Multijets in NC DIS and Jets in CC DIS at HERA

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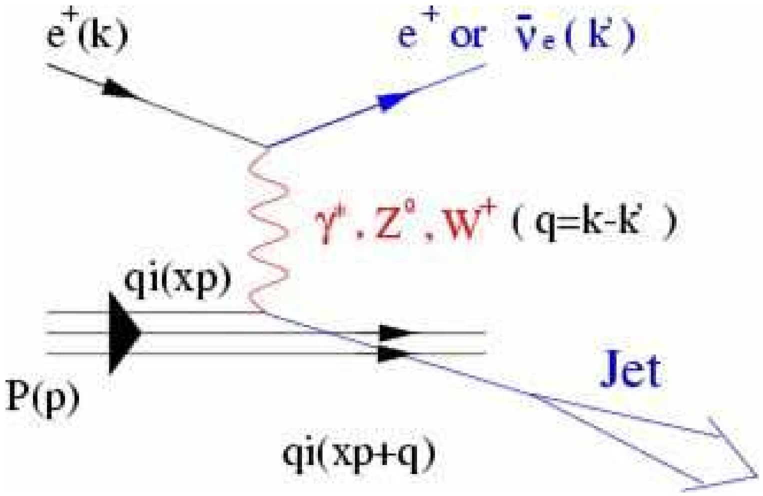
- Motivation
- Multijets in NC DIS
- Jets in CC DIS
- Jet Multiplicities in CC DIS
- Conclusions

Motivation

- QCD is the theory of the strong interaction
- HERA is a very good machine for studying QCD
- jet production provides a detailed test of perturbative QCD in a wide range of processes and over a wide range of scales
- multijets (2 and 3) enable tests of QCD matrix elements at higher orders in α_s
- measuring jets in charged current gives the possibility to test QCD matrix elements and flavour changing electroweak theory at the same time
- subjets allow a detailed study of the jet structure
- precision measurements allow the extraction of α_s

Kinematic variables



neutral current: $e^+ p \to e^+ X$
propagator: (γ, Z)

charged current: $e^+ p \to \nu X$
propagator: (W^+)

beam energies at HERA:
$E_p = 820$ GeV/920 GeV
$E_e = 27.52$ GeV

Variables:

- boson virtuality:
  $Q^2 = -q^2$
- fraction of proton energy carried by struck parton:
  $x = Q^2/2pq$
- fraction of electron energy transferred:
  $y = pq/pk$
- center of mass energy squared
  $s = (p+k)^2$
- angle of hadronic system in the lab:
  $\cos \gamma_h = \frac{(\Sigma p_x)^2 + (\Sigma p_y)^2 - (\Sigma E - p_z)^2}{(\Sigma p_x)^2 + (\Sigma p_y)^2 + (\Sigma E - p_z)^2}$

center of mass energy at HERA:
$1995 \to 97:$ $\sqrt{s} \approx 300$ GeV
$1998 \to 00:$ $\sqrt{s} \approx 318$ GeV

Jet Kinematics

jet definition:

- using longitudinally invariant KT algorithm
  (Catani et. al.; Ellis & Soper)

- distance between energy deposits:
  $d_{ij} = \min(E_{T,i}^2, E_{T,j}^2) * (\Delta\eta^2 + \Delta\phi^2)$

- merging deposits as long as
  $d_{ij} < \min(E_{T,i}^2, E_{T,j}^2)$

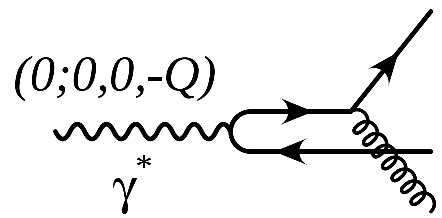
jet variables:

- pseudorapidity:
  $\eta = -\ln(tan(\theta/2))$

- transverse energy:
  $E_T = \sqrt{p_x^2 + p_y^2}$

- invariant mass:
  $m = \sqrt{\Sigma p_i^2}$

Breit frame:



frame in which:

- photon and quark hit head on

- photon is only space-like:
  ⇒quark gets reflected

- jets balance each other in p_T
  ⇒for dijets:
  ambiguity ordering jets in E_T

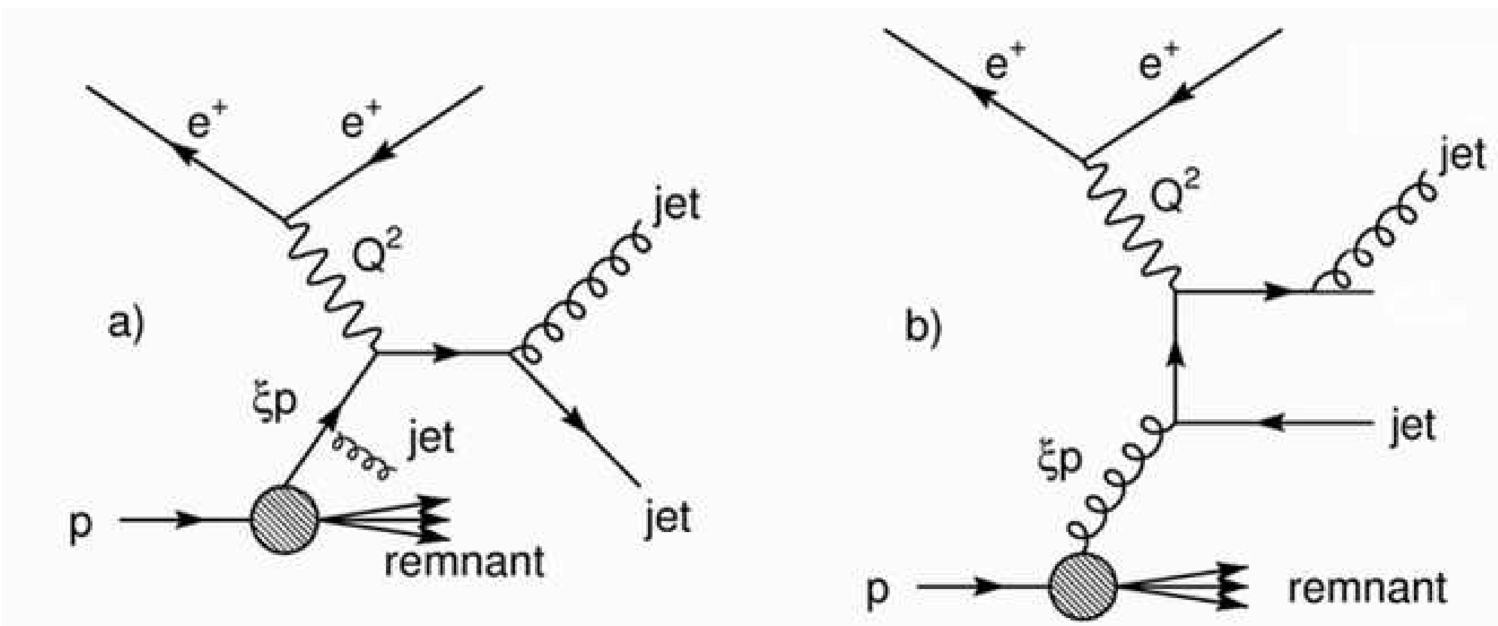
Motivation for studying Multijets

- trijets: adding a gluon radiation to dijets or splitting a gluon in a $q\bar{q}$ pair
  ⇒ direct test of QCD at intrinsically higher order

- trijet cross section: sensitive to $\mathcal{O}(\alpha_s^2)$ in LO
  ⇒ higher sensitivity to α_s

- more degrees of freedom
  ⇒ QCD test in detail

- looking at the cross section ratio trijets over dijets many theoretical and experimental uncertainties cancel out



Event selection for Multijets

- ZEUS data 98–00: 82.2 pb^{-1}
- reconstruction in Breit frame
- using longitudinally invariant KT jet cluster algorithm
- kinematic selection:
  - $10\,\text{GeV}^2 < Q^2 < 5000\,\text{GeV}^2$
  - $0.04 < y < 0.6$
  - $\cos\gamma_h < 0.7$
- jet selection:
  - for all jets: $E_T^{breit} > 5\,\text{GeV}$
  - for all jets: $-1 < \eta^{lab} < 2.5$
  - $m_{jets} > 25\,\text{GeV}$

Selecting events over a large kinematic range

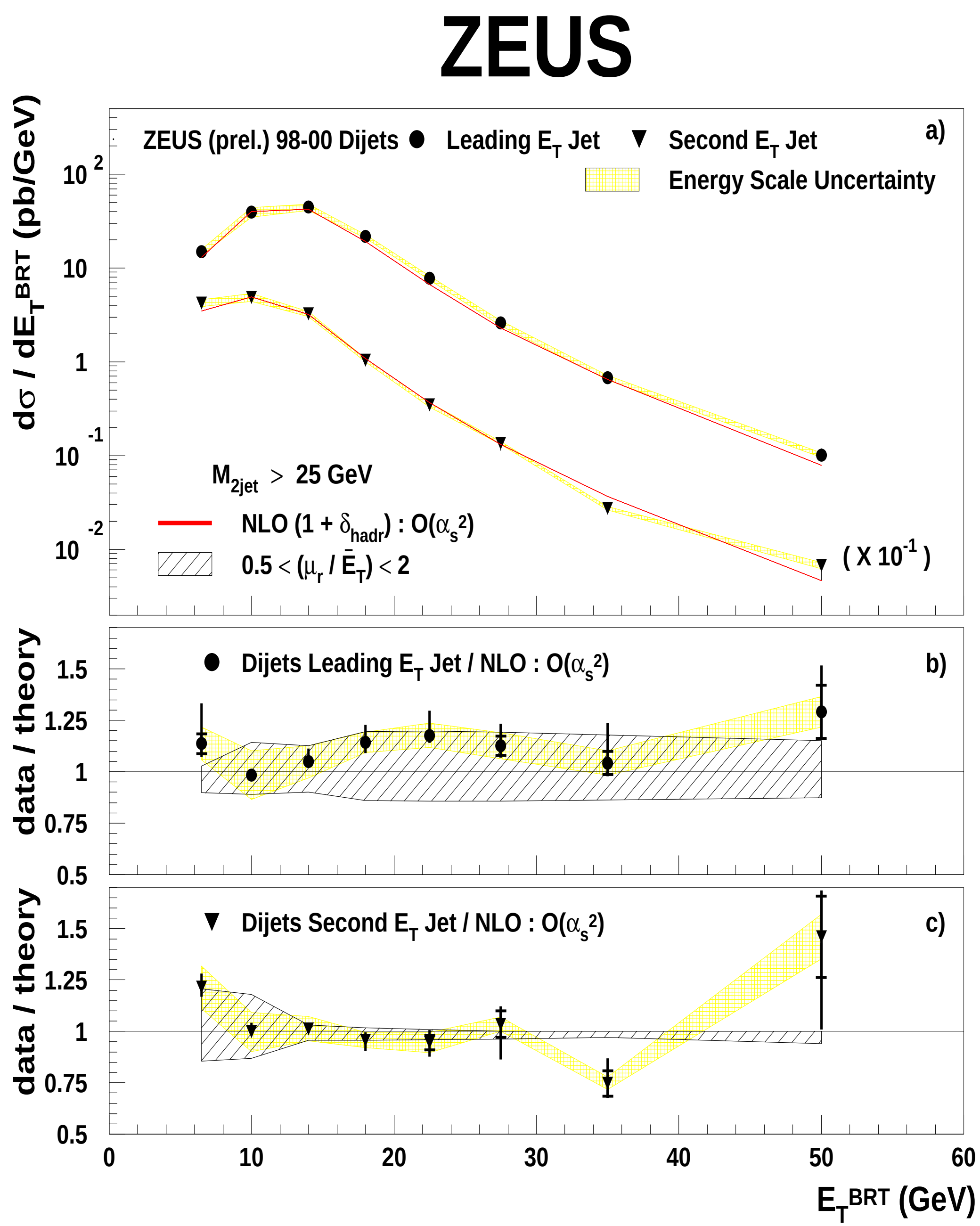
Selected 30668 dijet events

Selected 12436 trijet events

NLO calculation

- comparison with NLO QCD:
  dijets at NLO - $\mathcal{O}(\alpha_s^2)$: $d\sigma_{\text{2jets}}^{\text{NLO}} = \alpha_s(A_2 + B_2\alpha_s)$
  trijets at NLO - $\mathcal{O}(\alpha_s^3)$: $d\sigma_{\text{3jets}}^{\text{NLO}} = \alpha_s^2(A_3 + B_3\alpha_s)$
- provided by program NLOJET by Nagy, Trócsányi
- employs subtraction method
- renormalisation scale $\mu_r = \bar{E}_T$, factorisation scale $\mu_f = \bar{E}_T$
- dijets: $\bar{E}_T = (E_{T,1} + E_{T,2})/2$
- trijets: $\bar{E}_T = (E_{T,1} + E_{T,2} + E_{T,3})/3$
- estimated renormalisation scale uncertainty by varying $\bar{E}_T/2 < \mu_r, \mu_f < 2 * \bar{E}_T$
- PDF: CTEQ6
- corrected from partons to hadrons employing the Lund String Fragmentation model using the Monte Carlo event generator Lepto (6.5.1) in combination with Jetset

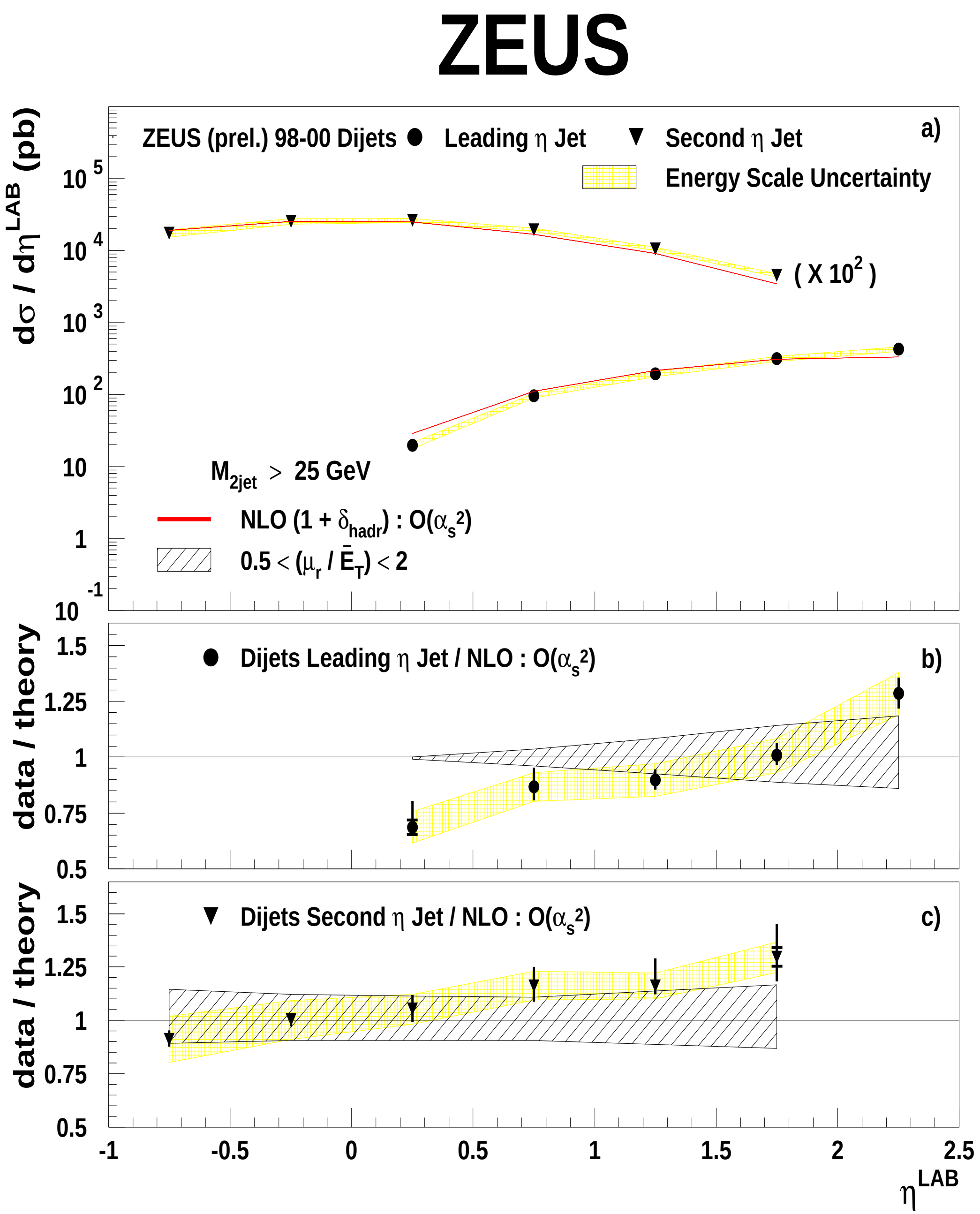
Dijets in NC: E_T dependence



jets ordered in E_T

NLO calculations describe the E_T distribution for dijets

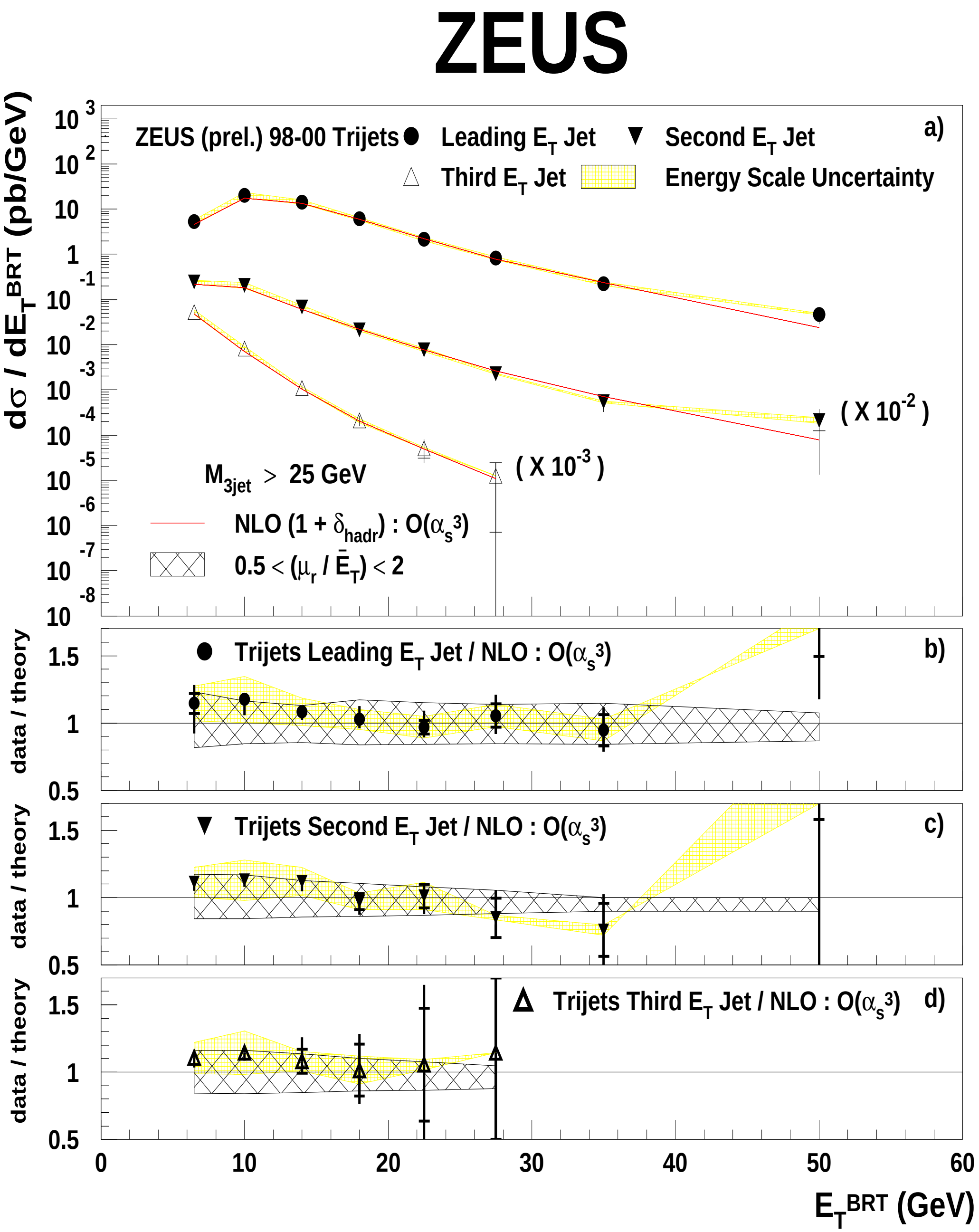
Dijets in NC: η dependence



jets ordered in η

NLO calculations describe the η distribution for dijets

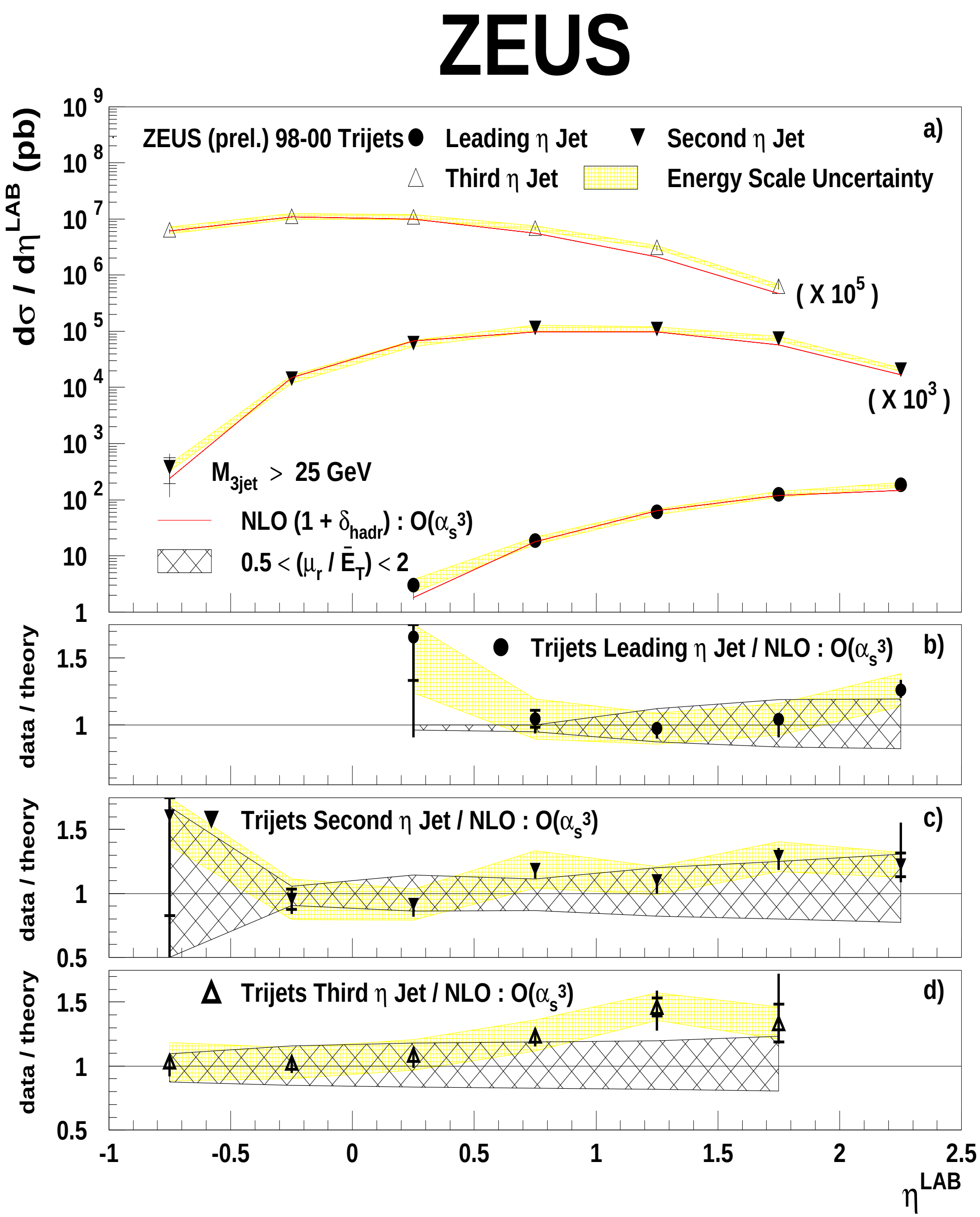
Trijets in NC: E_T dependence



jets ordered in E_T

NLO calculations describe the E_T distribution for trijets

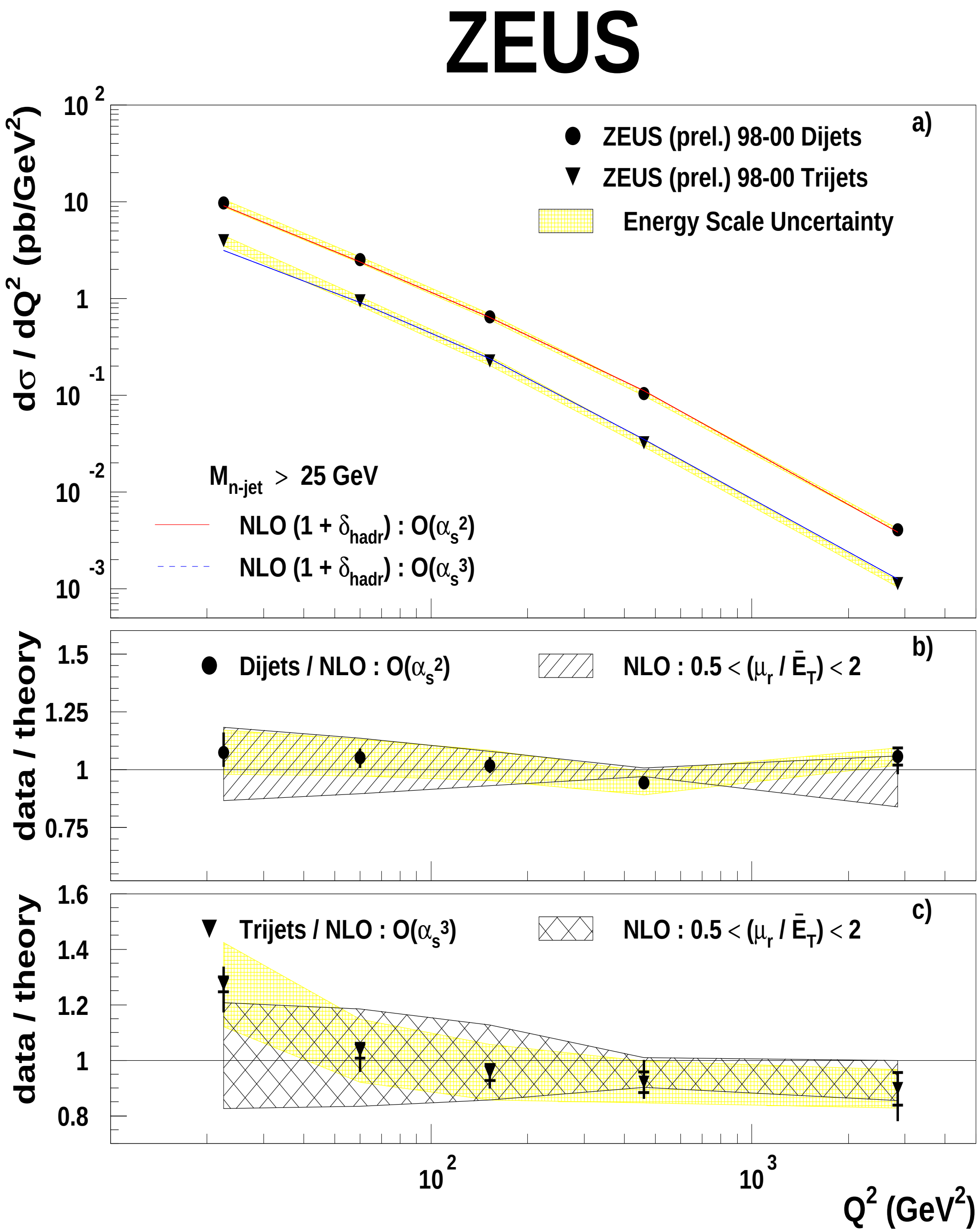
Trijets in NC: η dependence



jets ordered in η

NLO calculations describe the η distribution for trijets

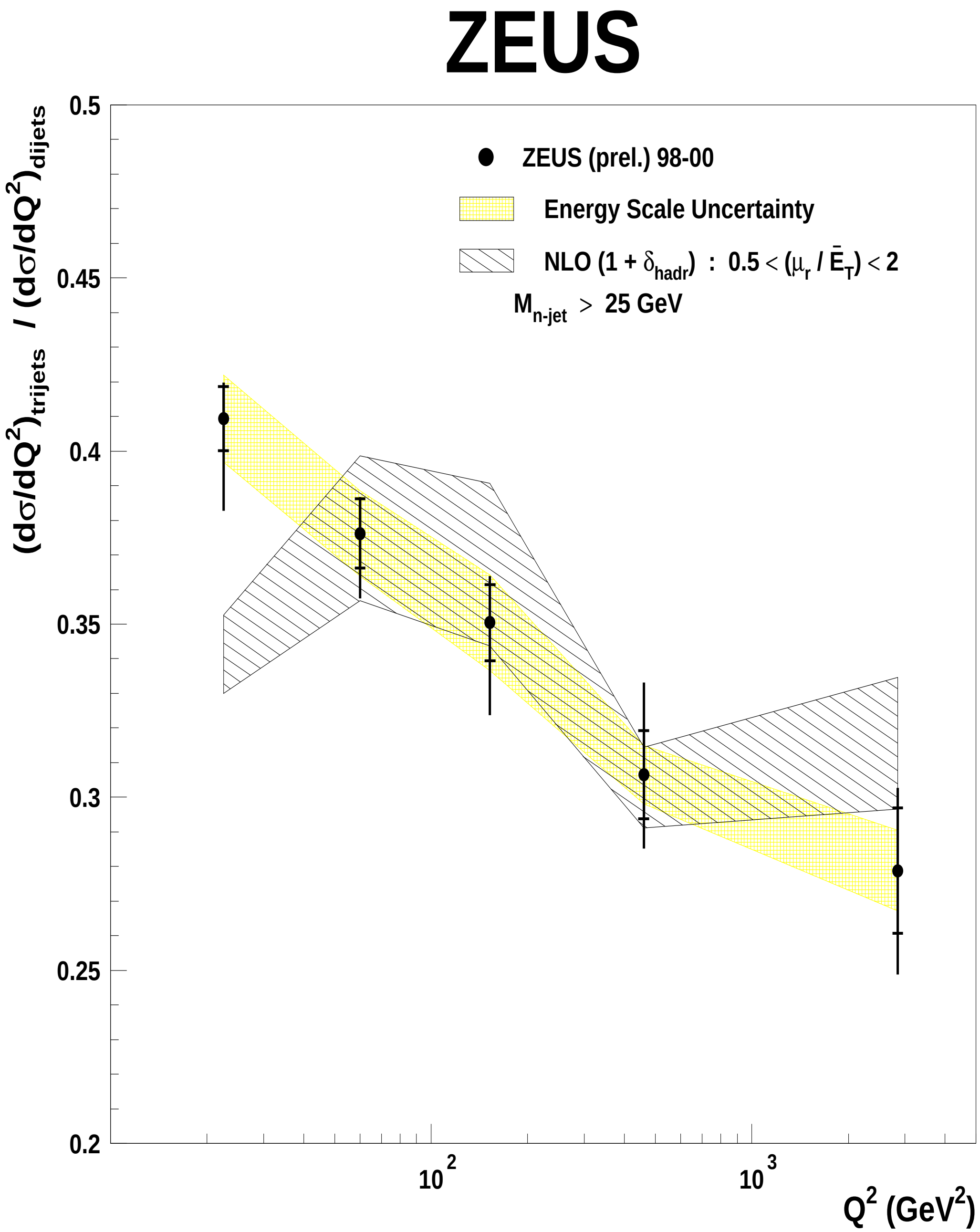
Multijets in NC: Q^2 dependence



NLO calculation changes shape during renormalisation scale variation problematic?

NLO calculations describe the Q^2 distribution for both di- and trijets

Multijets in NC: σ_3/σ_2

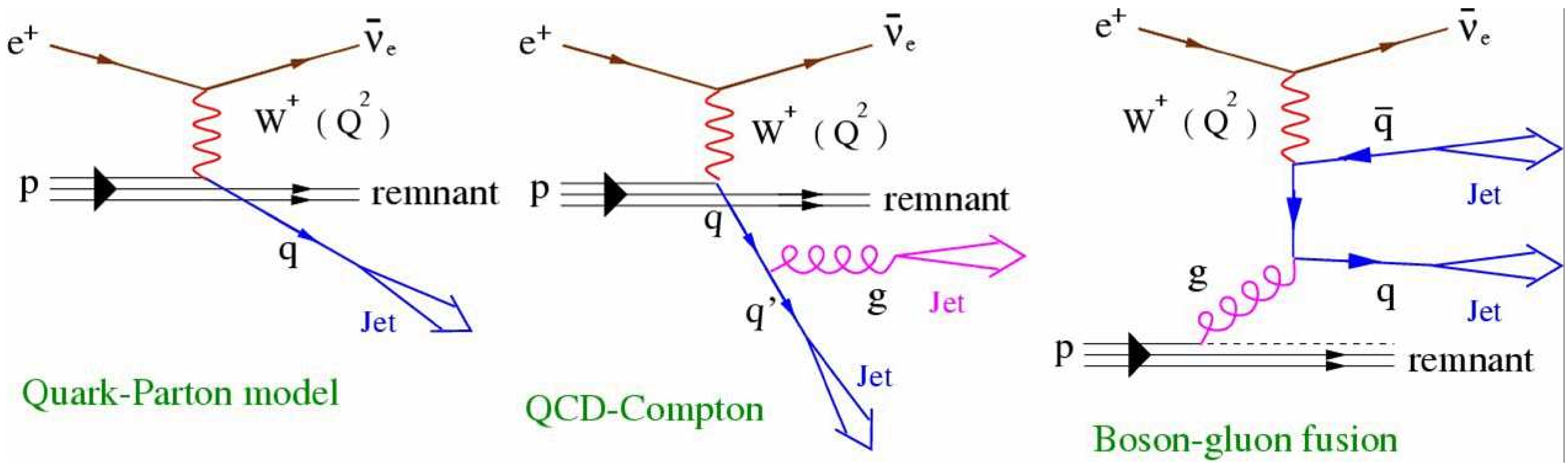


taking cross section ratio reduced both the theoretical and the experimental uncertainties

NLO calculations describe the cross section ratio trijets over dijets

Motivation for Charged Current Measurements

- measuring jet cross sections is a direct test of pQCD
- measuring jet cross sections in CC provides a test for flavour changing electroweak theory and QCD
- study of subjet multiplicities allows precision test of QCD calculation and extraction of α_s



Event selection for CC

- using 95–00 data (127.7 pb^{-1})
- reconstruction in lab frame
- using longitudinally invariant KT jet cluster algorithm
- kinematic selection:
  - $Q^2 > 200\,\text{GeV}^2$
  - $y < 0.9$
- jet selection:
  - $E_T > 14\,\text{GeV}$ (first jet)
  - $E_T > 5\,\text{GeV}$ (second jet)
  - $-1 < \eta_{jet}^{lab} < 2$

Selecting events over a controlled kinematic range

Selected 1865 one jet events

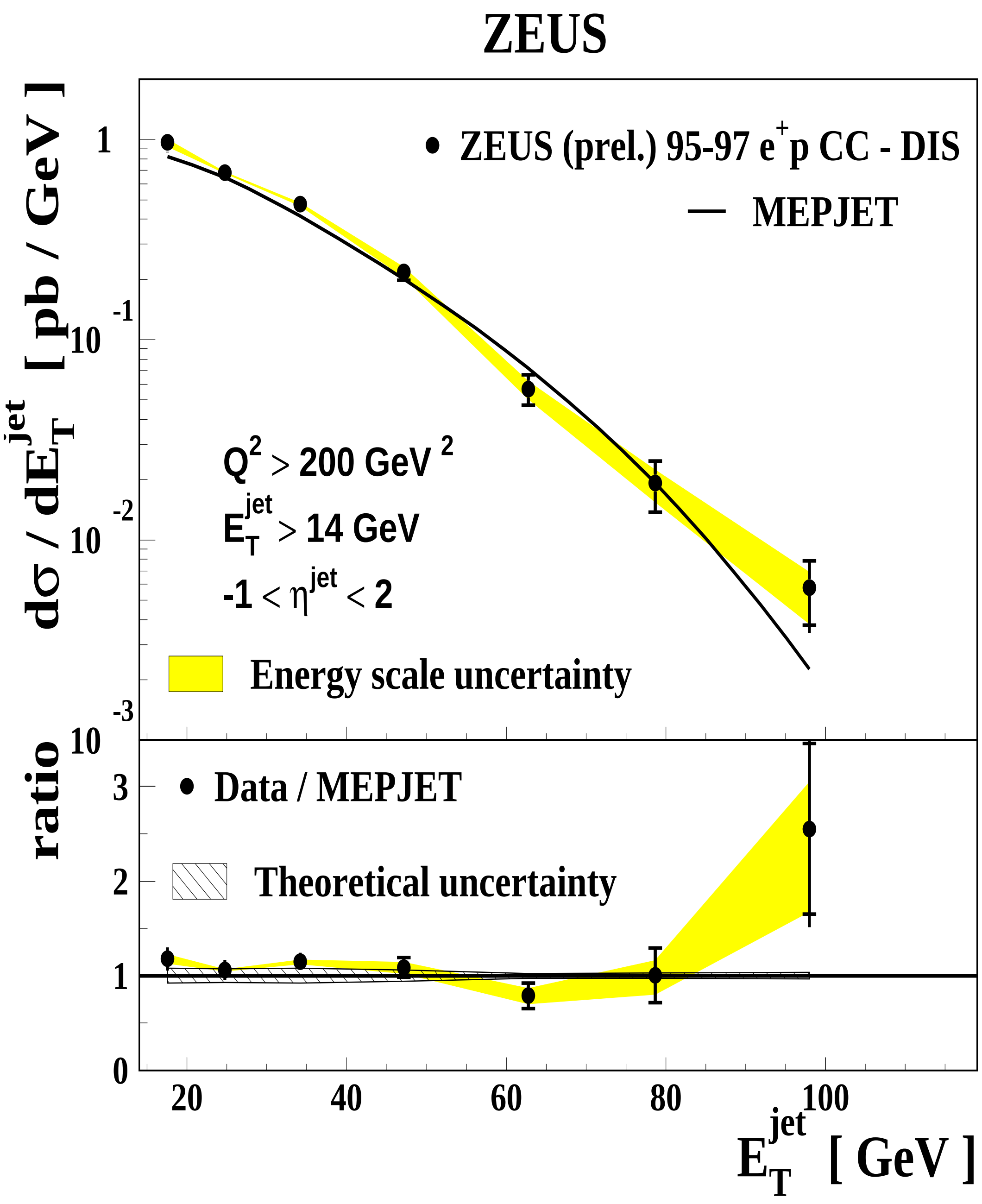
Selected 282 dijet events

NLO calculation

- comparison with NLO QCD:
  inclusive at NLO - $\mathcal{O}(\alpha_s^1)$: $d\sigma^{\text{NLO}}_{\text{inclusive}} = (A_1 + B_1\alpha_s)$

  dijets at NLO - $\mathcal{O}(\alpha_s^2)$: $d\sigma^{\text{NLO}}_{\text{2jets}} = \alpha_s(A_2 + B_2\alpha_s)$
- provided by program MEPJET by Mirkes, Zeppenfeld, Willfahrt
- employs phase space slicing method
- renormalisation scale $\mu_r = Q$, factorisation scale $\mu_f = Q$
- estimated renormalisation scale uncertainty by varying $Q/2 < \mu_r < 2 * Q$
- PDF: CTEQ4M
- corrected from partons to hadrons using leading order Monte Carlo Ariadne (4.08) and Lepto (6.5.1)

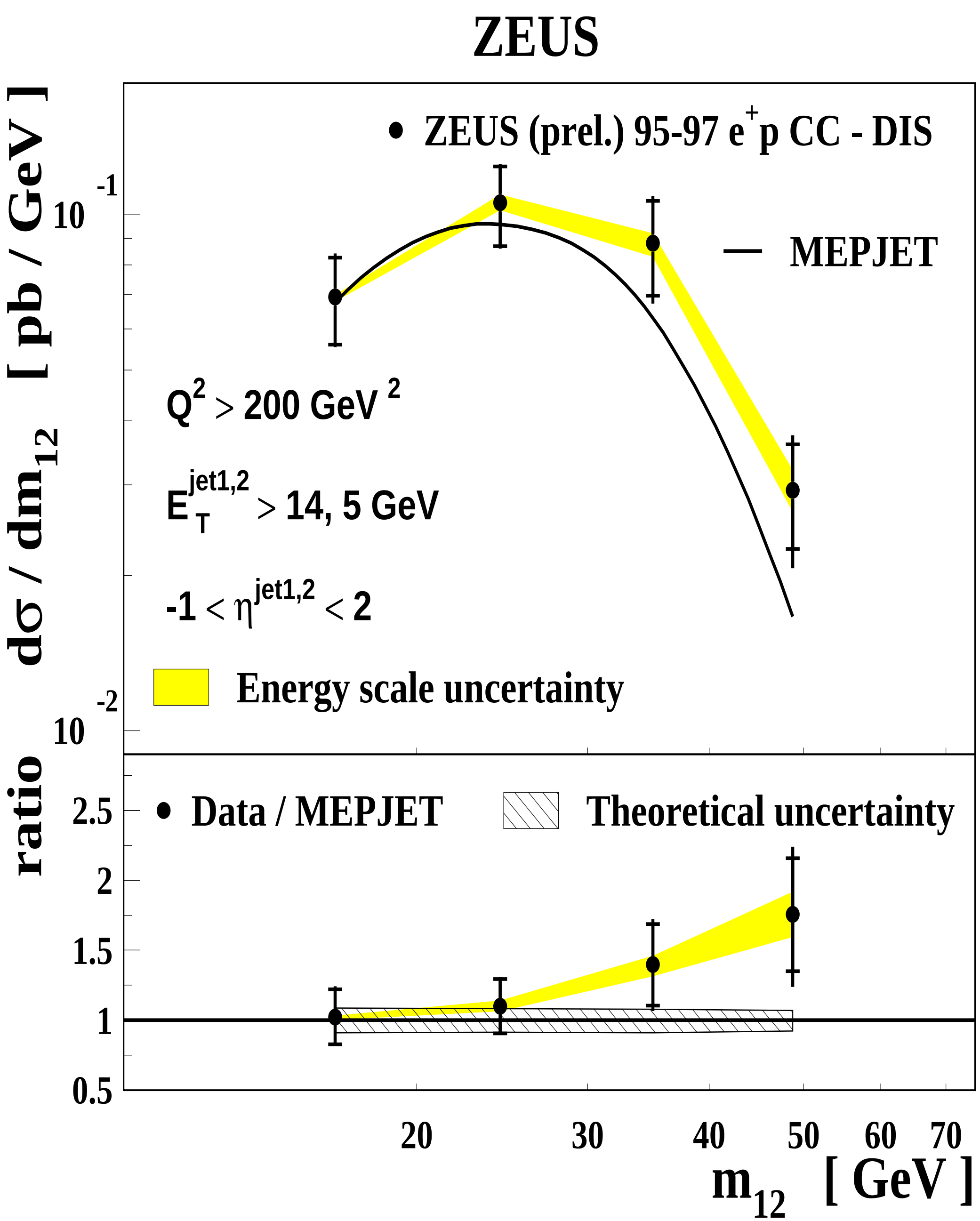
dependence of CC inclusive jets on E_T



counting all jets in the event

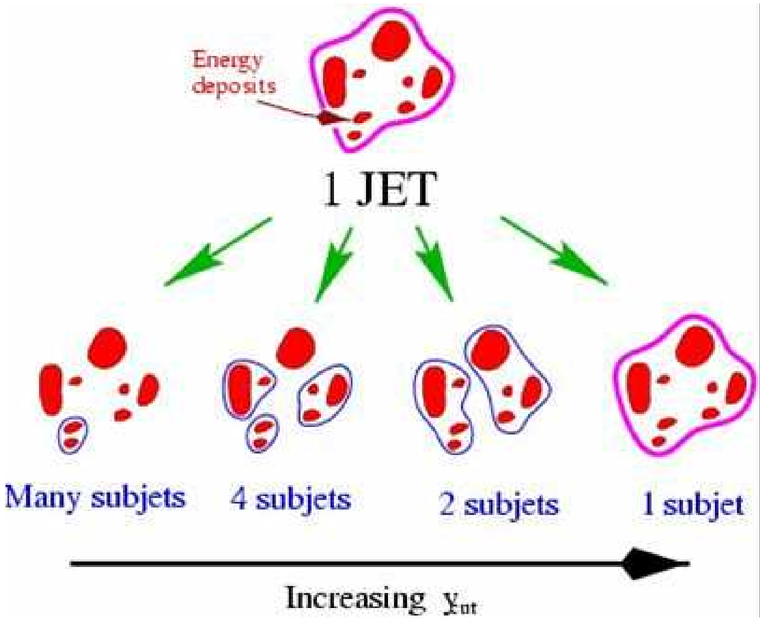
MEPJET describes the shape but underestimates the normalisitation at low E_T

dependence of CC dijets on m_{jets}



MEPJET describes the shape but underestimates normalisation by $\sim 25\%$.

measurement of subjets and subjet multiplicities



KT algorithm defines distance between energy deposits as
$d_{ij} = \min(E_{T,i}^2, E_{T,j}^2) * (\Delta\eta^2 + \Delta\phi^2)$

merging all energy deposits with KT algorithm until $d_{ij} \geq y_{cut} \cdot E_T^2$

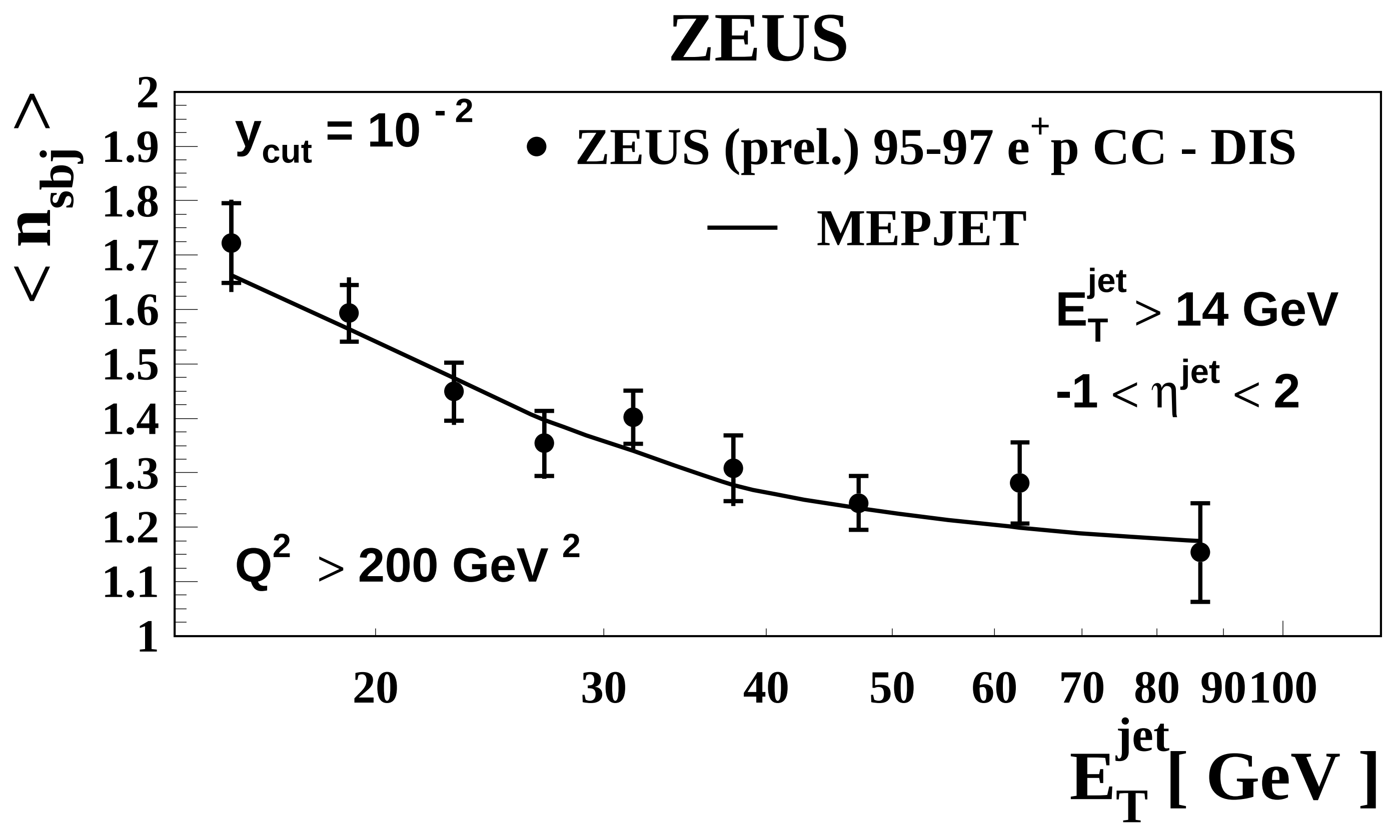
subjets are jet like structures within the jet.

definition ensures that
$\min(E_{T,1}, E_{T,2}) \cdot d \geq \sqrt{y_{cut}} \cdot E_T$

subjet multiplicity $< n_{sbj} >$ is the average number of subjets per jets.

measurement of subjet multiplicities allows for a precise test of the QCD calculations for the development of jet structure

dependence of CC subjets on E_T



E_T^{jet}: E_T of the jet for which the subjet multiplicity is measured.

measurement sensitive to α_s

extracted preliminary value: $\alpha_s = 0.1202 \pm 0.0052(\text{stat})^{+0.0060}_{-0.0019}(\text{syst})^{+0.0065}_{-0.0053}(\text{theo})$

Conclusions

- first ZEUS measurement of trijets over a large kinematic range
- measured NC dijet and trijet cross sections.
  ⇒test of higher order matrix elements
- NLO QCD (NLOJET) described the dijet and trijet cross sections

- measured CC inclusive, dijet and subjet cross sections
  ⇒test of flavour changing matrix elements
- NLO QCD (MEPJET) describes the shape of the cross section but underestimates its normalisation.
- extracted α_s from CC subject cross sections
- first measurement of α_s from jet production in CC events at HERA

- jet production measures with high precision for intrinsically higher order processes and the interplay with electroweak effects
- for most cases the data are more precise than the predictions
  ⇒ theory needs improvements
- looking forward to high precision measurements at even higher E_T and Q^2 with HERA II