Measurement of the Proton F_2 Structure Function from 1996 and 1997 ZEUS data

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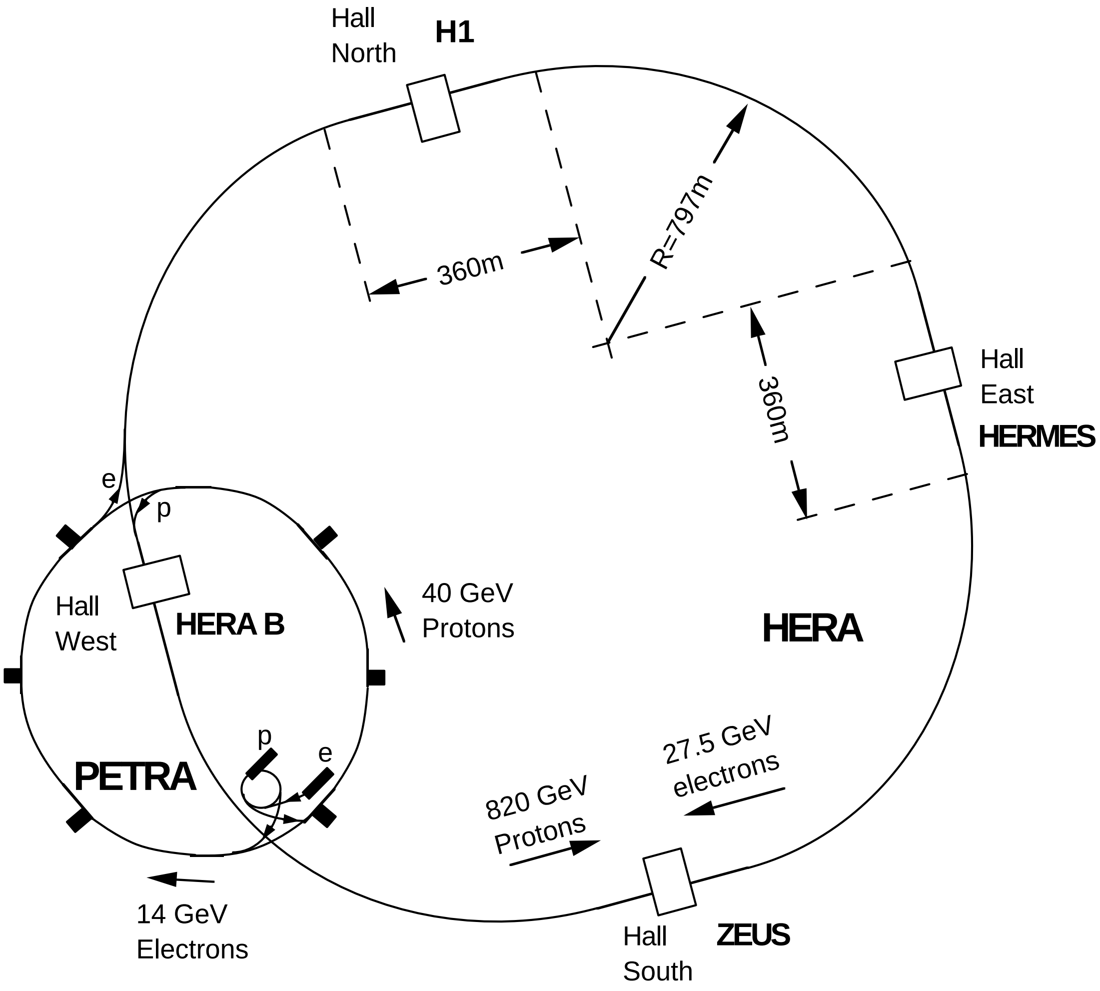
November 30, 1999

- HERA and ZEUS
- Kinematic Variables and Structure Functions
- F_2 History
- ZEUS Events
- F_2 Analysis Challenges
  - Electron Energy Angle
  - Vertex
  - Hadronic System
- F_2 Binning & Unfolding
- F_2 Result
- Conclusions

HERA



- Fixed Target C.O.M. energy (Max ~35 GeV)

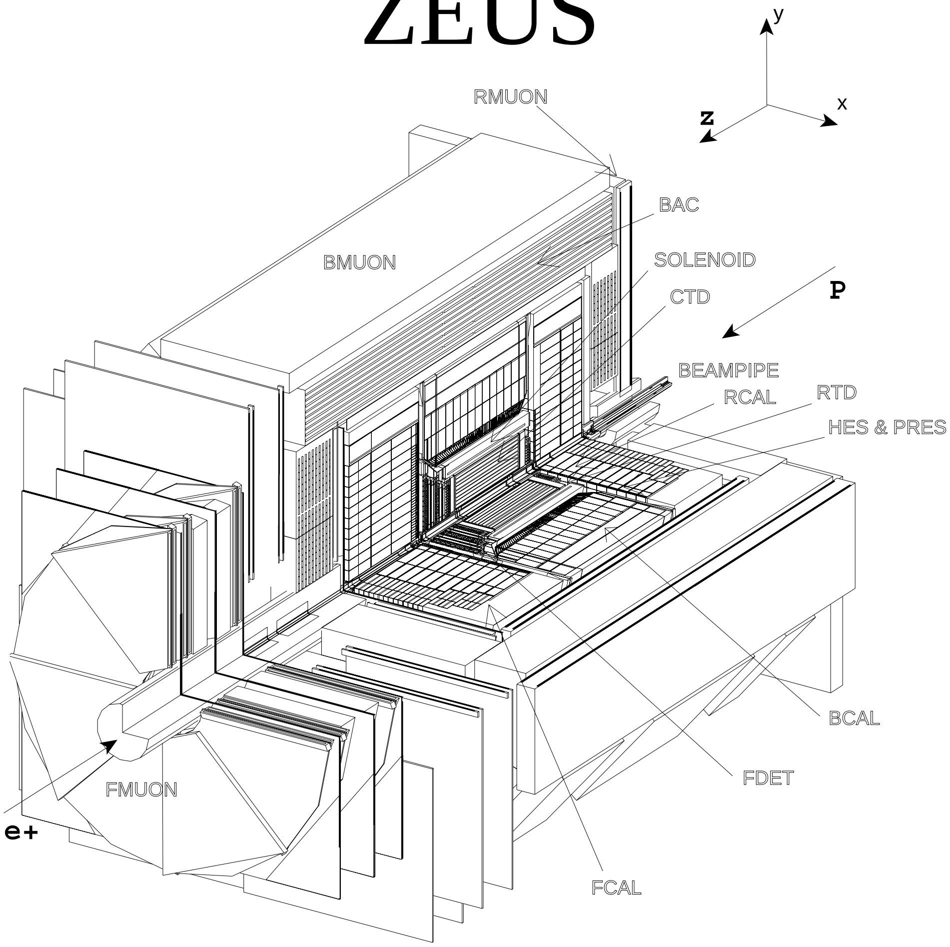
$$\sqrt{s} = \sqrt{2 * M_P * E_{beam}}$$

- HERA

$$\sqrt{s} = \sqrt{4 * E_{Beam} * P_{Beam}} = 300\ GeV$$

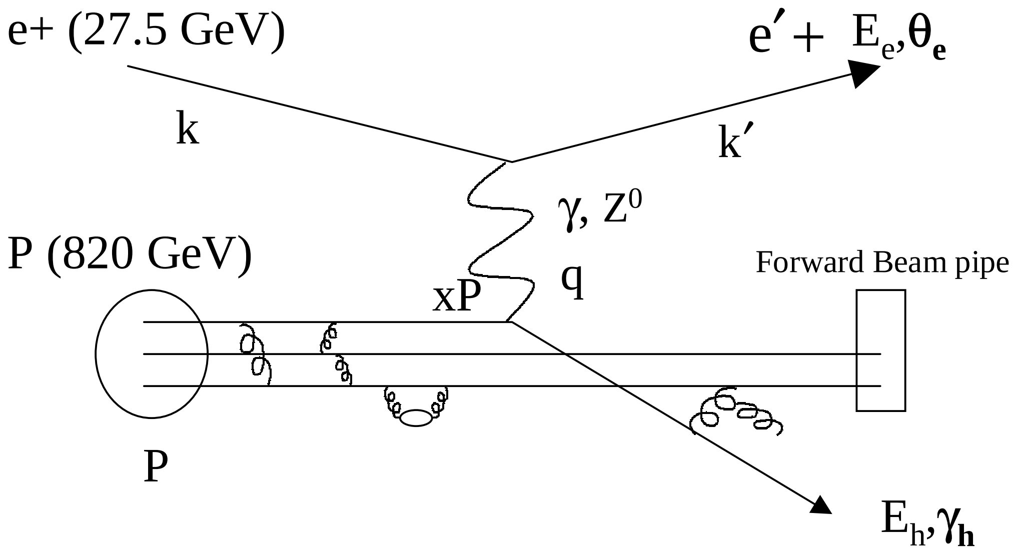
  - Equivalent to a 48 TeV Fixed Target experiment
  - Boosted C.O.M. in the proton direction

ZEUS



- Calorimeter
  - Rear, Barrel, Forward Calorimeters
  - Longitudinal segmentation (Electro-magnetic, Hadronic separation)
  - Transverse segmentation (Particle location)
- Central Tracking Detector (CTD)
  - Drift chamber (9 cylindrical layers, 8 sense wires per layer)
  - Inside a 1.4 T magnetic field
- Presampler / SRTD
  - Scintillator strips at the face of the rear calorimeter counting charged particles.

Kinematic Variables



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

Inverse scale at which the proton is probed

$$\lambda \approx \frac{2xM_P}{Q^2}$$

Virtual photon wavelength λ

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

Fraction of proton’s momentum carried by struck quark

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

Fraction of electron’s momentum transferred by the photon in the proton’s rest frame

- Only 2 independent variables

$$sxy = Q^2$$

Center of mass energy = √s

Structure Functions

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

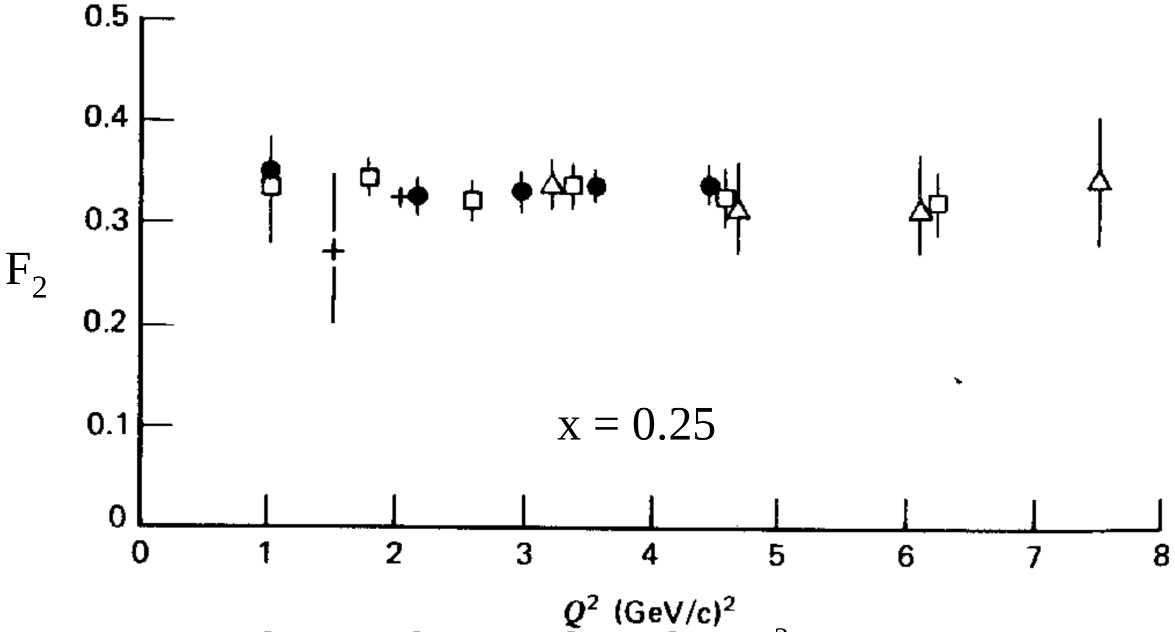
- e^+p cross section, σ, can be written in terms of unit-less structure functions F_2, F_L, xF_3
- Quark Parton Model
  - Proton is made up of quarks (uud..)and gluons

$$F_2(x,Q^2)=\sum_{q}^{quarks}e_q^2x[q(x,Q^2)+\overline{q}(x,Q^2)]$$

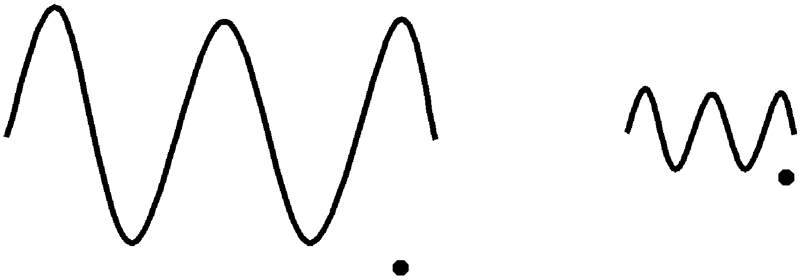
  - F_2 is the contributions of photon-quark interactions.
  - F_L is the contributions from photons with longitudinal polarization
    - F_L is 0 in leading order QCD theory
    - Contribution small at low y
  - xF_3 is the electro-weak contribution from Z^0 exchange.
    - Contribution small for $Q^2 << M_Z^2 = 8100\ \text{GeV}^2$

Historical Results

- SLAC (1972) e beam on fixed target p



  - Scaling; F_2 does not depend on Q^2
  - Number of quarks does not depend on $Q^2=1/\lambda$



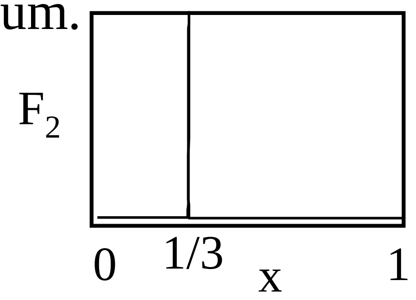
Low Q^2 High Q^2

  - Quarks are point-like objects in the proton

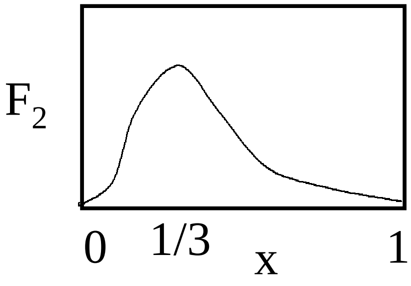
F_2

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

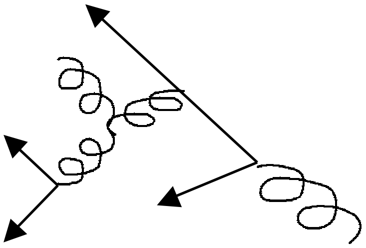
- What might one expect?
  - Proton is only 3 quarks (uud) which equally share the protons momentum.
    - $F_2=0$ except at $x=1/3$

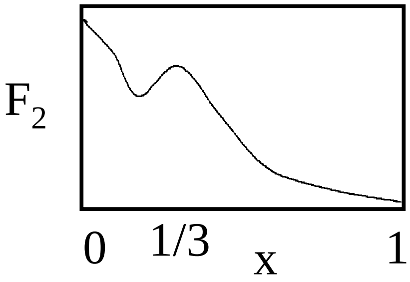


  - 3 quarks exchange momentum via gluons but still carry the full protons momentum



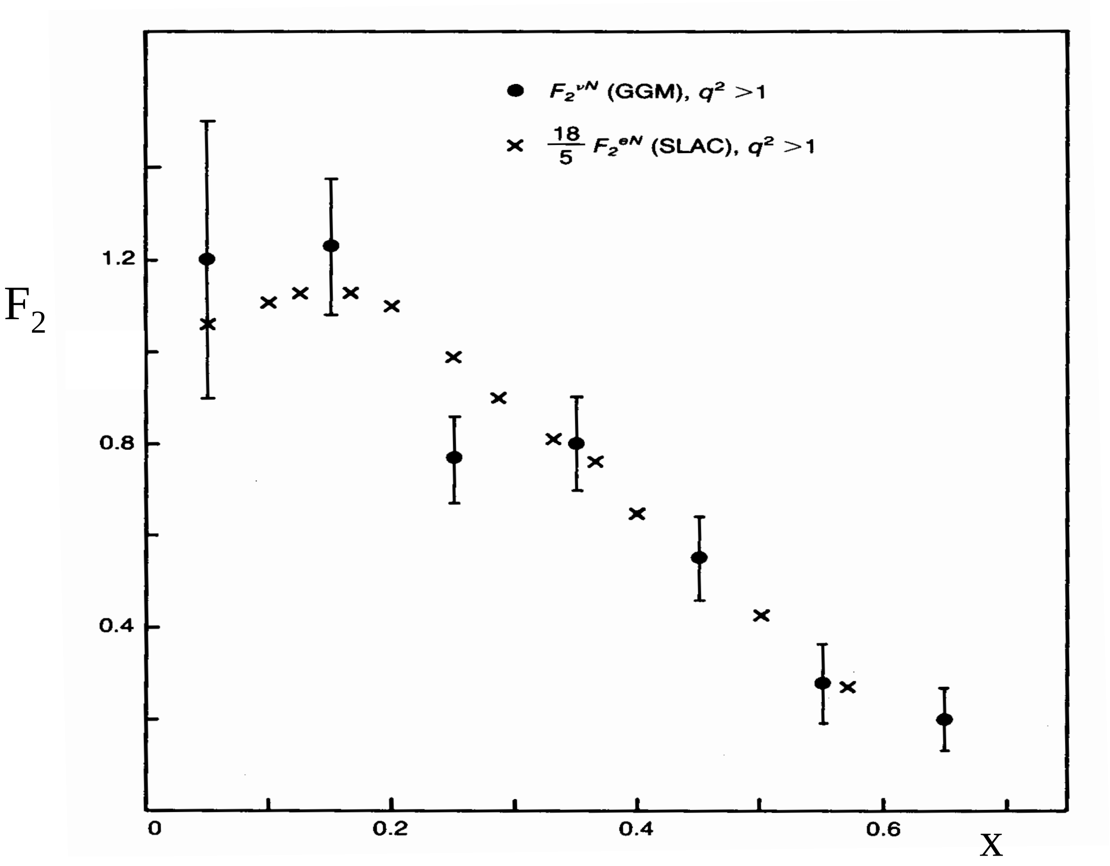
  - 3 quarks + a sea of quarks from pair production from gluons



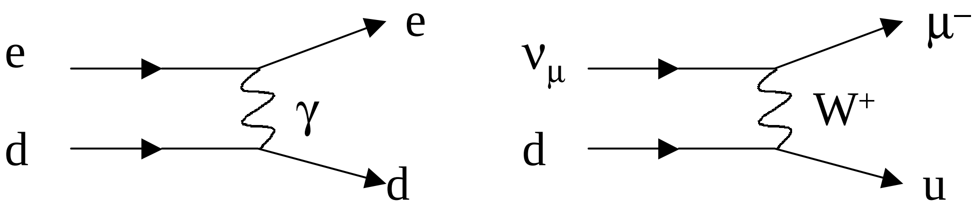


Decreasing x ←

CERN + SLAC



- Comparison of neutrino data and electron data



  - Confirms fractional charges of quarks

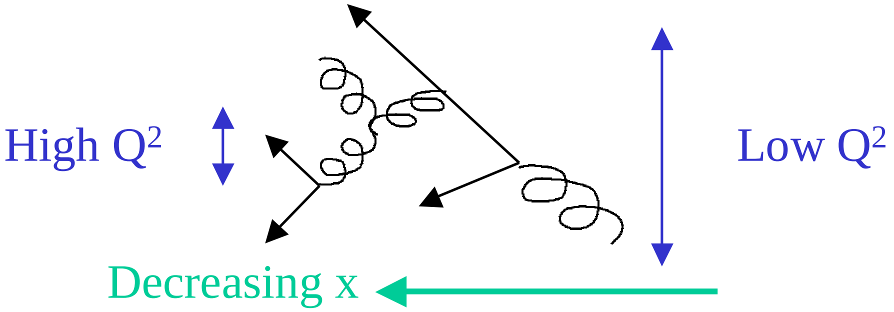
- Integral of quark momenta

$$\int_x F_2^{\nu N}(x)dx = \int_x x[u(x) + d(x) + \bar{u}(x) + \bar{d}(x) + \ldots]dx \approx 0.5$$

  - Only half of proton's momentum!
  - Remainder carried by gluons

DGLAP Evolution

  - Dokshitzer-Gribov-Lipatov-Alterelli-Parisi
- Prediction for the Q^2 evolution of F_2
  - From parton distribution functions at an initial Q^2 it predicts the PDFs at all Q^2

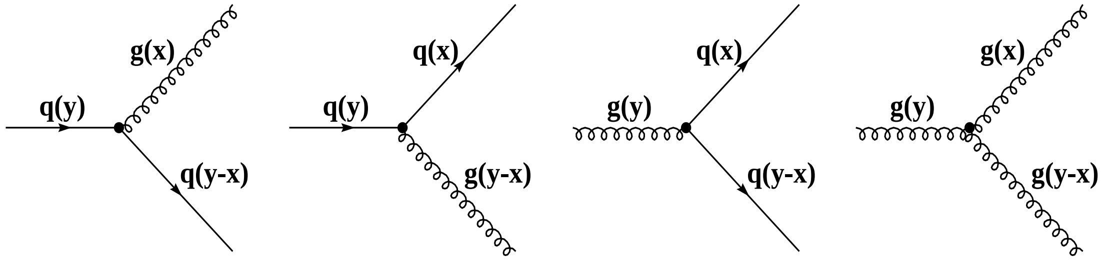


High Q^2

Low Q^2

Decreasing x

  - Uses QCD splitting functions



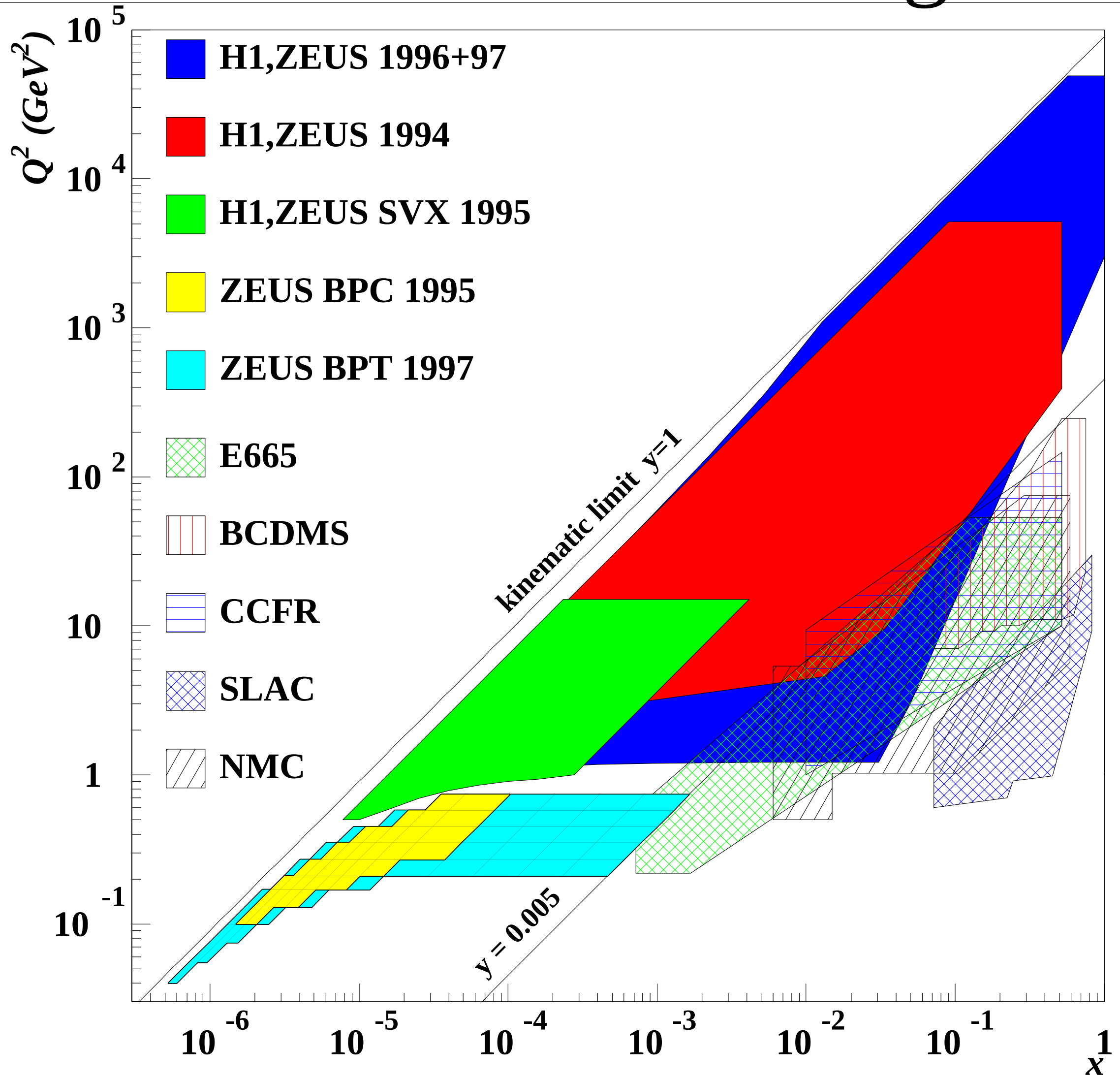
$P_{gq}(z=x/y)$ $P_{qq}(z=x/y)$ $P_{qg}(z=x/y)$ $P_{gg}(z=x/y)$

  - As scale gets smaller (Q2 increases) it is more likely for a parton to split into daughter partons at lower x

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

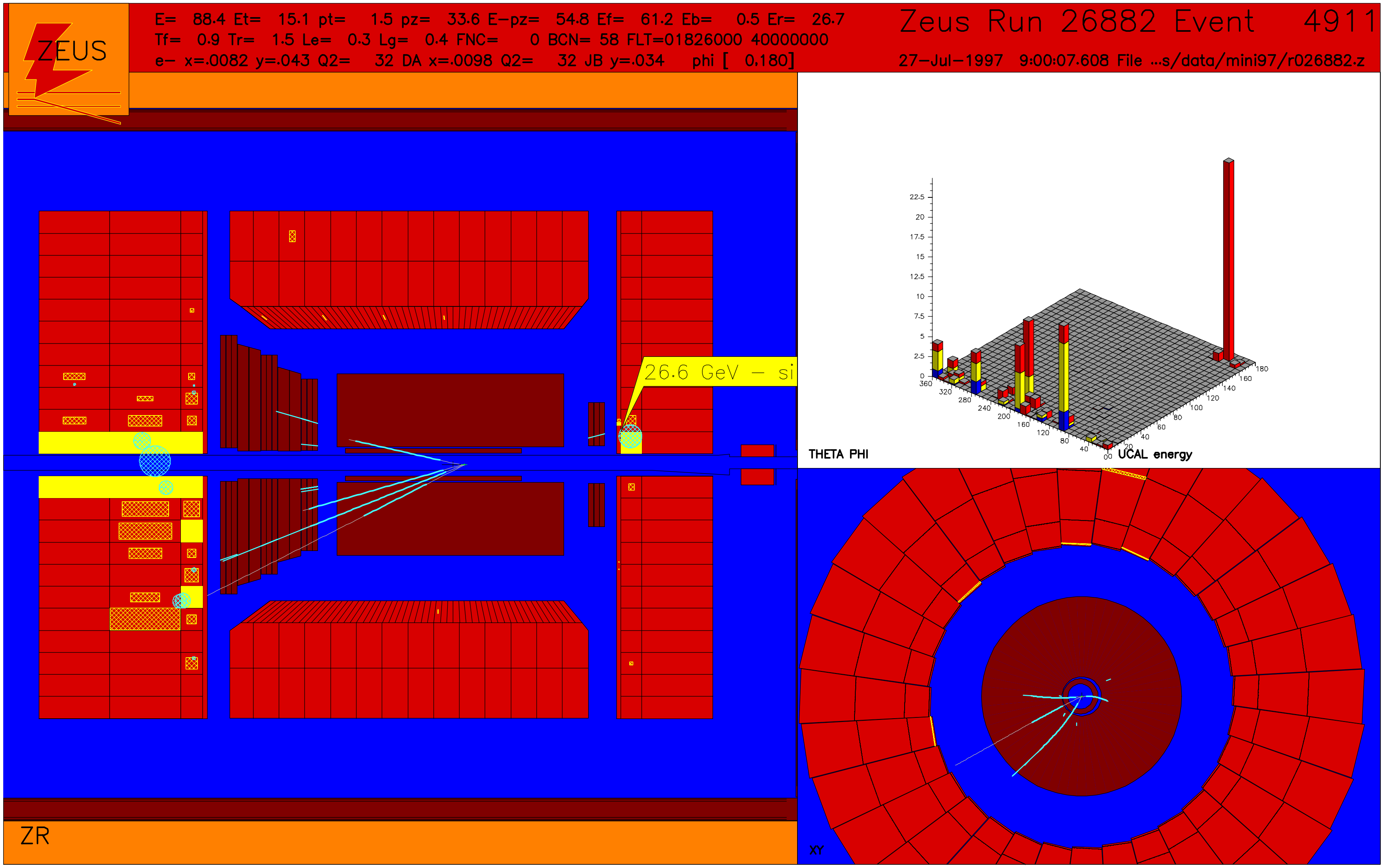
$$\frac{dg(x,Q^2)}{d\ln Q^2}=\frac{\alpha_s(Q^2)}{2\pi}\int_x^1\frac{dy}{y}\left[\sum_i q_i(y,Q^2)P_{gq}\left(\frac{x}{y}\right)+g(q,Q^2)P_{gg}\left(\frac{x}{y}\right)\right]$$

Kinematic Coverage

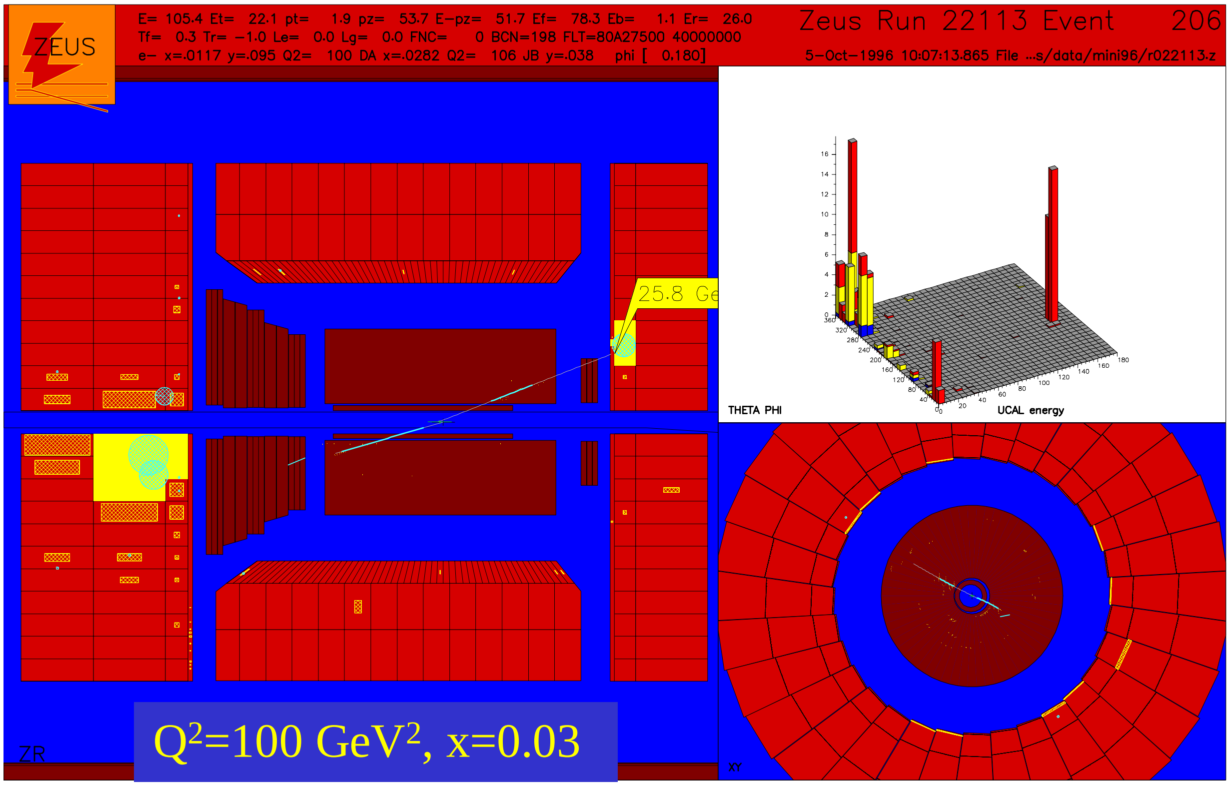


- 1997 and 1997 F_2 analysis
  - Covers 1994+1995 shifted vertex data
  - Reaches higher Q^2 and lower Q^2 in a single analysis
- BPC and BPT
  - electron detectors near the rear beam pipe to accept very low Q^2

Low Q^2 Event

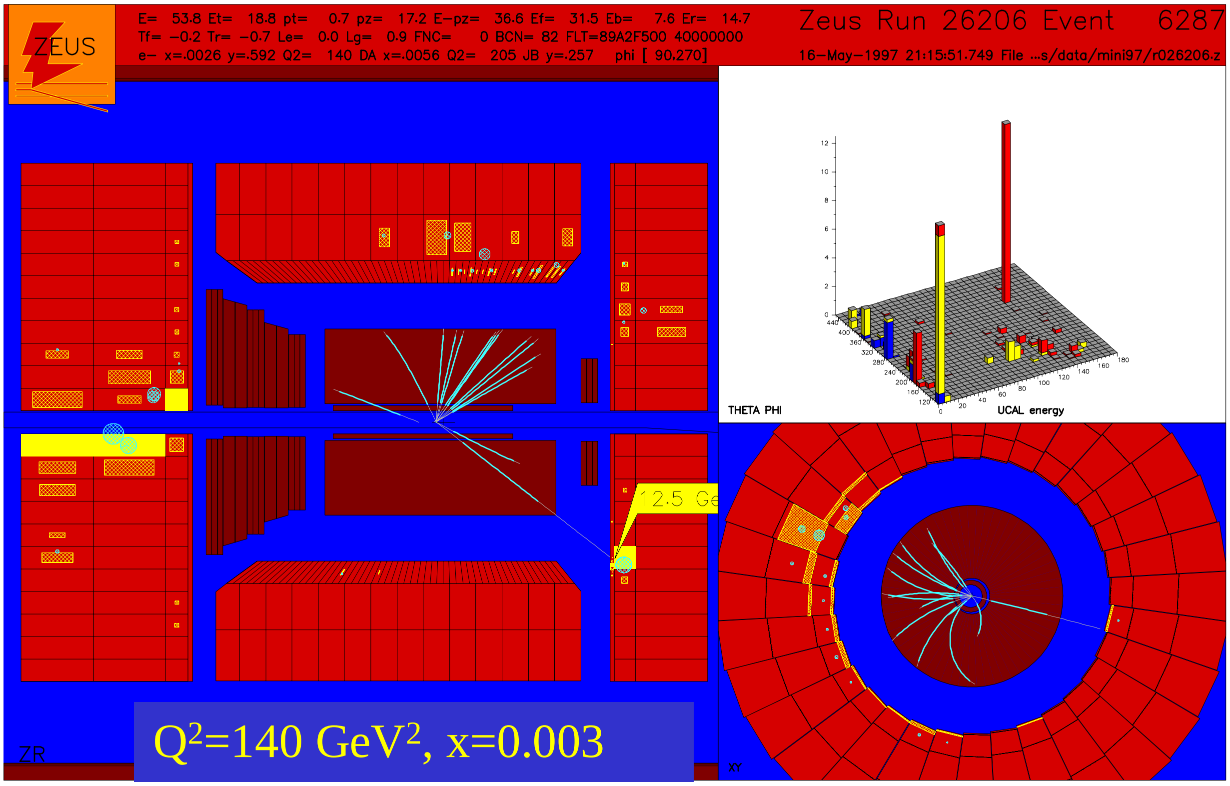

ZEUS
E= 88.4 Et= 15.1 pt= 1.5 pz= 33.6 E-pz= 54.8 Ef= 61.2 Eb= 0.5 Er= 26.7
Tf= 0.9 Tr= 1.5 Le= 0.3 Lg= 0.4 FNC= 0 BCN= 58 FLT=01826000 40000000
e- x=.0082 y=.043 Q2= 32 DA x=.0098 Q2= 32 JB y=.034 phi [0.180]
Zeus Run 26882 Event 4911
27-Jul-1997 9:00:07.608 File ...s/data/mini97/r026882.z
26.6 GeV – si
22.5
20
17.5
15
12.5
10
7.5
5
2.5
0
360
320
280
240
200
160
120
80
40
0
20
40
60
80
100
120
140
160
180
THETA PHI
UCAL energy
ZR
XY

Medium Q^2



```
E= 105.4 Et=  22.1 pt=   1.9 pz=  53.7 E-pz=  51.7 Ef=  78.3 Eb=   1.1 Er=  26.0
Tf=  0.3 Tr= -1.0 Le=  0.0 Lg=  0.0 FNC=     0 BCN=198 FLT=80A27500 40000000
e- x=.0117 y=.095 Q2=  100 DA x=.0282 Q2=  106 JB y=.038   phi [  0.180]
Zeus Run 22113 Event      206
5-Oct-1996 10:07:13.865 File ...s/data/mini96/r022113.z
```

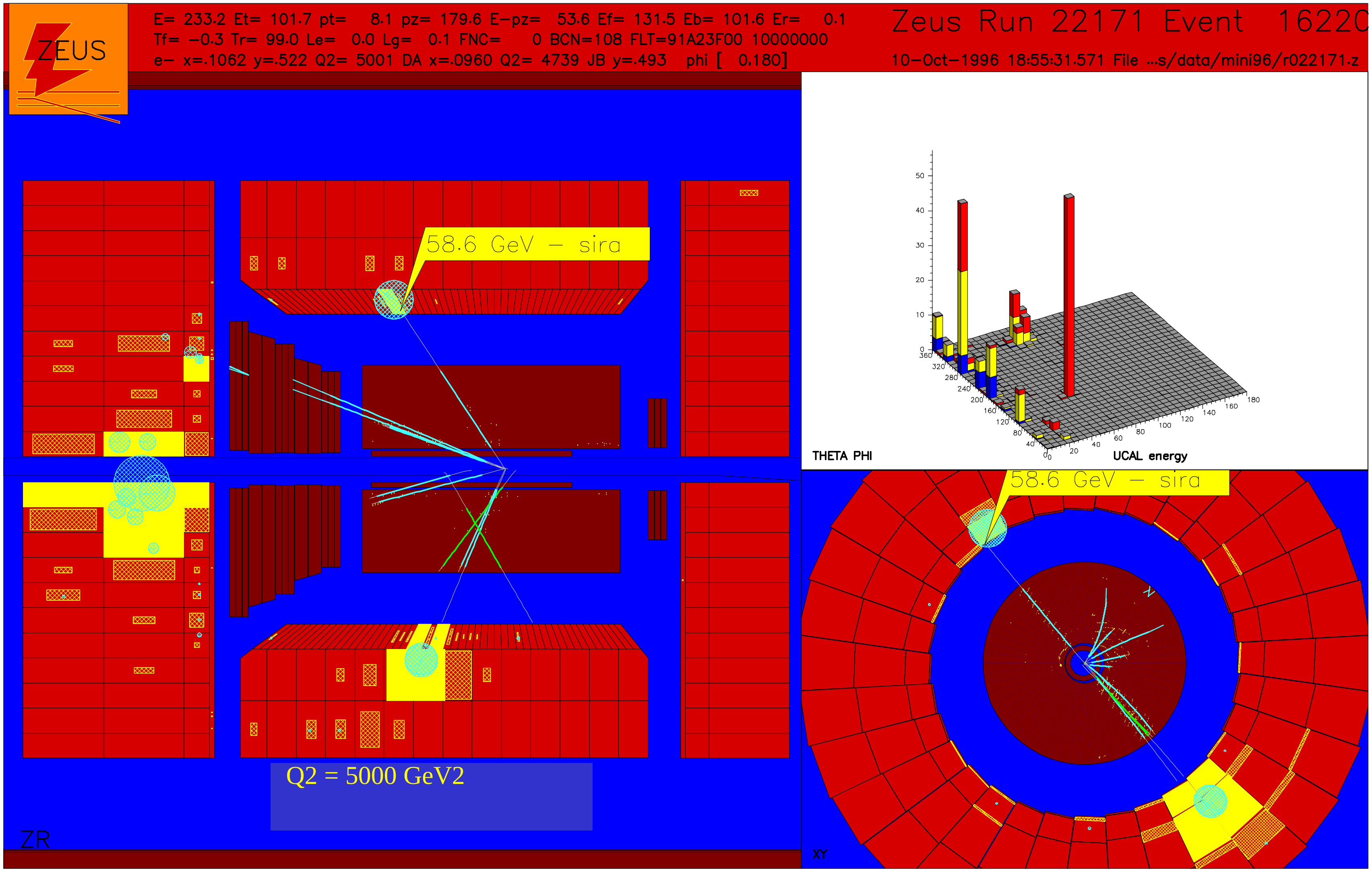
Q^2=100 GeV^2, x=0.03



```
E=  53.8 Et=  18.8 pt=   0.7 pz=  17.2 E-pz=  36.6 Ef=  31.5 Eb=   7.6 Er=  14.7
Tf= -0.2 Tr= -0.7 Le=  0.0 Lg=  0.9 FNC=     0 BCN= 82 FLT=89A2F500 40000000
e- x=.0026 y=.592 Q2=  140 DA x=.0056 Q2=  205 JB y=.257   phi [ 90.270]
Zeus Run 26206 Event     6287
16-May-1997 21:15:51.749 File ...s/data/mini97/r026206.z
```

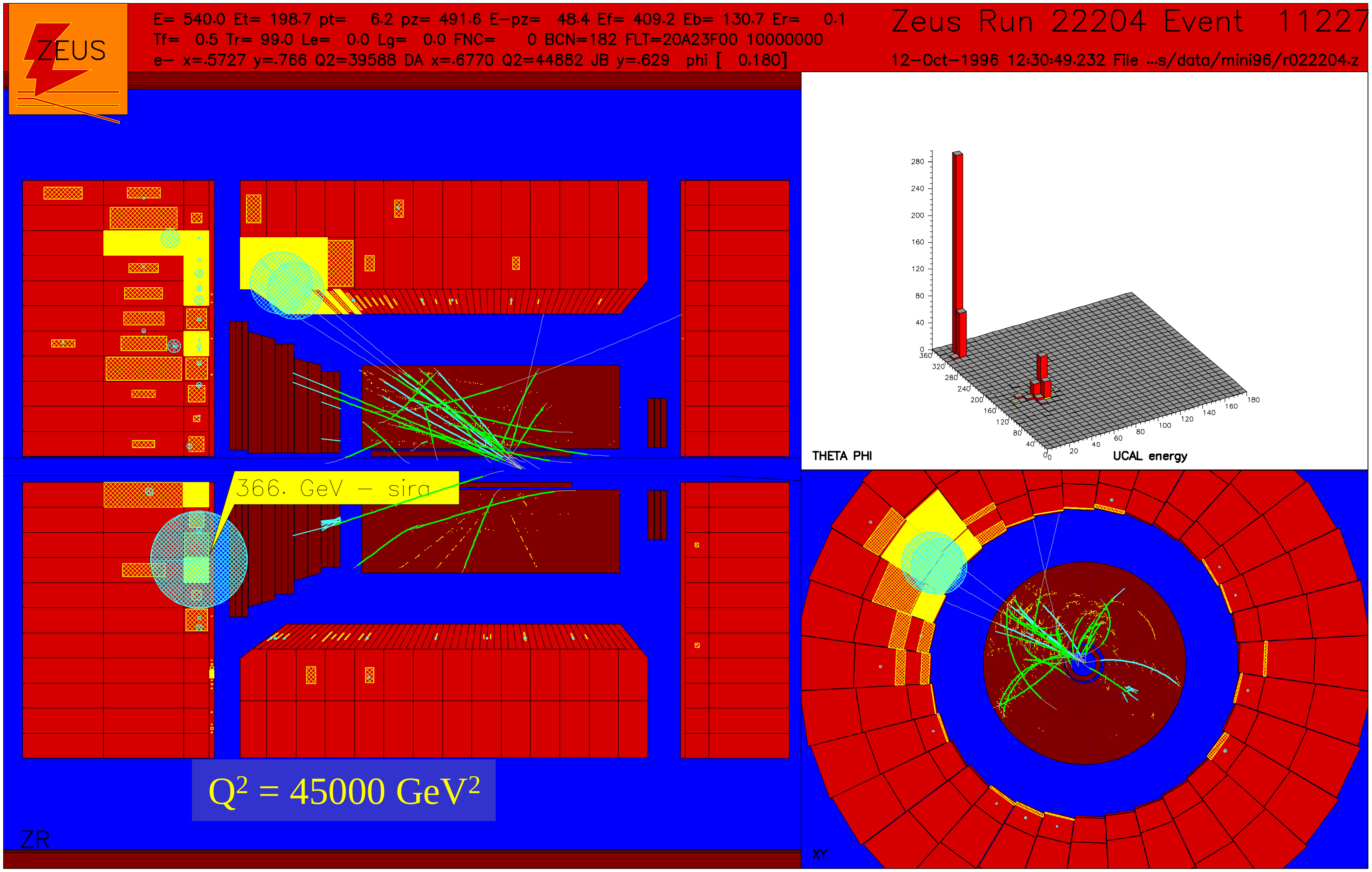
Q^2=140 GeV^2, x=0.003

High Q^2 Event



Q2 = 5000 GeV2

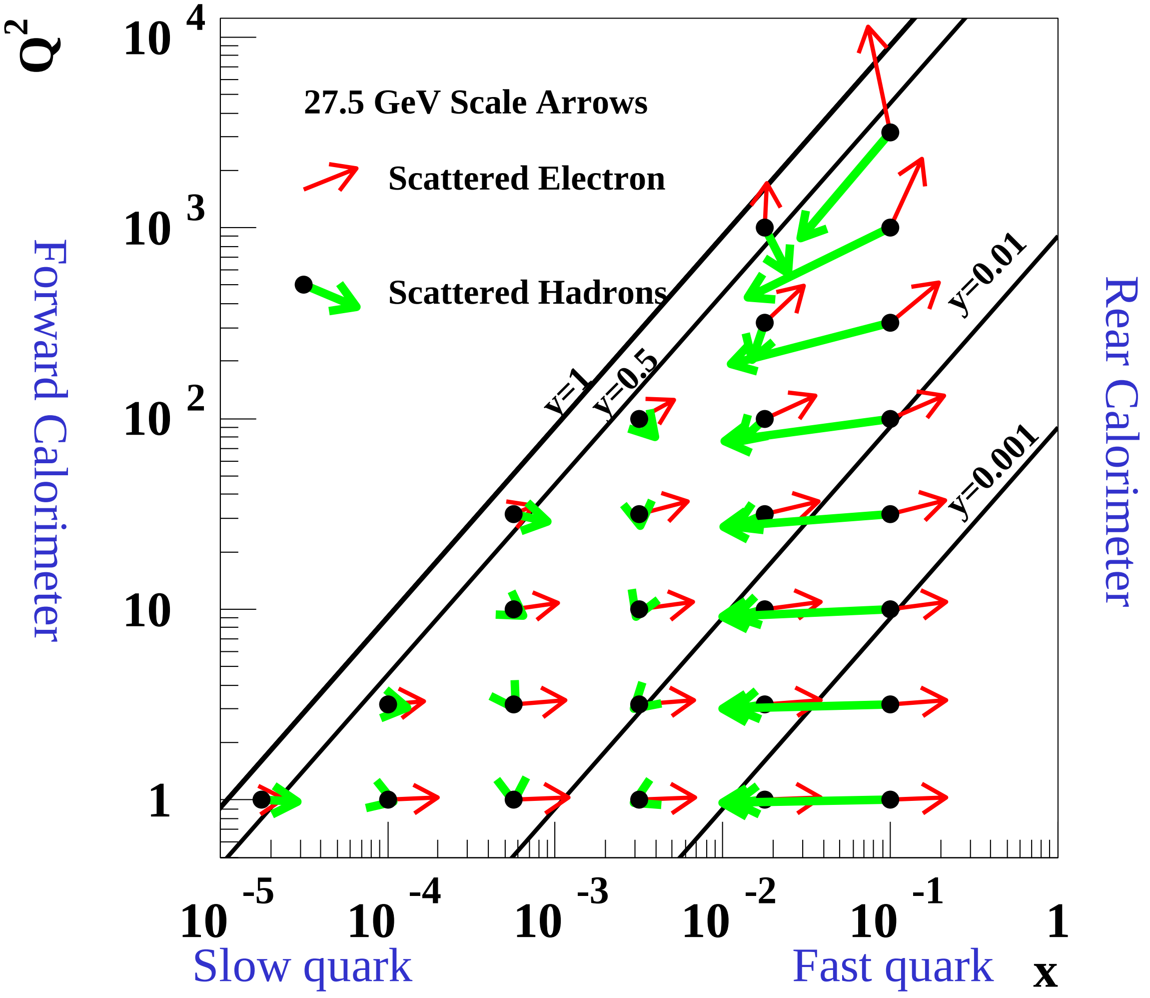
Highest Q^2 Event for 1996 and 1997



$Q^2 = 45000\ GeV^2$

Outgoing Particles.

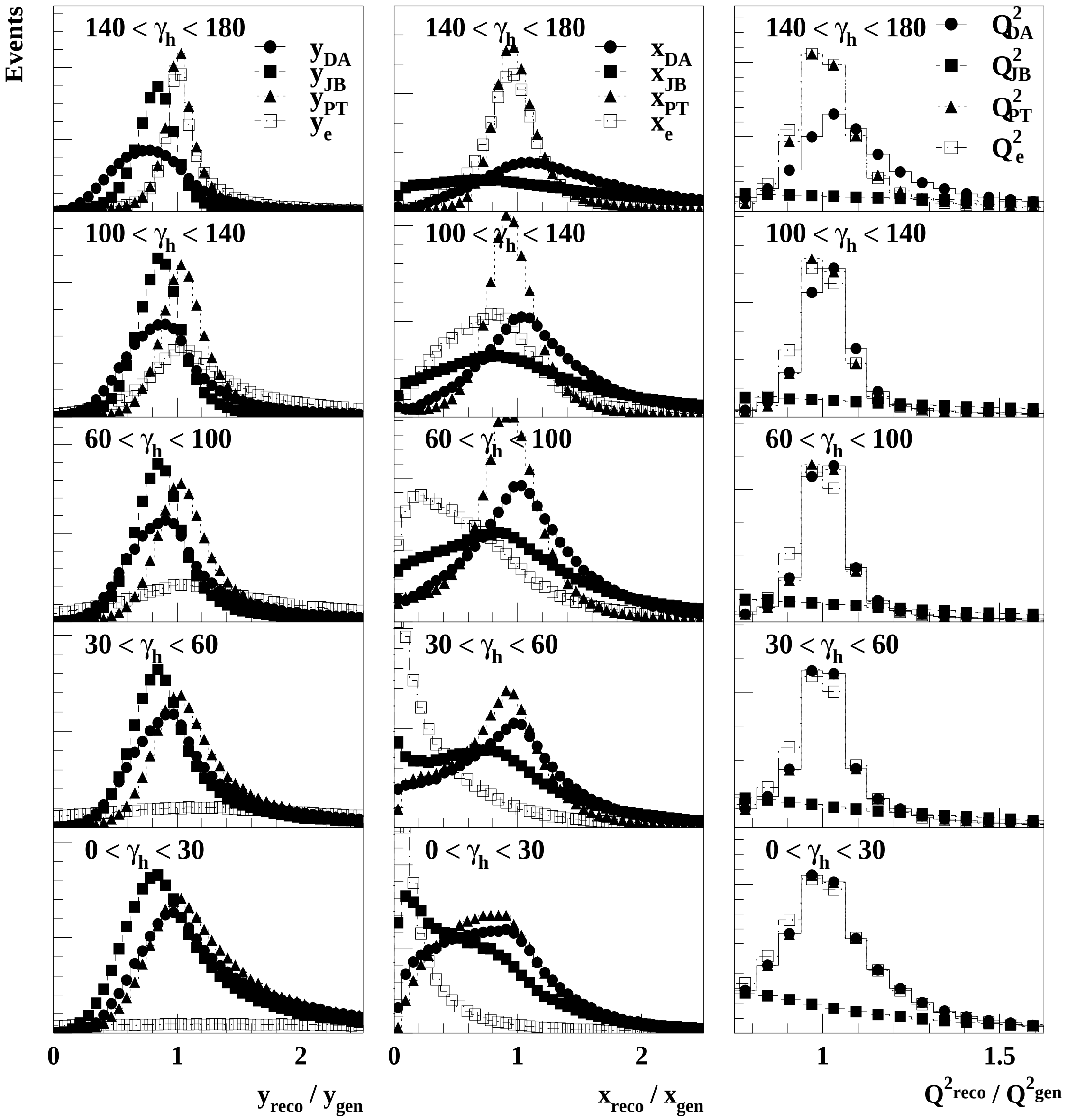
e =27.5 GeV   P = 820 GeV



- Any 2 variables (E_e,θ_e,E_h,γ_h) determine x,Q^2
  - Electron Method (E_e,θ_e)
  - Jacquet Blondel Method (E_h,γ_h)
  - Double Angle Method (θ_e,γ_h)
    - Can also be used to predict $E_e(\theta_e,\gamma_h)$!
  - P_T method combines (E_e,θ_e,E_h,γ_h)
- Beam pipe holes limit acceptance at low y and high y

Reconstruction Resolutions

- P_T method
  - Uses a combination of electron variables (E_e,θ_e) and hadronic variables ($P_{T,h}$, $(E\text{-}Pz)_h$ -> γ_h) to optimize the reconstructed x,Q^2

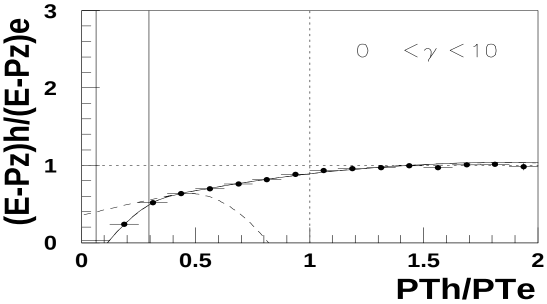


  - P_T method superior over widest kinematic range.

P_T Method of x,Q^2 Recon.

$$\gamma = A\cos\left(\frac{P_{T,h}^2 - (E-P_z)_h^2}{P_{T,h}^2 + (E-P_z)_h^2}\right)$$

- Improve γ by improving $P_{T,h}$ and $(E\text{-}Pz)_h$
  - E-Pz is the dominant contribution to γ
- Replace $P_{T,h}$ with $P_{T,e}$
  - electron energy better calibrated
- Scale $(E\text{-}Pz)_h$ by a correction related to $P_{T,h}/P_{T,e}$



  - P_T energy loss must also be E-Pz energy loss
  - small Q^2 and γ dependence to correction
  - Electron and hadrons at the same level of energy corrections.
- Scale $(E\text{-}Pz)_h$ by $2E_{beam}/(E\text{-}Pz)_{total}$
  - Corrects overall E-Pz energy scale
- Use angles (θ_e,γ_h) method to reconstruct x,Q^2

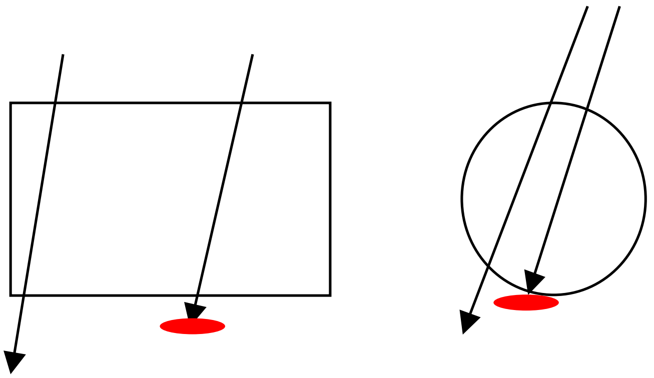
F_2 Measurement

- Select deep inelastic scattering events
  - Backgrounds
  - Selection cuts
- Reconstruct x, Q^2
  - Electron
    - Energy E_e
    - Angle θ_e
      - Event Vertex
      - Electron position in the detector
  - Hadronic
    - P_T, $E-P_z$ to calculate γ_h
- Unfold F_2
  - Count events in bins of x, Q^2
  - Divide by luminosity to produce a cross section.
  - Correct for detector acceptance (Monte Carlo)
  - Interpret cross section in terms of F_2

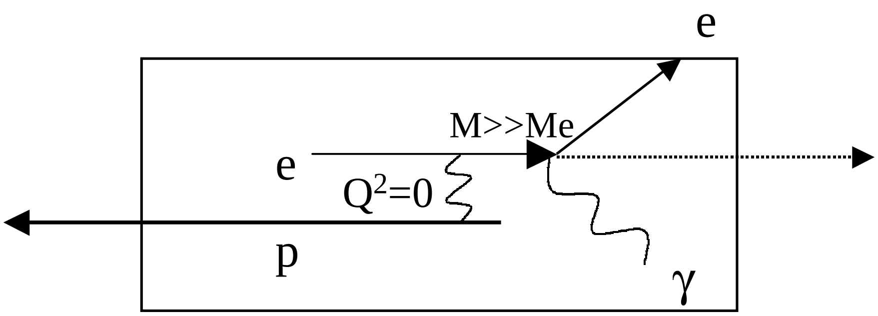
- Below $Q^2=800$ GeV^2 the F_2 error is dominated by the understanding of the measured variables

Backgrounds

- Any event with the DIS electron in the detector is a signal event!
- Photoproduction
  - Electron escapes down the rear beam pipe $Q^2 \sim 0$
  - Hadronic activity fakes an electron
  - Dominant low Q^2 background
  - E-Pz Cut!
- Cosmic muons
  - Reject with P_T balance cuts and vertex cuts

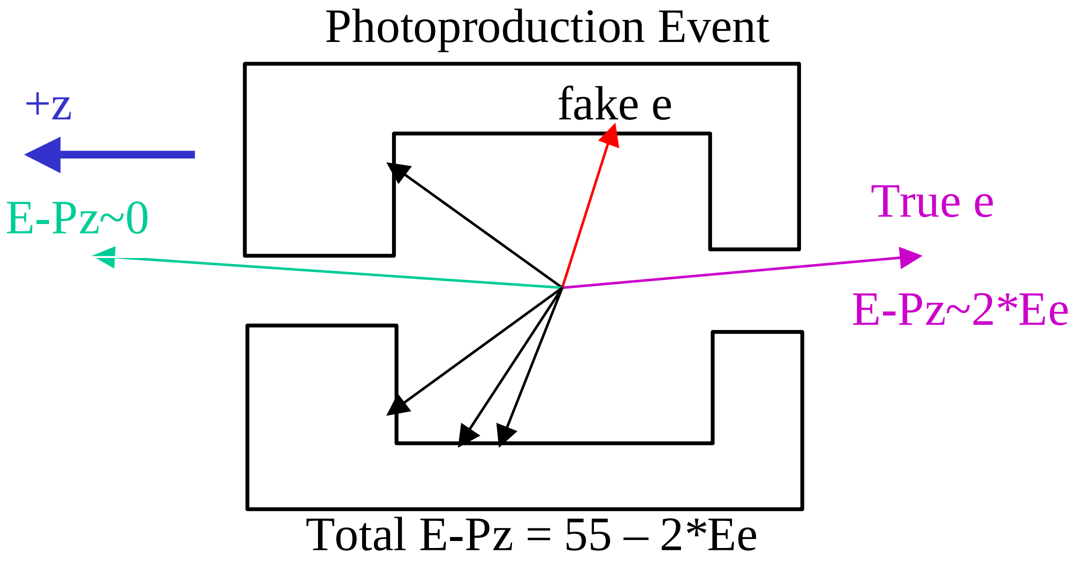


- QED Comptons ($Q^2=0$)
  - Reject events with only 2 electro-magnetic clusters



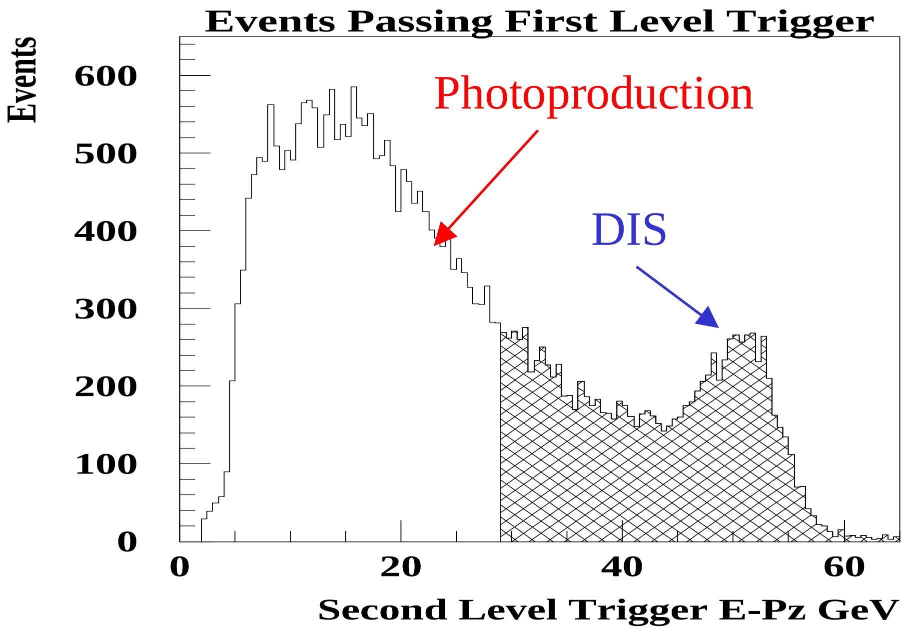
E-Pz Cut

- E-Pz is conserved
  - Before the event E-Pz = E-Pz(e beam) + E-Pz(P beam) = 27.5–(-27.5)+820-(820) GeV = 55 GeV
  - If all particles are measured, one should measure 55 GeV.



Photoproduction Event

Total E-Pz = 55 – 2*Ee

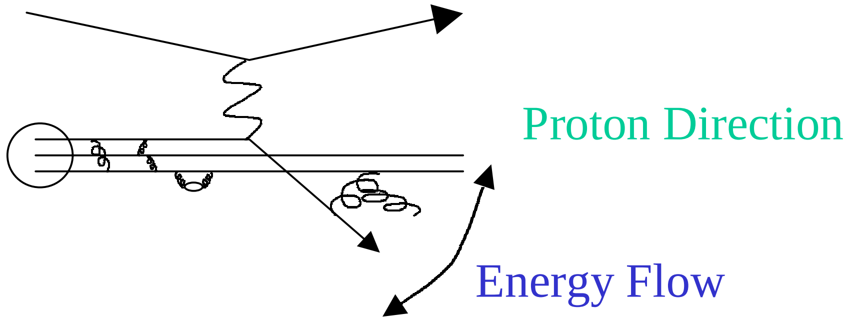


Selection Cuts

- Event Selection
  - First Level Trigger
    - Isolated calorimeter electromagnetic trigger tower E>2 GeV in Rcal
    - Rcal EMC E>3.4 GeV, Bcal EMC E>4.78 GeV
    - Calorimeter E_T>30 GeV, E_T>11.6 GeV and CTD track
  - Timing consistent with e+p interaction
  - 38 < E-Pz < 65 GeV (remove events with electron lost in rear beam pipe)
  - -50 < Vertex z < 50 cm
  - $P_T/E_T<0.7$ and $P_T/\sqrt{E_T}<3\ \sqrt{\mathrm{GeV}}$ (cuts cosmic events)
  - $P_{T,h} / P_{T,e} > 0.3$ (well contained hadrons)
- Electron Cuts
  - Neural Net probability cut (function of energy)
  - Energy > 8 GeV
  - Position away from rear beam pipe
  - Track Match (in tracking acceptance)
    - Distance of Closest Approach < 10 cm
    - Track Momentum > 5 GeV
  - Non-electron energy in cone around electron<5 GeV
  - Number of Calorimeter cells<30 in forward direction. (cut hadronic jets found as electrons)
  - $y_{el} < 0.95$ (removes high Q^2, high y fakes)
- **2 Data sets**
  - 1.5 $GeV^2<Q^2<27\ GeV^2$ 2.21 pb^{-1} of luminosity
  - $Q^2>27\ GeV^2$ 30.66 pb^{-1} of luminosity

Monte Carlos

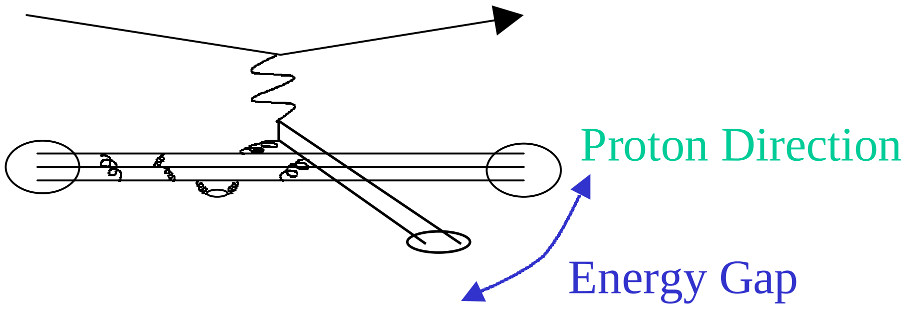
- DJANGO



Proton Direction

Energy Flow

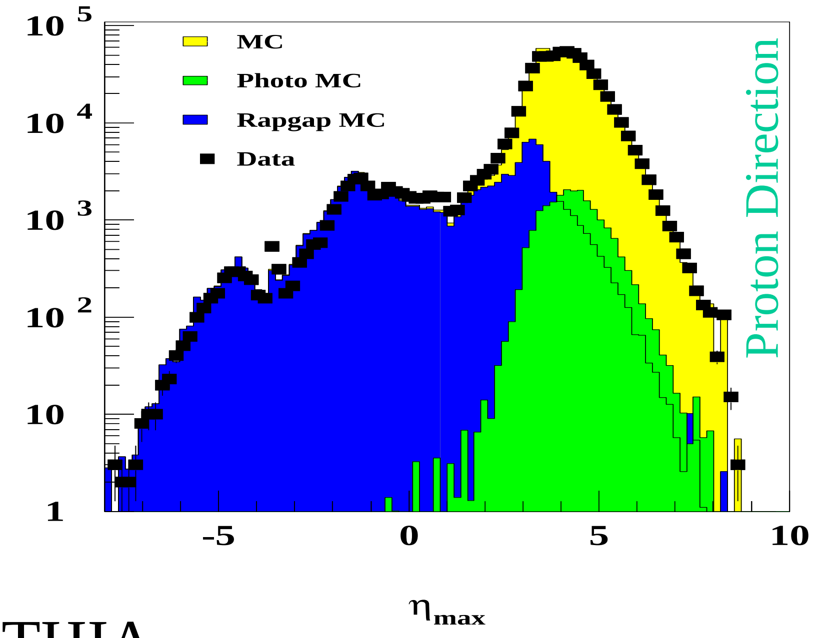
- RAPGAP



Proton Direction

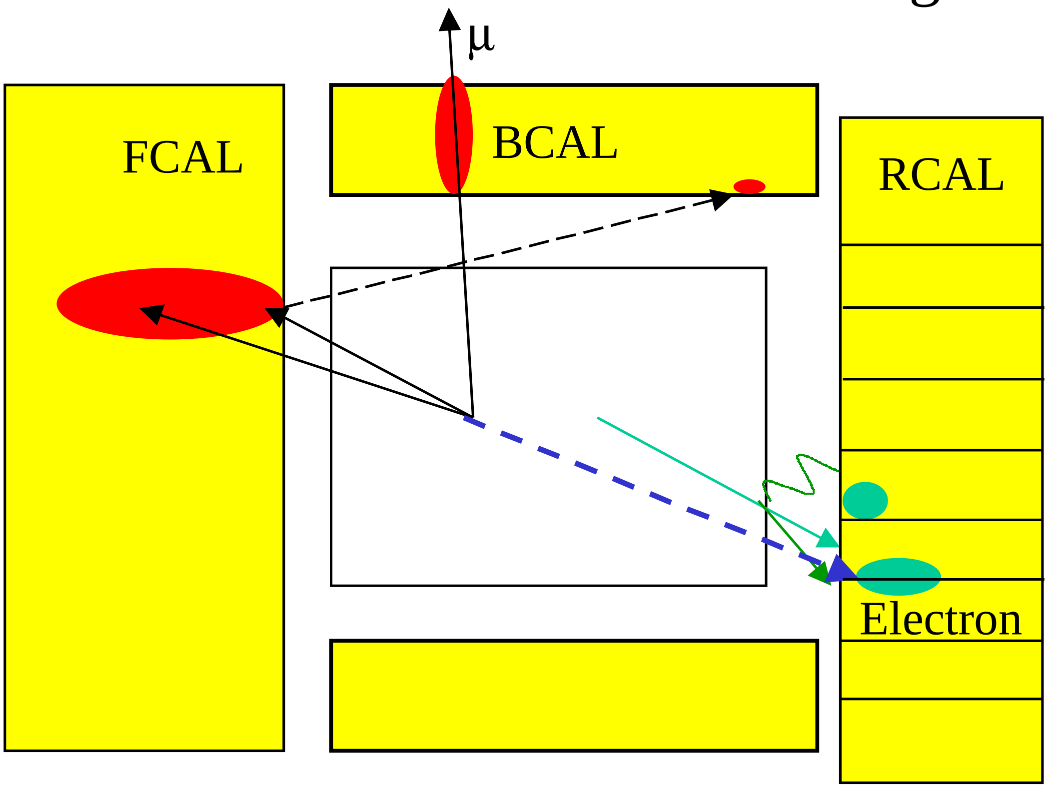
Energy Gap

“Angle” of Energy Deposit Closest to Proton’s Direction



- PYTHIA
  - Used for very low Q^2 background events where the electron escapes down the rear beam pipe

What are the reconstruction challenges?

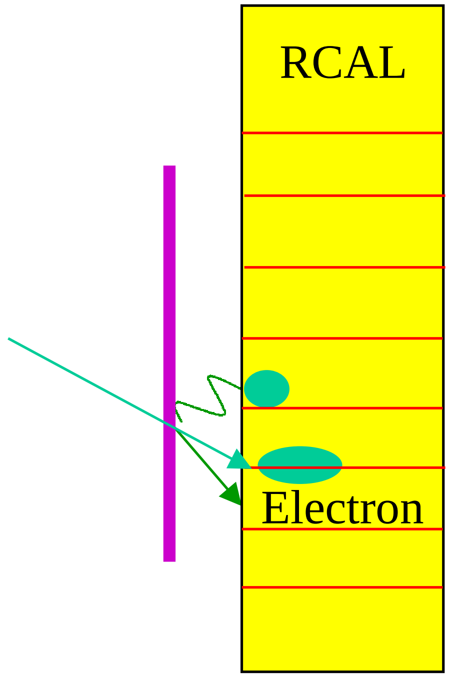


- E_e
  - Calibration, Calorimeter edges, Loss in inactive material
- θ_e
  - Vertex position, Detector alignment
- Hadrons
  - Energy Calibration, μ energies, Backsplash
  - Vertex position, Detector alignment
- Monte Carlo – Data Agreement
  - Monte Carlo used to remove detector effects!

Electron Energy

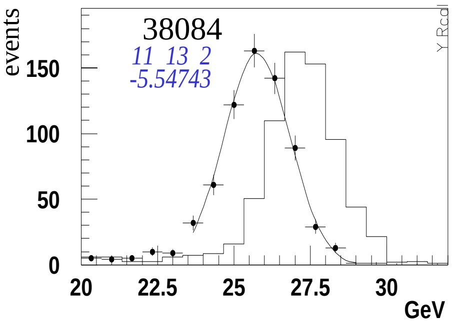
- Important to calibrate the energy
  - Electron Energy Cut for DIS event selection
  - Used in P_T balance with hadrons to correct γ_h

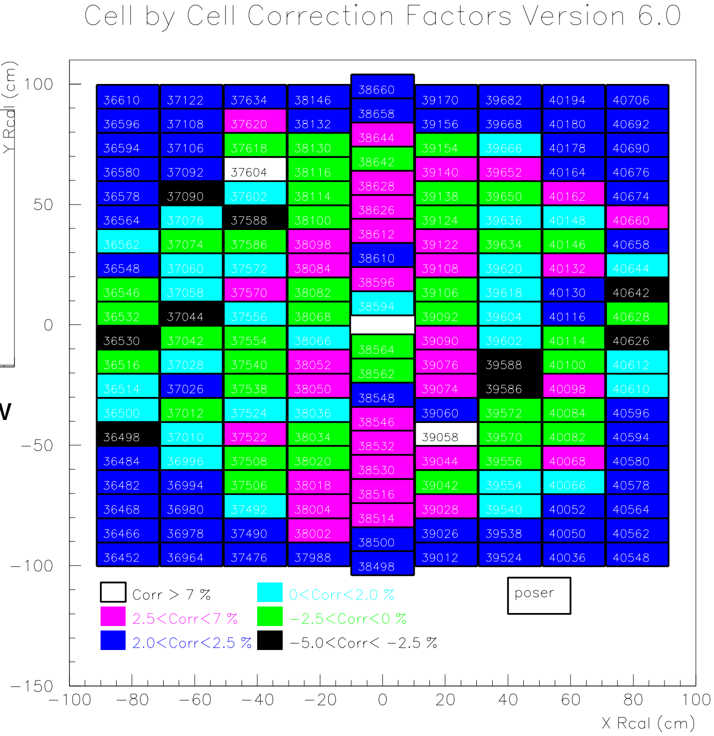
- Calibration Steps
  - Calorimeter Cell calibration
  - Non-uniformity (Calorimeter Edges)
  - Dead Material Correction



Calorimeter Cell Calibration

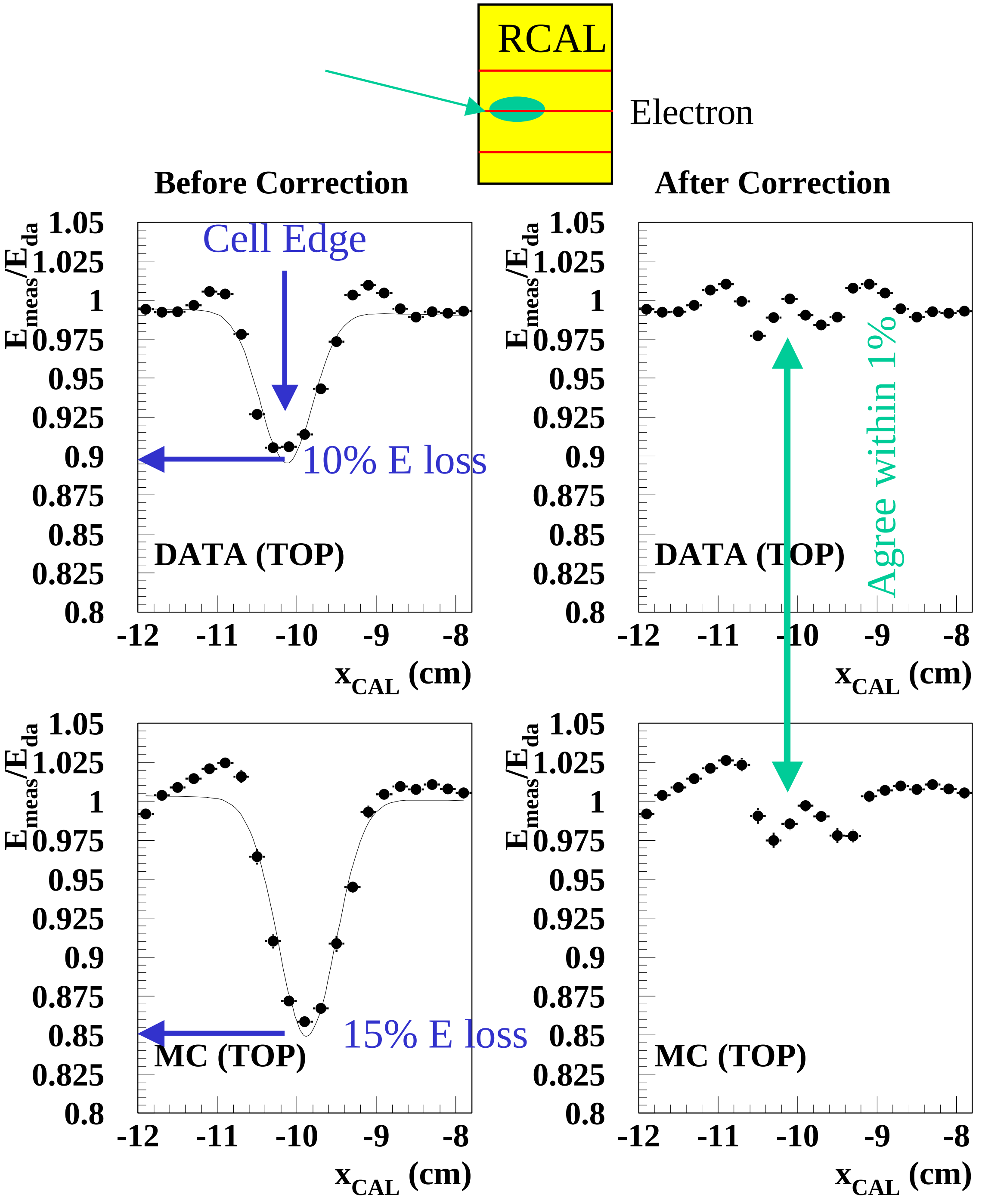
- Need a beam of known energy electrons
  - Double Angle Events.
    - From hadron and electron angles, the electron energy can be predicted. (2 independent variables)
  - Kinematic Peak events.
    - Special class of double angle events in which no hadronic activity is measured. ($\gamma_h = 0$)
- Force Data and Monte Carlo to be the same.


One KP Cell


Cell by Cell Correction Factors Version 6.0

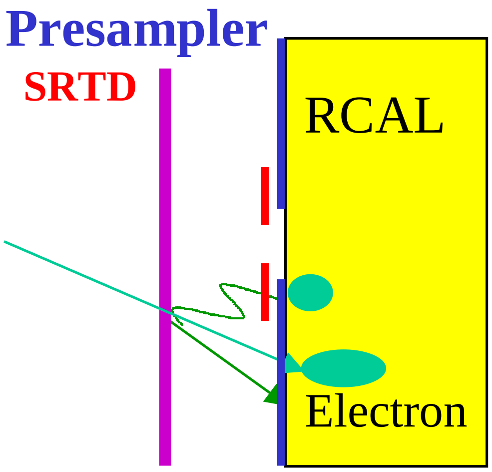
Non-Uniformity Correction

- Energy loss in calorimeter cell edges not well modeled by Monte Carlo.

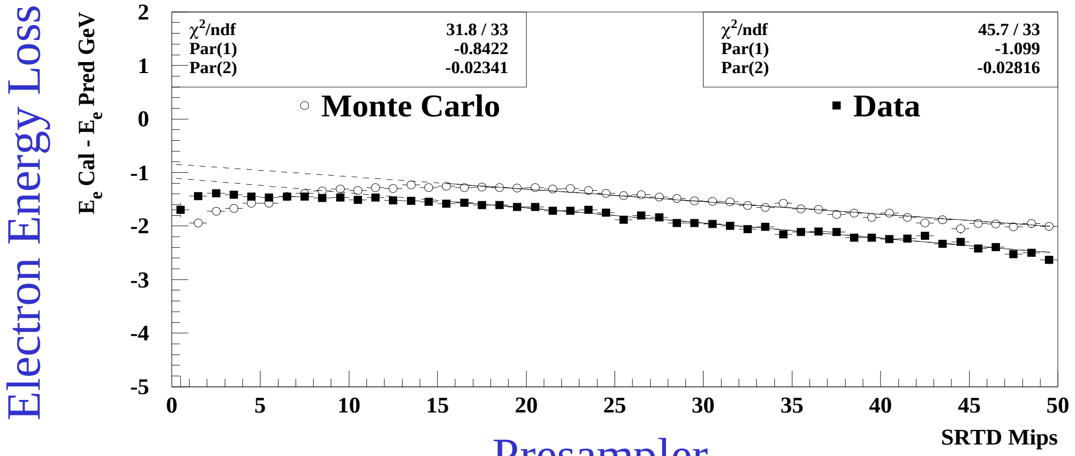


Dead Material Correction

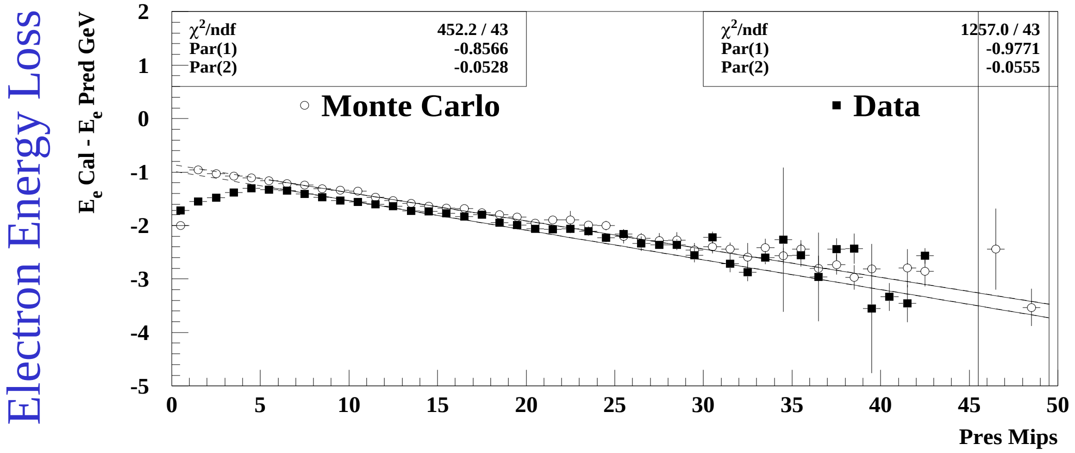
- Electrons passing through material before reaching the calorimeter lose energy and produce a shower of particles.
- "Presampler" Method
  - Measure the number of charged particles at the face of the calorimeter and correct for the energy loss.



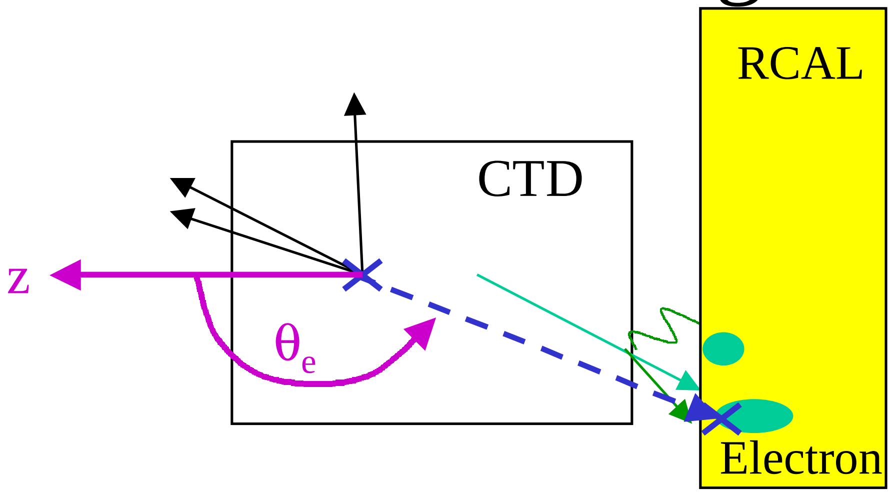
SRTD



Presampler



Electron Angle

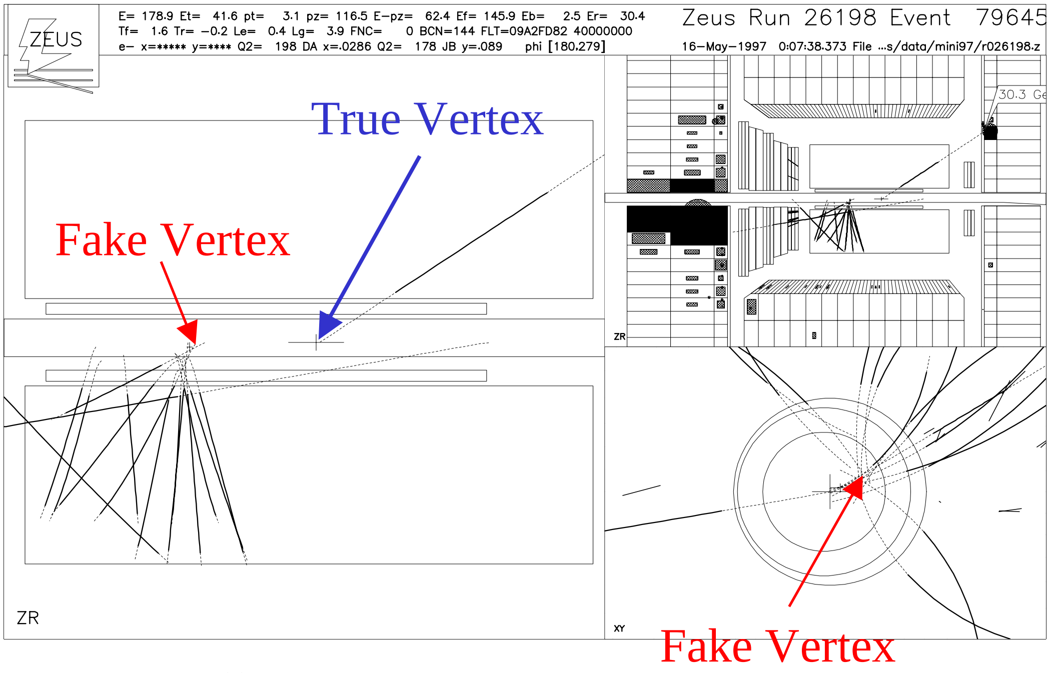


- “True” Scattering Angle
  - Tracking angle at vertex

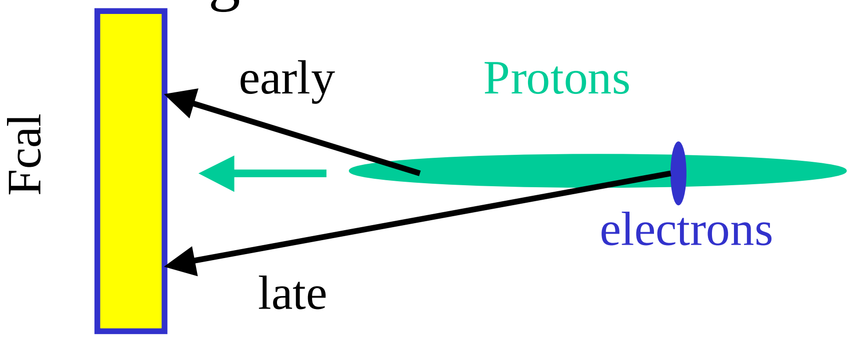
- A 2 point method is used when outside of tracking
  - Correct vertex z position
    - Electron track seed vertex
    - Fcal Timing vertex
  - Detector alignment
    - Aligned to track end point

Event Vertex

- Proton bunch length 12 cm long
- Event by event vertex measurement
  - Angles of electron and hadrons measured with respect to the event vertex.
  - Electron seed vertexing method. 4 mm resolution. (Finds true vertex)

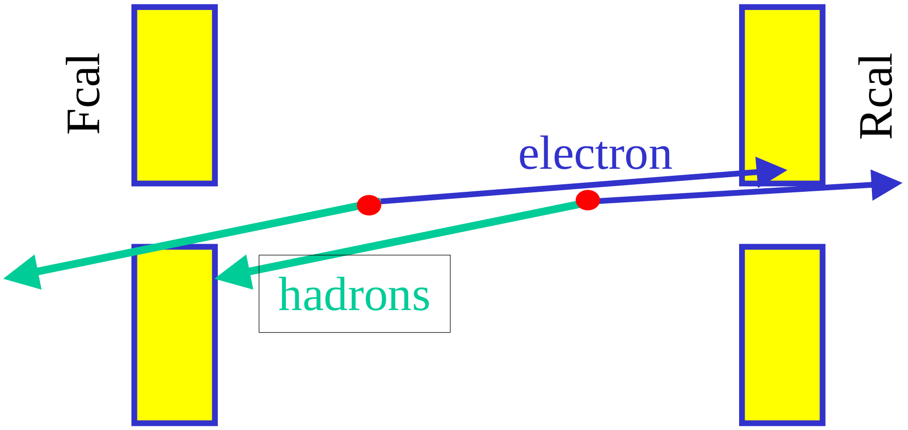


  - Cut off axis vertices
- Fcal timing for no track events 8.6 cm resolution

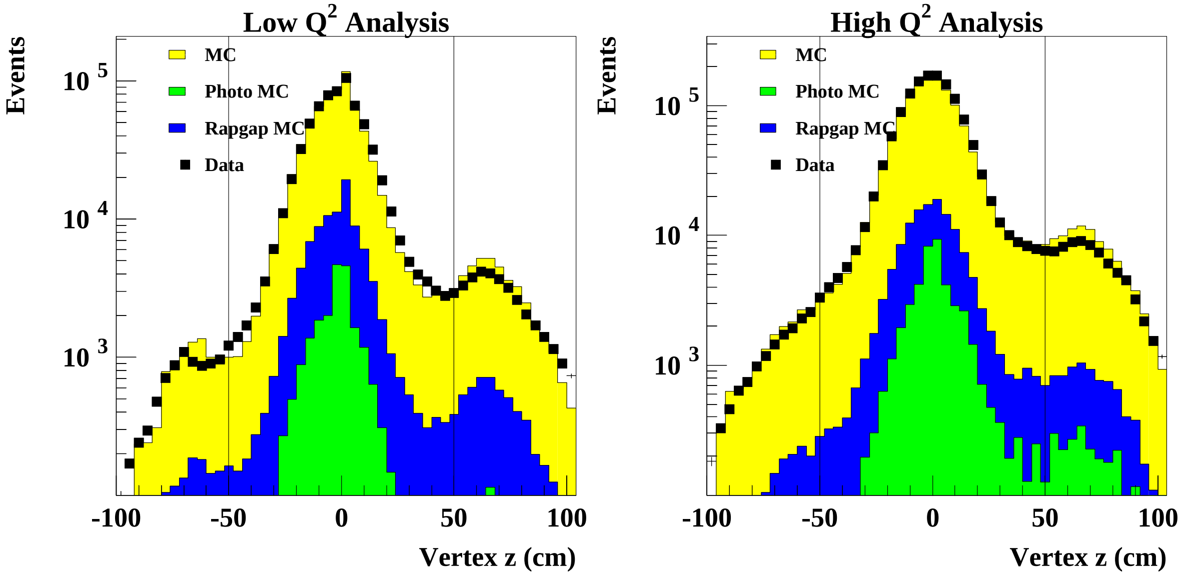


Vertex Distribution

- Acceptance depends on vertex



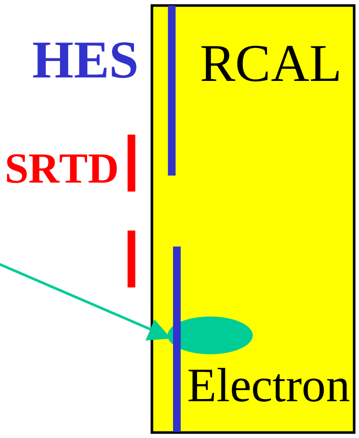
- Need same vertex distribution in data and Monte Carlo simulation!
  - Use unbiased event sample to measure data vertex distribution
  - Generate Monte Carlo events with this distribution.

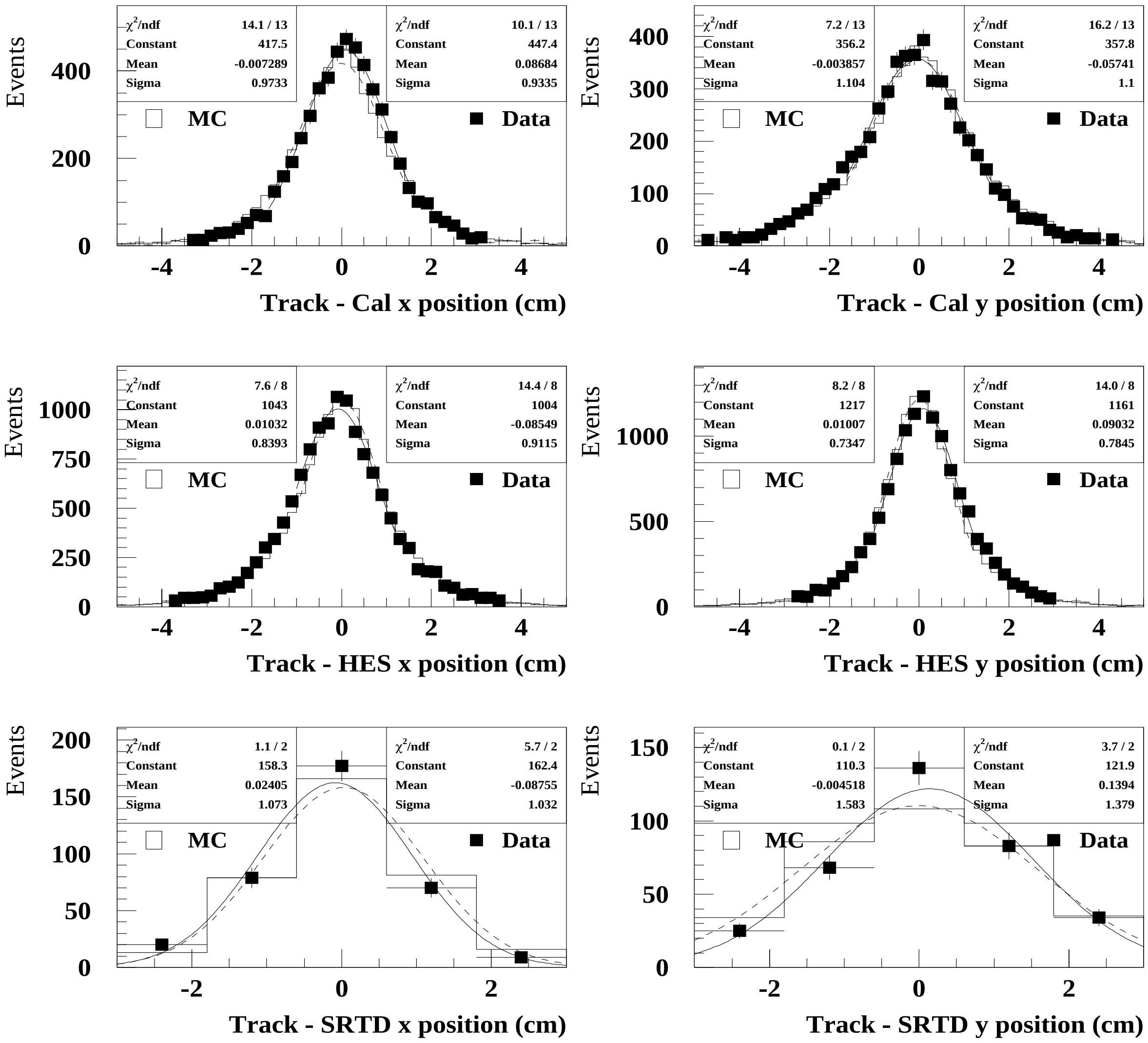


  - Good Agreement in final DIS event sample

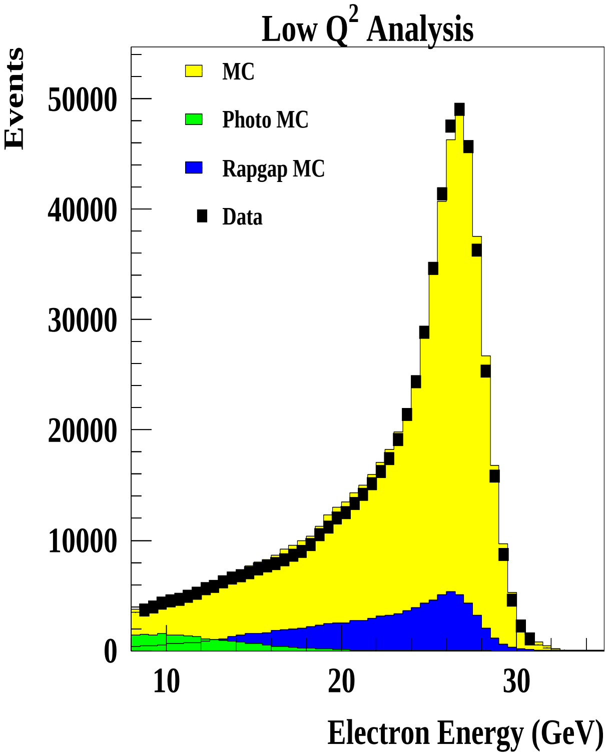
Detector Alignment

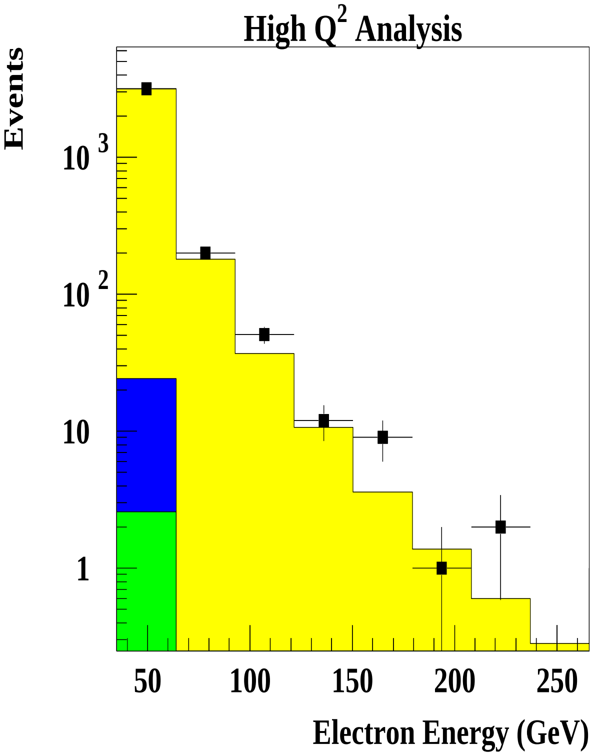
- Aligned to tracking
  - Calorimeter
  - HES (3cm x 3cm diodes 3cm inside rear calorimeter)
  - SRTD (1 cm wide scintillator strips near rear beam pipe)

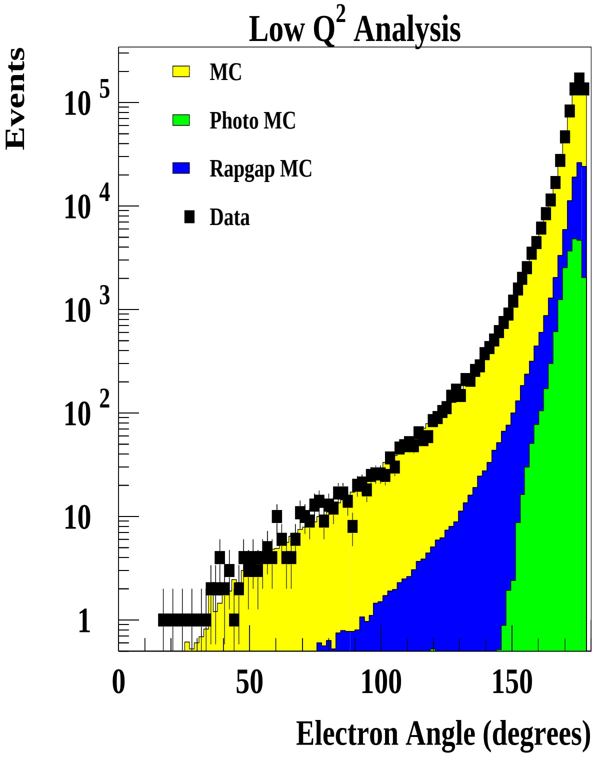




Electron Variables

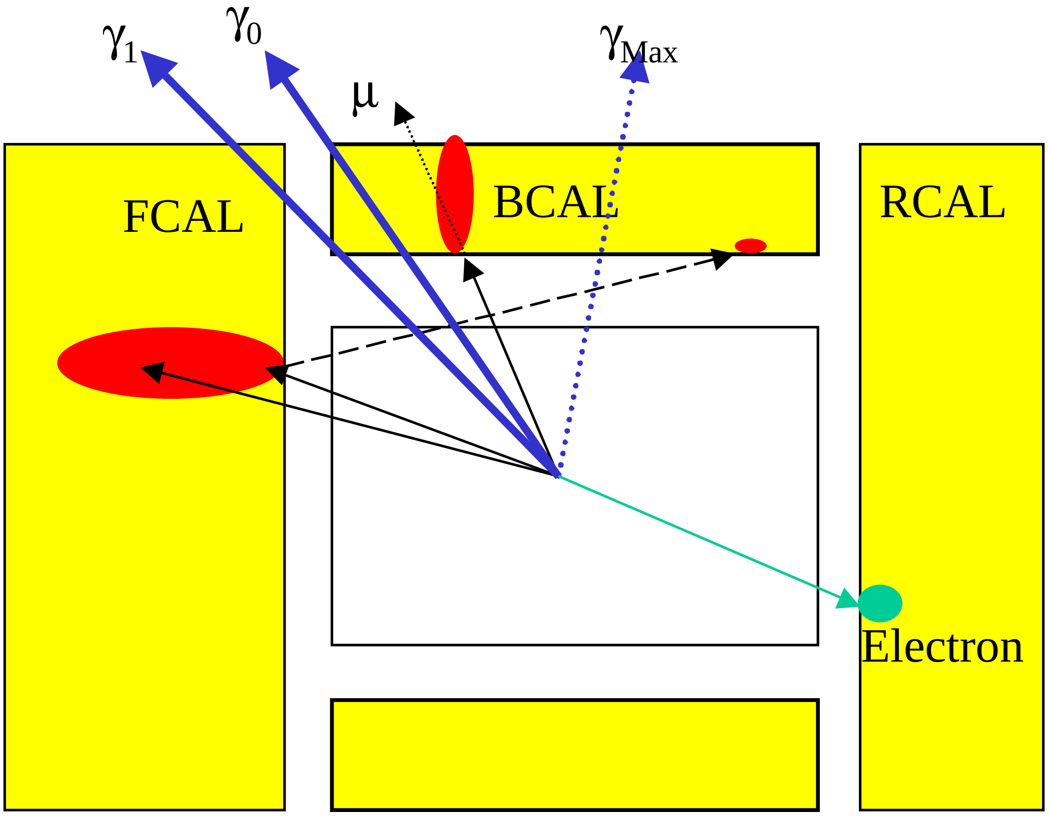






- Electron energy
  - Photoproduction at low energies
  - High energy side of MC peak doesn't agree
    - accounted for in systematic error
  - Excess of data at very high energies (high Q^2)
- Electron Angle
  - agrees over 5 orders of magnitude

Hadronic Reconstruction

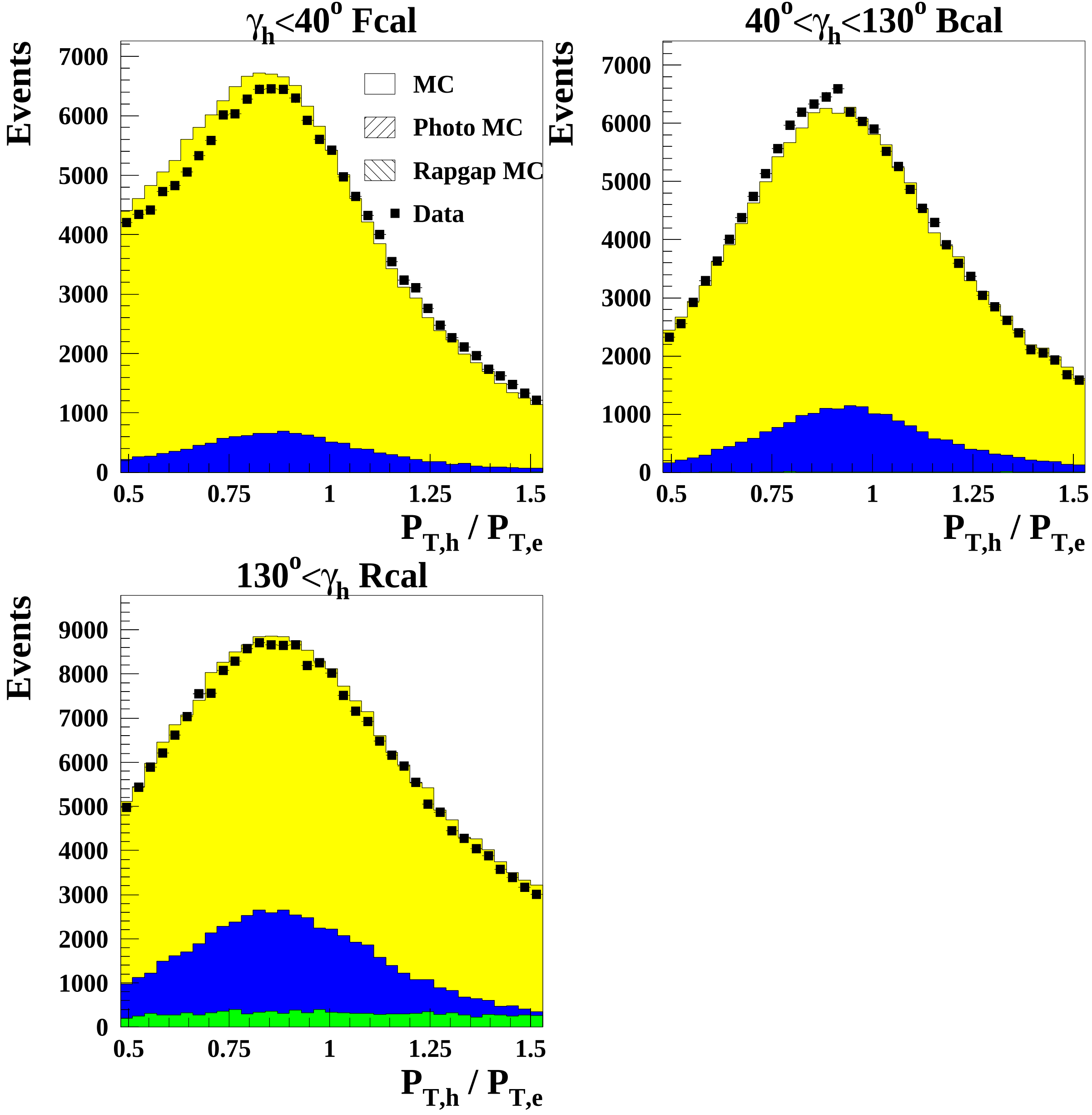


- Challenges… μ energies, Backsplash
- Combine tracking and calorimeter info. (P_{Th}, $E\text{-}Pz_h$)
  - Find calorimeter islands and match tracks to islands
  - Use tracking momentum if calorimeter energy << track momentum
    - Improves μ energies
  - Use tracking angle for 1 to 1 matches
- Remove backsplash
  - Calculate γ from islands and $\gamma_{Max} = \gamma + 50^o$

$$\gamma = A\cos\left(\frac{P_{T,h}^2 - (E - P_z)_h^2}{P_{T,h}^2 + (E - P_z)_h^2}\right)$$

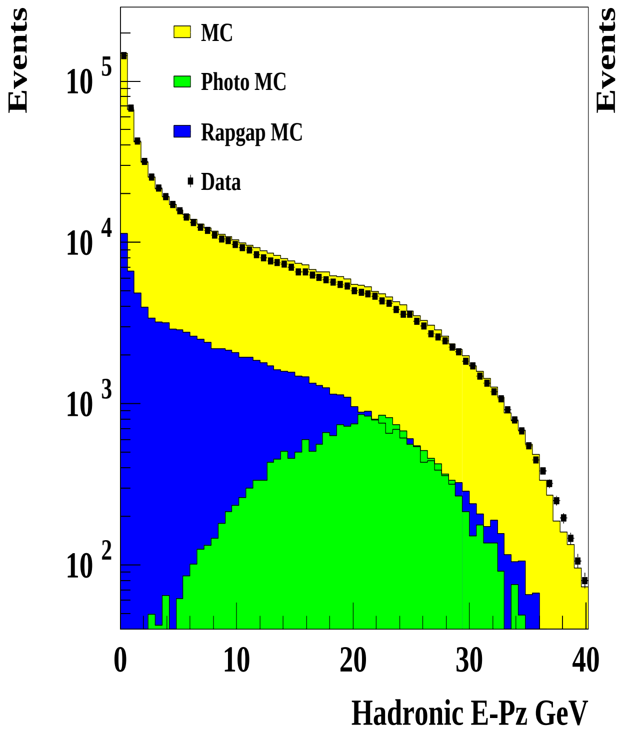
  - remove low energy, trackless, isolated islands beyond γ_{Max}
  - repeat up to 3 times or until γ is stable within 1%

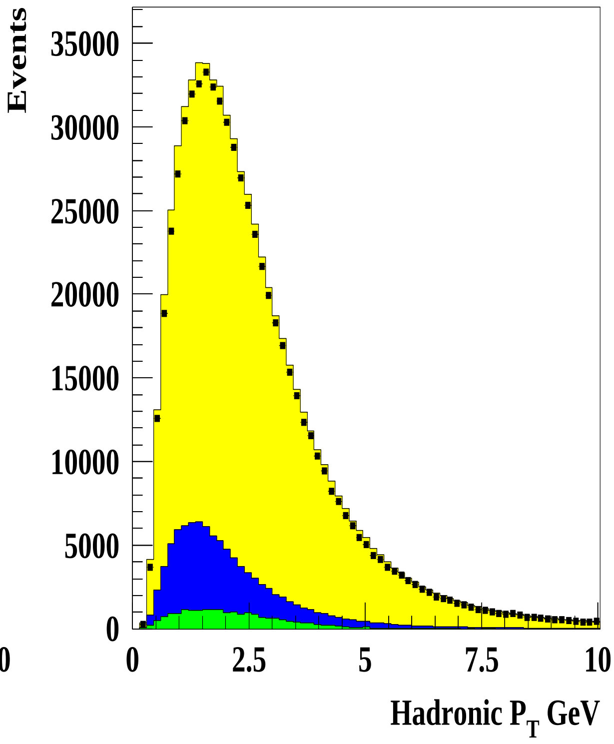
Hadronic Energy Scale

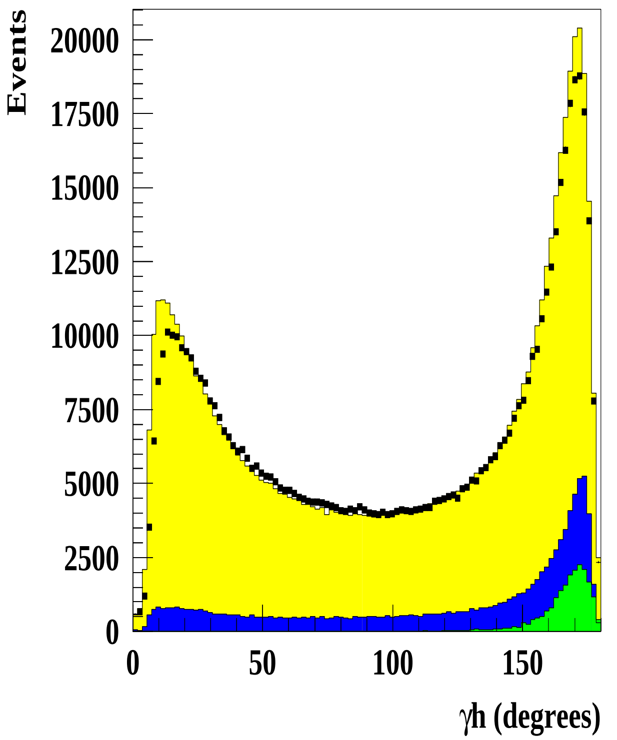


- Need a hadronic “test beam” of known energy.
  - – P_T balance with calibrated electron!
- Want Monte Carlo to match data.

Hadronic Variables

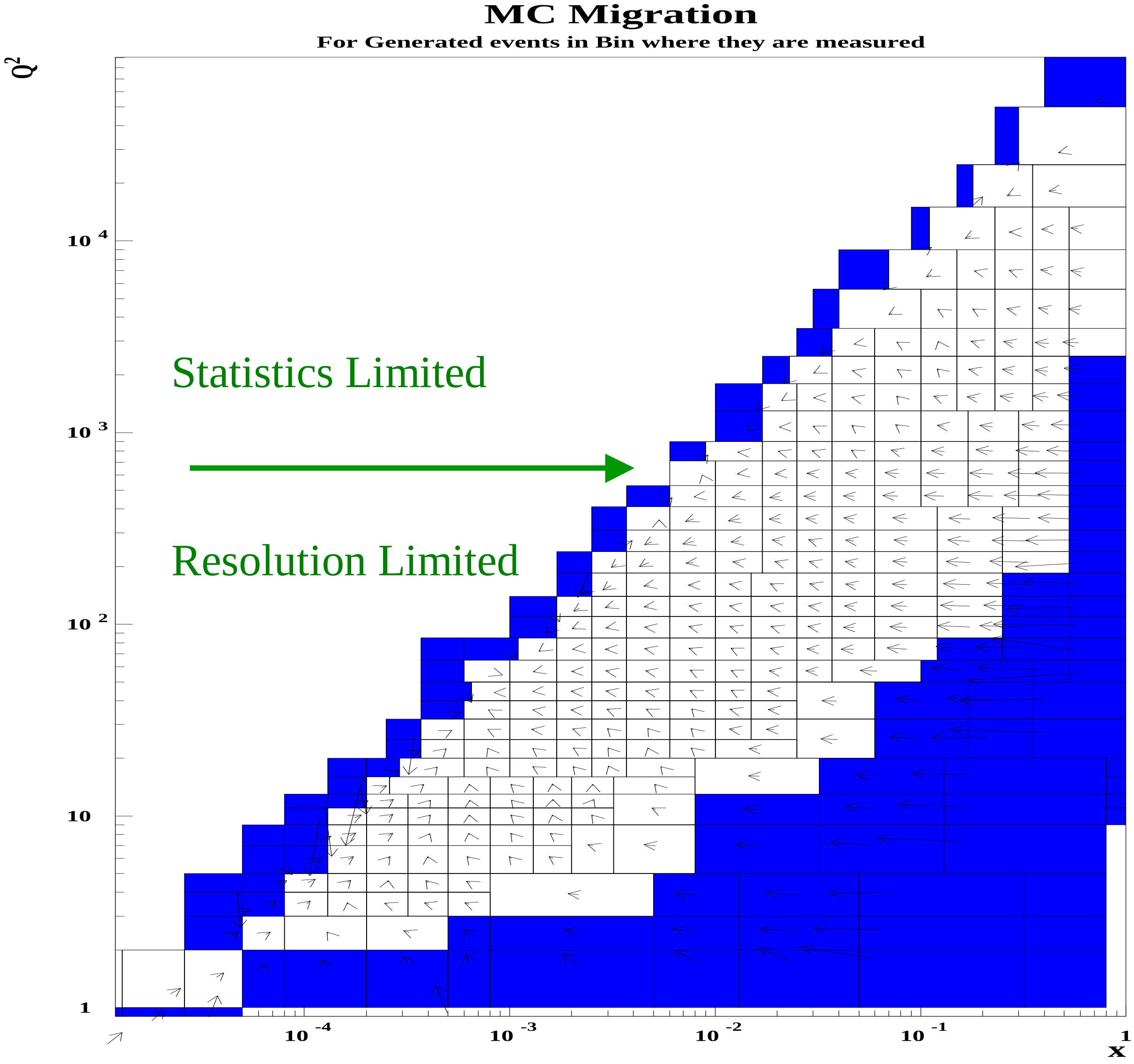






- RAPGAP/DJANGO fraction
  - Medium E-Pz
  - low P_T
- γ_h
  - very low γ not used
  - High γ RAPGAP fraction

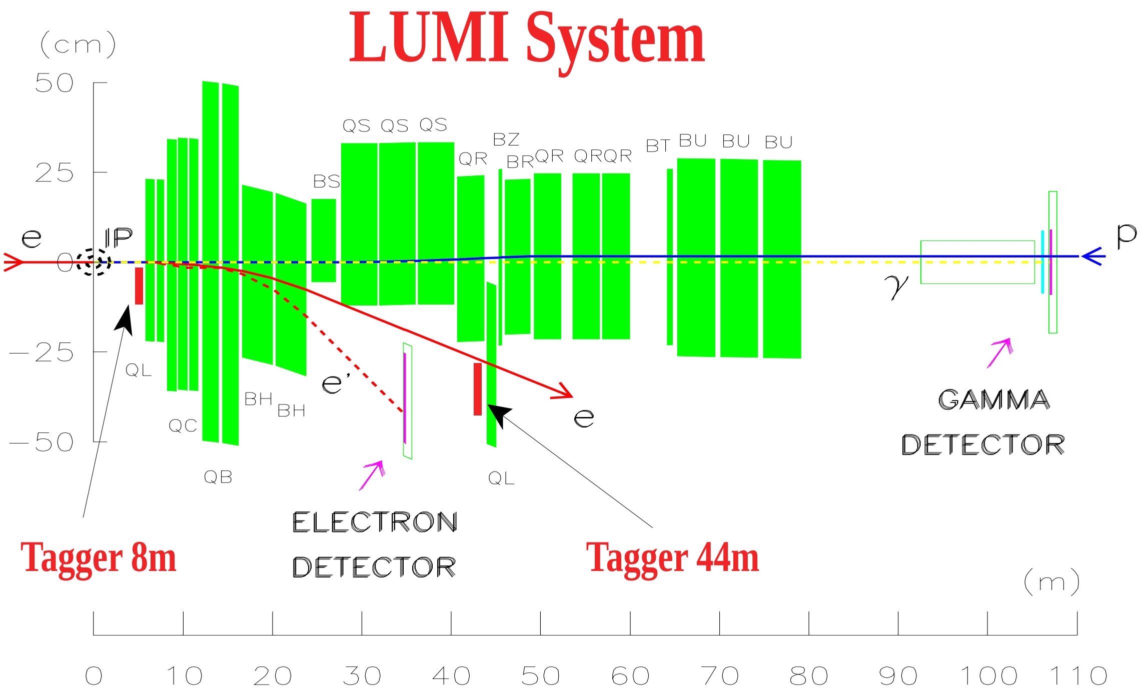
Binning and Unfolding



- Count events in bin in data N_{data} and Monte Carlo N_{MC} for the same luminosity
- Extract F_2 $$F_2^{data}(x,Q^2) = F_2^{MC}(x,Q^2) \times \frac{N_{data}}{N_{MC}}$$
- Fit F_2^{data}, Reweight MC to fit, and repeat

Luminosity

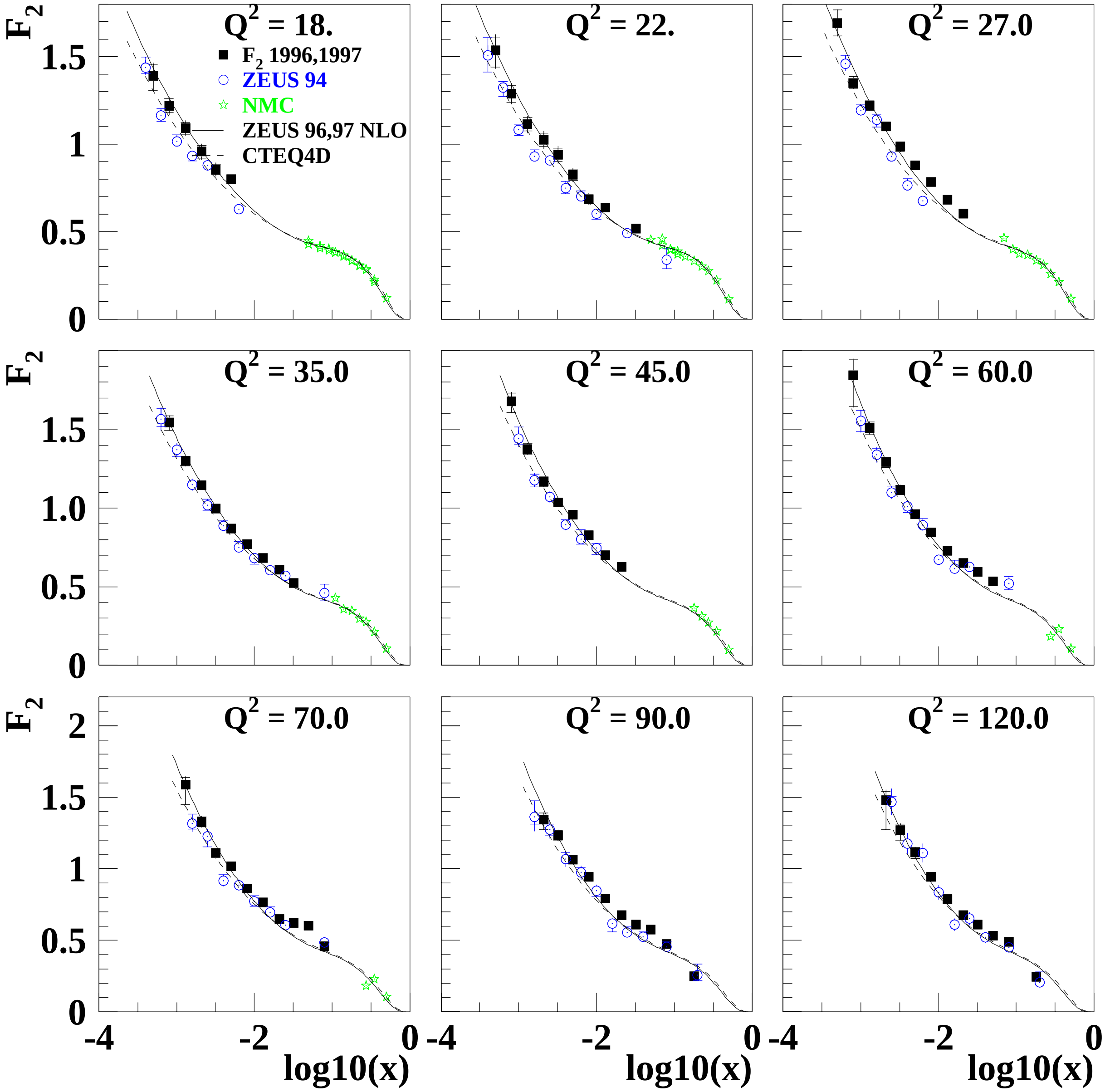
- Luminosity = how many particles pass per unit area (per unit time).



LUMI System

- Use precisely known cross section σ(ep->epγ)
  - Photon measured in gamma detector
  - Electron measured in 35 m tagger is used to calibrate the gamma detector energy.
- Luminosity = #γ events / σ(ep->epγ)
- Sets Normalization of F_2

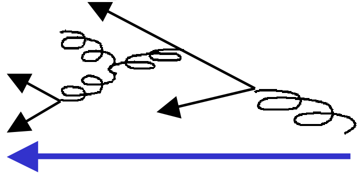
Med Q^2 F_2



– CTEQ4D is a QCD DGLAP fit to the 1994 DATA

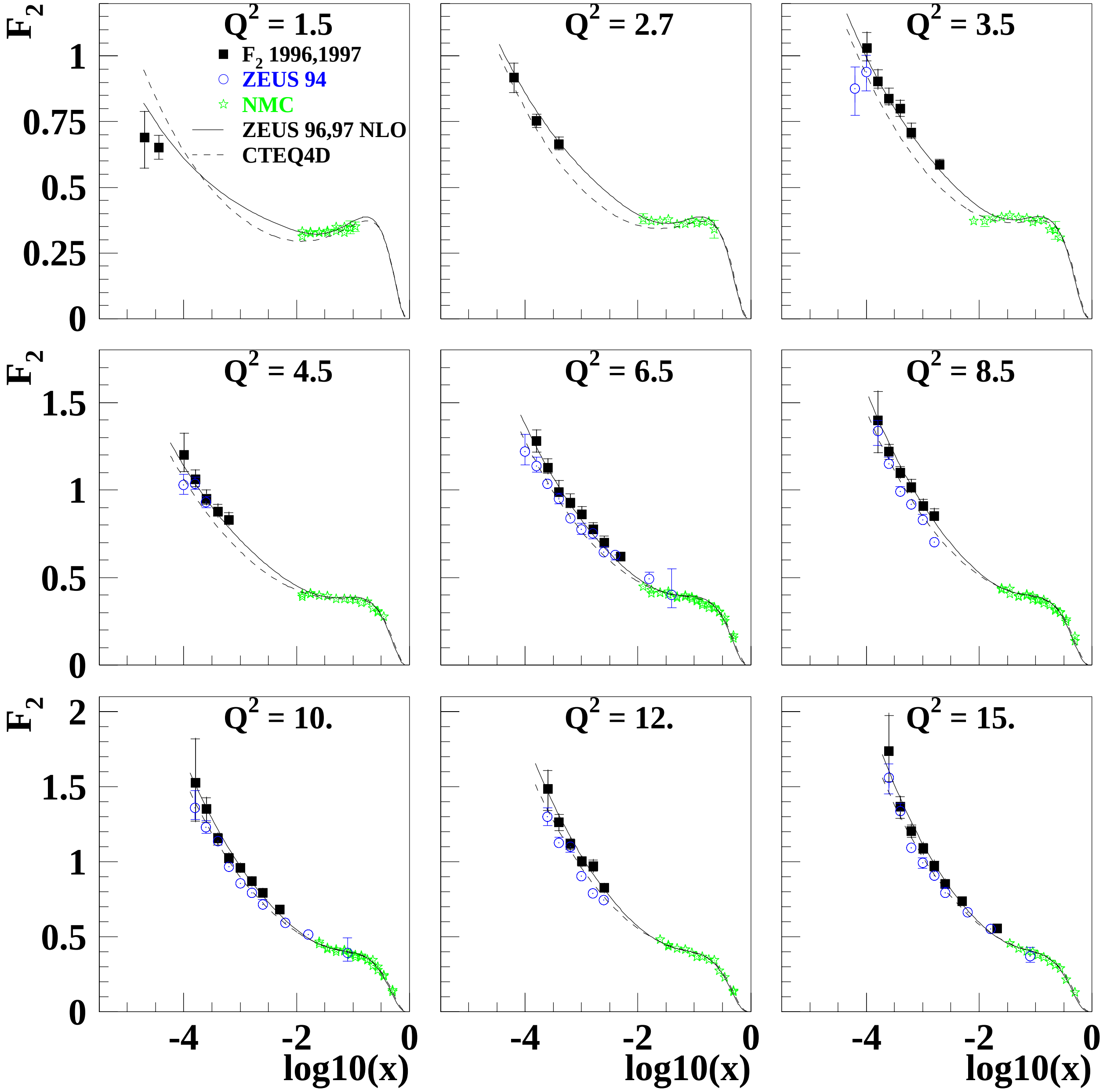
– ZEUS96&97 is a QCD DGLAP fit to this data

– Strong rise in F_2 at low x is from sea quarks

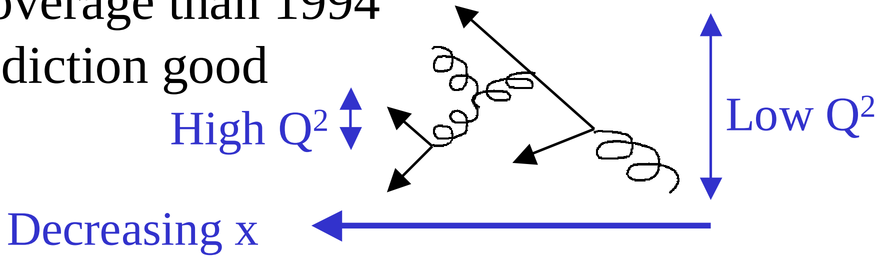


Decreasing x

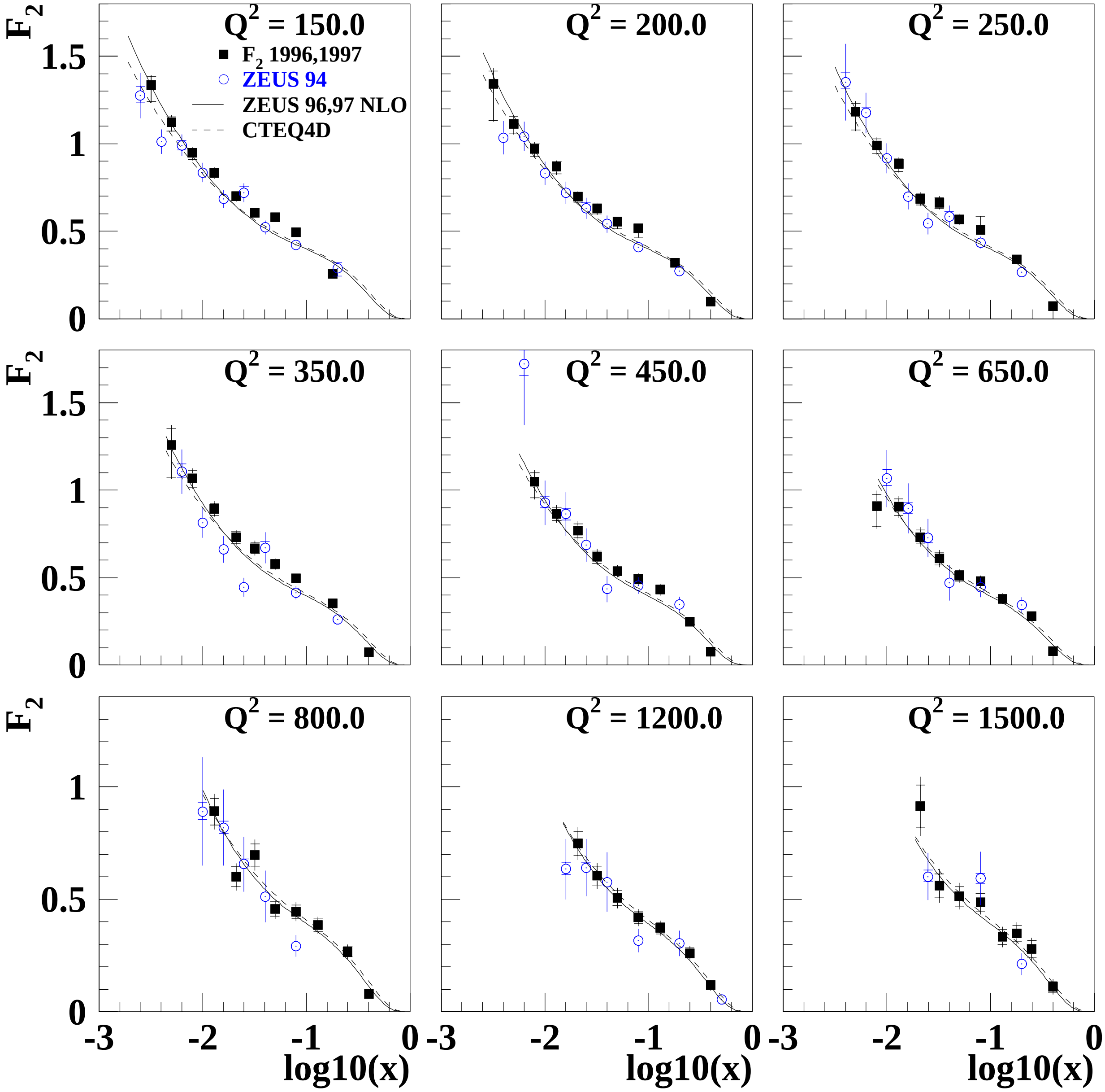
Low Q^2 F_2



- Strong rise at low x seen at very low Q^2!
- Lower Q^2 coverage than 1994
- DGLAP prediction good

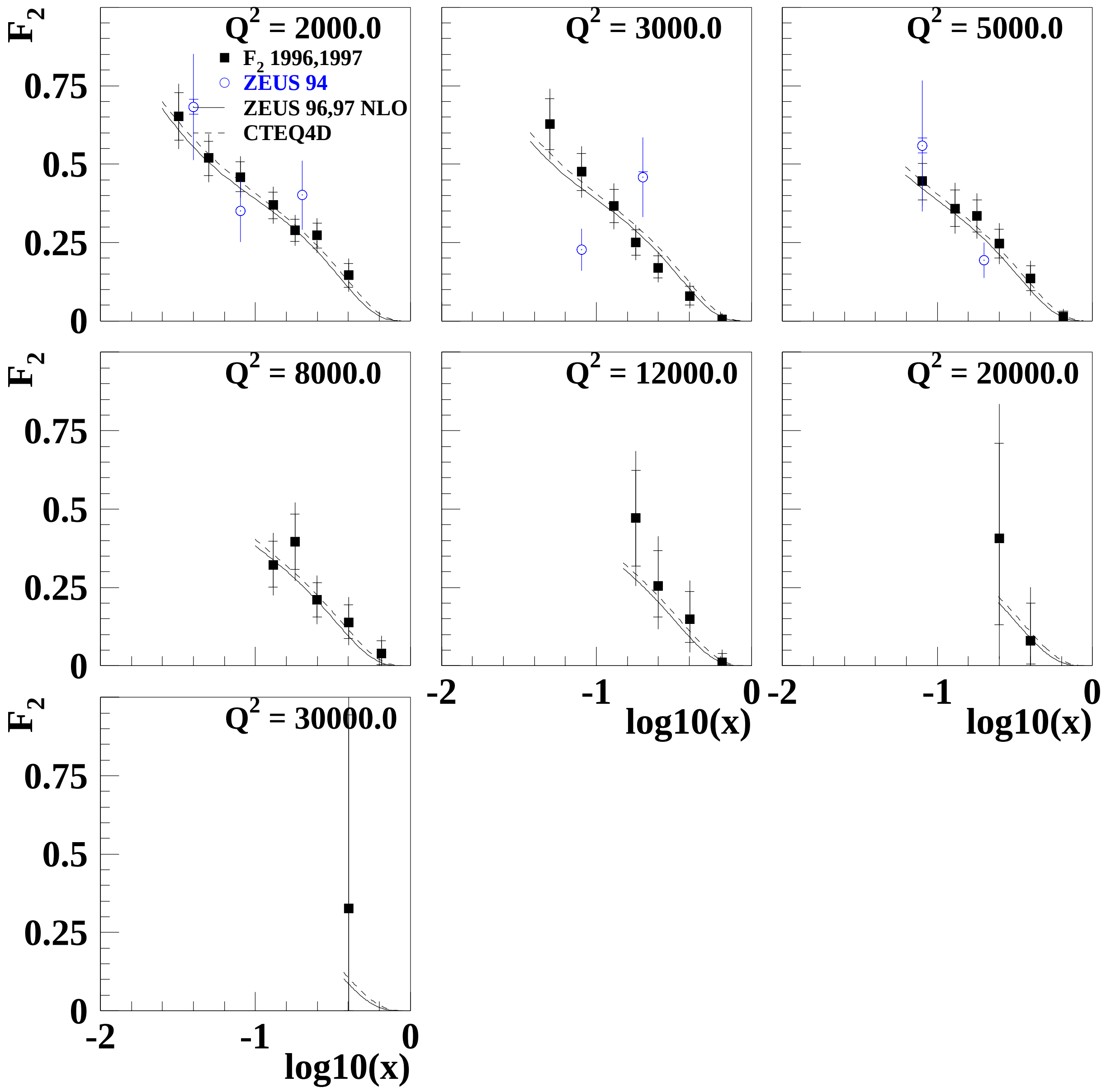


High Q^2 F_2



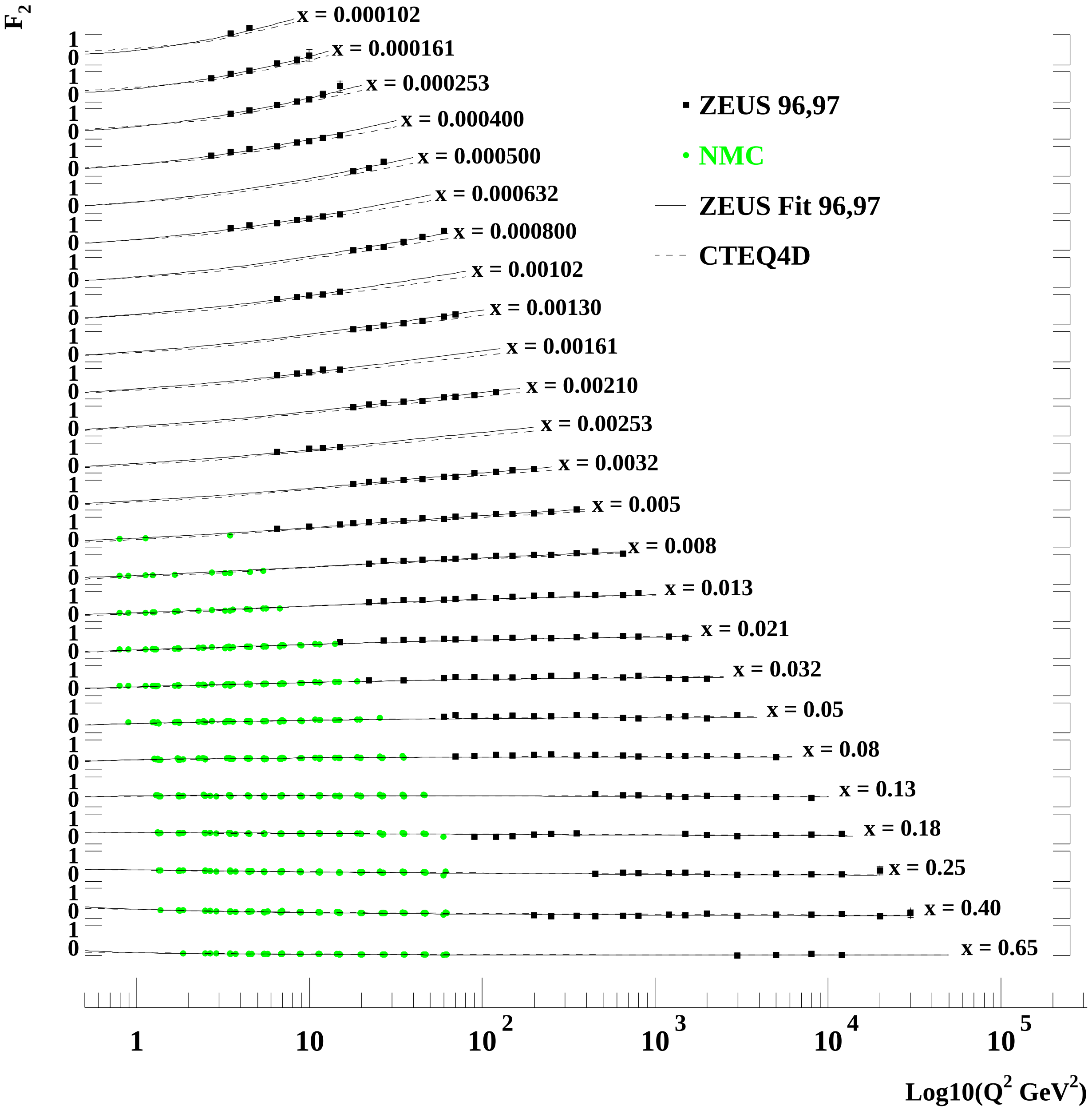
- Finer binning than 1994 at high Q^2
- Detector understanding (systematic error) is the dominant error up to Q^2=800 GeV^2

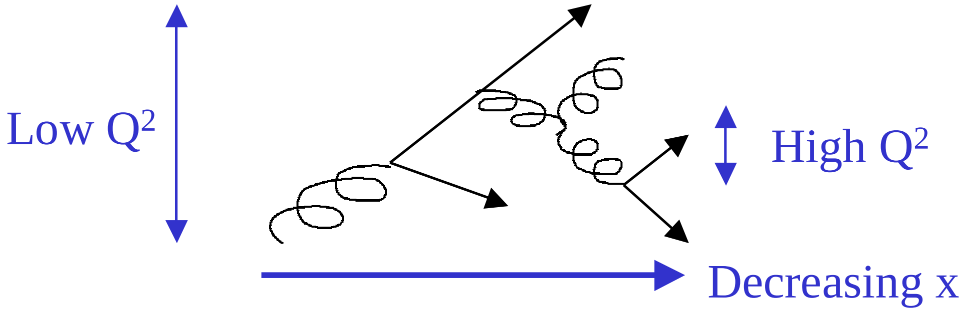
Very High Q^2 F_2



- Strong rise in F_2 seen at our highest Q^2
  - Over 4 orders of magnitude in Q^2
- DGLAP prediction good over whole range
- Increased coverage by an order of magnitude from 1994

F_2 vs. Q^2



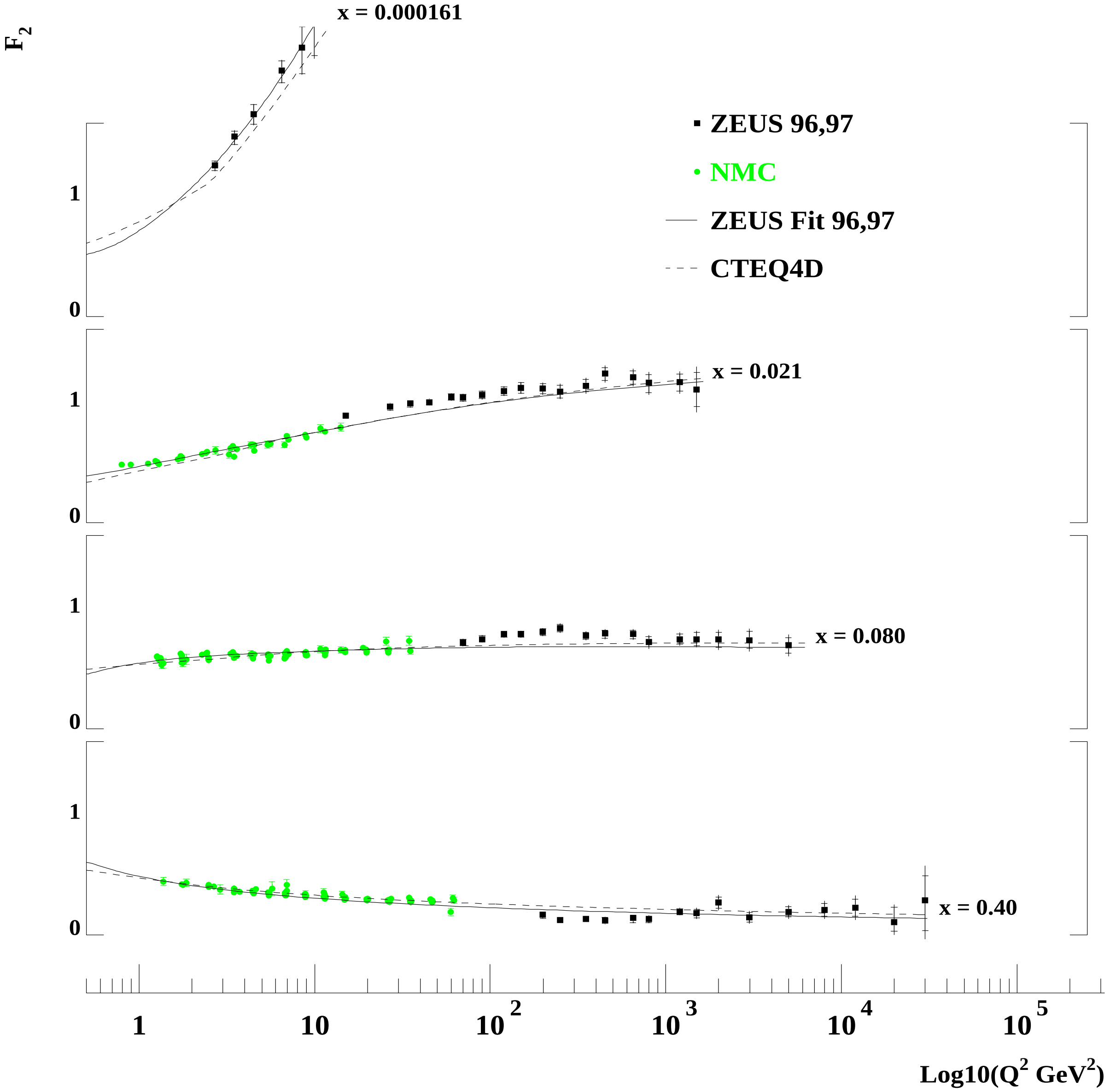


Low Q^2

High Q^2

Decreasing x

F^2 vs. Q_2 (Few x bins)



- High x, F_2 falls with Q^2
  - valance quarks contribution falls
  - gluon small at high x
- Low x, F_2 rises strongly with Q^2
  - Strong gluon -> sea quark contribution

Conclusions

- F_2 is a measure of the quark structure of the proton.

- It has been measured from 1996 and 1997 ZEUS data from e+p collisions.
  - $1.5 < Q^2 < 30000$ GeV^2
    - Wider Coverage at high and low Q^2 compared to 1994
  - $2(10^{-5}) < x < 0.65$

- F_2 shows a strong rise with decreasing x
  - Gluon quark cascade produces more quarks at lower momenta
  - Rise is seen at very low Q^2 (not expected!)

- The rise in F_2 becomes stronger with increasing Q^2
  - Parton splitting increases at smaller distances

- F_2 is described well by QCD DGLAP evolution over the full kinematic range covered.

- Dominant errors on F_2
  - Detector understanding for $Q^2 < 800$ GeV^2
  - Event statistics for $Q^2 < 800$ GeV^2

Future of ZEUS Structure Functions

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

- e+ and e- running to measure xF_3
  - – ZEUS has enough e+ data (used in this analysis)
    - HERA 70.92 pb^{-1} , ZEUS 48.08 pb^{-1}
  - – Plans are forming to get additional e- data
    - HERA 27.37 pb^{-1} ZEUS 17.61 pb^{-1}
- Lower P beam energy to measure F_L

  $sxy = Q^2$ Center of mass energy = √s
  - – Change √s and measure at two different y for the same x and Q^2
  - – After 2000 Luminosity upgrade
- Continue high Q^2>800 GeV^2 Analysis
- Longitudinal polarized electron beam
- Far future?…Polarized proton beams to measure polarized proton structure functions.