Three Jet Production in Neutral Current Deep Inelastic Scattering with ZEUS at HERA

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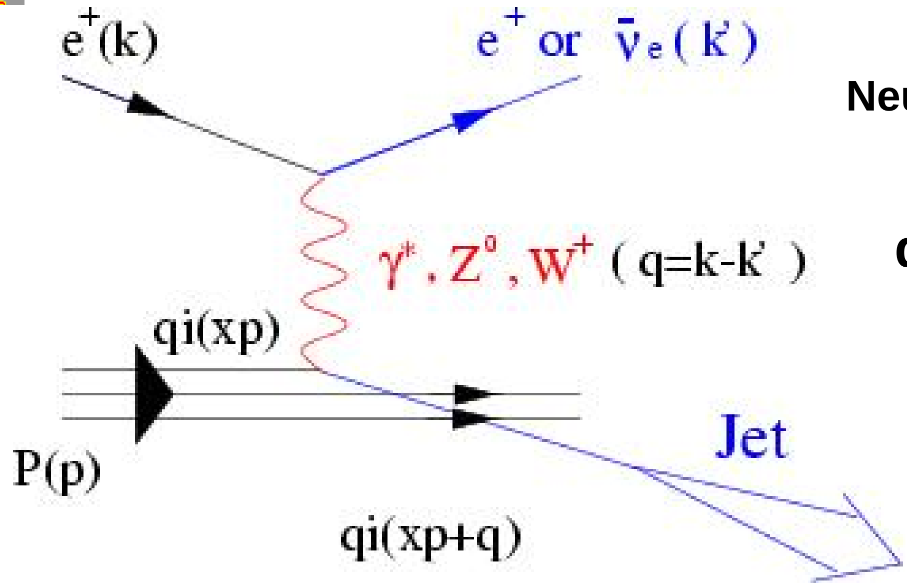
Deep Inelastic Kinematics



Neutral Current: $e^+p \rightarrow e^+ X \; (\gamma, Z)$

$q \equiv k-k'$: momentum transfer

$Q^2 \equiv -q^2$: exchanged boson virtuality

$x \equiv Q^2 / 2pq$: momentum fraction carried by struck quark (QPM)

$s = (p+k)^2$: center of mass energy (fixed value)

$y \equiv p \cdot q / p \cdot k$: fraction of positron energy transferred (in proton rest frame)

$Q^2 = x \cdot y \cdot s$: kinematics relation (two degrees of freedom)

Why DIS?

"inelastic":

- **proton breaks up -> quarks…**

"deep": photon $\lambda = 1/|q| \sim 2xM_p/Q2$

- **large momentum transfer -> "small distance"**

"deep inside proton":

- **probe internal structure of proton**

DIS Cross Section

$$\frac{d^2\sigma(e^\pm p \to e^\pm X)}{dx\, dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+F_2(x,Q^2) \mp Y_- xF_3(x,Q^2) - y^2 F_L(x,Q^2)]$$

$$Y_\pm = 1 \pm (1-y)^2$$

Proton Structure Functions

$F_2\,(x,Q^2)$: Interaction between transversely polarized photons & spin 1/2 quarks ; related to the quark and anti-quark densities inside proton

$F_L\,(x,Q^2)$: Interaction between longitudinally polarized photons & the quarks with transverse momentum; $F_L = F_2 - 2xF_1$

$F_3\,(x,Q^2)$: Parity-violating structure function from Z^0 exchange; Contribution small for $Q^2 << M_Z^2 = 8100\ \mathrm{GeV}^2$

Naïve Quark Parton Model

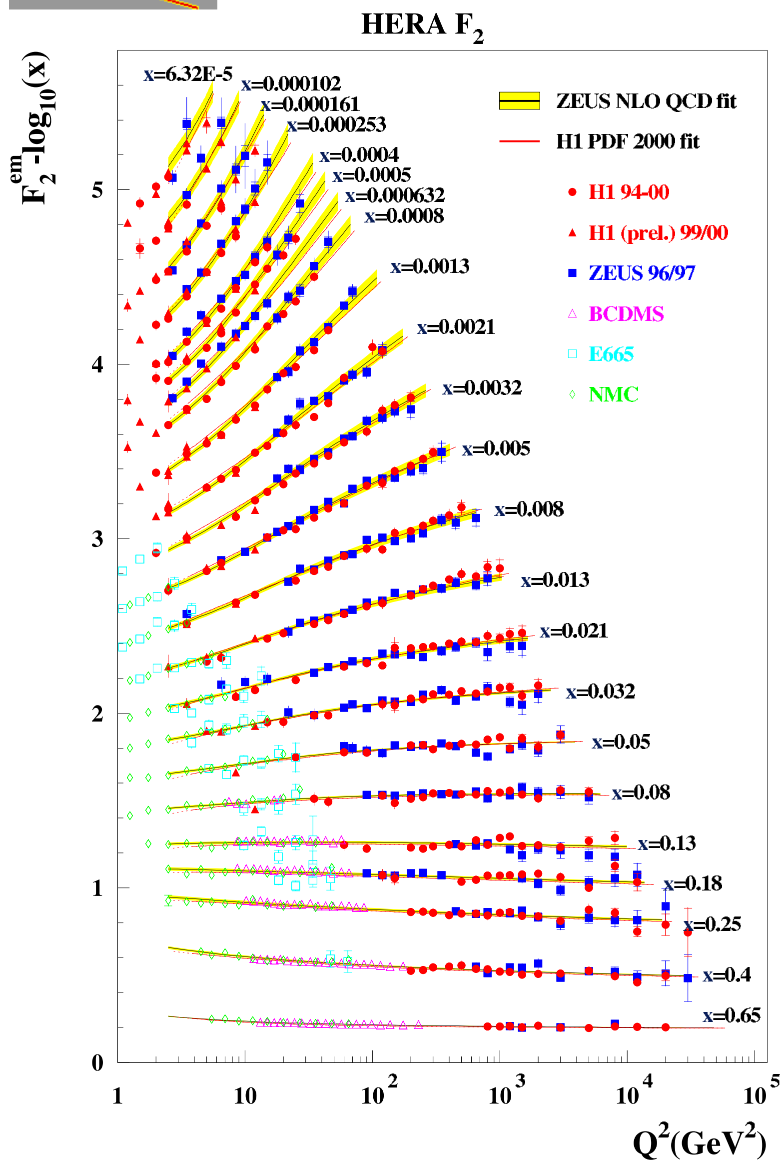
- Proton is made of "point-like" partons
- No interaction between the partons
- Structure functions do not depend on Q^2 since "point-like" structure cannot be "probed" any further

Bjorken Scaling (x) dependence:

$$F_i(x,Q^2) \rightarrow F_i(x)$$

$$F_L = 0$$

Scaling Violation



F_2 has a Q^2 dependence:

$$F_2(x,Q^2) = \sum_q e_q^2(Q^2)\cdot(xq(x,Q^2) + x\bar{q}(x,Q^2))$$

F_2: sum of the momentum distributions of the quarks and anti-quarks weighted by charge squared

at small x, strong rise of F_2 with Q^2

what happened at small x?

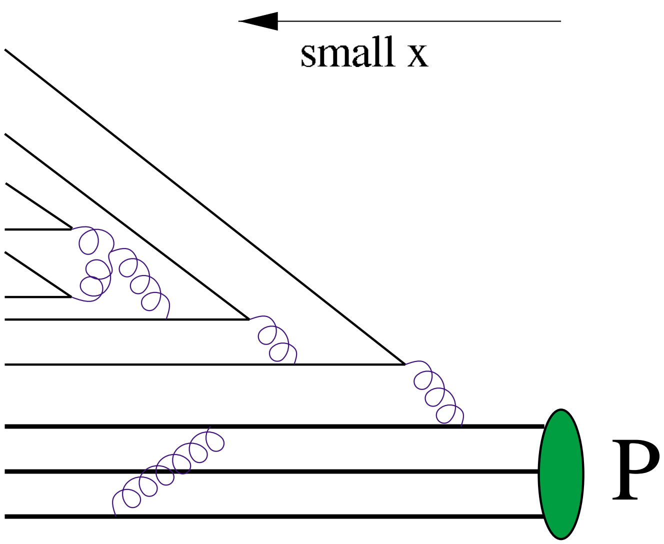
Proton: A QCD Story

Quarks radiate and absorb gluons
gluons split into quark anti-quark pairs:
A "sea" of quark anti-quark pairs,
No longer "point-like" structure

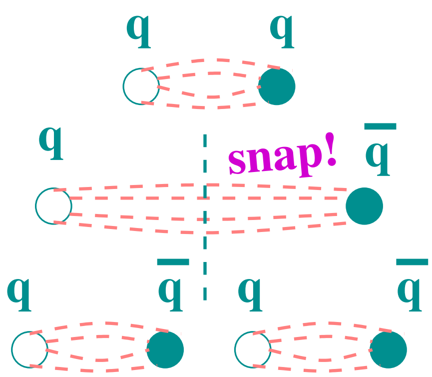
The structure functions gain a Q^2 dependence: **Scaling Violation**

Quark and quark interactions mediated by gluons: generate transverse momentum: **Non zero F_L**

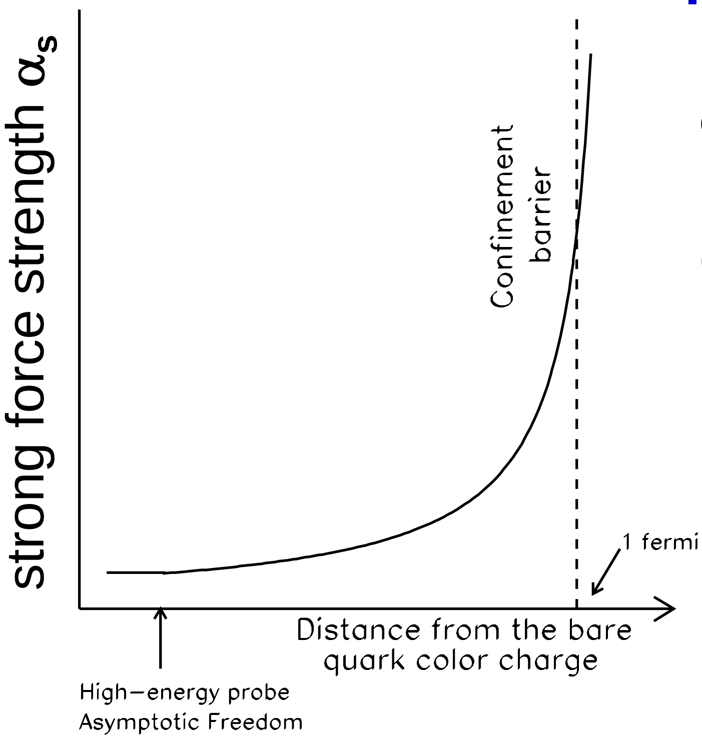
at small x, gluon-driven increase of "sea quarks"



QCD: Color Confinement and Asymptotic Freedom



Quarks and gluons cannot be observed as free particles: they are bound by the strong force to form colorless "hadrons"; The energy injected into a hadron creates new quark antiquark pairs and hence additional hadrons



α_s indicates the strength of the strong interaction between quarks and gluons: strong coupling "constant"

α_s decreases at short distances and increases rapidly at large distances; In the very short distance (high energy), quarks and gluons are treated as free: Asymptotic Freedom

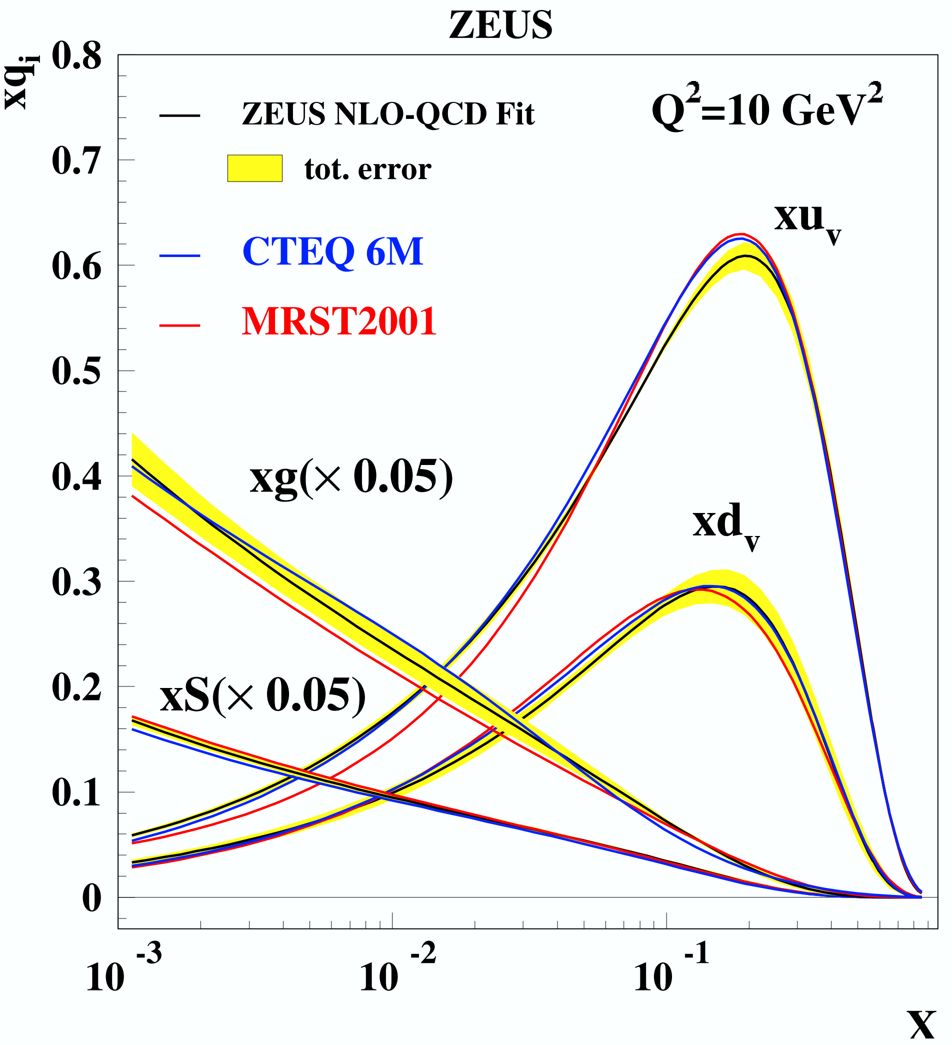
Perturbative QCD and Renormalization Scale

QCD only calculable at small distances:
approximate solution by perturbative expansion
of terms proportional to different orders of α_s:
$d\sigma = A_0\, \alpha_s^0 + A_1\, \alpha_s^1 + A_2\, \alpha_s^2 + A_3\, \alpha_s^3 + \ldots$
Leading order (LO): first non-zero order of α_s
Next-to-leading order (NLO): second non-zero order

However, divergencies appear in summing self-interactions, when the loop momenta tend to infinity:
Introduce a cutoff μ_R on the loop momenta → Renormalization

α_s dependence on μ_R: $\alpha_s = 12\pi/[(33-2n_f)\ln(\mu_R^2/\Lambda^2)]$ (LO)
$\mu_R \rightarrow \infty$, $\alpha_s \rightarrow 0$ ("asymptotic freedom")
$\mu_R \rightarrow \Lambda$, $\alpha_s \rightarrow \infty$ (pQCD not valid, "color confinement")
μ_R is the scale at which α_s is evaluated (extract $\alpha_s(\mu_R)$!)

Parton Density Functions and Factorization Scale



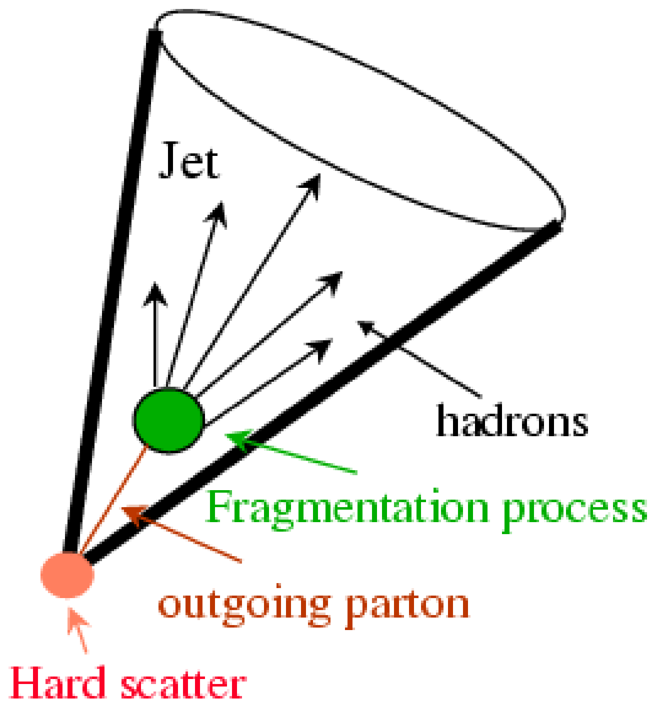
At large distances, α_s is large: non-perturbative → Factorization

$$\sigma_{DIS} = \sum_a f_a(x, \mu_F^2) \otimes \sigma_a(x, \mu_F^2)$$

Scale μ_F is introduced to separate long-range (soft) and short-range (hard) processes:
$K_T > \mu_F$, partons included in pQCD partonic cross-section
$K_T < \mu_F$, partons absorbed in non-pQCD parton density functions

Several groups derive PDF from experimental data:
CTEQ, MRST, ZEUS-S

Jets



Quarks and gluons can't be observed in the detector

Jets: colored partons evolve to a roughly collinear "spray" of colorless hadrons

Jet finding:

- Recombining energy deposits from one parton
- merging soft partonic radiation back to emitting parton

Jet algorithm:

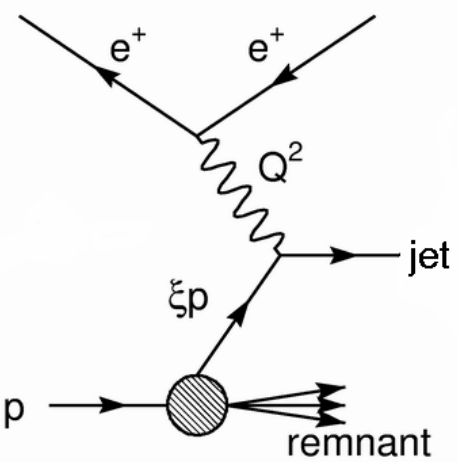
- measurable
- calculable (infrared safe)
- accurate

Single Jet Dijet Trijet

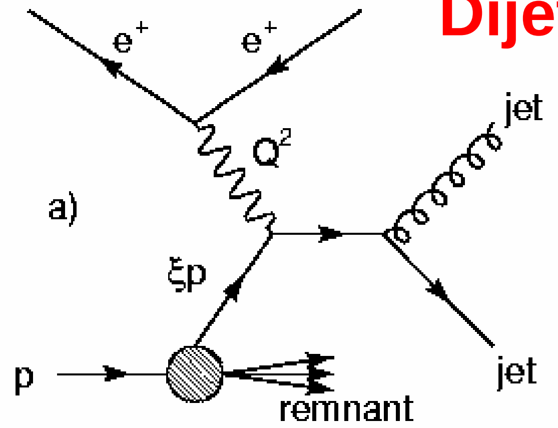
a) QCD Compton

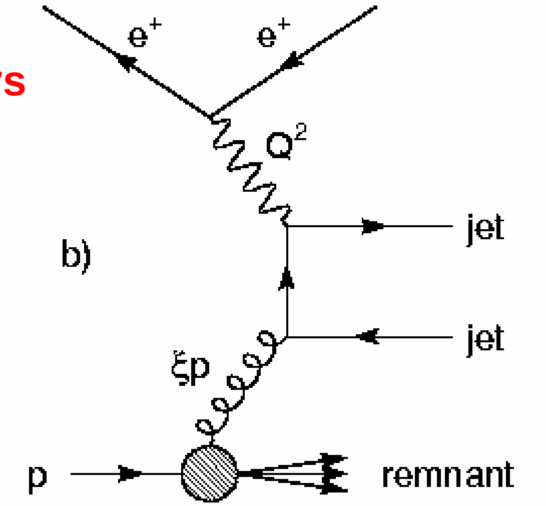
b) Boson-Gluon Fusion

Single Jet: α_s^0

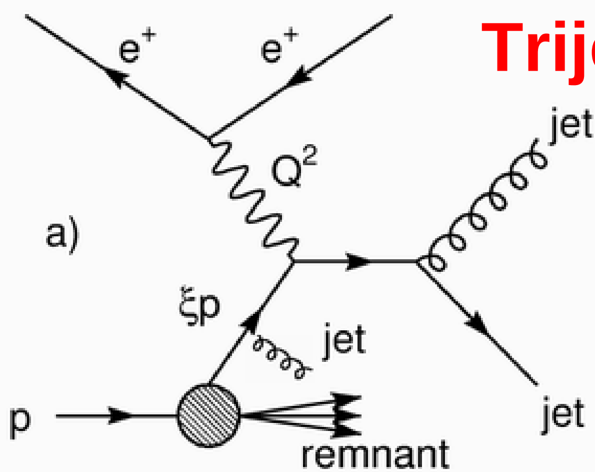


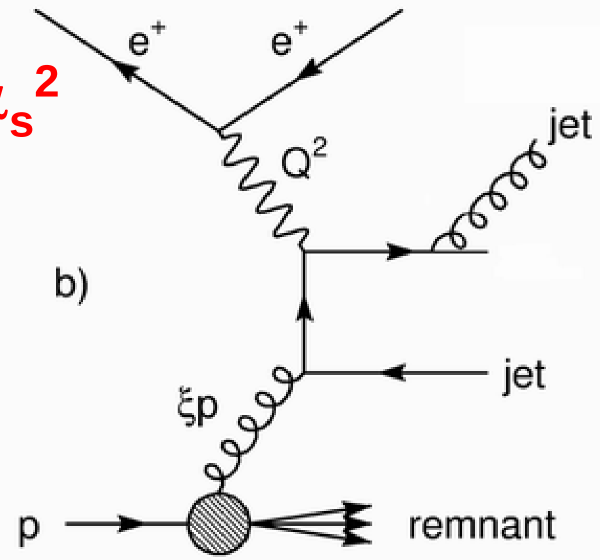
Dijet: α_s





Trijet: α_s^2





Motivation for Multijets Study

- **Add a gluon radiation to dijet or split a gluon to $q\overline{q}$**

  $\rightarrow$ direct test of QCD at $O(\alpha_s^2)$

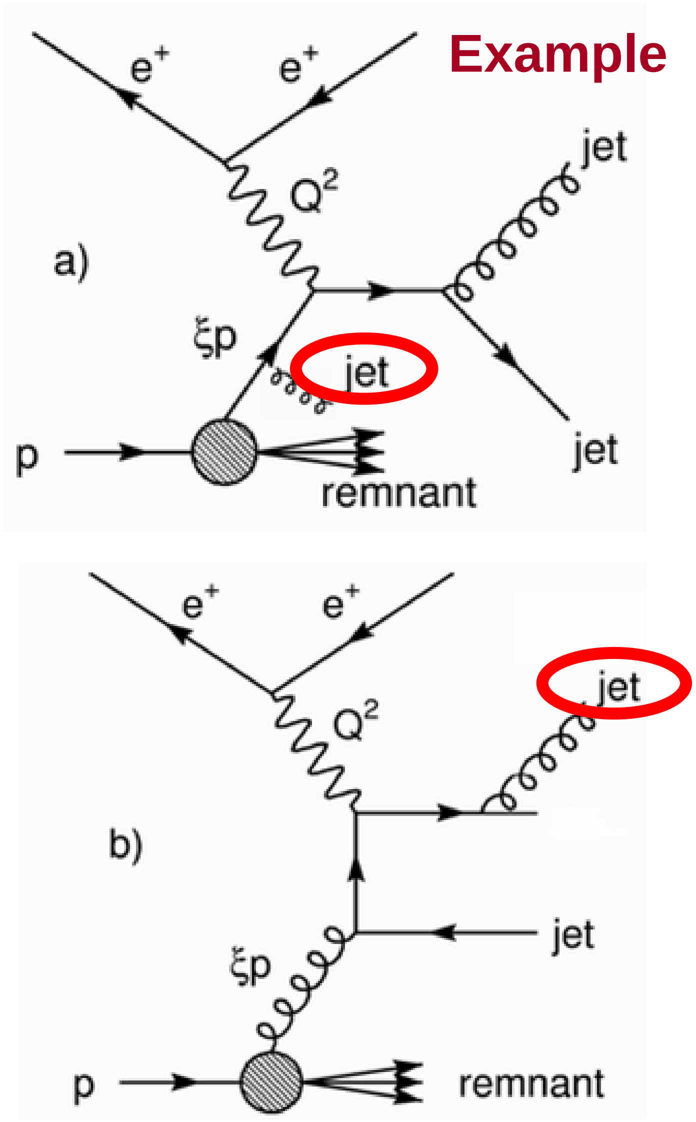
- **In the ratio $\sigma_{trijet}/\sigma_{dijet} = O(\alpha_s)$, cancellation of many correlated experimental and theoretical uncertainties.**

- **Measurement of α_s from $\sigma_{trijet}/\sigma_{dijet}$**
  $\rightarrow$ first α_s measurement from $O(\alpha_s^2)$ jet rate at HERA

- **Multijet NLO Calculations available**

  (Ref: Phys.Rev.Lett.87:082001,2001)

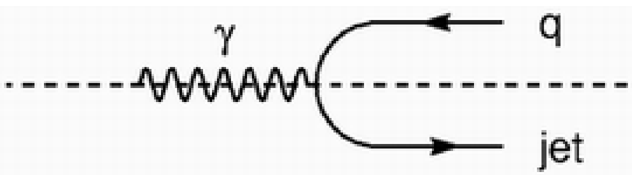
Example



Breit Frame

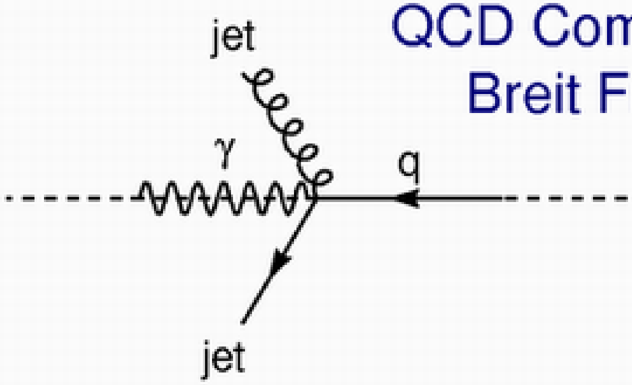
The proton and exchanged photon collide head-on, with the z-direction chosen to be the proton direction:

$$\boldsymbol{q} + 2x\boldsymbol{p} = 0$$



Single jet in Breit frame: similar to e^+e^-

In single jet events, struck quark rebounds with equal and opposite momentum, the resulting jet has zero E_T (transverse energy)



QCD Compton in Breit Frame

In multijets events, the outgoing jets are balanced in E_T:

high $E_T \rightarrow$ multijets

HERA Collider

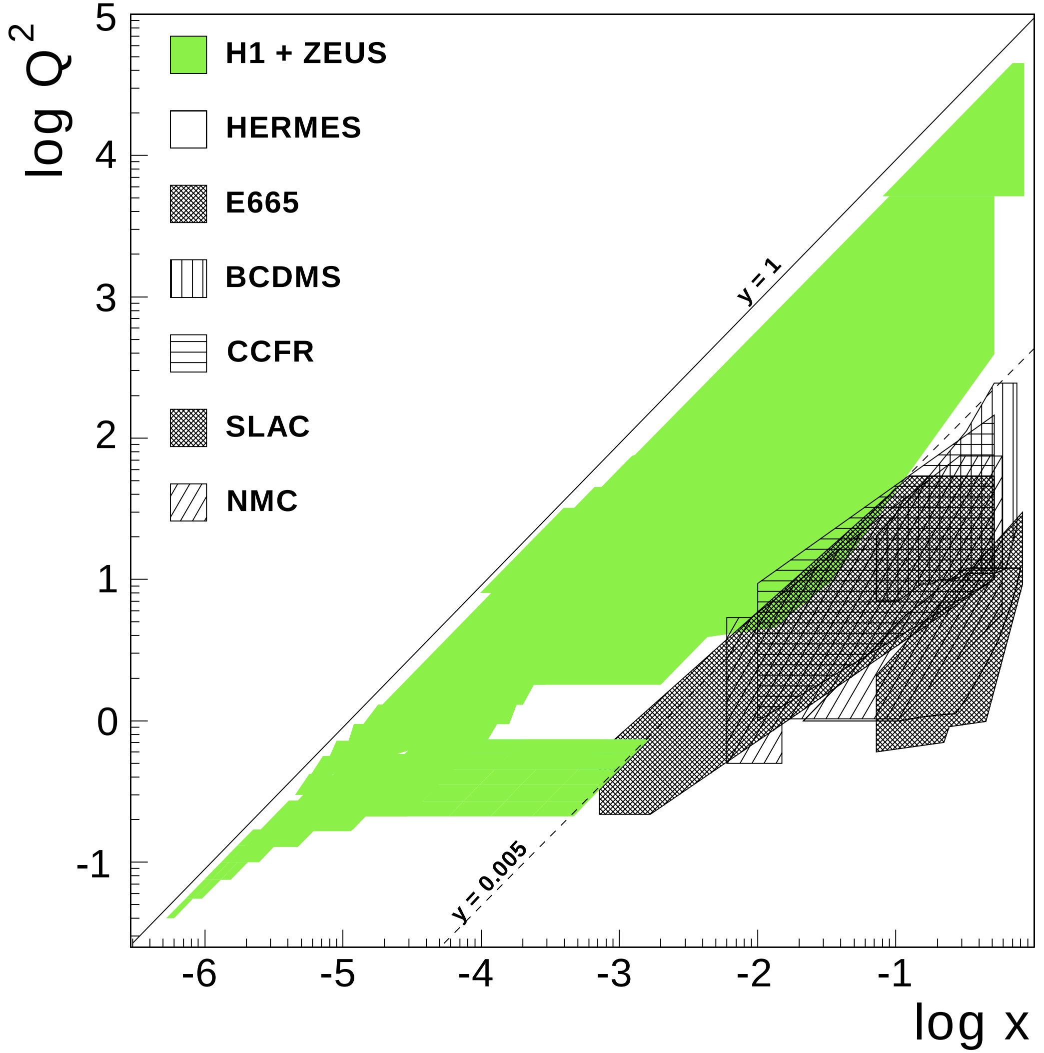
World's first electron-proton collider located at DESY, Hamburg

- 820/920 GeV proton
- 27.5 GeV electron or positron
- 300/318 GeV center of mass energy
- 220 bunches
  96 ns crossing time
- 90mA protons
  40mA positrons

2 collider detectors:
ZEUS, H1
2 fixed target detectors:
HERMES, HERA-B

Integrated luminosity:
HERAI (92-00): 121pb^{-1}, HERAII (03-07): 500pb^{-1}(exp.)

HERA Kinematic Range



Extended kinematic region over six-orders of x and Q^2

At $\sqrt{s}$ =318 GeV, HERA equivalent to 50 TeV fix-target experiment

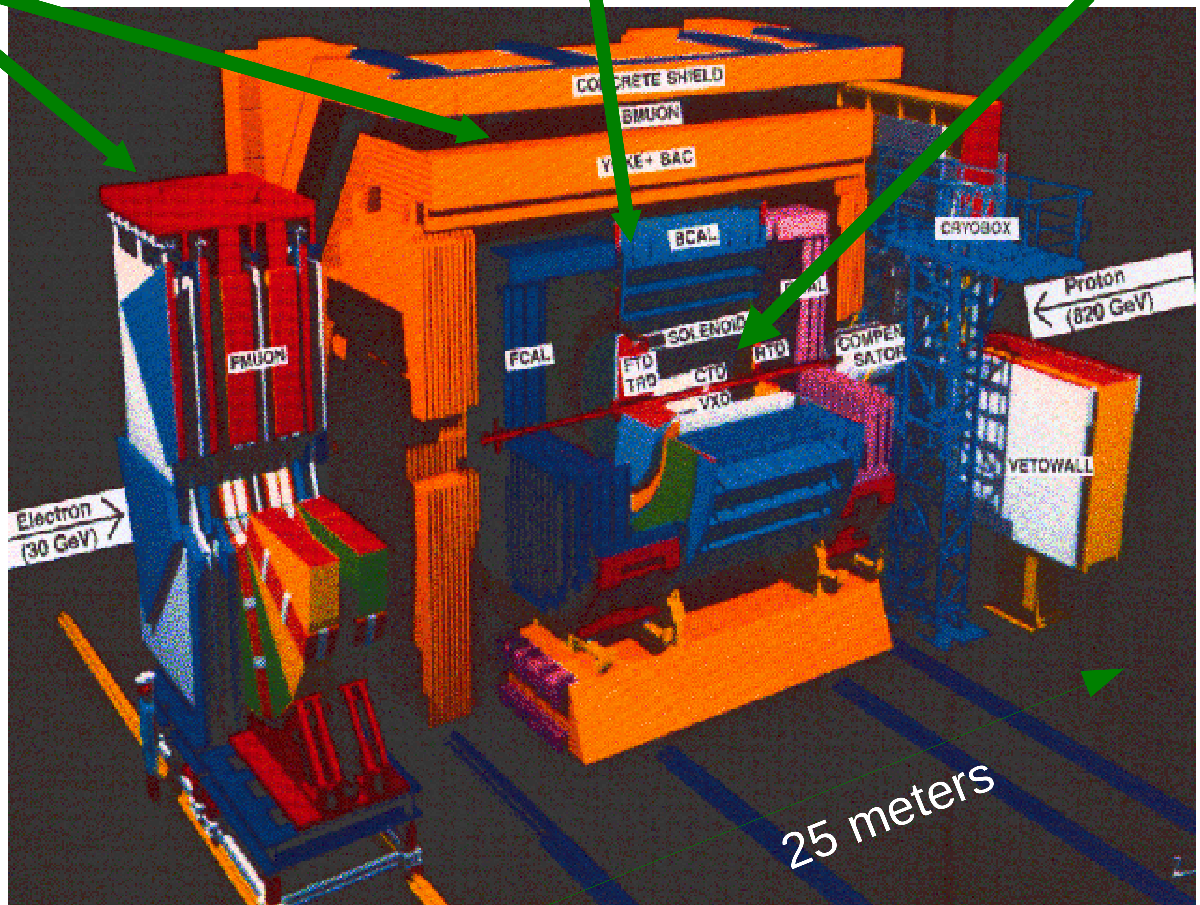
H1 and ZEUS: DESY e-p
HERMES: DESY e-A
E665: Fermilab μ-A
BCDMS: CERN μ-A
CCFR: Fermilab ν-A
SLAC: many experiments e-A
NMC: CERN μ-A

ZEUS Detector

Muon systems

Uranium−Scintillator Calorimeter

Drift Chamber Central Tracker

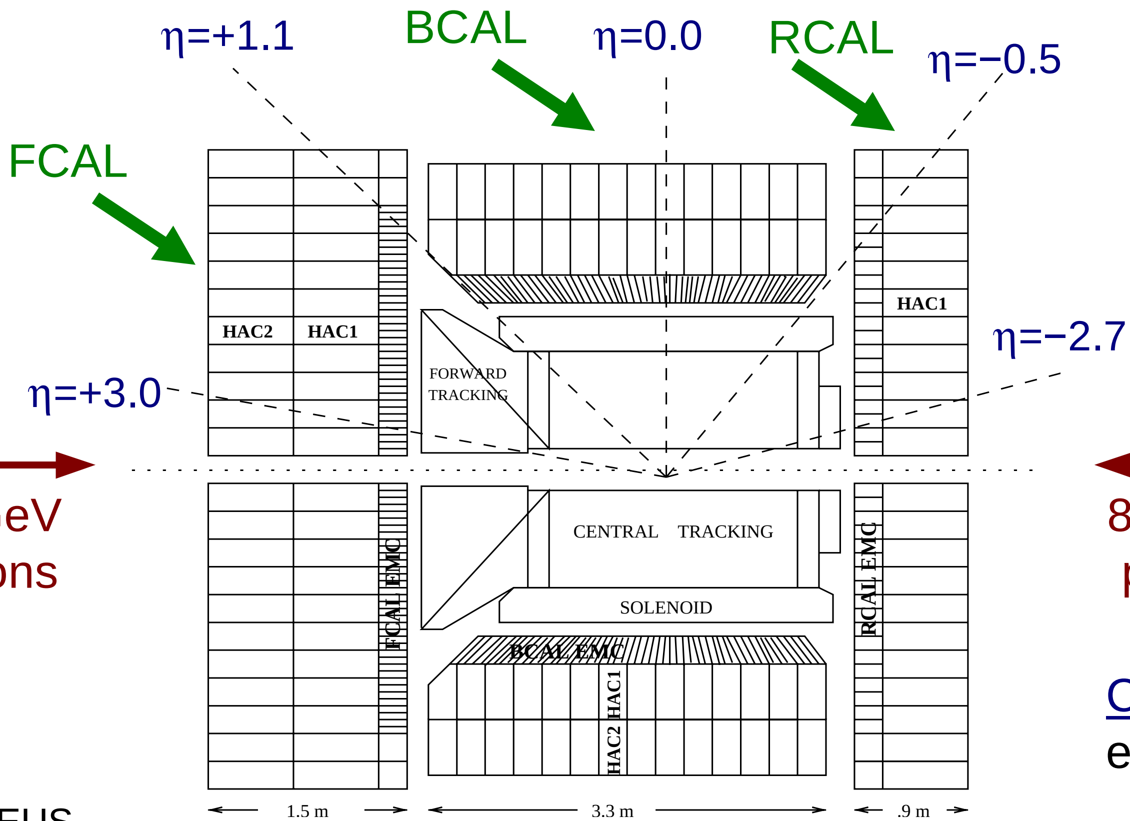


820 GeV protons

27.5 GeV positrons

25 meters

ZEUS Calorimeter



Depleted Uranium and scintillator

Energy Resolution

electromagnetic: 18%/√E

hadronic: 35%/√E

27.5 GeV positrons

820 GeV protons

Cell Dimensions

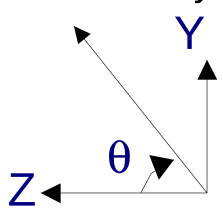
electromagnetic:

5x20cm (FCAL,BCAL)

10x20cm (RCAL)

hadronic: 20x20cm

ZEUS Coordinate System



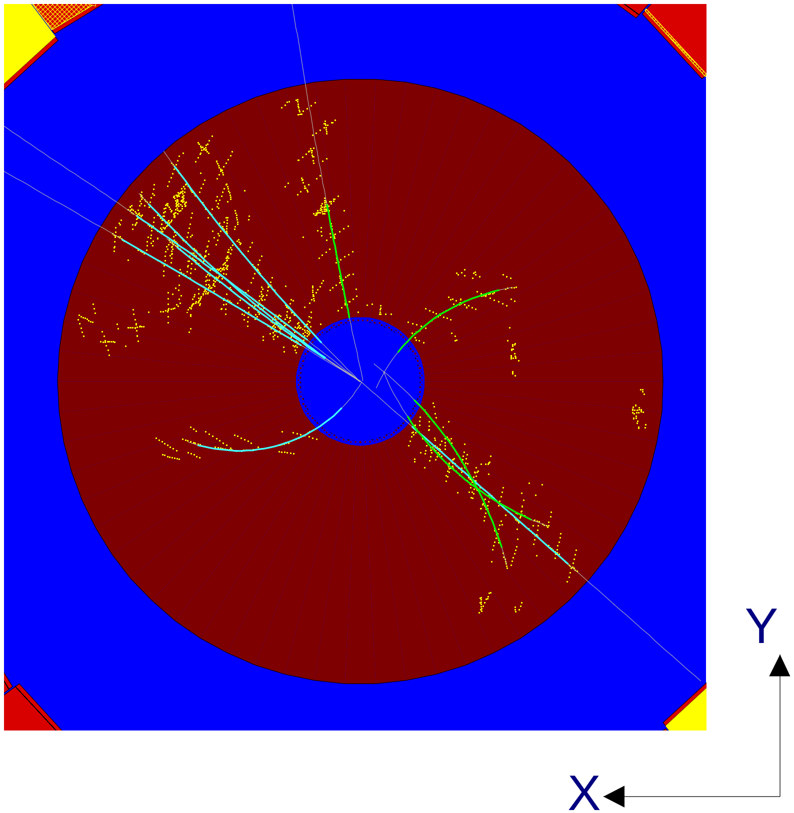
99.7% solid angle coverage

$-3.5 < \eta < 4.0$

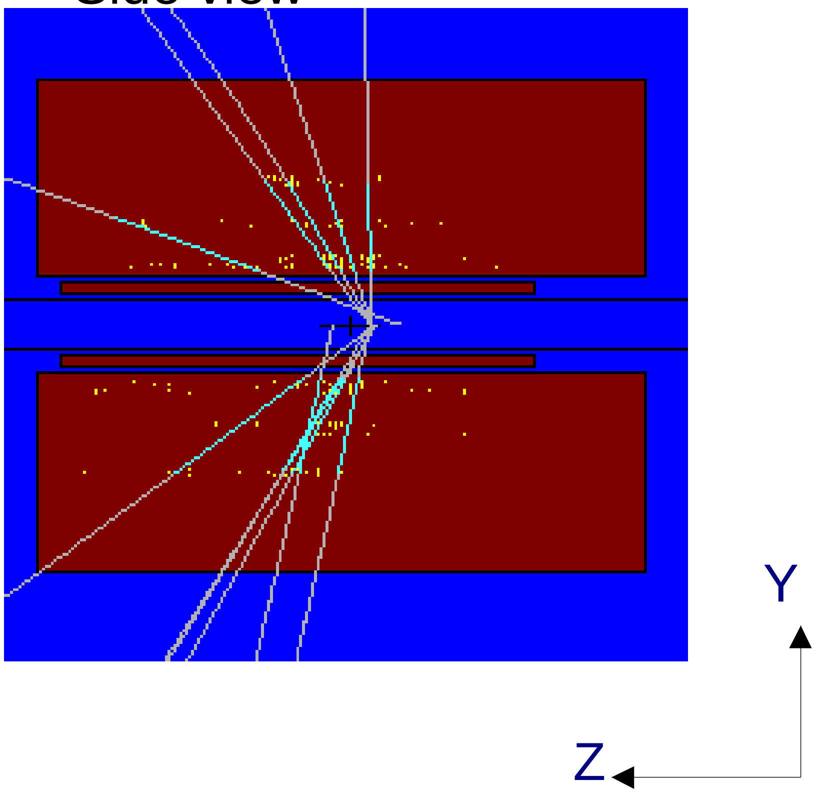
$$\eta = -\log\left[\tan\left(\vartheta/2\right)\right]$$

ZEUS Central Tracking Detector

View along beamline



Side view



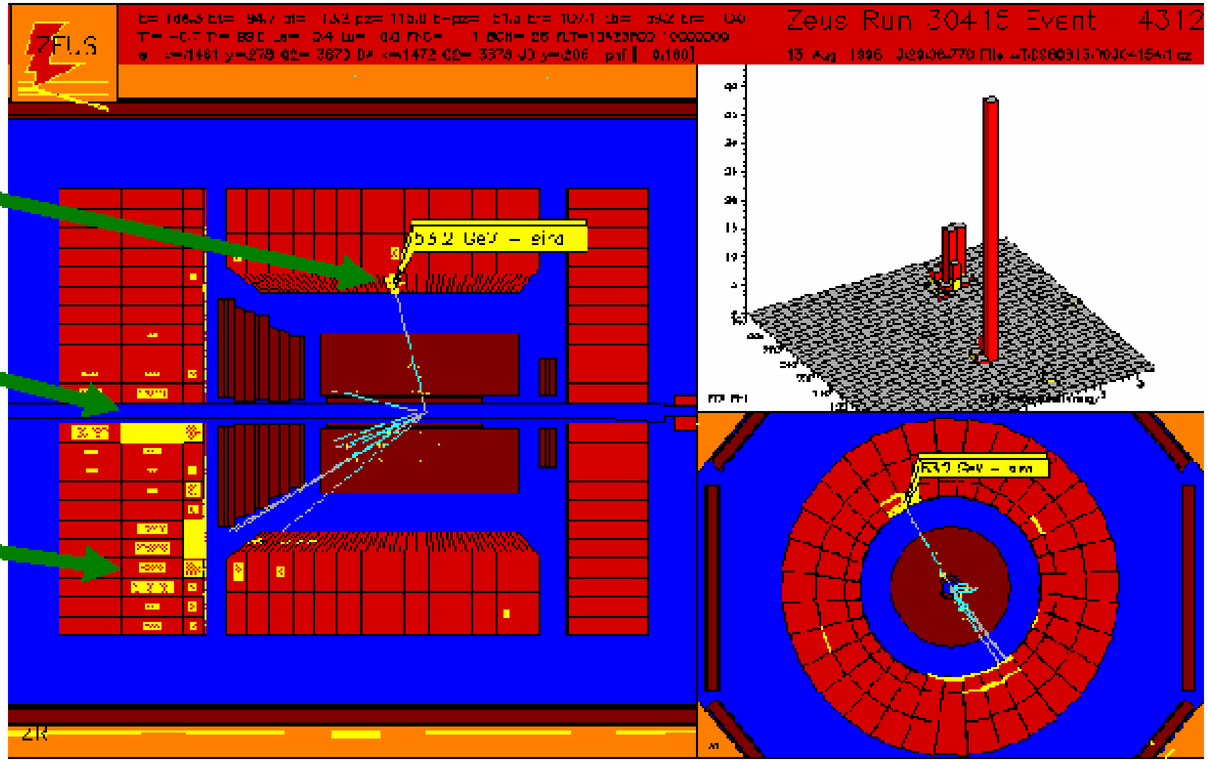
CTD: Drift chamber inside 1.4T solenoid
Vertex Resolution: 4mm in z-direction, 1mm transvers

DIS Event

Scattered Positron

Proton remnant

Jet

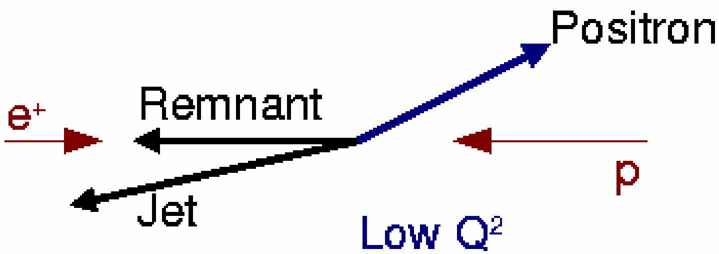


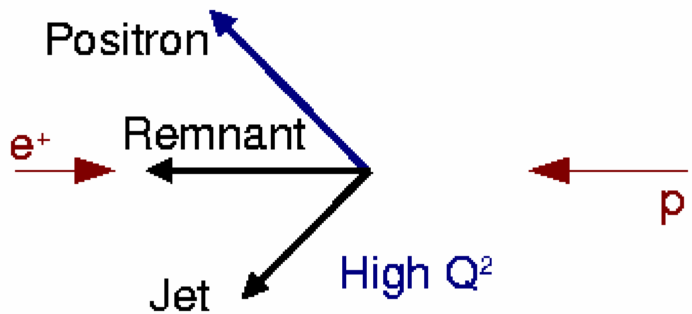
$Q^2 \sim 3600 GeV^2$

$X \sim 0.15$

$Y \sim 0.20$

(1+1) event





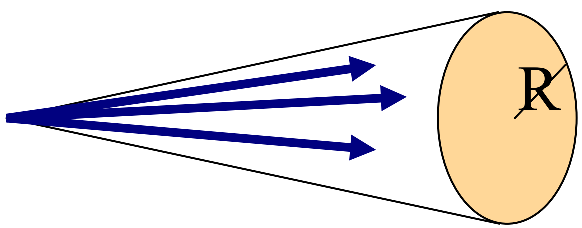
Jet Algorithm

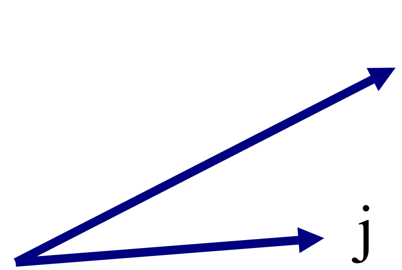
Cone algorithm:

- conceptually simple, fast to run
- ambiguities related to overlapping jets and merging of jets
- infrared unsafe at NNLO
- seeding requirements

k_T algorithm:

- no ambiguity in jets merging
- infrared safe at all orders
- seeding not necessary
- longitudinally invariant k_T algorithm in inclusive mode





$$d_i = E_{T,i}^2$$

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Maximize E_T within a cone of radius R

$$d_{ij} = \min\{E_{T,i}^2, E_{T,j}^2\}((\Delta\eta)^2 + (\Delta\phi)^2)$$

Combine i and j if d_{ij} is smallest of $\{d_i, d_{ij}\}$

ZEUS Trigger

Challenge

10 MHz bunch crossing rate

Extract 10Hz Physics from 100kHz background

10^5Hz →

Level 1
- Dedicated custom hardware
- Pipelined and Deadtimeless: decision made for every bunch crossing (96ns)
  - ~5μs latency
- Programable
  - Global and regional energy sums
  - Isolated positron recognition
- Track quality information

500Hz →

Readout ↓

Level 2
- "Commodity" Transputers
- Calorimeter timing cuts
- $E-p_z$ cuts (next slide)
- Initial vertex information
- Simple physics filters

100Hz →

Level 3
- Processor Farm (SGI)
- Full event available
- Offline tools available: jet finding, positron id, etc
- Complete tracking algorithms

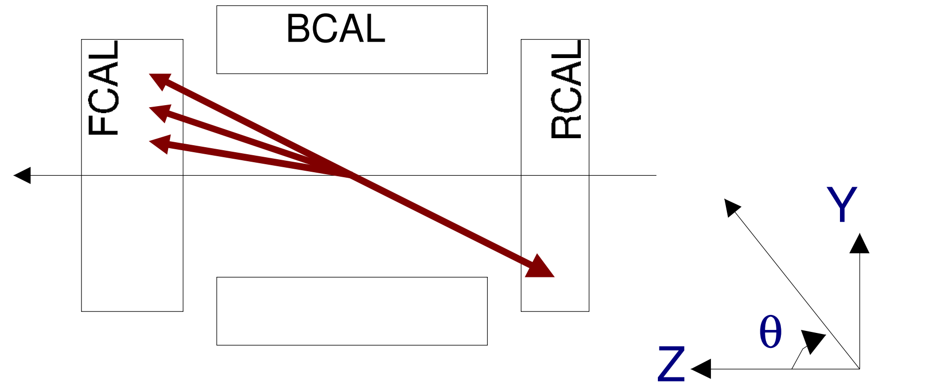
10Hz → Mass storage

Work on :
Calorimeter
First Level Trigger

E-P_Z Cut

$$E - p_z = \sum_i E_i (1 - \cos\vartheta_i)$$

Sum runs over calorimeter cells

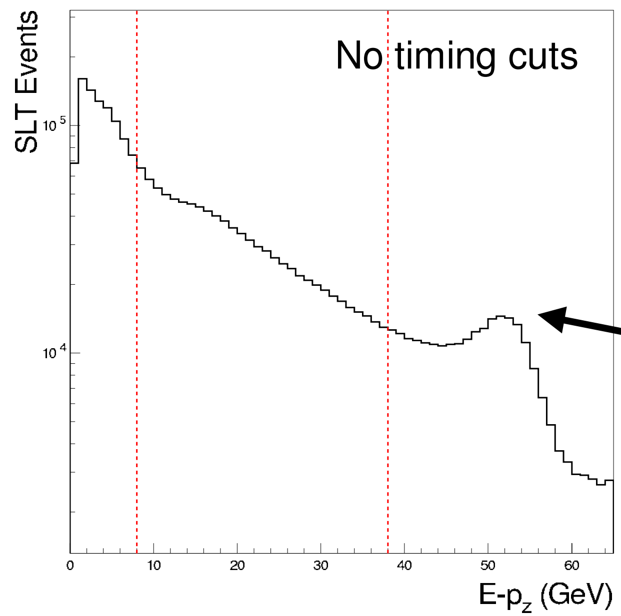


In a given frame, $E-p_z$ is conserved

E_{beam} P_{beam}

Before: $E-p_z = 2E_{beam}$=55GeV

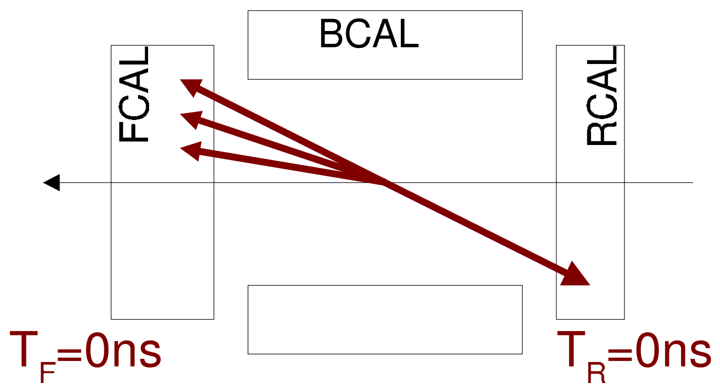
Unless energy escapes down rear beam pipe, $E-p_z$ after collision will be near $2E_{beam}$ for interesting physics at the nominal interaction point



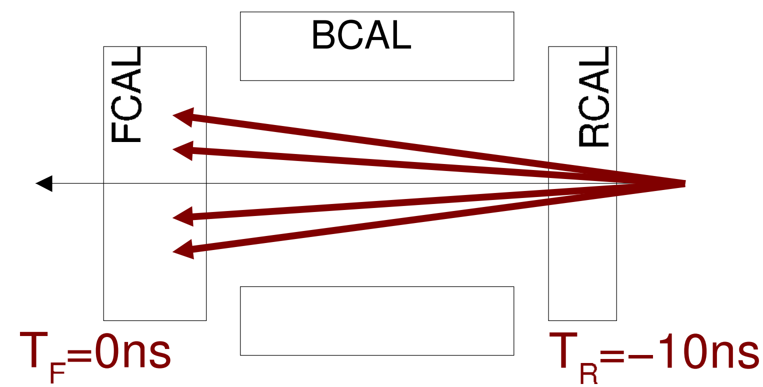
Contained NC DIS $E-p_z \approx 55$

Timing Cut

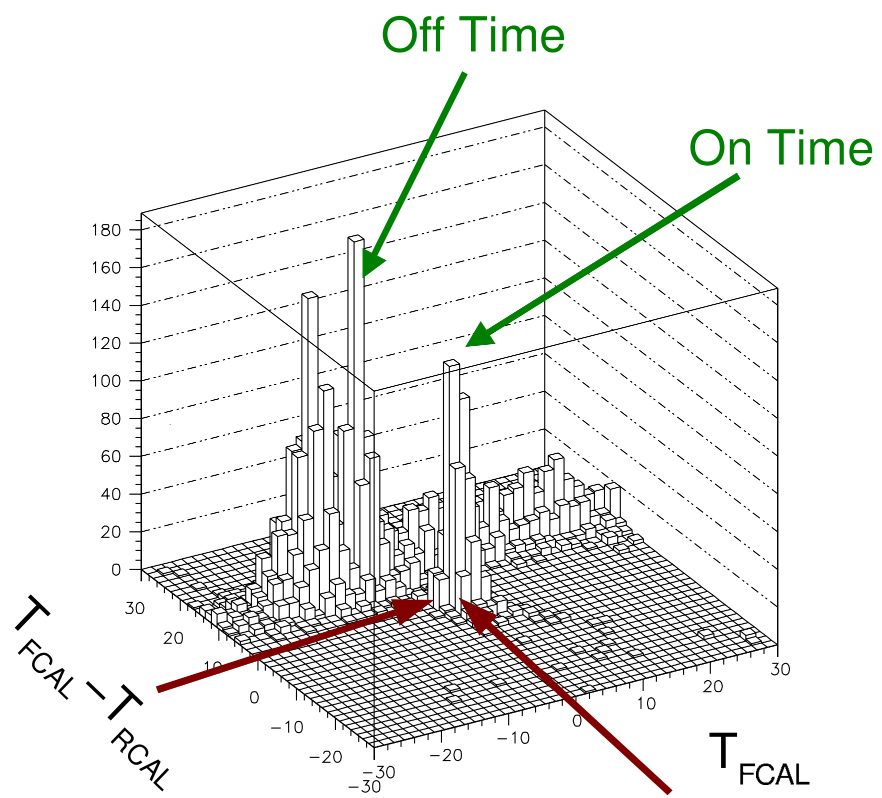
"Distance" between FCAL and RCAL is ~10ns



On Time Event



Beam Gas Event

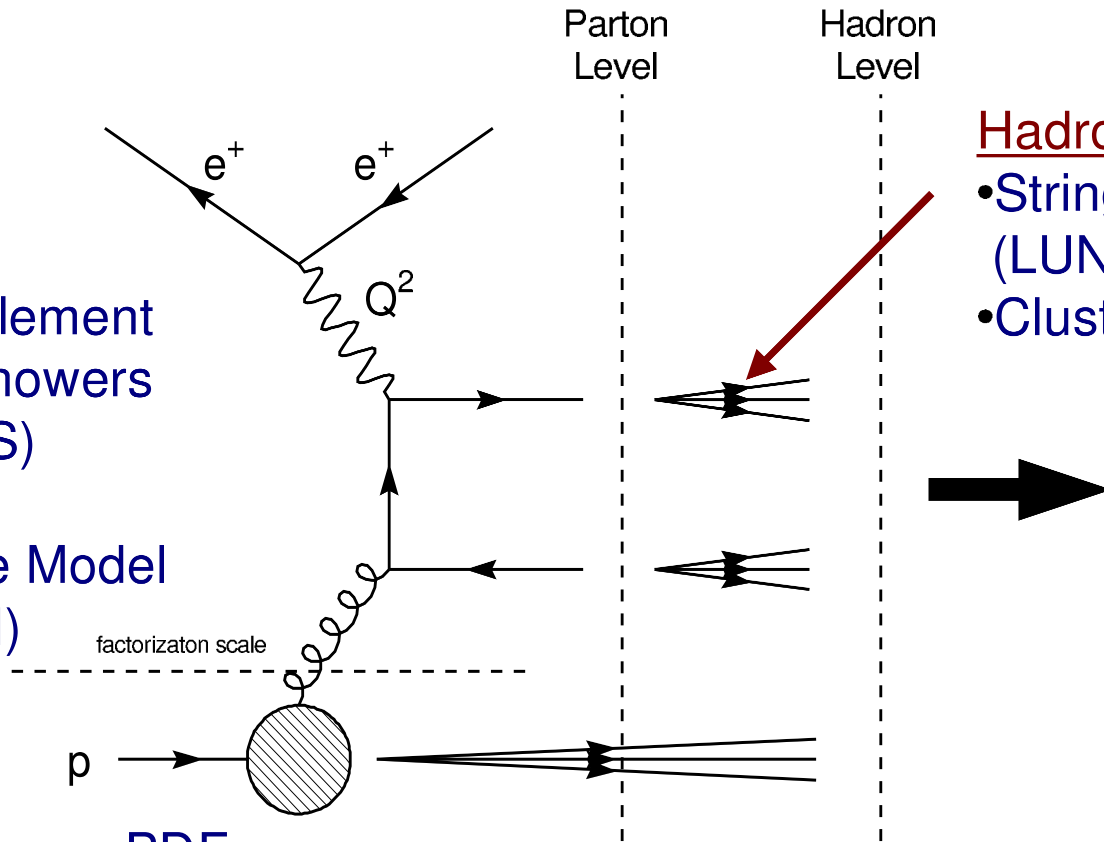


Calorimeter timing at Level 2

ZEUS Calorimeter timing resolution <1ns

LO Monte Carlo

LO Matrix Element
+ Parton Showers
(MEPS)
or
Color Dipole Model
(CDM)



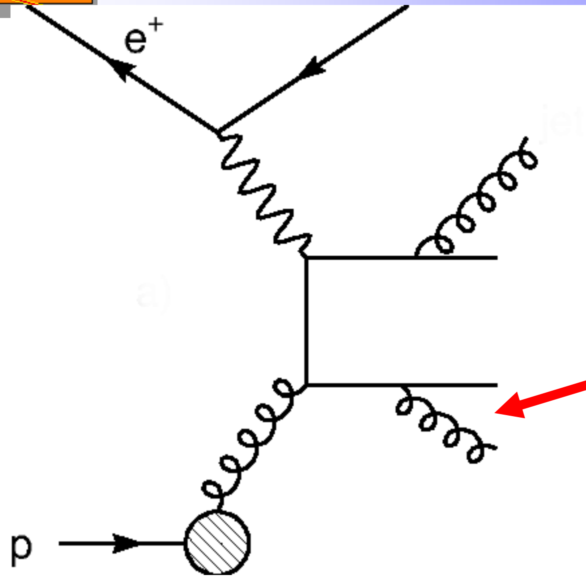
PDFs

Hadronization Models
- String Fragmentation (LUND)
- Cluster Model

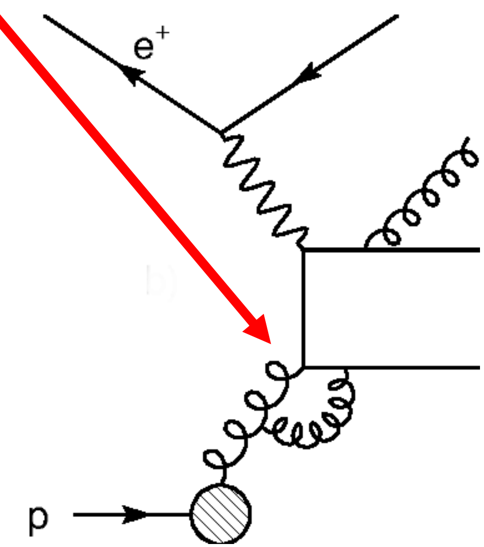
Detector Simulation

- Acceptance corrections: detector independent cross sections
- Hadronization corrections, QED corrections: for NLO calculation
- LEPTO (6.5.1) and ARIADNE (4.0.8) program used

NLO Calculation



- Four parton final states
- Most accurate pQCD calculation upto now
- Soft/collinear and virtual loop divergences cancel



- All finite order calculations have renormalization scale dependence (uncertainty), at NLO, scale uncertainty much reduced
- No hadronization and no high order QED effects
- Use LO MC to get these corrections
- NLOJET program: first NLO program for trijet
- DISENT program: double check NLOJET for dijet

Data Sample: Offline Selection

ZEUS 1998-2000 data

- 82.2 pb^{-1}
- $\sqrt{s}$ = 318 GeV
- E_p=920 GeV, E_e=27.5 GeV

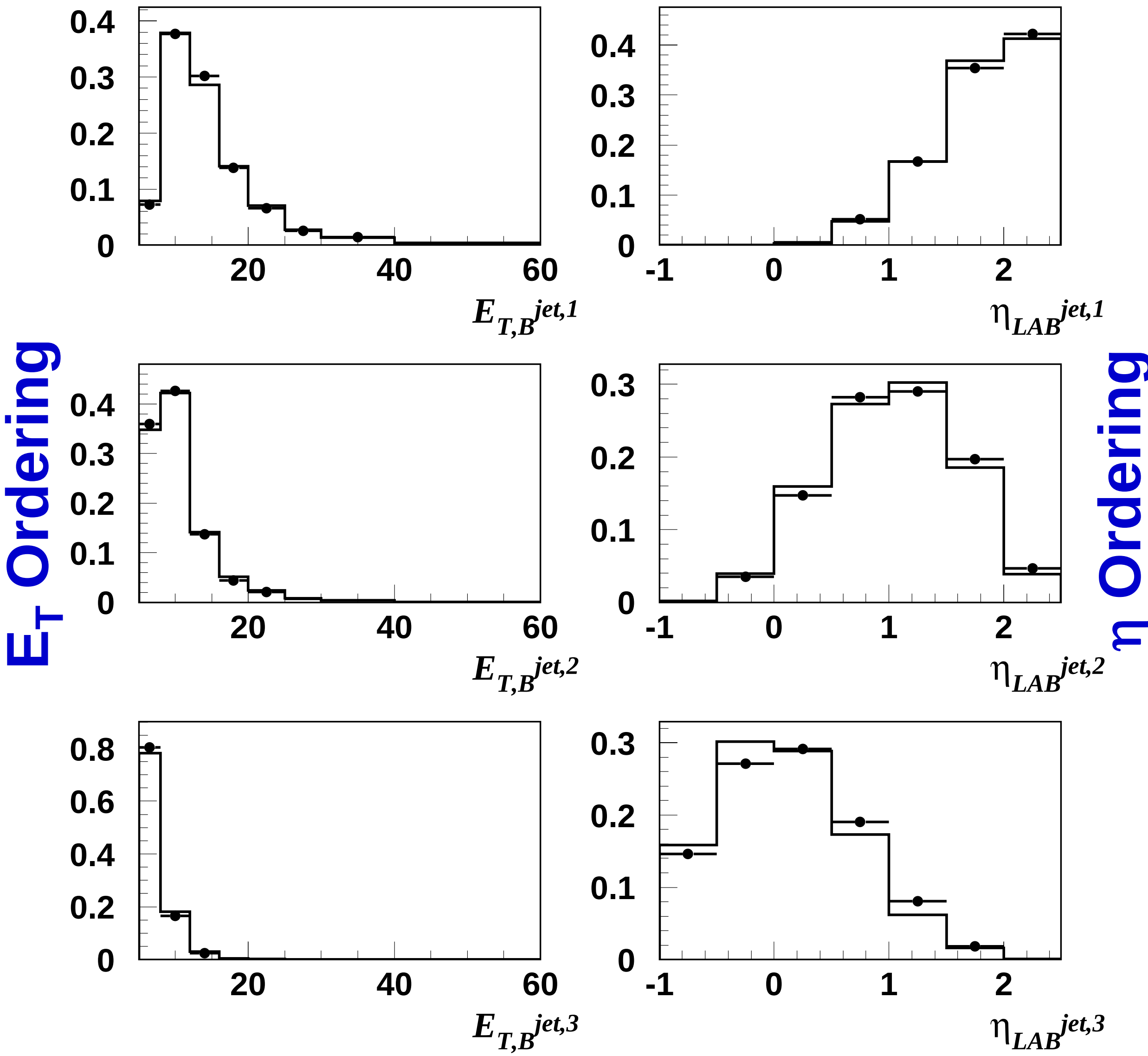
Kinematic Range

- 10 $GeV^2 < Q^2 <$ 5000 GeV^2: good acceptance, best use of statistics
- 0.04 <Y < 0.6: good reconstruction of hadronic system, reduce background
- $\cos\gamma_{had} < 0.7$: good reconstruction of jets in Breit frame

Jet Reconstruction

- Invariant KT algorithm in Breit frame (inclusive)
- $E_{T,jet}^{BRT} > 5$ GeV for each jet: hard process
- $-1 < \eta_{jet}^{LAB} < 2.5$: jets boosted back to lab to check CTD acceptance
- Invariant mass $M_{2,3jet}$ >25 GeV: avoid unphysical theoretical calculation

Trijet Kinematics

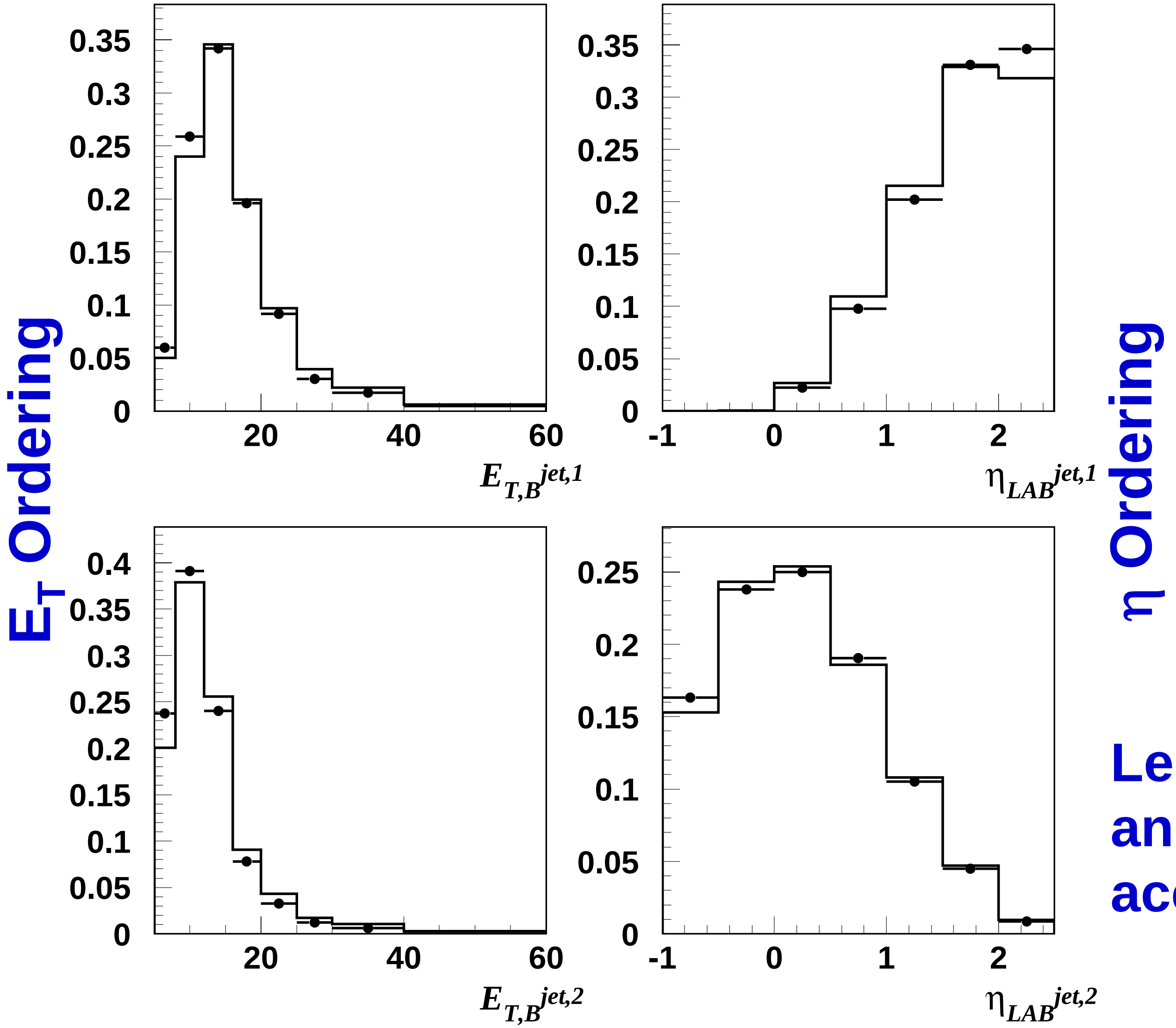


- ● Data
- ┐ Lepto

Area normalized to compare shapes

Lepto provides a good description of data

Dijet Kinematics

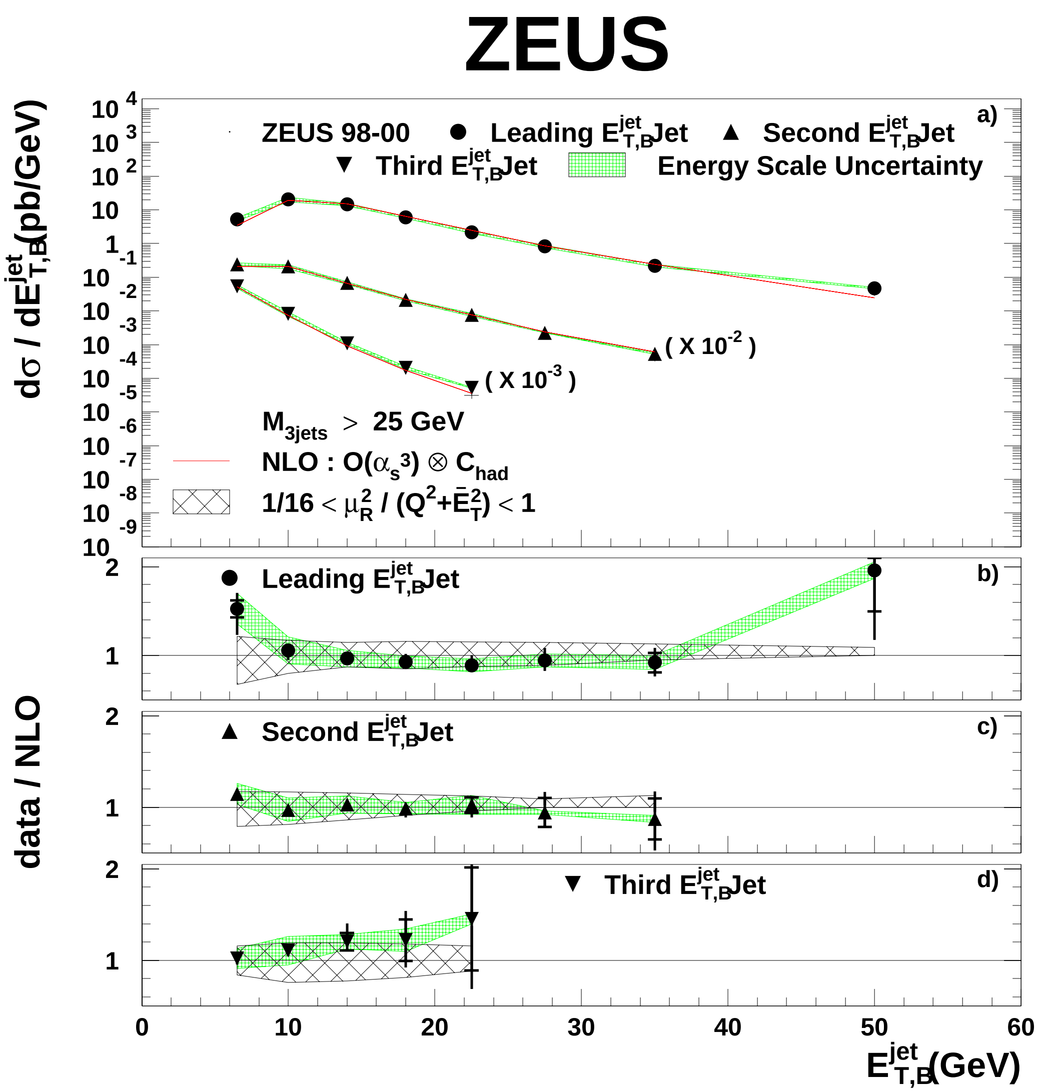


- ● **Data**
- ┐ **Lepto**

Area normalized to compare shapes

Lepto describes physics and detector, used for acceptance corrections

Trijet Cross Sections: E_T^{BRT} dependence



CTEQ6 PDF, $\alpha_s = 0.1179$

Scale $\mu_r^2 = \mu_f^2 = (\overline{E}_T^2 + Q^2)/4$

Jets ordered in E_T^{BRT}

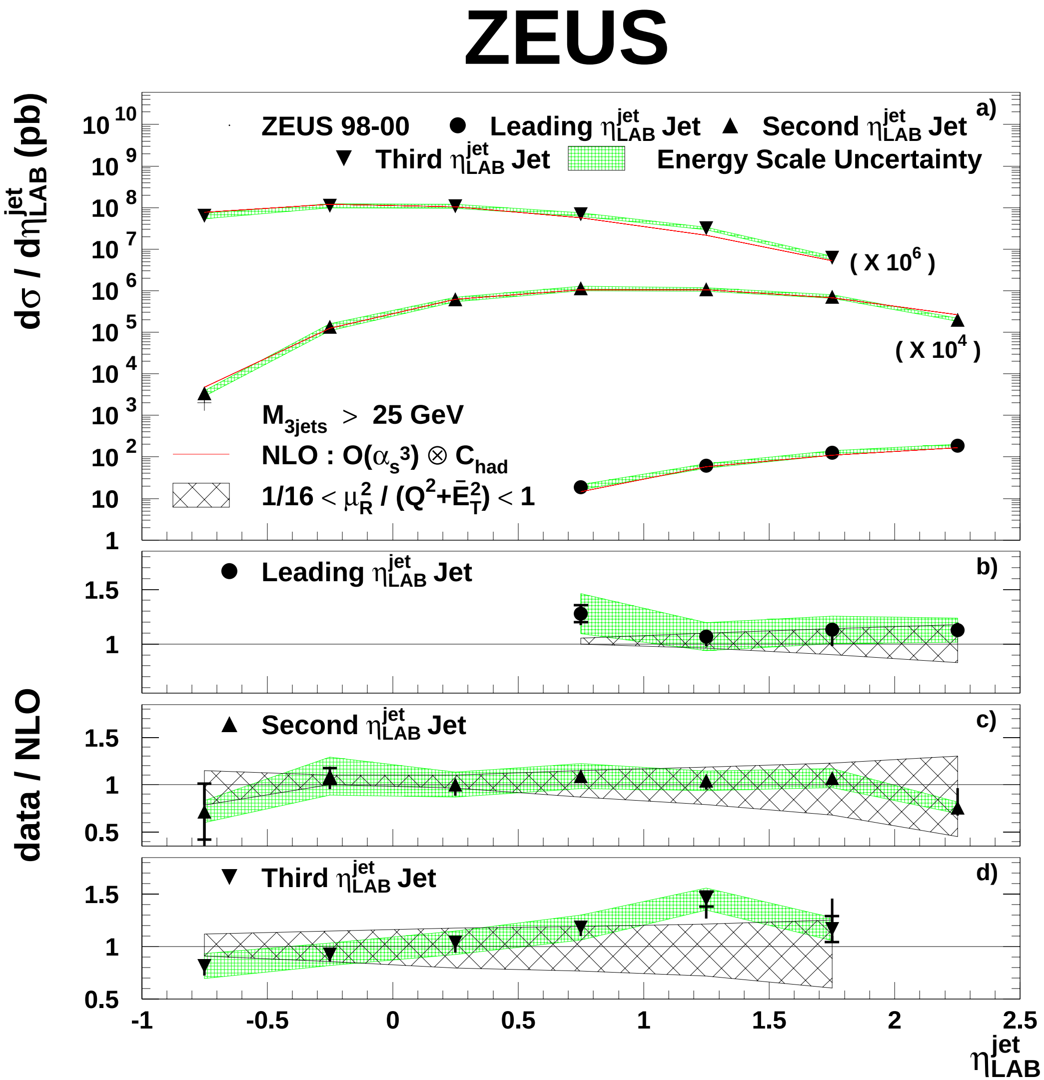
Measurement down to low E_T

Scale dependence

Good agreement for each jet

NLOJET describes data over large range of scales

Trijet Cross Sections: η^{LAB} dependence



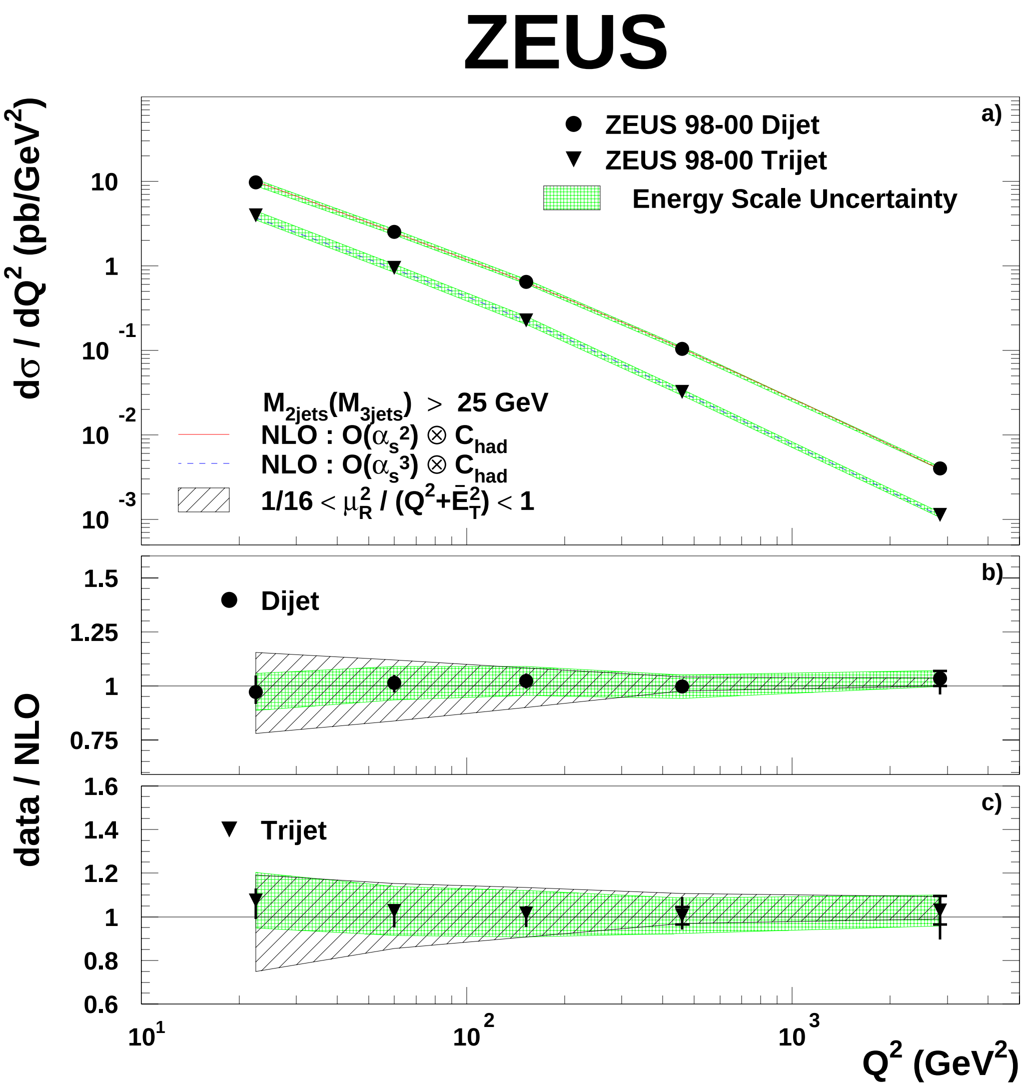
Jets ordered in η^{LAB}

Angular distribution

Good agreement for each jet

NLOJET describes data over whole η range

Multijet Cross Sections: Q^2 dependence



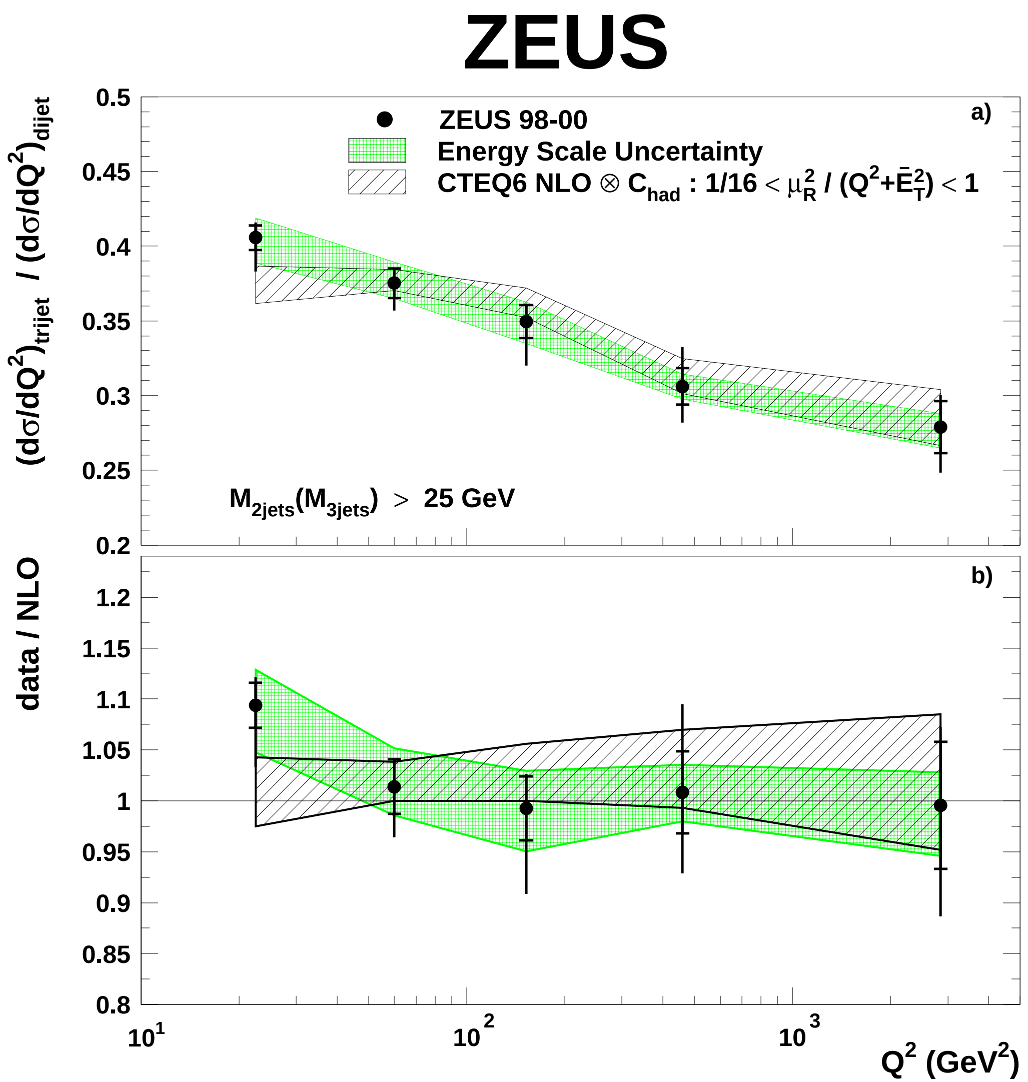
Dijet NLO: $O(\alpha_s^2)$
Trijet NLO: $O(\alpha_s^3)$

Measurement down to low Q^2

Scale dependence

NLOJET describes both dijet & trijet data over 3 orders of magnitude in Q^2

Multijet Cross Sections Ratio: Q^2 dependence



$R_{3/2}=\sigma_{trijet}/\sigma_{dijet}$

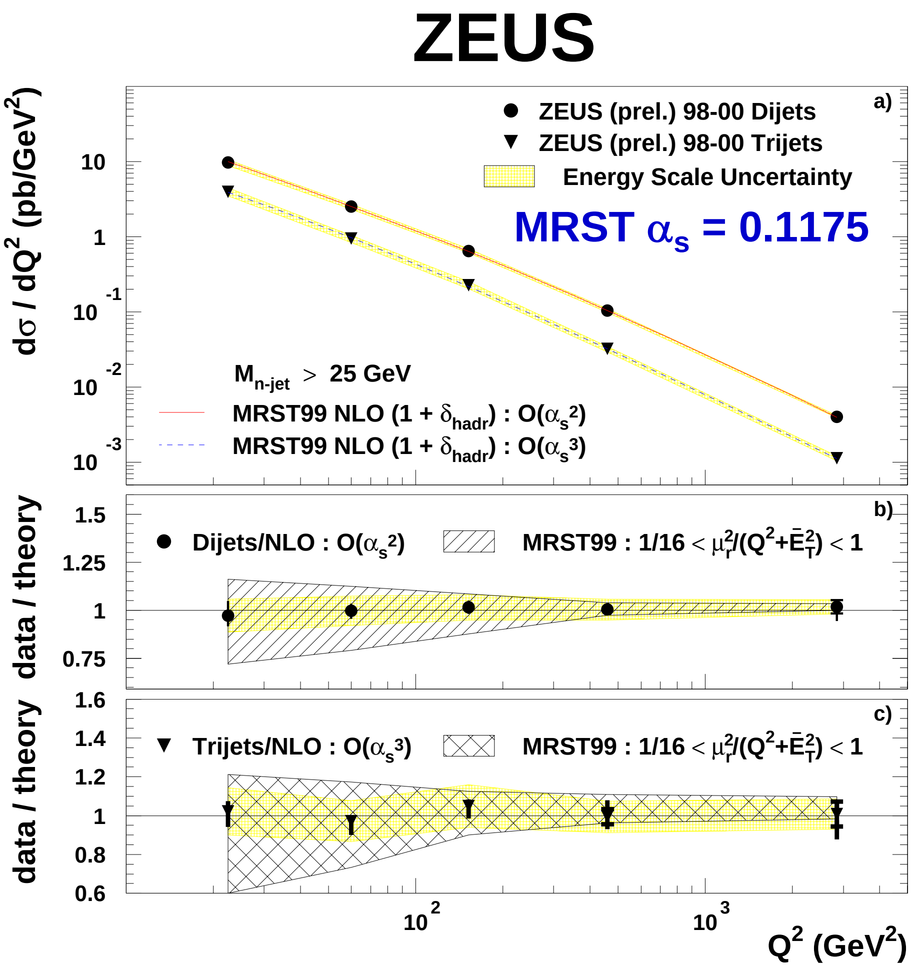
Systematic uncertainties substantially reduced

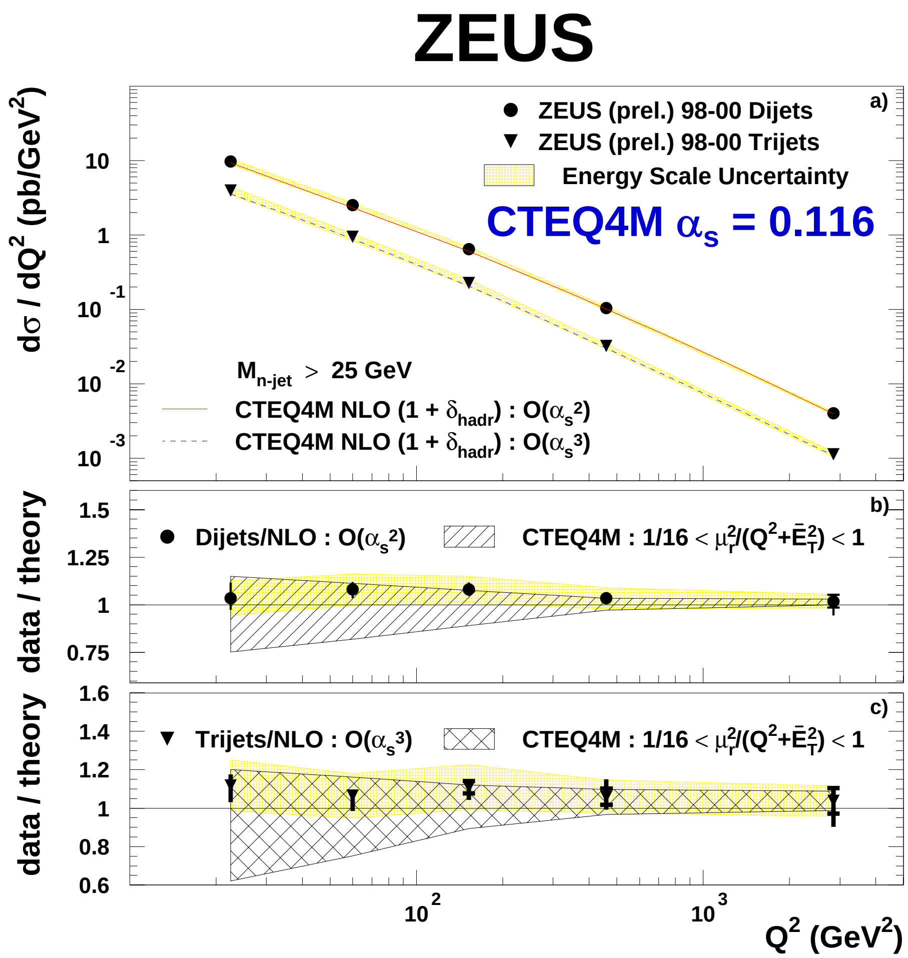
Scale dependence reduced

Very sensitive test of QCD calculation

NLOJET describes data over large range of scales

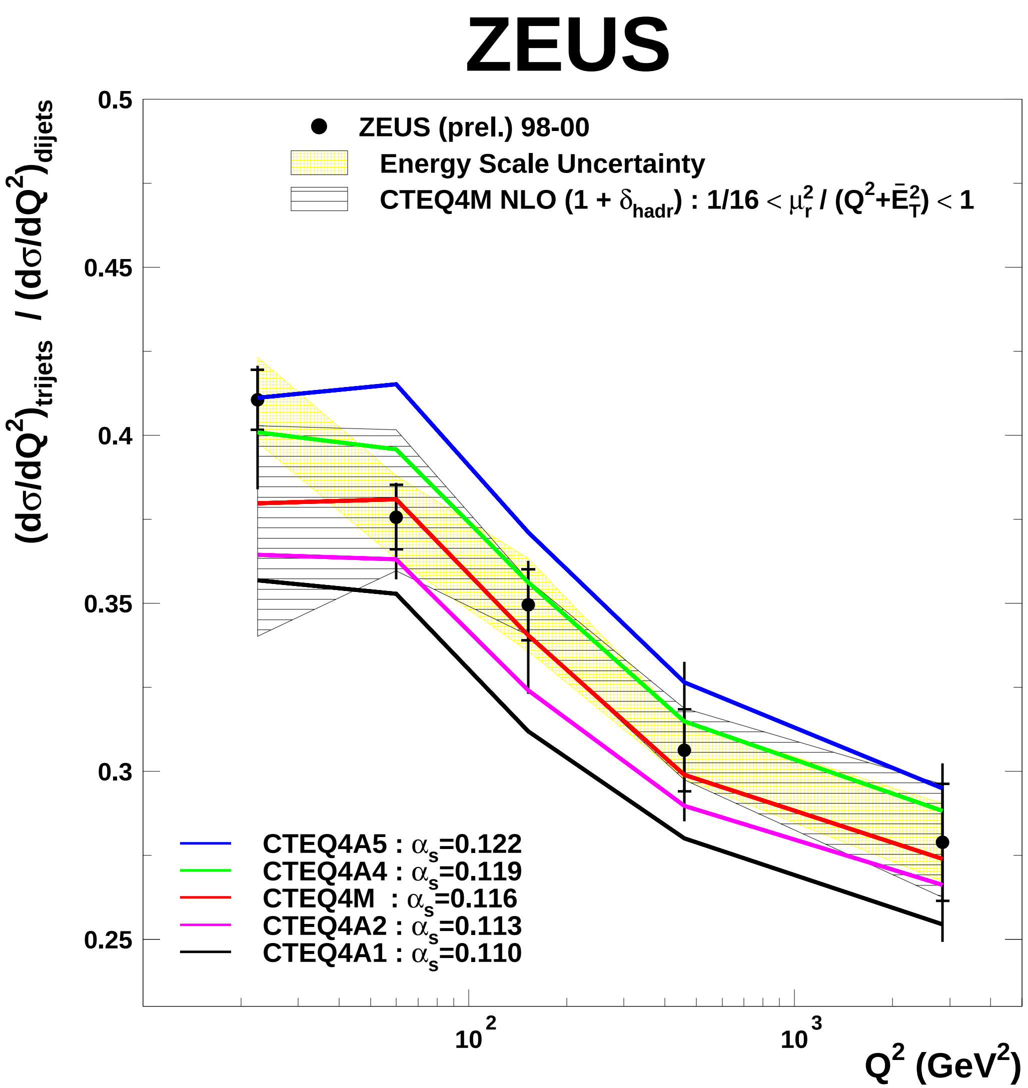
Multijet Cross Sections in Q^2: MRST99 and CTEQ4M PDF





NLOJET describes both dijets and trijets over 3 orders of magnitude in Q^2 for both PDFs —PDF independence

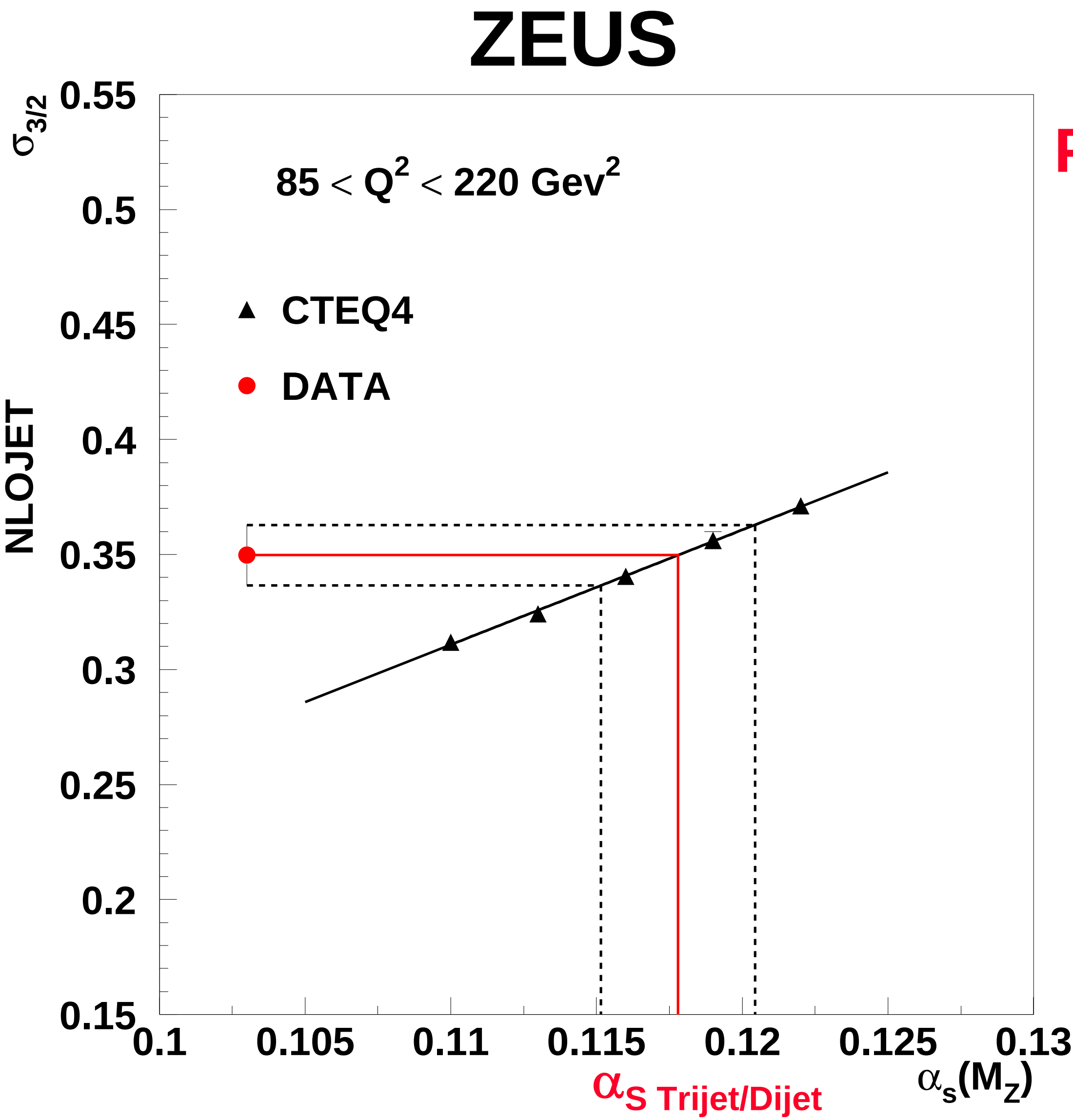
Trijet to Dijet Cross Section Ratio $R_{3/2}$: CTEQ4 with Different α_s value



$R_{3/2} = \sigma_{trijet} / \sigma_{dijet}$

- **As expected, predictions are sensitive to α_s**

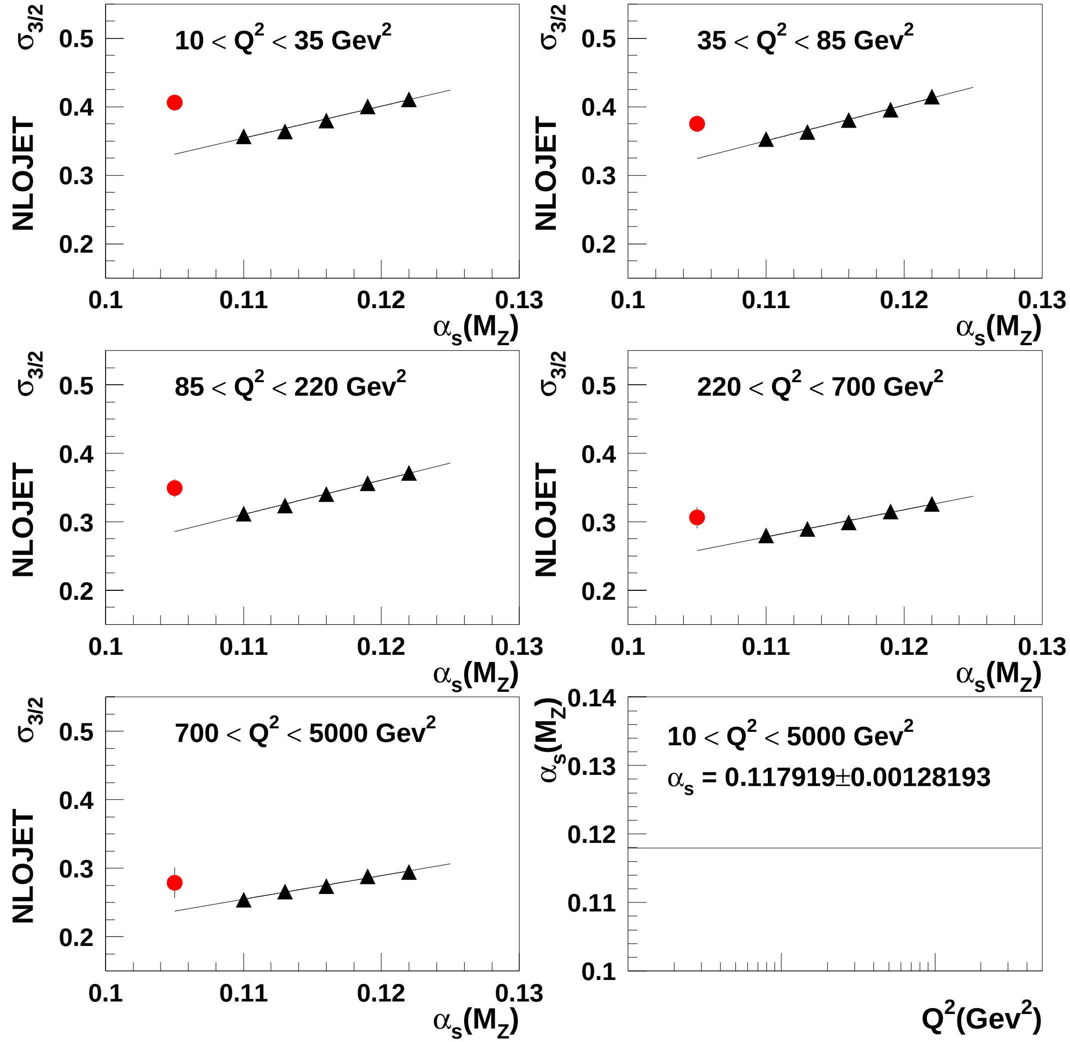
Parameterisation of $R_{3/2}$ with the value of $\alpha_s(M_z)$



Procedures:

- **Run NLOJET with several α_S values and fit with a linear function for each Q^2 bin**
- **Use this function to establish correlation of $R_{3/2}$ with $\alpha_S(M_z)$**
- **Extract α_S for each Q^2 bin and determine combined value with χ^2-fit.**

Extraction of α_S with CTEQ4 PDF



● Data
▲CTEQ4

- CTEQ4 provides more sets with different $\alpha_S(M_Z)$ than other PDF (i.e. MRST99)

Systematic uncertainties next page

$$\alpha_S(M_Z) = 0.1179 \pm 0.0013(\text{stat.})\ {}^{+0.0028}_{-0.0046}\ (\text{syst.})\ {}^{+0.0061}_{-0.0047}\ (\text{th.})$$

Systematic Uncertainties

Experimental (maximum change in any Q^2 bin)

- **Jet pseudo-rapidity cut: 1%**
- **Use of different LO MC model: 2%**
- **Jet transverse energy and invariant mass cuts: 2%**
- **The absolute energy scale of the CAL: 2.5%**
- **Other sources which have negligible effects: 0.4%**
  - Un-reweighted MC
  - Z_{Vertex} cuts
  - Y_{JB} cut
  - $E\text{-}P_Z$ cut
  - $\cos\gamma_{had}$ cut

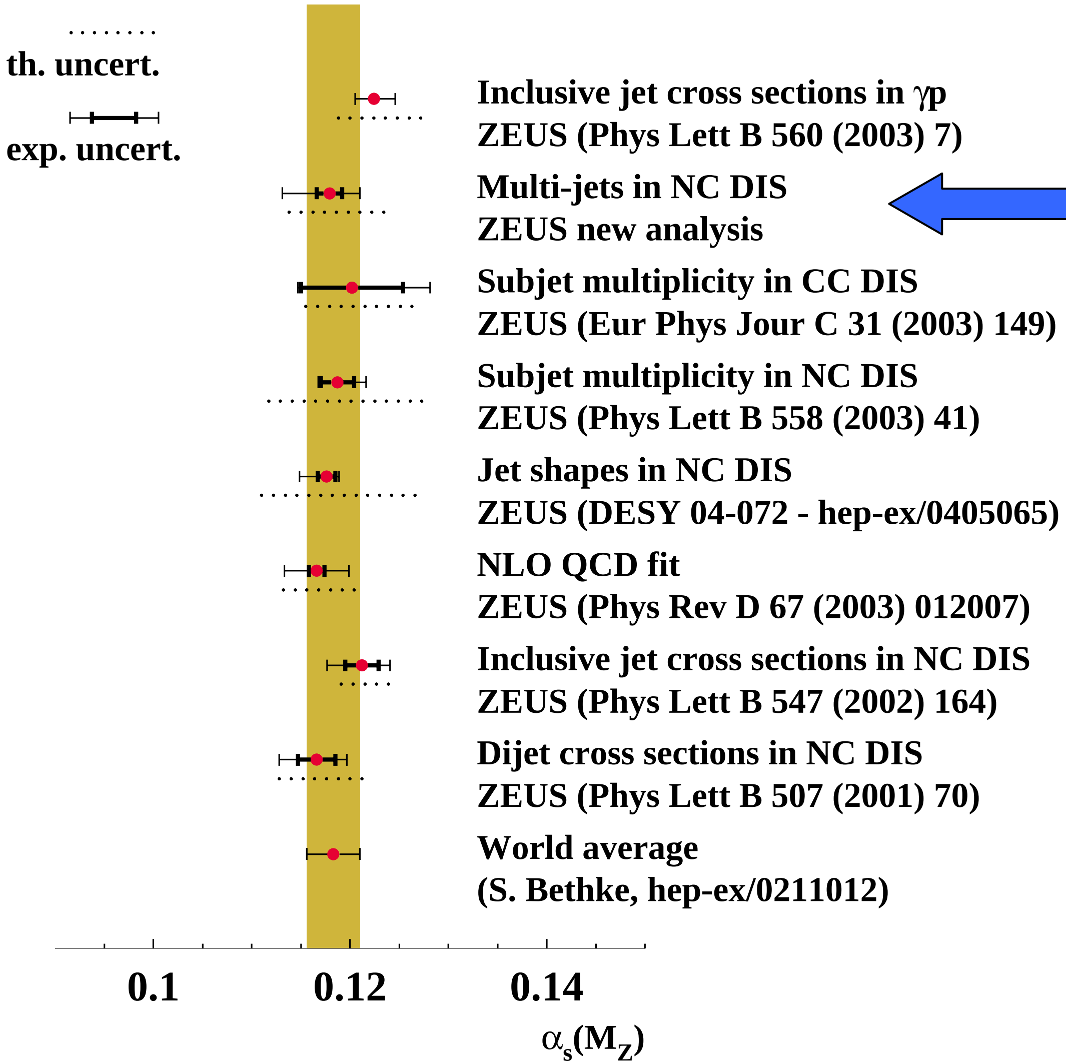
$$\Delta\alpha_S(M_Z) = {}^{+0.0028}_{-0.0046}$$

Theoretical (maximum change in any Q^2 bin)

- **Hadronisation correction factors: 2%**
- **Renormalization scale: 5%**
- **Uncertainties in the proton PDFs: 1.5%**

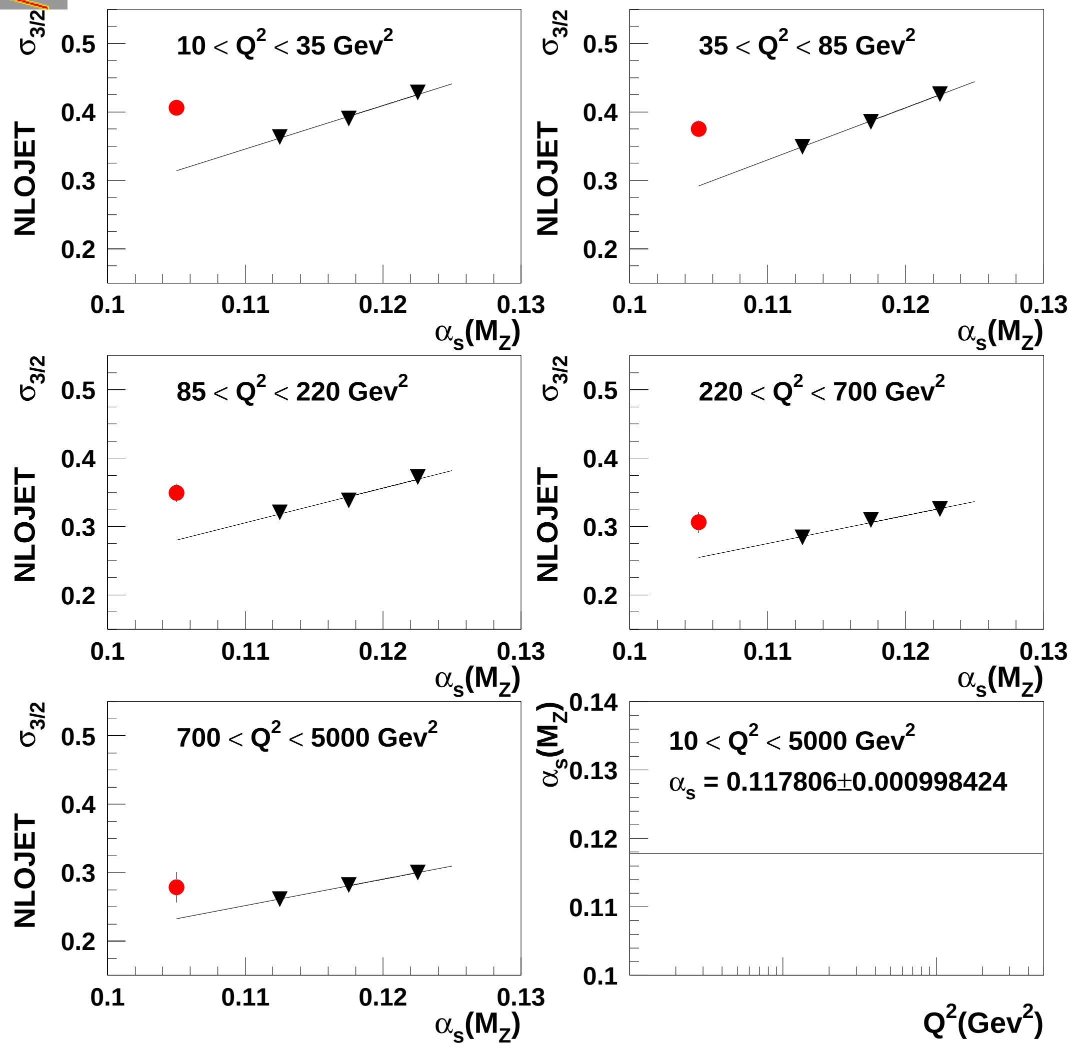
$$\Delta\alpha_S(M_Z) = {}^{+0.0064}_{-0.0046}$$

Other α_s measurements



- **Errors competitive**
- **See comparison with different PDF next page**

Extraction of α_s with MRST99 PDF



- ● Data
- ▼ MRST99

Excellent agreement between MRST99 and CTEQ4M ($\alpha_s(M_z)$=0.1179), 0.1% difference

$$\alpha_S(M_Z) = 0.1178 \pm 0.0010(\text{stat.})\ ^{+0.0021}_{-0.0035}\ (\text{syst.})\ ^{+0.0048}_{-0.0034}\ (\text{th.})$$

Summary

- NLO predictions give a good description of the dijet and trijet cross sections and the cross-section ratio $R_{3/2}$ over the whole kinematic range
- The value of strong coupling constant α_s at the conventional scale of M_Z=91.9 GeV is measured to be

$$\alpha_S(M_Z) = 0.1179 \pm 0.0013(\text{stat.})\ ^{+0.0028}_{-0.0046}\ (\text{syst.})\ ^{+0.0064}_{-0.0046}\ (\text{th.})$$

in good agreement with current world average

$$\alpha_S(M_Z) = 0.1182 \pm 0.0027$$

Outlook

- **Higher order calculations, e.g. NNLO calculation needed**
- **LO MC models need to be improved**
- **HERA II program aims at collecting a high luminosity DIS data of high E_T and Q^2**
  - Greatly increase statistics, higher precision
  - Improved jet and kinematic reconstruction
  - Lower experimental uncertainties at high E_T and Q^2