

# *Measurements of the Proton $F_L$ and $F_2$ Structure Functions at Low $x$ at HERA*

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DESY

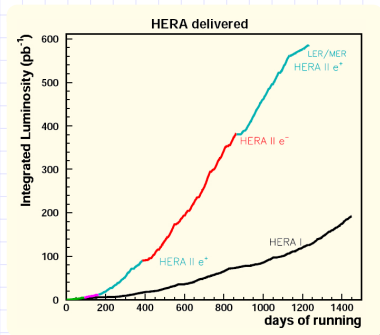
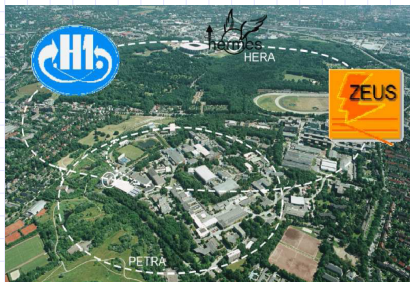
on behalf of the H1 and ZEUS collaborations

Moriond QCD, La Thuile, 13 March 2008

# The HERA Collider

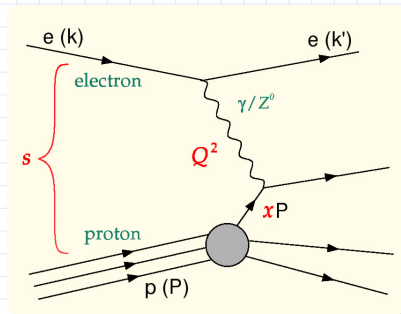
- HERA is a unique  $ep$  collider. Located at DESY, Hamburg
- Two collider experiments
- HERA II: after luminosity and detector upgrade in 2000-2002

HERA operation:  $E_e = 27.5$  GeV,  $E_p = \begin{cases} 820 \text{ GeV,} & 1992-1998 \\ 920 \text{ GeV,} & 1998-2007 \\ 460 \text{ GeV,} & 3-5 / 2007 \\ 575 \text{ GeV,} & 5-6 / 2007 \end{cases}$



# Deep Inelastic Scattering at HERA

*Neutral Current DIS:  $e^\pm p \rightarrow e^\pm X$*



Kinematics:

- $Q^2 = -(k - k')^2 = -q^2$   
virtuality of  $\gamma^*, Z^0$
- $x = Q^2 / 2(Pq)$  momentum fraction of proton carried by struck quark
- $y = (Pq) / (Pk)$  inelasticity
- $Q^2 = sxy$

- Deep Inelastic Scattering (DIS) is best suited tool for
  - Measurement of the substructure of the proton: quark and gluon content (PDFs)
  - Testing QCD dynamics: validity of DGLAP evolution equations at low  $Q^2$  and low  $x$

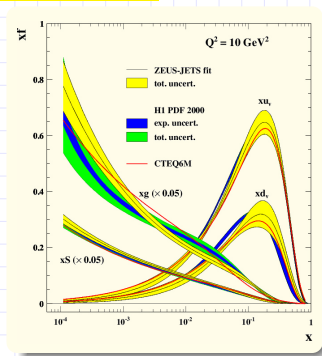
# Structure Functions $F_2$ and $F_L$

At low  $Q^2$  DIS cross section can be written via structure functions  $F_2$  and  $F_L$ :

$$\frac{d^2\sigma^{ep}}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x} (F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)), \quad Y_+ = 1 + (1 - y)^2$$

reduced cross section: 
$$\sigma_r = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{ep}}{dx dQ^2} = F_2 - \frac{y^2}{Y_+} F_L$$

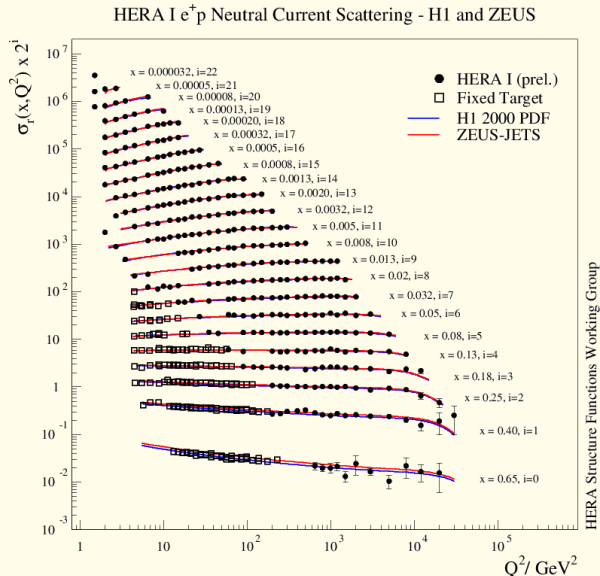
- $F_2$  is dominant ( $\sigma_r \sim F_2$ )
  - $F_2 = x \sum e_q^2 (q + \bar{q})$
  - Sensitive to  $4u + d$
  - Gluon PDF extraction from scaling violation of  $F_2$ :  $\frac{\partial F_2}{\partial \ln Q^2} \propto xg$
- $F_L$  is sizable only at high  $y$ 
  - $F_L = 0$  in QPM
  - Direct sensitivity to gluons at low  $x$



$$\text{QCD: } F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[ \frac{16}{3} F_2 + 8 \sum_q e_q^2 \left(1 - \frac{x}{z}\right) z g(z) \right]$$

# Neutral Current Cross Sections

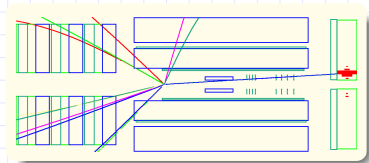
- New preliminary H1 and ZEUS combined results (submitted to EPS07, Manchester)
- 1.5-3% precision data
- 5 decades in  $x$
- 5 decades in  $Q^2$



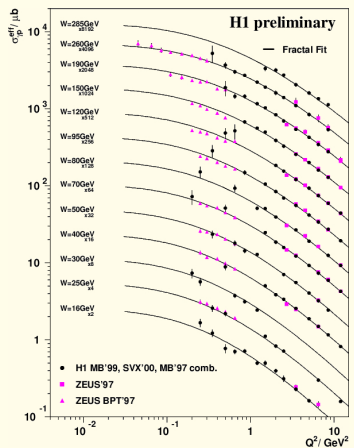
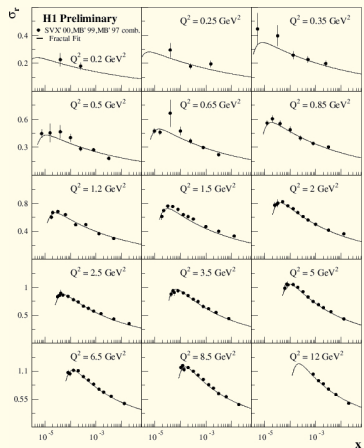
# Lowest $Q^2$ Region

- Transition to non-perturbative region  $Q^2 \rightarrow 0$  is of theoretical interest
- The lowest  $Q^2 < 10 \text{ GeV}^2$  region is accessed using specialised techniques to detect scattered lepton at very small angles:
  - Shifted collision vertex to increase acceptance at lowest  $Q^2$  (H1)
  - Events with tagged (ZEUS) or untagged (H1) Initial State Radiation
  - Special low angle calorimeter + tracker (BPT, ZEUS)
  - Minimum Bias Trigger data + Backward Silicon Tracker (H1)

Shifted vertex BST event (H1) at low  
 $Q^2 = 2.7 \text{ GeV}^2$  and  $x = 0.0003$



# Lowest $Q^2$ Data



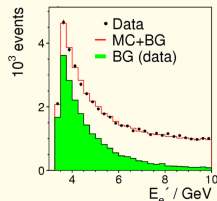
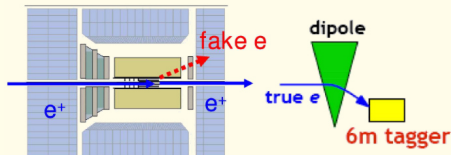
- New precision of preliminary H1 data: 1.5% for  $Q^2 > 5 \text{ GeV}^2$
- $\sigma_{\gamma^*p}^{\text{eff}}$ , effective virtual  $\gamma^*p$  cross section:  $\sigma_{\gamma^*p}^{\text{eff}} = \sigma_T + [1 - f(y)]\sigma_L$
- H1 combined data cover the gap between published ZEUS results and agree with them in regions of overlap

# The High $y$ Measurements

- Results are interesting because of sensitivity to  $F_L$
- Analysis in the high  $y > 0.6$  region especially challenging: difficult to identify the scattered lepton with low  $E'_e$  and high  $\gamma p$  background
- H1 and ZEUS have released the preliminary high  $y$  results:
  - ZEUS: Measurement uses  $\gamma p$  MC for BG subtraction, can be studied using tagged events. Analysis down  $E'_e = 5$  GeV and up to  $y = 0.8$
  - H1: Background determined directly from data using the track charge. Analysis down to  $E'_e = 3.3$  GeV and up to  $y = 0.9$

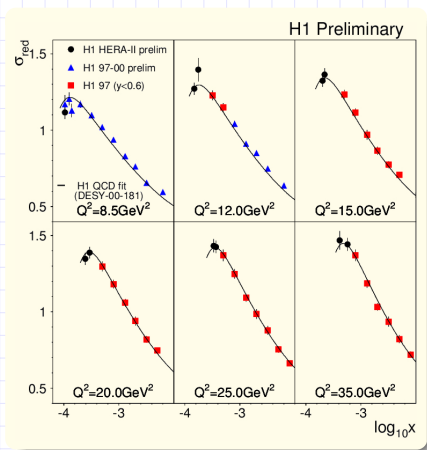
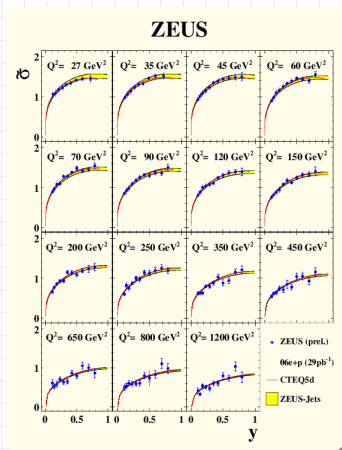
$$\sigma_r = F_2 - \frac{y^2}{Y_+} F_L$$

$$y \approx 1 - \frac{E'_e}{E_e}$$





# The High $y$ Results

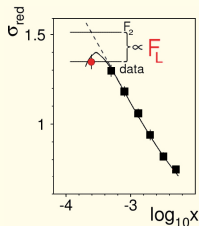
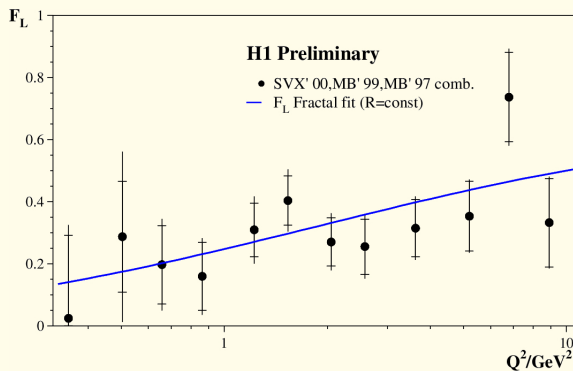


$$x = \frac{Q^2}{sy}$$

- First measurement at high  $y$  by ZEUS, covers the whole kinematic range, at higher  $Q^2$  statistics limited
- H1 uncertainties improved by a factor 2 over former publication (hep-ex/0012053), total errors 2-3%

# Indirect $F_L$ Extraction

- Extrapolate  $F_2$  from the low  $y$  region to the high  $y$
- $F_L$ : Compare  $\sigma_r$  with extrapolated  $F_2$



$$F_L \propto F_2 - \sigma_r$$

**Drawback:**  
extraction of  $F_L$   
requires  
assumption on  $F_2$

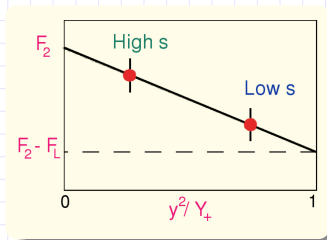
- Strong model dependence

*Direct Measurement  
of  $F_L$   
by H1 Collaboration*

# Direct $F_L$ Measurement

- Direct measurement of  $F_L$  can be performed by measuring cross section for the same  $(x, Q^2)$  but with different centre mass energies  $\sqrt{s}$  (different  $y$ ):

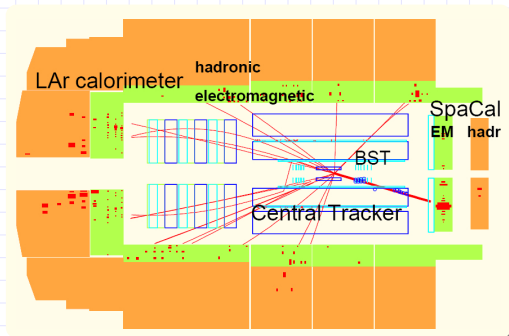
$$\sigma_r = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$



Higher  $y$  at low  $s$   
↓  
Larger difference of  $\frac{y^2}{Y_+}$   
↓  
Better  $F_L$  precision

- Use 2007  $e^+p$  data of different p-beam energy runs
- For same  $x, Q^2$ : low  $s$  high  $y$  corresponds to high  $s$  low  $y$

$E_p$	Lumi
460 GeV	12.4 pb $^{-1}$
575 GeV	6.2 pb $^{-1}$
920 GeV	21.9 pb $^{-1}$



## “High Y”

- High background contribution
- Require track link, higher  $R_{SpaCal}$
- Estimate background from wrong charged tracks

## Electron method:

$$Q_e^2 = 4E_e E'_e \cos^2\left(\frac{\theta_e}{2}\right)$$

$$y_e = 1 - \frac{E'_e}{E_e} \sin^2\left(\frac{\theta_e}{2}\right)$$

$$x_e = \frac{Q_e^2}{s y_e}$$

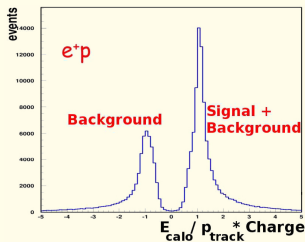
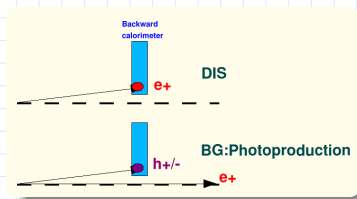
- Scattered electron produces isolated and compact energy deposition
- Identified using shape and size of e/m shower profile

## “Low Y”

- Background free area
- $R_{SpaCal} > 20$  cm. Do not require track match
- $\gamma p$  MC to estimate residual background

# Background Determination

- At high  $y$  there is a large photoproduction background in which hadronic final state can mimic the signature of the scattered lepton with low energy



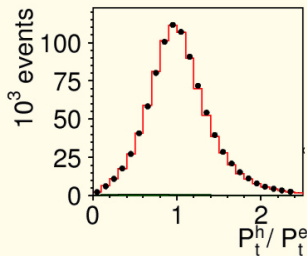
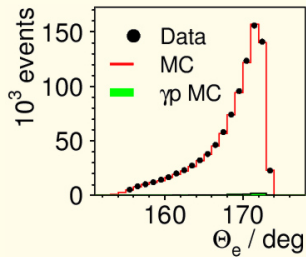
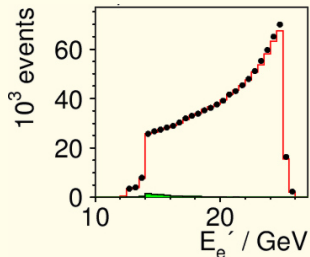
- Background is measured** using data events with the charge opposite to lepton beam charge
- A small **charge asymmetry** ( $\approx 5\%$ ) at low energies is generated by the difference of  $pA$  and  $\bar{p}A$  cross sections

- Background charge asymmetry is determined using  $e^+p$  and  $e^-p$  2003-07 data

$$N^{signal} = N^+ - kN^-$$

Charge asymmetry factor:  $k = \frac{N_{bkg}^+}{N_{bkg}^-}$

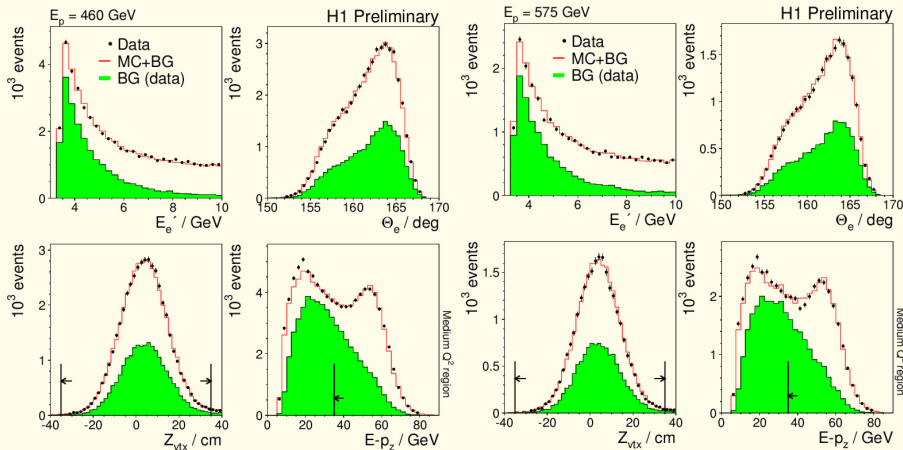
# Low $y$ Control Plots: $E_p = 920$ Data



- Low background contribution
- Good control on the e/m and hadronic energy scales
- Electron energy ( $E_e'$ ), scattering angle ( $\theta_e$ ), etc. are well described by MC

$E_p = 460$  Data

$E_p = 575$  Data



- Good description of the data by MC



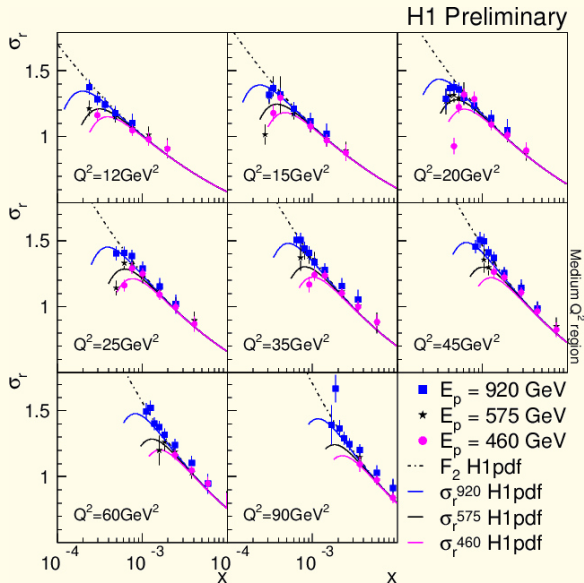
# Double Differential Cross Sections

Same  $Q^2, x$  range,  
different CME  $\rightarrow$   
different  $y$  ranges

$$y = Q^2 / (xs)$$

lower  $s \rightarrow$  higher  $y$

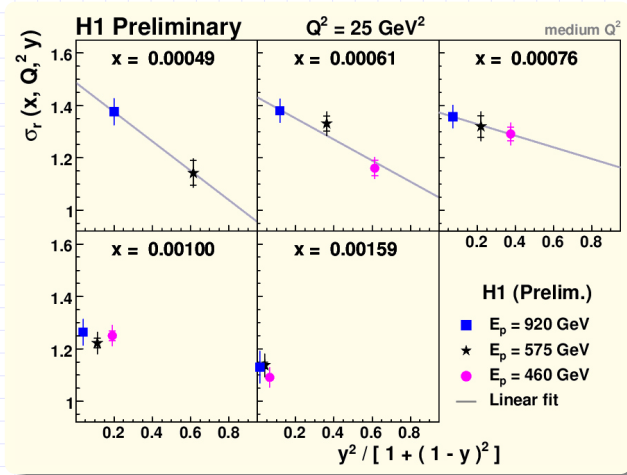
$\sigma_r$  turns over at low  $x$   
due to  $F_L$



# $F_L$ Extraction

$$\sigma_r = F_2 - \frac{y^2}{1+(1-y)^2} F_L$$

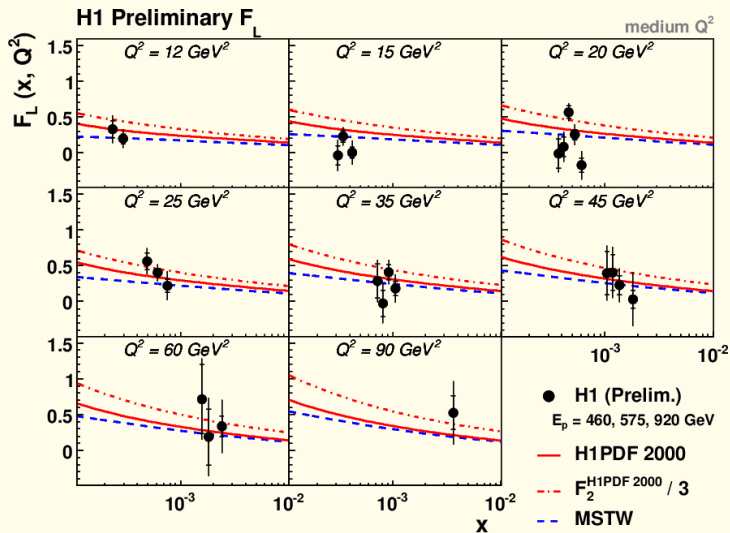
- Linear fit to points of different  $s$
- Slope determines  $F_L$
- Intercept at  $y = 0$  gives  $F_2$



$E_p = 575$  data:

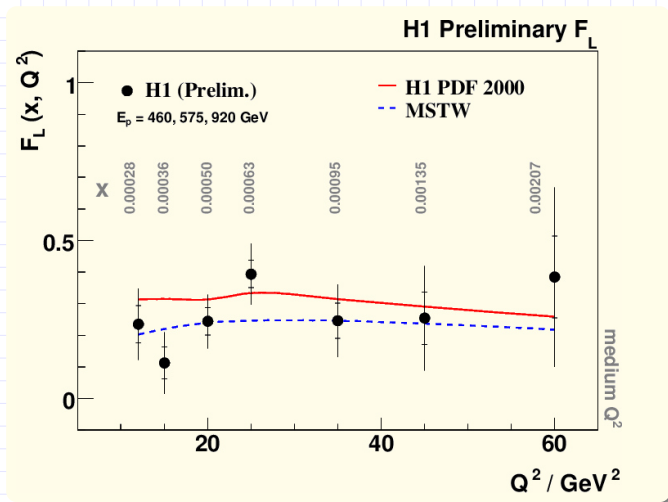
- cross check of  $\gamma p$  background control
- additional  $x$  bins

# $F_L$ Structure Function



First direct measurement  $F_L(x, Q^2)$  at low  $x$  at HERA

# $F_L$ Structure Function in Averaged $x$ Bins



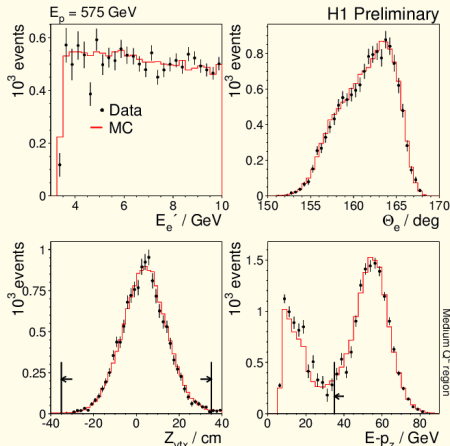
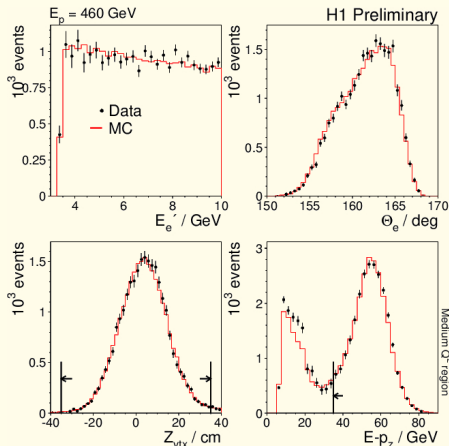
- $F_L$  predicted by higher order QCD using gluon that was derived from scaling violations of  $F_2$  is consistent with the measurement

- HERA performs precision measurements of the proton structure
- New results on inclusive measurements at lowest  $Q^2$  and in the high inelasticity  $y$  domain
- **First direct measurement of  $F_L$  at HERA has been presented, based on data taken in 2007**
  - Measured  $F_L$  is in agreement with higher order QCD expectations, based on HERA low  $x$  measurements of the scaling violations of  $F_2$
  - The extension of the measurement to the lower and higher  $Q^2$  regions is expected using other detection capabilities of H1. ZEUS measurement is also in progress.
- Novel precision measurements at HERA will improve the proton structure understanding  
... and prepare LHC era

# *Back-up Slides*

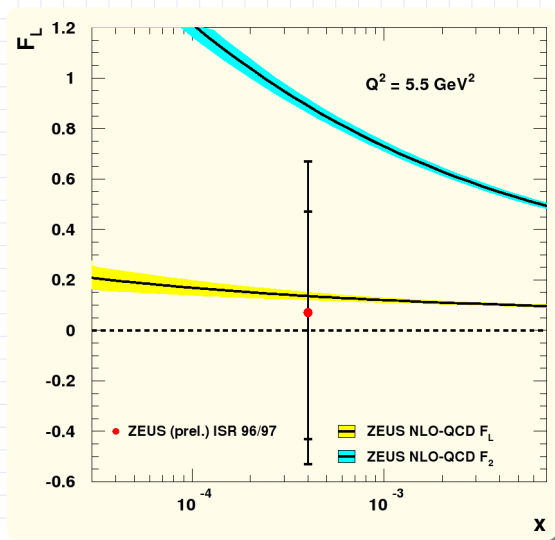
$E_p = 460$  Data

$E_p = 575$  Data



- Good description of the data by MC

# Measurement of $F_L$ Using ISR



- Direct method but limited by statistical precision