ep Collisions with the Zeus Detector at HERA

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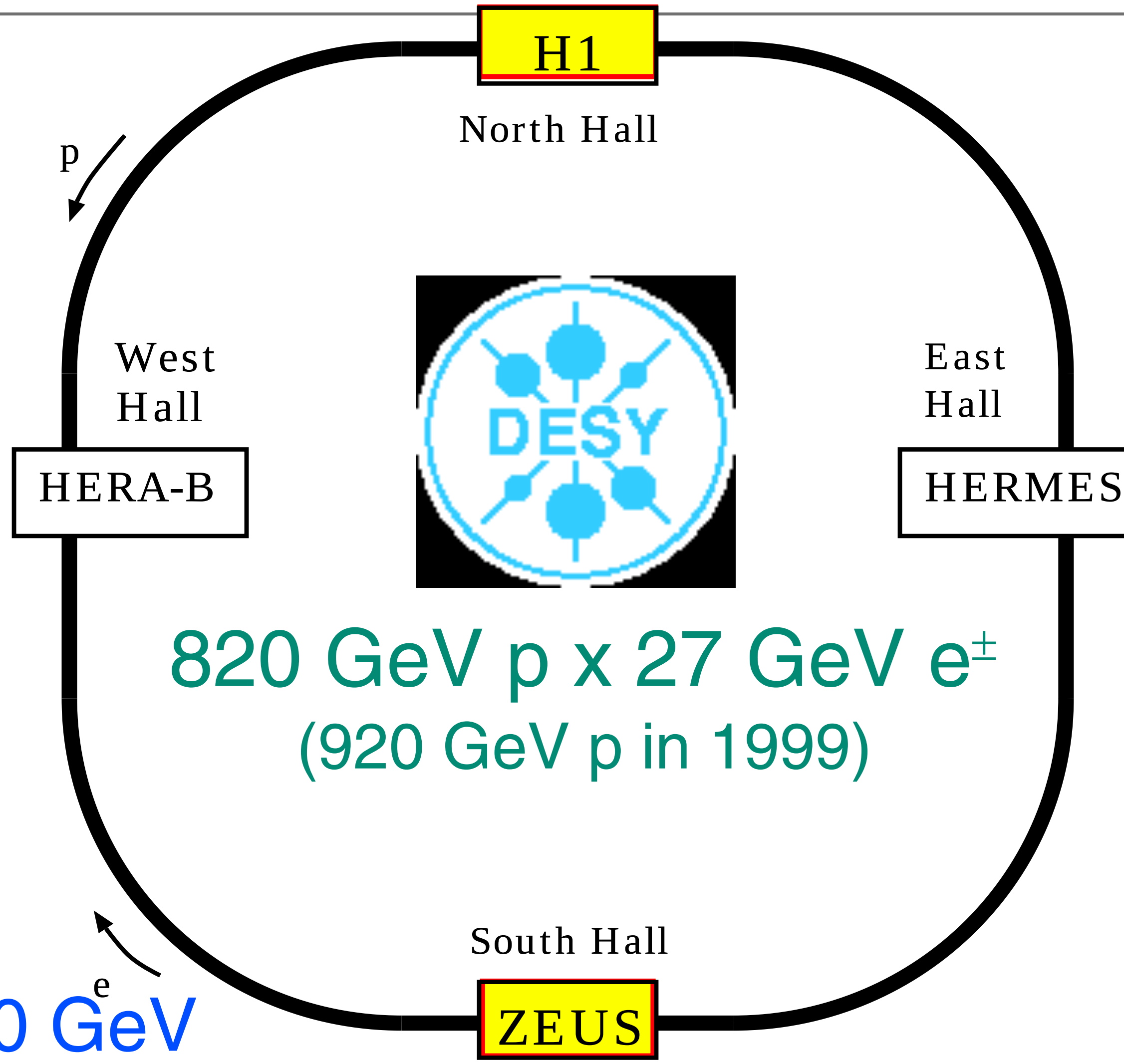
Outline:

- Proton Structure
- Photon Structure
- Conclusions

HERA



Collider:

- $\sqrt{s}$= 300 GeV
  - **Equivalent to 47 TeV fixed target**

Experiments:

- 2 general purpose detectors
  - **H1 & Zeus**
- Dedicated Fixed Target
  - **HERMES:**
    - Polarized electrons on polarized H target
  - **HERA-B**
    - Proton Halo on wire target

ZEUS Collaboration

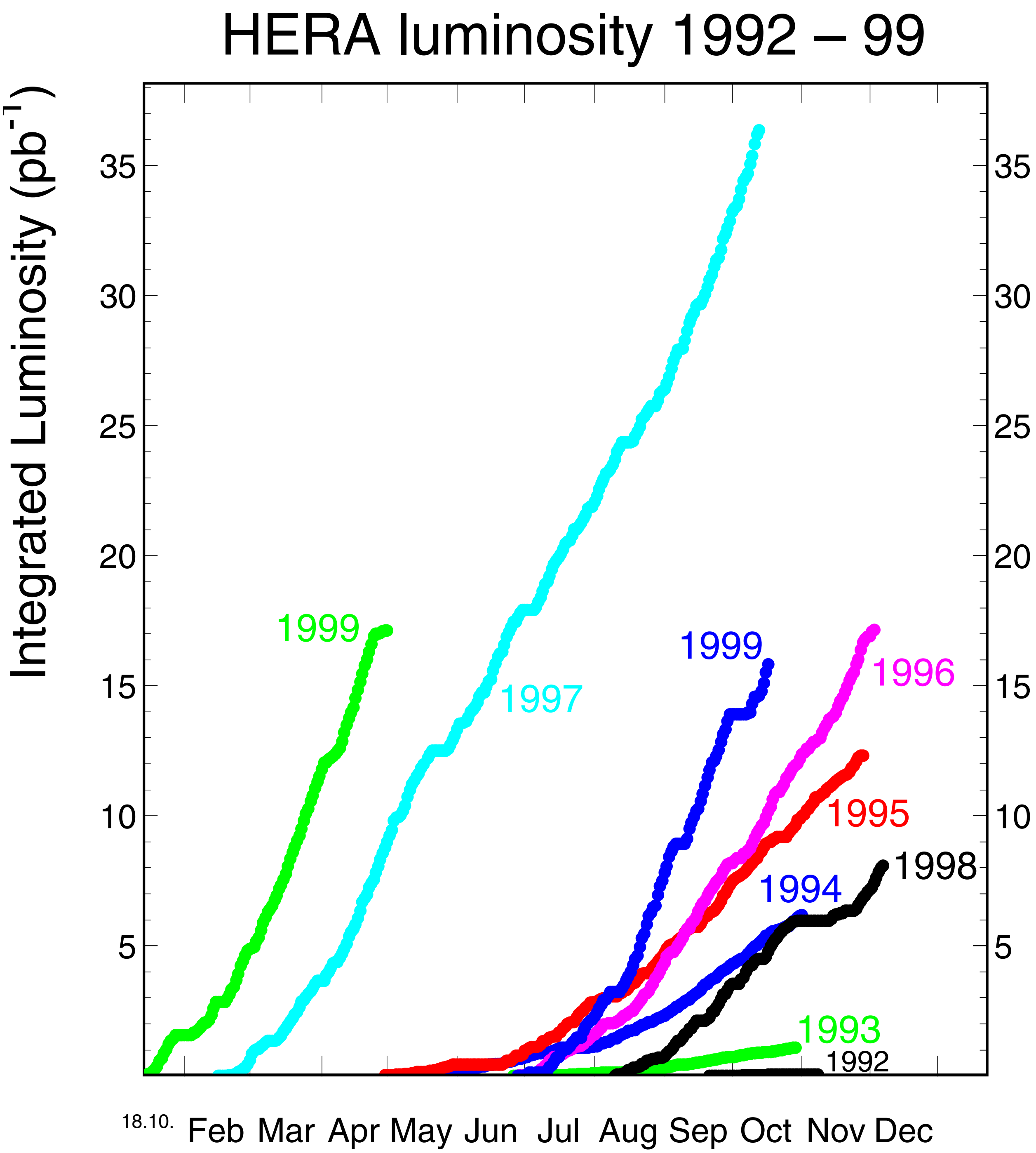
Manitoba, McGill,Toronto, York
CANADA
Bonn, DESY, DESY-Zeuthen, Freiburg,Hamburg I,
Hamburg II, Julich, Siegen
GERMANY
Tel Aviv, Weizmann
ISRAEL
Bologna, Cosenza, Florence, Frascati-Rome, Padua,
La Sapienza-Rome, Turin
ITALY
Tokyo-INS, Tokyo-Metropolitan
JAPAN
Seoul
KOREA
NIKHEF-Amsterdam
The NETHERLANDS
Cracow, Warsaw
POLAND
Moscow
RUSSIA
Madrid
SPAIN
Bristol, London(I.C.), London(U.C.),
Oxford, Rutherford
UNITED KINGDOM
Andrews, Argonne, Brookhaven, Columbia, Iowa,
Ohio State, Pennsylvania State,
U.C. Santa Cruz, Wisconsin, Yale
U.S.A.

50 Total Institutions
420 Total Physicists

HERA Data Runs

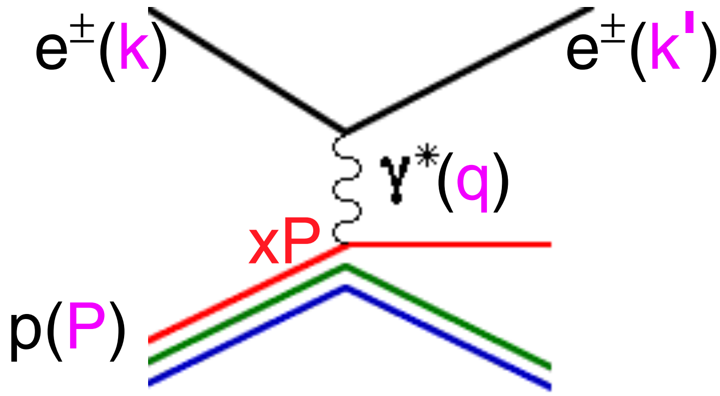
ZEUS Data Samples:

- 48 pb^{-1} e^+p (1994-1997)
- 22 pb^{-1} e^-p (1998-1999)
- 1999: 15.8 pb^{-1} e^+p (as of Oct. 18)

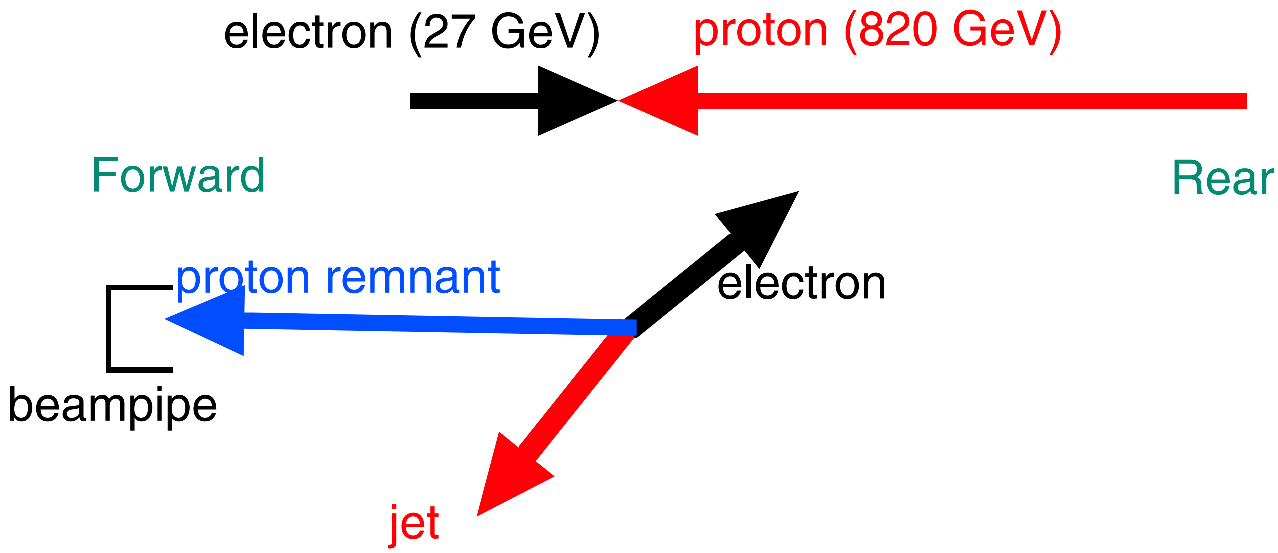


Deep Inelastic Scattering

The DIS process



Measuring DIS at HERA:



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

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

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

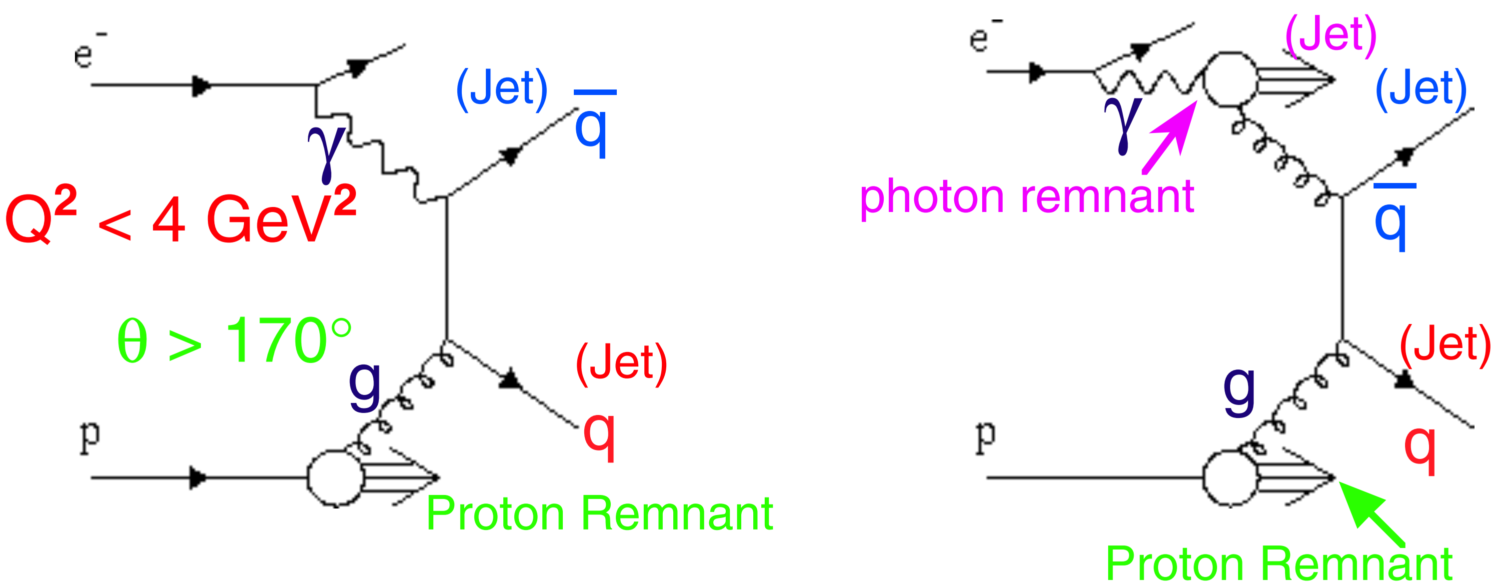
y = the fraction of the electron's energy lost in the proton rest frame

$$x = \frac{Q^2}{2P\bullet q} \qquad y = \frac{P\bullet k}{P\bullet q} \qquad Q^2 = sxy$$

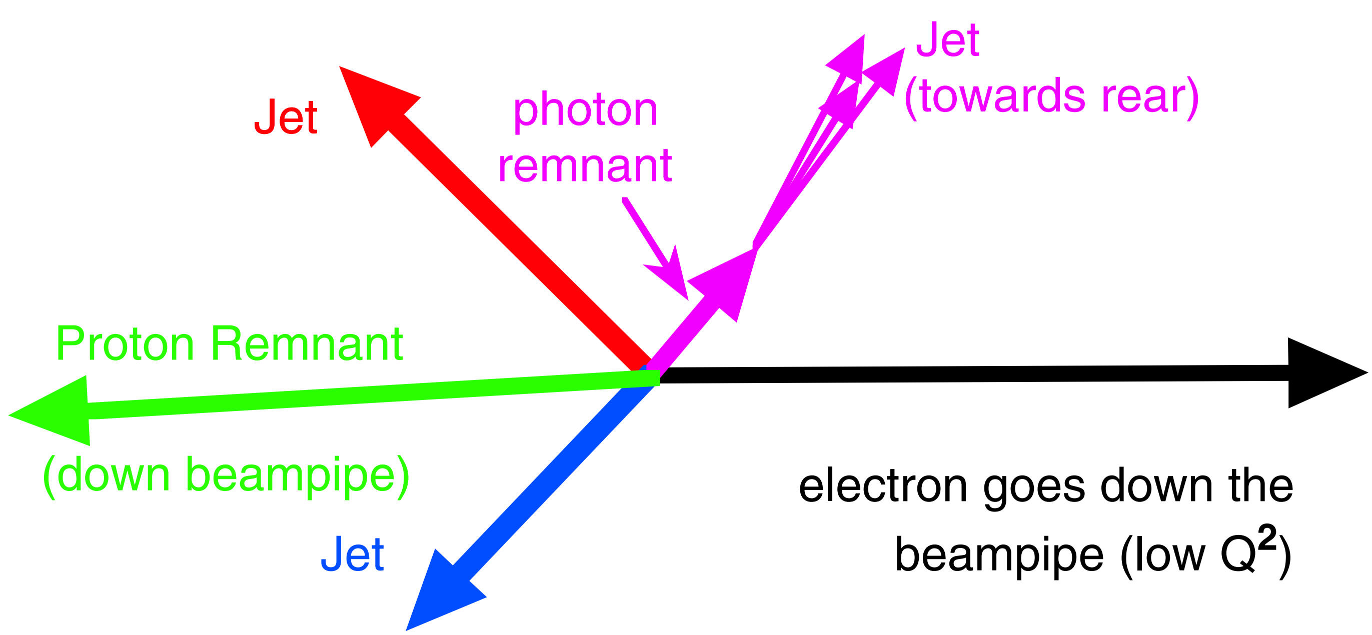
Photoproduction

Direct:

Resolved:

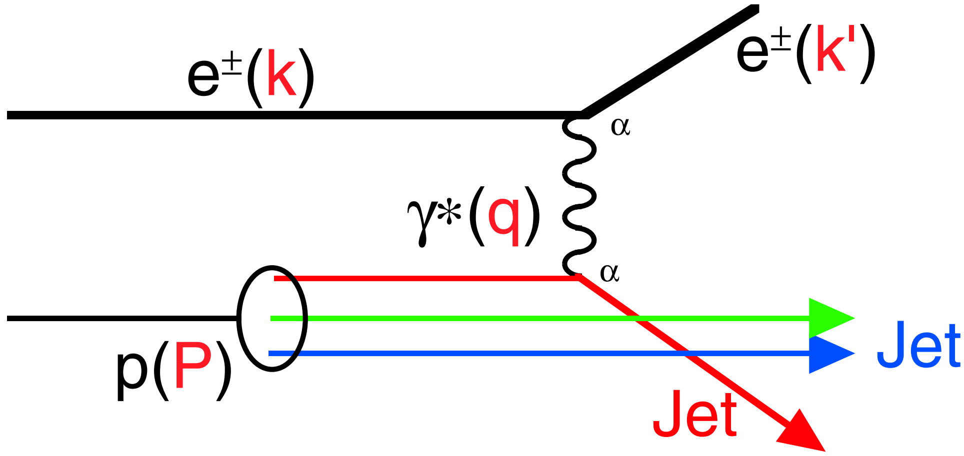


Almost real photon



Background for DIS

DIS cross section



DIS differential cross section:

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

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

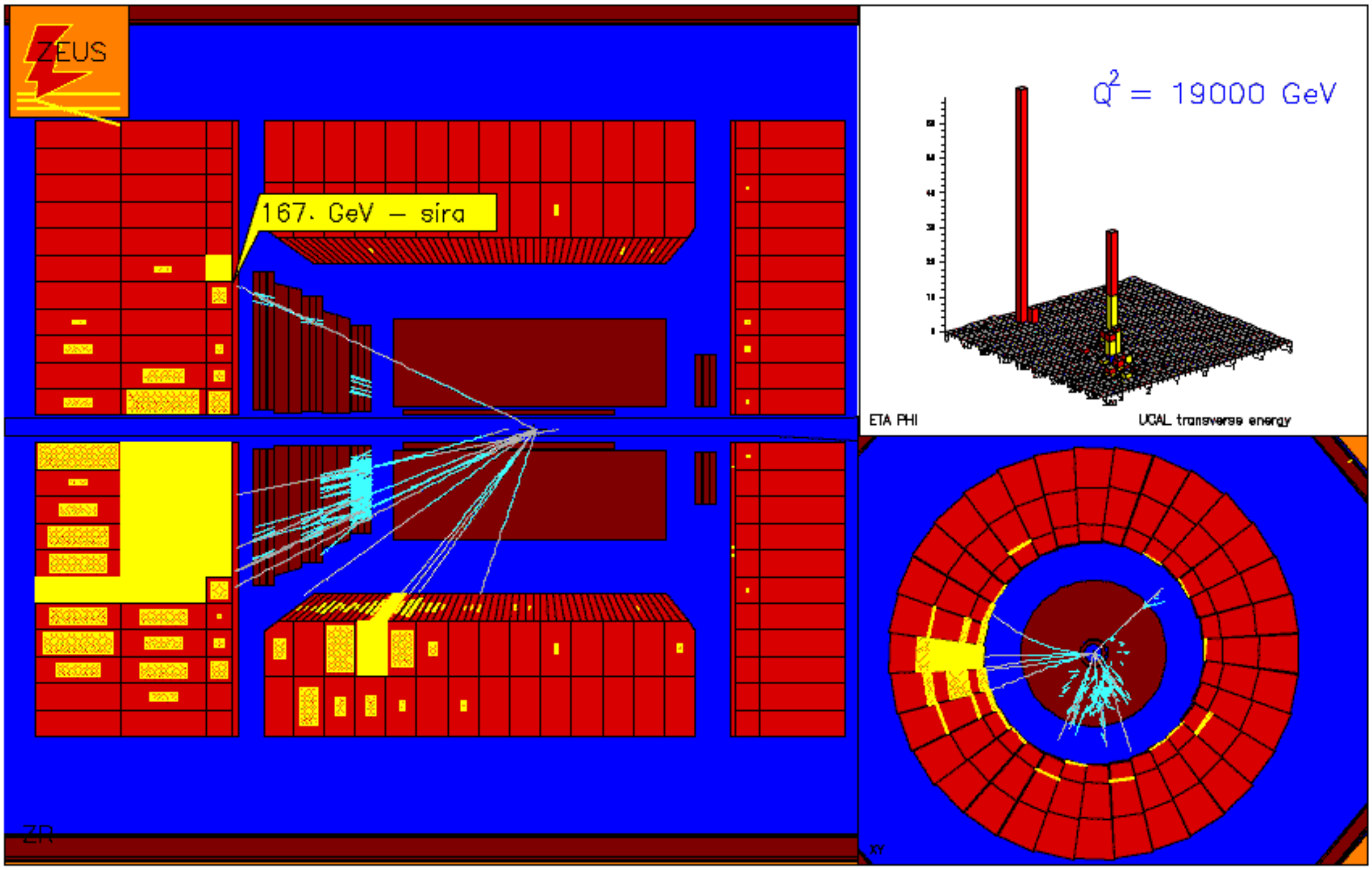
γ^* is longitudinally or transversely polarized

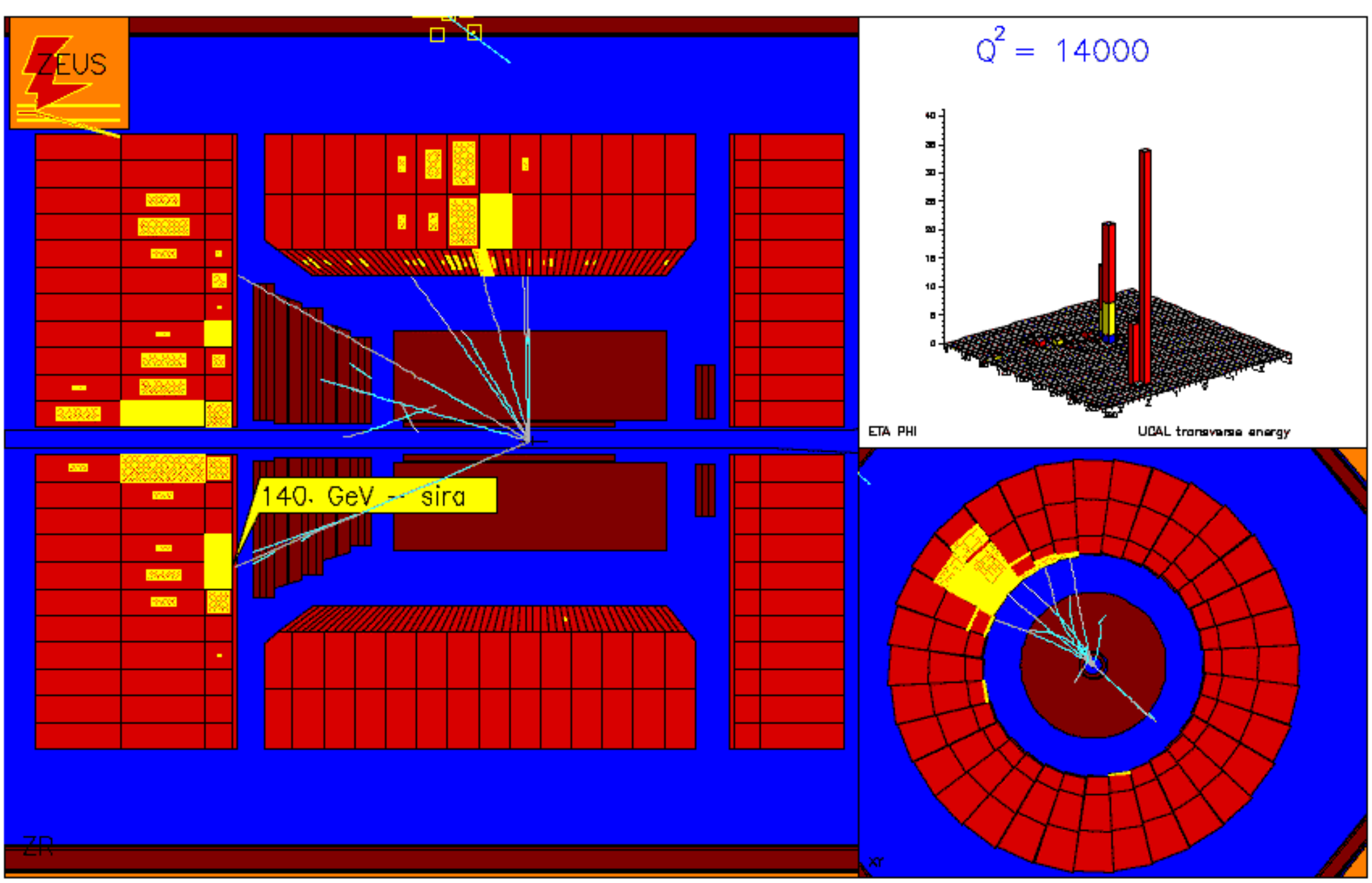
$F_2(x,Q^2)$ = Structure function = interaction btw. transversely polarized photons & spin 1/2 partons = charge weighted sum of the quark distributions.

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

$F_3(x,Q^2)$ = Parity-violating structure function from Z^0 exchange. (Important at high Q^2).

Two High -Q^2 DIS NC events

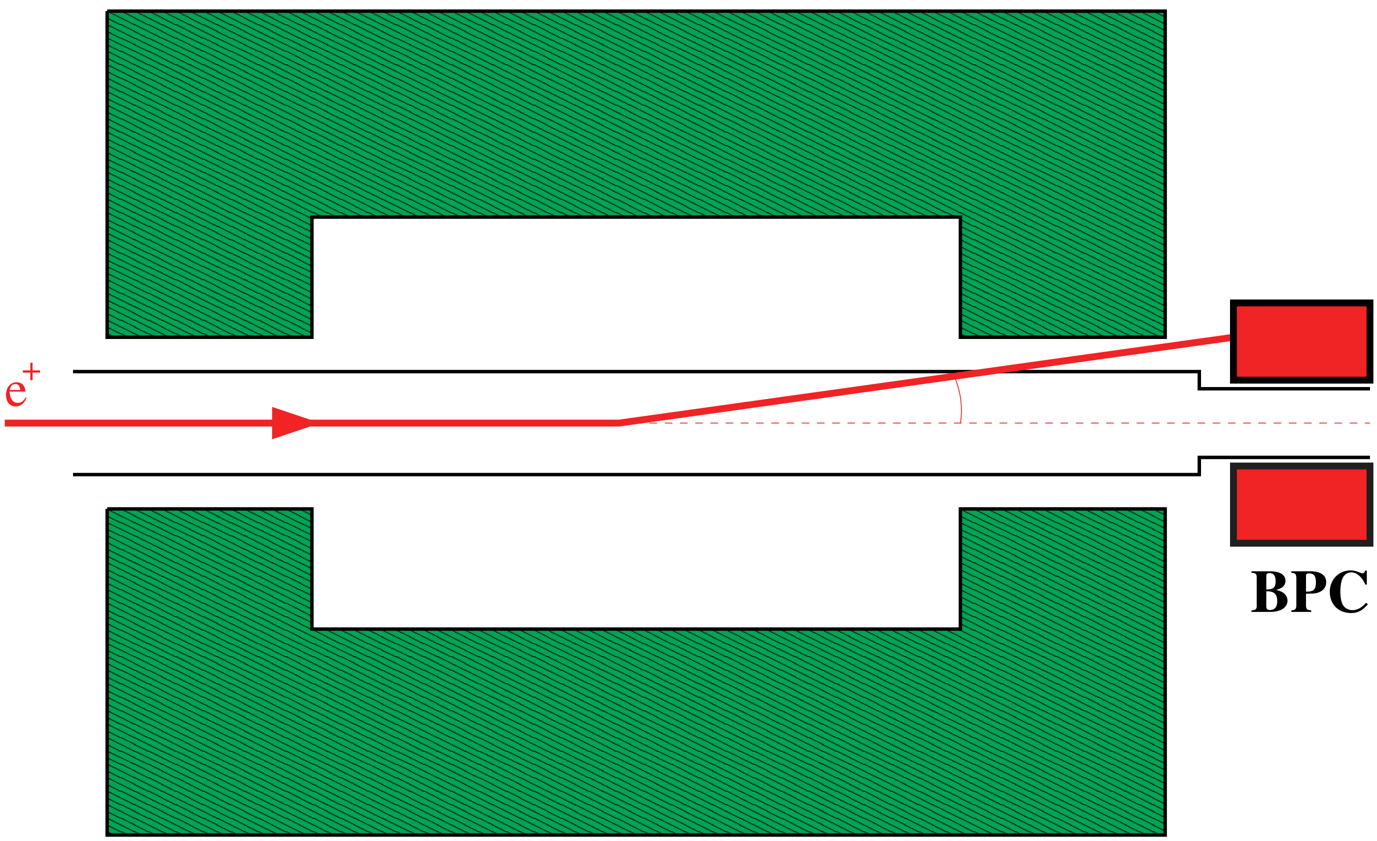




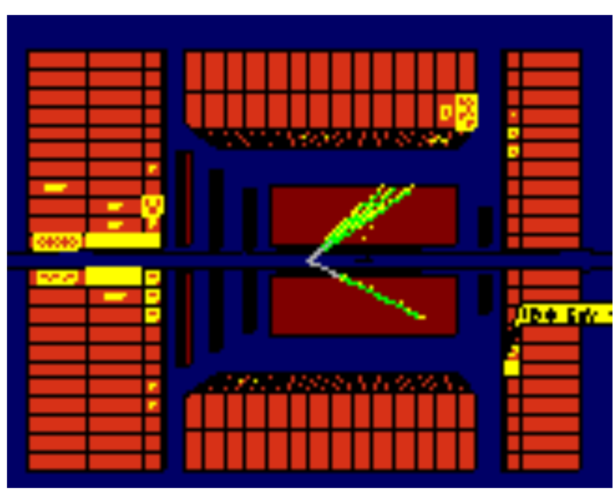
Low Q^2 Measurements

$$Q^2 = 4EE' \cdot sin^2(\frac{\Theta}{2})$$

Zeus Beampipe Calorimeter:

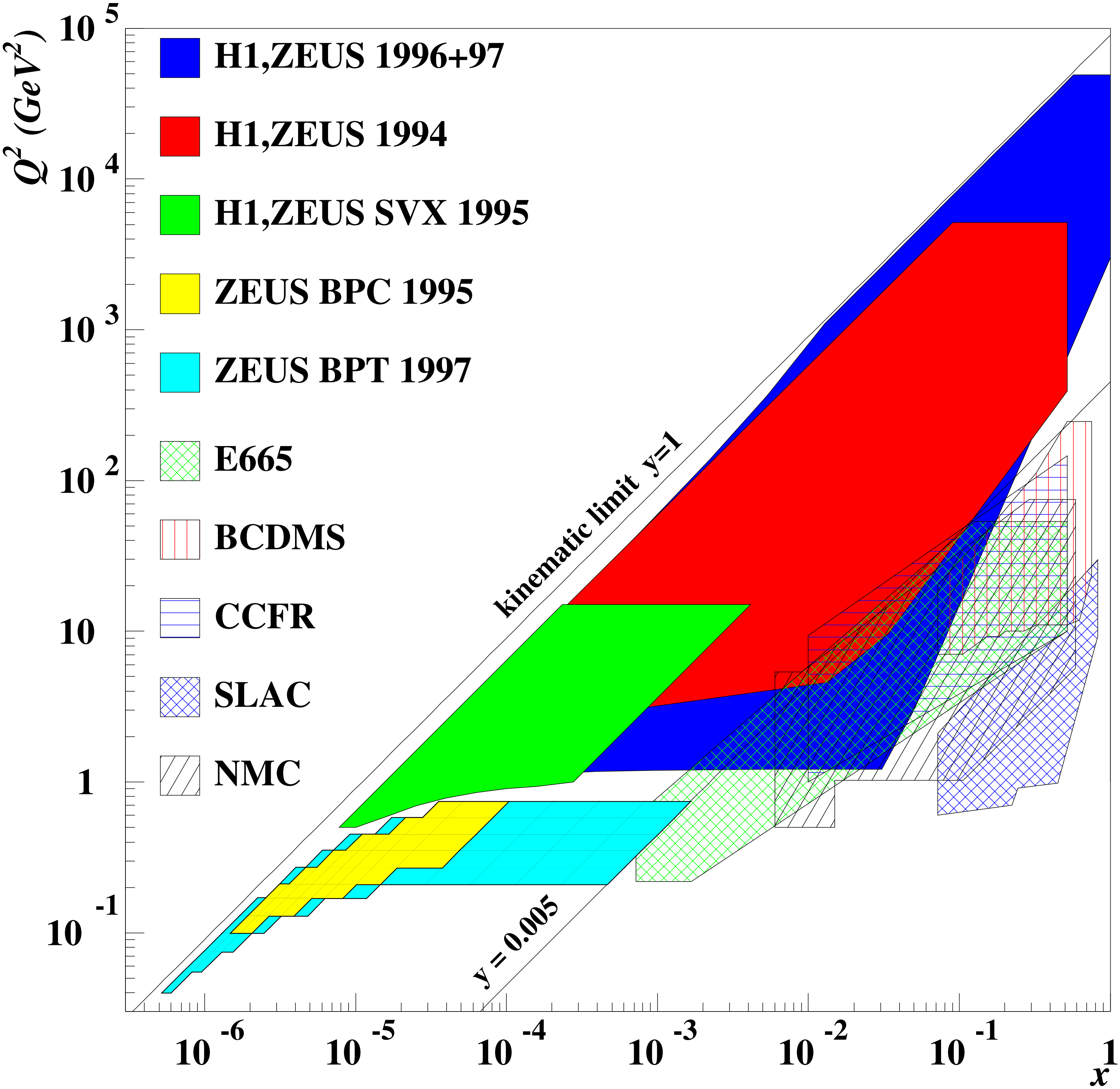


H1 & Zeus Shifted Vertex:



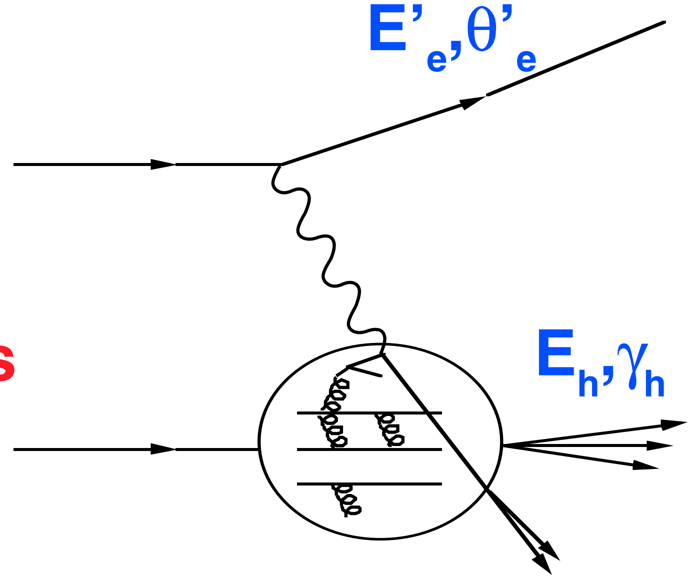
H1 & Zeus Initial State Radiation

HERA Kinematic Range



F_2 measurements span large region not accessible by fixed target experiments, from soft to hard scattering, with some overlap

Kinematic reconstruction



Two Kinematic Variables

- x, Q^2

Four Measured Quantities

- $E_e', \theta_e', E_h, \gamma_h$

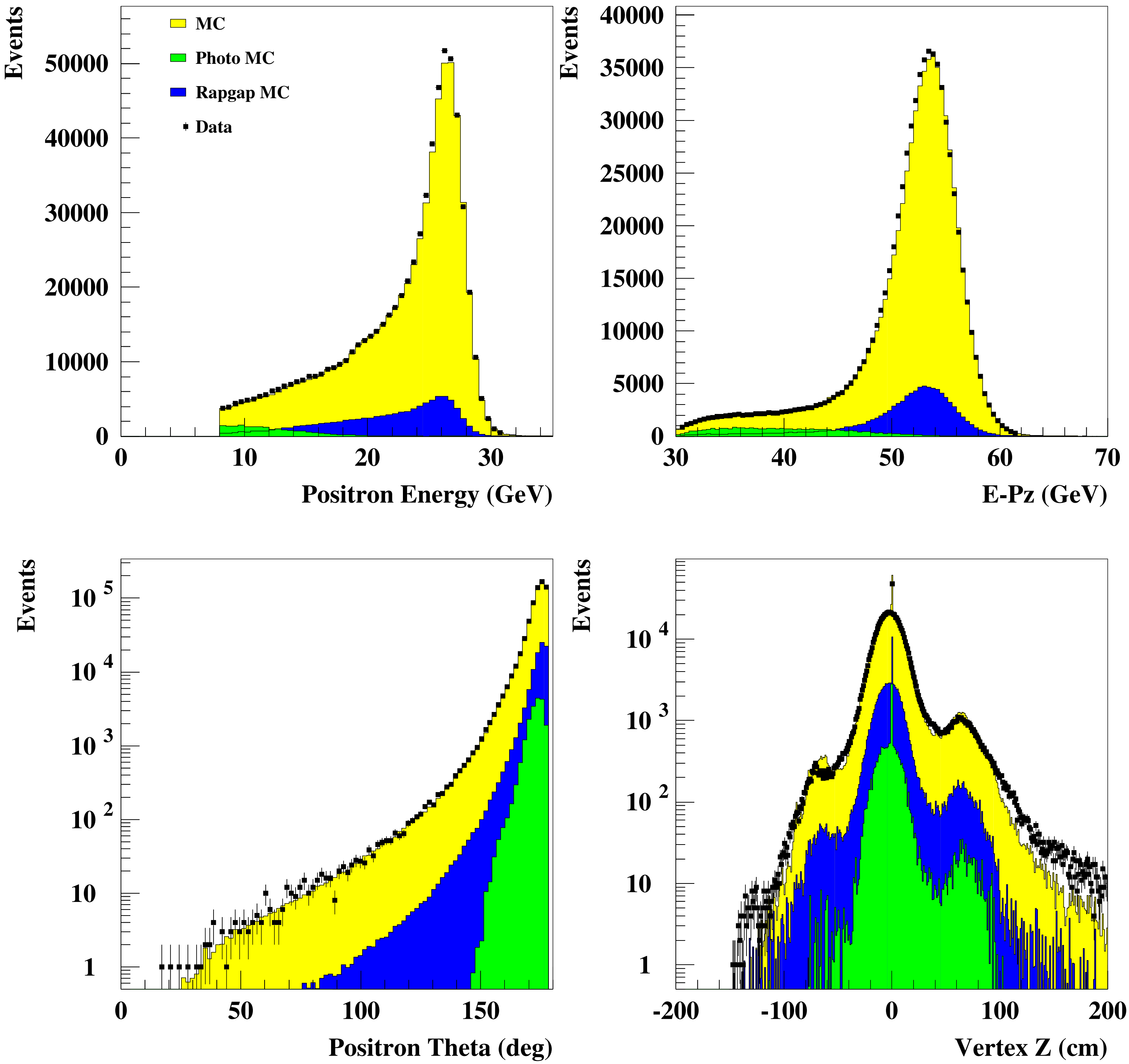
Energy Conservation

- $\Sigma = E - P_z = 2E_e$ - this quantity summed over all calorimeter cells yields a measure less sensitive to noise, jet fluctuations and lost proton remnant.

Multiple Reconstruction Methods

- Electron Method (E_e', θ_e')
  - Poor resolution at low y
  - Classic Fixed Target Technique
- Double Angle Method (θ_e', γ_h)
  - Less sensitive to energy scale
  - Subject to calorimeter noise at low Q^2
  - Commonly used by ZEUS
- Jaquet-Blondel Method (E_h, γ_h)
  - Hadronic energy mis-measurement results in large systematic error.
  - Only possibility for Charged Current events

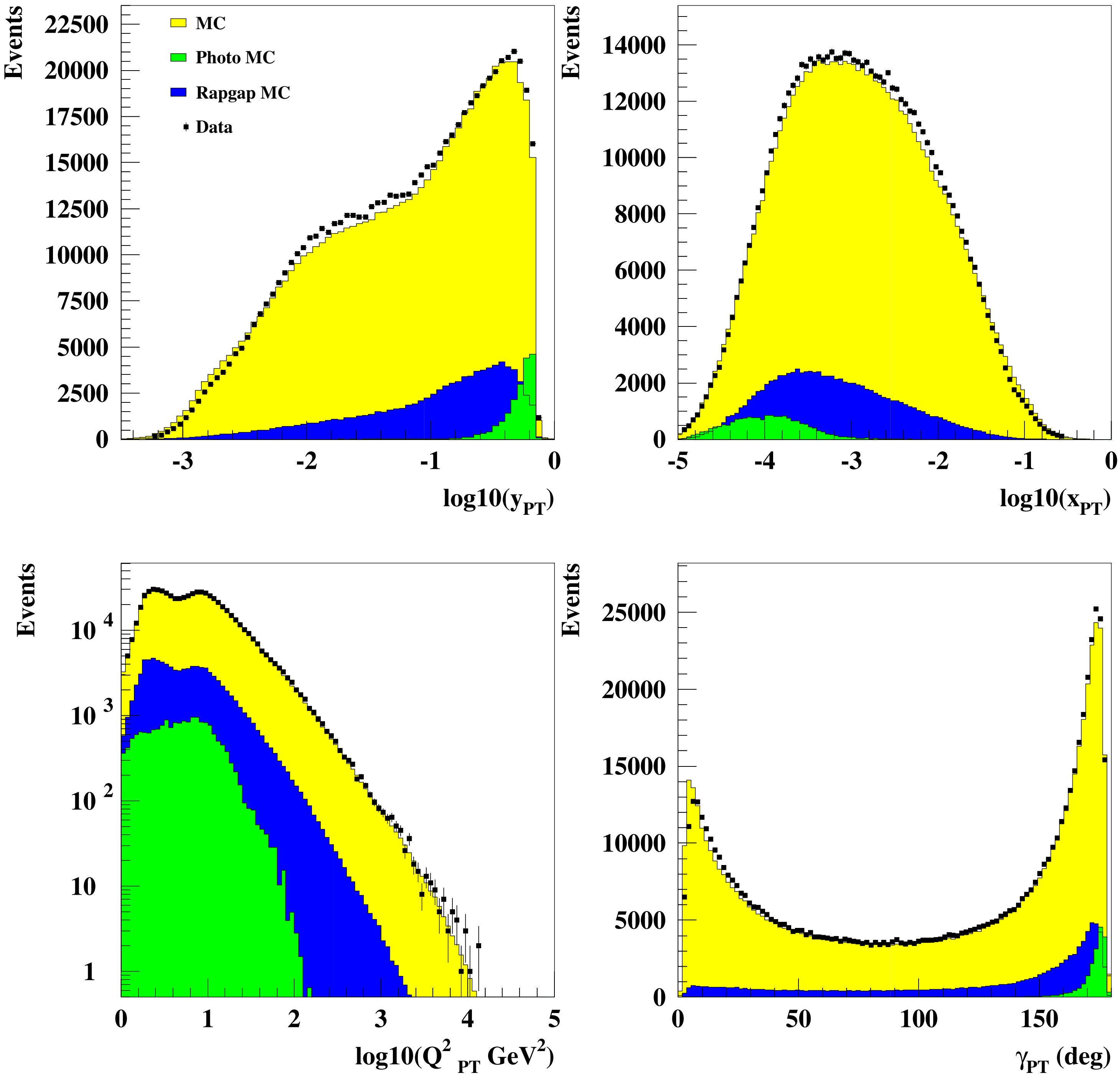
Kinematic Reconstruction



Electron energy, $E-P_z$, electron angle & Z vertex used to measure F_2

Data shown vs. DIS, Photoprod., Diffractive MC

Reconstructed Kinematics



Reconstructed x, y, Q^2, & hadron shower angle (γ_h)

- Photoproduction bkgd. contributes mostly at high y
- x & Q^2 used for binning & unfolding of F_2

Perturbative QCD

In the naive parton model the structure function F_2 is given by the charge weighted sum of parton momentum densities that depends only on x (scaling).

Perturbative QCD provides a scheme to characterize the Q^2 dependence (scaling violations):

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

Given an empirical parameterization for parton densities at $Q^2=Q_0^2$,e.g.:

$$xg(x) = A_g x^{\delta_g}(1-x)^{\eta_g}(1+\gamma_g x)$$

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

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

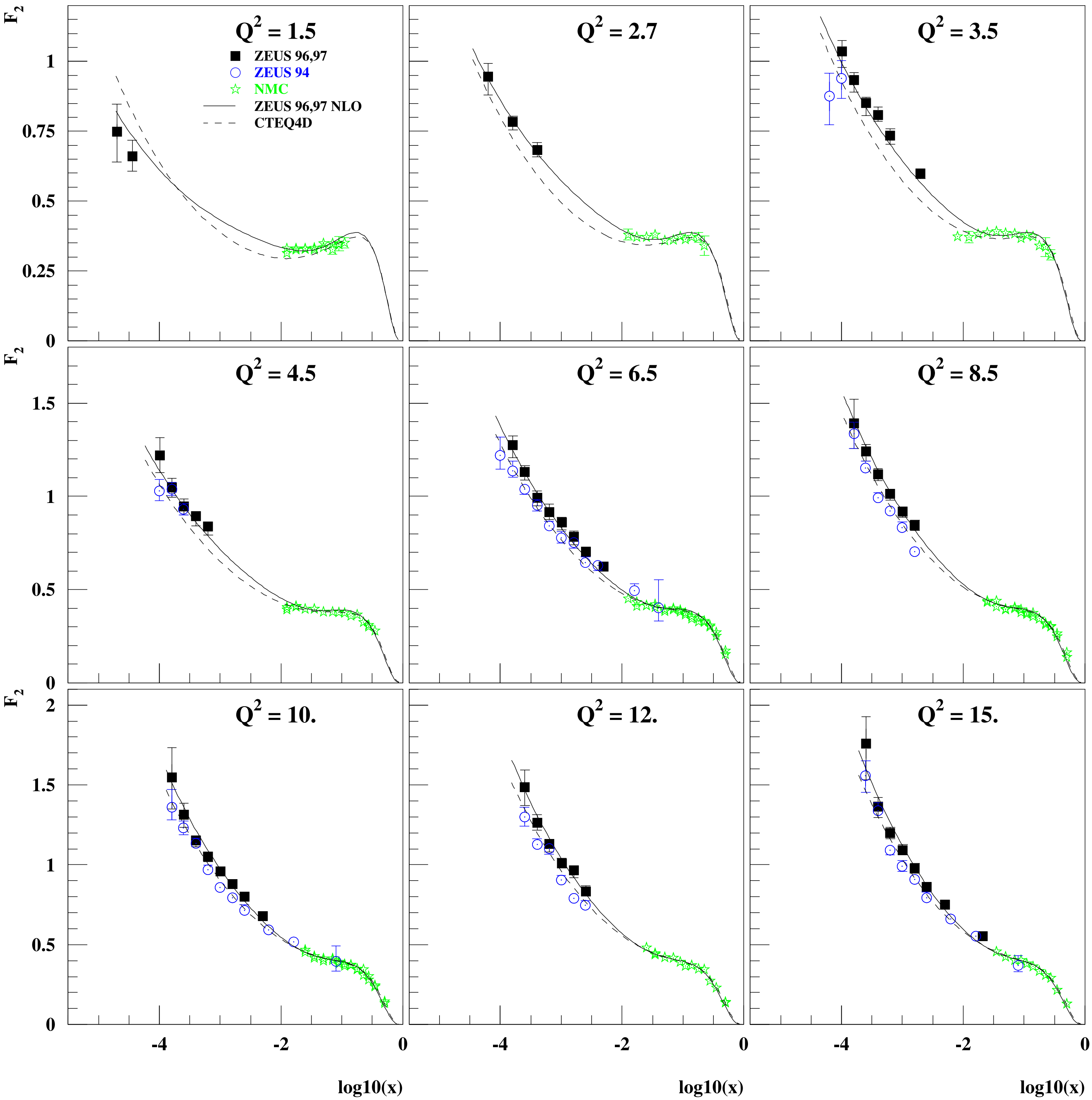
$$\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dw}{w}\left[\sum_i q_i(w,Q^2)P_{gq}\left(\frac{x}{w}\right) + g(w,Q^2)P_{gg}\left(\frac{x}{w}\right)\right]$$

Calculation of DIS cross section requires F_L:

$$F_L(x,Q^2) = \frac{\alpha_s(Q^2)}{\pi}\int_x^1 \frac{dw}{w}\left(\frac{x}{w}\right)^2 \left\{\frac{4}{3}F_2(w,Q^2) + 2\sum_i e_i^2\left(1-\frac{x}{w}\right)wg(w,Q^2)\right\}$$

The parameterization of gluon density can be determined by fitting QCD evolution to DIS data.

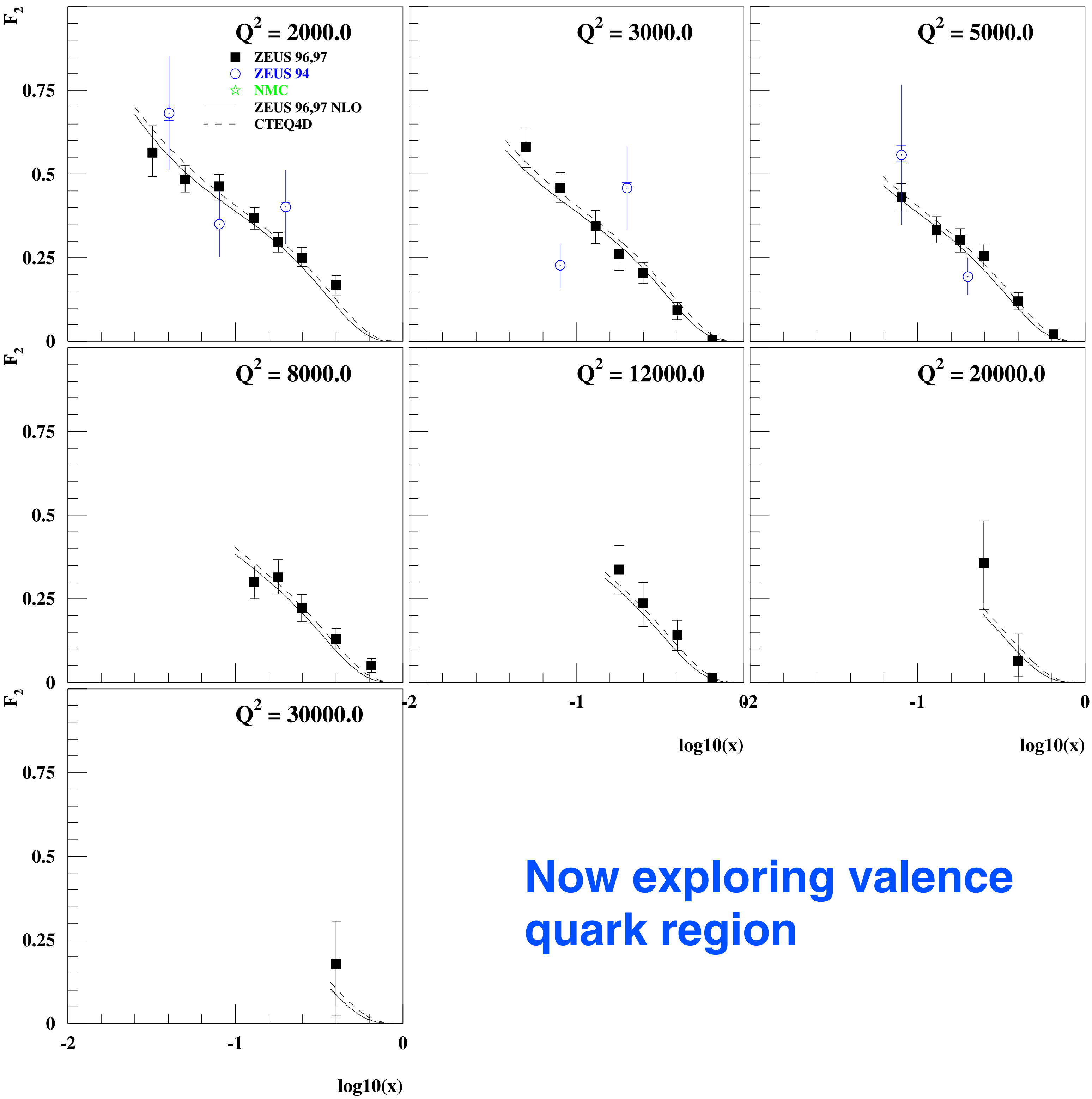
New F_2 vs. x at Lower Q^2



Can reach lower Q^2 than 1994 data

Steep rise in F_2 with decreasing x seen at low Q^2

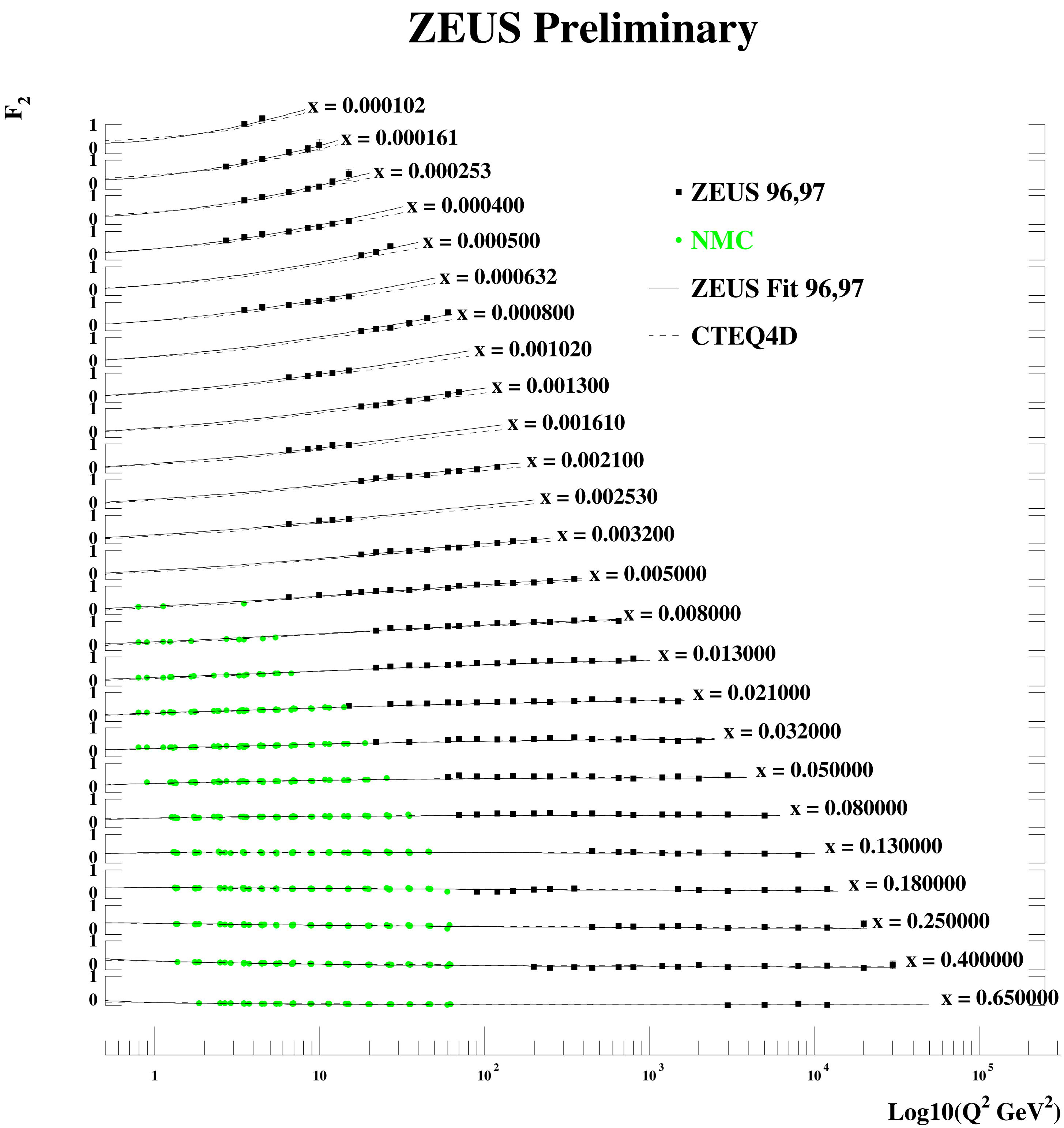
New F_2 vs. x at Higher Q^2



Now exploring valence quark region

Extension of measurement to higher Q^2
Steep rise in F_2 with decreasing x at high Q^2 confirmed

F_2 vs. Q^2 from '96-'97 Data



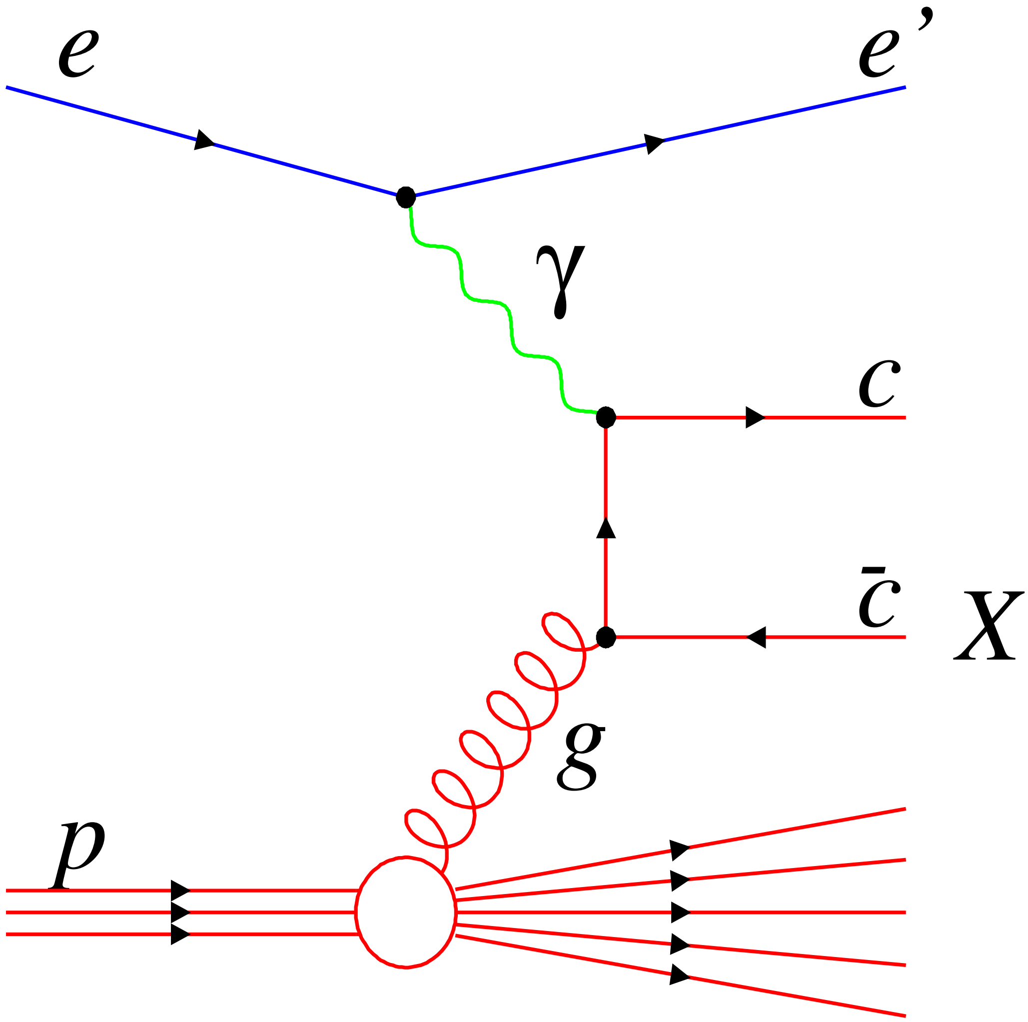
Scaling violation increasing at low x

QCD fits to scaling violation yields gluon

Charm Production in DIS

...a more direct probe of the gluon

Boson-gluon fusion process:



F_2^{charm} is the charm contribution to F_2
Charm almost exclusively from boson-gluon fusion
From F_2^{charm}, gluon content can be extracted

Zeus Structure Functions

Medium to High Q^2:

- NLO-pQCD provides a self consistent description of the data from $Q^2 = 1$ to 20,000 GeV^2.
- Strong rise of F_2 towards low x seen across kinematic range
- New precise (1% stat + 3% syst) higher statistics data
- Measurement of F_2^c provides additional consistency check
- Good agreement between HERA and fixed target
- Clear scaling violations enable calculation of gluons with 10-15% precision
- Gluon vs. sea density at $Q^2 = 1$?

Low Q^2:

- Observed transition from perturbative to non perturbative regime
- Regge models can describe the data
- At lowest Q^2 a soft Pomeron is sufficient
- At higher Q^2, need a hard/variable α Pomeron
- Need to understand coexistence of high Q^2 pQCD and low Q^2 Regge Theory

γ^*p Total Cross Section

HERA is a photon-proton collider

At low Q^2 , a source of almost real photons:

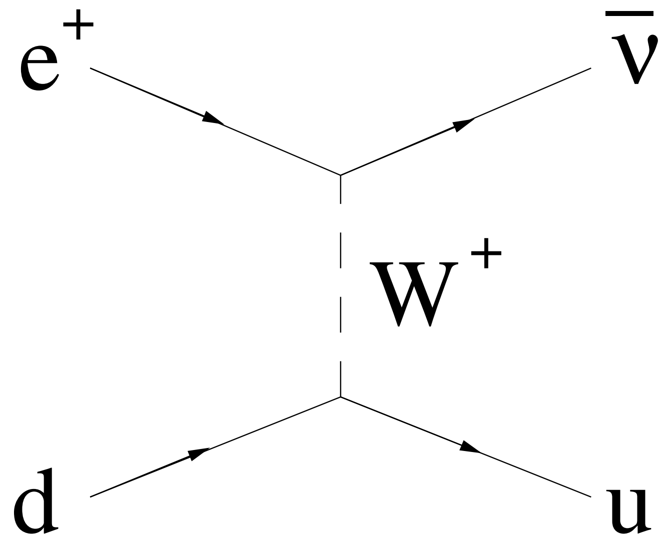
- Can measure cross section over a wide range of γ^*p center of mass energies, W
- ...also study transition region between non-perturbative and perturbative QCD in the range $0.3<Q^2<1.5$ GeV^2

$$\sigma_{\gamma^* p}^{total} = \sigma_L + \sigma_T$$

$$= \frac{4\pi\alpha^2}{Q^4} \frac{4M_p^2 x^2 + Q^2}{1-x} F_2$$

$$\approx \frac{4\pi^2\alpha}{Q^2} F_2(x,Q^2)$$

Charged Current DIS

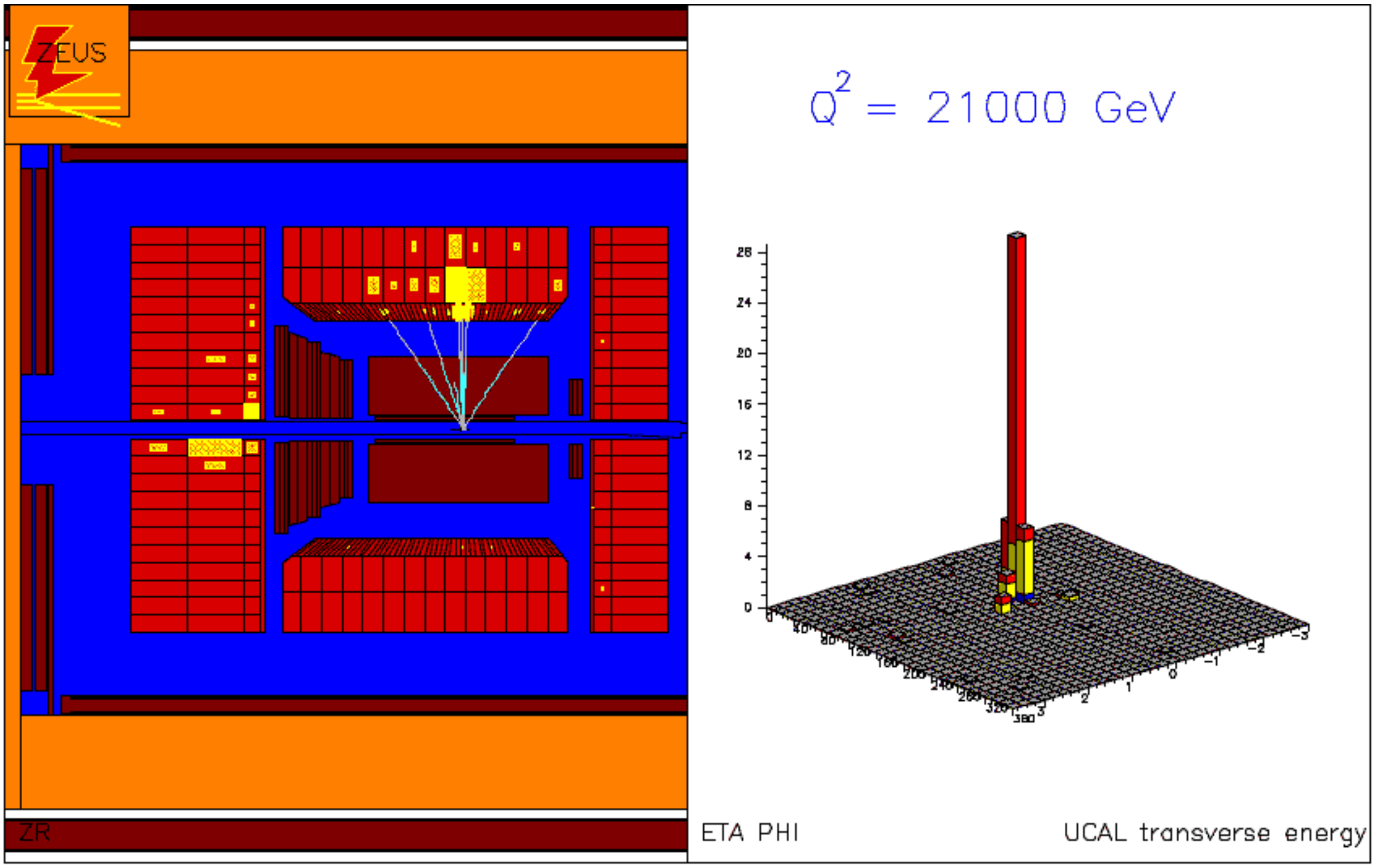


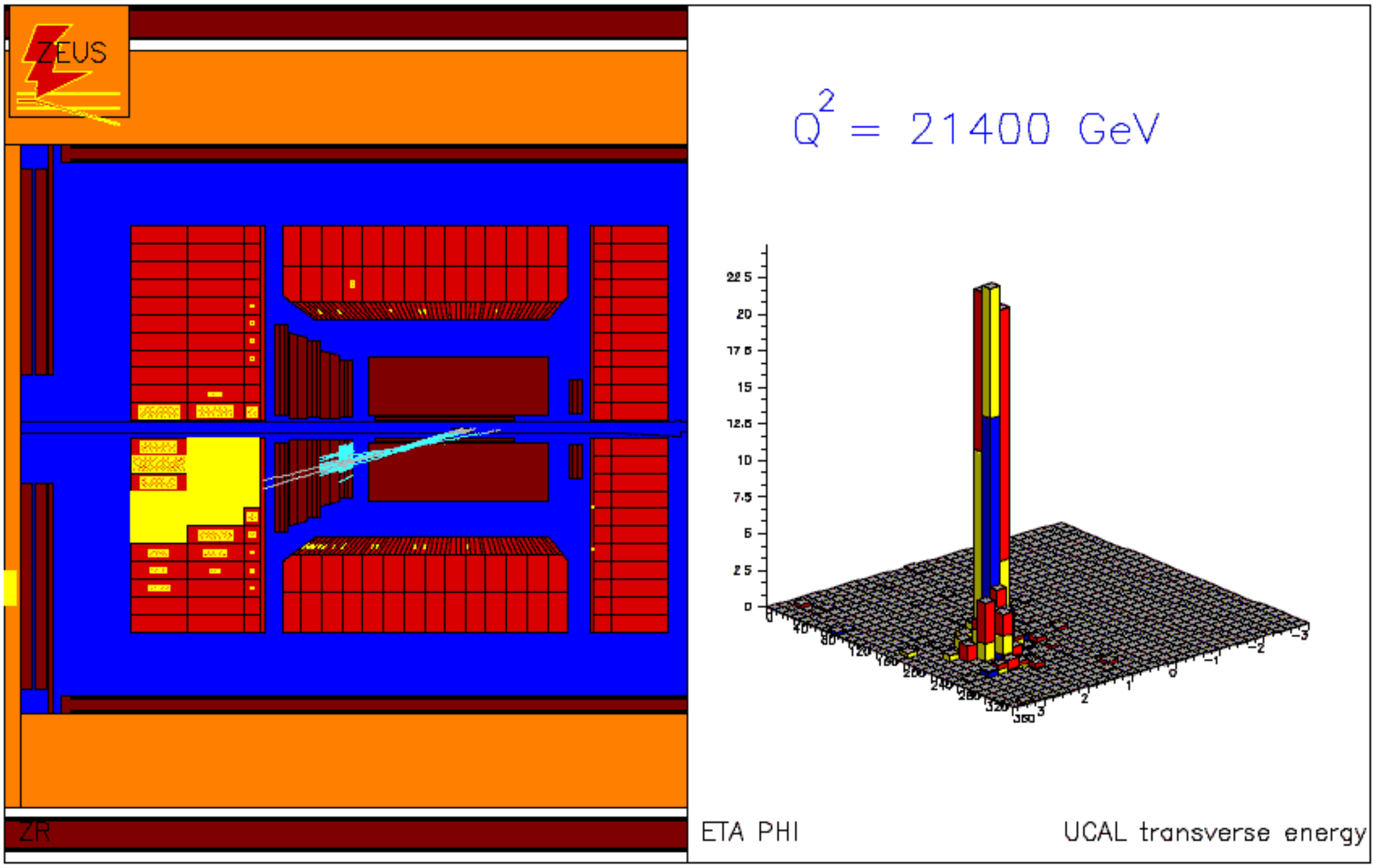
Cross Section for $e^+p \longrightarrow \bar{\nu}X$:

$$\frac{d^2\sigma_{CC}}{dx\,dQ^2} = \frac{G_F^2}{2\pi}\frac{1}{(1+Q^2/m_W^2)^2}\left(\bar{u}+\bar{c}+(1-y)^2(d+s)\right)$$

- For e^+p scattering the dominating contribution to the cross section comes from the d quark $\Rightarrow$ Largest theoretical error arises from uncertainty of the d quark density
- The main experimental uncertainty is the hadronic energy scale of the calorimeter

Charged Current Events

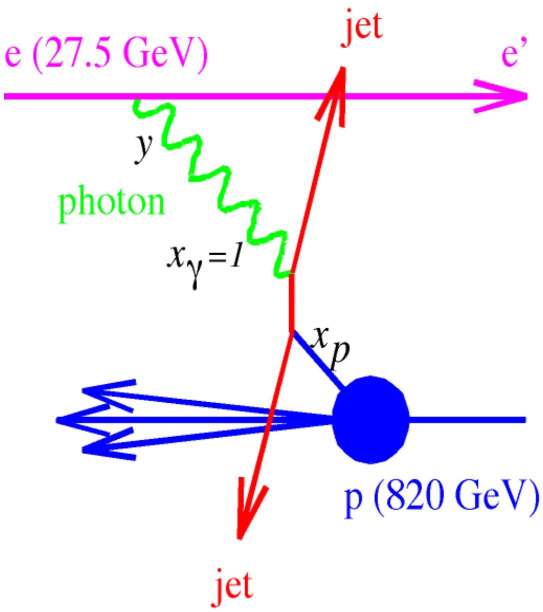


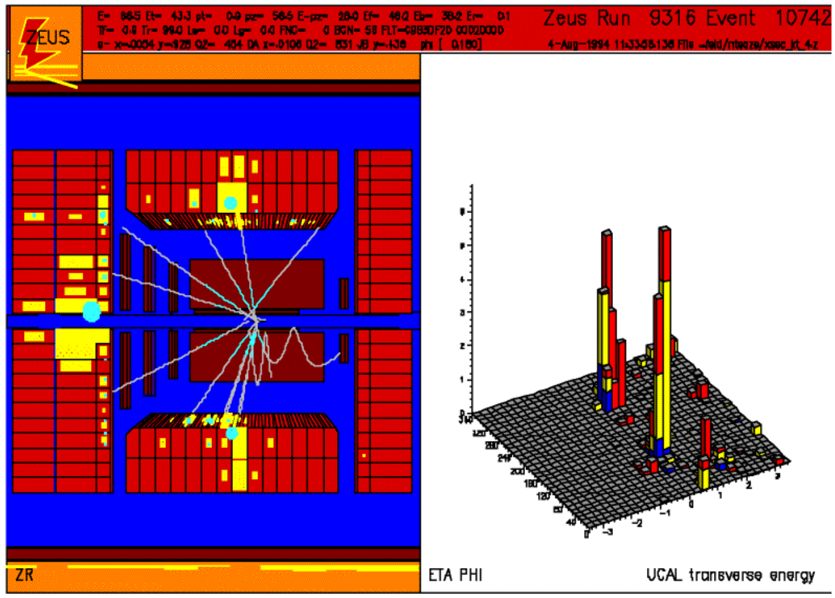


Jets in photoproduction

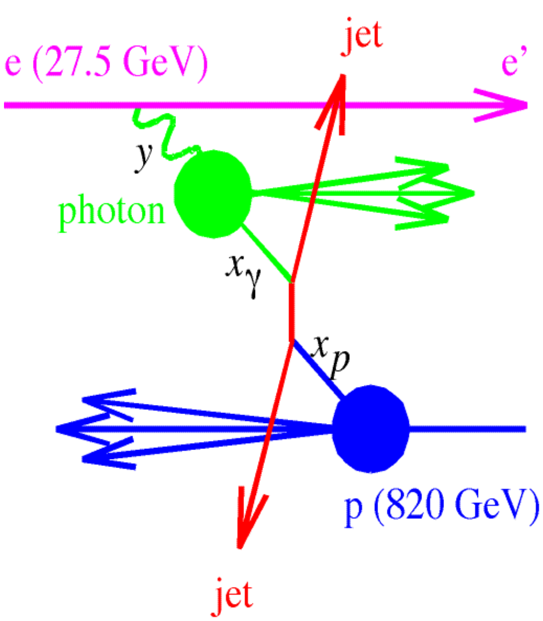
2 types of processes (at LO):

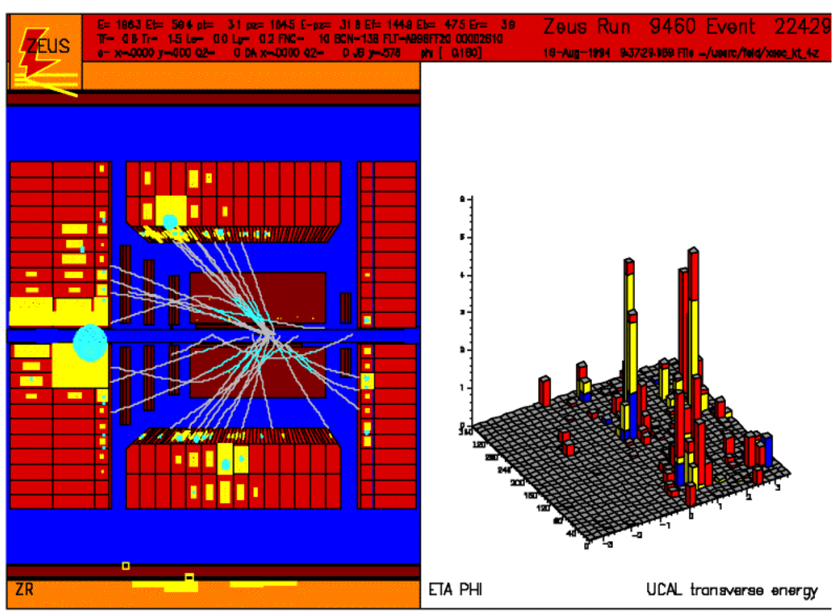
direct photon: $\gamma \equiv$ pointlike





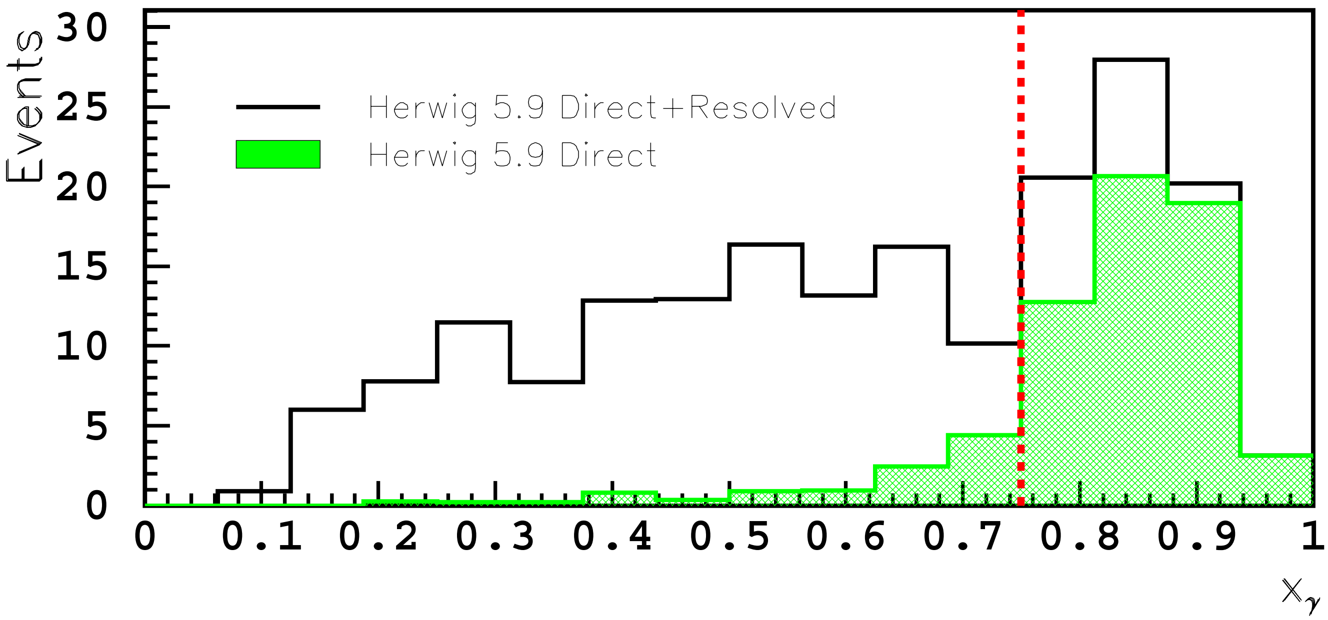
resolved photon: $\gamma \equiv$ source of partons





$$x_\gamma^{OBS} = \frac{1}{2yE_e}\left(E_t^{jet1} e^{-\eta^{jet1}} + E_t^{jet2} e^{-\eta^{jet2}}\right)$$

Jet Production (Real Photons)



$x_\gamma^{OBS} < 0.75$ - Resolved Enriched

$x_\gamma^{OBS} > 0.75$ - Direct Enriched

Use jets to probe photon structure

- Scale $\sim E_T^2$ of jets

HERA can probe higher scales than e^+e^-

- e^+e^- scale < 400 GeV^2
- HERA scale ~30 - ~1000 GeV^2
  (Higher w/ more luminosity)

Jet Production (Virtual Photons)

Probe virtual photon structure using jets

- Large virtuality range available

DIS (Q^2>0) usually assumes all structure is from proton (pointlike photon)

- When $E_T^2 > Q^2$ photon structure is important (small part of phase space)

Future Outlook

1998-1999:

- Modifications to HERA
- e^-p running
- Expect similar luminosity as e^+p

2000-2005:

- Major HERA upgrade
- New Silicon Vertex Detector
  - Charm tags: F_2(charm)
- Factor of 7 increase in luminosity
  - 1×10^{31} to 7×10^{31}
- Higher Proton energy: > 900 GeV?
- Polarized electrons & positrons
- Goal of 1 fb^{-1} by 2005
- Beyond: polarized protons?

Physics expectations by 2005:

- $\alpha_s(M_z)$ measured to .001
- xg(x) measured to 1%
- F_2: does the rise at low-x continue?, xF_3
- Quark couplings from NC, CC polarized $e^{+/-}$
- $WW\gamma$ couplings
- Leptoquarks?

Conclusions - I

New x,Q² range in Deep Inelastic Scattering

- $0.11 < Q^2 < 5000$ GeV^2 & down to x ~10^{-5} & growing
- F_2 observed to rise rapidly as x decreases
- F_2(charm) contributes large fraction (~25%) to F_2

pQCD fits to the F_2 data, with DGLAP evolution

- fit the data well even down to Q^2~1.5 GeV^2

F_2 measured at low Q^2

- Transition between perturbative and soft regime
- γ^*p cross section measured vs. W

The gluon distribution has been extracted

- Steep rise of gluon with decreasing x is observed

High Q^2 Neutral Current data:

- Typical systematic error ~ 2-3%
- Statistically limited for $Q^2 > 1000$ GeV^2
- Consistent w/SM up to $Q^2 \sim 30000$ GeV^2
- 2 exceptional events at $Q^2 > 35000$ GeV^2 (<1997)

High Q^2 Charged Current data:

- Typical systematics ~ 10%, increasing for $Q^2 > 10000$ GeV^2
- Consistent w/SM up to $Q^2 \sim 10000$ GeV^2
- 1 exceptional event at $Q^2 > 30000$ GeV^2 (<1997)
- $M_W = 78.6^{+2.5}_{-2.4}(stat.)^{+3.3}_{-3.0}(syst.)$ GeV (prelim.)

Conclusions - II

Jets in Photoproduction:

- Photon structure probed at scales up to ~10^3 GeV^2 and higher

Real Photons

- Jet cross sections sensitive to different photon parton density parametrisations
- Jet data give new constraints on photon parton distribution functions (higher scale)

Virtual Photons

- Virtual photon structure probed across large range of virtuality
- Virtual photon structure observed to be important when $Q^2 < E_T^{*2}$
- Suppression of low x_γ cross section with increasing Q^2 observed

Jet shapes in DIS & Photoproduction

- DIS & direct γp agree & w/e^+e^- (quarks)
- Resolved γp agrees w/p-p (gluons)

The Future

- Luminosity upgrade, polarization, e^- & e^+
- Much more physics!

Zeus Photoproduction

Dijets

- General agreement with models
  - worse at high E_t
- Resolved reduced but remains present at higher E_t

Isolated High-E_t (Prompt) Photons

- Consistent with LO QCD expectations
- Measured cross section and η-distribution consistent with NLO QCD prediction
  - σ = 15.3 +/- 3.8 (stat) +/- 1.8 sys pb
  - GRV favored over GS photon PDF

Virtual Photon Structure

- Resolved (low x_γ) processes are suppressed with increasing photon virtuality
- LO Resolved needed to describe the data at the highest photon virtuality measured (Q^2 = 4.5 GeV^2)