# Proton structure at high $Q^2$

Kunihiro Nagano (KEK/DESY)

on behalf of

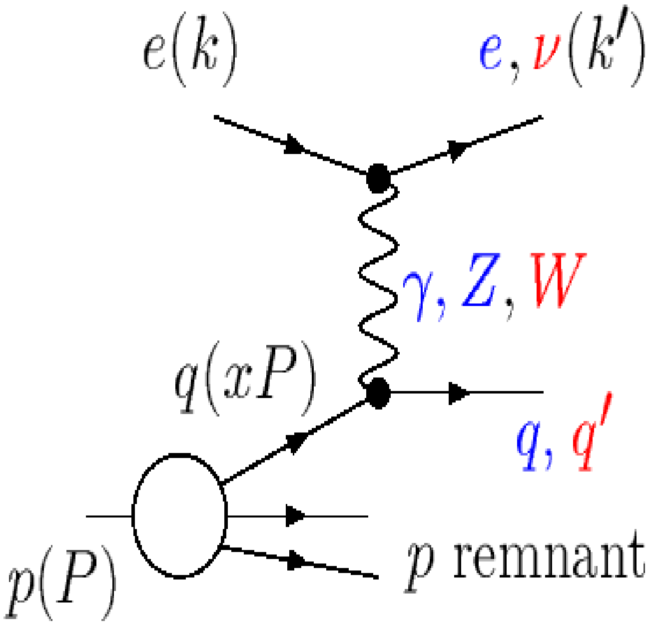
the H1 and ZEUS collaborations

30th International Conference on High Energy Physics
(ICHEP 2000)

July 27 – August 2, 2000 in Osaka, Japan.

# Deep Inelastic Scattering (DIS)

DIS is a straightforward tool to probe $p$ structure.



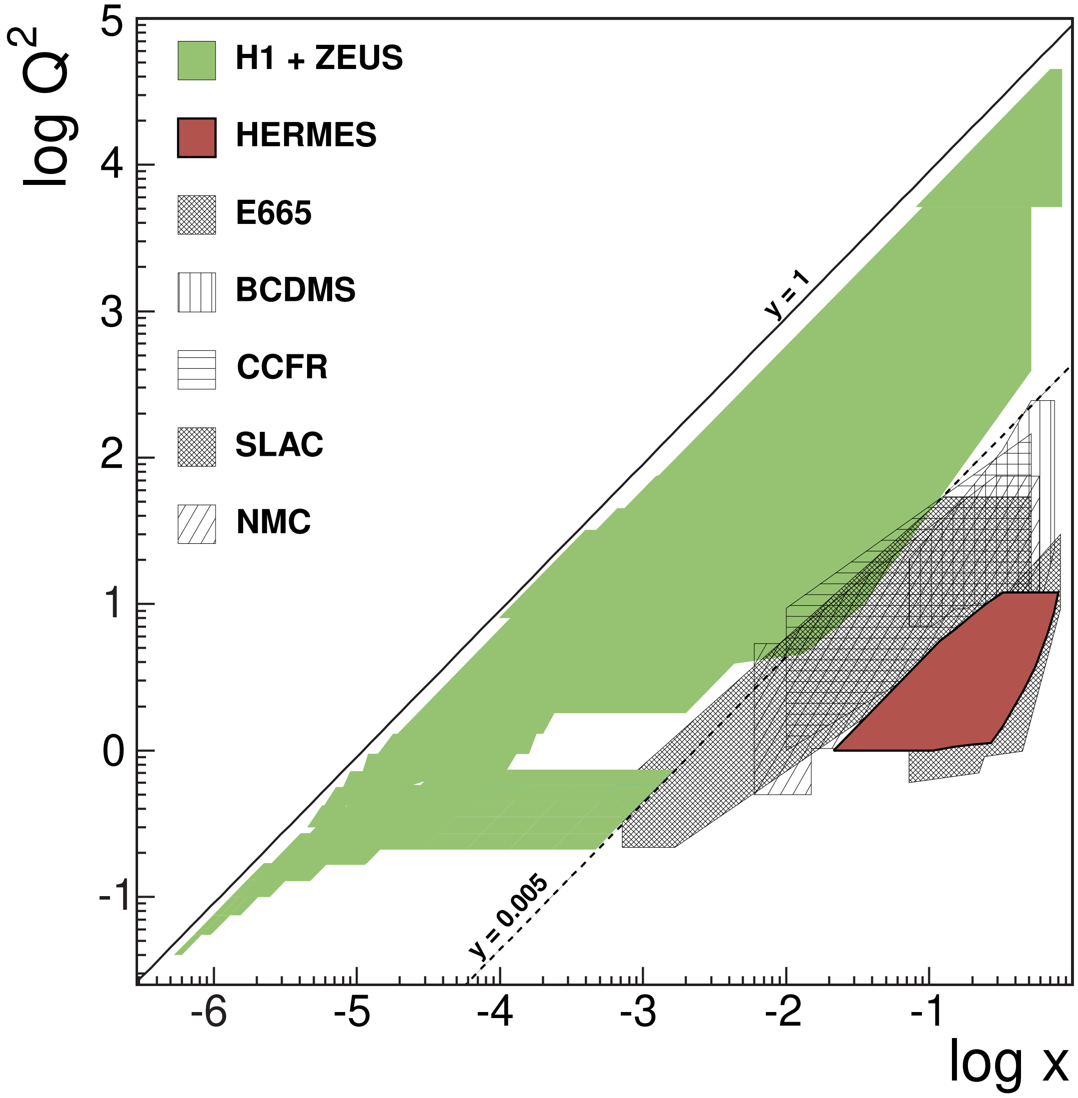

- $Q^2 \equiv -(k-k')^2 \equiv -q^2$
- Bjorken scaling variable (=momentum fraction)
$$x \equiv Q^2/2p \cdot q$$
- inelasticity of electron (reflects scattering angle of $e$ in $eq$ CMS, $\theta^*$)
$$y \equiv p \cdot q/p \cdot k = \frac{1-\cos\theta^*}{2}.$$
- $Q^2 = x \cdot y \cdot s$

Inclusive DIS cross-sections $\Leftrightarrow$ Structure functions (SFs)

# Parton densities and DGLAP evolution

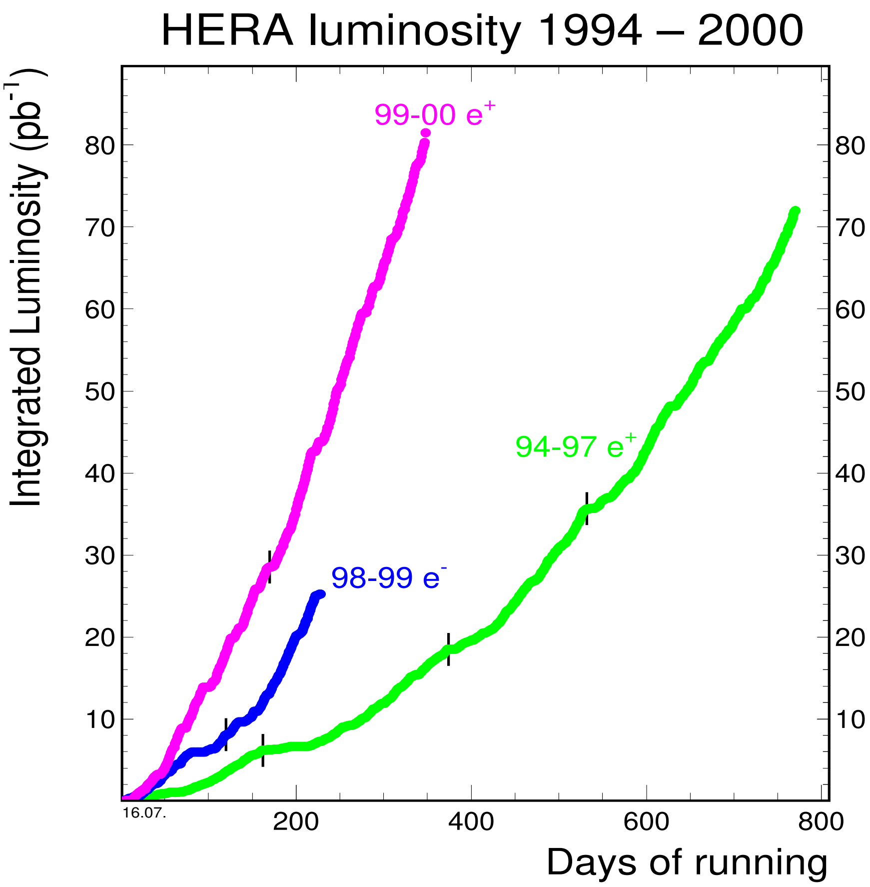
- SFs = sum of (short-range) $\otimes$ (parton density).
- Parton density includes long-range effects. In spite, pQCD can predict "evolution" of PDFs in $Q^2$; DGLAP equation.
- Needs experimental inputs to determine initial parton densities at $Q_0^2$ where evolution starts.

# DIS at HERA, the first $ep$-collider




- Medium $Q^2$: precise measurement of SFs.
  - determination of sea-quark and gluon densities at low-$x$.
  - high $y$ : $F_L$.
  - low $y$ : overlap to fixed-target.
- High $Q^2$: pQCD holds? search for QCD breakdown.
  - Smallest spatial-resolution: $\lambda \sim 1/\sqrt{Q^2}$.
    $Q^2_{\text{max}} \sim 1 \times 10^5$ GeV$^2 \Rightarrow \lambda < 10^{-16}$ cm.
  - NC and CC can be seen at the same place!

# HERA luminosity




- '94–'97 : 27.5 GeV $e^+$ with 820 GeV $p$.
  H1(ZEUS) : 36.6(47.7) pb$^{-1}$. $\Rightarrow$ Published.

- '98–'99 (Apr.): 27.5 GeV $e^-$ with 920 GeV $p$.
  H1(ZEUS) : 15.3(16) pb$^{-1}$. $\Rightarrow$ New preliminary!

- '99(Jul.)–'00: 27.5 GeV $e^+$. with 920 GeV $p$.
  H1 : 45.9 pb$^{-1}$ analyzed. $\Rightarrow$ New preliminary!

# Contents of this talk

High-$Q^2$ DIS ($Q^2 \gtrsim 200$ GeV$^2$).

We have all; $e^+$, $e^-$, NC, CC, at the same apparatus, HERA!

# DIS cross-section formula

NC($e^{\pm}p \rightarrow e^{\pm}X$)

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \times \{Y_+F_2^{NC} \mp Y_-xF_3^{NC} - y^2F_L^{NC}\}$$

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

- Structure functions, $F_2^{NC}$, $F_3^{NC}$, include quark structure of proton and quark coupling to gauge bosons as well $M_Z$.

$$\begin{pmatrix} F_2^{NC} \\ xF_3^{NC} \end{pmatrix} = \sum_f \begin{pmatrix} xA_f(q_f + \overline{q_f}) \\ xB_f(q_f - \overline{q_f}) \end{pmatrix}$$

- $F_3$ is a parity violating term. Sign changes in $e^+$/$e^-$.
- $F_L$ is non-zero at NLO-QCD and is only relevant at high $y$ in high $Q^2$ region.($\sim 10\%$)

CC($e^{\pm}p \rightarrow \nu X$) in LO QCD

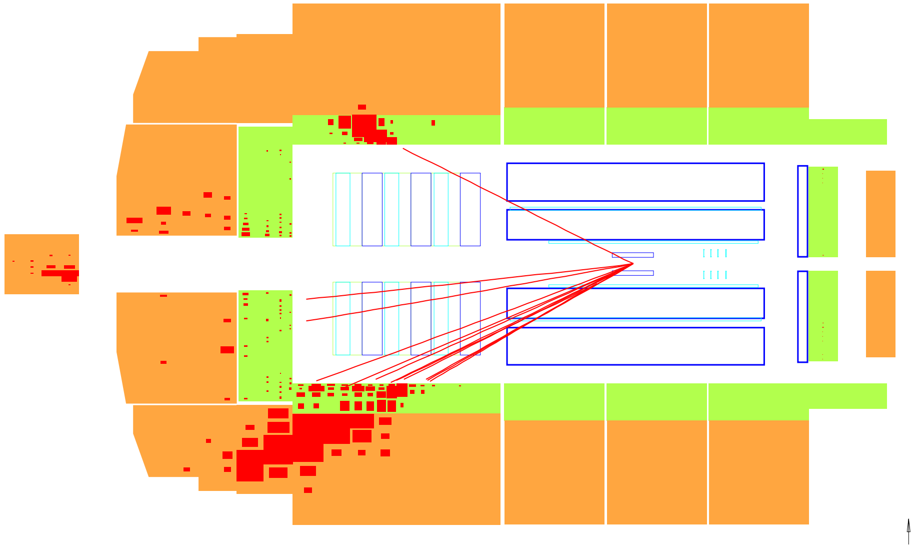
$$e^+p : \frac{d^2\sigma}{dxdQ^2} = \frac{{G_F}^2}{2\pi}\left(\frac{{M_W}^2}{{M_W}^2 + Q^2}\right)^2 \times \sum_{i=1,2}[\overline{u_i} + (1-y)^2 d_i]$$

$$e^-p : \frac{d^2\sigma}{dxdQ^2} = \frac{{G_F}^2}{2\pi}\left(\frac{{M_W}^2}{{M_W}^2 + Q^2}\right)^2 \times \sum_{i=1,2}[u_i + (1-y)^2 \overline{d_i}]$$

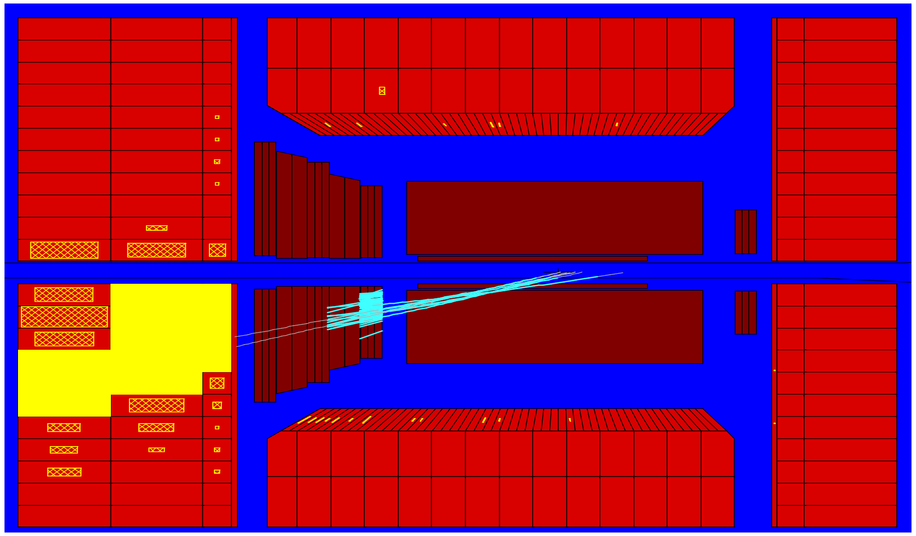
- Flavor selecting; $d$($u$)-quark contributes only to $e^+p$($e^-p$).
- Helicity suppression factor, $(1-y)^2$, is multiplied to quarks (antiquarks) in $e^+p$($e^-p$).

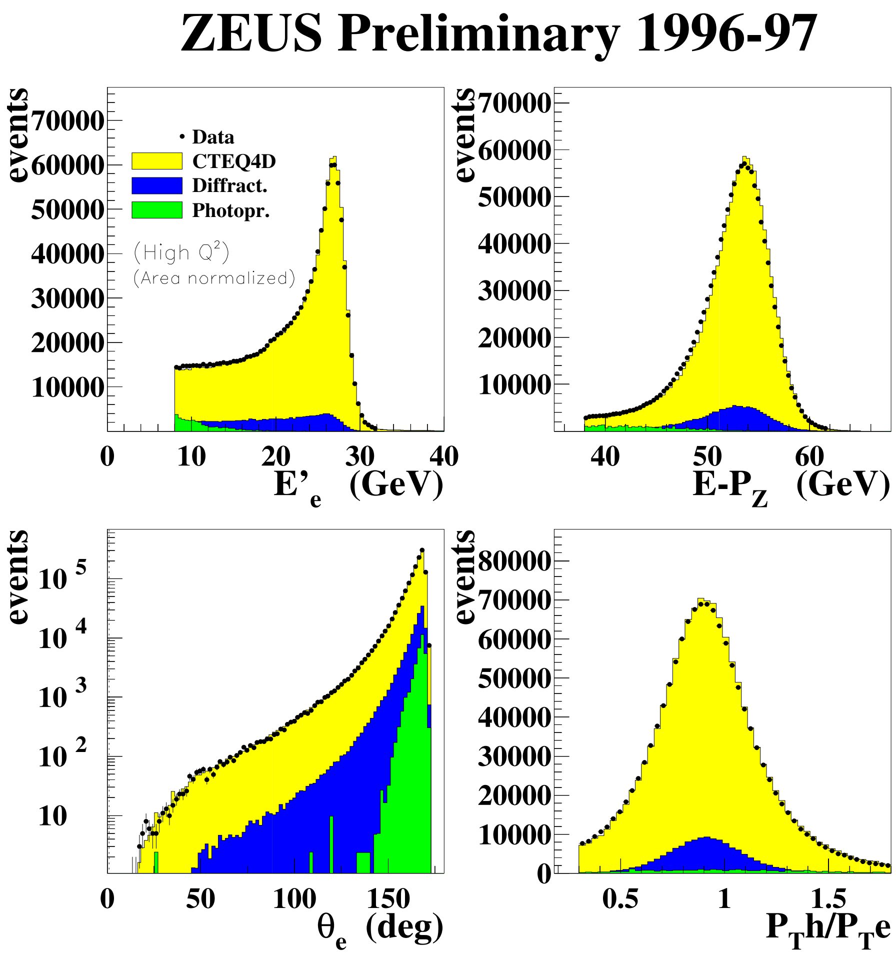
# DIS cross-section measurement

NC signature: a large $E_T$ scattered-$e$.



CC signature: a large $\not{P}_T$ (due to escaped-$\nu$).

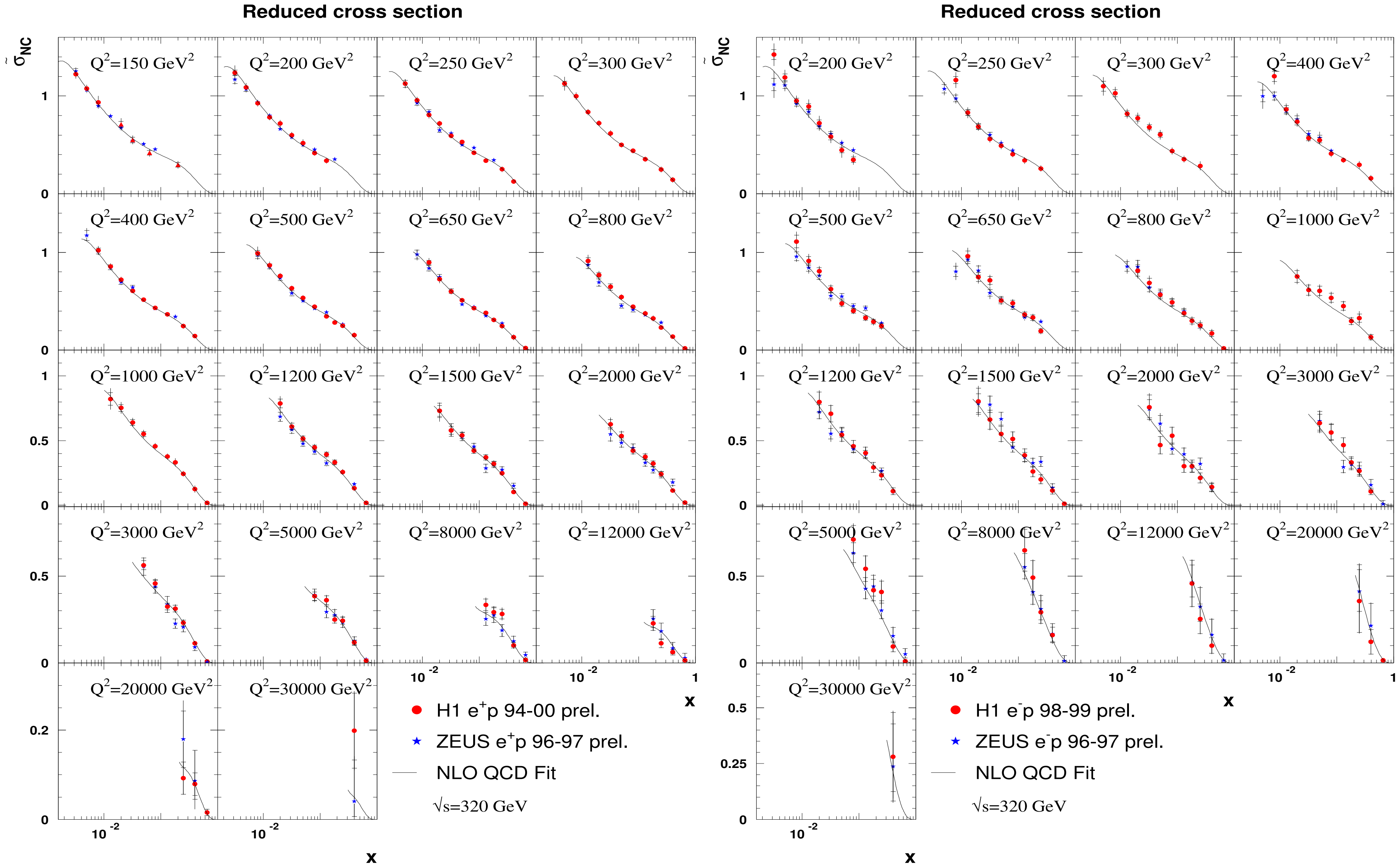





- NC: Both $E'_e$ and $\theta_e$ are well reproduced.
- CC: Hadronic energy measurement is crucial. Well understood and checked with $p_T h/p_T e$ in NC data.

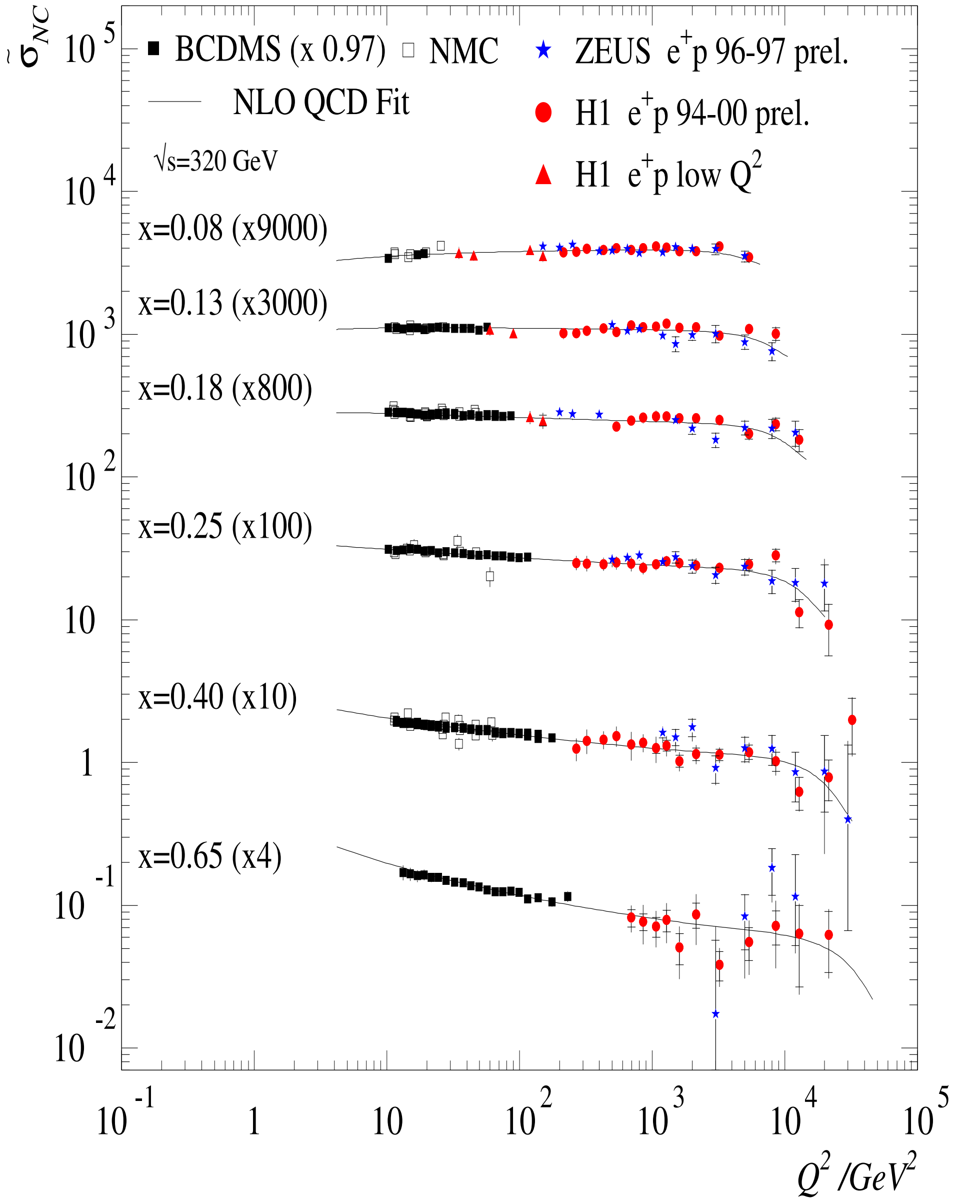
# NC reduced $\tilde{\sigma}_{NC}$: test of pQCD

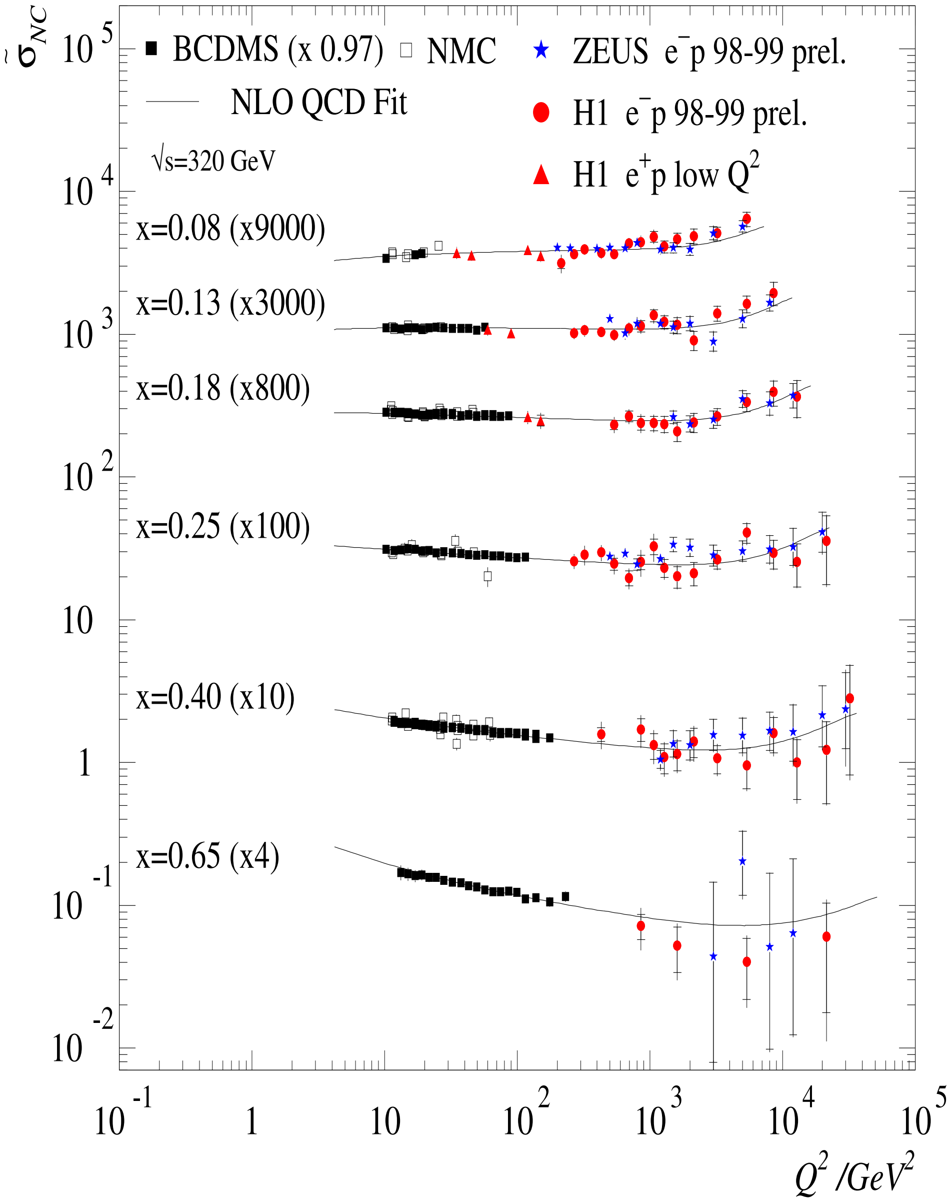
$$\tilde{\sigma}_{NC}(e^{\pm}p) \equiv \left(\frac{Q^2 x}{2\pi\alpha^2 Y_+}\right)\frac{d^2\sigma}{dx\,dQ^2} = F_2^{NC} \mp \frac{Y_-}{Y_+} x F_3^{NC} - \frac{y^2}{Y_+} F_L^{NC}$$




- $\tilde{\sigma}_{NC}$ measured up to $Q^2$=30000 GeV$^2$ $\Rightarrow$ NLO-QCD describes full body of data!

# NC reduced $\tilde{\sigma}_{NC}$ at large $x$, $Q^2$

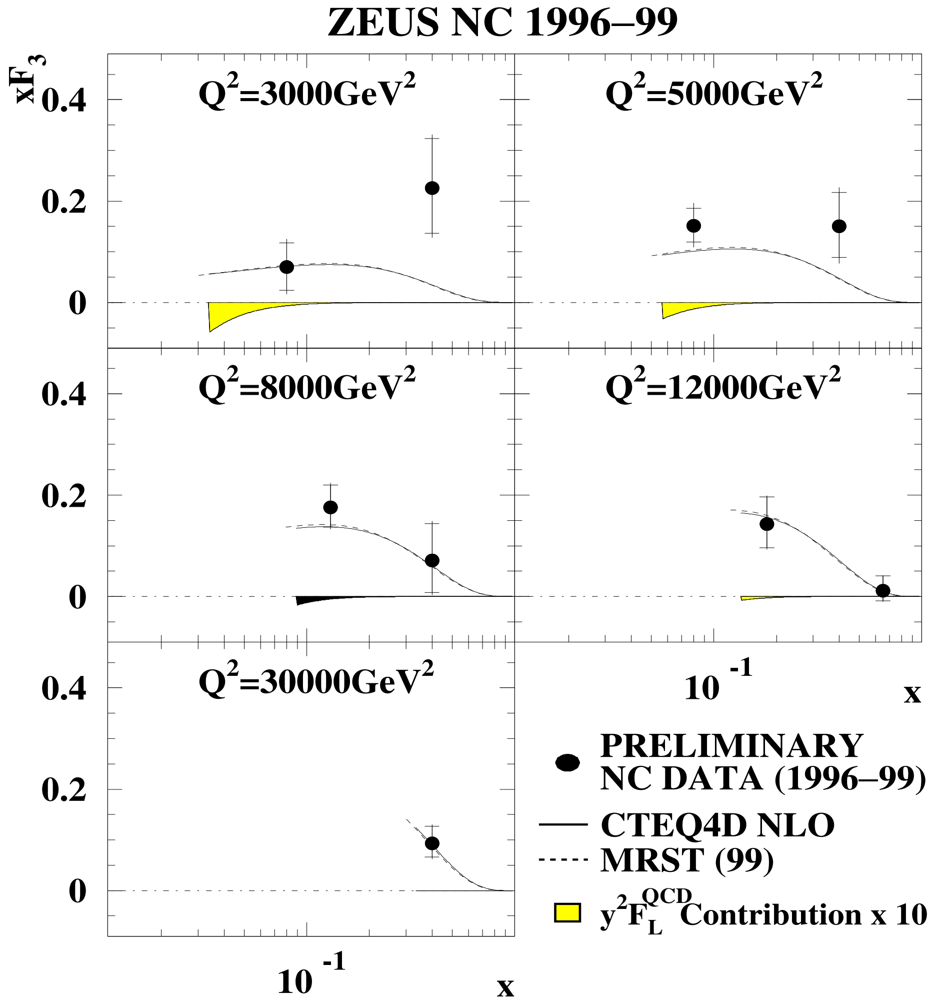


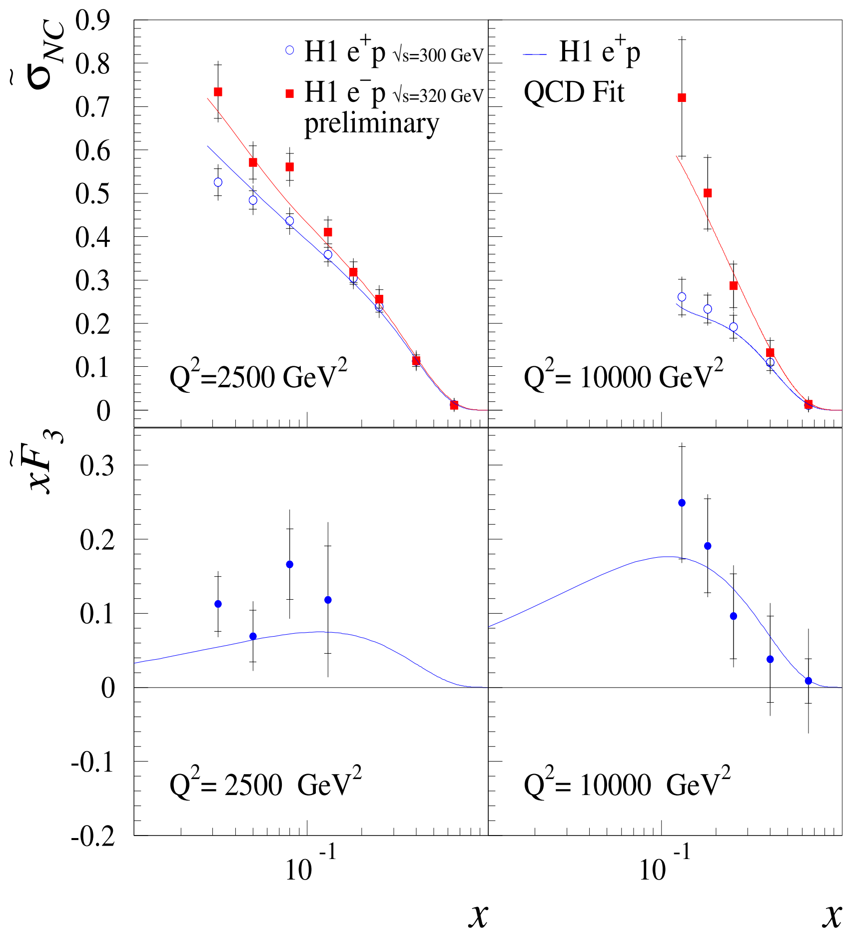

- An excess at $x$=0.4 observed in H1 $e^+p$ '94–'97 diminished by adding new '99–'00.
- Positive(negative) interference between $\gamma$-$Z$ was observed at high-$Q^2$ in $e^-$($e^+$).

# Extraction of $xF_3^{NC}$

$$\tilde{\sigma}_{NC}(e^{\pm}p) = F_2^{NC} \mp \frac{Y_-}{Y_+} xF_3^{NC} - \frac{y^2}{Y_+} F_L^{NC} \Rightarrow xF_3 = \left(\frac{Y_-^{920}}{Y_+^{920}} + \frac{Y_-^{820}}{Y_+^{820}}\right)^{-1} \{\tilde{\sigma}_{NC}(e^- p) - \tilde{\sigma}_{NC}(e^+ p)\} + \Delta F_L$$




(Different beam energy = different $y$ for same $(x,Q^2)$.)

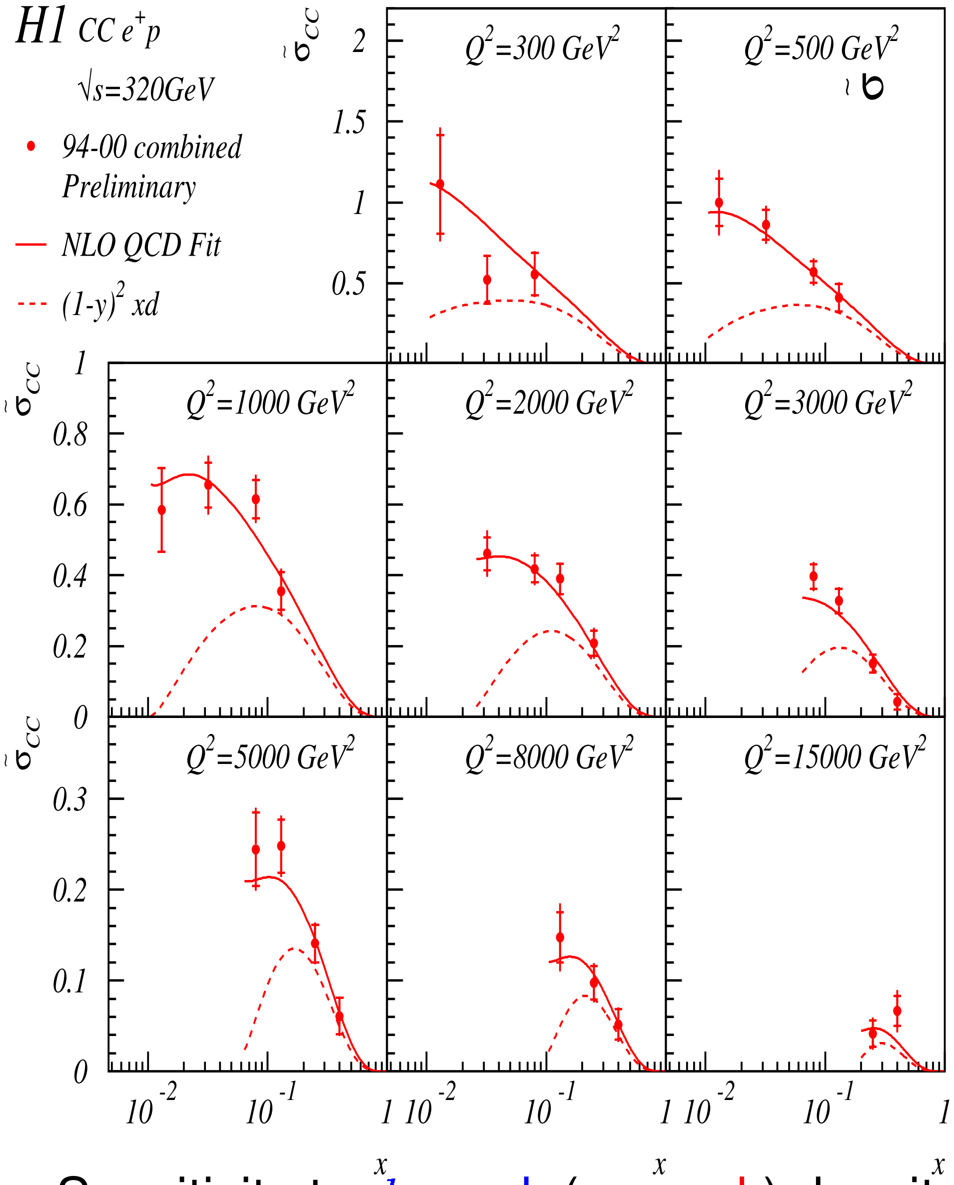


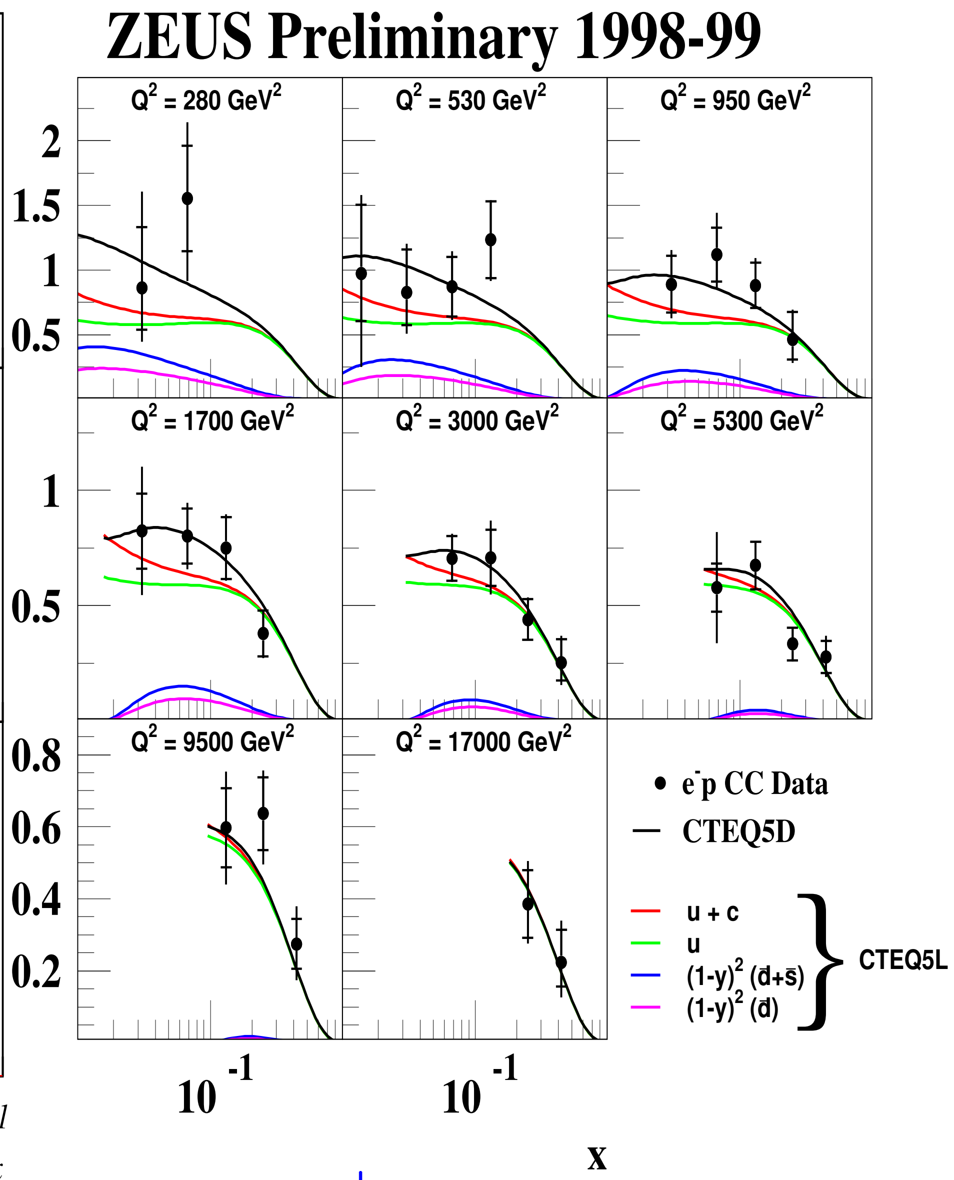

- First measurement of $xF_3^{NC}$ at large $Q^2$.
- $F_L$ correction is only 10% at lowest $Q^2$ and lowest $x$(=highest $y$).
- Errors are limited by $e^-$ statistics.

# Flavor-specific PDF: CC reduced $\tilde{\sigma}_{CC} \equiv \frac{G_F{}^2}{2\pi x}\left(\frac{M_W{}^2}{M_W{}^2+Q^2}\right)^2 \frac{d^2\sigma}{dx\,dQ^2}$

$$\tilde{\sigma}_{CC} = x \sum_{i=1,2} [\overline{u_i} + (1-y)^2 d_i]$$

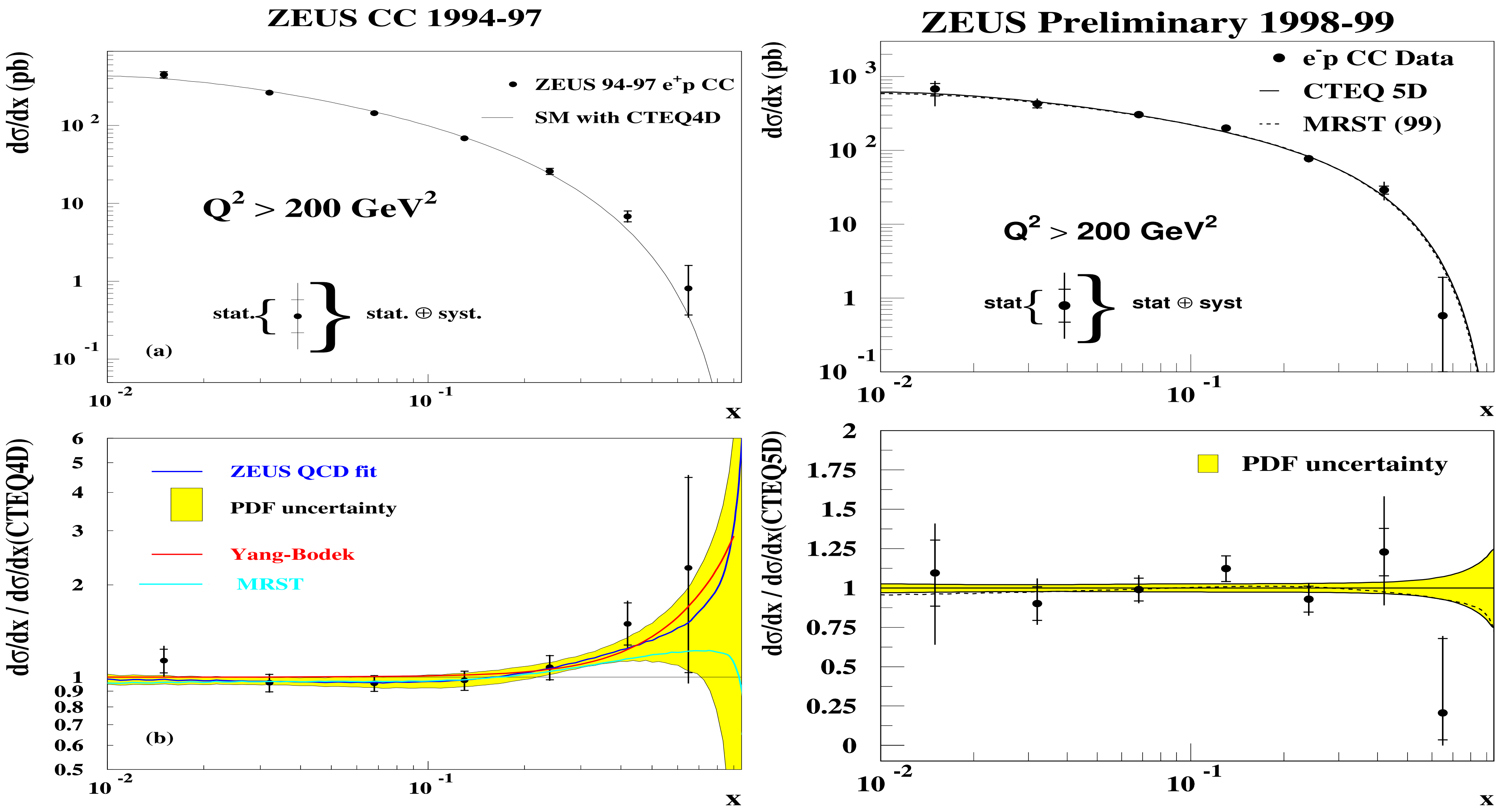
$$\tilde{\sigma}_{CC} = x \sum_{i=1,2} [u_i + (1-y)^2 \overline{d_i}]$$




- Sensitivity to $d$-quark ($u$-quark) density at high-$x$ in $e^+$($e^-$).

# $d/u$ at high-$x$: CC $d\sigma/dx$ (ZEUS)




- Large uncertainty at high-$x$ where $d$-quark dominantly contributes.
- Yang-Bodek (= a reanalysis of NMC $F_2{}^d$) $\Rightarrow$ increase $d$-quark.($d/u \to 0.2$ at $x \to 1$).

- $e^-p$ CC is sensitive to $u$-quark density at high-$x$.

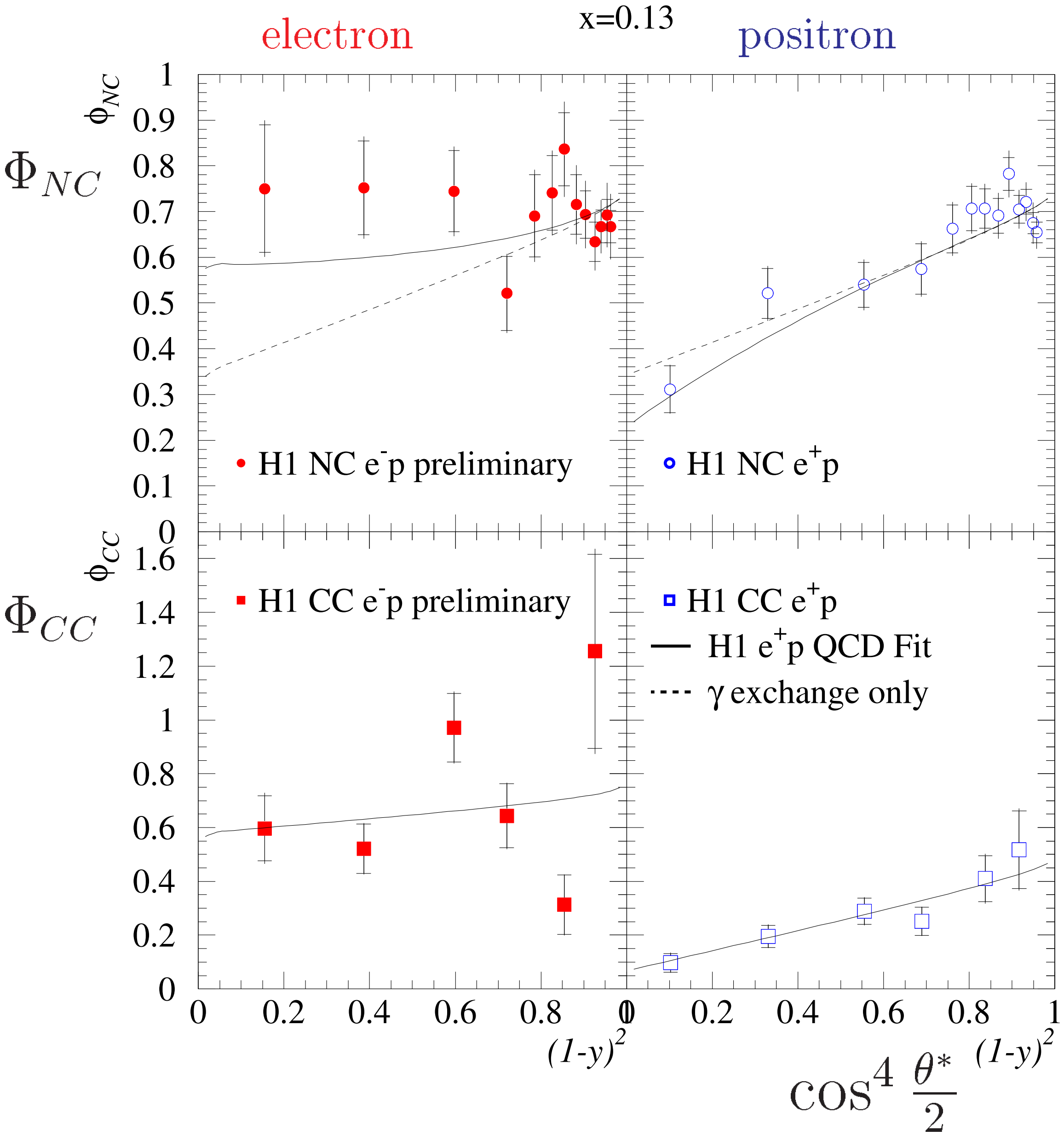
- HERA now provides $d/u$ at high-$x$ at high-$Q^2$ (=free from target-mass and higher-twist effects etc.) and suggests a higher $d/u$.

# An intuitive PDF visualization: $\tilde{\sigma}$ vs $(1-y)^2$

$$\Phi_{NC} \equiv Y_+ \tilde{\sigma}_{NC} = (F_2^{NC} \mp xF_3^{NC}) + (1-y)^2 (F_2^{NC} \pm xF_3^{NC})$$
$$= x\left(\tfrac{4}{9}u + \tfrac{1}{9}d\right)\{1 + (1-y)^2\} \quad \text{for } \gamma\text{-only, LO.}$$

$$\Phi_{CC} \equiv \tilde{\sigma}_{CC} = \begin{cases} x\bar{u} + (1-y)^2 xd & \text{for } e^+p \\ xu + (1-y)^2 x\bar{d} & \text{for } e^-p \end{cases}$$

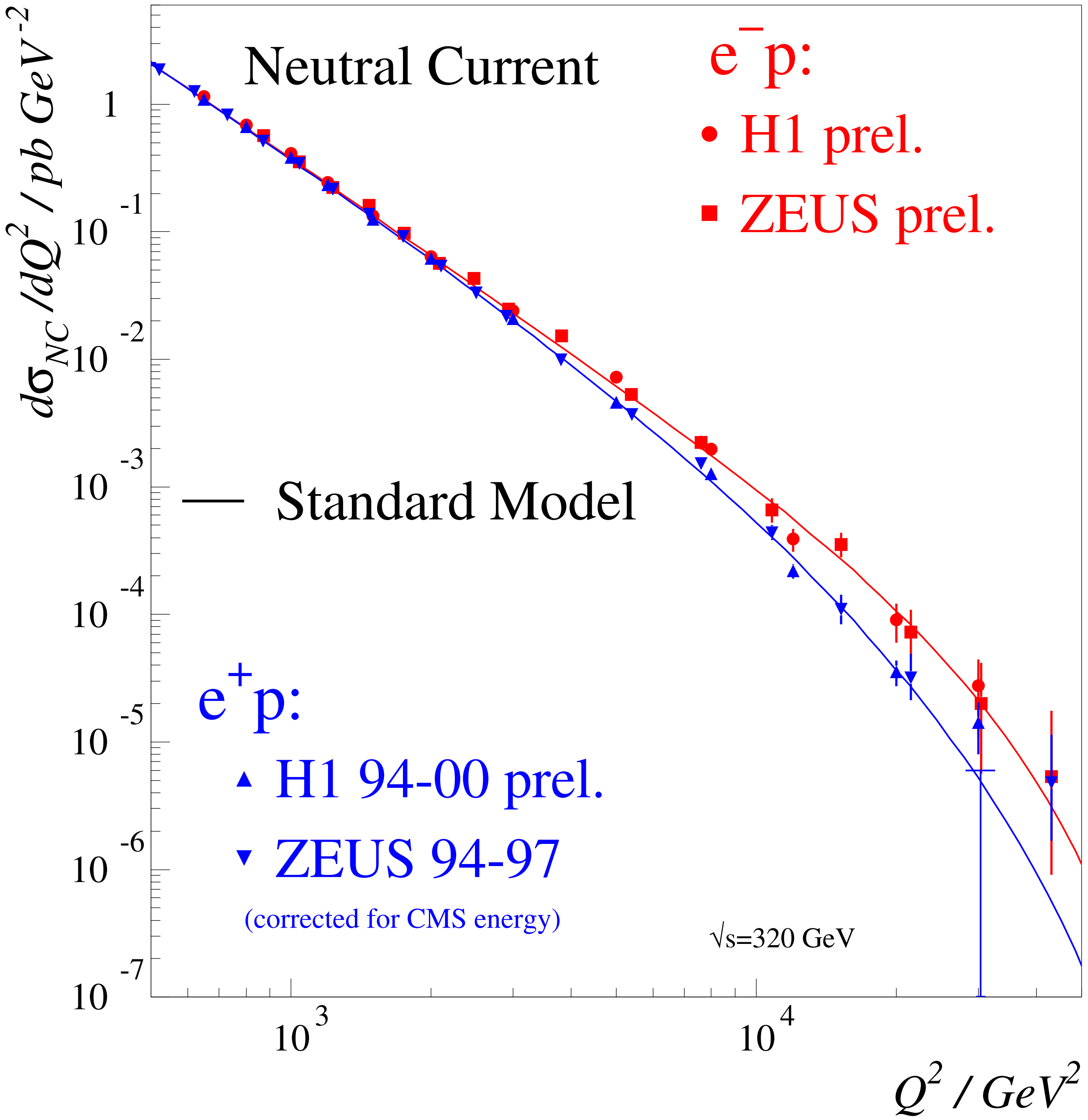
At $x \approx 0.1$, i.e. in an approximate Bjorken scaling region,
$\Rightarrow$ helicity structure can be seen separately: $(1-y)^2 = \cos^4 \theta^*/2$




- NLO-QCD gives a good description of data.
- Naive QPM gives an intuitive picture of PDF and agrees within $\sim 20\%$ level.

# NC $d\sigma/dQ^2$: investigate to the smallest $\lambda$

$$\frac{d^2\sigma(e^{\pm}p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \times \{Y_+ {F_2}^{NC} \mp Y_- x{F_3}^{NC} - y^2 F_L^{NC}\}$$

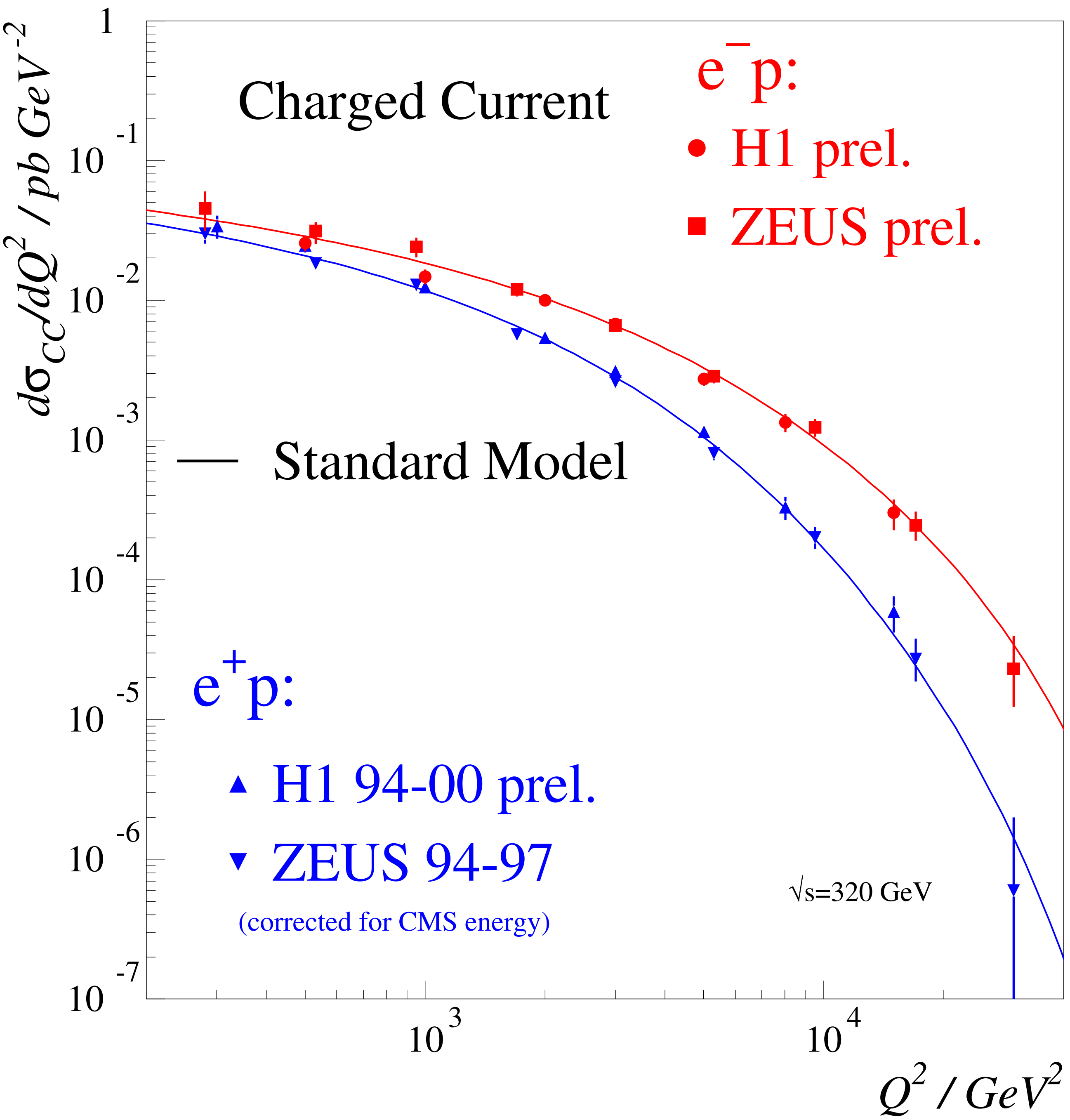



- Measured cross sections agree well with SM predictions 6 orders of magnitude.
- NLO-QCD describes data up to the very high $Q^2$: $Q^2 \lesssim 20000$ GeV$^2$!

## CC $d\sigma/dQ^2$: investigate to the smallest $\lambda$

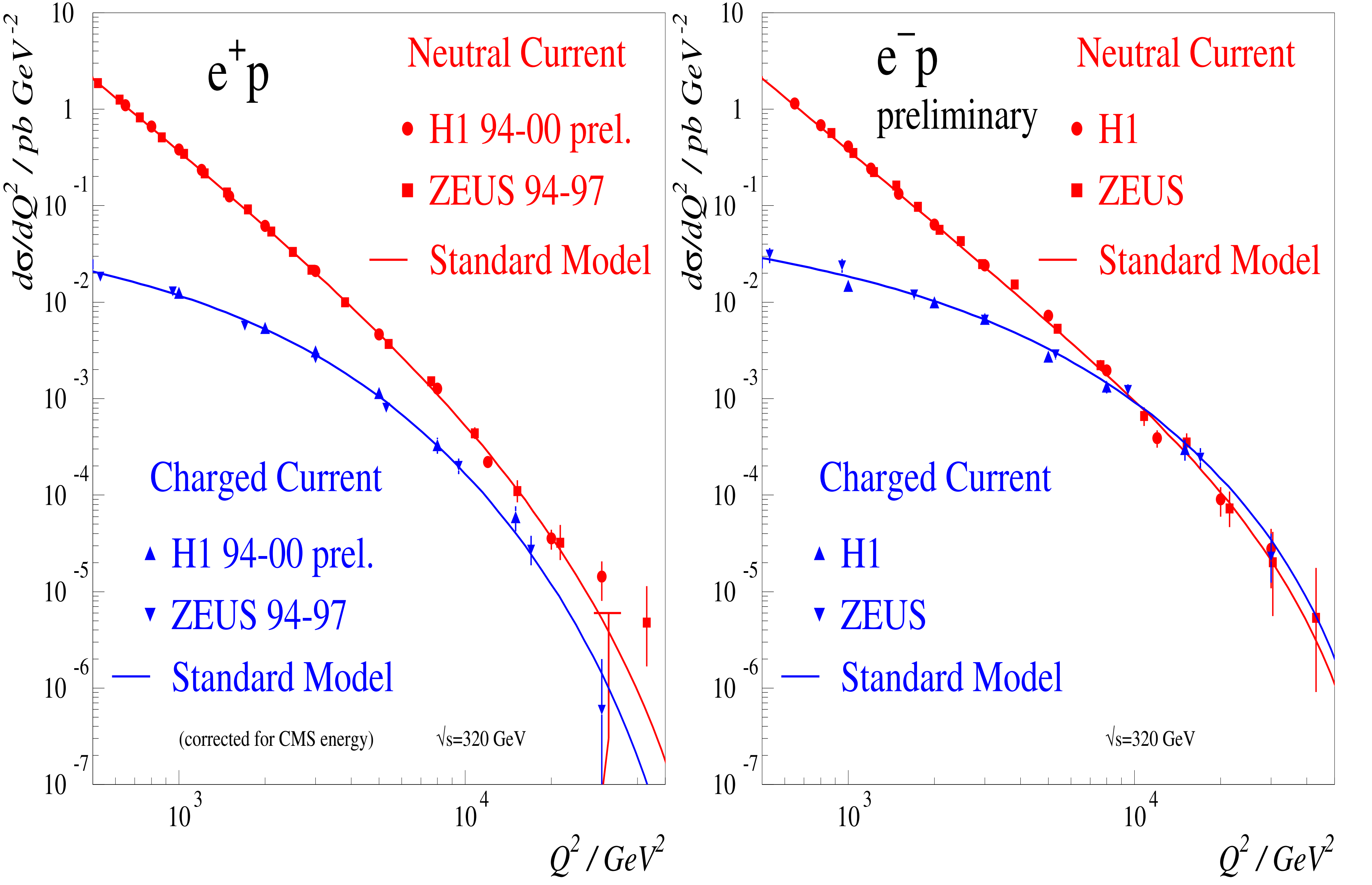
$$e^+p: \frac{d^2\sigma}{dxdQ^2} = \frac{{G_F}^2}{2\pi}\left(\frac{{M_W}^2}{{M_W}^2+Q^2}\right)^2 \times \sum_{i=1,2}[\overline{u_i} + (1-y)^2 d_i]$$

$$e^-p: \frac{d^2\sigma}{dxdQ^2} = \frac{{G_F}^2}{2\pi}\left(\frac{{M_W}^2}{{M_W}^2+Q^2}\right)^2 \times \sum_{i=1,2}[u_i + (1-y)^2 \overline{d_i}]$$




- Consistent with SM.
- $e^-p$ data order of magnitude above $e^+p$ due to: $\sigma(e^-p) \propto (u+c)$ while $\sigma(e^+p) \propto (1-y)^2(d+s)$ .

# High-$Q^2$ DIS at HERA: Electro-weak Unification



# EW sector in CC: $M_W$ determination

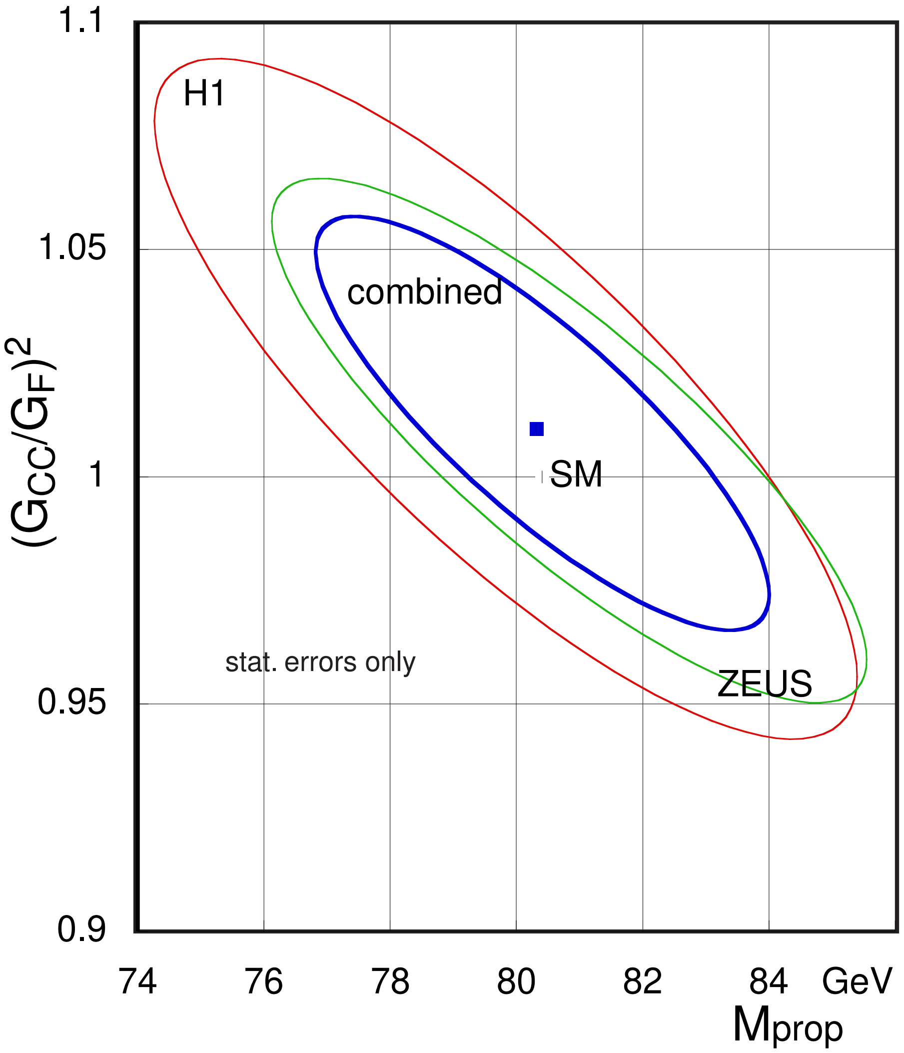
$$d\sigma/dQ^2 \propto {G_F}^2 \times (\frac{M_W^2}{M_W^2+Q^2})^2,$$

(PDG'98: $M_W = 80.41 \pm 0.10$ GeV).

- Unconstrained fit

⇒ spacelike measurement of $M_W$.

⇒ complementary to timelike measurements at LEP/Tevatron.




- $G_F$-fixed fit : Fitting the shape.

⇒ measurement of the propagator mass.

$$M_W = 81.4^{+2.7}_{-2.6}(\text{stat.}) \pm 2.0(\text{syst.})^{+3.3}_{-3.0}(\text{PDF})\ \text{GeV} \qquad (\text{ZEUS})$$

$$M_W = 80.9 \pm 3.3(\text{stat.}) \pm 1.7(\text{syst.}) \pm 3.7(\text{theo.})\ \text{GeV} \qquad (\text{H1})$$

# Summary

We have now all 4 cross-sections; NC, CC for $e^+$, $e^-$,

precisely measured at HERA!

NC double differential cross-sections: test of pQCD.

- First extraction of $xF_3^{NC}$ at large $Q^2$.

CC double differential cross-sections: flavor-specific PDF.

- Sensitivity to $d/u$-ratio at high-$x$.

$d\sigma/dQ^2$: to the very high $Q^2$.

- $Q^2 \lesssim 20000$ GeV$^2$: pQCD OK!
- EW-unification observed.

EW sector in DIS.

- $M_W$ determination.

# Outlook

$\rightarrow$ Sep. 2000 : End of HERA 1st era.
2001 $\rightarrow$ : HERA upgrade, high luminosity + $e$-polarization

- Luminosity: 100 pb$^{-1}$ ('92–'00) $\Rightarrow$ 1000 pb$^{-1}$ ('01–'06).
- $e$-polarization: 70% prospected.

$\Rightarrow$ High precision SF measurement at medium$\sim$high $Q^2$, e.g determination of $d/u$-ratio etc...
$\Rightarrow$ EW physics, e.g. determination of $u$,$d$-quark couplings to $Z^0$ etc...

# Summary: ALL 4 NOW.