Electroweak Physics with HERA Data

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Goals in DIS *ep* scattering

- ➜ High-precision measurements of the proton structure
- ➜ Search for new physics
- ➜ Electroweak physics:

  Tests of the standard model, and after LHC discoveries

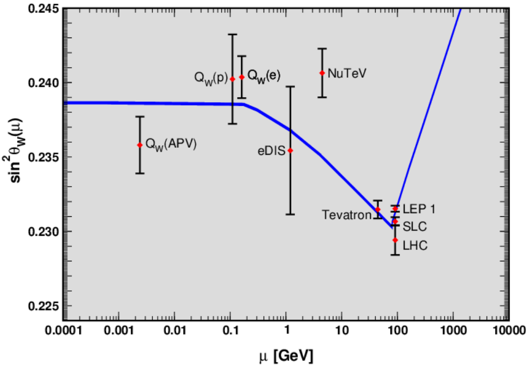
  Tests of the standard model extended with new physics

This talk:

- ➜ Some remarks about the present status of $\sin^2\theta_w$
- ➜ Electroweak parameters in DIS
- ➜ Expectations 20 years ago and present status

(not a complete review)

The Running Weak Mixing Angle: Present Measurements of $\sin^2 \hat{\theta}_W$ ($\overline{MS}$)



PDG 2014

- $Q_W(APV)$:
  atomic parity violation (Cs)
- $Q_W(e)$: Moller scattering
- NuTeV: Neutrino scattering
  (re-analysis needed)

Z-pole measurements:

- LEP1 and SLC
- Tevatron
- First results from LHC

Present situation

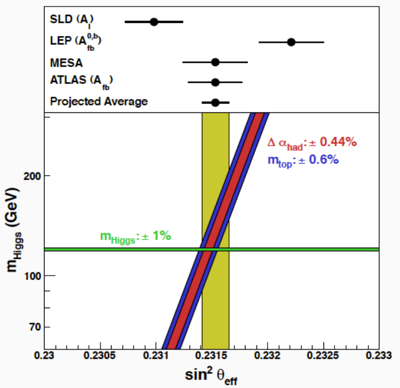
- $\sin^2\hat{\theta}_w(m_Z) = 0.23070 \pm 0.00026$ from A_{LR}, SLD
- $\sin^2\hat{\theta}_w(m_Z) = 0.23193 \pm 0.00029$ from $A_{FB}^{b\bar{b}}$, LEP1

  ➜ 3σ difference !
- $\sin^2\hat{\theta}_w(m_Z) = 0.23125 \pm 0.00016$ world average
- $\sin^2\hat{\theta}_w(m_Z) = 0.23104 \pm 0.00015$ from α, G_μ, m_Z and m_W

Very different implications for new physics:
look at S, T, U parameters, e.g.,

- from A_{LR} ➜ $S = -0.18 \pm 0.15$ ➜ Susy?
- from $A_{FB}^{b\bar{b}}$ ➜ $S = +0.46 \pm 0.17$ ➜ heavy Higgs? KK at 1 - 2 TeV?
- from average ➜ $S = +0.11 \pm 0.11$ ➜ new heavy doublets? KK above 3 TeV?

Standard Model Relation: Higgs Boson Mass versus $\sin^2 \theta_W$



Combination of precision measurements at the Z-pole
→ M_{Higgs} - $\sin^2 \hat{\theta}_W(\mu)$ SM relation (red-blue band)

Precision measurement of $\sin^2 \hat{\theta}_W(\mu)$ had provided indirect evidence for the allowed range of M_{Higgs}

Combination of measurements provide strong tests of the SM,
... and maybe evidence for new physics

MESA at Mainz:
Parity violating polarization asymmetry in elastic *ep* scattering, $Q^2 \simeq 0.0025$ GeV^2
expected precision: $\Delta \sin^2 \theta_w = 0.00037$

Neutral current at tree level, polarized $e^{\pm}$ scattering

$$\frac{d^2\sigma_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left(Y_+\mathbf{F_2} + Y_- x\mathbf{F_3} - y^2\mathbf{F_L}\right)$$

with

$$\mathbf{F_2} = F_2^{\gamma} + \kappa_Z(-v_e \mp P a_e)F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2P v_e a_e)F_2^Z$$

$$x\mathbf{F_3} = +\kappa_Z(\pm a_e + P v_e)xF_3^{\gamma Z} + \kappa_Z^2(\mp 2 v_e a_e - P(v_e^2 + a_e^2))xF_3^Z$$

$$\kappa_Z(Q^2) = \frac{Q^2}{Q^2 + m_Z^2}\frac{1}{4\sin^2\theta_w\cos^2\theta_w}$$

$$(F_2^{\gamma},\ F_2^{\gamma Z},\ F_2^Z) = x\sum(Q_q^2,\ 2Q_q v_q,\ v_q^2 + a_q^2)(q + \bar{q})$$

$$x(F_3^{\gamma Z},\ F_3^Z) = 2x\sum(Q_q a_q,\ v_q a_q)(q - \bar{q})$$

$$v_f = I_f^{(3)} - 2Q_f\sin^2\theta_w, \quad a_f = I_f^{(3)} \quad (f = e, u, d, \ldots)$$

Paramters: α, m_Z, $\sin^2\theta_w$; more general: also v_e, a_e; v_q, a_q

Charged current at tree level

$$\frac{d^2\sigma_{CC}}{dxdQ^2} = \frac{1 \pm P}{2} \frac{2\pi\alpha^2}{Q^4 x} \kappa_W^2 \left(Y_+ \mathbf{W_2} \pm Y_- x \mathbf{W_3} - y^2 \mathbf{W_L} \right)$$

with

$$\kappa_W(Q^2) = \frac{Q^2}{Q^2 + m_w^2} \frac{1}{4 \sin^2 \theta_w}$$

Paramters: α, m_W, $\sin^2 \theta_w$

Relations at tree-level, e.g.,

- $\cos\theta_W = m_W/m_Z$ (by definition in the on-mass-shell scheme)
- Muon decay constant: $G_F = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W m_W^2}$

➜ $\frac{d^2\sigma_{CC}}{dxdQ^2} = \frac{1\pm P}{2}\frac{G_F{}^2}{2\pi x}\left(\frac{m_W^2}{m_W^2+Q^2}\right)^2 \sigma_{r,CC}$

and

➜ $\frac{d^2\sigma_{NC}}{dxdQ^2}$ using $\kappa_Z(Q^2) = Q^2\,\frac{G_F}{2\pi\alpha}\frac{m_Z^2}{Q^2+m_Z^2}$

- One-loop corrections to the muon decay: Δr

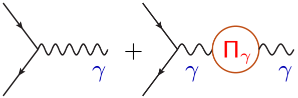
$$G_F = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W m_W^2}(1+\Delta r) \quad \text{with} \quad \Delta r = \Delta r(\alpha, m_W, \sin\theta_W, m_{top}, M_{Higgs}, \ldots)$$

- On-mass-shell scheme versus modified on-mass-shell scheme:
  $(\alpha,\, m_W,\, m_Z)$ or $(\alpha,\, m_W,\, \sin^2\theta_w)$ versus $(\alpha,\, G_F,\, m_Z)$

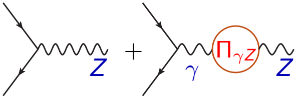
  Fits based on different parametrizations may lead to very different results

Including quantum loop corrections, universal contributions:

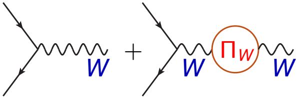
Self energy diagrams of the exchanged boson (γ, Z, W)



➜ $\alpha \to \alpha + \Delta\alpha = \alpha(Q^2)$

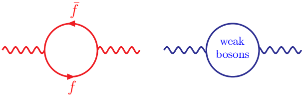


➜ $\sin^2\theta_W \to \sin^2\theta_W + \Delta\sin^2\theta_W = \sin^2\theta_{eff}(Q^2)$



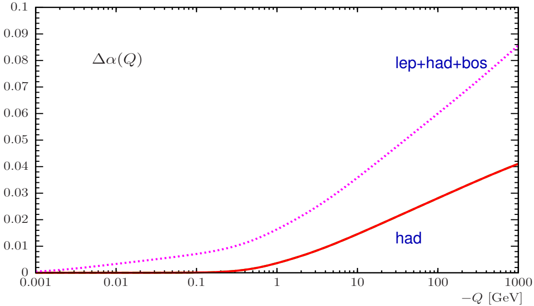
➜ $G_F \to G_F(1 + \Delta r)$

- Self energy diagrams:



$\propto \log \frac{Q^2}{m_f^2} \to O(10\,\%)$ small, $O(1\,\%)$

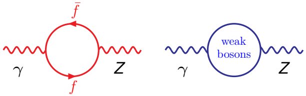
- Photon self energy = vacuum polarization, absorbed and resummed in the running fine structure constant: $\alpha \to \alpha(Q^2) = \frac{\alpha}{1-\Pi_\gamma(Q^2)}$



- Z-boson self energy: a small correction if written in terms of:

$$\frac{\alpha}{\sin\theta_W^2\cos\theta_W^2} \to \frac{m_Z^2 G_\mu \sqrt{2}}{\pi}\,\frac{1-\Delta r}{1-\Pi_Z(Q^2)}$$

- Photon-Z mixing



➜ $\Pi_{\gamma Z}(Q^2)$

can be absorbed into effective, running, scale-dependent weak mixing angle

Definitions of the weak mixing angle:

- On-shell definition: $\cos\theta_W = \frac{m_W}{m_Z}$ ($\to \Delta r$ contains large contribution from m_{top})
- $\sin^2\theta_{\text{eff}}(Q^2)$ absorbs $\Pi_{\gamma Z}(Q^2)$
- $\overline{\text{MS}}$ scheme: $\sin^2\hat{\theta}_W(\mu)$ (via $\tan\hat{\theta}_W(\mu) = g_1/g_2$)
  less sensitive to m_{top}, suited for comparisons with extensions of the SM

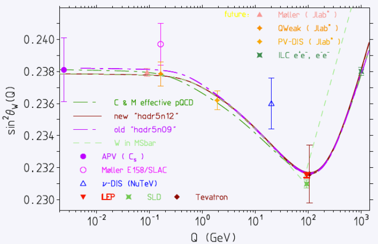
➜ Relation

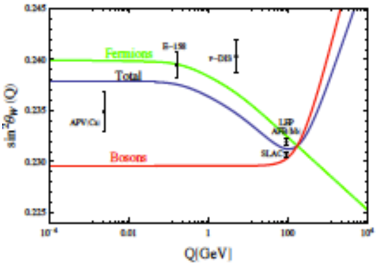
$$\sin^2\hat{\theta}_W(\mu) = \left(1 + \frac{\rho_t}{\tan^2\theta_W} + \ldots\right)\sin^2\theta_W$$

with $\rho_t = 3G_\mu m_{top}^2/8\sqrt{2}\pi^2 = 0.00939\,(m_{top}/173\,\text{GeV})^2$

➜ Additional uncertainty: $\Delta\sin^2\hat{\theta}_W \simeq \pm 0.0001$ for a 1 % error on m_{top}

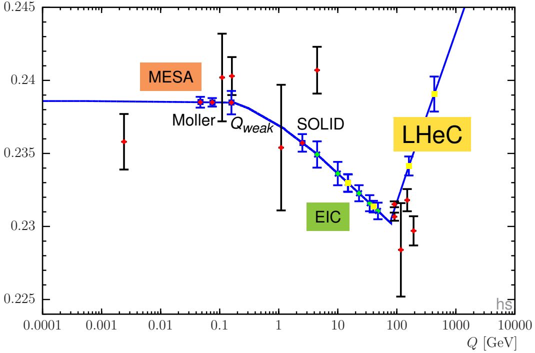
Definition of $\sin^2\theta_W(Q)$: absorbing $\Pi_{\gamma Z}$ and part of vertex+box corrections





- C&M: Czarnecki, Marciano: pQCD with $m_{q,eff}$ and bosonic contributions
- 'old' and 'new' program `hadr5` by Jegerlehner 2010-12, hadronic VP from data (different $SU(3)$ flavor splitting)
- Scheme dependence partly compensated by remaining δ_{1-loop}
- Include higher orders
- Parameter dependence m_t, m_H, ...
- Prescriptions known up to small uncertainties

- Use running $\sin^2\hat{\theta}_W(Q)$ to compare different measurements
- Match definition of $\sin^2\hat{\theta}_W(Q)$ with the complete 1-loop corrections



Present and future of $\sin^2\hat{\theta}_W(Q)$

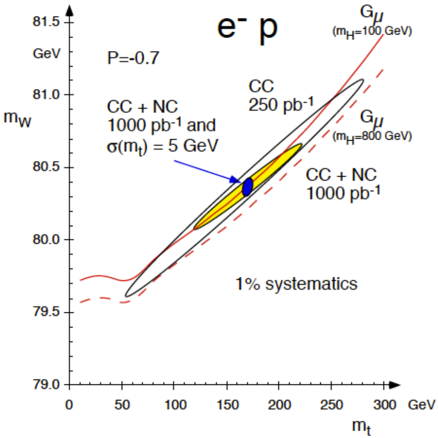
- Existing: APV, $Q_w(e)$, $Q_w(p)$, eDIS, NuTeV, LEP, SLD, Tevatron, CMS, ATLAS
- Low energy: MESA, Moller, Q_{weak}
- Medium energy: SOLID, EIC
- High energy: LHC, LHeC, ...

... and HERA ?

R. Beyer et al. in
Future Physics at HERA
1995/96

Sensitivity of NC+CC data
electrons with polarization
SM fit to m_W-m_t
(on-mass-shell scheme:
α, m_Z, m_W, m_t, m_H)

For 10^3 pb^{-1}, $\Delta m_t = \pm 5$ GeV
➜ $\Delta m_W = \pm 55$ MeV



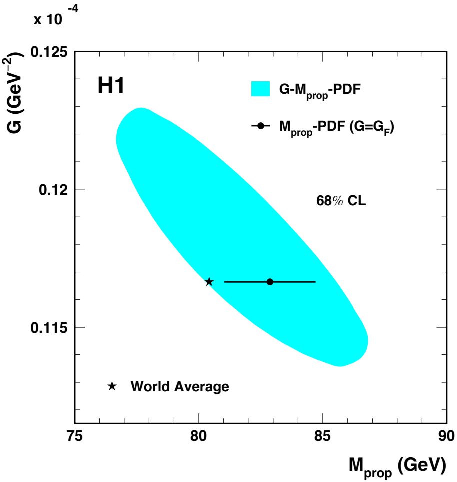
H1 2006 with $\simeq 120\ \text{pb}^{-1}$
unpolarized $e^{\pm}$ NC+CC
(Phys. Lett. B632)

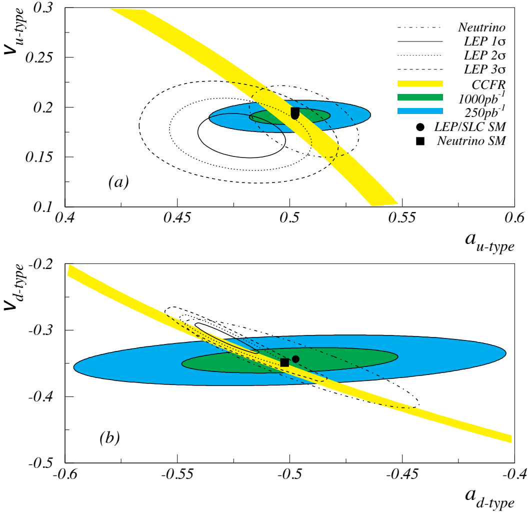
fit with fixed G_F:
$m_W = 82.87 \pm 1.82\ ^{+0.30}_{-0.16}$ GeV

SM fit:
$m_W = 80.786 \pm 0.205\ ^{+0.063}_{-0.098}$ GeV

corresponds to
$\sin^2\theta_W = 0.2151 \pm 0.0040\ ^{+0.0019}_{-0.0011}$

➜ Use full statistic!
➜ Use polarization!





A more general approach to test the Standard Model:

Quark coupling constants

v_q, a_q

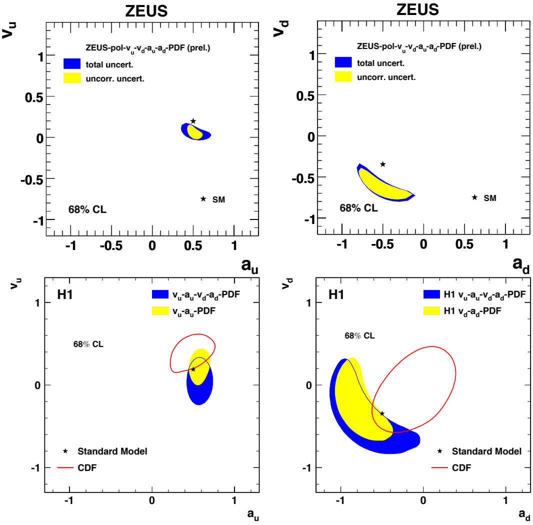
from fits to NC and CC for e_L^-, e_R^-, e_L^+, e_R^+

Polarization is essential

v_u, a_u, v_d, a_d:
13%, 6%, 17%, 17%

R. J. Cashmore et al. in
Future Physics at HERA
1995/96

Quark Couplings: Present Status



Present status

ZEUS-prel-07-027
H1, PLB632 (2006) 35

Unique at HERA:
flavor and v/a separation

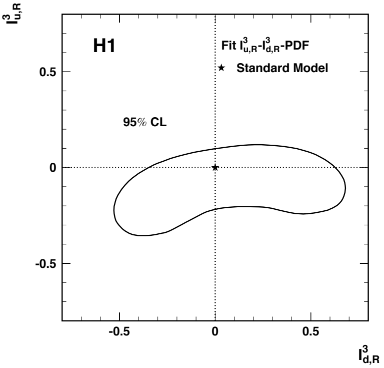
See next talk by Katarzyna Wichmann

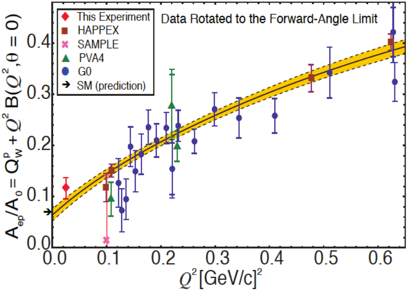
H1 2006 with $\simeq 120\ \mathrm{pb}^{-1}$
unpolarized $e^{\pm}$ NC+CC
(Phys. Lett. B632)

Light quarks with right-handed couplings:

$\left|I^3_{u,R}\right| = 0.5$ excluded at 95% CL

➜ Match to low-energy fits
using couplings $C_{1u} \pm C_{1d}$, $C_{2u} \pm C_{2d}$
(see contact interactions fits)



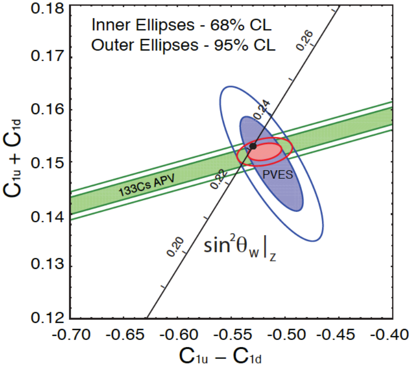


- 2-dim fit to quark couplings
- Best fit at $\sin^2\theta_W = 0.23116$ (expect $\Delta \sin^2\theta_W = 0.0008$)
- $Q^p_W = 0.064 \pm 0.012$ ($Q^p_W(SM) = 0.0710 \pm 0.0007$)

PRL111 (2013)

First results from Q_{weak}

- Analyzed 4% of data (expect factor 5 improved errors with full data taken)
- Used previous data to extrapolate to $Q^2 = 0$



Summary

- Present measurements of the weak mixing angle need improvement
- Expect results from LHC, Q_{Weak}, MESA, SOLID, ...
- Combined EW+QCD fit of HERA data is a 'must do'
- Significant improvements for EW analysis of HERA data can be expected

➜ Complementarity:
only many measurements from different experiments allow conclusive tests

of the SM and of its extensions