Electroweak measurements at HERA

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On behalf of

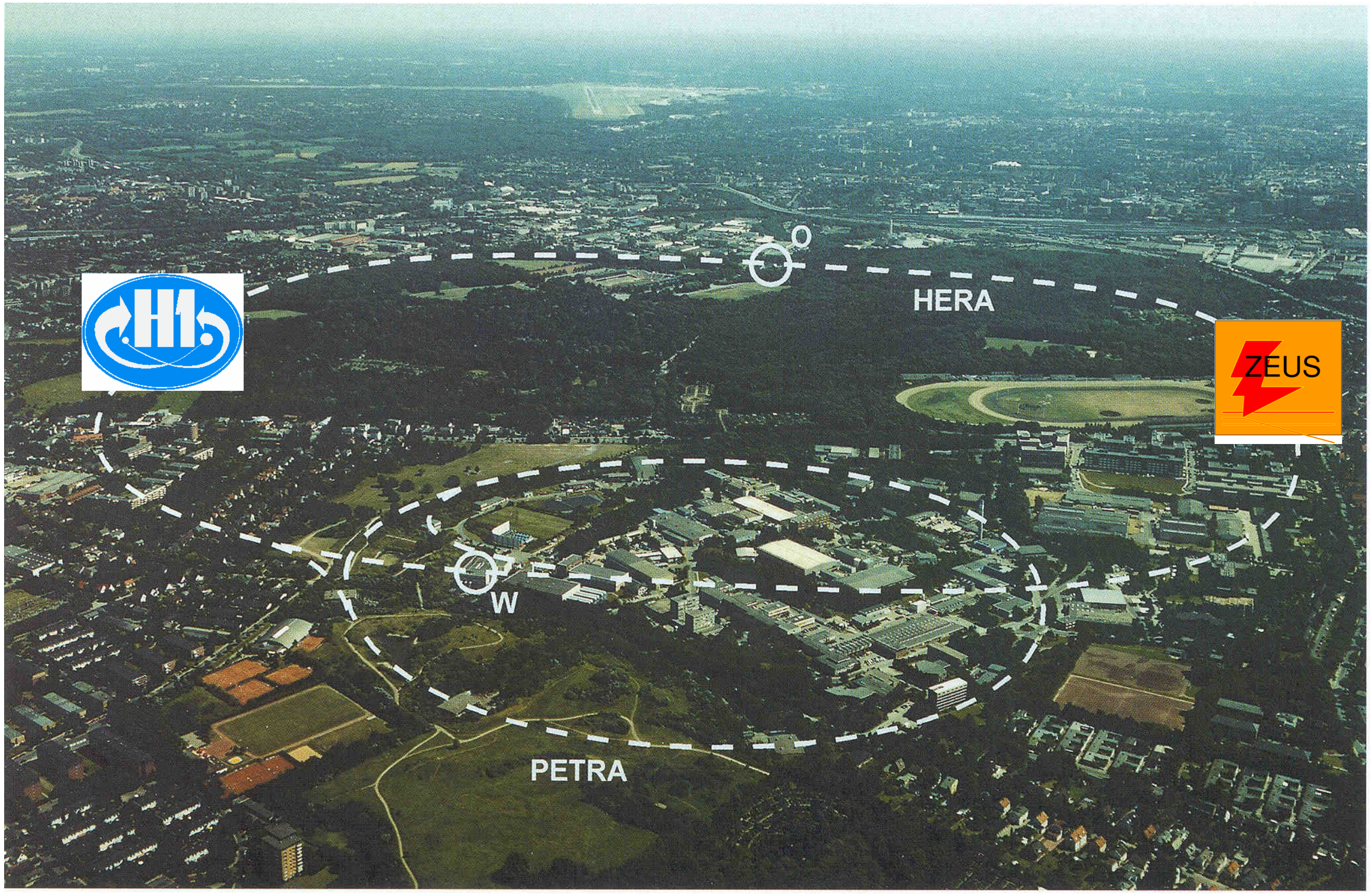
the H1 and ZEUS collaborations

Contents

- HERA and Deep Inelastic Scattering (DIS)
- HERA-I : unpolarised $e^{\pm}p$ scattering
  - DIS cross sections with unpolarised $e^{\pm}$ beam
  - Determination of Electroweak Parameters
- HERA-II : polarised $e^{\pm}p$ scattering
  - New feature at HERA-II
  - DIS cross sections with polarised $e^{\pm}$ beam
  - Measurement of CC and NC Cross Sections
- Summary and Outlook

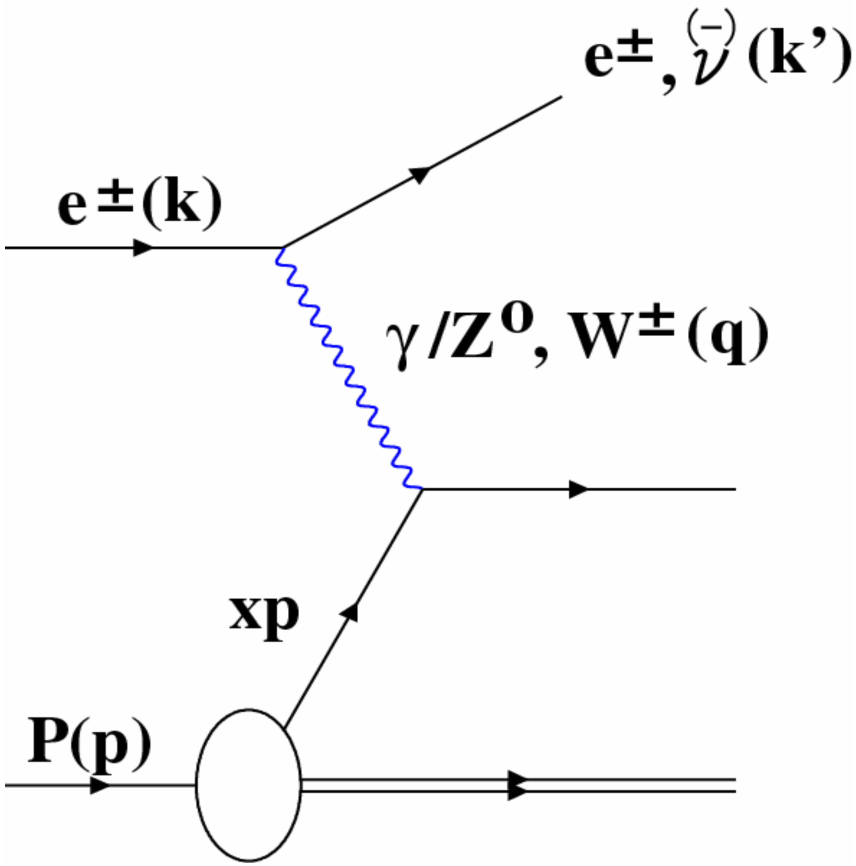
HERA is first and unique ep collider

$$E_p = 920\text{GeV}$$
$$E_{e^\pm} = 27.5\text{GeV}$$
$$\sqrt{s} = 318\text{GeV}$$



Two collider experiments **H1** and **ZEUS**

Deep Inelastic Scattering at HERA



$$Q^2 = -q^2 = -(k-k')^2$$

Virtuality of exchanged boson

$$\text{spatial resolution}: \lambda \approx \frac{1}{\sqrt{Q^2}}$$

$$x = \frac{Q^2}{2p\cdot q}$$

momentum fraction of the struck quark

$$y = \frac{p\cdot q}{p\cdot k}$$

inelasticity

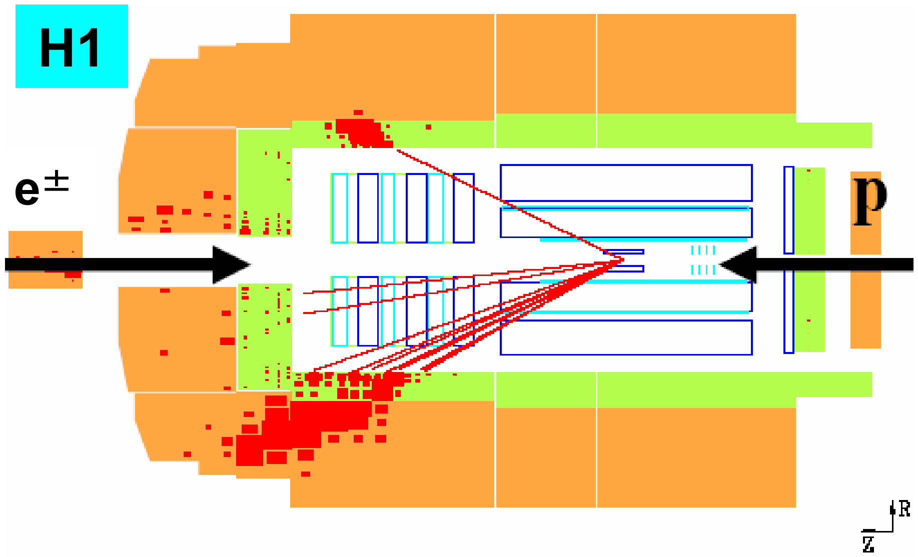
$$s = (p+k)^2 \quad Q^2 = s\cdot x\cdot y$$

Only two independent

- Neutral Current : exchange of γ or Z^0
- Charged Current : exchange of $W^\pm$

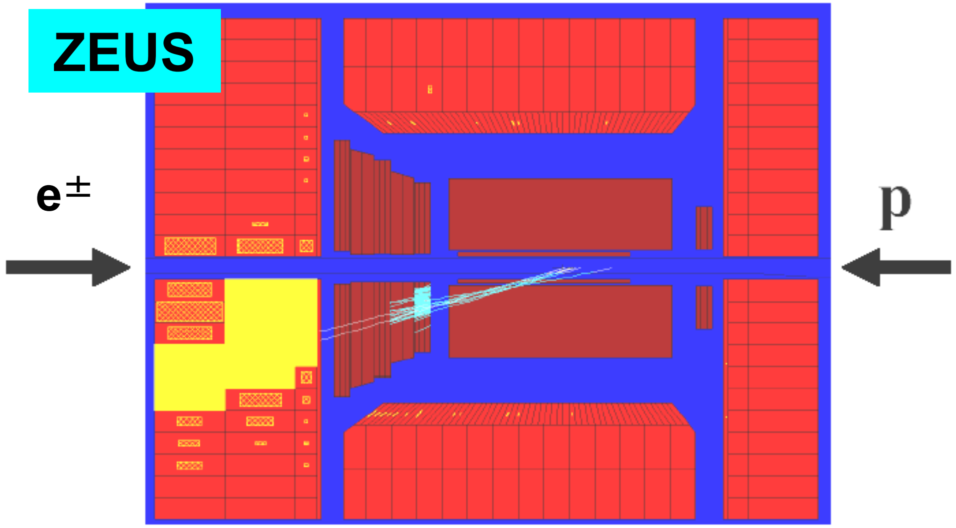
DIS Event Characteristics

Neutral Current



- Selection : presence of high P_T scattered electron
- Kinematics well reconstructed using either electrons or hadrons or both
- Accurate and high statistics which to check the detector response

Charged Current



- Selection : presence of large missing transverse momentum : P_{T},miss
- Kinematics reconstructed using hadrons (only possible)

Contents

NC and CC cross sections

NC Cross Section

$$\frac{d^2\sigma^{NC}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+ F_2^{NC} \mp Y_- xF_3^{NC} - y^2 F_L^{NC}] \qquad Y_{\pm} = 1 \pm (1-y)^2$$

Dominant contribution (F_2^{NC})

Contribution only important at high Q^2 (xF_3^{NC})

Sizeable only at high y (F_L^{NC})

CC Cross Section

e^+p

$$\frac{d^2\sigma^{CC}(e^+p)}{dxdQ^2} = \frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2[\bar{u}+\bar{c}+(1-y^2)(d+s)]$$

e^-p

$$\frac{d^2\sigma^{CC}(e^-p)}{dxdQ^2} = \frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2[u+c+(1-y^2)(\bar{d}+\bar{s})]$$

CC resolve quark flavours

Structure Functions (SFs)

NC structure functions, F_2^{NC} and xF_3^{NC}, can be decomposed as

γ exchange | **γ-Z interference** | **Z exchange**

$$F_2^{NC} = F_2^{\gamma} - v_e K_Z F_2^{\gamma Z} + (v_e^2 + a_e^2) K_Z^2 F_2^Z$$

$$xF_3^{NC} = - a_e K_Z xF_3^{\gamma Z} + 2 v_e a_e K_Z^2 \, xF_3^Z$$

$$K_Z = \frac{1}{4\sin^2\theta_W \cos^2\theta_W} \frac{Q^2}{Q^2 + M_Z^2}$$

$$[F_2, F_2^{\gamma Z}, F_2^Z] = x \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2](q + \bar{q})$$

$$[xF_3^{\gamma Z}, xF_3^Z] = 2x \sum_q [e_q a_q, v_q a_q](q - \bar{q})$$

Experiment measures **Cross-Sections** and extract **SFs**

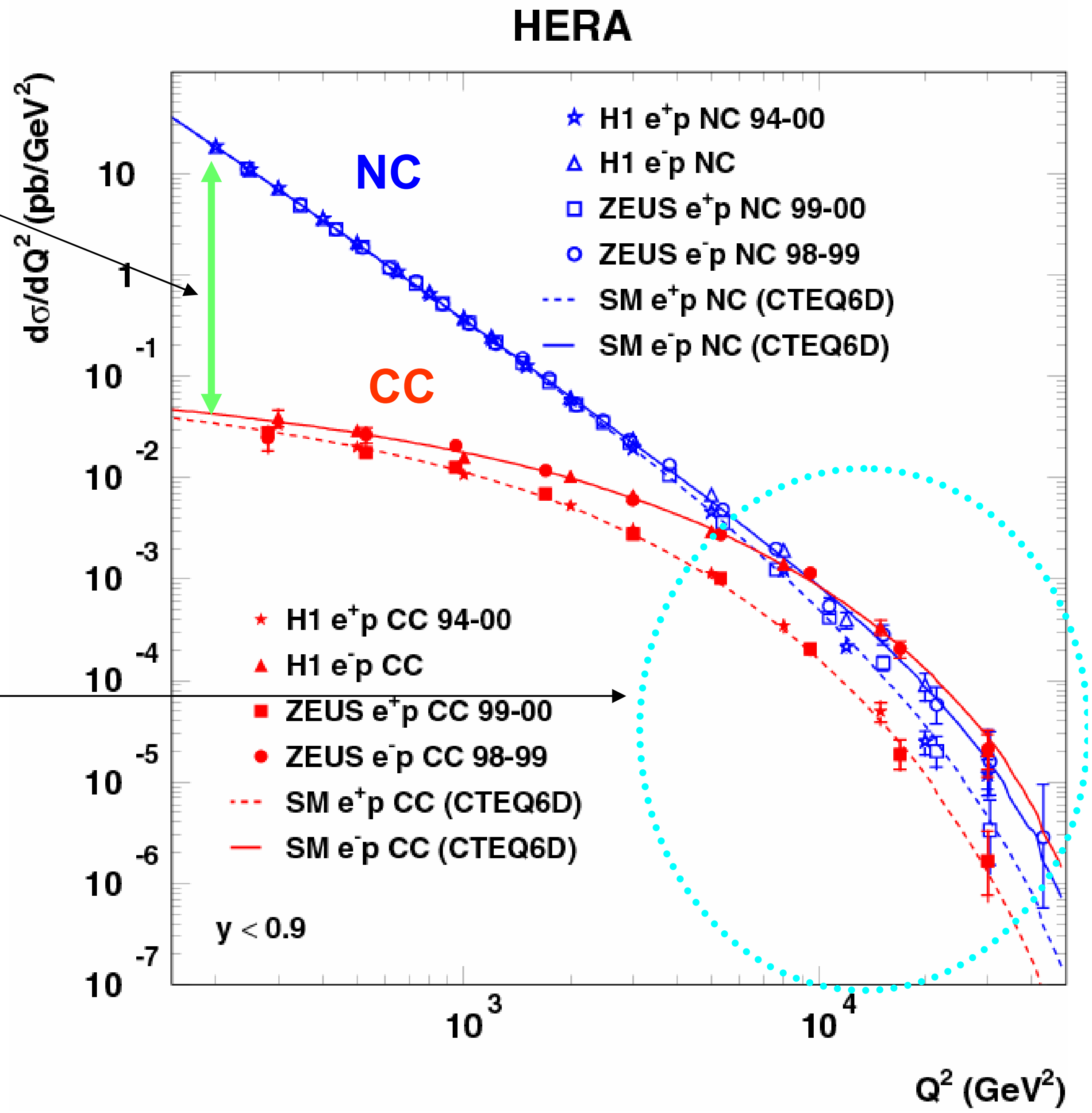
SFs : coupling constant ⊗ Parton Distribution Functions (PDFs)

SFs can constrain PDFs and quark couplings to the Z boson v_q, a_q

Measured NC and CC cross sections

Suppressed due to large mass of W boson compared to NC DIS

Electro-Weak unification at high Q^2



Combined EW-QCD fits (H1)

Using all H1 NC and CC data both $e^{+}p$ and $e^{-}p$,

a combined Electro-Weak (EW) and QCD analysis is performed to determine electroweak parameters accounting for their correlation with PDFs

1. Propagator mass analysis

   To determine the normalisation factor **G** and W propagator mass $\mathbf{M_{prop}}$

2. Determination of quark couplings to Z^0

   To extract $\mathbf{v_{u,d}}$, and $\mathbf{a_{u,d}}$

Propagator mass analysis (H1)

In fit **G-M$_{prop}$-PDFs**,

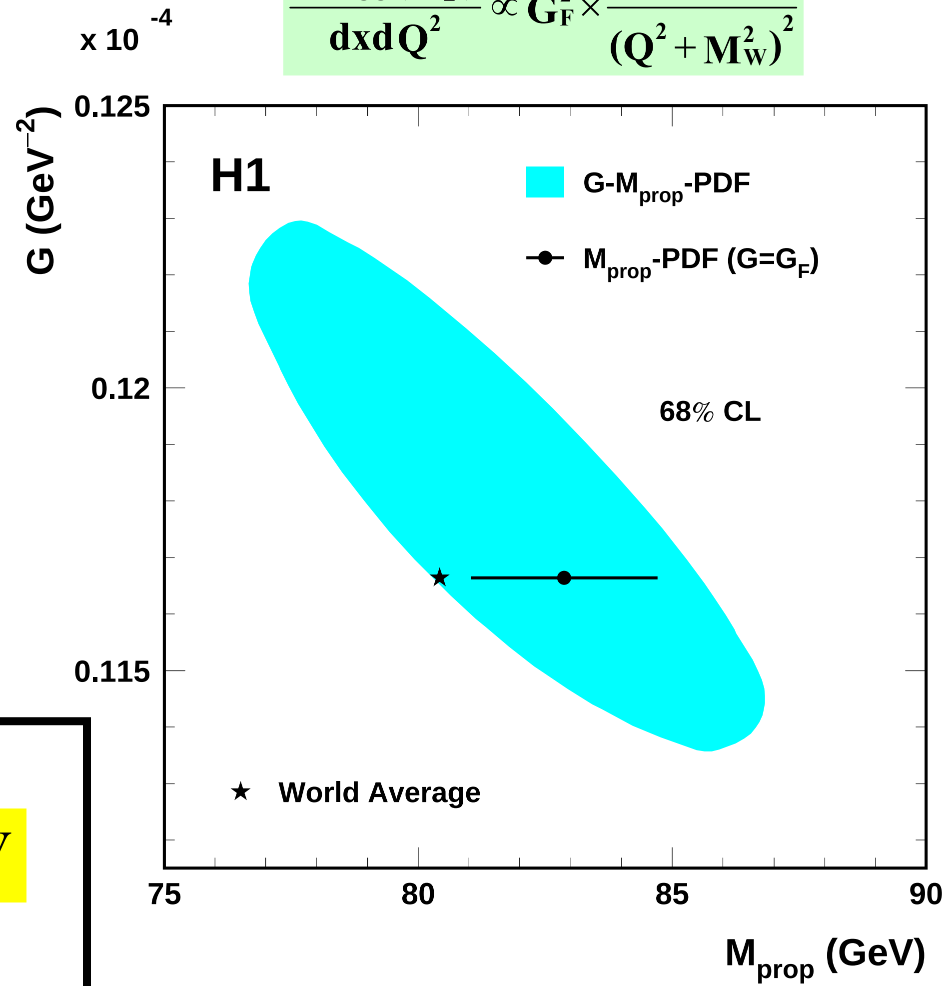
•Sensitivity to G : normalisation of the CC cross section

•Sensitivity to M_{prop} : Q^2 dependence

•G is consistent with G_F obtained from the muon lifetime measurement

•Demonstrating the universality of the CC interaction over a large range of Q^2 values

$$\frac{d^2\sigma_{CC}(e^{\pm}p)}{dx\,dQ^2} \propto G_F^2 \times \frac{M_W^4}{(Q^2+M_W^2)^2}$$



In fit **M$_{prop}$-PDFs**, fixing G to G_F,

$$M_{prop} = 82.87 \pm 1.82(\text{exp})^{+0.30}_{-0.16}(\text{mod})\,\text{GeV}$$

•Measurement of propagator mass in HERA **space-like** region is complementary and consistent with Tevatron/LEP **time-like** one

Determination of quark couplings to Z^0 (H1)

At high Q^2 and high x, NC cross sections are sensitive to the up- and down-type quark couplings dominated by the **light u and d quarks**

Complementary measurement of **heavy quark couplings** measured very precisely by LEP

$$a_q = I_q^3$$

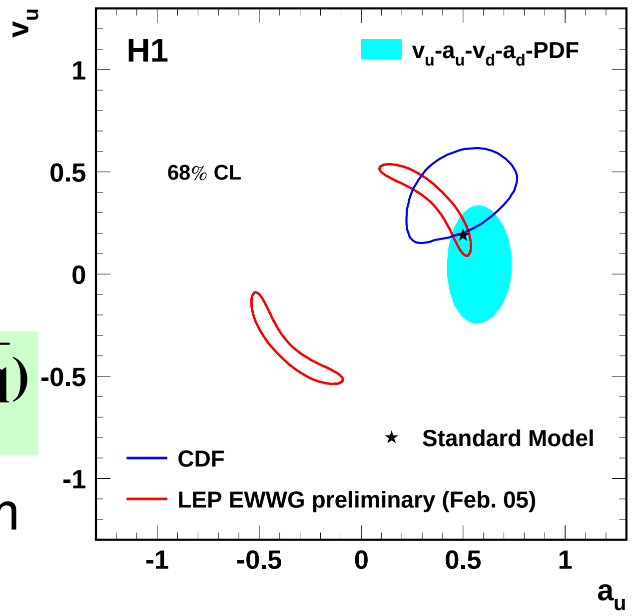
For u, a_q=+1/2

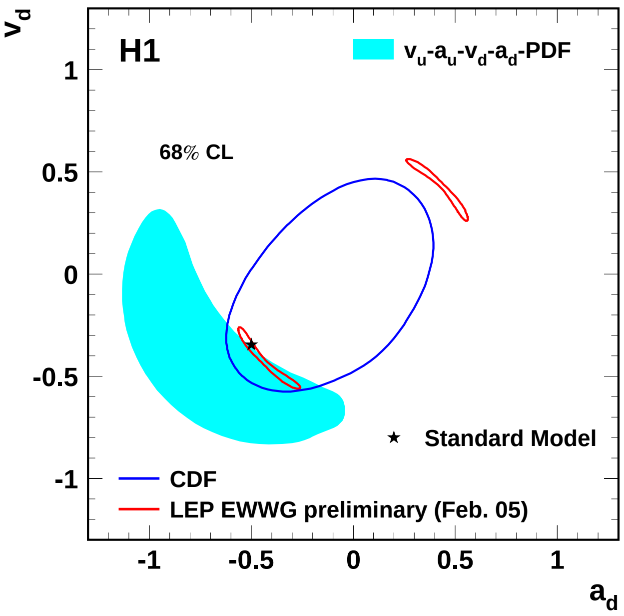
For d, a_q=-1/2

$$v_q = I_q^3 - 2e_q \sin^2\theta_w$$

$$xF_3^{NC} \approx -a_e K_z \cdot 2x \sum_q e_q a_q (q - \bar{q})$$

v_e is small, ignore K_z^2 term





More sensitivity to the U couplings than to D couplings due to PDFs and to the a_q couplings than to v_q couplings for U due to xF_3^{NC}

- **Comparable precision to that from the Tevatron**
- **Remove LEP ambiguities**

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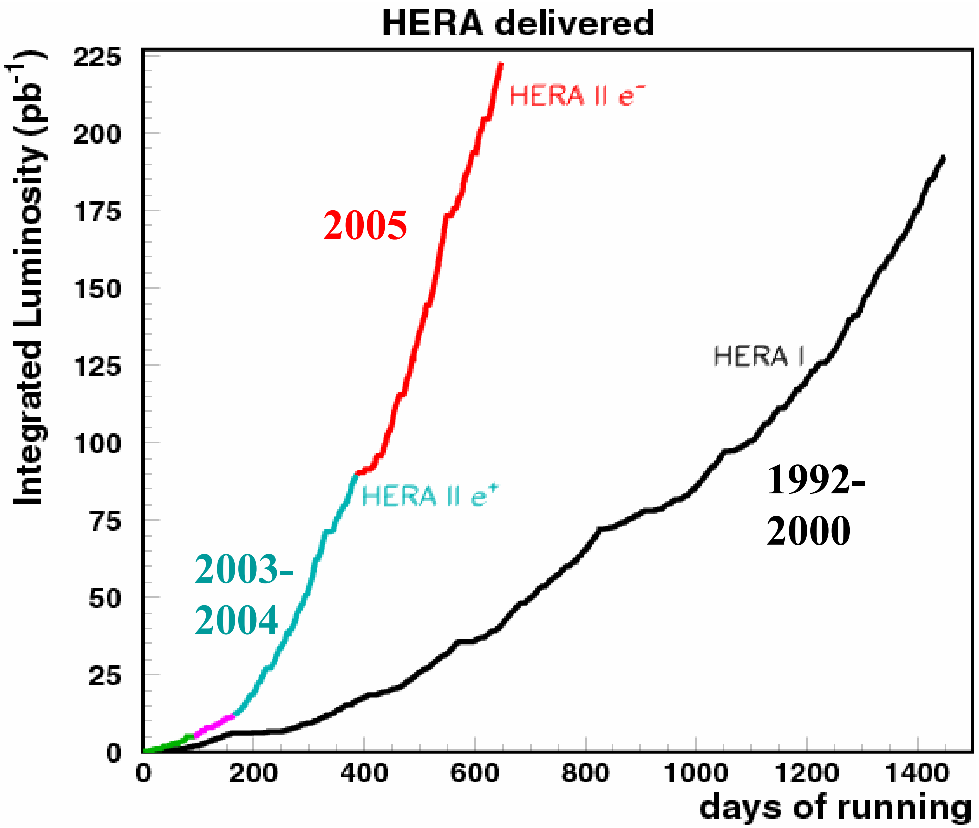
New feature at HERA-II

High Luminosity → sensitivity in High-Q^2 region



Luminosity used for physics analysis per experiment :

HERA-I : 100pb^{-1}(e^+p), 20pb^{-1}(e^-p)

HERA-II : 40pb^{-1}(e^+p), 100pb^{-1}(e^-p)

By the end of the HERA-II in July 2007,

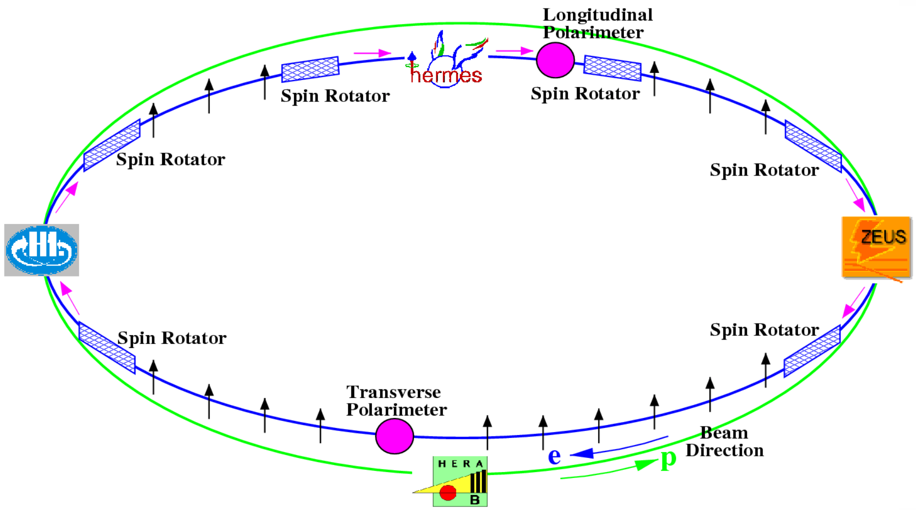
expect ~700pb^{-1}

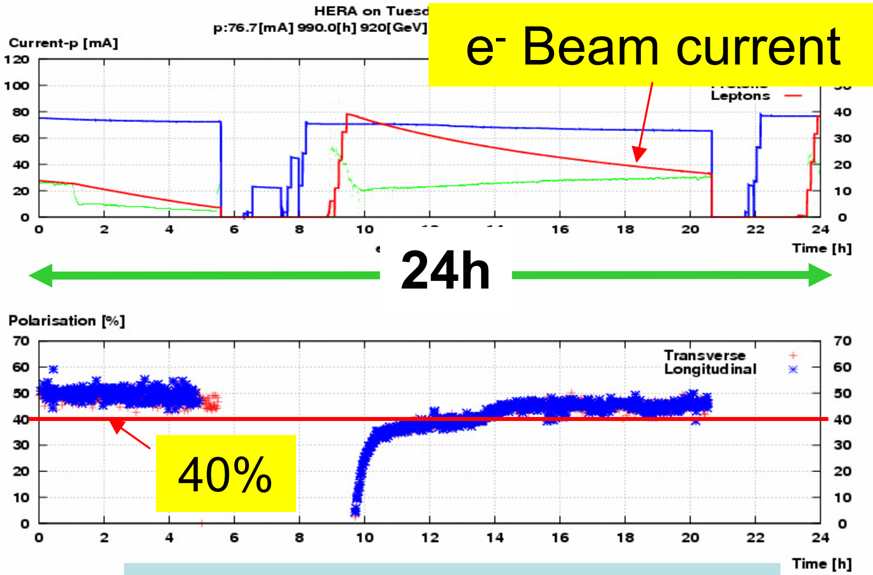
per experiment

New feature at HERA-II (cont'd)

Longitudinal Polarisation of lepton beam → improve EW sensitivity

$e^{\pm}$ beam naturally transversely polarised (Sokolov-Ternov effect) —Spin rotators→ Longitudinally polarised $e^{\pm}$ beam at interaction point





$$\textbf{Polarisation : } P_e = \frac{N_R - N_L}{N_R + N_L}$$

$N_R (N_L)$ is no. of right(left)-handed electrons in the beam

Recent typical P_e ～40%, build-up time ～30min

<u>Polarity is changeable for **RH** and **LH**</u>

<u>→ 4 kinds of data : e^+_{RH}, e^+_{LH}, e^-_{RH}, e^-_{LH}</u>

Polarisation effect on Cross Sections

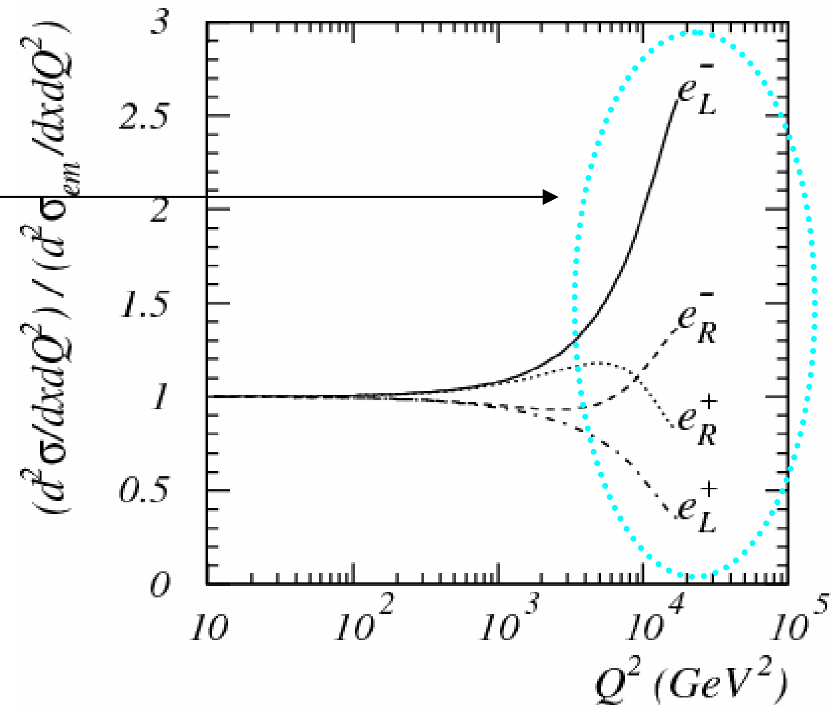
CC : clear and large effect at HERA

- CC is **pure weak**, Cross Section linearly depends on Polarisation
- Direct sensitivity to Right-Handed charged current interaction

$$\sigma_{CC}(P_{e^\pm}) = (1 \pm P_{e^\pm})\sigma_{CC}(P_{e^\pm} = 0)$$

NC : subtle effect at HERA

- Polarised contribution only significant at high Q^2
- Sensitivity to the quark coupling constants to Z^0 goes to be better through the polarisation effect especially for v_q → next slide



Polarised NC DIS cross section

$$\frac{d^2\sigma^{NC}(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[H_0^\pm + P_e H_P^\pm]$$

Unpolarised contribution ($H_0^\pm$)

Polarised contribution ($H_P^\pm$) : only includes γ-Z and Z terms

$$F_2^{NC} = F_2^\gamma - (v_e - P_e a_e) K_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 - 2P_e v_e a_e) K_Z^2 F_2^Z$$

$$xF_3^{NC} = -(a_e - P_e v_e) K_Z xF_3^{\gamma Z} + [2v_e a_e - P_e(v_e^2 + a_e^2)] K_Z^2 \, xF_3^Z$$

$$K_Z = \frac{1}{4\sin^2\theta_W \cos^2\theta_W}\frac{Q^2}{Q^2 + M_Z^2}$$

$$[F_2, F_2^{\gamma Z}, F_2^Z] = x\sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2](q + \bar{q})$$

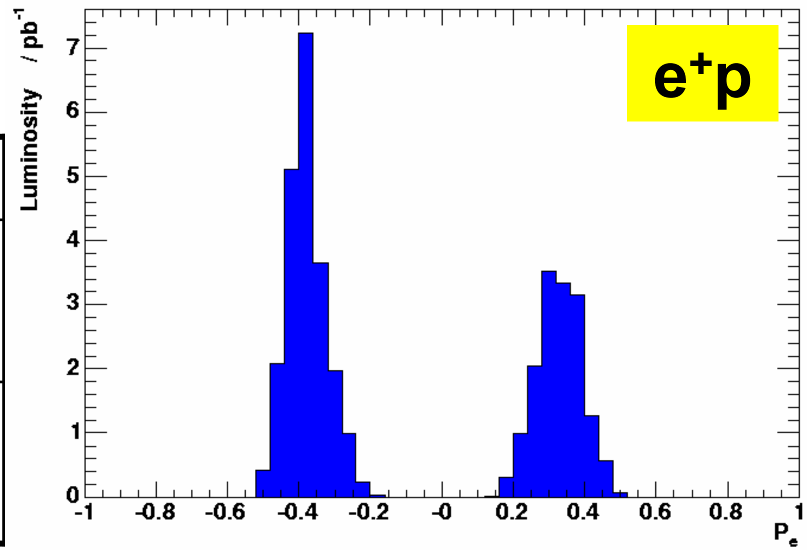
$$[xF_3^{\gamma Z}, xF_3^Z] = 2x\sum_q [e_q a_q, v_q a_q](q - \bar{q})$$

Polarised e$^\pm$ beam helps to constrain v_q

Data samples

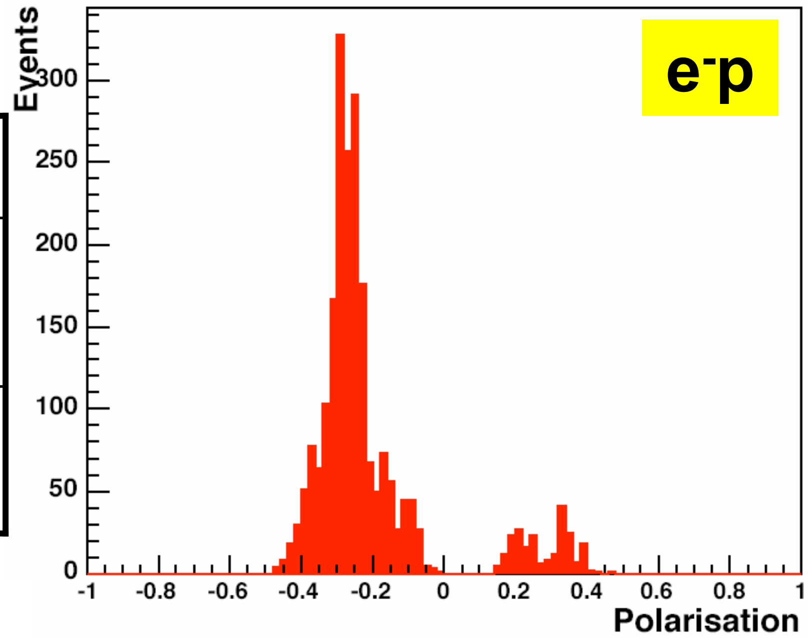
H1 data samples

	P < 0 (LH)	P > 0 (RH)
e^+p data	L = 21.7 pb^{-1} P = – 40.2 %	L = 15.3 pb^{-1} P = + 33.0 %
e^-p data	L = 17.8 pb^{-1} P = – 25.4 %	



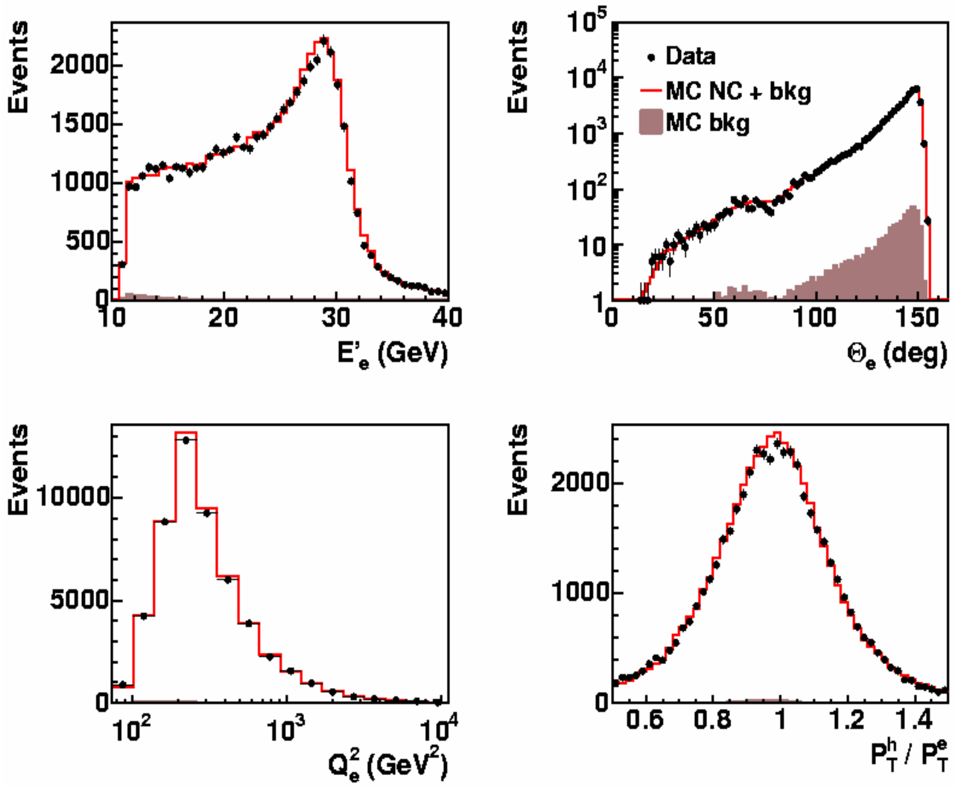
ZEUS data samples

	P < 0 (LH)	P > 0 (RH)
e^+p data	L = 16.4 pb^{-1} P = – 40.2 %	L = 14.1 pb^{-1} P = + 31.8 %
e^-p data	L = 35.3 pb^{-1} P = – 25.9 %	L = 6.5 pb^{-1} P = + 29.2 %



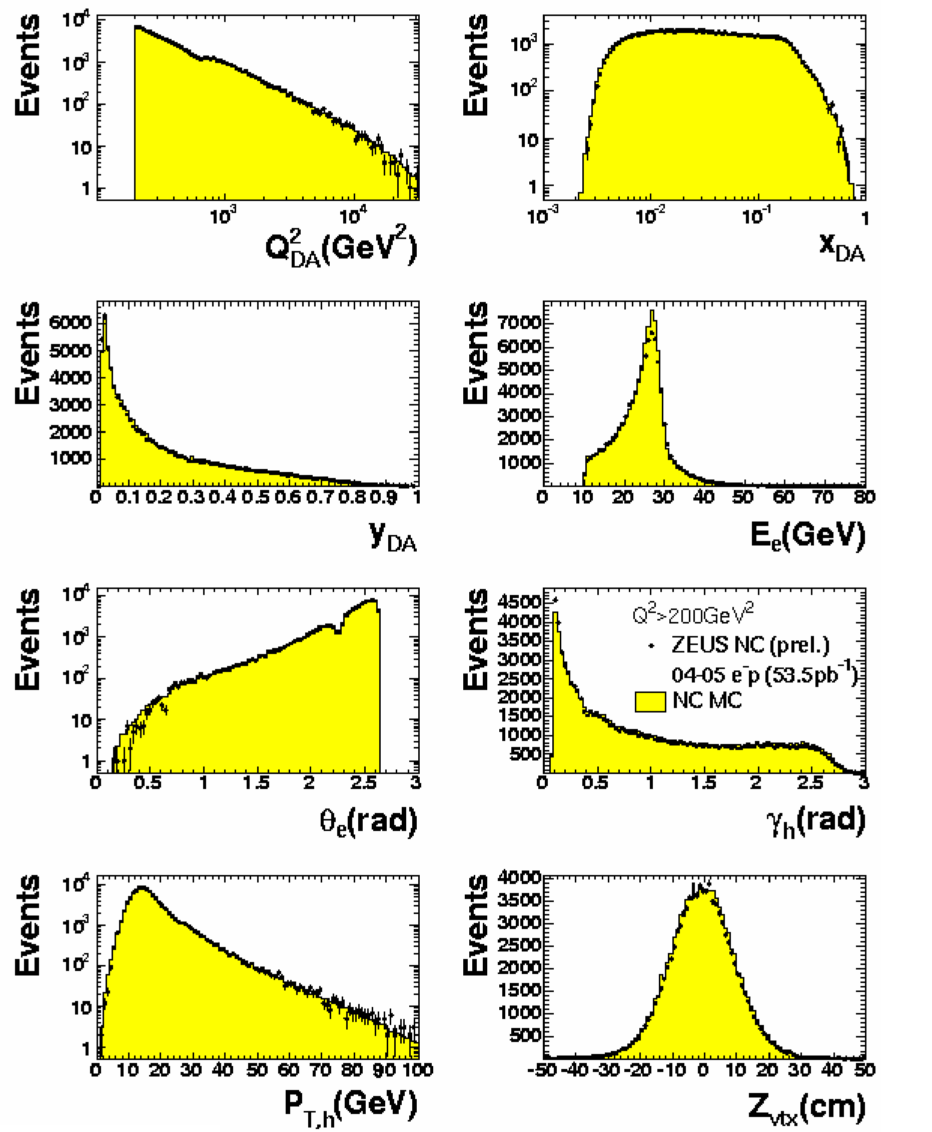
NC events

H1 e⁻p (LH) : Q^2>200GeV^2 and 0.03<y<0.85



ZEUS

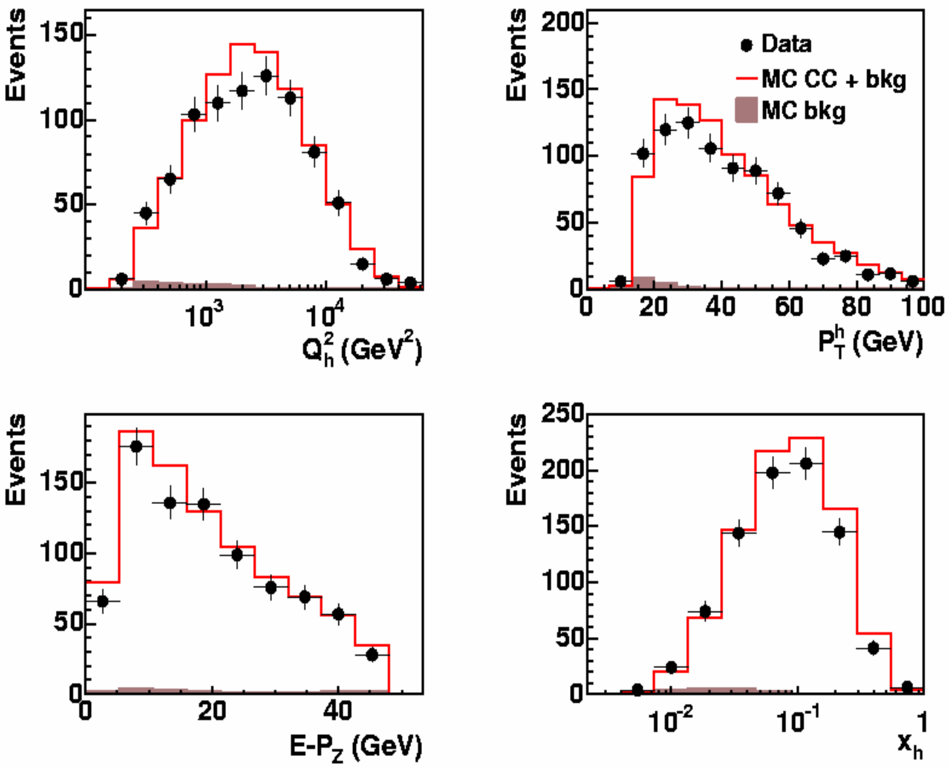
e⁻p Q^2>200GeV^2



- H1/ZEUS detectors are well performing and well understood.
- Hadronic system measurement well understood and checked with NC real data for CC measurement

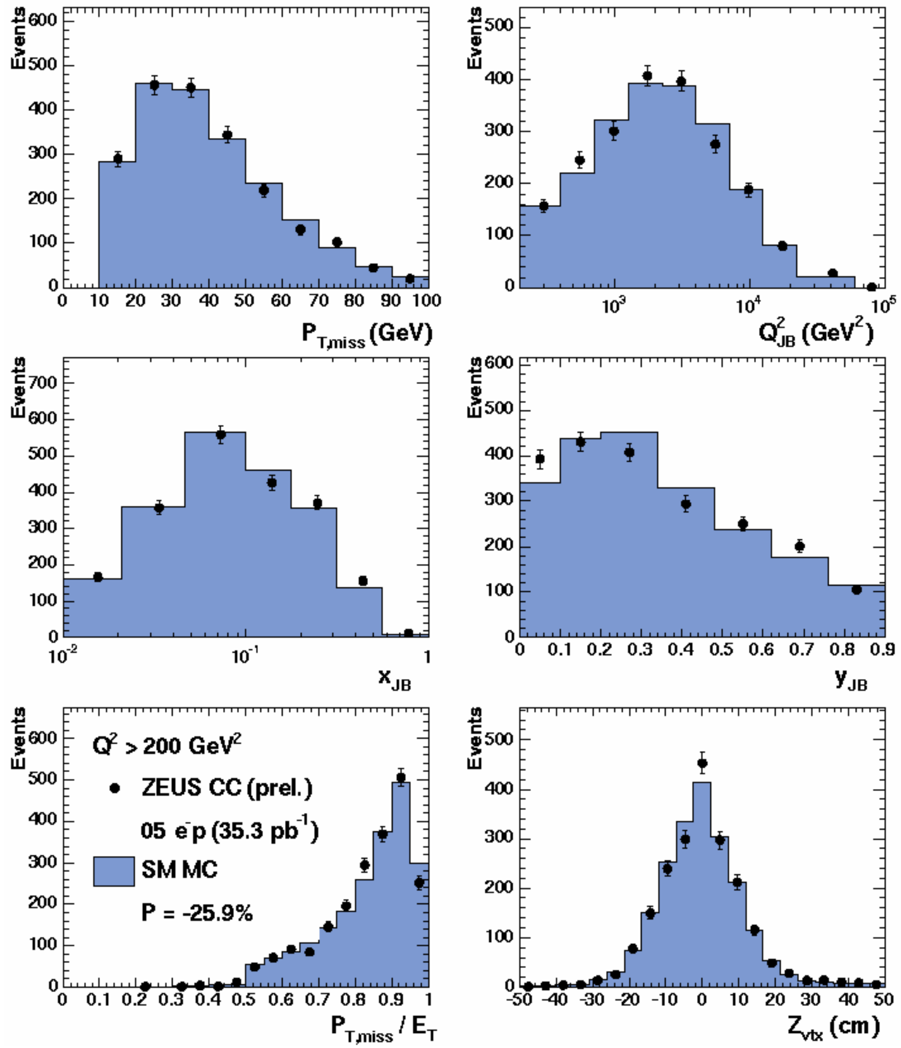
CC events

H1 e⁻p (LH) : Q^2>200GeV^2 and 0.03<y<0.85



ZEUS

e⁻p (LH)
Q^2>200GeV^2
and y<0.9



- Missing transverse momentum $P_{T,miss}$ and longitudinal hadronic energy E-P_z etc. are well described.

Ready to unfold data to get cross-sections!

CC Total Cross-Section (H1)

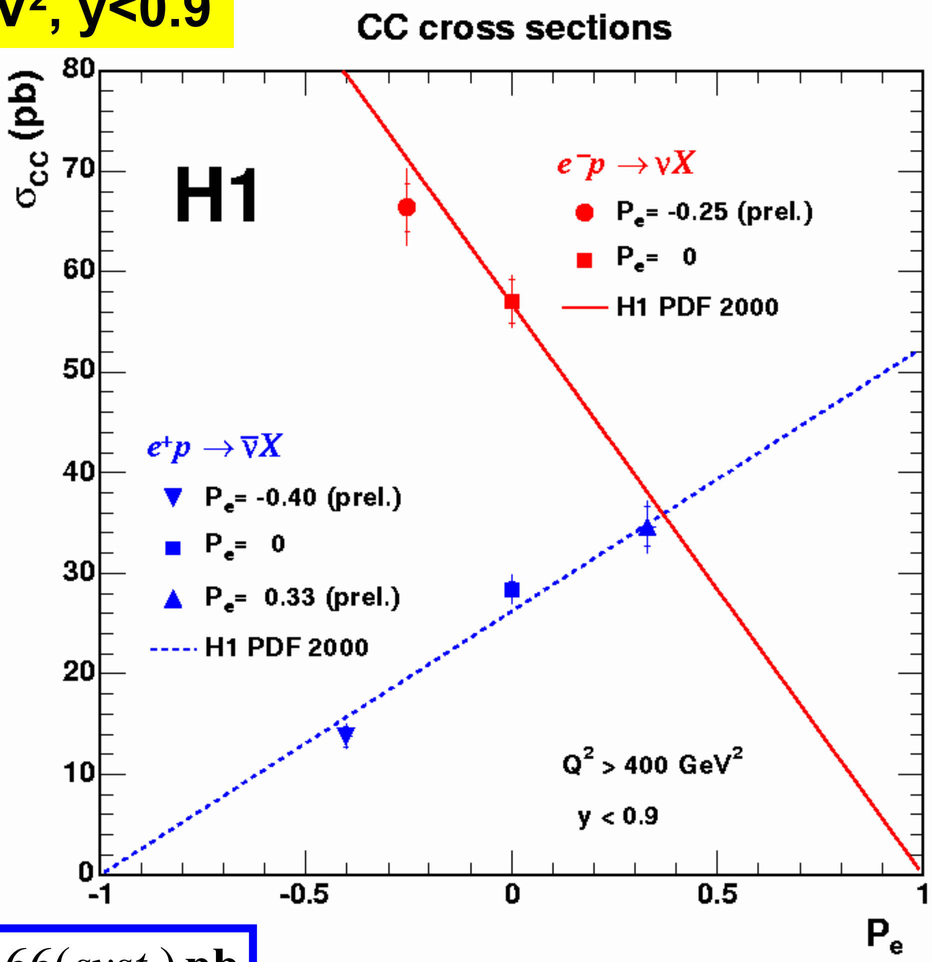
Q^2>400GeV^2, y<0.9

Remind : CC is pure weak

$$\sigma_{CC}(P_{e^\pm}) = (1 \pm P_{e^\pm})\sigma_{CC}(P_{e^\pm} = 0)$$

Direct observation of chiral structure of weak interaciton

- A clear linear dependence is observed both e^+ and e^-
- Data are in agreement with the SM prediction



e^+p

$$\sigma_{CC}(P_e = +33\%) = 34.67 \pm 1.94(stat.) \pm 1.66(syst.)\ \mathbf{pb}$$

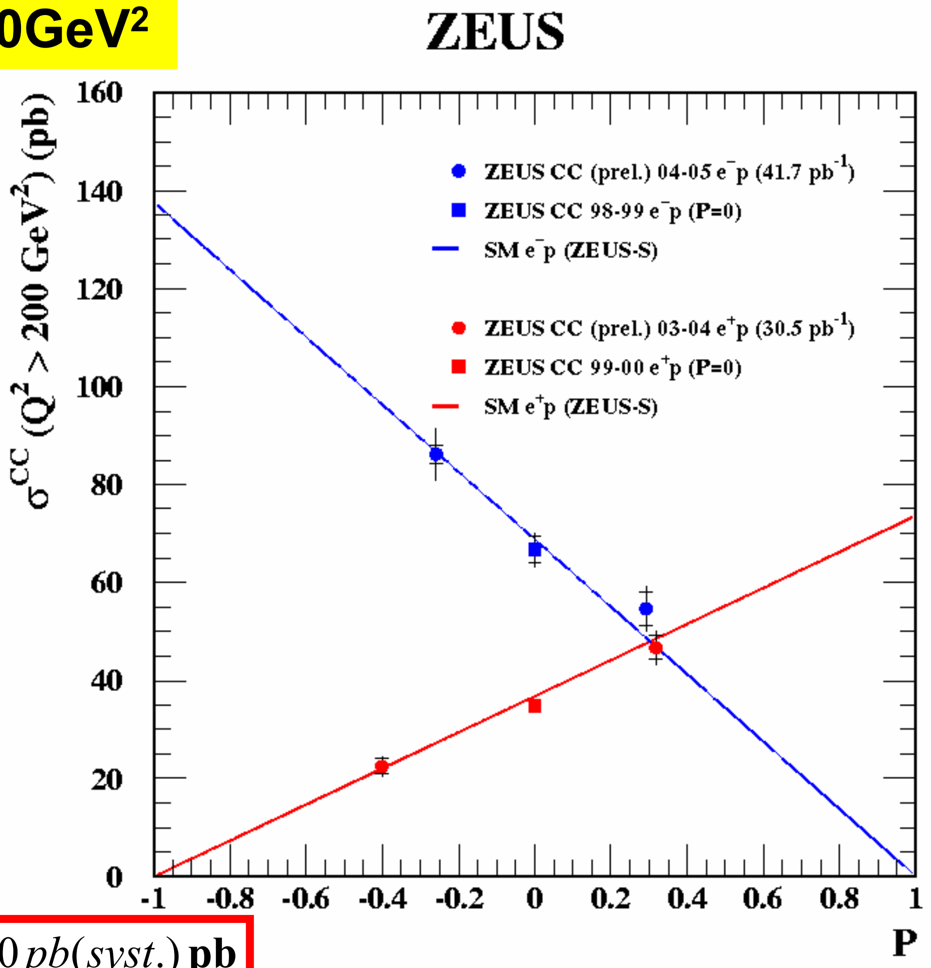
$$\sigma_{CC}(P_e = -40\%) = 13.80 \pm 1.04(stat.) \pm 0.94(syst.)\ \mathbf{pb}$$

e^-p

$$\sigma_{CC}(P_e = -25\%) = 66.42 \pm 2.39(stat.) \pm 2.99(syst.)\ \mathbf{pb}$$

CC Total Cross-Section (ZEUS)

Q^2>200GeV^2



The measurements

with four kinds of polarised beam

have been done

● Linear dependence is observed both e^+ and e^-

● Data are in agreement with the SM prediction

e^+p

$$\sigma_{CC}(P_e = +31.8 \pm 0.9\%) = 46.7 \pm 2.4(stat.) \pm 1.0\,pb(syst.)\ \mathbf{pb}$$

$$\sigma_{CC}(P_e = -40.2 \pm 1.1\%) = 22.5 \pm 1.6(stat.) \pm 0.5\,pb(syst.)\ \mathbf{pb}$$

e^-p

$$\sigma_{CC}(P_e = +29.2 \pm 0.5\%) = 54.6 \pm 3.5(stat.)^{+1.4}_{-1.1}(syst.)\ \mathbf{pb}$$

$$\sigma_{CC}(P_e = -25.9 \pm 0.5\%) = 86.2 \pm 1.9(stat.)^{+2.6}_{-2.2}(syst.)\ \mathbf{pb}$$

(5% of luminosity error not included)

CC Total Cross-Section : H1 and ZEUS

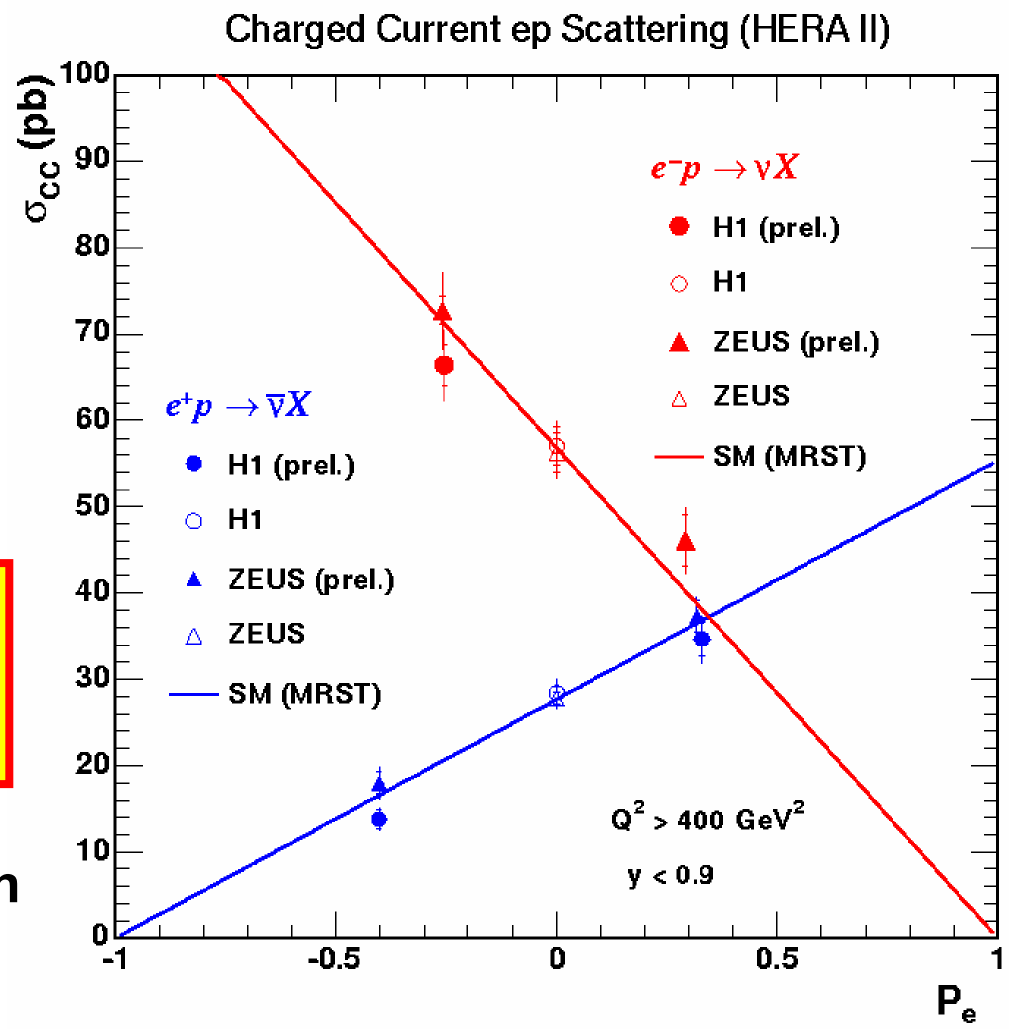
Q^2>400GeV^2, y<0.9

Right Handed CC cross section is extrapolated by linear fit to H1+ZEUS e^+p data

$$\sigma_{e^+p\to\bar{\nu}X}(P_{e^+}=-100\%)$$
$$=0.2\pm1.8(stat.)\pm1.6(syst.)\,\mathbf{pb}$$

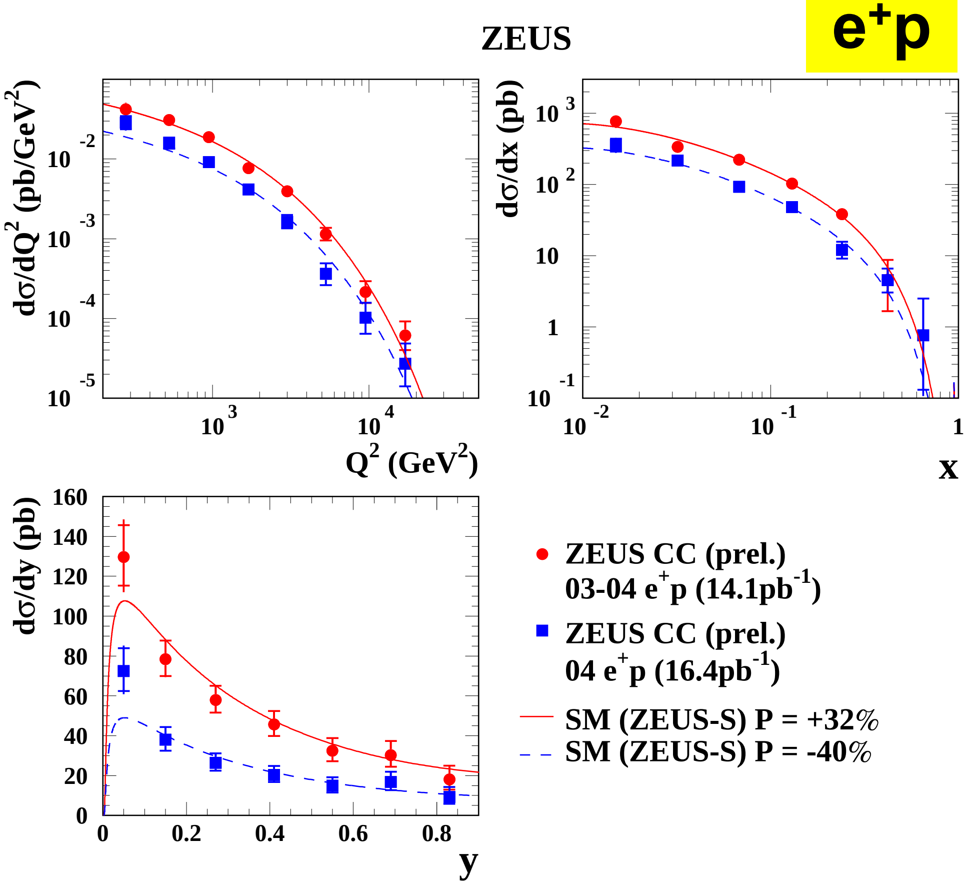
Consistent with the SM prediction

of : $\sigma_{CC}(RH)=0$

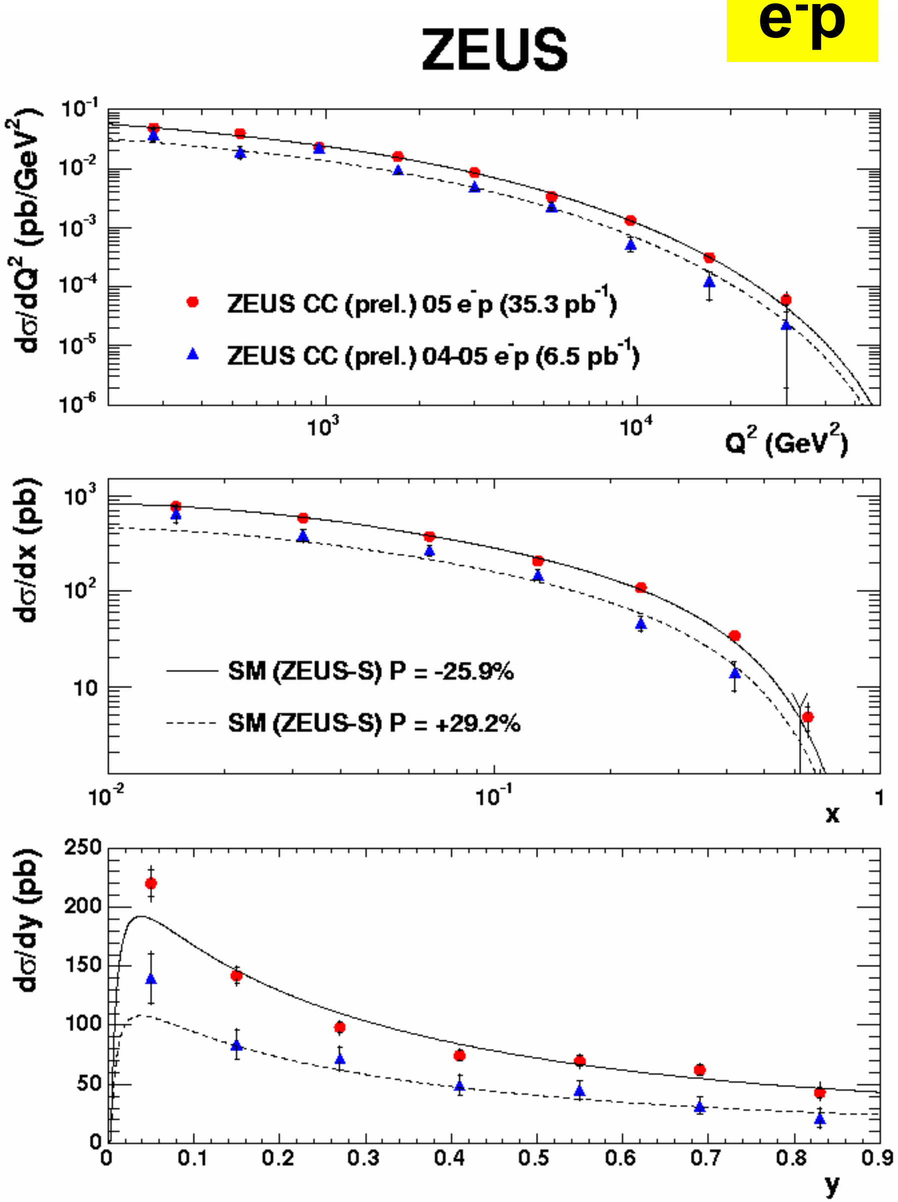


CC Differential Cross Sections (ZEUS)

e^+p



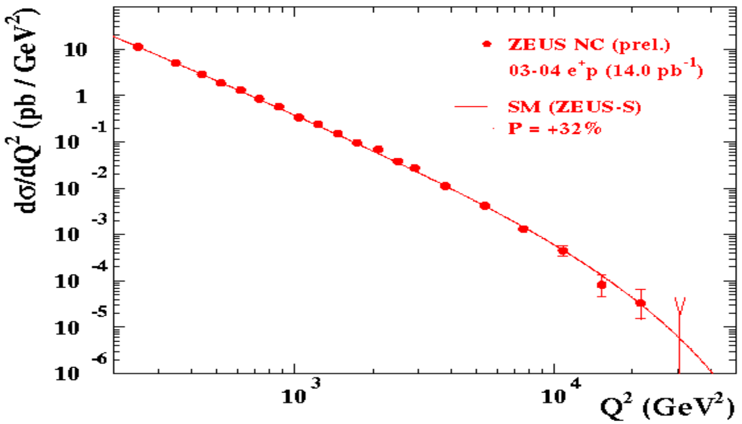
e^-p

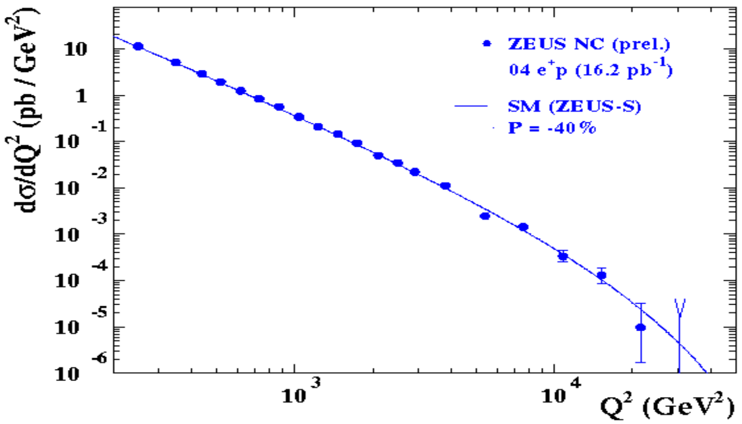


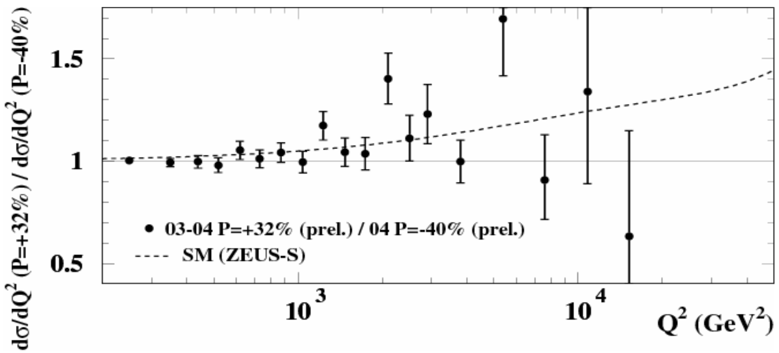
- **Polarisation effects observed in overall kinematic region**
- **Agree with the SM prediction of overall normalisation change by factor $(1 \pm P_{e^\pm})$**

NC Differential Cross Section (ZEUS)

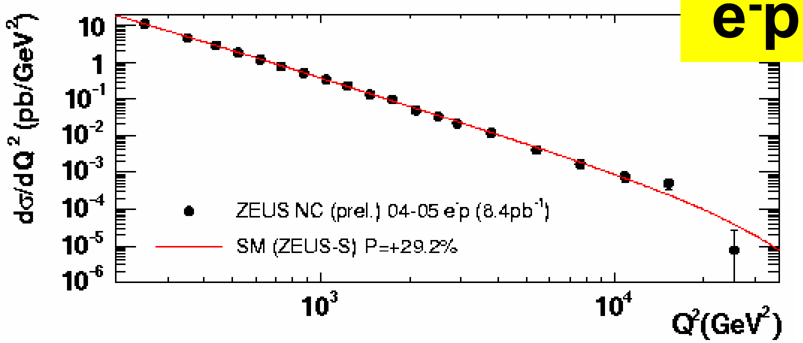
e^+p

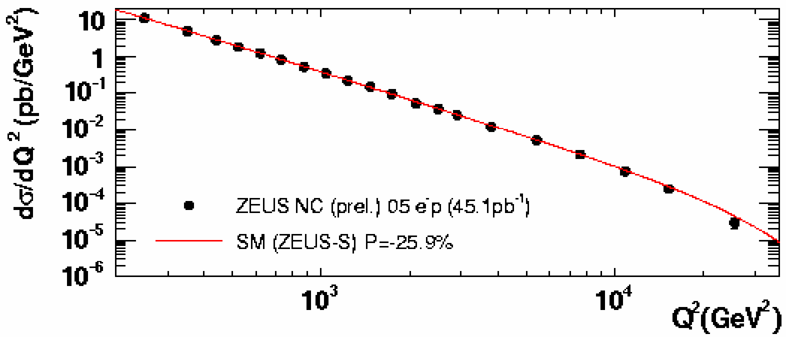


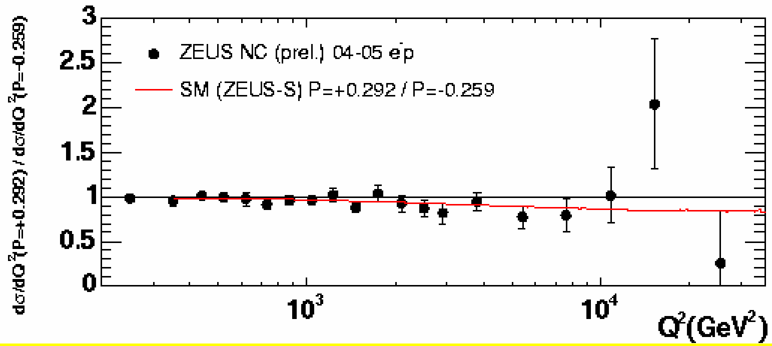




e^-p







- **Consistent with the SM prediction including the Polarisation effect**

Summary

HERA has sensitivities to EW parameters

- **HERA-I : Determination of Electroweak Parameters**
  - Propagator mass analysis
  - Determination of quark couplings to Z^0
- **HERA-II : Measurement of CC and NC Cross Sections**
  - Pure weak CC cross sections were consistent with the SM prediction, i.e. consistent with the $\sigma_{CC}(RH)=0$
  - NC cross sections were consistent with the SM prediction with polarisation effect included.

Outlook

HERA-II with polarised $e^{\pm}$ beam and higher luminosity will significantly improve the electroweak measurements