Electroweak Physics at HERA

Weak Interactions & Neutrinos
Kolkata, India
15th-20th Jan 2007

- Introduction
- H1 & ZEUS
- HERA & QCD
- HERA-II
- Charged Current Cross Sections
- Neutral Current Cross Sections
- EW Fits

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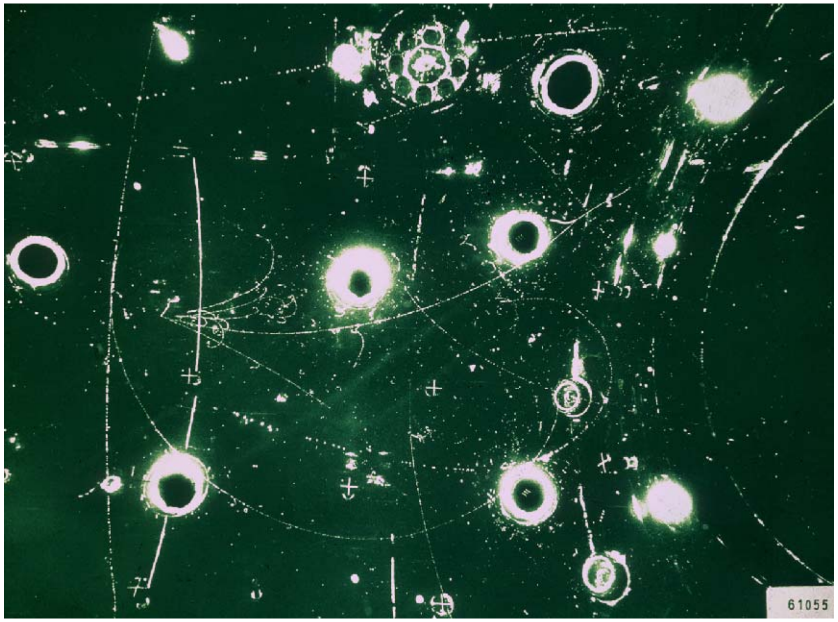
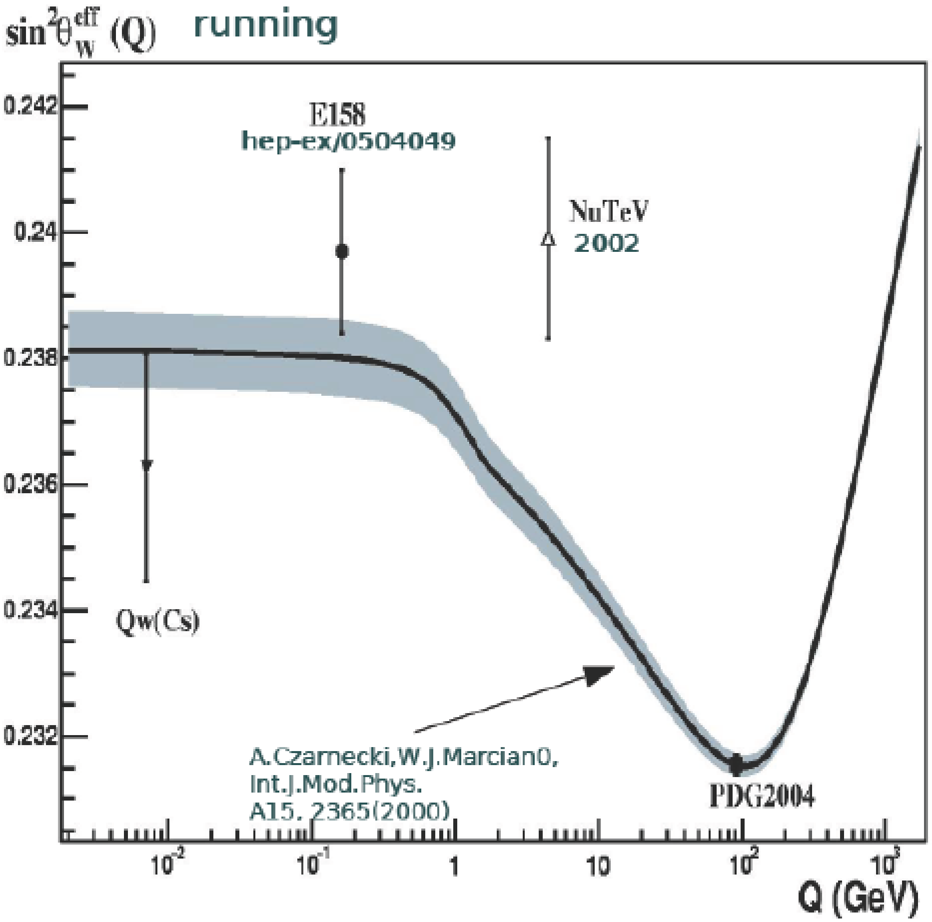


Lepton-nucleon experiments

provide rich harvest of EW physics results

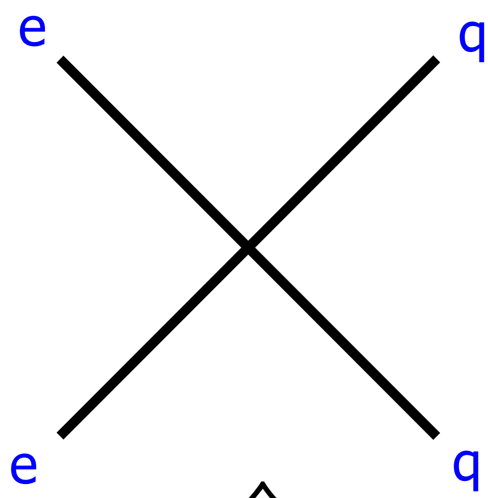
From Gargamelle's discovery of weak NCs

To NUTEV's measurement of $\sin^2\theta_W$



Measurements at $Q^2 \sim 0$

Colliders At EW Scale



LEP / SLD $\Rightarrow$

$M_Z, \Gamma_Z, R, A_{FB} \ldots$

$\Leftarrow$ Tevatron

m_t, M_W

$\Uparrow$

HERA

HERA probes t-channel of gauge boson exchange

- sensitive to propagator masses and EW couplings
- requires Parton Distribution Functions (PDFs)

$$\sigma(ep) \propto \sum \sigma(eq) \otimes \text{PDFs}$$

$$\text{EW} \otimes \text{QCD}$$

HERA performs measurements at Q^2 ~ EW scale
Tests Standard Model in region of large spacelike momentum transfer

HERA collides e and p
study strong, electromagnetic & weak forces through Deep Inelastic Scattering

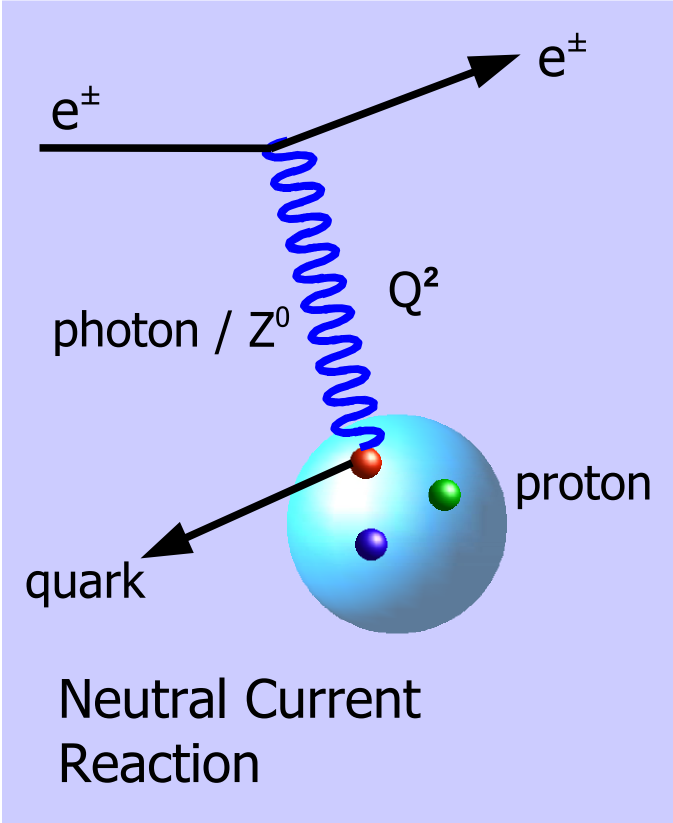
At fixed $\sqrt{s}$: two kinematic variables: x & Q^2

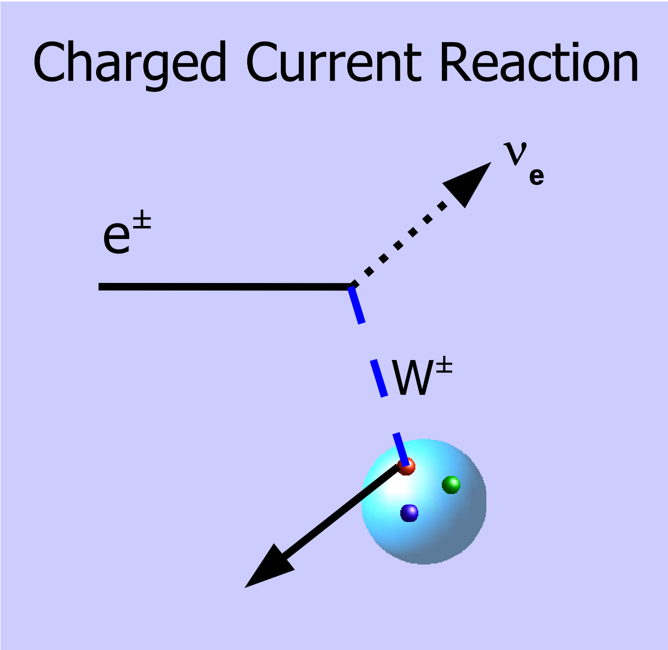
$Q^2 = s\ x\ y$

Q^2 = "resolving power" of probe

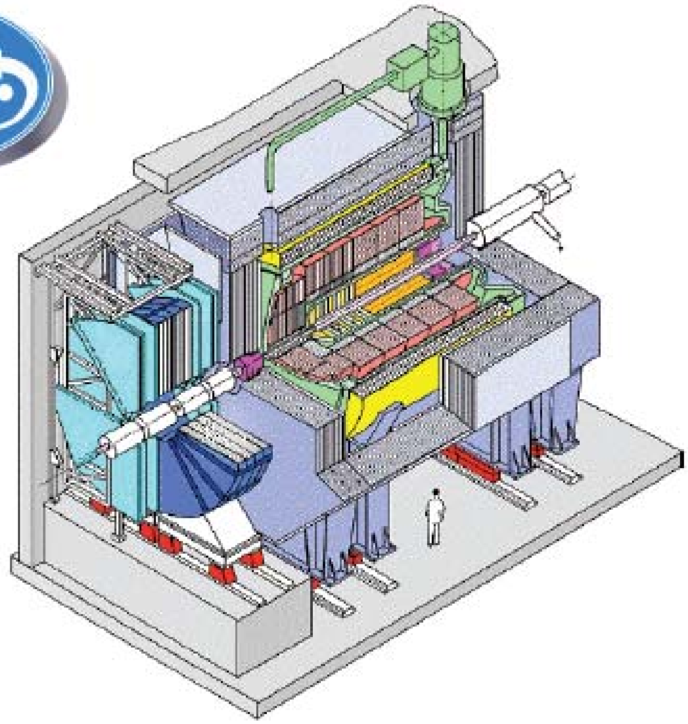
High Q^2 : resolve 1/1000th size of proton

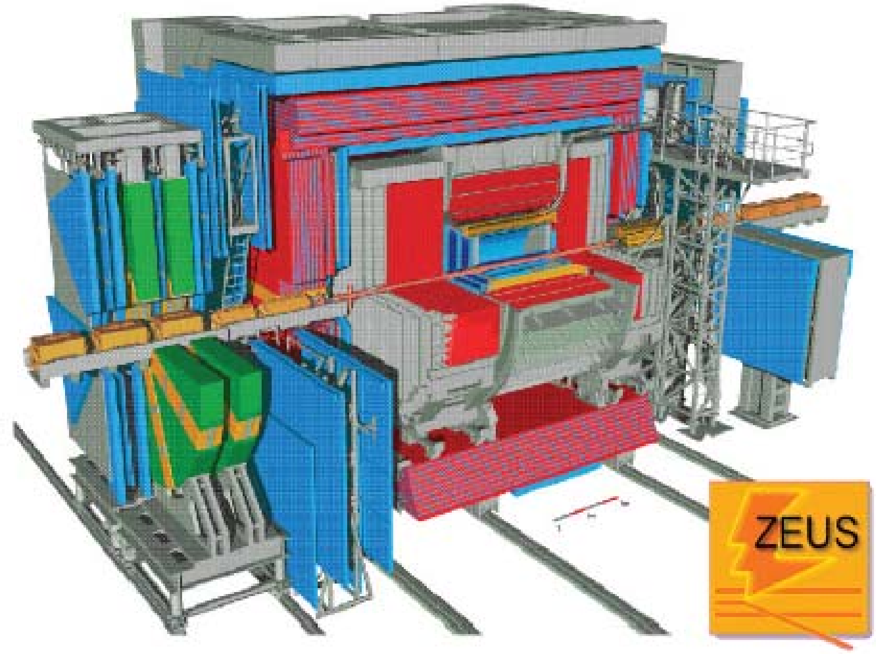
x = momentum fraction of proton carried by quark
HERA: ~10^{-6} - 1





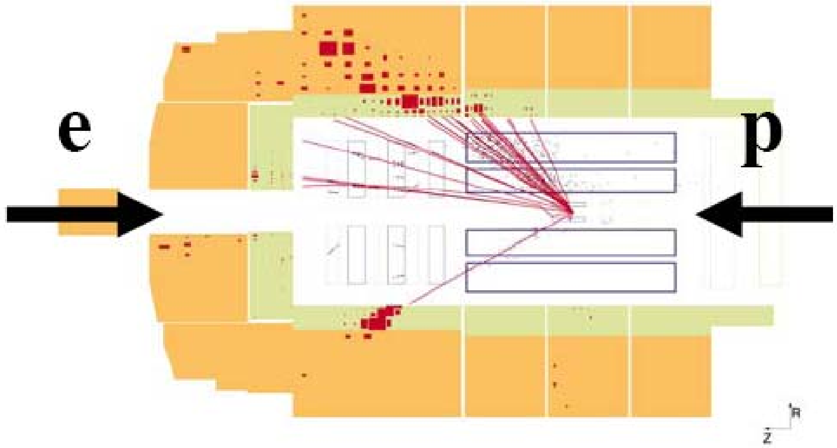
H1 & ZEUS

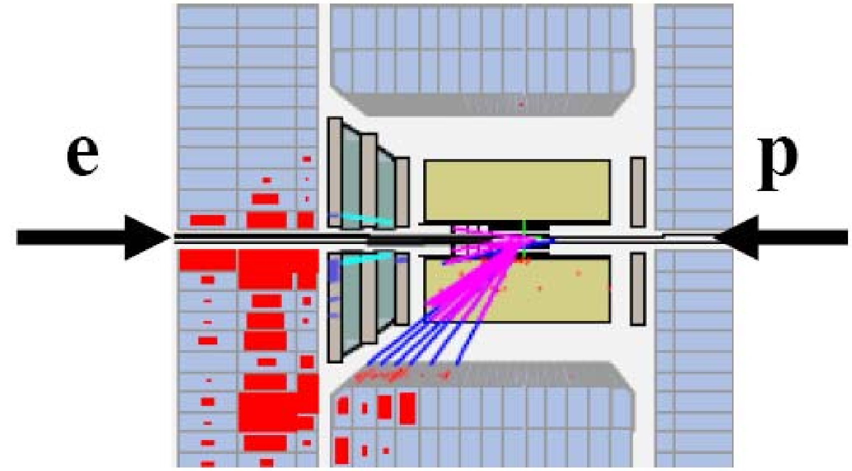




- LAr calorimeter (45000 cells)
- EM $$\frac{\sigma(E)}{E} = \frac{12\%}{\sqrt{E}} \oplus 1\%$$
- HAD $$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 1\%$$

- DU calorimeter (6000 cells)
- EM $$\frac{\sigma(E)}{E} = \frac{18\%}{\sqrt{E}}$$
- HAD $$\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E}}$$





Neutral current event selection:

- High P_T isolated scattered electron/positron
- Suppress huge phototproduction background by imposing longitudinal energy-momentum conservation
- Kinematics may be reconstructed in many ways: energy/angle of hadrons & scattered lepton provides excellent tools for sys cross checks
- Removal of scattered lepton provides a high stats "pseudo-charged current sample" Excellent tool to cross check CC analysis
- Final selection: ~10^5 events per sample

Charged current event selection:

- Large missing transverse momentum (neutrino)
- Suppress huge phototproduction background
- Topological finders to remove cosmic muons
- Kinematics reconstructed from hadrons
- Final selection: ~10^3 events per sample

$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} \approx \frac{e^4}{8\pi x}\left[\frac{1}{Q^2}\right]^2\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

Modified at high Q^2 by Z propagator

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} \approx \frac{1\pm P_e}{2}\frac{g^4}{64\pi x}\left[\frac{1}{M_W^2+Q^2}\right]^2\left[Y_+\tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm} - y^2\tilde{W}_L^{\pm}\right]$$

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

$$\tilde{F}_2 \propto \sum (xq_i + x\overline{q}_i)$$

dominant contribution

$$x\tilde{F}_3 \propto \sum (xq_i - x\overline{q}_i)$$

only sensitive at high Q^2

$$\tilde{F}_L \propto \alpha_s \cdot xg(x,Q^2)$$

only sensitive at low Q^2 and high y

similarly for $W_2^{\pm}$, $xW_3^{\pm}$ and $W_L^{\pm}$

For purely weak CC interaction xW_3 contributes over full phase space

Structure functions parameterise proton structure: how far from point like

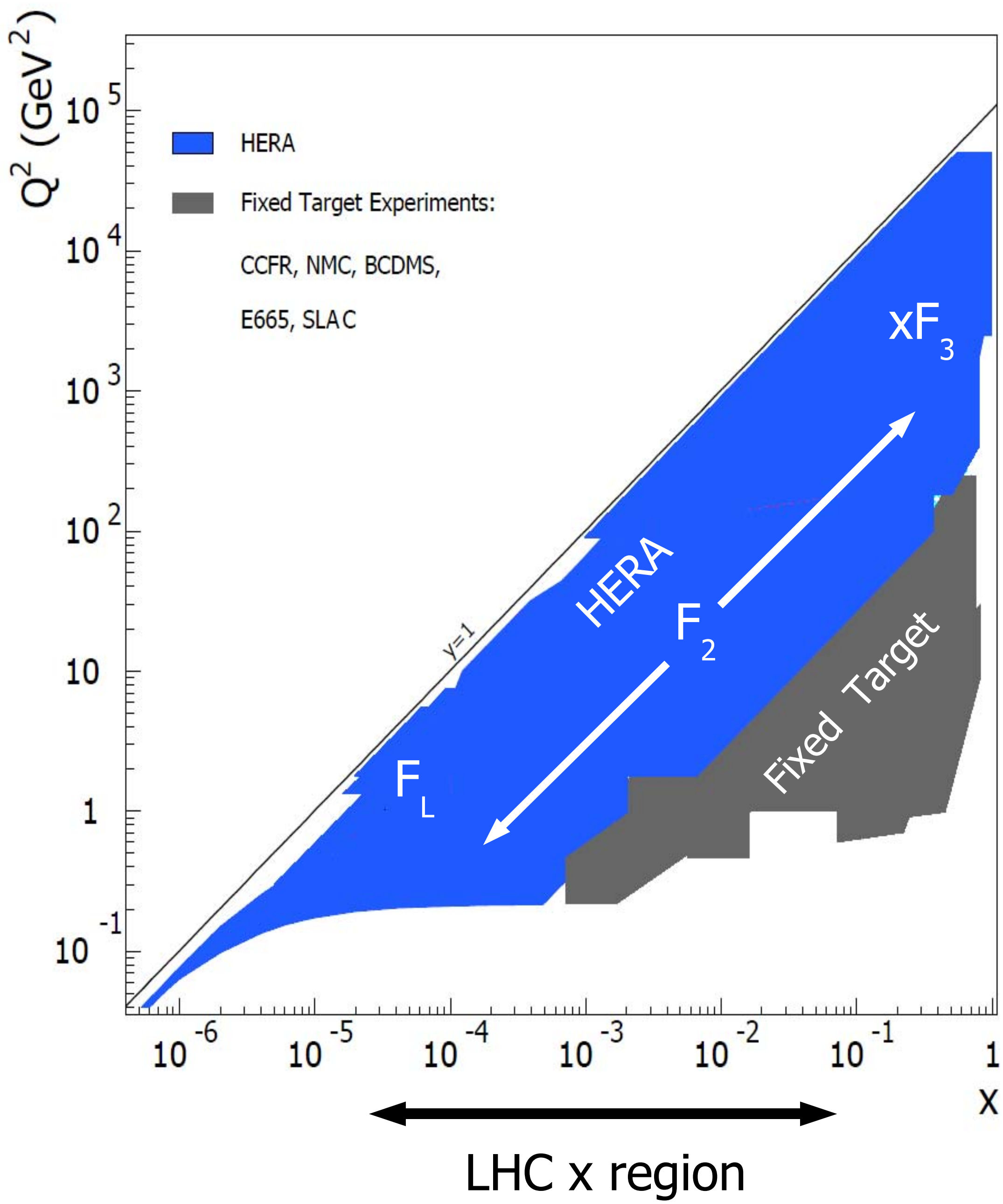
For pointlike proton: $\frac{d^2\sigma_{NC}}{dxdQ^2} = \frac{e^4}{8\pi x}\frac{1}{Q^4}Y_+$

SM predicts CC cross section $\frac{d^2\sigma^{\pm}_{CC}}{dxdQ^2} \propto \frac{1\pm P_e}{2}$

linear scaling of cross section

zero for LH e^+ or RH e^-

$P_e=-1$ $P_e=+1$



HERA has large kinematic reach

QCD understanding needed across full x, Q^2 range

NC process: EW physics lies at high Q^2

CC process: purely weak - flavour info for PDFs

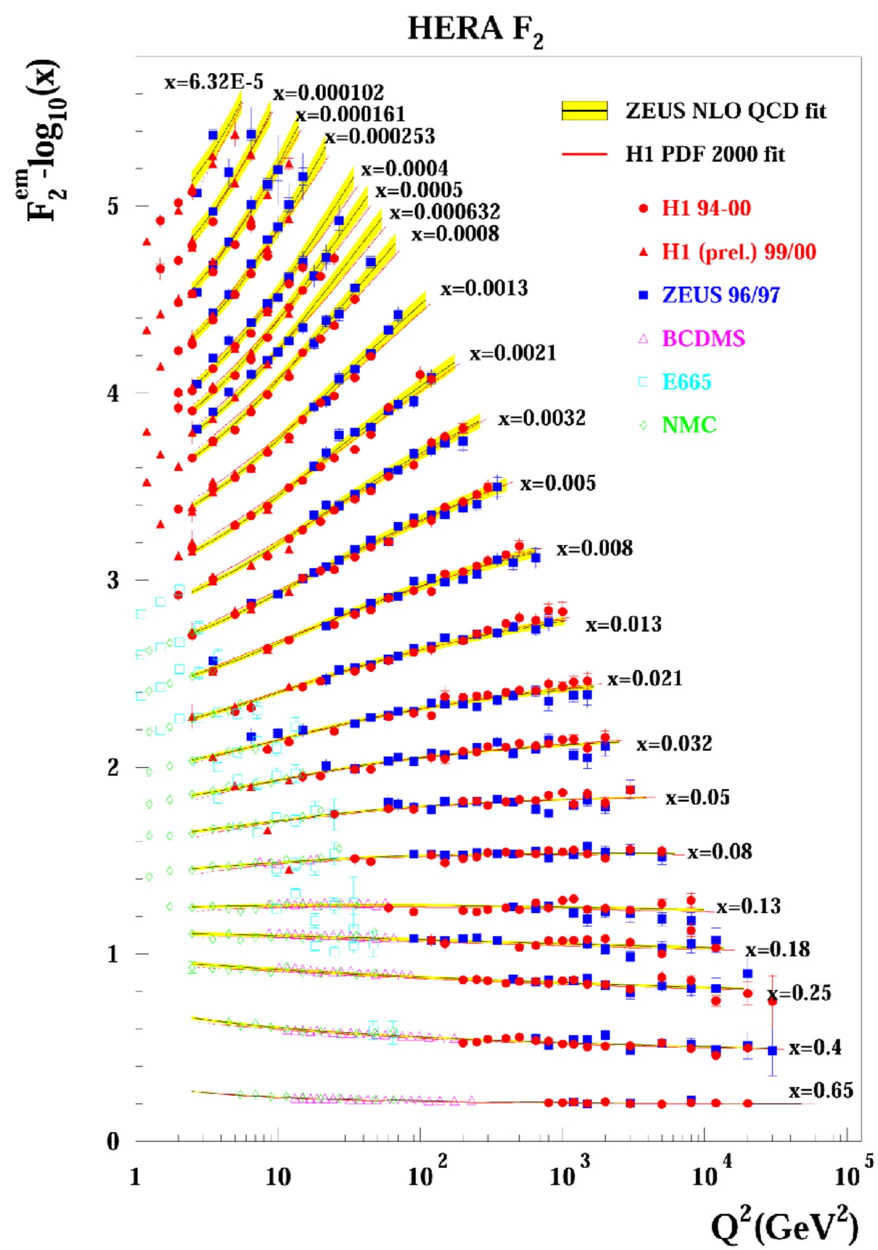
Measure cross sections

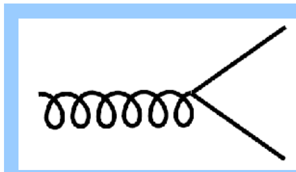
Fit data – extract PDFs & EW physics

HERA PDFs extrapolate into LHC region

LHC probes proton structure where gluon dominates (gluon collider)

HERA data crucial in calculations of new physics & measurements at LHC

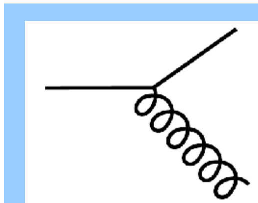




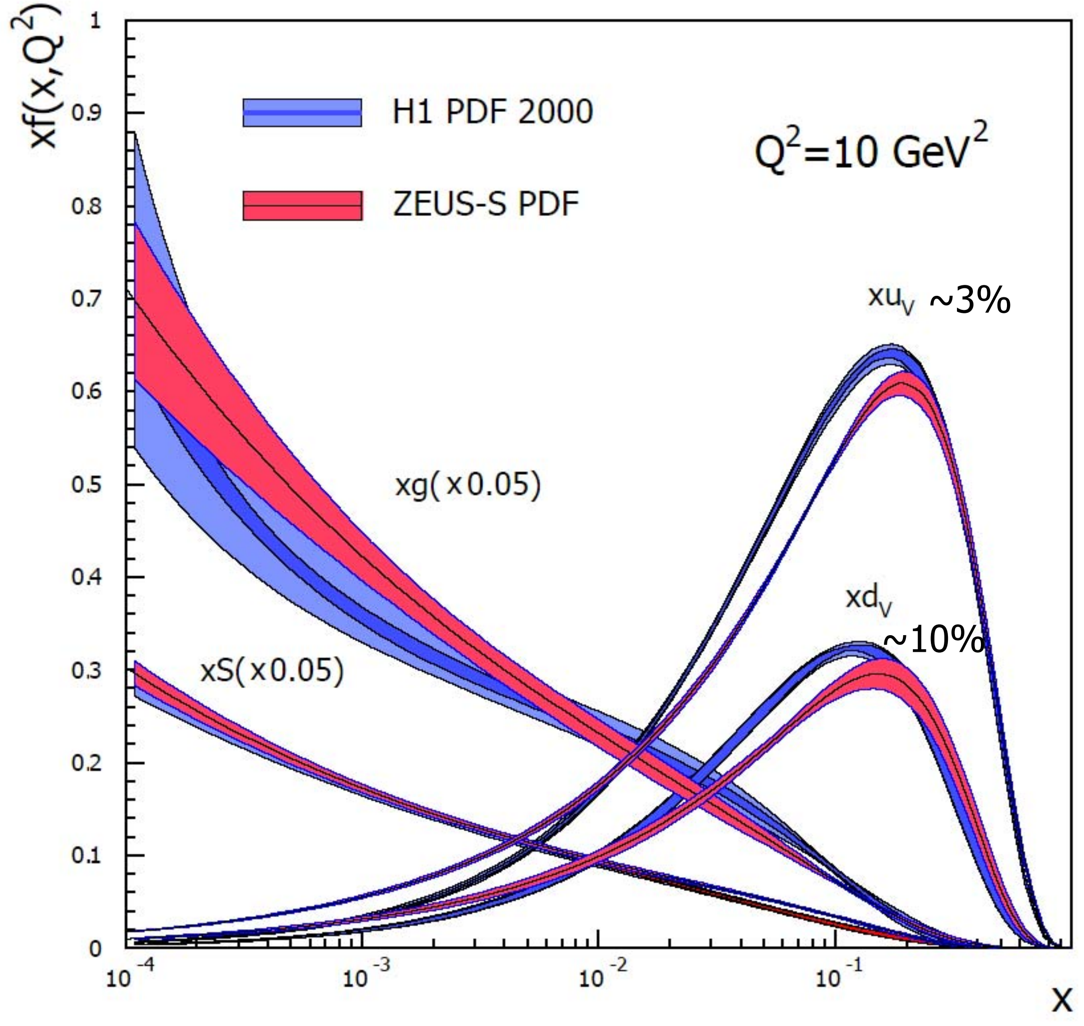
Low x: gluon splitting

- Both H1 and ZEUS fits provide good description of inclusive data
- Scaling violations of F_2 well described
- H1: χ^2 / ndf = 0.88 (621 data points, 10 pars.)
- ZEUS: χ^2 / ndf = 0.95 (1263 data points, 11 pars.)

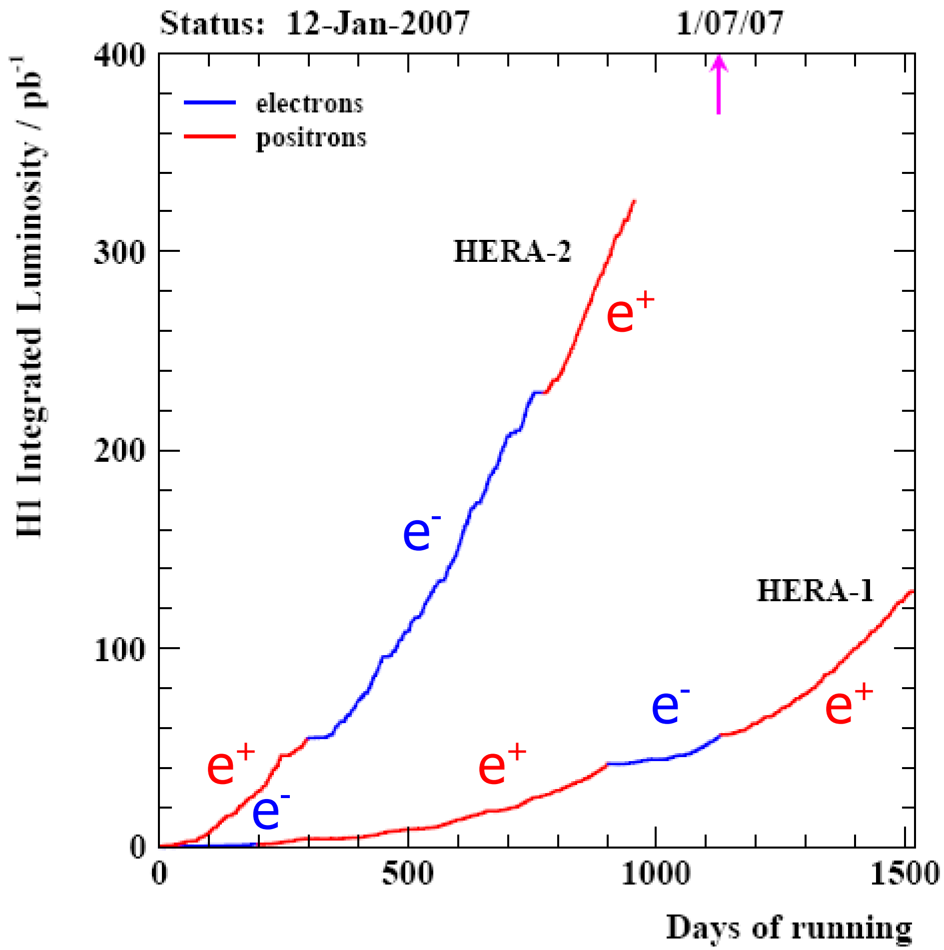
QCD in good shape



High x: gluon emission



HERA precision PDF determination based on ~120 pb^{-1} HERA-I data



Hope to collect factor 3 higher luminosity compared to HERA-I

Expect to start 3 month low energy run in March 2007

Precision gluon determination only possible at HERA

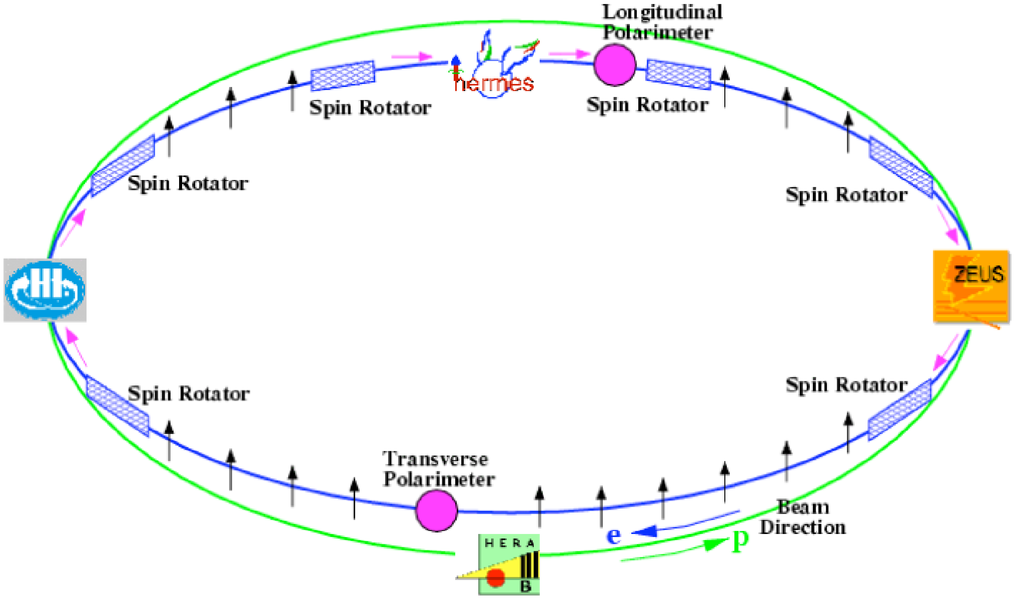
HERA shutdown July this year - end of exciting 14 year program

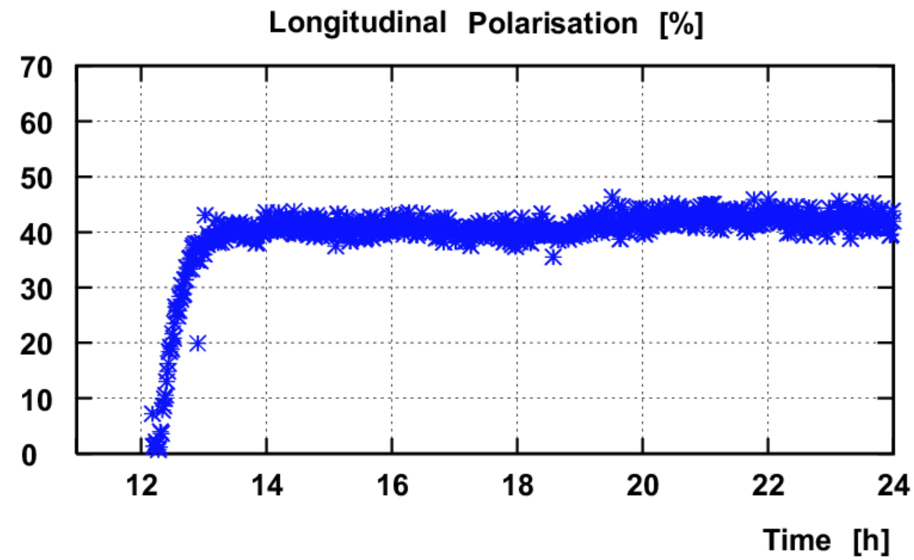
Final analysis of complete data sample in progress

HERA-II Upgrade

Synchrotron radiation off lepton beam induces transverse polarisation (Sokolov-Ternov effect)

Newly installed spin rotators flip transverse and long. polarisation



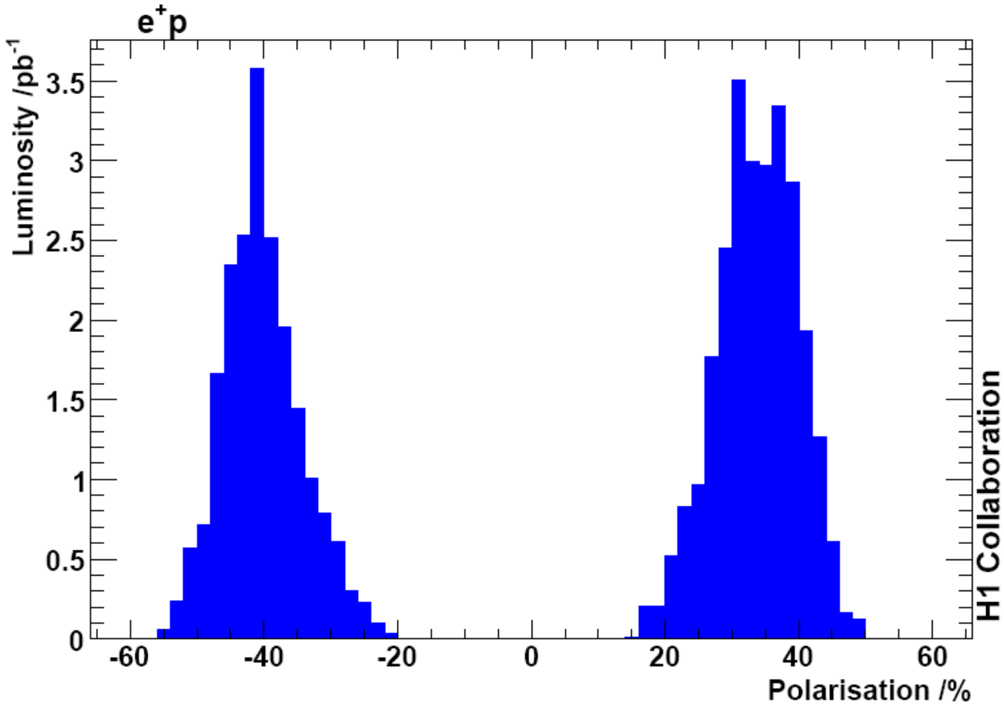


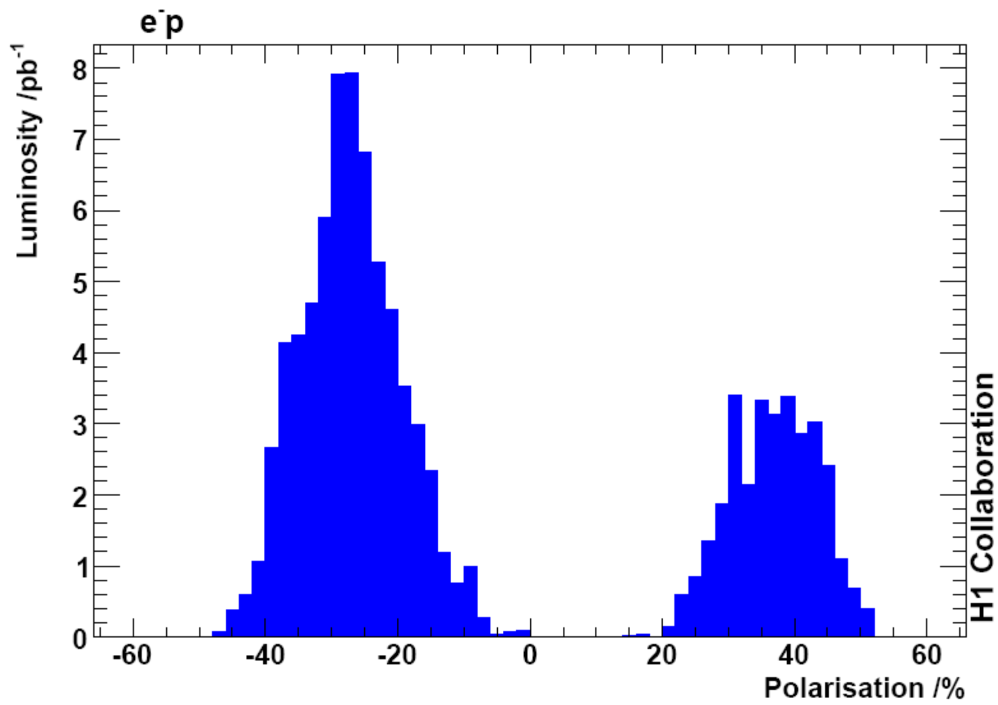
$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

Approx. 30 minute polarisation rise time

Polarisation constant around the HERA machine

Polarisation measured with 3 independent Compton polarimeters

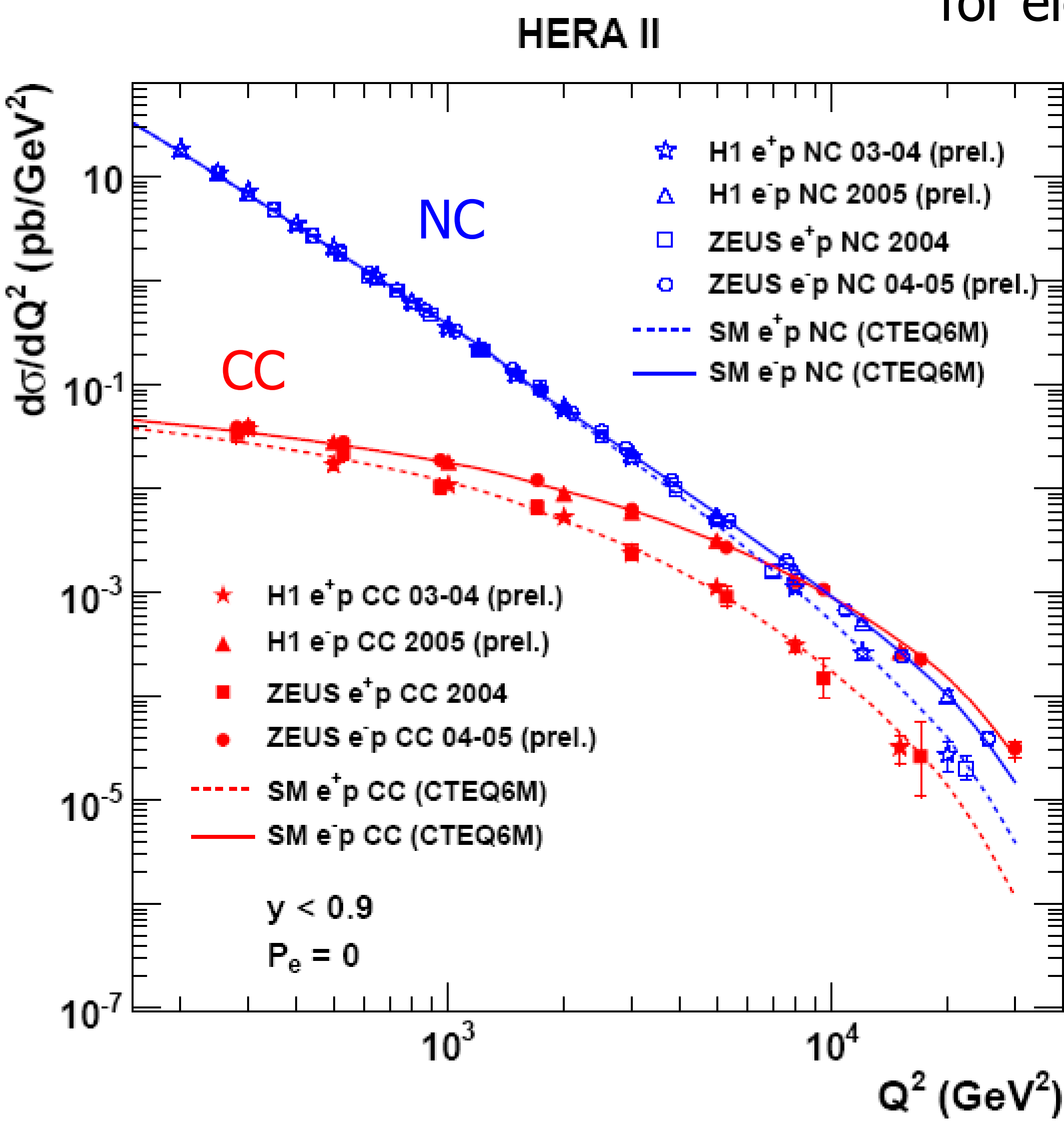




Data sample	H1		ZEUS	
	$P_e<0$	$P_e>0$	$P_e<0$	$P_e>0$
e^+p	P_e=-0.40±0.01 L = 20.7 pb^{-1}	P_e=+0.34±0.01 L = 26.9 pb^{-1}	P_e=-0.41±0.01 L = 11.5 pb^{-1}	P_e=+0.32±0.01 L = 12.3 pb^{-1}
e^-p	P_e=-0.27±0.01 L = 68.6 pb^{-1}	P_e=+0.37±0.02 L = 29.6 pb^{-1}	P_e=-0.27±0.01 L = 78.8 pb^{-1}	P_e=+0.33±0.02 L = 42.7 pb^{-1}

2006 luminosity not yet included in these analyses

Measurements of NC & CC cross sections for electron & positron scattering



Unpolarised cross sections

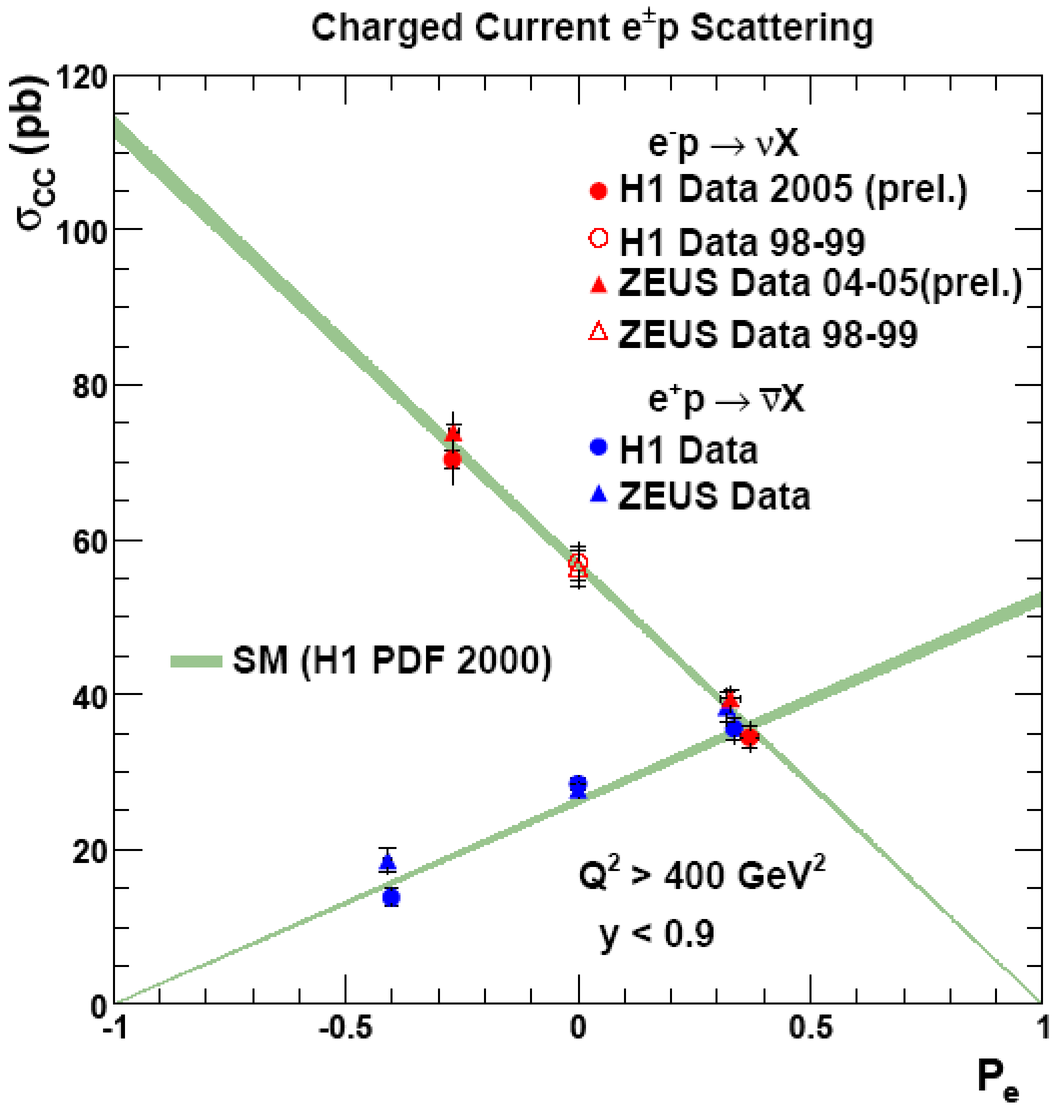
Cross sections measured over 6 orders of magnitude

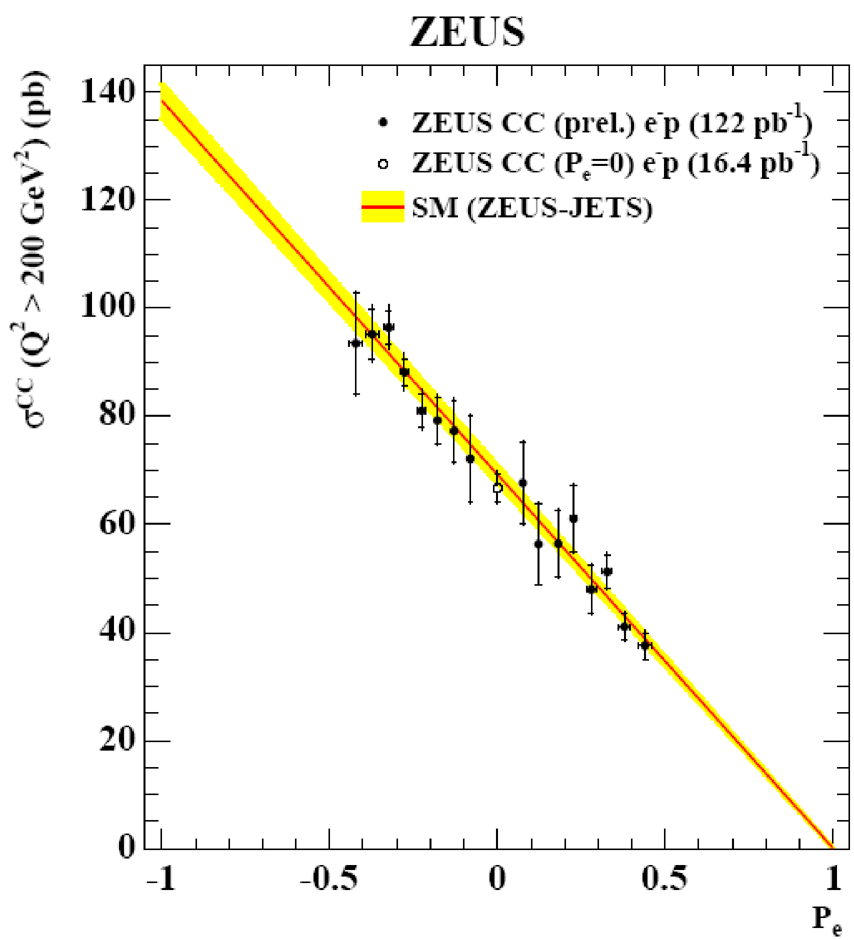
NC cross section dominated by photon exchange

NC e^+/e^- difference due to Z^0 exchange

CC cross section similar to NC cross section at high Q^2 $\rightarrow$ EW unification

Remaining difference due to PDFs



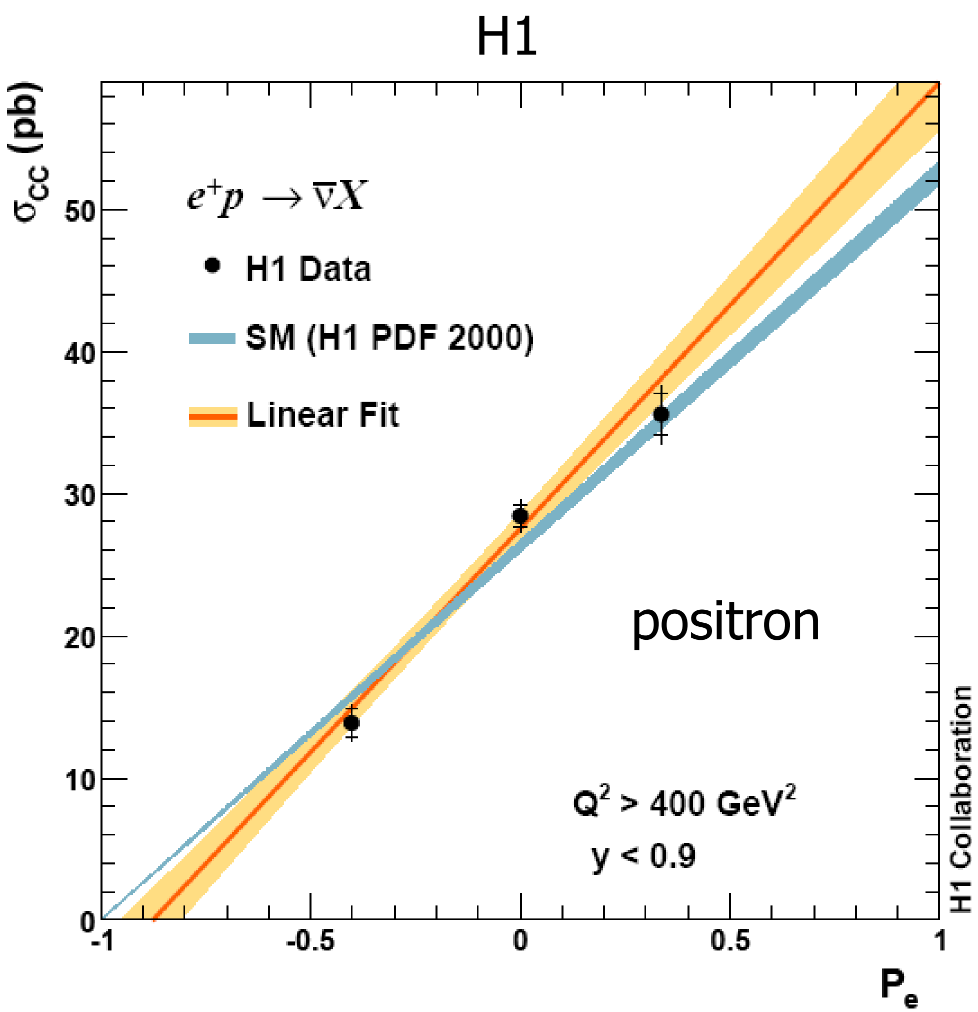


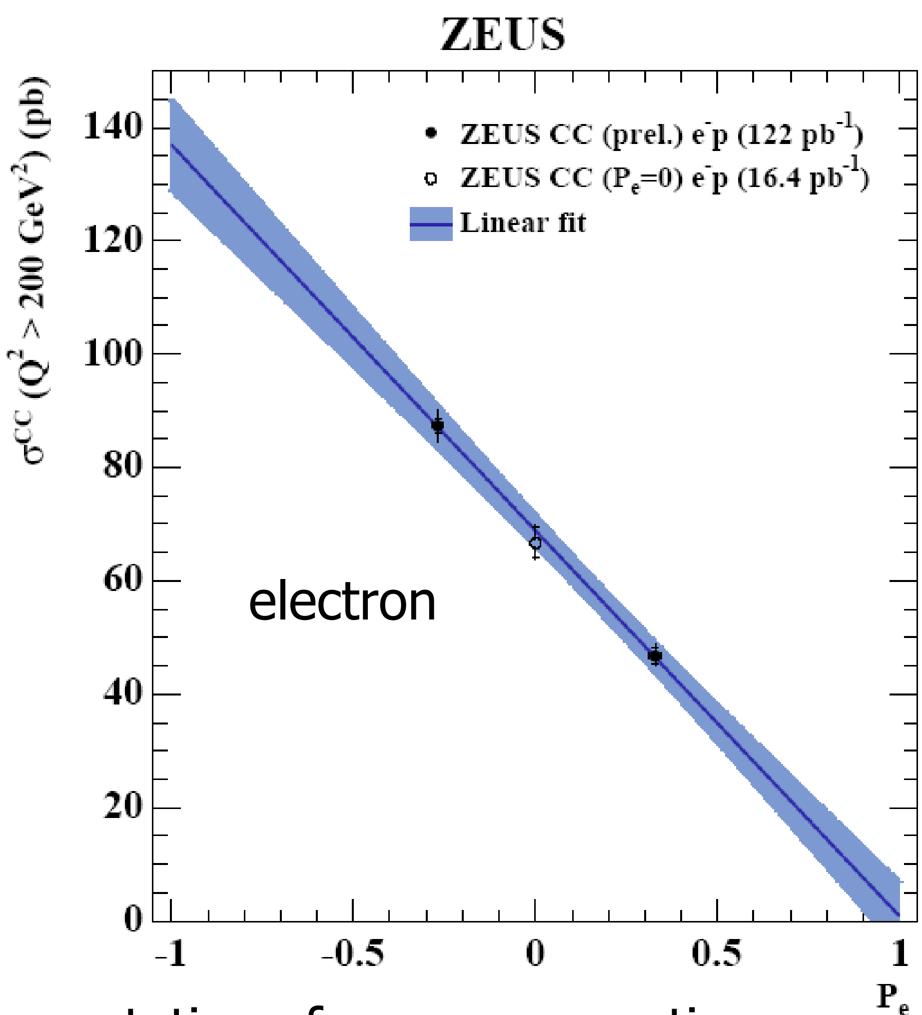
Polarisation dependence of CC cross section clearly seen ∝ ½(1-P)

Data consistent with SM prediction of no e^-_R or no e^+_L

Direct sensitivity of right handed W

Charged Current Channel





Do not constrain linear fit to SM expectation of zero cross section

Derive mass limit on W_R assuming g_L=g_R and massless ν_R

positron data: 208 GeV (H1) electron data: 186 GeV (H1)

180 GeV (Zeus)

Neutral Current Channel

Effect of polarisation is subtle in neutral current channel

$$\tilde{F}_2^{\pm} = F_2^{\gamma} - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm P_e 2 v_e a_e)\chi_Z^2 F_2^Z$$

$$x\tilde{F}_3^{\pm} = - (a_e \pm P_e v_e)\chi_Z xF_3^{\gamma Z} + (2 v_e a_e \pm P_e (v_e^2 + a_e^2))\chi_Z^2 xF_3^Z$$

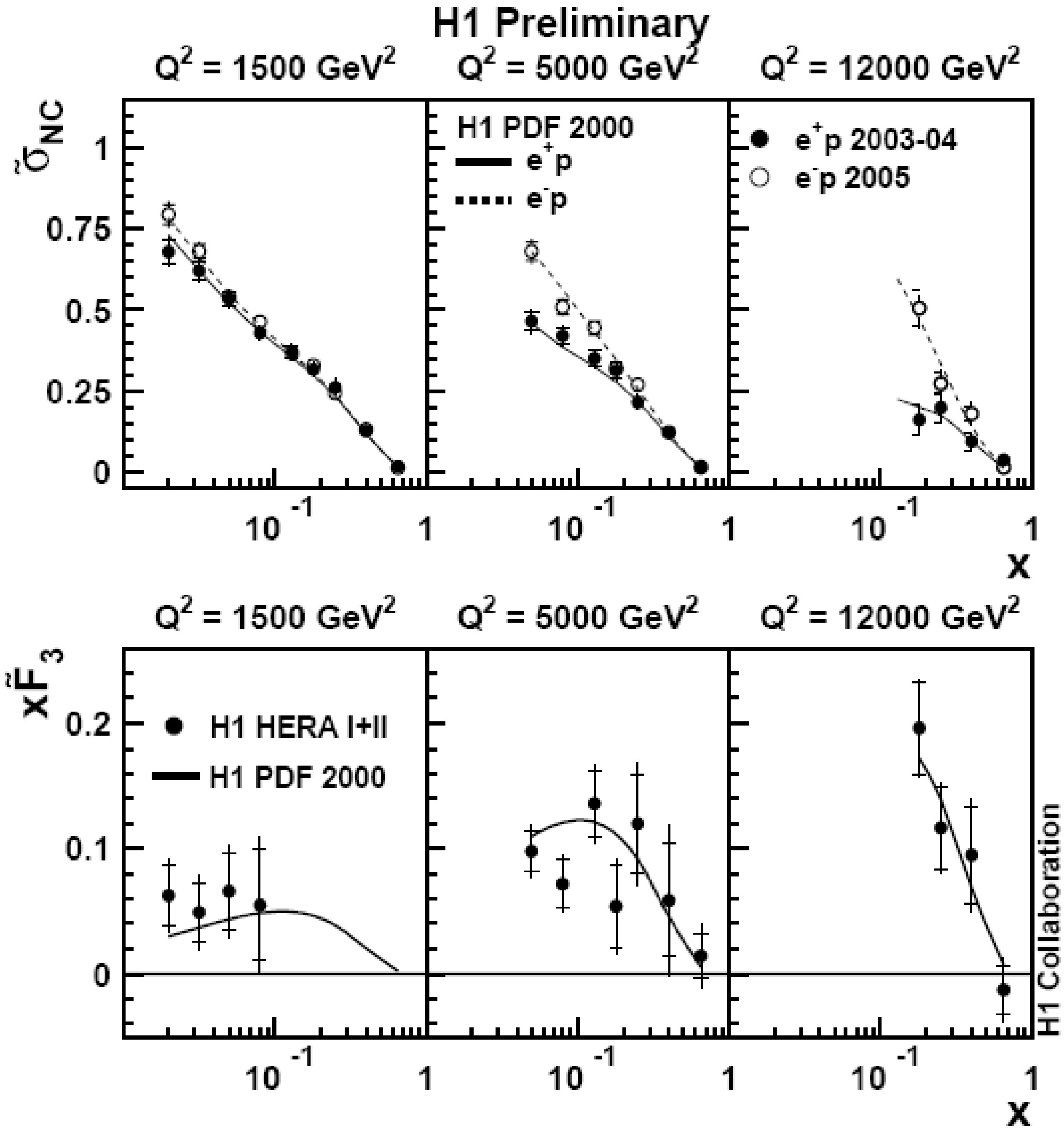
pure photon — photon/Z^0 interference — pure Z^0

χ_Z ~ Z^0 propagator

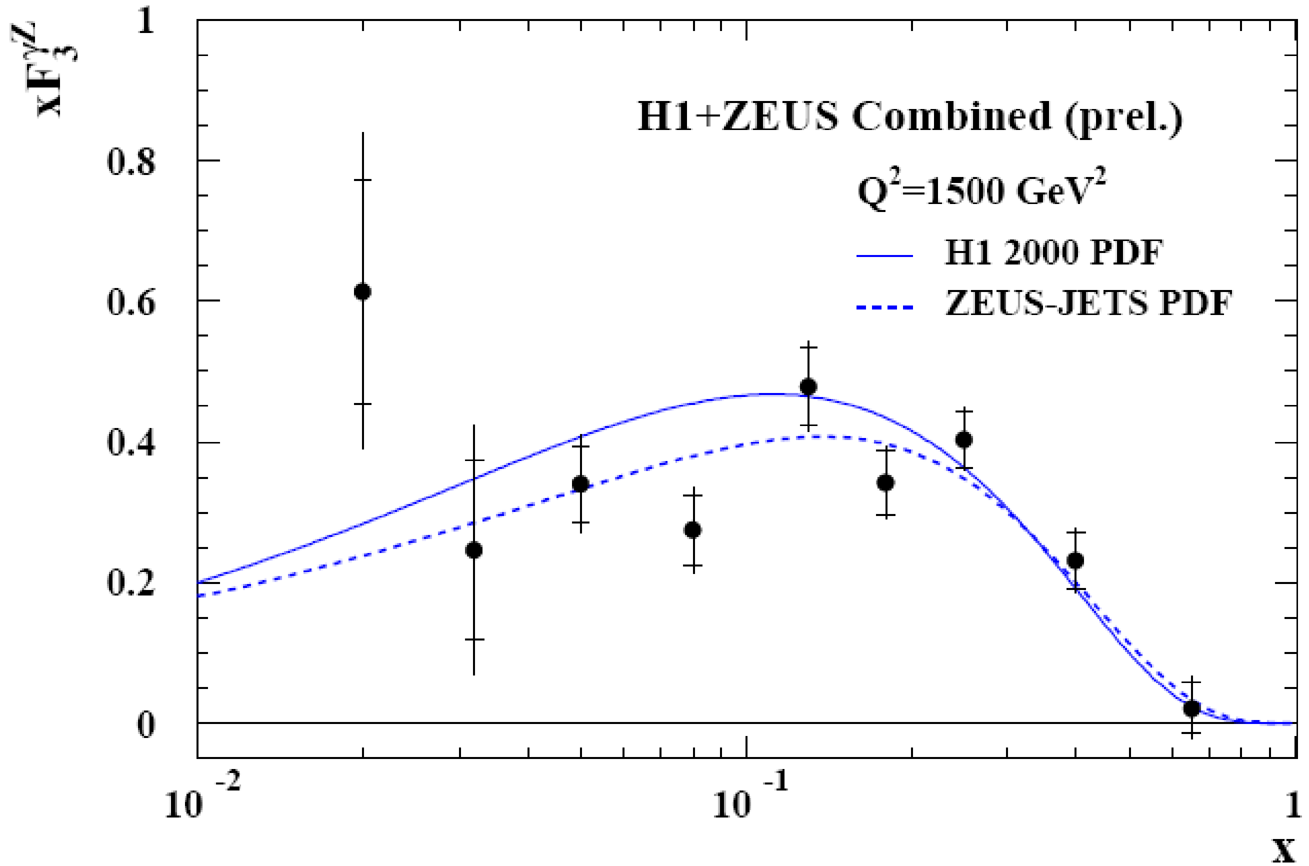
To first order: polarisation effects dominated by photon / Z^0 interference terms
pure Z exchange suppressed by additional propagator factor
i.e. $\chi_Z \gg \chi_Z^2$ and $v_e \approx 0.05$ we can neglect pure Z^0 terms

In unpolarised case $\tilde{\sigma}_{NC}^{\pm} \approx \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3$ neglecting F_L

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\tilde{\sigma}_{NC}^{-} - \tilde{\sigma}_{NC}^{+}) \approx a_e \chi_Z xF_3^{\gamma Z}$$


H1 Preliminary
Q^2 = 1500 GeV^2
Q^2 = 5000 GeV^2
Q^2 = 12000 GeV^2
$\tilde{\sigma}_{NC}$
H1 PDF 2000
e$^+$p
e$^-$p
e$^+$p 2003-04
e$^-$p 2005
x
$x\tilde{F}_3$
H1 HERA I+II
H1 PDF 2000
H1 Collaboration

Neutral Current Channel (Unpolarised)

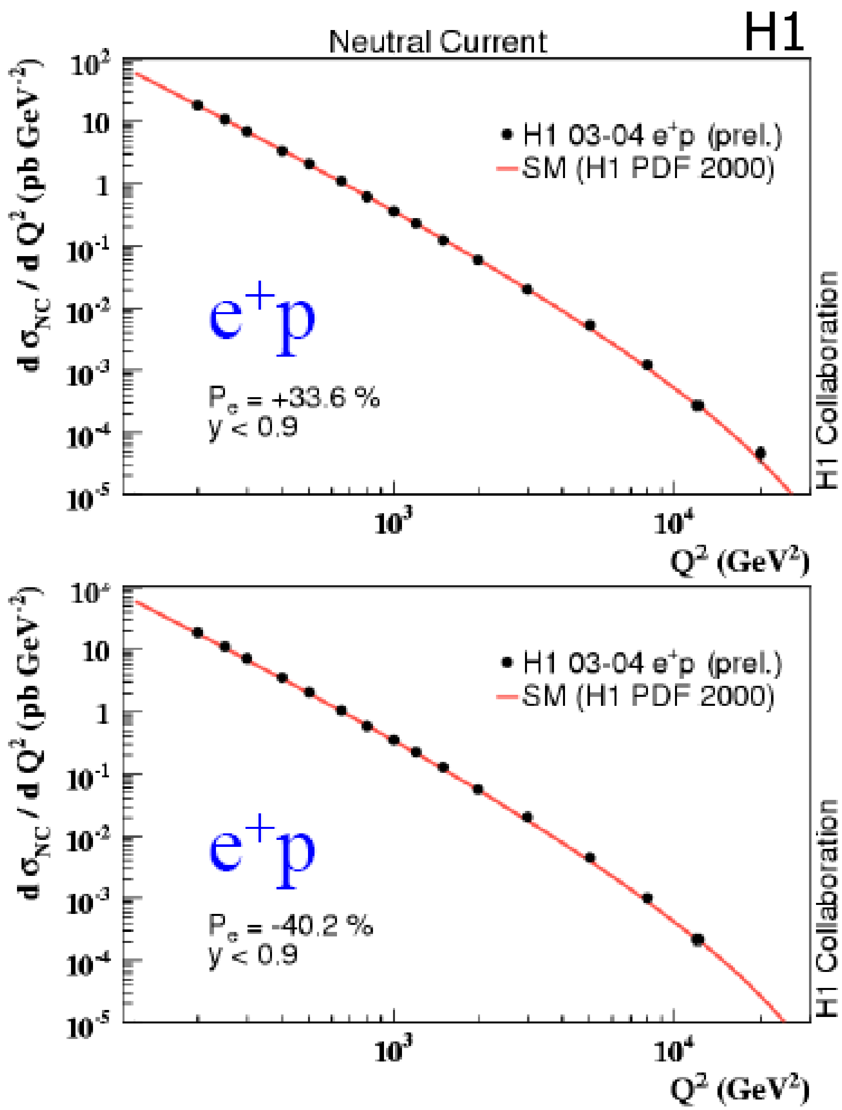


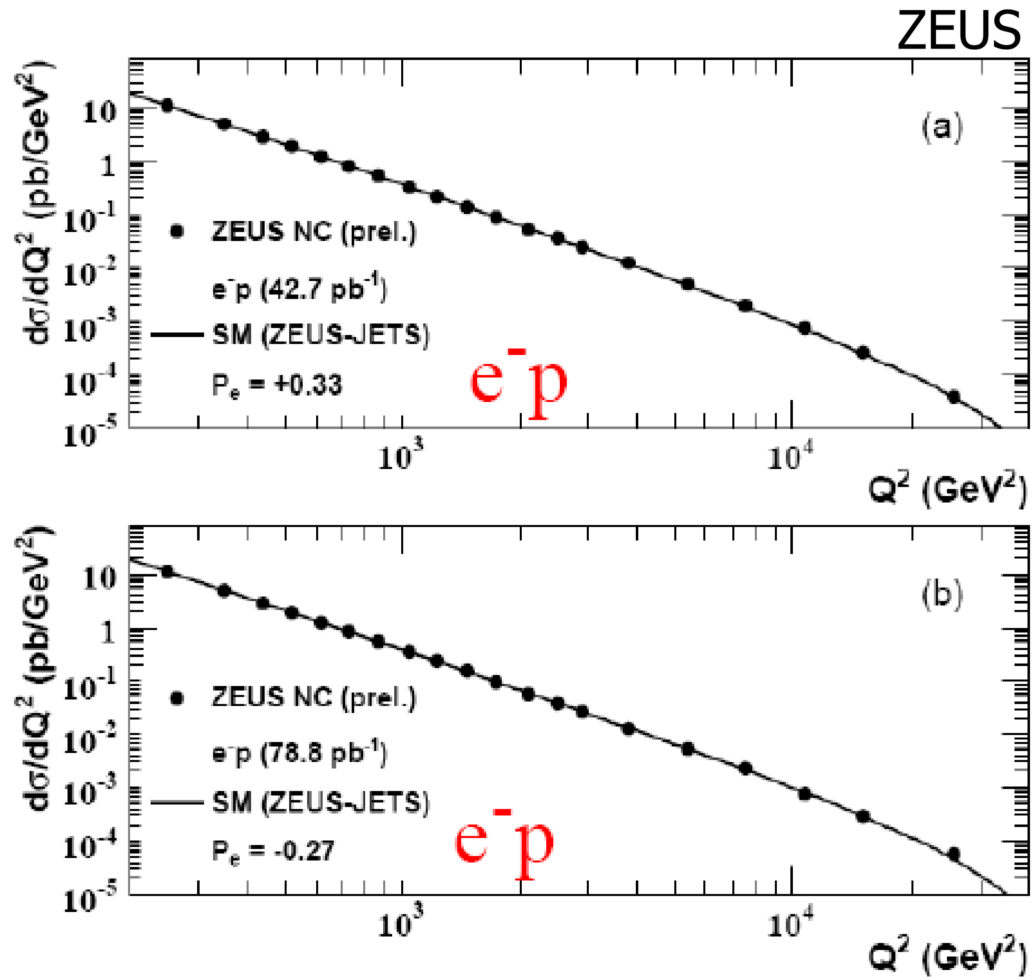
Large luminosity of HERA-II sample allows improved xF_3 measurement

Combine L & R handed datasets

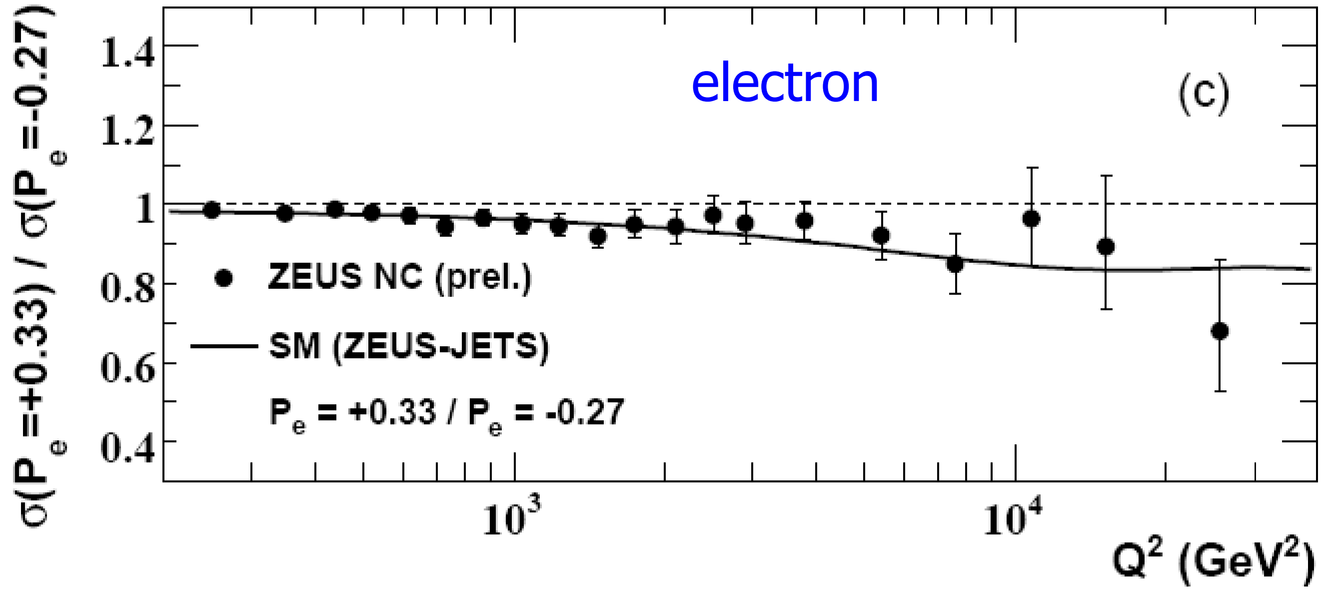
Precision further improved by combining H1 & ZEUS data

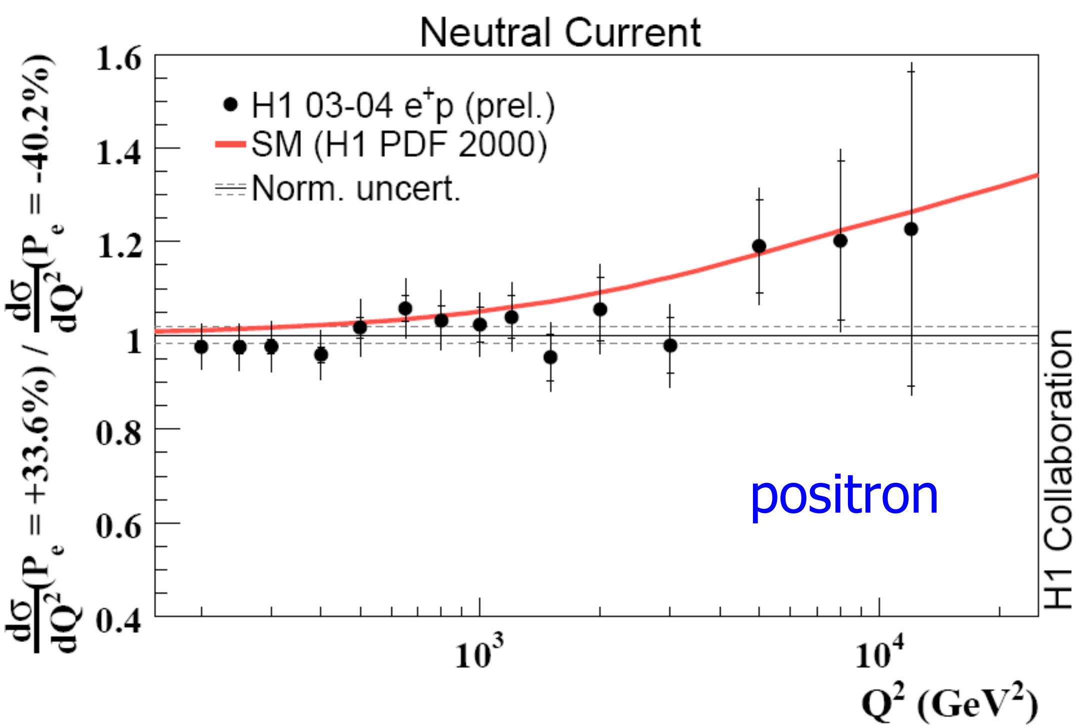
Measurement statistically limited





Both experiments measured positron/electron, left/right cross sections





Measure ratio of NC cross section

$$\frac{d\sigma}{dQ^2} \quad \text{R/L}$$

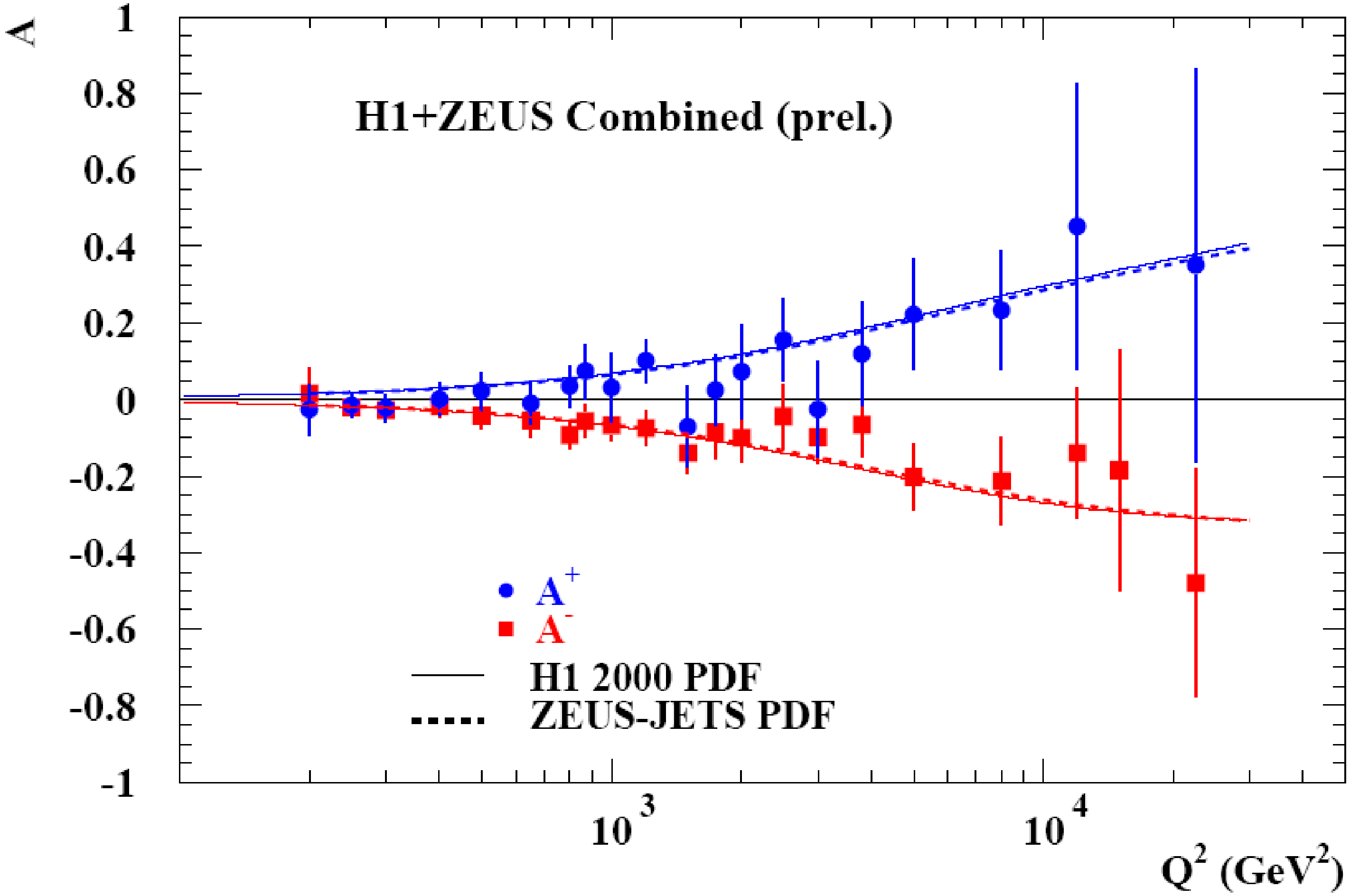
Effect increases with Q^2
As do the statistical uncertainties!

Data consistent with SM

suppression of electron R
enhancement of positron R

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)} \approx \chi_Z a_e \frac{F_2^{\gamma Z}}{F_2}$$

Direct measure of parity violation



define the difference of positron and electron polarisation asymmetries

$$\delta A = A^{+} - A^{-}$$

χ^2 of δA being different from zero = 4.0 (3.1 x 10^{-3} probability)

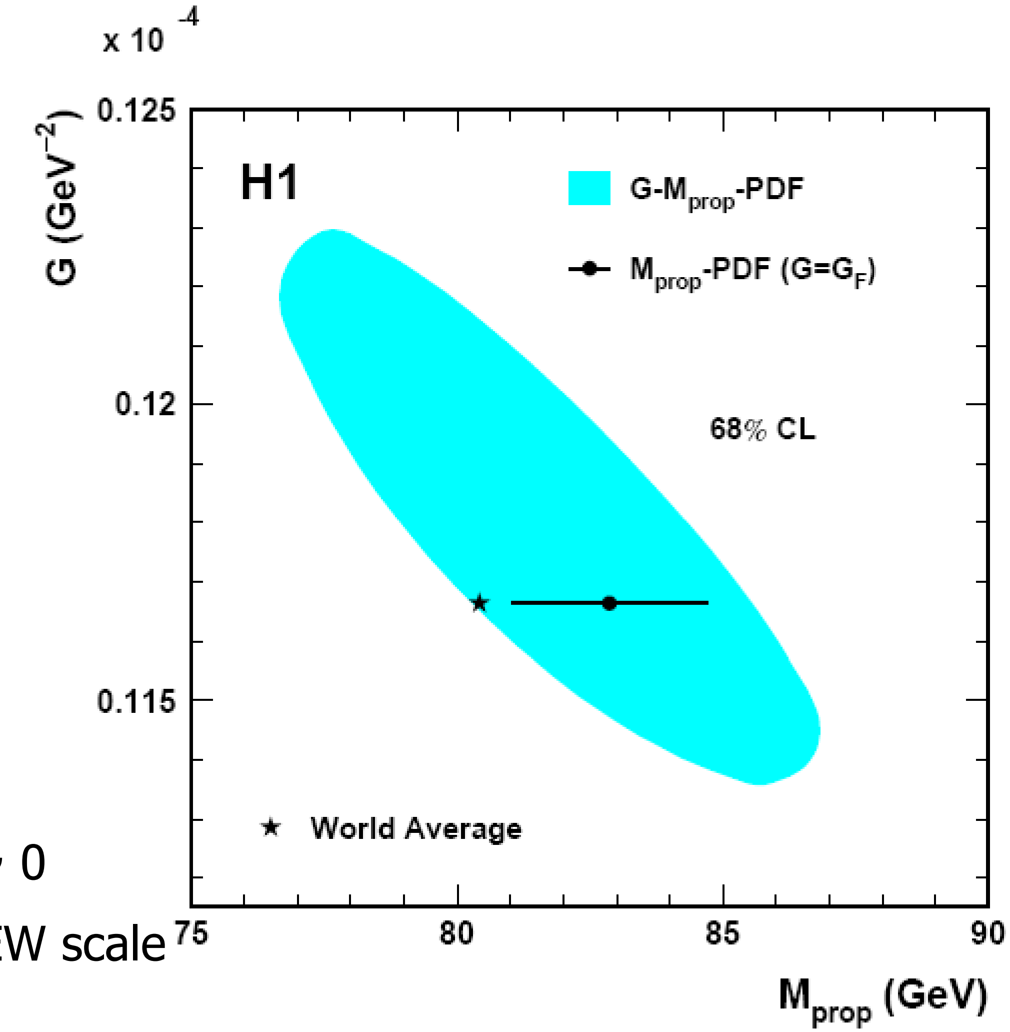
Fit cross sections to extract G & M_{prop}

PDFs are simultaneously fitted

$$\frac{d^2\sigma}{dxdQ^2} \propto G_F^2 \left(\frac{M_W^2}{M_W^2 + Q^2} \right)^2$$

G ~ normalises CC cross section

M_{prop} ~ controls Q^2 dependence



Allow G & M_{prop} to vary independently

PDFs simultaneously fitted - with NC data

G consistent with precise G_F measured at Q^2 ~ 0

indicates universality of CC interactions upto EW scale

Fixing G to precise value, fit M_W

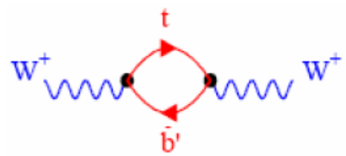
H1: $M_W = 82.9 \pm 1.8$ (exp) $^{+0.32}_{-0.18}$ (model) GeV

ZEUS: $M_W = 79.1 \pm 0.8$ (stat + unc. sys.) $\pm$ 1.0 (cor. sys.) GeV

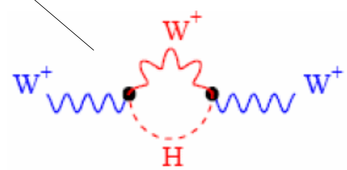
Complementary to LEP/Tevatron determination - now measured in spacelike domain

In SM G_F is related to weak boson masses (in OMS scheme)

$$\frac{d^2\sigma}{dxdQ^2} = \frac{\pi\alpha^2}{4M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)^2} \cdot \frac{1}{(1-\Delta r)^2} \cdot \left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \cdot \text{PDFs}$$



quadratic loop corrs.

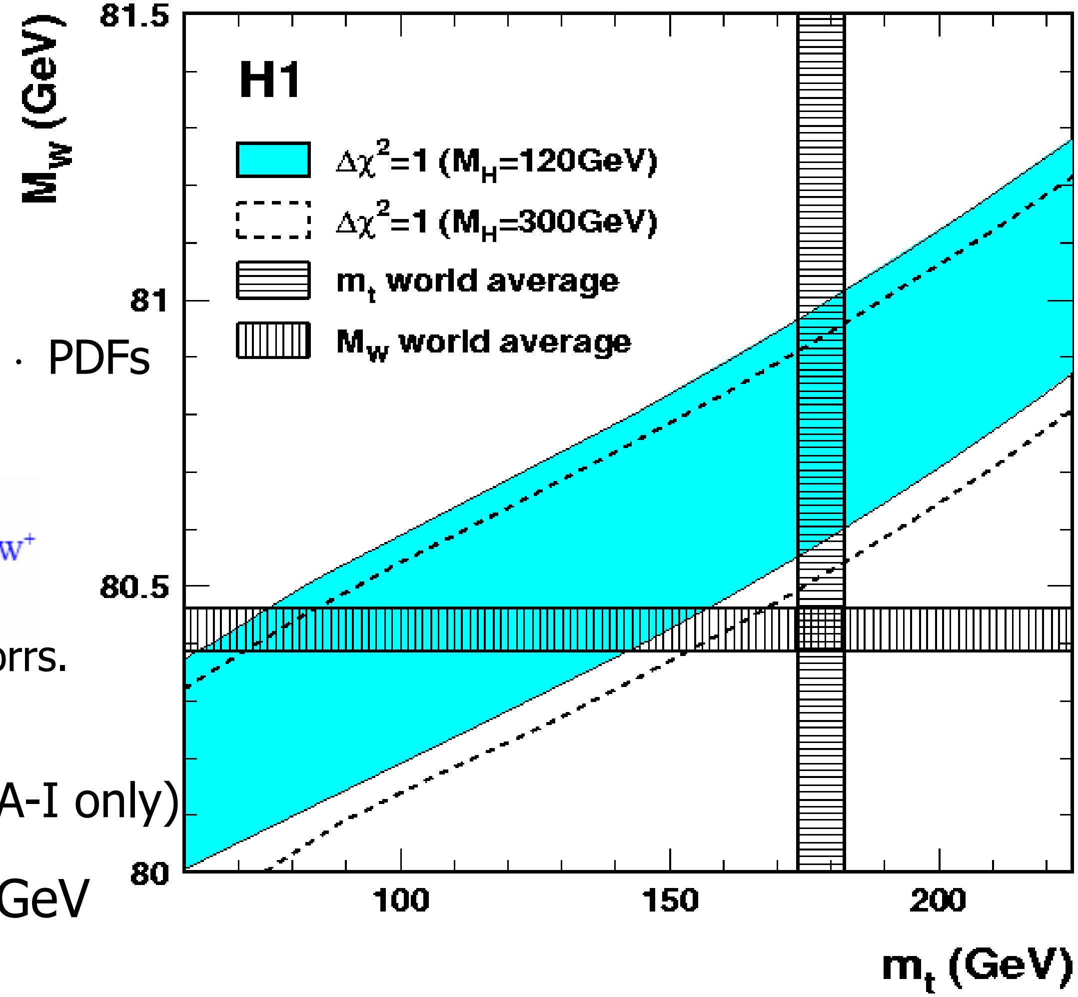


logarithmic loop corrs.

H1 Fit M_W with M_Z fixed at PDG value (HERA-I only)

$$M_W = 80.786 \pm 0.205 \text{ (exp) } ^{+0.048}_{-0.029} \text{ (model) GeV}$$

indirect consistency check of SM



Indirect sensitivity to m_t through loop corrections

Assume M_H=120 GeV and fix M_W to PDG value

m_t = 104 ± 44 (exp) GeV

First determination in DIS at EW scale

Neutral Current Channel

$$\tilde{F}_2^{\pm} = F_2^{\gamma} - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm P_e 2 v_e a_e)\chi_z^2 F_2^Z$$

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\chi_Z xF_3^{\gamma Z} + (2 v_e a_e \pm P_e(v_e^2 + a_e^2))\chi_z^2 xF_3^Z$$

Since $\chi_Z \gg \chi_Z^2$ and $v_e \approx 0.05$ we can neglect pure Z^0 terms

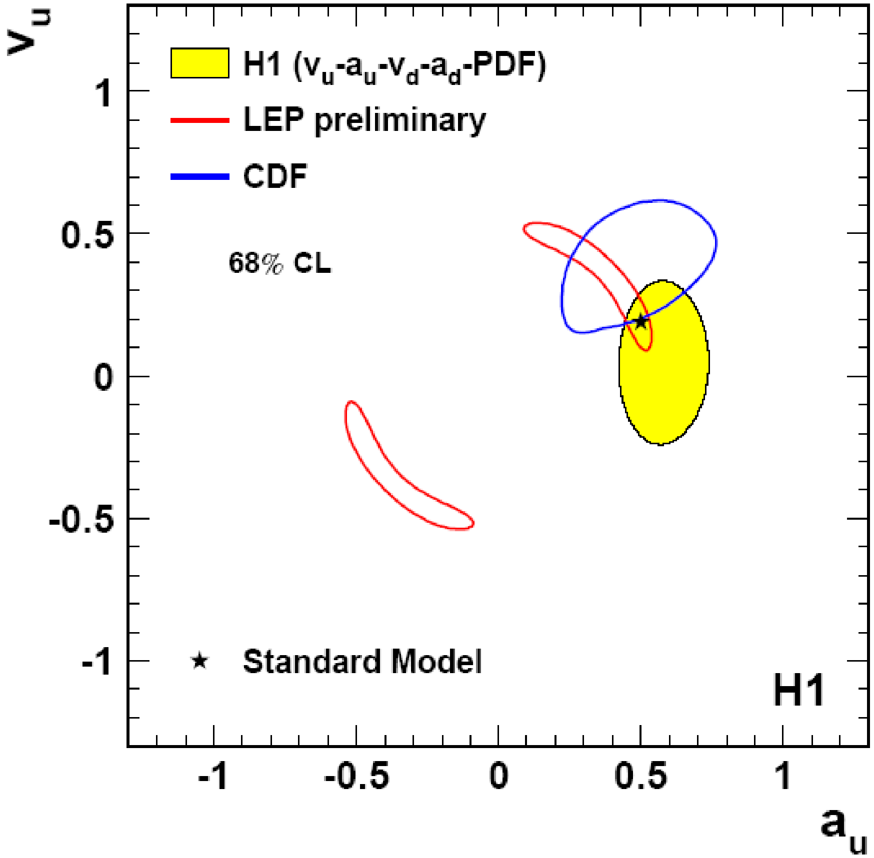
$$\tilde{F}_2^{\gamma Z} = \sum 2 e_i v_i (xq_i + x\overline{q}_i)$$

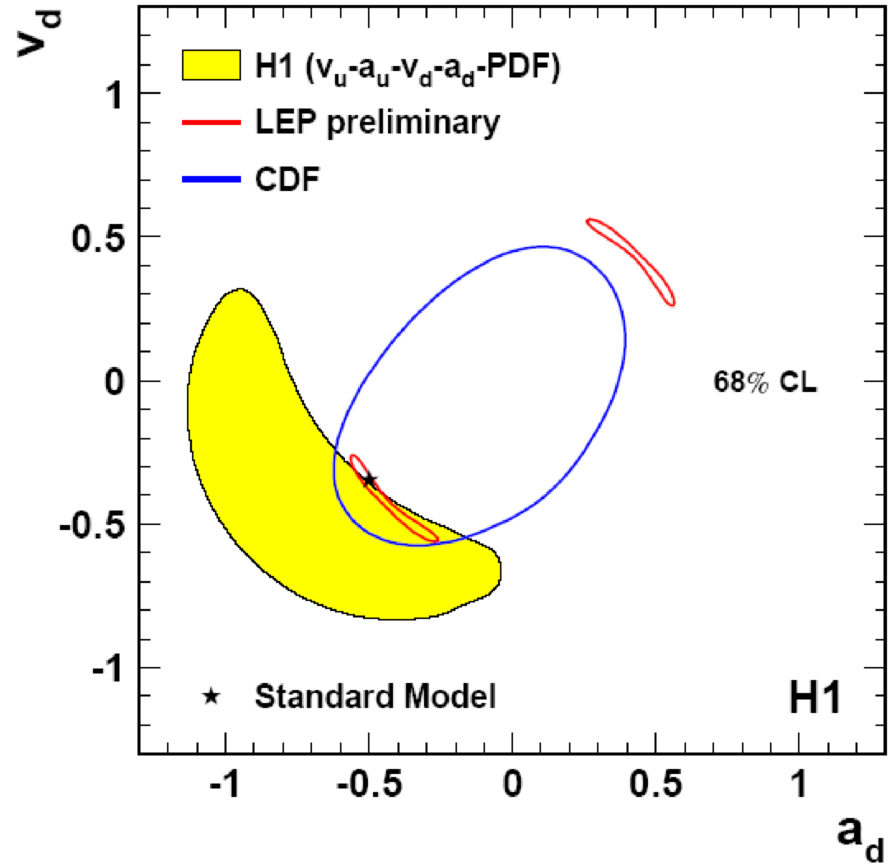
$$x\tilde{F}_3^{\gamma Z} = \sum 2 e_i a_i (xq_i - x\overline{q}_i)$$

Sensitivity to axial and vector couplings of quarks to Z^0

These can be extracted by fits to HERA-I and HERA-II data
Fitting NC and CC data allow simultaneous extraction of PDFs

Light Quark Couplings to Z^0



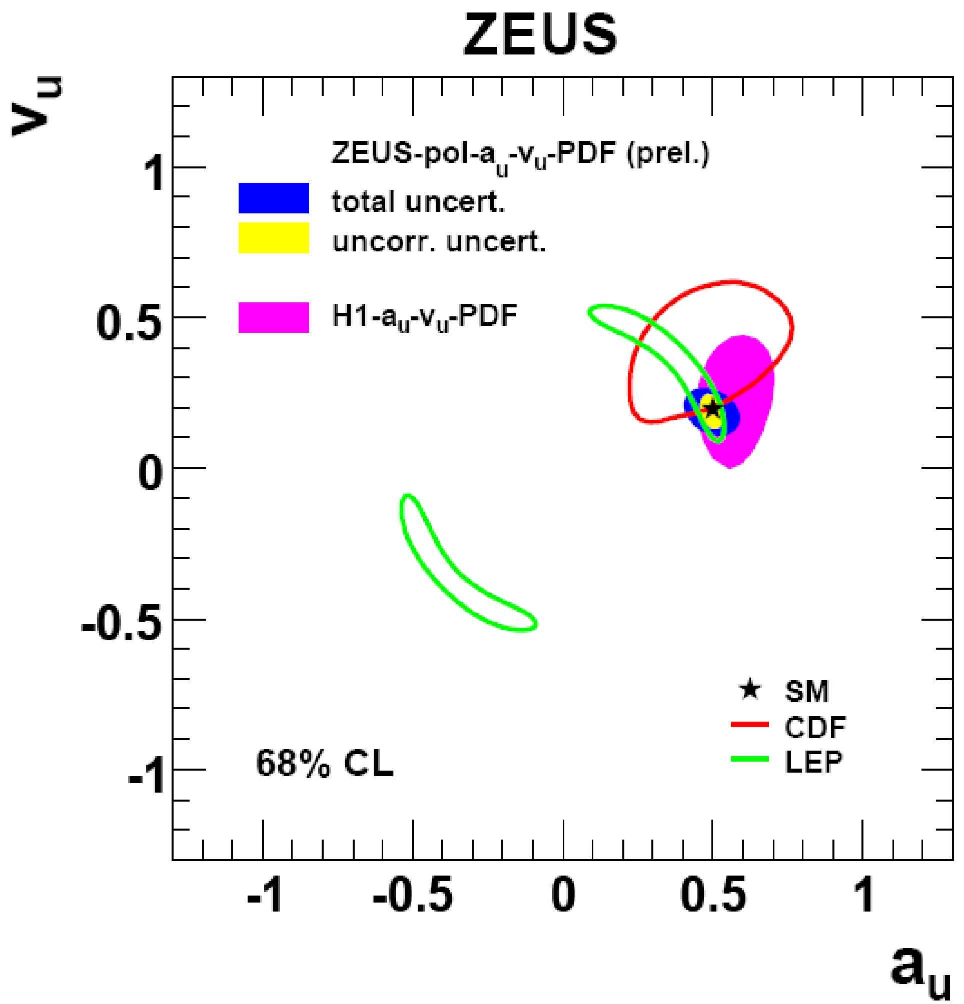


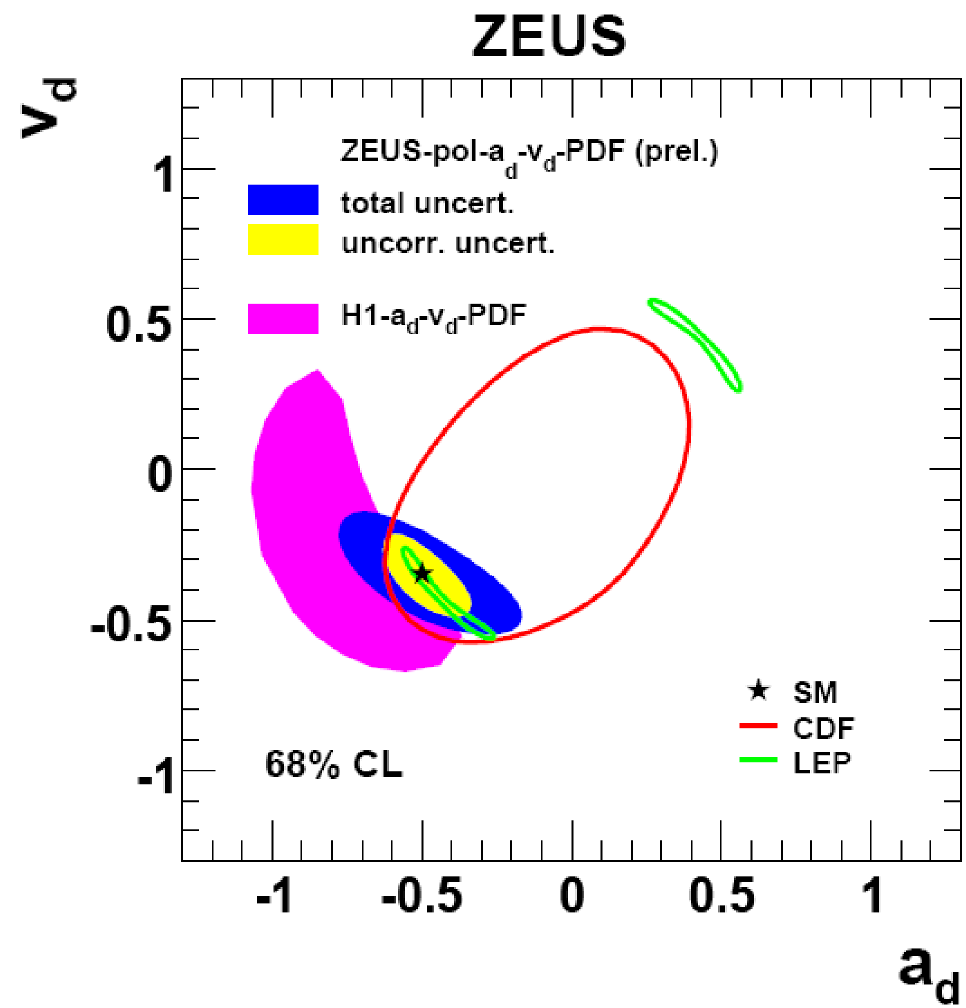
H1 determination based on QCD-EW fit to HERA-I data alone

Fit to a_u, v_u, a_d, v_d, PDFs

Comparable to Tevatron precision

Resolve LEP ambiguity





Inclusion of HERA-II polarised data improves vector precision

ZEUS fit to a_u/v_u/PDFs or a_d/v_d/PDFs

Many interesting results coming from HERA experiments

NC & CC measurements at EW scale

Improvement of statistical precision through H1 & ZEUS combination

Clear observation of parity violation in NC channel

Simultaneous QCD & EW fits performed on HERA data

Determination of spacelike propagator mass in CC interactions

Polarised CC date give direct sensitivity to $W_R \Rightarrow$ limit set

Extraction of light quark couplings to Z^0

The Standard Model performs excellently (as usual)

Last six months of HERA operation

Final analysis of complete HERA dataset will follow...