Dedicated to the memory of Bjoern Wiik

ep Cross Sections and Proton Structure Functions at HERA

Bruno Stella

(Roma III Univ. and INFN)

on behalf of

H1

ZEUS

Les Rencontres de Physique de la Valle'e d'Aoste

RESULTS AND PERSPECTIVES IN PARTICLE PHYSICS

LaThuile,2 March 1999

Selected results on e^+p, e^-p DIS

Introduction '94 – '97 :

$F_2(x, Q^2)$

The longitudinal structure function F_L

Charm contribution to F_2 (F^c)

Gluon density in the proton

High Q^2 Neutral Currents interactions

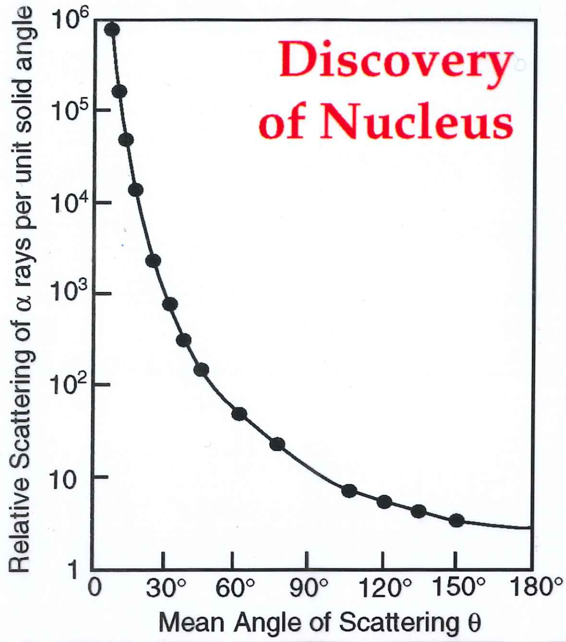
High Q^2 Charged Currents interactions

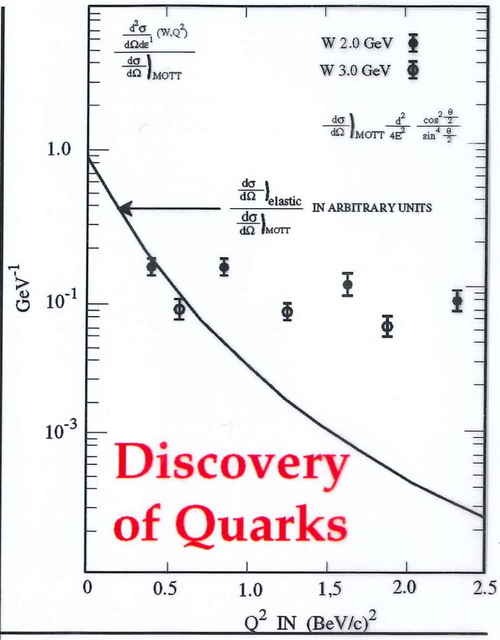
Running '98 – '99

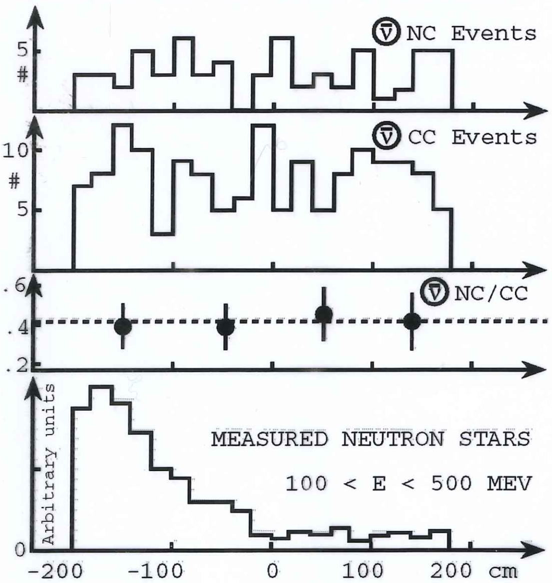
Future of HERA

D.I.S.covery Potential

- Historical Perspective

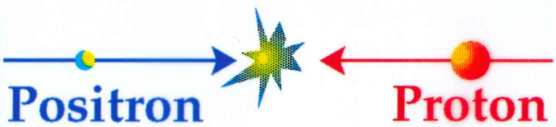






Discovery of Neutral Currents

HERA

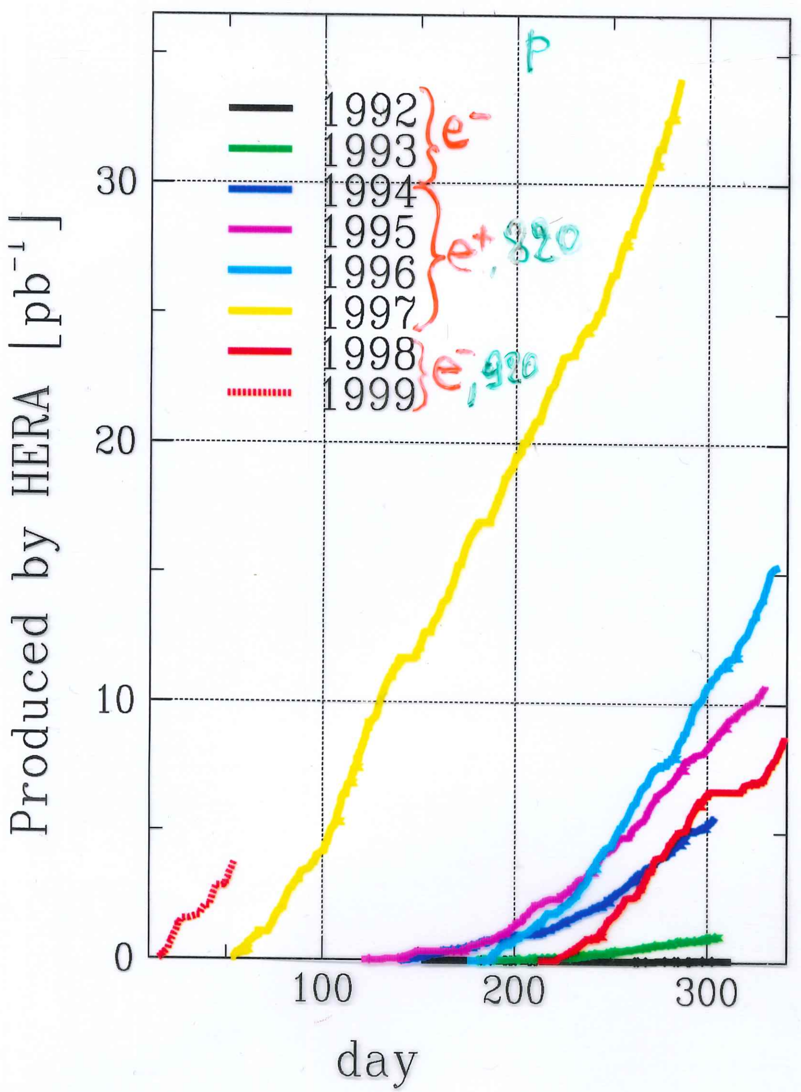


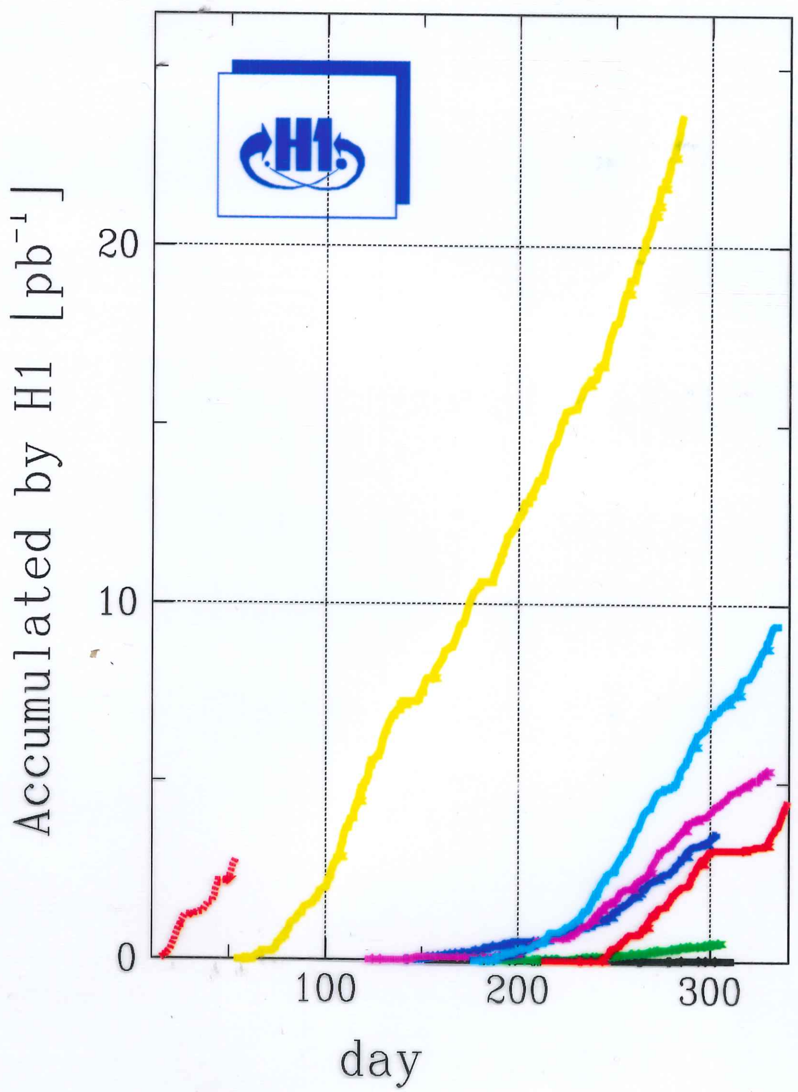
Positron 27.5 GeV	**Proton** 820 GeV
Electron 27.5 GeV	**Proton** 920 GeV

'98
'99

Geiger and Marsden; Proc. Roy. Soc. lxxxii P. 495 (1909)
Friedman, Kendall, Taylor; Rev. Mod. Phys. 63(3) (1991)

INTEGRATED LUMINOSITY



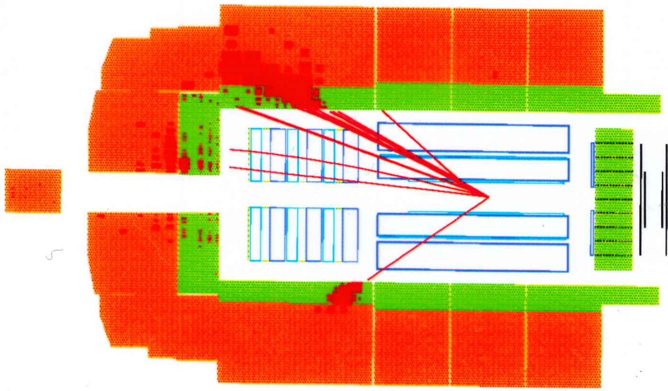


H1 Detector

Neutral Current Event: $e^+p \to e^+X$

$Q^2 = 17000\,\mathrm{GeV}^2,\ x = 0.43,\ E'_e = 170\,\mathrm{GeV}$

$e^+ \to$



$\leftarrow p$

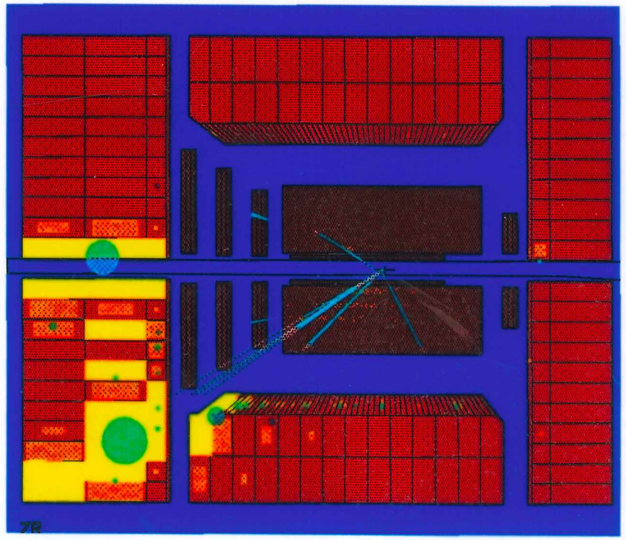
Liquid Argon Calorimeter
44000 Cells
σ_{θ_e} = 2-5 mrad
$\sigma/\sqrt{E}$ (e) = 12 %
$\sigma/\sqrt{E}$ (had) = 50 %
$\Delta E/E$ (syst) ±3 %

ZEUS Detector

Charged Current Event: $e^+p \to \bar{\nu}X$

$Q^2 = 17\,200\,\mathrm{GeV}^2,\ x = 0.34,\ p_t = 86\,\mathrm{GeV}$

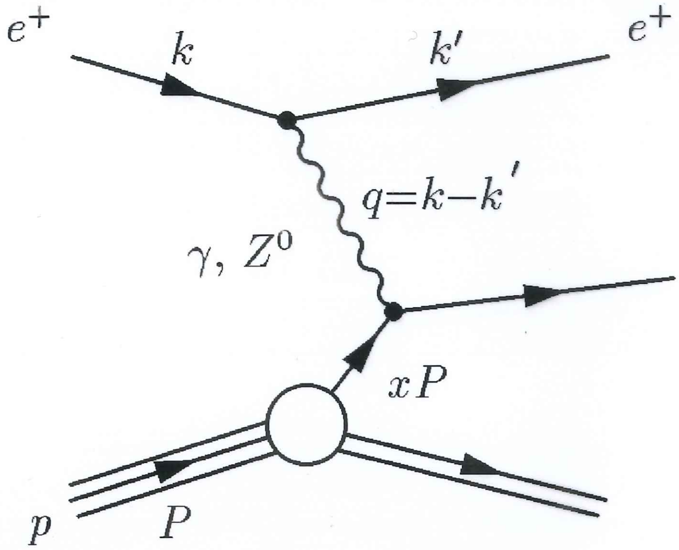
$e^+ \to$



$\leftarrow p$

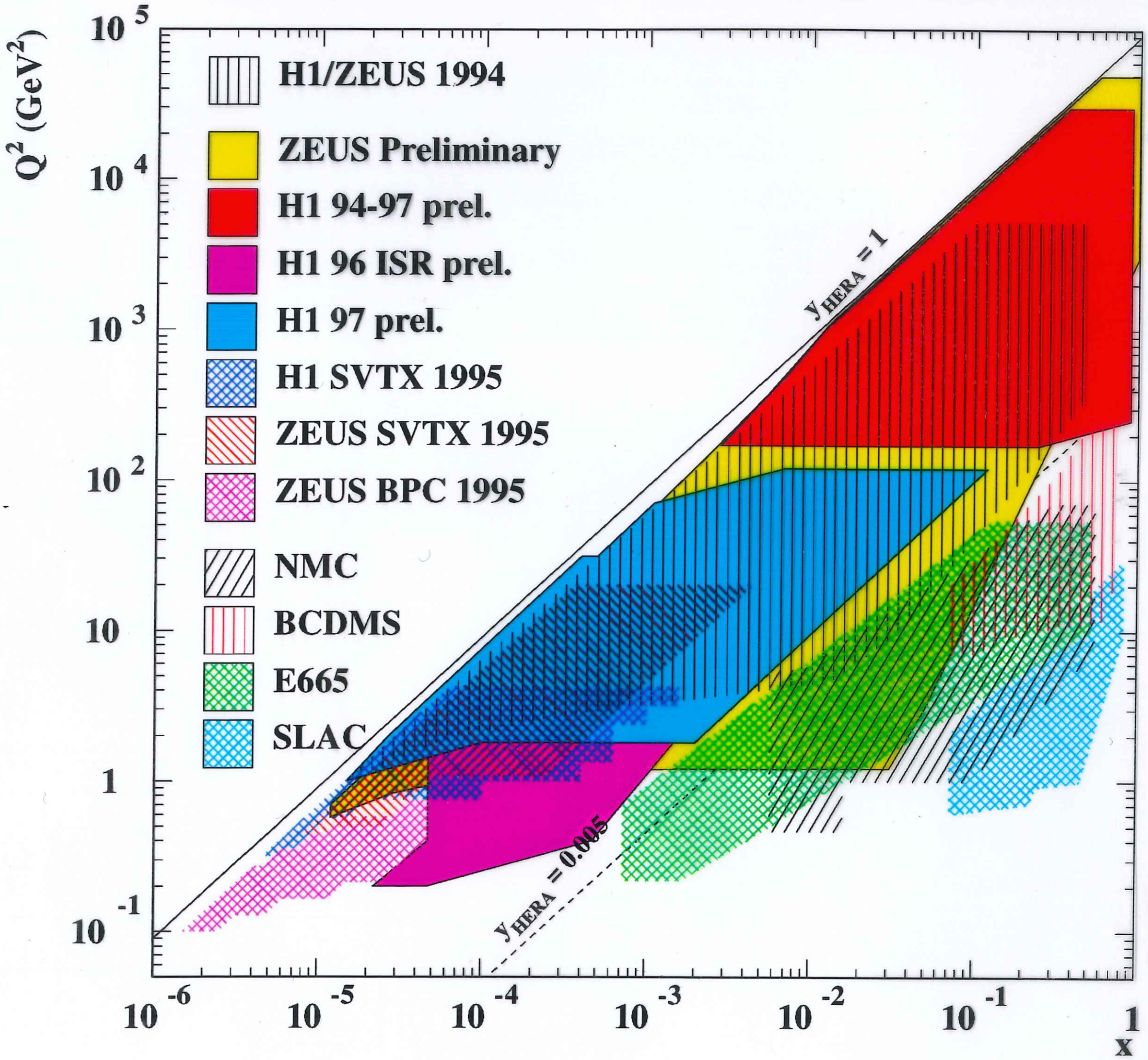
Uranium-Scintillator Calorimeter
6000 Cells, each read out by 2 PMTs
σ_{θ_e} = 5 mrad
$\sigma/\sqrt{E}$ (e) = 18 %
$\sigma/\sqrt{E}$ (had) = 35 %
$\Delta E/E$ (syst) = 3 %

DIS Kinematics



- $Q^2 = -q^2 = -(k-k')^2$
  4-momentum transfer squared
- $x = Q^2/(2P \cdot q)$
  parton momentum fraction
- $y = (P \cdot q)/(P \cdot k)$
  inelasticity
- $s = (k+P)^2$
  total energy squared
- $W^2 = (P+q)^2$
  hadronic mass squared
- $Q^2 \approx sxy$ Quasi-two body Kin.: only 2 indep. var.

HERA Kinematic Range



$Q^2 \to 0$:	transition to γp
$Q^2 \to s$:	electro-weak unification, substructure
$y \to 1$:	sensitivity to F_L
$y \to 0.005$:	overlap with fixed target experiments
$x \to 1$:	probe valence quarks at high Q^2

Probe proton structure down to $\boxed{1/1000}$ r_p

(Q^2 > 40.000 GeV^2)

and at very high number of partons for very short time

(very high $1/x$)

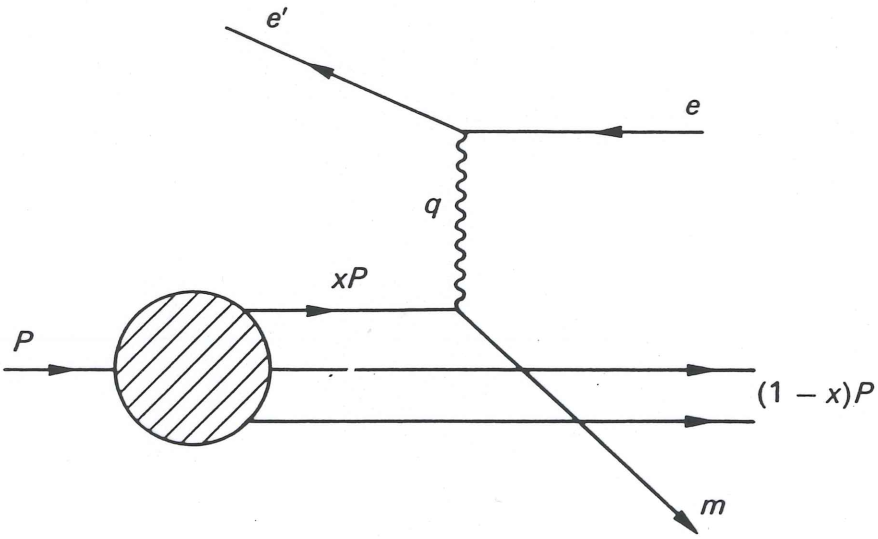
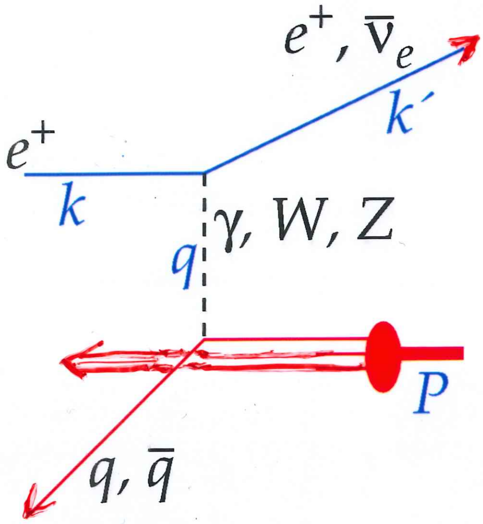


Figure 8.9 The parton model of a deep-inelastic collision.

$$F_2^{NC}$$

NC

Formalism



$$Q^2 = -q^2 \qquad x = \frac{Q^2}{2P\cdot q}$$

$$y = \frac{P\cdot q}{P\cdot k} \qquad W^2 = (P+q)^2$$

$$Q^2 = sxy$$

$$\frac{d^2\sigma(l^\pm N)}{dx\, dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\cdot [Y_+ F_2^{lN}(x,Q^2) - Y_- xF_3^{lN}(x,Q^2) - y^2 F_L^{lN}(x,Q^2)]\ \mathbf{(1+\delta_r)}$$

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

- Contribution from F_L^{lN} important only at large y
- Contribution from xF_3^{lN} is negligible for $Q^2 << M_Z^2$
- Either F_L^{lN} and xF_3^{lN} treated as QCD corrections
- Or reduced cross section:

$$\tilde{\sigma}(e^+p) \equiv \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma(e^+p)}{dxdQ^2} = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

In QPM (QCD DIS scheme),

$$F_2^{lN}(x,Q^2) = \sum_i e_i^2 x[q_i(x,Q^2) + \bar{q}_i(x,Q^2)]$$

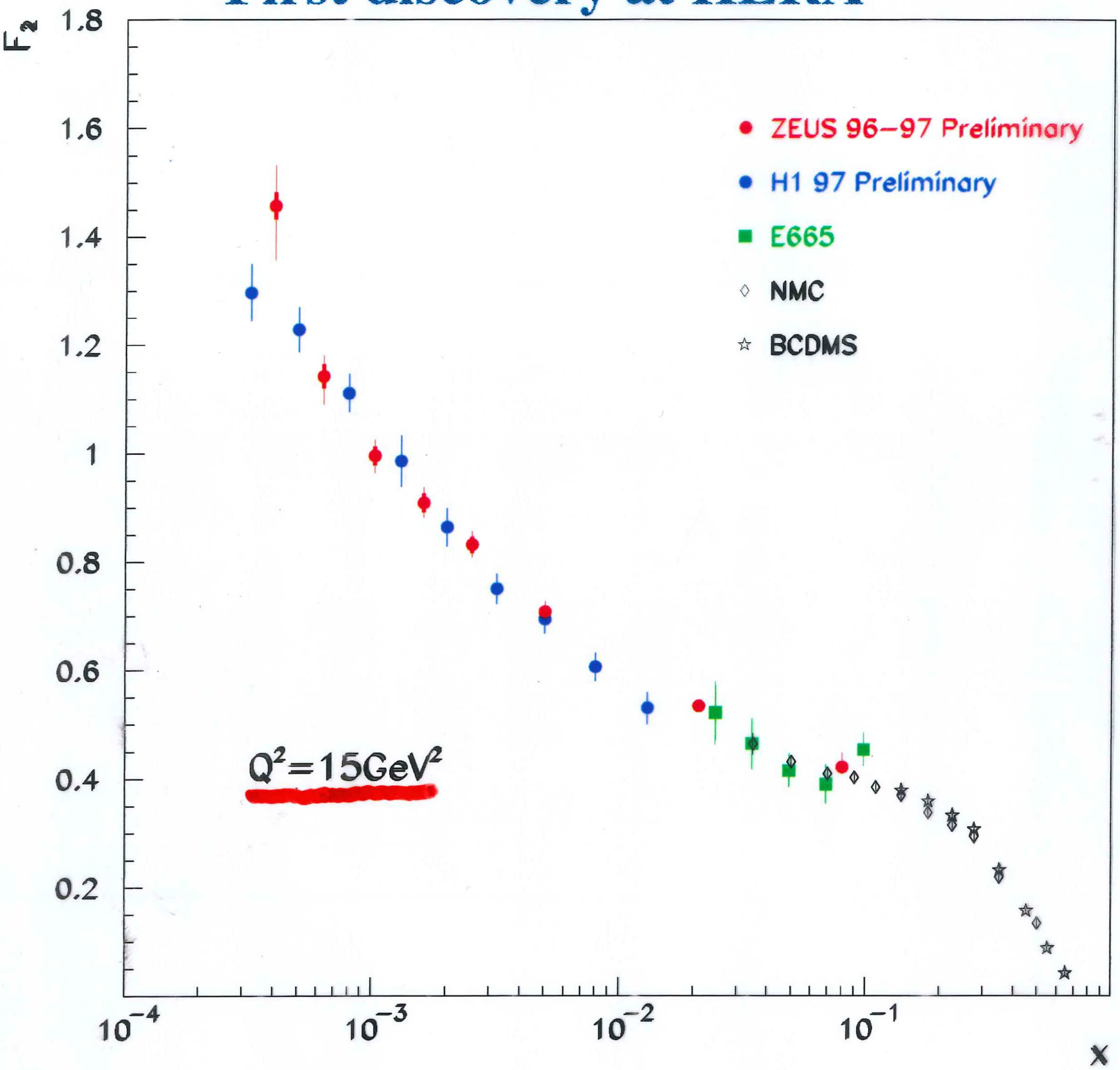
Measurement of Kinematics

- measure: $E'_e, E_h, \theta_e, \theta_h$ 2 needed
- calculate: x, Q^2

- **Electron Method (H1):**
  - x, Q^2 from E_e, θ_e
  - good Q^2 resolution in full range
  - $\delta x/x = 1/y \cdot \delta E'_e/E'_e$
    poor x resolution at low y
  - sensitive to QED radiation
- **Σ Method (H1):**
  - include hadronic information
  - good x resolution also at low y
  - independent of QED initial state radiation
- **Double Angle Method (ZEUS):**
  - x, Q^2 from θ_e, θ_h
  - independent of energy scale $\Rightarrow$ use for calibration
  - sensitive to QED radiation

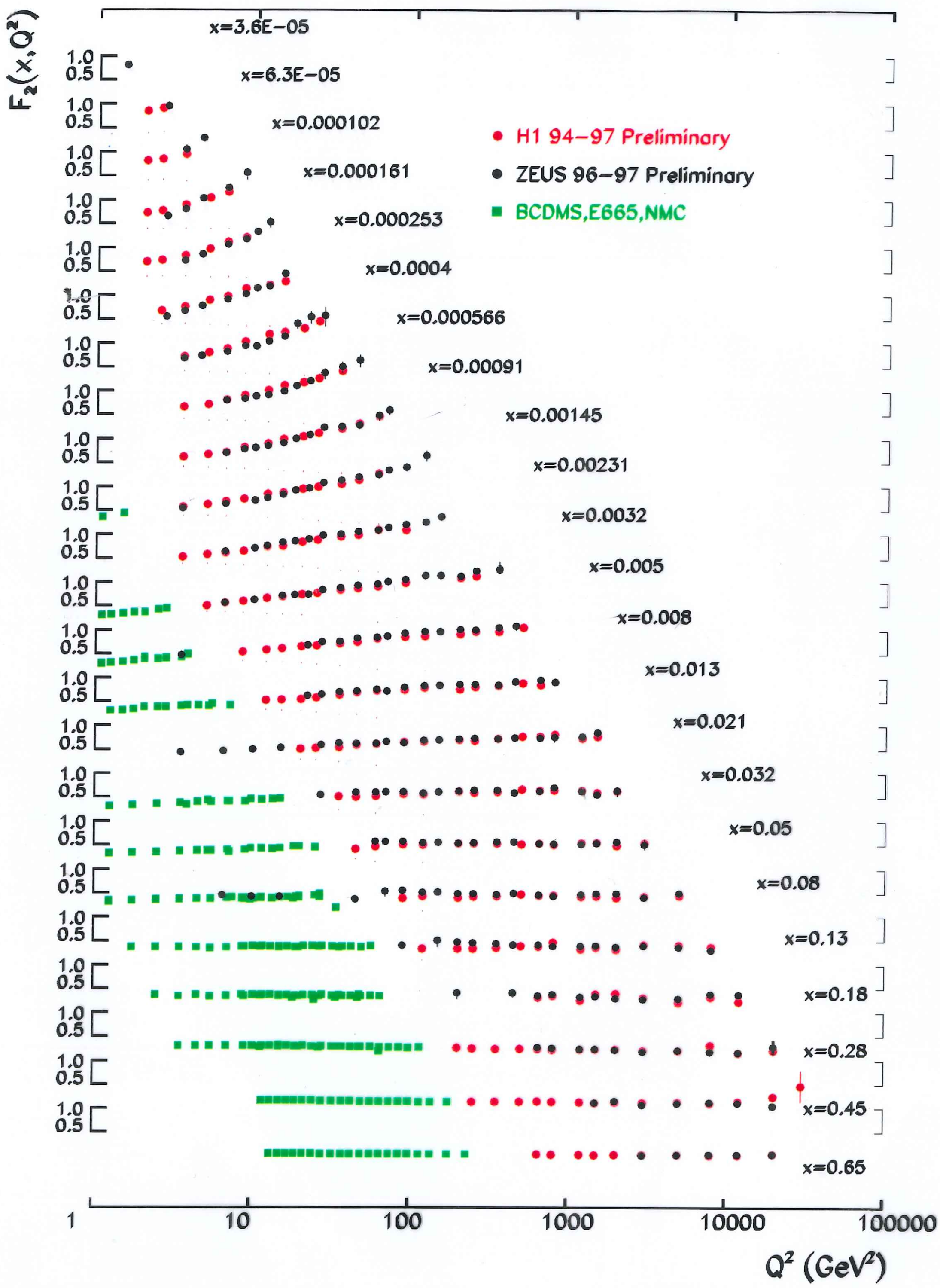
$F_2(x)$ by ZEUS + H1 at medium Q^2

First discovery at HERA



- H1 and ZEUS **agree** well
- **Precision** improved by a factor 2
- **Fixed target:** high x : valence quark structure
- **HERA:** low x : strong rise of $F_2 \sim x^{-\lambda(Q^2)}$

F_2 vs Q^2

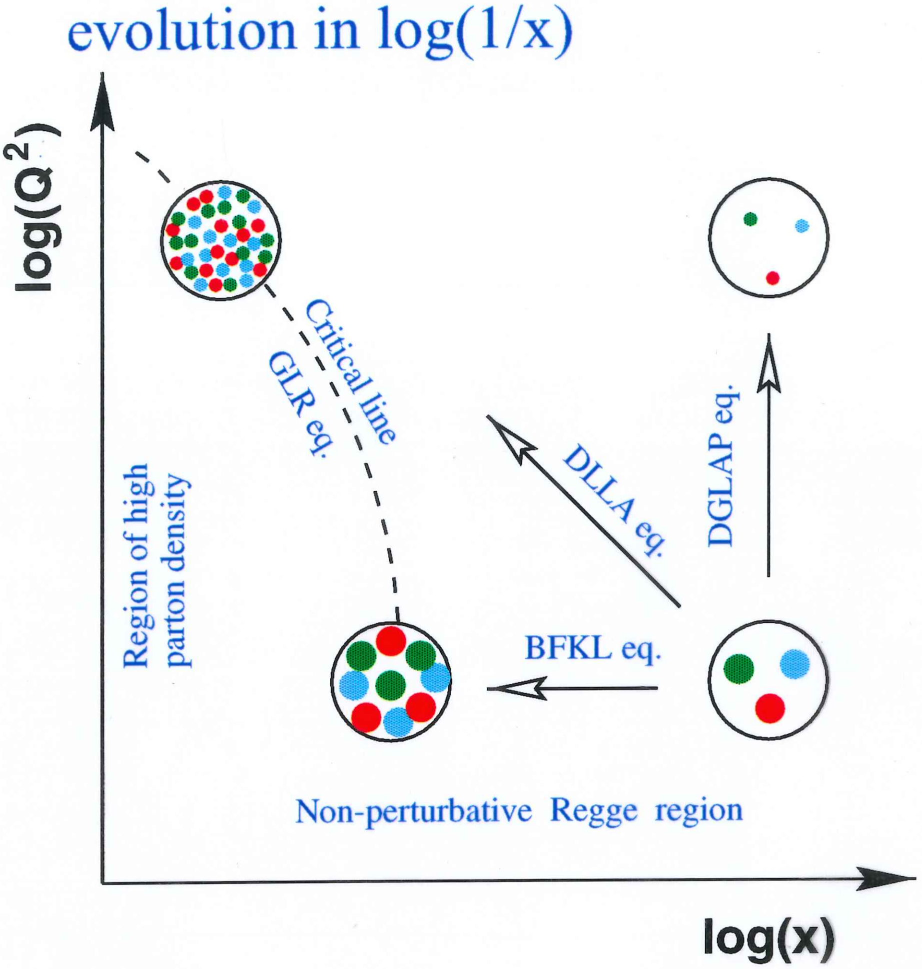


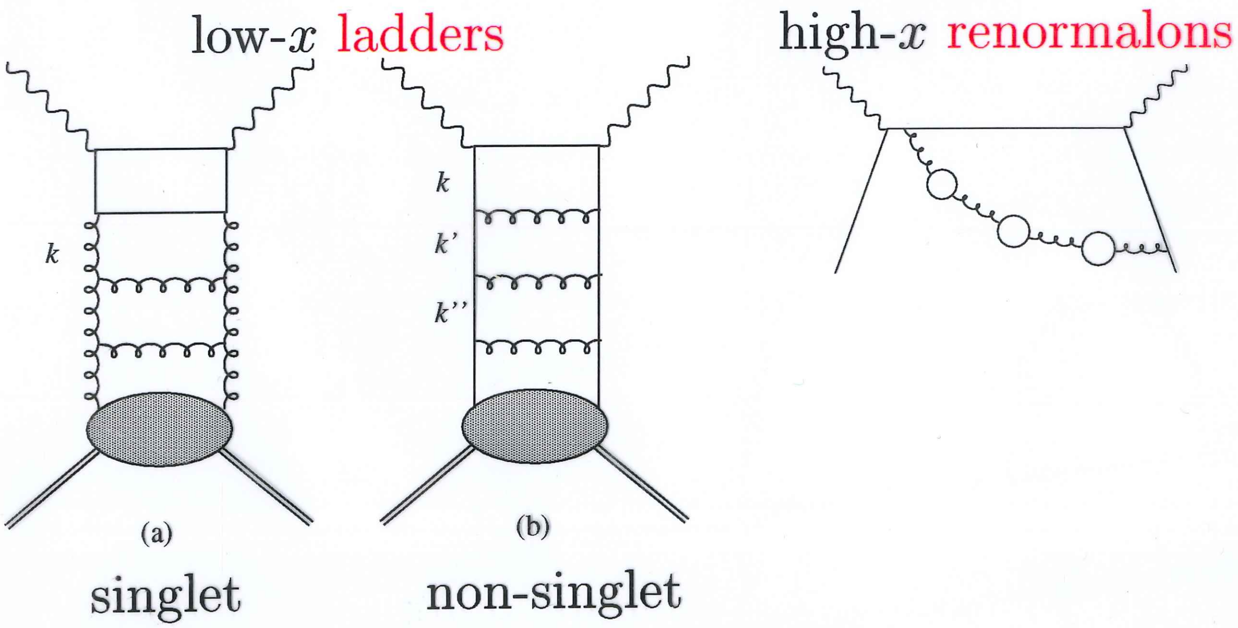
$F_2(x,Q^2)$
x=3.6E-05
x=6.3E-05
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.000566
x=0.00091
x=0.00145
x=0.00231
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.28
x=0.45
x=0.65
H1 94-97 Preliminary
ZEUS 96-97 Preliminary
BCDMS,E665,NMC
1.0
0.5
1
10
100
1000
10000
100000
Q^2 (GeV^2)

Low-x Road Map

- Theoretical Expectations

- High Gluon Density Regime
- Importance of NLO BFKL ?





DGLAP Equations

- NLO $\overline{\text{MS}}$:

$$F_2(x,Q^2) = \sum_{i=1}^{n_f} [e_i^2 C_q \otimes x(q_i + \overline{q_i}) + C_g \otimes xg]$$

- describe evolution of parton densities $q^{NS}(x,Q^2)$, $q^{SI}(x,Q^2)$, $x\,g(x,Q^2)$

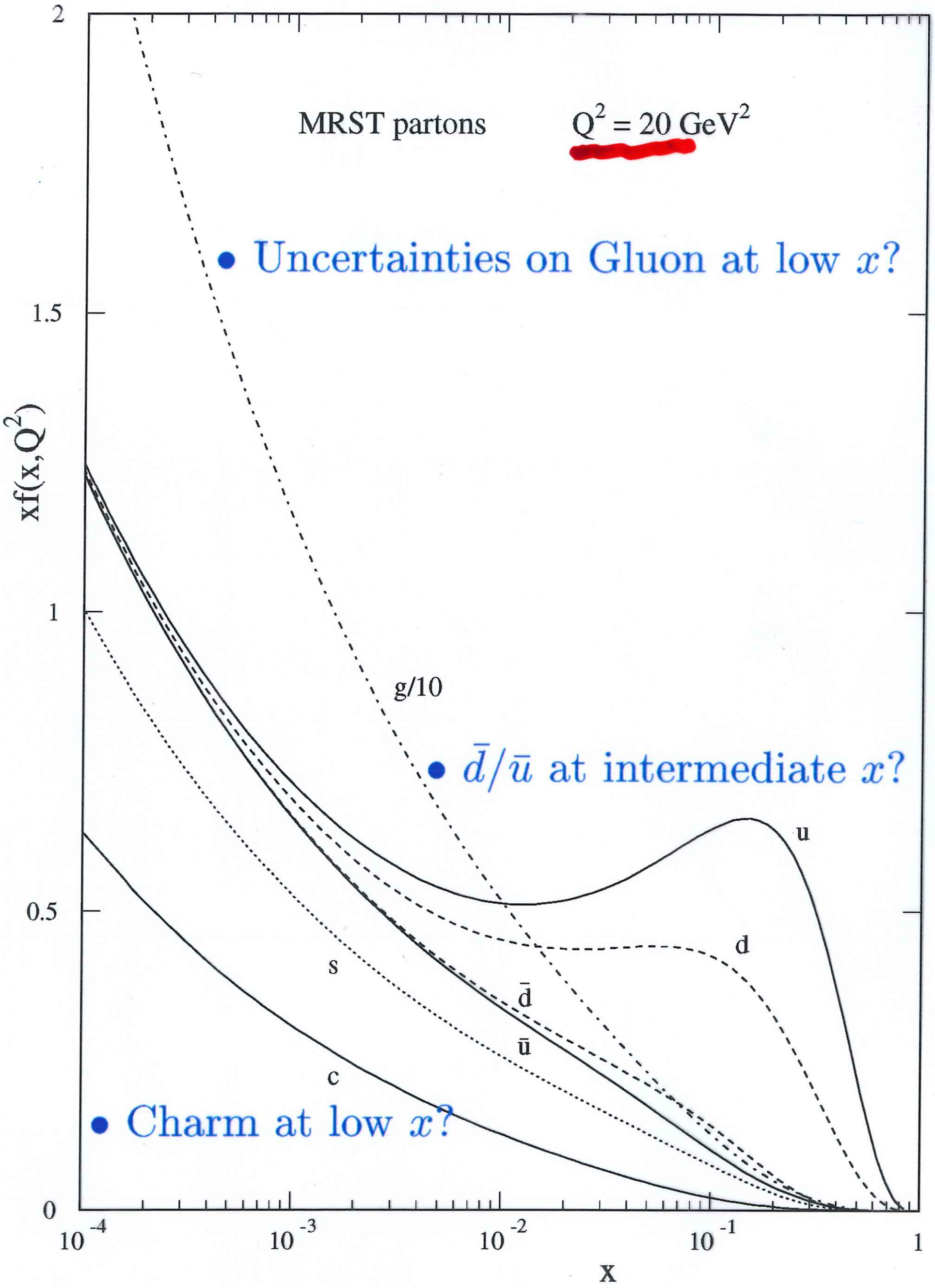
$$\frac{\partial}{\partial \ln Q^2} q^{NS} = \frac{\alpha_s}{2\pi} q^{NS} \otimes P_{qq}^{NS}$$

$$\frac{\partial}{\partial \ln Q^2} \begin{pmatrix} q^{SI} \\ xg \end{pmatrix} = \frac{\alpha_s}{2\pi} \begin{pmatrix} q^{SI} \\ xg \end{pmatrix} \otimes \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix}$$

- Coefficient and Splitting Functions C_i and P_{ij} known to NLO
- $q(x) \otimes P = \int_x^1 dz/z\; q(x/z)\; P(z)$ convolution over momentum splitting
- Q^2 depend. predicted by QCD
- x depend. parametrized at Q_0^2 + fitted

Proton Structure MRST

- Output Parton Distributions

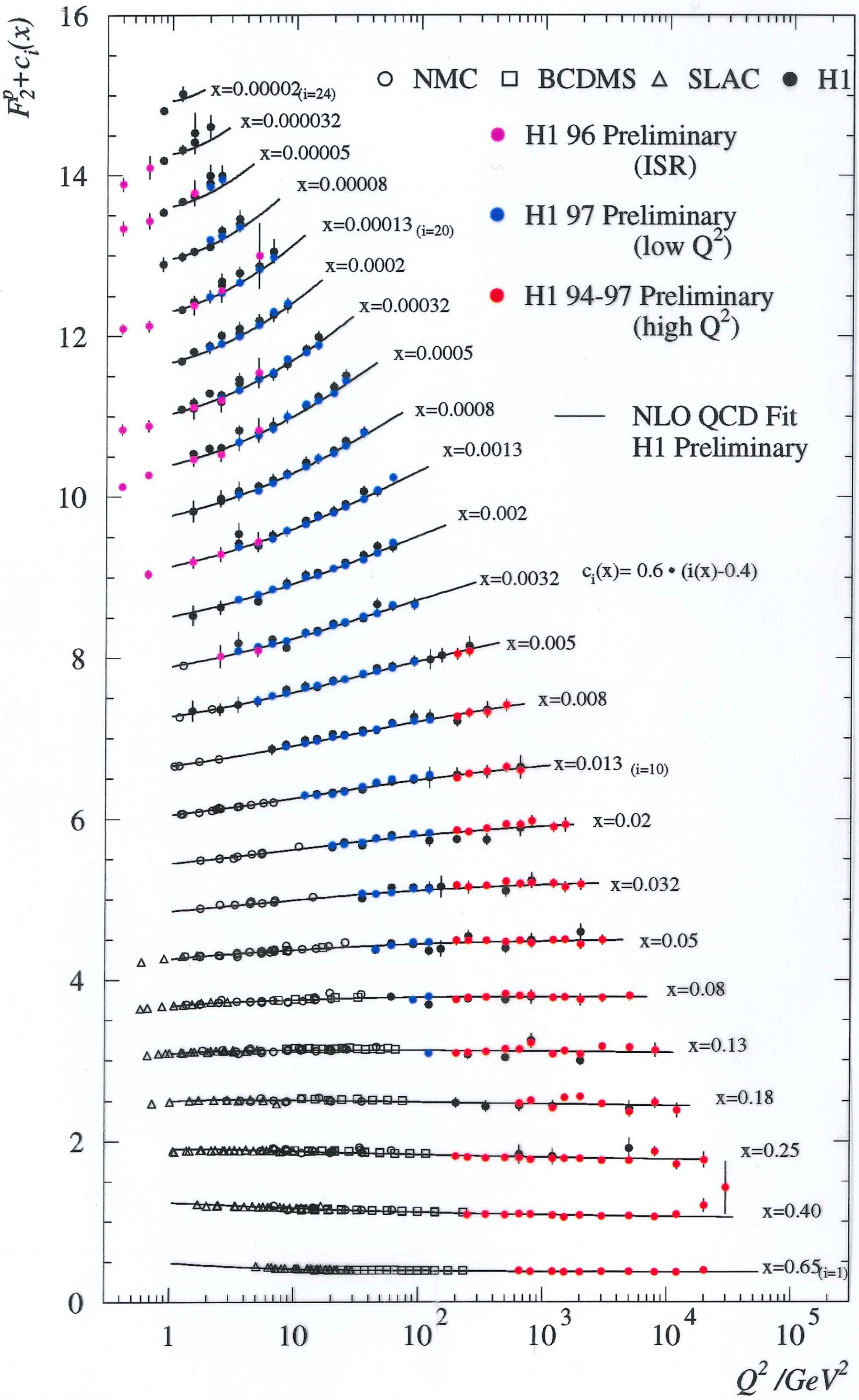


- Uncertainties on Gluon at low x?
- $\bar{d}/\bar{u}$ at intermediate x?
- Charm at low x?
- Uncertainties at Large x - HT? d/u?

▶ New Cross Section Data at Highest Q^2

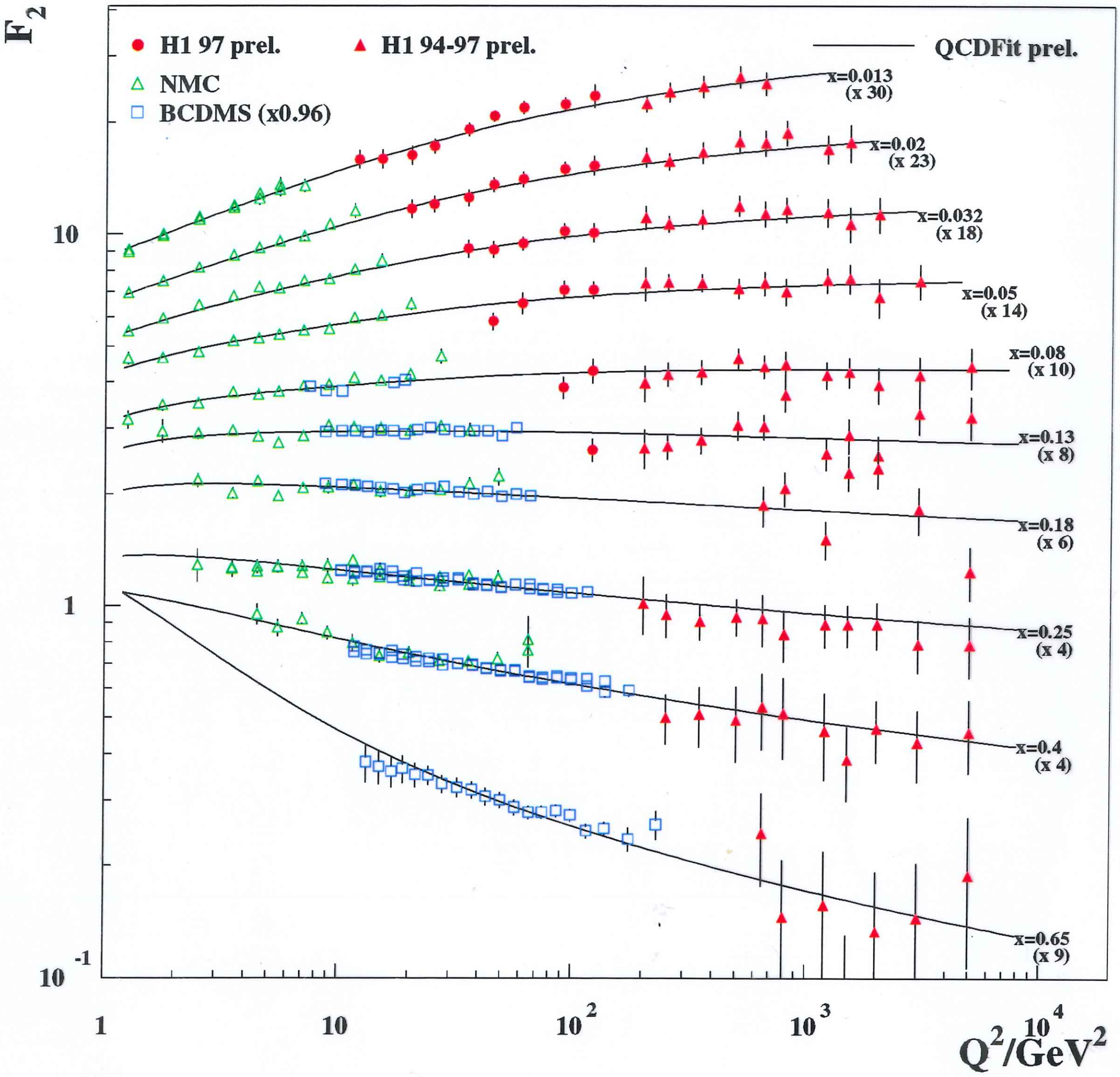
Martin, Roberts, Stirling and Thorne, hep-ph/9803445.

F_2 and perturbative QCD



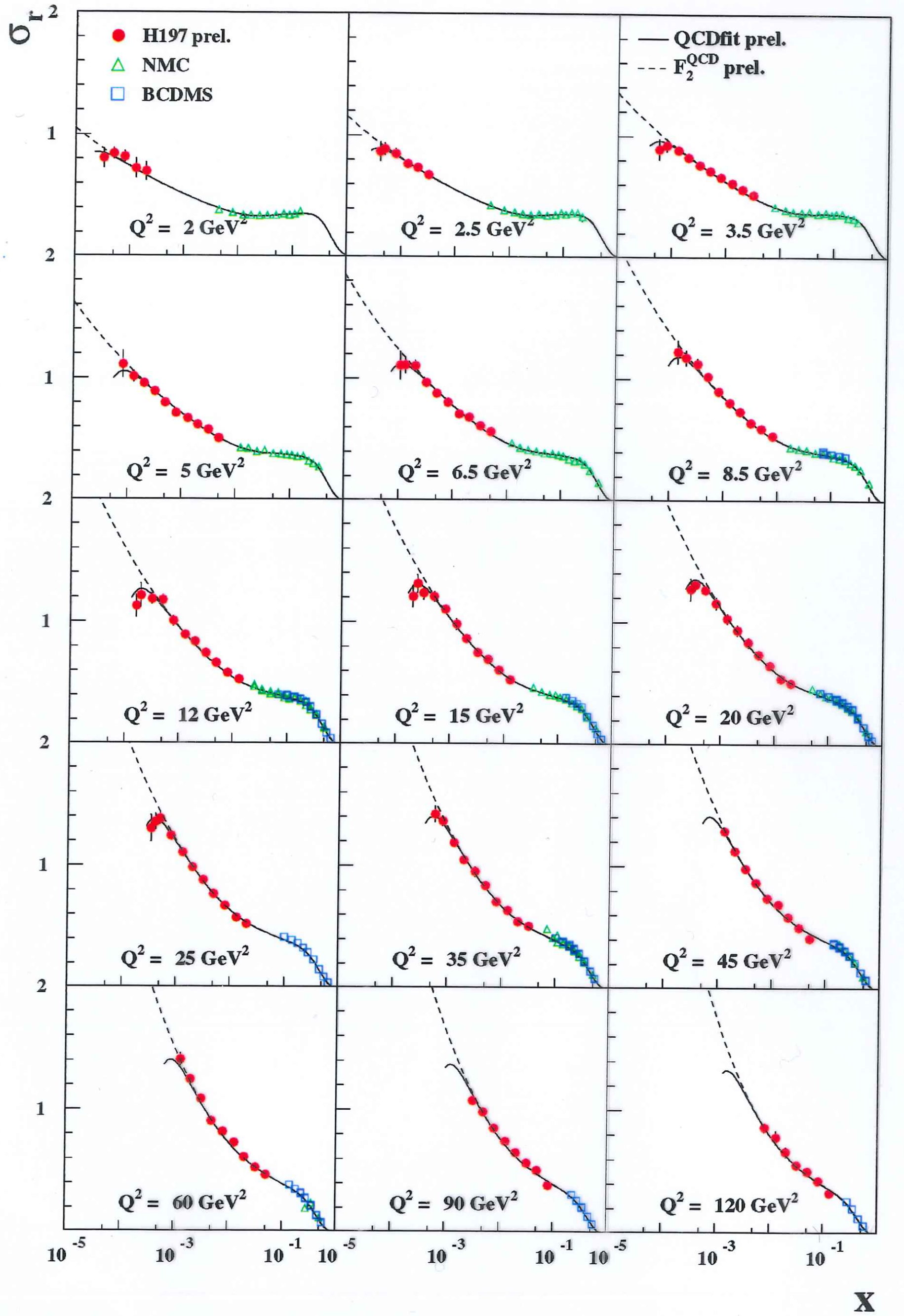
- Good description of the data by the NLO DGLAP fit over more than 4 orders of magnitude in x and Q^2

Scaling at $x \sim 0.1$



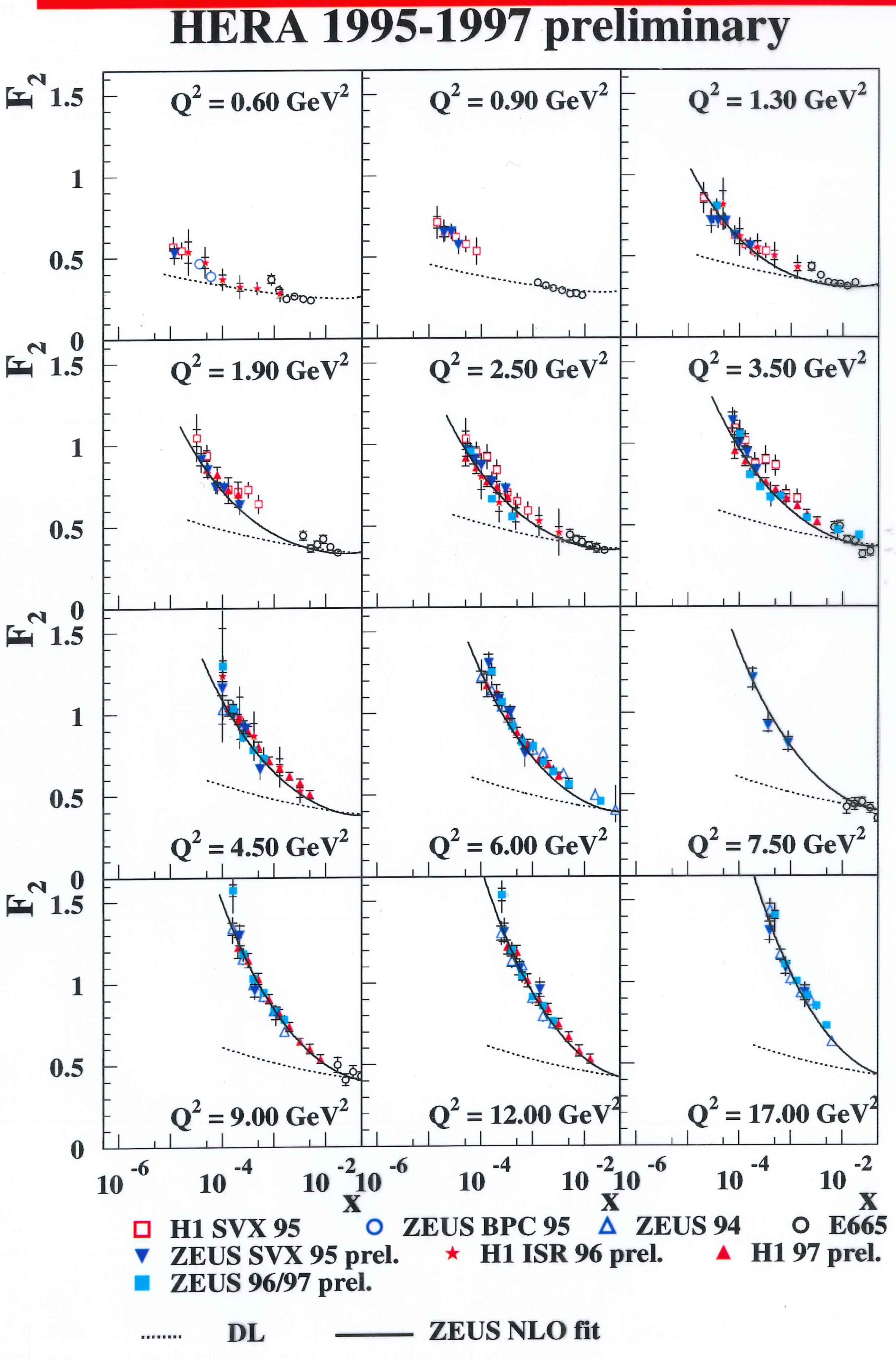
- **HERA** and fixed target experiments agree well
- **Scaling** at $x \sim 0.1$ observed up to 5000 GeV^2

QCD fit to $\sigma_r(x)$



- NLO DGLAP works down to $Q^2 \sim 2$ GeV^2
- $F_2(x) \sim x^{-\lambda}$: steepness increases with Q^2
- low x: $F_2(x)$ deviates from $\sigma_r \Rightarrow$ extract F_L

Transition Region



- New datasets using different methods give consistent results

F_L

F^{charm}

gluon $g(x, Q^2)$

F_L Extraction

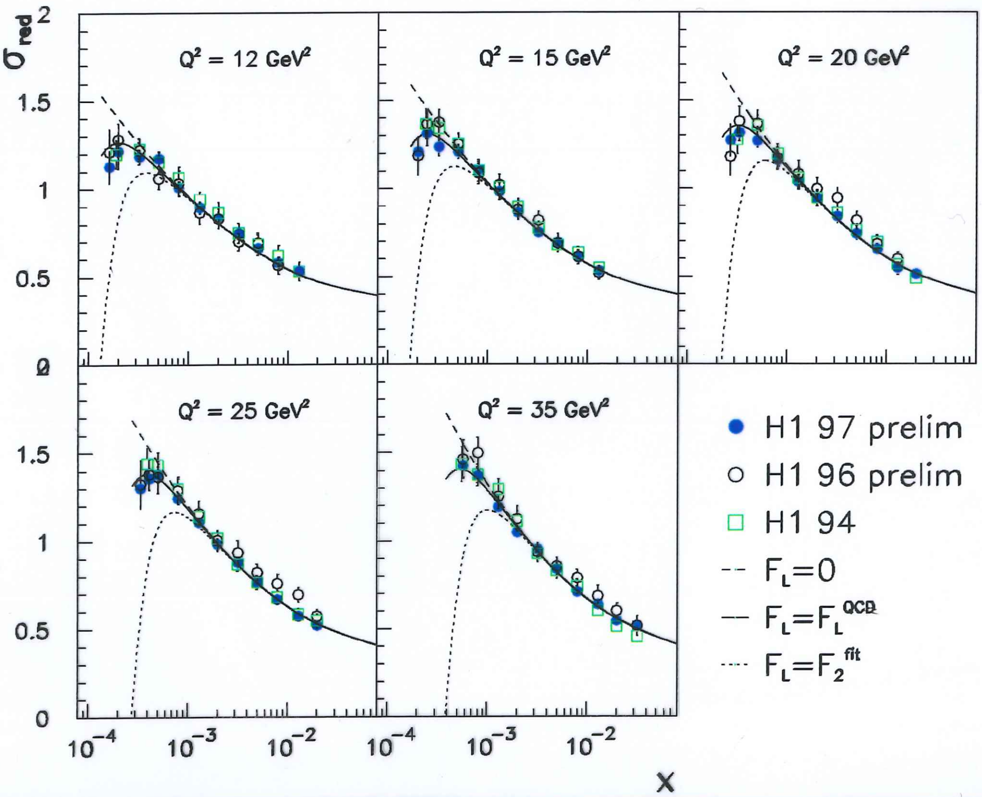
- Reduced cross section:

$$\sigma_r = \frac{1}{\kappa}\frac{d^2\sigma}{dxdQ^2} = F_2 - \frac{y^2}{Y_+}F_L$$

with $\kappa = \dfrac{2\pi\alpha^2 Y_+}{Q^4 x}$ and $Y_+ = 1 + (1-y)^2$

- **H1:**
  - QCD fit to F_2 where F_L is negligible: $y < 0.35$
  - extrapolate to high y
  - subtract measured reduced cross section:

$$F_L = \frac{Y_+}{y^2}\left(F_2^{fit} - \frac{1}{\kappa}\frac{d^2\sigma^{exp}}{dxdQ^2}\right)$$

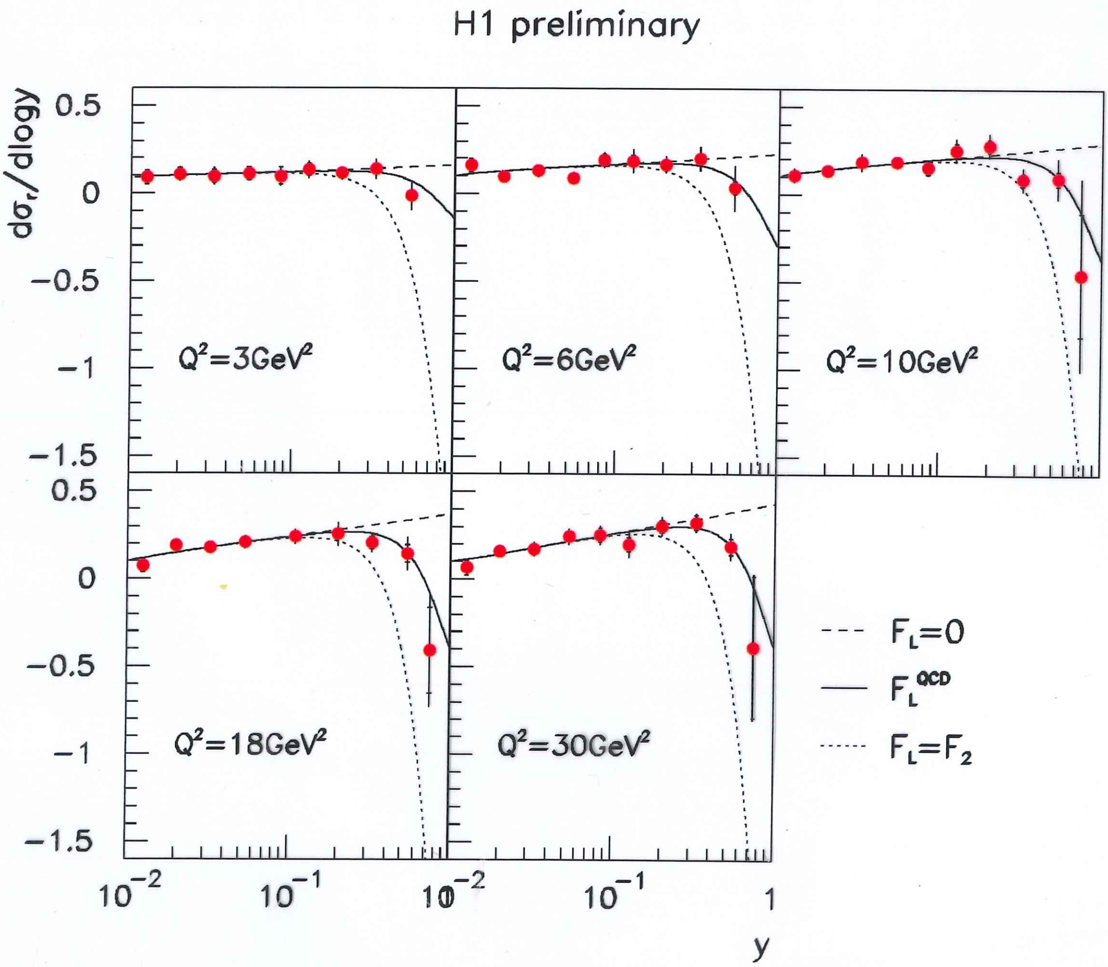


F_L from $\partial\sigma_r/\partial \ln y$

- Derive reduced cross section at fixed Q^2:

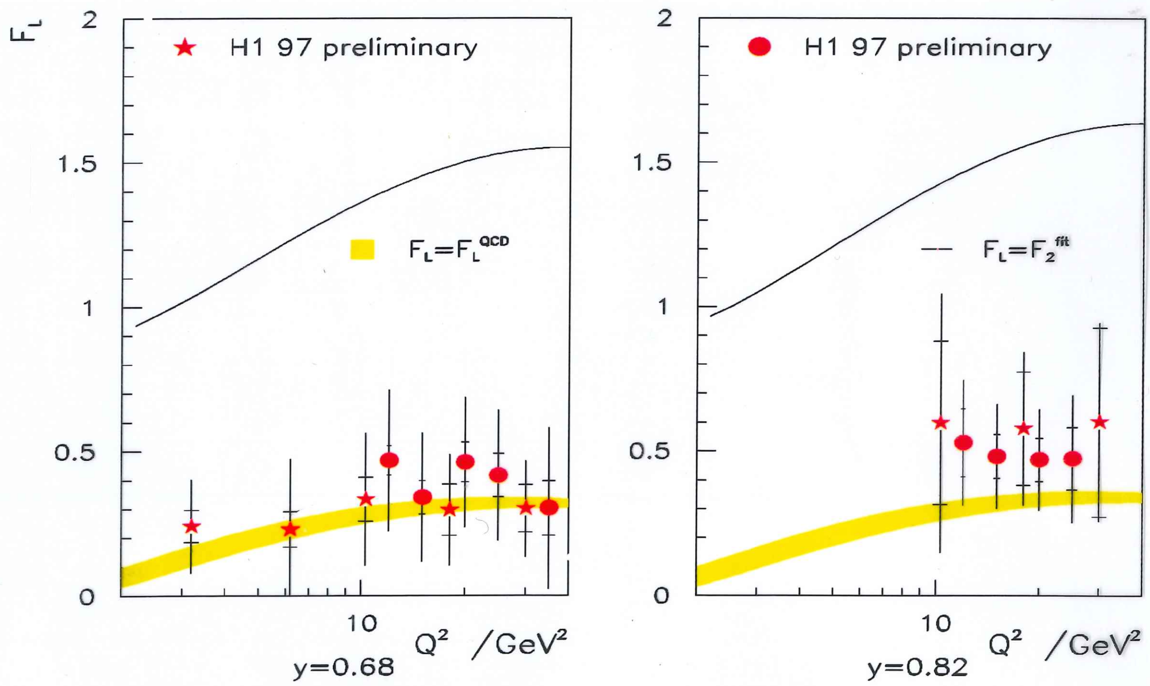
$$\frac{\partial\sigma_r}{\partial \ln y} = -\frac{\partial F_2}{\partial \ln x} - F_L \cdot 2y^2 \cdot \frac{2-y}{Y_+^2} + \frac{\partial F_L}{\partial \ln x} \cdot \frac{y^2}{Y_+}$$

- Assume $\partial F_2/\partial \ln y = A \ln y + \mathrm{B}$
  checked with QCD fit and put to error
- Straight line fit to $\partial\sigma/\partial \ln y$ in Q^2 bins at $y < 0.2$
- Access lower Q^2 than with subtraction method



F_L Determination

- Two methods to determine F_L: subtraction (•) and derivative (⋆) method
- Methods use different aspects of F_2 and F_L behaviour
- Systematic errors at same y correlated



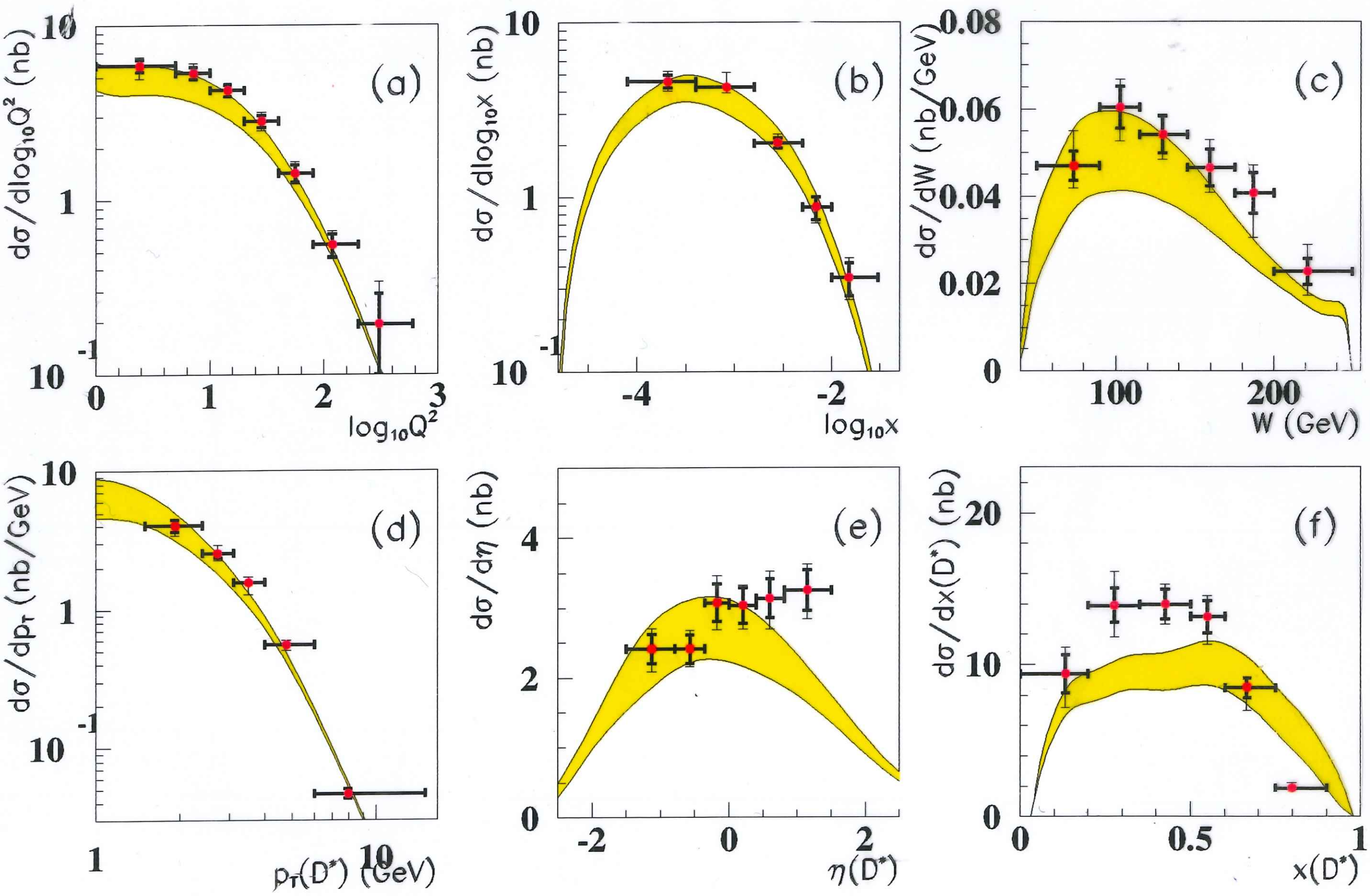
- F_L determination from both methods consistent
- F_L agrees with QCD prediction but
- **Direct** F_L measurement not assuming QCD still important: vary beam energies !

Charm in DIS

New ▸ "Precision" results from HERA

For $1 < Q^2 < 600$ GeV^2, $0.02 < y < 0.7$,
$1.5 < p_T(D^*) < 15$ GeV, $|\eta(D^*)| < 1.5$

$$\Rightarrow \sigma(ep \rightarrow eD^*X) = 8.55 \pm 0.31^{+0.30}_{-0.50} \text{ nb}$$



$\Rightarrow$ agreement with "massive" NLO pQCD BGF†
band: m_c uncertainty (1.2-1.6 GeV)
$f(c \rightarrow D^{*+}) = 0.222 \pm 0.014 \pm 0.014$†

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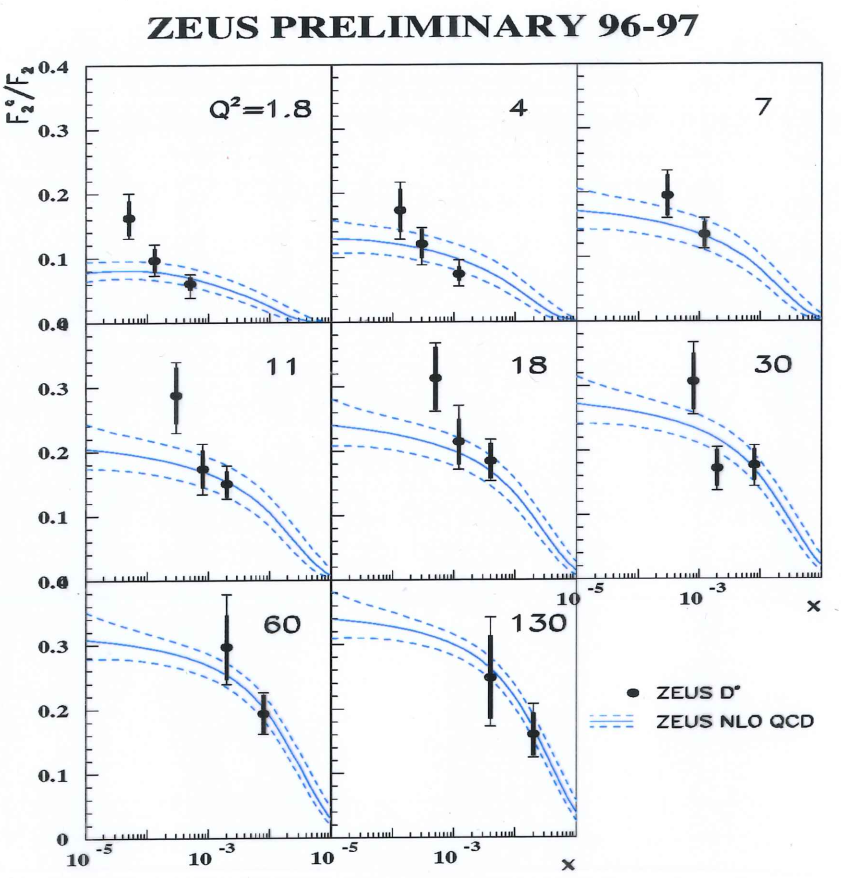
†B. W. Harris and J. Smith, hep-ph/9706334
†OPAL Collab., Eur. Phys. J C1(1998)439

Charm in the Proton

$$\frac{d^2\sigma_{c\bar{c}X}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[1+(1-y)^2]\; F_2^c(x,Q^2)$$



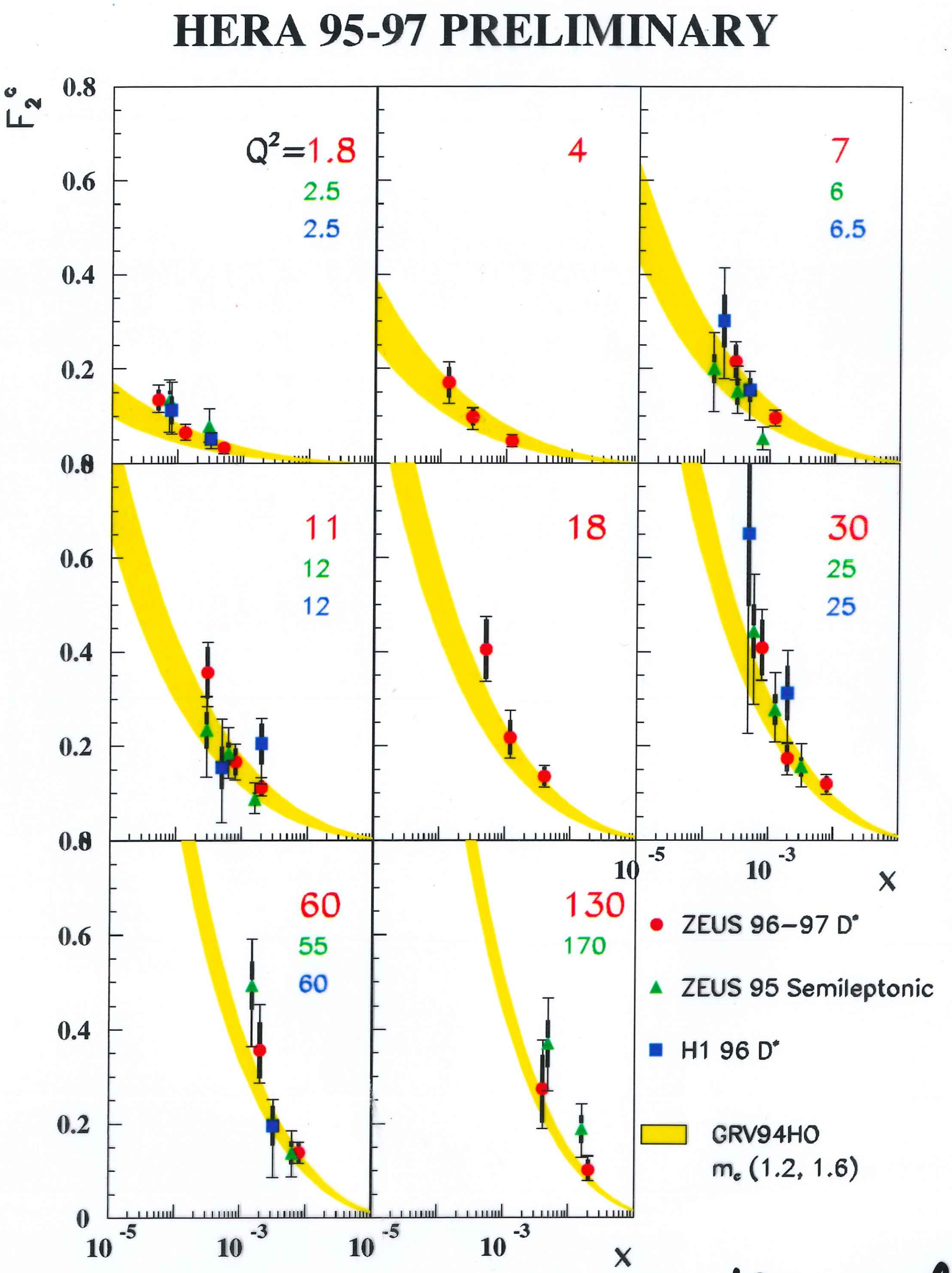
$$\frac{F_2^{\text{Charm}}}{F_2}$$

- Charm content of the proton grows from 10 to 25 % between $Q^2 = 1.8$ and 130 GeV^2

F_2^{charm}

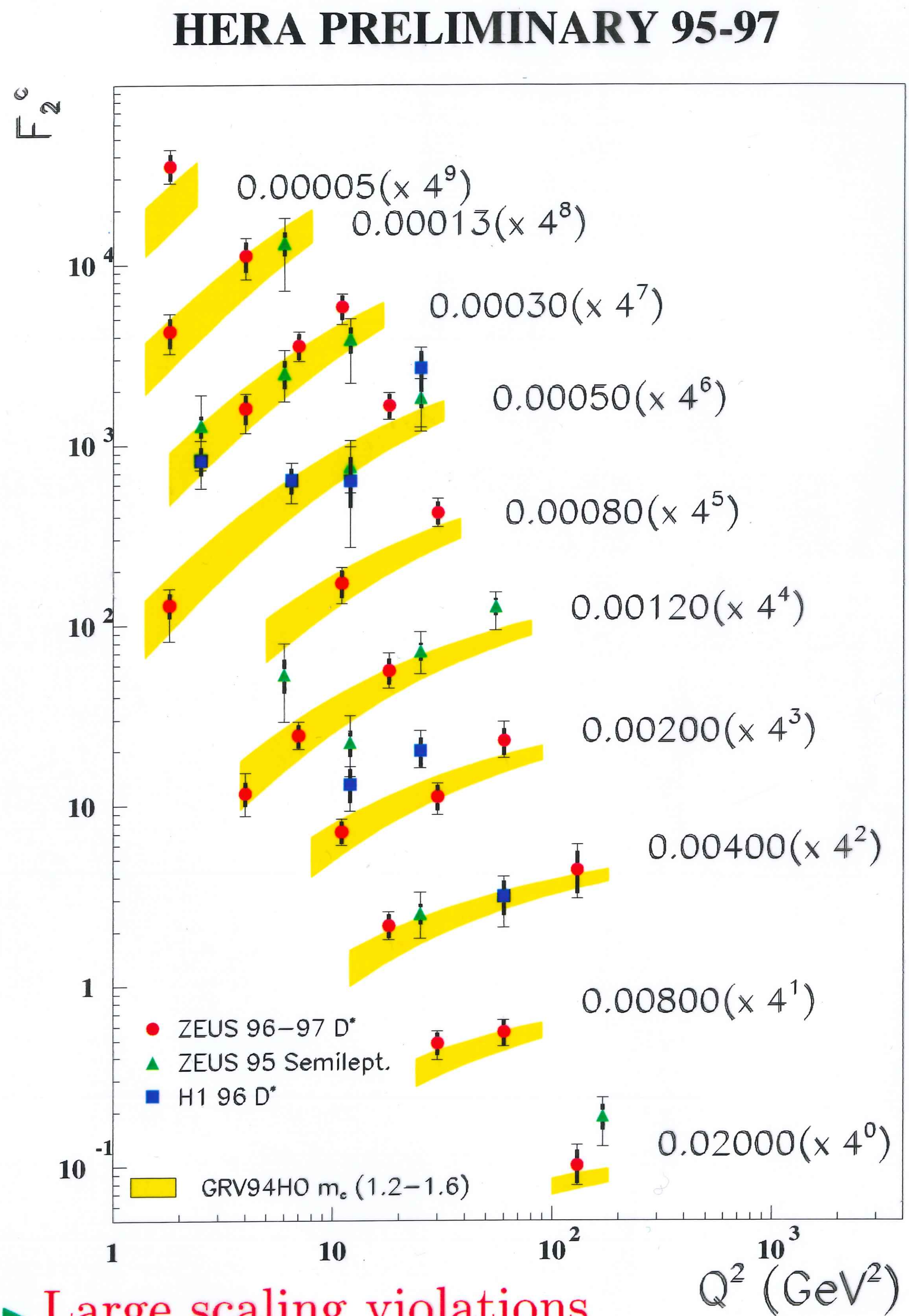
$$\frac{d^2\sigma_{c\bar{c}X}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[1 + (1-y)^2 F_2^c(x,Q^2) - y^2 F_L^c(x,Q^2)\right]$$

Extraction of F_2^c is made possible by the large acceptance in $\{\eta, p_T\}$ of D^*



- Precision $\simeq$ 15 – 20% (much better than earlier m.)

F_2^c Scaling Violations

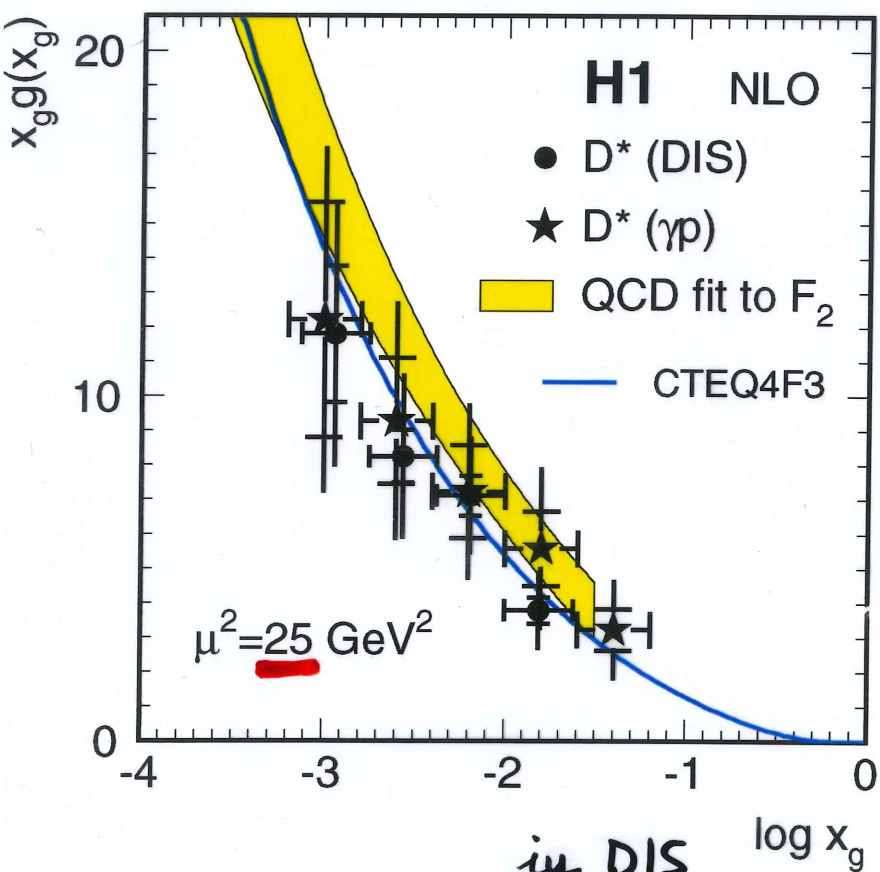


▶ Large scaling violations

ZEUS semileptonic and H1 D^* plotted at closest x values

Gluon Density from Charm

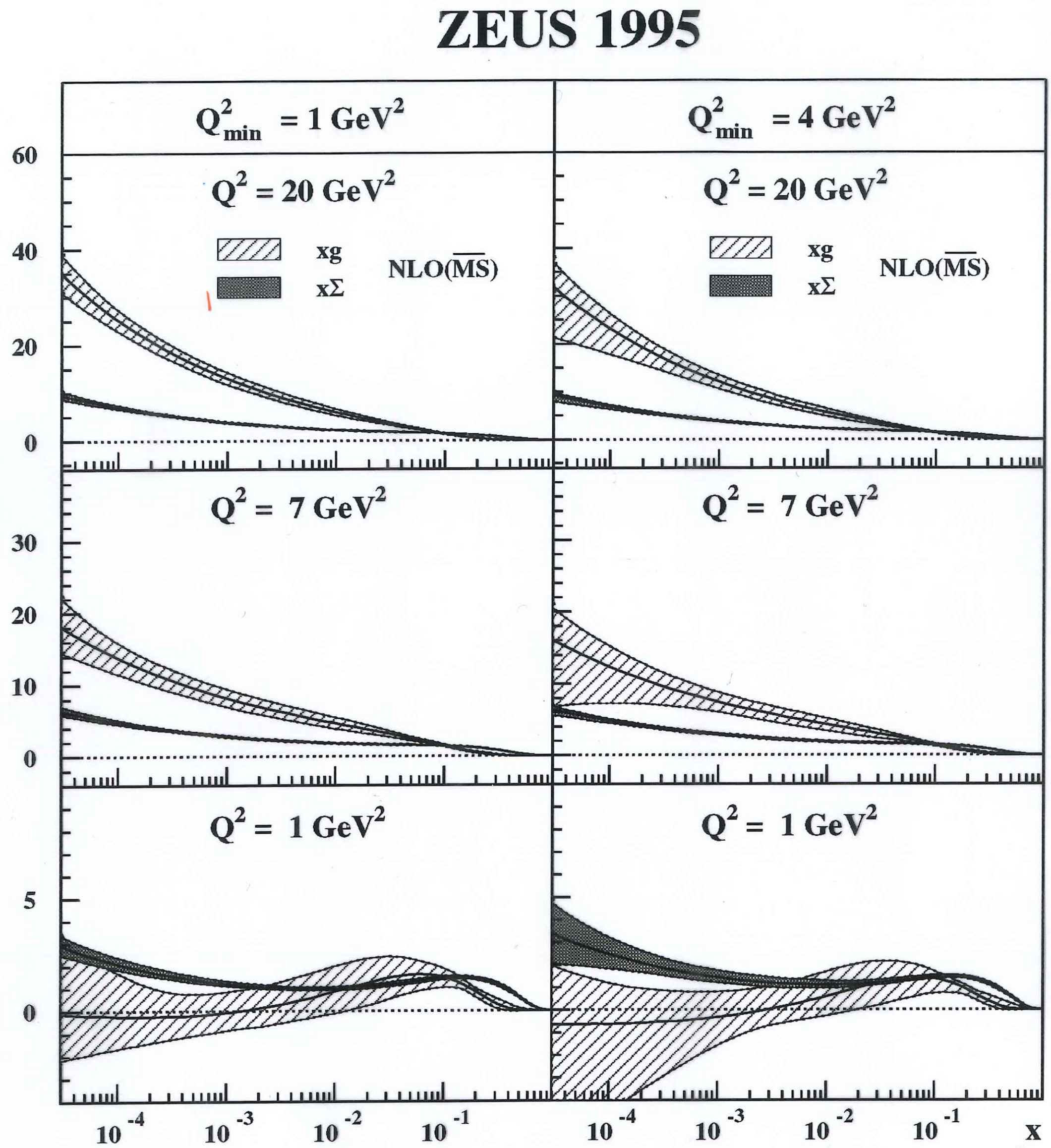
- Measure x_g from scattered e and p_t and $(E - p_z)$ of D*
- Cut p_t and η of D^* in MC (no extrapolation!)
- Iteratively unfold true x_g using
  - NLO Heavy Quark DIS QCD Monte Carlo
  - Peterson fragmentation

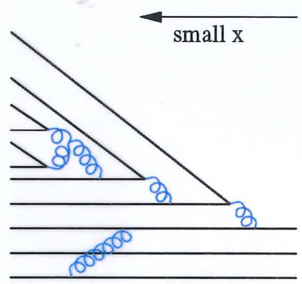


- **Gluon** from D^* cross section agrees with
- **Gluon** from D^* photoproduction and
- **Gluon** from QCD fit to inclusive cross section
- **Same** gluon + boson-gluon fusion generate cross sections

The transition region

Comparison of xg and $x\Sigma$ resulting from QCD fit including F_2 down to $Q^2_{min} = 1$ GeV^2:





Different behavior of gluon and $q\bar{q}$ sea distributions at $Q^2 \approx 1$ GeV^2:

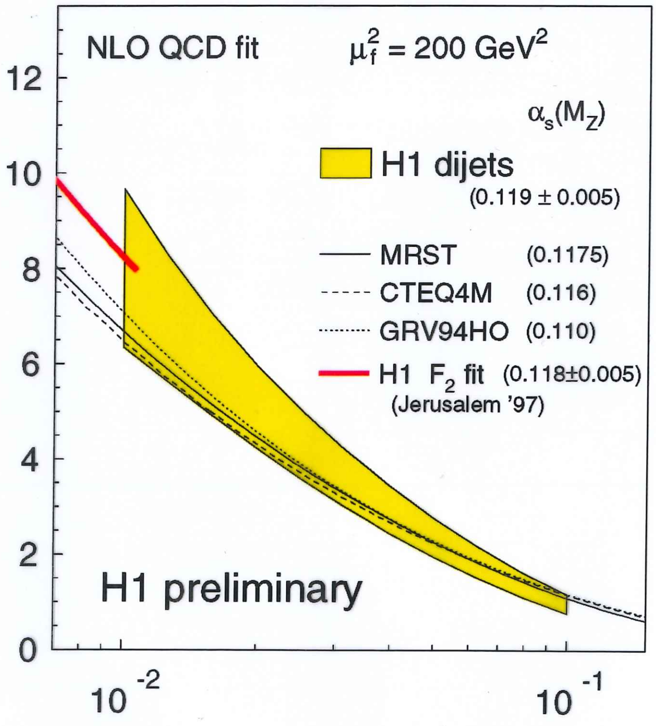
- at high Q^2 gluon drives sea;
- at low Q^2 sea drives gluon.

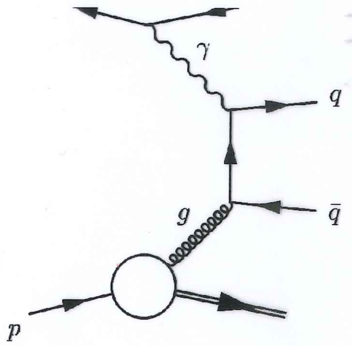
Also found by MRST, while in GRV94 sea and gluon both singular at $Q^2 \approx 1$ GeV^2.

The Gluon from Di-Jets

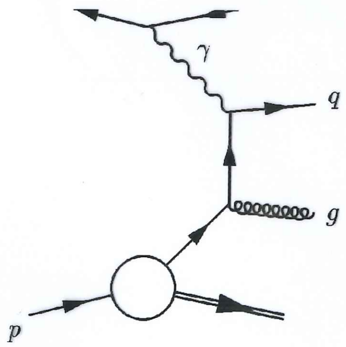
- Similar to $c\bar{c}$, but $M_{jj} \gg M_{c\bar{c}} \Rightarrow$ get gluon at higher x
- more stat. but also more backgr. than g from charm
- Data: $200 \leq Q^2 \leq 5000$ GeV^2

fit: $$\frac{d^2\sigma}{dQ^2dx} \quad \text{and} \quad \frac{d^2\sigma_{dijet}}{dQ^2d\xi} \quad \text{with } \xi = x(1 + \frac{M_{jj}^2}{Q^2})$$





Boson–Gluon–Fusion



QCD–Compton

- consistent with gluon from scaling violations and charm
- more direct in x_g than gluon from scaling violations

HIGH

Q^2

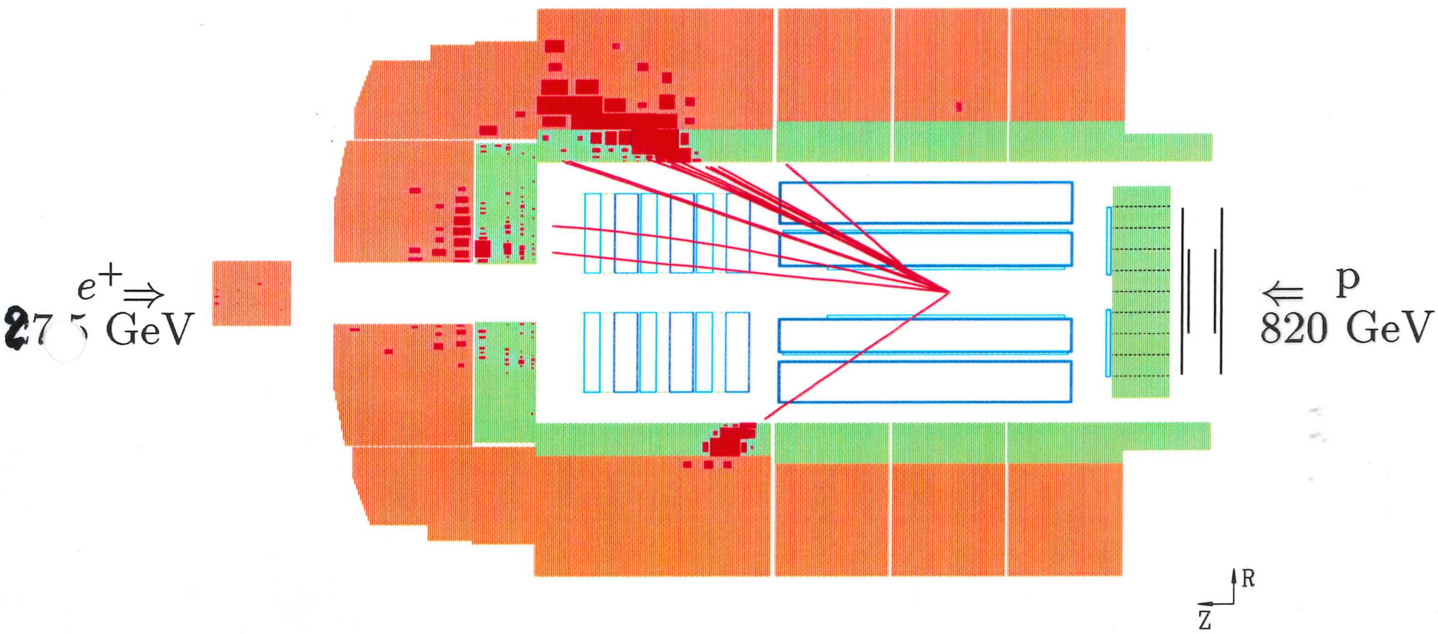
Neut. Currents

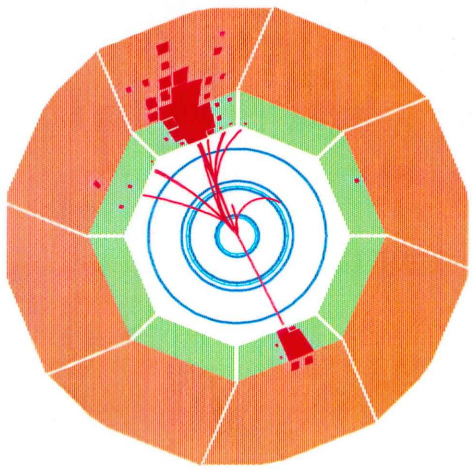
interactions

First look to F_3 effect

NC DIS Event

$Q^2 = 16950\ \text{GeV}^2, \quad y = 0.44, \quad M = 196\ \text{GeV}$





Liquid Argon Calorimeter:

44000 Cells

$\sigma(E)/E(em) \simeq 12\%/\sqrt{E/\text{GeV}} \oplus 1\%$

$\sigma(E)/E(had) \simeq 50\%/\sqrt{E/\text{GeV}} \oplus 2\%$

$\Delta E/E_{em} = 1 - 3\%$

$\Delta E/E_{had} = 4\%$

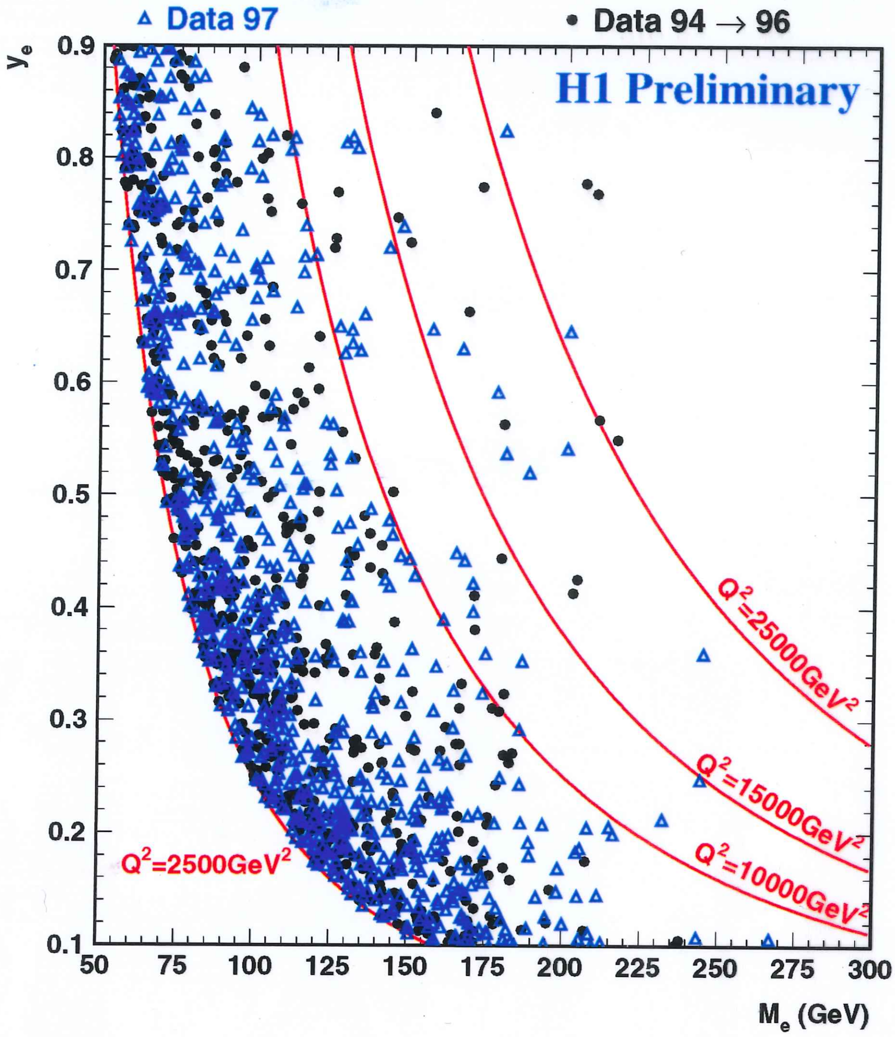
$\Delta\theta_e = 2 - 5$ mrad

measured quantities:

e^+: energy E
polar angle θ

hadrons: $\Sigma = \sum_{hadrons}(E_h - p_{z,h})$
$\tan \gamma/2 = \Sigma/p_{t,h}$

H1 High Q^2 Events



$Q_e^2 > 15000\text{GeV}^2$

Obs. $= 22 \Leftrightarrow$ Exp. $= 14.7 \pm 2.1$

- accumulation of events in mass window?

$M_e = 200 \pm 12.5$ GeV

Obs $= 8$ for 94-97 $\Leftrightarrow$ Exp $= 3.01 \pm 0.54$

(Obs $= 7$ for 94-96 $\Leftrightarrow$ Exp $= 0.95 \pm 0.18$)

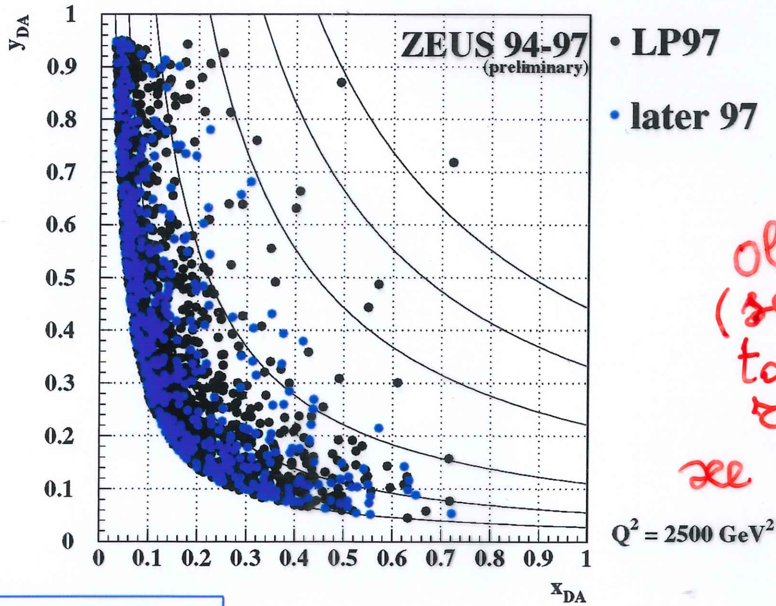
▶ compatible, but less significant with '97 data

▶Cross Section Measurements

ZEUS High Q2 Events

Neutral Current

No new high $Q^2 > 20,000$ GeV^2 events after LP97

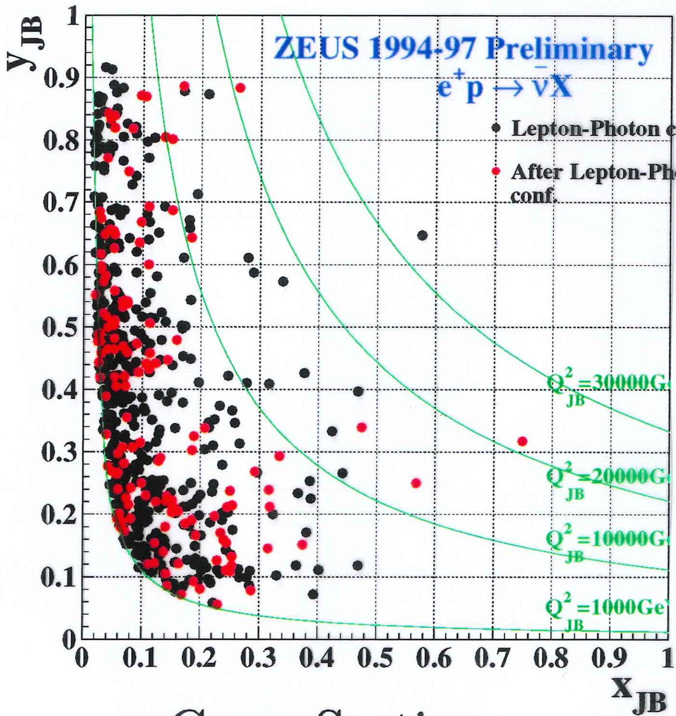


olol: (see tomorrow) see next...

Q^2_{min}	N_{obs}	N_{exp}
10000	66	60 ± 4
15000	20	17 ± 2
35000	2	0.29 ± 0.02

Charged Current

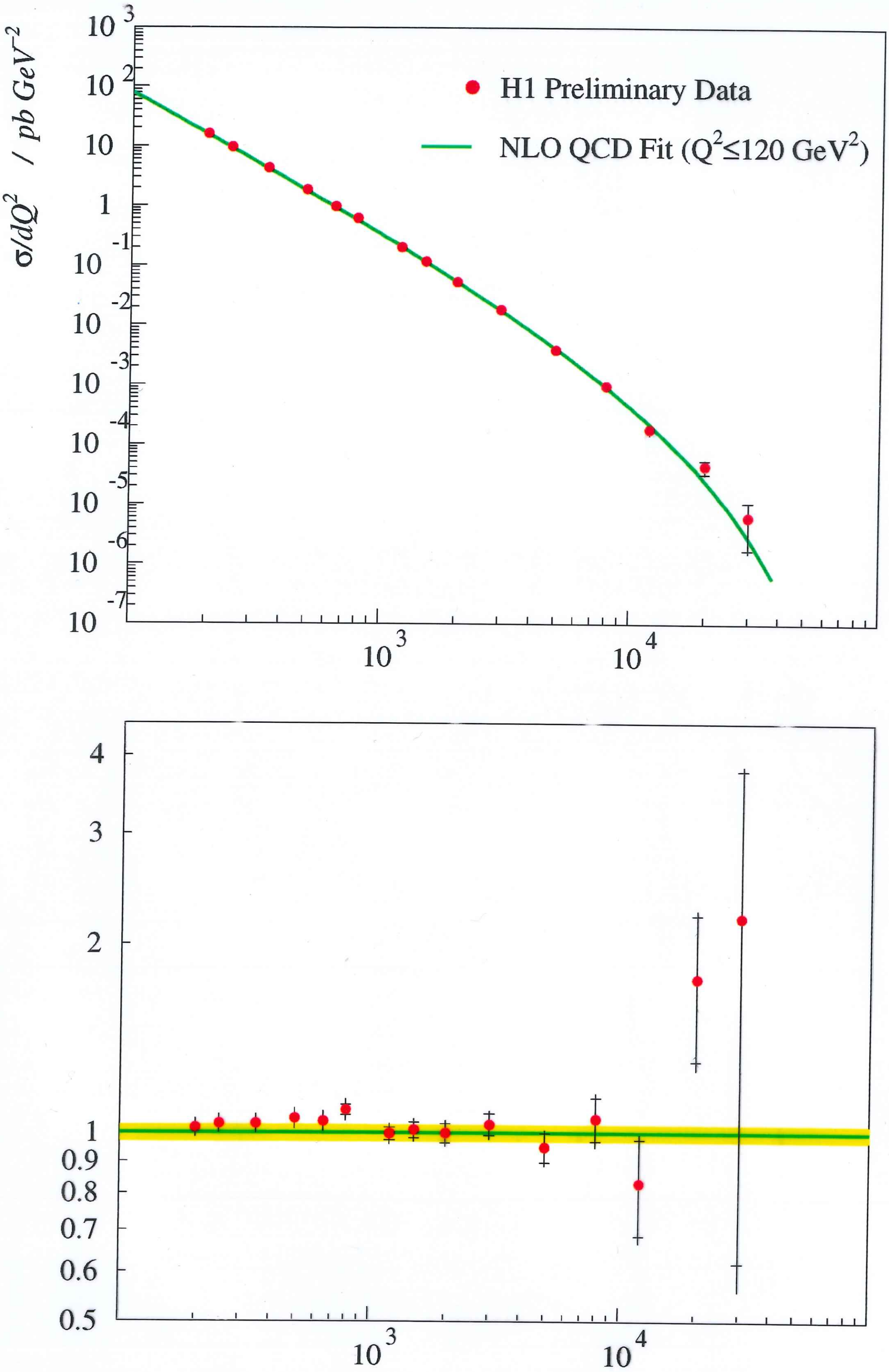
Two new high $Q^2 > 20,000$ GeV^2 events after LP97



Q^2_{min}	N_{obs}	N_{exp}
10000	22	$17^{+5.7}_{-5.2}$
15000	8	$3.9^{+1.9}_{-1.6}$
30000	1	$0.06^{+0.08}_{-0.04}$

▶ Cross Section Measurements

$d\sigma^{NC}/dQ^2$

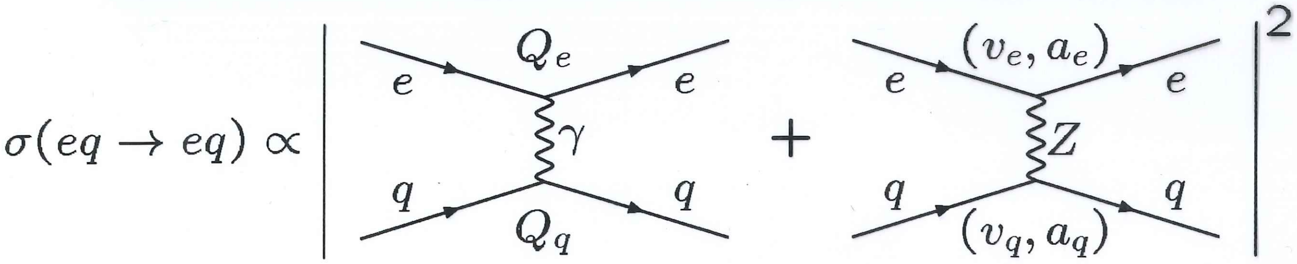


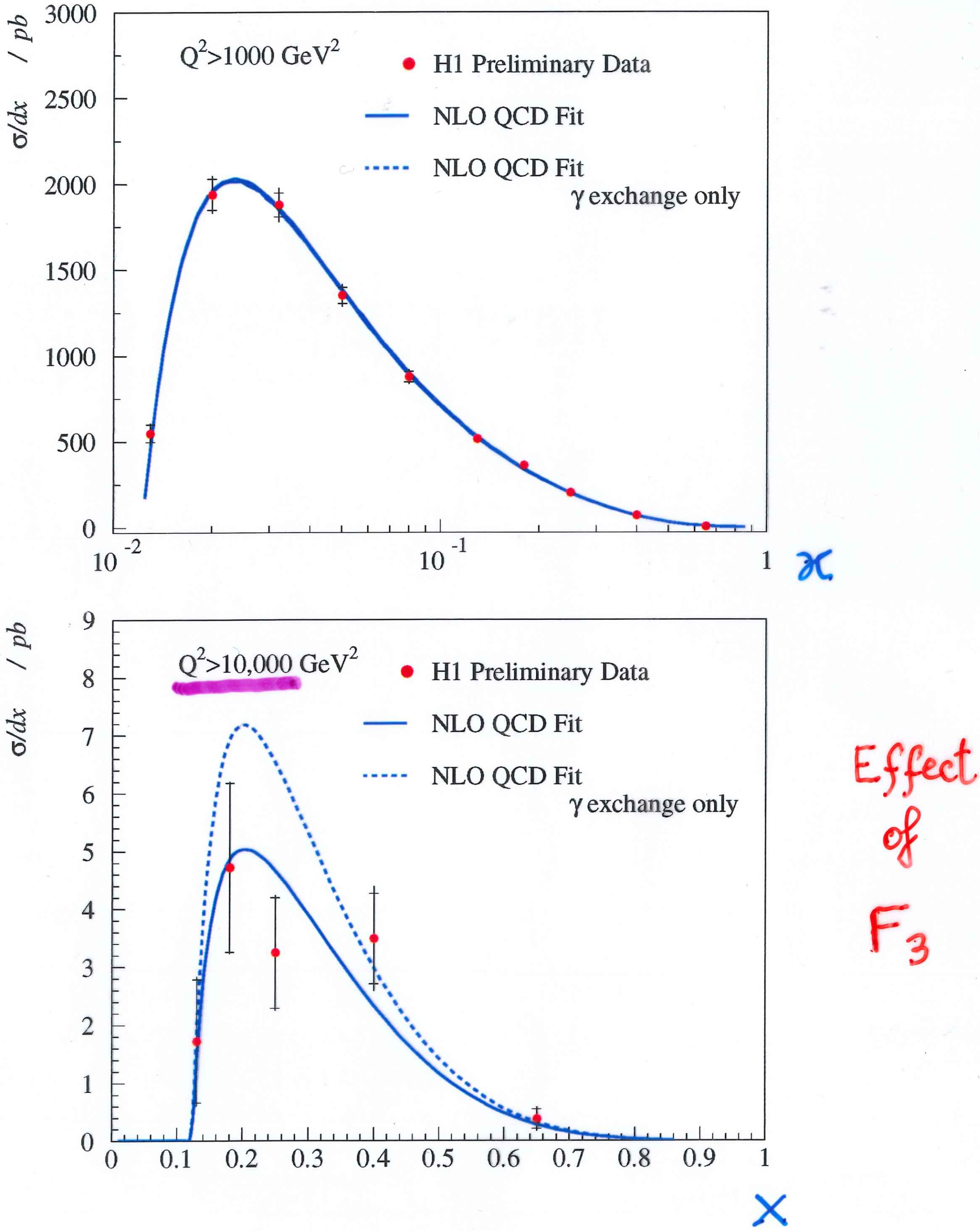
Good agreement with Standard Model
up to $Q^2 \simeq 10,000$ GeV²

H1 and ZEUS precision sufficient to constrain PDFs

→ Benchmark for Standard Model

Sensitivity to Z





Sensitivity through propagator

CHARGED CURRENTS INTERACTIONS AND W PROPAGATOR AT HIGH Q^2

Charged Current Cross-Sections

Cross Section for $e^+p \longrightarrow \bar{\nu}X$:

$$\frac{d^2\sigma}{dxdQ^2} = \frac{G_F^2}{2\pi}\frac{1}{(1+Q^2/M_W^2)^2}\left(\bar{u}+\bar{c}+(1-y)^2(d+s)\right)$$

- Propagator dependence $\Rightarrow$ W mass determination

  H1 (94-97): $81.2 \pm 3.3 \pm 4.3$ GeV

  ZEUS (94-97): $78.6^{+2.5+3.3}_{-2.4-3.0}$ GeV

- parton densities $\Rightarrow$ sensitivity to d-quark density
- helicity dependence $\Rightarrow$ V-A coupling
- QED radiative Corrections ($< 10\%$) applied

Reduced Charged Current Cross-Section:

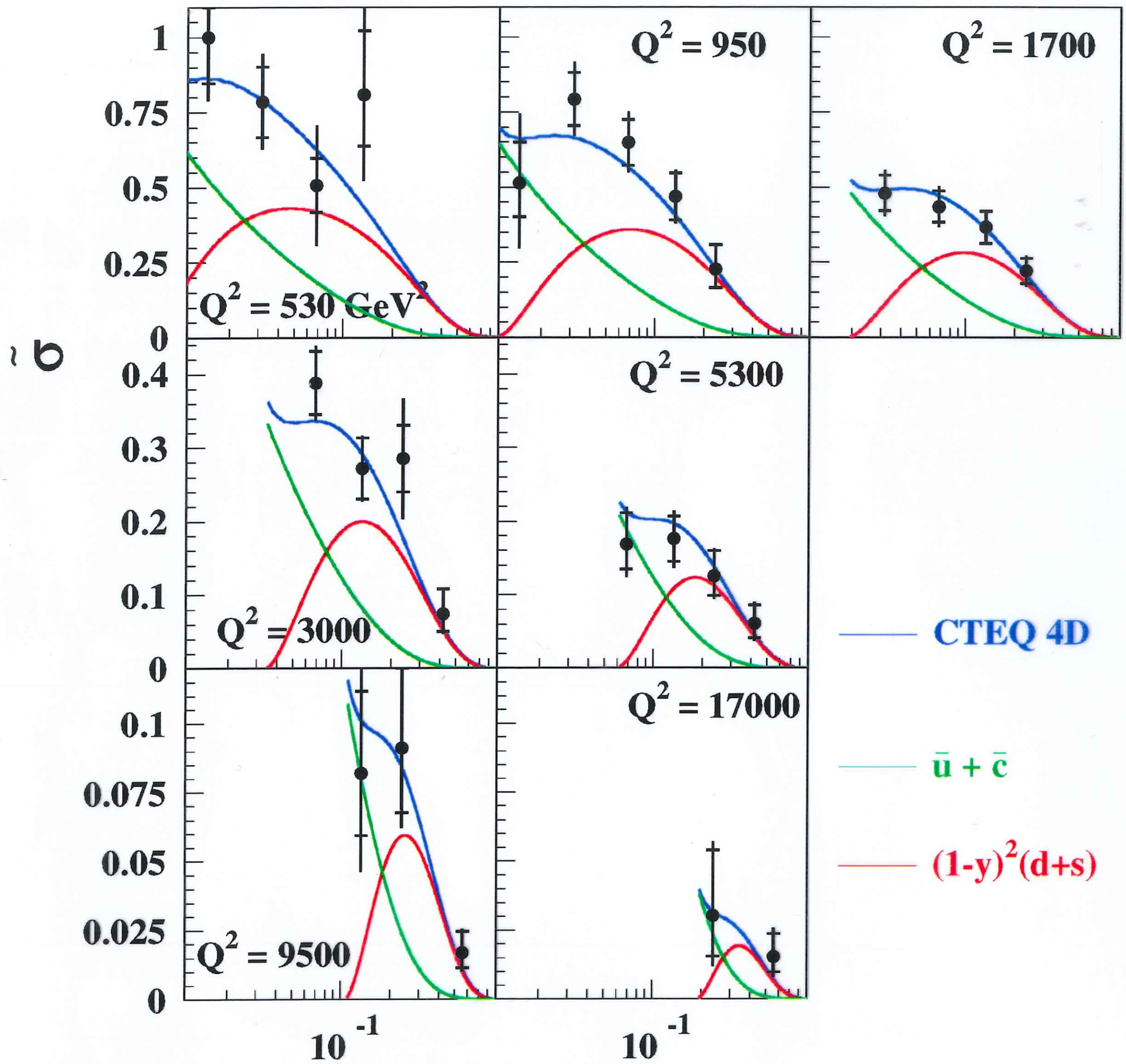
$$\sigma_{CC} \equiv x \cdot \frac{2\pi}{G_F^2}(1+Q^2/M_W^2)^2\frac{d^2\sigma}{dxdQ^2}$$
$$= x \cdot \left(\bar{u}+\bar{c}+(1-y)^2(d+s)\right) \textit{ in } QPM$$

- definition in analogy to the Reduced Neutral Current Cross-Section
- different relation to the parton densities: supression of the valence quark contribution at high y due to the helicity factor

$d^2\sigma^{CC}/dx dQ^2$

$$\frac{d^2\sigma_{e^+p}}{dx\,dQ^2} \simeq \frac{G_F^2}{2\pi}\frac{1}{(1+Q^2/M_W^2)^2}[\overline{u}+\overline{c}+(1-y)^2(d+s)]$$

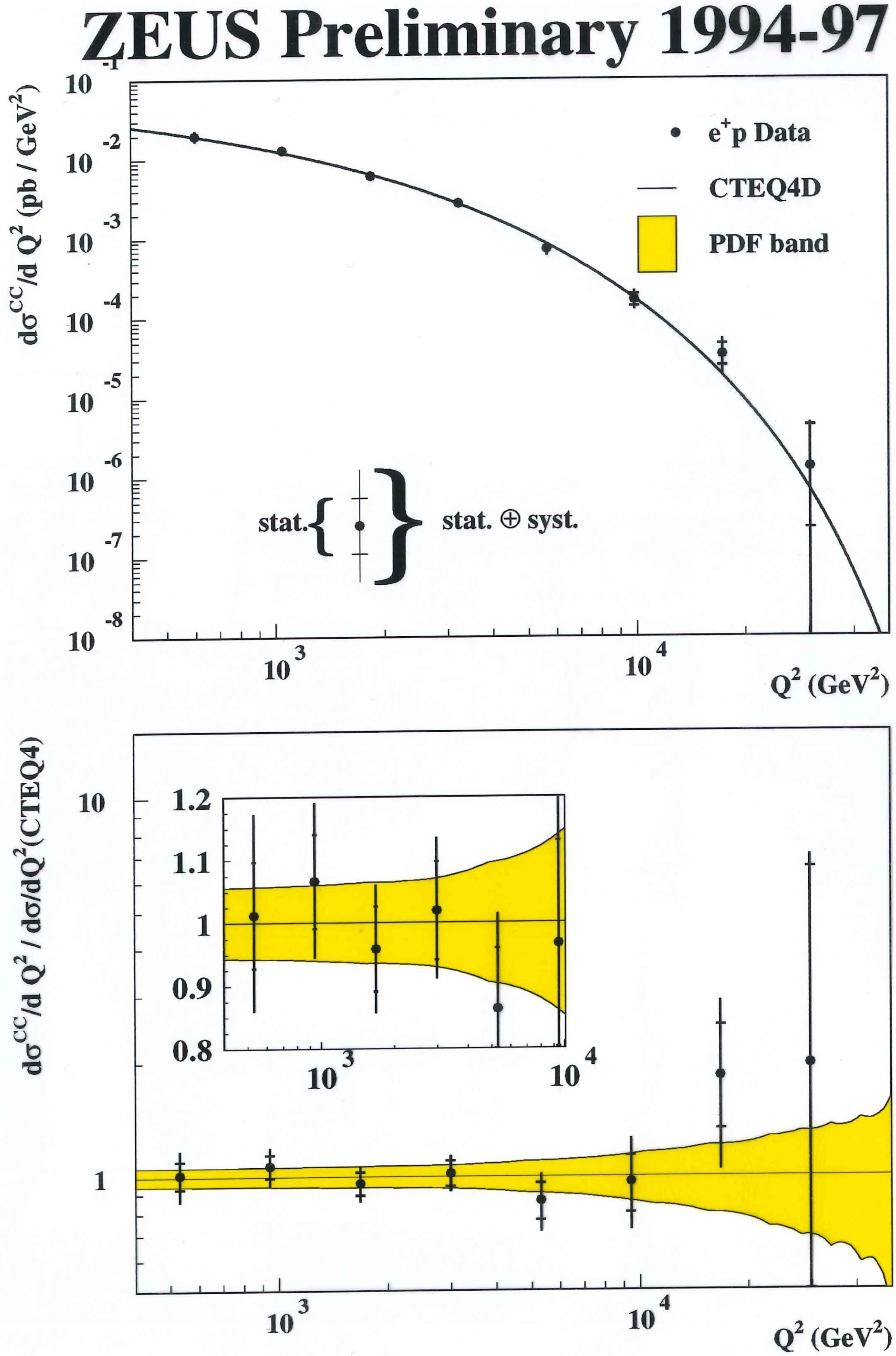
ZEUS CC Preliminary 1994-97



Good agreement with Standard Model

Sensitivity to *d* and sea

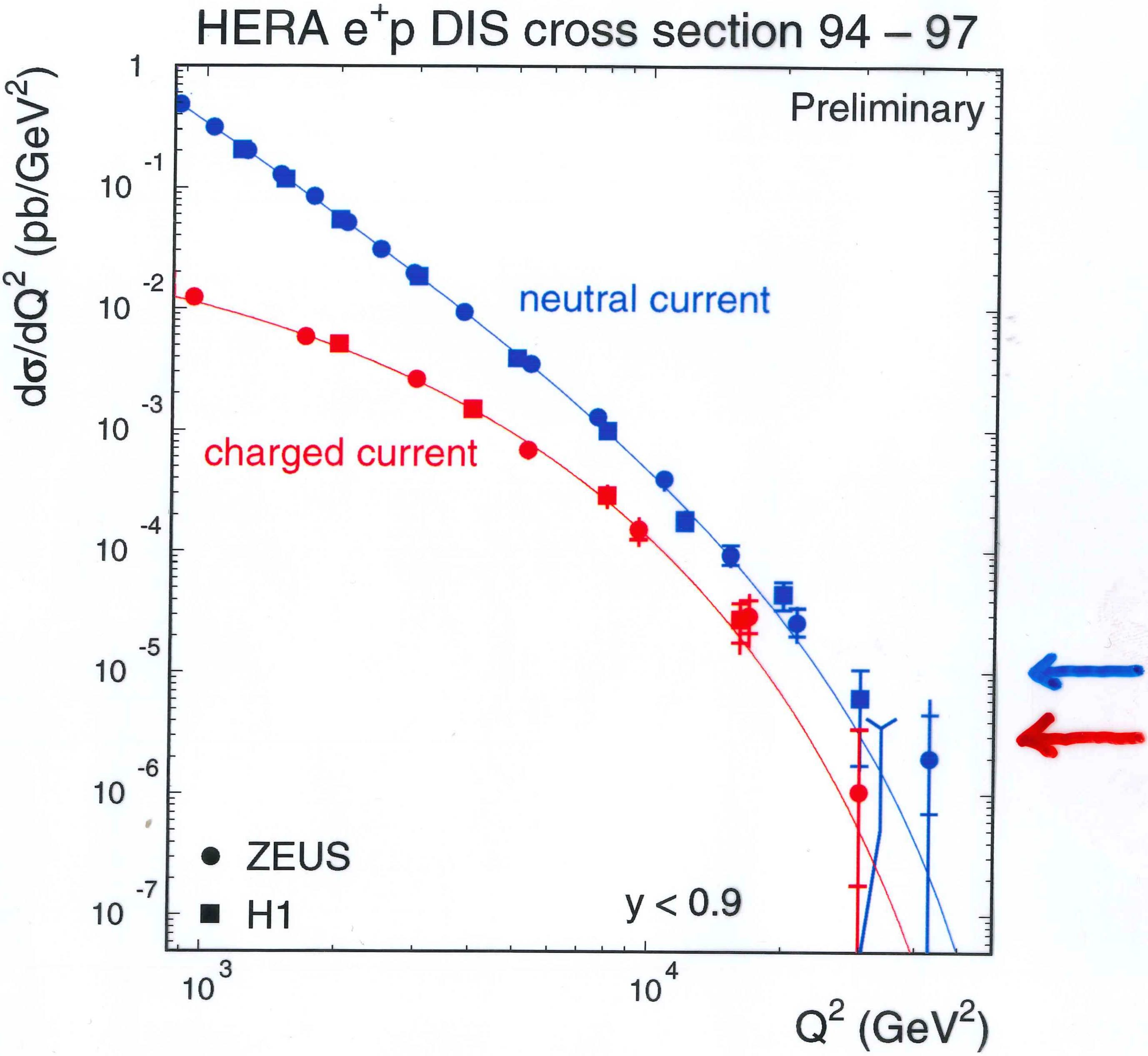
$d\sigma^{CC}/dQ^2$



Test of EW propaga-tor

Good agreement with Standard Model
up to $Q^2 \simeq 10,000$ GeV^2

High Q^2 Cross Sections



RUNNING

'98 , '99

WITH

e^- (27,5 GeV)

AND

p (920 GeV)

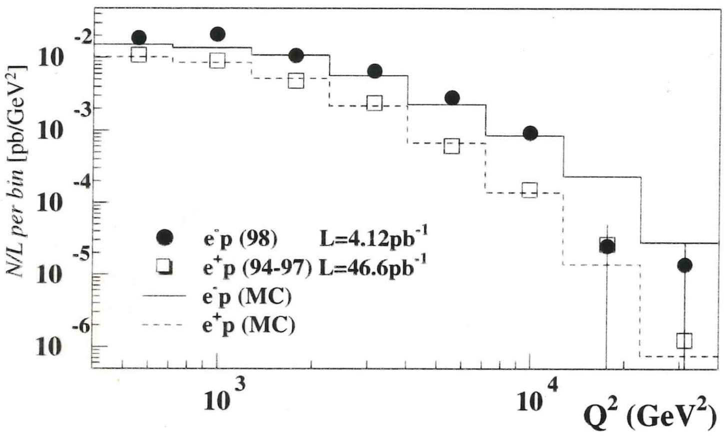
Running in 1998

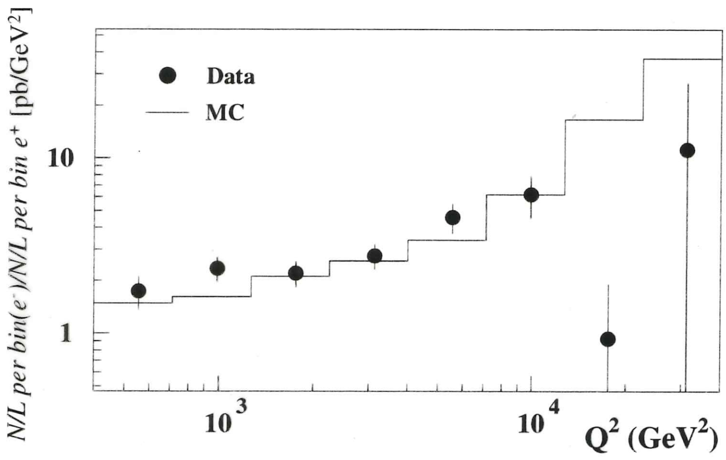
(A Different Machine!)

- ***Electrons on Protons***
- ***Proton Energy = 920 GeV***

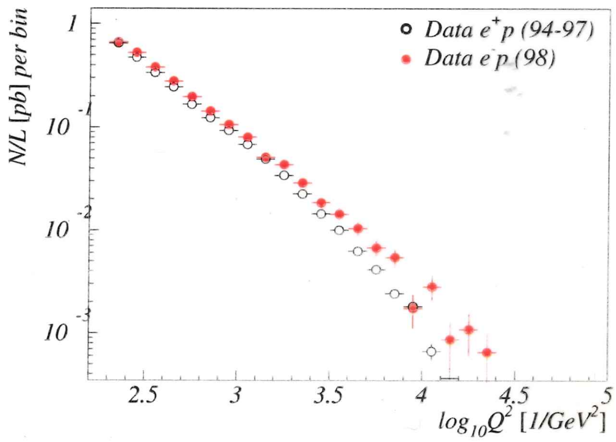
ZEUS (in progress)

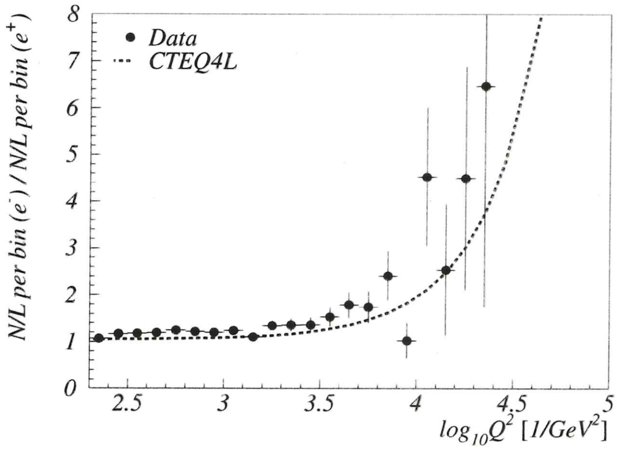
Charged Currents



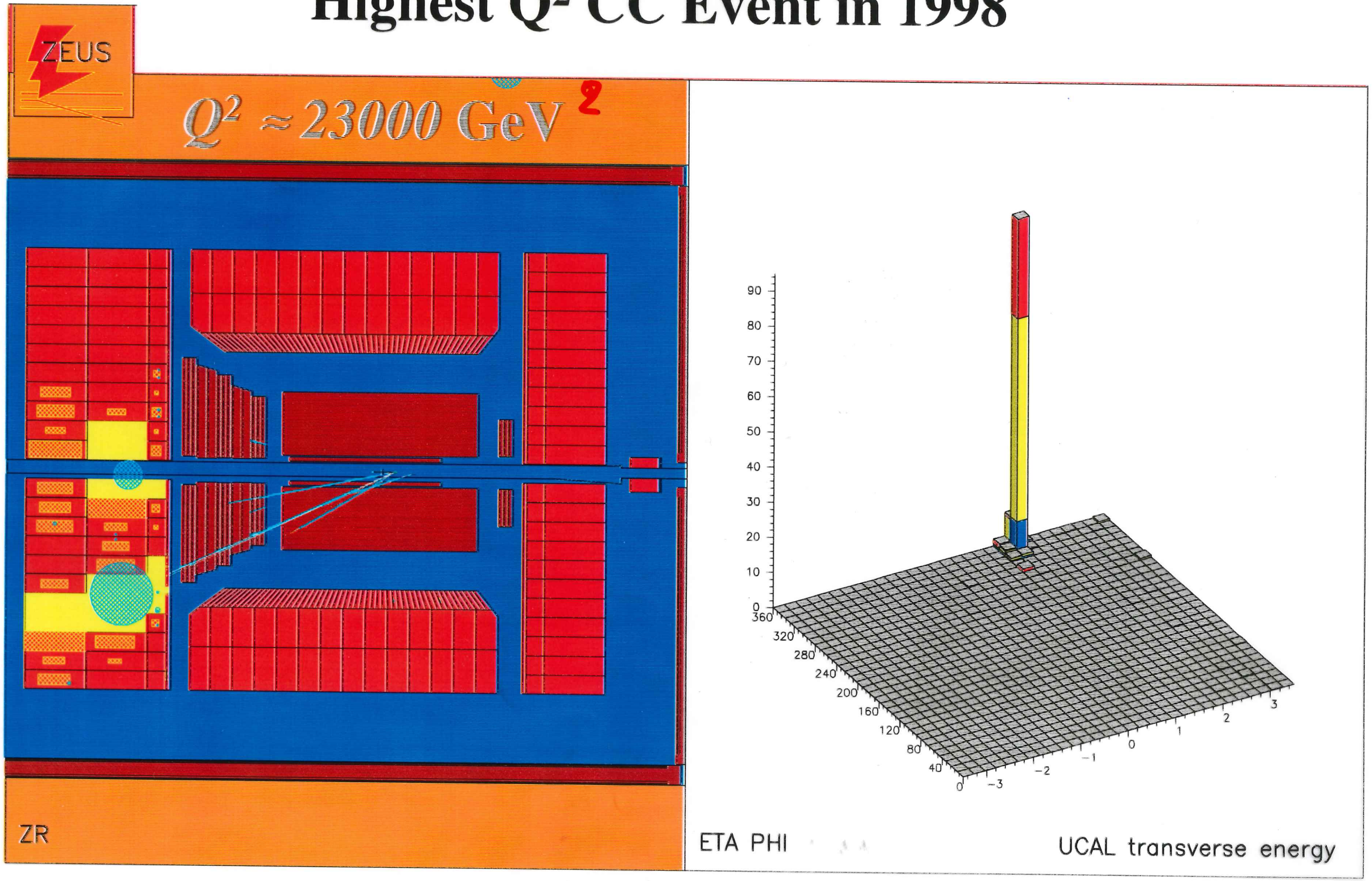


Neutral Currents





Highest Q^2 CC Event in 1998



H1 (in progress)

e^- / e^+ Comparison

e^- beams have an easier time to find a matching parton in the proton

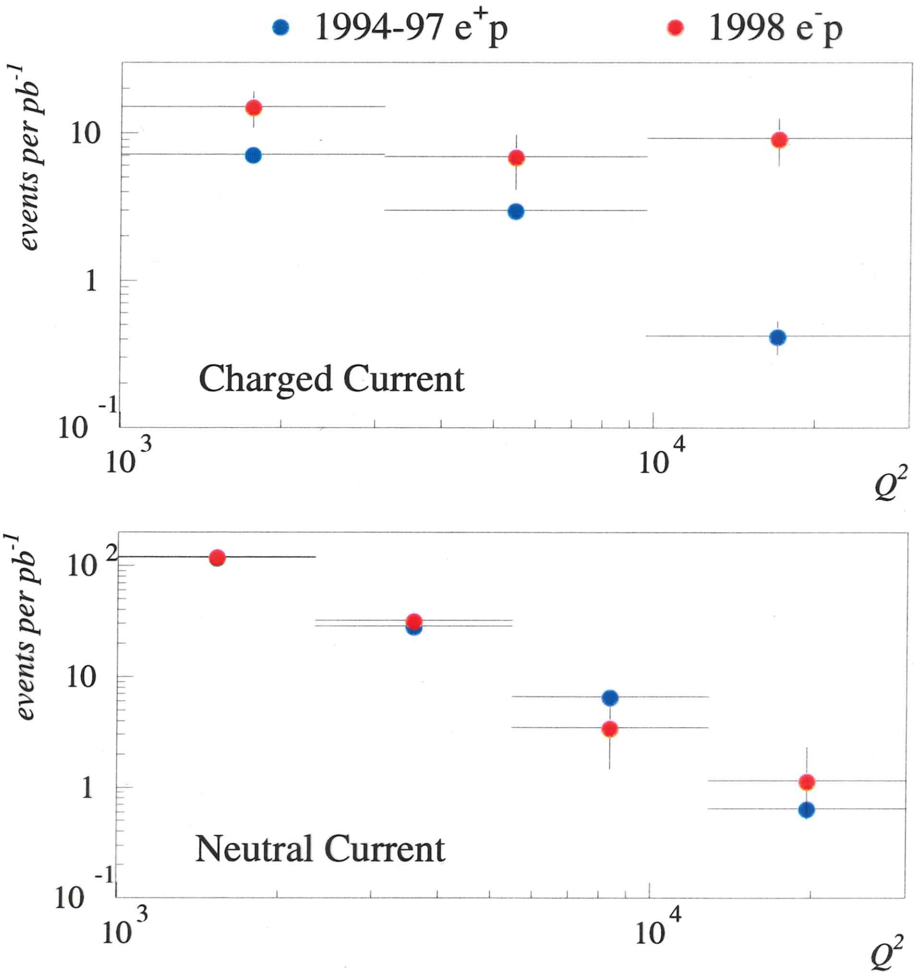
- Standard Model Cross sections for $Q^2 > 10000\ \mathrm{GeV}^2$

NC

$$\frac{\sigma(e^- p \to e^- X)_{920\ \mathrm{GeV}}}{\sigma(e^+ p \to e^+ X)_{820\ \mathrm{GeV}}} = 2.3$$

CC

$$\frac{\sigma(e^- p \to \nu X)_{920\ \mathrm{GeV}}}{\sigma(e^+ p \to \nu X)_{820\ \mathrm{GeV}}} = 11.0$$



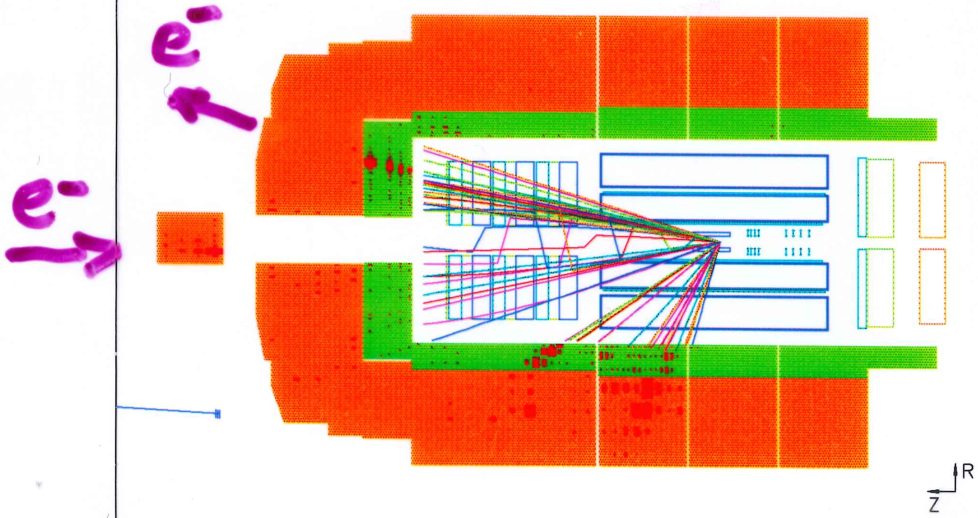
Run 229365 Event 96751 Class: 4 5 6 7 8 11 19 22 26 28 29 Date 16/02/1999

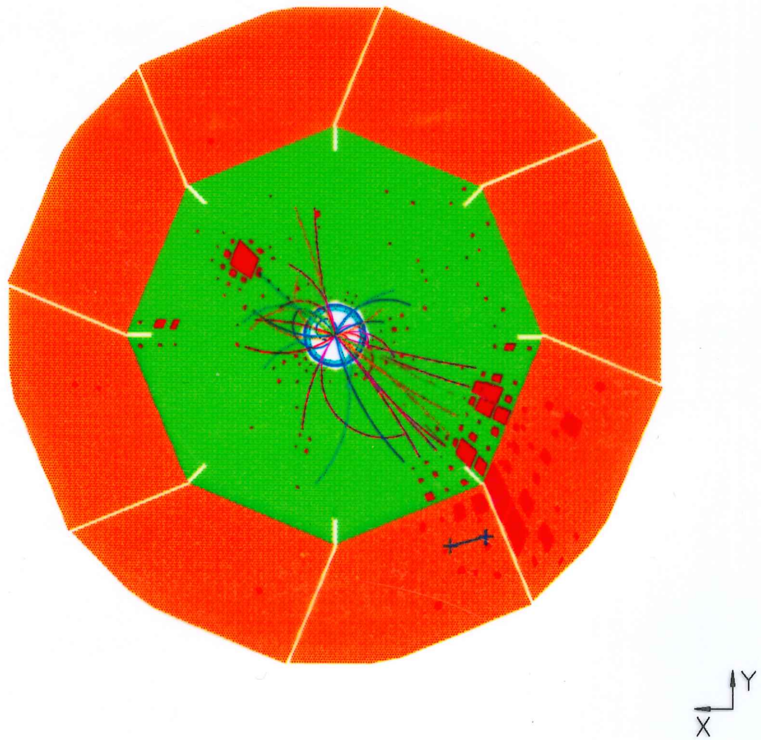
H1 Event Display 1.17/03
DSN=/data_98/data/CDST1.C98.PRESEL.DST.INDEX

E= −27.6 x 820.0 GeV B=11.6 kG

AST (DMIS) =	0	D	0	0
RST (DMIS) =	C0	D	0	0

$Q^2 \simeq 41.000\ GeV^2$





FUTURE

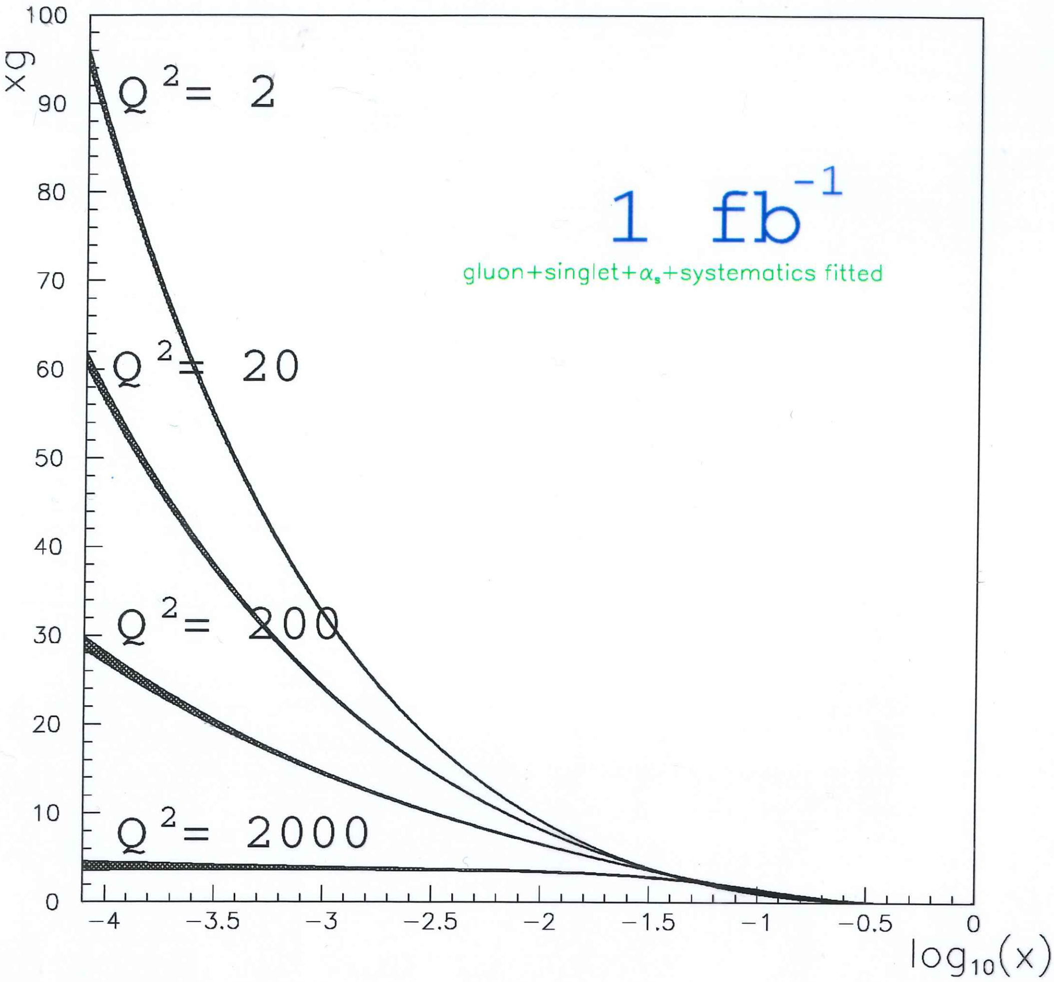
2000 - 2001

Luminosity upgrade (x~5)

$\mathcal{L} \approx 100\ pb^{-1}/year$

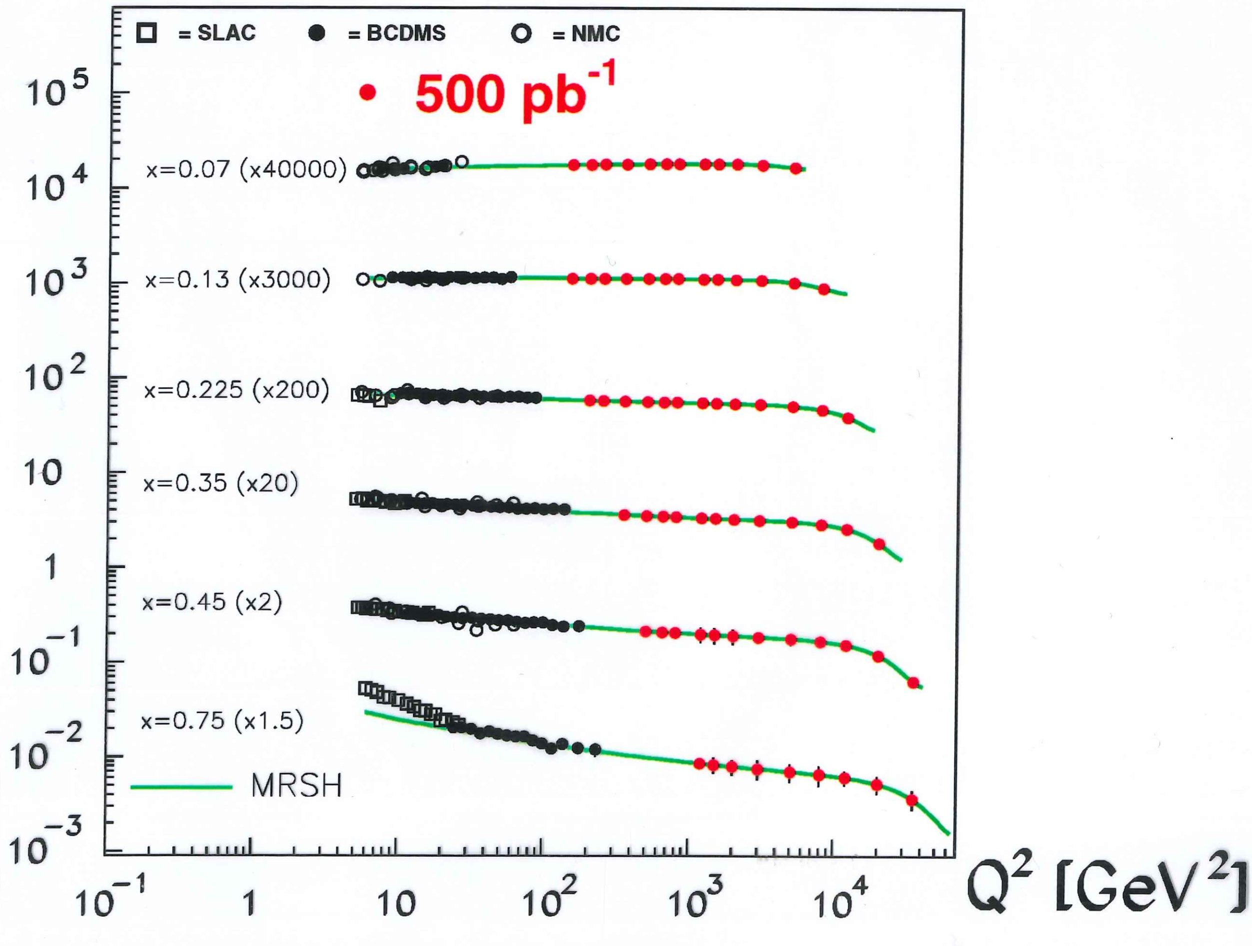
Electron polarization

- New phenomena
- Rare effects
- Electroweak physics
- Precise systematics



xg
Q 2= 2
Q 2= 20
Q 2= 200
Q 2= 2000
1 fb-1
gluon+singlet+αs+systematics fitted
log10(x)

b



= SLAC
= BCDMS
= NMC
500 pb-1
x=0.07 (x40000)
x=0.13 (x3000)
x=0.225 (x200)
x=0.35 (x20)
x=0.45 (x2)
x=0.75 (x1.5)
MRSH
Q2 [GeV2]

SUMMARY

- Proton being probed down to ~1.5/1000 of r_p
- 5 order of magnitudes in Q^2 and x measured.
- Experimental agreement be-tween H1, ZEUS, fixed target.
- NLO QCD fits, with DGLAP evolution, good in the range $1 < Q^2 < 10^4$ GeV^2
- Gluon density measurement confirmed in 4 different ways; at various Q^2
- F^C **contribution sizable and rising with** Q^2
- F_L different from zero.
- Z_0 contribution observed.
- Very high Q^2: a little more than expected .
- CC agree with SM. Test of W propagator at high Q^2: a novel aspect.
- Recent exper. interest for very low Q^2 physics; transition region betweed perturbative and non pert. physics studied.
- '98 -'99 e^- runs will provide e^- data comparable in statistics with previous e^+ ones.
- Future: luminosity upgrade 2000-2001; 500 pb^{-1} possible; --> new physics; precise systematics.

Thanks to our friend Bjoern Wiik !