# DIS Physics at Low and Very High $Q^2$ at HERA

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**on behalf of the**

H1 Collaboration

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DESY

# PLAN:

- Introduction
  - HERA & H1
  - Kinematics
- Structure Functions
  - Definitions & Methods
  - $F2$, $xg(x)$, $F_L$
- Searches for New Physics at Very High $Q^2$

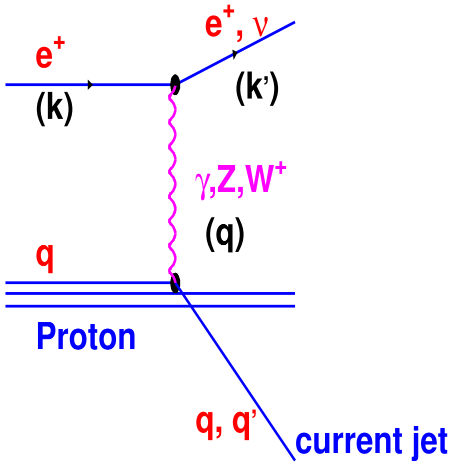
  $$\mathcal{L} = 14.2 \rightarrow 23.7 \text{ pb}^{-1}$$

  - the Standard Model
  - Kinematics & Selection
  - Quality Plots
  - $Q^2$ dependance, cross-sections
  - Mass dependance
  - Charged Currents
- Conclusions

# Introduction

HERA: $\underset{(27.5\ \mathrm{GeV})}{e} \rightarrow\Leftarrow \underset{(820\ \mathrm{GeV})}{p}$

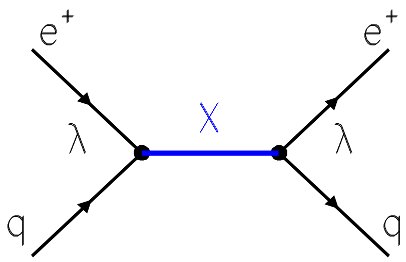
- Probe the proton at very small distances ($\geq 10^{-3}$fm)
  e.g. $t$-channel exchange of virtual gauge bosons




$$Q^2 = -(k-k')^2 = -q^2 = sxy$$
$$x = \frac{Q^2}{2(P.q)}$$
$$y = \frac{(P.q)}{(P.k)}$$
$$M = \sqrt{sx} \quad y = \frac{1+\cos\theta_e^*}{2} \quad (+z \leftarrow p)$$
$$\mathrm{d}\sigma/\mathrm{d}y\,|_{\text{fixed } x} \propto 1/y^2$$

$\Rightarrow$ proton SF's, pQCD tests, jets, EW propagators

- Search for $s$-channel production of new particles possessing Yukawa couplings to $e$-parton pairs



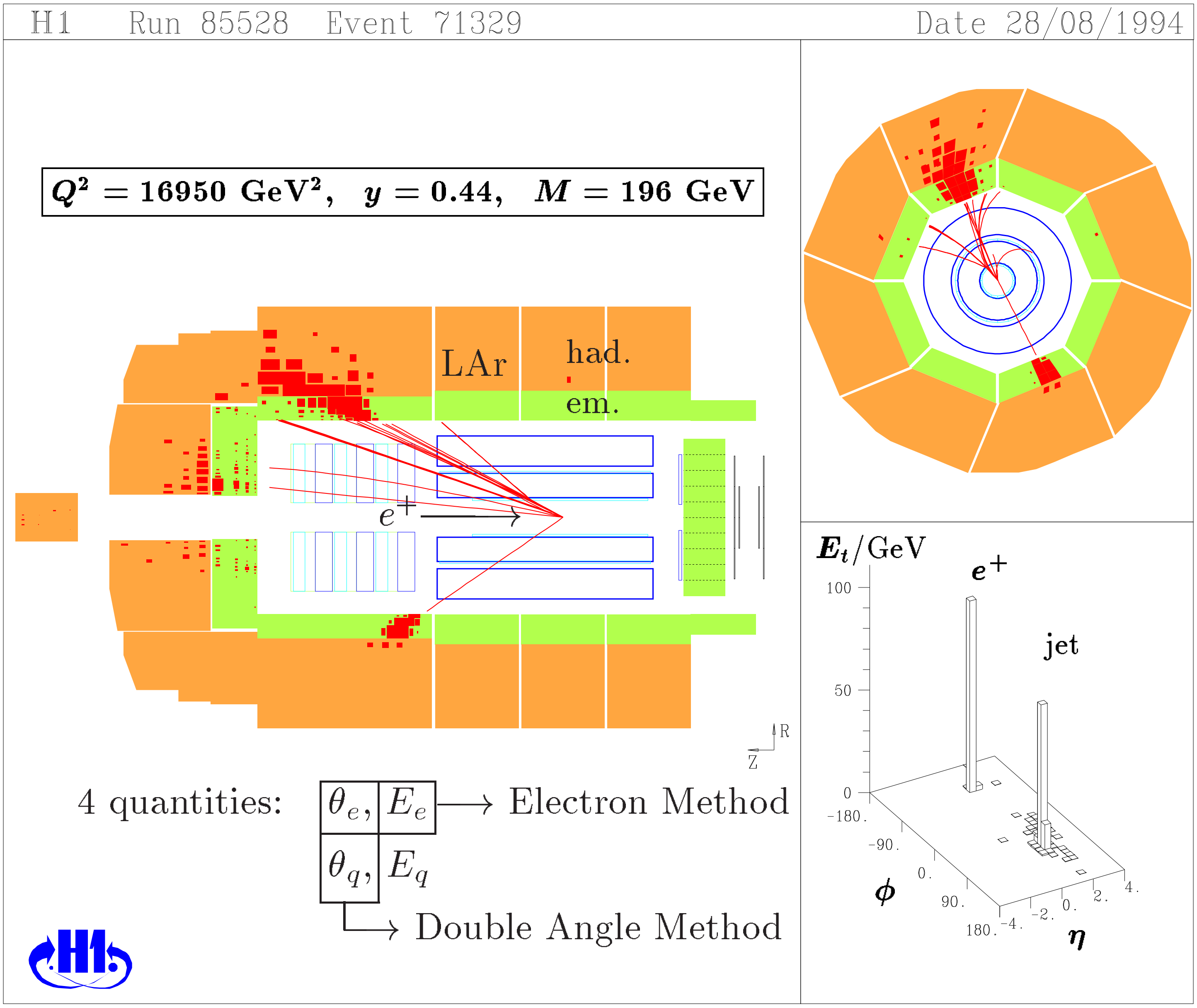

$M_X \leq 300$ GeV

| | | |
|---|---|---|
| e.g. | leptoquarks | $S = 0, 1$ |
| | $\not{R}_p$ squarks | $S = 0$ |
| | leptogluons | $S = 1/2$ |

$$\mathrm{d}\sigma/\mathrm{d}y\,|_x \sim cst_{(S=0)} \quad \propto (1-y)^2_{(S=1)} \quad \propto (1-y)_{(S=1/2)}$$

- Search for new $t$- or $u$-channel boson exchange or contact interactions for $M \gg \sqrt{s}$

# NC DIS Candidate




## LAr Calorimetry

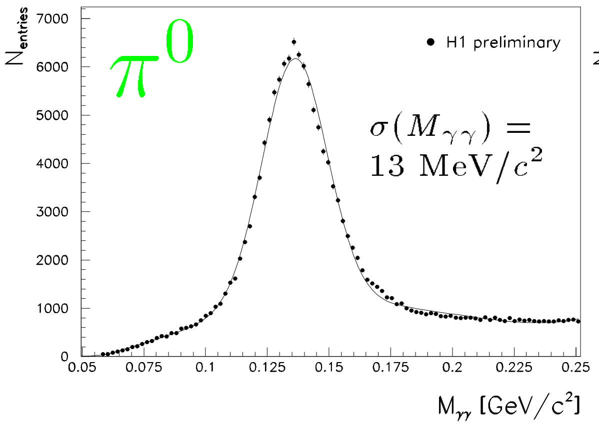
- Very fine granularity ($\approx$ 44000 cells)
- Optimal for $e$-identification
- Hadronic energy compensation by offline weighting

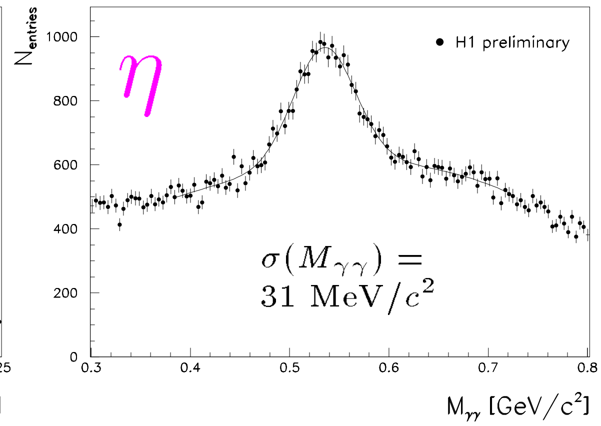
- $\Delta\theta_e \sim 2$ mrad for $10^\circ < \theta_e < 30^\circ$
  $\Delta\theta_e \leq 5$ mrad for $30^\circ < \theta_e < 145^\circ$
- $\sigma(E)/E \simeq 12\%/\sqrt{E/\mathrm{GeV}} \oplus 1\%$
- $\sigma(E)/E \simeq 50\%/\sqrt{E/\mathrm{GeV}} \oplus 2\%$

TEST BEAMS: $E_e$ up to 166 GeV $E_\pi$ up to 205 GeV

# The SPACAL Performance

Tagged photoproduction $(0.3 < y < 0.7, Q^2 < 0.01\ \mathrm{GeV}^2/c^2)$



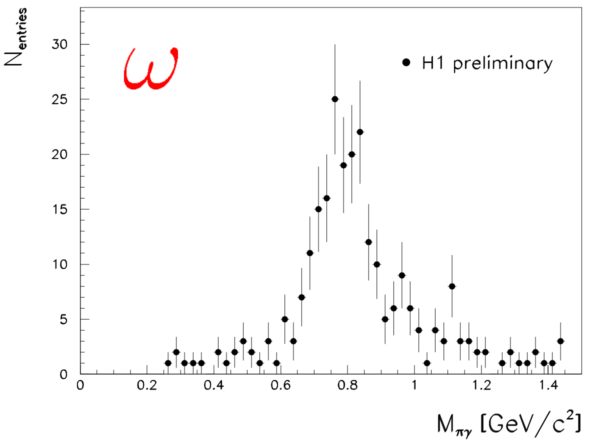




New detector: **SpaCal** (**Spa**ghetti **Cal**orimeter)

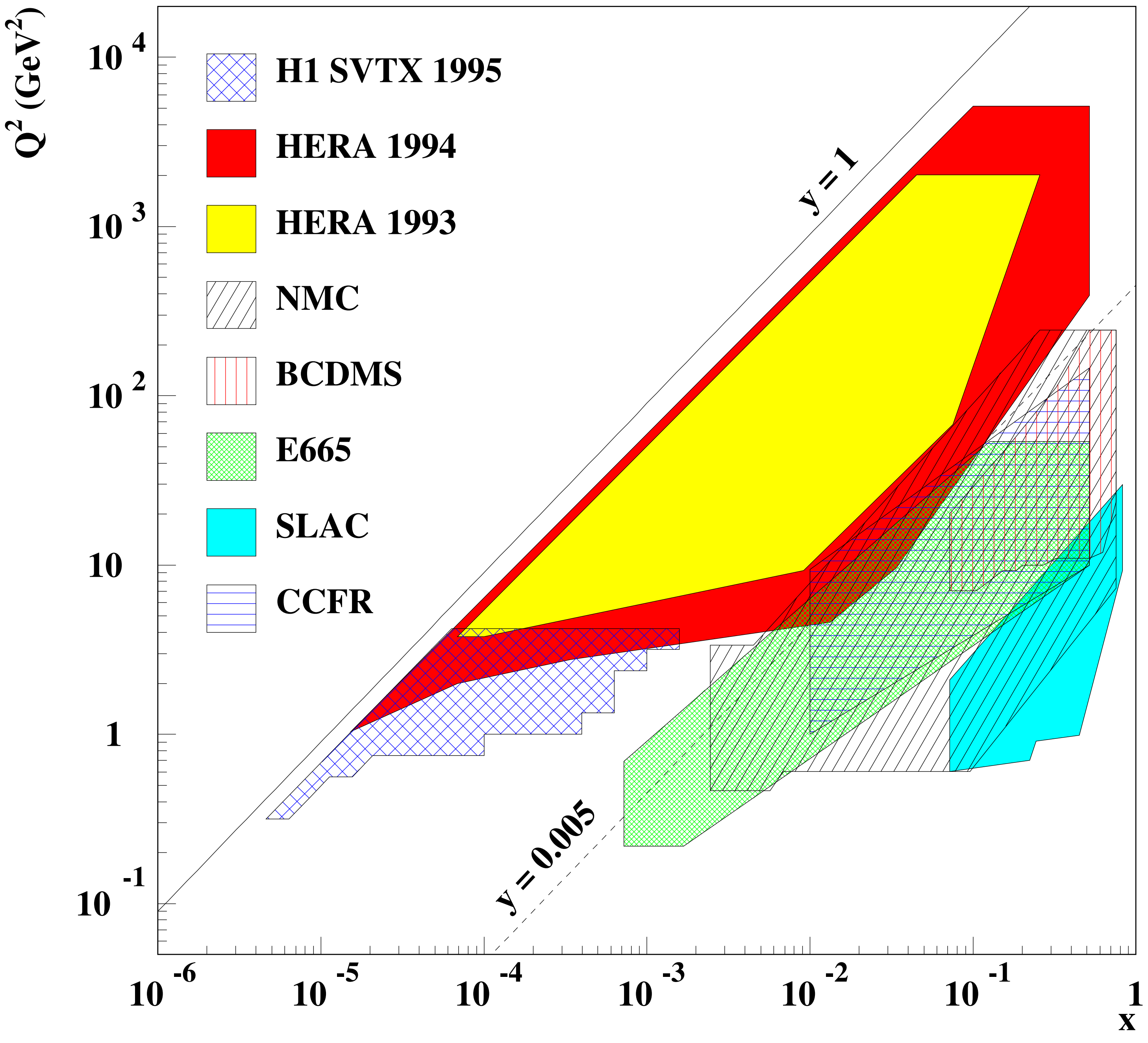
- lead/scintillating-fibre matrix (photomultiplier readout)
- wider angular acceptance: $\boxed{153° < \theta < 177.8°}$
- lower energy threshold ($\approx$ 100 MeV), timing capabilities
- fine granularity: cell size $4 \times 4\ \mathrm{cm}^2$
- very good energy resolution: $\boxed{\sigma/E = 7\ \%/\sqrt{E/\mathrm{GeV}} \oplus 1\ \%}$
- very low noise ($\sim$ 1 MeV/channel)

$$\omega \to \gamma\pi^0$$
$$\hookrightarrow \gamma\gamma$$

B.R. $= 8.5\ \%$



# $\mathcal{F}_2^p$ in the $(x, Q^2)$ Kinematic Plane




- Central region well explored (1994 $\mathcal{F}_2$ fits)
  $\Rightarrow$ amazingly good description by NLO DGLAP evolution (down to $Q^2 \sim 1.5$ GeV$^2$)

# Structure Functions

- For unpolarized beams:

$$\frac{d^2\sigma^{NC}(e^{\pm}p)}{dx dQ^2} =$$

$$\frac{2\pi\alpha^2}{xQ^4} \cdot [Y_+ \mathcal{F}_2(x,Q^2) - \underbrace{y^2 \mathcal{F}_L(x,Q^2)}_{\text{only at high } y} \mp Y_- \underbrace{x\mathcal{F}_3(x,Q^2)}_{\text{negligeable for } Q^2 \ll M_Z^2} ]$$

where:

$\mathcal{F}_2 \supset \gamma$ and $Z^0$ exchanges

$\mathcal{F}_L \supset$ longitudinal SF $R = \dfrac{\mathcal{F}_L}{\mathcal{F}_2 - \mathcal{F}_L} = \dfrac{\sigma_L}{\sigma_T}$

$\mathcal{F}_3 \supset$ parity violations

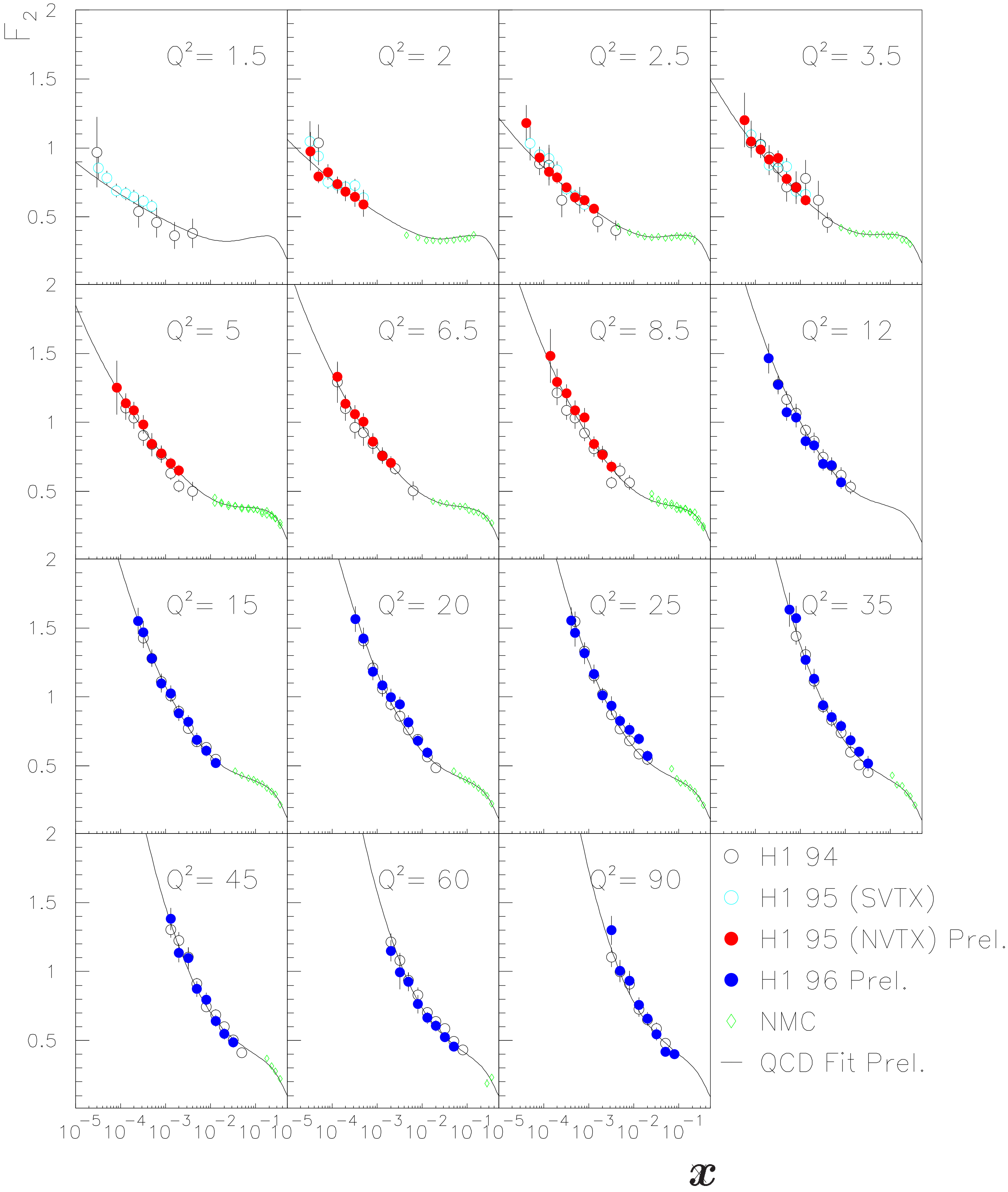
and:

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

- Measurement and QCD analysis of $\mathcal{F}_2$:
  - Moderate $Q^2 \longrightarrow \mathcal{F}_3$ neglected
  - $\mathcal{F}_L$ is assumed
  - PDF are extracted using a NLO DGLAP fit of H1, BDCMS & NMC data.

# $\mathcal{F}_2$ QCD fit on '94, '95 and '96 data

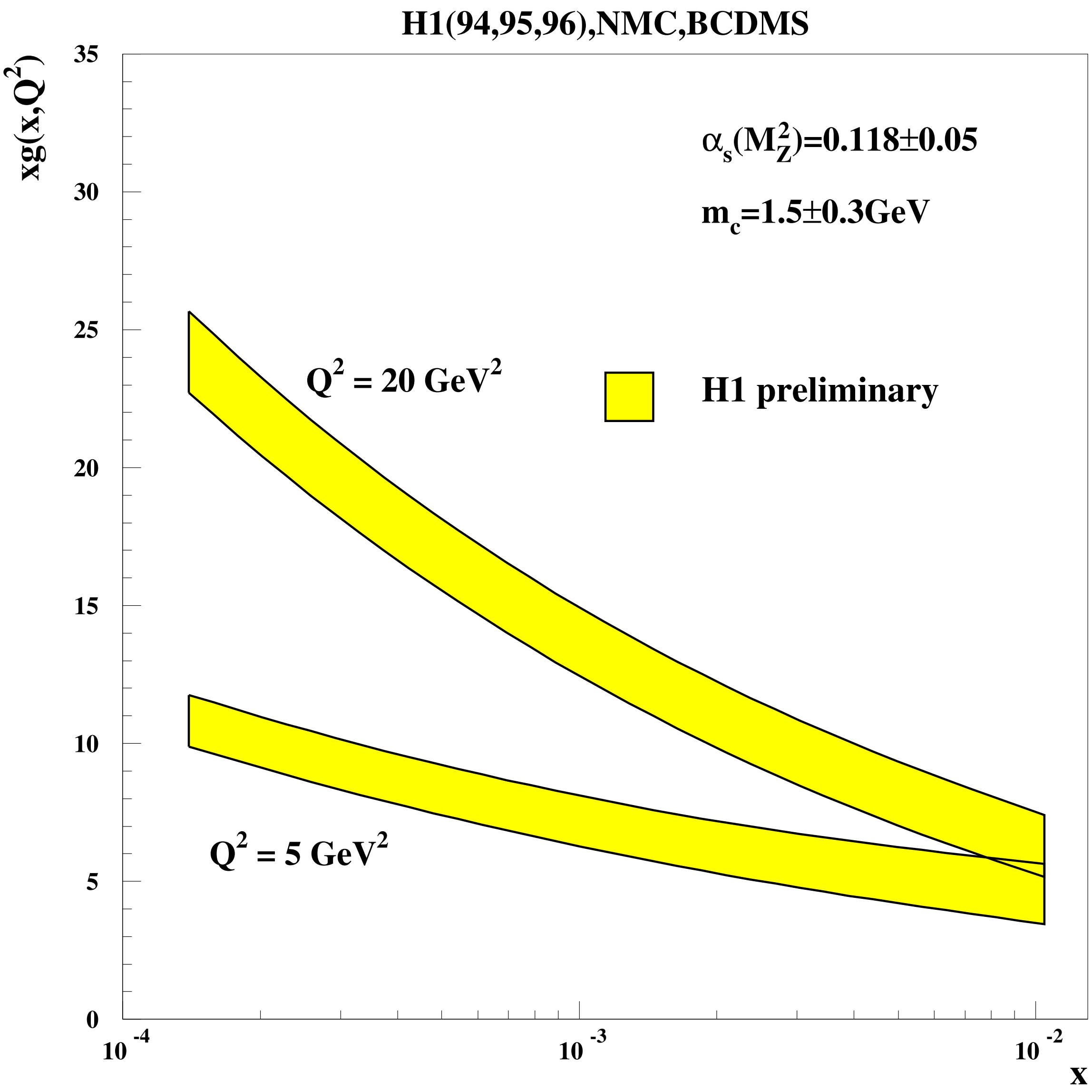
$\mathcal{F}_2$




$\mathcal{F}_2 = \mathcal{F}_2^{n_f=3} + xg(x) * BGF$ evolved by NLO DGLAP with $Q_0^2 = 1$ GeV$^2$

$\Longrightarrow \boldsymbol{xg(x)}$

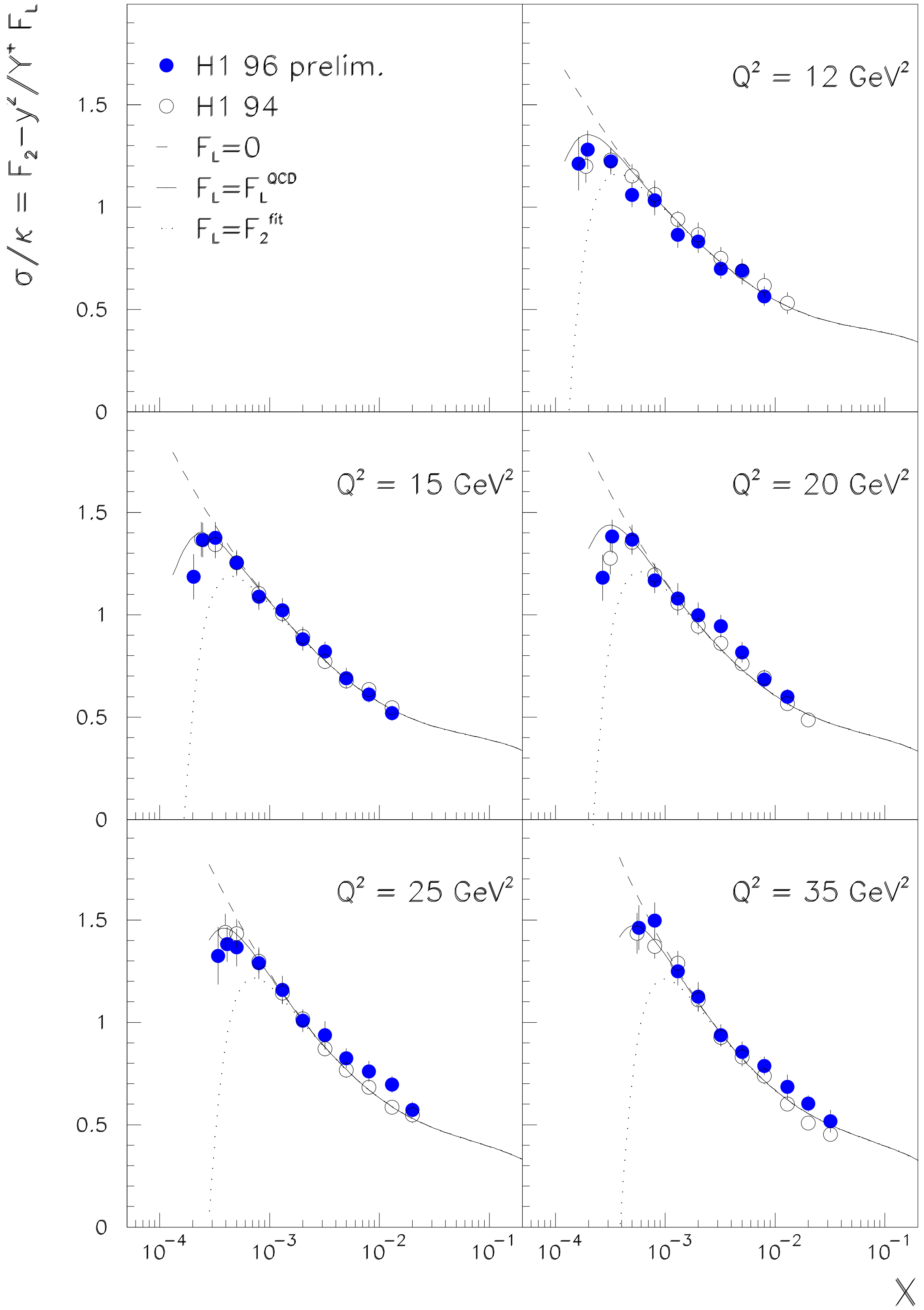
# Gluon density from $\mathcal{F}_2$ QCD fit




- Errors $\sim \frac{1}{2}$ those of the previous H1 measurement
- Values slighly lower than due to a small increase of $\alpha_s$
- Strong rise at small $x$

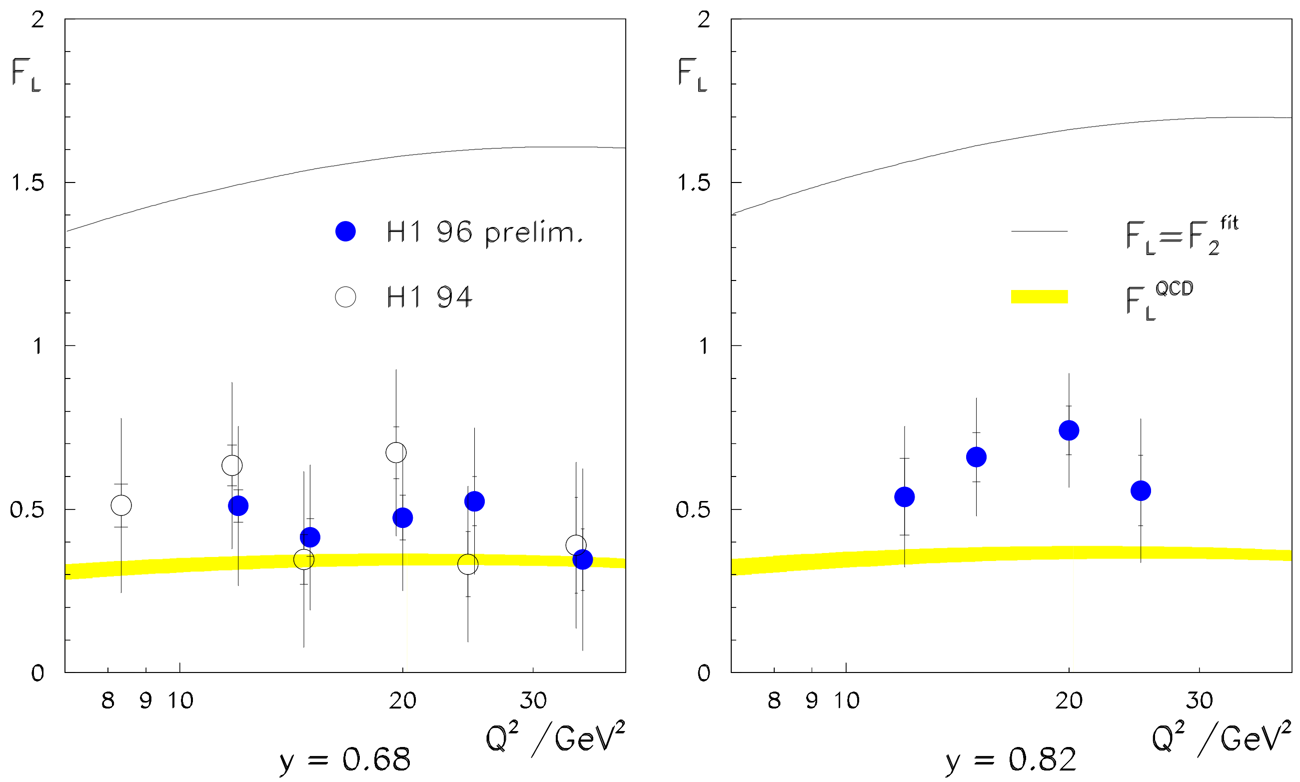
# cross section at high-y

Reduced cross section $\sigma/\kappa = \mathcal{F}_2 - \frac{y^2}{Y_+}\mathcal{F}_L \longrightarrow \mathcal{F}_2$ at high $y$



# The Longitudinal Structure Function

- Conventional Method:
  - measure $\sigma(x, Q^2)$ at different $\sqrt{s}$
- New Subtraction Method by H1:
  - measure $\sigma(x, Q^2)$ at high y
  - extrapolate $\mathcal{F}_2$ with NLO DGLAP fit from the data at $y \leq 0.35$ up to $y = 0.68$, $0.82$ ($y$ bins: $[0.6; 0.7]$, $[0.7; 0.85]$)
  - subtract $\mathcal{F}_2$ part from $\sigma(x, Q^2)$ $\Rightarrow \mathcal{F}_L$



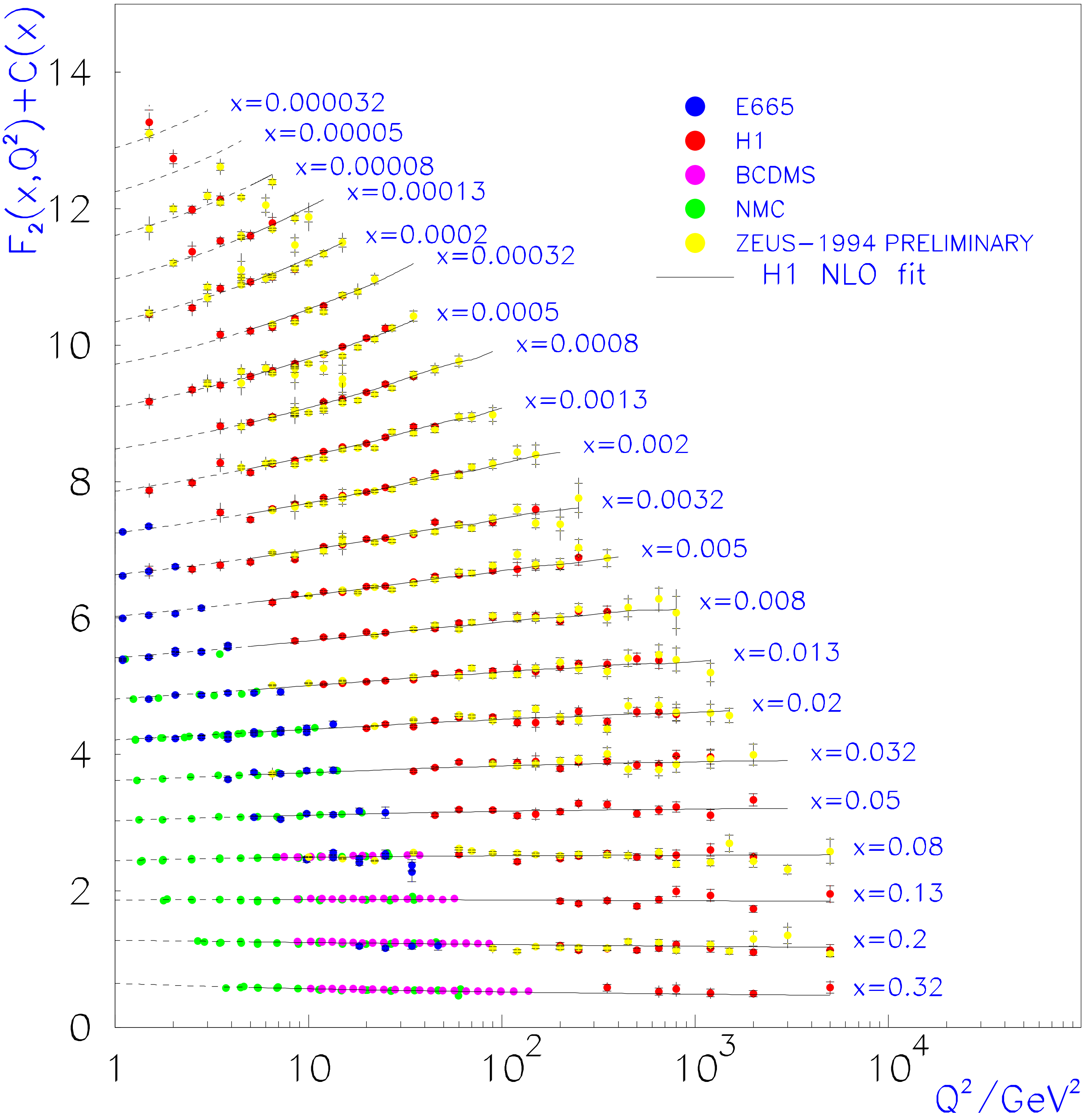

- lowest $y$ bin: $F_L$ compatible with $F_L^{QCD}$ evolved from the fitted PDF and with the previous measurement.
- highest bin (*newly covered region*), disagreement:

$\Rightarrow$ higher orders?

$\Rightarrow$ inconsistencies?

$\Rightarrow$ more checks needed...

# Scaling Violations




Very good description of H1 data by NLO DGLAP evolution over 4 orders of magniture in $Q^2$.

# The Standard DIS Model

## parametrisation of NC and CC DIS:

- Parton densities evolved to high $Q^2$ using next-to-leading order DGLAP equations

## "Theoretical" errors : $\rightarrow \pm 7\ \%$

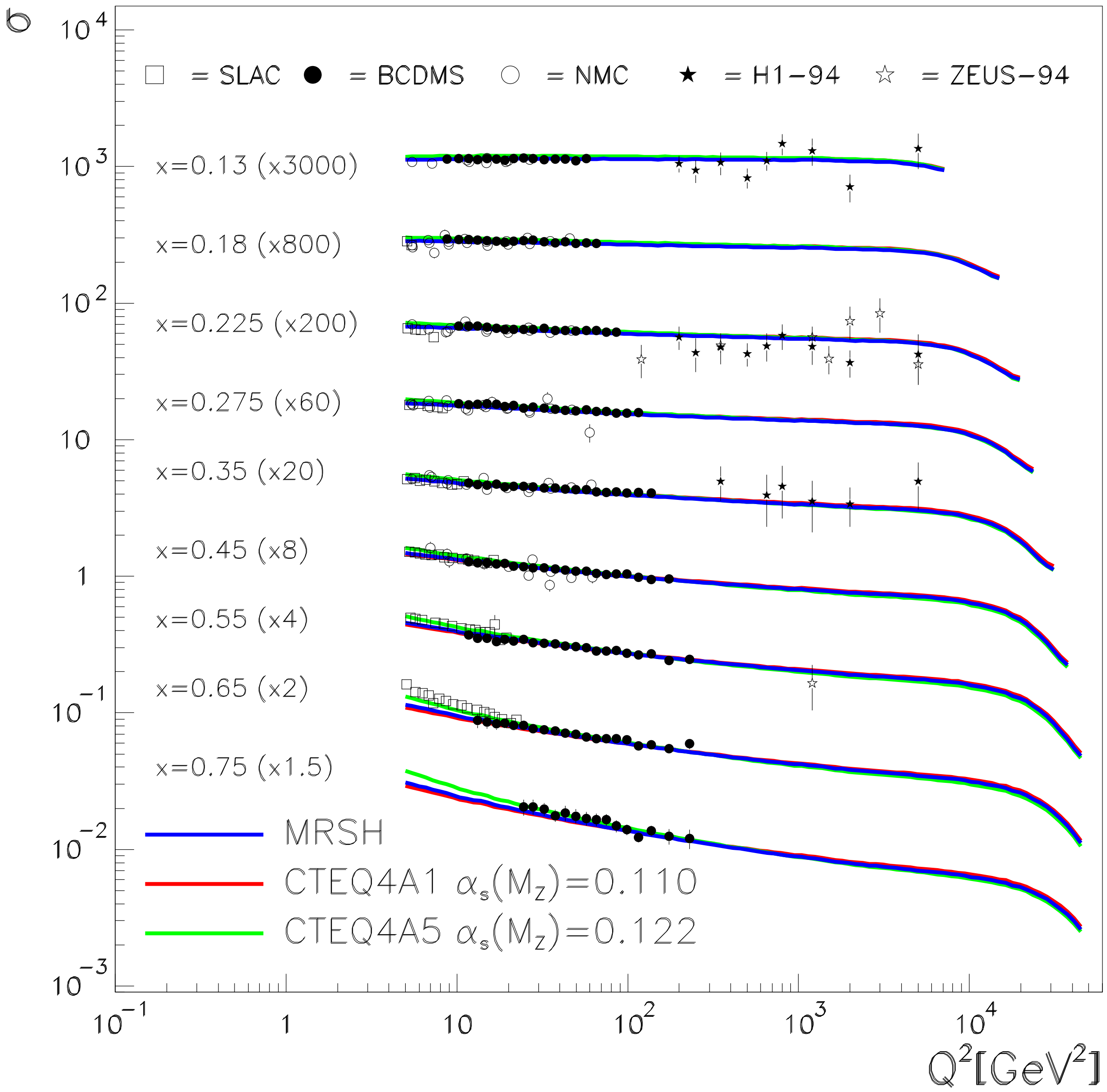
- parton density distribution $\rightarrow \pm 5\ \%$
  1. input data (e.g. BCDMS at high $x$ and low $Q^2$)
  2. initial shapes of distributions ($Q_0^2$)
- value of $\alpha_s$ $\rightarrow \pm 4\ \%$
  comparison CTEQ4 (A1) $\rightarrow$ (A5)
  MRS (R1) $\rightarrow$ MRS (R2)
- higher order QED corrections $\rightarrow \pm 2\ \%$

## Experimental errors :

- integrated luminosity $\rightarrow \pm 2.3\ \%$
- electromagnetic energy scale $\rightarrow \pm 3\ \%$
- hadronic energy scale $\rightarrow \pm 4\ \%$

# $Q^2$ Evolution of the Neutral Current Cross-Section at High $x$

For 3 parametrizations, varying $\alpha_s = 0.110$, 0122...



# Kinematic Reconstruction

- **Electron Method:** **Use of $\theta_e, E_e$**

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

$$M_e = \sqrt{s x_e} = \sqrt{Q^2/y_e} \qquad \frac{\delta M_e}{M_e} \propto \frac{1}{y_e}$$

  - most precise at high $y$ / low $x$
  - degrades severly at low $y$

- **Hadron Method:** **Use of $\theta_h, E_h$**

$$y_h = \frac{\Sigma}{2E_e} \qquad Q^2_h = \frac{p^2_{t,h}}{1-y_h}$$

$$\frac{\delta M_e}{M_e} \propto \frac{1}{1-y_e} \ @\ y \sim 1$$

$$\frac{\delta Q_2}{Q_2} \propto \frac{1}{1-y_e} \ @\ y \sim 1$$

  - rather unprecise
  - only method for charged current

- **Double Angle Method:** **Use of $\theta_e, \theta_h$**
  - high precision at high $Q^2$ **For X-check**
  - degrades at low $Q^2$ and sensitive to QED radiation

- **$\Sigma$ Method:** **Use of $\theta_e, \theta_h, E_e, E_h$**

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

  - precise over the whole kinematic range
  - Independent of QED initial state radiation

with
$$\Sigma = \sum_{\text{hadrons}} (E_h - p_{z,h}) \qquad \tan\theta_h/2 = \frac{\Sigma}{p_{t,h}}$$

# Event Selection

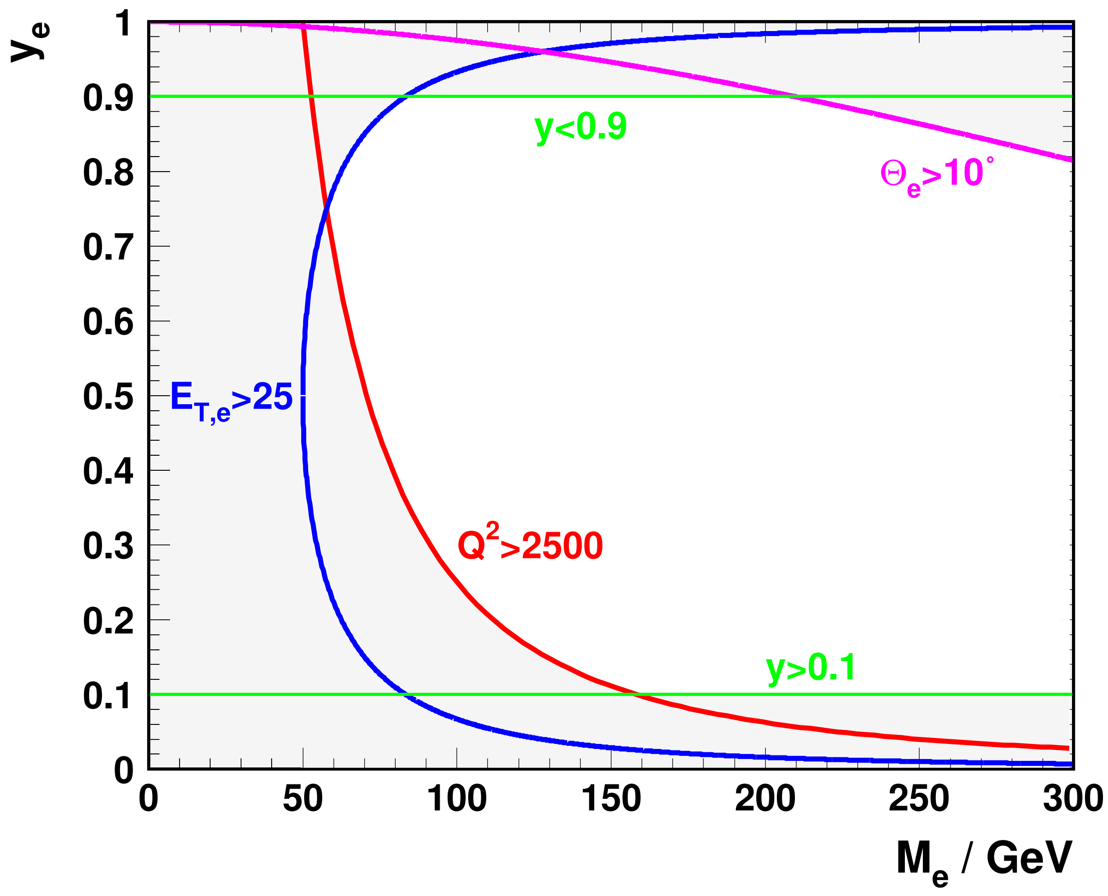
## Data Sample:

| | | | |
|---|---|---|---|
| 1994-1996 | 14.2 $\text{pb}^{-1}$ | $\Rightarrow$ | 65 % increase of luminosity. |
| 1994-1997(→June) | 23.7 $\text{pb}^{-1}$ | | |

## Event Selection: NC

**Same as published in February**

- Kinematic cuts:




- Momentum balance:
  - longitudinal: $43 < \sum E - P_z < 63$ GeV
    $2E_e^o = 55$ GeV expected
    cuts events with *initial state radiation*

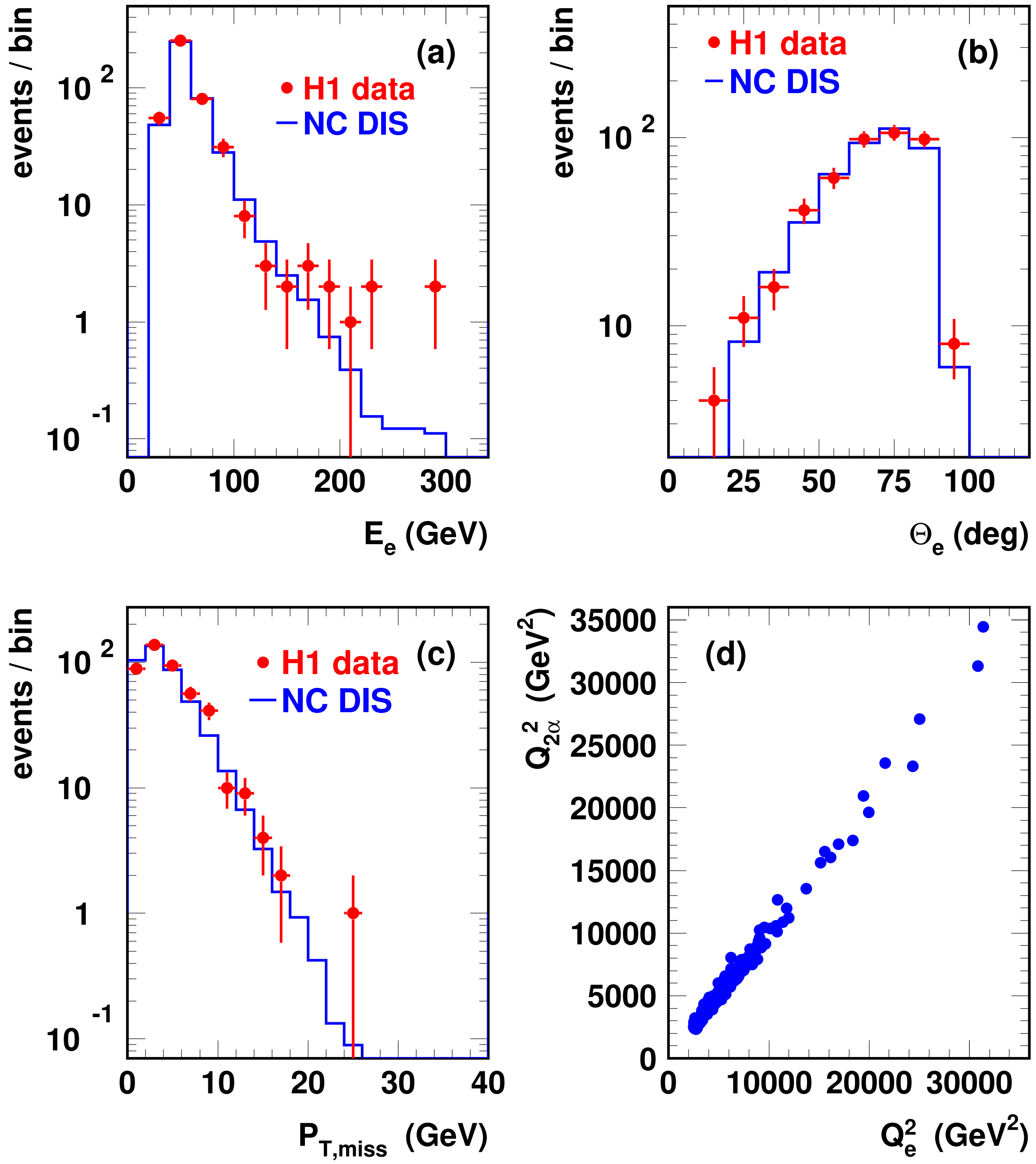
## Event Selection: NC

- $\boxed{P_{T,miss} > 50 \text{ GeV}}$
- $E_T - P_{T,h}/E_T < 0.5$

$\Rightarrow$ Background contamination $< 1$ event.

# Control Plots: Energy Flow

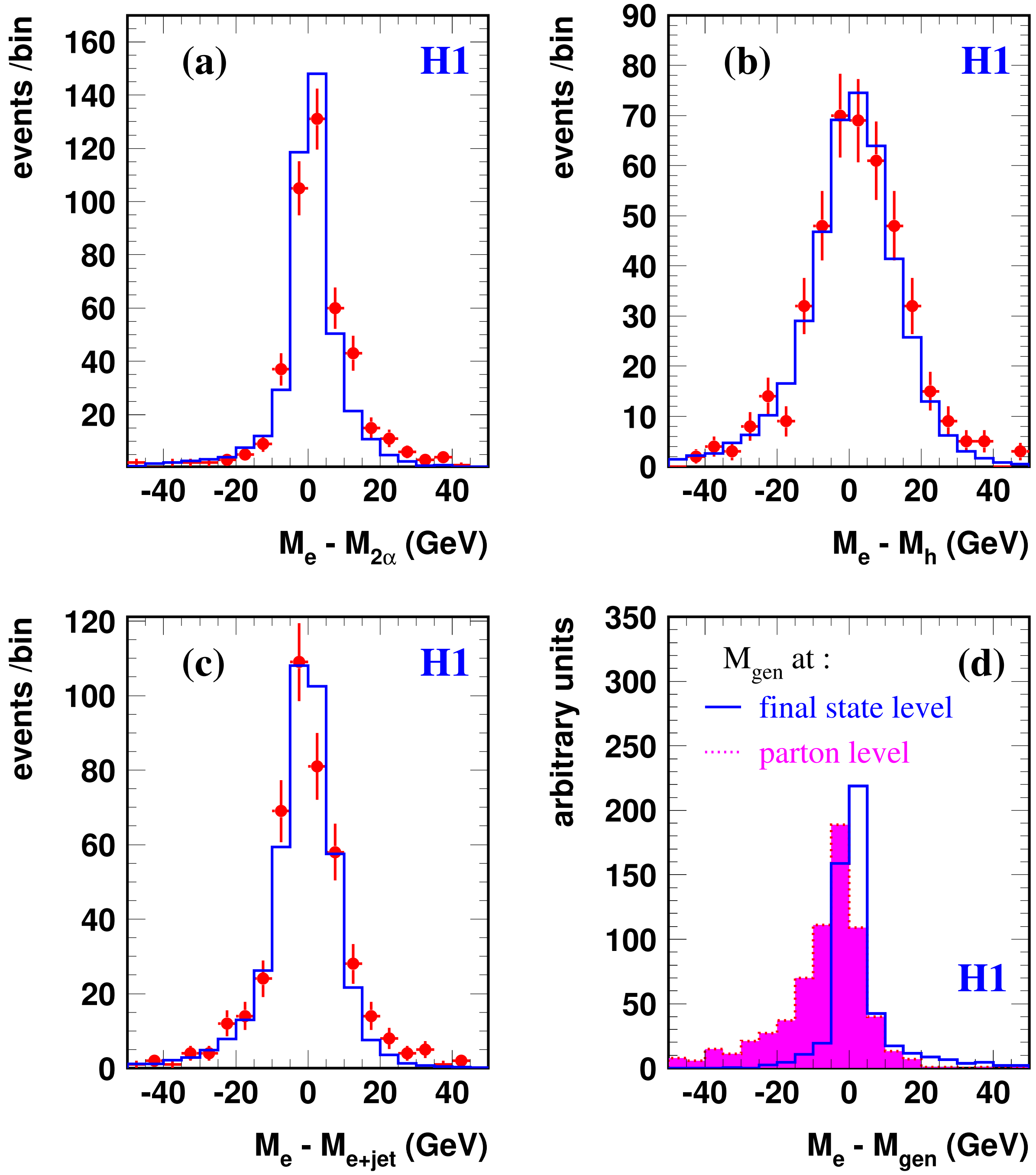
(1994-1996 data)




- Excess of event at high $E_e$,
- For the bulk of the distribution: *good agreement of the MC with the data*,
- Agreement of the reconstructed $Q^2$ with DA and E methods.

# Control Plots: Mass Methods

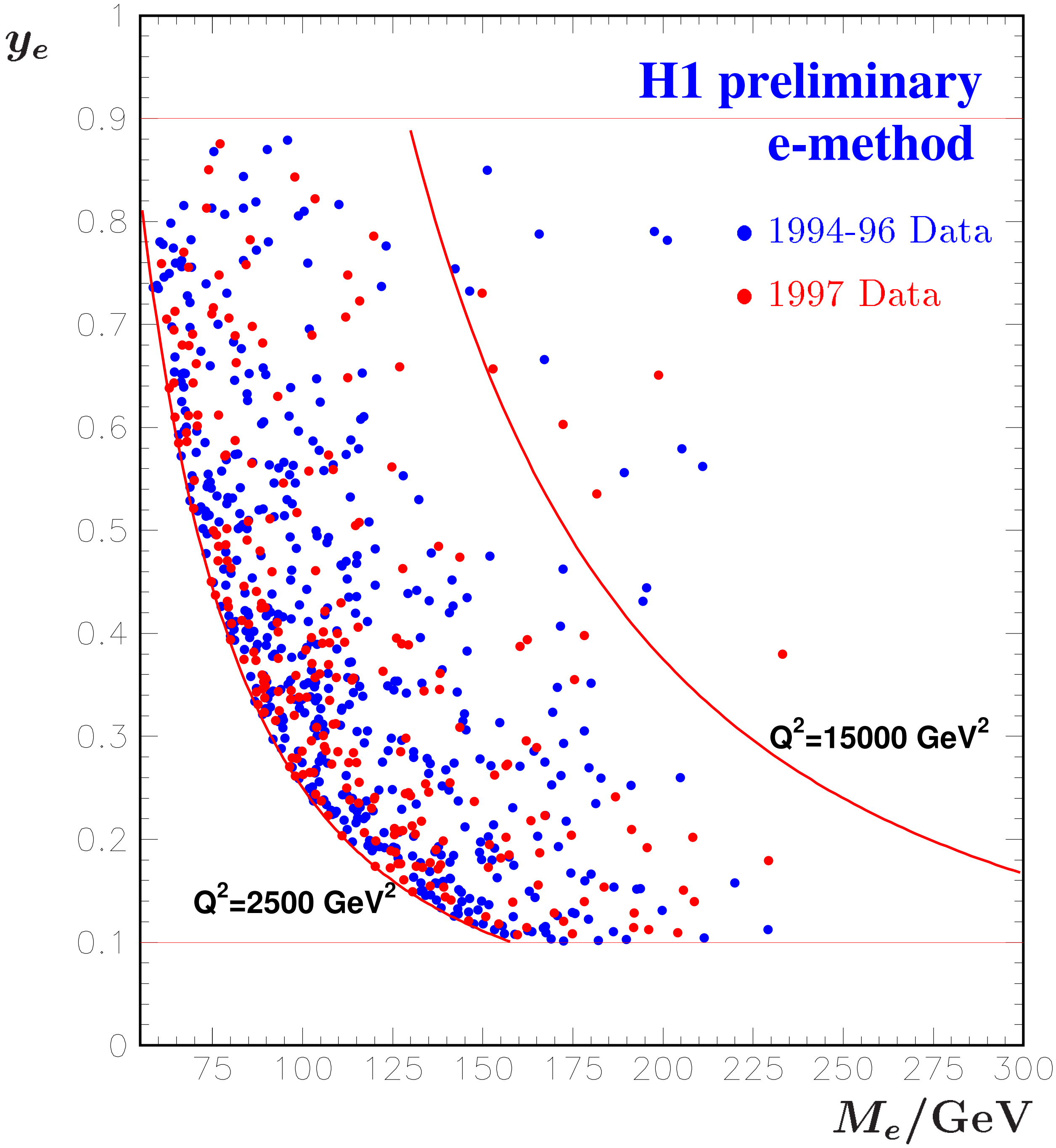
(1994-1996 data)




- Good description of the variations between the various mass reconstruction methods by the MC.
- Good agreement with $M_e$ (reference) of:
  - $M_{2\alpha}$ - $M_h \Rightarrow$ validity for CC
  - $M_{e+\mathrm{jet}} \Rightarrow$ DIS $\simeq e +$ parton $\rightarrow e +$ parton
- $\sigma(M_e - M_e^{\mathrm{gen}}) \simeq 3$ GeV
- $\sigma(M_e - M_{\mathrm{res.}}^{\mathrm{gen}})$: broadening due to QED+QCD corrections.

# H1 Preliminary

## NC Data Sample in the $M$-$y$ Plane



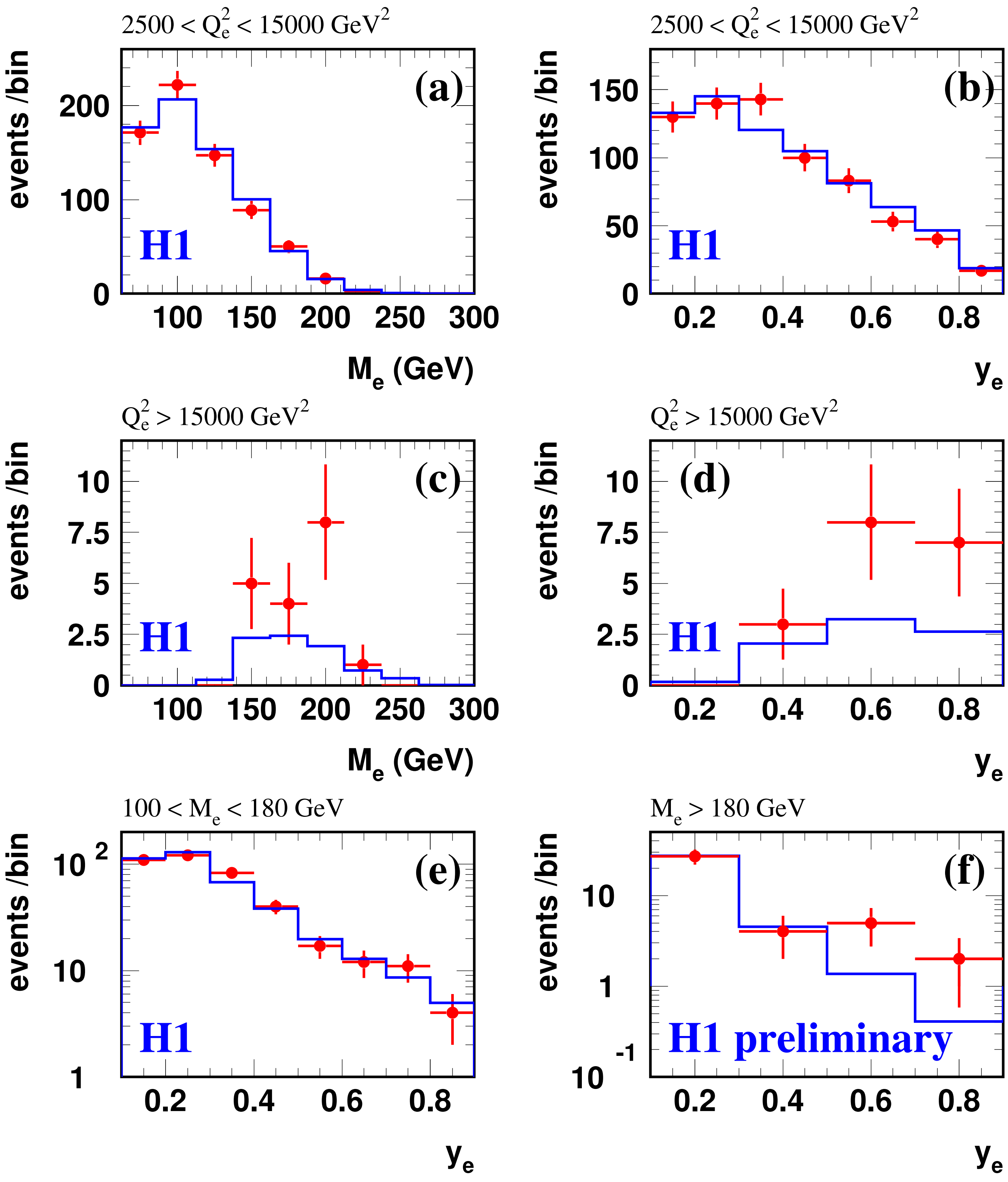

$0.1 < y_e < 0.9$ $\quad \mathcal{L} = 23.69 \pm 0.35 \text{ pb}^{-1}$

- $Q_e^2 > 2500 \text{ GeV}^2$ Obs. $= 724 \Leftrightarrow$ Exp. $= 714 \pm 69$
- $Q_e^2 > 15000 \text{ GeV}^2$ Obs. $= 18 \Leftrightarrow$ Exp. $= 8.0 \pm 1.2$

Efficiency of geometrical acceptance & event selection: $\sim 80$ %
(kinematics from the electron, for events generated within the measured kinematical range)

# H1 Preliminary

## Basic Kinematics

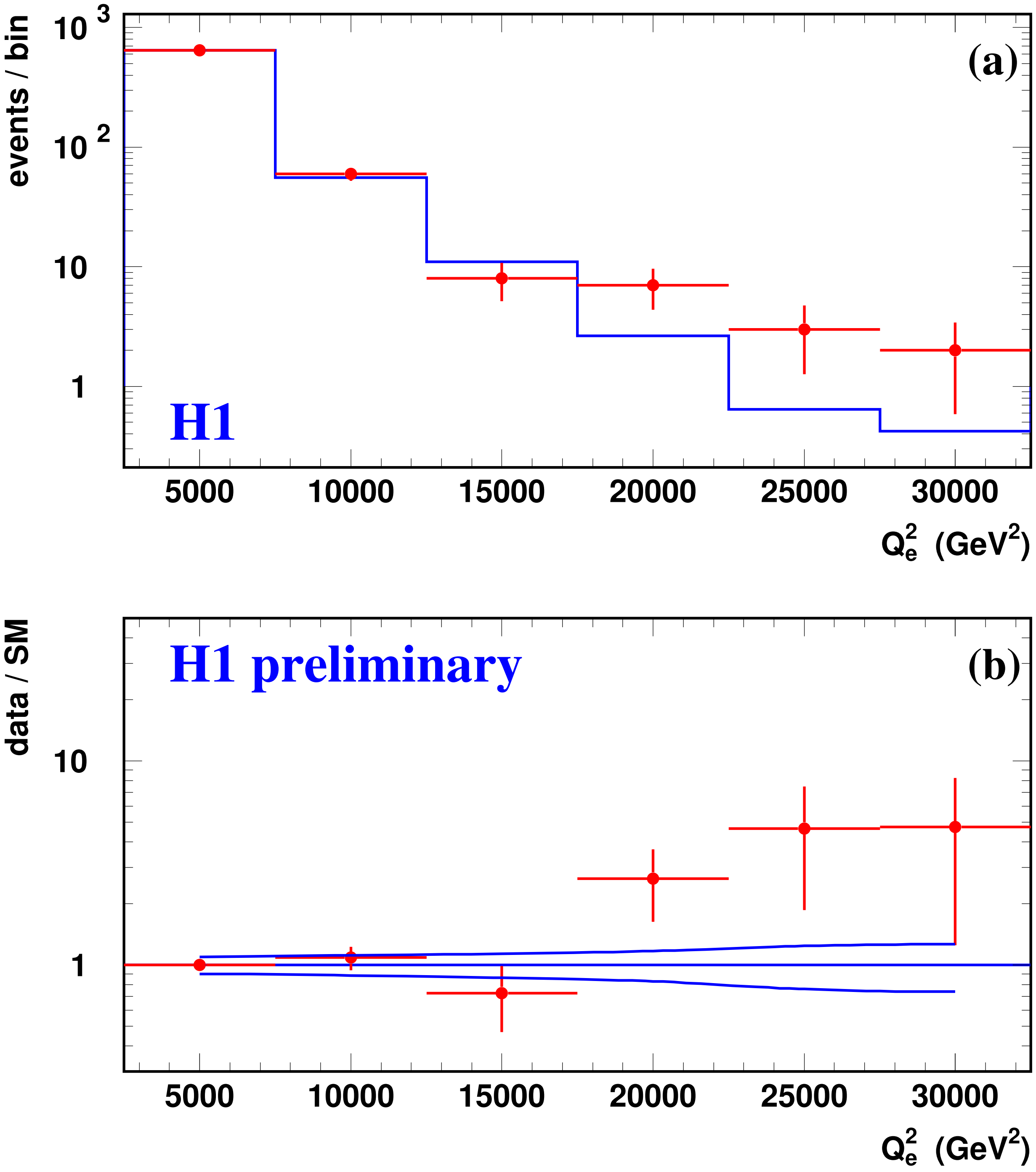



The basic observations remain:

- data exceeds NC DIS expectation at high $Q^2$ (especially at $M_e \sim 200$ GeV);
- at high $M_e \Rightarrow$ difference apparent at large $y_e$.

# H1 Preliminary

## NC $Q^2$ Dependence




Significant excess for $Q_e^2 \gtrsim 15000$ GeV$^2$

Errors dominated by uncertainty on e.m. energy scale

$\sim 8.5\%$ at low $Q_e^2$ $\qquad$ $\sim 30\%$ at highest $Q_e^2$

## $Q^2$ Dependence, Integrals

| 1994 - 1996 Data | | | | | | |
|---|---|---|---|---|---|---|
| $Q^2_{\mathrm{min}}$/ GeV$^2$ | 2500 | 5000 | 10000 | 15000 | 20000 | 30000 |
| $N_{obs}$ | 443 | 122 | 20 | 12 | 5 | 2 |
| $N_{DIS}$ | 426.7 $\pm 38.4$ | 116.2 $\pm 11.6$ | 18.3 $\pm 2.4$ | 4.71 $\pm 0.76$ | 1.32 $\pm 0.05$ | 0.23 |
| $\mathcal{P}$ | 0.35 | 0.35 | 0.39 | $6 \cdot 10^{-3}$ | $1.4 \cdot 10^{-2}$ | $2.3 \cdot 10^{-2}$ |
| **1994 - 1997 Data** | | | | | | |
| $Q^2_{\mathrm{min}}$/ GeV$^2$ | 2500 | 5000 | 10000 | 15000 | 20000 | 30000 |
| $N_{obs}$ | 724 | 193 | 31 | 18 | 7 | 2 |
| $N_{DIS}$ | 714.1 $\pm 69.0$ | 193.9 $\pm 20.7$ | 31.0 $\pm 3.90$ | 8.00 $\pm 1.16$ | 2.28 $\pm 0.38$ | 0.40 $\pm 0.14$ |
| $\mathcal{P}$ | 0.44 | 0.51 | 0.49 | $3.4 \cdot 10^{-3}$ | $1.1 \cdot 10^{-2}$ | $6.6 \cdot 10^{-2}$ |

$\mathcal{P} \equiv \mathcal{P}(N \geq N_{\mathrm{obs.}})$

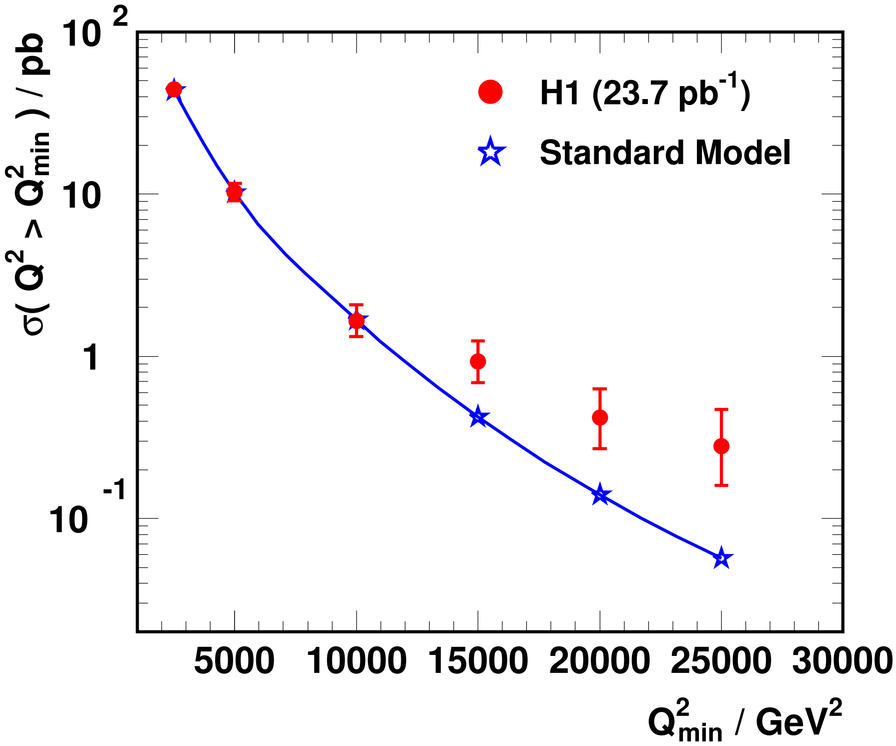
- Excellent agreement up to $Q^2_{\mathrm{min}} = 10000$ GeV$^2$ with NC DIS Standard Model
- The significance of the deviations increases with 1997 data above $Q^2_{\mathrm{min}} = 15000$ GeV$^2$; the rates of events stayed roughly constants.

# H1 Preliminary

## Integrated NC cross-section for $Q^2 > Q_0^2$

| $Q^2_{\rm min}$ | $N_{\rm obs}$ | $\sigma/$ pb | $\sigma_{\rm SM}/$ pb |
|---|---|---|---|
| 2500 | 724 | $43.3^{+4.6}_{-3.9}$ | 43.7 |
| 5000 | 193 | $10.3^{+1.4}_{-1.2}$ | 10.6 |
| 10000 | 31 | $1.67^{+0.42}_{-0.33}$ | 1.79 |
| 15000 | 18 | $0.93^{+0.32}_{-0.24}$ | 0.49 |
| 20000 | 7 | $0.42^{+0.21}_{-0.15}$ | 0.16 |
| 25000 | 4 | $0.28^{+0.19}_{-0.12}$ | 0.059 |

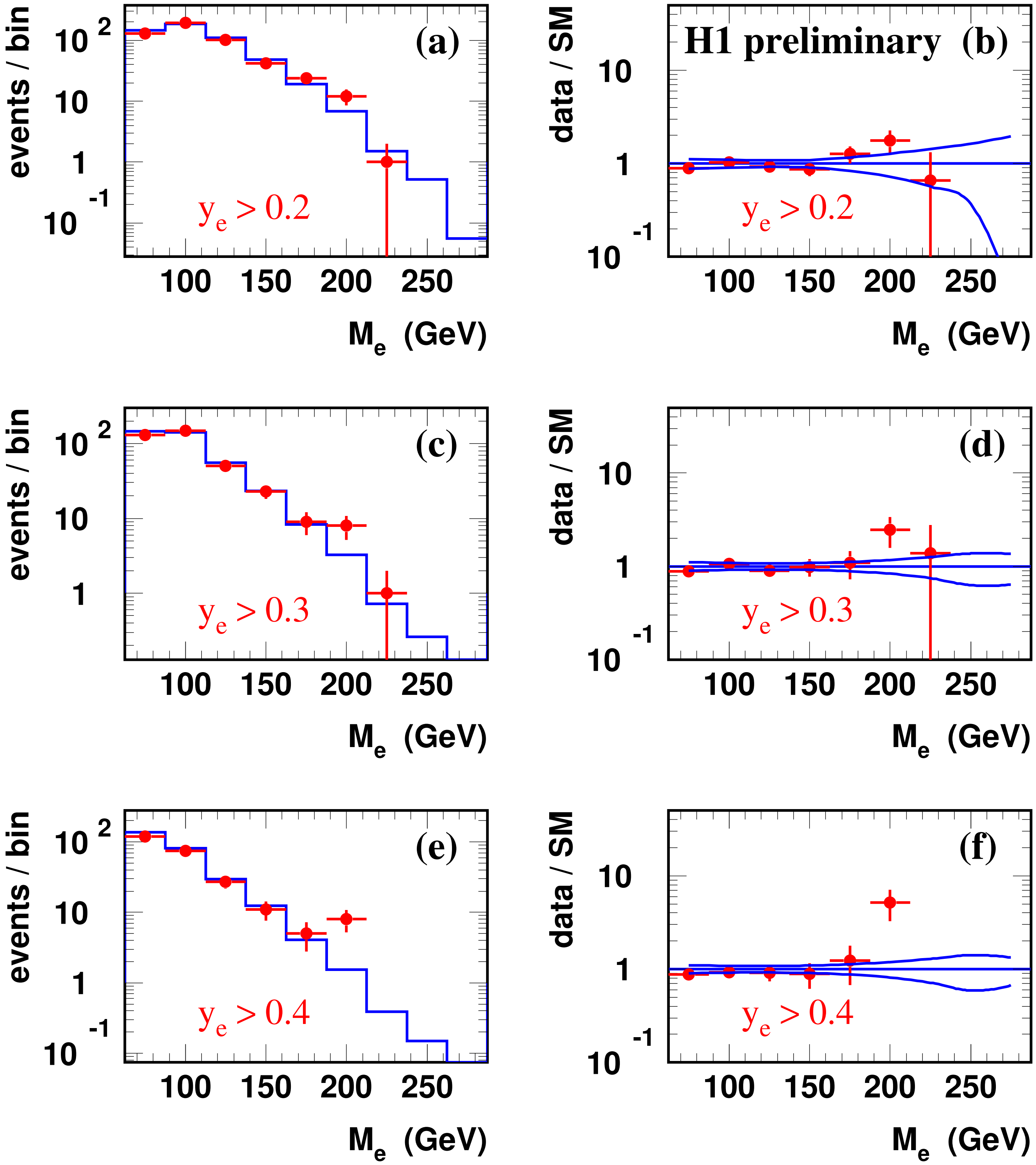
H1 Preliminary




- Error combination assumes Gaussian systematics and Poisson distributed $N_{obs}$.
- Corrected (assuming NC DIS Standard Model) for migrations due to real QED emission, acceptance and resolution $\rightarrow$ the $Q^2$ scale = true hard scale from exchanged EW bosons.

# H1 Preliminary

## Mass Dependence




The basic observations remain:

- Excess seen at highest mass
- More visible at large $y_e$

# H1 Preliminary

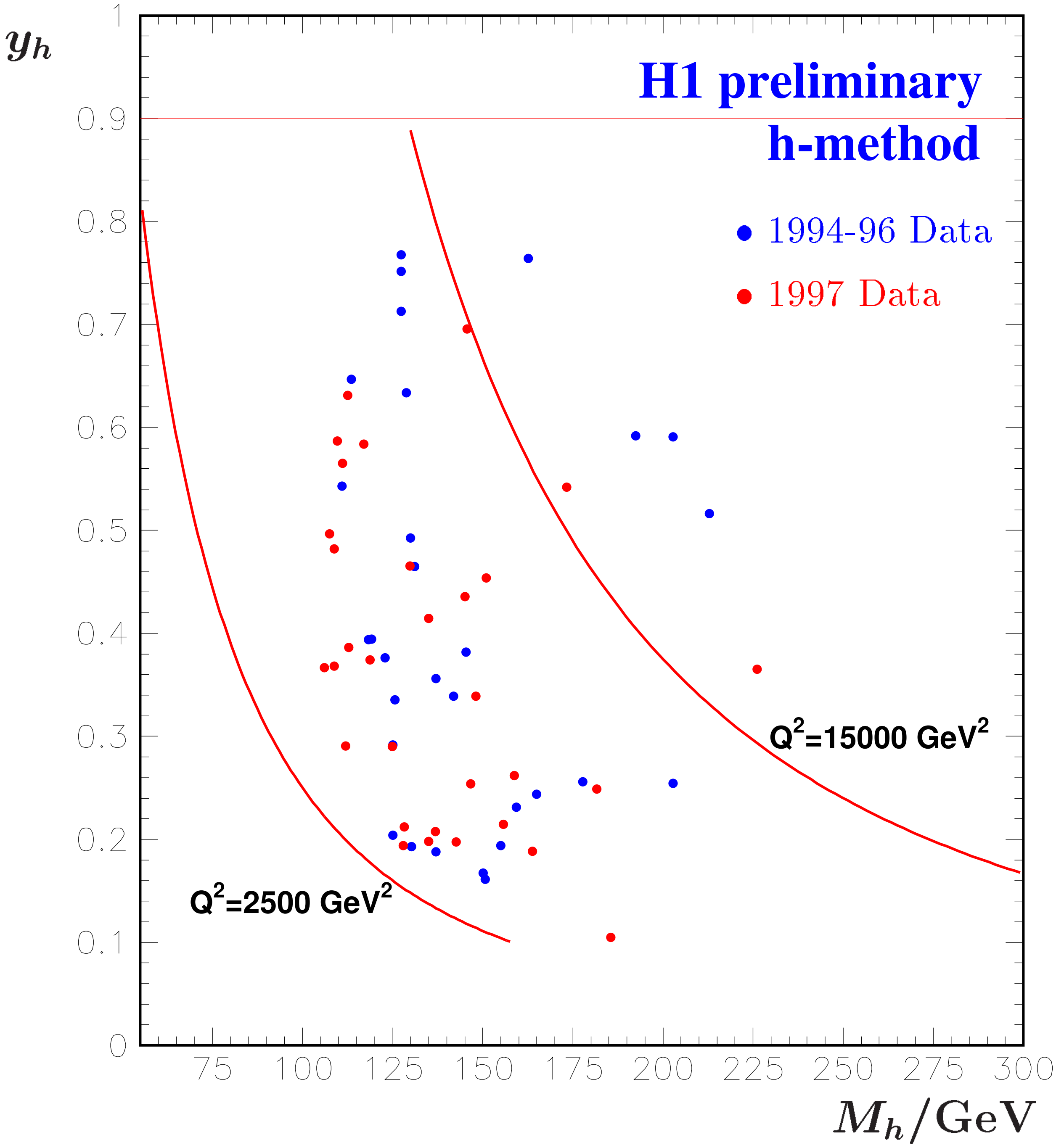
## Mass Windows

| 1994 - 1996 Data, $y_e > 0.4$, $M_e = 200$ GeV | | | | |
|---|---|---|---|---|
| $\Delta M_e$ ( GeV) | 20 | 25 | 30 | 40 |
| $N_{obs}$ | 5 | 7 | 7 | 7 |
| $N_{DIS}$ | 0.63 $\pm 0.13$ | 0.95 $\pm 0.18$ | 1.10 $\pm 0.19$ | 1.57 $\pm 0.28$ |
| $\bar{\mathcal{P}}(N \geq N_{obs})$ | $5.0 \cdot 10^{-4}$ | $2.6 \cdot 10^{-4}$ | $2.5 \cdot 10^{-4}$ | $1.6 \cdot 10^{-3}$ |
| 1994 - 1997 Data, $y_e > 0.4$, $M_e = 200$ GeV | | | | |
| $\Delta M_e$ ( GeV) | 20 | 25 | 30 | 40 |
| $N_{obs}$ | 6 | 8 | 8 | 9 |
| $N_{DIS}$ | 1.01 $\pm 0.21$ | 1.53 $\pm 0.29$ | 1.75 $\pm 0.32$ | 2.54 $\pm 0.49$ |
| $\mathcal{P}(N \geq N_{obs})$ | $9.1 \cdot 10^{-4}$ | $3.3 \cdot 10^{-4}$ | $7.3 \cdot 10^{-4}$ | $2.2 \cdot 10^{-3}$ |
| 1994 - 1997 Data, $M_e > 180$ GeV | | | | |
| $y_{min}$ | 0.2 | 0.3 | 0.4 | 0.5 |
| $N_{obs}$ | 18 | 11 | 9 | 7 |
| $N_{DIS}$ | 12.9 $\pm 3.58$ | 6.1 $\pm 1.04$ | 2.96 $\pm 0.52$ | 1.73 $\pm 0.27$ |
| $\mathcal{P}(N \geq N_{obs})$ | 0.18 | $6.1 \cdot 10^{-2}$ | $5.3 \cdot 10^{-3}$ | $2.6 \cdot 10^{-3}$ |

- Lower rate of entries at large $y_e$ around $M_e \sim 200$ GeV in 1997
  $\Rightarrow$ slighly decreased significance.

# H1 Preliminary

## CC Data Sample in the $M$-$y$ Plane



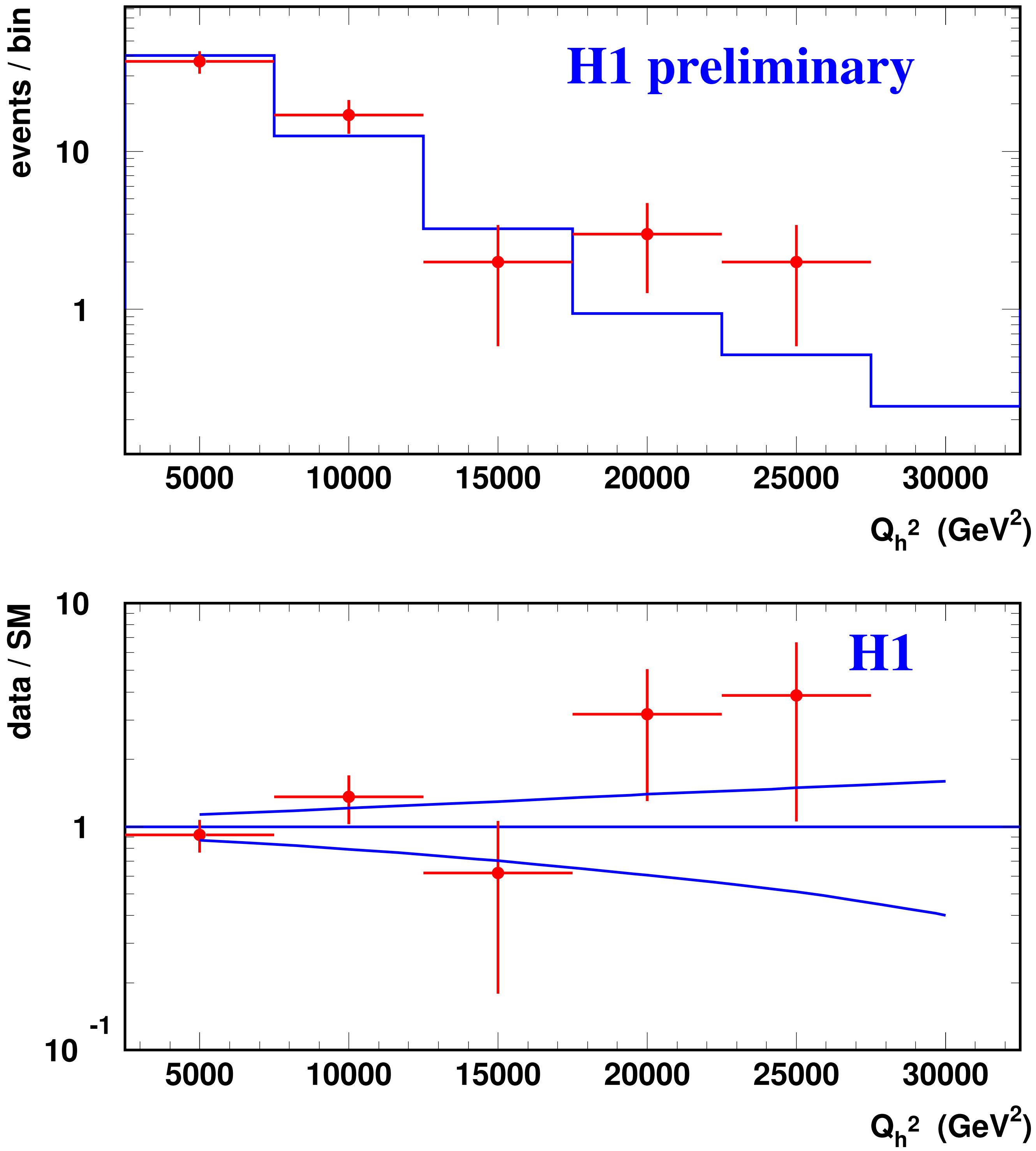

$y_h < 0.9 \quad \mathcal{L} = 23.69 \pm 0.35 \text{ pb}^{-1}$

- $Q_h^2 > 2500 \text{ GeV}^2$ Obs. $= 61 \Leftrightarrow$ Exp. $= 56.3 \pm 9.4$
- $Q_h^2 > 15000 \text{ GeV}^2$ Obs. $=6 \Leftrightarrow$ Exp. $= 2.9 \pm 1.4$

Efficiency of geometrical acceptance & event selection: $\sim 80\ \%$
(kinematics from the hadrons, for events generated within the measured kinematical range)

H1 Preliminary

## CC $Q^2$ Dependence




Slight excess of events observed at high $Q_h^2$

# H1 Preliminary

## CC $Q^2$ Dependence

| 1994 - 1996 Data | | | | | |
|---|---|---|---|---|---|
| $Q^2_{\text{min}}/\ \text{GeV}^2$ | 2500 | 5000 | 10000 | 15000 | 20000 |
| $N_{obs}$ | 31 | 24 | 10 | 4 | 3 |
| $N_{DIS}$ | 34.2 $\pm5.8$ | 21.1 $\pm4.2$ | 5.07 $\pm1.88$ | 1.77 $\pm0.87$ | 0.74 $\pm0.39$ |
| $\mathcal{P}(N \geq N_{obs})$ | 0.64 | 0.31 | $7 \cdot 10^{-2}$ | 0.14 | $5.4 \cdot 10^{-2}$ |
| **1994 - 1997 Data** | | | | | |
| $Q^2_{\text{min}}/\ \text{GeV}^2$ | 2500 | 5000 | 10000 | 15000 | 20000 |
| $N_{obs}$ | 61 | 43 | 13 | 6 | 4 |
| $N_{DIS}$ | 56.3 $\pm9.4$ | 34.7 $\pm6.9$ | 8.33 $\pm3.10$ | 2.92 $\pm1.44$ | 1.21 $\pm0.64$ |
| $\mathcal{P}$ | 0.34 | 0.18 | 0.16 | 0.13 | $5.7 \cdot 10^{-2}$ |

$\mathcal{P} \equiv \mathcal{P}(N \geq N_{\text{obs.}})$

- Good agreement up to $Q^2_{\text{min}} = 10000\ \text{GeV}^2$ with CC DIS Standard Model
- The significance of the deviations remains with 1997 data above $Q^2_{\text{min}} = 10000\ \text{GeV}^2$

# Summary

## On Structure Fonctions: (preliminary results)

- A new QCD $\mathcal{F}_2$ fit performed in an extended region up to $y < 0.85$,
- $xg(x)$ extracted at $Q^2 = 5$ and $20~\mathrm{GeV}^2$, with an error half of the one of the previous measure, shows a strong rise towards low $x$,
- $\mathcal{F}_L$ has been measured following the "subtraction" method in two bins of $\langle y \rangle = 0.68, 0.82$. In the highest bin, it departs from the $\mathcal{F}_L^{QCD}$ (NLO DGLAP) calculated from the extracted PDF.

## On Very High $Q^2$ events: (preliminary results)

- The presented analysis includes 1994-1996 + early 1997 data $\Rightarrow$ 65 % increase of luminosity w.r.t. the published data.
- For $Q^2 \leq 15000~\mathrm{GeV}^2$, the $Q^2$ , $M$ and $y$ distributions are well reproduced by the expectations from standard Neutral Current and Charged Current DIS processes.
- For $Q^2 > 15000~\mathrm{GeV}^2$:
  18 Neutral Current observed, for $8.00 \pm 1.16$ expected,
  i.e. $\mathcal{P}(N \geq N_{obs}) = 3.4 \times 10^{-3}$; **the significance increased!!**

  A slight excess is also observed for Charged Currents.
- Preliminary values for integrated cross section at the born level is given: $\sigma(Q^2 > 15000~\mathrm{GeV}^2) = 0.93^{+0.32}_{-0.24}$ (0.49 predicted)
- The excess of observed NC events is the most prominent in a mass window of $M = 200~\mathrm{GeV} \pm 12.5~\mathrm{GeV}$. For $y > 0.4$, slighly decreased significance: 8 NC events observed for $1.53 \pm 0.29$ expected

Despite numerous publications no clean mecanism was yet found to explain the excess observed in the framework of the SM...

# Prospects

- By the end of 1997 running (October):

$$\mathcal{L}_{1997} \sim \mathcal{L}_{1994\text{-}1966}$$

- 1998-1999: $e^- p$ collisions

$\Rightarrow$ Increased production of CC DIS events

$\Rightarrow$ Test invariance of the results w.r.t. quark flavour.

- 2000+: upgrade of HERA:
  - Increase of luminosity by $\sim 7$
  - possibility to run with polarized $e^{\pm}$ beams.

# Influence of Initial State Radiation