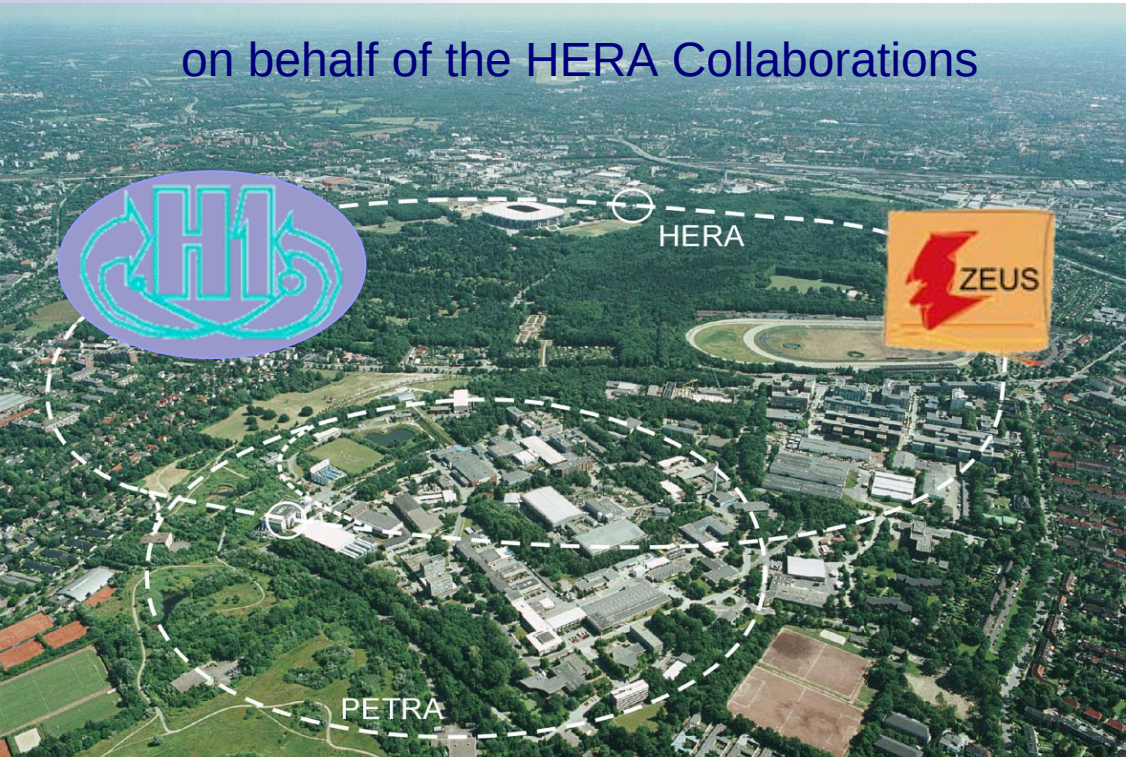
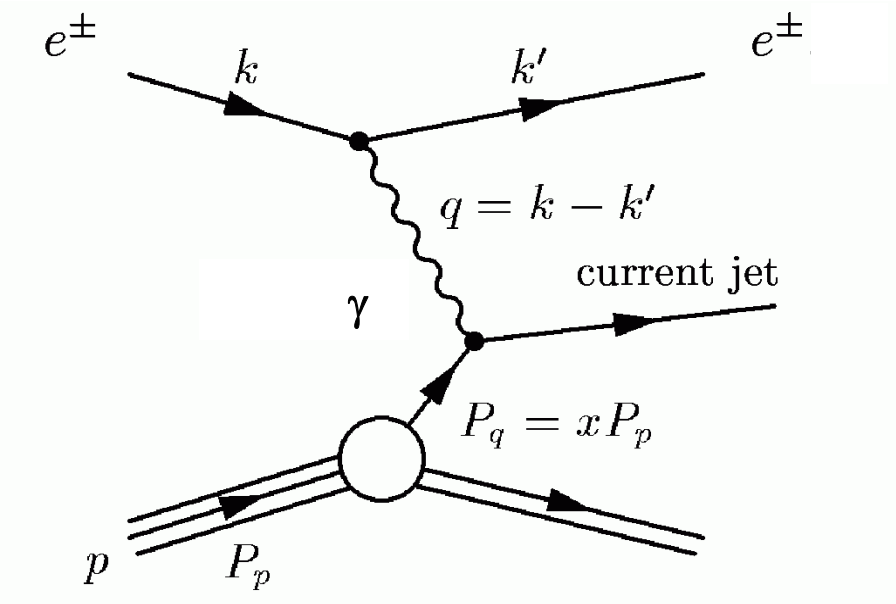
# Proton Structure Function $F_L$ at HERA

Burkard Reisert,
Max Planck Institut für Physik,
on behalf of the HERA Collaborations




- **Deep Inelastic Scattering (DIS)**
- **Experimental Setup**
- **Results on FL**
- **Conclusion**

# Deep Inelastic Scattering




## Kinematic Variables

- **4-momentum transfer resolving power**

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

- **Bjørken scaling variable momentum fraction of struck parton**

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

- **Inelasticity:**

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

**Center of mass** energy $\sqrt{s}$: $s = (k + p)^2$

**relation for fixed s:** $Q^2 = sxy$

- **Neutral current DIS cross section expressed by structure functions:**

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

reduced cross section

# Deep Inelastic Scattering

Reduced ep DIS Cross section:

$$\frac{Q^4 x}{2\pi\alpha^2 Y_+}\frac{d^2\sigma}{dxdQ^2} = \sigma_r = F_2\left(x,Q^2\right) - \frac{y^2}{Y_+}F_L\left(x,Q^2\right)$$

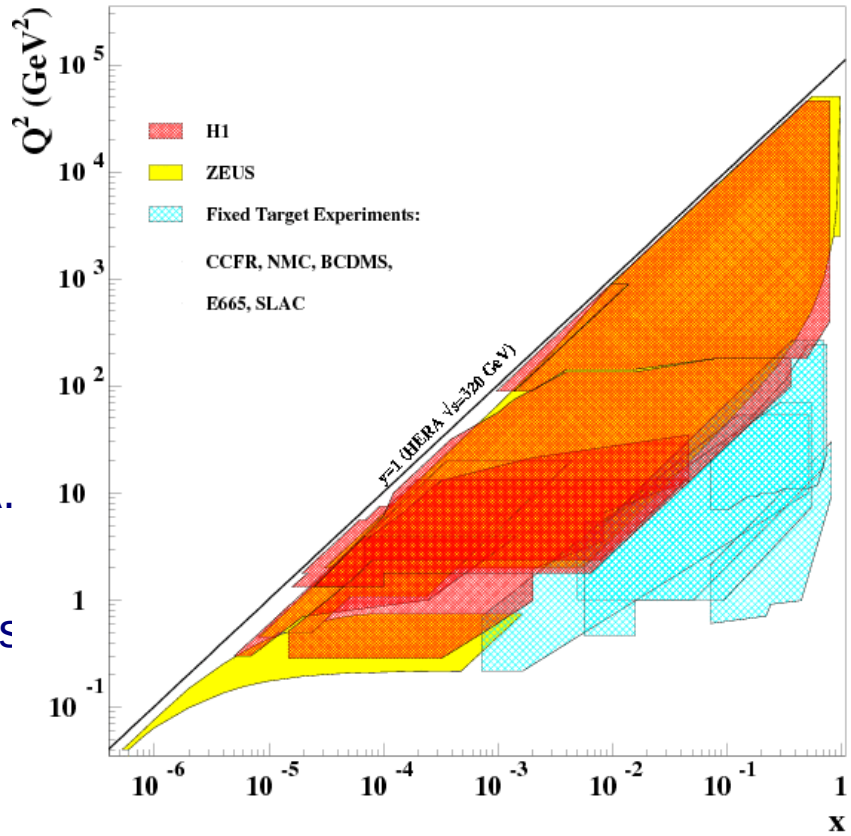
Two proton structure functions define inclusive DIS ep scattering cross section.

$F_2$ determines sum of quark distributions.

$F_L$, at low x, determines gluon distribution.

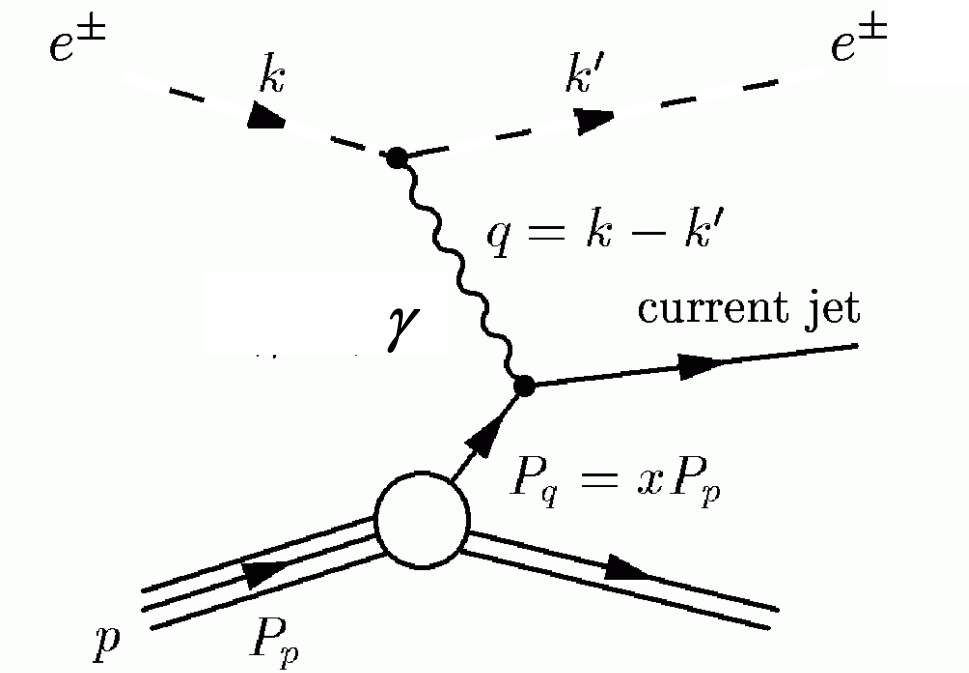
The F2 term dominates the cross section, has been measured for 15 years at HERA.

The $F_L$ term is sizeable only at large values of inelasticity y. It was directly accessed on in the last 4 months of HERA's operation



# Photon Proton Scattering

- The same process may be interpreted as scattering of an virtual photon off an proton
- The virtual photon may be transversely or longitudinally polarized




## $\gamma p$ Cross Sections:

$$\sigma_T^{\gamma p} = \frac{4\pi\alpha}{Q^2} 2xF_1 = \frac{4\pi\alpha}{Q^2}\left(F_2 - F_L\right)$$

$$\sigma_L^{\gamma p} = \frac{4\pi\alpha}{Q^2}\left(F_2 - 2xF_1\right) = \frac{4\pi\alpha}{Q^2} F_L$$

$$\frac{\sigma_L^{\gamma p}}{\sigma_T^{\gamma p}} = R = \frac{F_L}{F_2 - F_L}$$

## Quark Parton Model (QPM)

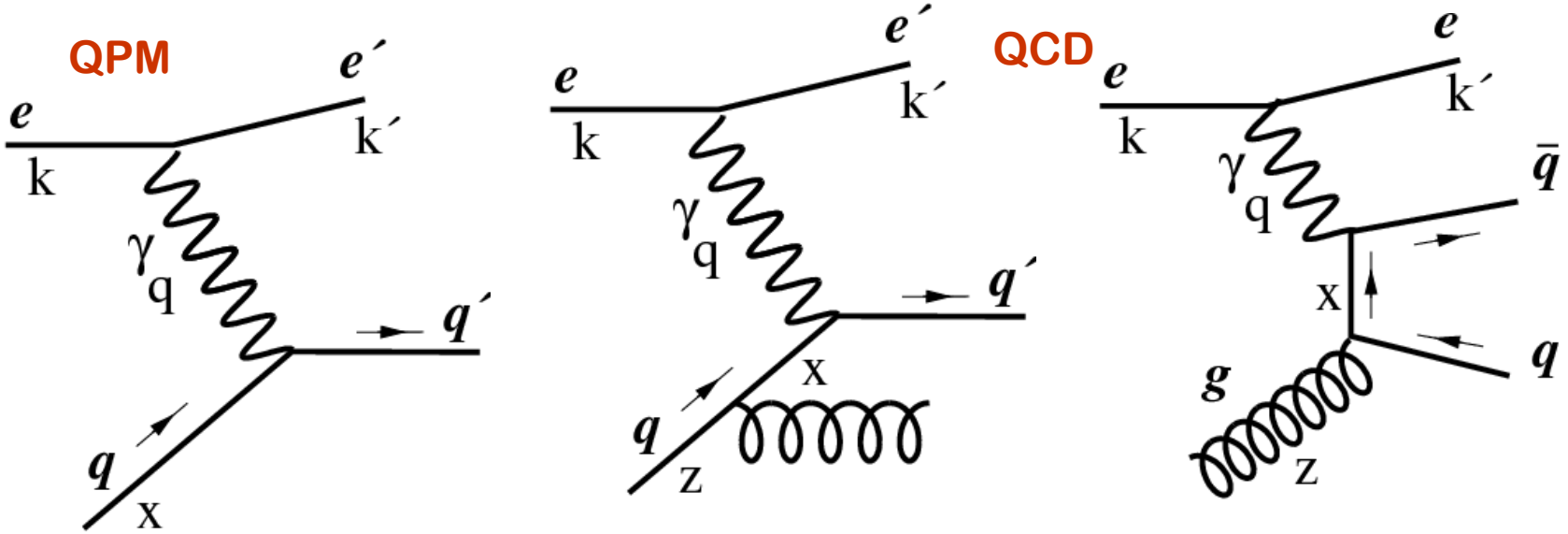
$$F_1(x) = \frac{1}{2x}\sum_q e_q^2 xq(x)$$

$$F_2(x) = \sum_q e_q^2 xq(x)$$

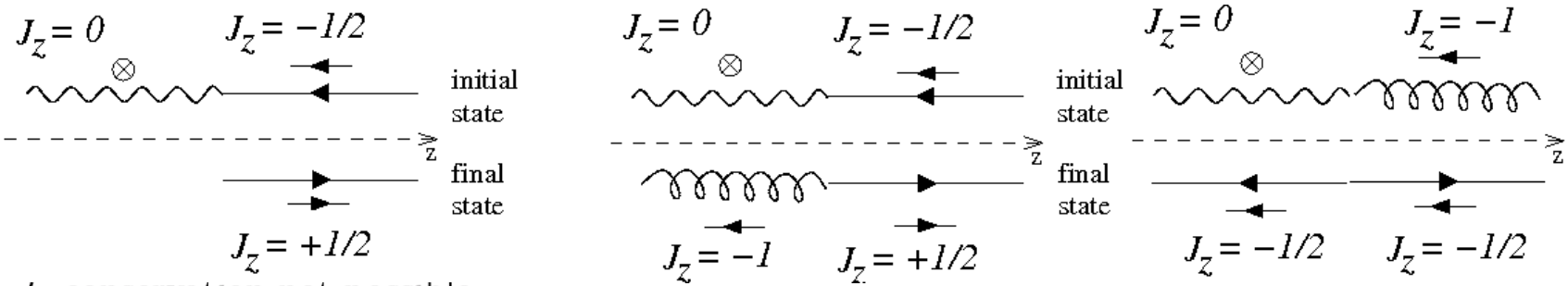
$$F_L(x) = F_2 - 2xF_1 = 0$$

Callan Gross relation

# Longitudinal Structure Function $F_L$




**Scattering of longitudinally polarized photons on quarks in helicity frame**



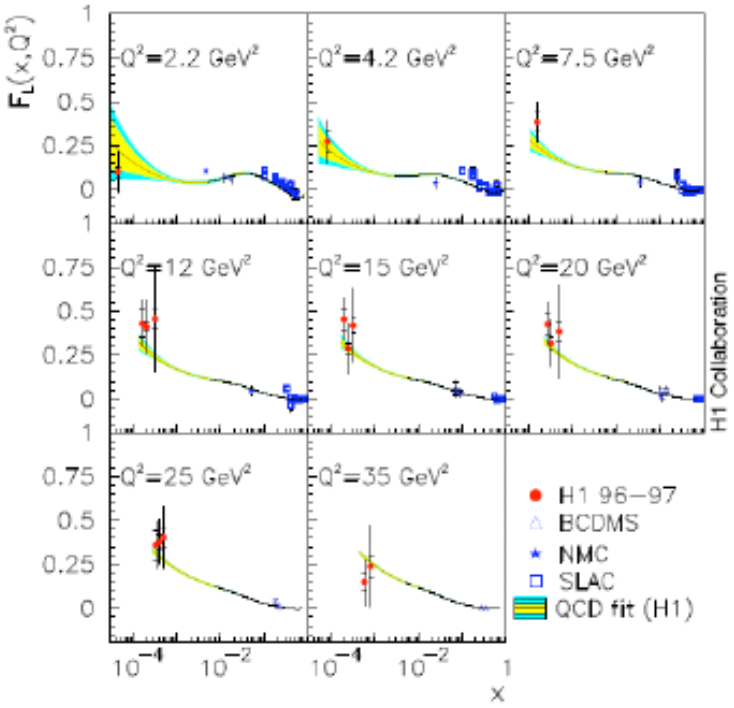

$$F_L \propto \sigma_L = 0$$

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{\mathrm{d}z}{z^3} \left[ \frac{16}{3} \sum_q z e_q^2 (q + \bar{q}) + 8 \sum_q e_q^2 \left(1 - \frac{x}{z}\right) \cdot zg \right]$$

**access to gluon density**

# Expectations on FL

## Experiment




Fixed target: $F_L$ is small at large x (spin 1/2 quarks)
indications for increase towards low x

H1: hints to large $F_L$ when $F_2$ is assumed to be known

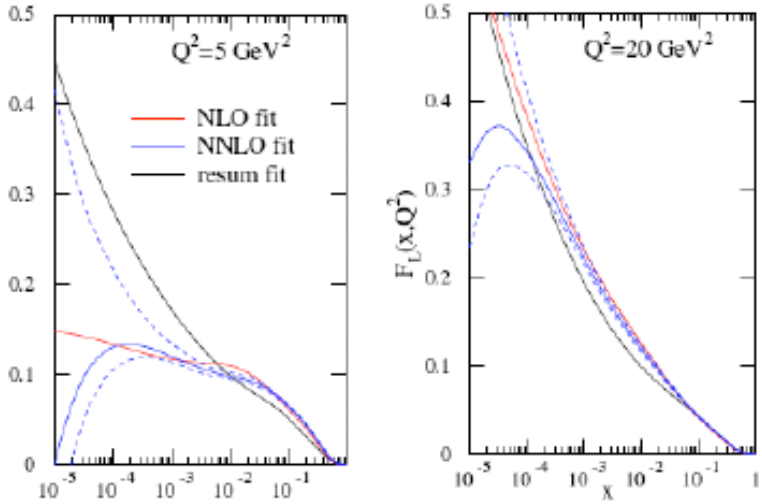
Eur.Phys.J.C21:33-61,2001

## Theory (pQCD)

$F_L$ prediction related to the gluon density, the size and the uncertainties on xg - constraints require max accuracy and range

Theory developed to NNLO
[W.van Neerven (†), J.Vermaseren, et al.]

Global/detailed pdf analyses
[CTEQ, MRST, Alechin, HERA, …]

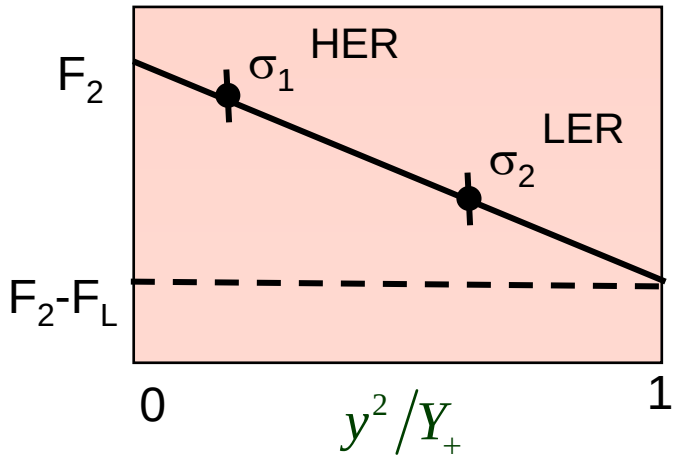



R.Thorne, DIS08

# How to Measure $F_L$ ?

- **Measure cross sections** $\sigma_r = F_2\left(x,Q^2\right) - \frac{y^2}{Y_+} F_L\left(x,Q^2\right)$

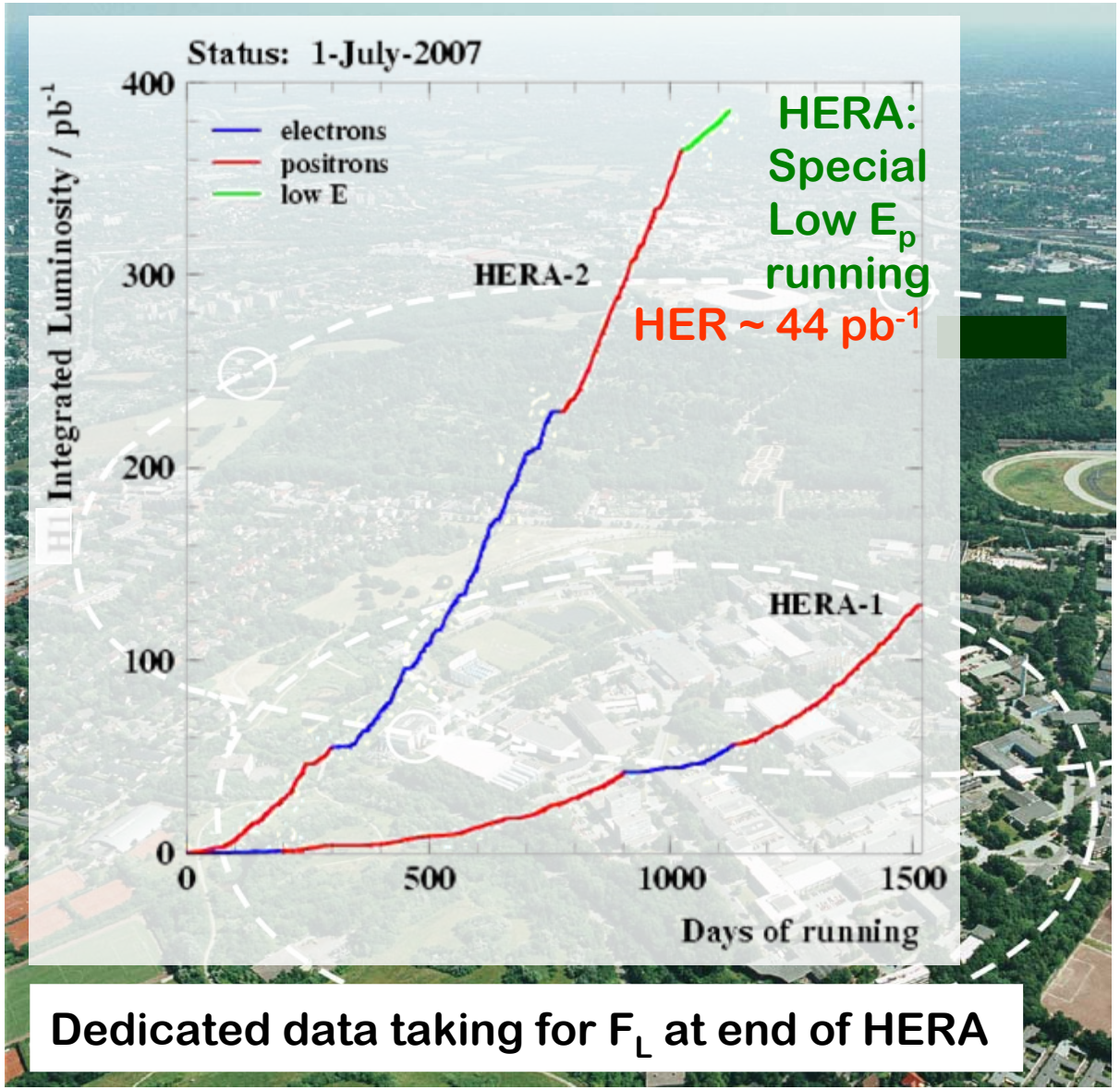
  **at same *x* and $Q^2$ but different $y = Q^2/y \cdot s$ → vary s**

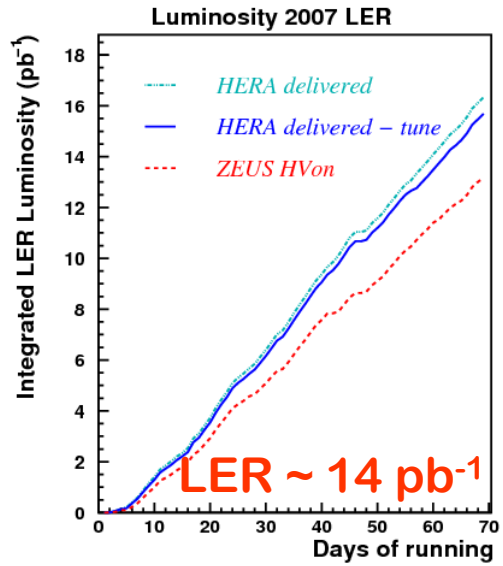


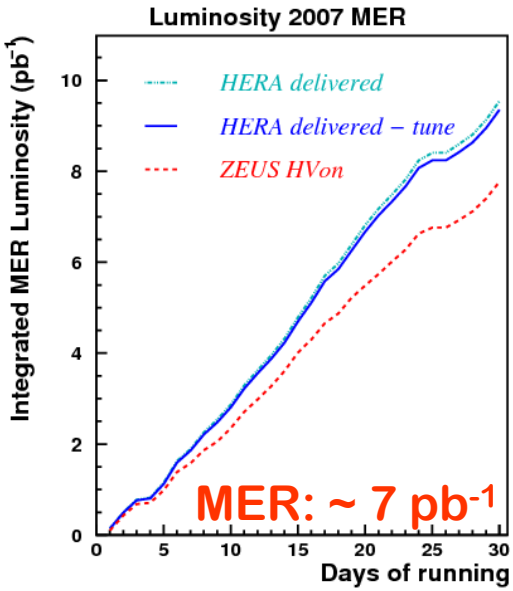

- **Change proton beam energy to change cms energy**
- **Large level arm in $y^2/Y_+$**
- **Measure at high *y* in LER**

- **Extended measurement to high y region**
  $y = 1-E'_e/E_e(1-\cos\theta)$ →high *y* means low $E'_e$
- **Estimate: Need ~10pb$^{-1}$ for measurement**

# HERA Accelerator Performance

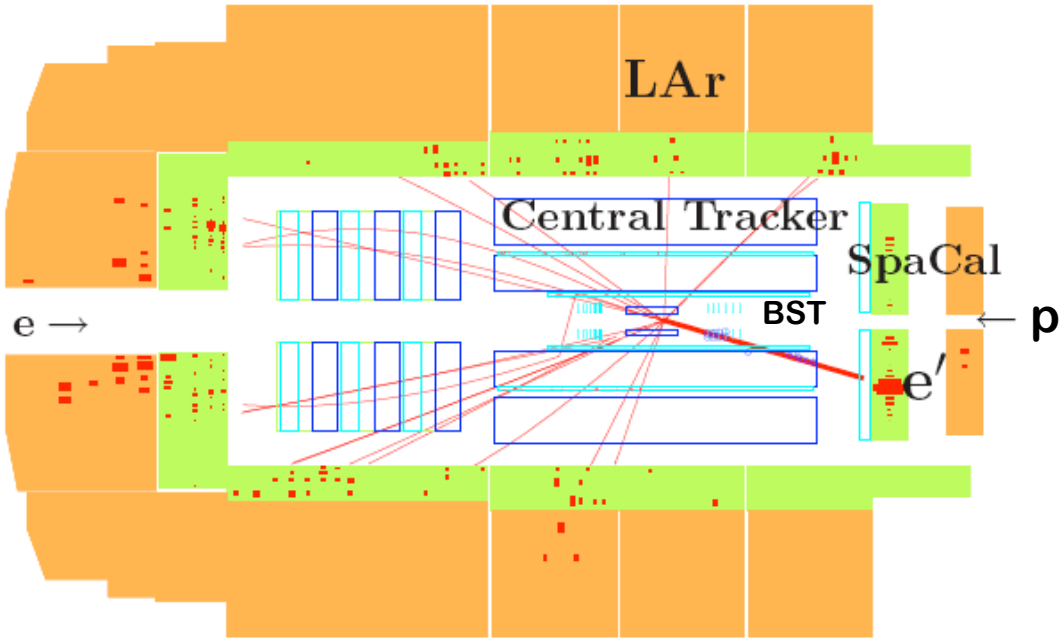


# Measuring $F_L$ with H1

DIS event of $Q^2$ near 30 $GeV^2$




**Upgrades for FL**

**SpaCal (94)**

**BST (95+03)**

**Triggers (03-07)**
- **Inner Chamber (CIP)**
- **SpaCal**
- **Fast Tracking (CJC)**
- **Jet Trigger (LAr)**

**Three $Q^2$ ranges**

| | | |
|---|---|---|
| **3 to** | **12 $GeV^2$** | **SpaCal+BST prelim. 04/09** |
| **12 to** | **90 $GeV^2$** | **SpaCal+CT: published 06** |
| **35 to 800** | **$GeV^2$** | **LAr+CT: prelim. 03/08** |

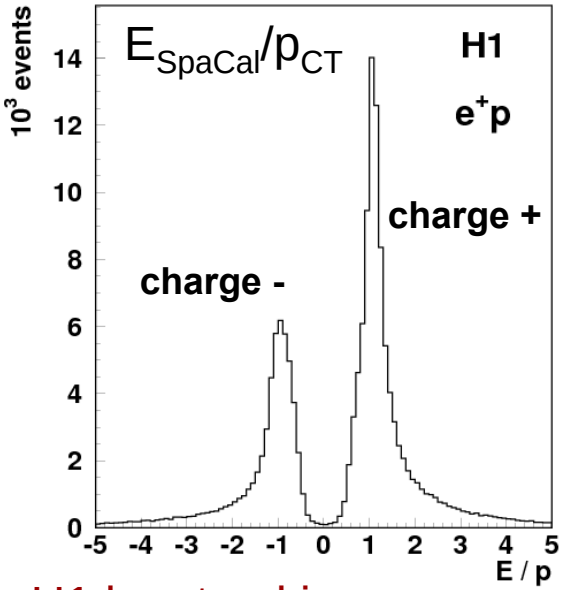
**Event selection Criteria**

El. in SpaCal or LAr (Calo & Trig) $E'_e$ >3 GeV
Track in CT or BST (veto neutrals, e/p)
Interaction vertex
$E\text{-}Pz = \Sigma_i E_i(1-\cos\theta_i)$ >35 GeV
Reduces largely radiative corrections

# Background Subtraction – H1

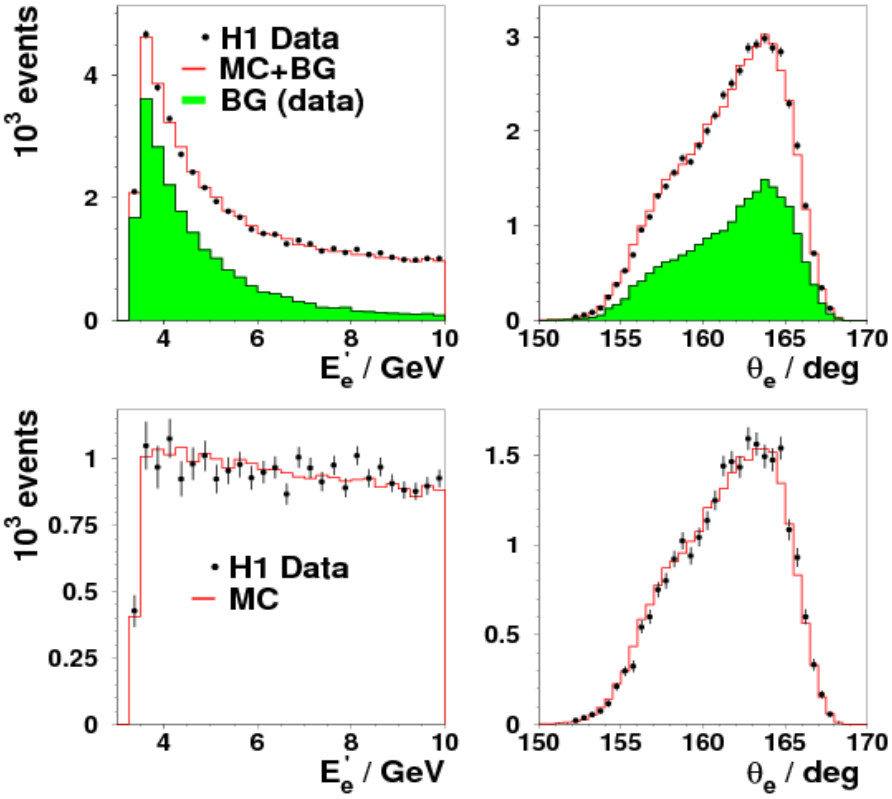
**At small energies severe contamination by γp events.**

**Those are charge symmetric, apart from small effects due to anti-proton vs protons, which is measured using e+p and e-p data, and corrected for**



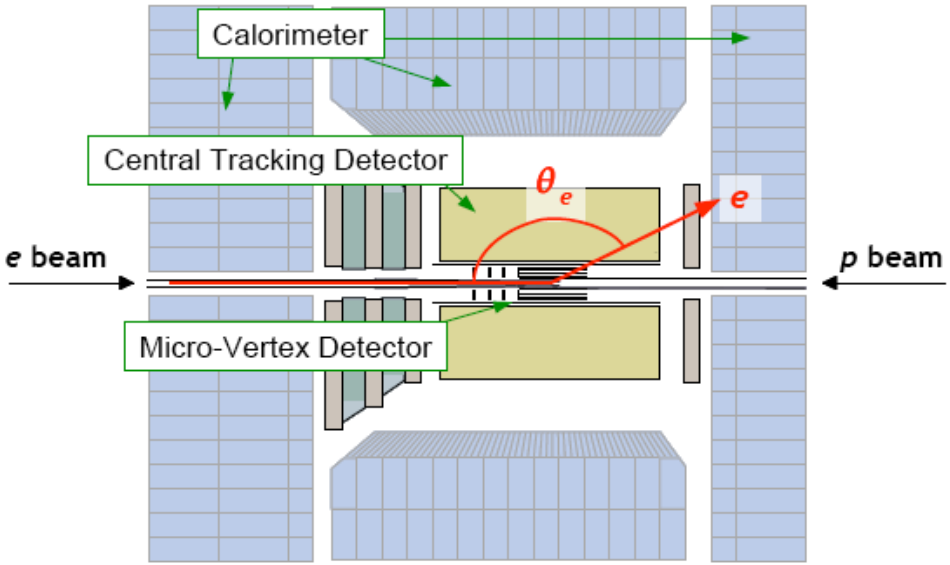

H1 has tracking coverage for the electron candidates for all full Q2 ranges (CT & BST)

**Scattered electron distributions (SpaCal + CT)**




**H1 background subtraction based on data. Trade off between background rejection and stat. unc. of background sample (wrong chrg.)**

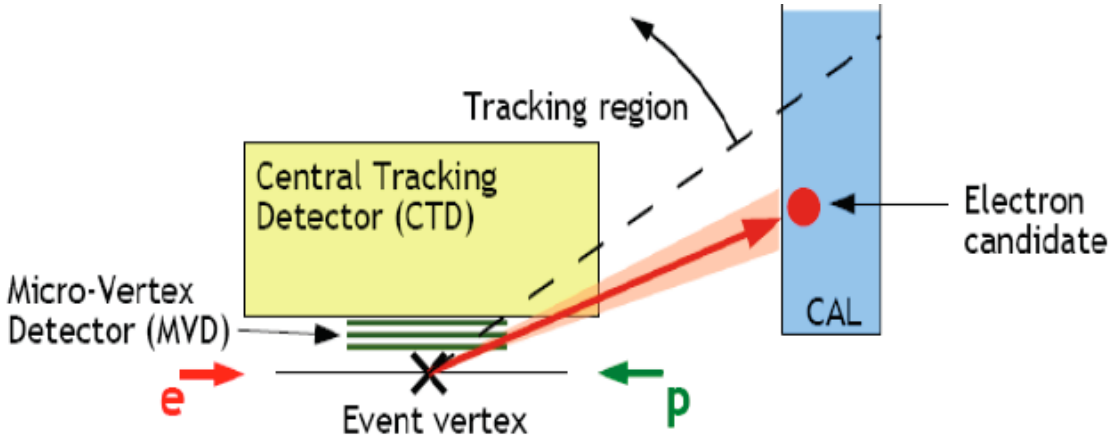
# Measuring FL with ZEUS



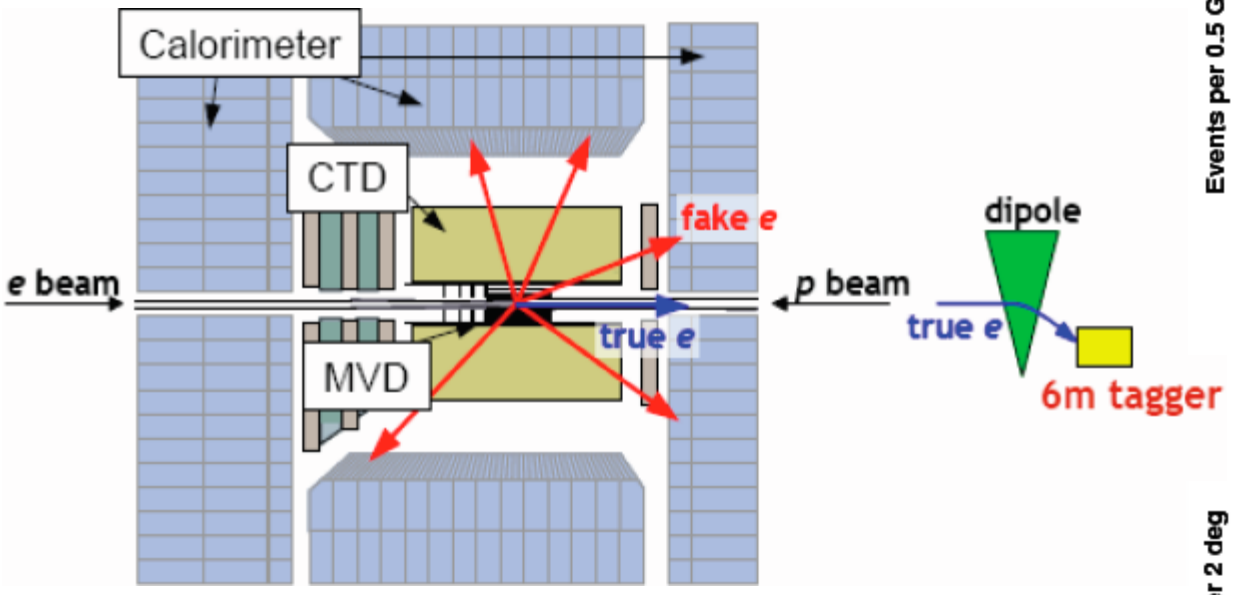

**Event Selection:**

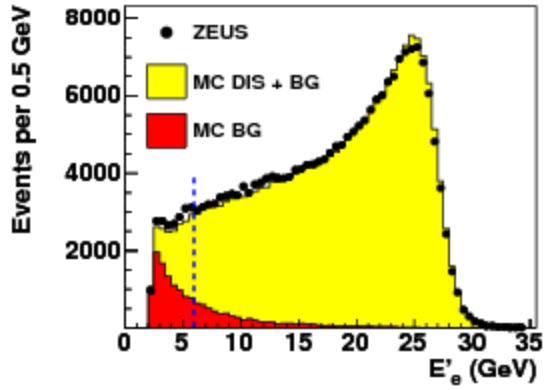
**Electron in backward Calo**
**$E'_e$ >6 GeV (Cluster & Trigger)**
**Hits in CTD & MVD (reject neutrals)**
**Event vertex**
**$42 < E-p_z < 65$ GeV**

$Q^2$ range between
24 and 110 $GeV^2$

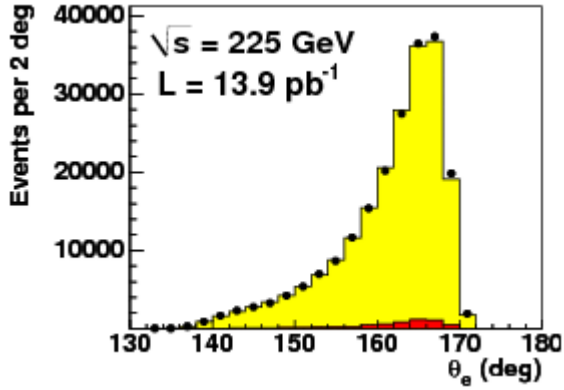


# Background Subtraction - ZEUS




ZEUS



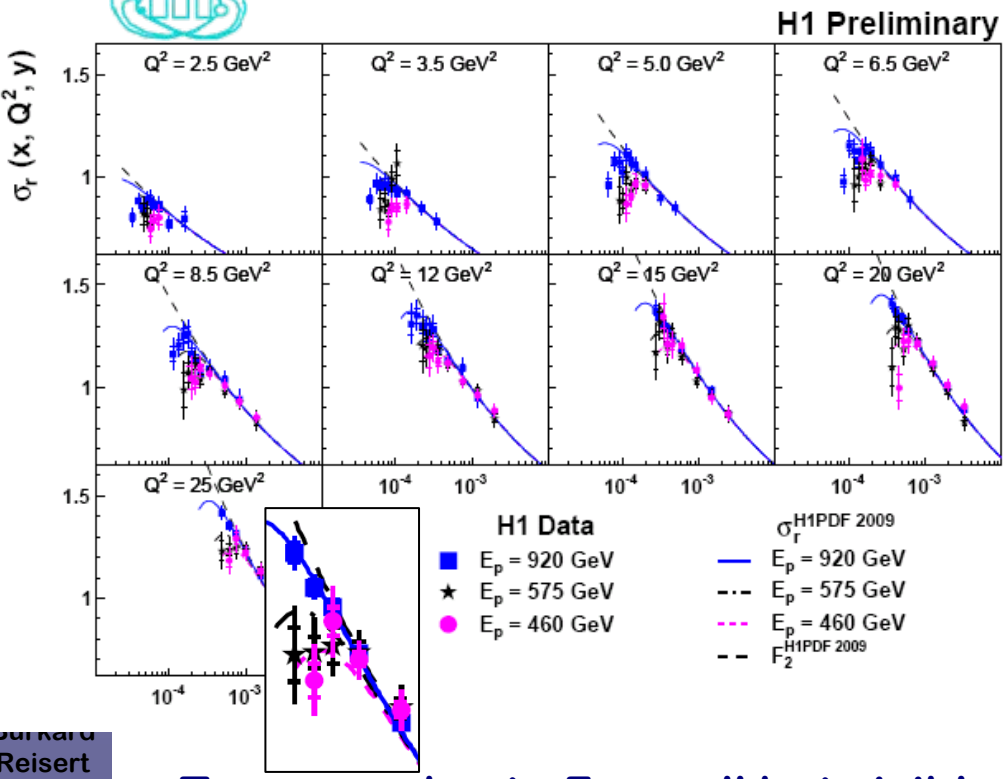

**Photoproduction BG removed using PYTHIA MC with subprocesses (direct, resolved, diffractive,…) weights**
**Adjusted to γp cross section measurement.**
**Control using 6m electron tagger. Complimentary studies with γp enriched data sample.**

# Cross Sections for direct FL extraction

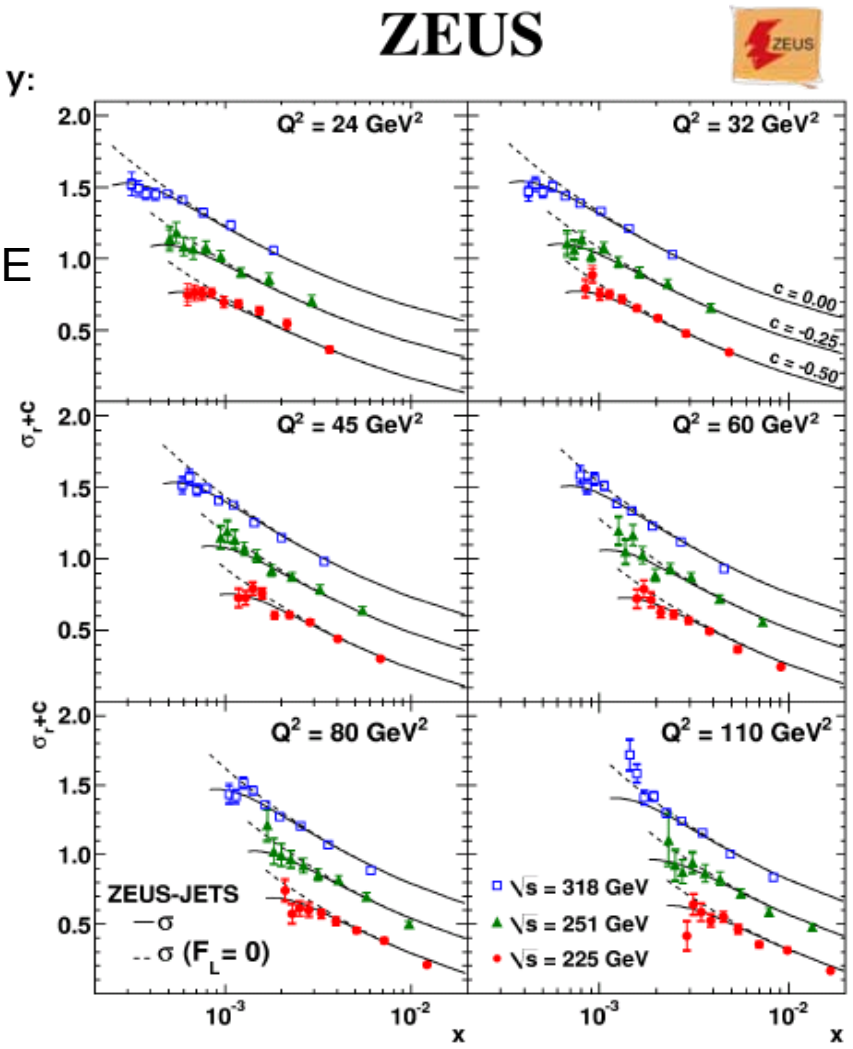
Direct $F_L$ measurement requires measurement of the reduced cross sections at **same x and $Q^2$ but different y:**

$$\sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} \cdot F_L(x, Q^2)$$

$$y = \frac{Q^2}{x \cdot s}$$ different y → different s → different beam E




**Turnover due to $F_L$ small but visible**




most precise $\sigma_r$ from ZEUS

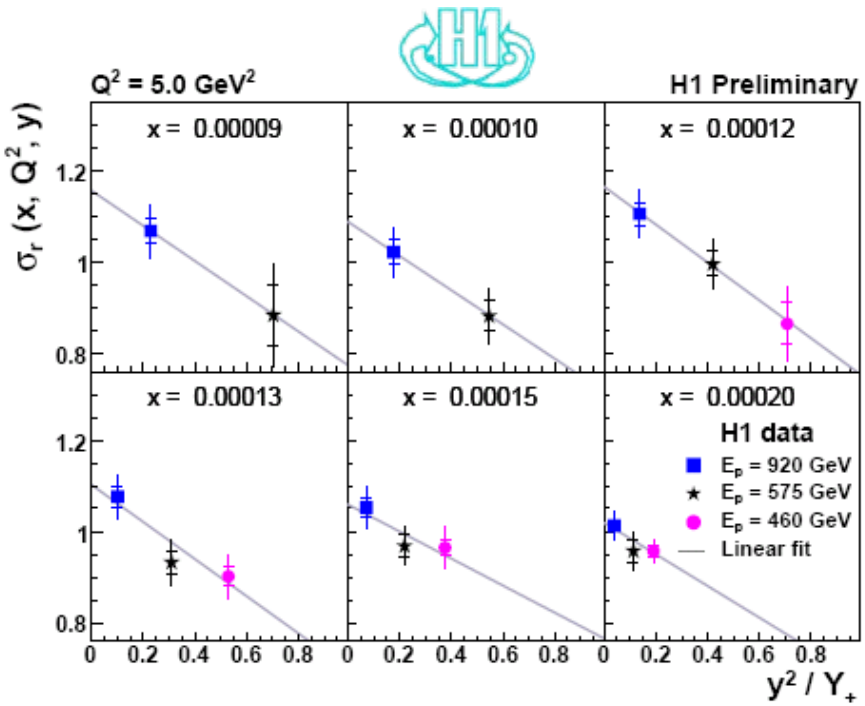
arXiv:0904.1092v1

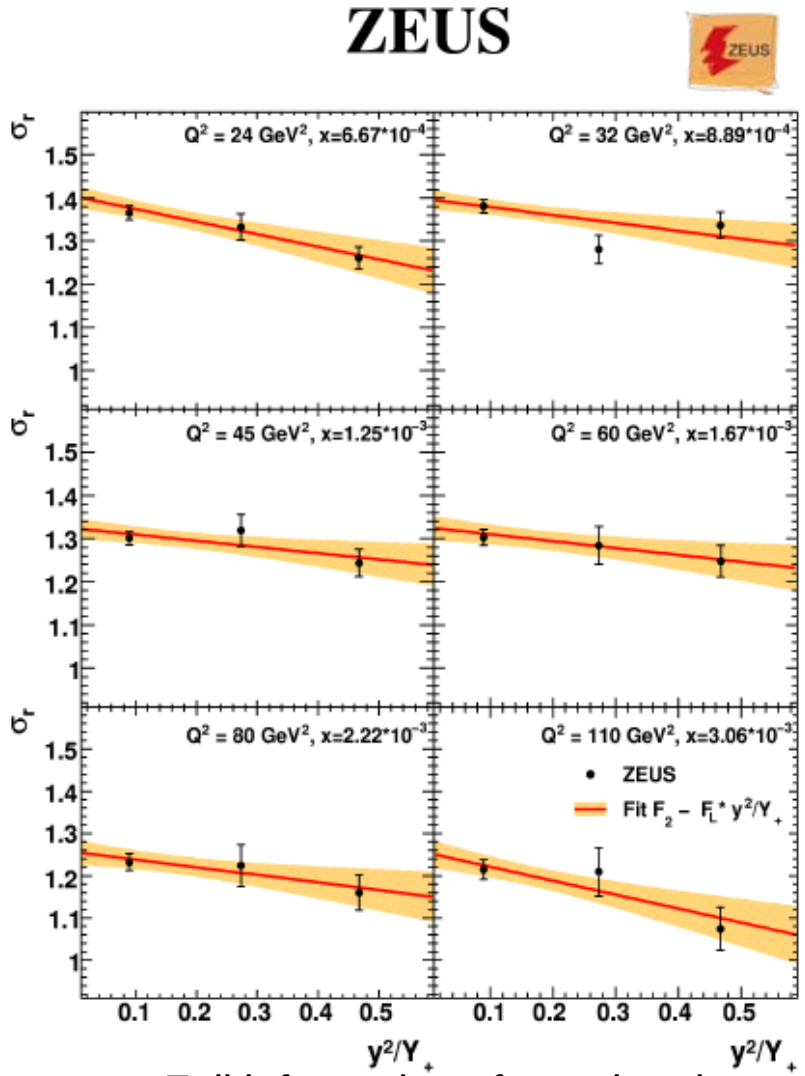
# $F_L$ Extraction: Rosenbluth plots

$$\sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} \cdot F_L(x, Q^2)$$

Straight line fit of $\sigma_r$ vs $y^2/Y_+$

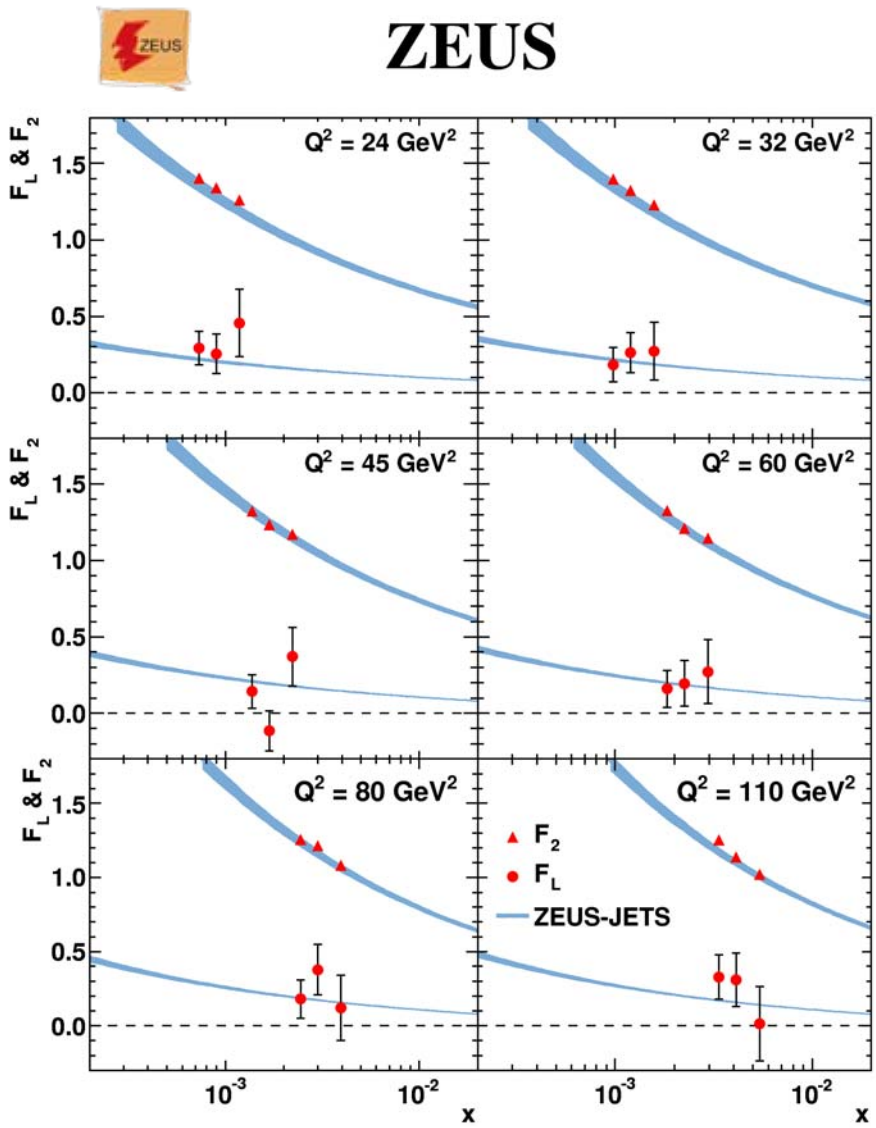
$F_L$ slope, $F_2$ intercept



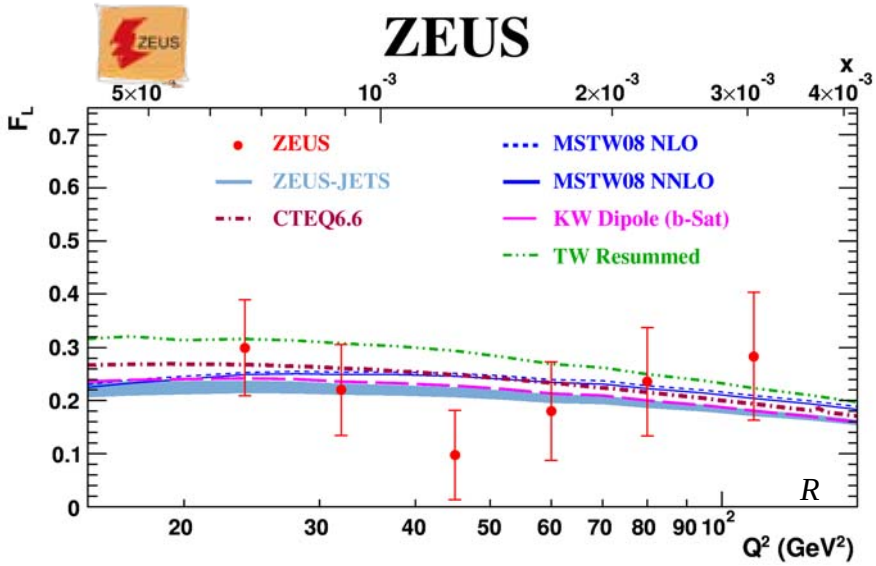

Full information of correlated systematics taken into account

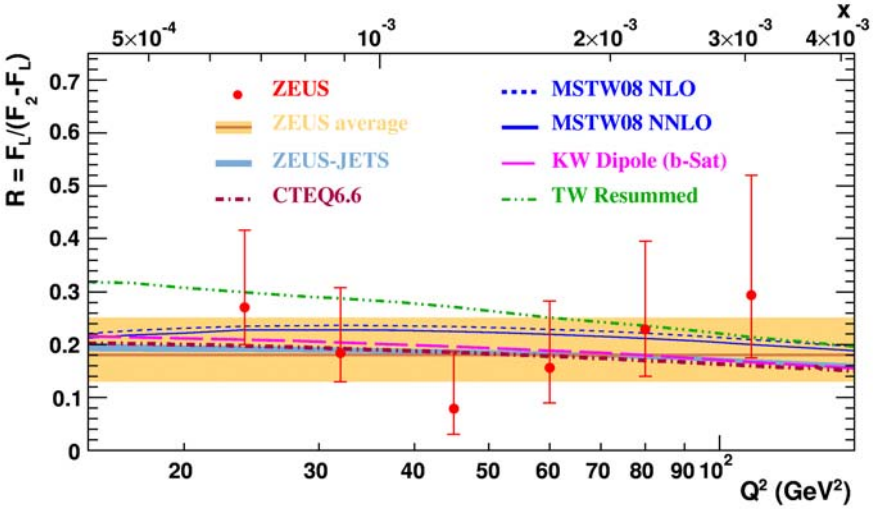
# Extracted $F_L$ and $F_2$ – ZEUS




- Most precise $F_2$ measurement from ZEUS in kinematic region studied
- First $F_2$ measurement without assumptions on $F_L$
- Data support a non-zero $F_L$
- Predictions for $F_2$ and $F_L$ are consistent with data

# Average $F_L$ and R – ZEUS



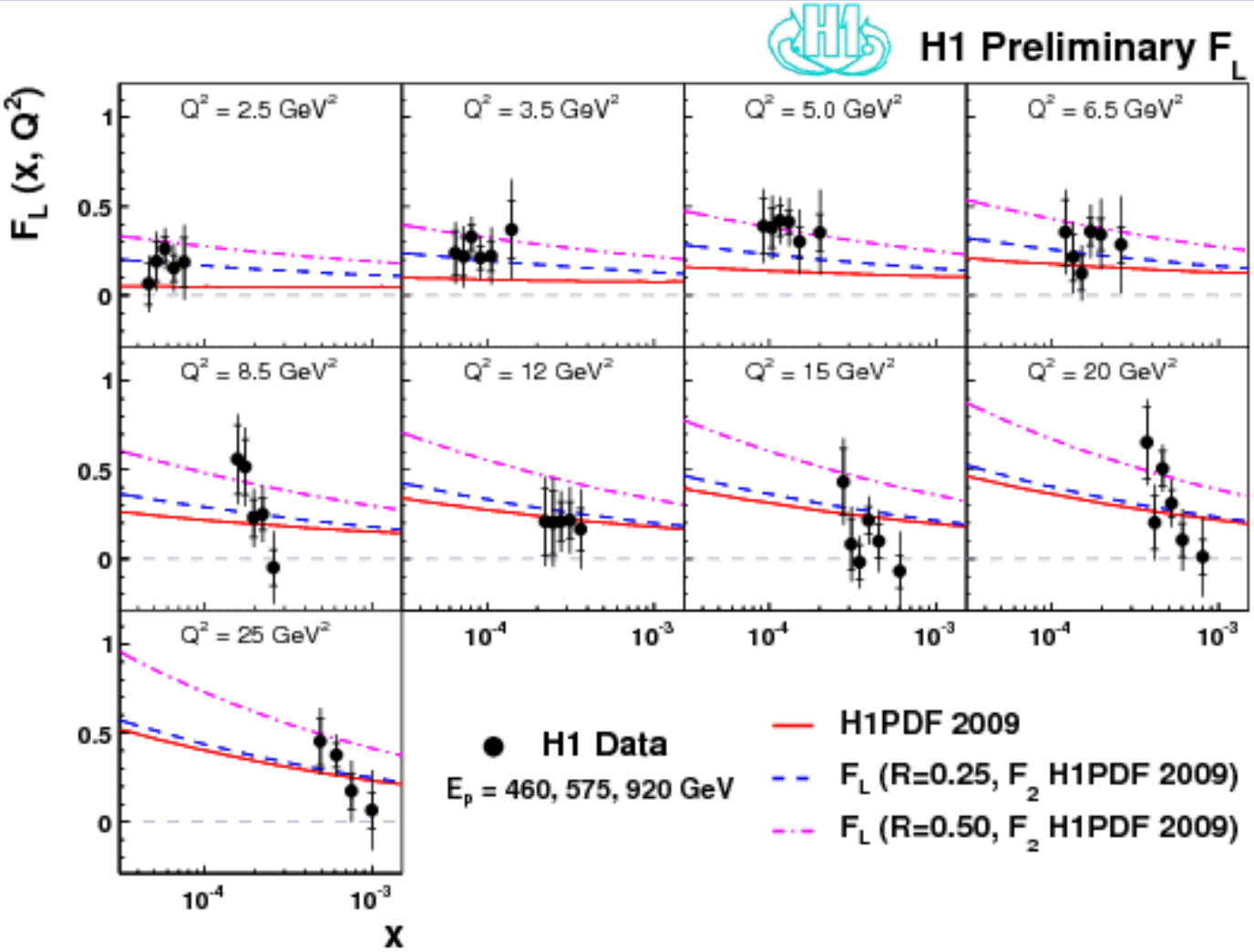

## Averaged FL

- Data support non-zero FL
- Predictions are consistent with data

## Averaged $R = F_L/(F_2-F_L)$

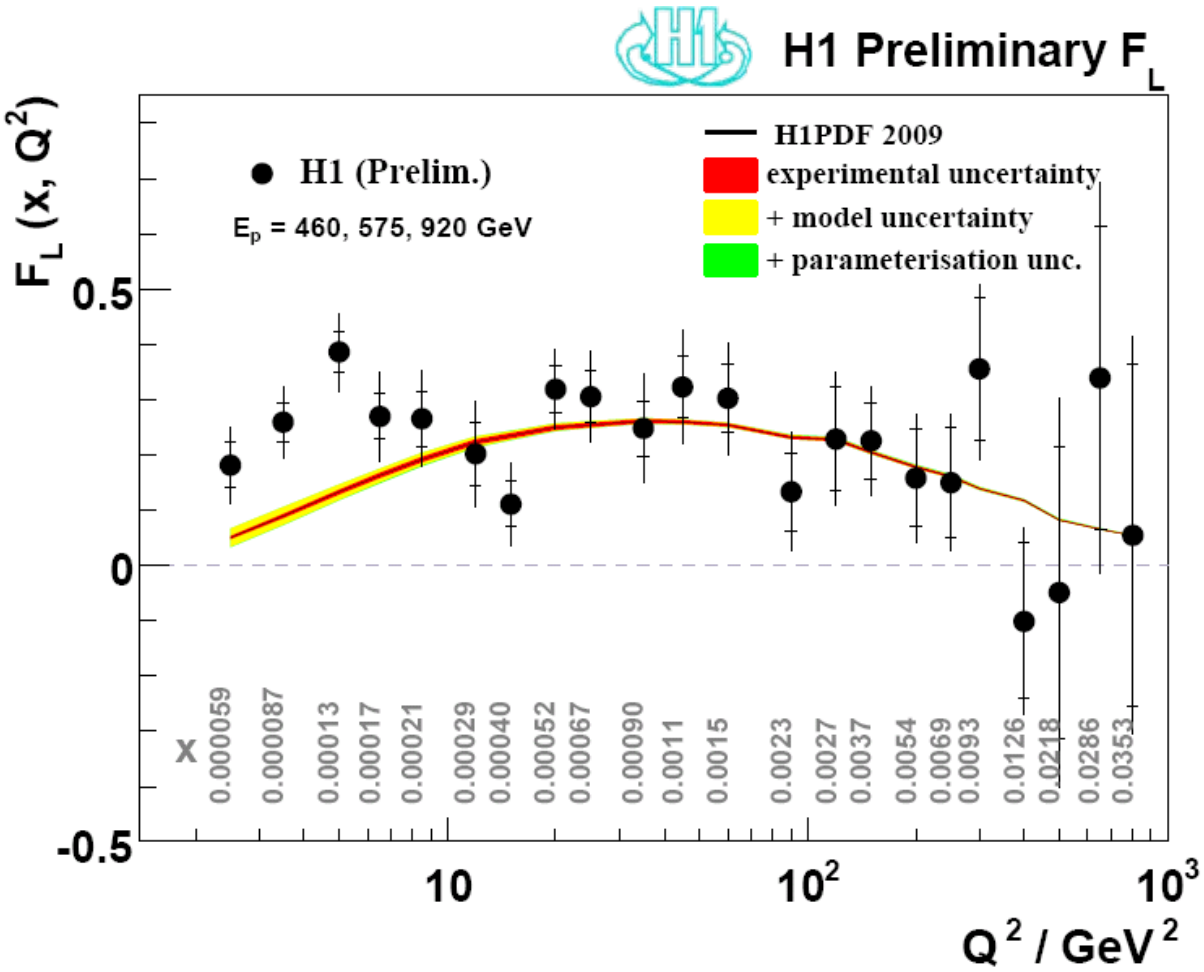
- $R = 0.18^{+0.07}_{-0.05}$

# Extracted $F_L$ – H1



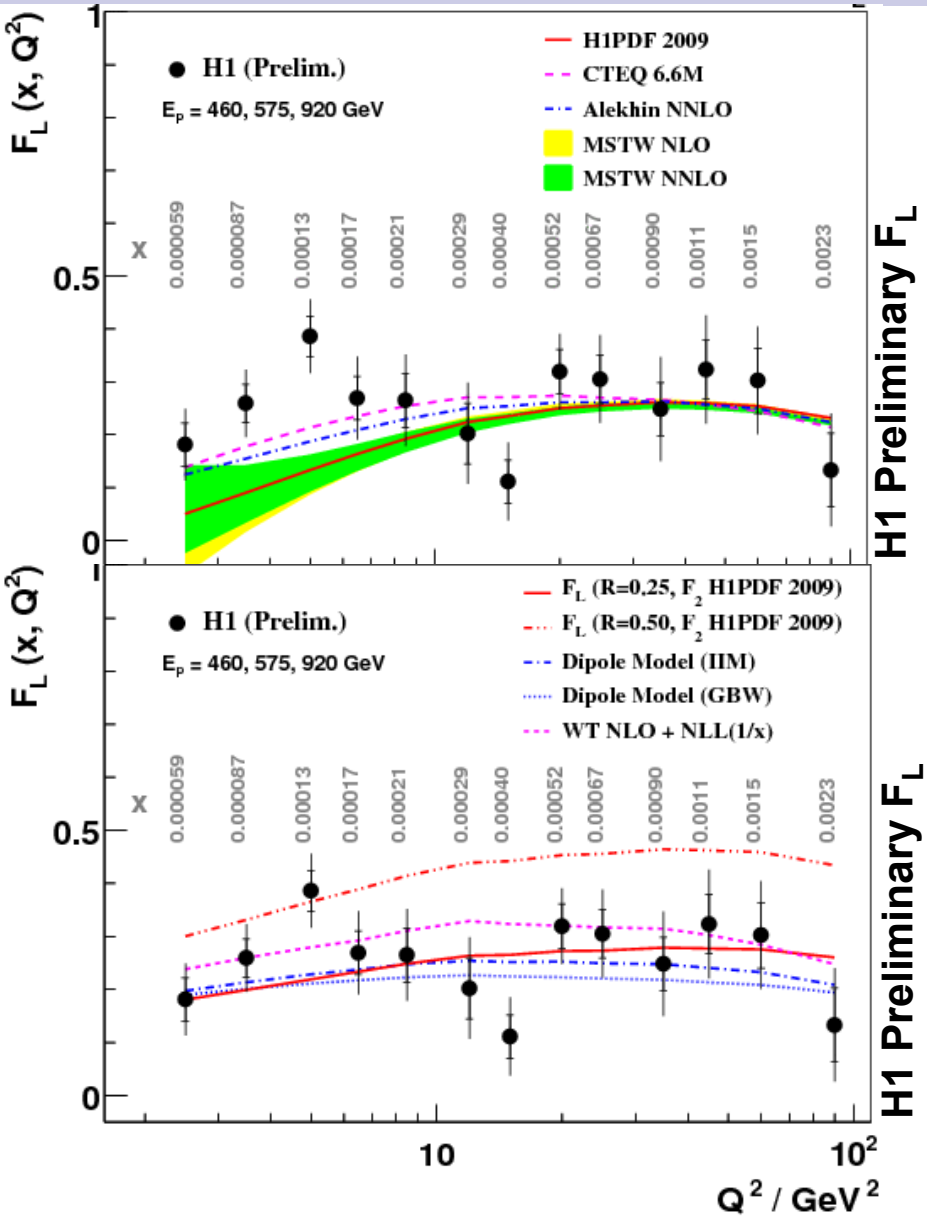

Data are consistent with R~0.25 ($F_L = 0.2 \cdot F_2$)

# Average $F_L$ – H1




**H1 measurements cover $2.5 \le Q^2 \le 800$ GeV$^2$ and $0.00005 \le x \le 0.05$**
**For $Q^2 \ge 10$ GeV$^2$, agree well with H1PDF 2009 prediction.**

# Average $F_L$ < 100 GeV$^2$




- MSTW and H1PDF 2009 predictions use the same scheme to calculate $F_L$.
- Data agree better with calculation of CTEQ
- Data is consistent with constant $R$ ~ 0.25.
- Good agreement with IIM and GBW dipole models, NLL(1/x) prediction.

# Summary and Outlook

Longitudinal structure function $F_L$ has been measured by H1 & ZEUS

FL has thus been measured for the first time in a new kinematic range:
$Q^2$ = 24 -110 $GeV^2$ (ZEUS) and 2.5 - 800 $GeV^2$ (H1), x = 0.00005 - 0.05

Data are consistent with constant R ~ 0.2 (H1), $R = 0.18^{+0.07}_{-0.05}$ (ZEUS)

For $Q^2 > 10\ GeV^2$, data are in good agreement with pQCD predictions and thus confirm expectations on the behaviour of *xg* in the DIS kinematic region.

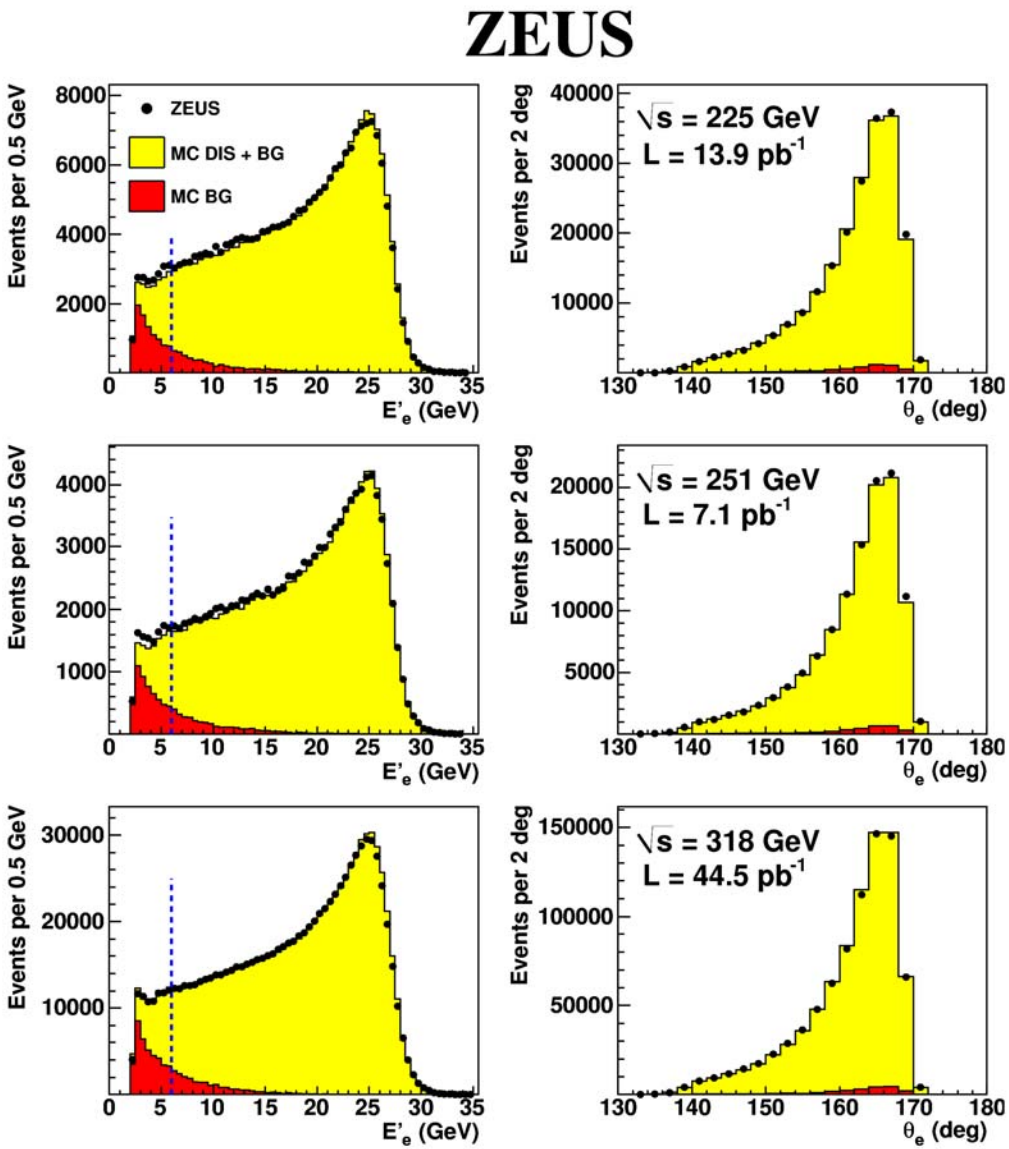
Measured $F_L$ is higher than the predictions of MSTW at NLO and NNLO as well as H1PDF2009 for $Q^2 < 10\ GeV^2$, agree better with the CTEQ 6.6M and Alekhin NNLO predictions.

The FL data thus can be expected to further constrain low x theory.

# Backupslides

- ZEUS Control Plots
- H1 Control Plots
- H1 cross sections
- H1 FL (x,Q2)
- H1 averaged FL(Q2)

# ZEUS Control Plots




Low Energy Run

Ep=460GeV

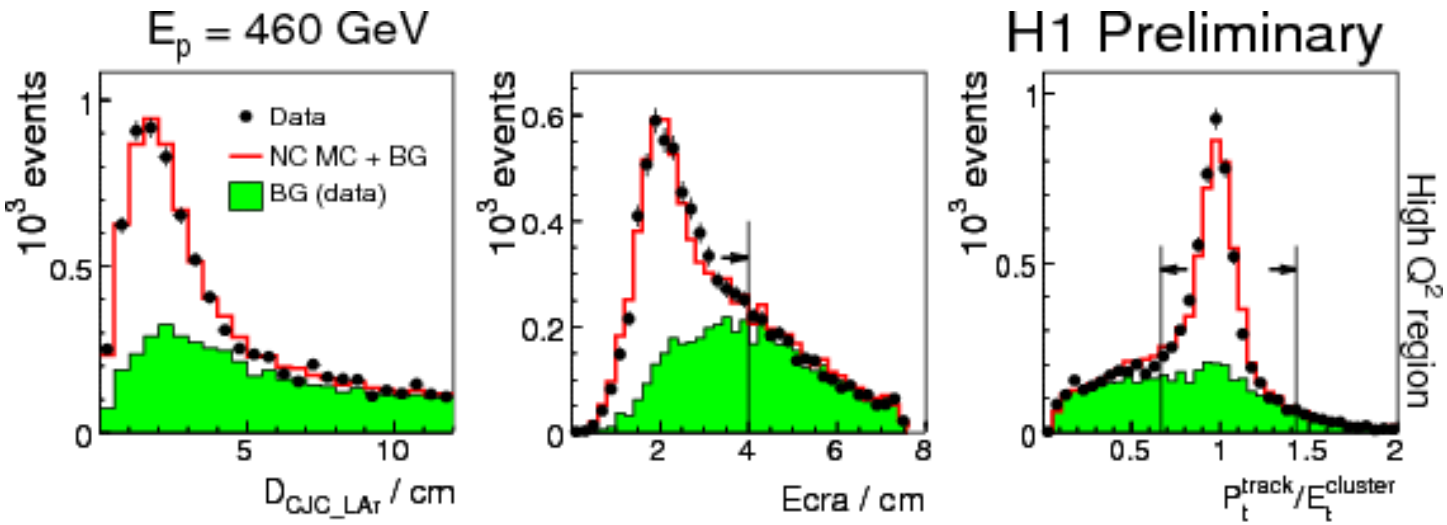
Medium Energy Run

Ep=575GeV

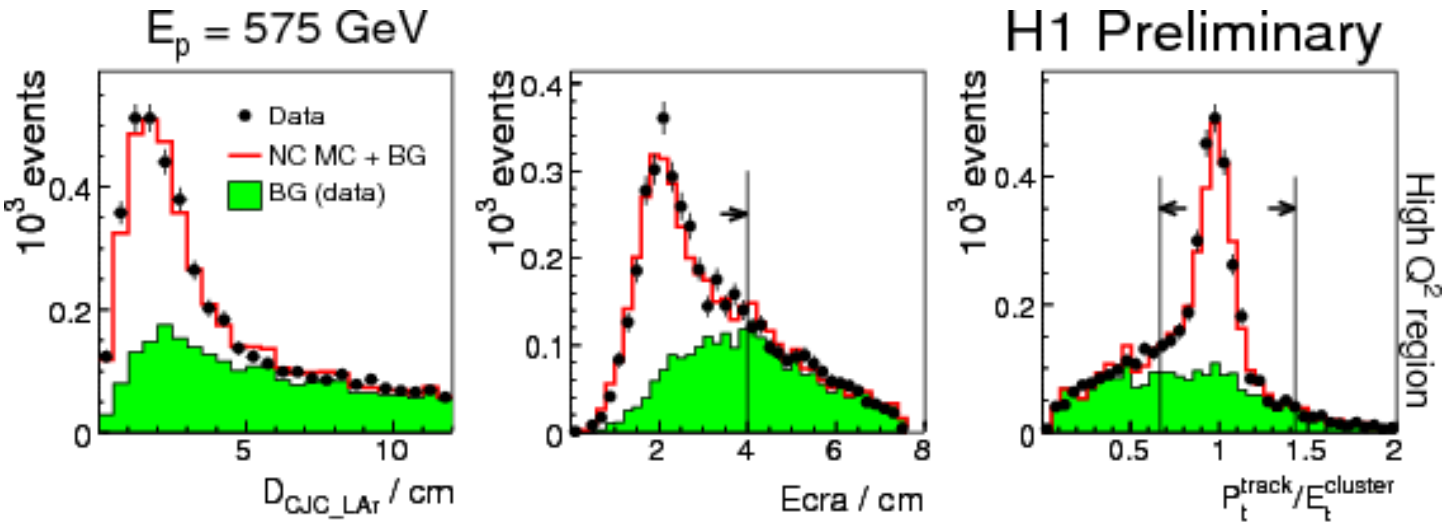
High Energy Run

Ep=920GeV

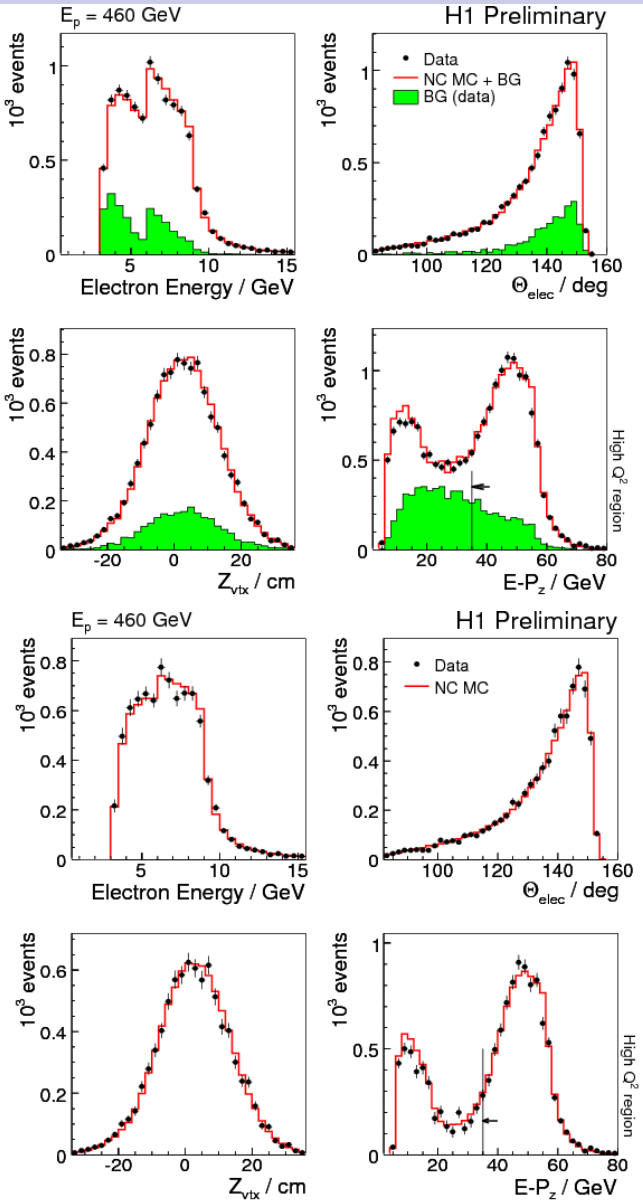
# H1 Control Plots: Electron Variables



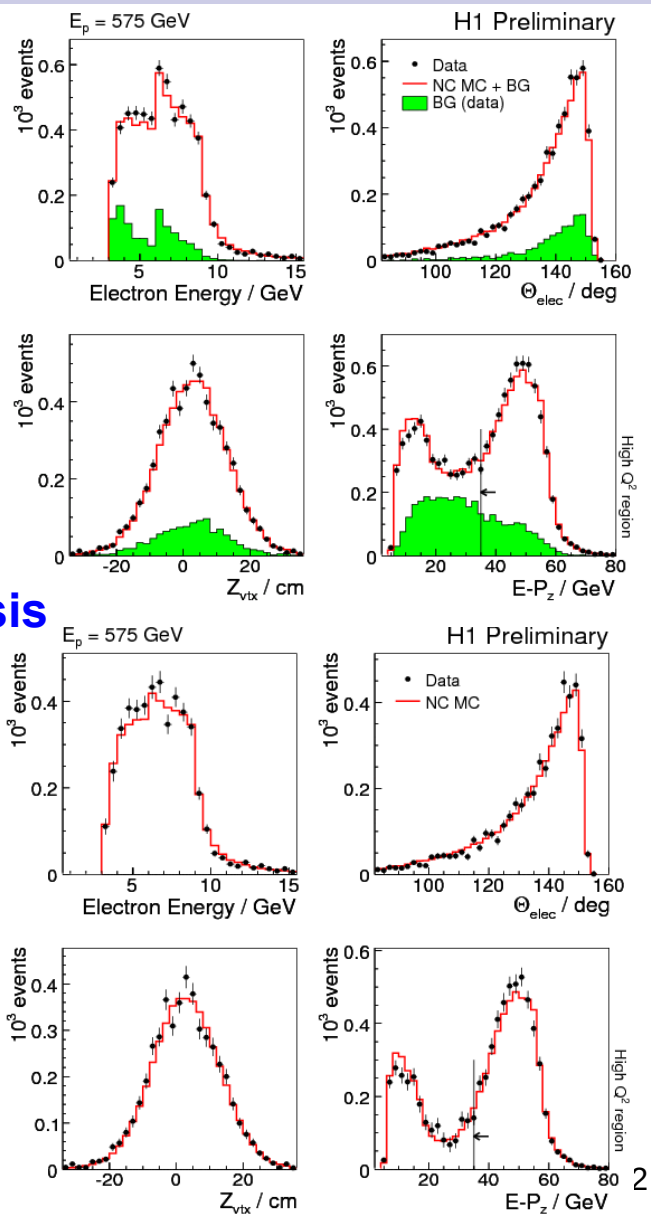

**High Q2 Analysis**



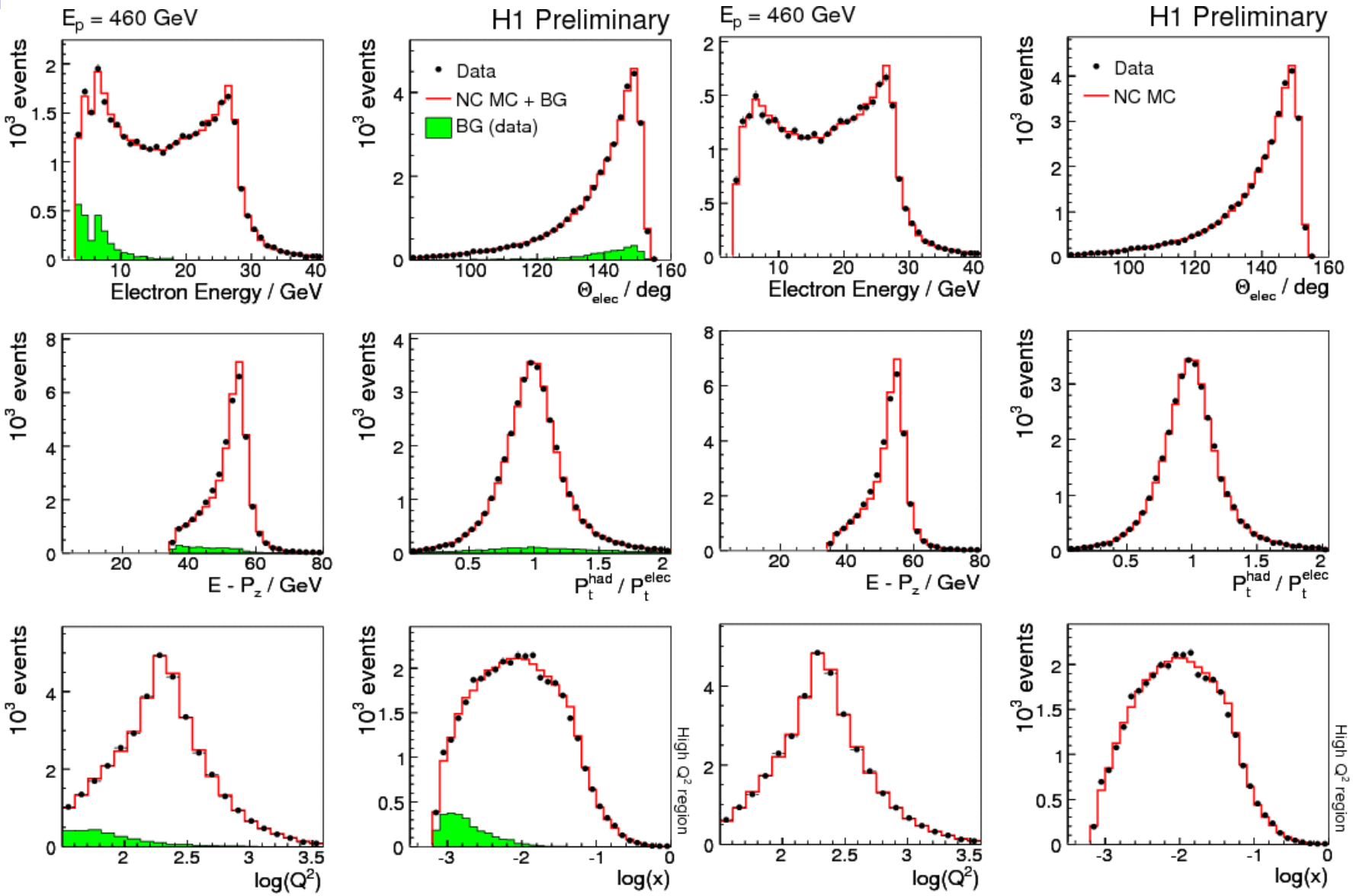
# H1 Control Plots: BG Subtraction



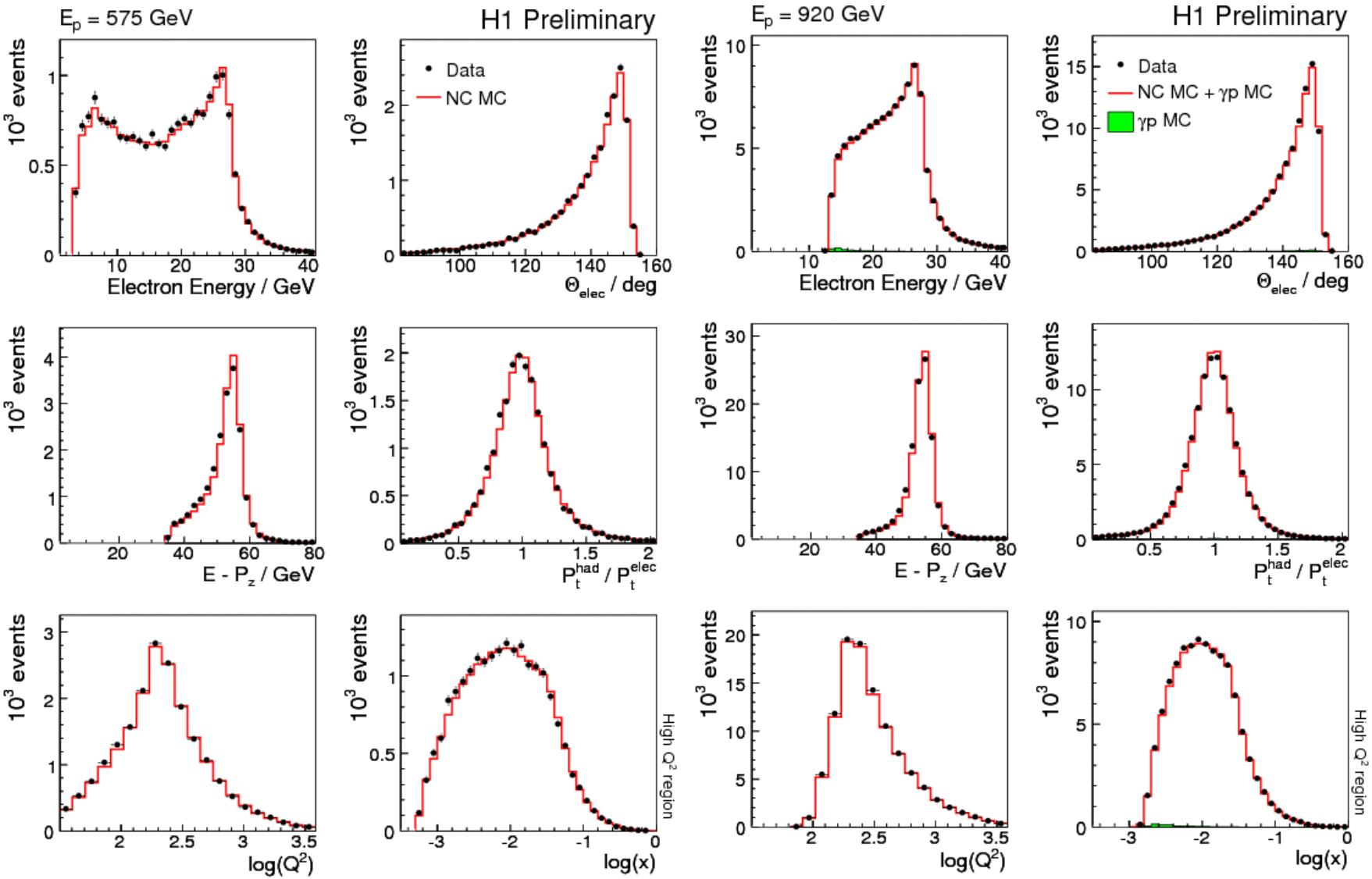

**High Q2 Analysis**



# H1 Control Plots: Event Variables



# H1 Control Plots: Event Variables

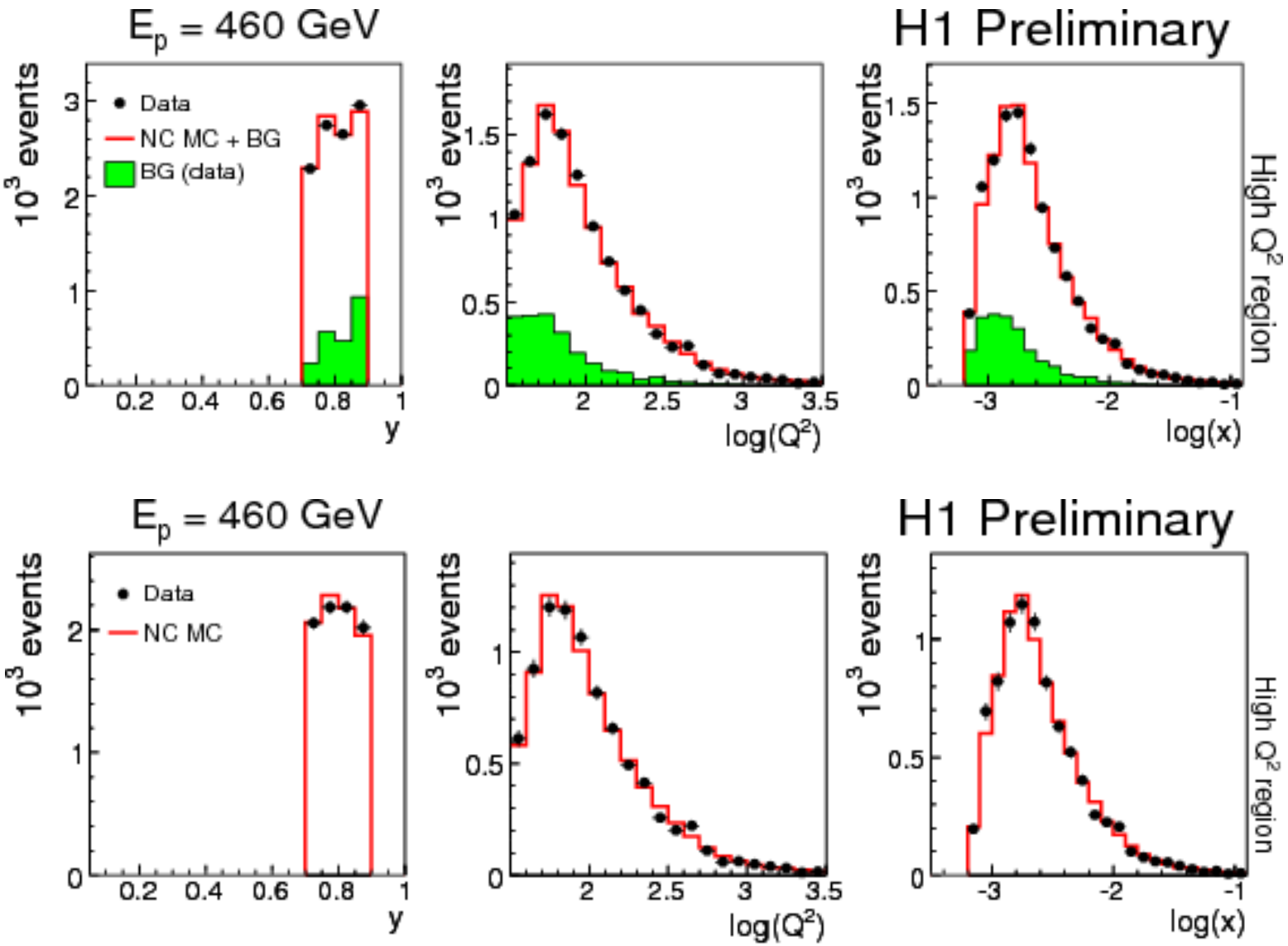



MPP Munich

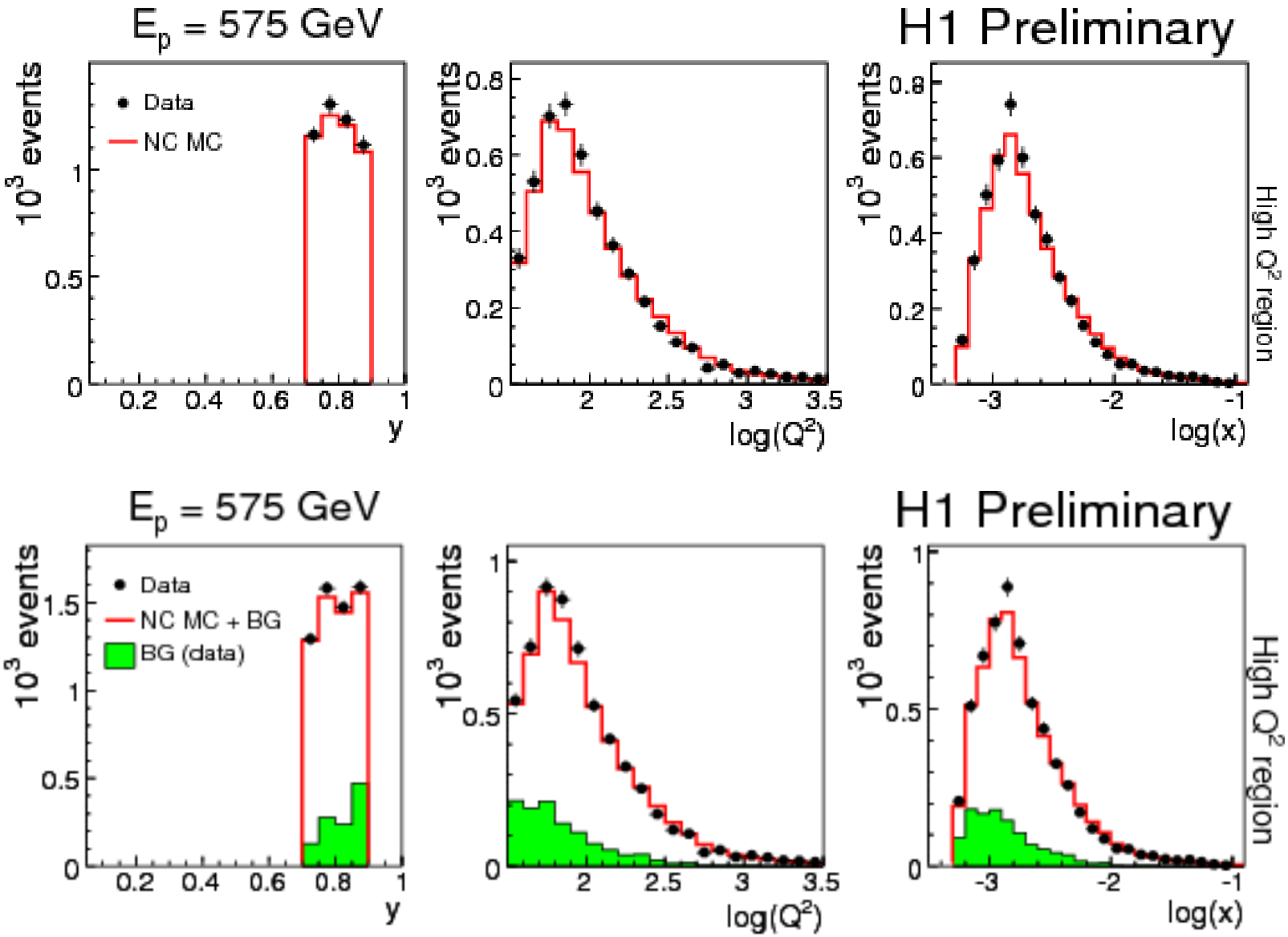
Burkard Reisert

EPS09

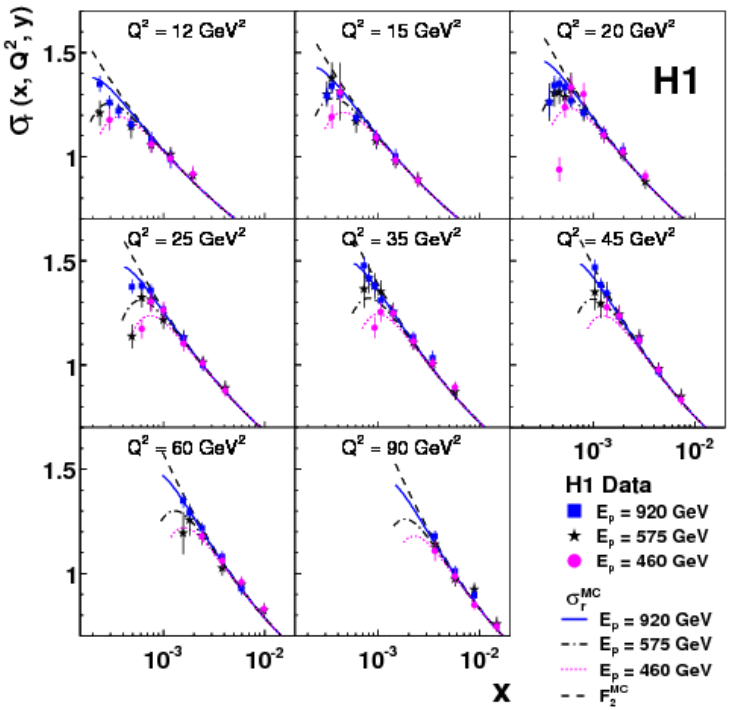
# H1: Kinematic Variables

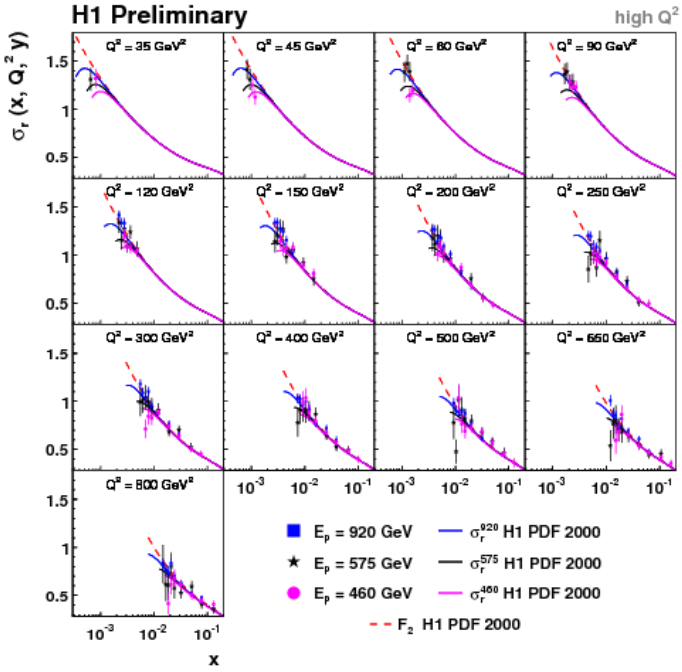


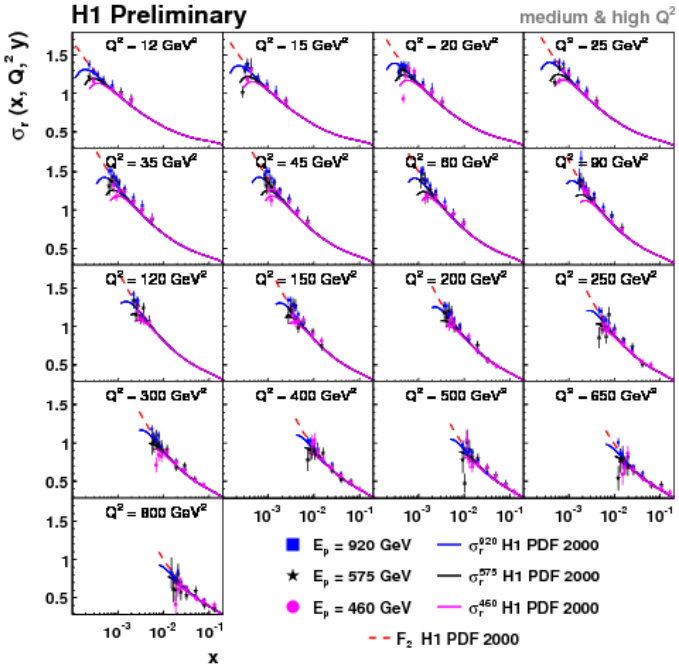
# H1: Kinematic Variables

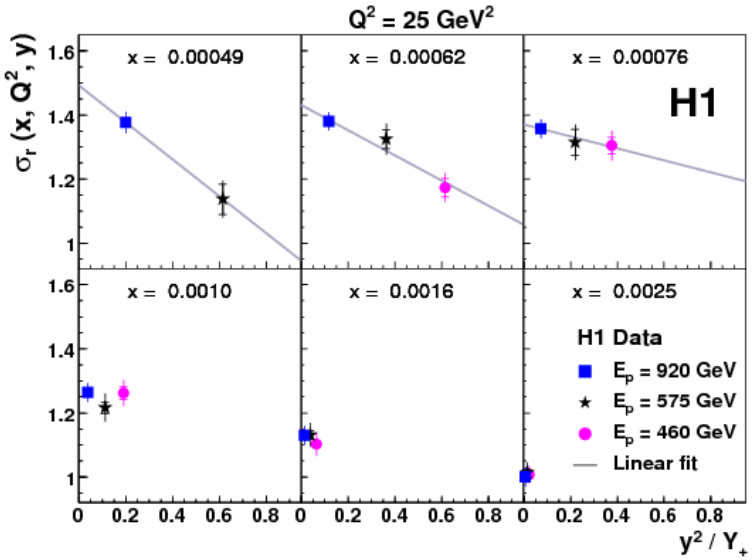


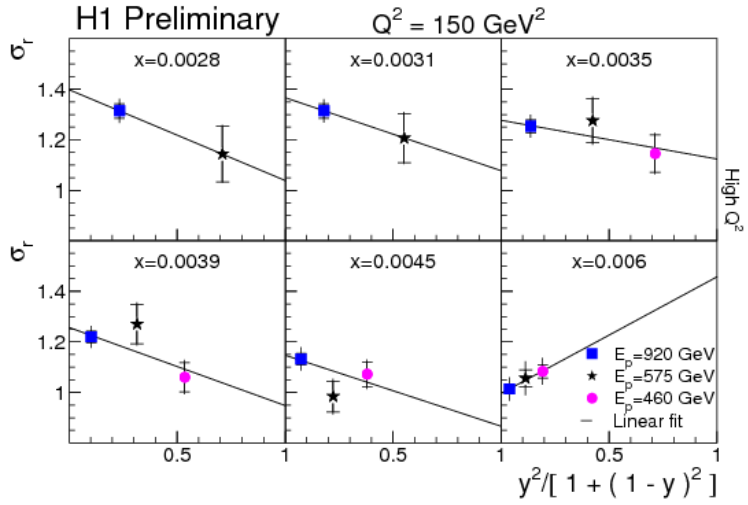
# H1: Cross Sect.



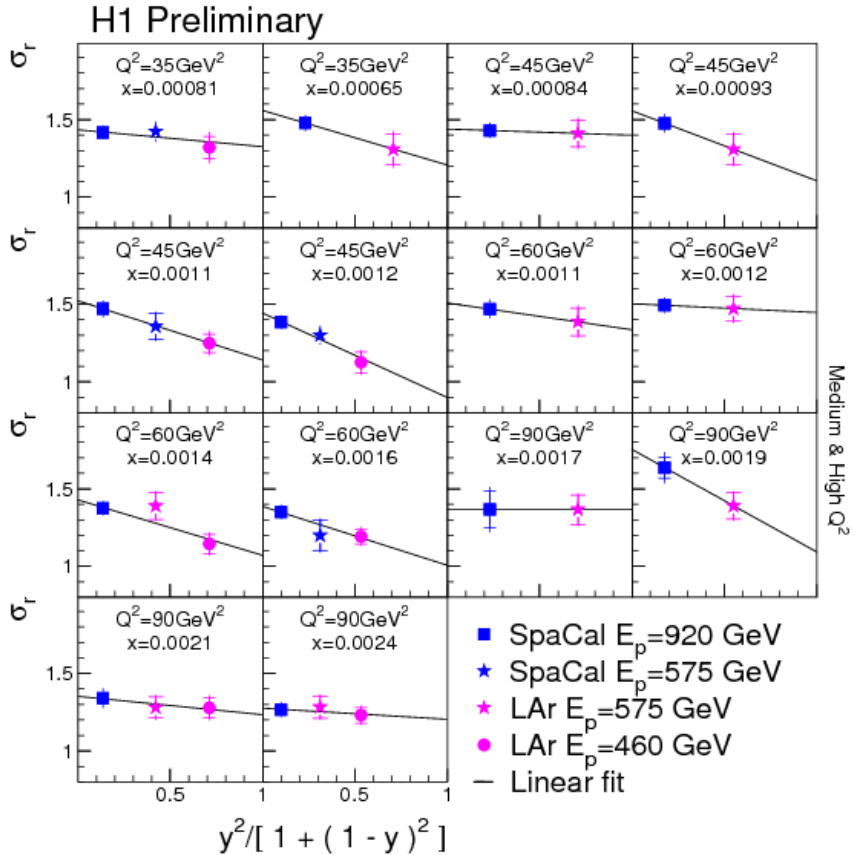



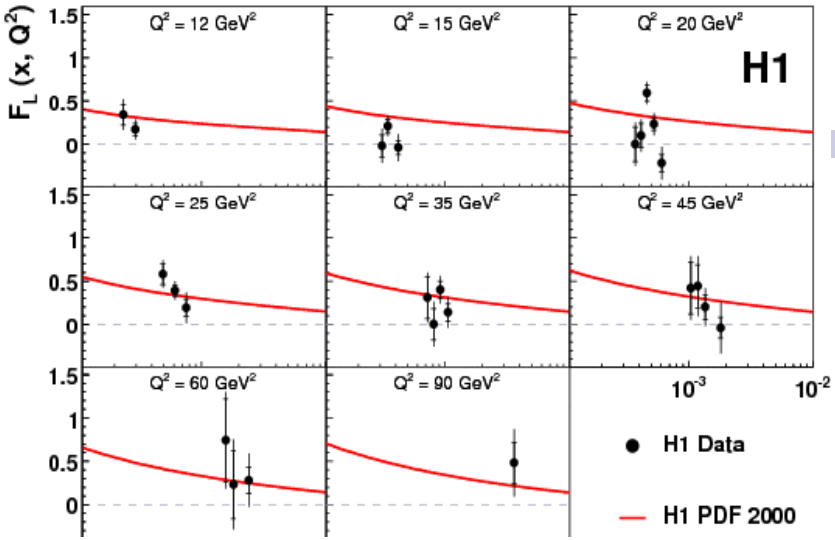



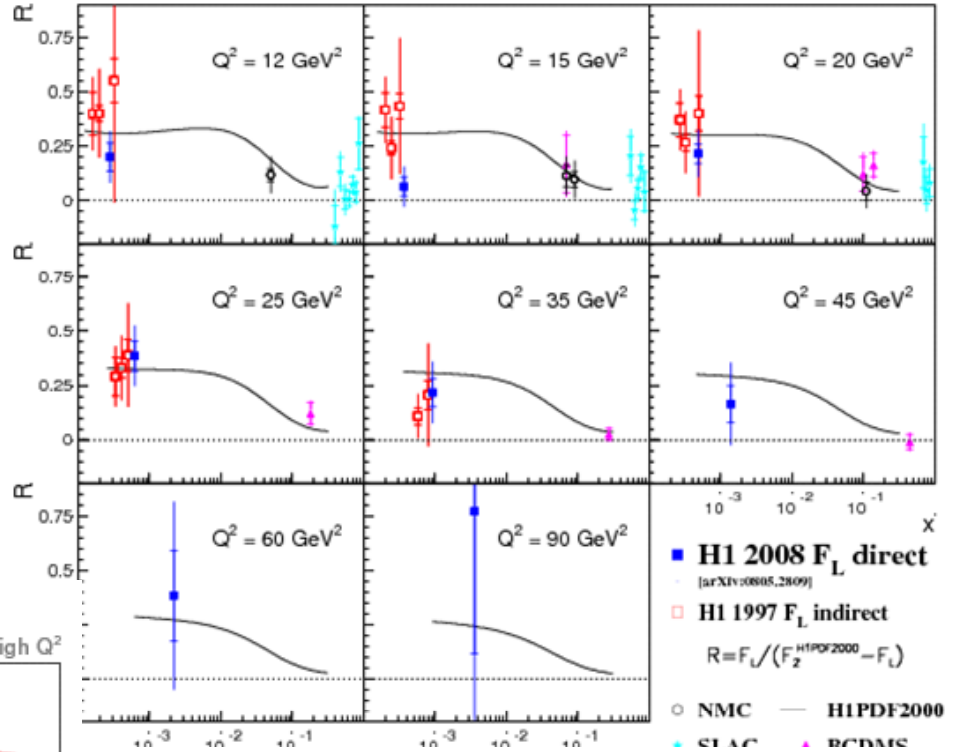


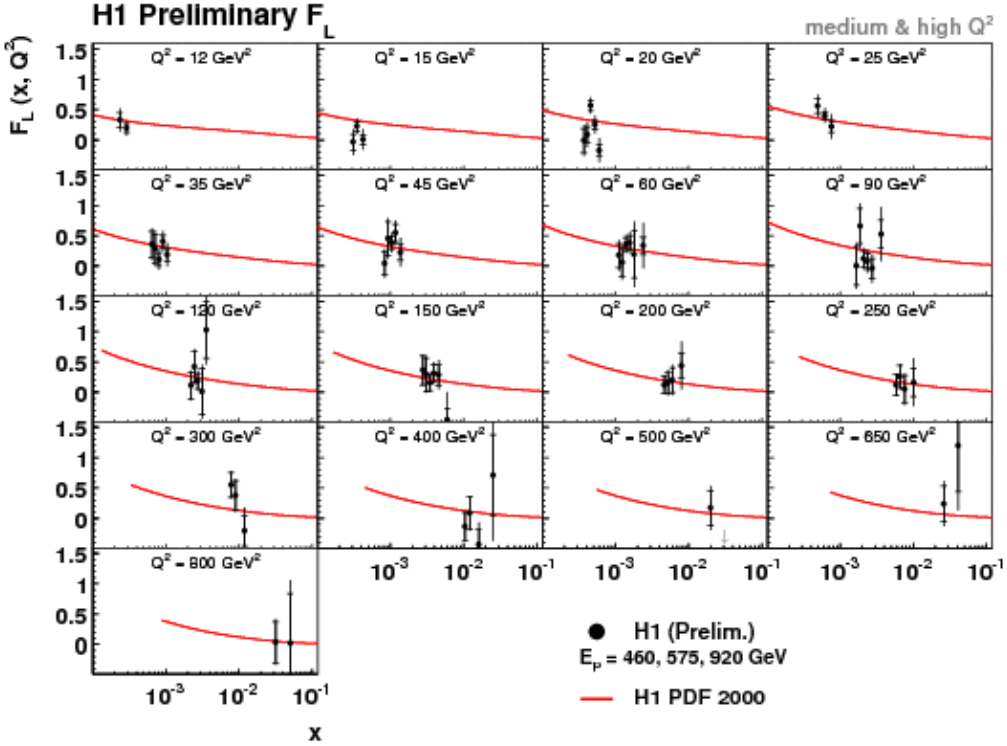



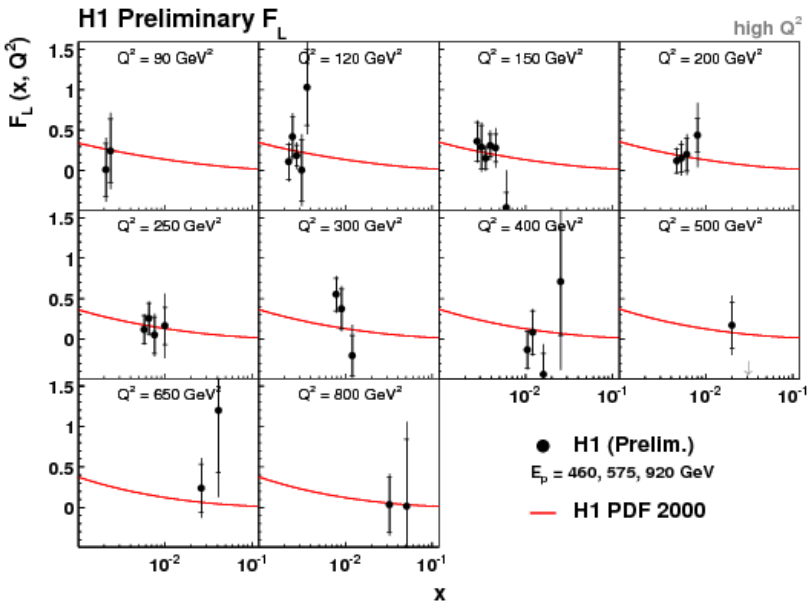

# H1 Rosenbuth Plots (Examples)




H1
$F_L(x, Q^2)$
$Q^2$ = 12 GeV$^2$
$Q^2$ = 15 GeV$^2$
$Q^2$ = 20 GeV$^2$
$Q^2$ = 25 GeV$^2$
$Q^2$ = 35 GeV$^2$
$Q^2$ = 45 GeV$^2$
$Q^2$ = 60 GeV$^2$
$Q^2$ = 90 GeV$^2$
H1 Data
H1 PDF 2000


R
$Q^2$ = 12 GeV$^2$
$Q^2$ = 15 GeV$^2$
$Q^2$ = 20 GeV$^2$
$Q^2$ = 25 GeV$^2$
$Q^2$ = 35 GeV$^2$
$Q^2$ = 45 GeV$^2$
$Q^2$ = 60 GeV$^2$
$Q^2$ = 90 GeV$^2$
x
H1 2008 $F_L$ direct
[arXiv:0805.2809]
H1 1997 $F_L$ indirect
$R = F_L/(F_2^{H1PDF2000} - F_L)$
NMC
H1PDF2000
SLAC
BCDMS


H1 Preliminary $F_L$
medium & high $Q^2$
$F_L(x, Q^2)$
$Q^2$ = 12 GeV$^2$
$Q^2$ = 15 GeV$^2$
$Q^2$ = 20 GeV$^2$
$Q^2$ = 25 GeV$^2$
$Q^2$ = 35 GeV$^2$
$Q^2$ = 45 GeV$^2$
$Q^2$ = 60 GeV$^2$
$Q^2$ = 90 GeV$^2$
$Q^2$ = 120 GeV$^2$
$Q^2$ = 150 GeV$^2$
$Q^2$ = 200 GeV$^2$
$Q^2$ = 250 GeV$^2$
$Q^2$ = 300 GeV$^2$
$Q^2$ = 400 GeV$^2$
$Q^2$ = 500 GeV$^2$
$Q^2$ = 650 GeV$^2$
$Q^2$ = 800 GeV$^2$
x
H1 (Prelim.)
$E_p$ = 460, 575, 920 GeV
H1 PDF 2000


H1 Preliminary $F_L$
high $Q^2$
$F_L(x, Q^2)$
$Q^2$ = 90 GeV$^2$
$Q^2$ = 120 GeV$^2$
$Q^2$ = 150 GeV$^2$
$Q^2$ = 200 GeV$^2$
$Q^2$ = 250 GeV$^2$
$Q^2$ = 300 GeV$^2$
$Q^2$ = 400 GeV$^2$
$Q^2$ = 500 GeV$^2$
$Q^2$ = 650 GeV$^2$
$Q^2$ = 800 GeV$^2$
x
H1 (Prelim.)
$E_p$ = 460, 575, 920 GeV
H1 PDF 2000

# H1 FL vs Q2 (Three Analyses)