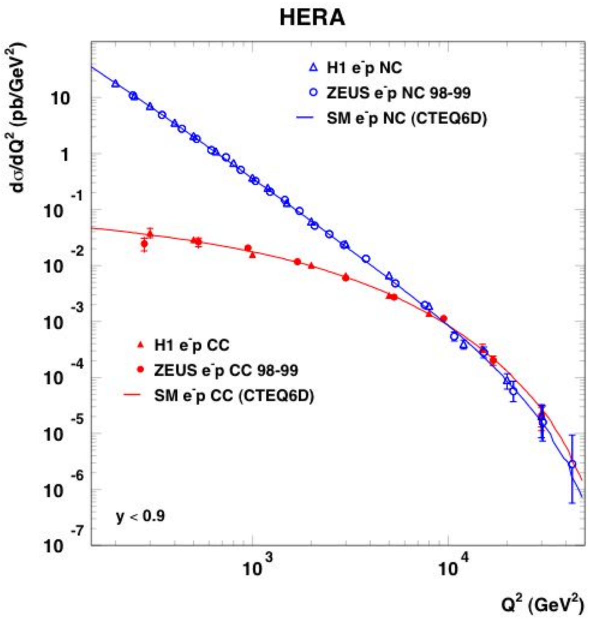
Electroweak Physics at HERA

Joachim Meyer
DESY

The conference logo really fits this talk …….



Outline

Test of electroweak SM at high spacelike momentum transfers

HERA I :

- Electroweak Unification
- Electroweak DIS cross section fits
- Propagator mass
- NC quark couplings

HERA II :

- Polarized CC cross sections
- Polarized NC cross sections

Outlook

Inclusive Neutral Current (NC) & Charged Current (CC) Cross Sections

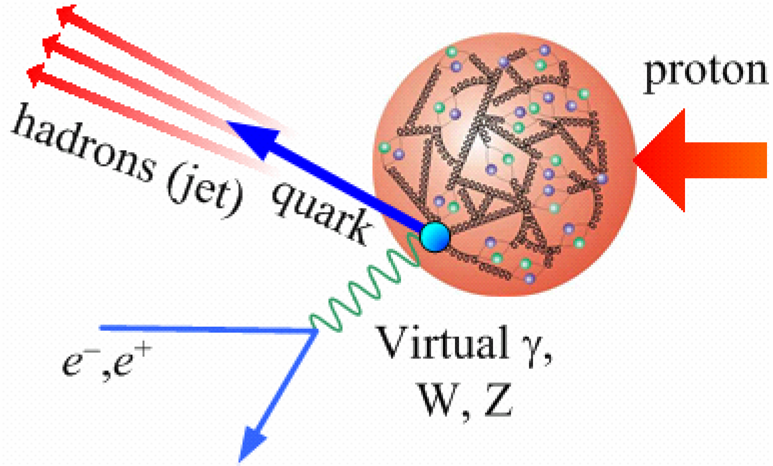
This talk

Structure Functions (SFs)

Electroweak Parameters

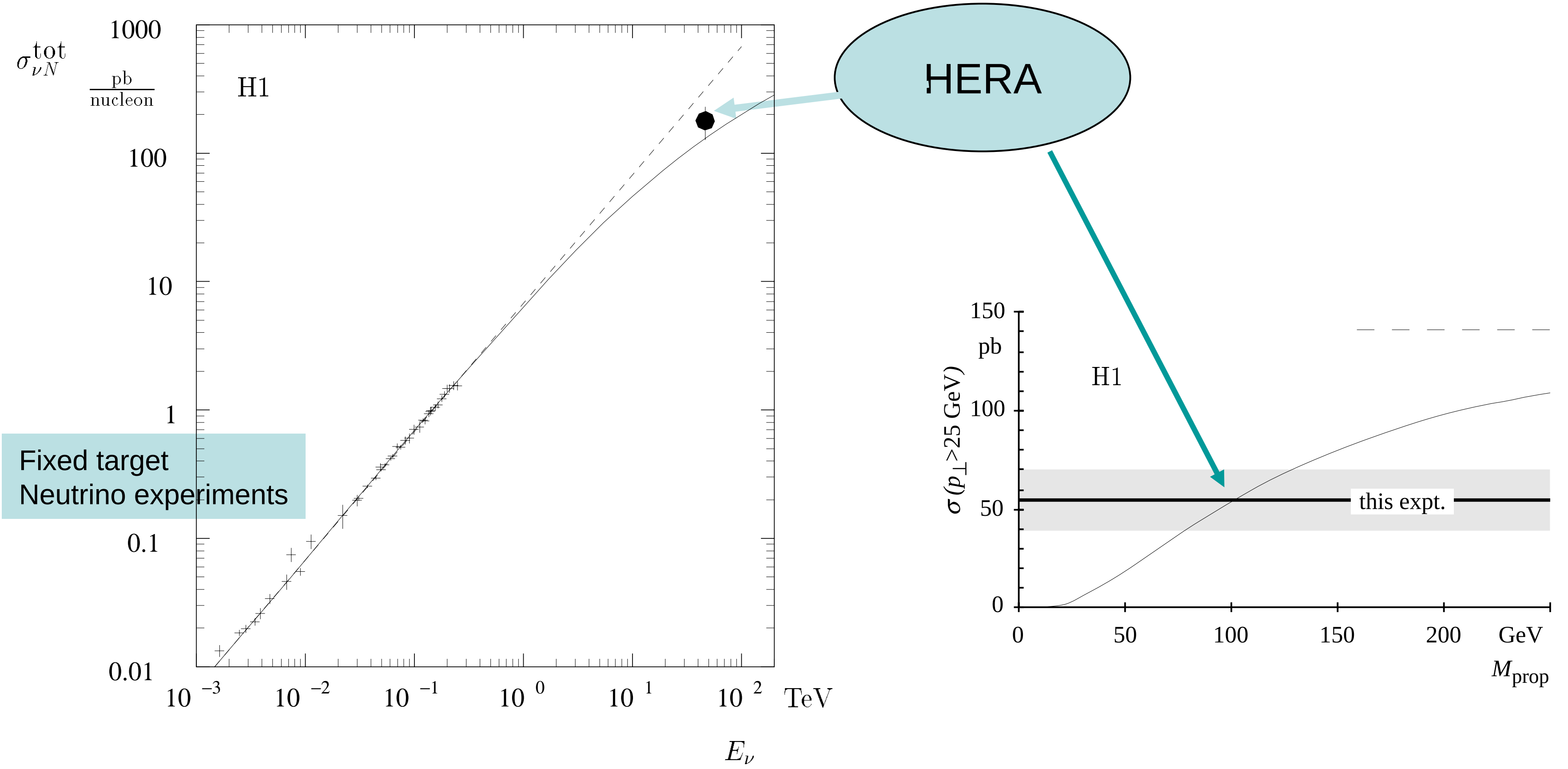
Polarization P_e (HERA-II only)

Parton Distribution Functions (PDFs)



1993 :Very first electroweak result at HERA from 0.3 pb^{-1}

HERA total CC cross section converted to equivalent neutrino cross section



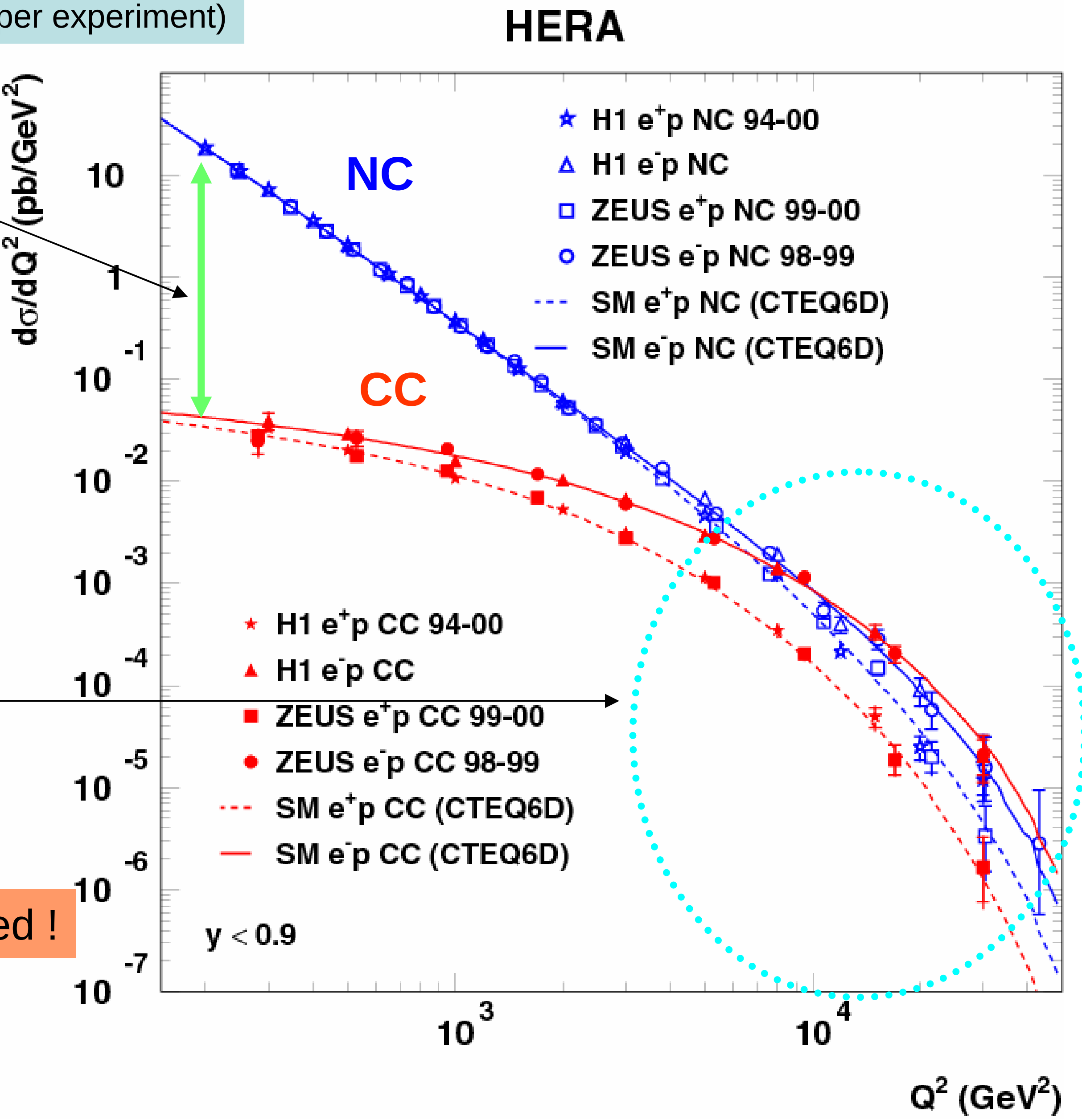
HERA

Fixed target
Neutrino experiments

First evidence of W-Propagator effect in Charged Current DIS

Measured NC and CC cross sections

HERA I Data 1994 – 2000 (100 pb^{-1} per experiment)

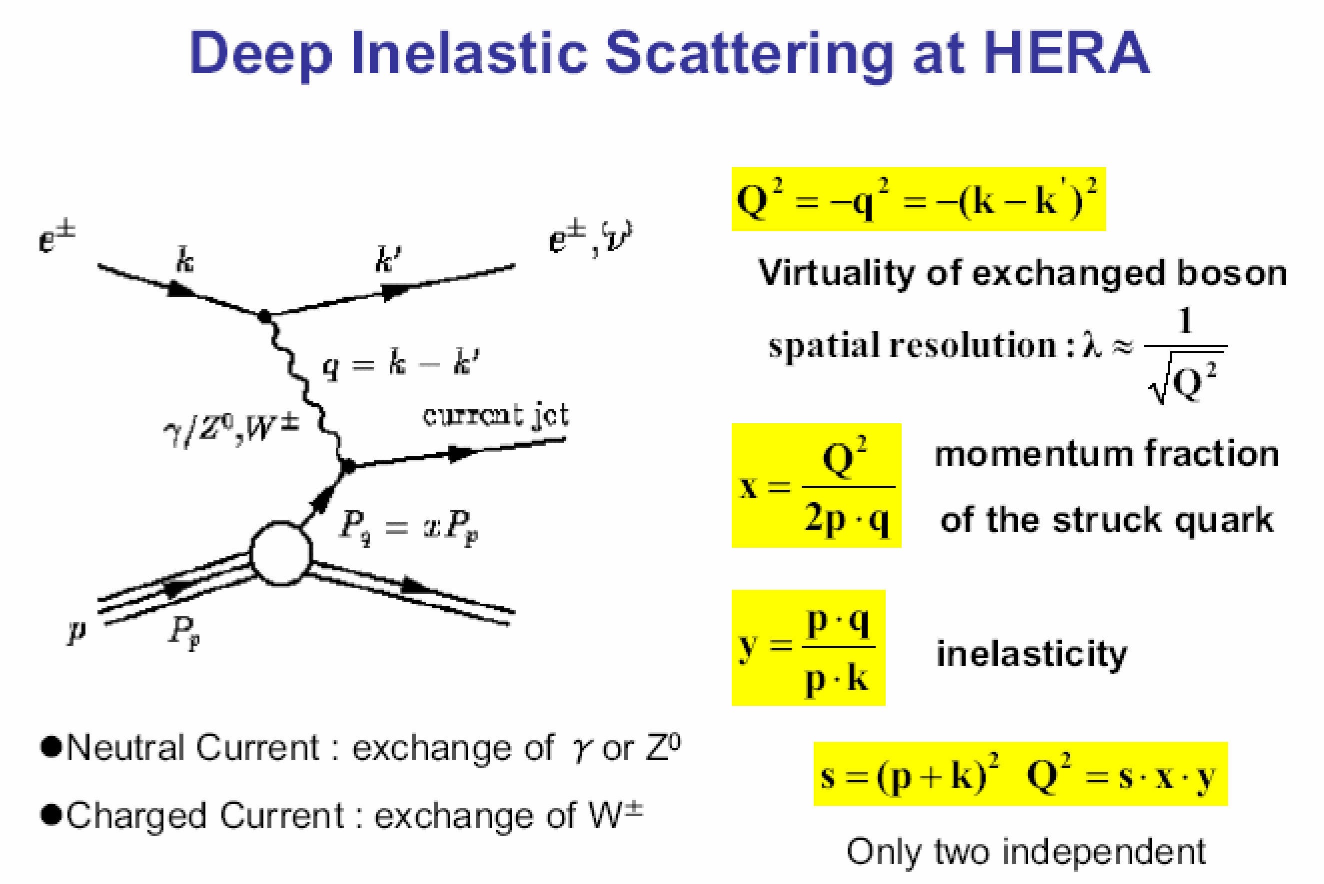


Suppressed due to large mass of W boson compared to NC DIS

Electro-Weak unification at high Q^2

High Q^2 results statistics limited !

Kinematics :



Deep Inelastic Scattering at HERA

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

Virtuality of exchanged boson

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

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

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

Only two independent

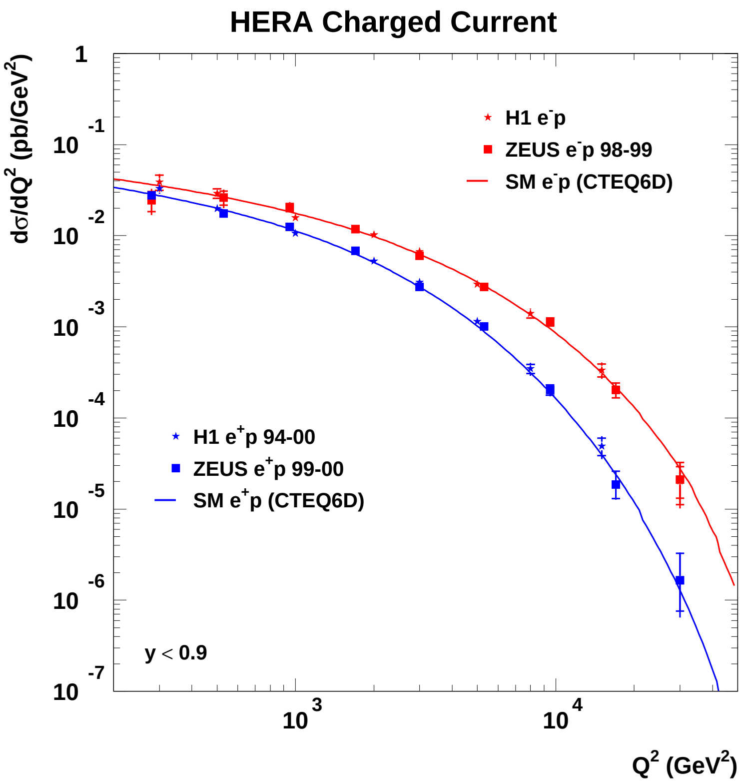
CC Cross Section

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

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



NC Cross Section

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

Dominant contribution

Contribution only important at high Q^2

Sizeable only at high y

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

γ exchange

γ-Z interference

Z exchange

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

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

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

$$[F_2, F_2^{\gamma Z}, F_2^Z] = x\sum_q [e_q^2, 2e_q \underline{v_q}, \underline{v_q^2 + a_q^2}](q + \bar{q}) \qquad [xF_3^{\gamma Z}, xF_3^Z] = 2x\sum_q [e_q \underline{a_q}, \underline{v_q a_q}](q - \bar{q})$$

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

SFs : coupling constant $\otimes$ Parton Distribution Functions (PDFs)

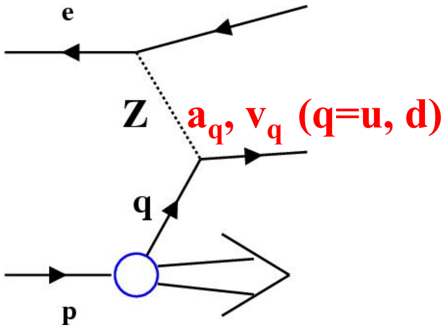
HERA-I Results : Combined EW+PDF Fit (H1)

- The low Q^2 precision cross section data +
  the high Q^2 NC e^+p & e^-p data +
  the high Q^2 CC e^+p & e^-p data

constrain
5 sets of PDFs:

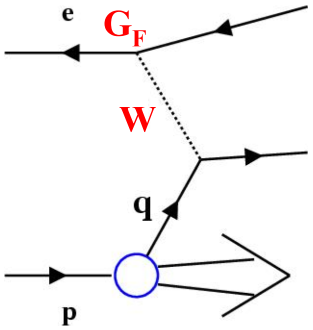
gluon, up-type quark, down-type quark & their anti-quarks

- NC data at high Q^2 also sensitive to quark couplings to the Z boson



- CC data also sensitive to
  - G, W propagator mass [model independent]
  - M_W, m_t [within the SM framework]

$$\frac{d^2\sigma_{CC}(e^\pm p)}{dxdQ^2} = \frac{G_F^2}{2\pi x}\frac{M_W^4}{(Q^2+M_W^2)^2}\,\Phi(\mathrm{PDFs})$$



Combined EW+PDF Analysis Strategies

- Model independent fits:

1) Fit a_u-v_u-a_d-v_d-PDF
to extract light quark couplings to the Z boson

2) Fit G-M_{prop}-PDF
to determine the normalization factor G and W propagator mass M_{prop}

3) Fit M_{prop}-PDF [fix G to G_F]
to determine the W propagator mass M_{prop}

- Fits within the SM framework:

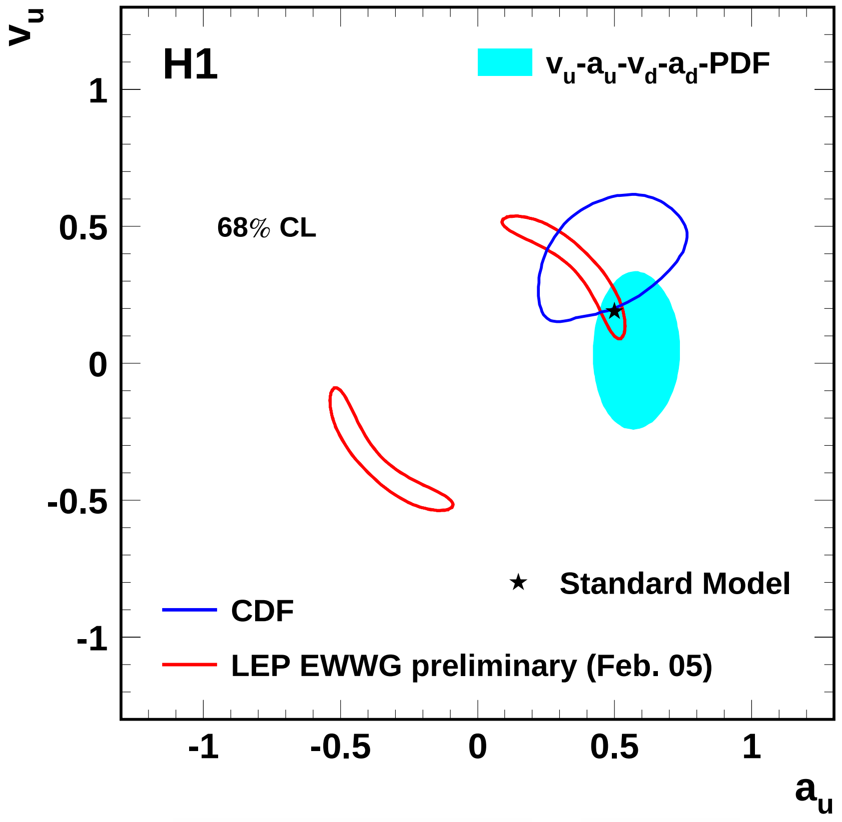
$$G_F^2 = \frac{\pi\alpha}{\sqrt{2}\, M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)} \frac{1}{1 - \Delta r}$$

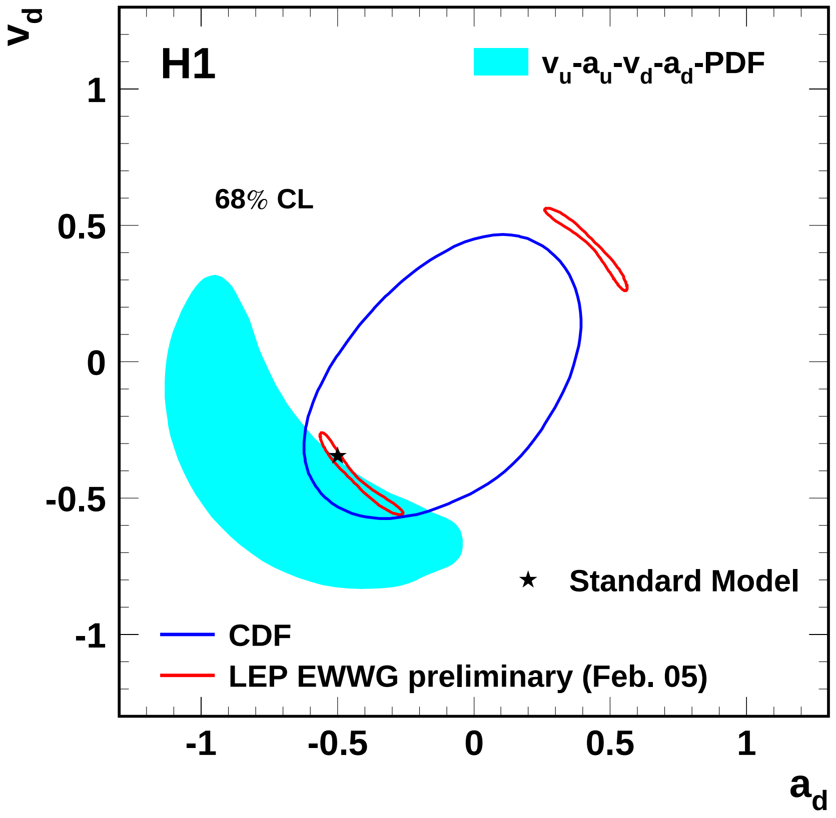
Δr contains - quadratic dependence on m_t
- logarithmic dependence on M_H

4) Fit M_W-PDF [fix m_t to 178GeV, M_H to 120GeV]
to determine the SM W mass M_W

5) Fit m_t-PDF [fix M_W to 80.425GeV, M_H to 120GeV]
to determine the top quark mass m_t

First Results on Light Quark Couplings to Z at HERA

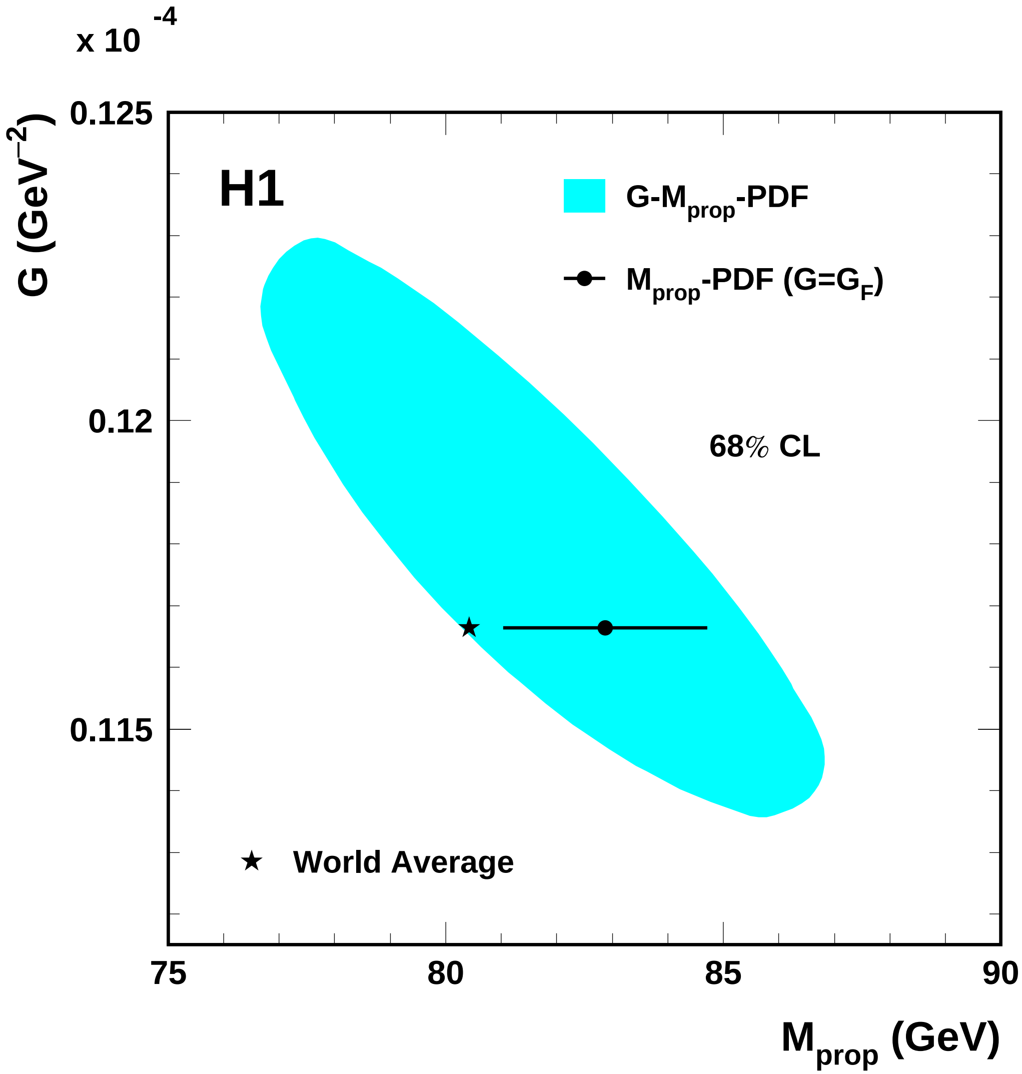




SM : $v_q = I^3_q - 2e_q \sin^2\theta_w$ $a_q = I^3_q$

Tevatron: qq→ee **Drell-Yan,** A_{FB}: CDF Collab., Phys. Rev. D71(2005)052002, hep-ex/0411059
LEP: ee→qq(γ) [$a^2_q+v^2_q$]: http://lepewwg.web.cern.ch/LEPEWWG/plots/winter2005/

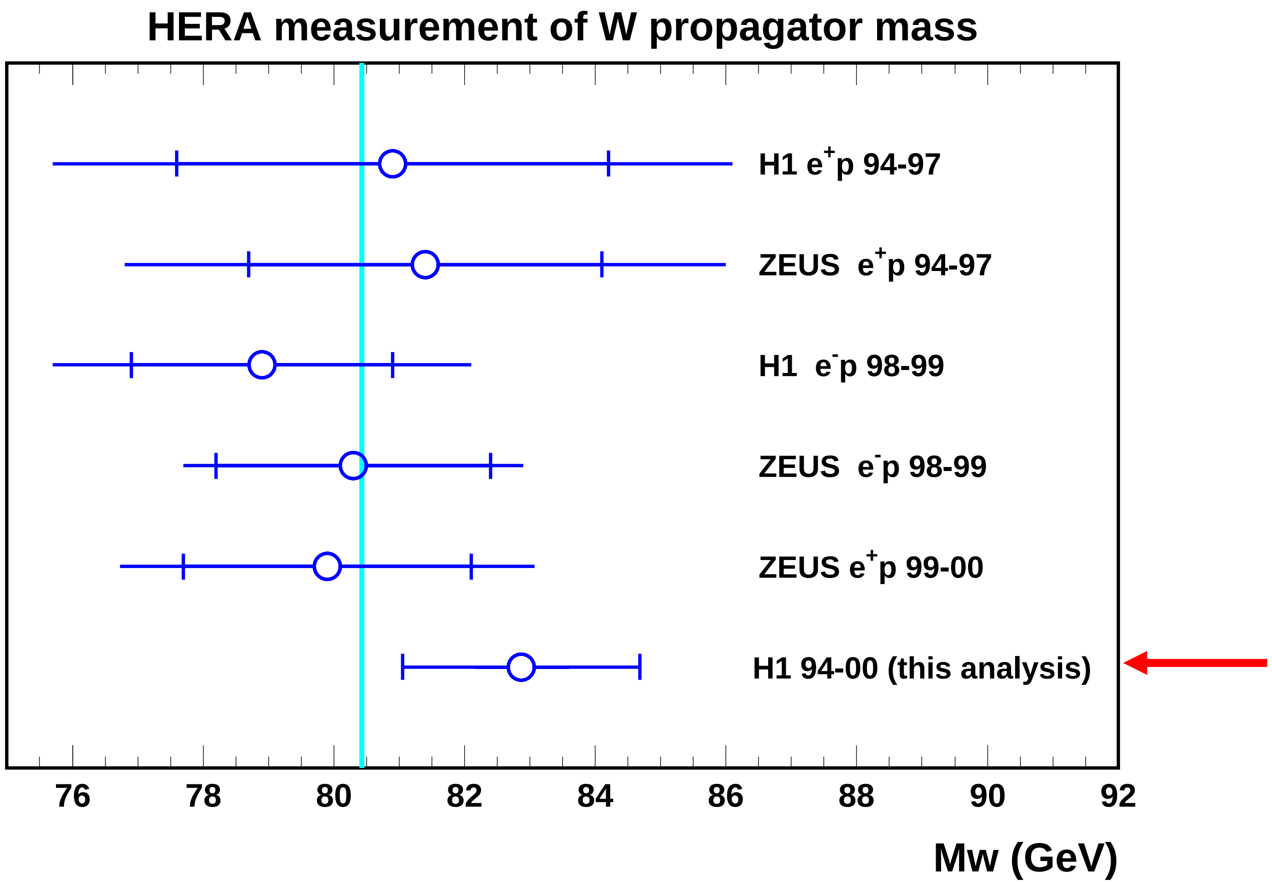
W Propagator Mass and Coupling



With G_F from PDG :

M_{Prop}= 82.9 +- 1.9 GeV

Improved Precision on W Propagator Mass



Fits Imposing the SM Constraints

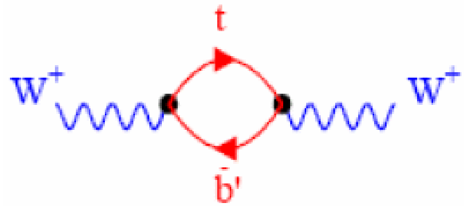
$$\frac{d^2\sigma^\pm_{CC}}{dx\,dQ^2} = \frac{G^2}{2\pi}\cdot\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\cdot\Phi^\pm(pdfs)$$

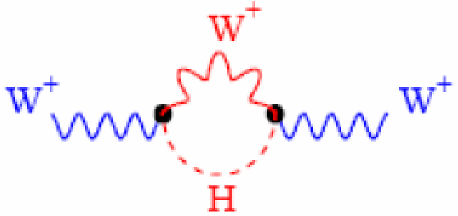
Introducing SM G_F-M_W relation in On-Mass-Shell (OMS) scheme

$$\frac{d^2\sigma^\pm_{CC}}{dx\,dQ^2} = \frac{\pi\alpha^2}{4M_W^4\left(1-\frac{M_W^2}{M_Z^2}\right)^2}\cdot\frac{1}{(1-\Delta r)^2}\cdot\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\cdot\Phi^\pm(pdfs)$$

Quadratic dependence on m_t

Logarithmic dependence on M_H





Determination of SM Parameters

- **W mass value:**

  $M_W = 80.786 \pm 0.205_{exp}$ GeV

  + the world average M_Z

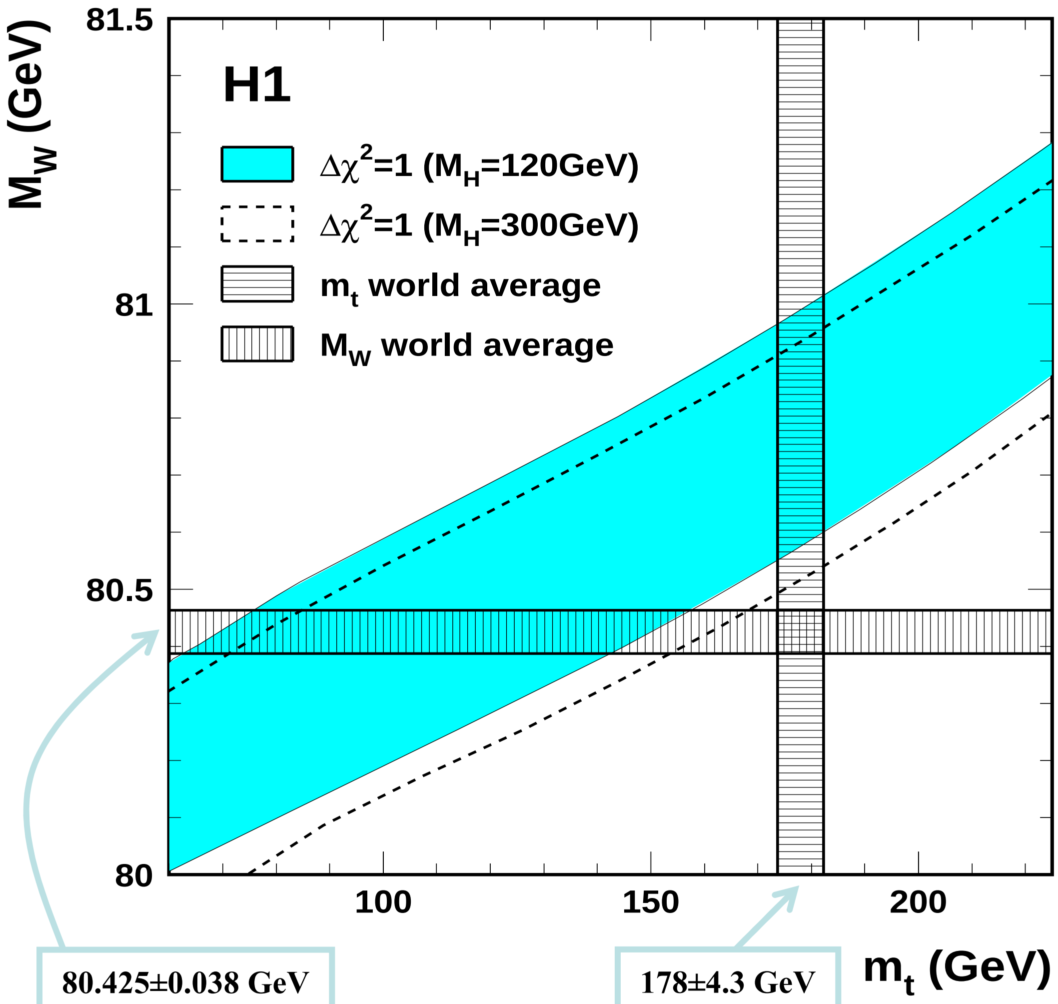
  ➔ indirect determination of

  $\sin^2\theta_W = 1 - M^2_W / M^2_Z$
  $= 0.2151 \pm 0.0040_{exp}$

Using M_W (PDG) restricts top quark mass

$m_t = 104 \pm 44_{exp}$ GeV

➔ First determination in DIS at EW scale



80.425±0.038 GeV

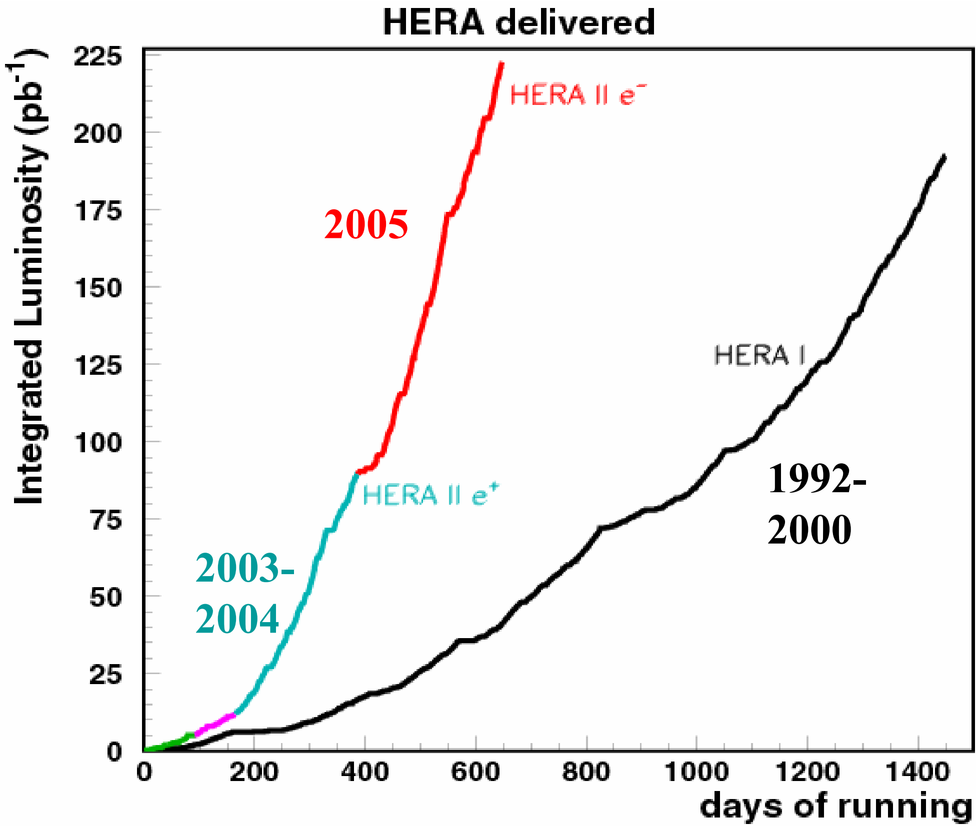
178±4.3 GeV

HERA II

- Substantial increase in luminosity
- Longitudinally polarized lepton beams

Luminosity 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

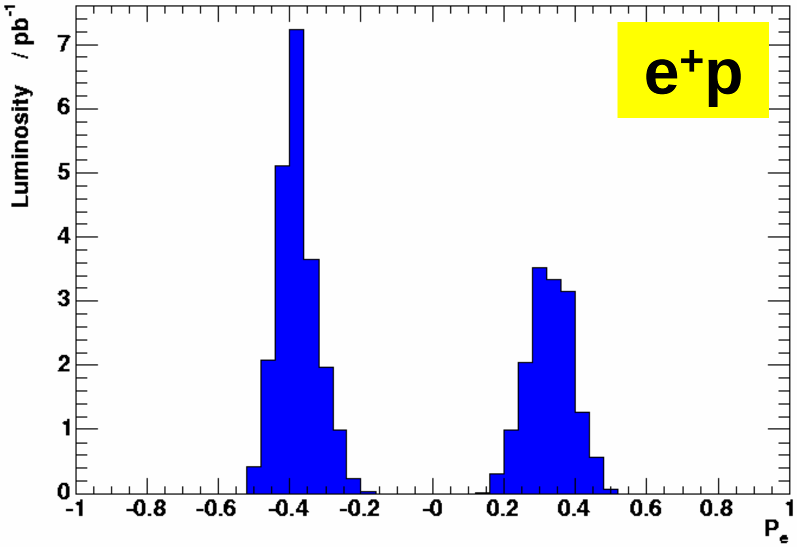
Data samples

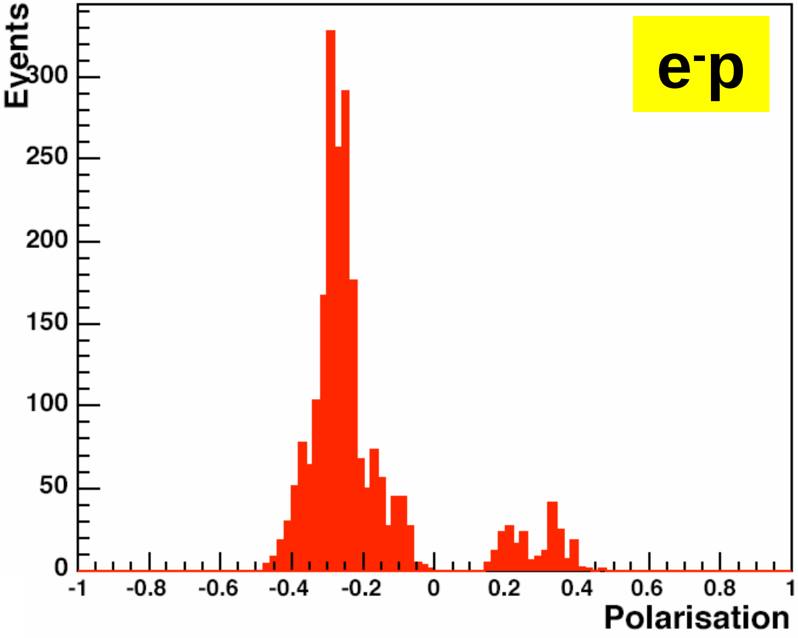
H1 data samples

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

ZEUS data samples

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





Joachim Meyer

Charged current physics at HERA II

CC Total Cross-Section (H1)

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

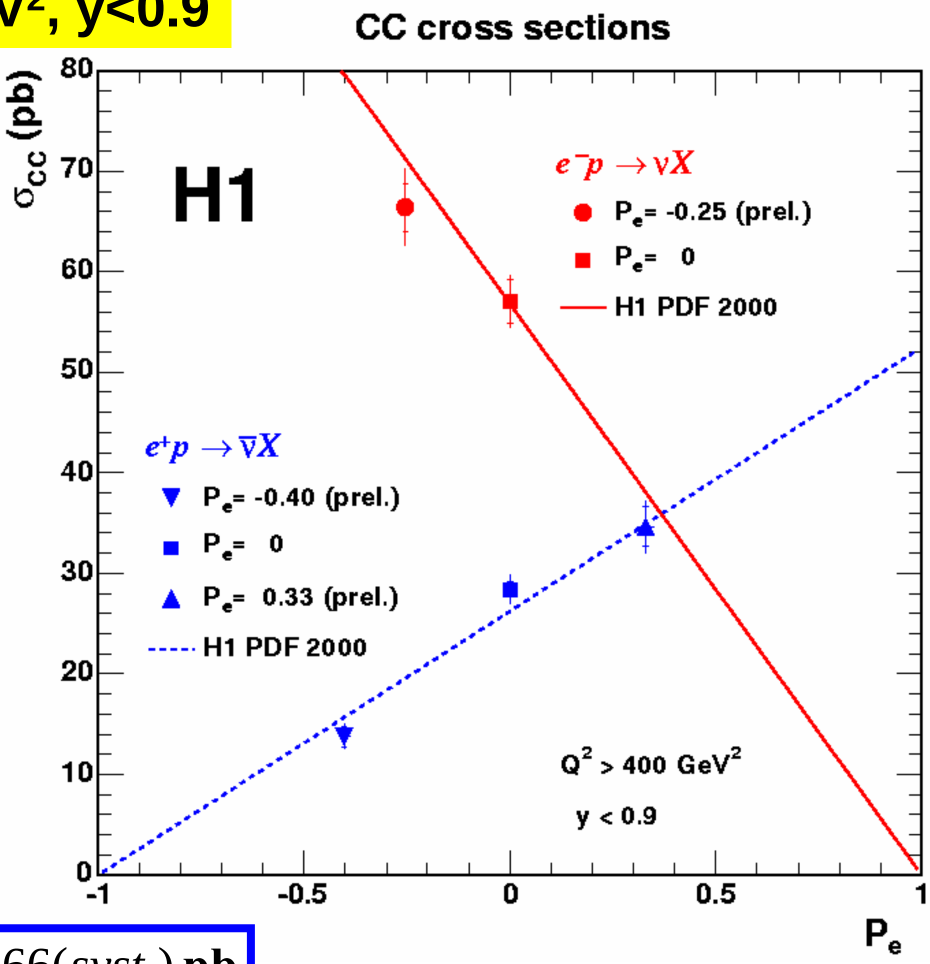
Remind : CC is pure weak

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

⇓

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 : H1 and ZEUS

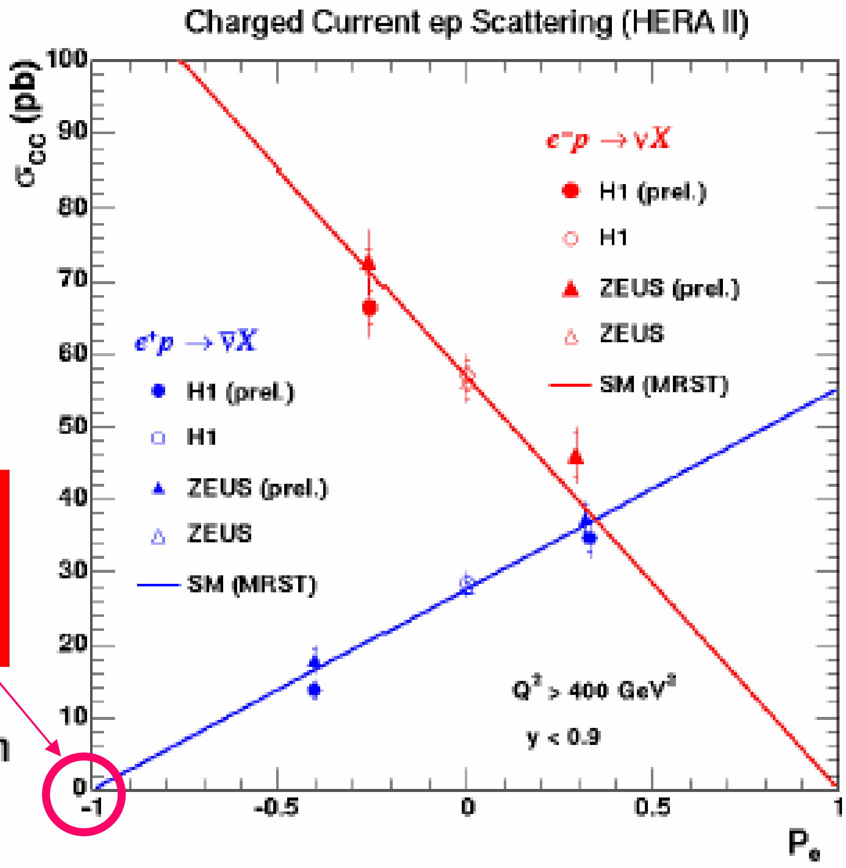
$Q^2>400\,\text{GeV}^2$, $y<0.9$

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

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

Consistent with the SM prediction

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

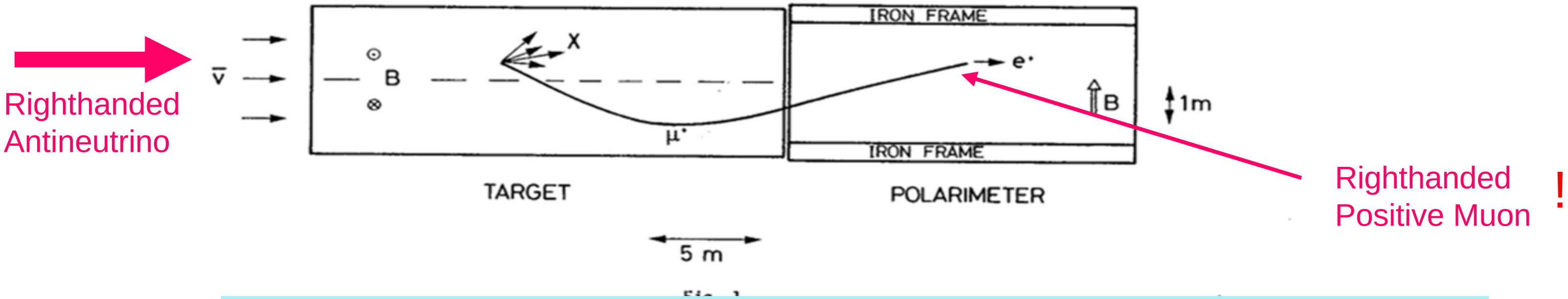


History:

The polarization dependence of CC – DIS scattering has already been measured in 1979 at the CERN Neutrino beam. (Phys.Lett. B86 ; 222 (1979))

Neutrino Interaction in CDHS Detector

Measurement of muon longitudinal Polarization in CHARM detector



Righthanded Antineutrino

Righthanded Positive Muon !

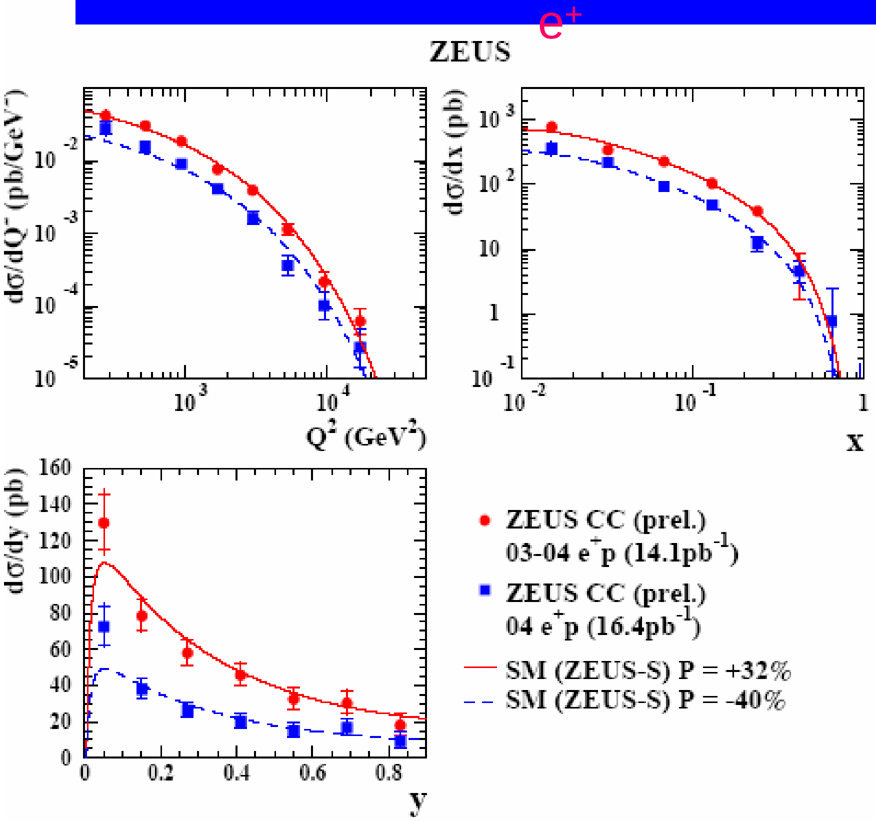
Result :

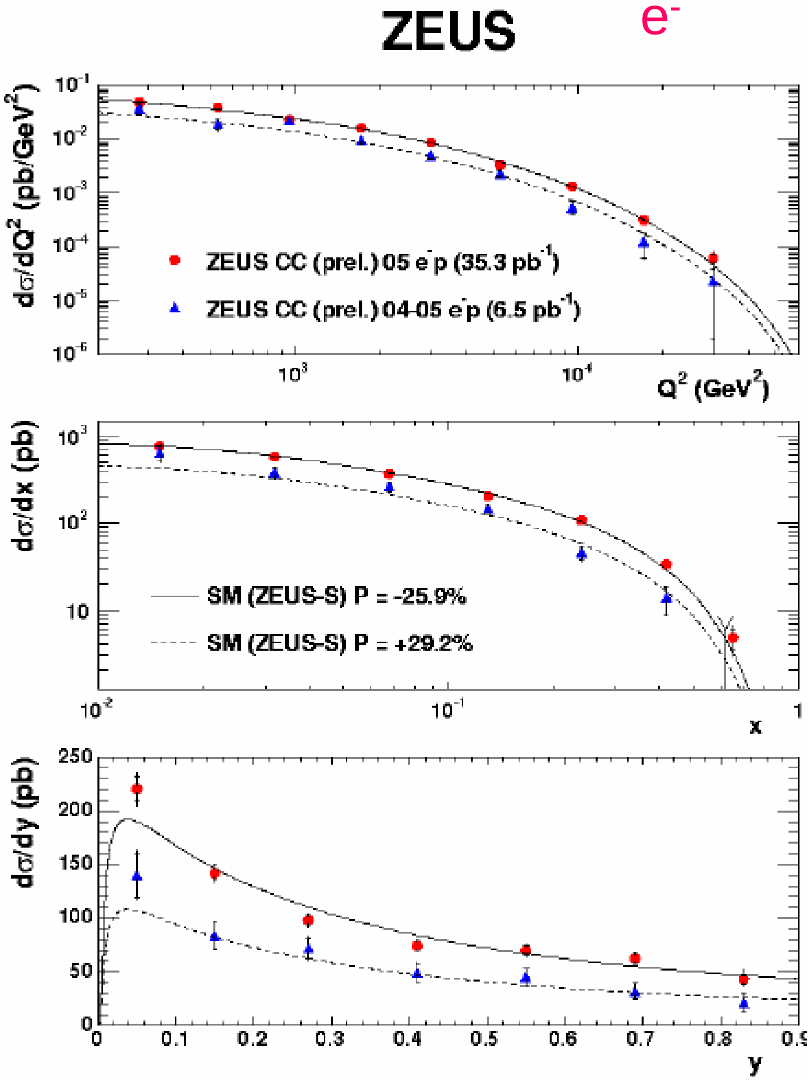
The longitudinal Polarisation of the positive muons is

$$P = +\ 1.09 \pm 0.22$$

(at an average momentum transfer 3.2 GeV^2 !!!)

CC Differential Cross Sections (ZEUS)





polarisation dependence seen not only total cross section

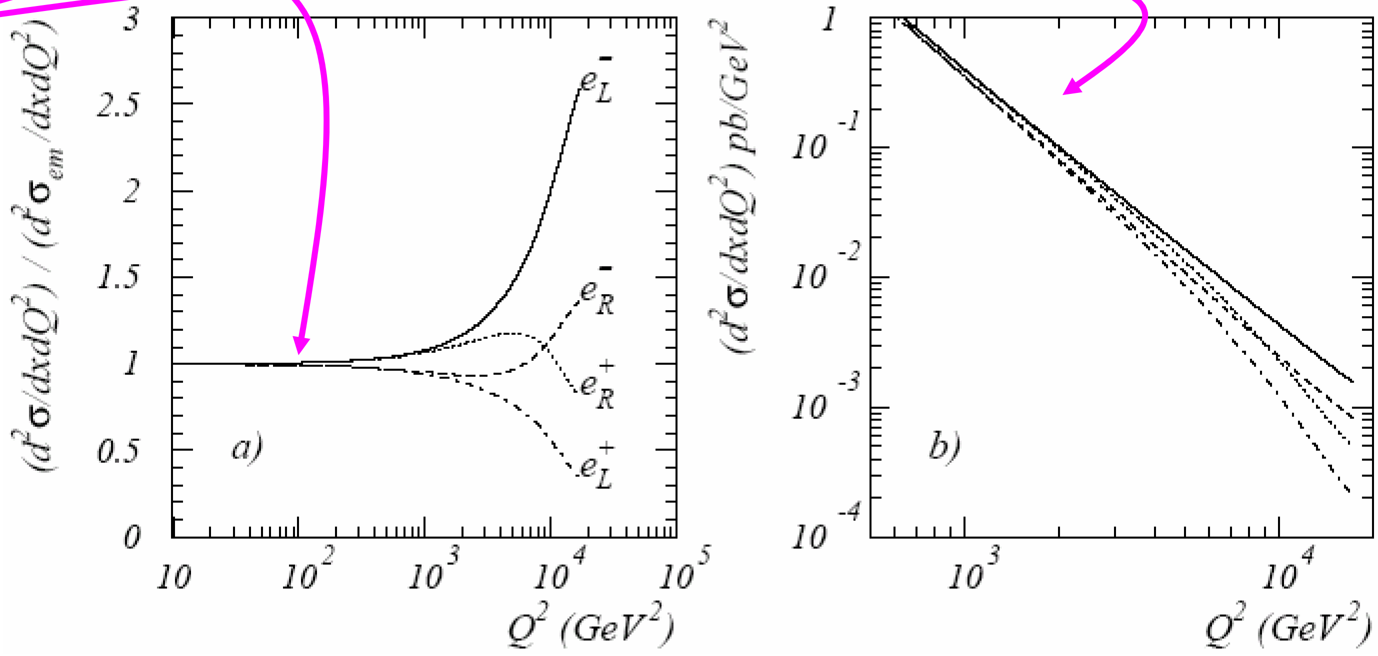
but differential cross section in all kinematic regions

Neutral current physics
At HERA II

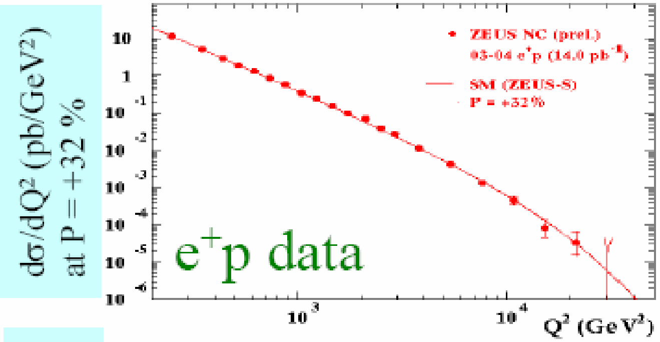
NC & CC Cross Sections Dependence on Polarization P_e

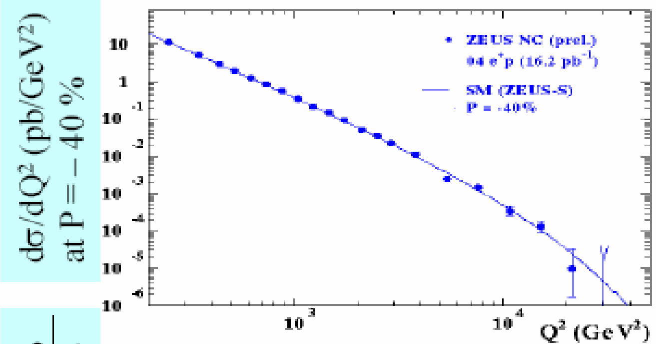
For NC: em contribution dominating at low Q^2 is independent of P_e.

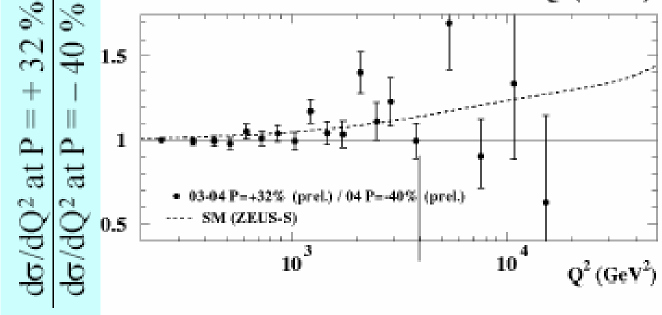
weak NC only significant at high Q^2

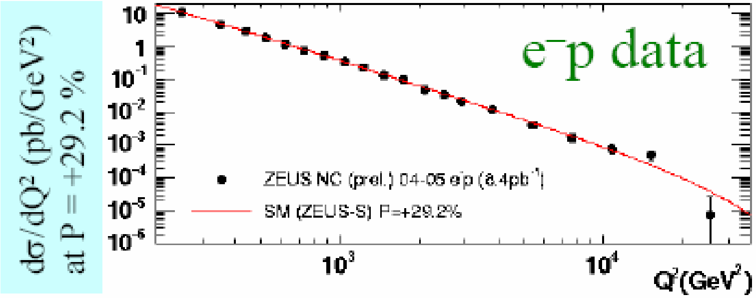


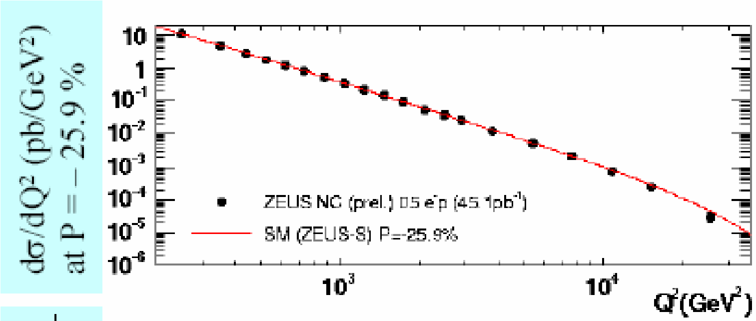
NC Differential Cross Section (ZEUS)

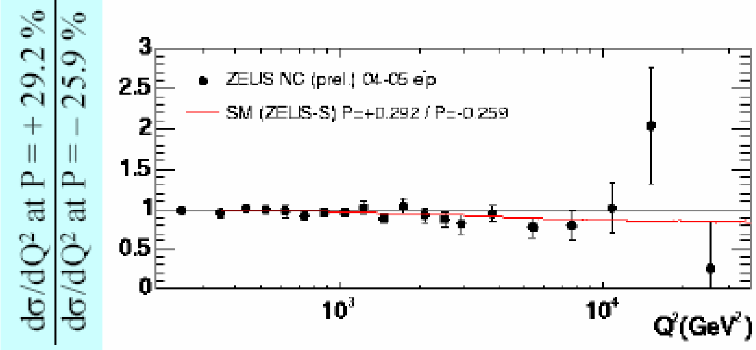












- $d\sigma/dQ^2$ for NC : Polarisation dependence is not observed conclusively with the current limited statistics

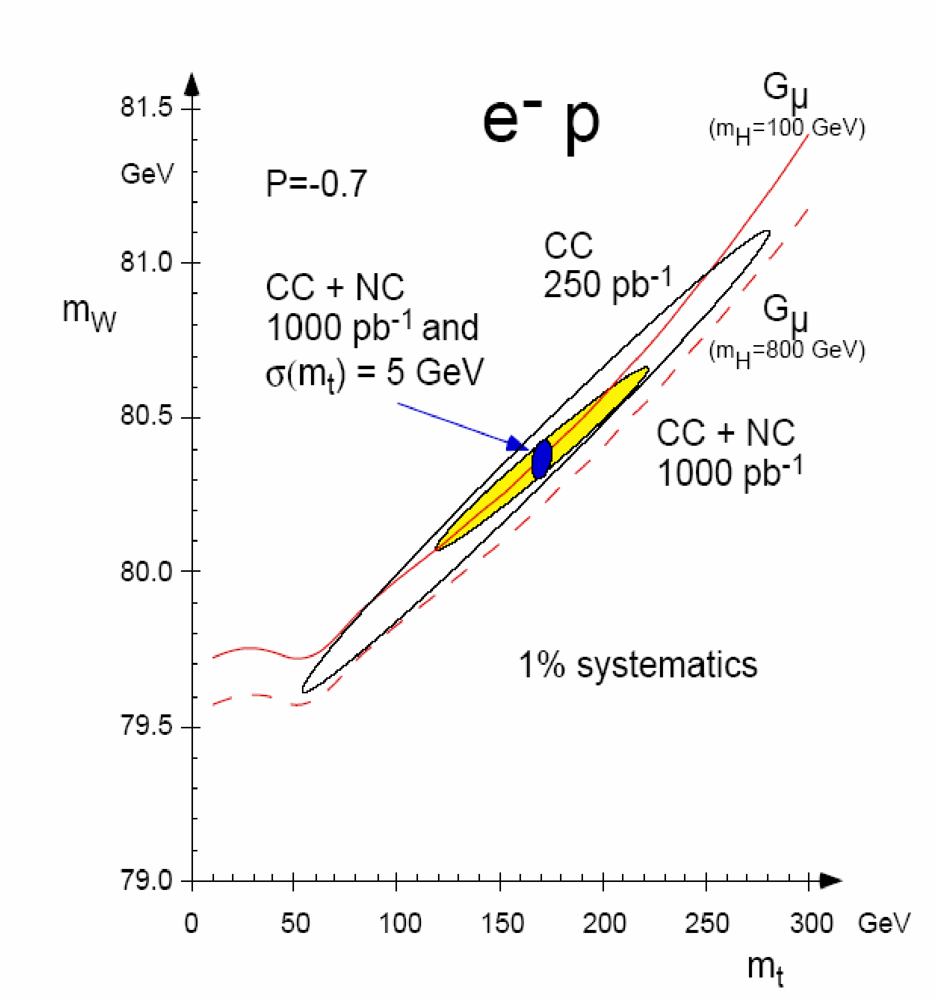
Outlook

HERA II is expected to deliver approx 700 nb^{-1} to each experiment. There will be an equal share of e^+ and e^-, left- and righthanded polarized.

More precise checks of electroweak SM possible :

- Better M_W determination (spacelike Propagatormass)
- More precise Z_0 couplings to light quarks

HERA Physics workshop studies : W - Propagator Mass



H1 Result :

HERA I (100 pb^{-1} , unpol.) :

M_{prop} = 82.9 +- 1.9 GeV

M_W = 80.8 +- 0.2 GeV

Precise check of EW theory when combined with Mtop from Tevatron (LHC)

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

Polarised contribution : only includes γ -Z and Z terms

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

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

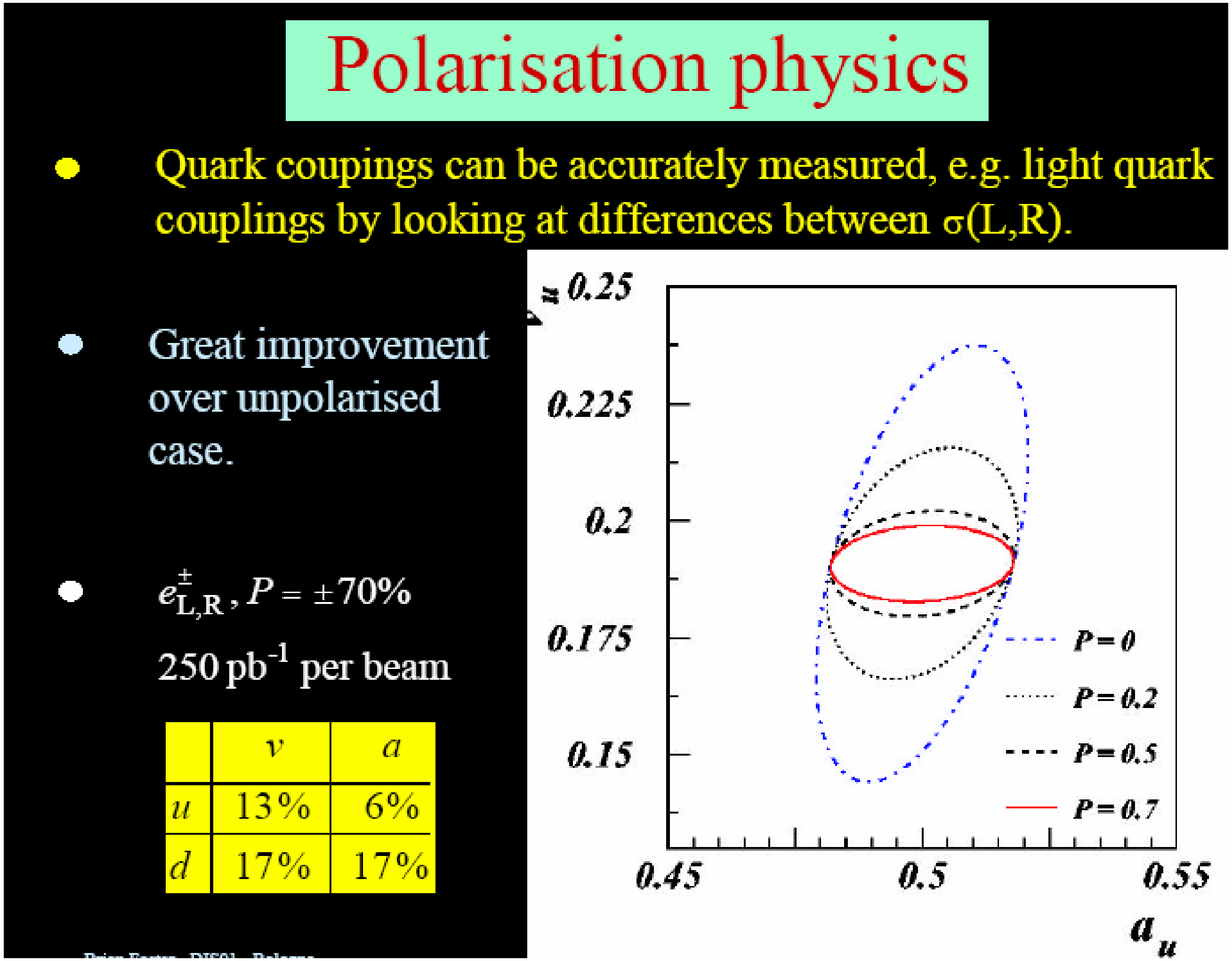
$$K_Z = \frac{1}{4\sin^2\theta_W\cos^2\theta_W}\,\frac{Q^2}{Q^2+M_Z^2}$$

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

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

→ Polarised e± beam helps to constrain v_q

HERA Physics workshop studies : Light Quark Couplings to Z_0



Polarisation physics

- Quark coupings can be accurately measured, e.g. light quark couplings by looking at differences between σ(L,R).
- Great improvement over unpolarised case.
- $e^{\pm}_{\mathrm{L,R}}, P = \pm 70\%$

  250 pb^{-1} per beam

	v	*a*
u	13%	6%
d	17%	17%

Brian Foster - DIS01 - Bologna

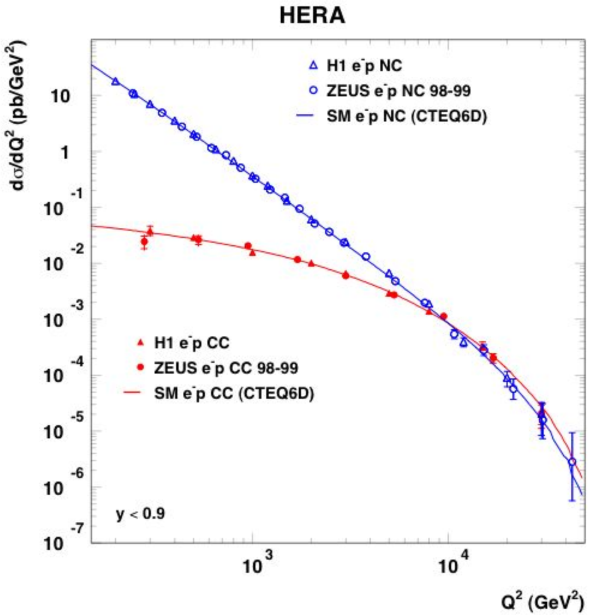
H1 RESULT :

Hera I (unpol):
a_u = 0.56 +- 0.10
v_u = 0.04 +- 0.19

Conclusion

- With approx. 200 pb^{-1} significant tests of the SM electroweak sector at high spacelike momentum transfers have been performed :
  -Electroweak unification, CC-Propagator mass,
  -Light quark Z_0 couplings, CC-chiral structure,
  -NC polarisation dependences
- A factor 3 more luminosity still to come at HERA II and the availibility of longitudinally polarized electrons and positrons will significantly enhance the sensitivity of these SM tests.

Despite ‘HERA is a QCD machine’ there are also interesting electroweak results which I hope justify the conference logo …



Many thanks for your attention

Thanks to my colleagues from Zeus and H1 for supplying some of these slides

Backups

Analysis Strategies

- **Following the published H1PDF2000 fit procedure:**

  Eur. Phys. J. C30(2003)1, hep-ex/0304003

  - Use all H1 NC & CC data (e^+p & e^-p) for $Q^2_{min}=3.5\text{GeV}^2$
  - Parameterize 5 PDF sets: with a functional form:

$$xP(x) = A\ \underset{\substack{\uparrow\\ \text{small-x}}}{x^b}\quad \underset{\substack{\uparrow\\ \text{medium-x}}}{P_n(x)}\quad \underset{\substack{\uparrow\\ \text{high-x behavior}}}{(1-x)^c}$$

  at $Q^2_0=4\text{GeV}^2$, with 10 free PDF parameters after applying momentum sum rule and u, d quark flavor counting rule

  - Fit in NLO MSbar, massless scheme

- **Introducing additional EW parameter(s) in the combined EW+PDF fits** → Next slide