Three-jet Production in Neutral Current Deep Inelastic Scattering with ZEUS Detector at HERA

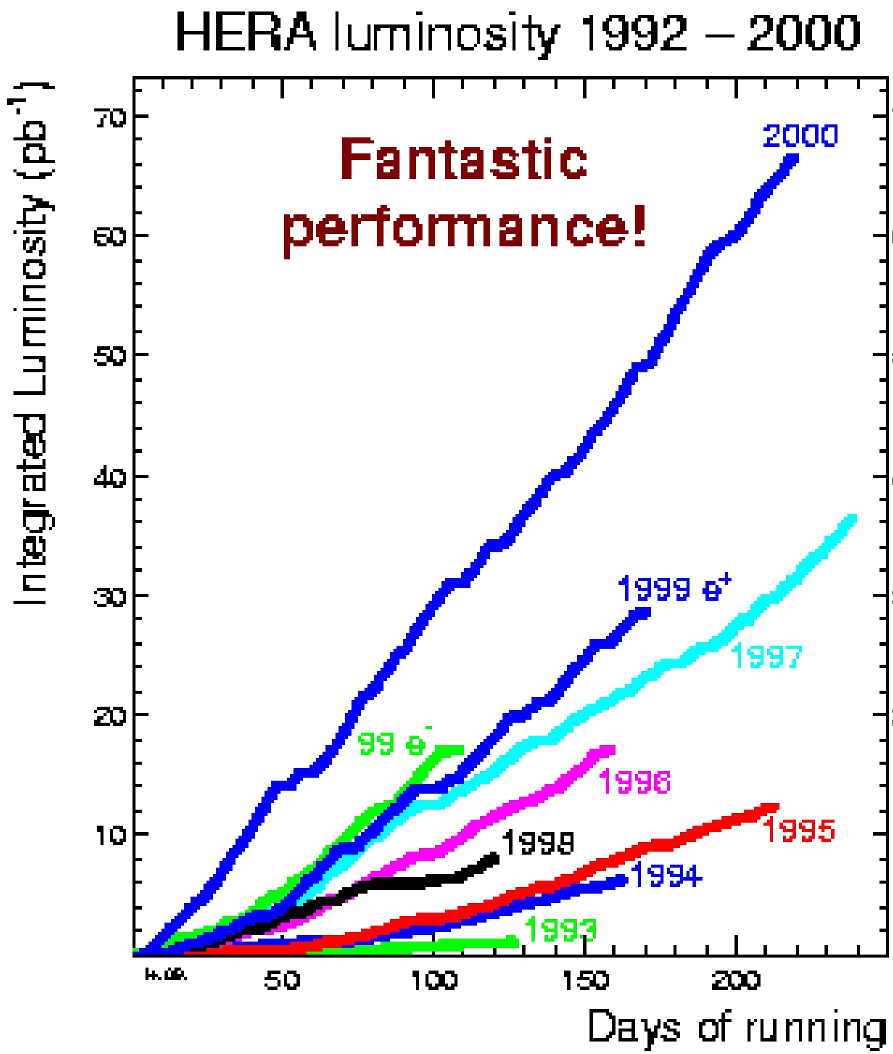
Preliminary Examination

Liang Li
University of Wisconsin
Nov 27,2001

HERA

- 820/920 GeV proton
- 27.5 GeV electrons or positrons
- 300/318 GeV center of mass energy
- 220 bunches
  96 ns crossing time
- Instantaneous luminosity
  1.8×10^{31} $cm^{-2}s^{-1}$
- Currents:
  ~90mA protons
  ~40mA positrons

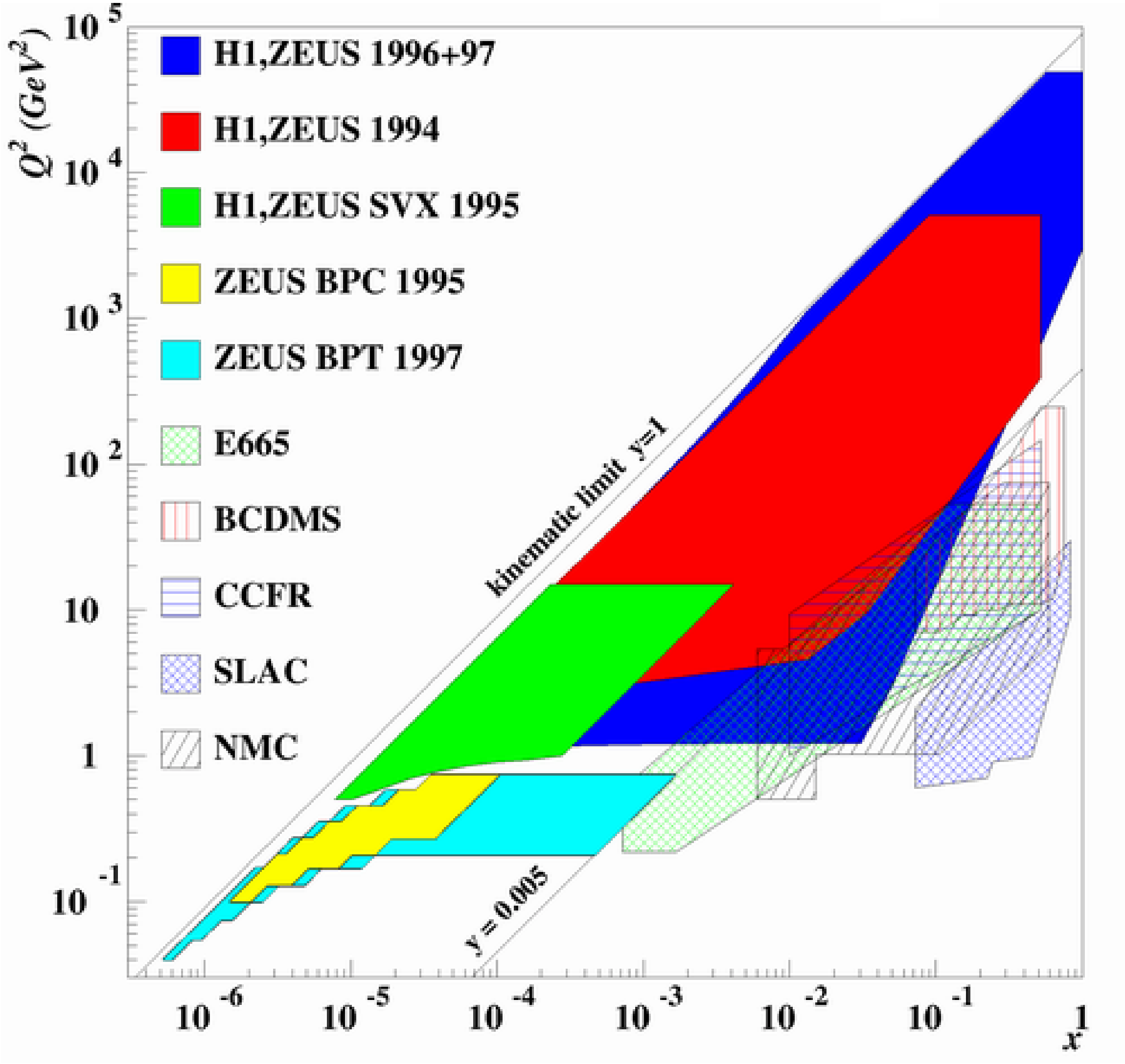
HERA Luminosity



- 820 GeV protons through 1997

  920 GeV since 1998
- ZEUS integrated luminosity since 1992: ~185 pb^{-1}
- Expect 1fb^{-1} by end of 2005

HERA Kinematic Range

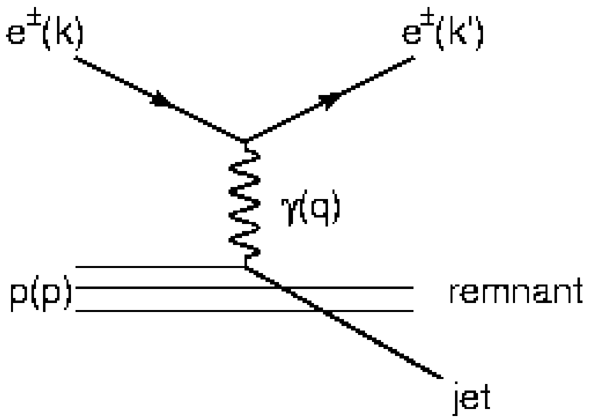


Extended kinematic region not accessible by fixed target experiments, with some overlap.

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

Deep Inelastic Scattering

electron–proton scattering



Can also exchange Z,W±

Any lepton – hadron pair

e–p (HERA)

e–A (SLAC)

υ–Fe (CCFR)

μ–A (E665,NMC,BCDMS)

DIS kinematic variables

$$Q^2 = -q^2 = -(k - k')^2$$

Momentum transfer

$$x = \frac{Q^2}{2p \cdot q}$$

Fraction of the proton's momentum that participates in the hard scatter

$$y = \frac{p \cdot q}{p \cdot k}$$

Fraction of the electron's energy available in the proton's rest frame

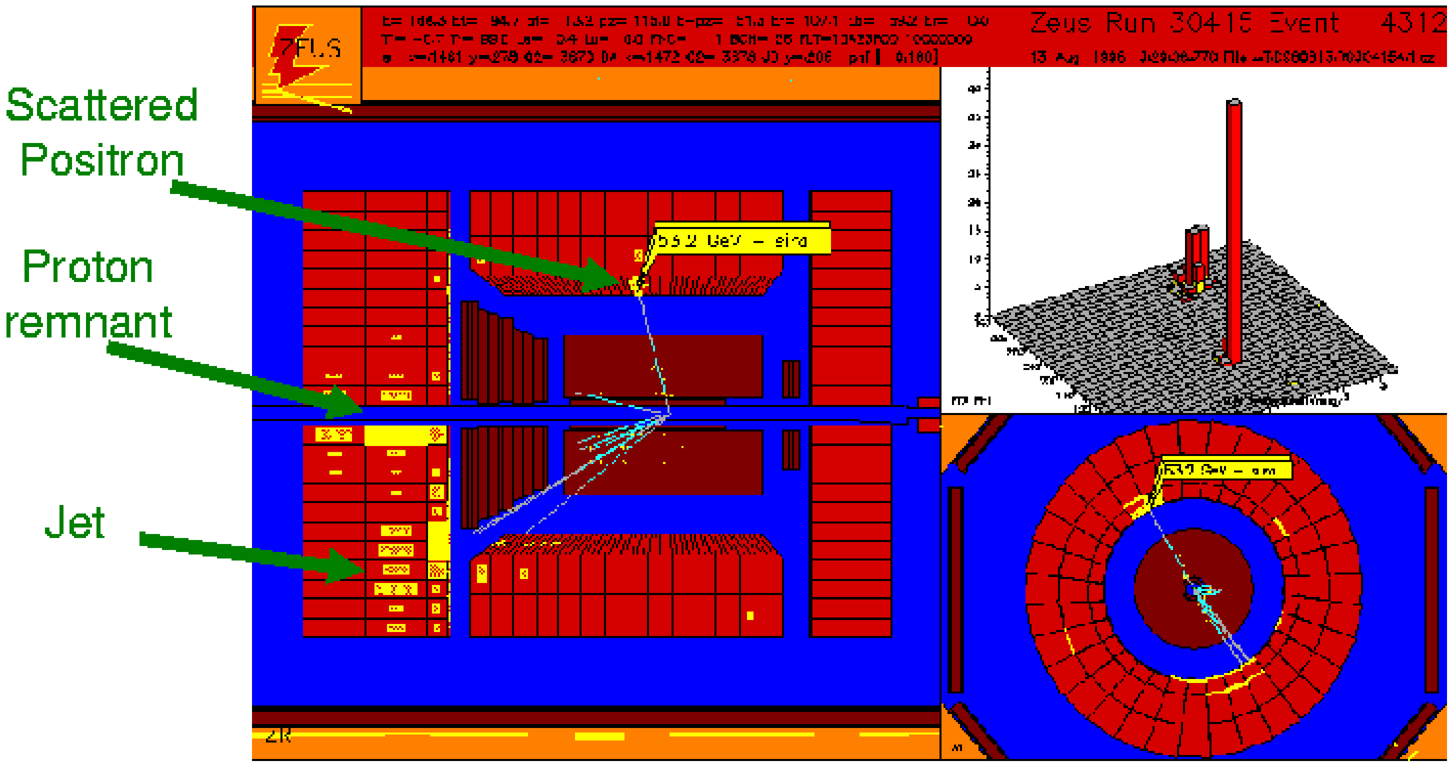
$$Q^2 = sxy$$

s=center of mass energy squared

$$W^2 = (p+q)^2$$

W=invariant mass of the final hadronic system

e^+p DIS Event at HERA

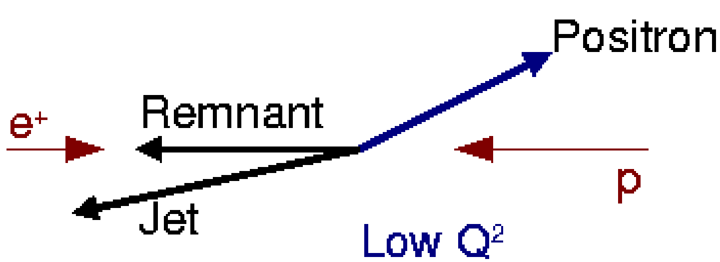


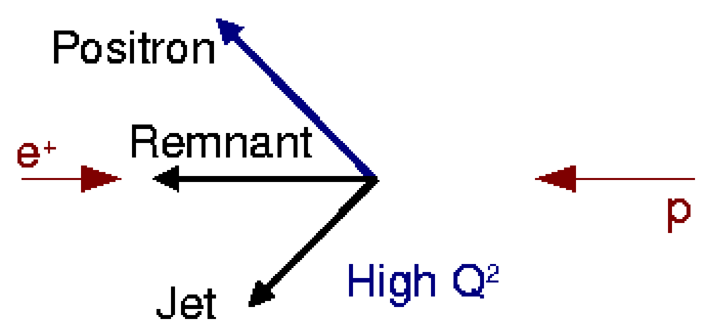
Q^2~3600GeV^2

X ~0.15

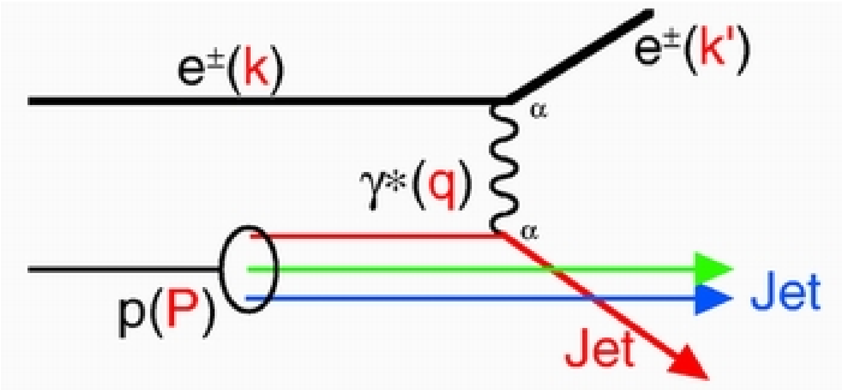
Y ~0.20

(1+1)
event





DIS Cross Section



$$\frac{d^2\sigma(e^+p)}{dxdQ^2}(x,Q^2) = \frac{2\pi\alpha^2}{xQ^4}\left[\left(1+(1-y)^2\right)F_2(x,Q^2) - y^2F_L(x,Q^2) - \left(1-(1-y)^2\right)xF_3(x,Q^2)\right]$$

$F_2\ (x,Q^2)$: Interaction between transversely polarized photons & spin 1/2 partons ; Charge weighted sum of the quark distributions

$F_L\ (x,Q^2)$: Interaction between longitudinally polarized photons & the partons with transverse momentum.

$F_3\ (x,Q^2)$: Parity-violating structure function from Z^0 exchange.

Naïve Quark Parton Model

- Partons are point-like objects
- No interaction between the partons
- Structure function independent of Q^2

Bjorken Scaling (x) dependence:

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

$$F_2(x,Q^2) \rightarrow F_2(x),\ F_L = 0$$

QCD

Physics picture: presence of gluons

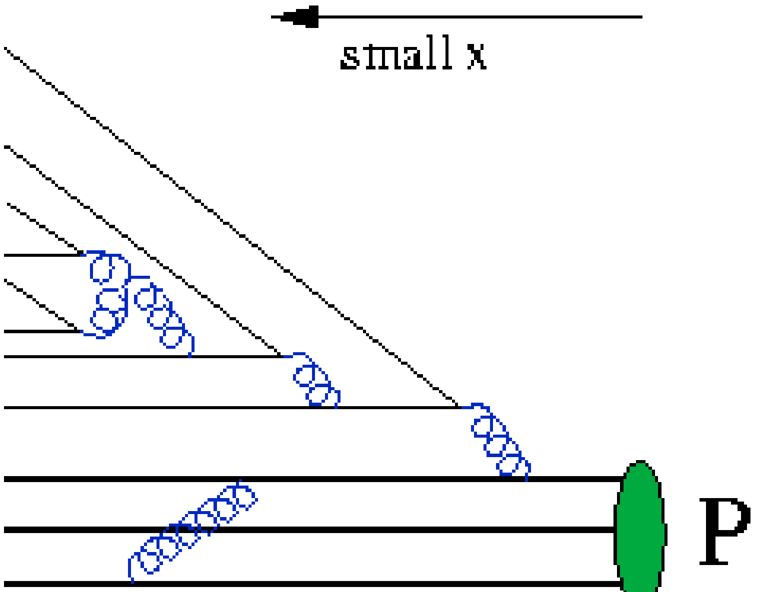
Parton Parton interactions, mediated by gluons

Generate parton transverse momentum

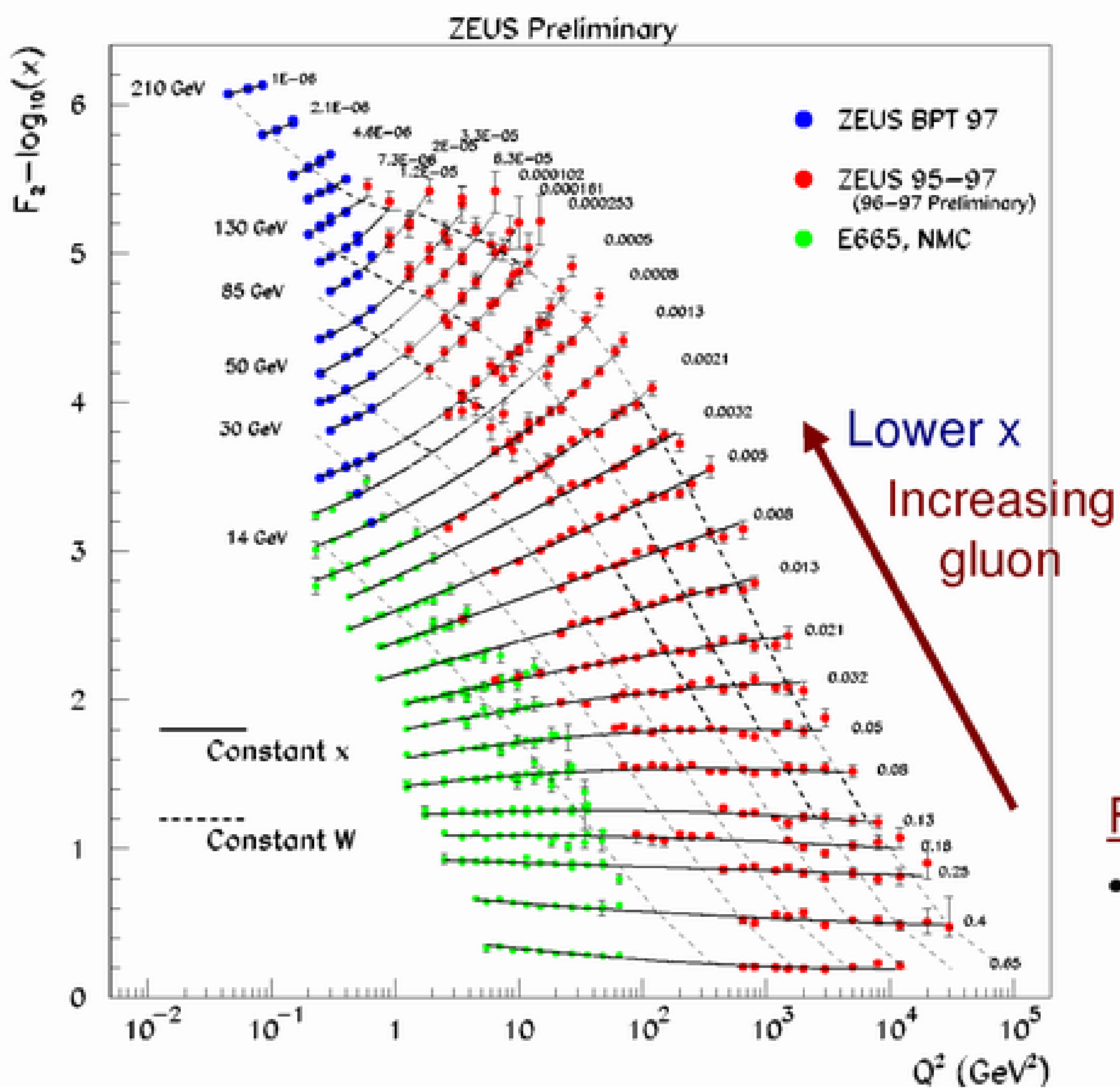
Non zero F_L

The structure functions gain a Q^2 dependence

Scaling Violation



Scaling Violation



<u>Scaling Violation</u>

- F_2 has a Q^2 dependence due to gluon

$$F_2(x) \rightarrow F_2(x,Q^2)$$

- More significant at smaller x

<u>F_2 scaling violation –> gluon density</u>

- QCD evolution equations (Altarelli–Parisi) predict

$$g(x,Q^2) \sim dF_2(x,Q^2)/d\log Q^2$$

Parton Distribution Functions

16% uncertainty at $x\sim10^{-3}$

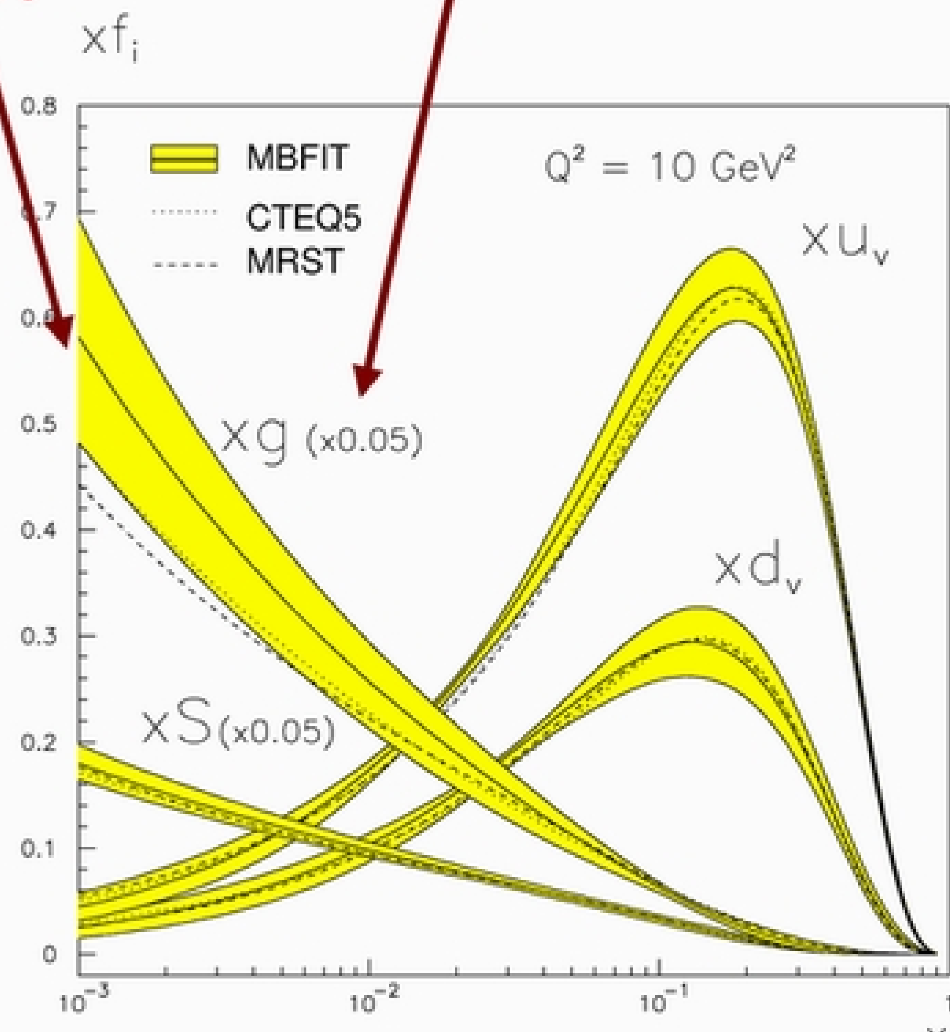
Factor of 20

Several different groups make global fits to DIS structure function data

- Parton Density Functions (PDFs)
  - CTEQ, MRST,GRV,MBFIT
  - needed by Tevatron and LHC

Gluon density extracted indirectly from scaling violation of F_2

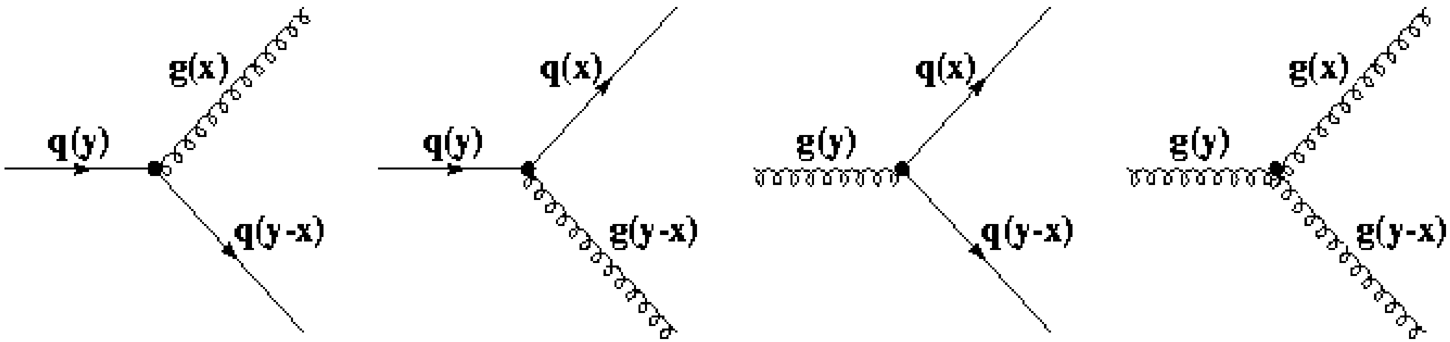
- $g(x,Q^2)\sim dF_2(x,Q^2)/d\log Q^2$
- relatively large uncertainty on $g(x,Q^2)$
- A measurement with direct sensitivity to the gluon would be nice...



Derived from the experiment

DGLAP Evolution

– Uses QCD splitting functions



$P_{gq}(z=x/y)$ $P_{qq}(z=x/y)$ $P_{qg}(z=x/y)$ $P_{gg}(z=x/y)$

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi equations describe evolution of parton densities to higher Q^2 — QCD prediction

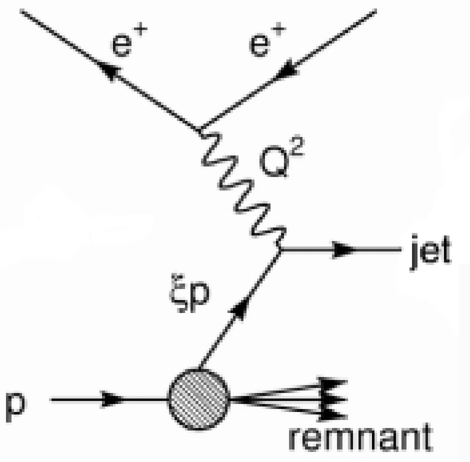
$$\frac{dq_i(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[q_i(y,Q^2)P_{qq}\left(\frac{x}{y}\right) + g(q,Q^2)P_{qg}\left(\frac{x}{y}\right)\right]$$

$$\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_i q_i(y,Q^2)P_{gq}\left(\frac{x}{y}\right) + g(q,Q^2)P_{gg}\left(\frac{x}{y}\right)\right]$$

α_s is the strong coupling constant.

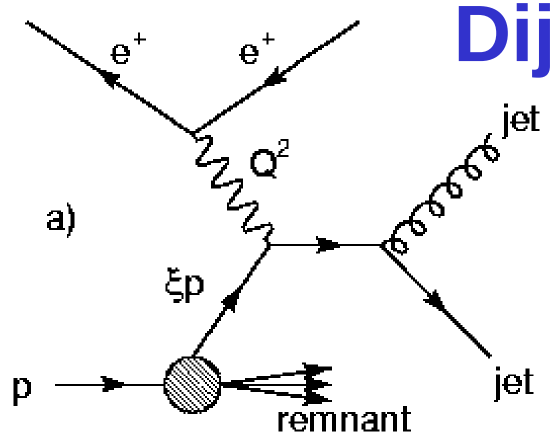
Single Jet Dijet Trijet

Single Jet

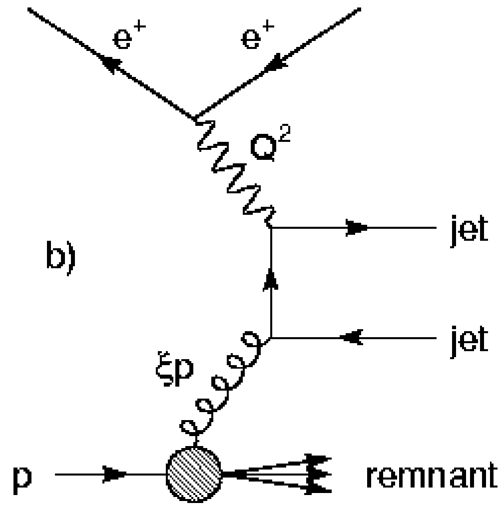


Dijet

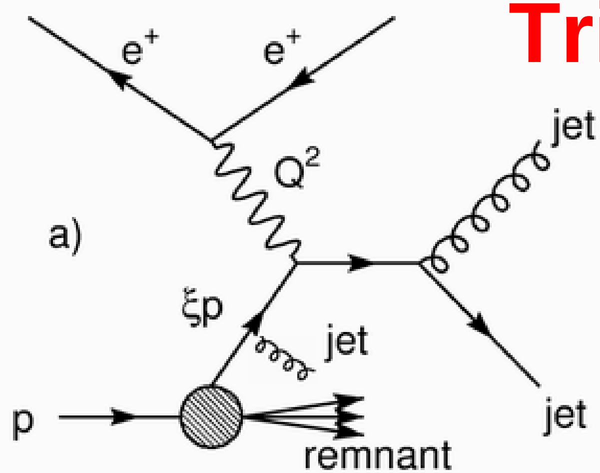
a) QCD Compton

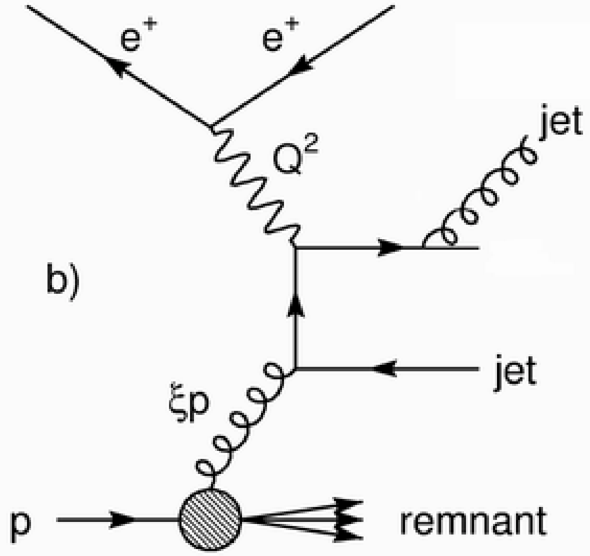


b) Boson-Gluon Fusion



Trijet





Why Trijet?

- Adding a gluon radiation to dijet

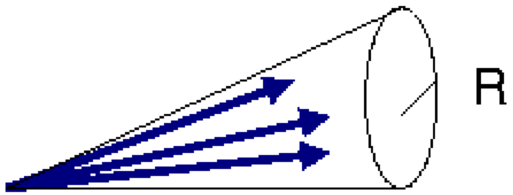
  $\rightarrow$ A direct test of QCD.

- Recent important advance in understanding QCD in dijets makes it an ideal laboratory for studying added gluon radiation.
- Measure α_s at a wide range of Q^2
- In the the ratio of $R_{3/2} = \sigma_{trijet}/\sigma_{dijet} = O(\alpha_s)$, there is a cancellation of some experimental and theoretical uncertainties

Jet Algorithms

Cone algorithms

- conceptually simple
- theoretical/implementation issues
  - seed requirements
  - infrared unsafe at NNLO



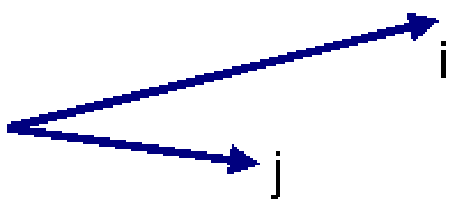
Maximize E_T within a cone of radius R

Inclusive–mode k_T–algorithm (KTCLUS)

- No known theoretical or implementation issues
  - infrared safe
  - seeding not necessary
- Smaller hadronization corrections in some regions

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

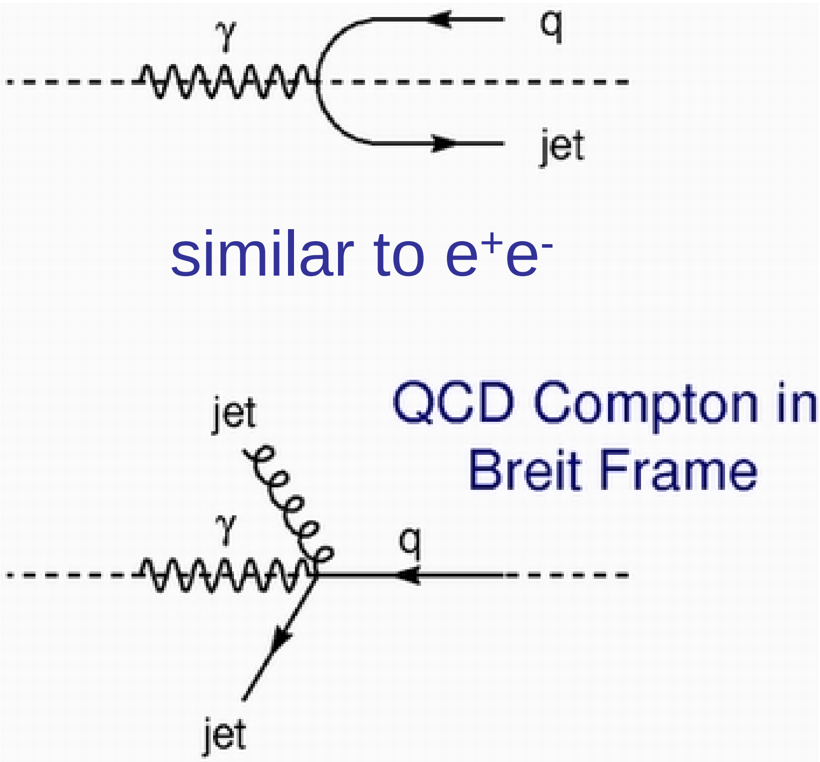
$$d_{i,j} = min\{E_{T,i}^2, E_{T,j}^2\}(\Delta\eta^2 + \Delta\phi^2)/R^2$$



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

Breit Frame

Single jet event in Breit Frame



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

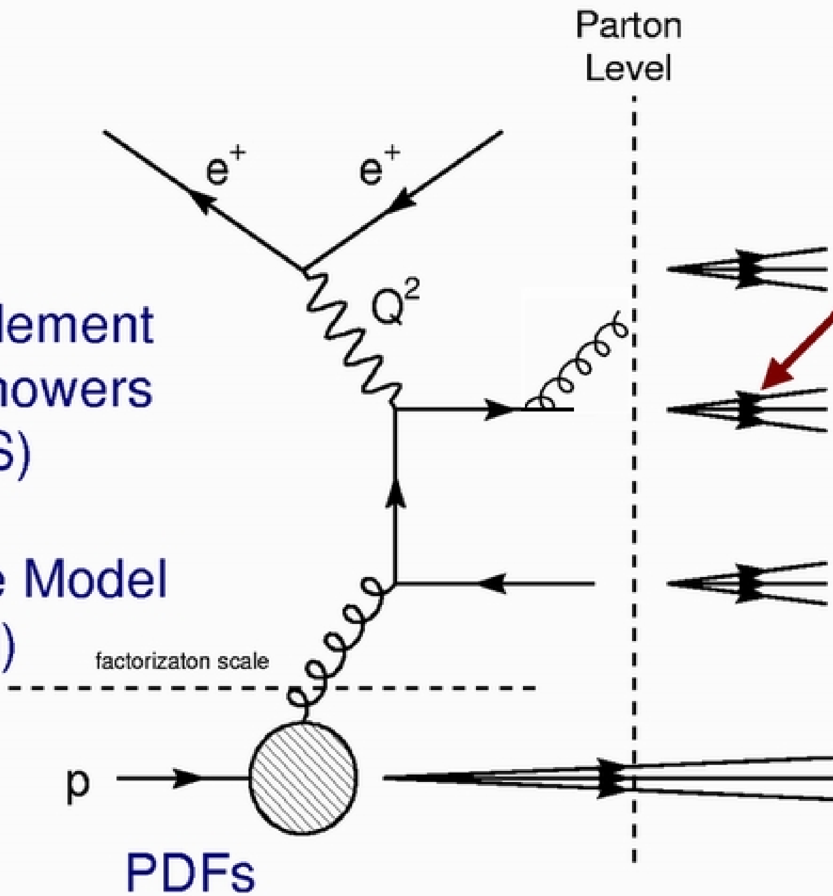
In single jet events, struck quark rebounds with equal and opposite momentum, the resulting jet has zero E_T (transverse energy)

In multi-jet events, the outgoing jets are balanced in E_T

The proton and exchanged photon collide on a common axis, with the z-direction chosen to be the proton direction.

Leading Order MC

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



Hadronization Models
- String Fragmentation (LUND)
- Cluster Model

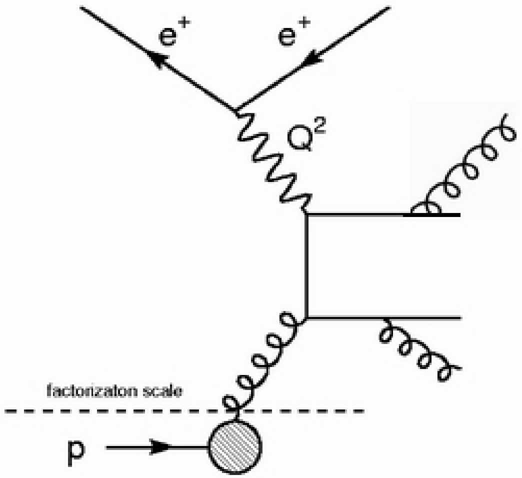
Detector Simulation

Choose

Programs
- LEPTO (MEPS+LUND)
- ARIADNE (CDM+LUND)
- HERWIG (MEPS+CLUSTER)

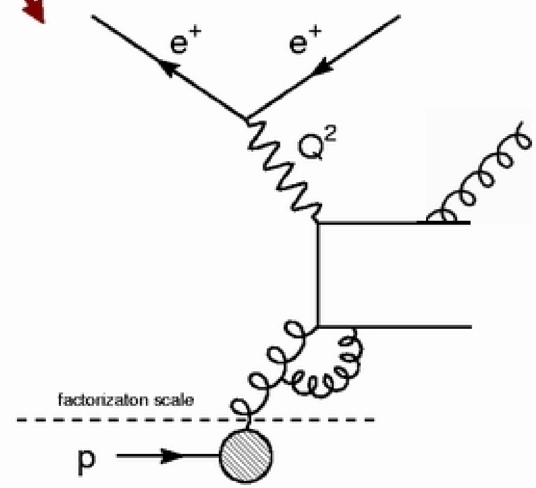
LO models used only for
- detector corrections
- hadronization corrections

Next Leading Order MC



NLO Matrix Elements

- Four parton final states
- Large improvement over LO
- Soft/colinear and virtual loop divergences cancel



Programs for DIS

- DISENT (subtraction method)
- DISASTER++ (subtraction method)
- MEPJET (phase space splicing method)
- JETVIP (phase space splicing method)

NLO calculations do not include hadronization models

MC Scales

Factorization scale

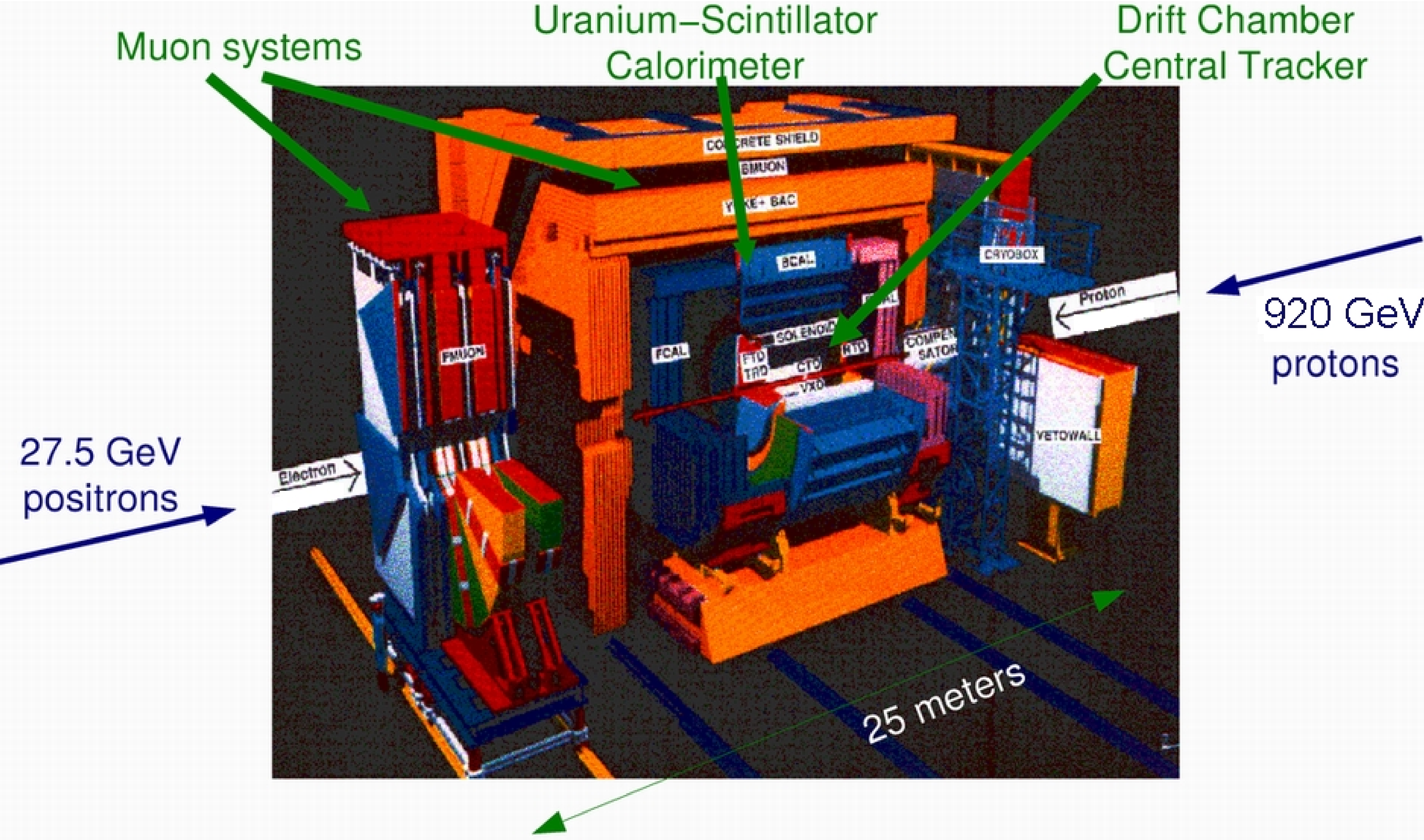
$f_q(x,\mu^2_f)$, scale μ_f at which the parton densities are evaluated and where the hadronization begins

Renormalization scale

$\alpha_s(\mu^2_r)$, scale μ_r at which the constant α_s is evaluated

- NLO reduces renormalization scale dependence with respect to LO MC
- Renormalization scale uncertainty is the largest contribution to NLO theoretical uncertainty

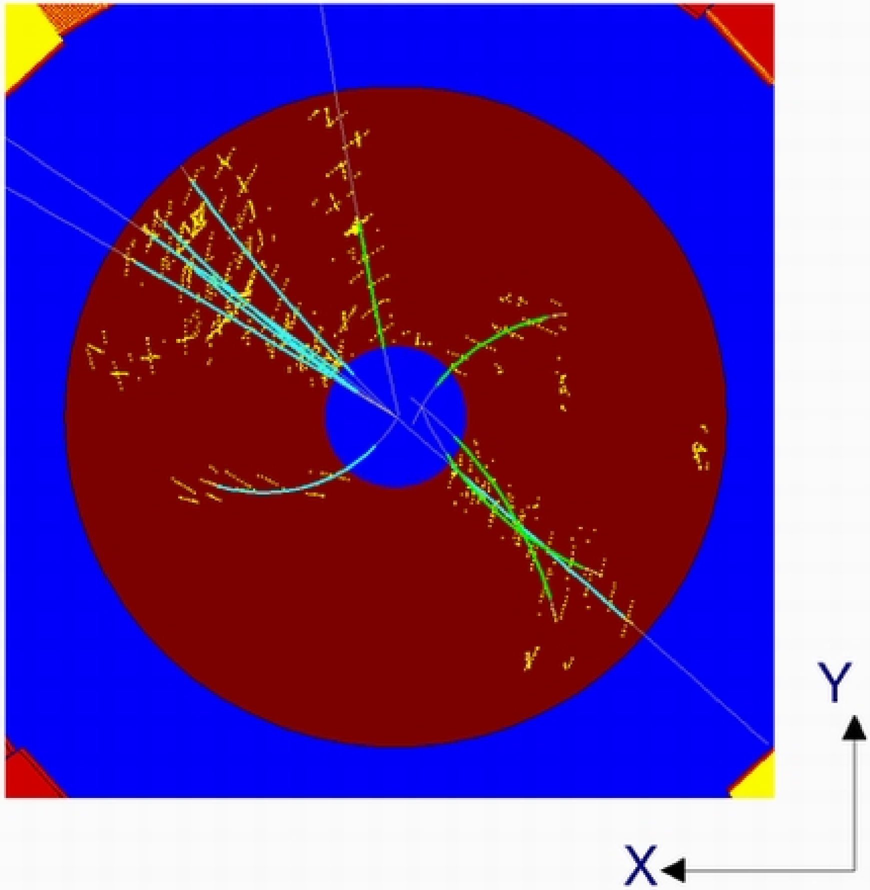
ZEUS Detector

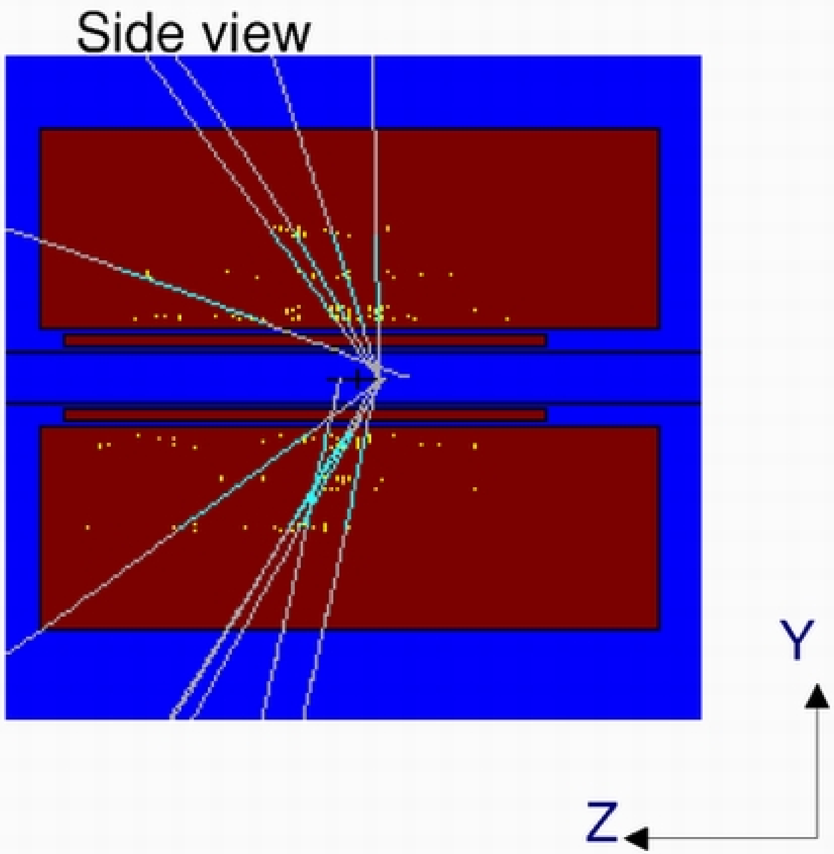


Central Tracking Detector

Drift Chamber
inside1.43T solenoid

View along beamline

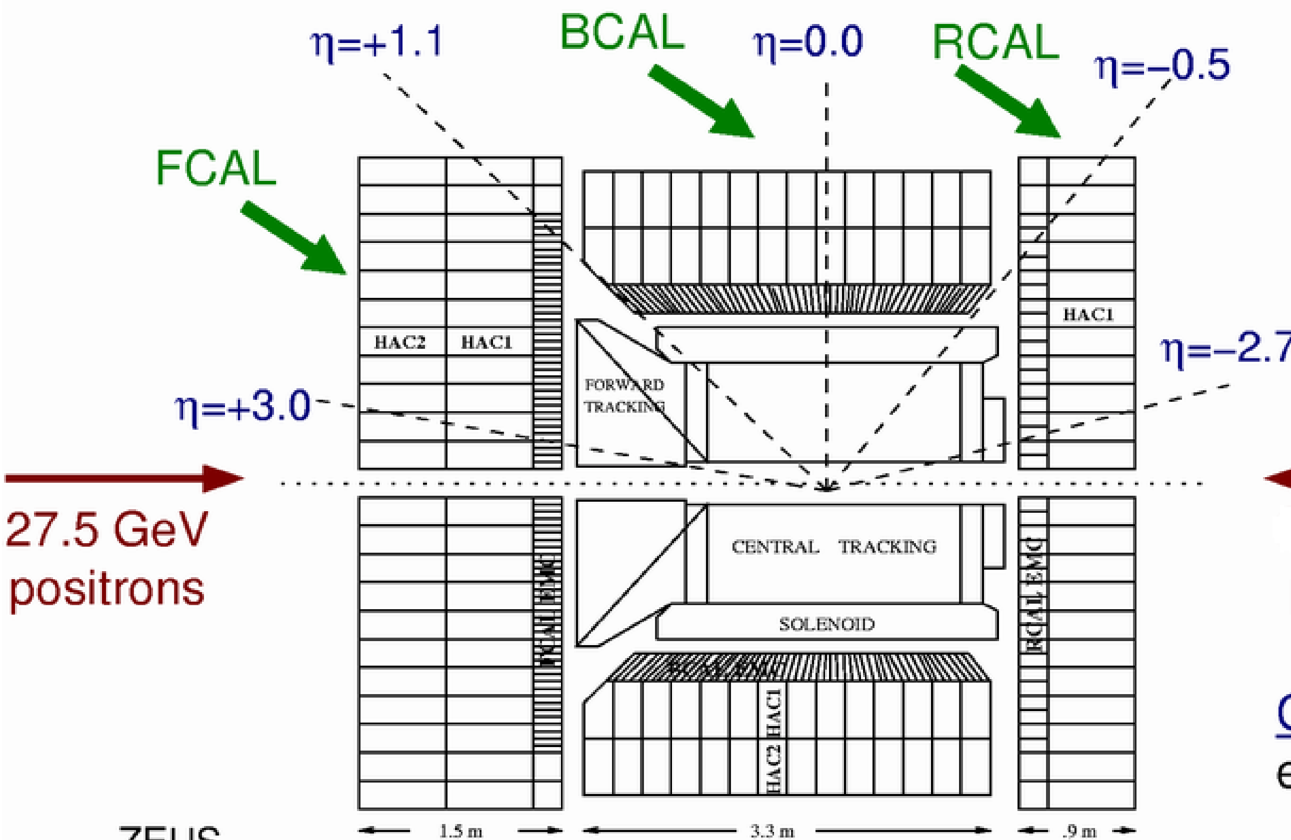




Vertex Resolution

longitudinal (z): 4mm
transverse (x–y): 1mm

ZEUS Uranium Calorimeter



Depleted Uranium and scintillator

Energy Resolution

electromagnetic: 18%/√E

hadronic: 35%/√E

Cell Dimensions

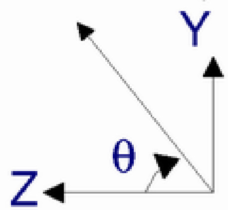
electromagnetic:

5x20cm (FCAL,BCAL)

10x20cm (RCAL)

hadronic: 20x20cm

ZEUS Coordinate System



99.7% solid angle coverage

$-3.5 < \eta < 4.0$

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

US groups, including Wisconsin are responsible for barrel calorimeter

ZEUS Trigger

10 MHz bunch crossing rate
Extract 10Hz Physics from 100kHz background

10^5Hz →

Readout ↓

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 →

Level 2

- "Commodity" Transputers
- Calorimeter timing cuts
- E−p_z cuts
- Initial vertex information
- Simple physics filters

100Hz →

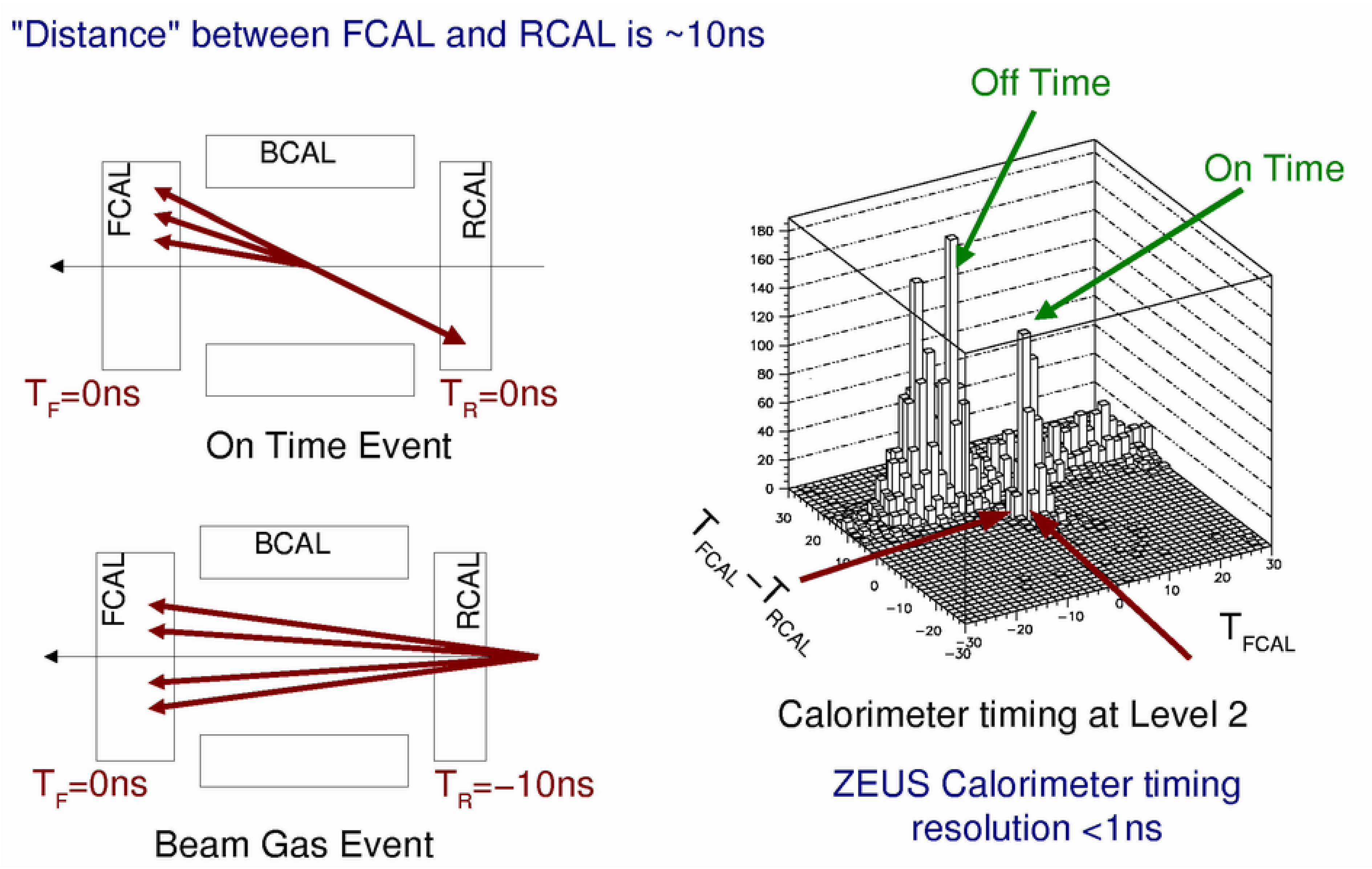
Level 3

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

→ 10Hz → Mass storage

Wisconsin group is responsible for Level 1CAL trigger

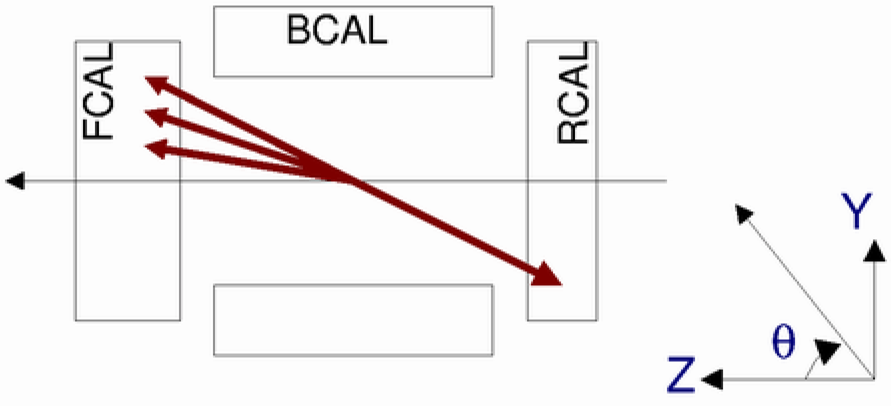
Background Rejection: Timing



Background Rejection: E-P_z

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

Sum runs over calorimeter cells

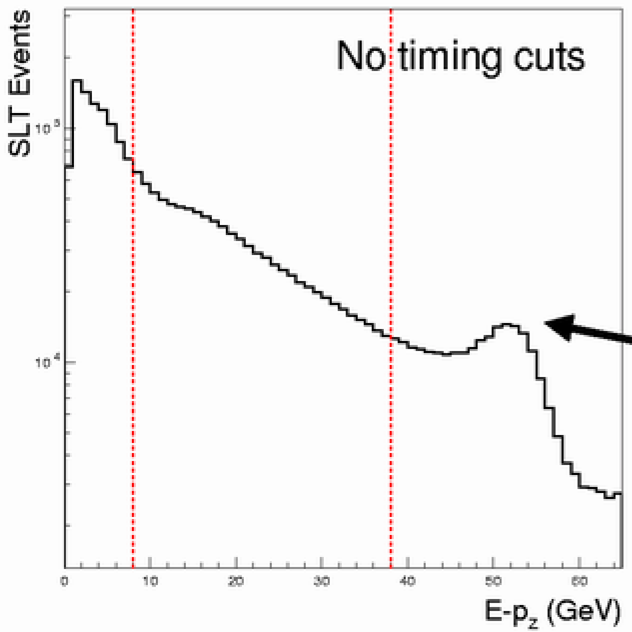


In a given frame, E–p_z is conserved

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 NC DIS



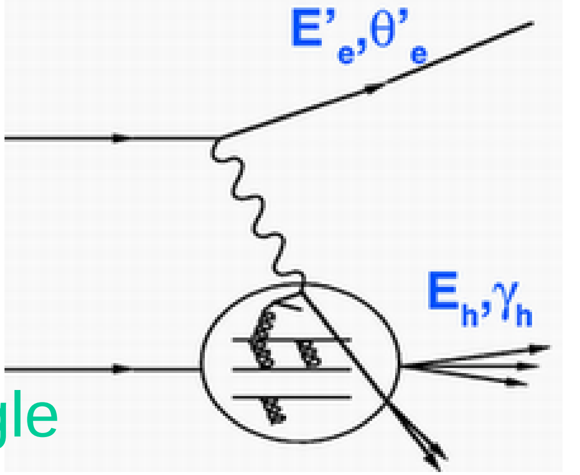
Contained NC DIS E–p_z ≈ 55

Event Reconstruction

- Track finding and the event vertex
  - Require good track.
  - Use good track to find event vertex

- Electron finding
  - Find electrons by looking for isolated EM energy deposits in Calorimeter cells.
  - The ZEUS primary electron finder is > 95% efficient for electron energy > 10 GeV.

Kinematic Reconstruction



Two Kinematic Variables: x Q^2

Four Measured Quantities: E_e' θ_e E_h γ_h

Electron Method

Use scattered electron energy, electron angle

Good resolution in x and Q^2, best at low Q^2

Sensitive to miscalibrations (energy scale uncertainties)

Double Angle Method

Use electron angle and hadronic jet angle

Depends only on ratios of energies

Better mean resolution in x and Q^2

Weakly affected by miscalibrations

Jacquet-Blondel Method

Use hadronic energy and hadronic jet angle

Gives an accurate determination of y for small values of y

Data Offline Cuts

- **Detector Acceptance and Efficiency**

  $y_{JB} > 0.04$

  positron found with E > 10 GeV

  vertex cut: -50cm < z < 50cm

  positron position cut: |X| > 14 cm or |Y| > 14 cm

- **Signal Selection**

  38 GeV < $E\text{-}P_z$ < 65 GeV

  A well found track with p > 5 GeV & DCA < 15 cm

  $y_{EL} < 0.95$

- **Physics and Kinematic Requirement**

  100 $GeV^2 < Q^2 < 10000\ GeV^2$

  Three jets found using KTCLUS algorithm

  $|\eta| < 2.0$

  $E_T^{LAB} > 5$ GeV

  Asymmetric cut, MC calculation requirement

  $E_{T,1}^{BRT} > 8$ GeV, $E_{T,2}^{BRT} > 5$ GeV , $E_{T,3}^{BRT} > 5$ GeV

First Comparison of Data and MC DIS Trijets at ZEUS

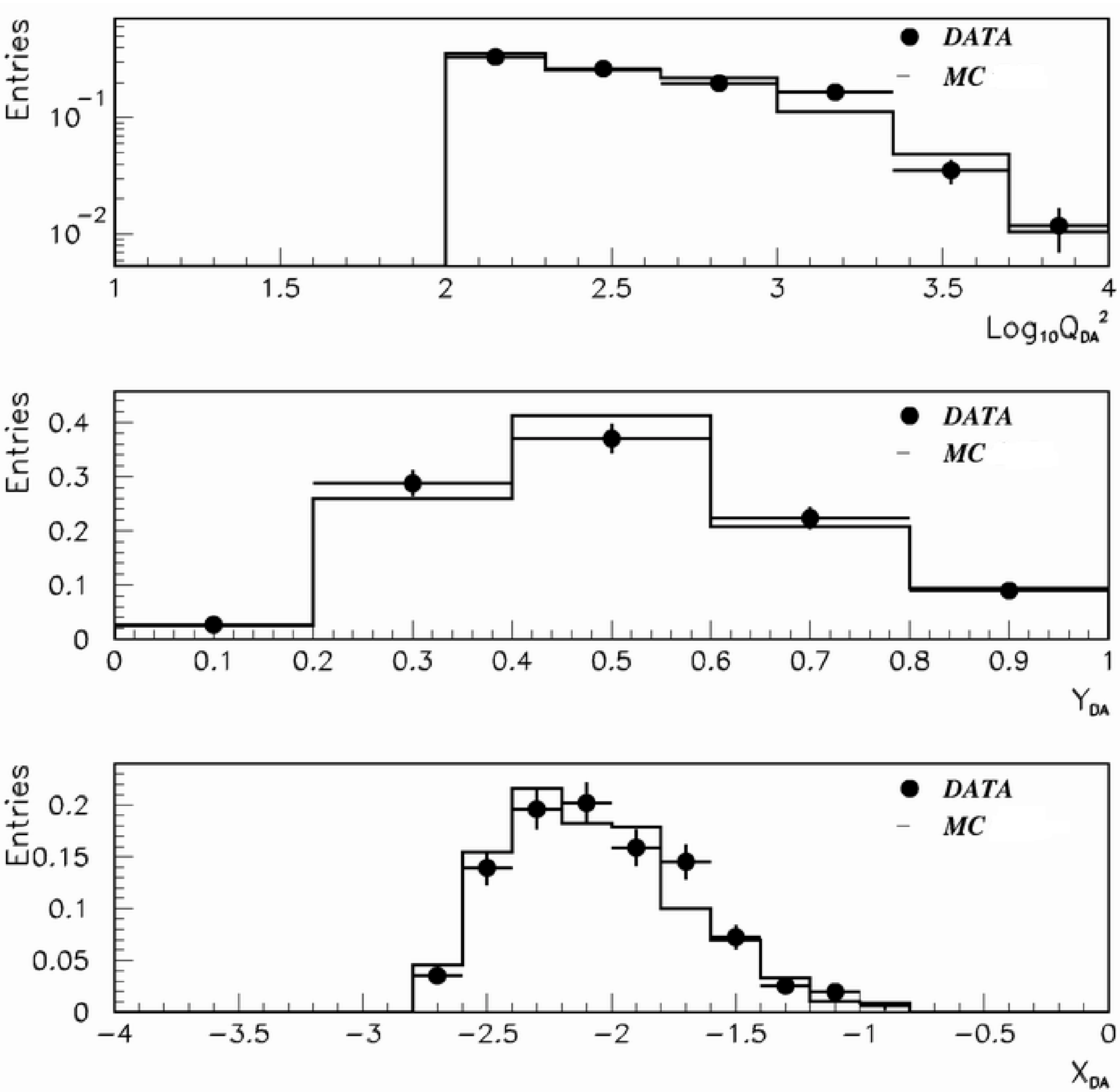
Data:

- HERA 1996-1997 running period
- ZEUS data sample: integrated luminosity 38.4pb^{-1}
- 510 DIS trijets passed offline cuts in a sample of 39576 DIS events

MC:

- Use leading order MC program **Ariadne**
- 568 DIS trijets selected from MC
- No Adjustment, run with default ZEUS settings

DIS Trijets — A First Look

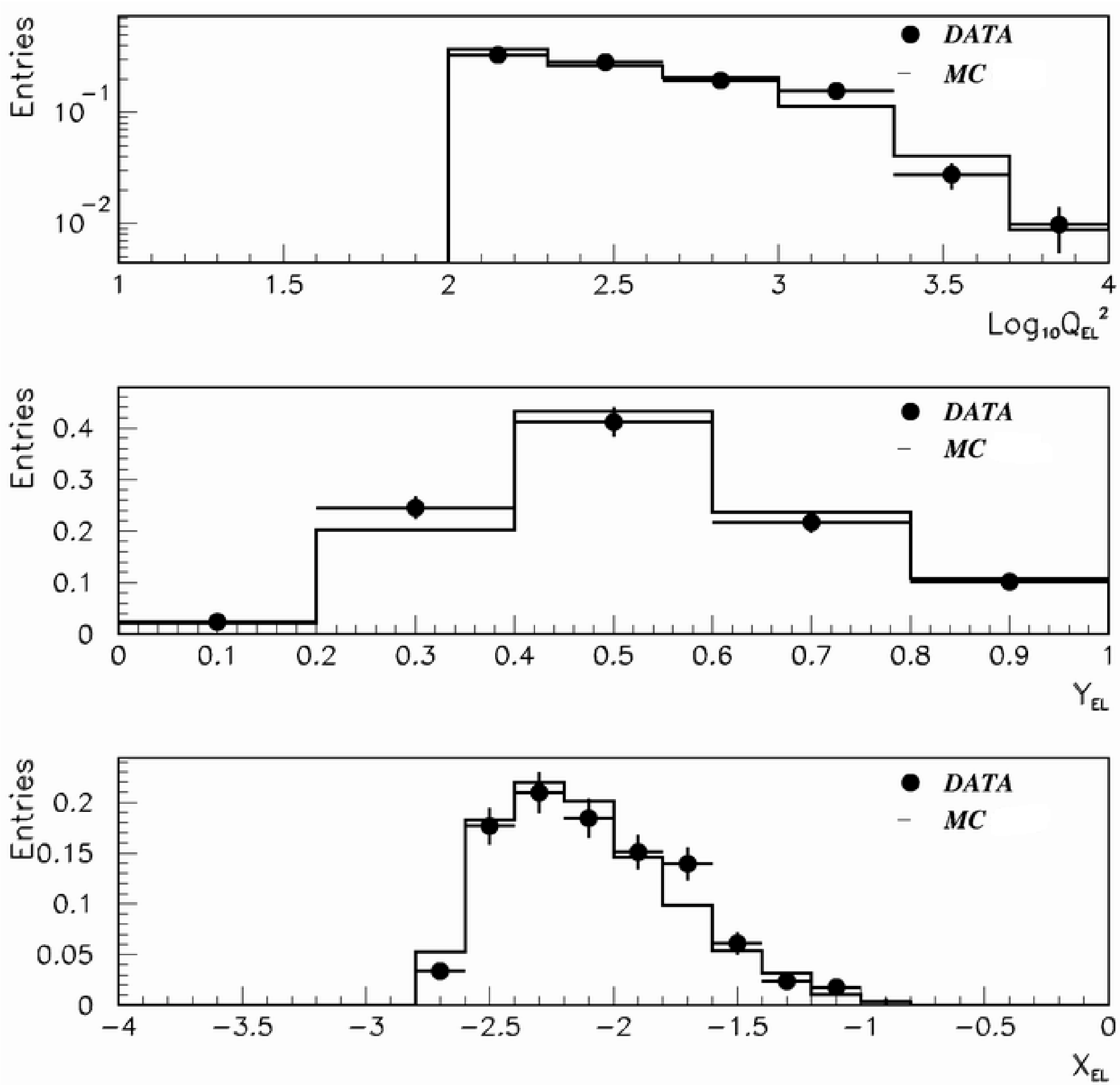


Reconstructed Q^2, y, x by Double Angle method

Use Ariadne for all MC

OK agreement between data and MC

DIS Trijets — A First Look

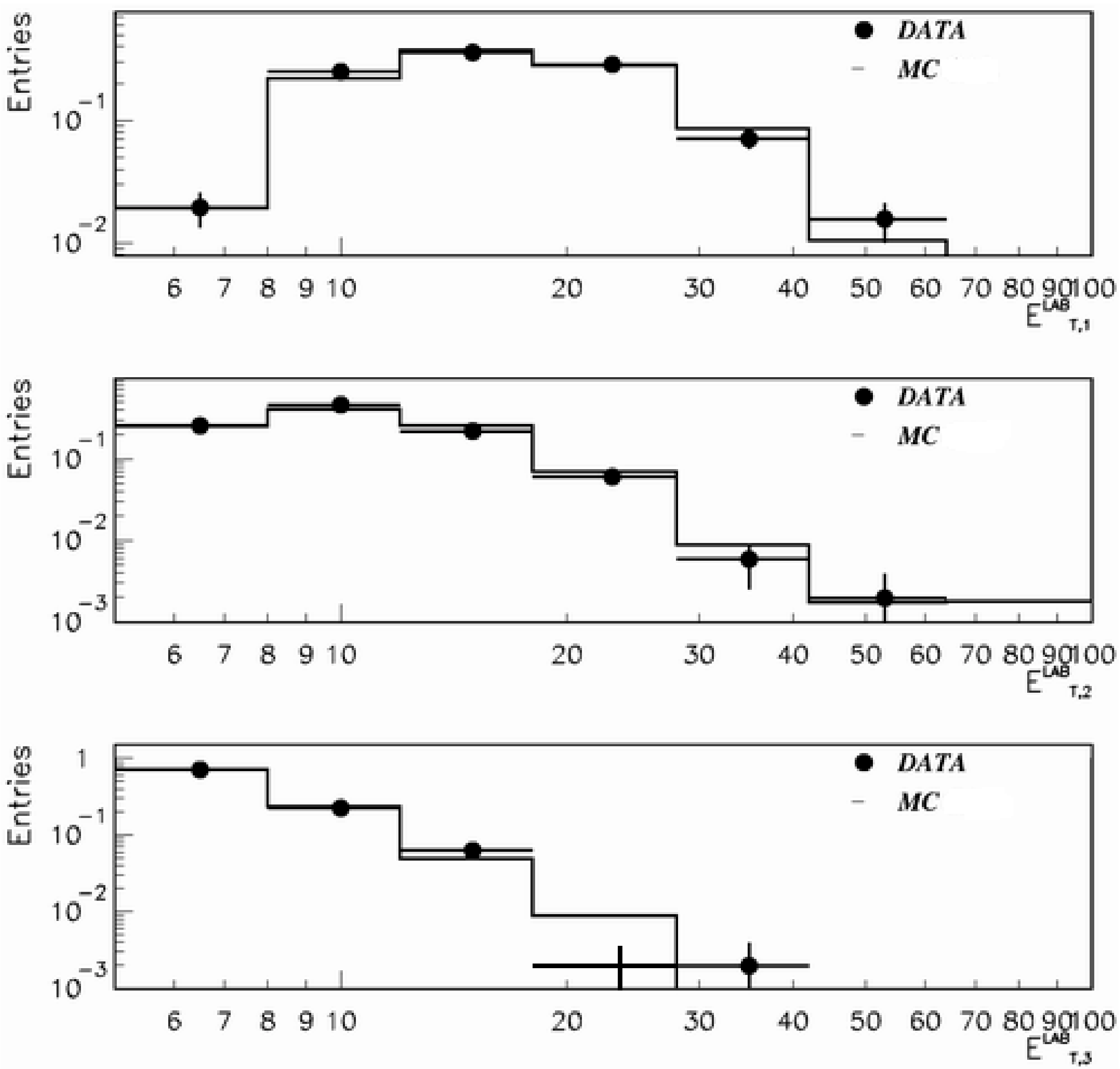


Reconstructed Q^2, y, x by Electron method

Better agreement between data and MC

→ Pick Electron method

DIS jet E_T in the Lab Frame



E_T Ordered:

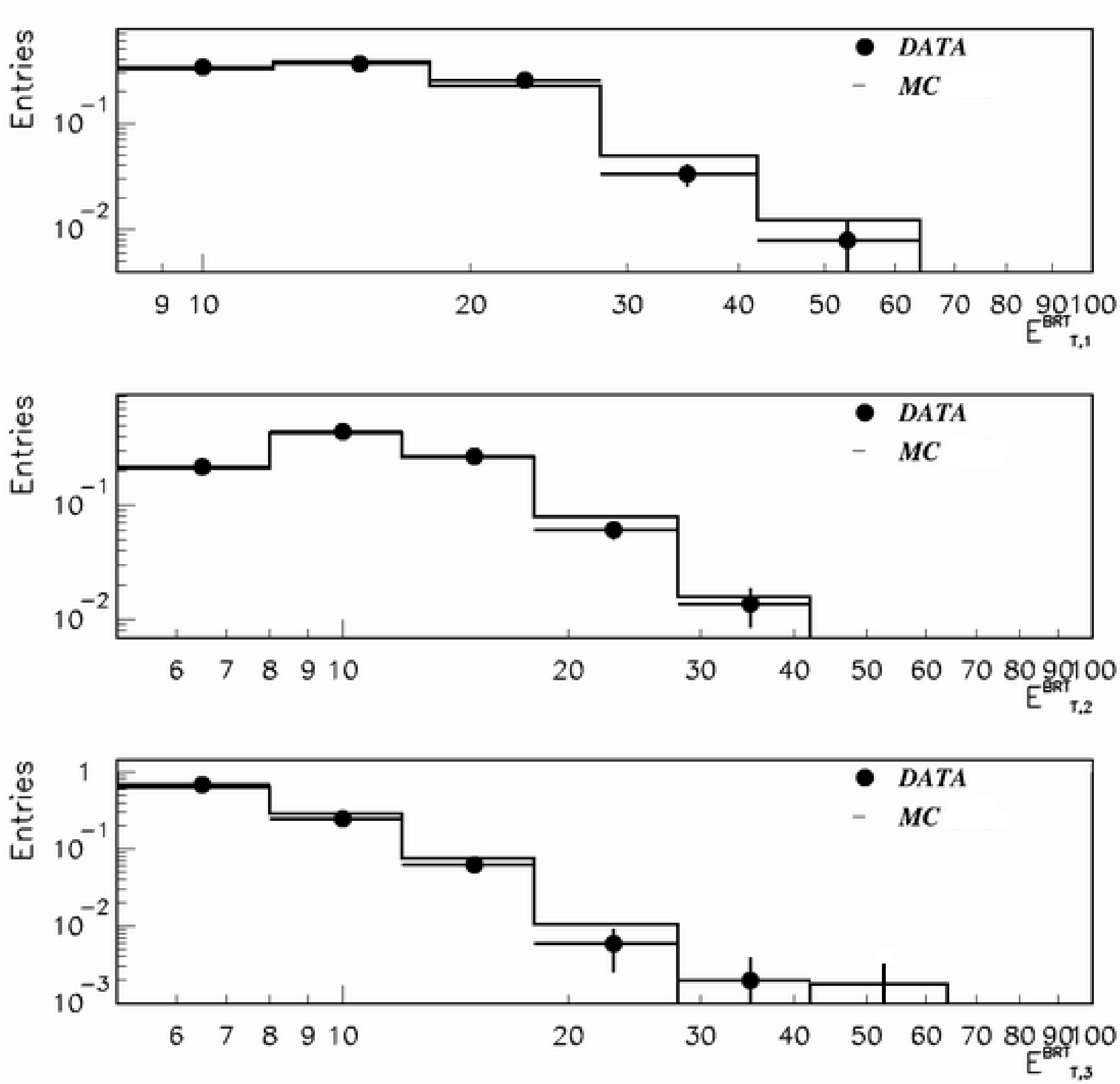
First Jet

Second Jet

Third Jet

Reasonable agreement

DIS jet E_T in the Breit Frame



E_T Ordered:

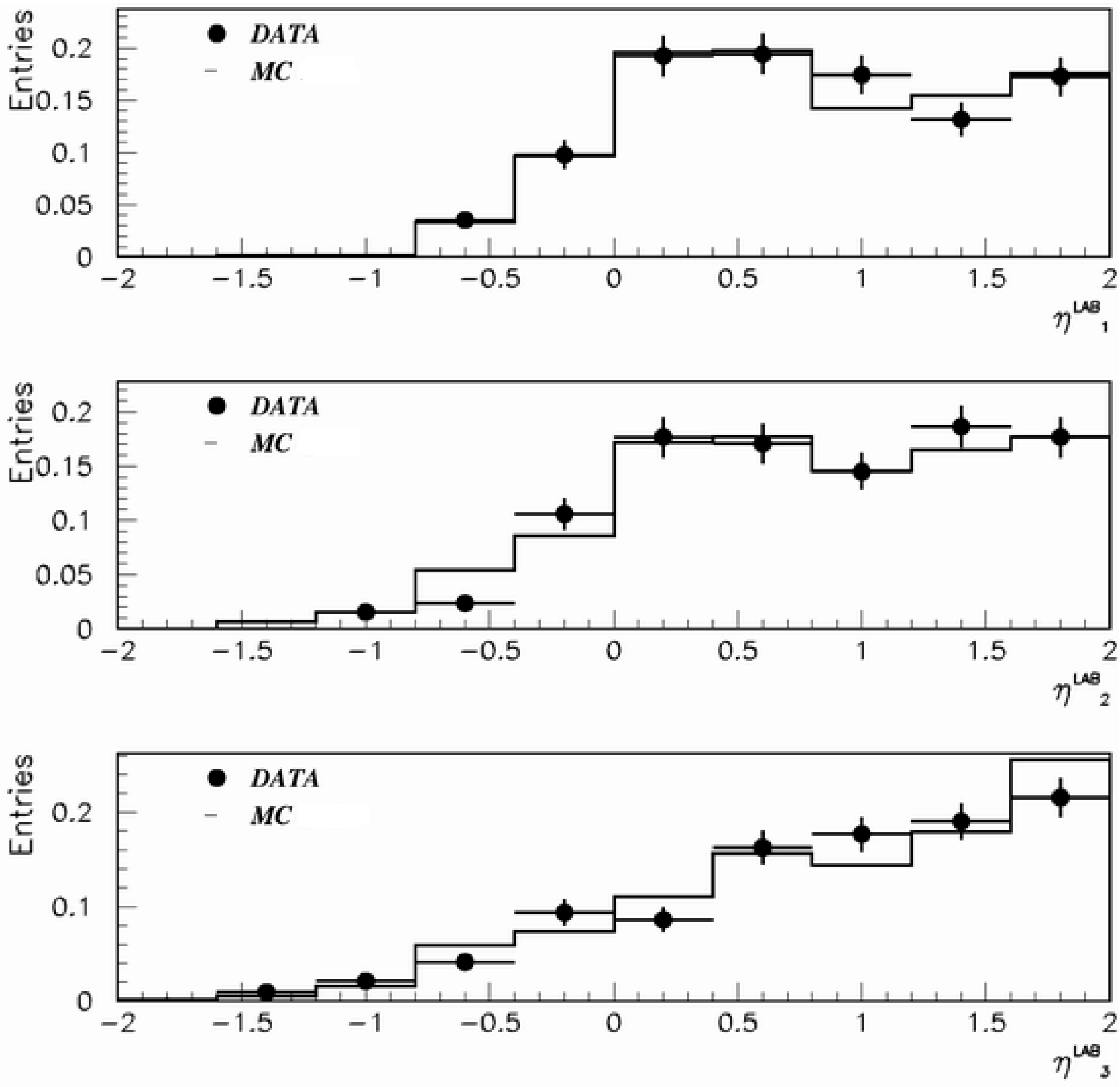
First Jet

Second Jet

Third Jet

Reasonable agreement

DIS jet η in the Lab Frame



E_T Ordered:

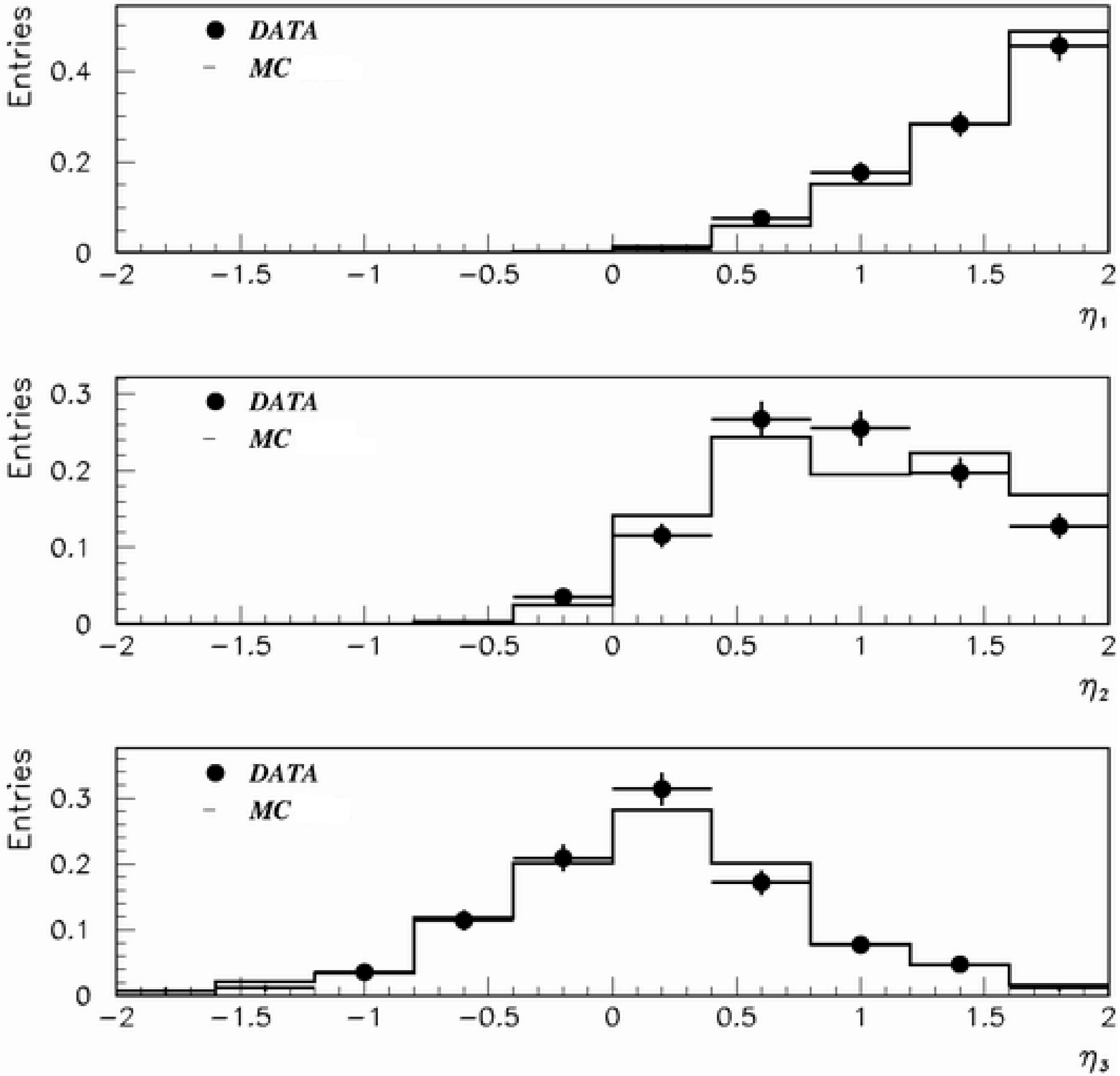
First Jet

Second Jet

Third Jet

Reasonable agreement

DIS jet η in the Lab Frame



η Ordered:

First Jet

Second Jet

Third Jet

Reasonable agreement

Conclusions and Expectations

- First look at DIS Trijets at ZEUS, reasonable agreement
- Ariadne used as it is, a good starting point
- Need to calculate cross sections and compare in detail with other QCD calculations and different MC programs
- Add new data (99-00) to have more statistics
- Explore systematic uncertainties