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

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

Goals:

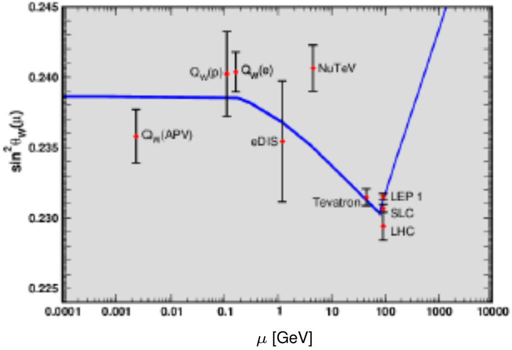
- High-precision measurements of the nucleon structure
- Search for new physics
- Electroweak physics:

  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



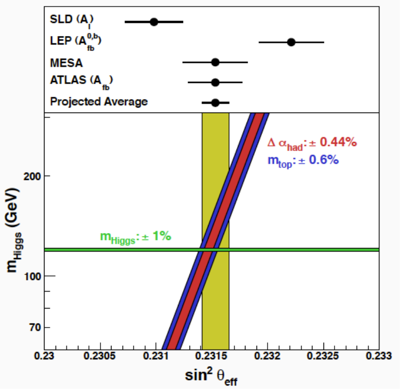
PDG 2014

- $Q_W(APV)$: 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



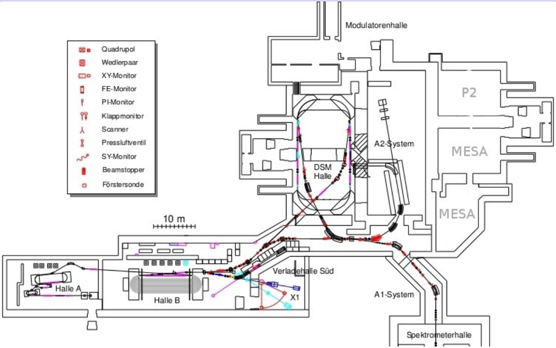
Combination of precision measurements at the Z-pole
➜ M_{Higgs} - $\sin^2\hat{\theta}_W(\mu)$ SM relation (red-blue band)

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

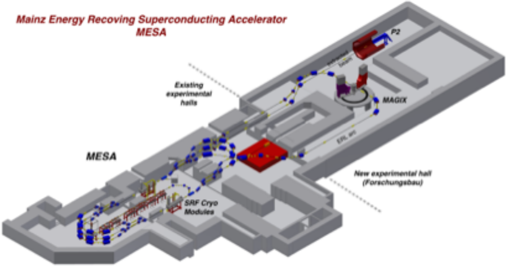
Combination of measurements provide strong tests of the SM,
. . . and maybe evidence for new physics

- 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
- Commissioning planned for 2019
- cf. Qweak at LJAB

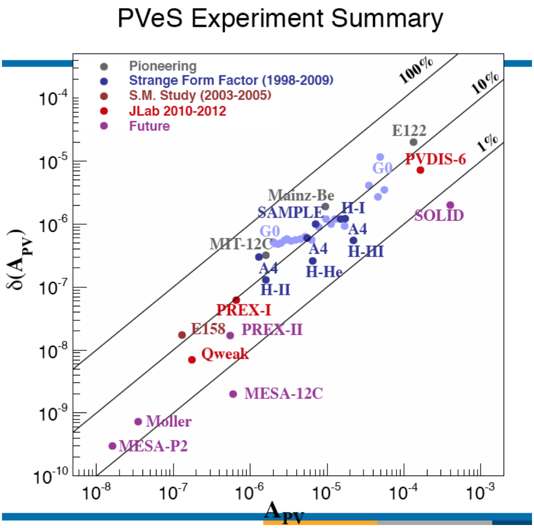


MAMI (Mainzer Mikrotron) and MESA



MESA Parameters

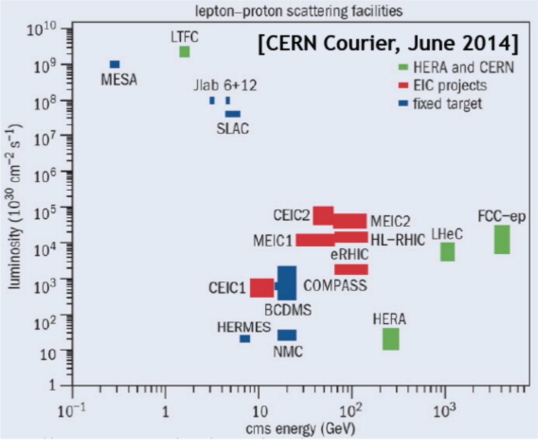
Parameter	P2 (Mainz)
Beam energy	155 MeV
Central scattering angle θ_e	$35°$
Detector acceptance for θ_e	$25°$ to $45°$
Azimuthal detector acceptance ϕ_e	2π
Central Q^2	$\simeq 0.0071$ (GeV/c)^2
Averaged Q^2	$\simeq 0.0045$ (GeV/c)^2
Polarization	(85 ± 0.5) %
Beam current	150μA
ℓ H_2 Target length	60 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
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}

(10,000 h)
data taking →

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

LHeC / FCC-he Context



P. Newman

Polarization Asymmetry

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:

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

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

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

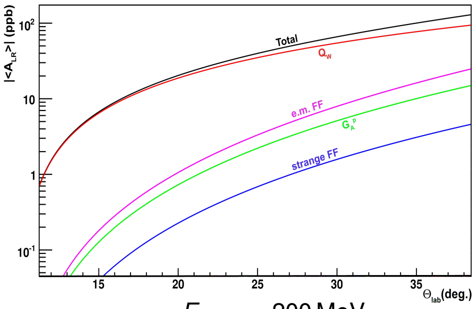
$$F(Q^2) = F_{\text{EMFF}}(Q^2) + F_{\text{Axial}}(Q^2) + F_{\text{Strangeness}}(Q^2)$$

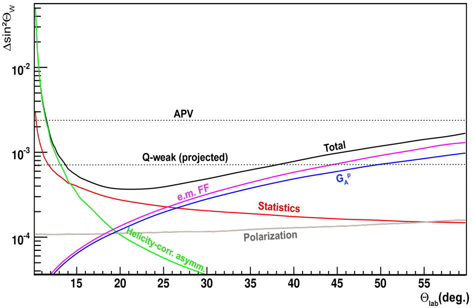
$$A_{LR} = A_{\text{Q}_{\text{weak}}} + A_{\text{EMFF}} + A_{\text{Axial}} + A_{\text{Strangeness}}$$

$$\begin{aligned}
F_{\text{EMFF}}(Q^2) &= -\frac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}\,, \\
F_{\text{Axial}}(Q^2) &= -\frac{(1-4\sin^2\theta_W)\sqrt{1-\epsilon^2}\sqrt{\tau(1+\tau)}\,G_M^p G_A^p}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}\,, \\
F_{\text{Strangeness}}(Q^2) &= -\frac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} - \frac{\epsilon G_E^p G_E^{ud} + \tau G_M^p G_M^{ud}}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}\,,
\end{aligned}$$

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

Contributions to the PV Asymmetry and Expected Error





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

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

$\langle Q \rangle = 0.067$ GeV

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

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

Polarization asymmetry including higher-order corrections:

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

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

Universal corrections: Δ_e and κ from loop diagrams:
scale-dependence ($\mu \to Q$) ➜

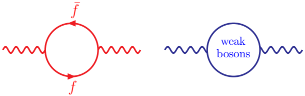
$$\sin^2\theta_{\rm eff}(\mu^2) = \kappa(\mu^2)\sin^2\theta_W$$

and scheme-dependent

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

Including quantum corrections, universal contributions at one-loop:

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

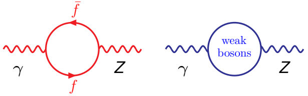


at large Q^2: $\propto \log \frac{Q^2}{m_f^2}$ small, $O(1\,\%)$

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

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

One-loop Corrections: Scale-Dependent $\sin^2\theta_W$

- 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)
- $\sin^2\theta_{\text{eff}}(Q^2)$ absorbs $\Pi_{\gamma Z}(Q^2)$, usually together with parts of vertex corrections (e.g. Czarnecki, Marciano)
- $\overline{\text{MS}}$ 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

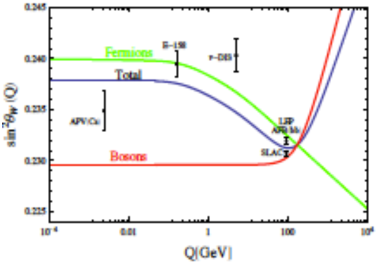
➜ Relation

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

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 assumptions ...

Prescriptions are known, with small uncertainties ...

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

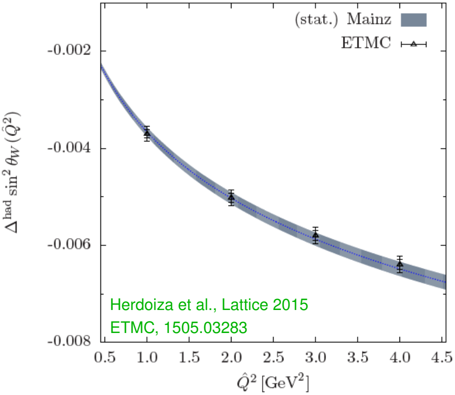
→ Use dispersion relation, e.g.

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

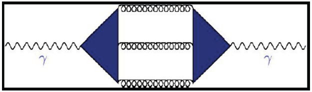
→ Similar approach for $\Pi^{\gamma Z}$ requires data for $\sigma_{tot}(\nu\bar{\nu} \to hadrons)$ or use flavor-separated e^+e^- data, isospin symmetry and OZI-rule

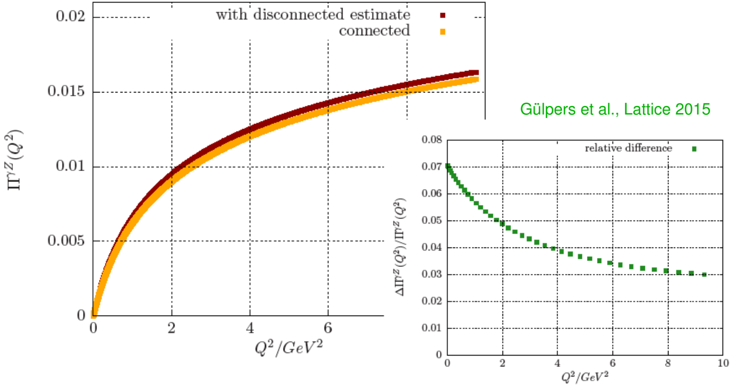
→ Use lattice techniques

First results available, errors start to be competitive

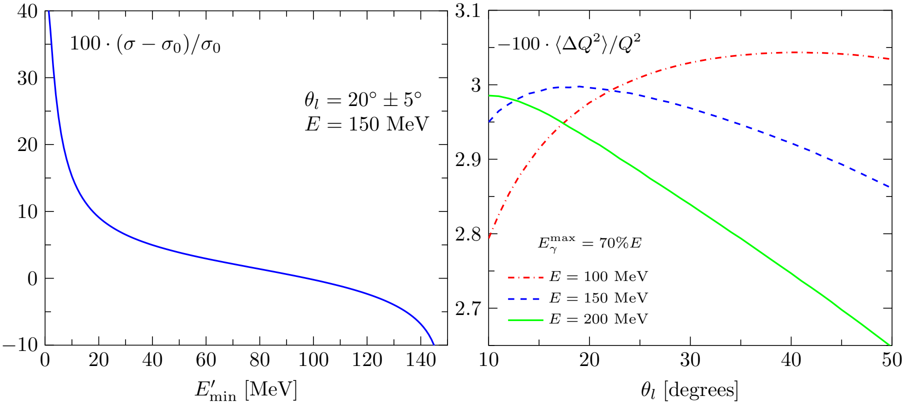


➜ OZI-rule violating contributions?
Lattice QCD
still with large statistical errors
but obtain an upper limit

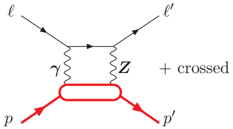




Gülpers et al., Lattice 2015



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



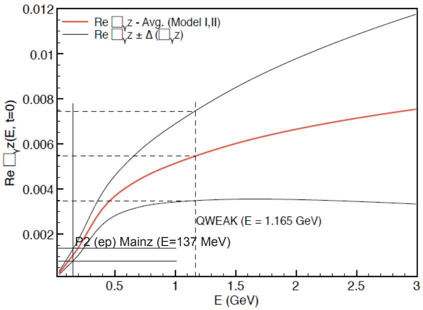
γZ box graphs

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

3 groups with independent analyses agree in size, but disagree on errors

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

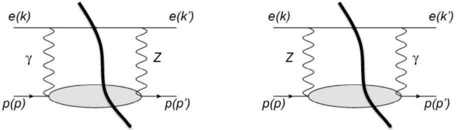
Gorchtein, Horowitz, Ramsey-Musolf



Advantage at MESA/P2: low energy

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

More work needed to reduce the error ...



Optical theorem and dispersion relations:

$$\mathrm{Im}\Box_{\gamma Z}(E) = \frac{\alpha}{(s-M_Z^2)^2} \int_{W_\pi^2}^{s} dW^2 \int_0^{Q^2_{max}} dQ^2 \frac{M_Z^2}{Q^2+M_Z^2} \times \left\{ F_1^{\gamma Z}(x,Q^2) + A F_2^{\gamma Z}(x,Q^2) + \frac{g_V^e}{g_A^e} B F_3^{\gamma Z} \right\}$$

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

$$\mathrm{Re}\Box^V_{\gamma Z}(E) = \frac{2E}{\pi} \int_{\nu_\pi}^{\infty} \frac{dE'}{E'^2 - E^2} \mathrm{Im}\Box^V_{\gamma Z}(E')$$

$$\mathrm{Re}\Box^A_{\gamma Z}(E) = \frac{2}{\pi} \int_{\nu_\pi}^{\infty} \frac{E' dE'}{E'^2 - E^2} \mathrm{Im}\Box^A_{\gamma Z}(E')$$

Box Graphs: Sensitivity to Hadronic Input

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

W_{max} / Q^2_{max}	2 GeV	4 GeV	∞
∞	1%	1%	3%
2 GeV²	3%	2%	1%
1 GeV²	76%	10%	2%

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

$\mathrm{Re}\Box^V_{\gamma Z} = 0.00104$

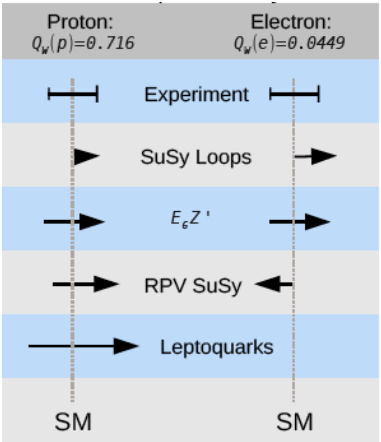
W_{max} / Q^2_{max}	2 GeV	4 GeV	∞
∞	0.5%	0.5%	4.6%
2 GeV²	6.7%	6.7%	0.5%
1 GeV²	60%	20%	0.5%

M. Gorshteyn

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

$\Delta\mathrm{Re}\Box^V_{\gamma Z} = 0.00015$

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

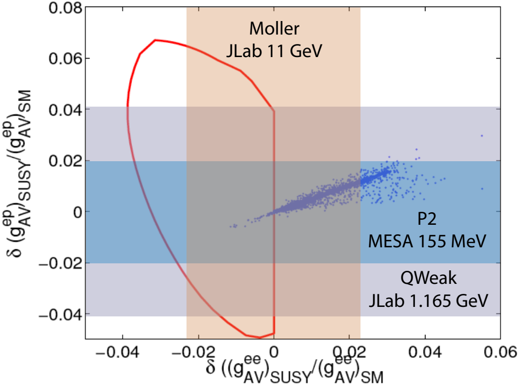


Searches based on

- 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

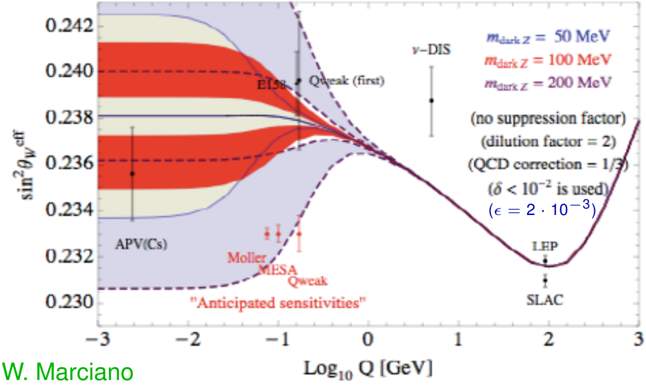
Perspective will shift after LHeC discoveries

Dark Photon and $\sin^2 \hat{\theta}_W(Q)$

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

The Scale of New Physics: Contact Interactions

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

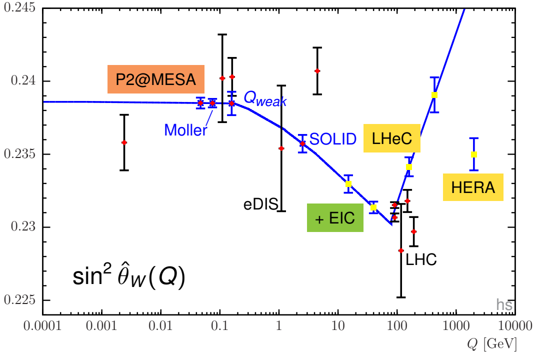
Convention: $g^2 = 4\pi$

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

comparable with
LHC (300 fb^-1)

	precision	$\Delta \sin^2\bar{\theta}_W(0)$	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 combined analysis

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

EIC: see K.Kumar's talk

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

- Still interesting theory work to be completed ...