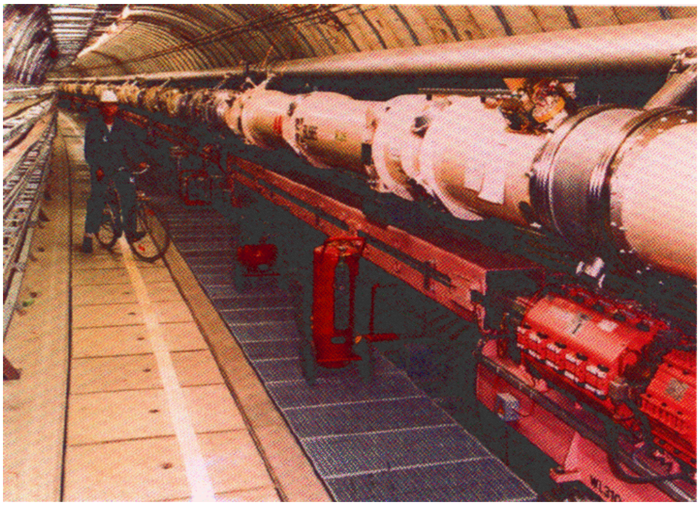
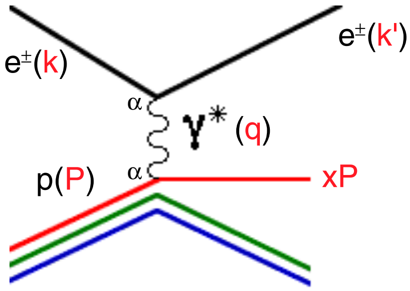
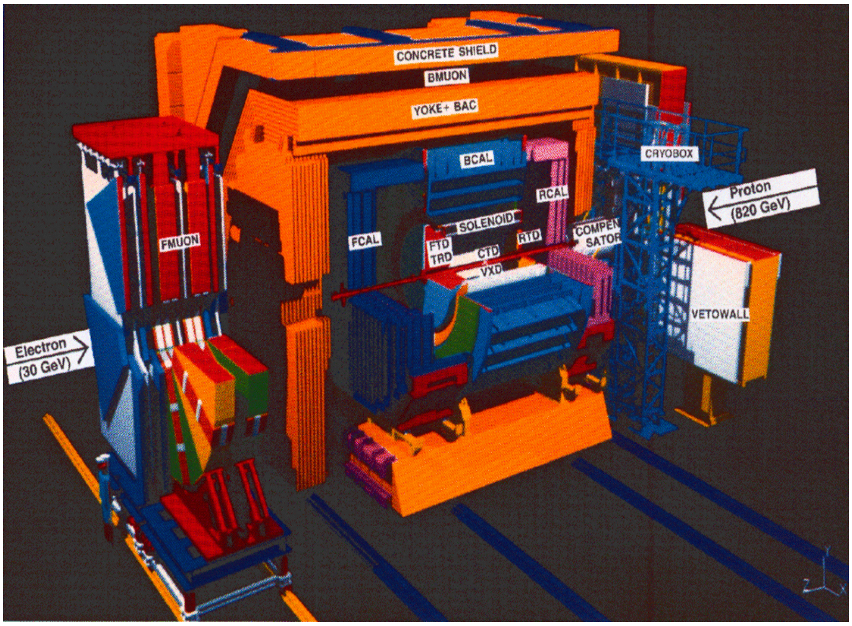
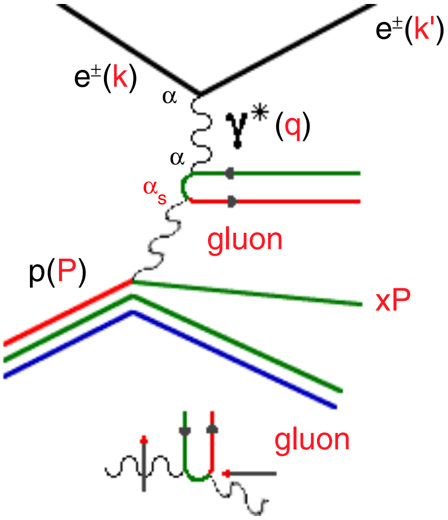
Deep inelastic scattering at ZEUS/HERA





Measurement of F_L, the longitudinal structure function





Richard Cross, UW-Madison

November, 1995

Measuring F_L at ZEUS

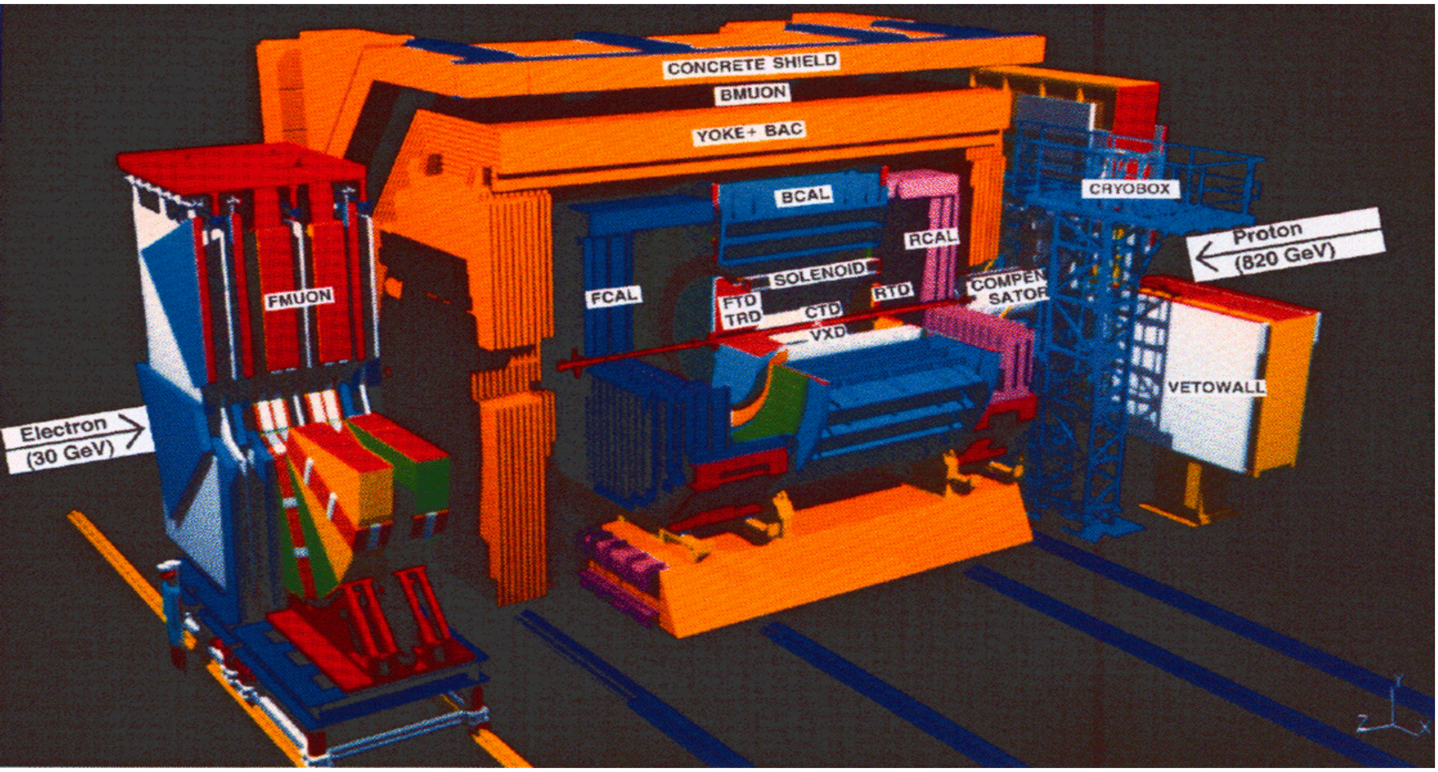
Outline:

- Description of ZEUS experiment
- ZEUS structure function measurements and errors
    - Past structure function measurements
- Effect of longitudinal structure function on ZEUS structure function measurements
- Importance of a longitudinal structure function measurement?
    - Theory behind structure functions
    - Measured gluon distribution from F_2 structure function
- ZEUS longitudinal structure function measurement
    - Measure cross section at the same x, Q^2 but different s
- Conclusions

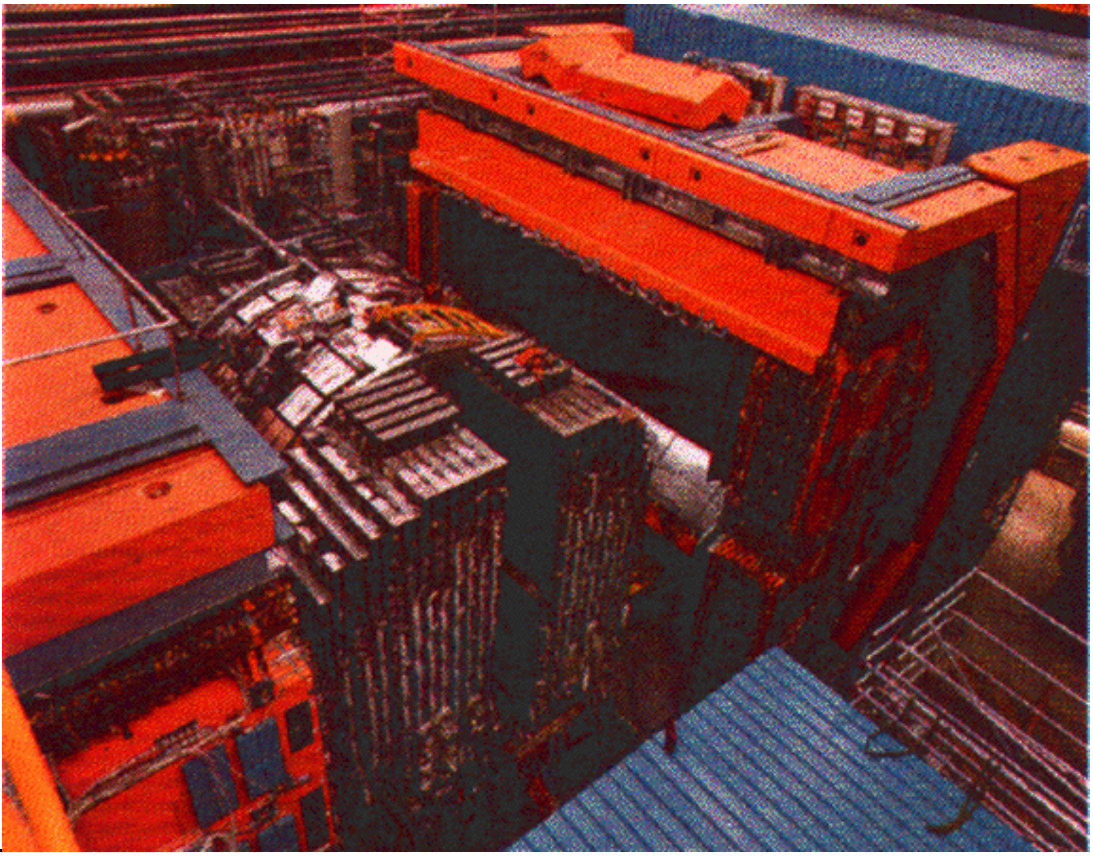
ZEUS HERA

- ZEUS is a detector on HERA
  - HERA is an accelerator ring at DESY lab
  - DESY lab is a German national lab in Hamburg
- HERA stands for Hadron Elektron Ring Anlage
  - HERA accelerates Proton bunches to 820 *GeV* and Electron bunches to 27 *GeV*
  - Center of mass energy($\sqrt{s}$) = 300 *GeV*
  - Equivalent to a 47 *TeV* fixed target experiment
  - de Broglie wavelength ~ $1.5\ X10^{-18}\ m$
  - Bunches cross every 96 *ns*
  - Radius of 1 *km*

- The ZEUS detector

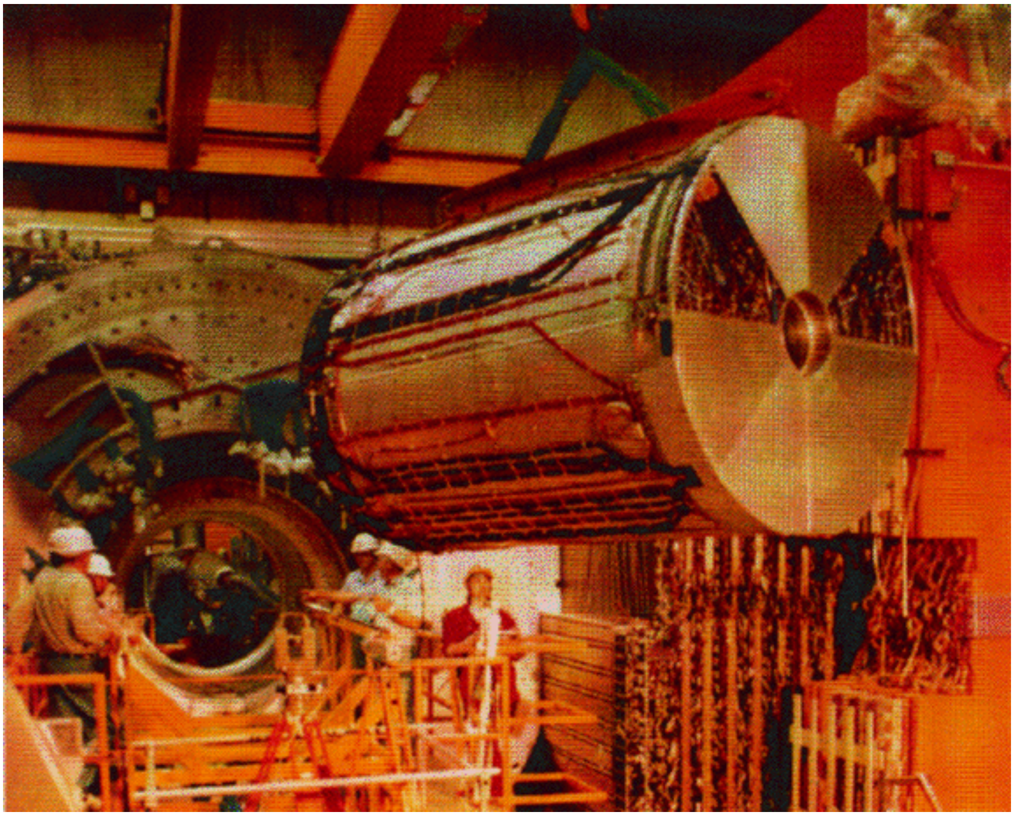


- The Calorimeter



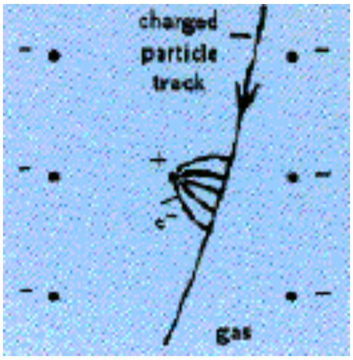
Tracking

- A solenoid surrounds the tracking chambers
  - The Vertex Detector (VXD) and Central Tracking Detector(CTD) are cylindrical drift chambers
  - The Solenoid creates a magnetic field of 1.43 *T*
  - Tracking information can be used to check Calorimeter energies



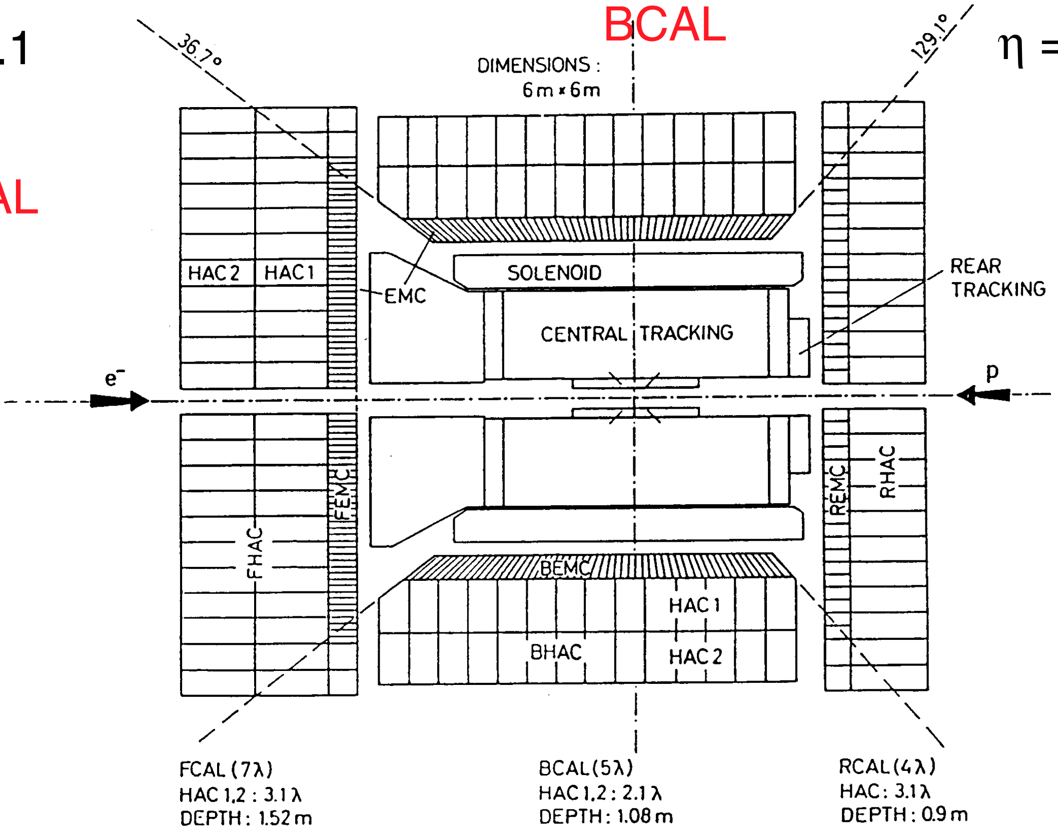
- Installing the CTD

- Drift chamber



The Calorimeter

- The ZEUS calorimeter is made of alternating layers of scintillator and depleted uranium
  - Uranium is dense - Calorimeter is compact
  - Layers are designed so the Calorimeter has a linear response to hadrons and electrons to ±3%
  - Calorimeter has energy resolution of 35%/√E ±1% for hadrons and 17%/√E ±1% for electrons
  - ZEUS Calorimeter covers 99.8% of the solid angle
  - Angular resolution of 10 mrad
  - Timing resolution is 1 *ns* << 96 *ns* crossing time



$\eta = 1.1$

BCAL

$\eta = -0.75$

FCAL

RCAL

$\theta = 0$

$$\eta = -\log \tan\theta/2$$

Range $4.2 > \eta > -3.5$

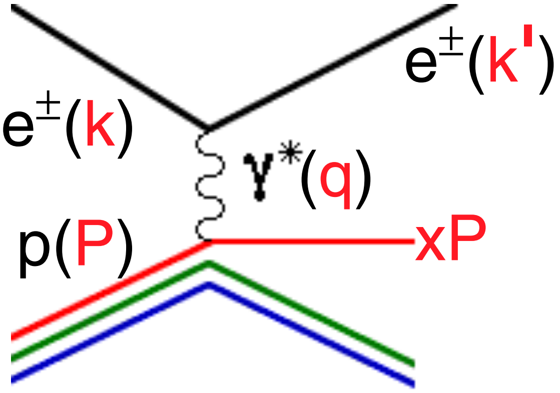
Physics studied at ZEUS

- Deep Inelastic Scattering
  - Studies structure of the proton
  - Sea quark and gluon density
  - Scaling violations
- Photoproduction
  - Scattering at energies where the photon is almost real
  - Studies the structure of the photon
  - Resolved and direct process
- Physics seen in Deep Inelastic Scattering and Photoproduction
  - Jet production
  - Rapidity gap events
  - Vector meson production
- $W^{\pm}$, Z^{o} exchange
- Exotic particles
  - Leptoquarks
  - Excited quarks

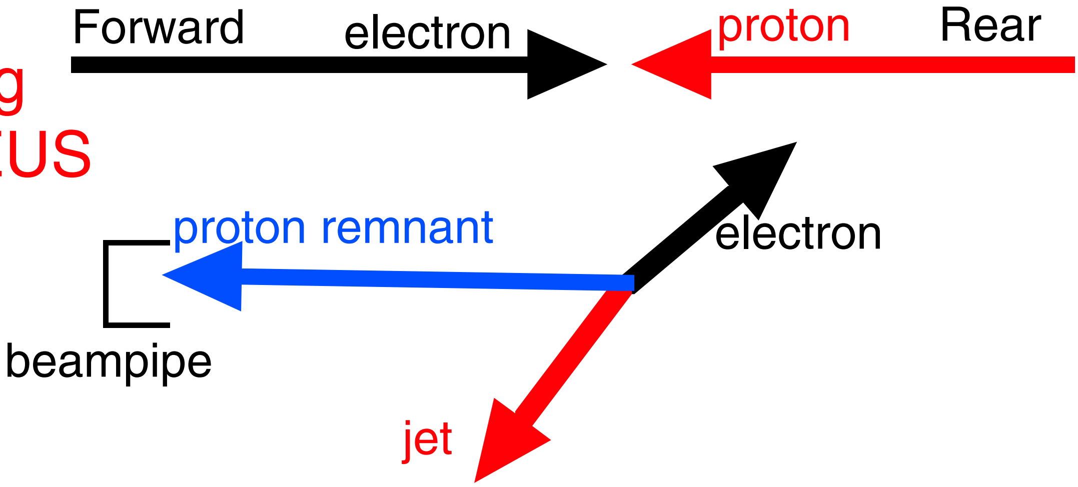
What is Deep Inelastic Scattering?

- Deep Inelastic Scattering is the scattering of a lepton from constituents of nucleons at high momentum transfer
  - The electron-proton interaction is mediated by the exchange of a single vector boson (a photon, $W^{\pm}$ or Z^{o} force carrier)
  - $W^{\pm}$ and Z^{o} collisions are **rare** at ZEUS energies
  - The photon is virtual - it can be polarized transversely or longitudinally.
  - Jets - clusters of hadrons formed by scattered quarks and radiated gluons

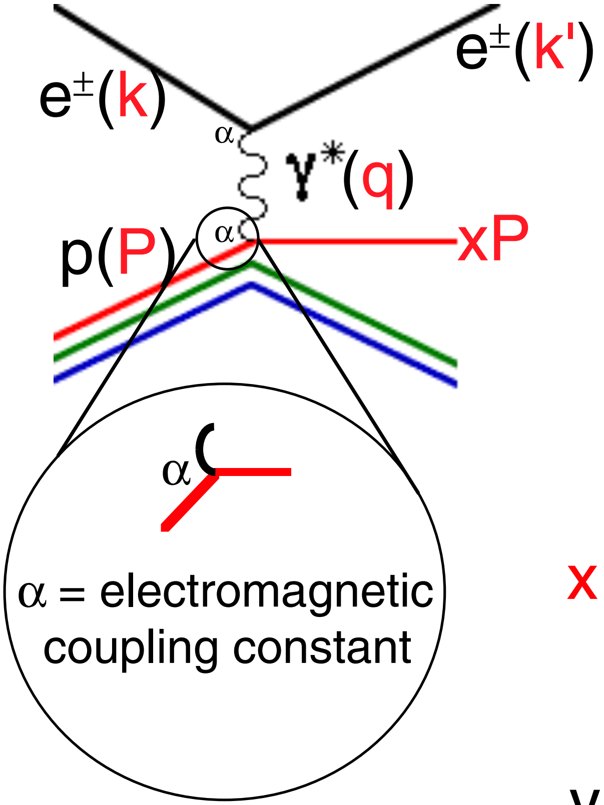
The DIS process



Measuring DIS at ZEUS



DIS Variables



α = electromagnetic coupling constant

$s = (k + P)^2 =$
The center of mass energy

$Q^2 = -q^2 = -(k-k')^2 =$
The square of the momentum transferred

$$x = \frac{Q^2}{2P \bullet q}$$

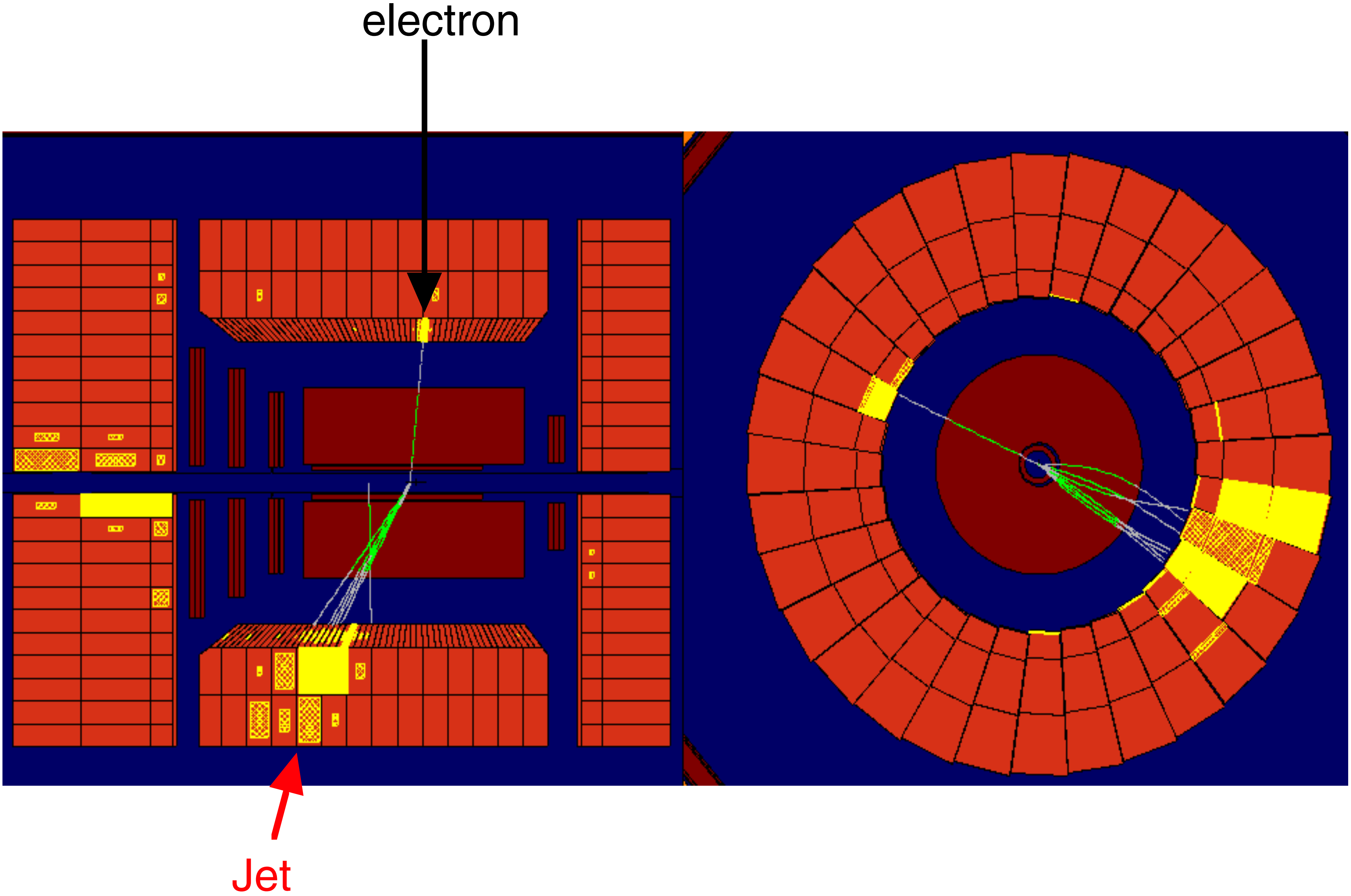
$$y = \frac{P \bullet k}{P \bullet q}$$

x = the fraction of the proton's momentum carried by the struck parton

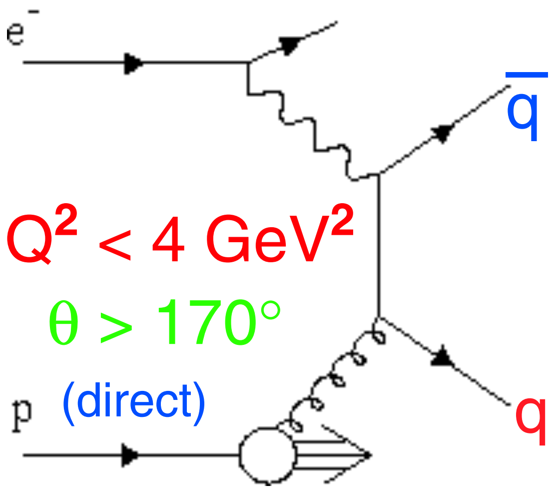
y = the fraction of the electron's energy lost in the proton rest frame

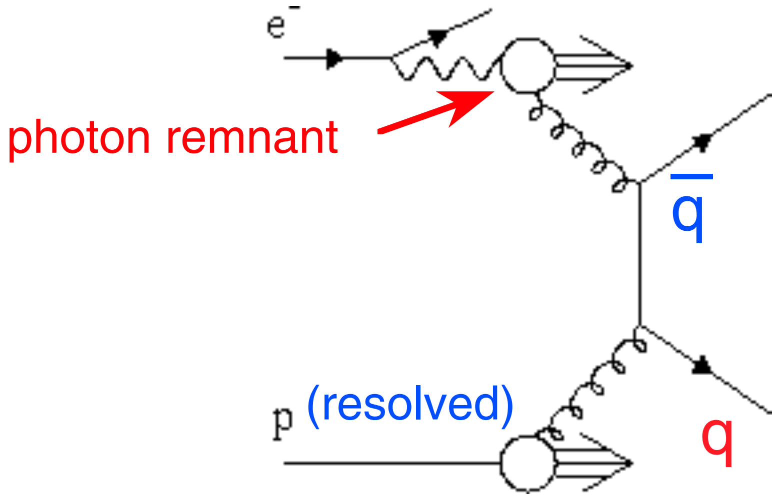
$$Q^2 = sxy$$

DIS event Q^2 = 1600 GeV^2

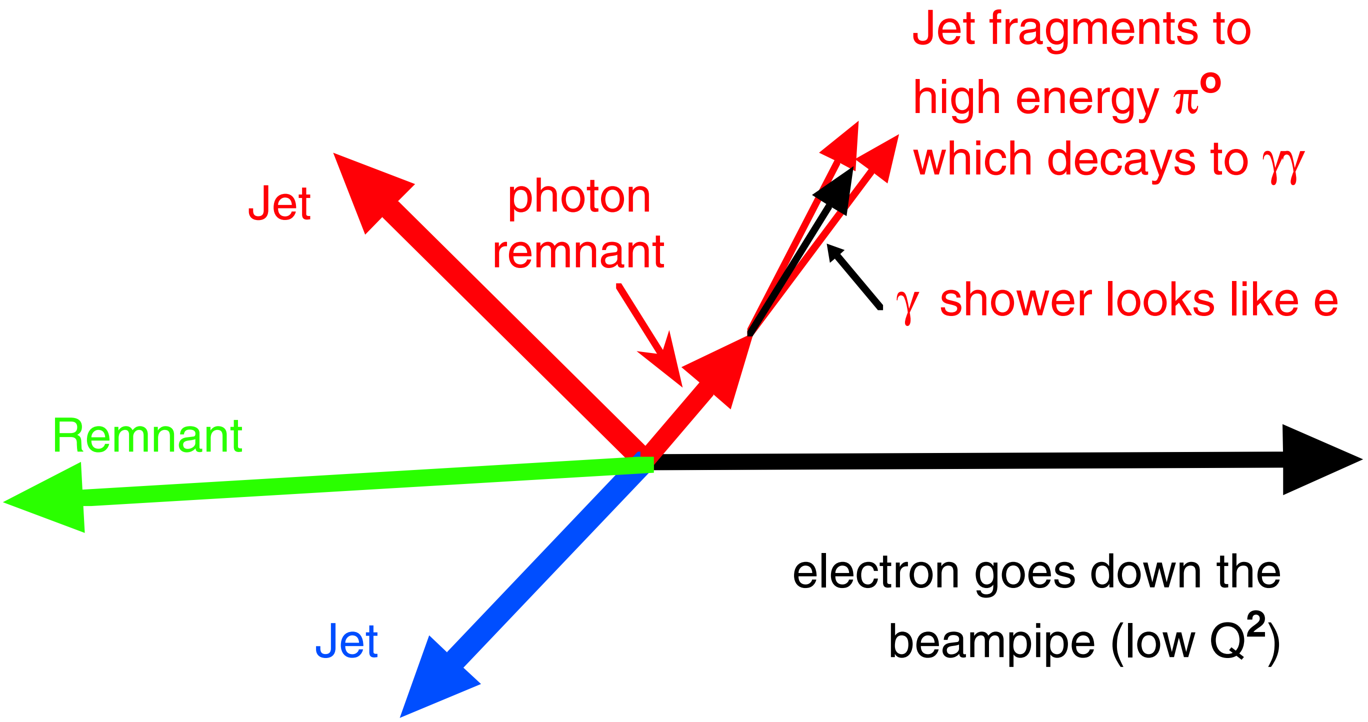


Photoproduction





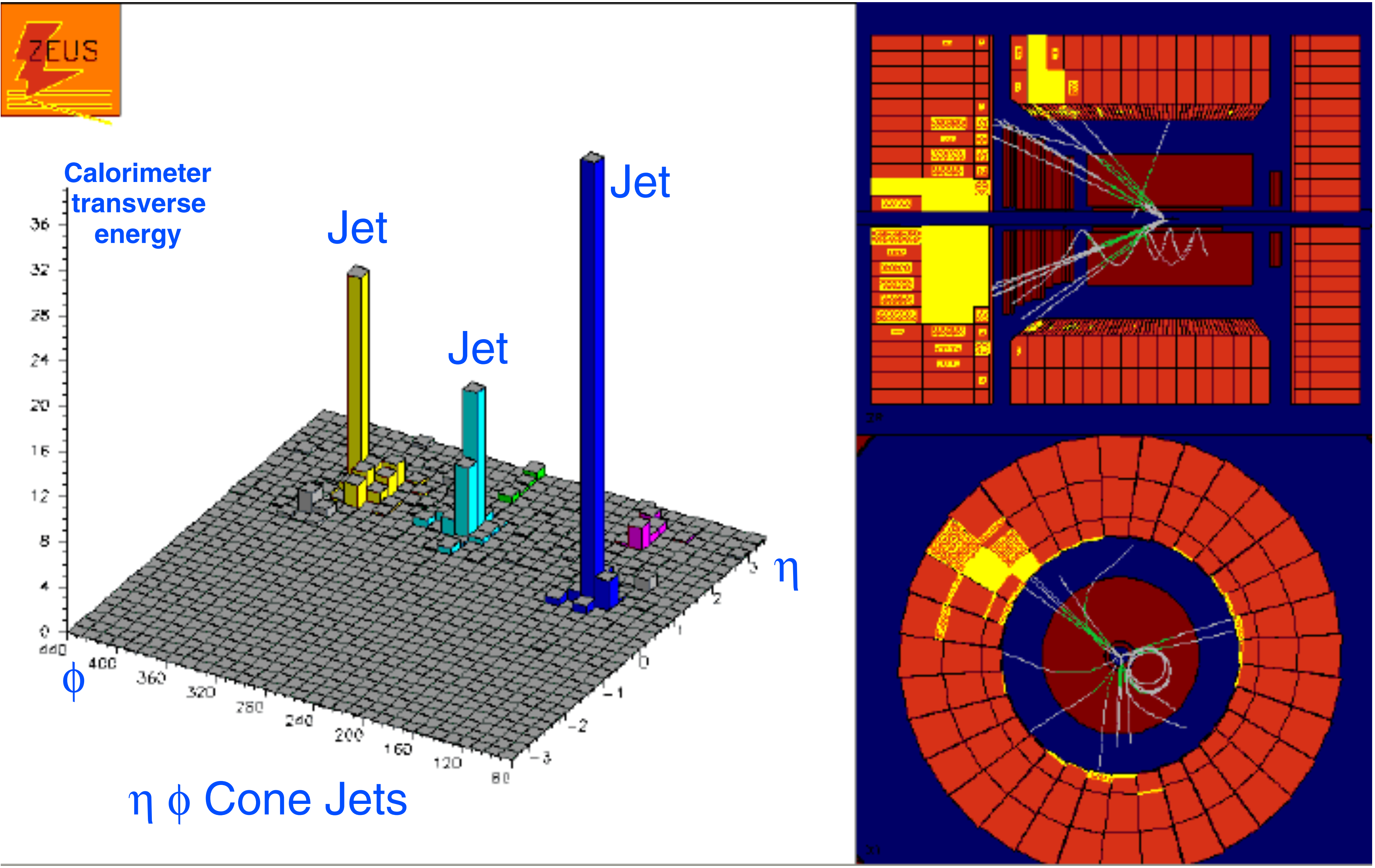
- Almost real photon



Jet fragments to
high energy π^o
which decays to $\gamma\gamma$

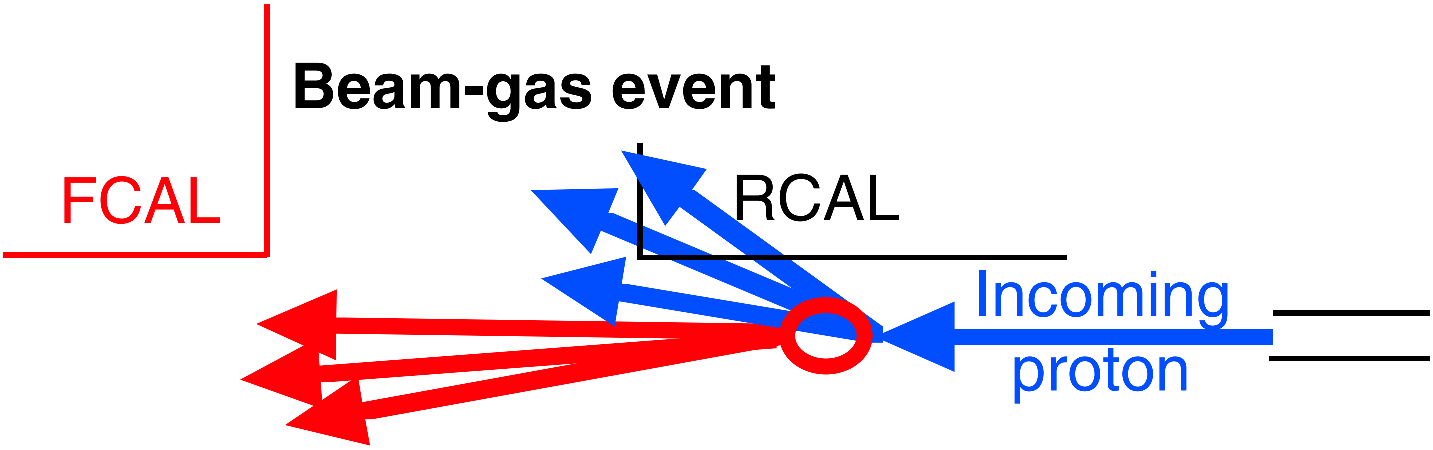
electron goes down the
beampipe (low Q^2)

Photoproduction event



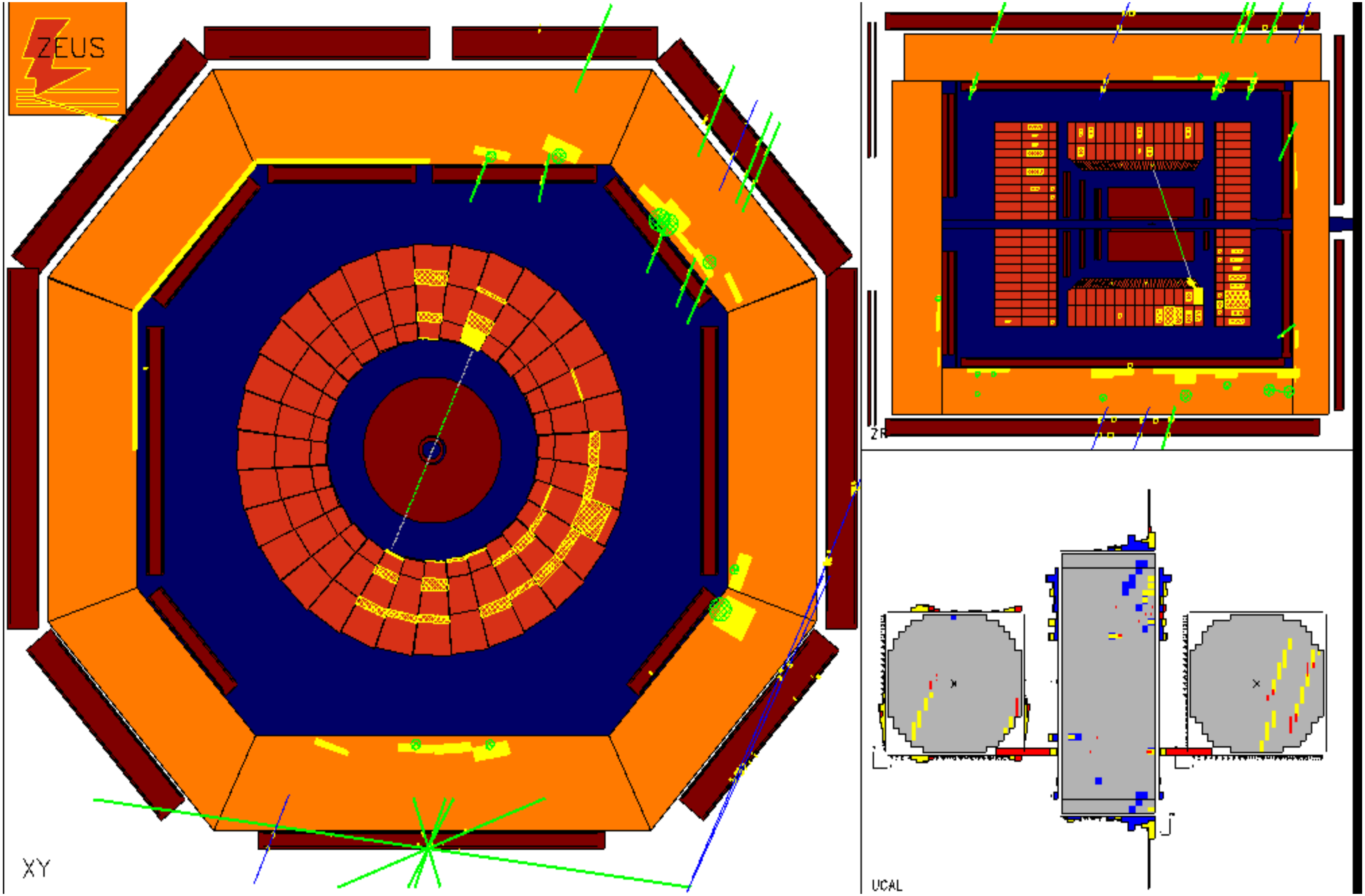
DIS Backgrounds

- Backgrounds at ZEUS are beam-gas interactions (100 *kHz*), cosmic rays (1 *kHz*) and electronic noise (> 0.1 *kHz*).
  - Beam crossings every 96 *ns*.
  - Events pipelined over 5 μs.



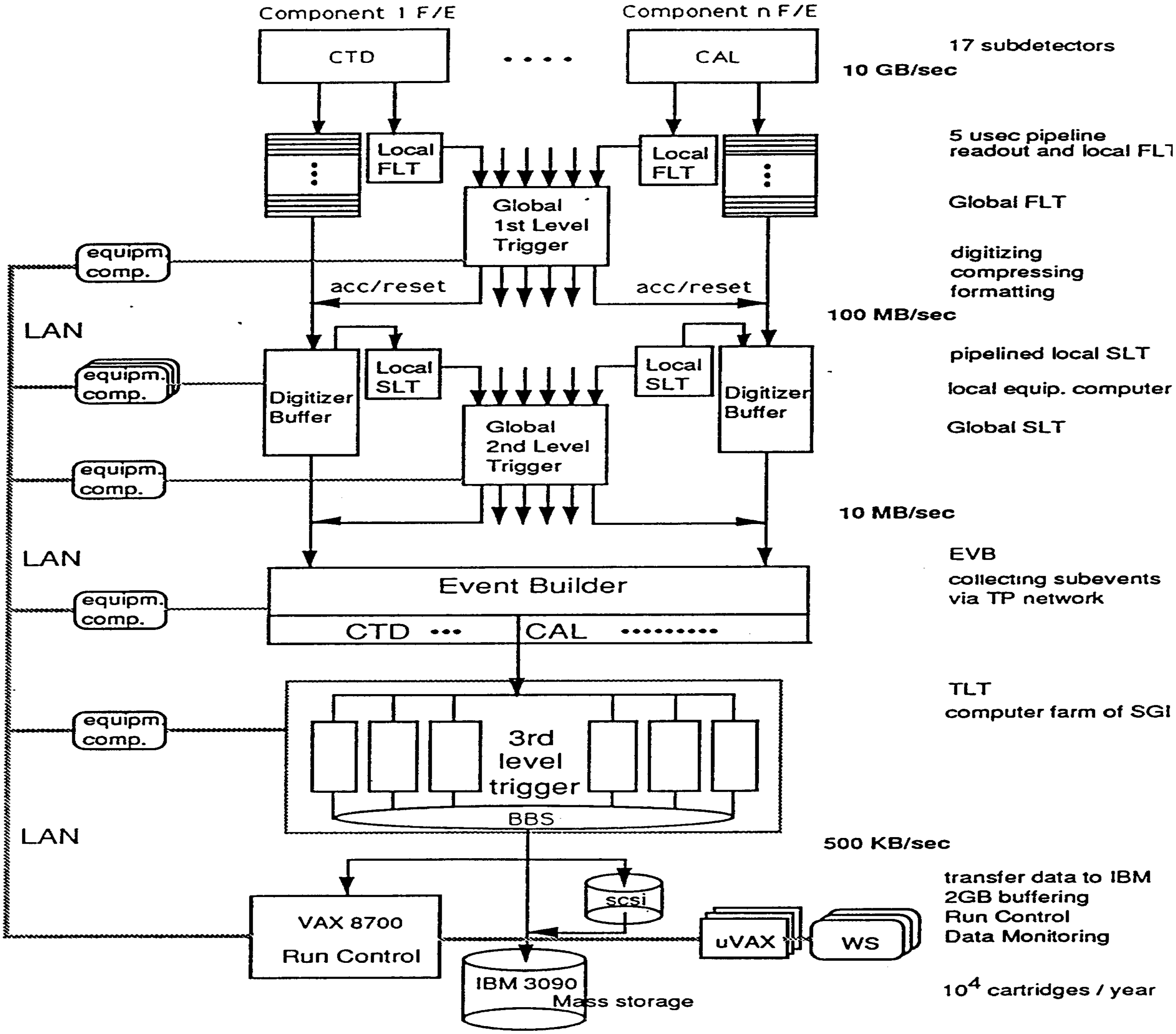
Energy deposit in RCAL
mimics electron
FCAL deposit mimics
current jet

Cosmic background event



The ZEUS data acquisition chain

- Pipeline all events
- Discard background events
- Select DIS and photoproduction events
- Loose cuts at FLT are tightened at SLT and TLT



17 subdetectors
10 GB/sec

5 usec pipeline
readout and local FLT

Global FLT

digitizing
compressing
formatting

100 MB/sec

pipelined local SLT

local equip. computer

Global SLT

10 MB/sec

EVB
collecting subevents
via TP network

TLT
computer farm of SGI

500 KB/sec

transfer data to IBM
2GB buffering
Run Control
Data Monitoring

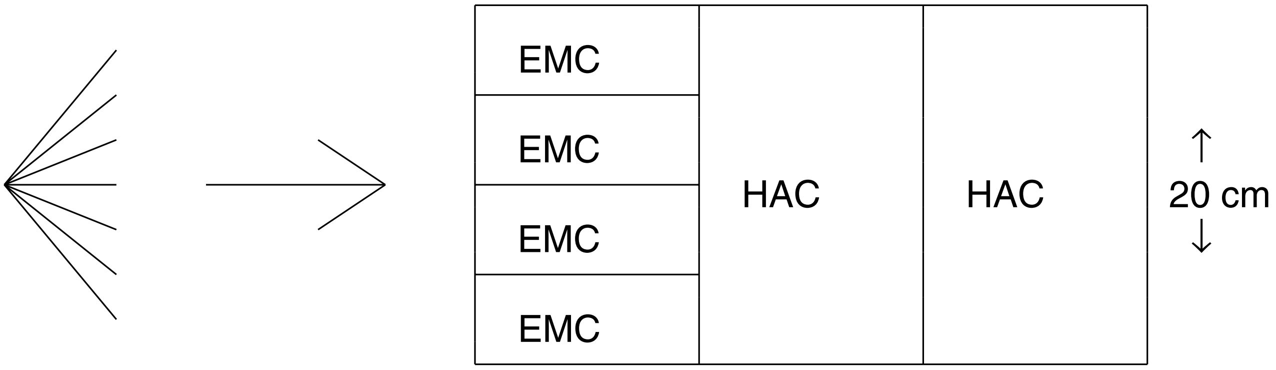
10^4 cartridges / year

Trigger rates

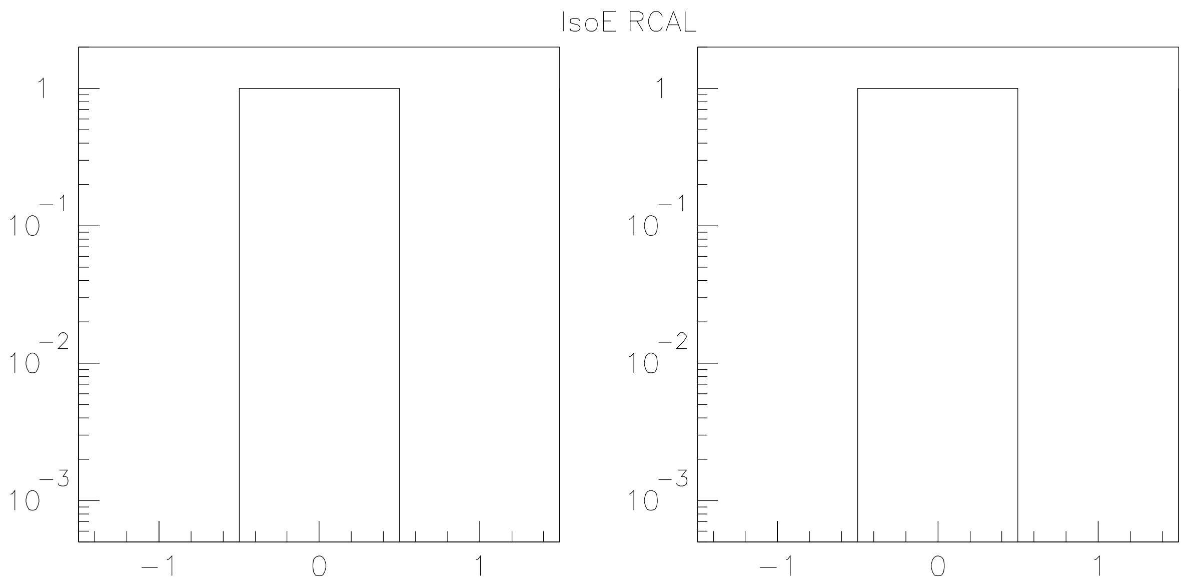
- ZEUS uses a 3 level trigger.
  - The Global First Level Trigger(GFLT) triggers at the rate of 1 *kHz* and digitizes the events in 46 crossings.
  - Global Second Level Trigger(GSLT) triggers at 100 *Hz.*
  - Third Level Trigger SGI farm reduces the rate to 5 *Hz*, or a data rate of 500 *kilobytes/s*.

The CFLT - electron ID

- The Calorimeter First Level Trigger(CFLT) has the primary responsibility for getting the First Level Trigger below 400*Hz*.
  - Searches for isolated electrons in Calorimeter cells.
  - If the electromagnetic energy in a Calorimeter cell is above a threshold and HAC/EMC < 0.25, an isolated electron trigger bit is set.
  - **The isolated electron trigger is essential for measuring structure functions.**
  - The Calorimeter First Level Trigger calculates regional and global total energy, E_{tot}, and the missing transverse energy E_{Tmiss} from E_x and E_y.

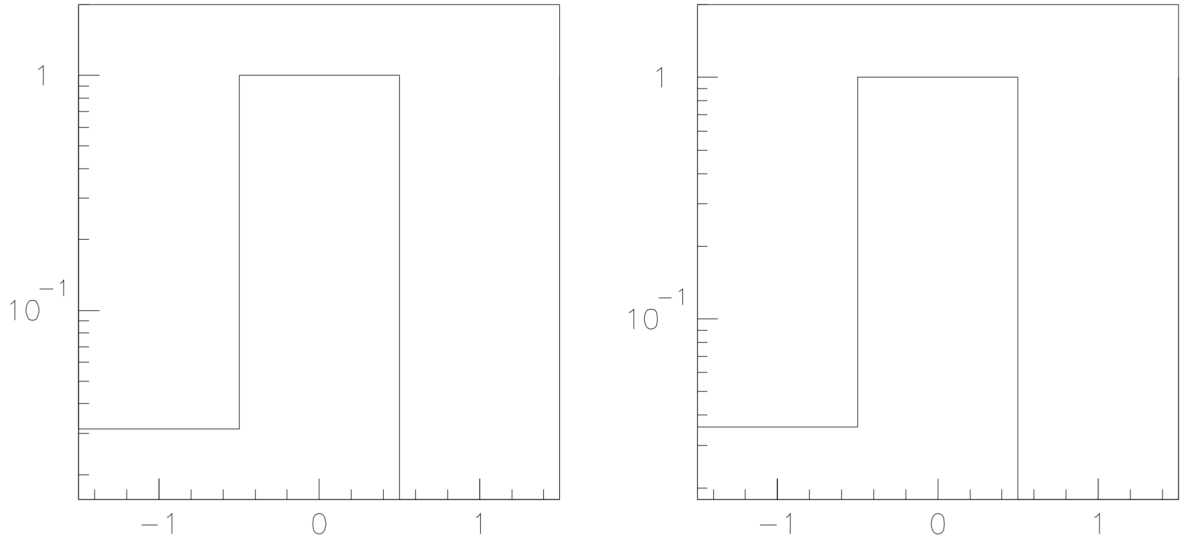


Online presenter



IsoE in Region 4 with 30 entries

IsoE in Region 5 with 63 entries



IsoE in Region 6 with 33 entries

IsoE in Region 7 with 58 entries

- As data is taken, the online presenter calculates trigger efficiency vs simulated trigger efficiency

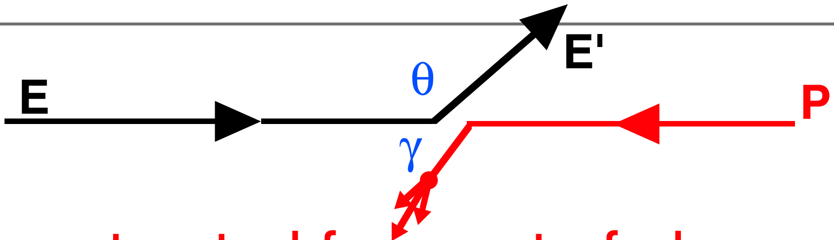
DIS trigger - further cuts

- Calorimeter
  - The Trigger finds electrons by looking for isolated electromagnetic energy deposits.
  - The Calorimter First Level Trigger looks at cells in the Calorimeter that have energy above the electron energy threshold.
  - If one of these regions is surrounded by quiet bits, we send the Global First Level Trigger an isolated electron signal.
  - Isolated electron trigger allows us to set lower electron energy threshold.
- Tracking
  - The CTD and VXD veto the event if there is no track in the whole detector. Triggers on a jet track.

Offline electron identification

- Isolated electron signature is
  - Energy deposit in Electromagnetic Calorimeter cells
  - Above a threshold - currently 5 GeV
  - Contained in a few Calorimeter cells
  - Tracking curve can be used to check energy
  - Tracks leading to interaction point
- Primary electron finder - neural net.
- The experiment has several cluster finders.
- UW group is working on an electron finder that will be tuned to lower energies to measure F_L.

Kinematic reconstruction

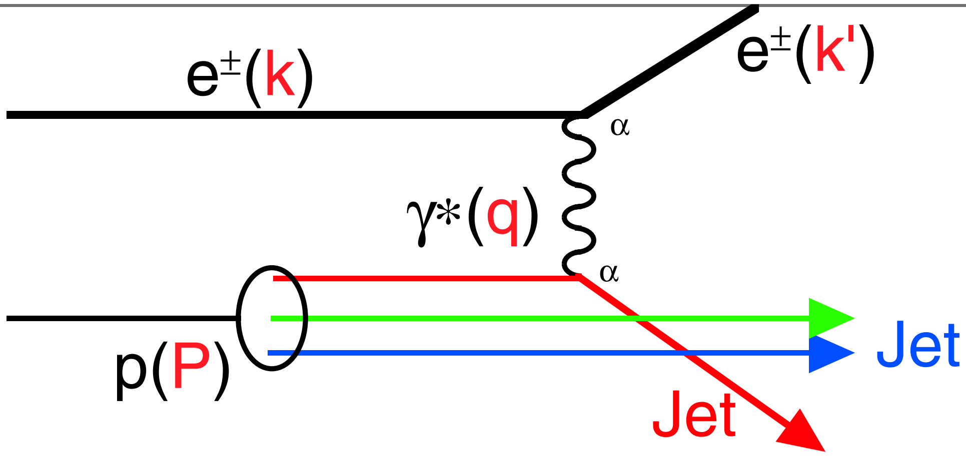


- x,y,Q^2 reconstructed from set of observables
- 2 independent variables - 4 observables
  - Electron energy, electron angle
  - Summed hadronic jet energy, jet angle
- Electron Method
  - Reconstructed from scattered electron energy, angle θ
  - Good resolution in x at low Q^2
  - Sensitive to miscalibrations
  - $y_{electron} = 1 - E'/2E(1 - \cos\theta)$
  - $Q^2_{electron} = 2EE'(1 + \cos\theta)$
  - $x_{electron} = (E/P)*E(1 + \cos\theta)/(2E - E'(1-\cos\theta))$
- Double Angle method
  - Reconstructed from electron angle, hadronic jet angle
  - Depends only on ratios of energies
  - Better mean resolution over whole x-Q^2 plane
  - Weakly affected by miscalibrations
  - $y_{\theta\gamma} = \sin\theta(1 - \cos\gamma)/(\sin\theta + \sin\theta - \sin(\theta + \gamma)$
  - $Q^2_{\theta\gamma} = 4E^2 \sin\theta(1 + \cos\gamma)/(\sin\theta + \sin\theta - \sin(\theta + \gamma)$
  - $x_{\theta\gamma} = (E/P)*(\sin\theta + \sin\theta + \sin(\theta + \gamma)/(\sin\theta + \sin\theta - \sin(\theta + \gamma)$

ZEUS x-Q^2 range

- ZEUS covers a much greater range of x-Q^2 than any previous experiment
- ZEUS x-Q^2 range now overlaps earlier experiments because of new components

DIS cross section



DIS photon differential cross section

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2)\right](1+\delta_r)$$

Virtual photon can be longitudinally or transversely polarized

$F_2(x,Q^2)$ = Structure function gives the interaction between transversely polarized photons and spin 1/2 partons. This is the charge weighted sum of the quark distributions.

$F_L(x,Q^2)$ = Structure function that gives the cross section due to longitudinally polarized photons that interact with the proton. The partons that interact have transverse momentum.

$Q^2 = -(k - k')^2 = -q^2 = sxy$ $\qquad$ $x = Q^2 / 2P\bullet q$

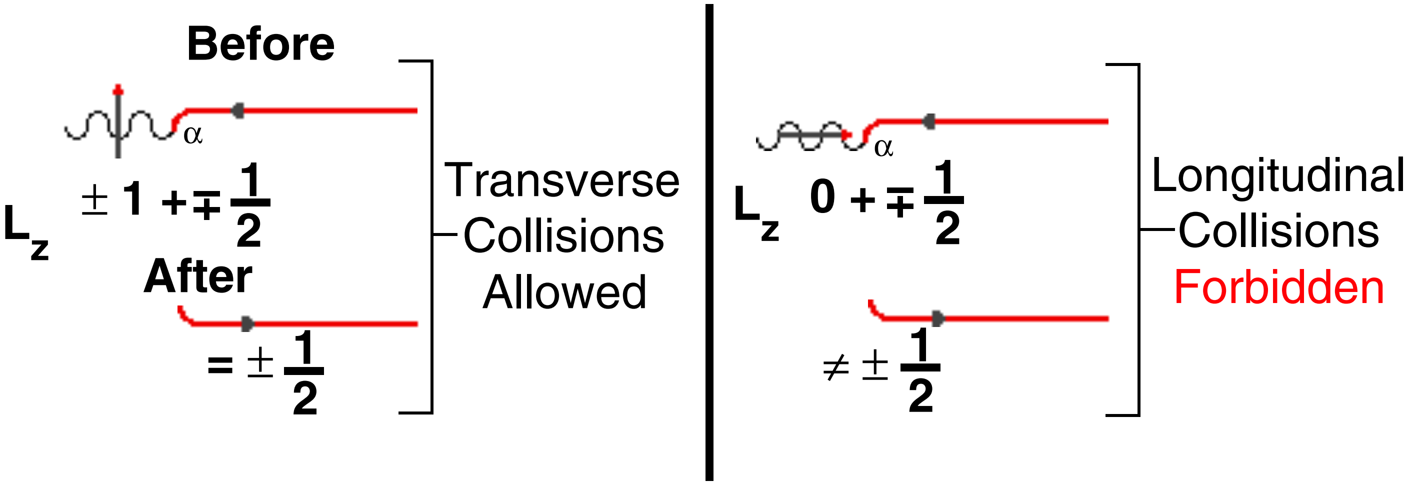
$y = P\bullet q / P\bullet k$ $\qquad$ $Y_\pm = 1 \pm (1 - y)^2$

δ_r = radiative corrections

Parton model

- Bjorken Scaling
  - x - fraction of proton momentum carried by the struck quark
  - No parton - parton interactions
  - Parton has no transverse momentum
  - $F_2 = F_2(x)$
  - No longitudinal collisions
  - $F_2(x) = x\sum_i e_i^2 q_i(x)$
  - Charge weighted sum of quark distributions

Infinite momentum frame



Before

$L_z \quad \pm 1 + \mp\frac{1}{2}$

After

$= \pm\frac{1}{2}$

Transverse Collisions Allowed

$L_z \quad 0 + \mp\frac{1}{2}$

$\neq \pm\frac{1}{2}$

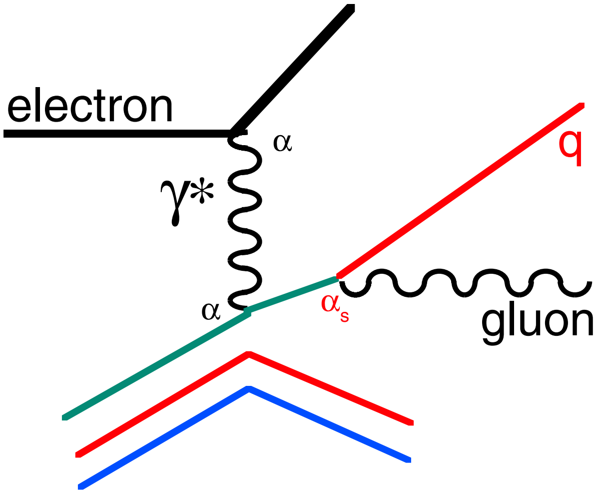
Longitudinal Collisions Forbidden

- Parton Distribution Functions describe sharing nucleon's momentum among constituents
- But scaling is violated...

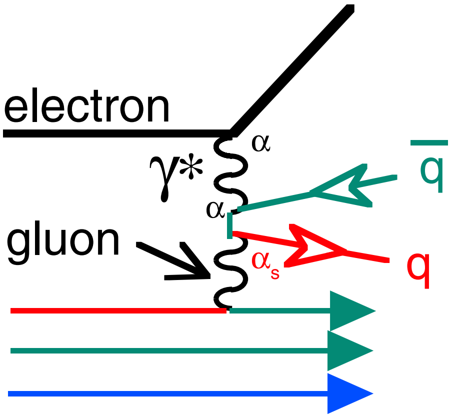
QCD

- Transverse momentum for quarks generated due to parton interactions
- Causes scaling violation

QCD Compton



Boson-Gluon Fusion



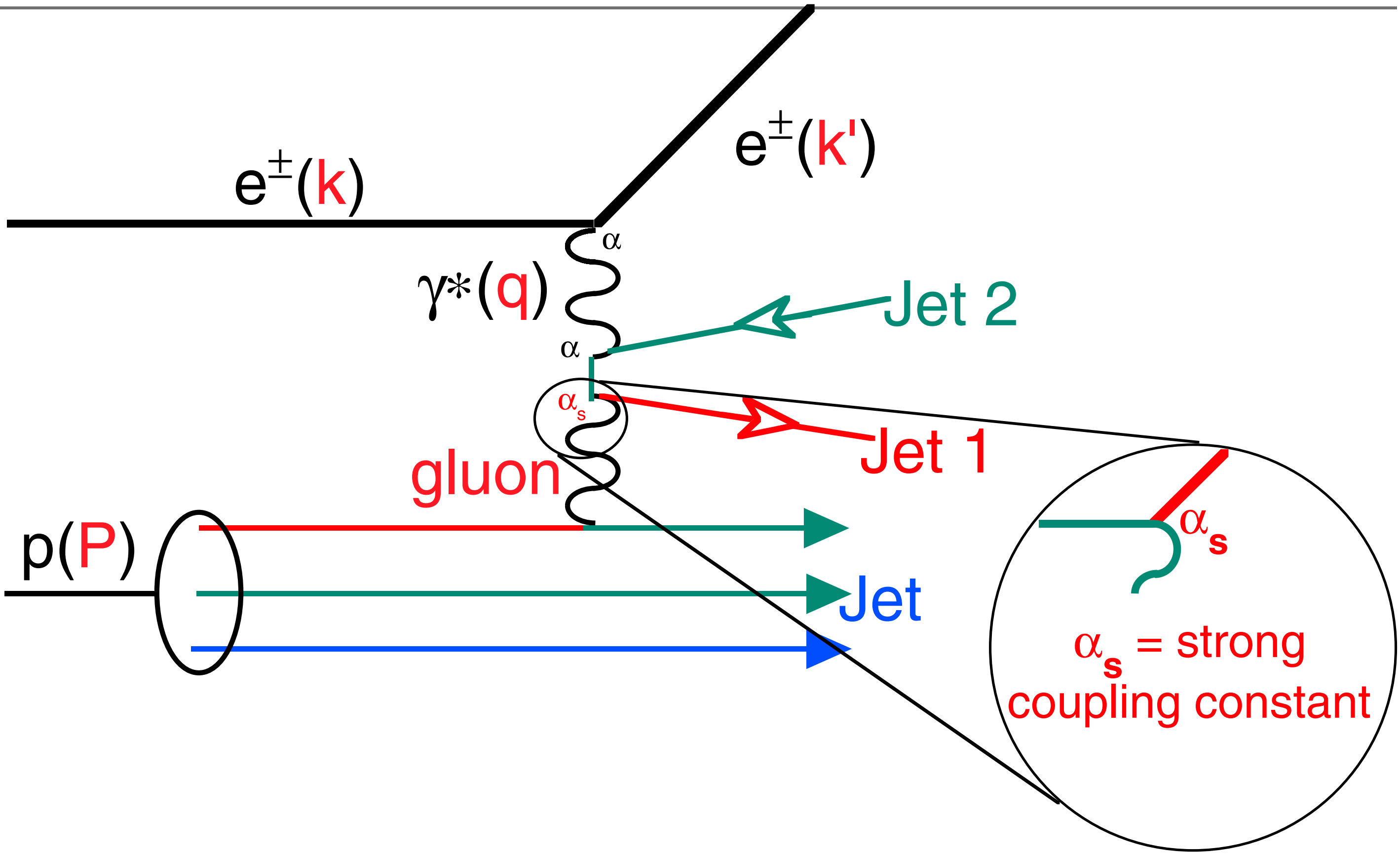
$$F_L = \frac{\alpha_s(Q^2)x^2}{2\pi}\int_x^1 \frac{dz}{z^3}\,\frac{8}{3}\,F_2(z,Q^2) + 4\Sigma e_q^{\,2}(1-x/z)\;xg(z,Q^2)$$

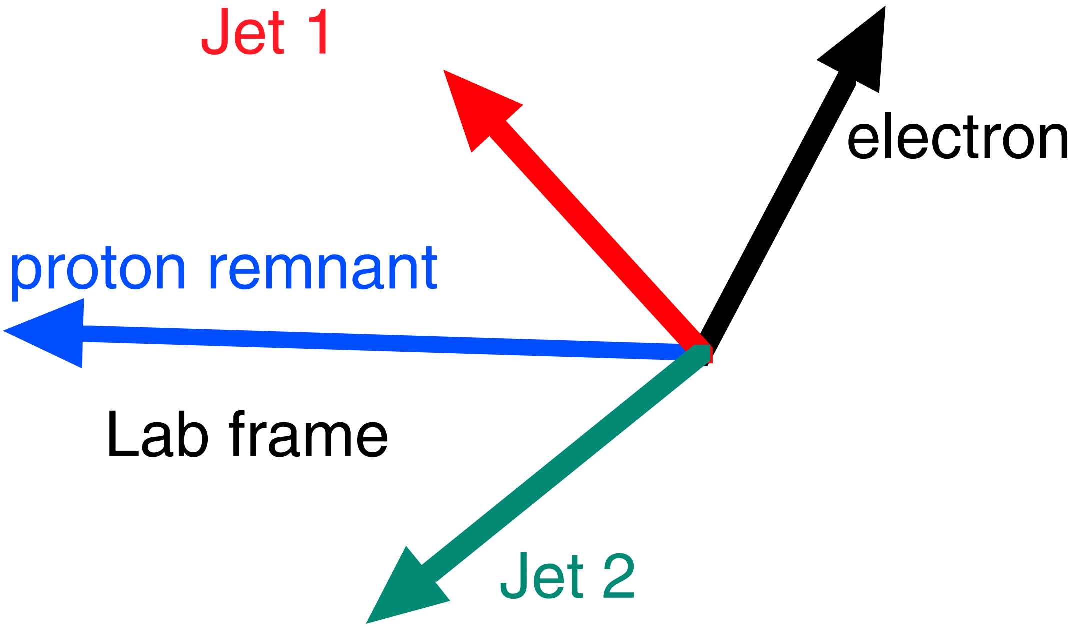
$$F_2(x,Q^2) = x\sum_i e_i^2\, q_i(x,Q^2)$$

Extraction of F_2 requires knowledge of F_L.

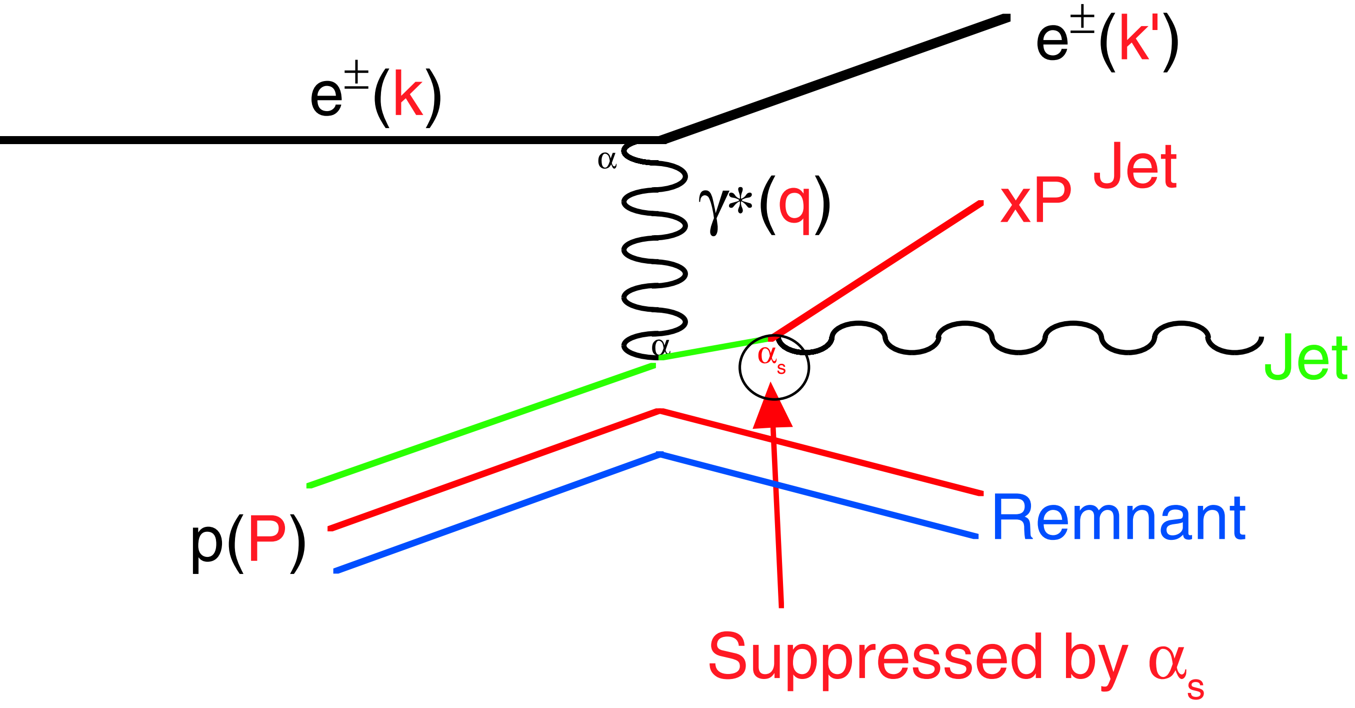
The existing measurements use these QCD inspired calculations of F_L to obtain F_2.

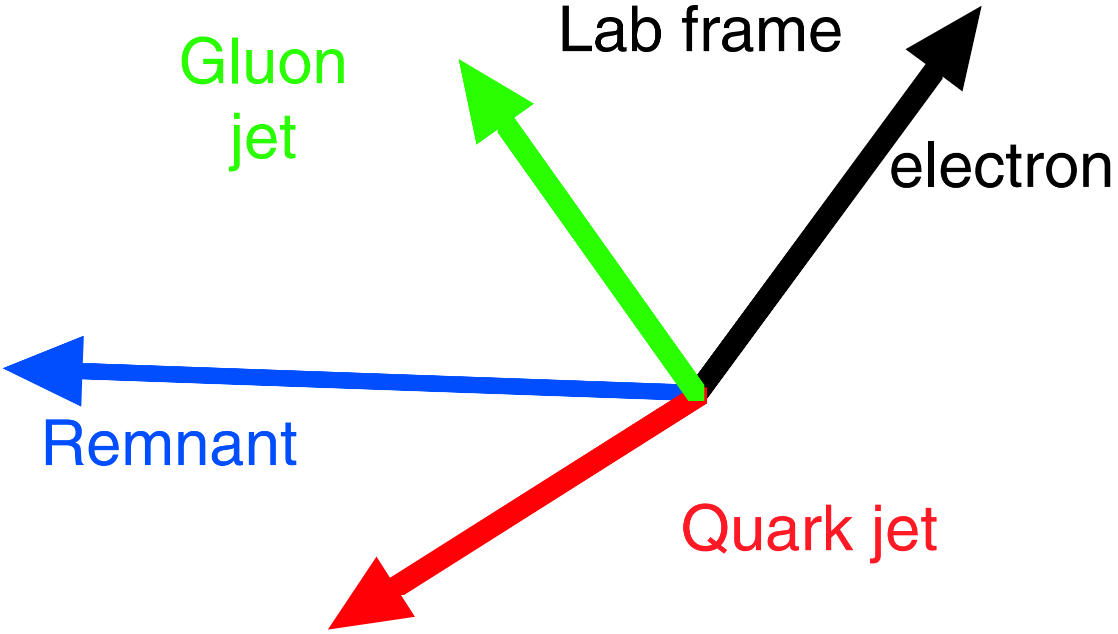
Boson Gluon fusion





QCD Compton


$e^{\pm}(k)$
$e^{\pm}(k')$
α
$\gamma^{*}(q)$
xP
Jet
α
α_s
Jet
p(P)
Remnant
Suppressed by α_s

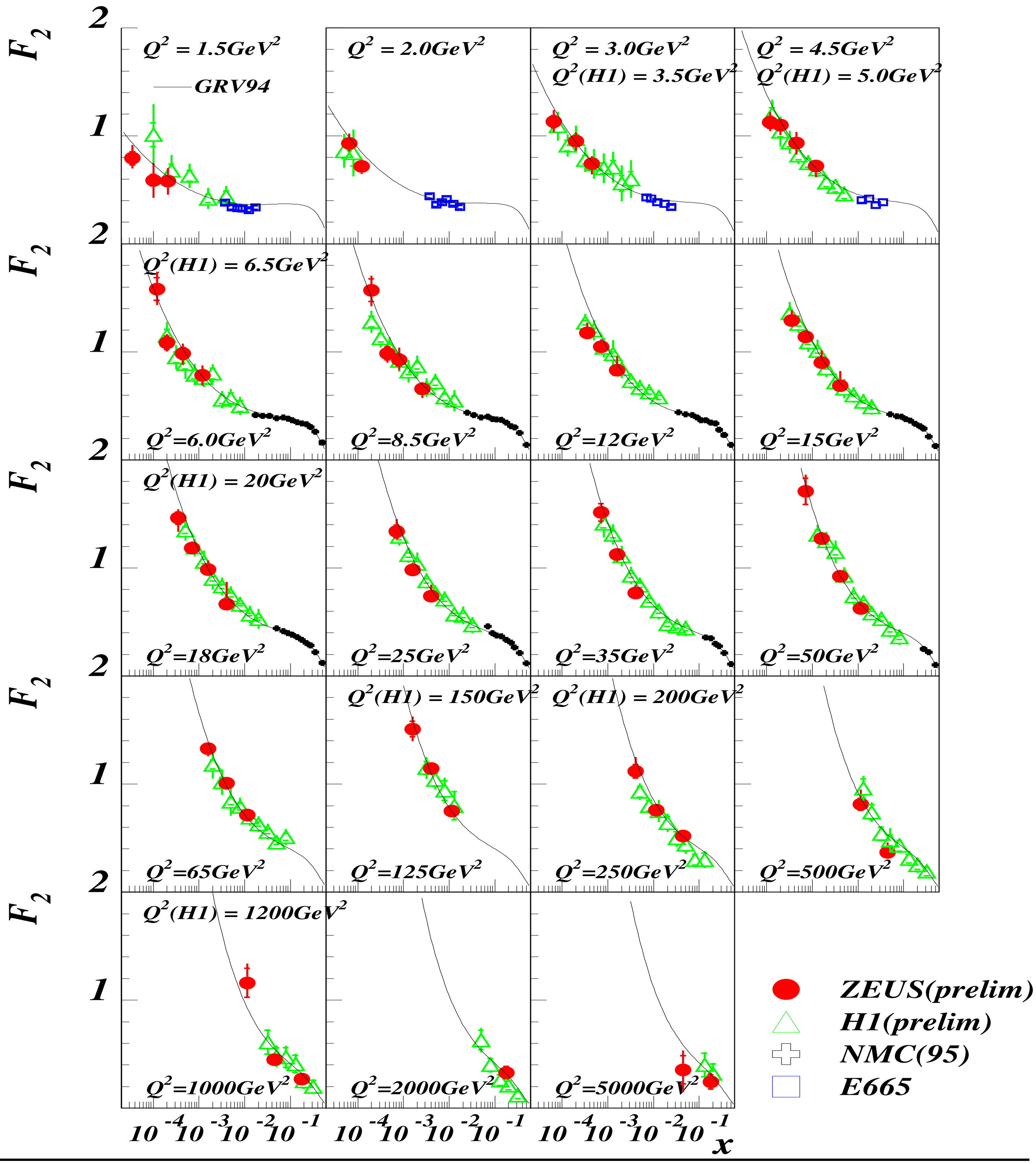

Lab frame
Gluon jet
electron
Remnant
Quark jet

Extracting F_2

- Bin data in x, Q^2
- Subtract background
- Cross section multiplied by QCD F_L calculation using existing parameterizations of $q(x,Q^2)$ and $G(x,Q^2)$
- Acceptance estimated from Monte Carlo
- F_2 unfolded iteratively until MC matches data
- Estimate Systematic Error

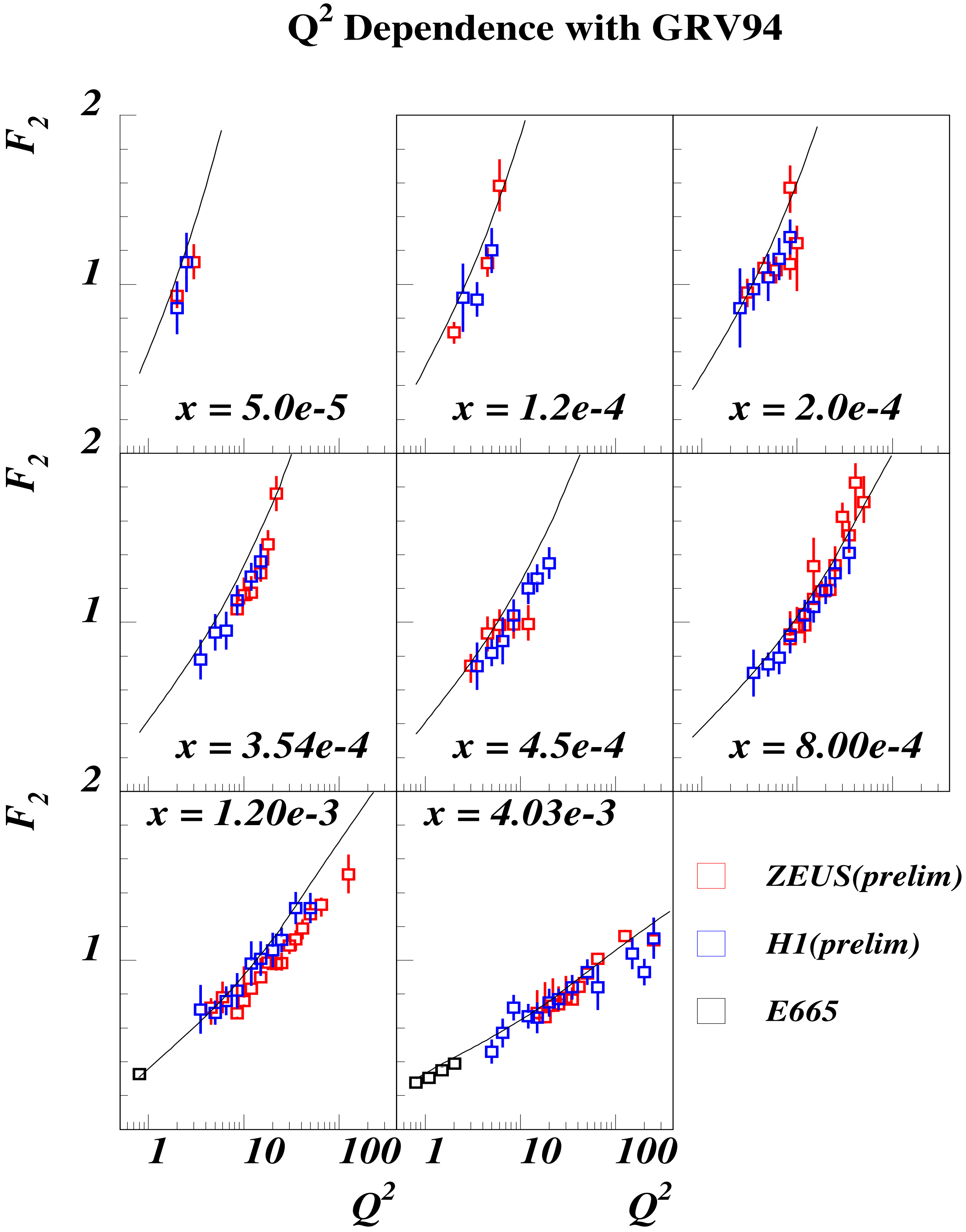
F_2 results - increase at low x!

- GRV94 PDF - $xq(x,Q^2)$ -> 0 as x ->0



Scaling Violations

- Slope gets steeper as x decreases



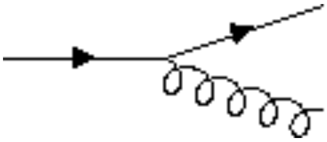
Extracting gluon Density

- $G(x,Q^2) = xg(x,Q^2)$ from $dF_2(x,Q^2)/d\ln Q^2$
- QCD interactions $\propto \ln(Q^2)$
- Given by DGLAP equations (LO) QCD
  - DGLAP - Dokshitzer-Gribov-Lipatov-Altarelli-Parisi

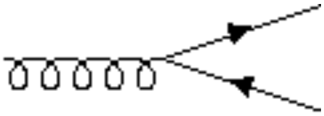
$$\frac{dF_2(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\left[\int_x^1 \frac{dy}{y} P_{qq}\left(\frac{x}{y}\right) F_2(y,Q^2) + 2\sum_f e_f \int_x^1 \frac{dy}{y}\left(\frac{x}{y}\right) P_{qg}\left(\frac{x}{y}\right) yg(y,Q^2)\right]$$

Splitting functions

P_{qq}



P_{qg}

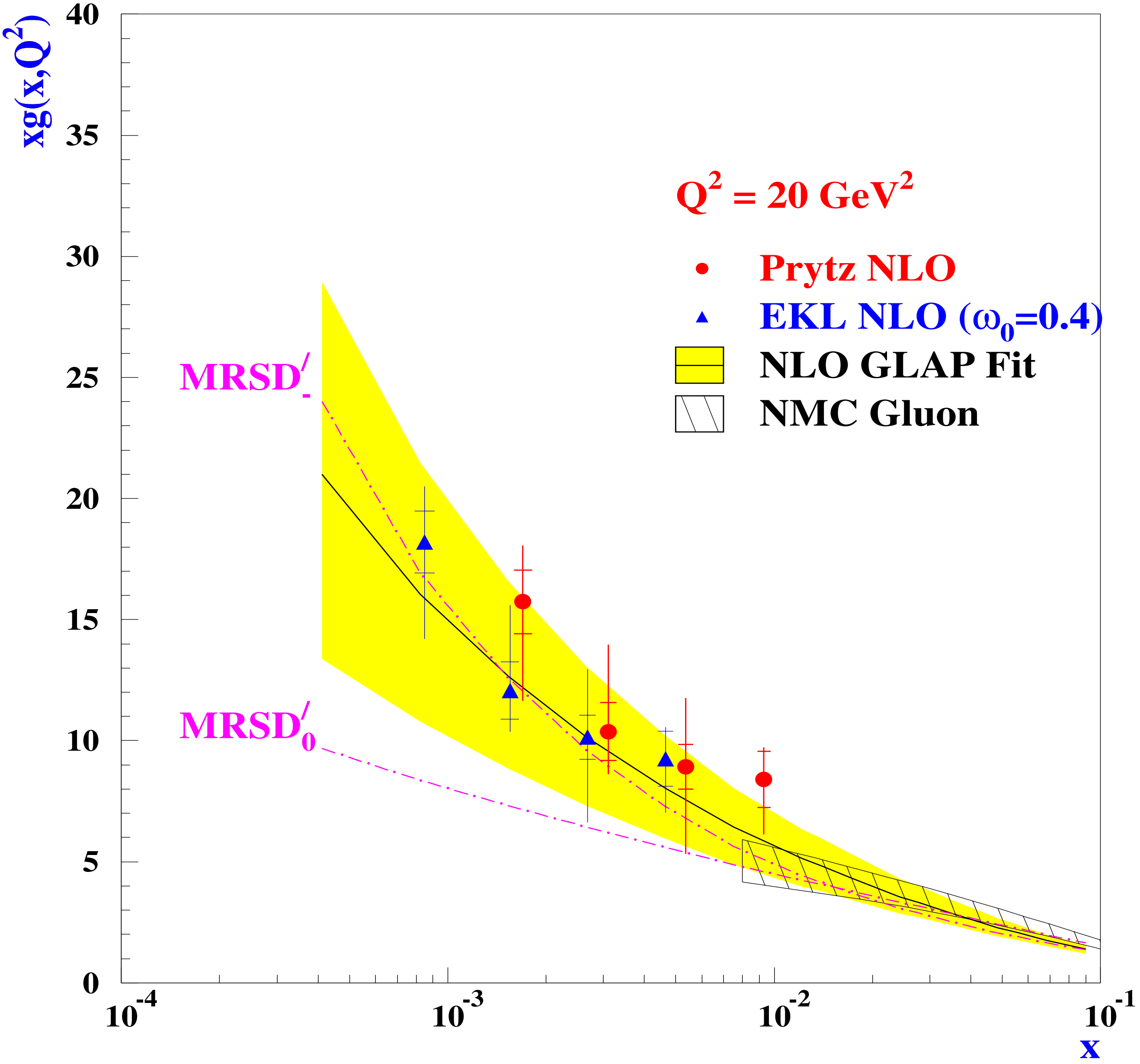


- Prytz method:
  - Neglect quark term (P_{qq})
  - Approximate $G(x,Q^2)$ –

$$\frac{dF_2(\frac{x}{2},Q^2)}{d\ln Q^2} \approx \frac{10\alpha_s(Q^2)}{27\pi} G(x,Q^2)$$

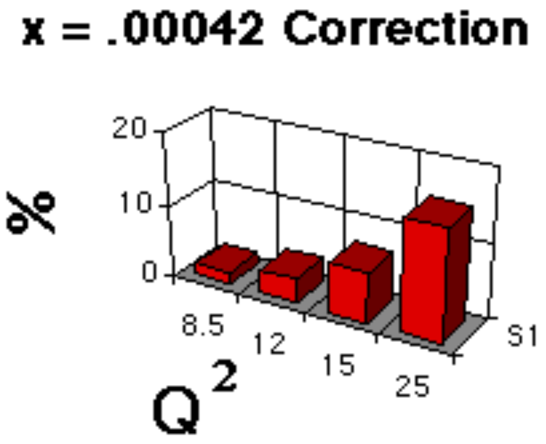
- Ellis-Kunszt-Levin (EKL) method:
  - solution to DGLAP equations in momentum space
  - include quark term
  - **assume** functional form of $x^{-\omega_o}$ for F_2 and G
  - predict ω_o of $G(x,Q^2)$

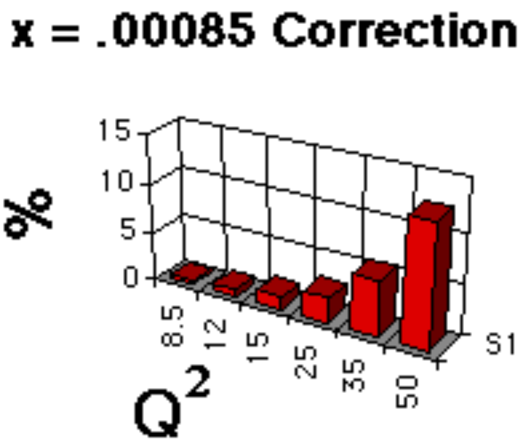
Gluon distribution

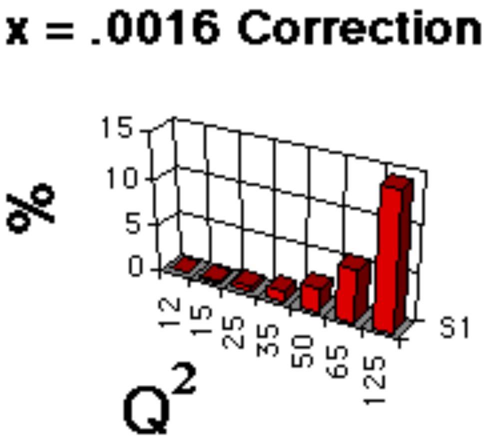


- MRSD'_{-} - singular gluon distribution
- MRSD'_{0} - constant gluon distribution
- $\alpha_s = .203 \pm .010$ at $Q^2 = 20$ GeV^2
- DGLAP fit - $x^{-.33}$

F_L Correction to 1993 Data


x = .00042 Correction

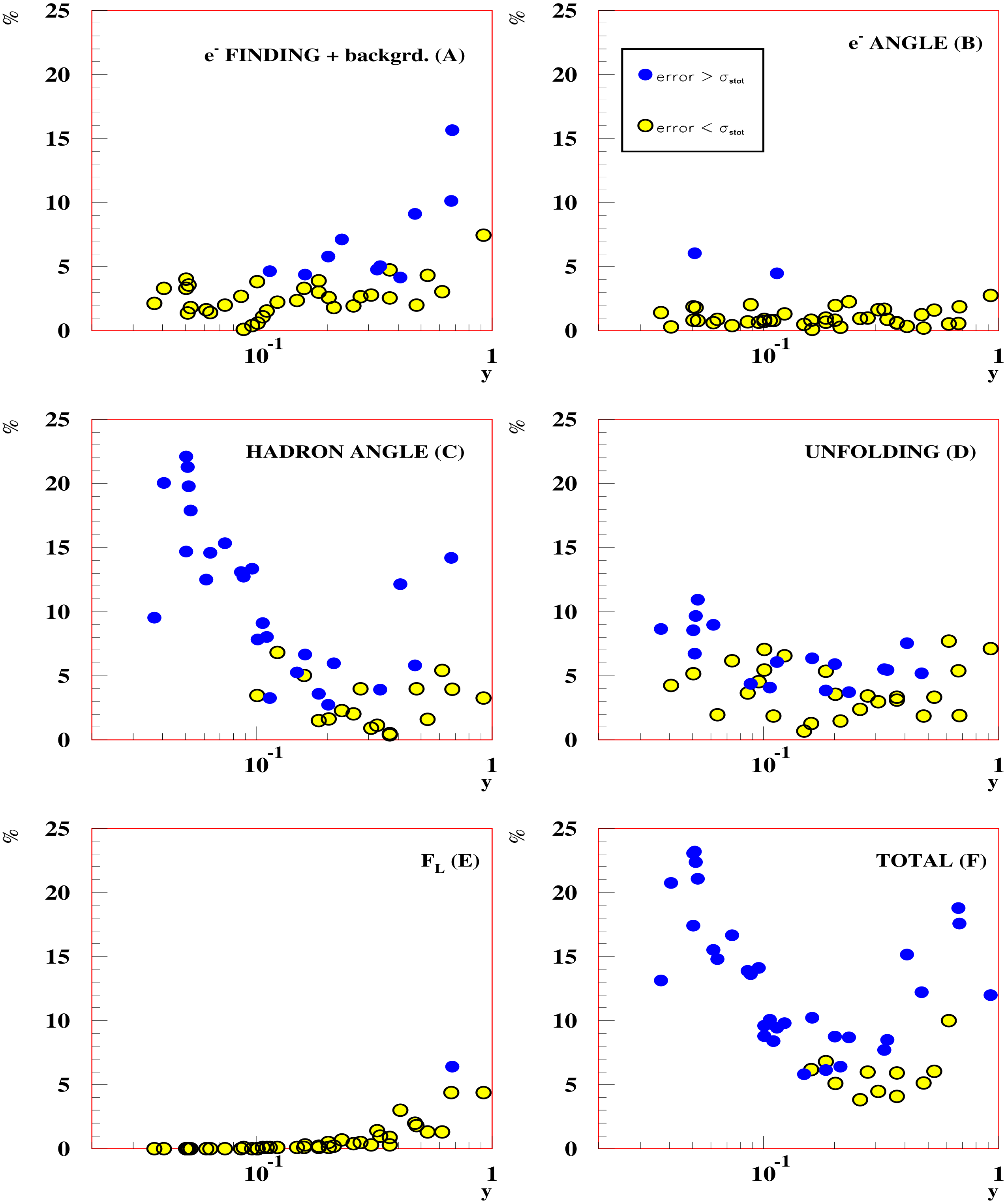

x = .00085 Correction


x = .0016 Correction

- Estimated F_L correction is large for low x.
- Statistical uncertainty will be ~1% by 1995.
- Systematic uncertainty from other sources dominate published 1993 data.
- In the future, dominant uncertainty will be due to F_L.

Systematic uncertainty of F_2

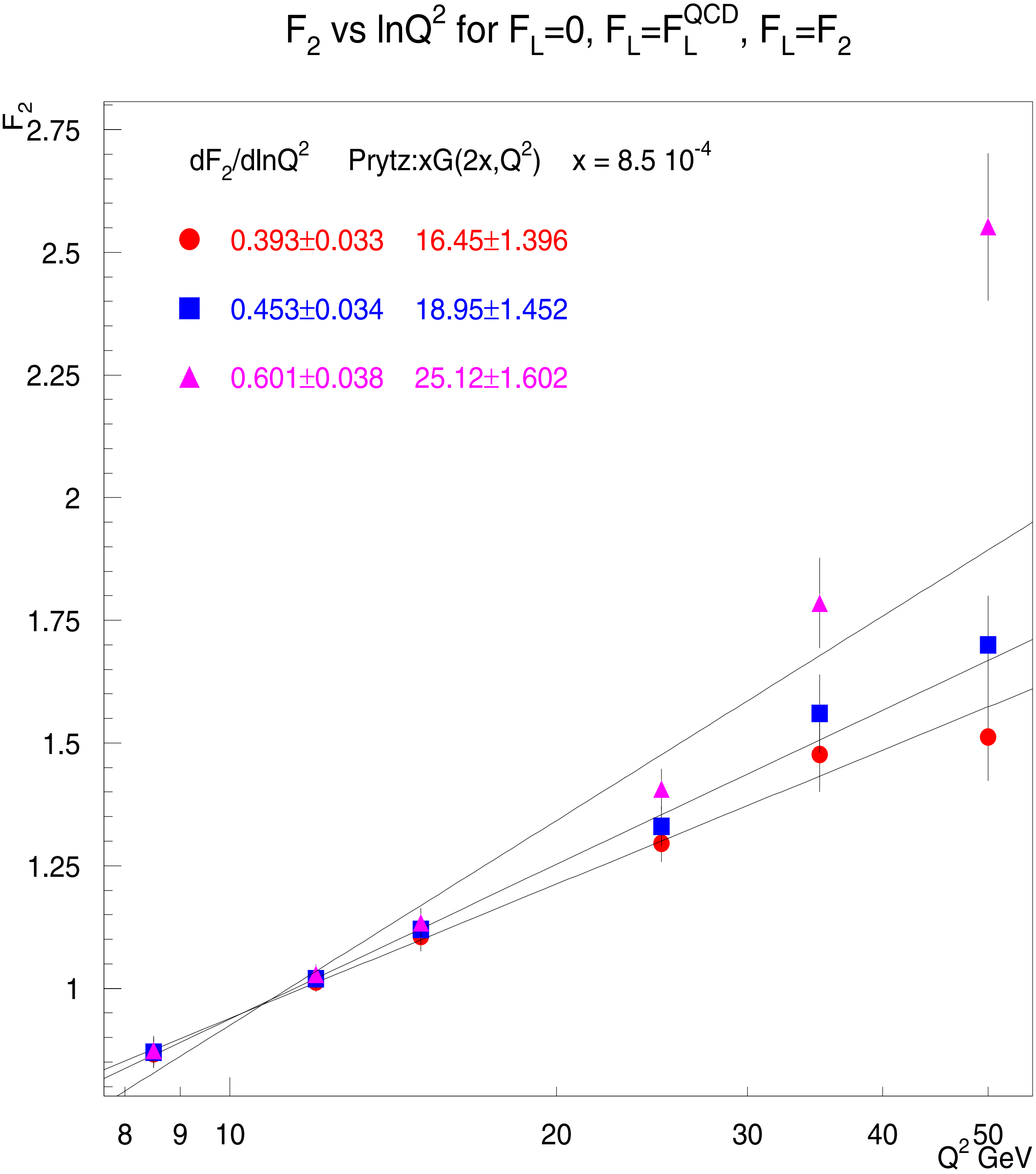
• 1993 systematics



Systematic Uncertainties

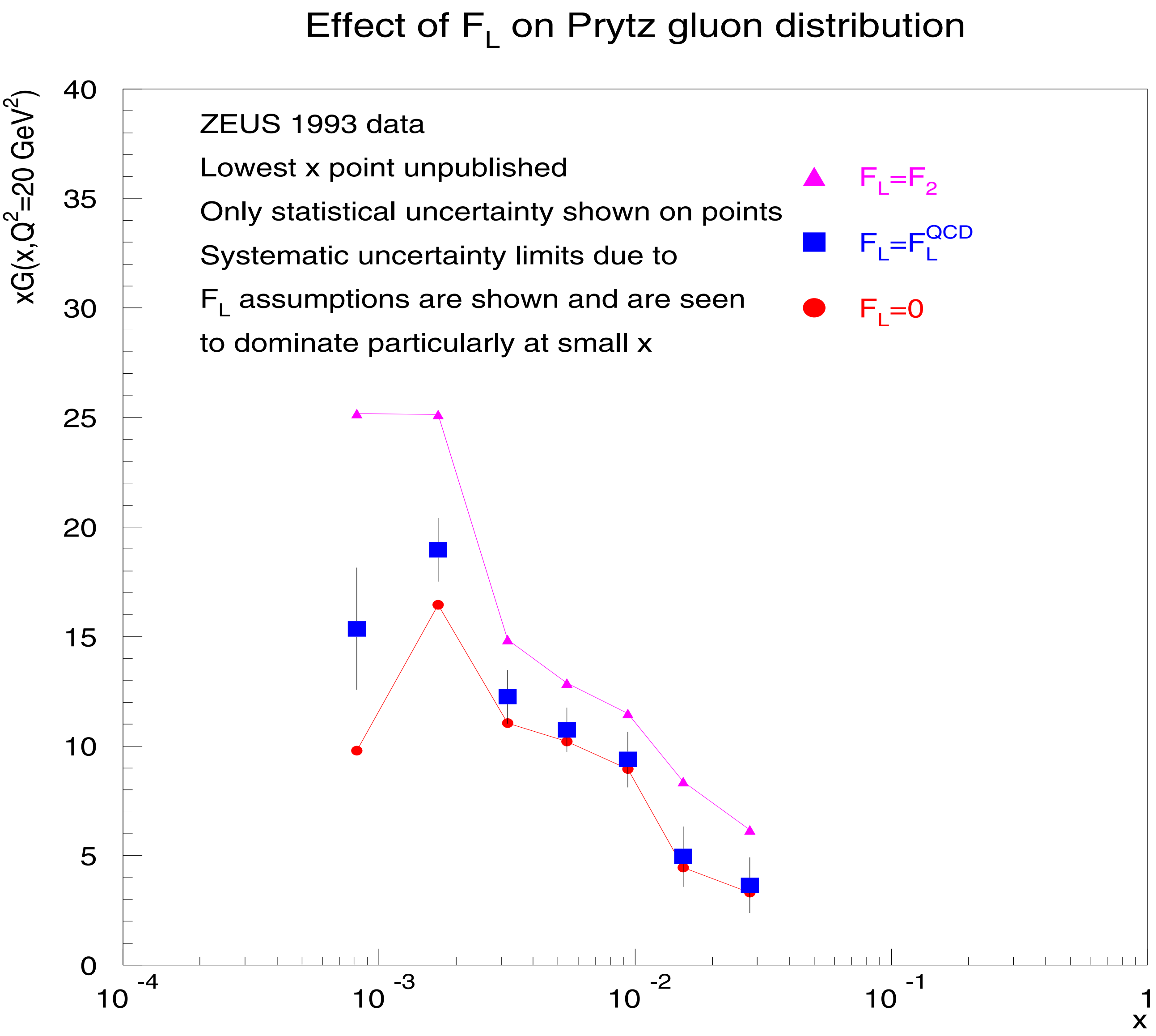
- Better electron finder reduces background while improving efficiency.
- New detectors improve acceptance, position and energy resolution making electron method more viable.
- Hadron variable uncertainty is removed by using electron method.
- Radiative correction and other unfolding uncertainties will improve by iterating with measured F_2.
- So, systematic error in high y bins will reduce substantially due to all causes except F_L.

Uncertainty in F_2 slope due to F_L



- Slopes in F_2 vs $\ln Q^2$ enable measurement of gluon.

Effect of F_L on gluon distribution



ZEUS 1993 data
Lowest x point unpublished
Only statistical uncertainty shown on points
Systematic uncertainty limits due to
F_L assumptions are shown and are seen
to dominate particularly at small x

$$R \approx F_L / (F_2 - F_L)$$

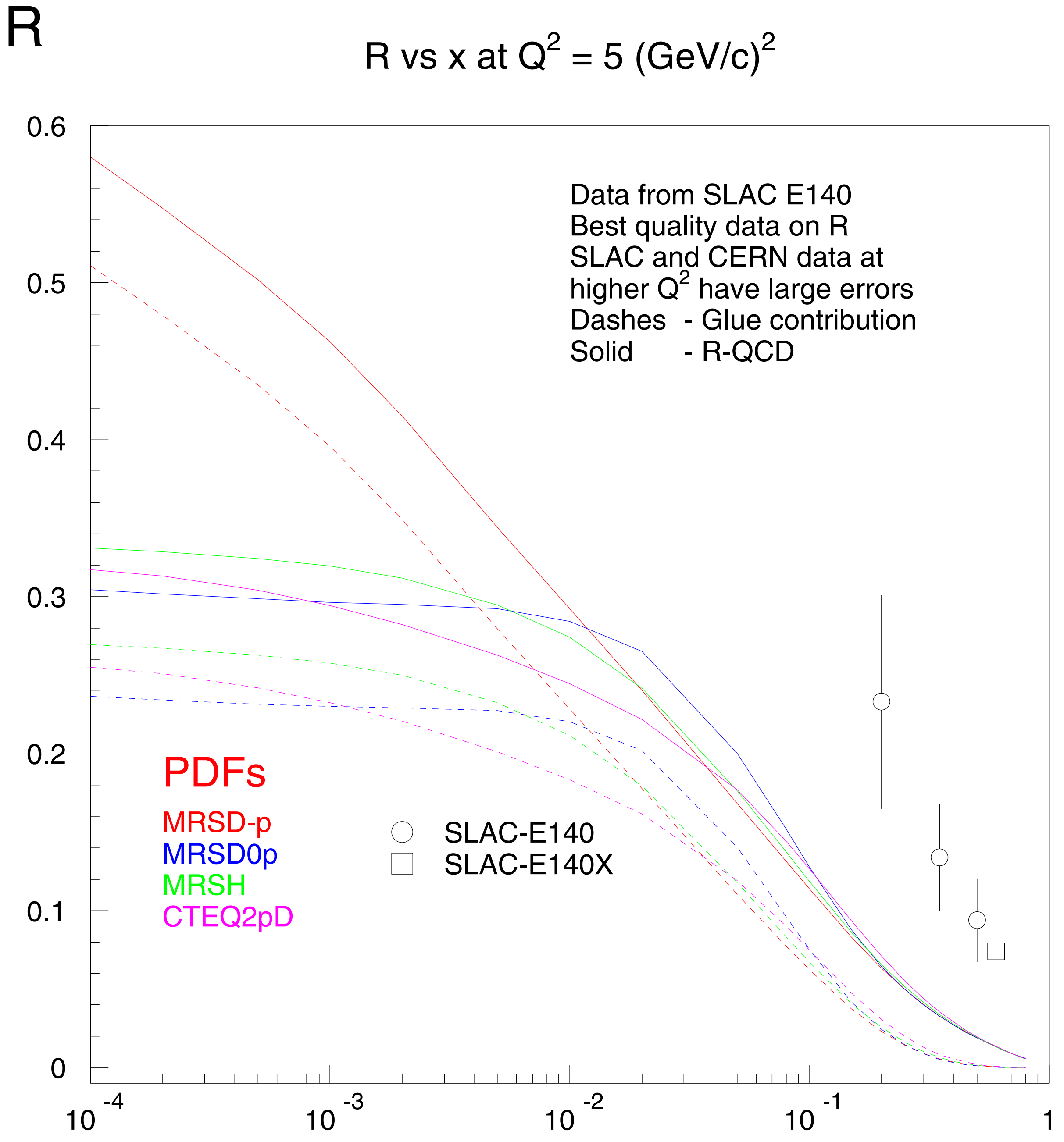
- Lack of knowledge of R dominates the systematic uncertainty in $xG(x,Q^2)$.
- In Prytz's method, illustrated here, one can tune the central values by varying the input gluon distribution which constrains the $R(x,Q^2)$.
- QCD analysis, using $d^2\sigma/dxdQ^2$, i.e., fitting quark and gluon simultaneously, assumes that F_L is calculable.

Past F_2 & F_L measurements

- Fixed target
- F_L - SLAC electron beam - 4-20 GeV
- F_2 -
  - CERN
    - BCDMS EMC NMC SMC - muon beam - 100-280 GeV
    - Minimum x of .05 at $Q^2 = 20$ GeV^2
    - CDHSW CHARM - neutrino beam - 100-280 GeV
  - FNAL
    - CCFR - 30-600 GeV
    - E665 - 490 GeV
    - Minimum x of .02 at $Q^2 = 20$ GeV^2
  - $10^{-2} < x < .9$
  - $.1 < Q^2 < 200$ GeV^2
- ZEUS
  - $10^{-5} < x < .1$
  - $1 < Q^2 < 5000$ GeV^2
- F_L not verified in ZEUS kinematic range.
- Where F_L is best measured QCD prediction does not explain the data

Data and QCD fits at Q^2=5 GeV^2

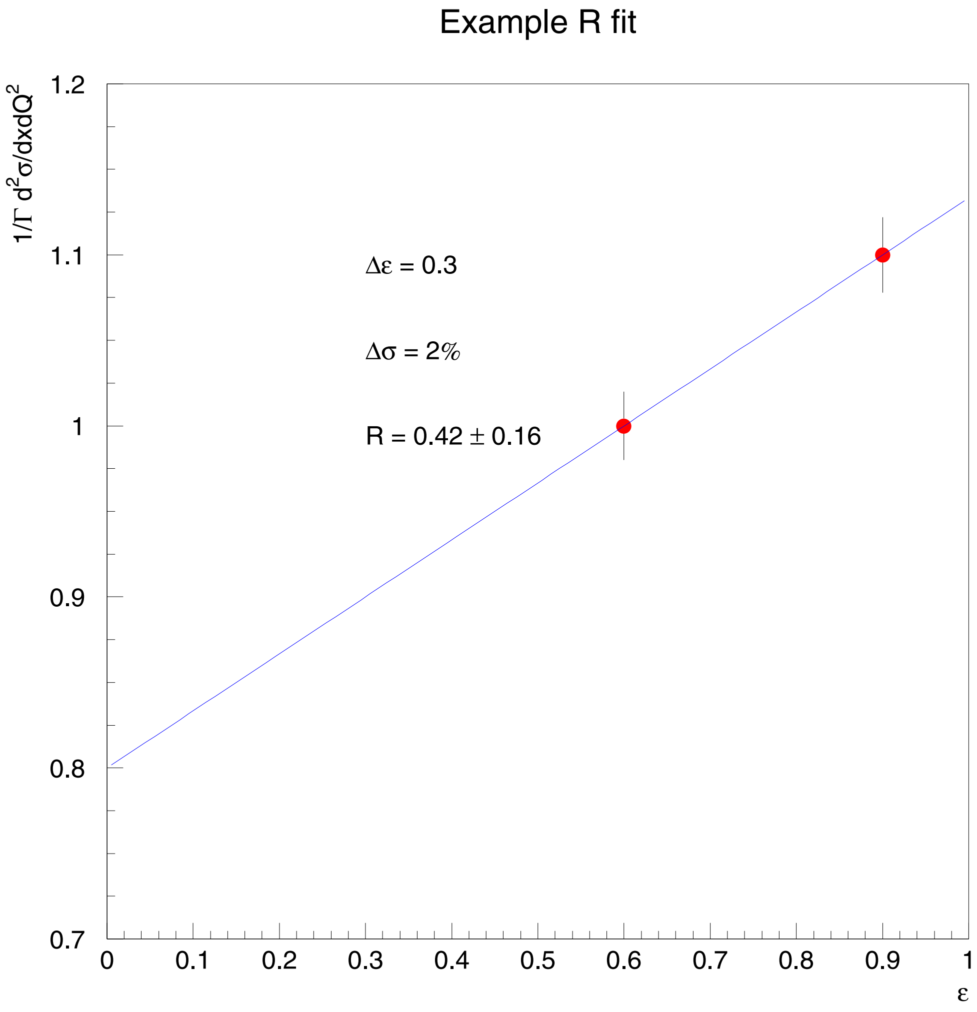
- How good is F_L calculation in ZEUS $x < 10^{-3}$ range?



$R \approx F_L / (F_2 - F_L)$

R is not well understood in ZEUS kinematic region

ZEUS F_L measurement method



$$\frac{1}{\Gamma}\frac{d^2\sigma}{dxdQ^2} = [\sigma_T(x,Q^2) + \varepsilon\,\sigma_L(x,Q^2)](1+\delta_r)$$

$$R = \sigma_L / \sigma_T \approx F_L / (F_2 - F_L)$$

$\varepsilon \approx (1 - y) / (1 - y + y^2/2)$

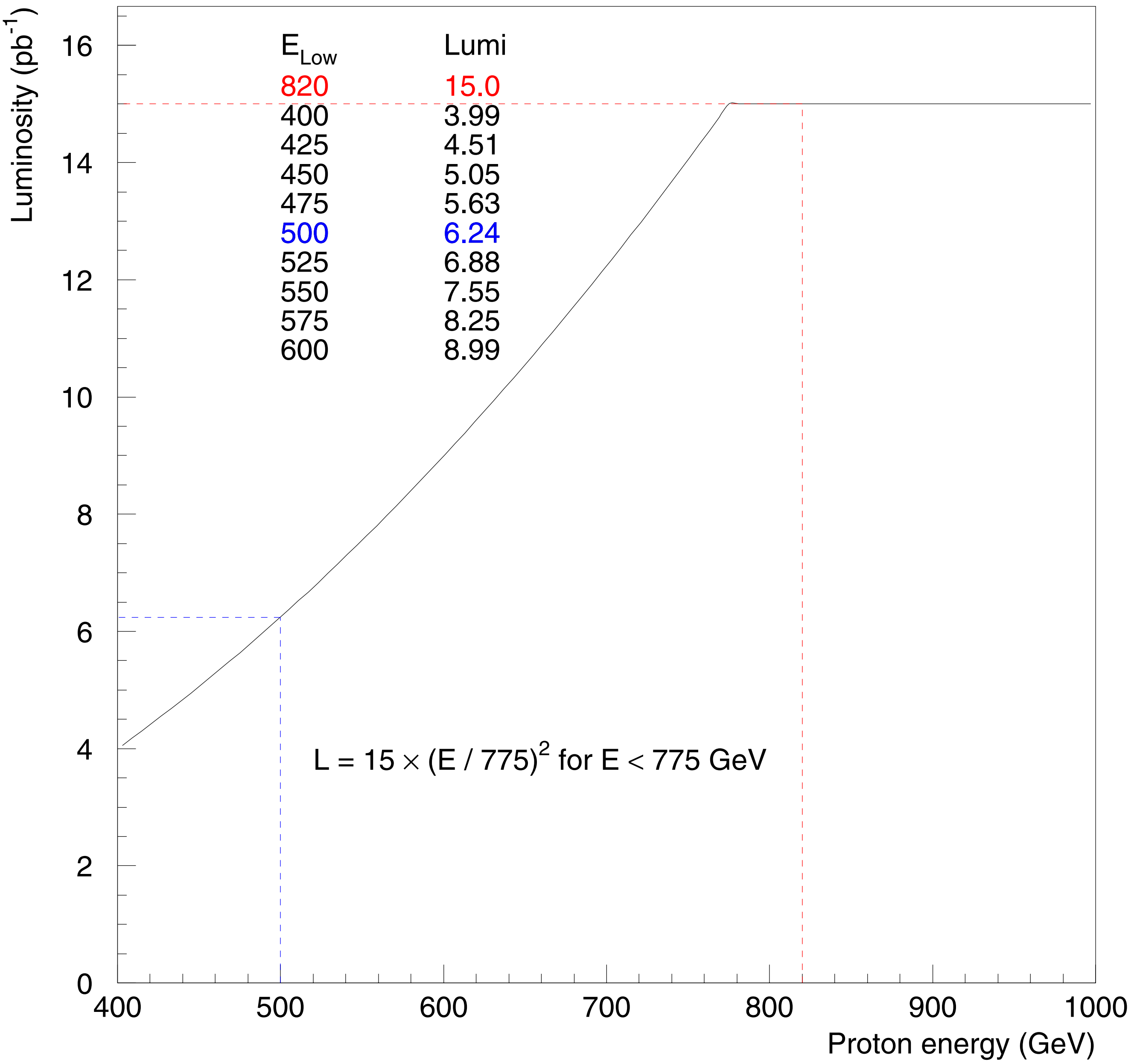
ε is the polarization of the virtual photon

- Measure $d\sigma/dxdQ^2$ in same x,Q^2 bins at two different values of $s \to Q^2 = sxy$
- Straight line fit yields R = slope/intercept
- To measure R = 0 ± 0.1 requires measuring cross section to 3% with ε separation of 0.3

F_L Experimental issues

- Must change s to get F_L
  - Luminosity is lower at lower √s
  - Conflicts with other measurements/searches
- Lower electron or proton beam energy
  - At lower electron energies, electron ID is more difficult
  - Photoproduction background - same as at high proton beam energy
  - Electron and proton energies are still being optimized, but if other systematic errors remain at 5% either choice is fine.
- Best points for gluon density are at high y - low electron energy
  - Look most like photoproduction
  - Low transverse energy - hard to id

Variation of luminosity with energy



Luminosity vs machine energy

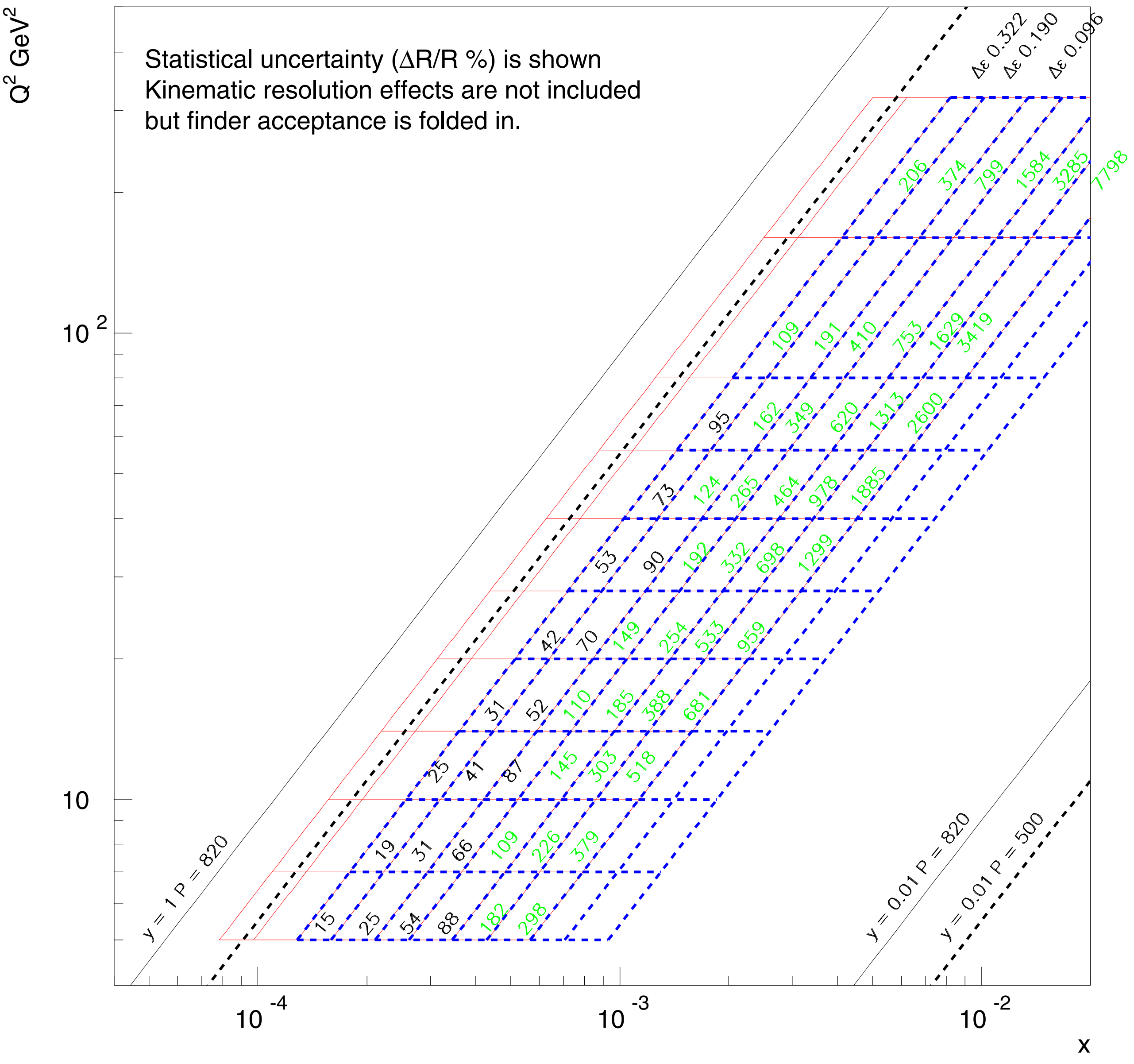
E_{Low}	Lumi
820	15.0
400	3.99
425	4.51
450	5.05
475	5.63
500	6.24
525	6.88
550	7.55
575	8.25
600	8.99

$L = 15 \times (E / 775)^2$ for $E < 775$ GeV

- HERA tuned to run best at 30/820
- 15 pb^{-1} nominal - 5 pb^{-1} lower
- 500 GeV run will give a third as much data

Lowering proton energy

Statistical uncertainty in R at P = 820, 500 GeV for L = 15, 5 pb^{-1}



Statistical uncertainty (ΔR/R %) is shown
Kinematic resolution effects are not included
but finder acceptance is folded in.

- Binning chosen to ensure 100 % overlap at two energy settings
- Maximizes ε reach and acceptance

Conclusions

- ZEUS can measure a new kinematic range of x, Q^2
- F_L error to F_2 is large in low x, Q^2 range
- F_2 can be used extract the gluon distribution
    - Low x, Q^2 range is most sensitive to gluon distribution
    - F_L measurement will test constant vs singular gluon models
- We can measure F_L by changing √s (center of mass energy) and measuring the cross section at the same x, Q^2 points as old √s
- Lowering proton or electron energy to make an F_L measurement will reduce our F_2 and gluon errors