

ELECTROWEAK PHYSICS AT THE LHeC

Chavannes-de-Bogis, June 14, 2012

H. Spiesberger

Goals in DIS at high Q^2

- High-precision measurements of the nucleon structure
- Search for new physics
- Electroweak physics:
 - Test of the standard model, and after LHC discoveries
 - Test of the standard model extended with new physics

This talk:

- Choice of electroweak parameters
- Scheme and scale dependence of $\sin^2 \theta_W$
- Quark couplings
- Nothing about radiative corrections

CROSS SECTIONS: NC

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

$$\frac{d^2\sigma_{NC}}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4 x} \left(Y_+ \mathbf{F}_2 + Y_- x \mathbf{F}_3 - y^2 \mathbf{F}_L \right)$$

with

$$\mathbf{F}_2 = F_2^\gamma + \kappa_Z(-v_e \mp Pa_e) F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2Pv_e a_e) F_2^Z$$

$$x \mathbf{F}_3 = +\kappa_Z(\pm a_e + Pv_e) x F_3^{\gamma Z} + \kappa_Z^2(\mp 2v_e a_e - P(v_e^2 + a_e^2)) x F_3^Z$$

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

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

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

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

Parameters: $\alpha, m_Z, \sin^2 \theta_w$; maybe $v_e, a_e; v_q, a_q$

CROSS SECTIONS: CC

Charged current at tree level

$$\frac{d^2\sigma_{CC}}{dx dQ^2} = \frac{1 \pm P}{2} \frac{2\pi\alpha^2}{Q^4 x} \kappa_W^2 \left(Y_+ \mathbf{W}_2 \pm Y_- x \mathbf{W}_3 - y^2 \mathbf{W}_L \right)$$

with

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

Parameters: $\alpha, m_W, \sin^2 \theta_W$

PARAMETER RELATIONS IN THE STANDARD MODEL

Relations at tree-level (Born), e.g.,

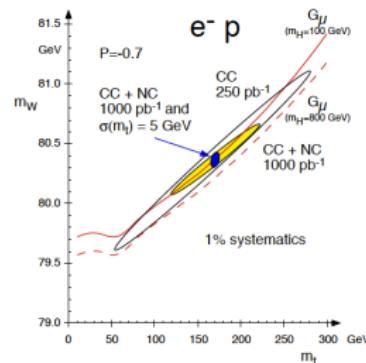
- Electric charge $e = \sqrt{4\pi\alpha} = g_1 \cos\theta_W = g_2 \sin\theta_W$
- $\cos\theta_W = m_W/m_Z$
- Muon decay constant: $G_\mu = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W m_W^2}$

$$\rightarrow \frac{d^2\sigma_{CC}}{dx dQ^2} = \frac{1 \pm P}{2} \frac{G_\mu^2}{2\pi x} \left(\frac{m_W^2}{m_W^2 + Q^2} \right)^2 \sigma_{r,CC}$$

and

$$\rightarrow \frac{d^2\sigma_{NC}}{dx dQ^2} \quad \text{using} \quad \kappa_Z(Q^2) = Q^2 \frac{G_\mu}{2\pi\alpha} \frac{m_Z^2}{Q^2 + m_Z^2}$$

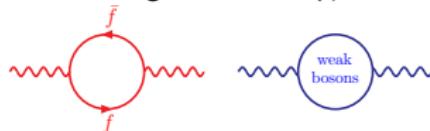
Fits based on different parametrizations
may lead to very different results:
e.g. from H1: $\Delta M_{prop} \simeq 2 \text{ GeV}$, $\Delta m_W \simeq 0.2 \text{ GeV}$



ONE-LOOP CORRECTIONS

Including quantum corrections, universal contributions at one-loop:

- Self energy diagrams of the exchanged boson (γ and Z)



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

- Photon self energy = vacuum polarization, absorbed in the running fine structure constant:

$$\alpha \rightarrow \alpha(Q^2) = \frac{\alpha}{1 - \Pi_\gamma(Q^2)}$$

- One-loop corrections to the muon decay: Δr

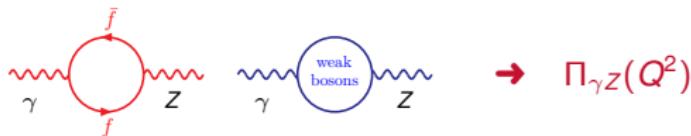
$$G_\mu = \frac{\pi \alpha}{\sqrt{2} \sin^2 \theta_W m_W^2} (1 + \Delta r) \quad \text{with} \quad \Delta r = \Delta r(\alpha, m_W, \sin \theta_W, m_{top}, M_{Higgs}, \dots)$$

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

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

ONE-LOOP CORRECTIONS: SCALE-DEPENDENT $\sin^2 \theta_W$

- Photon-Z mixing



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

Definitions of the weak mixing angle:

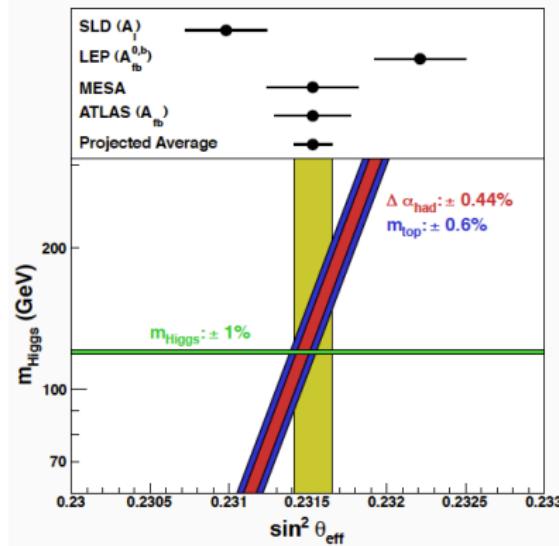
- On-shell definition: $\cos \theta_W = \frac{m_W}{m_Z}$ ($\rightarrow \Delta r$ contains large contribution from m_{top})
 - $\sin^2 \theta_{eff}(Q^2)$ absorbs $\Pi_{\gamma Z}(Q^2)$
 - **\overline{MS} scheme:** $\sin \hat{\theta}_W(\mu)$ (via $\tan \hat{\theta}_W(\mu) = g_1/g_2$)
less sensitive to m_{top}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

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

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

- Additional uncertainty: $\Delta \sin^2 \hat{\theta}_W \simeq \pm 0.0006$ for a 1% error on m_{top}

STANDARD MODEL RELATION: HIGGS BOSON MASS VERSUS $\sin^2 \theta_W(\mu)$



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

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

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

Notice conflicting measurements from LEP/SLD

THE WEAK MIXING ANGLE: PRESENT SITUATION

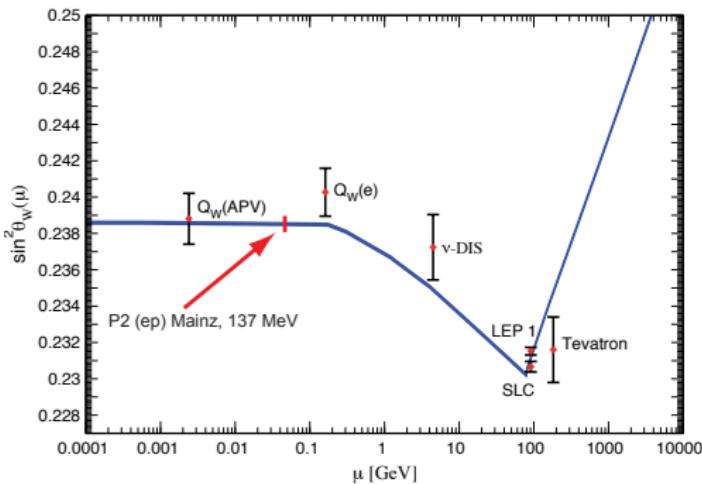
Present situation

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

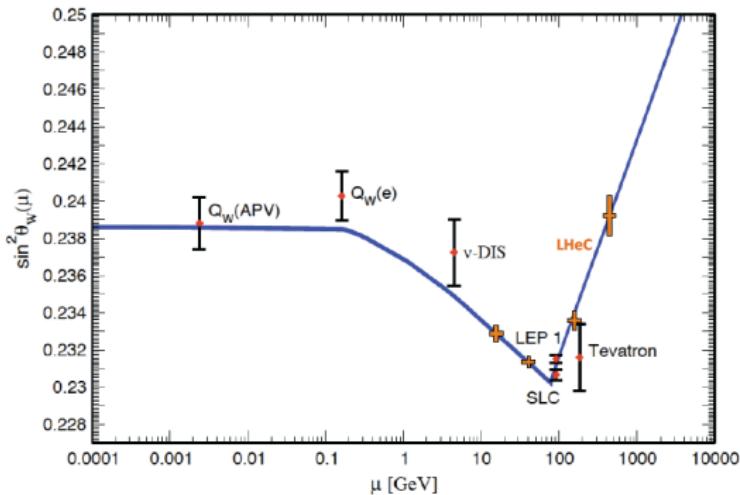
SCALE DEPENDENCE OF $\sin^2 \hat{\theta}_W$: PRESENT AND FUTURE



Existing and projected measurements

- Atomic parity violation (Cs)
- Neutrino scattering
- LEP and SLC (Z -pole)
- Tevatron
- Moller (expect 0.1 % after 2020)
- Q-weak (started running, 0.3 %?)
- LHC
- Mainz MESA, at $\mu = 0.05$ GeV:
 $\Delta \sin^2 \hat{\theta}_W = \pm 0.00037$ (i.e. 0.15 %)

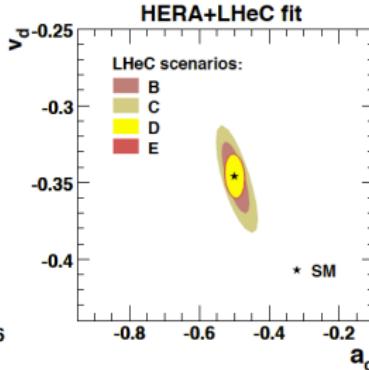
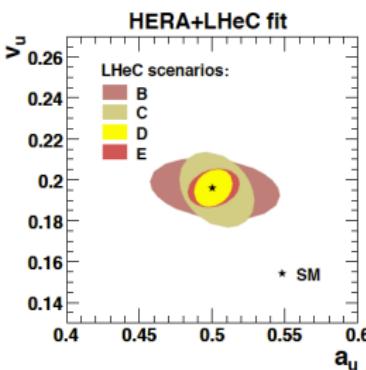
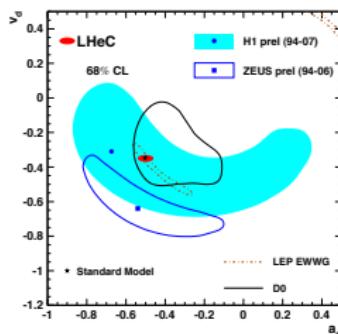
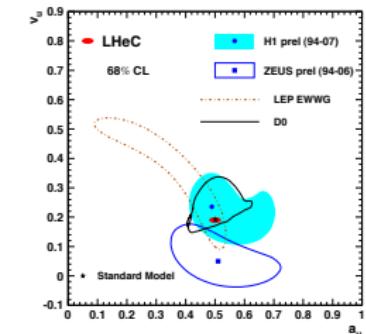
SCALE DEPENDENCE OF $\sin^2 \hat{\theta}_W$: LHeC



Existing measurements and

- LeHC
 - LR asymmetries
 - Maybe CC/NC ratio (PDFs?)
 - Energy range 10 – 400 GeV
 - Scale dependence from one experiment
- but additional theory uncertainties (m_{top} , M_{Higgs})

QUARK COUPLINGS



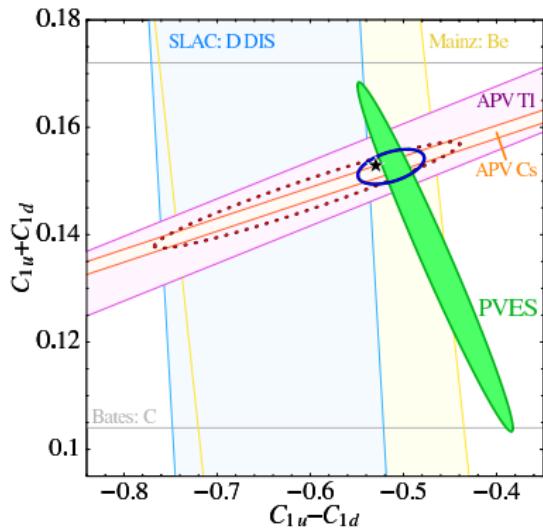
A more general approach
for extensions of the
Standard Model:
Quark coupling constants
as free parameters

LHeC: v_q, a_q

From fits to NC and CC
great improvement
on measurements
of quark vector and
axial-vector couplings

LHeC-CDR
H1prelim-10-042
ZEUS-prel-06-003

QUARK COUPLINGS AT LOW ENERGY



Young, Carlini, Thomas, Roche, PRL99

Conventionally used at low-energy:
Effective 4-fermion interaction

C_{1q} : $2a_e \otimes v_q$, C_{2q} : $2v_e \otimes a_q$

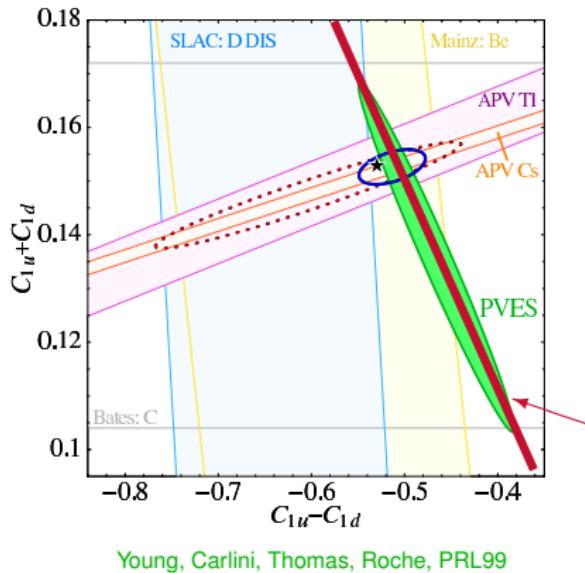
Low-energy experiments probe

$$C_{1q} = -I_q^{(3)} + 2Q_q \sin^2 \theta_W$$

i.e., quark vector couplings

Example:
Parity-violating electron scattering
at JLAB and MAMI (green)
SM prediction (black star)

QUARK COUPLINGS AT LOW ENERGY



Effective 4-fermion interaction
from low-energy experiments

$$C_{1q}: a_e \otimes v_q$$

$$C_{1q} = -l_q^{(3)} + 2Q_q \sin^2 \theta_W$$

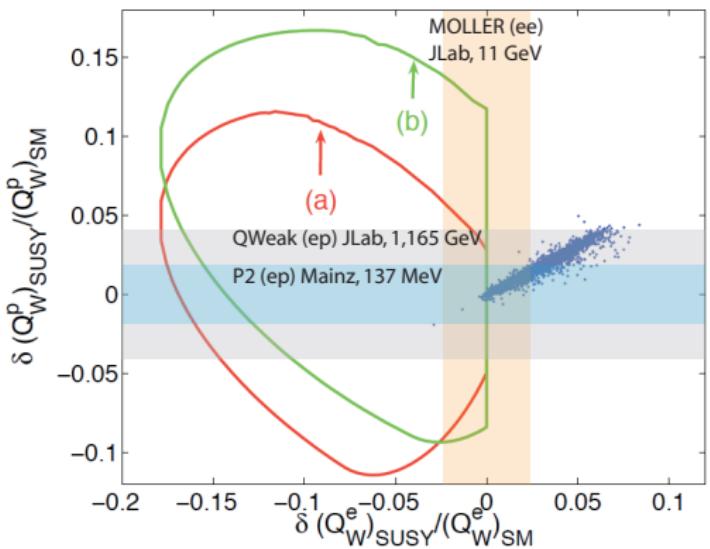
Proton weak charge:

$$Q_W(p) = -2(2C_{1u} + C_{1d})$$

Mainz MESA: $\Delta Q_W(p) = \pm 0.0097$ (2.1 %)

How do expected measurements at LHeC
compare with low-energy results?

SUPERSYMMETRIC MODELS AND THE WEAK CHARGE



Kurylov, Ramsey-Musolf, Su, PRD68

Characteristic shifts of Q_W predicted by extensions of the Standard Model

Example: supersymmetric models with and without R -parity violation

Also precision measurements at low-energy are sensitive to TeV-scale physics

Perspective on quark couplings will shift after LHeC discoveries

SUMMARY

- Different choices of the free parameters may lead to very different results
- Present situation calls for a better determination of the weak mixing angle
- Meaningful comparisons rely a consistent choice of definitions: MS scheme
- Coming LHC results will shift the focus
What can we learn from precision measurements about physics beyond the Standard Model after LHC discoveries?
Cross-check and support the interpretation of LHC discoveries? Complementarity?