PRECISION MEASUREMENT OF $\sin^2\theta_W$ AT MESA

Loops & Legs 2016

H. Spiesberger

PRISMA Cluster of Excellence,
Institut für Physik,

Johannes Gutenberg-Universität Mainz

Electron proton / ion scattering at low and high Q^2

Goals:

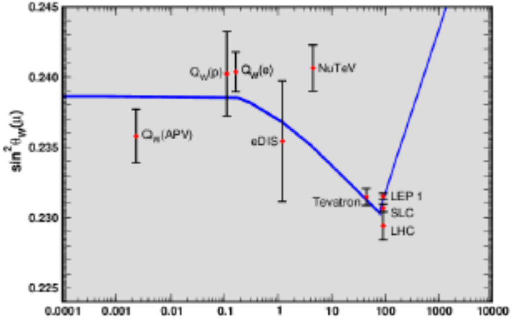
- High-precision measurements of the nucleon structure
- Search for new physics
- Electroweak physics:

  Test of the standard model, and after LHC discoveries

  Test of the standard model extended with new physics
- Key parameter of the standard model: $\sin^2\theta_w$

This talk:

- The MESA project at Mainz University
- Theory for precision measurements of $\sin^2\theta_W$
  in low-energy elastic *ep* scattering



μ [GeV]

PDG 2014

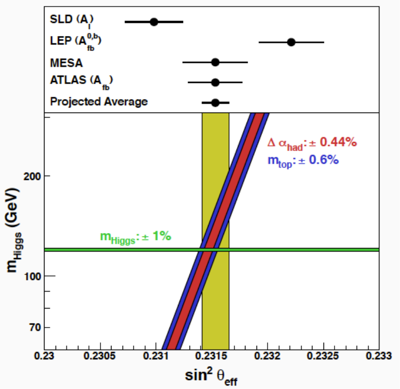
- $Q_W(APV)$:
  atomic parity violation (Cs)
- $Q_W(p)$: Q_{Weak}
- $Q_W(e)$: Moller scattering
- NuTeV: Neutrino scattering
  (re-analysis needed)

Z-pole measurements:

- LEP1 and SLC
- Tevatron
- LHC: CMS and ATLAS

- Most precise single measurements disagree (3σ)

➜ very different implications for new physics



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

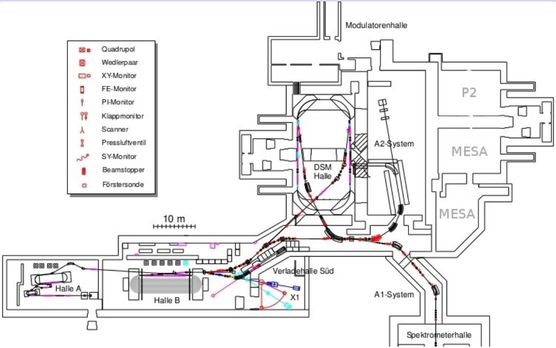
Precision measurement of $\sin^2\hat{\theta}_W(\mu)$ has provided indirect evidence for the allowed range of M_{Higgs}

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

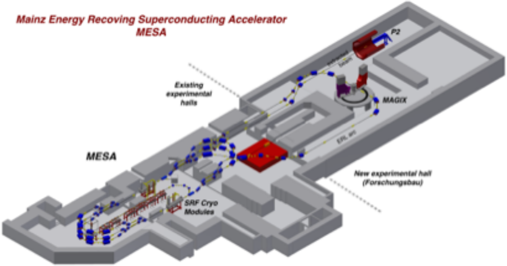
- MESA =
  Mainz Energy-recovering Superconducting Accelerator
  A small superconducting accelerator for particle and nuclear physics
- Funded by PRISMA - Cluster of Excellence and
  Collaborative Research Center 1044

  German Science Foundation (DFG)
- P2 (Project Precision 2):
  Parity-violating electron proton scattering
- Other Projects: Search for a dark photon,
  Nuclear physics program, proton radius
- Commissioning planned for 2019
- Main competition from Qweak at JLAB

MESA Layout

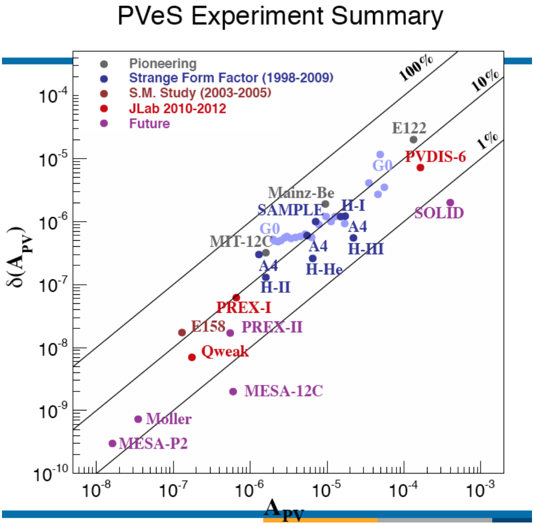


MAMI (Mainzer Mikrotron) and MESA



MESA Parameters

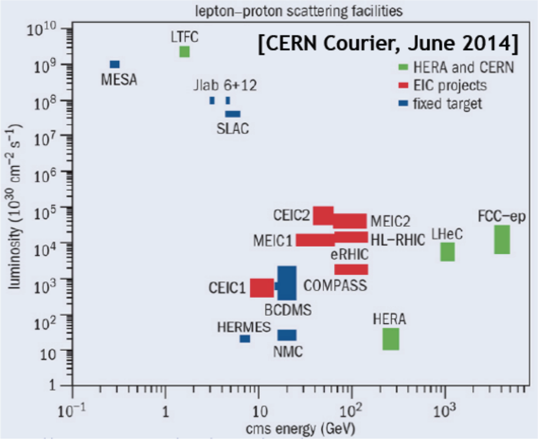
Parameter	P2 (Mainz)
Beam energy	155 MeV
Central scattering angle θ_e	$35°$
Detector acceptance for θ_e	$25°$ to $45°$
Azimuthal detector acceptance ϕ_e	2π
Central Q^2	$\simeq 0.0071$ (GeV/c)^2
Averaged Q^2	$\simeq 0.0045$ (GeV/c)^2
Polarization	(85 ± 0.5) %
Beam current	150μA
ℓ H_2 Target length	60 cm
A_{exp}	-28.35 ppb
$\Delta A(G_A)$ (0.4 %)	± 0.11 ppb
$\Delta A(\gamma Z$ box) (0.3 %)	± 0.09 ppb
ΔA_{stat} (1.3 %)	± 0.38 ppb
ΔA_{sys} (0.6 %)	± 0.17 ppb
ΔA_{tot} (1.5 %)	± 0.44 ppb
$\sin^2 \theta_W$	0.238
$\Delta \sin^2 \theta_W$	$3.1 \cdot 10^{-4}$
$\Delta \sin^2 \theta_W / \sin^2 \theta_W$	0.13 %


PVeS Experiment Summary
Pioneering
Strange Form Factor (1998-2009)
S.M. Study (2003-2005)
JLab 2010-2012
Future
100%
10%
1%
E122
PVDIS-6
G0
Mainz-Be
SAMPLE
H-I
SOLID
G0
A4
MIT-12C
A4
H-III
A4
H-He
H-II
PREX-I
E158
PREX-II
Qweak
MESA-12C
Moller
MESA-P2
$\delta(A_{PV})$
A_{PV}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}

LHeC / FCC-he Context

(10,000 h)
data taking ➜

$\int \mathcal{L} dt \simeq 8.6\ \mathrm{ab}^{-}1$



P. Newman

Measure the (tiny) difference between cross sections for
electrons with positive and negative helicity to filter out the weak interaction

$$A_{LR} = \frac{\sigma(e_\downarrow) - \sigma(e_\uparrow)}{\sigma(e_\downarrow) + \sigma(e_\uparrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\Big(Q_W(\mathcal{N}) - F(Q^2)\Big)$$

Weak charge of the proton (SM at LO):

$$Q_W(p) = 1 - 4\sin^2\theta_W$$

$$\frac{\Delta \sin^2\theta_W}{\sin^2\theta_W} = \frac{1 - 4\sin^2\theta_W}{4\sin^2\theta_W}\,\frac{\Delta Q_W(p)}{Q_W(p)}$$

1.5 % precision for $Q_W(p)$ corresponds to 0.13 % precision for $\sin^2\theta_W$

Measurement errors from: statistics, polarization ($A_{exp} = P_e\, A_{LR}$),
systematic effects and required hadronic phyiscs: form factors

Higher-order corrections

Form Factors

$$F(Q^2) = F_{\text{EMFF}}(Q^2) + F_{\text{Axial}}(Q^2) + F_{\text{Strangeness}}(Q^2)$$

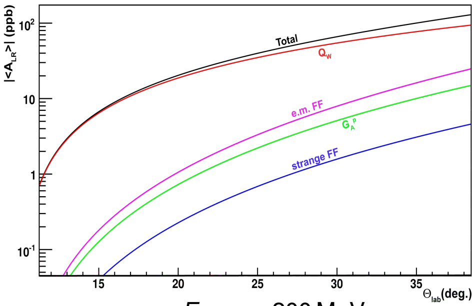
$$A_{LR} = A_{\text{Q}_{\text{weak}}} + A_{\text{EMFF}} + A_{\text{Axial}} + A_{\text{Strangeness}}$$

$$F_{\text{EMFF}}(Q^2) = -\frac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2},$$

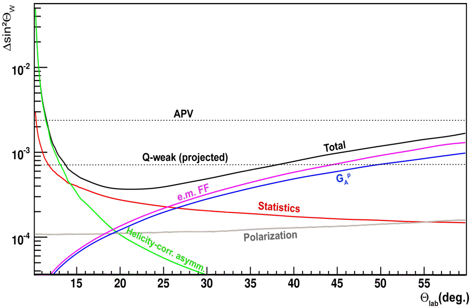
$$F_{\text{Axial}}(Q^2) = -\frac{(1 - 4\sin^2\theta_W)\sqrt{1-\epsilon^2}\sqrt{\tau(1+\tau)}G_M^p G_A^p}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2},$$

$$F_{\text{Strangeness}}(Q^2) = -\frac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} - \frac{\epsilon G_E^p G_E^{ud} + \tau G_M^p G_M^{ud}}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2},$$

$$\epsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}, \qquad \tau = Q^2/4m_p^2$$



$E_{beam} = 200\,\text{MeV}$



➜ Optimal measurement for $E = 155$ MeV, $\theta_e = 35^\circ \pm 10^\circ$

$$\langle Q \rangle = 0.067\ \text{GeV}$$

SM prediction: $A_{LR} = -2.8 \times 10^{-8}$, precision goal: 1.5 %

$$\Delta \sin^2\theta_W = \pm 0.00031, \quad \text{i.e. } 0.13\ \%$$

Polarization asymmetry including higher-order corrections:

$$A_{LR} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(\mathcal{N})(1+\delta_1) - \widetilde{F}(Q^2)\right)$$

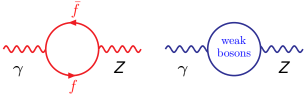
$$Q_W(\mathcal{N})(1+\delta_1) = (\rho_{\rm NC} + \Delta_e)\left(1 - 4\,\kappa\sin^2\theta_W + \Delta_e'\right) + \delta_{\rm Box}$$

Universal corrections: $\rho_{\rm NC}$ and κ from loop diagrams:
scale-dependence ($\mu \to Q$) ➜

$$\sin^2\theta_{\rm eff}(\mu^2) = \kappa(\mu^2)\sin^2\theta_W$$

and scheme-dependent

$\delta_{\rm Box}$ from box graphs for WW, ZZ, $Z\gamma$ exchange,
non-universal vertex correction Δ_e, Δ_e', QED corrections
Match complete 1-loop corrections to the definition of $\sin^2\theta_W$

- 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, $\kappa(Q^2)\sin^2\theta_W$:

- On-shell definition: $\cos\theta_W = \frac{m_W}{m_Z}$ (fixed)
- $\sin^2\theta_{\rm eff}(Q^2)$ absorbs $\Pi_{\gamma Z}(Q^2)$, usually together with parts of vertex corrections (e.g. Czarnecki, Marciano for Moller scattering)
- $\overline{\rm MS}$ scheme: $\sin\hat{\theta}_W(\mu)$ (via $\tan\hat{\theta}_W(\mu) = g_1/g_2$ and RGE) less sensitive to m_{top}, suited for comparisons with extensions of the SM

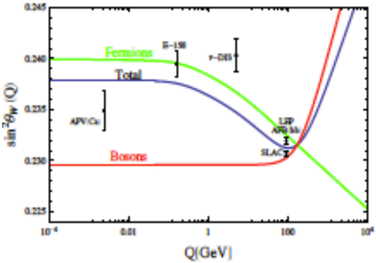
➜ Relation

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

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

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

- 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



Czarnecki-Marciano, Jegerlehner

- Scheme dependence,
  partly compensated by $\delta_{non-universal}$
- Include higher orders
  ➜ 2-loop corrections
- Parameter dependence? m_t, m_H, . . .
- Hadronic contribution!
  need data and models (e.g. ChPT)

Prescriptions are known, with small uncertainties . . .

$\Pi^{\gamma\gamma}$ and $\Pi^{\gamma Z}$ are sensitive to low-scale hadronic physics

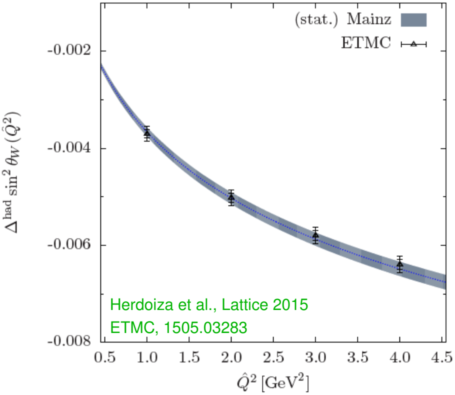
➜ Use dispersion relation, e.g.

$$\Delta\alpha(q^2) = \frac{q^2}{12\pi^2} \int_{4m_\pi^2}^{\infty} \frac{ds}{s} \frac{R^{\gamma\gamma}(s)}{s - q^2} \quad \text{with} \quad R^{\gamma\gamma}(s) = \frac{\sigma_{tot}(e^+e^- \to \gamma^* \to hadrons)}{4\pi\alpha^2/3s}$$

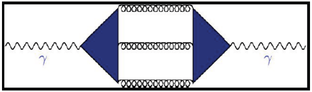
➜ Similar approach for $\Pi^{\gamma Z}$ requires data for $\sigma_{tot}(\nu\bar{\nu} \to hadrons)$ or use flavor-separated e^+e^- data, isospin symmetry and OZI-rule

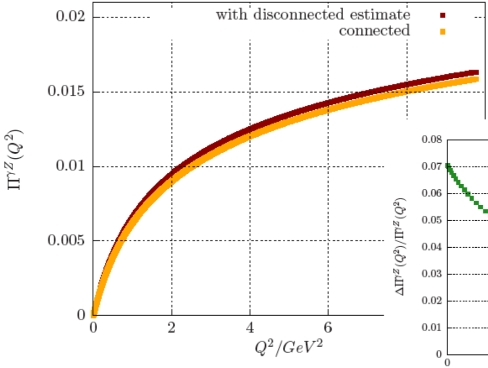
➜ Use lattice techniques

First results available, errors start to be competitive

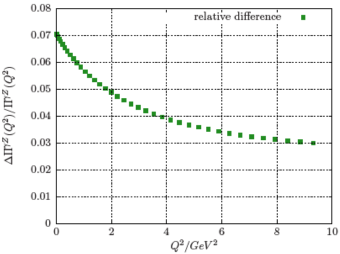


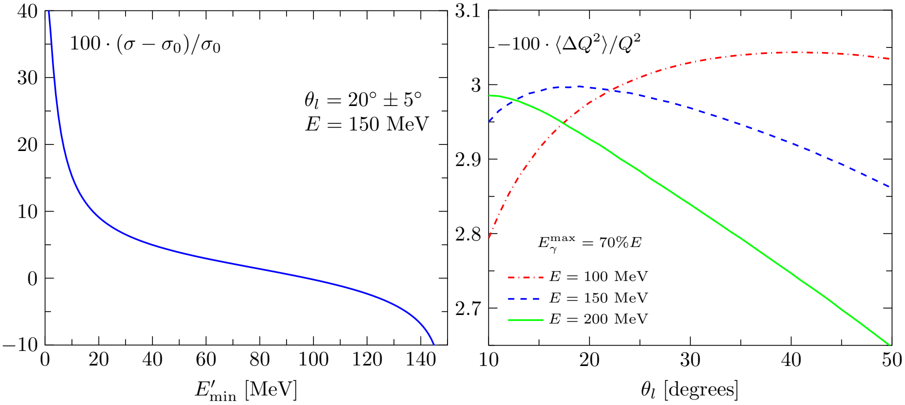
➜ OZI-rule violating contributions?
Lattice QCD
still with large statistical errors
but obtain an upper limit



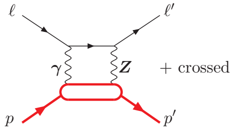


Gülpers et al., Lattice 2015





- QED does not violate parity symmetry,
  but real photon emission leads to a shift of Q^2
- Straightforward to calculate, but need flexible MC simulation



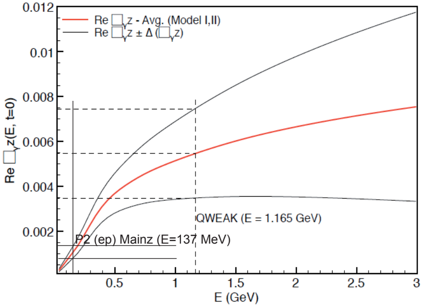
γZ box graphs

Sensitivity to hadronic physics at low Q^2 ➜ an important source of error

Status ∼ 3 years ago:
3 groups with independent analyses agree in size, but disagree on errors

Hall et al.; Carlson and Rislow; Gorchtein et al.

Gorchtein, Horowitz, Ramsey-Musolf (2011)

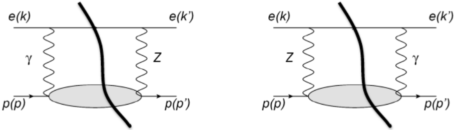


For Qweak at JLAB, $E = 1.165$ GeV: 7σ(theory) effect

Advantage at P2@MESA: low energy $E = 0.155$ GeV

$$\Delta A_{LR}^{box} / A_{LR} = \pm 0.4\,\%$$

More work needed to reduce the error ...



Optical theorem and dispersion relations:

$$\mathrm{Im}\Box_{\gamma Z}(E) = \frac{\alpha}{(s-M_Z^2)^2}\int_{W_\pi^2}^{s} dW^2 \int_0^{Q^2_{max}} dQ^2 \frac{M_Z^2}{Q^2+M_Z^2} \times \left\{ F_1^{\gamma Z}(x,Q^2) + AF_2^{\gamma Z}(x,Q^2) + \frac{g_V^e}{g_A^e} BF_3^{\gamma Z} \right\}$$

Separated into vector and axial-vector parts of the proton current:

$$\mathrm{Re}\Box_{\gamma Z}^V(E) = \frac{2E}{\pi}\int_{\nu_\pi}^{\infty} \frac{dE'}{E'^2-E^2}\mathrm{Im}\Box_{\gamma Z}^V(E'), \qquad \mathrm{Re}\Box_{\gamma Z}^V(E=0)=0$$

$$\mathrm{Re}\Box_{\gamma Z}^A(E) = \frac{2}{\pi}\int_{\nu_\pi}^{\infty} \frac{E'dE'}{E'^2-E^2}\mathrm{Im}\Box_{\gamma Z}^A(E'), \qquad \mathrm{Re}\Box_{\gamma Z}^A(E=0)\neq 0$$

Different calculations due to different assumptions about the structure function input (regions, parametrizations)

Q^2_{max} \ W_{max}	2 GeV	4 GeV	∞
∞	1%	1%	3%
2 GeV^2	3%	2%	1%
1 GeV^2	76%	10%	2%

Contributions to $\mathrm{Re}\Box^V_{\gamma Z}$

$\mathrm{Re}\Box^V_{\gamma Z} = 0.00107$

from recent 2015 update:

M. Gorchtein, HS, X. Zhang

Q^2_{max} \ W_{max}	2 GeV	4 GeV	∞
∞	0.5%	0.5%	4.6%
2 GeV^2	6.7%	6.7%	0.5%
1 GeV^2	60%	20%	0.5%

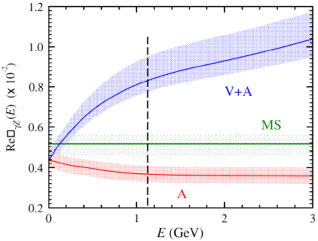
Contributions to the uncertainty of $\mathrm{Re}\Box^V_{\gamma Z}$

$\Delta\mathrm{Re}\Box^V_{\gamma Z} = 0.00018$

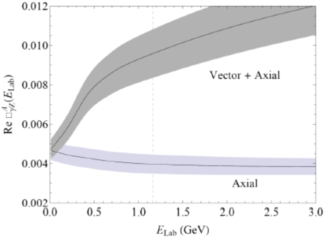
$(Q_W(p) = 0.0712 \pm 0.0007,$
$E = 150$ MeV, $\theta_e = 0)$

Axial Box Calculations

Blunden *et al.*
PRL 107, 081801 (2011)



Carlson and Rislow
PRD 88, 013018 (2013)



$$\mathrm{Re}\Box^{A}_{\gamma Z}(E = 1.165\ \mathrm{GeV})$$

$$(3.7 \pm 0.4) \times 10^{-3} \qquad\qquad (4.0 \pm 0.5) \times 10^{-3}$$

And more: $\gamma\gamma$-box graph corrections with parity violation in the proton:
Anapole moment, vanishes at $E = 0$, $\Box^{PV}_{\gamma\gamma} \sim \frac{\alpha}{\pi} EQ^2$ (M. Gorchtein, HS, to appear)

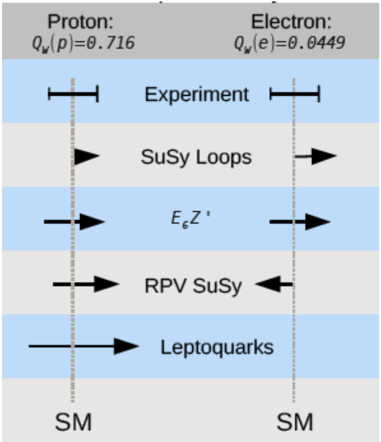
Box graphs are energy dependent
➜ Formal definition of the nucleon's weak charge

Conventional (old) formulation (assuming $F(Q^2) = -Q^2 B(Q^2)$):

$$A_{exp} = A_0 \left(Q_W(\mathcal{N}) + Q^2 B(Q^2) \right) \quad \rightarrow \quad Q_W(\mathcal{N}) = \lim_{Q^2 \to 0} \frac{A_{exp}}{A_0}$$

New: including E-dependent box-graph corrections:

$$A_{exp} = A_0 \left(Q_W(\mathcal{N}) + Q^2 B(Q^2) + \square(E) \right) \quad \rightarrow \quad Q_W(\mathcal{N}) = \lim_{Q^2, E \to 0} \frac{A_{exp}}{A_0}$$

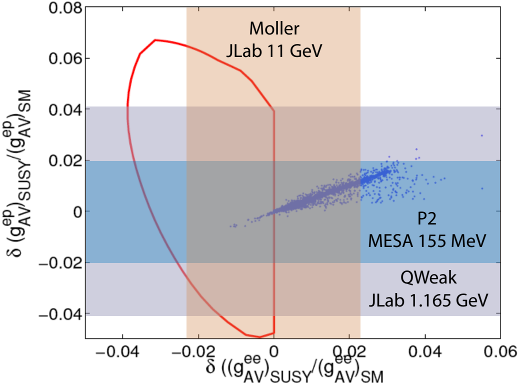


Searches based on

- model-dependent analyses
- effective quark couplings
- contact interactions

Characteristic shifts of Q_W predicted by extensions of the Standard Model

Complementarity between elastic *ep* ($Q_W(p)$) and Moller ($Q_W(e)$) scattering



Erler, Su, 2013

Example: supersymmetric models with and without *R*-parity violation

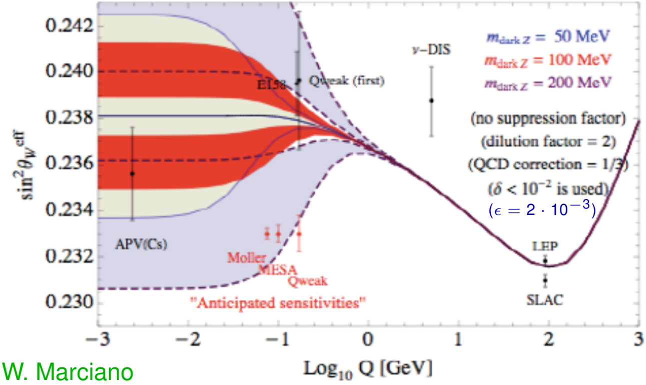
Also precision measurements at low-energy are sensitive to TeV-scale physics

Perspective will shift after LHeC discoveries

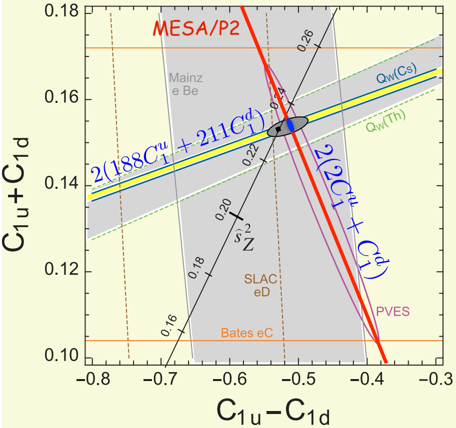
Dark matter and extra $U(1)$ symmetry with kinetic mixing (B. Holdom)

➜ Dark photon with very small mass: $m_D = O(50)$ MeV

- Free mixing parameter $\epsilon = O(10^{-3})$, possibly generated by loop effects
- Model with parity violation, like ordinary Z, but suppressed by ϵ_Z
- Combine kinetic and mass mixing ➜ shift $\Delta \sin^2 \theta_w(Q^2) \simeq 0.42\epsilon \frac{\delta m_Z^2}{Q^2+m_D^2}$



W. Marciano



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

Parity-violating electron scattering:
PVES at JLAB and MAMI
and at MESA (red)

Atomic PV (Cs, yellow)

SM prediction (black square)

$$\mathcal{L}_{eq} = \left(\frac{G_F}{\sqrt{s}} g_{VA}^{eq}(SM) + \frac{g^2}{\Lambda^2} \right) \bar{e}\gamma_\mu e\, \bar{q}\gamma^\mu \gamma_5 q$$

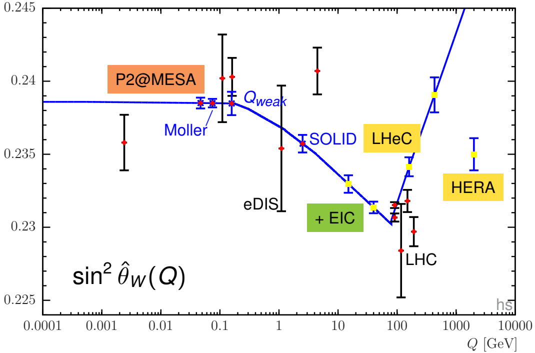
Convention: $g^2 = 4\pi$

P2@MESA probes
Λ up to $\simeq$ 50 TeV

comparable with
LHC (300 fb^{-}1)

	precision	$\Delta \sin^2\overline{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

J. Erler



Future additions to the PDG

Expected from low-energy:

- Mainz: P2@MESA
- Moller at JLAB
- Q_{weak} at JLAB
- SOLID at JLAB

HERA estimate (see DIS2016)

LHeC: from A_{LR} and σ_{NC}/σ_{CC}, energy range 10 - 1000 GeV

future EIC

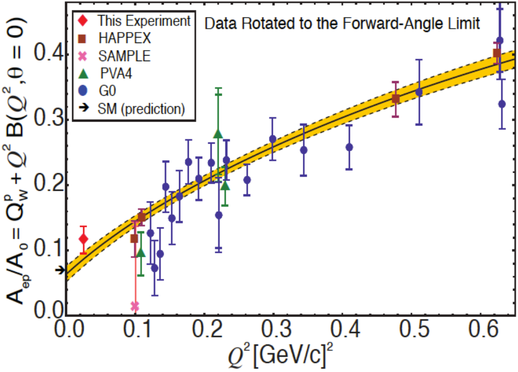
Summary

- Present measurements of the weak mixing angle need improvement
- MESA, a new high-precision measurement of $\sin^2\theta_w$ from parity-violating electron scattering
- Combined with possible future measurements at low energies, EIC, LHeC:

➜ Precision measurements will cover a wide range of energy scales

- Uncertainties for PVES
  - short-range, perturbative contributions, 1-loop under control
  - long-range effects in $\square^A_{\gamma Z}$ suppressed by $Q_W(e)$ (main limitation at P2@MESA)
  - long-range effects in $\square^V_{\gamma Z}$ suppressed by low E at P2@MESA
  - form factor corrections $F(Q^2)$ suppressed by low Q^2
- Still interesting theory work to be completed ...

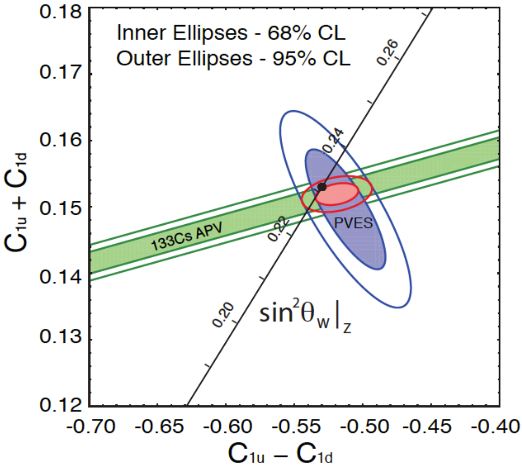
Extra Slides



arXiv:1307.5275 - PRL111(2013)

First results from Q_{weak} at JLAB

- $E = 1.165$ GeV, $Q^2 = 0.025$ GeV^2
- Analyzed 4% of data (expect factor 5 improved errors with full data taken)
- Used previous data to extrapolate to $Q^2 = 0$
- $Q^p_W = 0.064 \pm 0.012$ $(Q^p_W(SM) = 0.0710 \pm 0.0007)$



arXiv:1307.5275

First results from Q_{weak}

- 2-dim fit to quark couplings
- Best fit at $\sin^2\theta_w = 0.23116$

Dark matter and $U(1)$ symmetry ➜

- Kinetic mixing $B_{\mu\nu} D^{\mu\nu}$ (parameter ϵ) (B. Holdom)
- ➜ Dark photon, interacts via $\epsilon e D^{\mu} J_{\mu}^{em}$, like $e A^{\mu} J_{\mu}^{em}$
- Very small mass: $m_D = O(50)$ MeV
- $\epsilon = O(10^{-3})$, possibly generated by loop effects
- Negligible effect at the Z pole
- May provide solution to the $g-2$ discrepancy
- Model with parity violation, like ordinary Z, but suppressed by ϵ_Z W. Marciano