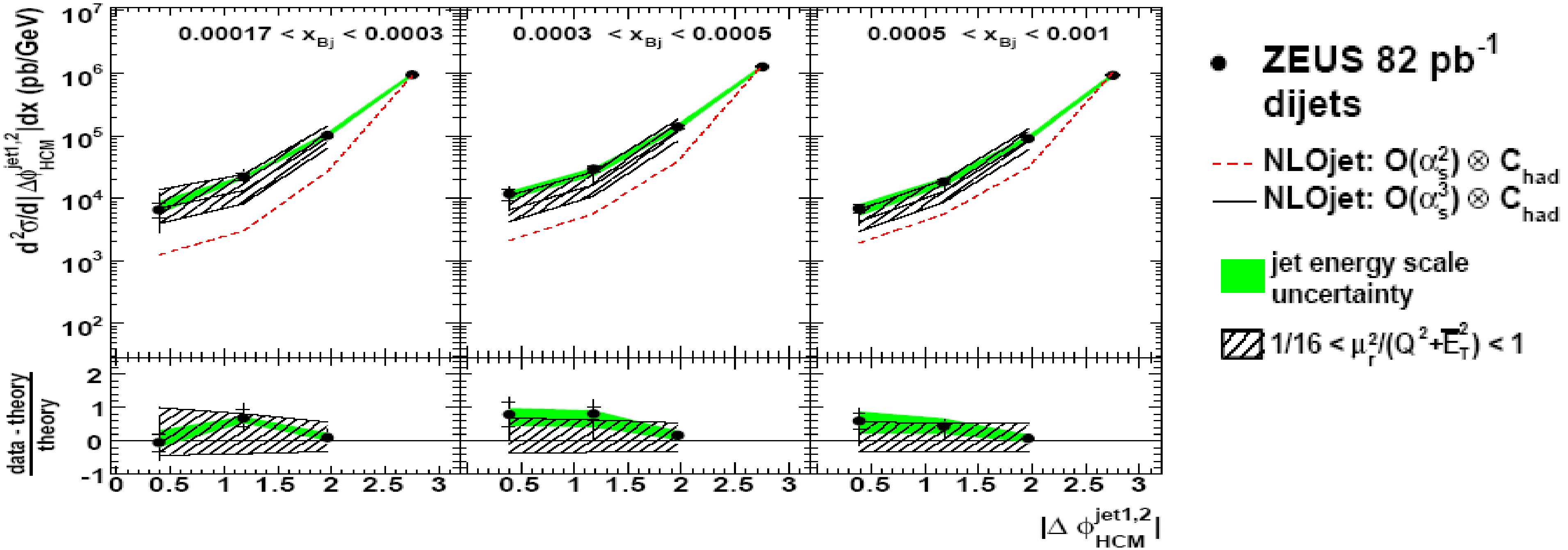


Calculations agree with data within theoretical uncertainty

ϕ correlations for dijets

Separation in azimuthal angle ϕ of two jets, NLOjet vs data

$|\Delta\phi| = \pi$ without gluon radiation



- **NLOjet calculations at $O(\alpha_s^2)$ are much below data**
- **Difference seemingly increases with decrease of x_{Bj}, reaching almost one order of magnitude for smallest x_{BJ} and most decorrelated jets**
- **Addition of $O(\alpha_s^3)$ leads to agreement with data**

One additional gluon is not enough, at least two are needed

Forward Jets

Event & Jet selection

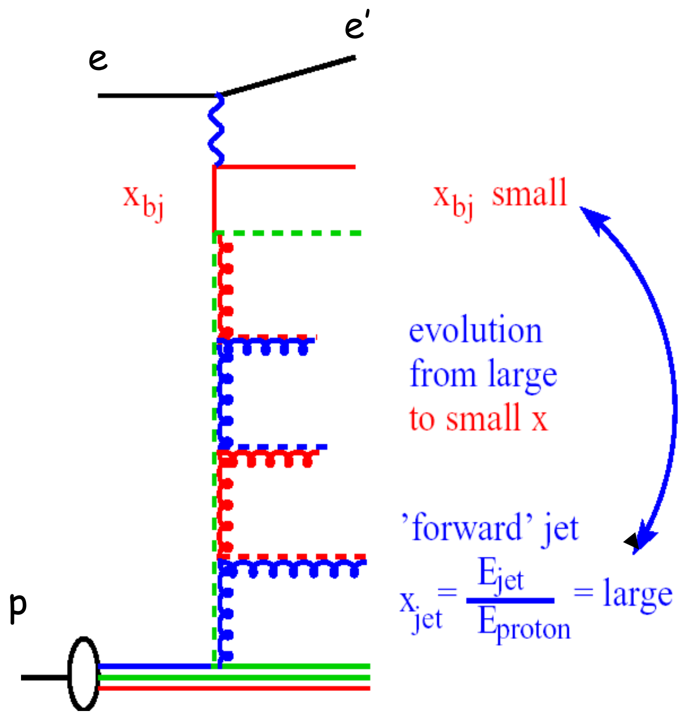
Kinematic range

98-00 Data, L ≅ 82 pb^{-1}

20 < Q^2 < 100 GeV^2

0.0004 < x_{Bj} < 0.005

0.04 < y < 0.7



Forward Jet selection

Inclusive K_T algorithm

E_t^{jet} > 5 GeV

2< η^{jet}<4.3

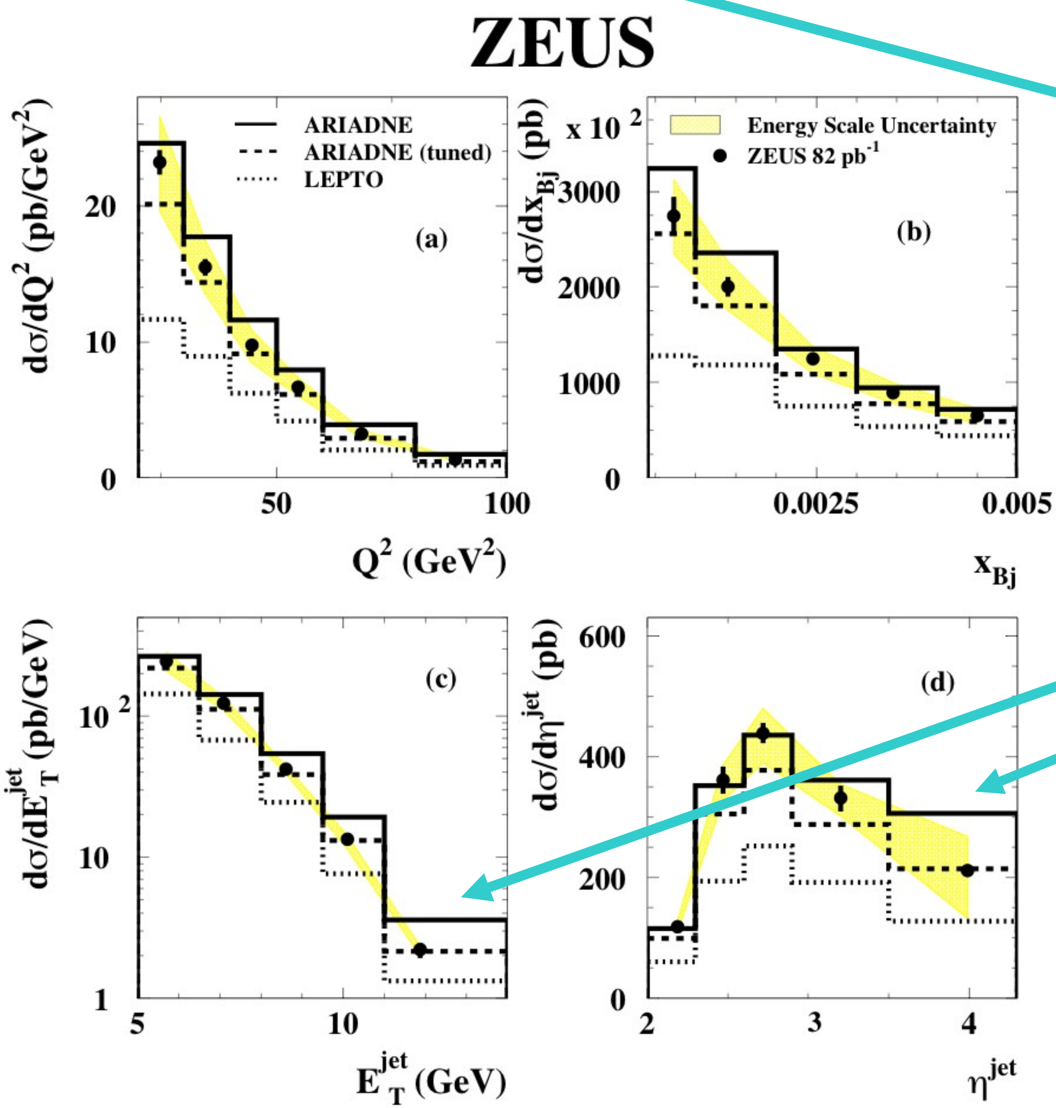
1.4 unit more forward than before

0.5 < $(E_t^{jet})^2/Q^2$ < 2 → $(E_t^{jet})^2 \sim Q^2$ suppresses DGLAP evolution

x_{jet} > 0.036 → $x_{jet} = E_{jet}/E_{proton} >> x_{Bj}$ enhances BFKL evolution

Inclusive Forward Jets

LEPTO & ARIADNE vs data

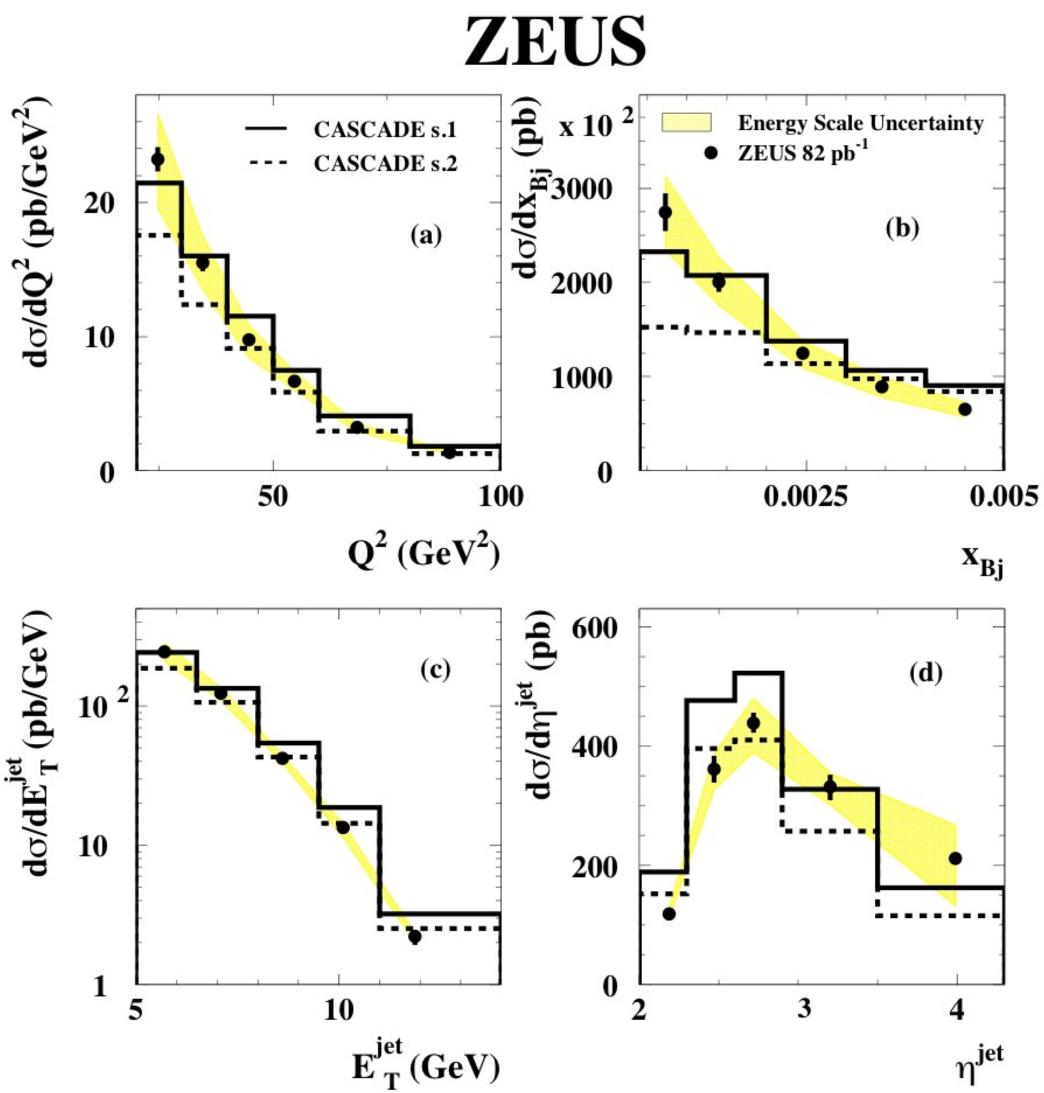


Two versions, with default tuning ("default") and retuned by H1 ("tuned")

- **Lepto doesn't suffice**
- **Ariadne "default " overestimates high E_t^{jet}, overestimates high η^{jet} (proton remnant)**
- **Ariadne "tuned" is good**

Inclusive Forward Jets

CASCADE vs data



Non singular term (in set 2) reduces cross section, but not improves agreement

Shape of all distributions disagrees with data

Shape is a problem

Trijet with a Forward Jet

Event & Jet selection

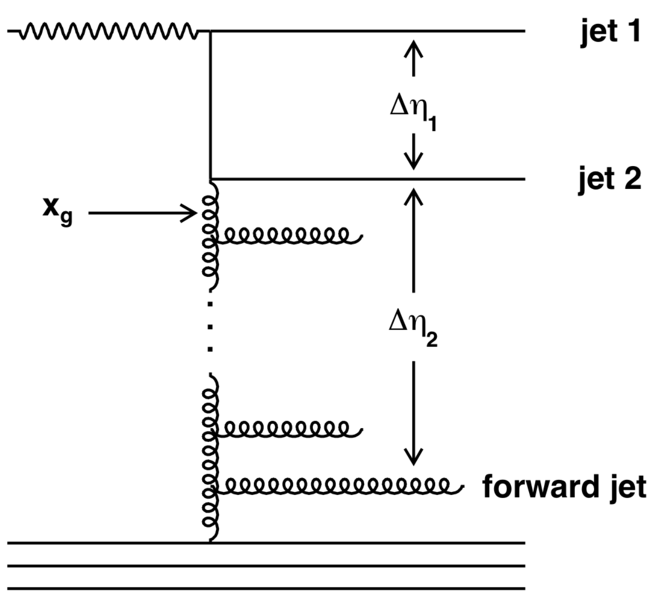
<u>Kinematic range the same as for inclusive forward jets</u>

Forward jet the same,

$0.5 < (E_t^{jet})^2/Q^2 < 2$ **constraint excluded**

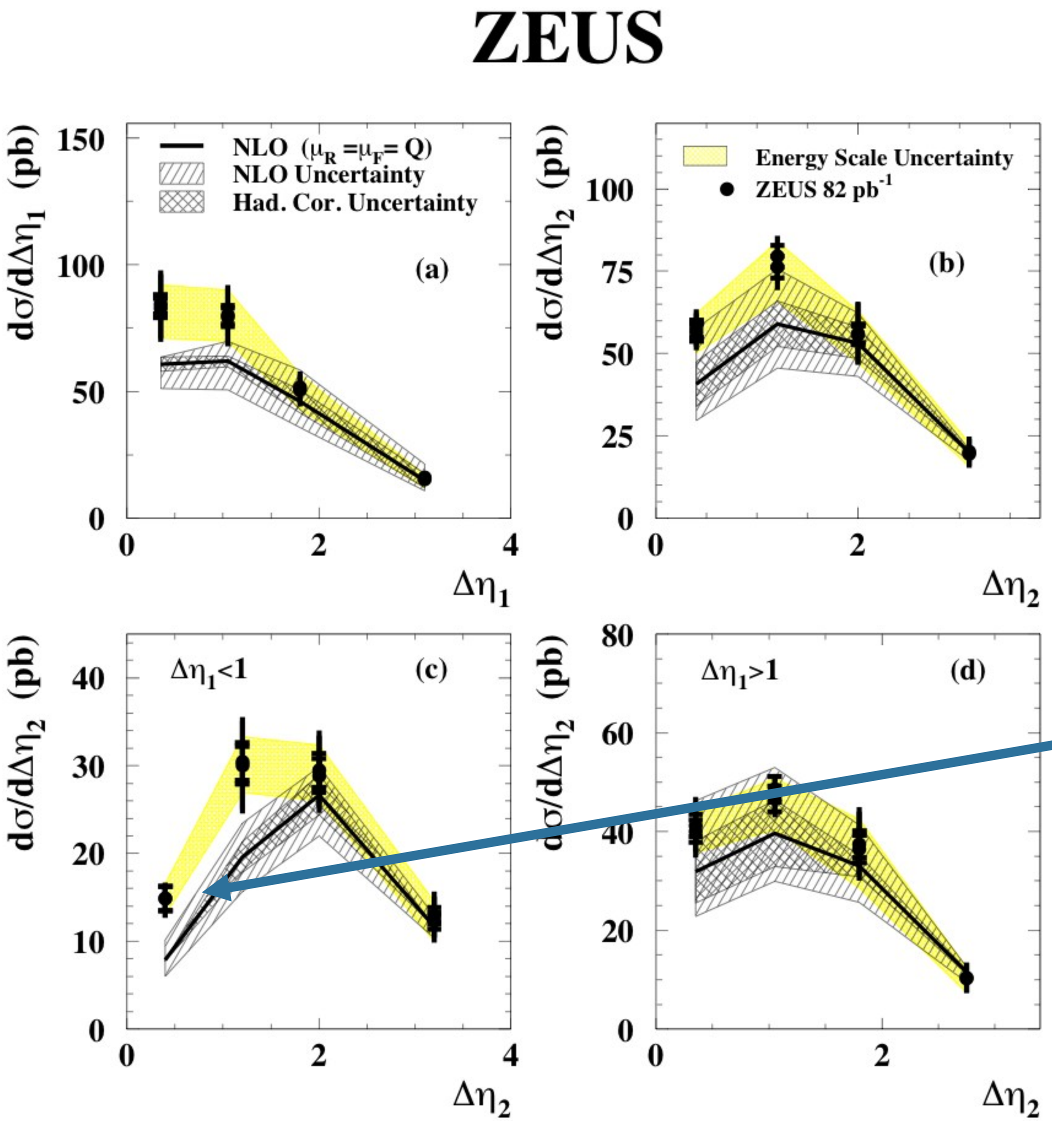
Two additional jets with $E_t^{jet} > 5$ **GeV**

$\eta_{el} < \eta_{jet\ 1} < \eta_{jet\text{-}2} < \eta_{forward\text{-}jet}$



Trijet with a Forward Jet

NLOJET++ vs data

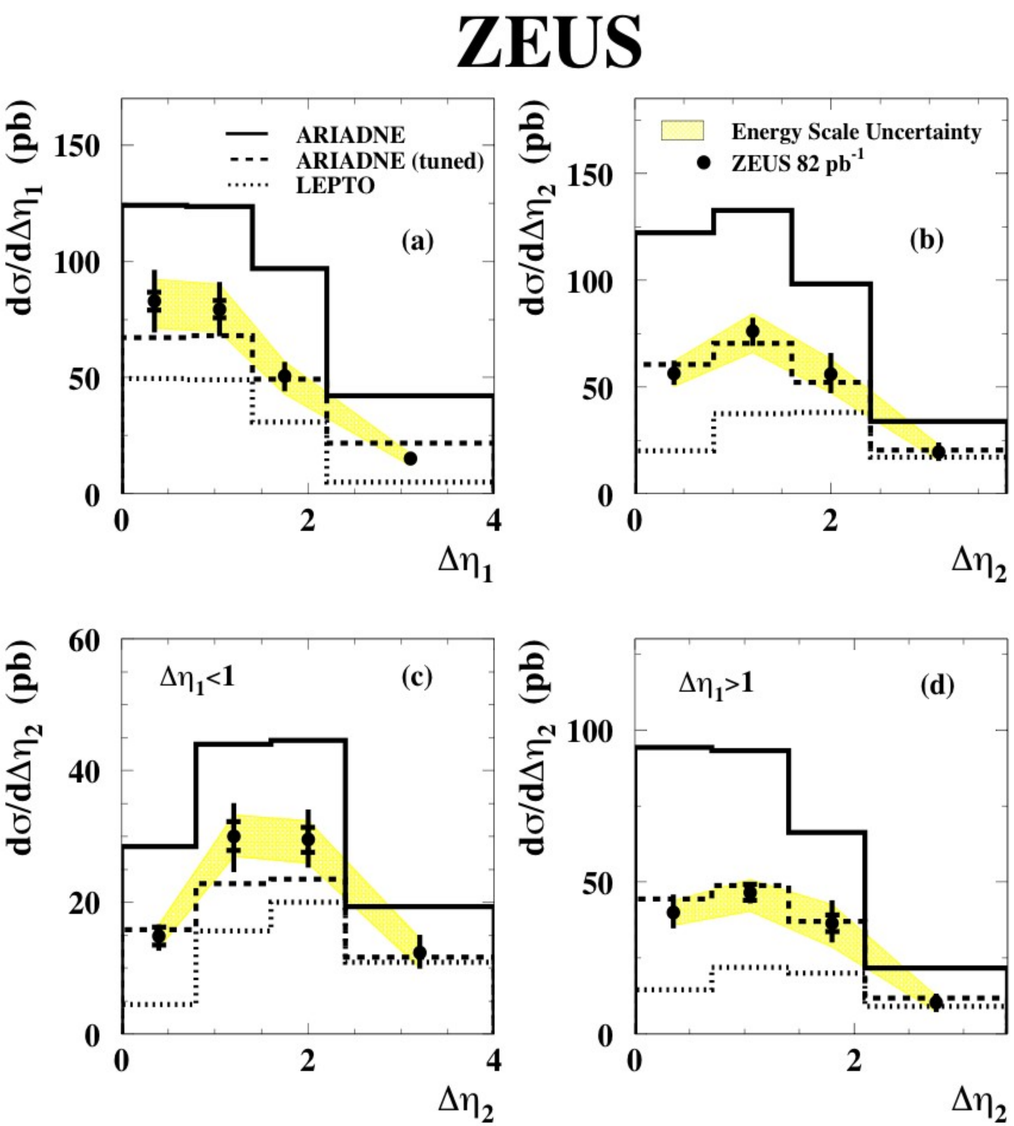


For NLOjet scales $\mu_R^2 = \mu_F^2 = Q^2$

Small $\Delta\eta_1$ and $\Delta\eta_2$ → jets are most forward. At small x_{Bj} space is left for additional partons closer to the photon. NLOJET++ underpredicts many partons → below data

Trijet with a Forward Jet

LEPTO & ARIADNE vs data



Lepto below data

Ariadne "default" pronouncedly above data –> too high multigluon emission rate

Ariadne "tuned" is fine

Summary & Conclusions

☎ ZEUS measured jets at small x_{Bj} in highly extended forward region

☎ Inclusive cross-sections of dijets and trijets without forward jets are satisfactorily described by collinear factorisation based NLO

☎ Correlations are more sensitive to parton dynamics, in particular they reveal failure of NLO for dijets, where only NNLO, i.e. $O(\alpha_s^3)$, suffices ⇒ four partons at HERA's lowest x_{BJ} are needed.

☎ Further insight provides addition to analysis of a forward jet, in particular η correlations for trijets with a forward jet reveal in certain phase space deficiency of $O(\alpha_s^3)$, here at least five partons are needed.

☎ Resummed DGLAP, realized by MC with LO matrix element and parton showers, LEPTO, yields about twice too low forward jet cross-sections.

☎ LO CCFM based MC, CASCADE, cannot fully describe data on forward jets, other sets of uPDF are to be tried (and/or more serious problems show up, i.e. lack of quarks).

☎ Only CDM (ARIADNE MC), featured by BFKL-like non-ordered in k_T parton cascade, is capable of successful description of the whole volume of data on forward jets. A problem could to be, nevertheless, that being based on phenomenology ARIADNE is too free in tuning.