Determination of F_L at HERA

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On behalf of

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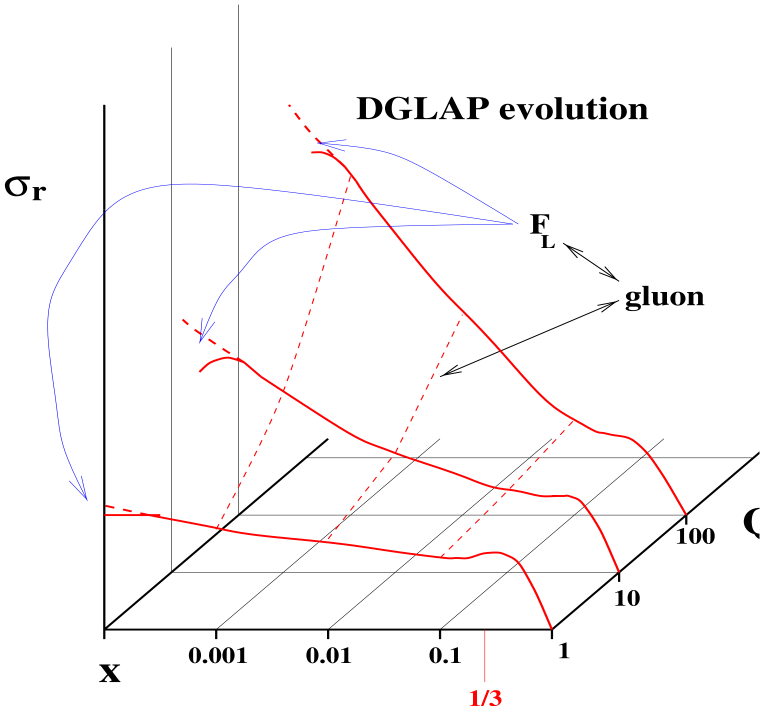
Motivation

Why measure F_L ?



rise of σ towards low $x \Rightarrow xg(x)$ large at low x

F_L :

powerful cross-check of $xg(x)$

test of QCD at low x

"One cannot understand low x physics without having measured F_L. No doubts, no questions, no jokes."

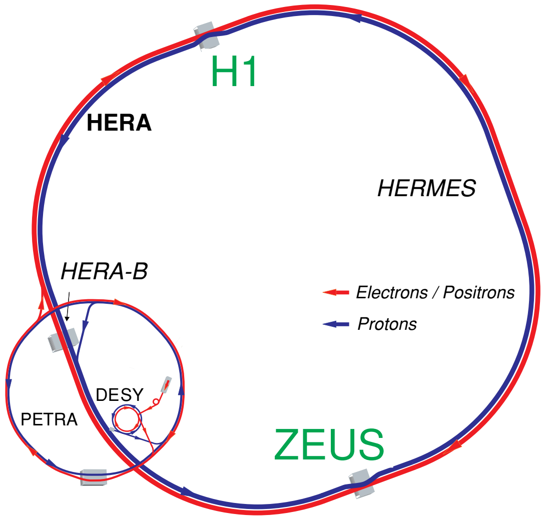
M. Klein

Outline

- **Introduction**
  - ▷ HERA parameters and kinematic variables
  - ▷ NC cross-section definition
  - ▷ F_2 results at HERA
  - ▷ Upgrade of the H1 detector
  - ▷ QCD fits to H1 and ZEUS F_2 data
- **Experimental Procedure**
  - ▷ Background estimation
  - ▷ Event selection and data samples
- **Results of F_L measurements**
- **Summary and Outlook**

The HERA ep collider

H E R A I



$$e^{\pm} \quad \Longrightarrow \quad \Longleftarrow \quad p$$

27.5 GeV $\qquad$ **820 – 920 GeV**

$$\sqrt{s} = 300 - 319 \text{ GeV}$$

1993-1994

e^-p at $\sqrt{s} = 300$ GeV

H1 (ZEUS) 0.92 (0.82) pb^{-1}

1994-1997

e^+p at $\sqrt{s} = 300$ GeV

H1 (ZEUS) 36.6 (47.7) pb^{-1}

1998-1999

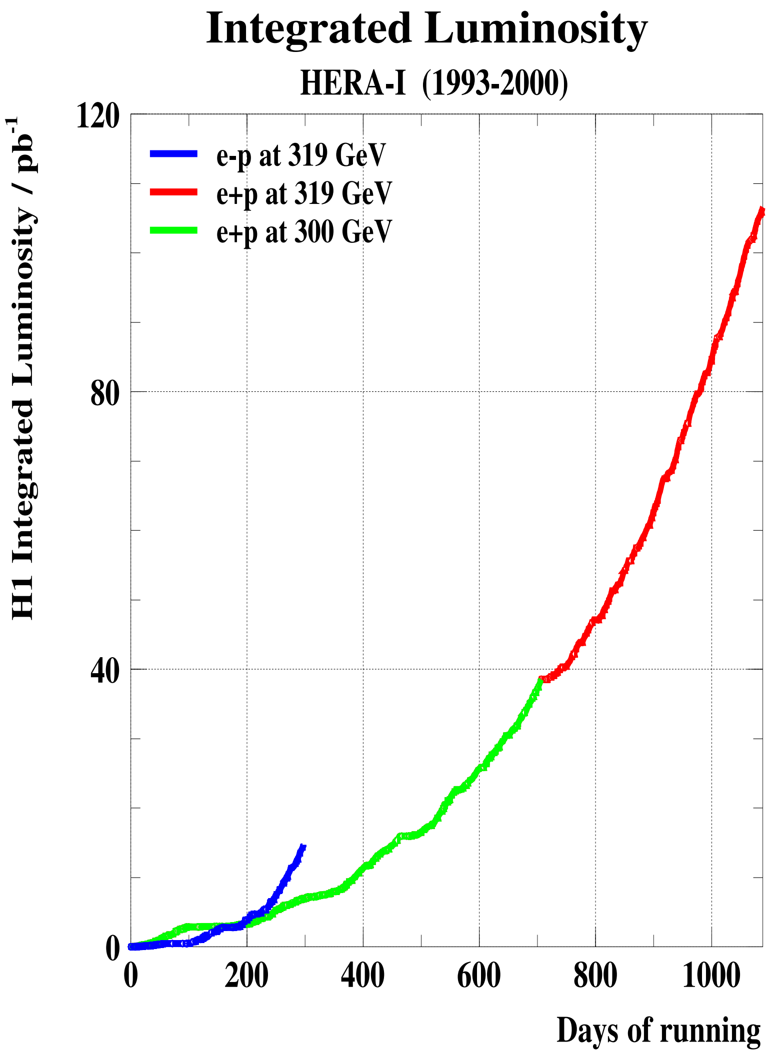
e^-p at $\sqrt{s} = 319$ GeV

H1 (ZEUS) 16.4 (17) pb^{-1}

1999-2000

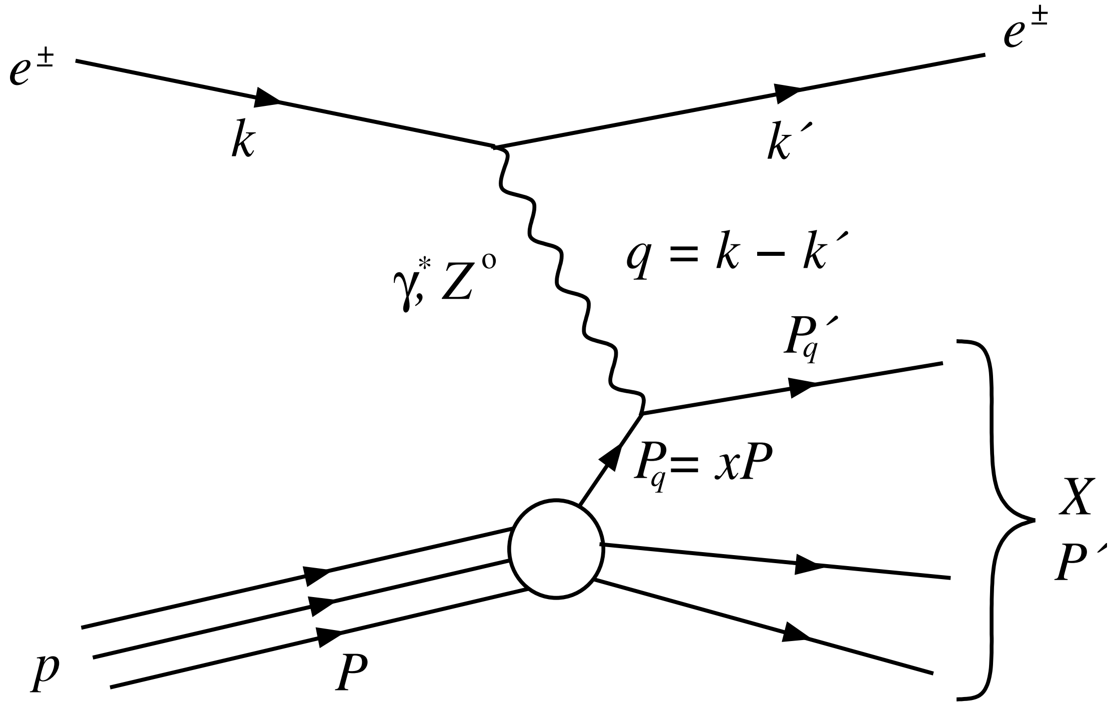
e^+p at $\sqrt{s} = 319$ GeV

H1 (ZEUS) 65 (70) pb^{-1}



HERA Kinematic Variables

NC process in ep DIS



$$Q^2 = -q^2$$

Virtuality of exchanged boson

$$x = Q^2/2(P \cdot q)$$

Parton momentum fraction (Bjorken scaling variable)

$$y = (P \cdot q)/(P \cdot k)$$

Inelasticity (fractional energy transfer in p rest frame)

$$s = xy/Q^2$$

ep CM Energy squared

$ep \rightarrow eX$, Kinematic Reconstruction

Variables x (or y) and Q^2 reconstructed using : $E'_e, \theta_e, E_h, \theta_h$
$\Rightarrow$ overconstrained kinematics

• Electron Method :

$$y_e = 1 - \frac{E'_e}{E_e} \sin^2 \frac{\theta_e}{2} \qquad Q^2_e = 4E'_e E_e \cos^2 \frac{\theta_e}{2}$$

- $\triangleright$ good Q^2 resolution in full range
- $\triangleright$ poor x resolution at low y : $\delta x / x = 1/y \cdot \delta E'_e / E'_e$
- $\triangleright$ sensitive to QED initial state radiation

• Σ Method:

$$y_\Sigma = \frac{\Sigma}{\Sigma + E'_e(1 - \cos\theta_e)} \qquad Q^2_\Sigma = \frac{E^2_e \sin^2\theta_e}{1 - y_\Sigma}$$

$$\Sigma = \sum_h (E_h - p_{z,h})$$

- $\triangleright$ good x resolution also at low y
- $\triangleright$ independent of QED ISR

• $e\Sigma$ Method :

$$x_{e\Sigma} = x_\Sigma \qquad Q^2_{e\Sigma} = Q^2_e$$

- $\triangleright$ precise over the whole kinematic range

The NC DIS Cross Section

- NC inclusive, double differential cross section

  (at $Q^2 \ll M_Z^2$)

$$\frac{d^2\sigma^{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}[Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2)]$$

$$Y_+ = 1 + (1-y)^2$$

- Reduced cross section

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

positive cross section $\Rightarrow \quad 0 \leq F_L \leq F_2$

F_L contribution to σ_r sizeable only at large y

- In Quark Parton Model (spin 1/2 partons)

$$F_2(x) = x\sum_{i=1}^{n_f} e_i^2(q_i(x) + \overline{q}_i(x))$$

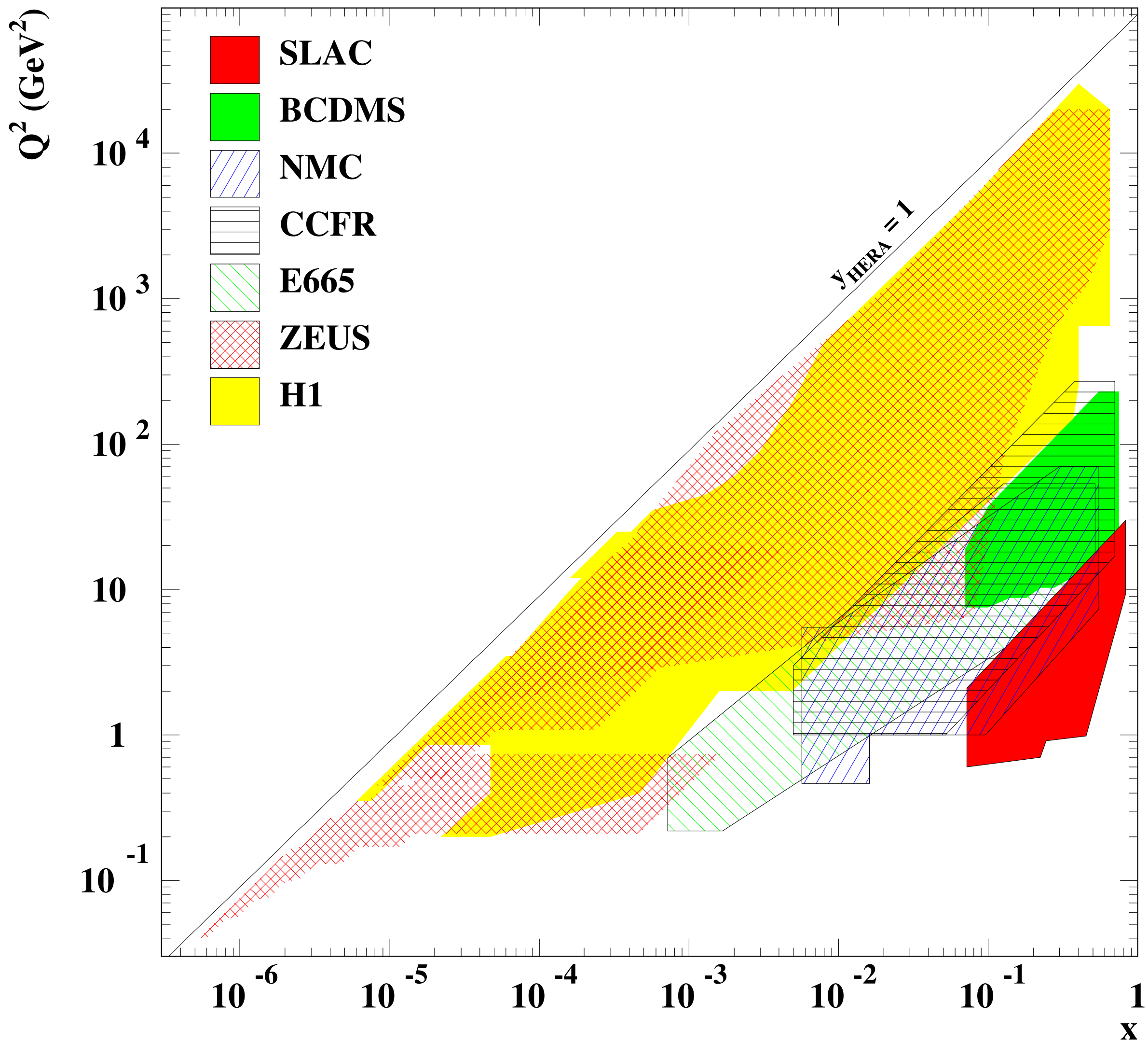
$$F_L = 0$$

- In QCD, gluon interactions give rise to

Scaling violations of $F_2(x,Q^2) \quad \frac{dF_2}{d\ln Q^2} \sim xg(x,Q^2)$

$$F_L(x,Q^2) \sim \frac{\alpha_s}{\pi}\beta_2 \otimes xg(x,Q^2)$$

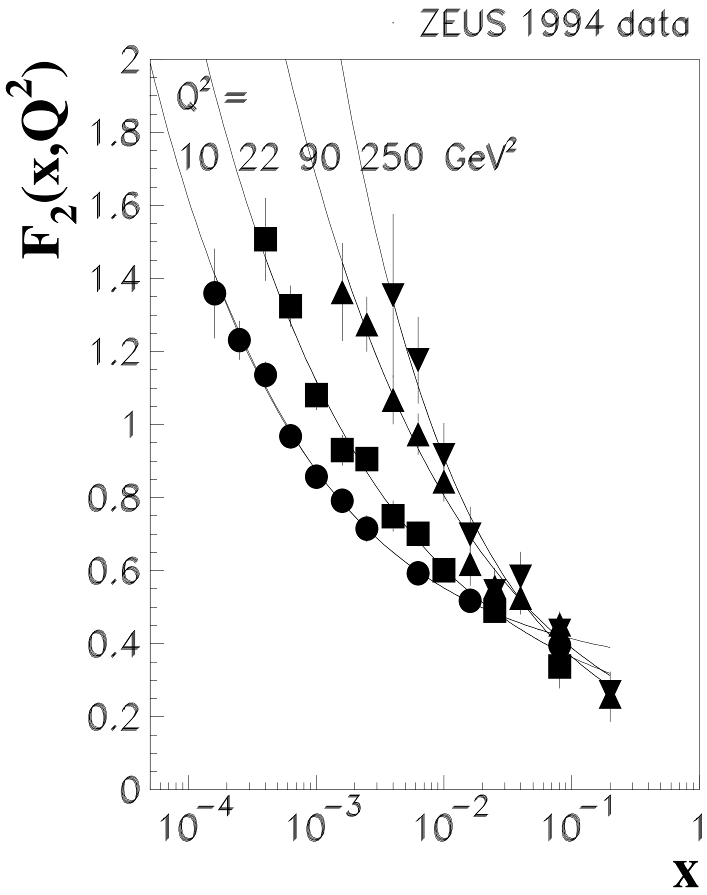
Kinematic Range at HERA



$y < 0.9$	sensitivity to F_L
$y < 0.4$	measurements of F_2
$y \to 0.005$	overlap with fixed target experiments
$Q^2 > 10000$	sensitivity to electroweak effects, exotic searches
$Q^2 \to 0$	transition to photoproduction (γp)

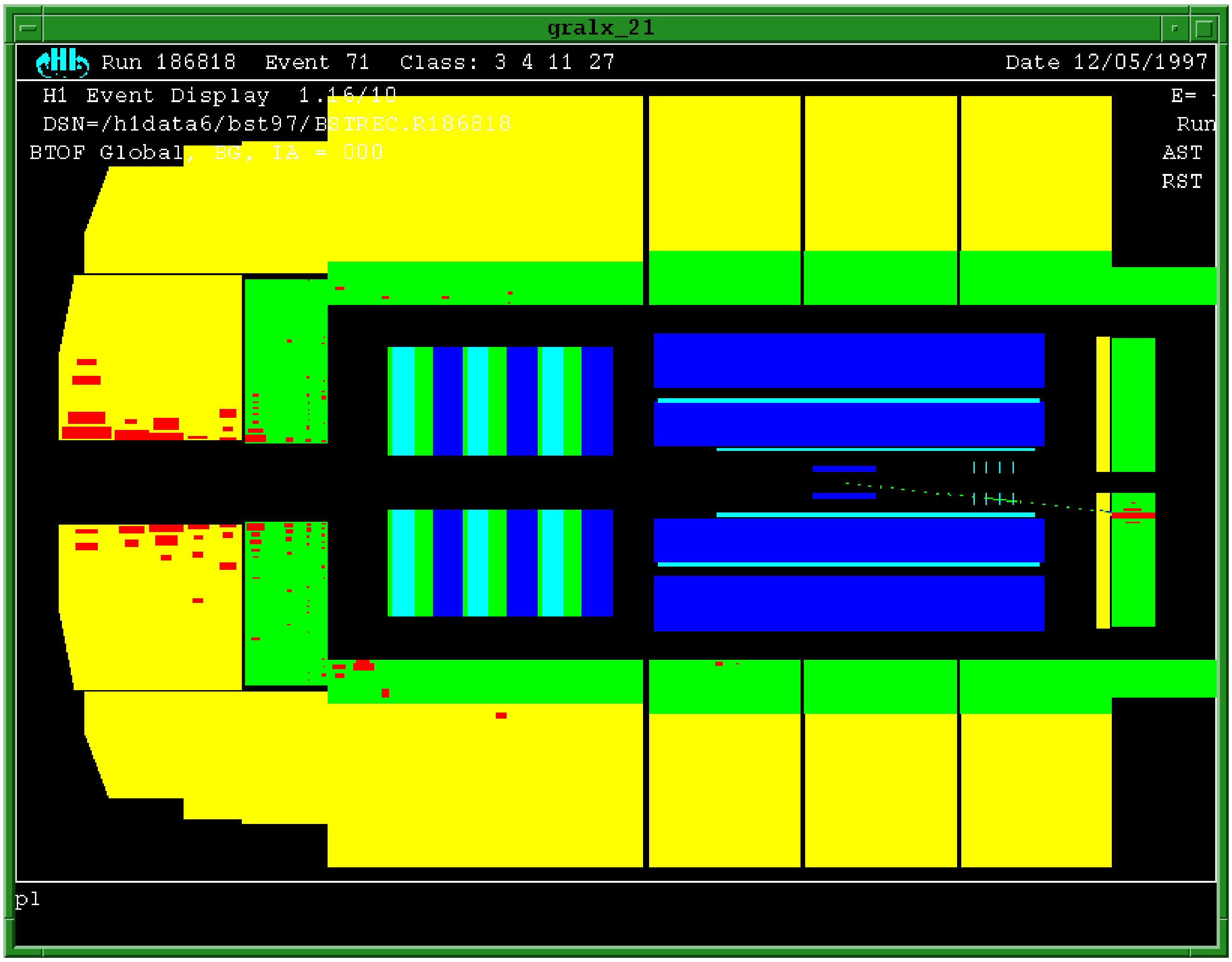
$F_2(x, Q^2)$ results at HERA

- **1992 -** already the first data showed a remarkable rise of the structure function F_2 towards low x ($x < 10^{-2}$)
  $\Rightarrow$ increasing parton density at low x
- **1993 -** the rise was confirmed with more than ten times the luminosity ($\sim 0.3pb^{-1}$)
- **1994 -** statistical error $2 - 3\%$,
  systematic error $\sim 5\%$ (except at high Q^2)



- **1995 -** H1 and ZEUS detectors upgrade

H1 detector

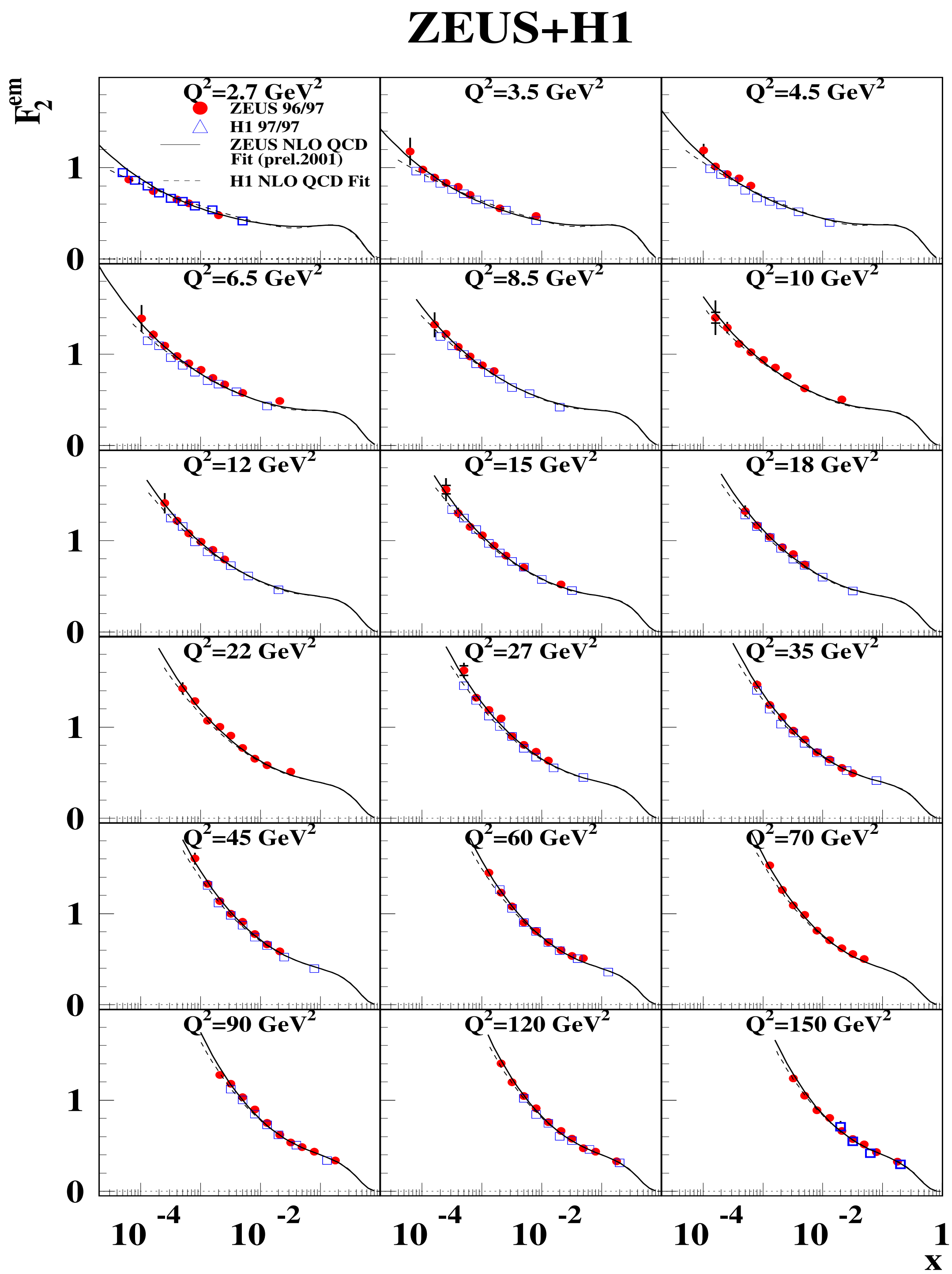


- **SPACAL (lead - fibre calorimeter) :**

$$\sigma(E)/E: \quad 7\%/\sqrt{E}; \quad 153^0 < \theta_e < 177^0$$

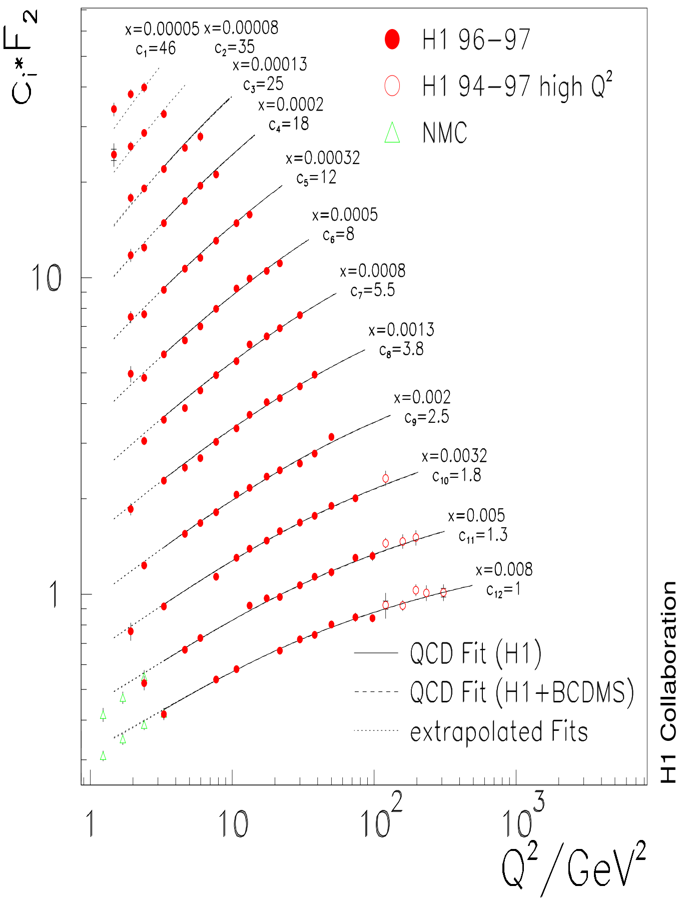
- **BDC : improved angular resolution and track verification**
- **BST : 4 planes of Si detectors, used for θ_e measurement and track verification**

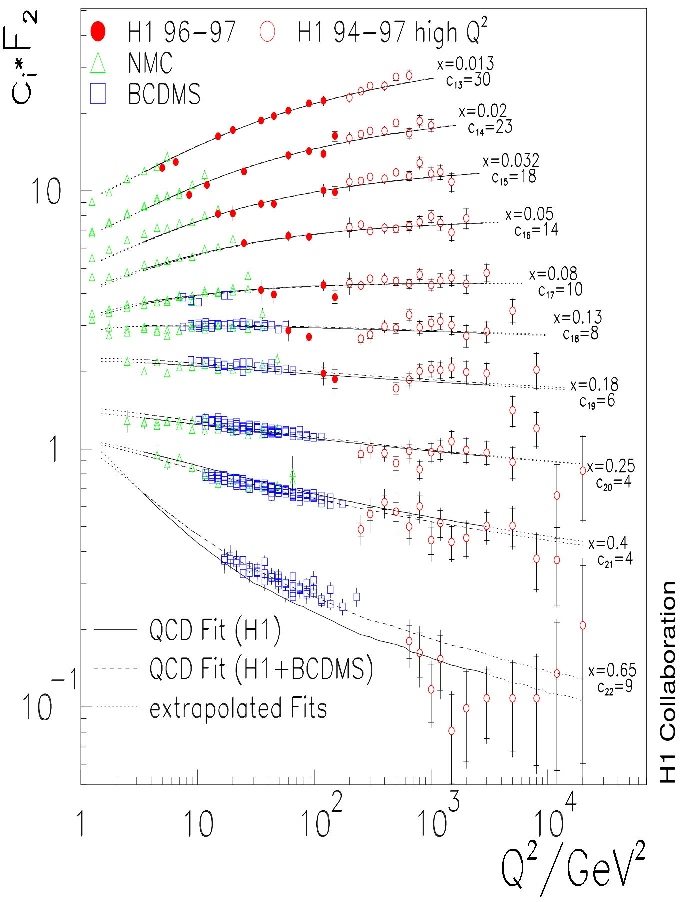
H1 and ZEUS Precision $F_2(x, Q^2)$



- High precision measurements
  (1% statistical and 2-3% systematic errors)
- Good agreement and overlap
  with data of fixed target experiments
- NLO QCD fits describe data well

$F_2(x, Q^2)$ continued





$$\frac{\partial F_2}{\partial \log Q^2} \sim \alpha_s x g \qquad\qquad \frac{\partial F_2}{\partial \log Q^2} \sim \alpha_s F_2$$

- Bjorken scaling at $x \sim 0.1$
- Scaling violations:

  positive at low x (strong increase of gluons at low x)
  and negative at high x
- NLO QCD fits describe the data well

  over 4 orders of magnitude
  down to surprisingly low Q^2 (~ 1 GeV^2)

NLO QCD fit

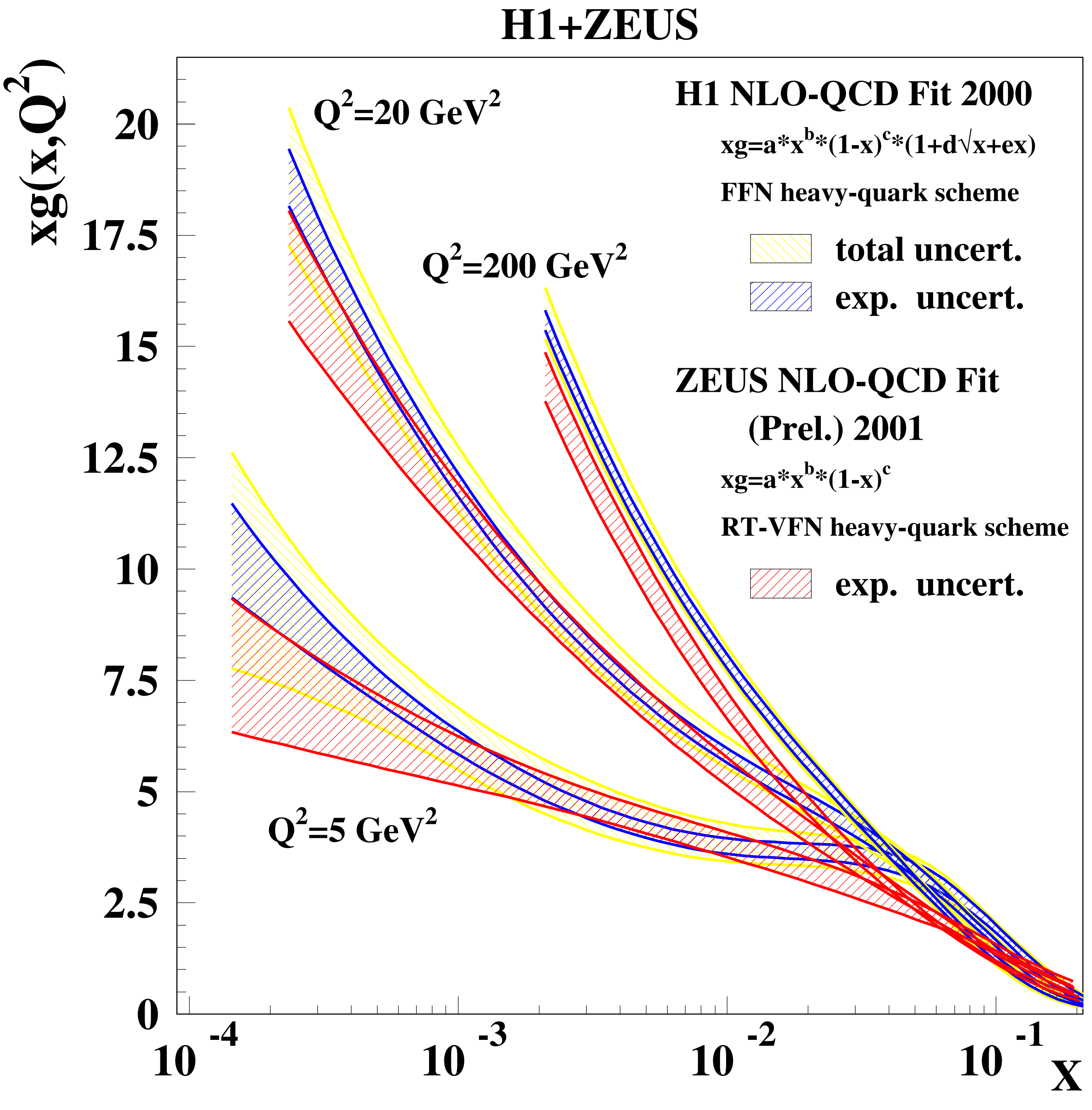
Some difference in assumptions:

- **H1 :**
  - ▷ lepton - proton data (H1 + BDCMS) only
  - ▷ parameterise effective valence and effective sea at $Q_0^2 = 4GeV^2$
  - ▷ number of parameters in gluon and sea chosen so that χ^2 saturates
  - ▷ FFN massive heavy quark scheme
  - ▷ careful treatment (Pascaud-Zomer) of point-to-point correlated systematic errors
  - ▷ systematic offsets determined by the fit

- **ZEUS :**
  - ▷ ZEUS, BDCMS, E665, NMC, CCFR data
  - ▷ parameterise u_v, d_v, xg, xS, $x(d-u)$ at $Q_0^2 = 7GeV^2$
  - ▷ RT-VFN heavy quark scheme
  - ▷ careful treatment (Pascaud-Zomer) of point-to-point correlated systematic errors
  - ▷ systematic offsets not modified by the fit

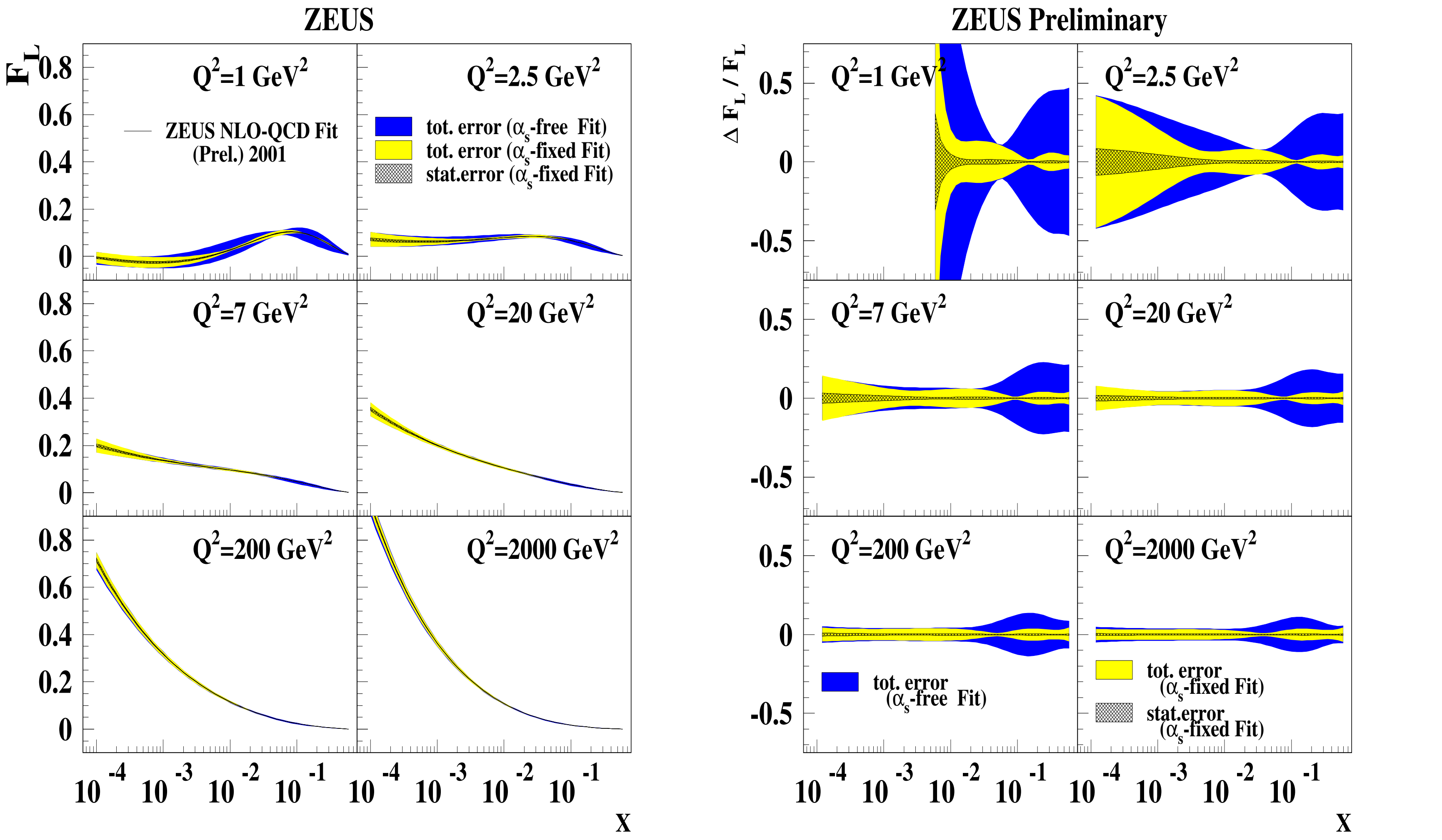
Gluon

Simultaneous fit to gluon and α_s



$xg(x)$ rises towards low x

ZEUS F_L estimation from QCD fit



- breakdown of pQCD at low Q^2 ?

BUT ...

The structure function measurement at HERA remains incomplete until the longitudinal structure function

F_L

is actually measured !

Up to now: only H1

Experimental challenge :

- need high y $\Rightarrow$ low $E_{e'}$
- low $E_{e'}$ $\Rightarrow$ higher background

How to estimate this background?

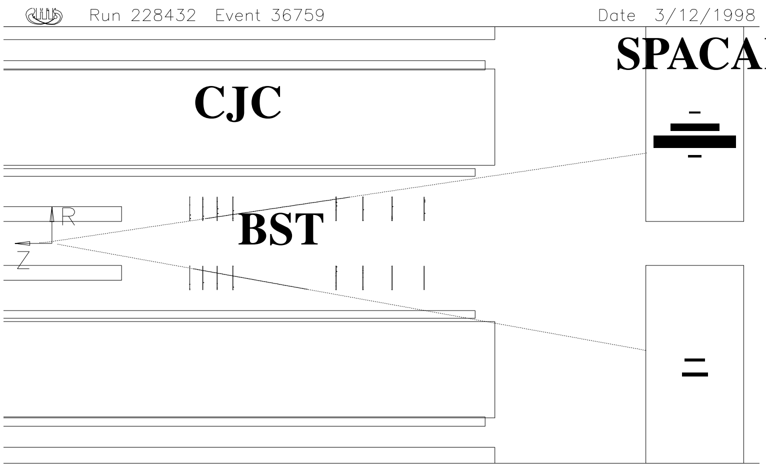
Background estimation

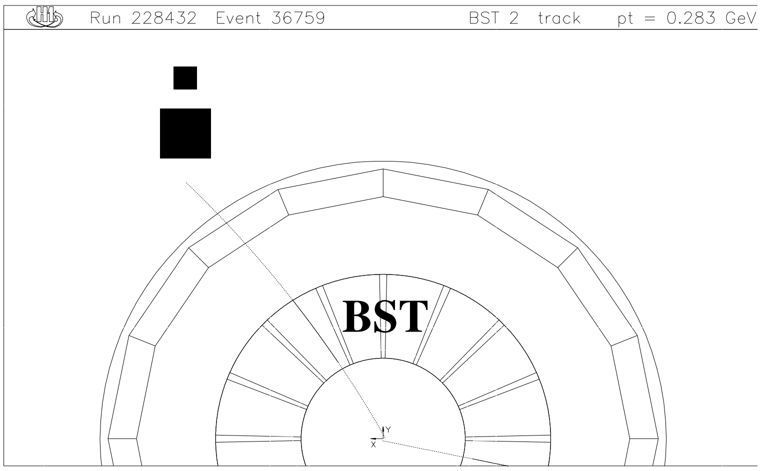
neutral background : e.g. $\pi^0 \to \gamma\gamma$

reduced by track-cluster link verification (CJC, BDC, BST)

charged background : $\pi^0 \to \gamma\gamma,\ \gamma \to e^+e^-$

such low energy electrons can fake signal of scattered electrons in SPACAL (for the lowest E'_e range - highest y)

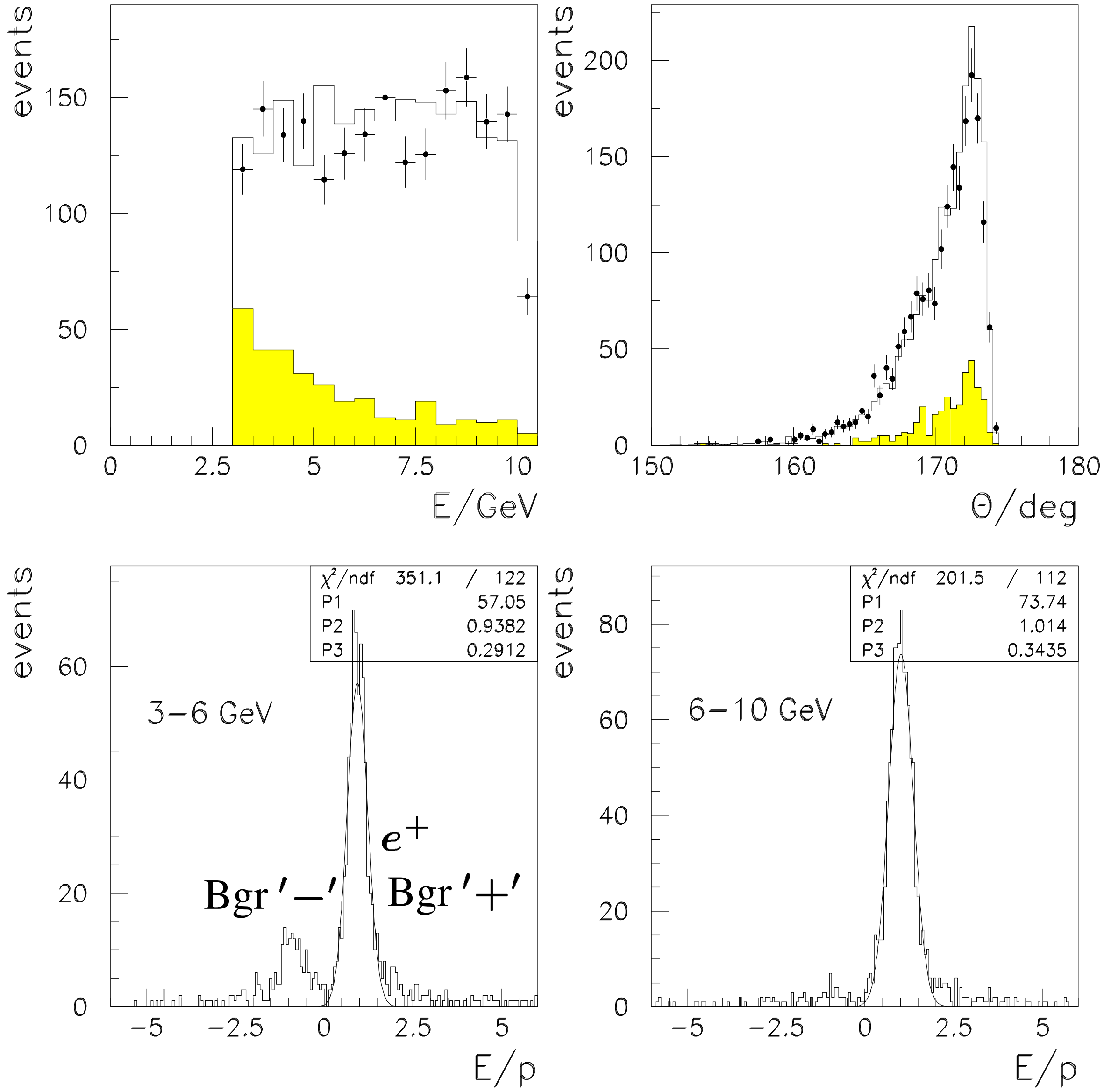




- **measure with BST (in 1/16 of 2π) the track momentum and charge**
  - ▷ main sample $e^+p \to e^+X$
  - ▷ use negative "electrons" $e^+p \to e^-X$ as estimate of background in main sample

Background estimation (cont.)

• Data '+' □ Data '−' ⊓ MC '+'



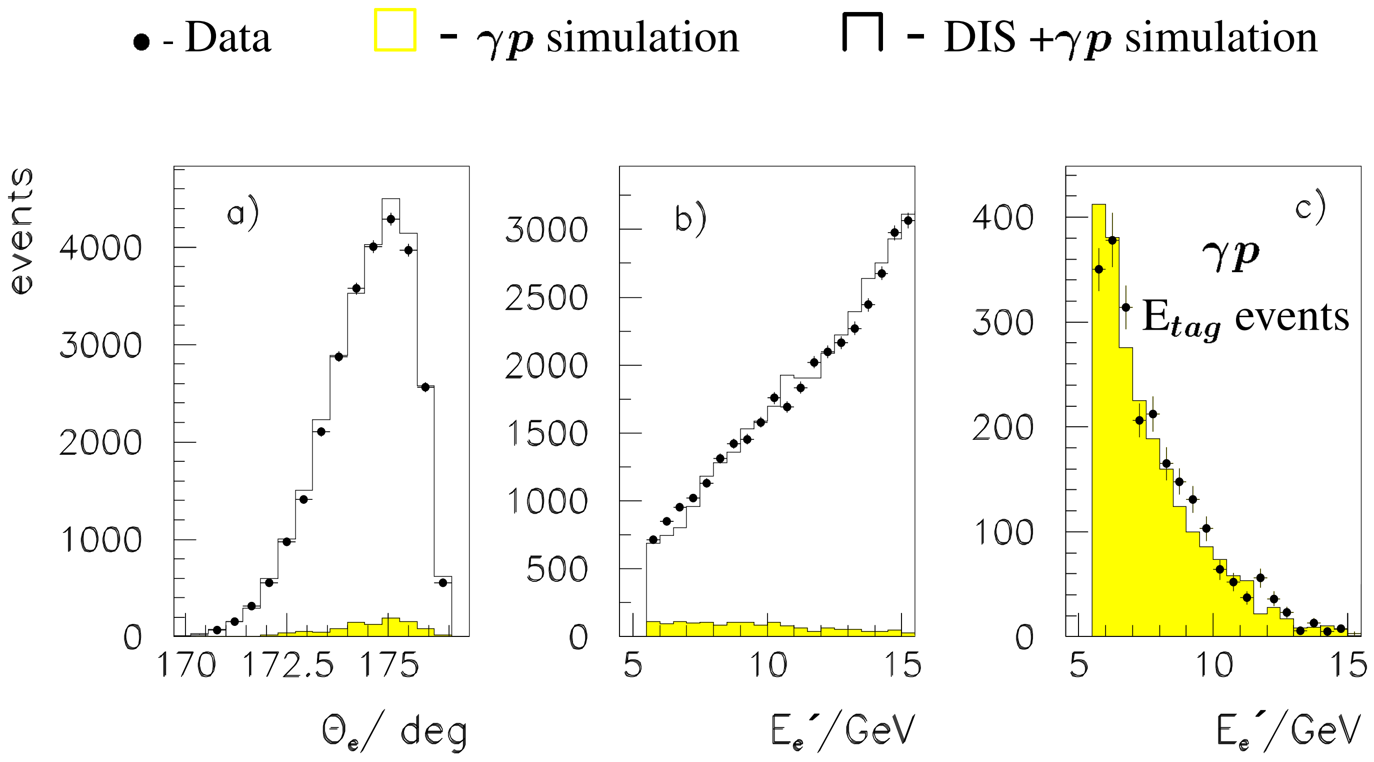
- **statistical subtraction**

  ⇒ need to take into account a small charge asymmetry
  (-4.8 ± 1.9) : studied and corrected for

  [same method using CJC at high Q^2]

Background estimation (cont.)

- remaining (small) background
  - $\Rightarrow$ subtracted bin by bin using MC (PHOJET)
  - $\Rightarrow$ cross check :
    also estimated experimentally using
    γp events triggered by Electron Tagger

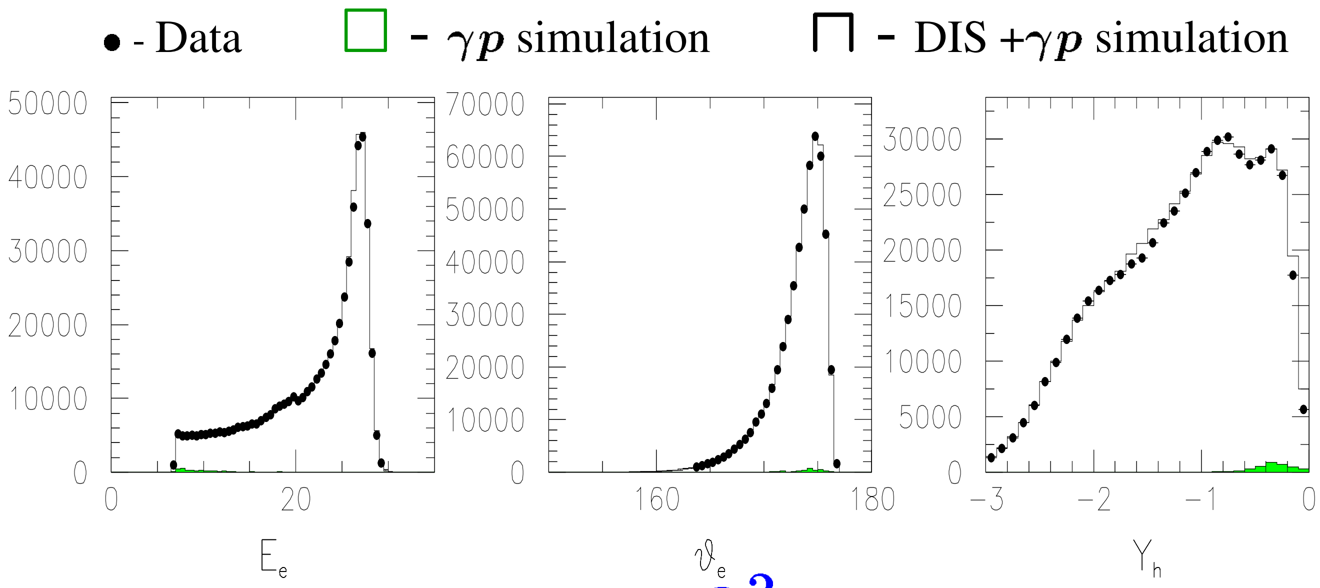


Background very well understood and systematic errors well under control

Event selection

Low and Medium Q^2

- event vertex $\pm\ 30\ cm$ w.r.t. nominal position
- electron in SPACAL
  - ▷ cluster with highest energy
  - ▷ compact cluster $R\ <\ 4\ cm$
- track verification
- total $E - p_z > 35\ GeV$
- fiducial and kinematic cuts

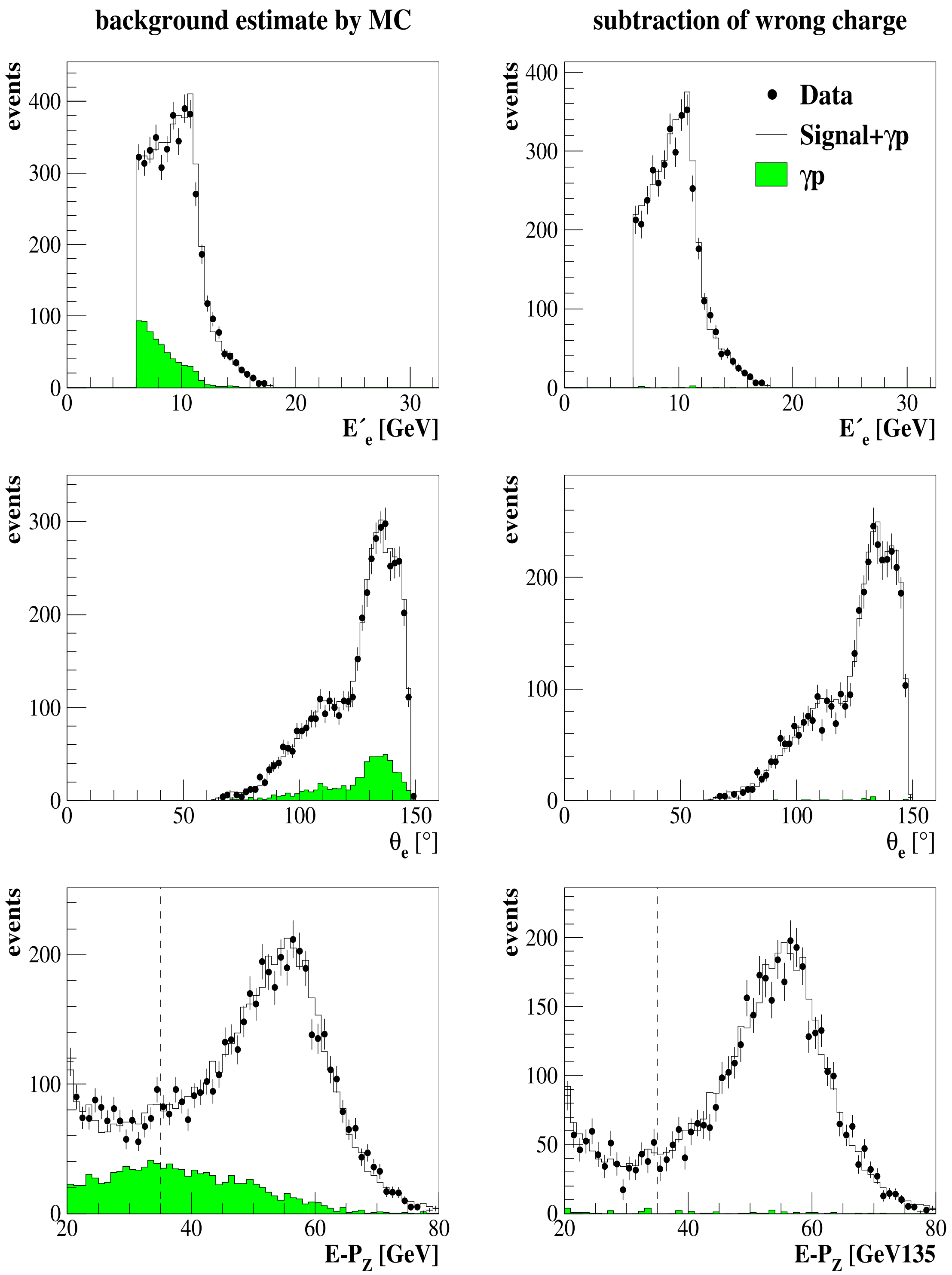


High Q^2

- event vertex $\pm\ 30\ cm$ w.r.t. nominal position
- electron in LAr
  - ▷ large p_t
  - ▷ compact, isolated cluster
- track verification for $\theta_e > 35^0$
- total $E - p_z > 35 GeV$
- fiducial and kinematic cuts

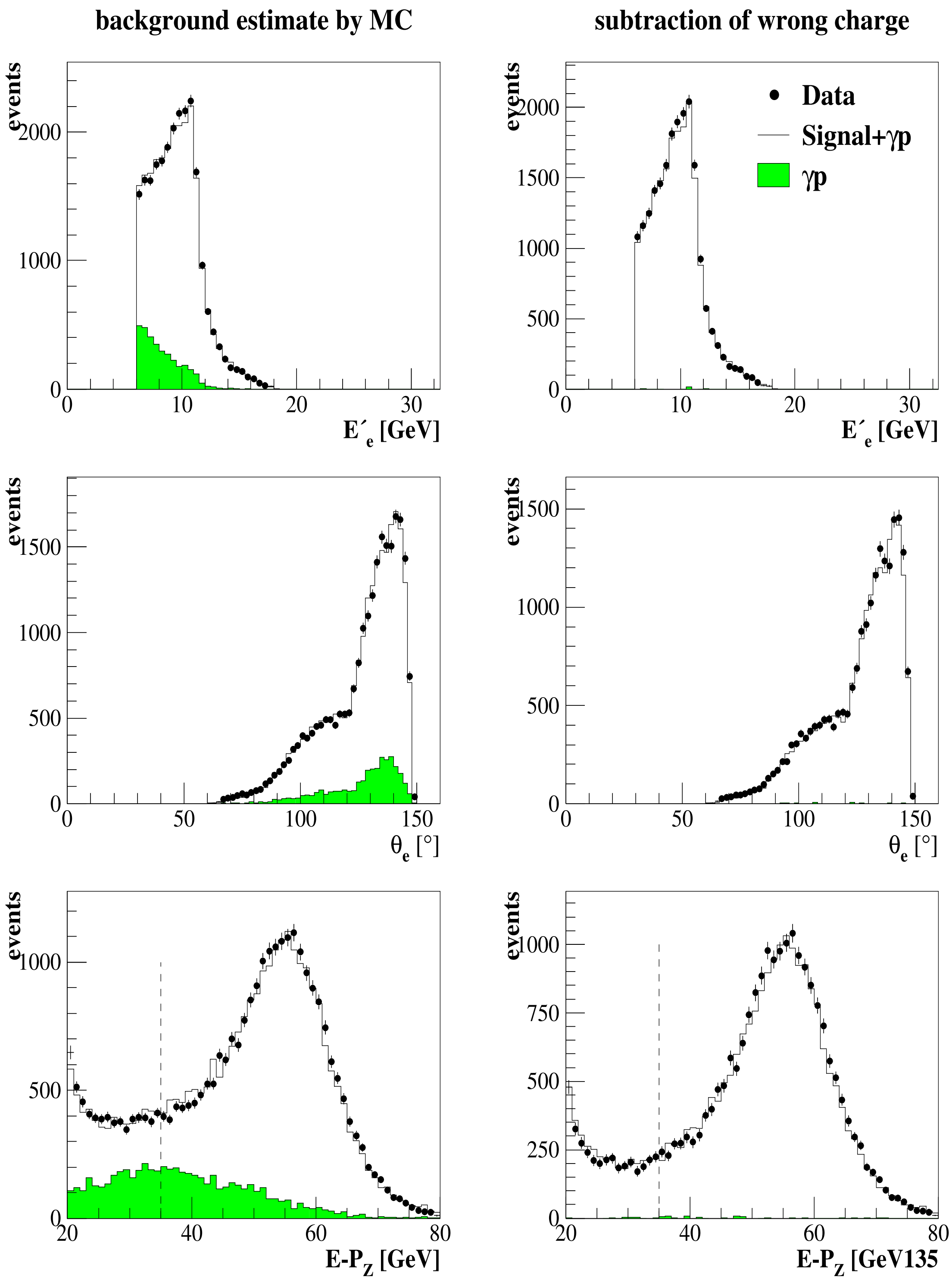
High Q^2 e^- data

Control plots with and without subtraction of fake, wrong charge electron candidates



High Q^2 e^+ data

Control plots with and without subtraction of fake, wrong charge electron candidates



Data Samples

Low Q^2 (1.5 - 12 GeV^2), minimum bias data

- 1996/1997 820 GeV $\mathcal{L} \simeq 1.8\ pb^{-1}$

  (hep-ex/0012053 , DESY - 00 - 181)
- 1999 920 GeV $\mathcal{L} \simeq 2.8\ pb^{-1}$

  (NEW preliminary)

Medium and High Q^2

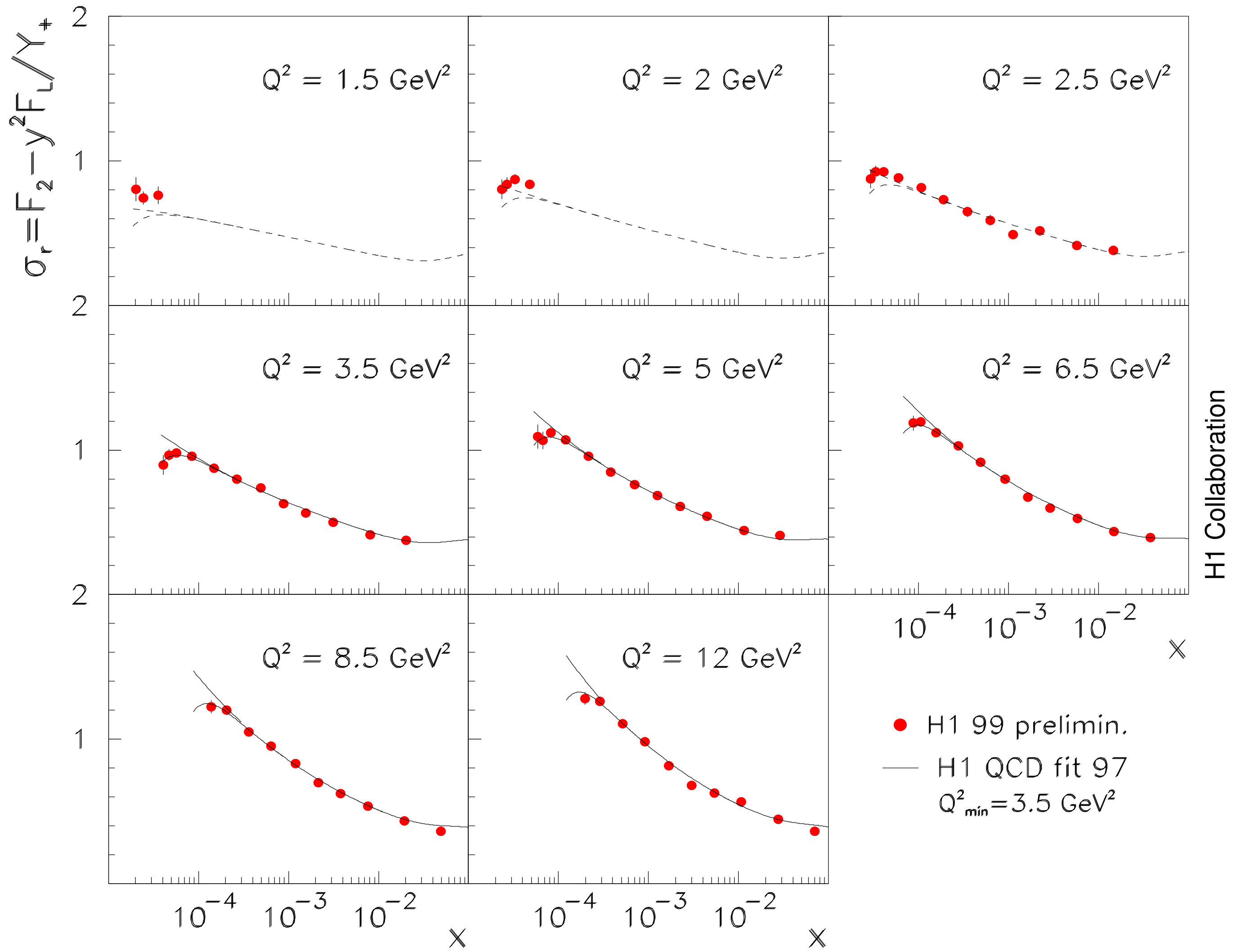
- 1996/1997 820 GeV e^+p
  - ▷ $12\ GeV^2 \leq Q^2 \leq 150\ GeV^2$ $\mathcal{L} \simeq 17.9\ pb^{-1}$

    (hep-ex/0012053 , DESY - 00 - 181)
- 1998/1999 920 GeV e^-p
  - ▷ $100\ GeV^2 \leq Q^2 \leq 800\ GeV^2$ $\mathcal{L} \simeq 16.4\ pb^{-1}$

    (NEW preliminary)
- 1999/2000 920 GeV e^+p
  - ▷ $100\ GeV^2 \leq Q^2 \leq 800\ GeV^2$ $\mathcal{L} \simeq 65.5\ pb^{-1}$

    (NEW preliminary)

σ_r , H1 1999 data



- $*$ QCD fits with and without F_L
- $*$ at low and medium y:

  $$\sigma_r \sim F_2$$

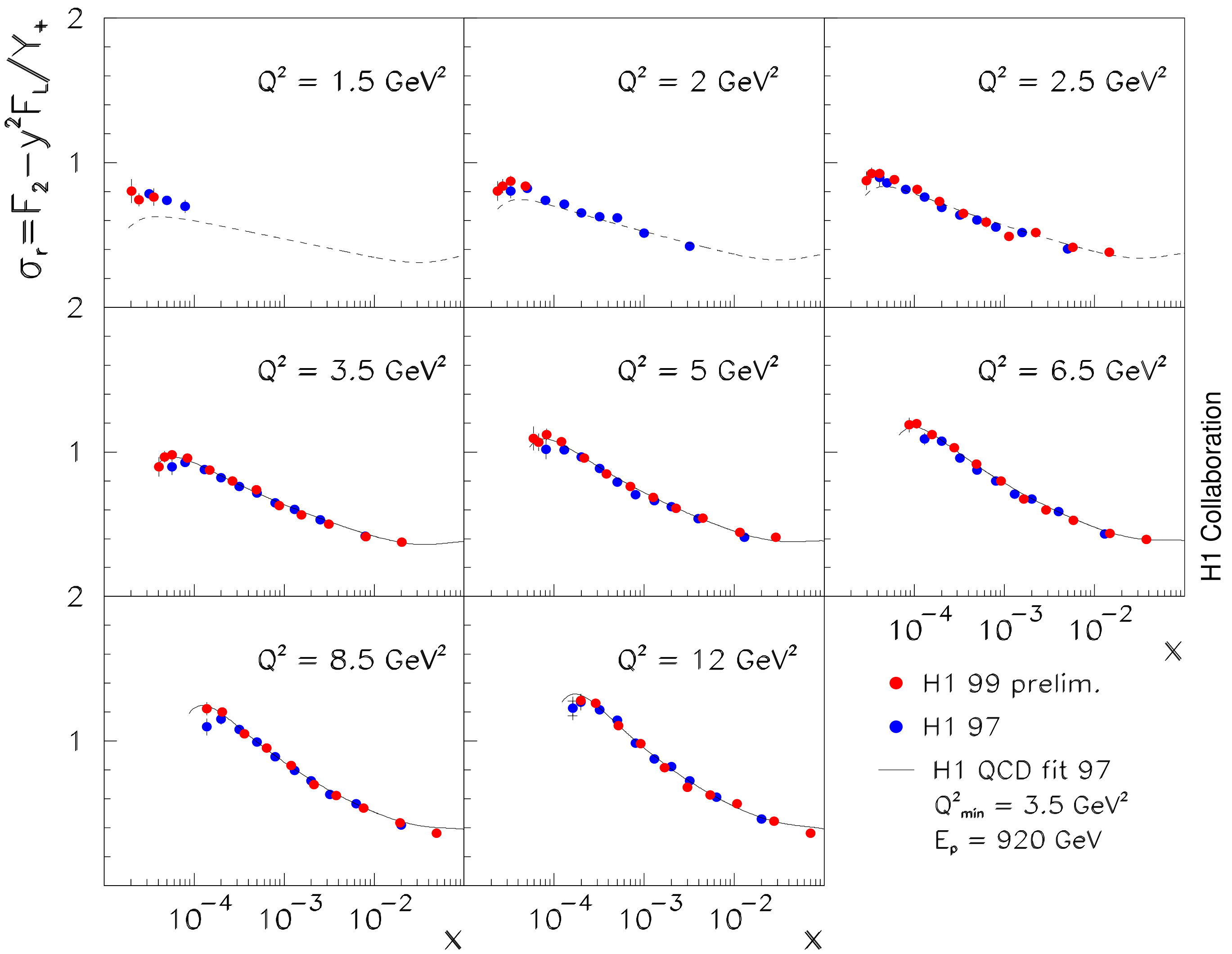
- $*$ at high y :

  F_L contribution to σ_r clearly visible

σ_r , H1 1997 and 1999 data

Proton beam energies 820 GeV and 920 GeV

920 GeV $\Rightarrow$ higher cross-section, lower x values



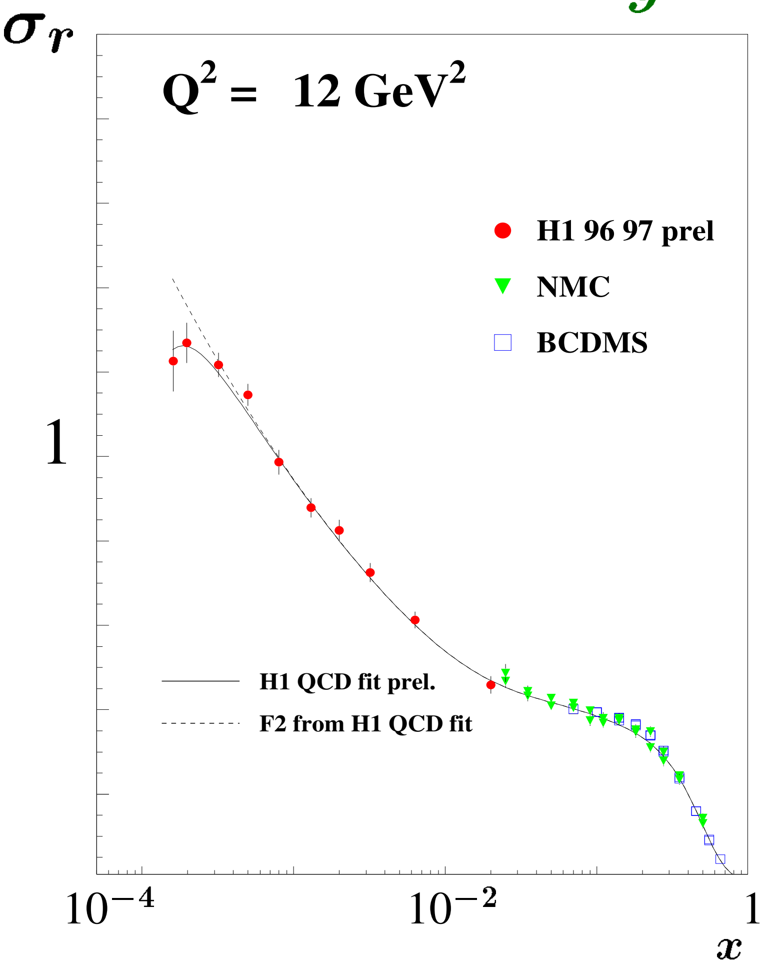
QCD fit :

- ∗ made with 97 data $\Rightarrow$ PDF's defined
- ∗ shown with 920 GeV beam energy

Determination of F_L: Subtraction Method

- measure reduced cross section σ_r
- QCD fit to F_2 in the region where F_L contribution is negligible ($y < 0.35$)
- extrapolate F_2^{QCD} to high y
- subtract σ_r:

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



Use this method for $Q^2 > 10\ GeV^2$

First measurement of F_L at HERA with H1 94 data:

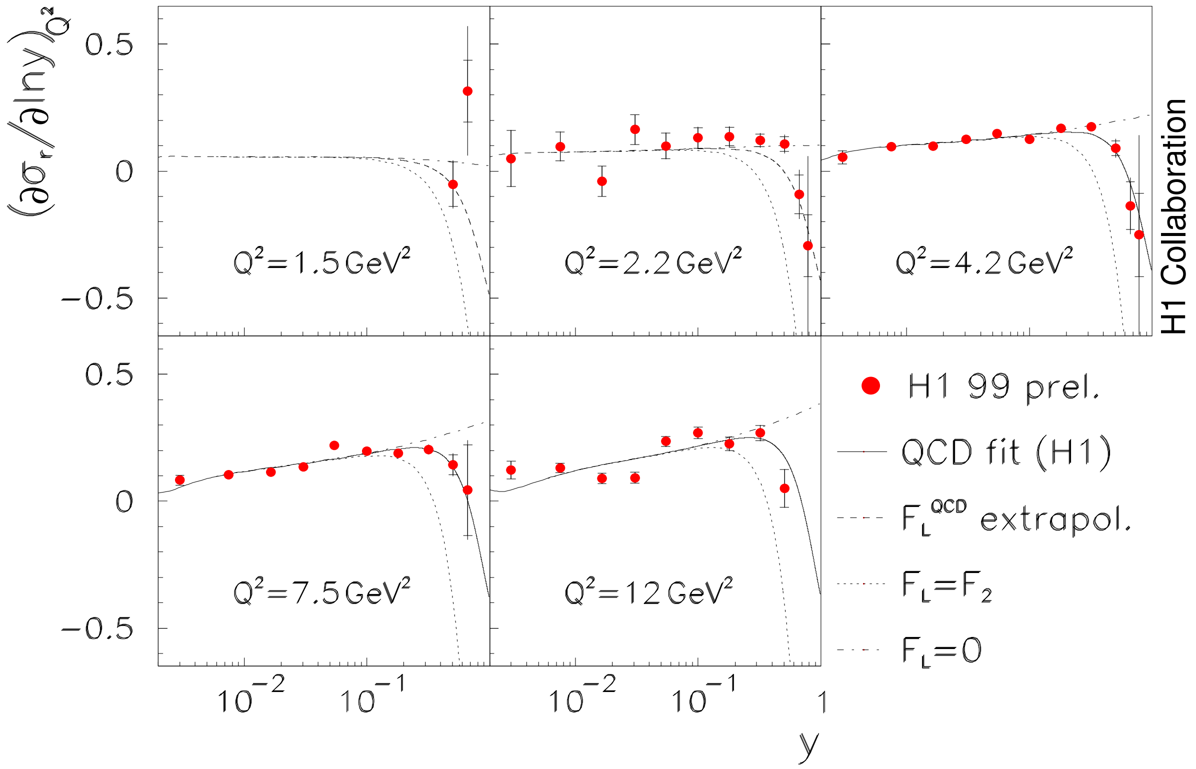
Phys.Lett. 393B (1997) 452

Determination of F_L: Derivative Method

- form derivatives w.r.t. $\ln y$ from σ_r in bins of Q^2 and y:

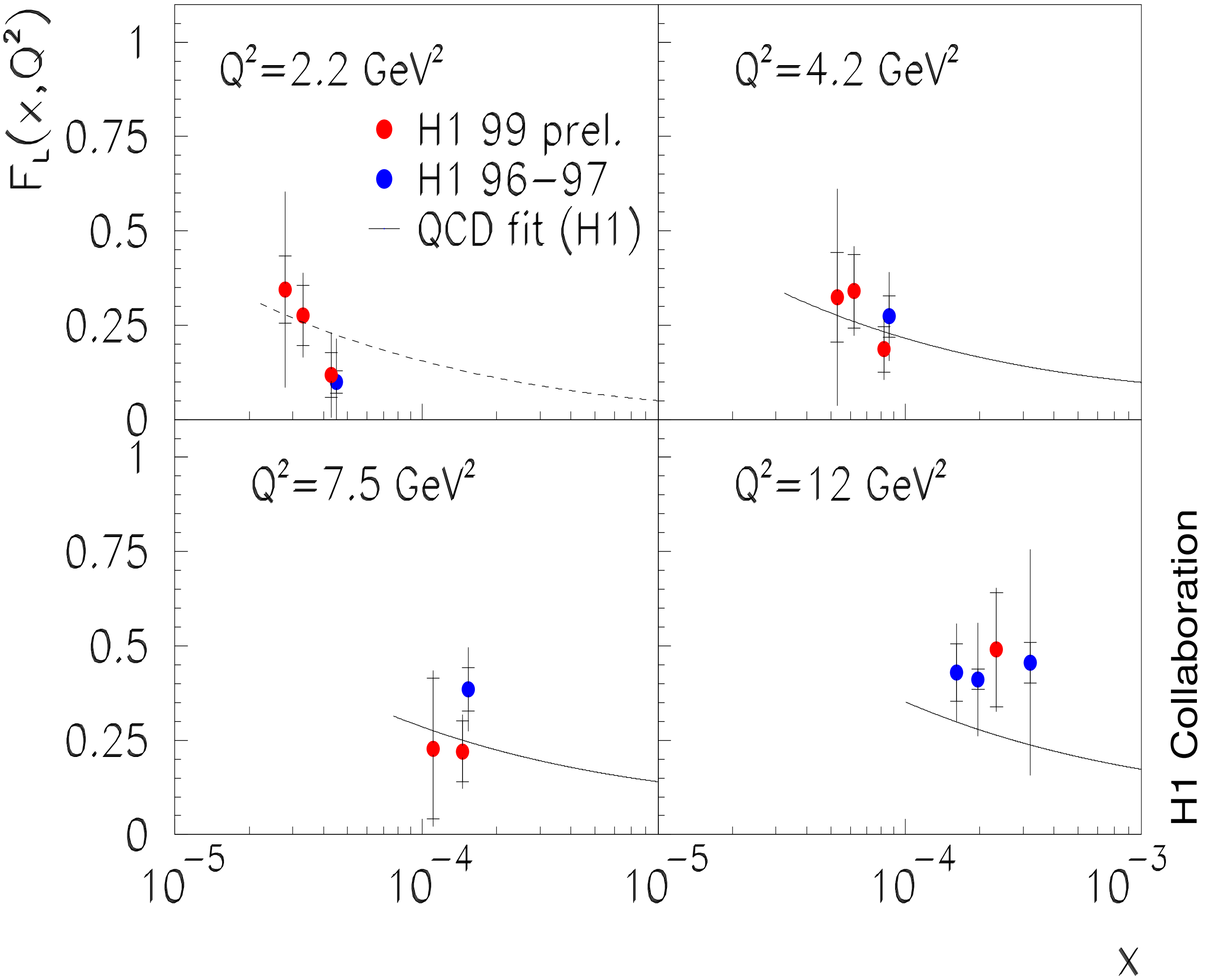
$$\frac{\partial \sigma_r}{\partial \ln y} = \frac{\partial F_2}{\partial \ln y} - F_L \cdot 2y^2 \cdot \frac{(2-y)}{Y_+^2} - \frac{\partial F_L}{\partial \ln y} \cdot \frac{y^2}{Y_+^2}$$

- $y \to 1 \quad \Rightarrow \quad \partial \sigma_r / \partial \ln y \approx \partial F_2 / \partial \ln y - 2 \cdot F_L$
  ($\partial F_L / \partial \ln y$ neglected, uncertainty included in error)
- for given $Q^2 \quad \Rightarrow \quad F_2 \sim x^{-\lambda} \sim e^{\lambda \ln y}$
  low $Q^2 \Rightarrow$ small λ : $\frac{\partial F_2}{\partial \ln y}$ linear in $\ln y$ to good approximation
  $\Rightarrow$ confirmed with QCD fit and deviations included in error
- straight-line fit to $\partial \sigma_r / \partial \ln y$ in bins of Q^2 for $y < 0.2$
- extrapolate the fitted line to high y
- subtract $\frac{\partial \sigma_r}{\partial \ln y} \quad \Rightarrow \quad F_L$



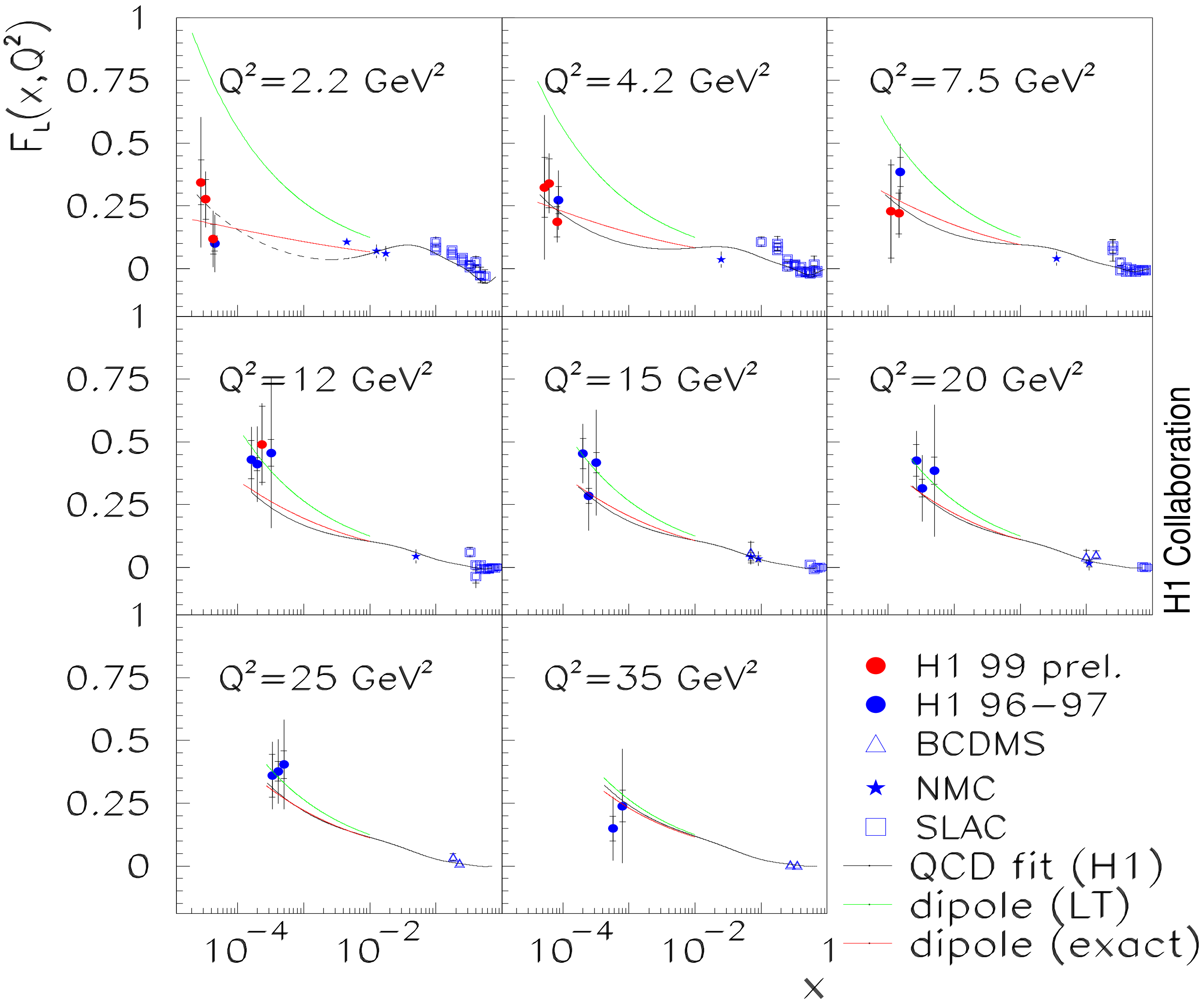
Use this method for $Q^2 < 10 \ GeV^2$

F_L



* F_L measured at $x \sim (3 \cdot 10^{-5} - 3 \cdot 10^{-4})$
* x range extended towards low values
* in agreement with QCD prediction based on scaling violation of F_2

F_L
H1 and fixed target experiment data



Comparison with expectations based on fits to the F_2 data:

* Golec-Biernat and Wüsthoff saturation model with (exact) and without (LT) higher twists

(J.Bartels, K.Golec-Biernat, K.Peters, Eur.Phys.J. C17, 121-128 (2000))

$\Rightarrow$ higher twist contributions needed to describe data at low Q^2

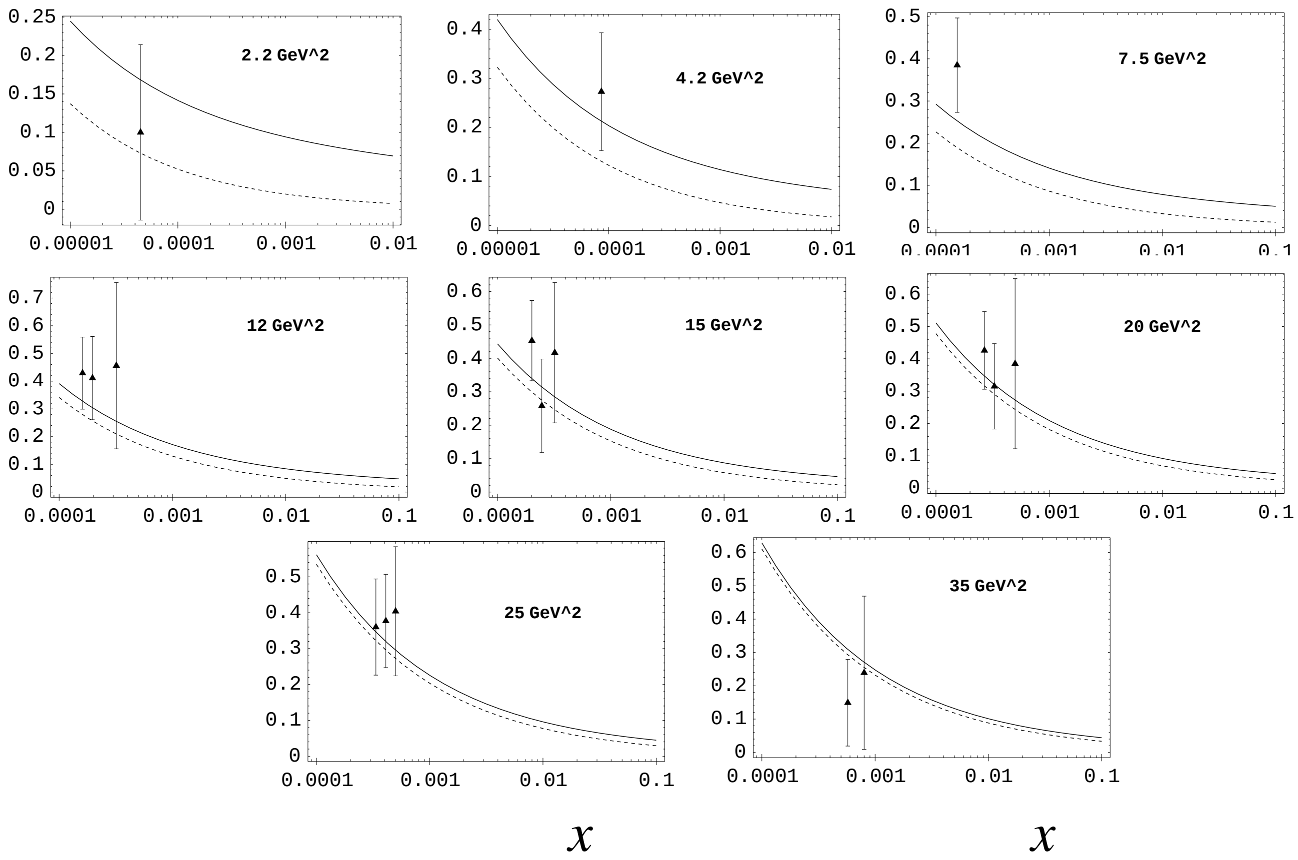
F_L
Comparison with Donnachi-Dosch model

(A. Donnachi and H.G. Dosch, hep-ph/0106169)

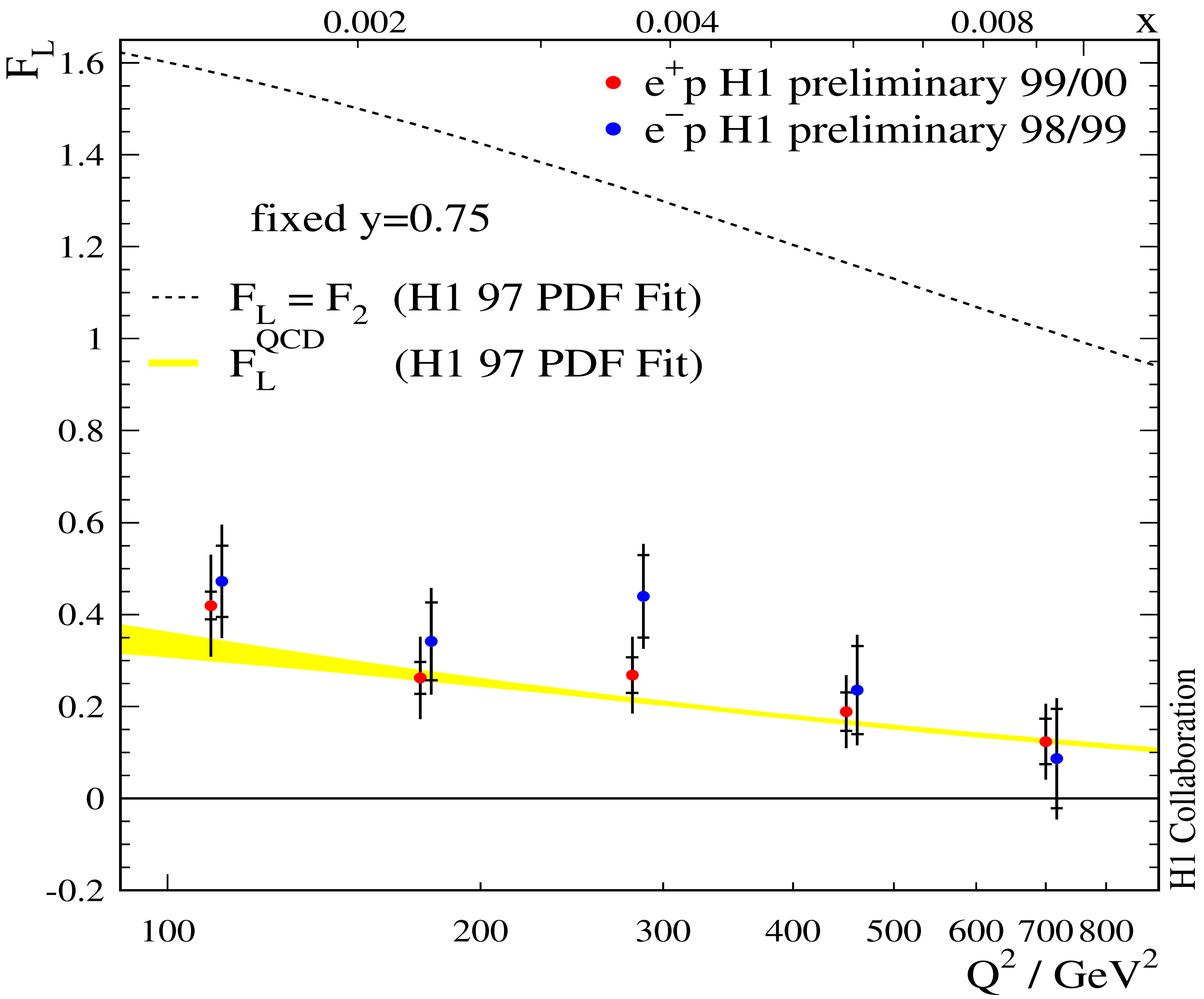
- Model based on
  - ▷ non-perturbative QCD (MSV) and dipole picture of scattering
  - ▷ Soft and Hard Pomerons (DL)
  - ▷ large(small) dipole couples to Soft(Hard) Pomeron

- Model describes well
  - ▷ γp, $\gamma^* p$ and $\gamma\gamma$ reactions
  - ▷ F_2, F_2^{charm}, F_L

(— Soft + Hard pomeron ; - - - Hard pomeron)

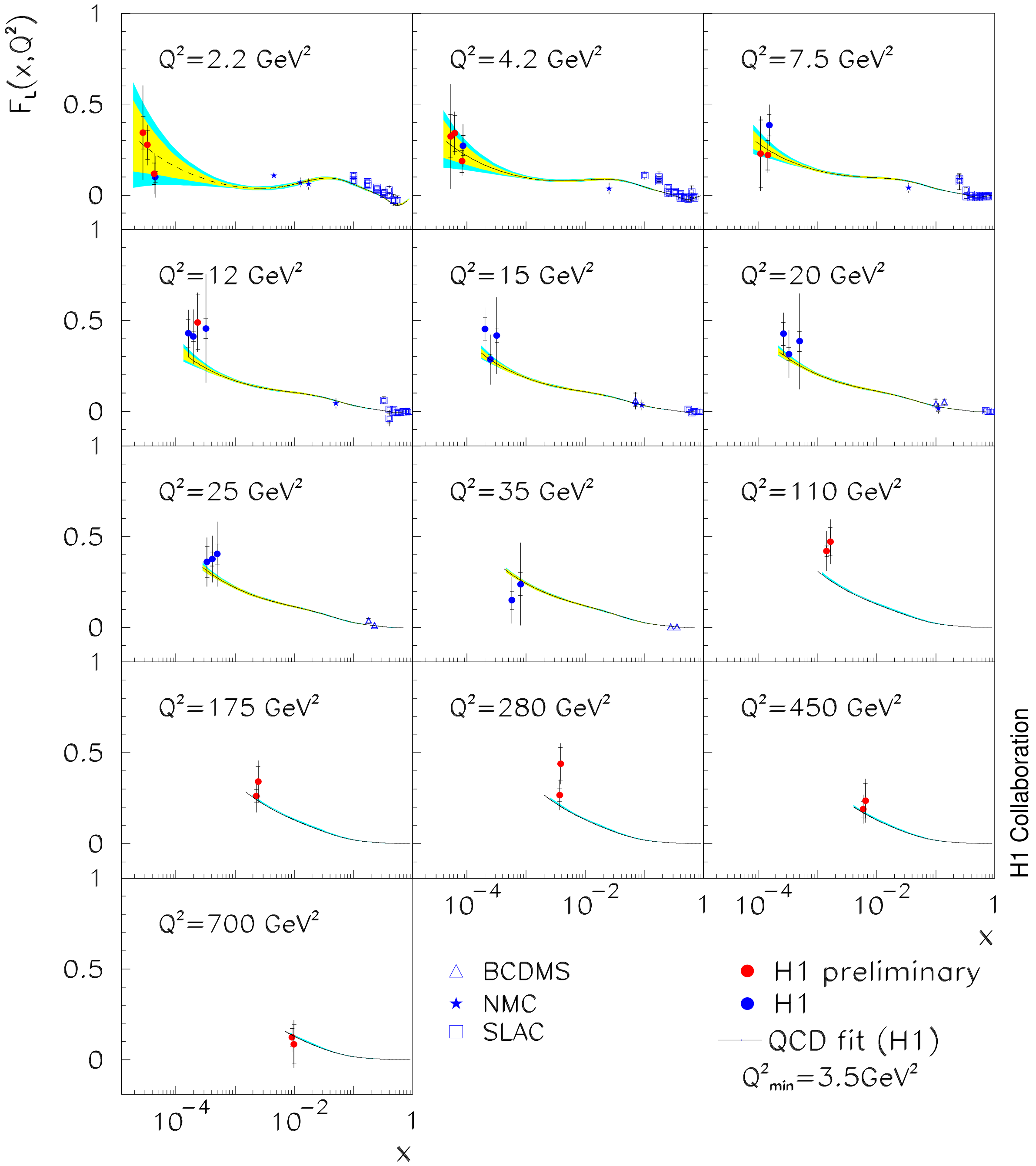


F_L at high Q^2



- $*$ e^+ and e^- data are in good agreement
- $*$ consistent with QCD (H1 NLO QCD fit)

H1 results on F_L at low and high Q^2



All data consistent with QCD

Summary

Longitudinal Structure Function F_L determined at HERA

- with two methods:
  $Q^2 < 10GeV^2$ - 'derivative' (independent of QCD)
  $Q^2 > 10GeV^2$ - 'subtraction' (uses H1 QCD fit)
- in wide range of Q^2, **2.2 - 800 GeV^2**
- for e^+p and e^-p data samples

- so far no significant deviation from QCD expectation in HERA low x domain
  $\Rightarrow$ gluon rise at low x directly seen in F_L

BUT ...

Outlook

Direct measurements of F_L,
without any extra assumptions
are very important
and only possible by varying beam energies

$$\sigma_1 - \sigma_2 = [(y^2/Y_+)_1 - (y^2/Y_+)_2] \cdot F_L$$

(as done in the fixed target experiments)

Should be done at HERA II !