Dijets at HERA:
A QCD Story

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<u>OUTLINE</u>

HERA and ZEUS

Deep Inelastic Scattering and pQCD

Structure functions and the gluon

Dijets and pQCD

Dijet cross section measurement

The Future

The HERA Collider at DESY

hermes

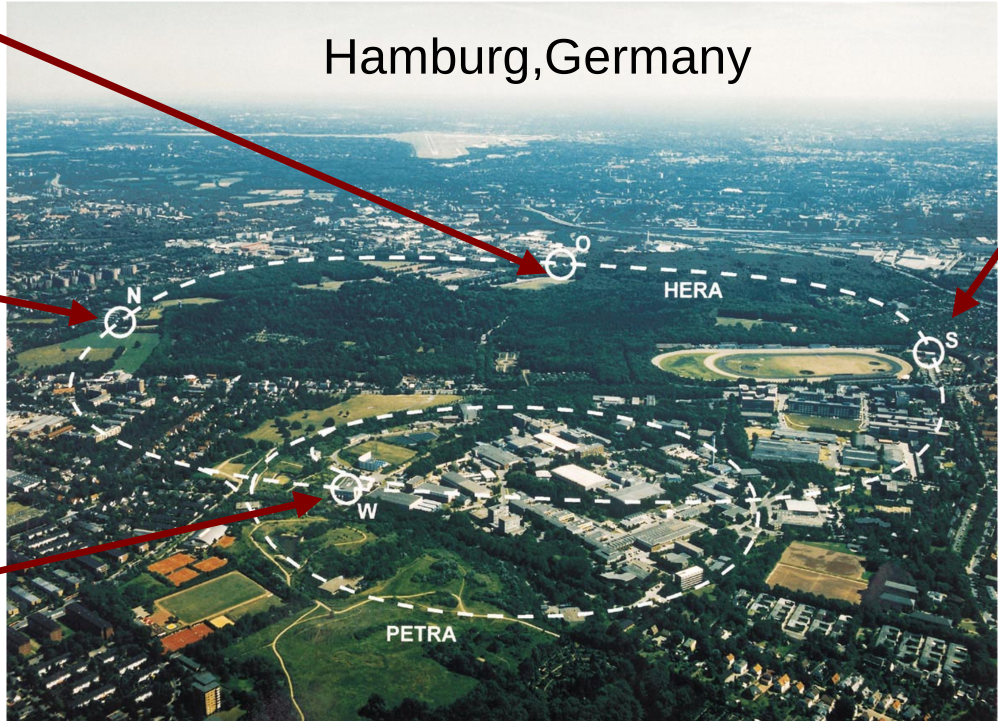
Polarized $e^{\pm}$ on fixed target

H1

Collider Detector

HERA B

Proton on fixed target



ZEUS

Collider Detector

6.4km circumference

920 (820) GeV protons

27.5 GeV electrons or positrons

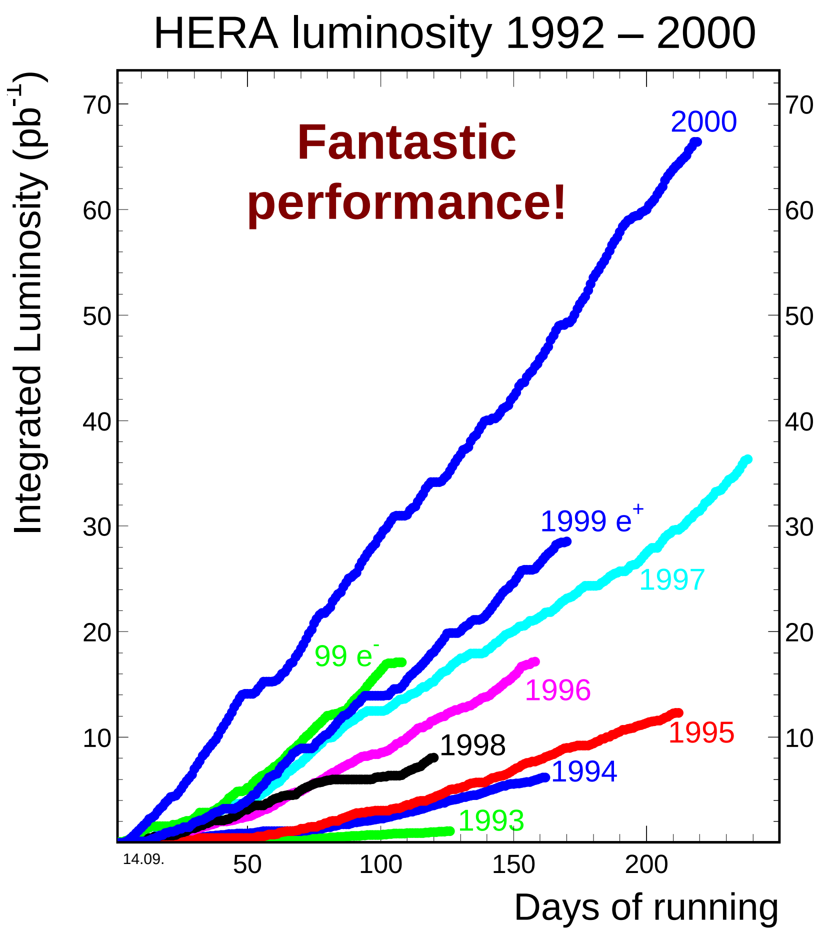
220 bunches 96ns crossing interval

$\sqrt{s} \approx 320$ GeV

equivalent to a 50TeV fixed target beam

Instantaneous luminosity $\approx 1.8 \times 10^{31} cm^{-2}s^{-1}$

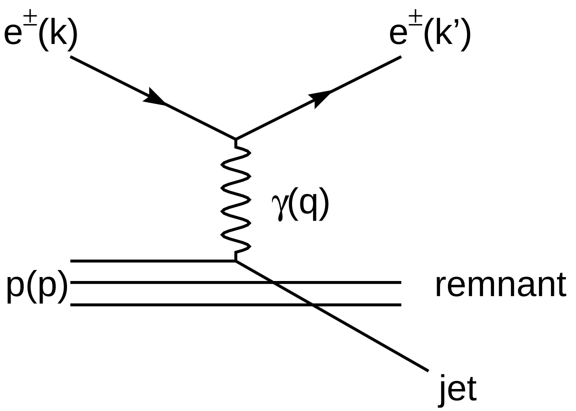
HERA Delivered Luminosity



- e^- in 92−94,98,99: 27pb^{-1}
- e^+ in 95−97,99−00: 166pb^{-1}
- 820GeV protons through 1997
  920 GeV since 1998
- ZEUS integrated lumi since 1992: ~130pb^{-1} (70% of delivered)
- Currently undergoing a luminosity upgrade
  - ready Summer 2001
  - expect 1fb^{-1} by end of 2005
    - 5 times current integrated total

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

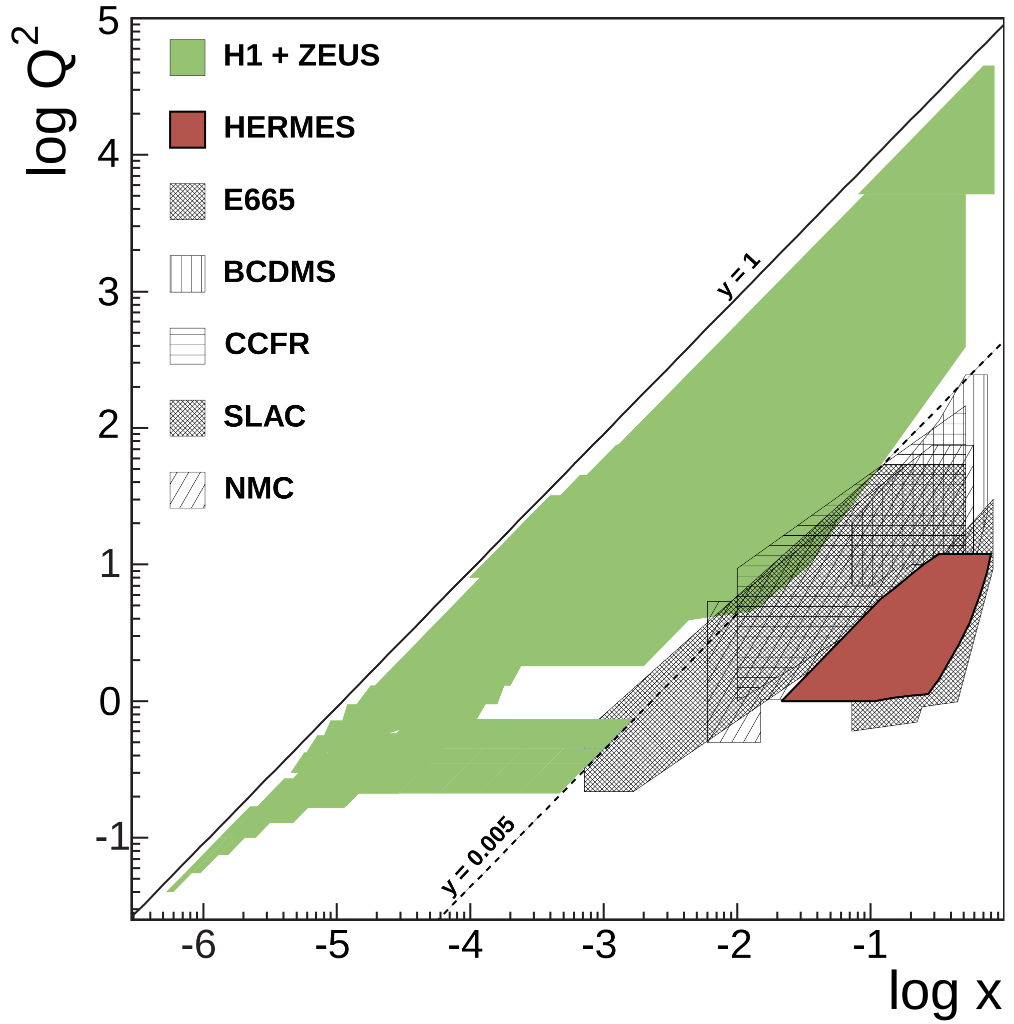
$$y = \frac{p\cdot q}{p\cdot k}$$

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

$$Q^2 = sxy$$

s=center of mass energy squared

HERA Kinematic Range



$$Q^2 = sxy$$

Extended kinematic region available at HERA

Additional ZEUS components provide overlap with fixed target experiments

$0.45\ GeV^2 < Q^2 < 20000\ GeV^2$
$10^{-6} < x < 0.9$

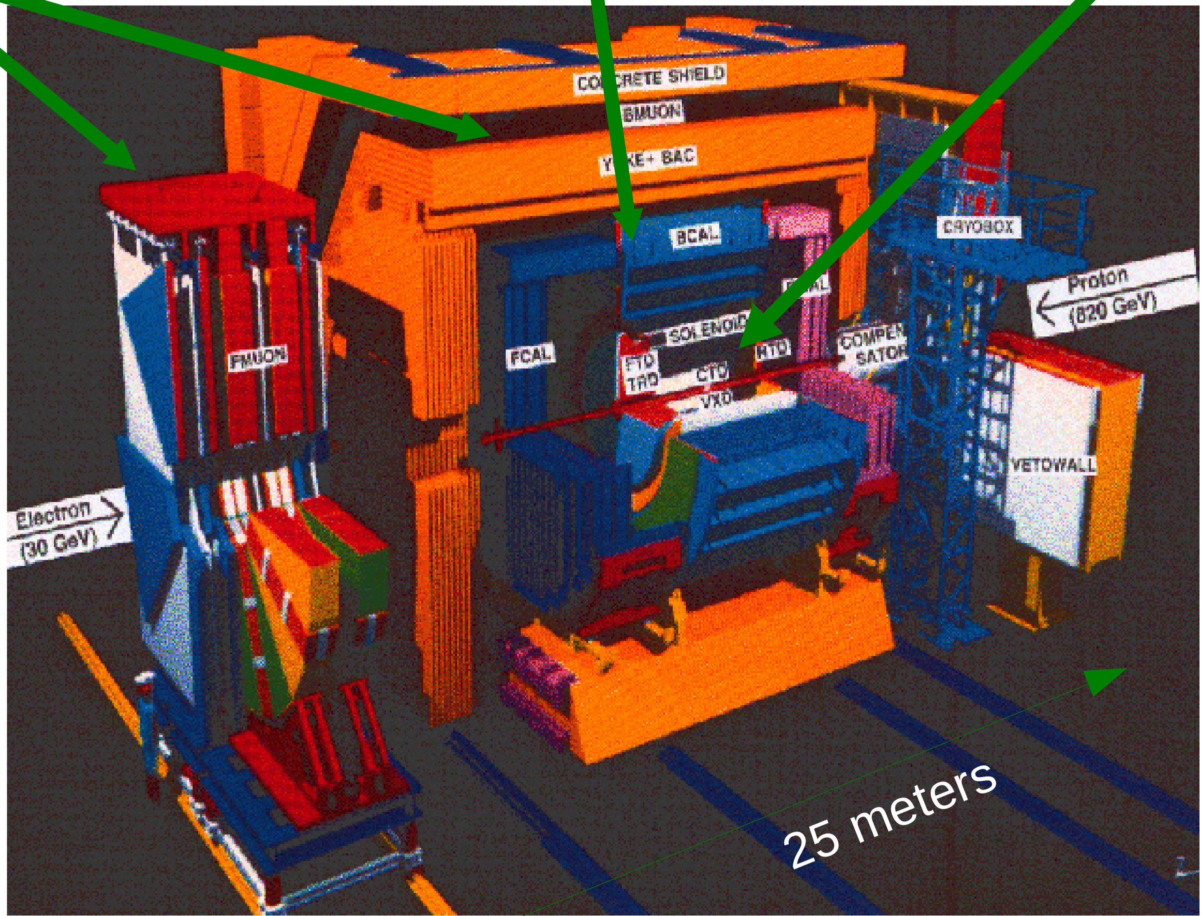
H1 and ZEUS: DESY e−p
HERMES: DESY e−A
E665: Fermilab μ−A
BCDMS: CERN μ−A
CCFR: Fermilab ν−A
SLAC: many experiments e−A
NMC: CERN μ−A

The ZEUS Detector at HERA

Muon systems

Uranium−Scintillator Calorimeter

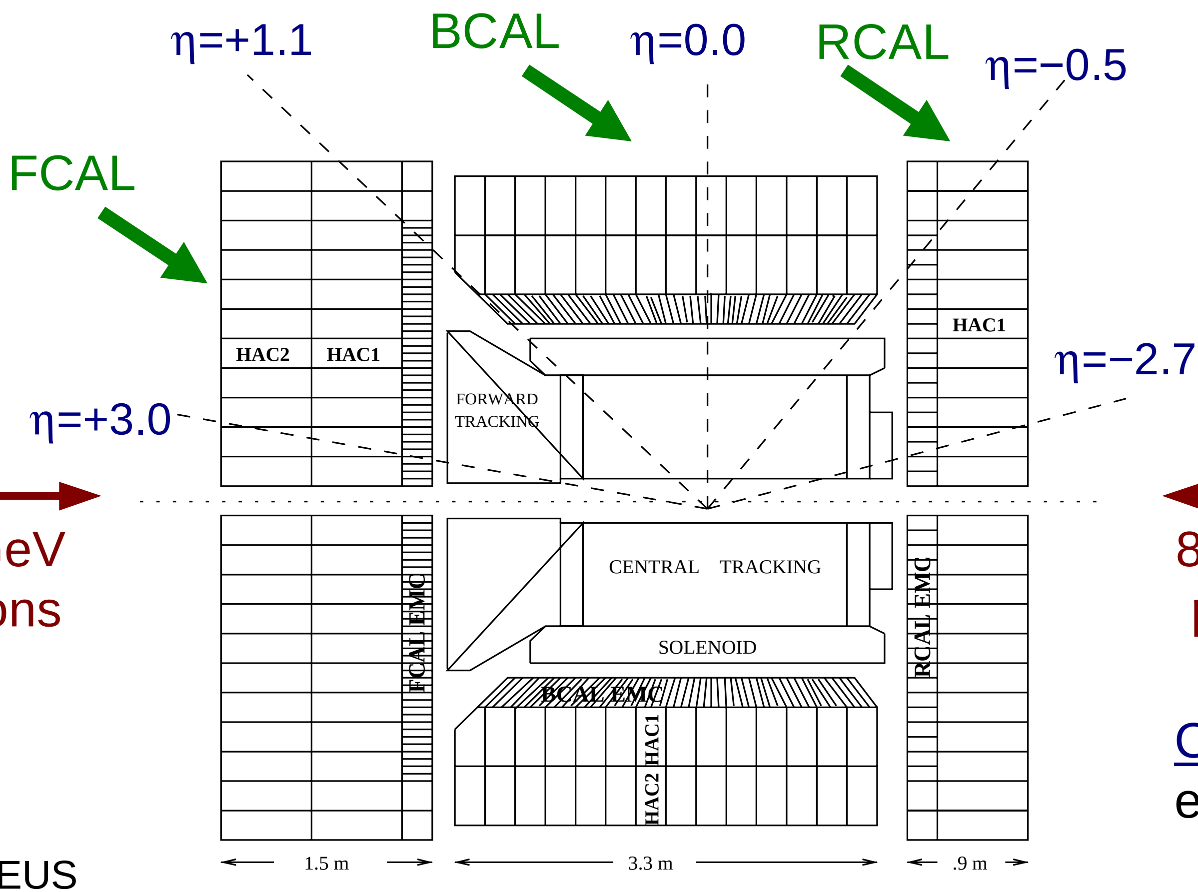
Drift Chamber Central Tracker



820 GeV protons

27.5 GeV positrons

ZEUS Calorimeter



27.5 GeV positrons

820 GeV protons

Depleted Uranium and scintillator

<u>Energy Resolution</u>

electromagnetic: 18%/√E

hadronic: 35%/√E

<u>Cell Dimensions</u>

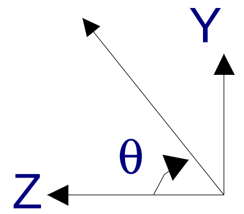
electromagnetic:

5x20cm (FCAL,BCAL)

10x20cm (RCAL)

hadronic: 20x20cm

ZEUS Coordinate System



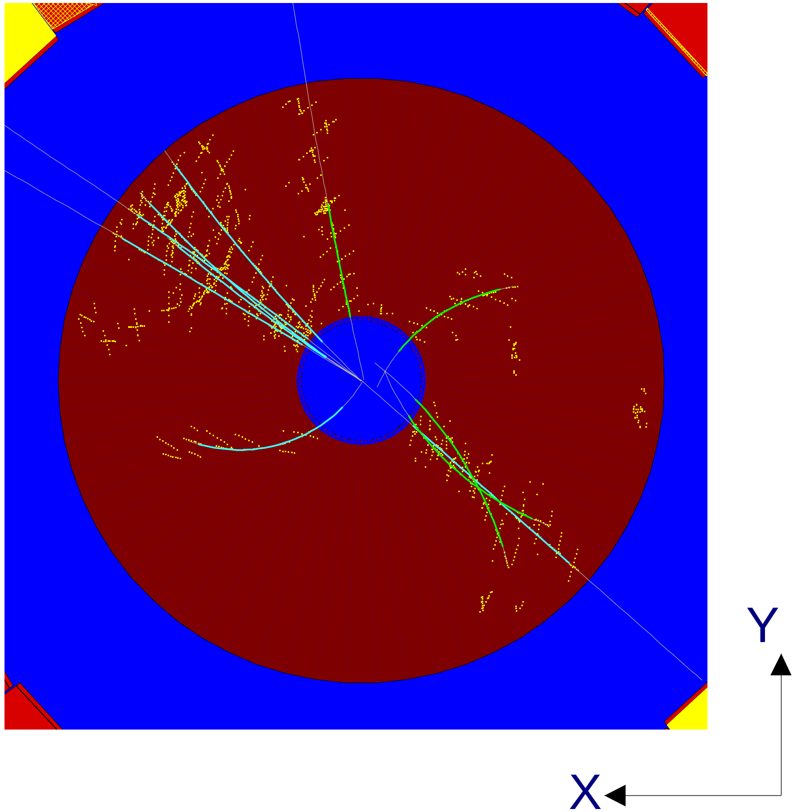
99.7% solid angle coverage

$-3.5 < \eta < 4.0$

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

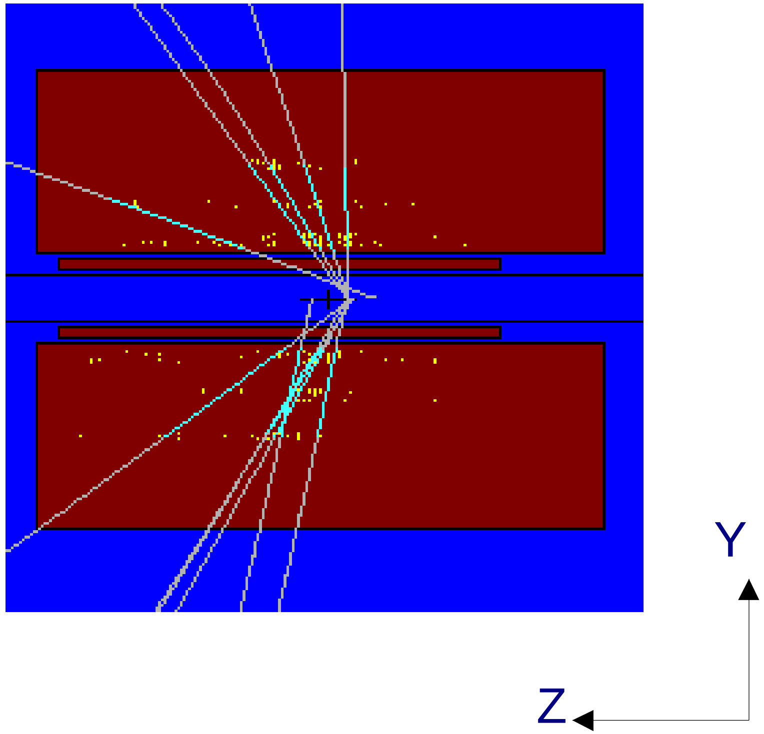
ZEUS Central Tracking Detector

View along beamline



Drift Chamber
inside1.43T solenoid

Side view



<u>Vertex Resolution</u>
longitudinal (z): 4mm
transverse (x−y): 1mm

Micro Vertex Detector to be installed next year

ZEUS Trigger

<u>Challenge</u>

10 MHz bunch crossing rate

Extract 10Hz Physics from 100kHz background

10^5Hz →

<u>Level 1</u>

- 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

<u>Level 2</u>

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

100Hz →

<u>Level 3</u>

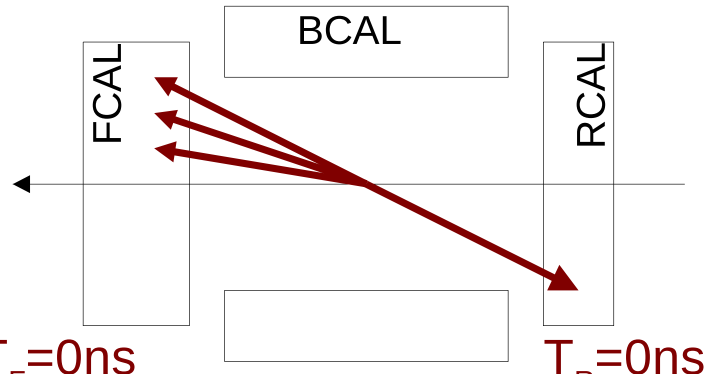
- Processor Farm (SGI)
- Full event available
- Offline tools available: jet finding, positron id, etc
- Complete tracking algorithms

→ Mass storage

10Hz

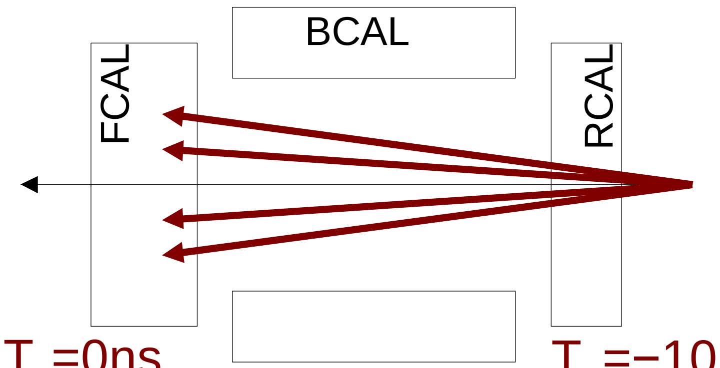
Beam Gas
Background Rejection

"Distance" between FCAL and RCAL is ~10ns



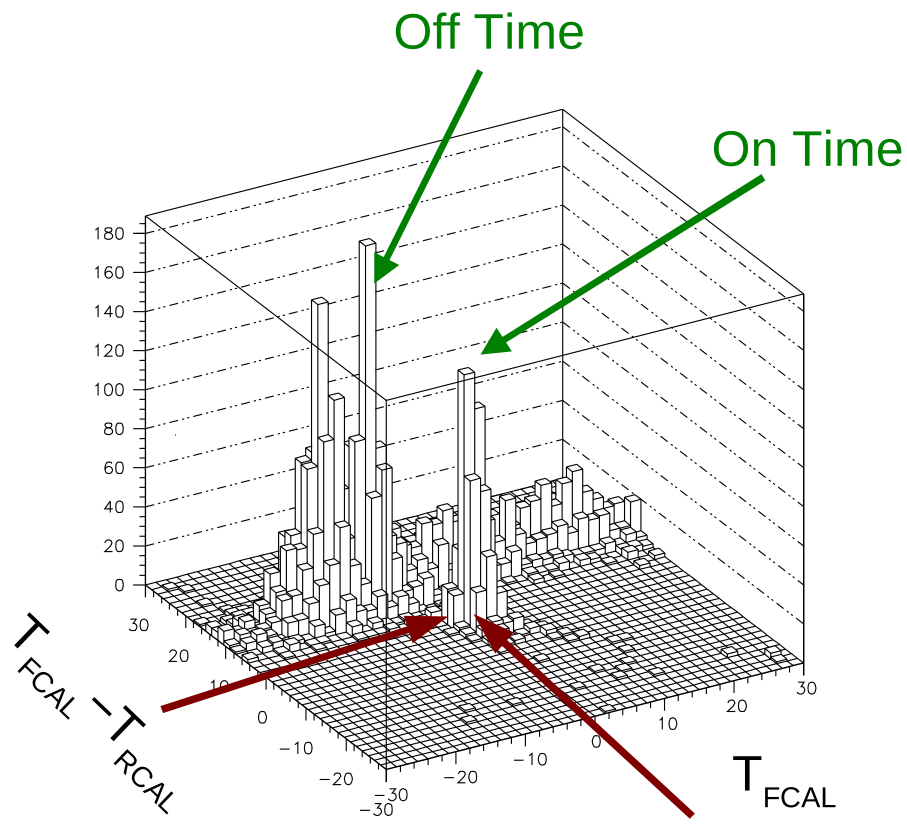
T_F=0ns T_R=0ns

On Time Event



T_F=0ns T_R=−10ns

Beam Gas Event



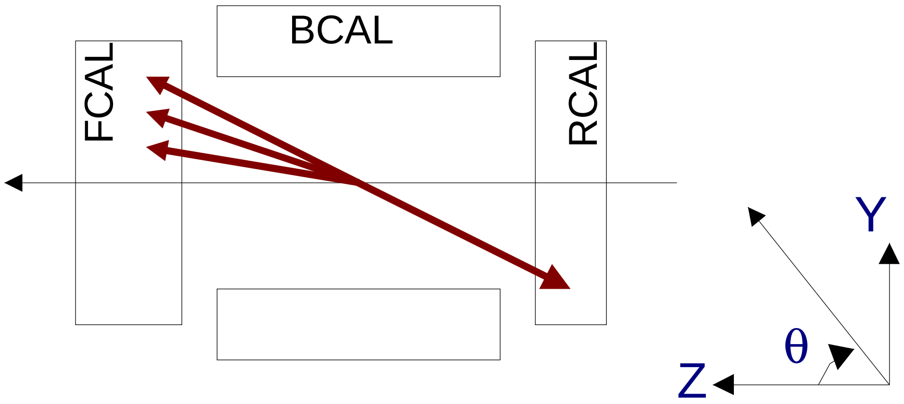
Calorimeter timing at Level 2

ZEUS Calorimeter timing resolution <1ns

Background Reduction: $E-p_z$

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

Sum runs over calorimeter cells

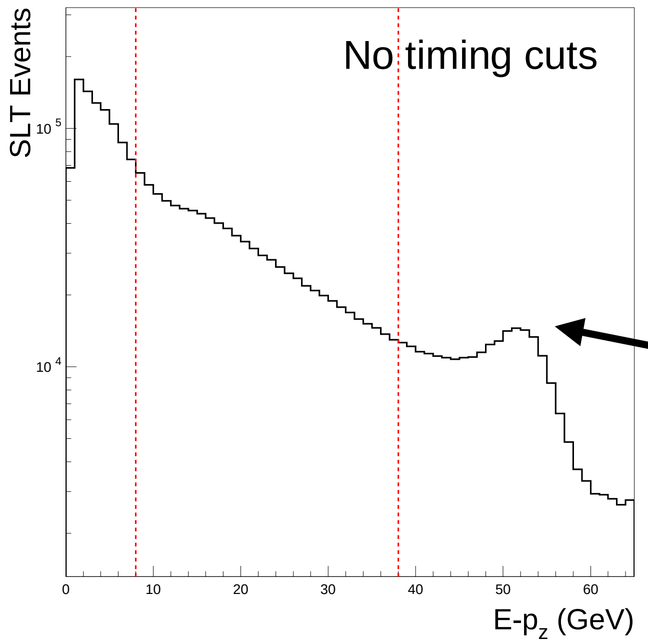


In a given frame, $E-p_z$ is conserved

E_{beam} P_{beam}

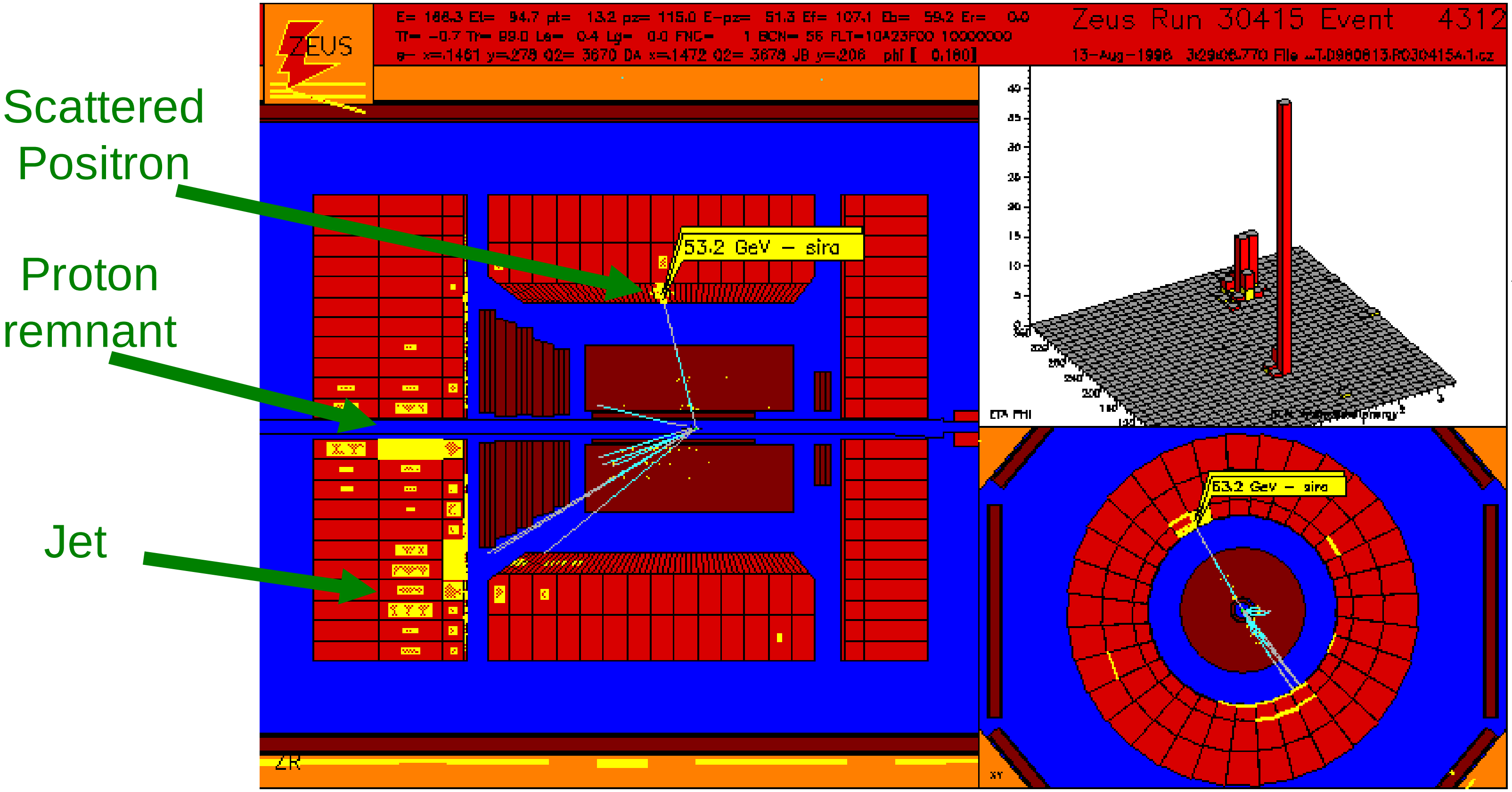
Before: $E-p_z = 2E_{beam}$=55GeV

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



Contained NC DIS $E-p_z \approx 55$

Deep Inelastic Scattering Event

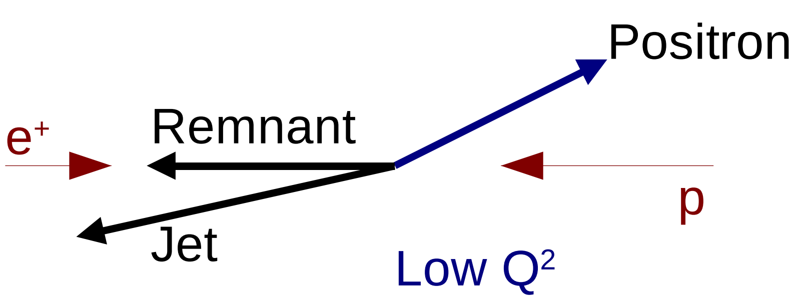


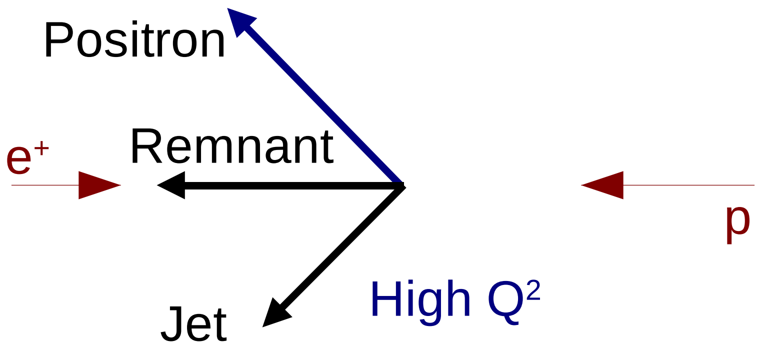
Q^2~3600GeV^2

X ~0.15

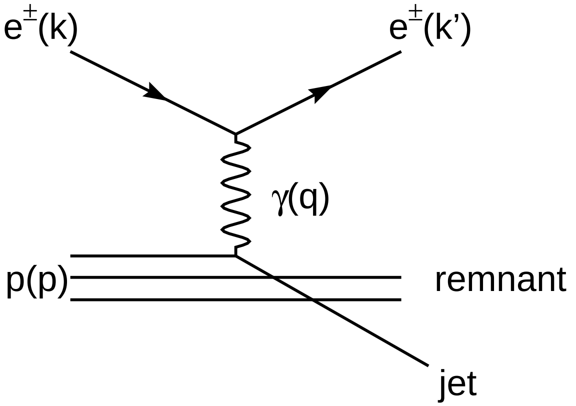
Y ~0.20

(1+1) event





DIS Cross Section



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

$$x = \frac{Q^2}{2p \cdot q} \quad y = \frac{p \cdot q}{p \cdot k} \quad Q^2 = sxy$$

Neutral Current:

$e^{\pm} p \rightarrow e^{\pm} + X$

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha_{em}}{xQ^4}[Y_+ F_2 \mp Y_- xF_3 - y^2 F_L] \qquad Y_{\pm} = 1 \pm (1-y)^2$$

F_2 due to photon exchange with spin ½ partons.

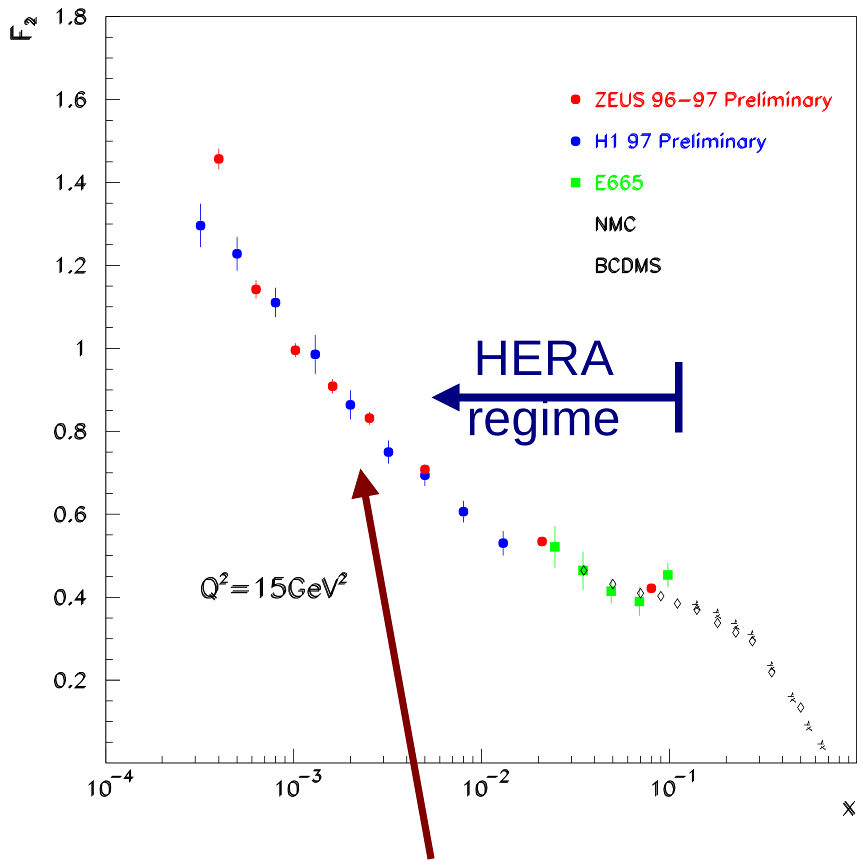
Related to quark densities f_i

$$F_2(x) = \sum_i x Q_i^2 f_i(x)$$

F_3 contribution due to Z exchange.

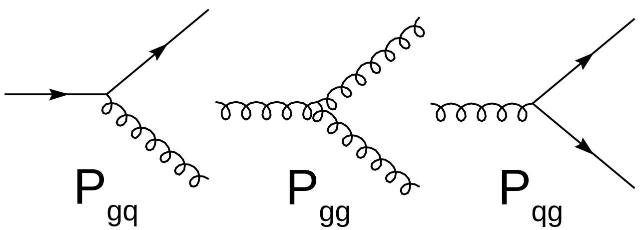
F_L contribution due to exchange of longitudinally polarized photons.

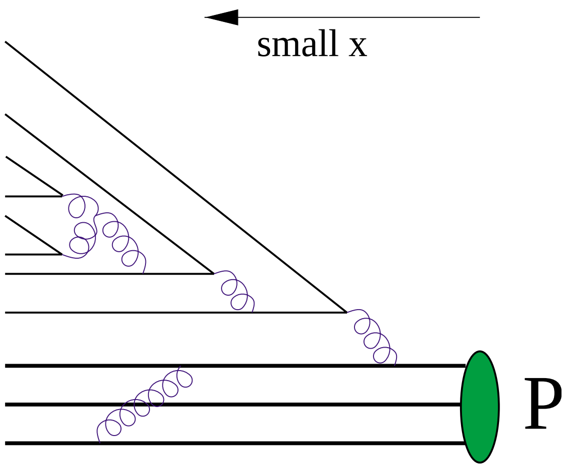
The Role of the Gluon



HERA discovery!
Strong rise of F_2 at low x !

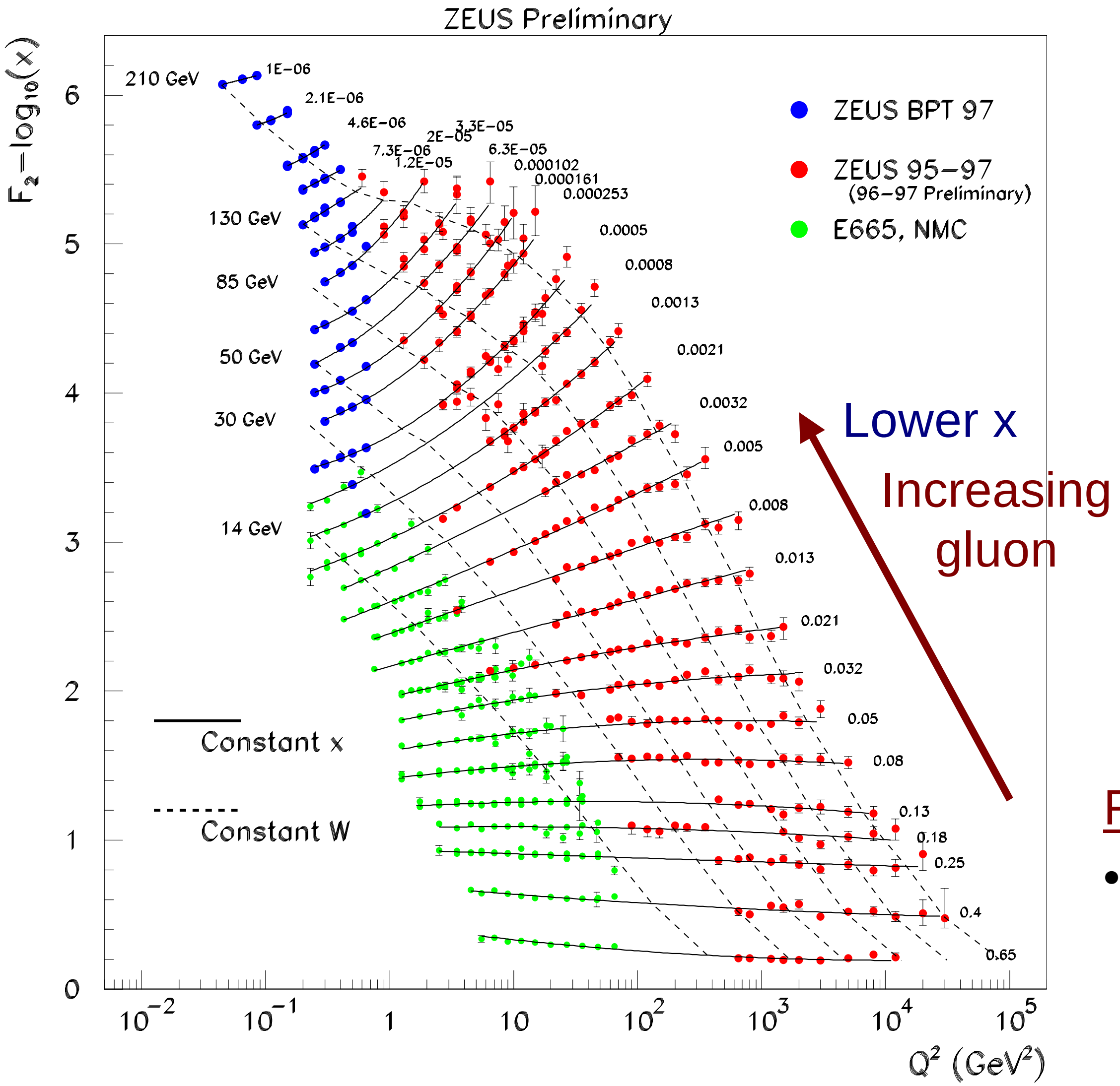
Splitting Functions from QCD





Gluon−driven increase of
small x quarks is reflected in F_2

Scaling Violation and the Gluon



Scaling Violation

- F_2 has a Q^2 dependence due to gluon

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

- More significant at smaller x

F_2 scaling violation −> gluon density

- QCD evolution equations (Altarelli−Parisi) predict

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

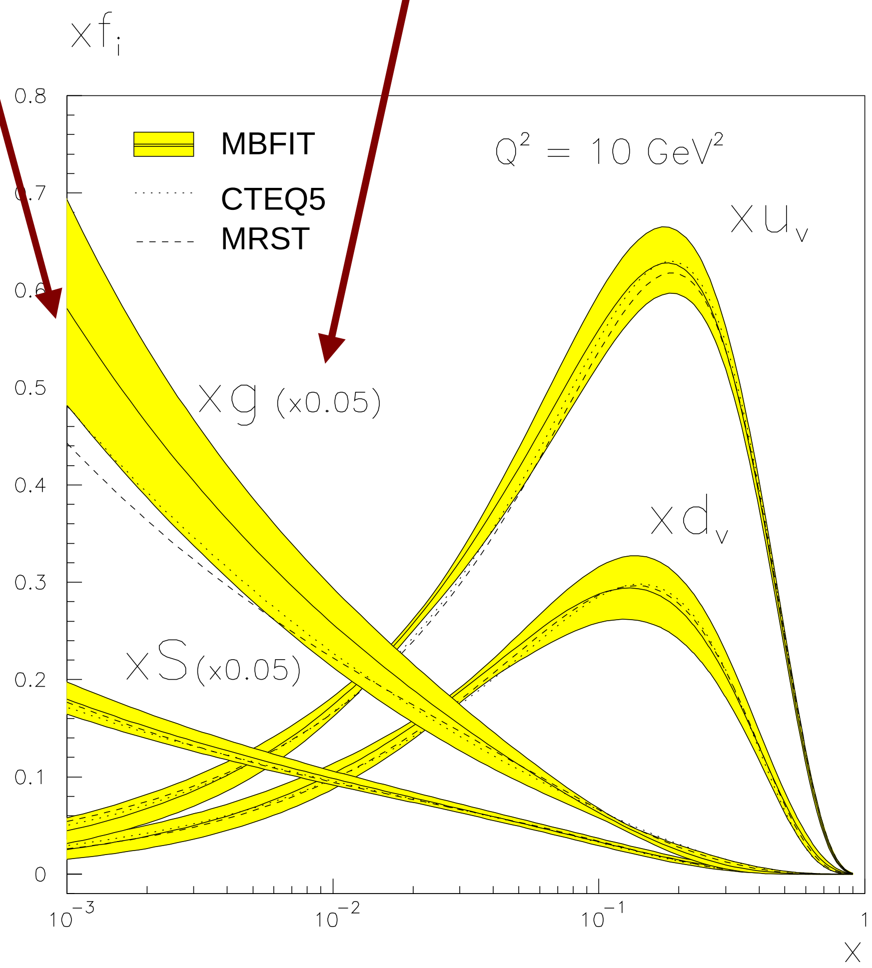
Parton Density Functions

Several different groups make global fits to DIS structure function data

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

16% uncertainty at $x \sim 10^{-3}$

Factor of 20!



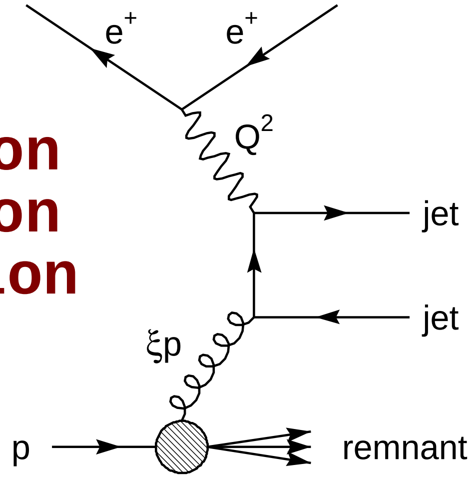
Gluon density extracted indirectly from scaling violation of F_2

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

Dijet Production at HERA

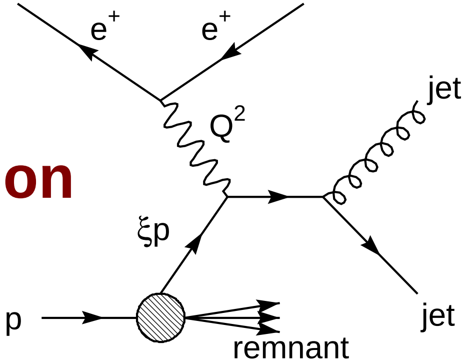
Why settle for one jet, when you can have two! → HERA $\sqrt{s}$ provides high E_T final hadronic state

Boson Gluon Fusion



(2+1) event

QCD Compton



(2+1) event

DIS variables still apply

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

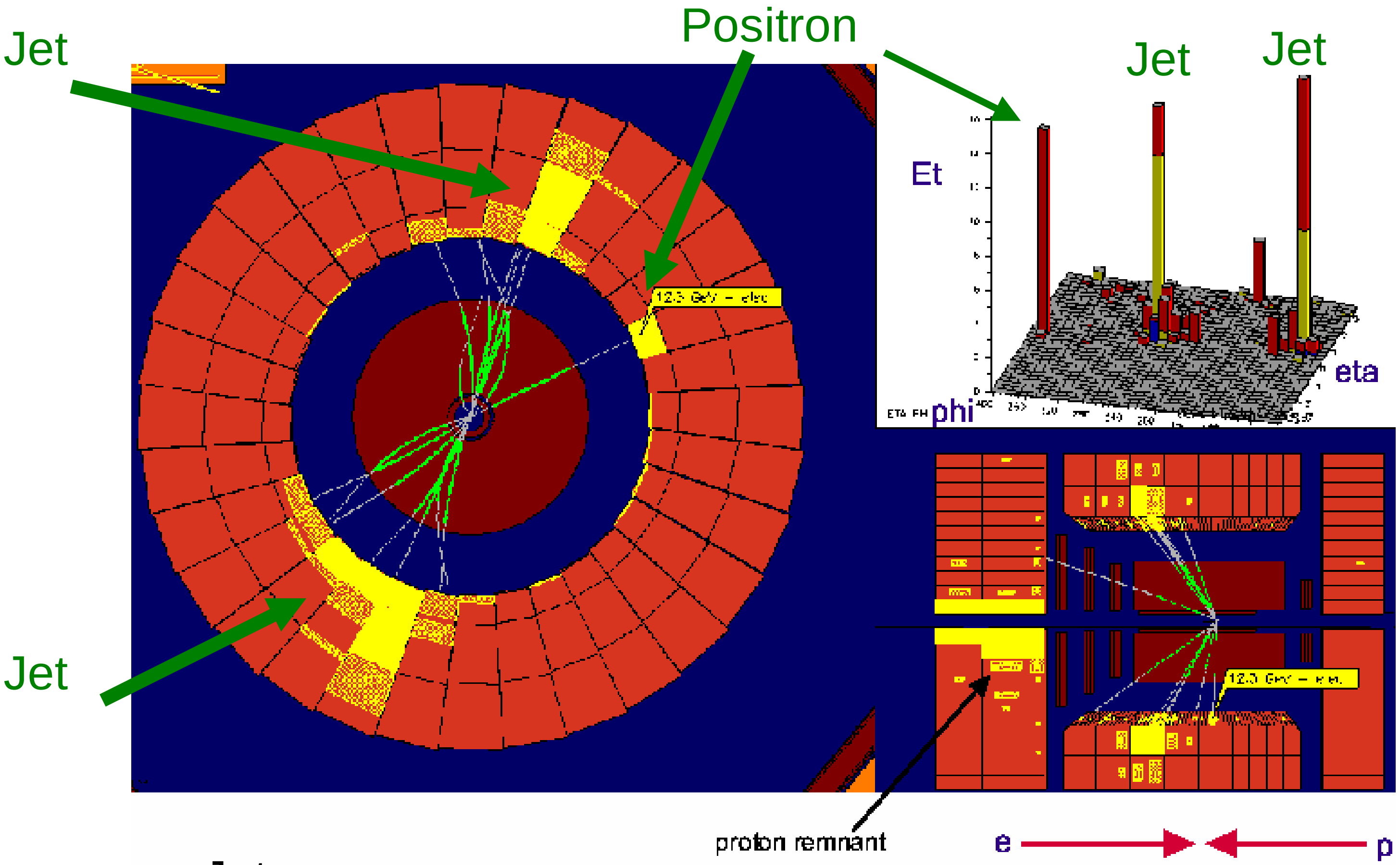
$$y = \frac{p \cdot q}{p \cdot k} \qquad x = \frac{Q^2}{2p \cdot q}$$

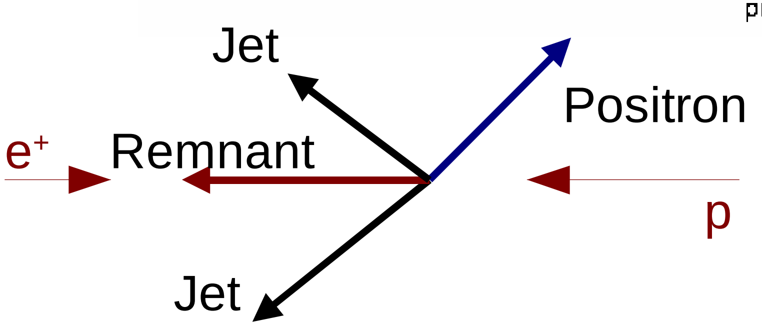
But now the momentum fraction of the incident parton (at LO) is

$$\xi = x\left(1 + \frac{M_{jj}^2}{Q^2}\right)$$

M_{jj}=dijet mass

Dijet Event at ZEUS

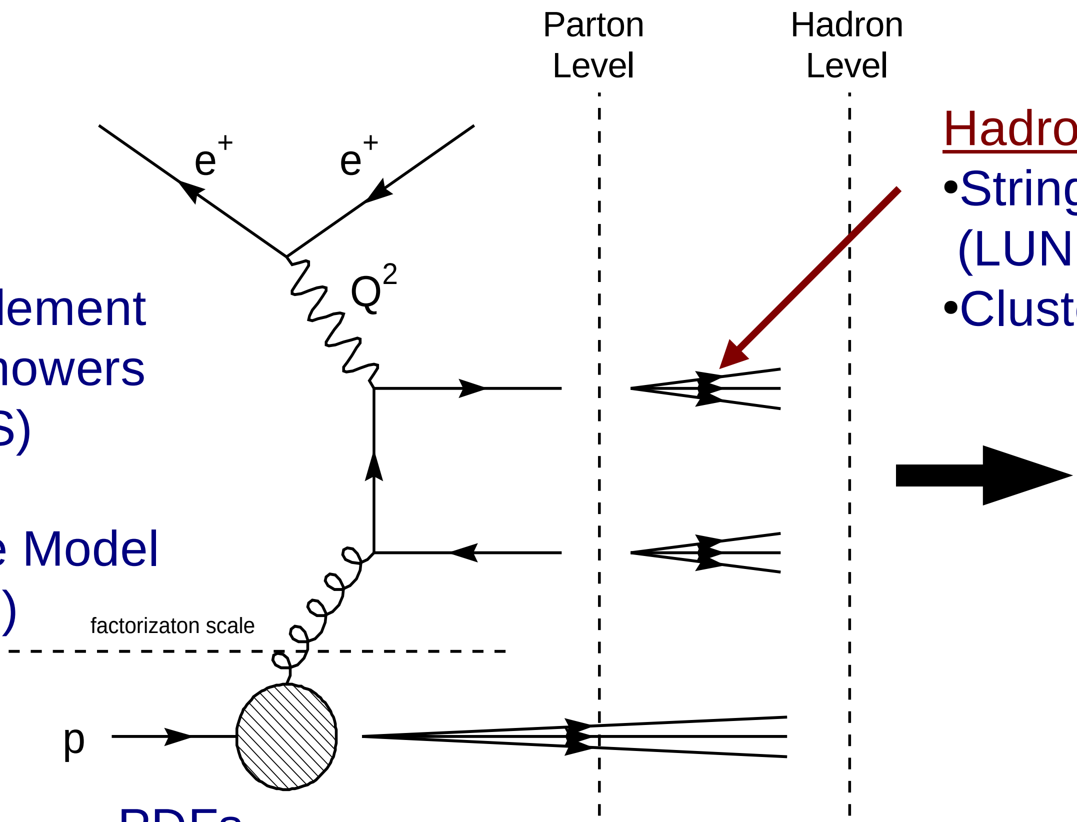




How is this type of event understood within the context of pQCD?

Leading Order
Monte Carlo Models

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



PDFs

Hadronization Models

- String Fragmentation (LUND)
- Cluster Model

Detector Simulation

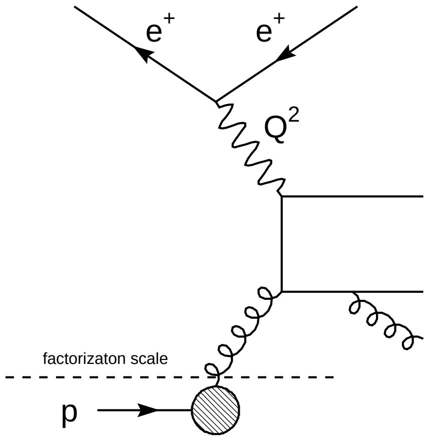
Programs

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

LO models used only for

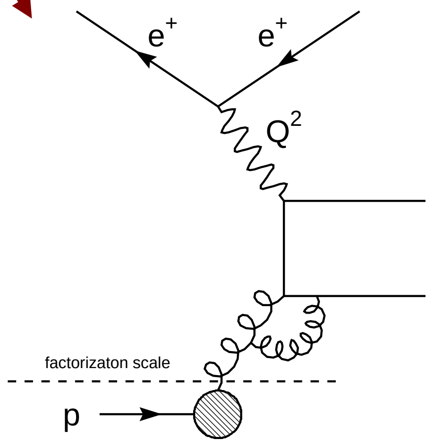
- detector corrections
- hadronization corrections

NLO Calculations



NLO Matrix Elements

- Three 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)

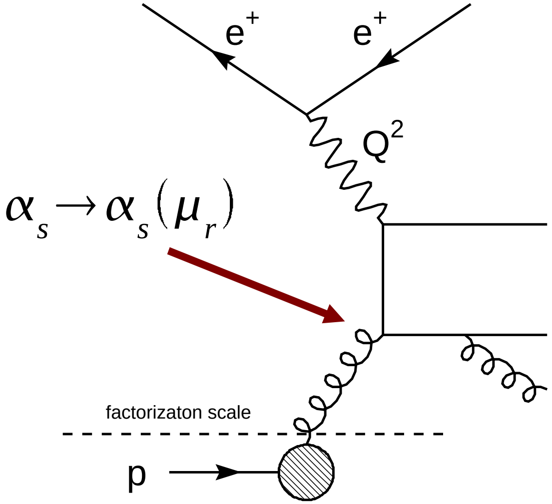
Issues

- Renormalization scale uncertainty (next slide)
- Hadronization effects (discussed later)
  - non−perturbative: Partons −> Hadrons
  - NLO calculations provide only 3−parton final states

Renormalization Scale

Renormalization scale (μ_r): Scale at which the strong coupling constant is evaluated

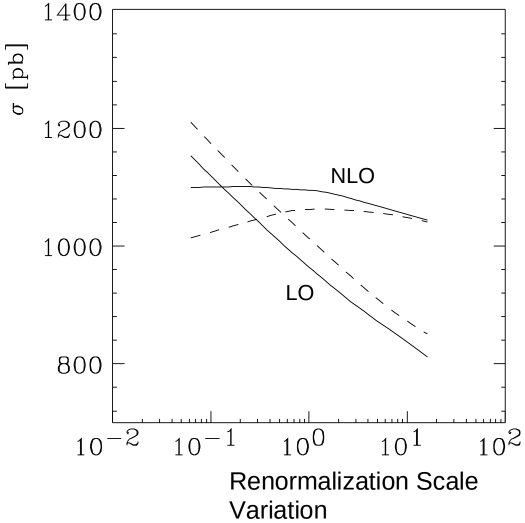
Factorization scale (μ_f): Scale at which the parton densities are evaluated



$d\sigma/d\mu_r=0$ only for all−order perturbation

Otherwise uncertainty in final cross section

Example: Inclusive DIS Cross Section



- Uncertainty due to factorization scale is typically small (<5% for this analysis)
- Uncertainty due to renormalization scale can be large (>50%) even at NLO

Renormalization Scale Choices and Resulting Uncertainty

Choices for renormalization scale

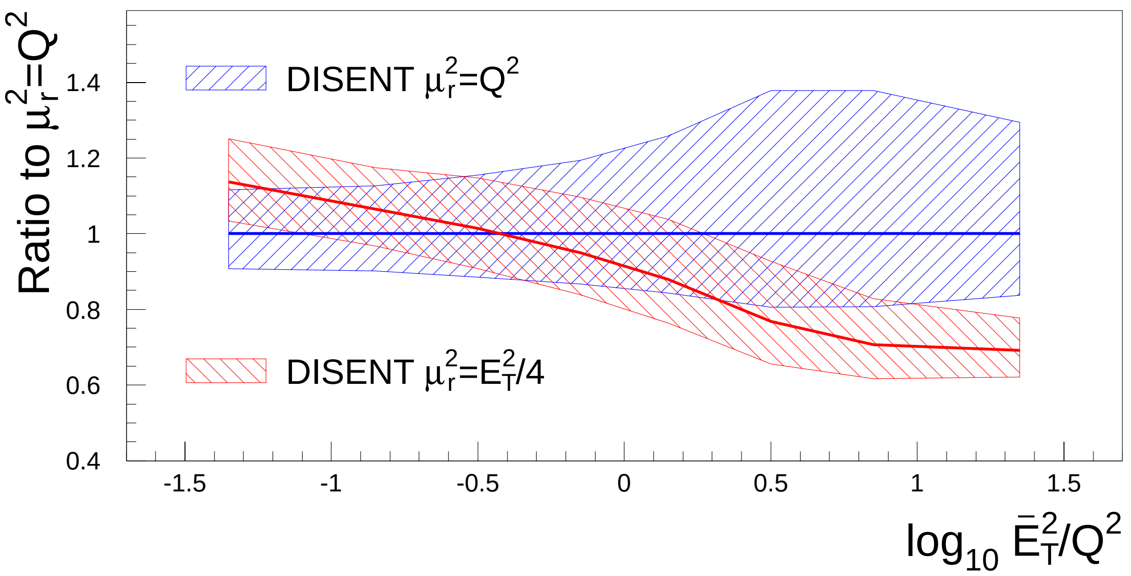
- Typically choose the hardest scale available
- In single jet DIS: $\mu_r^2=Q^2$
- In dijet events, jet E_T^2 can be larger than Q^2
  - $\mu_r^2=E_T^2/4$ also reasonable
    - E_T=sum of jet E_ts
    - $E_T^2/4$ ~ square of mean dijet E_T

Estimate of renormalization scale uncertainty

- vary μ_r by factor of 2 (conventional)

NLO Calculation of Inclusive Dijet Cross Section

- mean jet E_T > 6.5GeV
- Q^2>10GeV^2



Uncertainty due to renormalization scale can be large

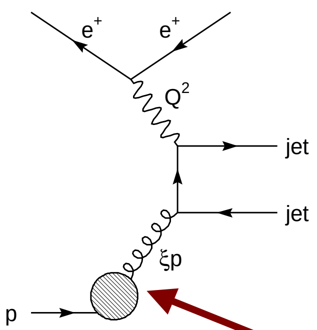
- at least 40%

Dijets −> Gluon Density

BGF process dominates at low Q^2

BGF contribution directly proportional to the gluon density

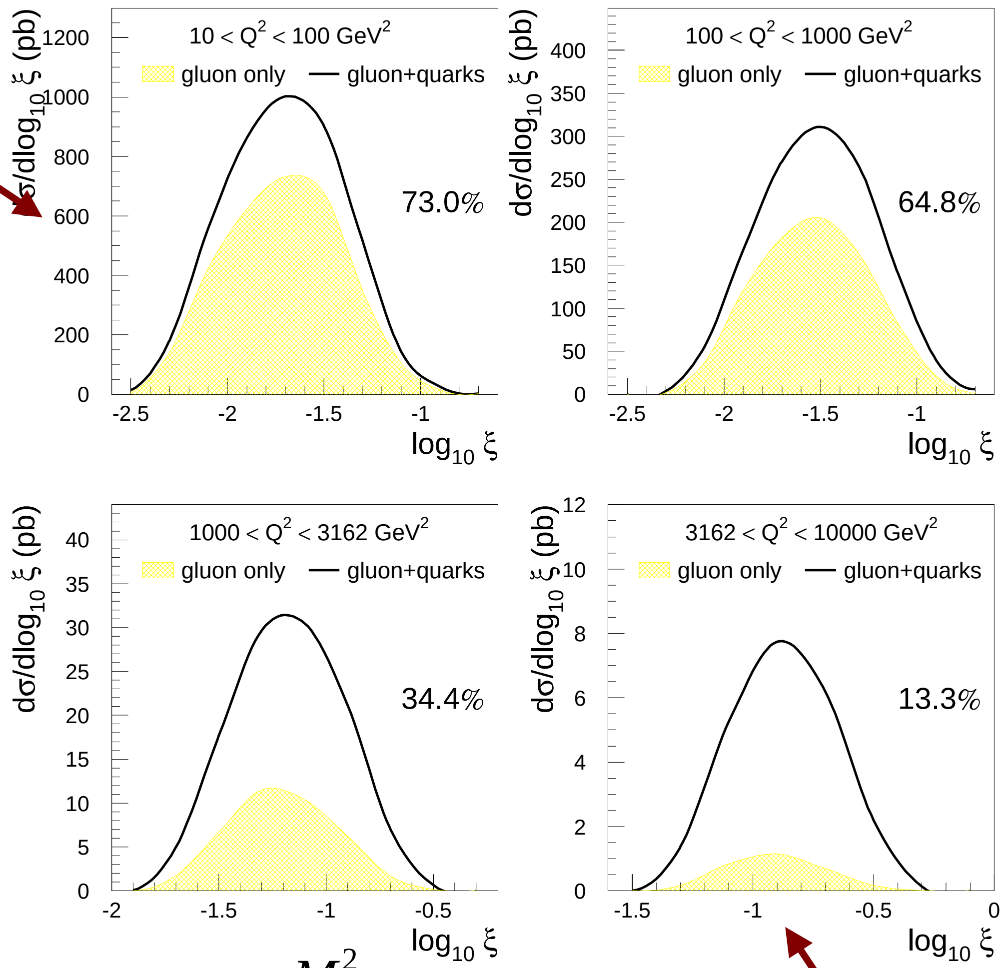
$$\sigma^{2+1} \sim \hat{\sigma}_{BGF} \cdot g(x, Q^2)$$



Use matrix elements from pQCD

Probe gluon in proton

Opportunity for a direct extraction of the gluon density.



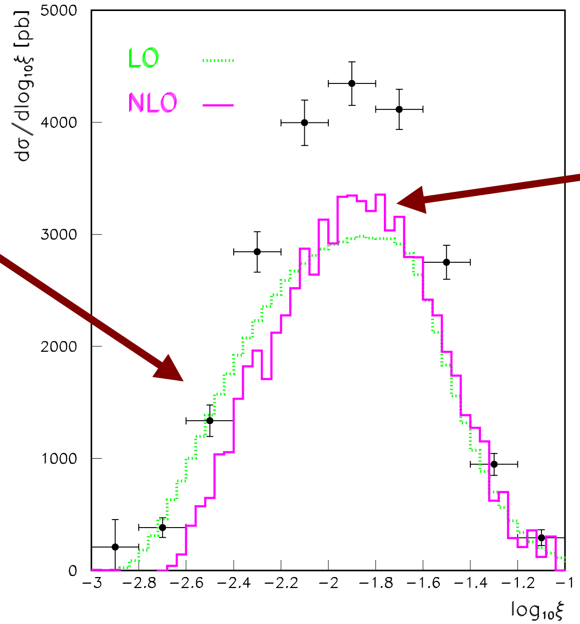
$$\xi = x\left(1 + \frac{M_{jj}^2}{Q^2}\right)$$

Momentum fraction of incident parton

At high Q^2 sensitive to high x quarks

Previous ZEUS Dijet Results

LO calculation fails to describe shape and normalization of the data



NLO calculation fails to describe normalizaiton of the dijet cross section

<u>ZEUS 1994 Dijet Preliminary Result</u>

- Lower Q^2 region $7<Q^2<100$
  - maximum sensitivity to gluon
- Compared dijet cross section with NLO pQCD calculations
  - Normalization difference of ~40%
  - Shape of distributions accurately described

<u>Result inspired new set of goals</u>

- Measure cross section over large Q^2 range
- Understand normalization discrepancy with NLO calculations
- Quantify measurement and theoretical uncertainties

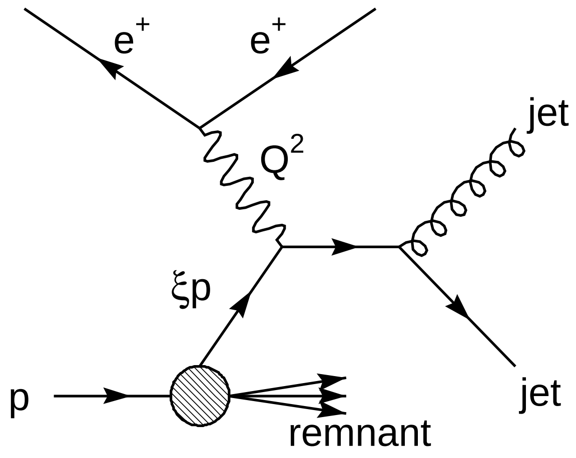
Analysis: Data Selection

HERA 1996 and 1997 running period

- 820 GeV protons −− 27.5 GeV positrons

ZEUS data sample

- integrated luminosity: 38.4 pb^{-1}



Cross Section Definition

$10 < Q^2 < 10000$ GeV^2

- acceptance understood above 10 GeV^2
- statistics limited above 10000 GeV^2

$y > 0.04$ and $E_e > 10$ GeV

- detector efficiency and background reduction

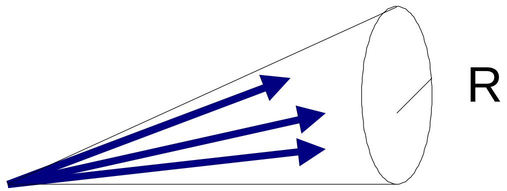
Jets defined by inclusive−mode k_T−algorithm run in Breit Frame (next slides)

- Lab Frame: Jet $E_T > 5$ GeV, $|\eta|<2.0$
  - well understood acceptance region
- Breit Frame: Jet $E_{T,1} > 8$ GeV and Jet $E_{T,2} > 5$ GeV
  - asymmetric cut: controlled region of NLO calculations (explained later)

Jet Algorithms

<u>Cone algorithms</u>

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



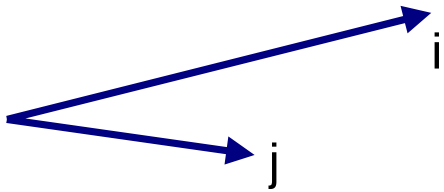
Maximize E_T within
a cone of radius R

<u>Inclusive−mode k_T−algorithm (KTCLUS)</u>

- 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

Breit Frame axis is γ−proton axis

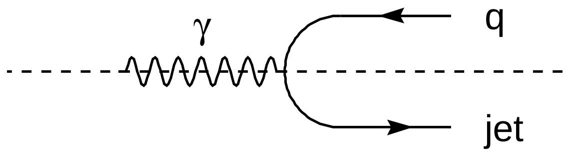
Exchanged γ 4−mom has only a z−component

Experimentally: constructed from measured 4−mom of scattered positron

Example: single jet DIS (Quark Parton Model event)

- Struck quark rebounds with equal and opposite momentum
  - "Brick Wall" Frame
- Jet has no E_T

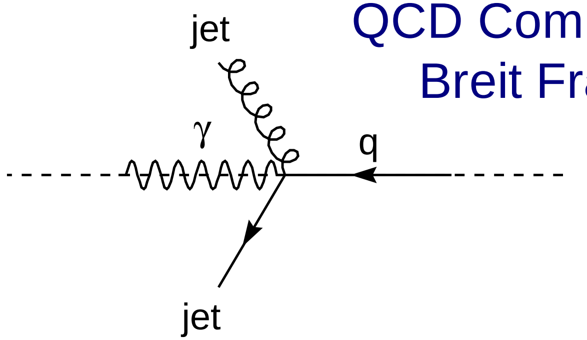
QPM event in Breit Frame



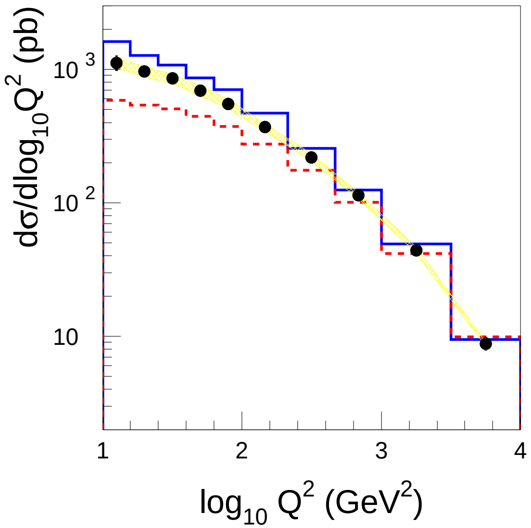
Example: Dijet in DIS (QCDC or BGF)

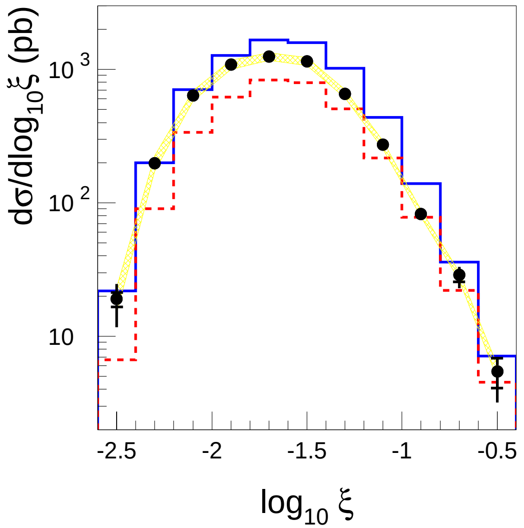
- Jets have balanced E_T in breit frame

QCD Compton in Breit Frame

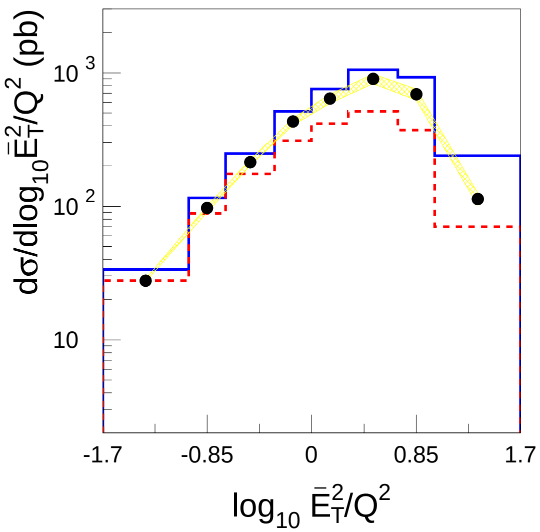


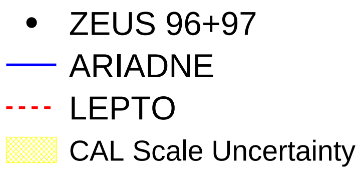
Comparison with LO Models





$$\xi = x\left(1+\frac{M_{jj}^2}{Q^2}\right)$$





$$\bar{E}_T = \frac{jet\,E_{T,1}^{BRE} + jet\,E_{T,2}^{BRE}}{2}$$

Inclusive Dijet Cross Section

$10<Q^2<10000$ GeV^2

$y>0.04$, $E_e>10$ GeV

asymmetric jet E_T cut: 5Gev, 8GeV

$-2.0 <$ jet $\eta < 2.0$

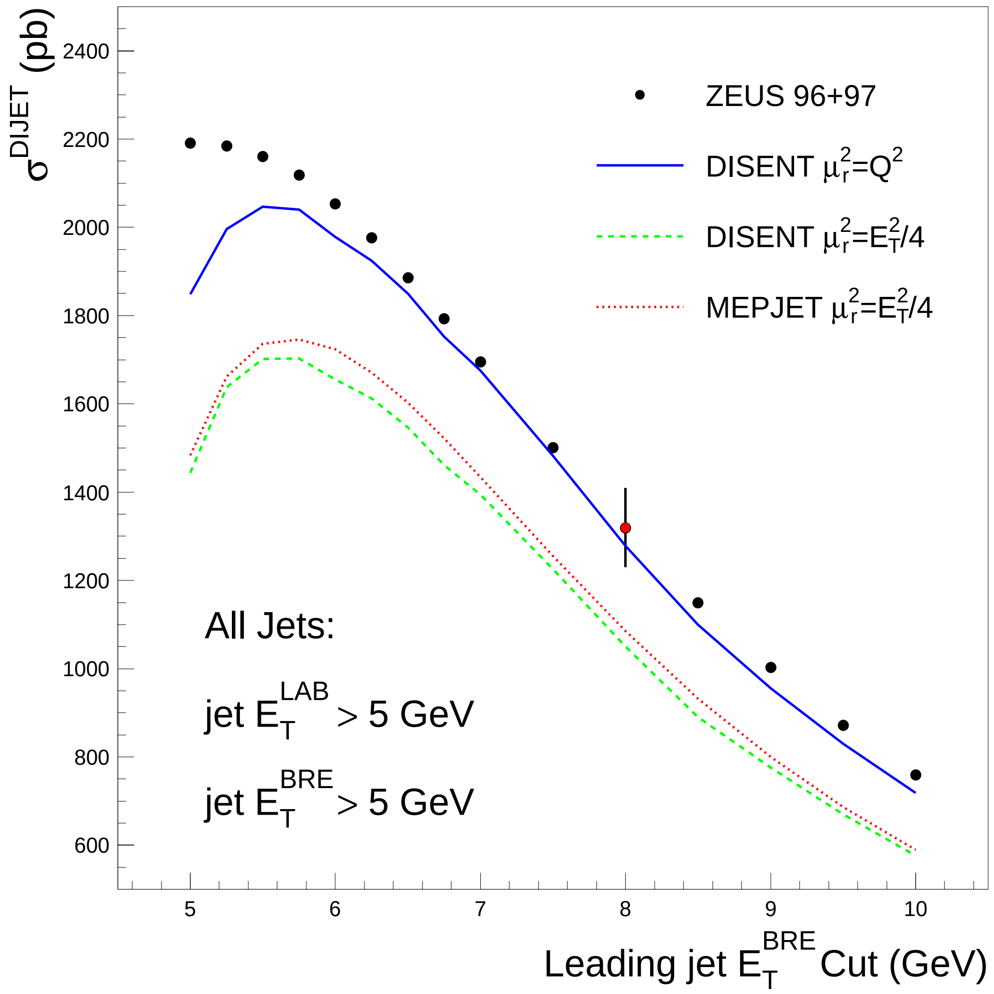
- Data corrected for detector effects to hadron level

LO MC models fail to describe normalization

- Attempts to model higher order effects inadequate
  - parton showers and CDM
- Large renormalization scale dependence

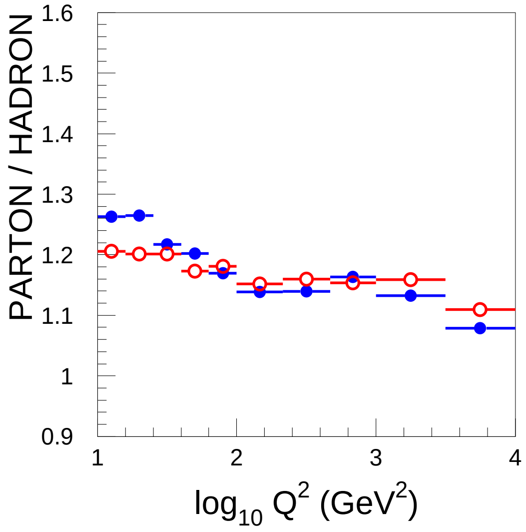
Comparing with NLO Calculations

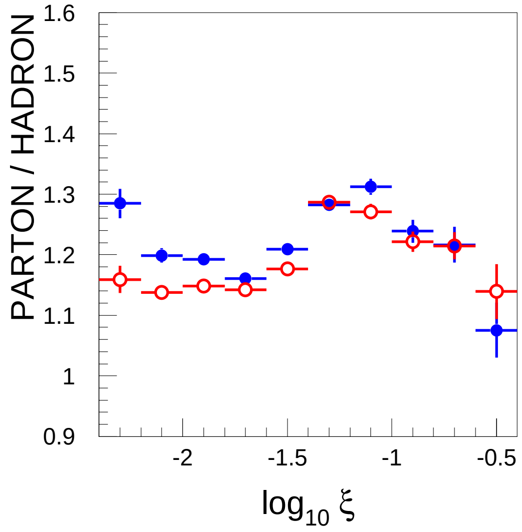
Total Inclusive Dijet Cross Section

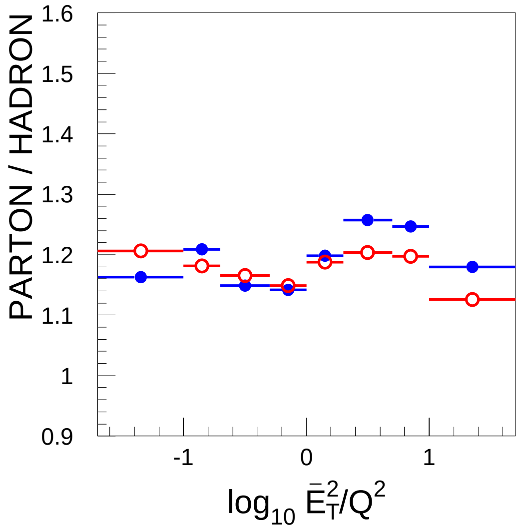


- NLO calculations MEPJET and DISENT behave unphysically near the symmetric cut
  - Reduced phase space for 3−parton final states that cancel negative−weight 2−parton final states
  - Asymmetric jet cut of $E_{T,1}$>8GeV, $E_{T,2}$>5GeV avoids sensitive region
- Large difference due to choice of renormalizatoin scale
- 40% normalization difference between NLO and ZEUS 1994 results understood!

Hadronization Effects







$$\xi = x\left(1 + \frac{M_{jj}^2}{Q^2}\right)$$

• ARIADNE: CDM + LUND

○ LEPTO: MEPS + LUND

$$\bar{E}_T = \frac{jet\, E_{T,1}^{BRE} + jet\, E_{T,2}^{BRE}}{2}$$

- NLO calculations do not include hadronization models
- Use LO MC models to estimate non−perturbative hadronization effects

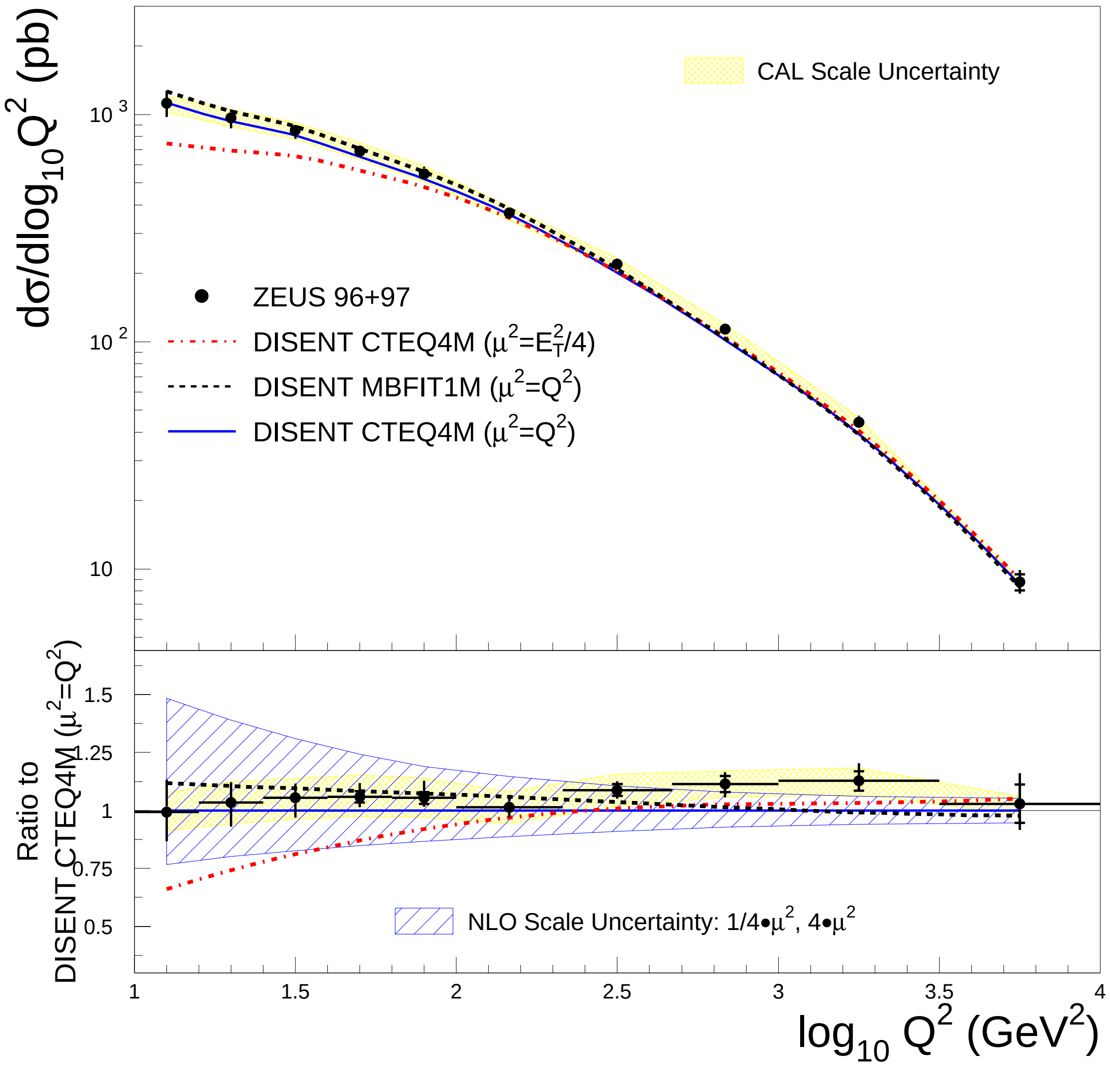
- Apply corrections from LO MC model esitmates to NLO calculations
  - Ariadne used by default

- Hadronization corrections vary between 10% and 30%

- Estimates from Ariande and Lepto LO models vary typically by 5%, and no more than 10%
  - additional theoretical uncertainty

Inclusive Dijet Cross Section vs Q^2

Asymmetric jet cut: 5, 8GeV; E_e>10, y>0.04



NLO Comparison

Success for pQCD!

Within NLO scale uncertainty estimate, NLO calculations reproduce measured cross section to within 10%

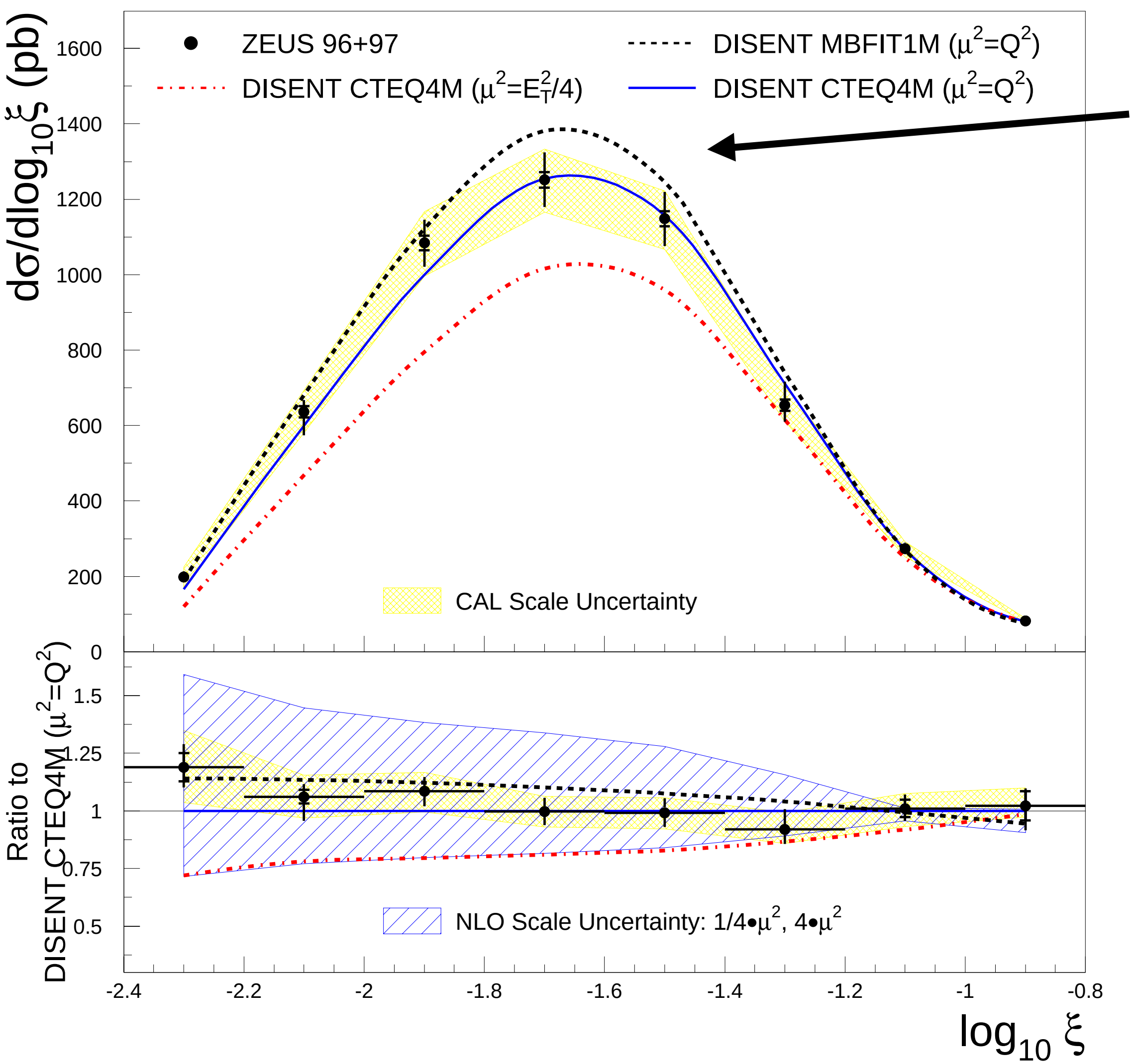
- over three orders of magnitude in Q^2
- over 2 orders of magnitude in value

For Q^2<~200 measurement uncertainties less than renormalization scale uncertainty

- Need improved theoretical calculations with reduced renormalization scale dependence

Inclusive Dijet Cross Section vs ξ

Asymmetric jet cut: 5, 8GeV; E_e>10, y>0.04



NLO Comparison

NLO calculation shows dependence on input parton densities

- MBFIT has larger gluon

All NLO calculations are consistent with the data

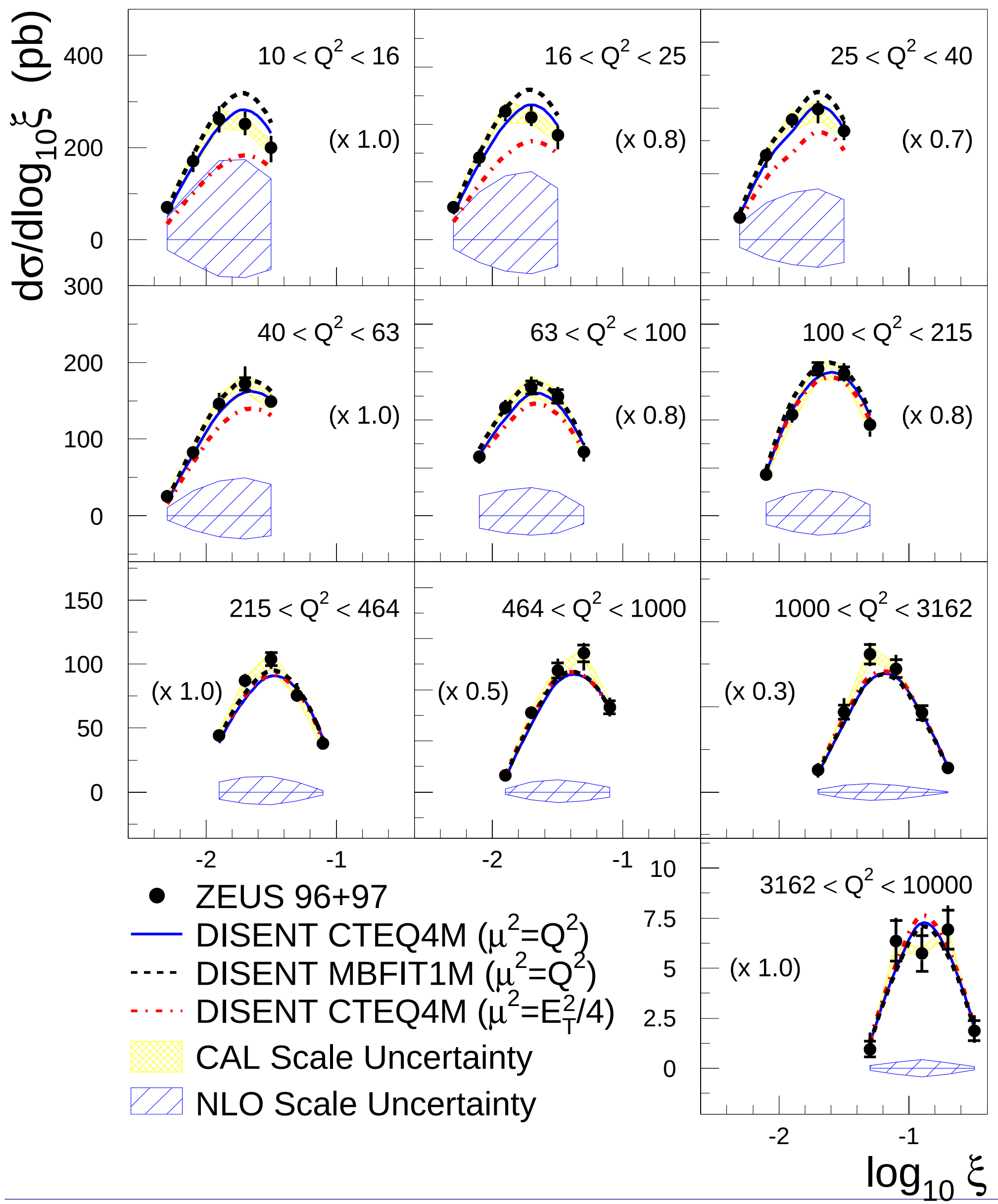
- within all uncertainties
- regardless of input parton densities

Gluon densities in current PDFs

- consistent with the data and pQCD calculations

$$\xi = x\left(1+\frac{M_{jj}^2}{Q^2}\right)$$

Inclusive Dijet Cross Section vs ξ and Q^2



NLO Comparison

Gluon density sensitivity of NLO calculation seen for Q^2<~200GeV^2

NLO calculations converge at higher Q^2

- quark densities well constrained
- smaller renormalization scale uncertainty

For Q^2<~200 renormalization scale uncertainty larger than measurement uncertainty

Future improved pQCD calculations will enable use of the dijet cross section measurement for Q^2<~200

- used in global fits
- or used to extract gluon density directly

Conclusions on Dijet Cross Section and pQCD

Inclusive dijet cross section measured for $10<Q^2<10000$ GeV^2 and asymmetric jet E_T cuts of 5 and 8 GeV

NLO pQCD reproduces the dijet cross section within 10% over three orders of magnitude in Q^2 and over 2 orders of magnitude in value. Triumph for pQCD!

Universality of gluon density: Gluon extracted from scaling violation of F_2 can be used to describe the dijet cross section.

NLO calculations exhibit large renormalization scale dependence for Q^2<~200GeV^2; exactly where sensitivity to gluon density is largest.

- Extraction of gluon density using dijet cross section possible with future improved calculations