QCD Studies in ep Collisions

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Outline:

- **Introduction**
  - HERA & ep scattering
- **Structure Functions**
  - Parton Model & Scaling Violation
  - F_2: Gluons, charm, total γ^*P σ
  - High Q^2 NC & CC
- **Jets**
  - Deep Inelastic Scattering (DIS): α_s
  - Photoproduction
    - resolved vs. direct
- **Diffraction**
  - Deep Inelastic Scattering
    - structure of diffractive exchange
  - Photoproduction
    - σ's & jets
- **Vector mesons**
  - Photoproduction & DIS
- **Conclusions**

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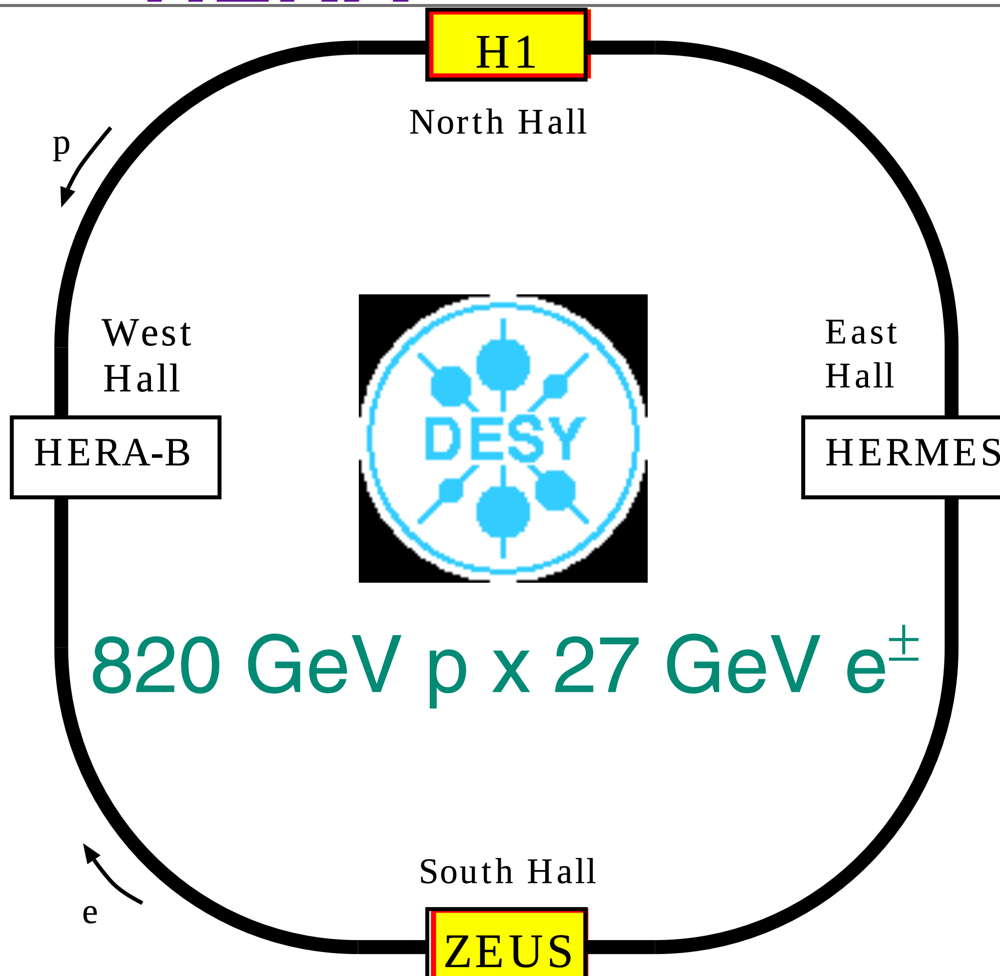
HERA



Collider:

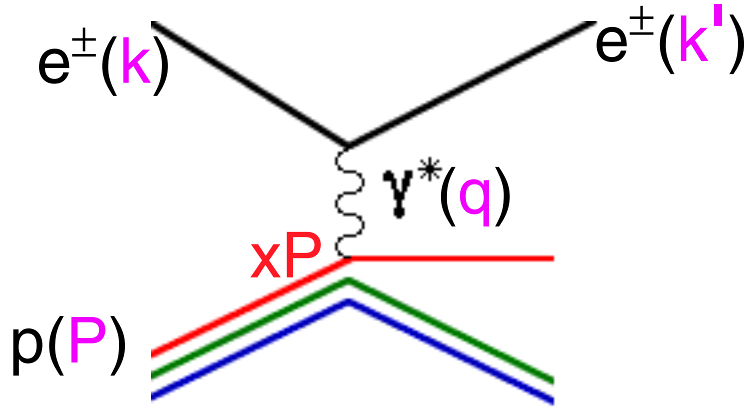
- $\sqrt{s}$= 300 GeV
  - Equivalent to 47 TeV fixed target

Experiments:

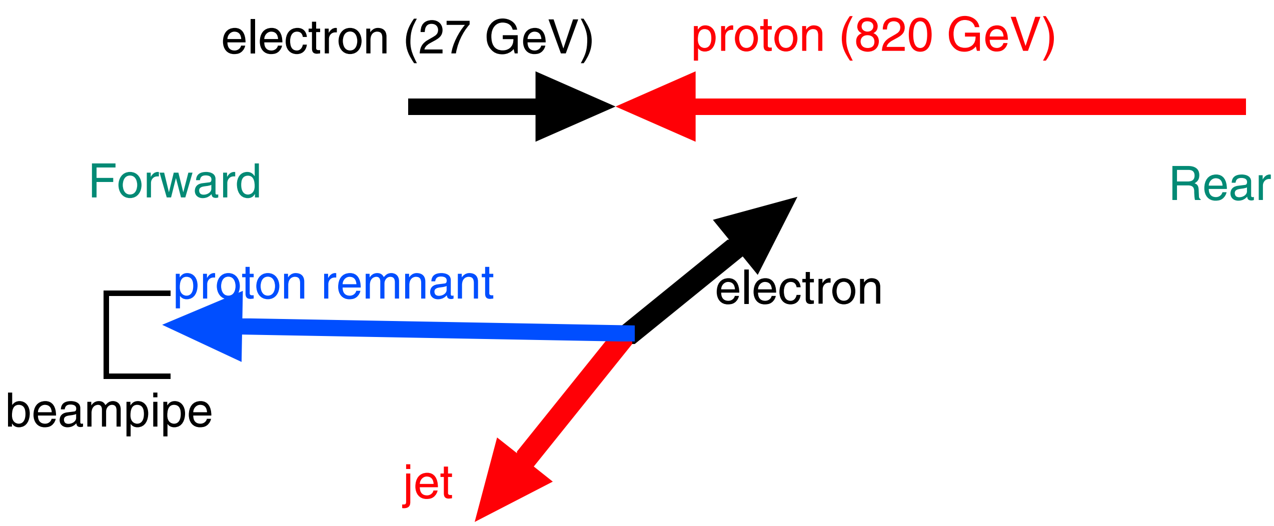
- **2 general purpose detectors (discussed):**
  - H1 & Zeus
- **Dedicated Fixed Target (not discussed):**
  - HERMES:
    - Polarized electrons on polarized H target
  - HERA-B
    - Proton Halo on wire target

Deep Inelastic Scattering

The DIS process



Measuring DIS at HERA:



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

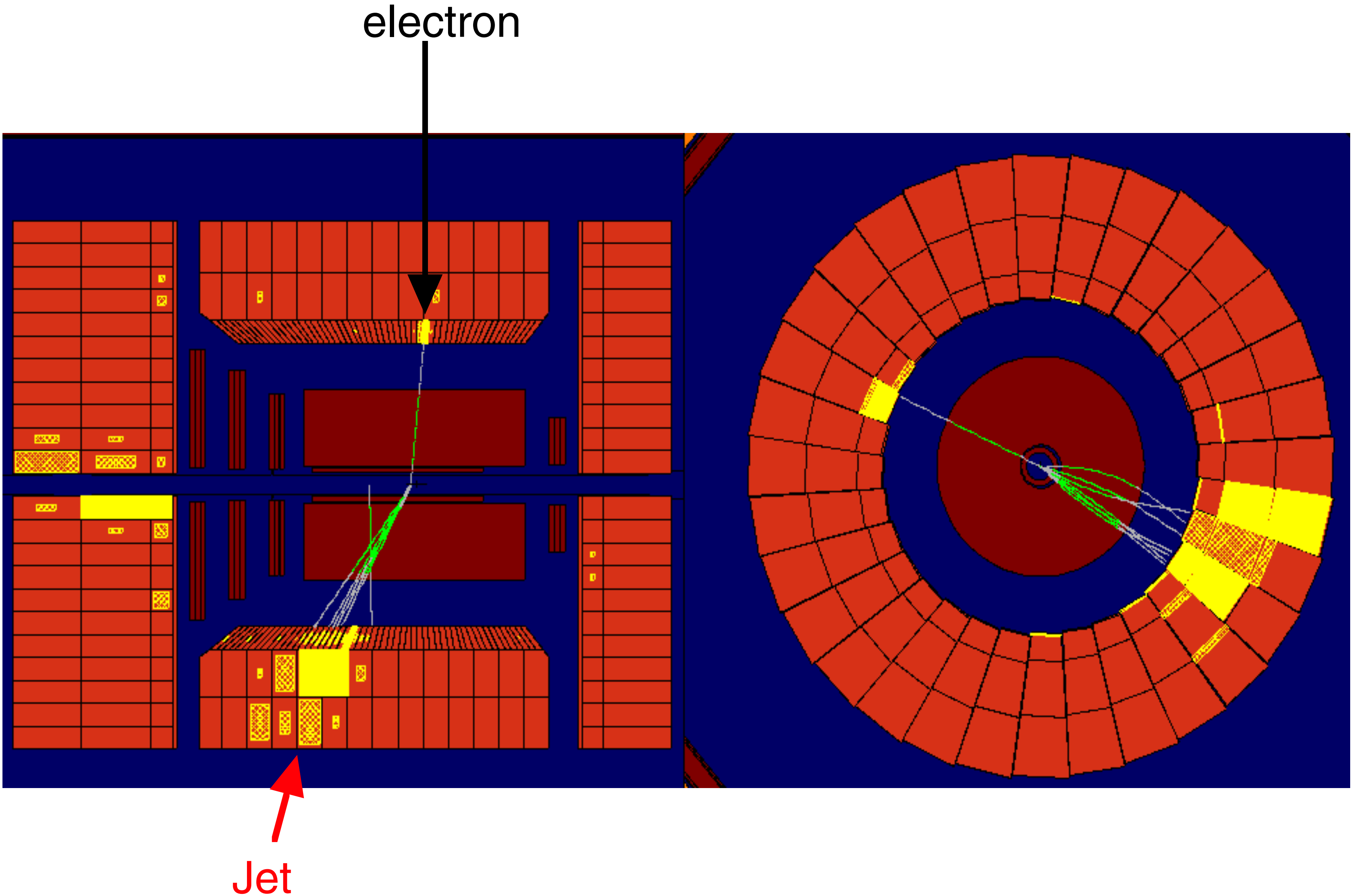
$Q^2 = -q^2 = -(k-k')^2 =$ (momentum transferred)^2

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

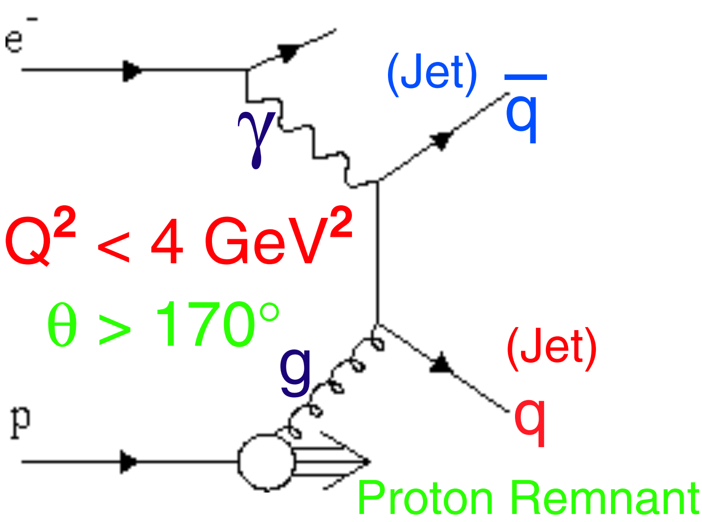
$$x = \frac{Q^2}{2P \bullet q} \qquad y = \frac{P \bullet k}{P \bullet q} \qquad Q^2 = sxy$$

DIS event Q^2 = 1600 GeV^2

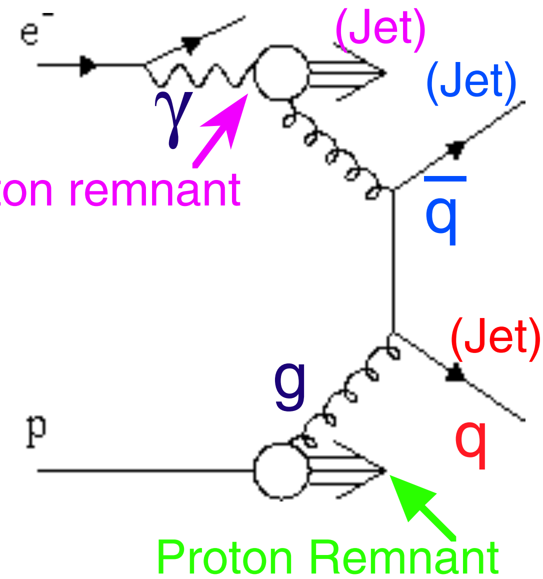


Photoproduction

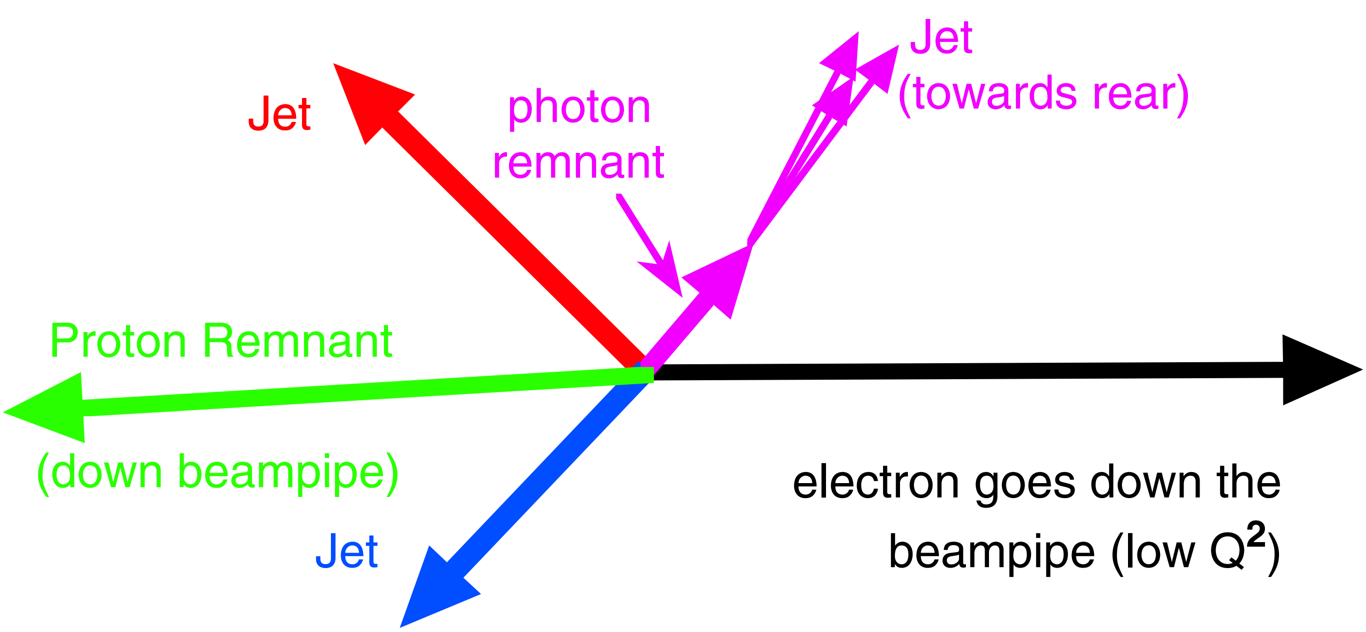
Direct:



Resolved:

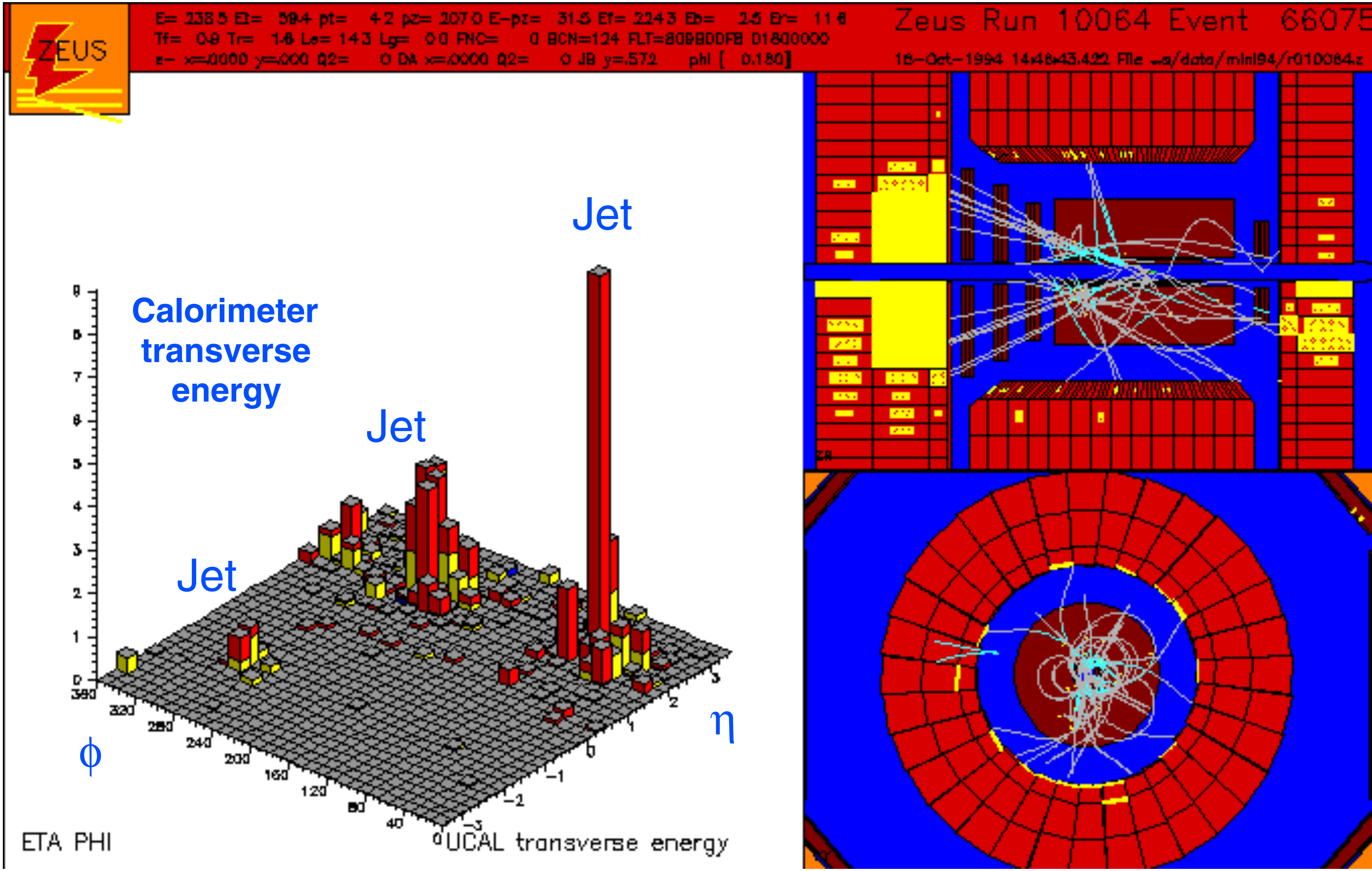


Almost real photon



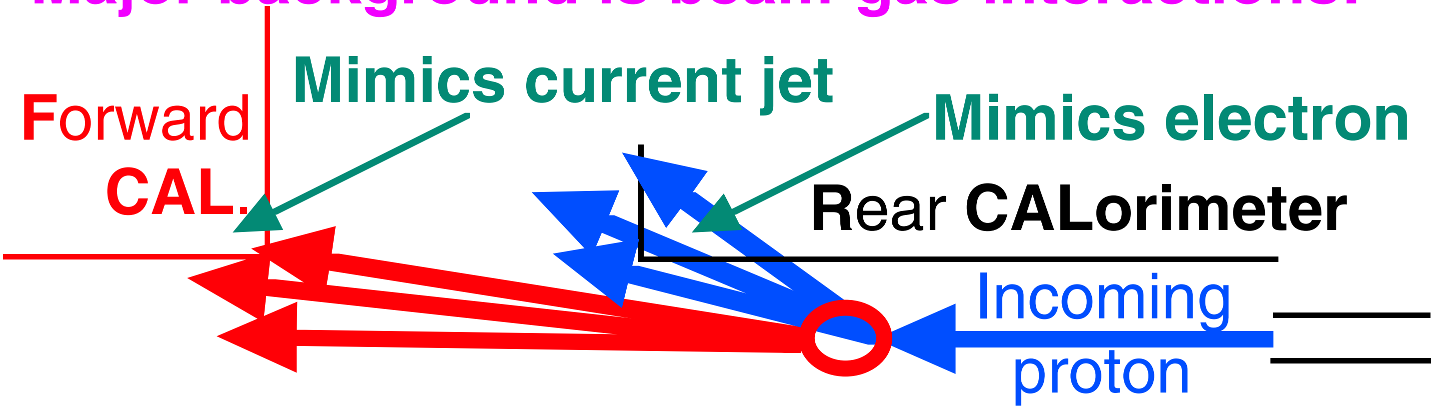
Background for DIS

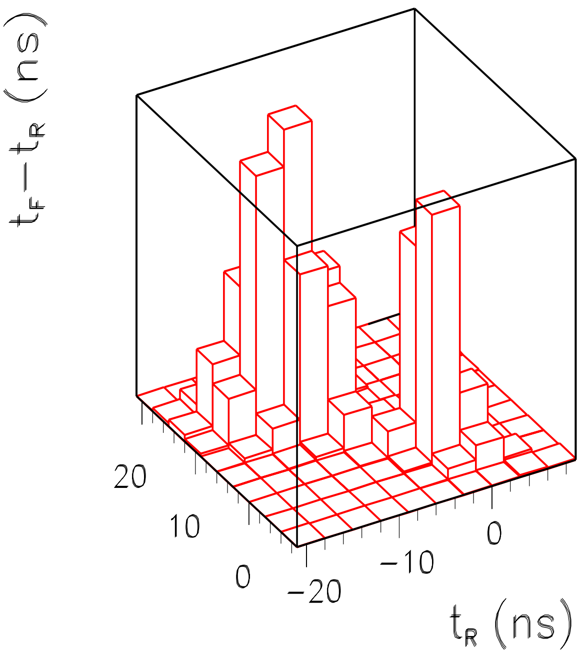
Photoproduction event



Background rejection

Major background is beam-gas interactions:





reject beam gas

*vertex cut

*timing σ_t ~ 1 ns

← Cal. timing

$(E - P_z)$ is conserved

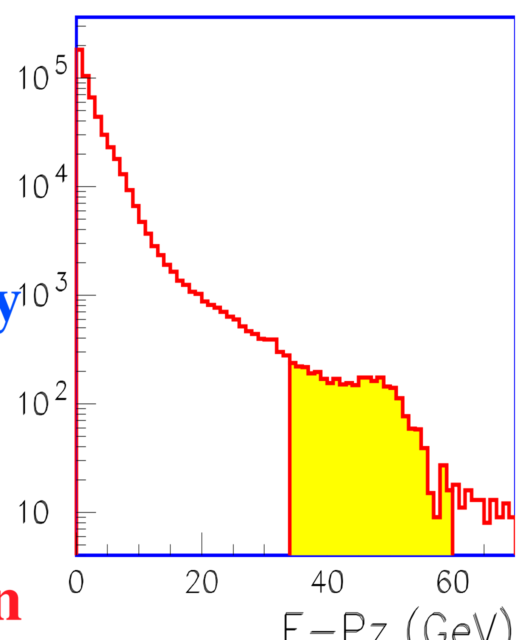
Initially:

$E_P - P_P + E_e - (-P_e) = 2E_e$

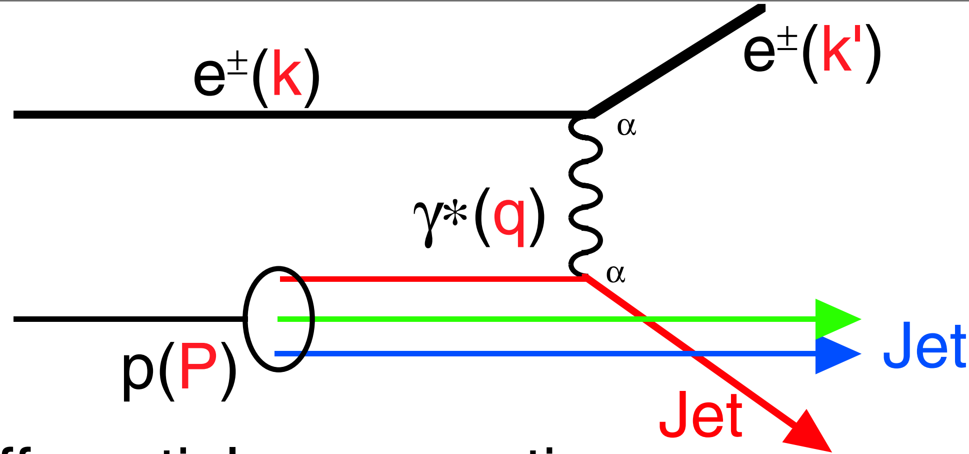
remains same if no energy down rear beam pipe.

True for DIS

False for photoproduction



DIS cross section



DIS differential cross section:

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

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

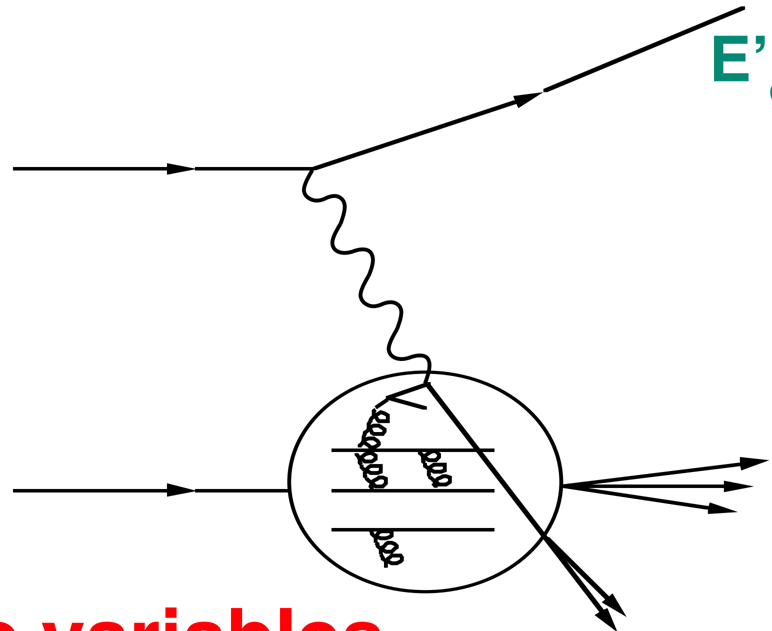
γ^* is longitudinally or transversely polarized

$F_2(x,Q^2)$ = 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).

Kinematic Reconstruction



2 kinematic variables

- x, Q^2

4 measured quantities

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

Any 2 measured variables can be used to reconstruct x, Q^2

- Reconstruction may not be optimal.

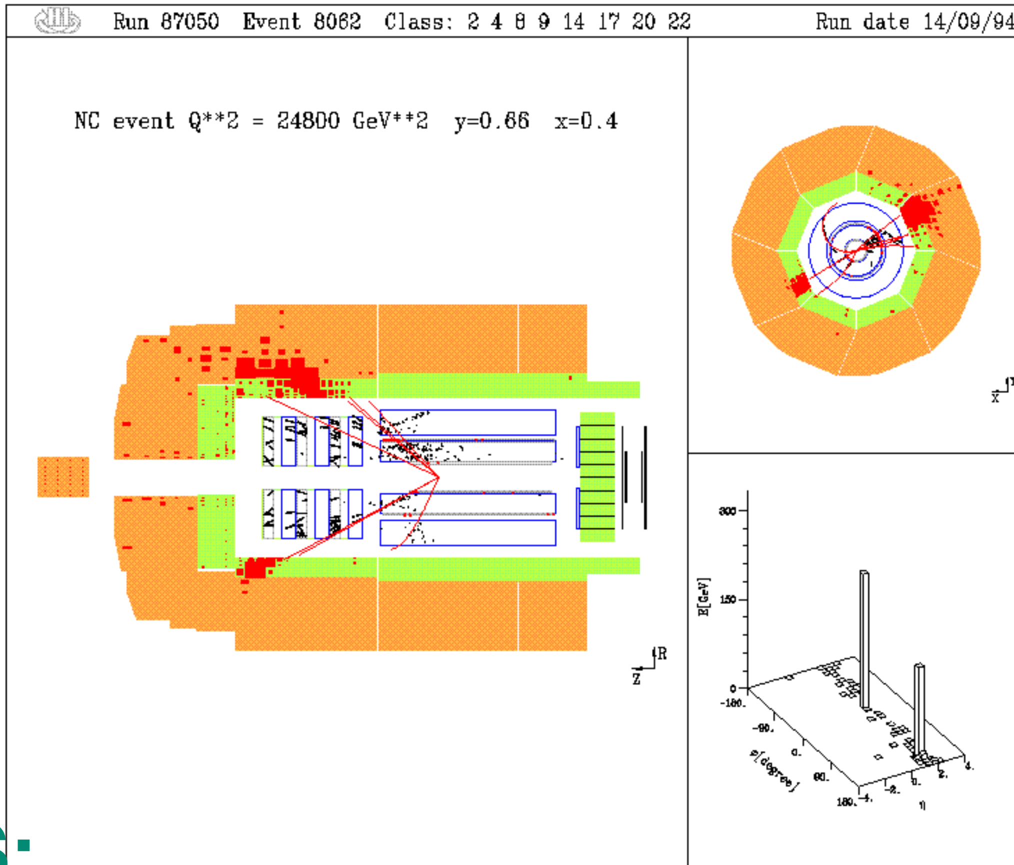
P_T method

- Best performance for full kinematic range
- Uses ($E_e', \theta_e', E_h, \gamma_h$), $E-P_z$ conservation, and P_T balance between the electron and current jet

Experiments - High Q^2

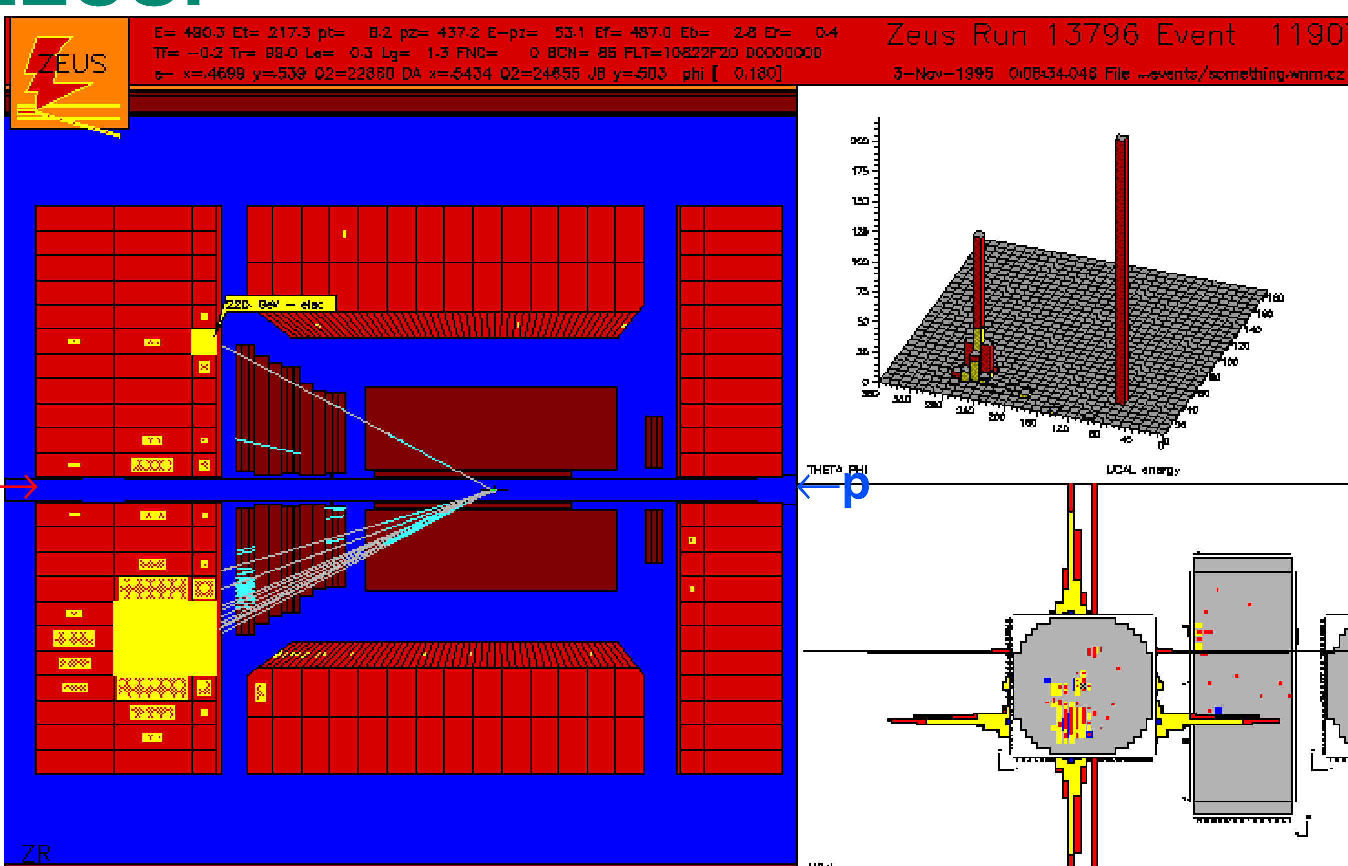
H1:

e→ ←p



ZEUS:

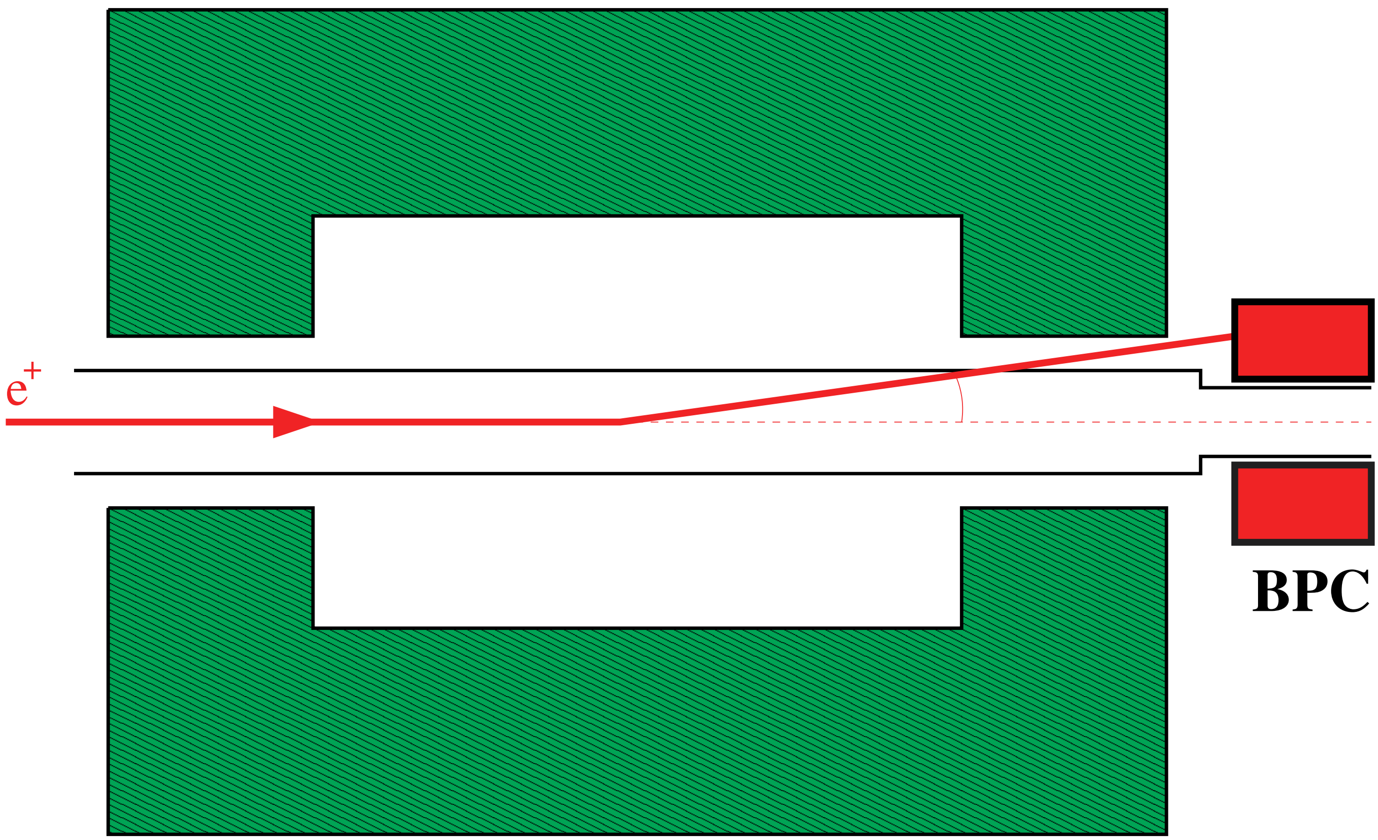
e→ ←p



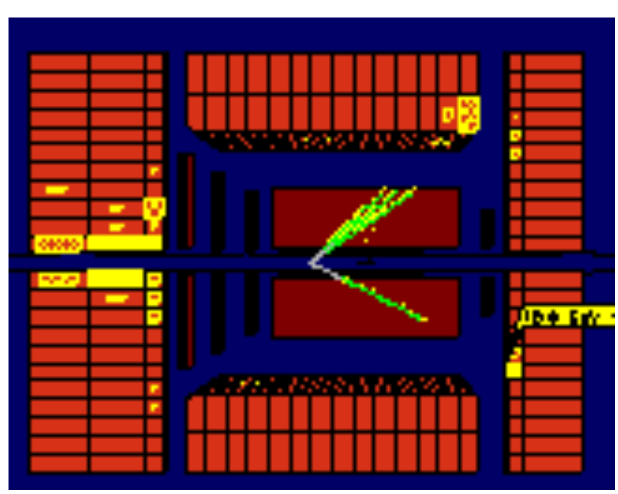
Experiments - Low Q^2

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

Zeus Beampipe Calorimeter:

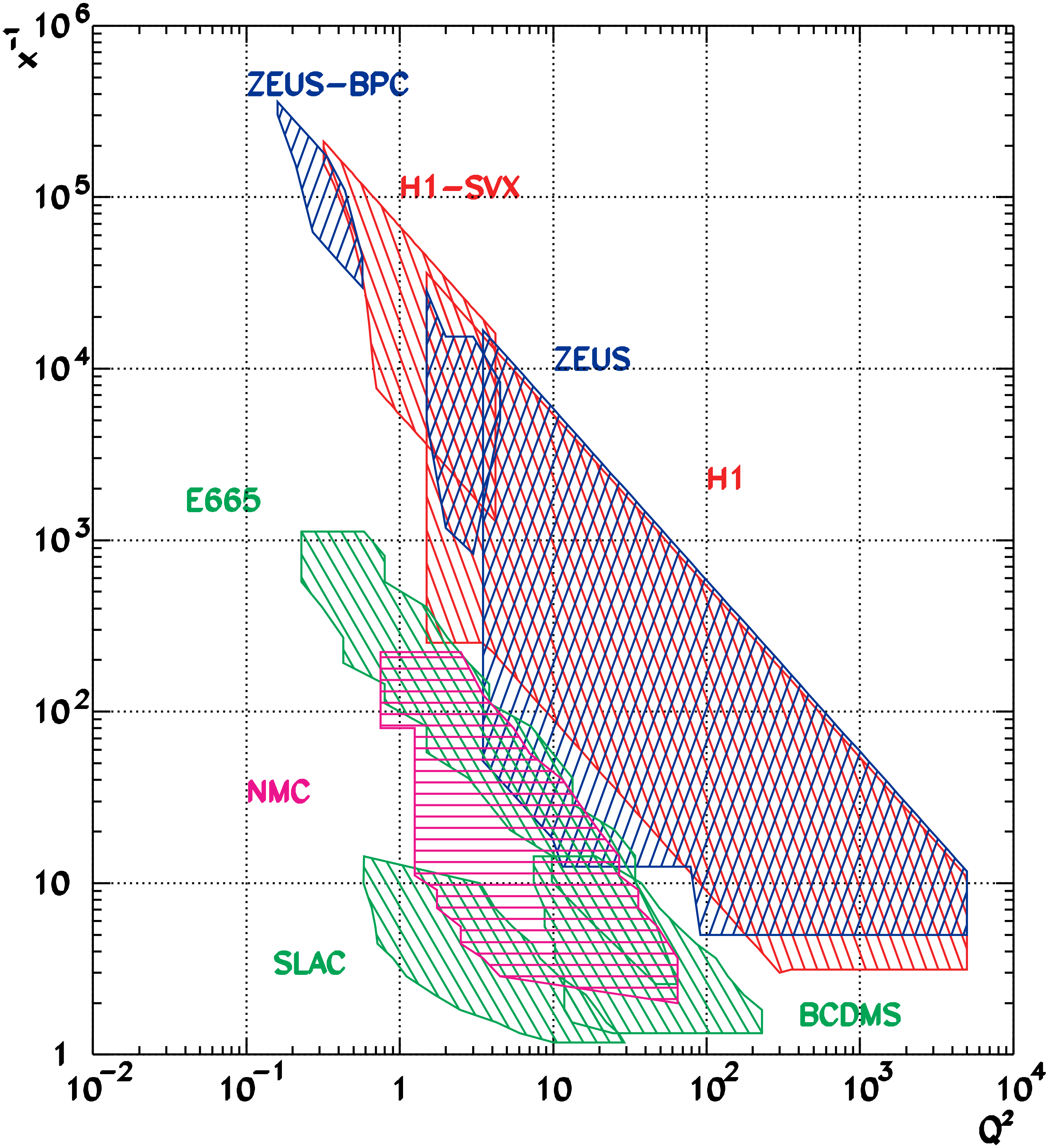


H1 & Zeus Shifted Vertex:



H1 & Zeus Initial State Radiation

Experimental Kinematic Range



Parton model

Proton is made up of non-interacting partons.

Bjorken scaling, i.e., Q^2 independence of structure functions holds. SLAC-MIT experiments obseved approximate scaling in data.

Structure function is given by the charge weighted sum of parton momentum densities

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

For spin-half partons

$$F_L = 0$$

For spin-zero partons

$$F_L = F_2$$

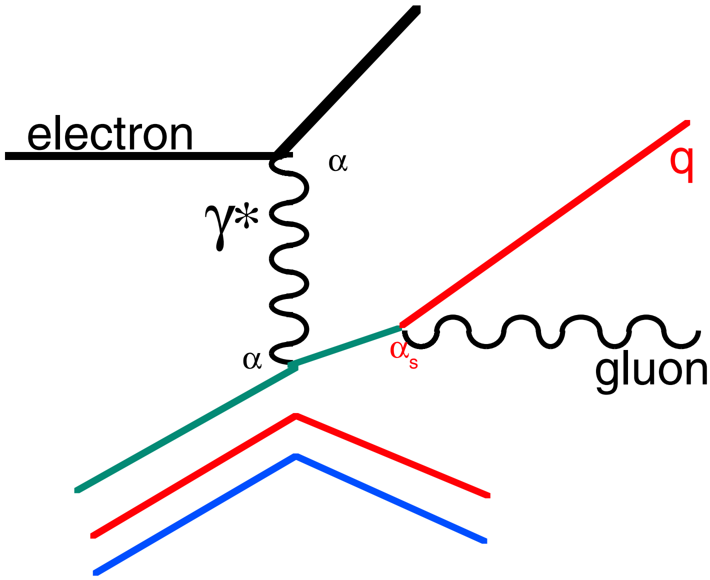
The parton densities $f_i(x)$ are not calculable in the model and are to be derived from experiment.

Deep inelastic scattering provides a good laboratory for parton density extraction because the electromagnetic probe is well understood.

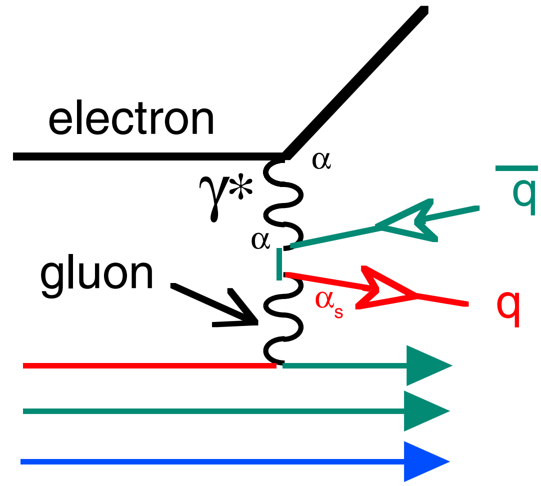
Scaling violations

Quark transverse momentum from quark-gluon interactions causes scaling violation: $F_2(x) \rightarrow F_2(x,Q^2)$.

QCD Compton

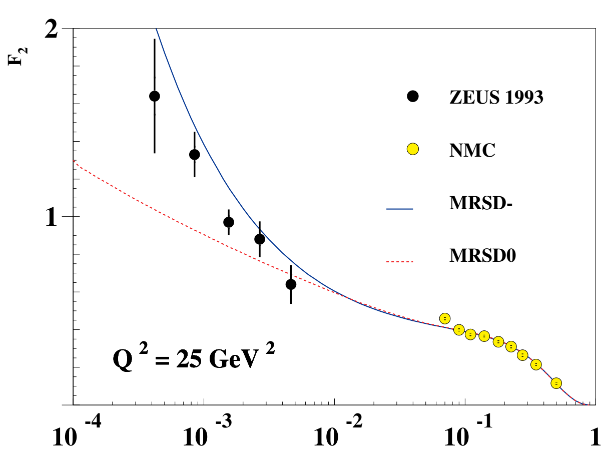


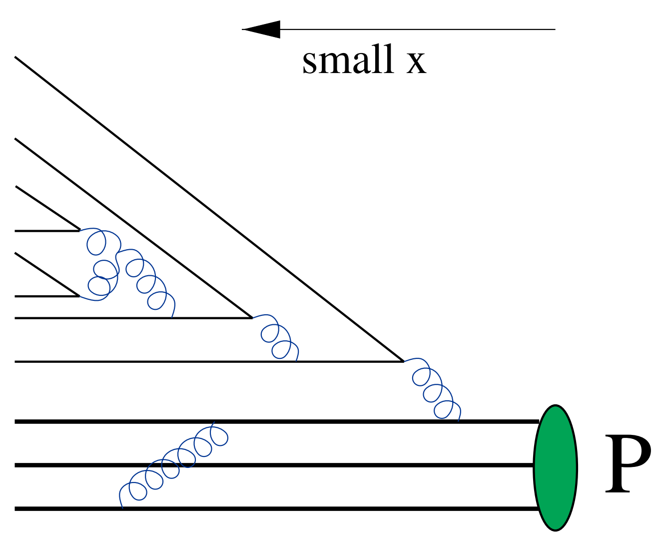
Boson-Gluon Fusion



Splitting functions, probablities for these interactions, are calculated in 2nd order perturbative QCD.

These interactions drive $F_2(x)$ to grow with decreasing x:





Perturbative QCD

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

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

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

Next-to-leading order splitting functions, P, are now available.

The structure function F_2 is given by,

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

Calculation of DIS cross section requires F_L:

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

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

Expected low-x behavior of F_2

- **Regge Approach**
  - **Donnachie-Landshoff (DL)**

$$\text{since}: \quad F_2 = \frac{Q^2}{4\pi\alpha^2}\sigma(\gamma^* p)$$

$$\text{but at } Q^2 = 0 : \sigma(\gamma^* p) = C(W^2)^{-0.08}$$

$$\text{and at low } x : W^2 = \frac{Q^2}{x} \rightarrow \sigma(\gamma^* p) = C'(Q^2)X^{-0.08}$$

$$\text{Therefore}: \quad \lim_{Q^2 \to 0} F_2(x, Q^2) = f(Q^2)x^{-0.08}$$

- **Martin-Roberts-Stirling (MRS)**
  - Assume $g(x,Q_0^2) \sim x^{\gamma 1}$ & $F_2(x,Q_0^2) \sim x^{\gamma 2}$
  - Evolve in Q^2 according to QCD
- **Gluck-Reya-Vogt (GRV)**
  - Use "valence-like" distributions at low Q^2
  - Evolve in Q^2 according to QCD
  - Empically produces $\gamma << -0.08$
- **Balitsky-Fadin-Kuraev-Lipatov (BFKL)**
  - Summation of many QCD graphs in powers of ln(1/x)

$$g(x, Q_0^2) \sim x^{\gamma} \text{ and } \gamma = -\frac{12\ln(2)}{\pi}\alpha_s \sim -0.5$$

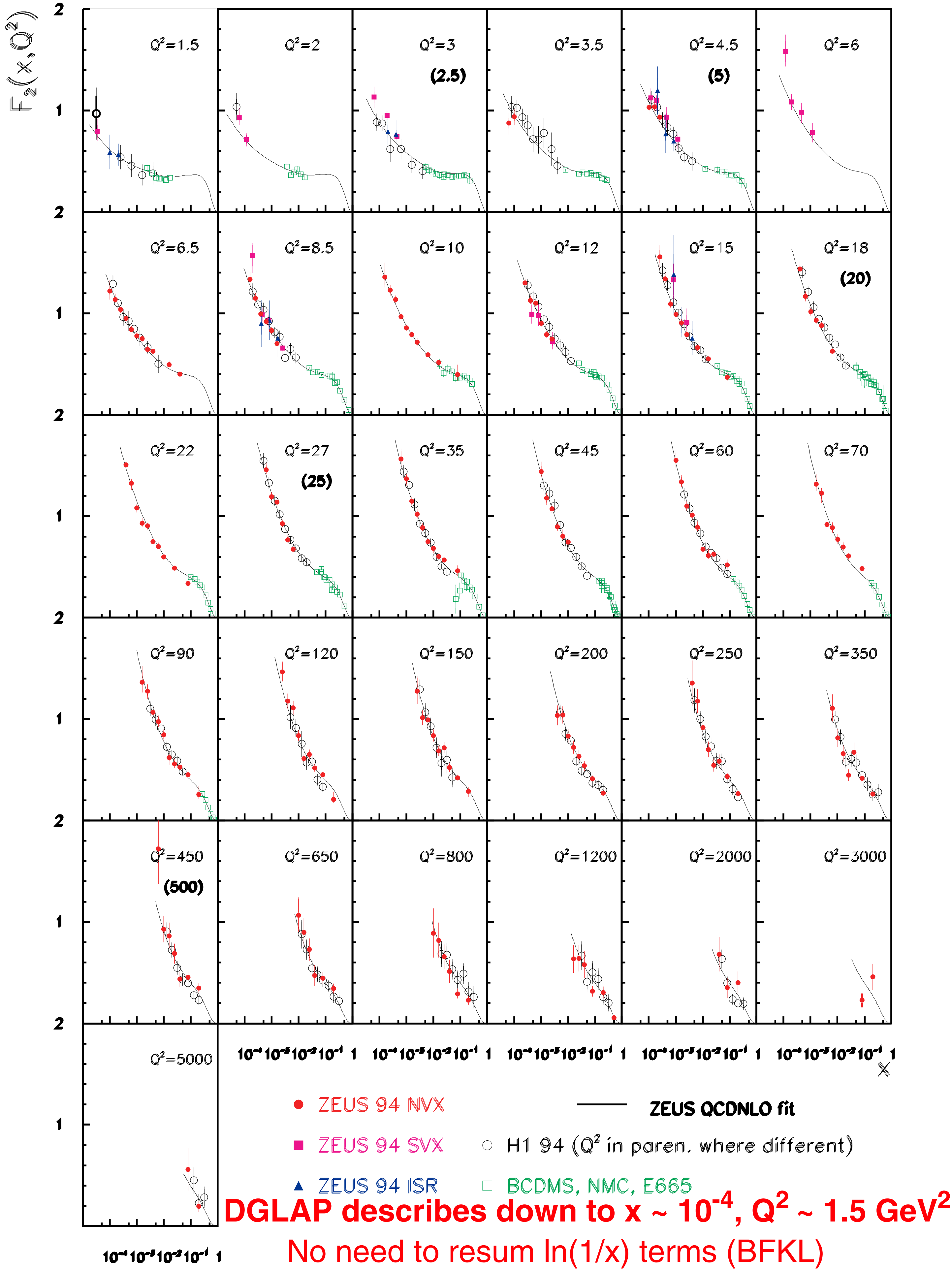
F_2 Results

Extraction:

- Bin data in x, Q^2
- Subtract background
- Cross section multiplied by QCD F_L calculation using 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

Issues:

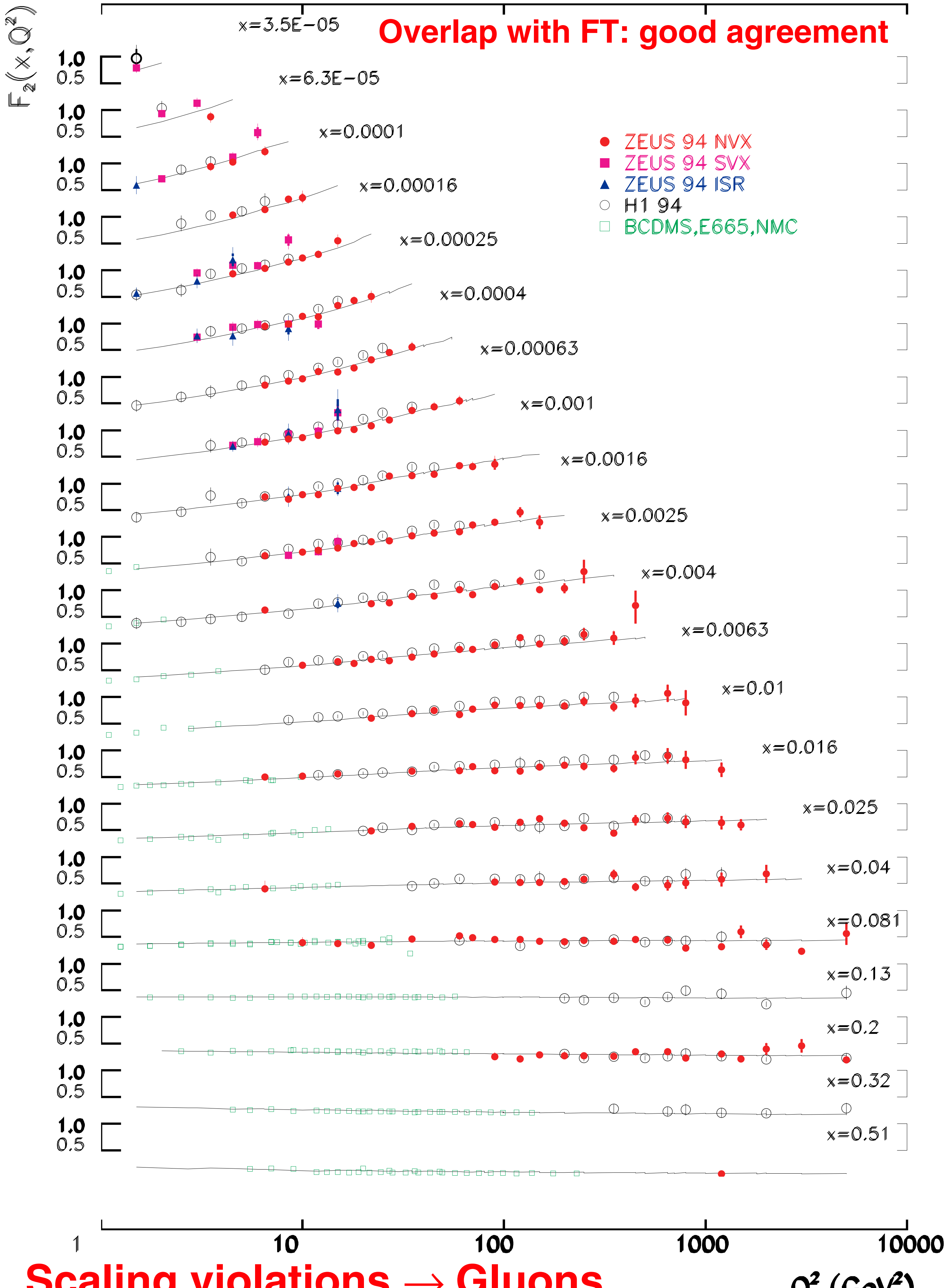
- Does rise at low x continue?
- Over what kinematic range is rise observed?
- Agreement with fixed target experiments?



DGLAP describes down to $x \sim 10^{-4}$, $Q^2 \sim 1.5$ GeV^2

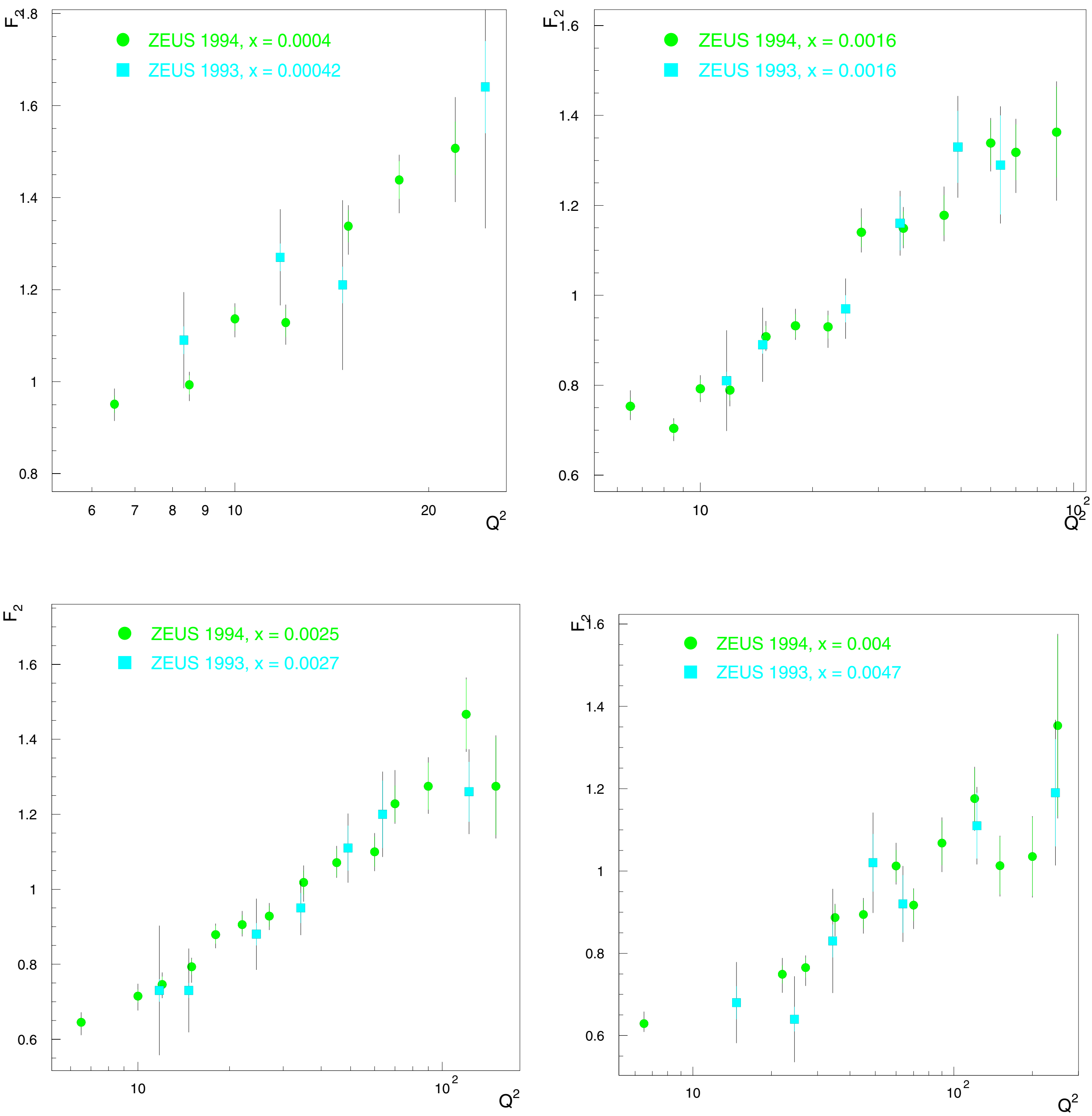
No need to resum ln(1/x) terms (BFKL)

Overlap with FT: good agreement



Scaling violations → Gluons

Scaling Violation - Gluon sensitivity



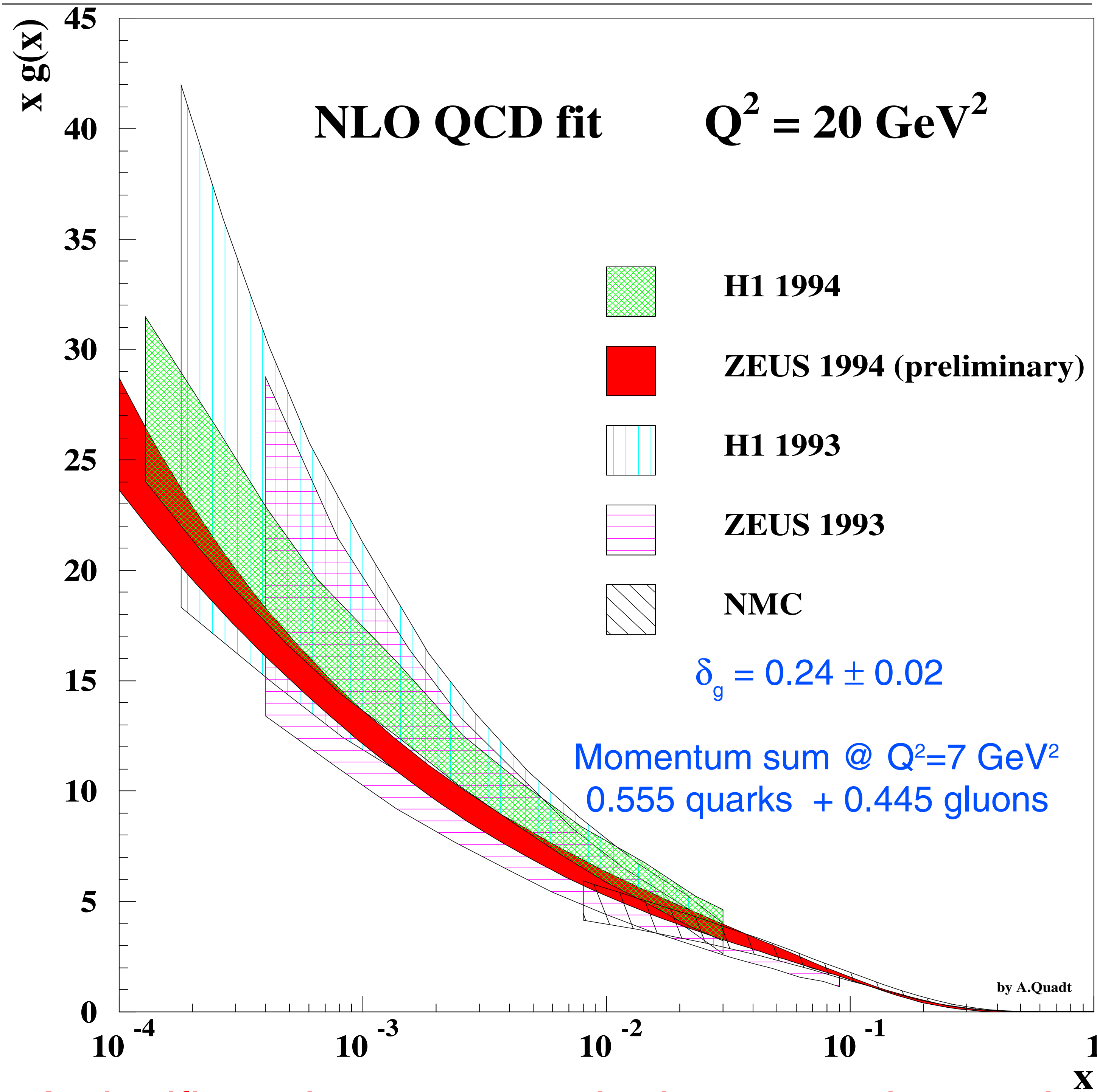
Sensitivity to the gluon distribution is in the slope of F_2 versus $\log Q^2$ plots. 1994 and 1993 ZEUS F_2 data is shown above. It is seen that 94 data constrains $dF_2/d\log Q^2$ with high precision.

Extraction of gluon density

Example: fit to ZEUS 1994 F_2 data:

- Used NMC data to constrain fit at larger values of x.
- Assumed momentum sum rule to constrain gluon density.
- Assumed quark and gluon density functional forms.
- Assumed (SLAC/BCDMS) $\alpha_s(M_Z^2)=0.113$ and evolved to higher Q^2.
- Evolved the distributions using GLAP eq'ns to measured Q^2 bins to calculate F_2.
- In computation of χ^2 for agreement with the fit only the statistical errors were included.
- Performed nonlinear minimization of χ^2 to find fit parameters for assumed functional forms of quarks and gluons.
- Systematic uncertainty estimated separately by varying each of the 31 different systematic effects individually and performing a new fit.

Gluon results



A significant improvement in the uncertainty and in the validity range in kinematic plane is seen in the gluon density extracted from the 1994 H1 and ZEUS DIS data. Agreement with 1993 extraction is remarkable.

Caveats on F_2 & Gluons

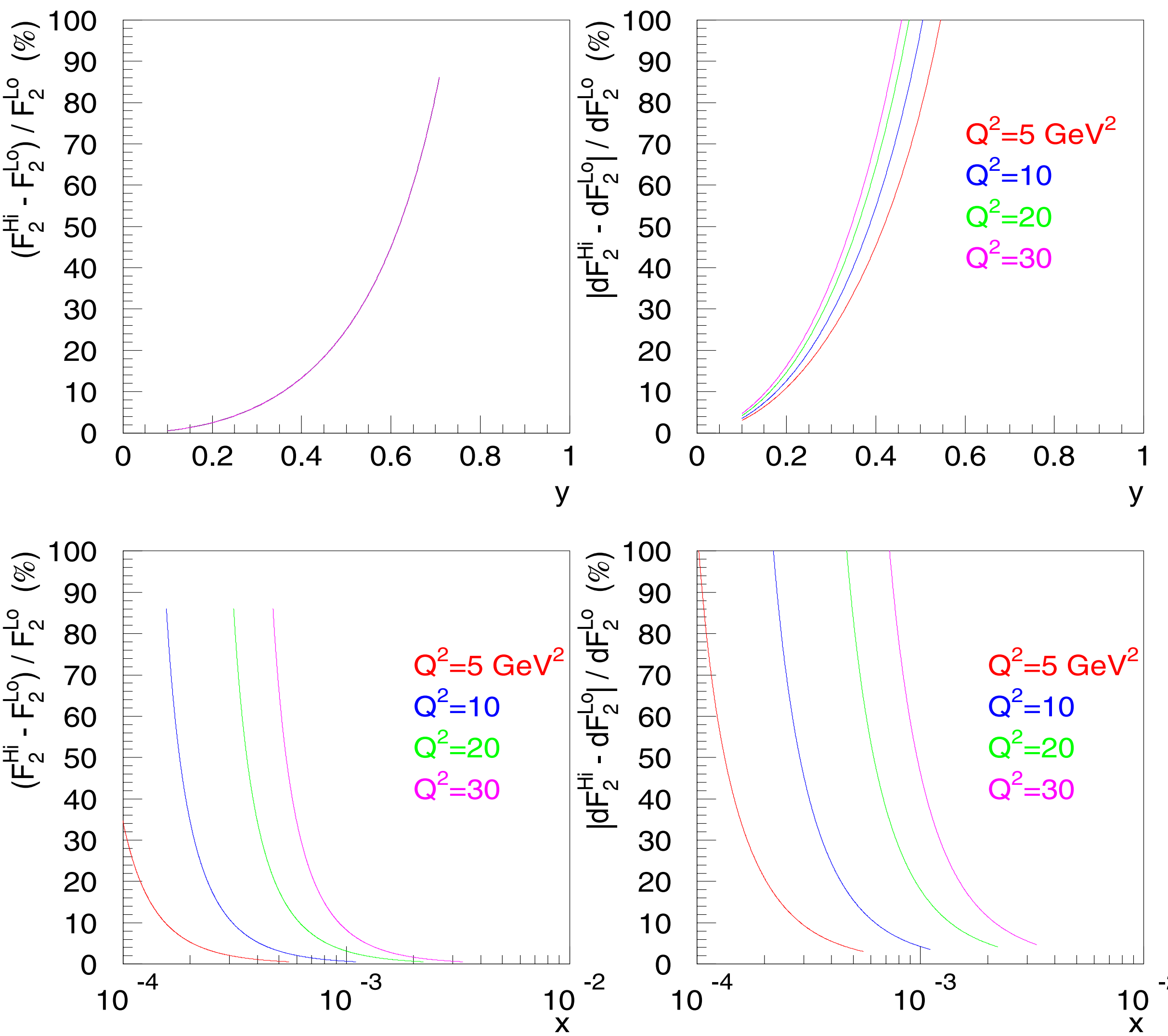
ZEUS F_2 extraction, as is true with most world F_2 data, involved apriori assumptions for α_s and quark-gluon parameterizations in computing F_L and F_3 corrections for DIS cross section.

The extracted F_2 is sensitive to these assumptions, particularly for high y kinematic range data, which is sensitive to the gluon.

Therefore, an assumption independent analysis needs to be done by fitting directly to the cross section data.

The results of such analysis can yield consistent values for α_s, quark and gluon parameterizations.

Impact of F_L uncertainty (F_L: $0 \rightarrow F_2$) on F_2 and $dF_2/d\ln Q^2$



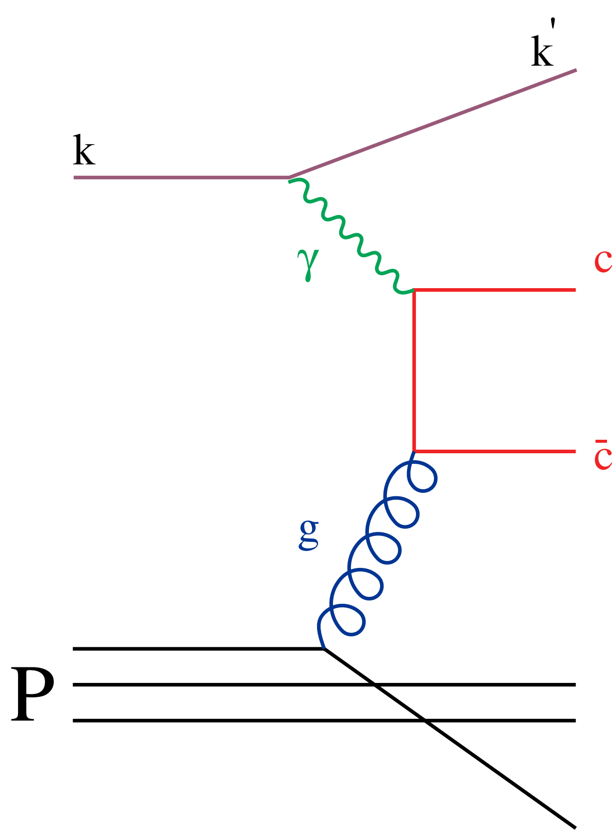
Charm F_2

Analyze components of F_2

- Identify Flavor in the final state
- Justify NLO QCD assumptions
- Further understand the rise in F_2

Evolution of charm from the sea:

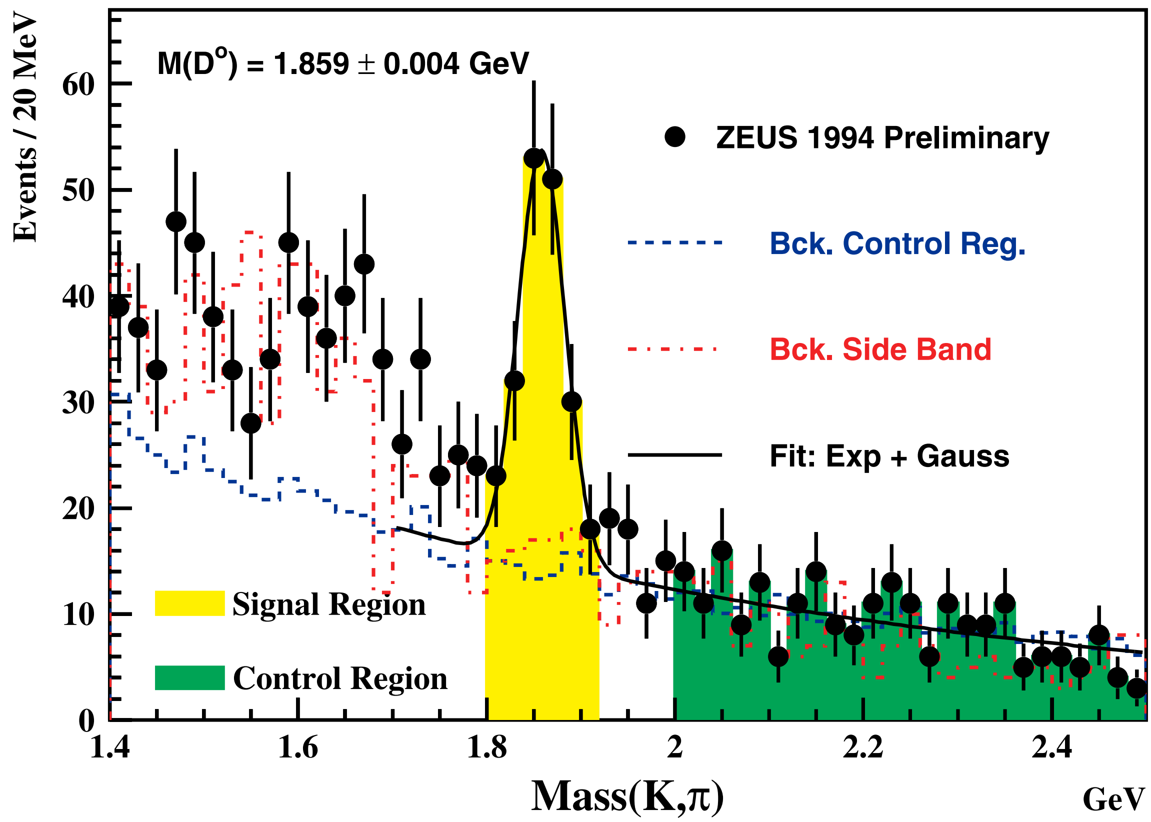
- Boson Gluon Fusion:

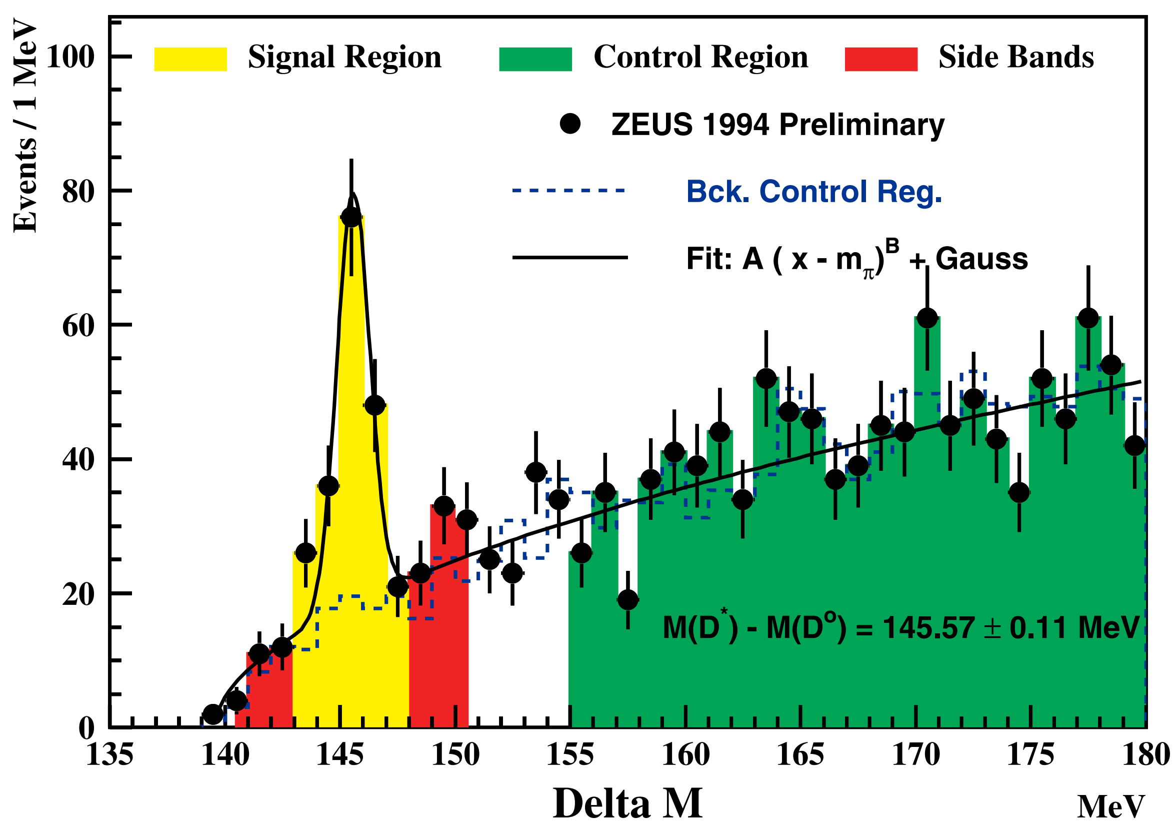


- Small Contribution from framentation
- Higher sensitivity to gluon density than F_2

Identifying open charm/D* signals

$D^* \rightarrow (K\pi)\pi_S$ in DIS





$F_2^{c\bar{c}}$ versus x

H1 Result:

- $\frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}(1+(1-y)^2)\,F_2^{c\bar{c}}(x,Q^2)$
- Range extended by $1/100$ in x with respect to EMC
- Steep rise in $F_2^{c\bar{c}}$ at small x
- In agreement with NLO calculations BUT currently statistics too poor to draw any conclusions
- Eventually alternative handle on the gluon