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Electroweak measurements at HERA

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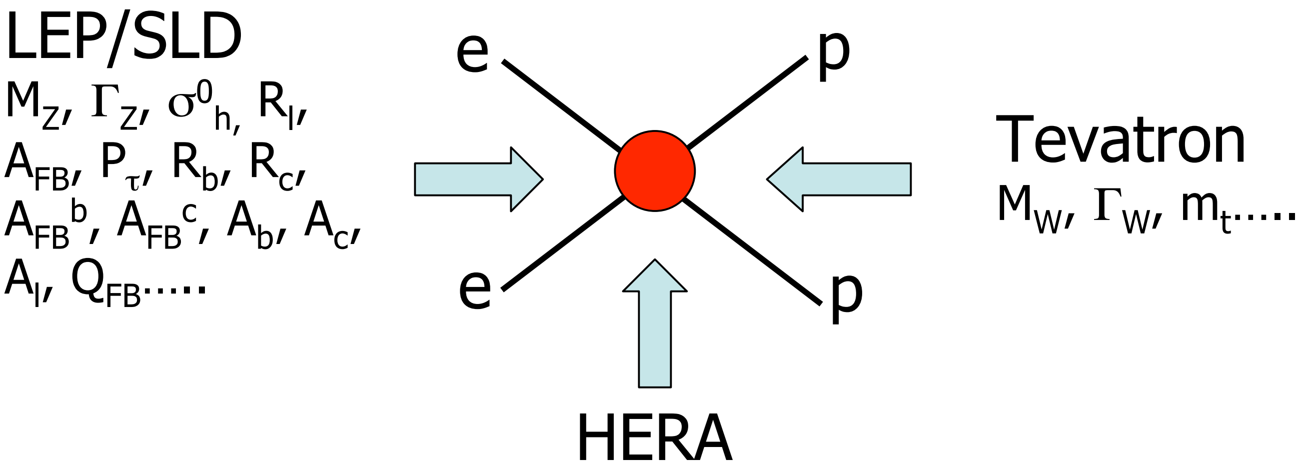
DESY forum 12th & 13th September 2006

Precision electroweak measurements: What can HERA contribute?

Outline

- Introduction
- High Q^2 physics at HERA
- Review of recent results
- Future prospects
- Summary

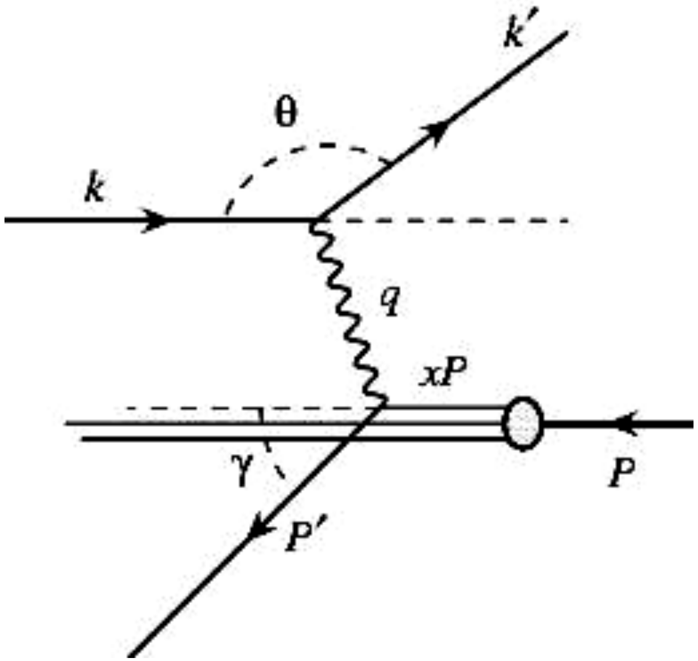
Introduction



- HERA ➔ t-channel exchange of $W^\pm$ and Z^0
  - High Q^2 at HERA ➔ Q^2~electroweak scale
  - Need high luminosity
  - Longitudinal polarisation of lepton beam
- Cross sections are convolution with proton structure functions
  - Need to take care of this in EW measurements

$$\sigma(ep) = \sum_q \sigma(eq) \otimes q(x,Q^2) \Rightarrow \mathrm{EW} \otimes \mathrm{QCD}$$

Introduction



Two deep inelastic scattering processes:

— Neutral current: exchange of γ or Z^0

— Charged current: exchange of $W^{\pm}$

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

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

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

Q^2 is the probing power
x is the Bjorken scaling variable
y is the inelasticity

Charged current DIS at HERA

CC e^+p cross section:

Sensitive to density of d quark

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

CC e^-p cross section:

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

Sensitive to density of u quark

Electroweak couplings and propagators the same but electron/positron-proton collisions probe different quark content of proton

Big difference in cross section magnitude
- — u-quark density larger than d-quark
- — d-quark contribution suppressed by helicity factor $(1-y)^2$

Neutral current DIS cross section

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

Dominant contribution

Sizeable only at high y

Contribution only important at high Q^2

$$F_2 = F_2^{em} + \frac{Q^2}{Q^2+M_Z^2} F_2^{\gamma Z} + \left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 F_2^Z \propto \sum_{q=u\ldots b} (q+\bar{q})$$

$$xF_3 = \frac{Q^2}{Q^2+M_Z^2} xF_3^{\gamma Z} + \left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 xF_3^Z \propto \sum_{q=u\ldots b} (q-\bar{q})$$

Recent results: Combined fits

- Fit only HERA data
  - Neutral current DIS cross sections
  - Charged current DIS cross sections
  - Inclusive jet cross sections in NC DIS
  - Di-jet cross sections in photoproduction

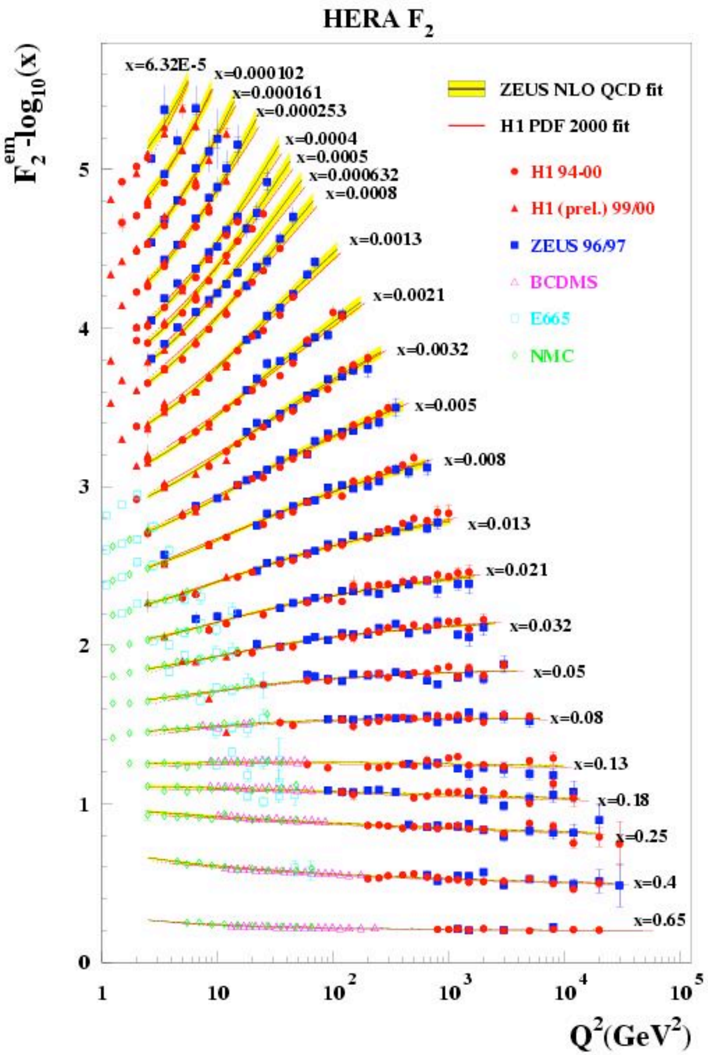
- Fit for BOTH the PDFs at NLO in QCD and electroweak parameters

- Fits for PDFs follow previous publications

  H1 PDF 2000 - Eur. Phys. J. C30 (2003) 1.

  ZEUS-JETS - Eur. Phys. J. C42 (2005) 1.

Reminder of QCD fits for PDFs



- F_2 dominates cross section
  - Directly sensitive to sum of quarks and antiquarks
  - Gluon density via scaling violations at low x (and jet data is ZEUS fit)

- Valence quark distributions from high Q^2 CC and NC cross sections and sum rules

- Idea that low Q^2 data dominate the PDFs and high Q^2 the EW parameters

➔ First H1 fit, then ZEUS….

Combined fit: M_W

Phys. Lett. B636 (2000) 1

Look at the EW part of CC DIS cross section in more detail

$$\frac{d^2\sigma^{CC}(e^\pm p)}{dxdQ^2} = \frac{G_F}{2\pi} \cdot \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 \cdot \Phi^\pm(x, Q^2)$$

Simplest fit:

- M_W & PDF parameters free (α_s fixed)
- G_F fixed to value from muon decay
- NC EW parameters (α, M_Z, G_F) fixed to PDG values

Sensitivity comes solely from shape of cross section as a function of Q^2

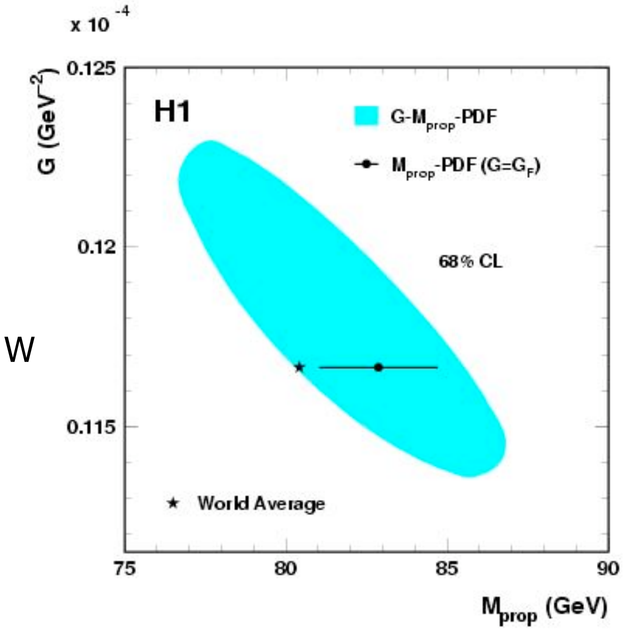
Combined fit: M_W

Phys. Lett. B636 (2000) 1

Fit for M_W and PDFs simultaneously yields

$$M_W = 82.87 \pm 1.82(\exp)^{+0.30}_{-0.16}(\mathrm{mod}) \quad GeV$$

- Model uncertainties include α_s, Q_0, Q^2_{min} etc.
- χ/ndf=0.87
- 2006 PDG M_W=80.403±0.029 GeV
- Small correlation between PDFs and M_W
- Model independent measurement of mass of whatever mediates CC DIS reaction at HERA



Combined fit: M_W

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Replace G_F with SM expression in the on mass shell scheme

$$\frac{d^2\sigma^{CC}(e^\pm p)}{dxdQ^2} = \frac{G_F}{2\pi} \cdot \left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \cdot \Phi^\pm(x,Q^2)$$

$$\frac{d^2\sigma^{CC}(e^\pm p)}{dxdQ^2} = \frac{\pi\alpha^2}{4M_W^4\left(1-\frac{M_W^2}{M_Z^2}\right)^2} \cdot \frac{1}{|1-\Delta r|^2} \cdot \left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \cdot \Phi^\pm(x,Q^2)$$

Not a measurement but determination of a parameter within the SM framework

But what about Δr?

Combined fit: M_W

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- Need to calculate Δr (α, M_Z, M_W, M_H, m_t)
- W propagator self energy
- Use EPRC by H. Spiesberger

$$\Delta r = \Delta\alpha - \frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + \Delta r_{rem}$$

$\Delta\alpha_{lep}$ $\Delta\alpha_{had}$

Photon vacuum polarisation:
lep is computable
had from e^+e^- data
(combined 0.059)

$\Delta\rho \propto m_t^2$

Large mass difference between top and b-quarks (combined 0.03)

$\Delta r_{rem} \propto \ln M_H$

Log dependence on Higgs mass, m_t and higher order corrections (0.01)

Combined fit: M_W

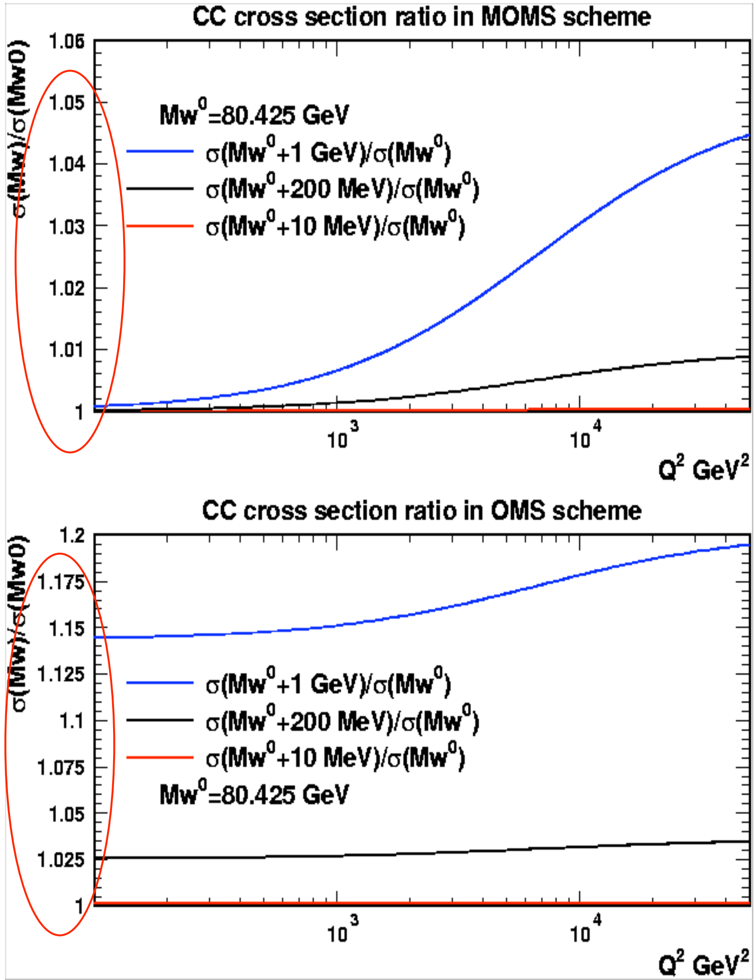
B. Portheault DIS '05

So what did we gain?

Now the normalisation of the CC DIS cross section also contributes

Increase in sensitivity ➔

(also do a similar thing with NC cross section to gain some sensitivity from there too)



Combined fit: M_W

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Use m_t=178 GeV, M_H=120 GeV → χ/ndf=0.87

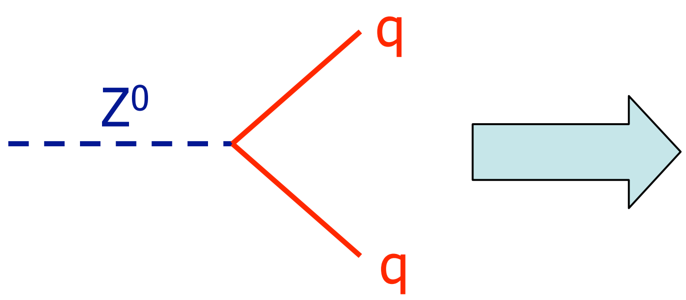
$$M_W = 80.786 \pm 0.205(\exp)^{+0.048}_{-0.029}(\text{mod}) \pm 0.025(m_t)$$
$$-0.084(M_H) \pm 0.033(\Delta r) \quad GeV$$

Use world average M_Z to get $\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$

$$\sin^2\theta_W = 0.2151 \pm 0.0040(\exp)^{+0.0019}_{-0.0011}(th)$$

Can also turn this around and using world average M_W estimate m_t or even M_H from HERA data!

Neutral current DIS cross section



$$\frac{ig}{\cos\theta_W}\gamma^\mu \frac{v_q - a_q\gamma^5}{2}$$

Axial coupling: $a_q = T^3_L$ (=+1/2 for u, -1/2 for d)

Vector coupling: $v_q = T^3_L - 2e_q \sin^2\theta_W$

$$F_2 = F_2^{em} + \frac{Q^2}{Q^2+M_Z^2} F_2^{\gamma Z} + \left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 F_2^Z \propto \sum_{q=u...b} (q+\bar{q})$$

$$xF_3 = \frac{Q^2}{Q^2+M_Z^2} xF_3^{\gamma Z} + \left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 xF_3^Z \propto \sum_{q=u...b} (q-\bar{q})$$

Combined fit: $a_{u,d}$ and $v_{u,d}$

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$$F_2 = \sum_{q=u...b} \left(e_q^2 - 2e_q v_q v_e P_Z + (v_e^2 + a_e^2)(v_q^2 + a_q^2) P_Z^2 \right) \cdot x(q + \bar{q})$$

$$xF_3 = \sum_{q=u...b} (-2e_q a_q a_e P_Z + 4a_q v_q v_e a_e P_Z^2) \cdot x(q - \bar{q})$$

$$P_Z = \frac{1}{\sin^2\theta_W} \frac{Q^2}{Q^2 + M_Z^2}$$

Remember that $P_Z >> P_Z^2$ and $v_e \sim 0.04$

- ➔ xF_3 γ-Z^0 interference term is largest
- ➔ Expect axial coupling of u-quark to be best constrained

Fix G_F and M_W in CC and α, M_Z and M_W in NC and fit for all four couplings a_u,v_u,a_d,v_d

Combined fit: $a_{u,d}$ and $v_{u,d}$

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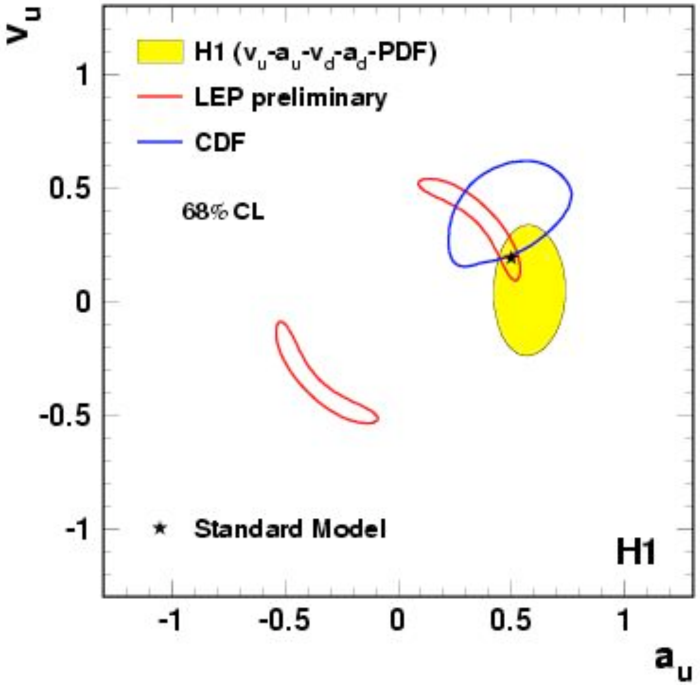

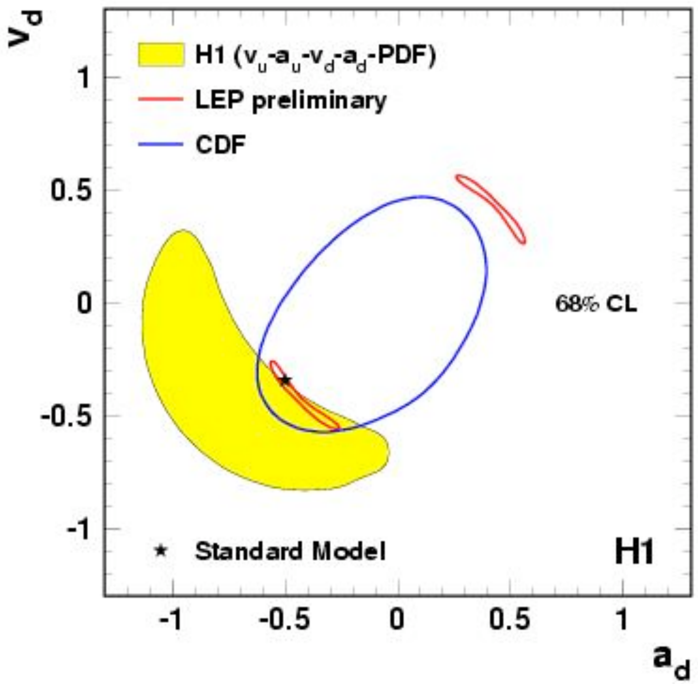

First HERA measurements

More sensitive to u-quark as we expected

Combined fit: Isospin

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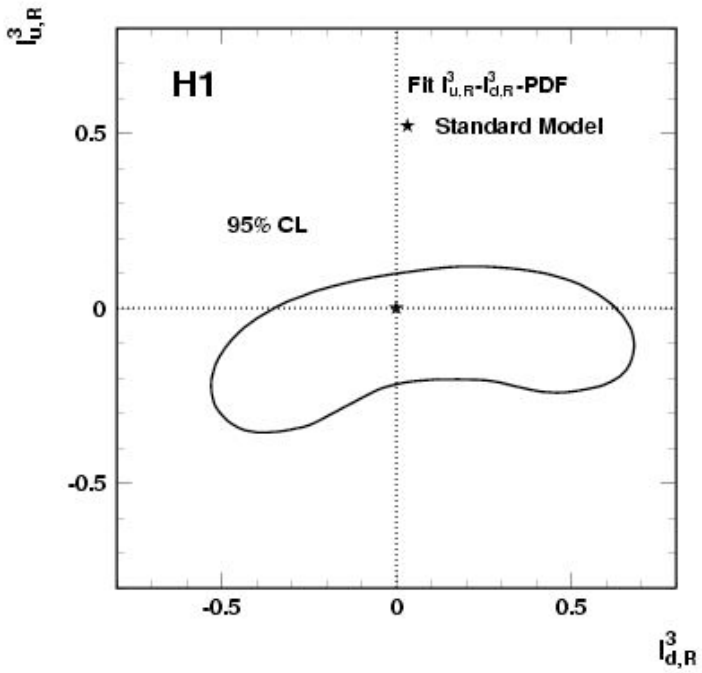
Test sensitivity to right-handed weak isospin

$$v_q = T^3_{q,L} - T^3_{q,R} - 2e_q \sin^2\theta_W$$

$$a_q = T^3_{q,L} + T^3_{q,R}$$

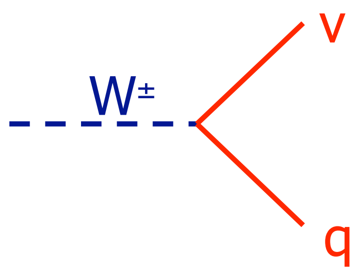
Fix $T^3_{q,L}$ and $\sin^2\vartheta_W$ to SM values and fit gives right handed values

➔consistent with zero



Polarised charged current DIS

Charged current is left-handed in Standard Model



$$\frac{ig}{\sqrt{2}}\gamma^{\mu}\frac{1-\gamma^{5}}{2}$$

Polarisation is asymmetry of helicity states

➔ Can use polarised beams to directly test chiral structure of the Standard Model

CC cross section modified by P_e:

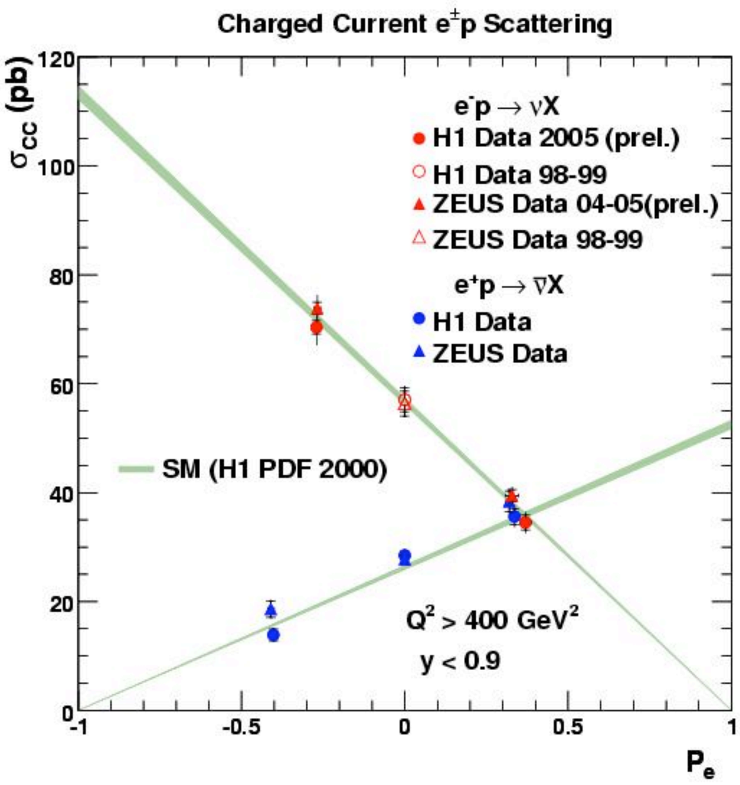
$$\sigma_{CC}^{e^{\pm}p}(P_e) = (1 \pm P_e)\cdot\sigma_{CC}^{e^{\pm}p}(P_e = 0) \qquad P_e = \frac{N_R - N_L}{N_R + N_L}$$

Polarisation scales P_e=0 cross section linearly - clear and large effect at HERA

Standard Model predicts zero cross section for P_e=+1(-1) in $e^{-(+)}$p scattering

Dependence on P_e

Submitted to ICHEP '06



- Clearly demonstrate linear dependence on P_e
- Consistent with left-handed weak interaction in SM

$$\sigma^{e^+p}(P_e=-1) = -3.9 \pm 2.3(stat.) \pm 0.7(syst.) \pm 0.8(pol.)$$

$$\sigma^{e^+p}(P_e=-1) = 7.4 \pm 3.9(stat.) \pm 1.2(syst.)$$

$$\sigma^{e^-p}(P_e=+1) = -0.9 \pm 2.9(stat.) \pm 1.9(syst.) \pm 2.9(pol.)$$

$$\sigma^{e^-p}(P_e=+1) = 0.8 \pm 3.1(stat.) \pm 5.0(syst.)$$

Best constraint so far $M_{W,R}$>208 GeV

Combined fit: M_W

Submitted to ICHEP '06

	M_W (GeV)
ZEUS (HERA I 60 pb^{-1})	78.9 ± 2.0 (stat.) ± 1.8 (syst.) ± 2.0 (PDF)
H1 (HERA I 120 pb^{-1})	82.87 ± 1.82 (stat.) ± 0.25 (syst.)
ZEUS (HERA-II 240 pb^{-1} (prel.))	79.1 ± 0.77 (stat.) ± 0.99 (syst.)

Improvements in precision from:

- Extra luminosity
  - Remember e^-p has much higher CC DIS cross section and HERA II data is e^-p
- Combined fit
  - Reduction in systematic error by fitting PDFs too

Polarised NC DIS cross sections

NC cross section modified by P:

$$\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[H_0^\pm + PH_P^\pm\right] \qquad P = \frac{N_R - N_L}{N_R + N_L}$$

Unpolarised contribution ($H_0^\pm$)

Polarised contribution - only includes Z and γZ terms ($PH_P^\pm$)

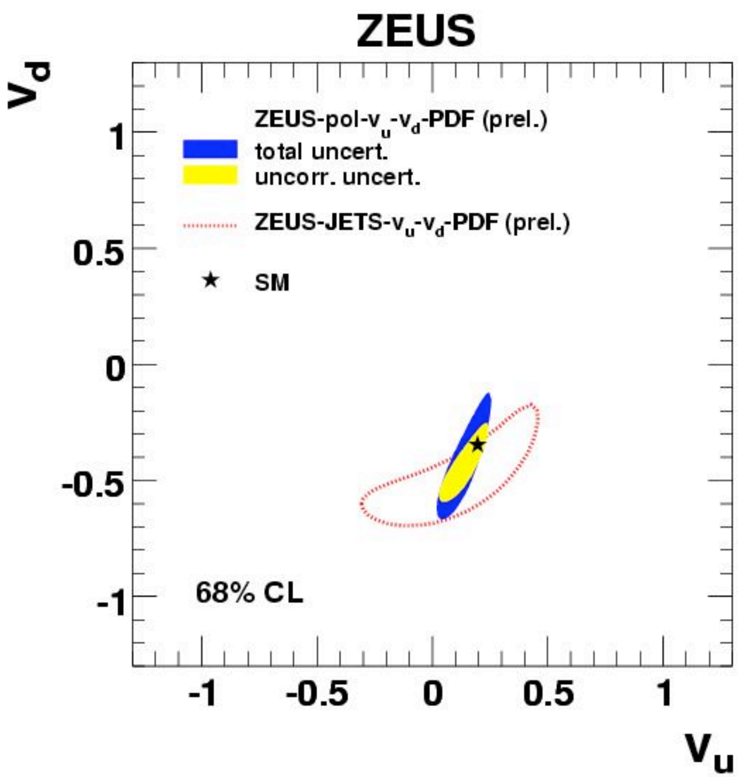
$$F_2^P = \sum_{q=u...b}\left(2e_q a_e v_q P_Z - 2a_e v_e (v_q^2 + a_q^2)P_Z^2\right)\cdot x(q+\bar{q})$$

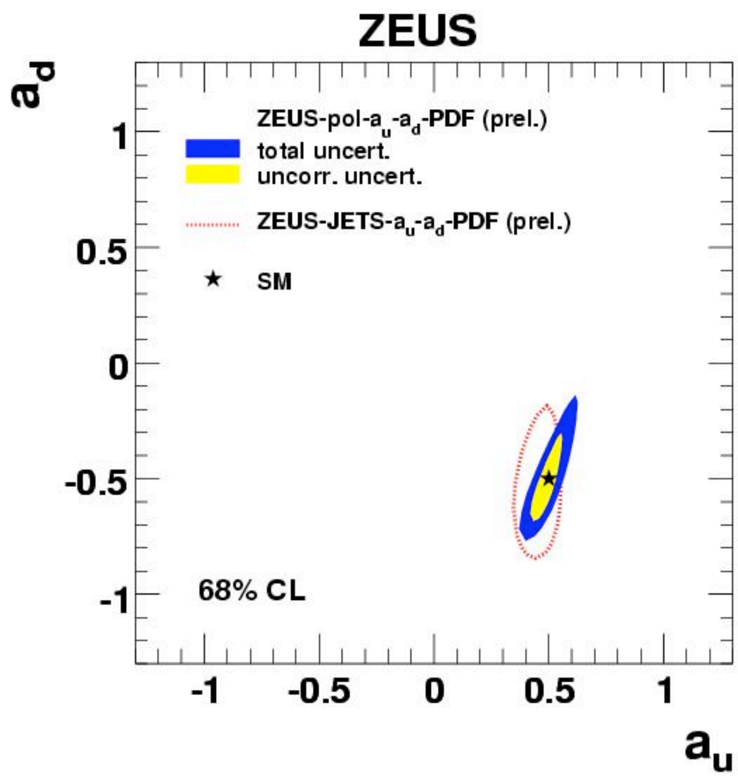
$$xF_3^P = \sum_{q=u...b}(2e_q a_q v_e P_Z - 2a_q v_q (v_e^2 + a_e^2)P_Z^2)\cdot x(q-\bar{q})$$

➔ Expect vector couplings to improve with polarised data

Combined fit: $a_{u,d}$ and $v_{u,d}$

Submitted to ICHEP '06



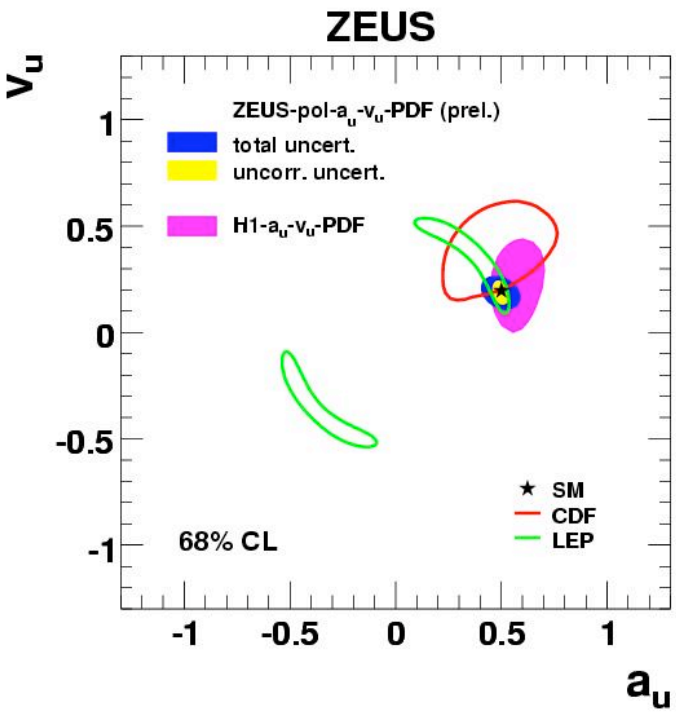


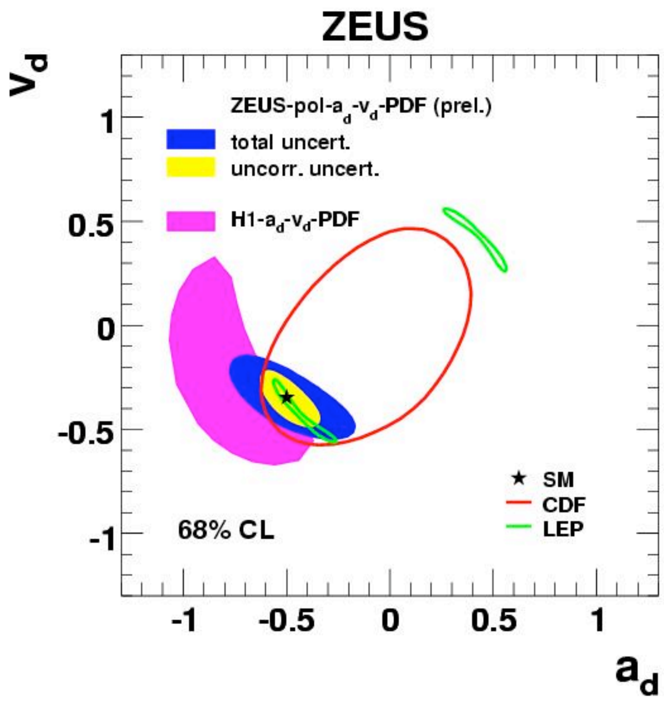
Polarised lepton beam gives substantial improvement

- particularly in $v_{u,d}$ as expected
- fit is for $v_{u,d}$ ($a_{u,d}$) while fixing $a_{u,d}$ ($v_{u,d}$)

Combined fit: $a_{u,d}$ and $v_{u,d}$

Submitted to ICHEP '06





HERA measurements competitive

Combined fit: Isospin

Submitted to ICHEP '06

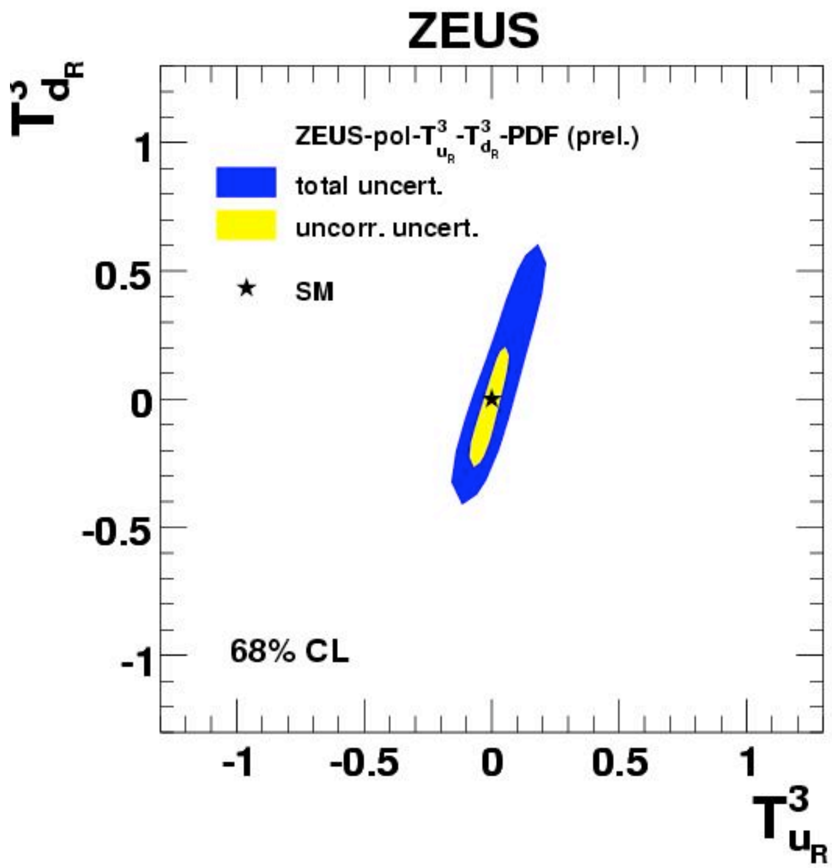
Test sensitivity to right-handed weak isospin

$$v_q = T^3_{q,L} - T^3_{q,R} - 2e_q \sin^2\theta_W$$

$$a_q = T^3_{q,L} + T^3_{q,R}$$

Fix $T^3_{q,L}$ to SM values and fit gives right-handed values

→consistent with zero



Other ideas…

- Variety of ratios and asymmetries of cross sections possible, for example
  - $$R^{\pm} = \frac{\sigma^{NC}(e^{\pm}p)}{\sigma^{CC}(e^{\pm}p)}$$ ➔ DESY-THESIS-2006-005 $\sin^2\theta_W = 0.227 \pm 0.013^{+0.008}_{-0.009}$
  - $$A^{\pm} = \frac{\sigma^{NC}(e^{\pm}_{R}p) - \sigma^{NC}(e^{\pm}_{L}p)}{\sigma^{NC}(e^{\pm}_{R}p) + \sigma^{NC}(e^{\pm}_{L}p)}$$ ➔ Next slide
  - $$B^{\pm} = \frac{\sigma^{NC}(e^{\pm}_{R}p) - \sigma^{NC}(e^{\mp}_{L})}{\sigma^{NC}(e^{\pm}_{R}p) + \sigma^{NC}(e^{\mp}_{L}p)}$$
  - $$C_{L,R} = \frac{\sigma^{NC}(e^{-}_{L,R}p) - \sigma^{NC}(e^{+}_{L,R}p)}{\sigma^{NC}(e^{-}_{L,R}p) + \sigma^{NC}(e^{+}_{L,R}p)}$$
- Idea that experimental systematics and PDF dependency reduced by cancellation
- WWγ coupling from radiative charged current, real W and Z production…. sensitivity modest.

Neutral current P_e asymmetry

Form the polarisation asymmetry:

$$A^{\pm} = \frac{2}{P_R - P_L} \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

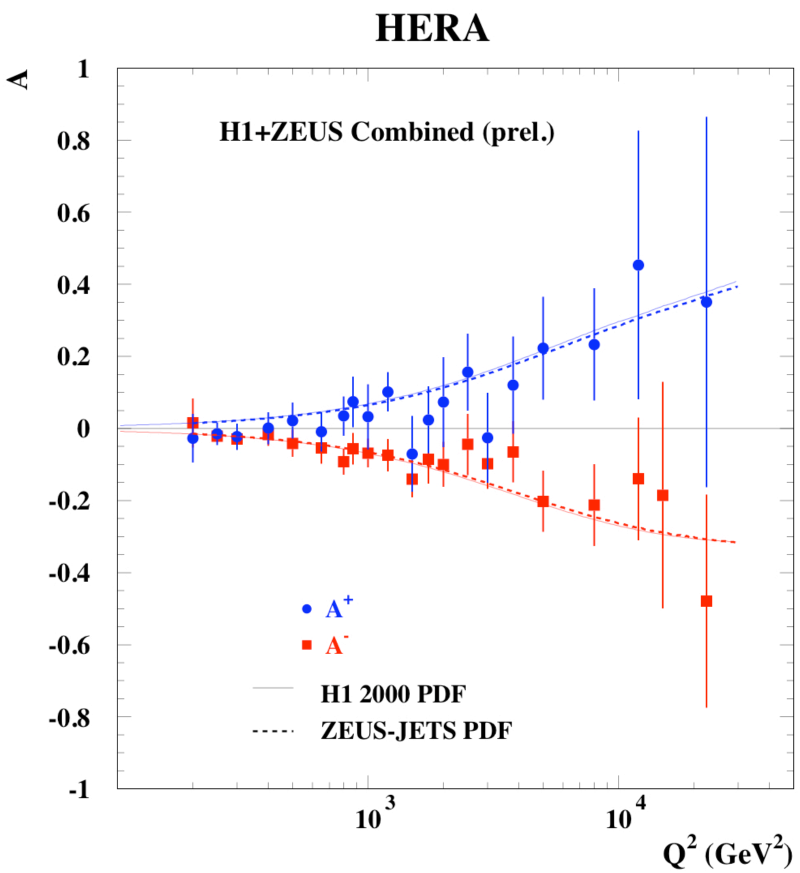
to a good approximation

$$A^{\pm} \approx \mp k a_e \frac{F_2^{\gamma Z}}{F_2} \qquad k = \frac{1}{4\sin^2\theta_W \cos^2\theta_W} \frac{Q^2}{Q^2 + M_Z^2}$$

which is quite insensitive to the PDFs and proportional to $a_e v_q$ and therefore a direct measure of parity violation

More accurate determination with more data (this with 0.48 fb^{-1})

Submitted to ICHEP '06



Future prospects: Luminosity

H1 fit (~120 pb^{-1})	a_u	v_u	a_d	v_d
v_u-a_u-v_d-a_d-PDF	0.56±0.10	0.05±0.19	-0.77±0.37	-0.5±0.37
v_u-a_u-PDF	0.57±0.08	0.27±0.13		
v_d-a_d-PDF			-0.80±0.24	-0.33±0.33
SM	0.5	0.196	-0.5	-0.346

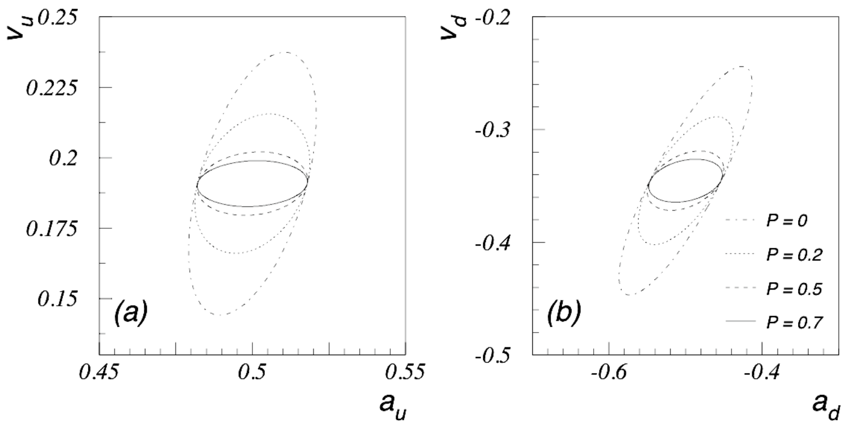
ZEUS fit (~240 pb^{-1})	a_u	v_u	a_d	v_d
v_u-a_u-PDF	0.5±0.04±0.09	0.19±0.06±0.06		
v_d-a_d-PDF			-0.49±0.14±0.28	-0.37±0.14±0.16
a_d-a_u-PDF	0.48±0.06±0.10		-0.55±0.10±0.21	
v_d-v_u-PDF		0.12±0.10±0.06		-0.47±0.15±0.19

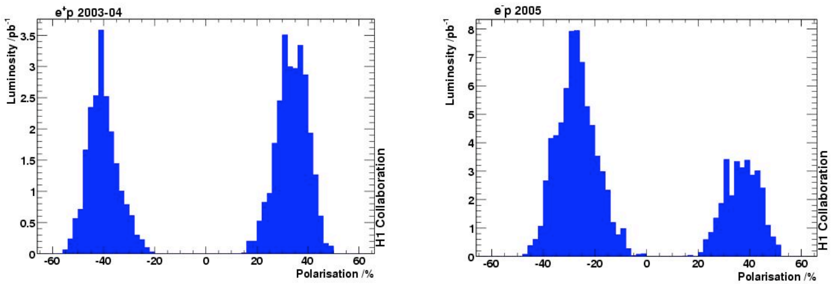
- u-quark better constrained (e^+p data will help d-quark)
  - precision better than 20% for u-quark but ~50% for d-quark
- Basically measurements scale with luminosity

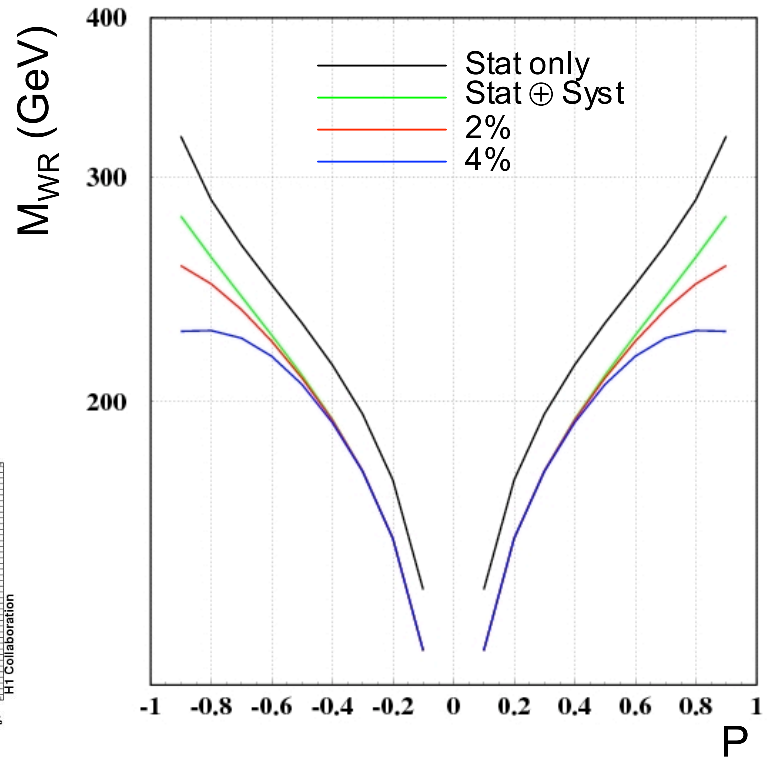
Future prospects: Polarisation

HERA workshop '95

M. Kataoka







Results a strong function of polarisation

- higher polarisation would offer improvement

Summary

- First simultaneous determinations of the PDFs and EW parameters
- Couplings of u and d quarks to Z^0 competitive with determinations from LEP and Tevatron experiments
- Can expect improvements in precision with increasing data sets (and polarisation)
- Need to combine H1 and ZEUS data
- Sensitivity to other EW parameters at a level which is complementary to other experiments, so we should stress the differences and attack the Standard Model from different angles