Weak mixing angle measurements at different Q^2

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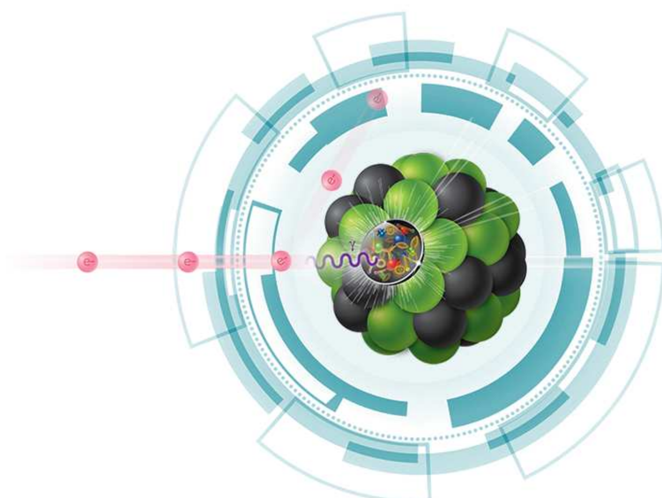
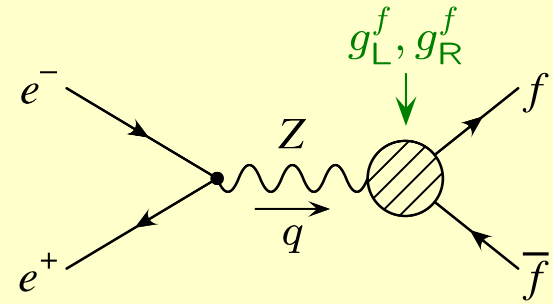


- Theory of $\sin^2\theta_W$
- Measurement at Z pole
- Measurement at low energies
- Measurement at EIC

Types of weak mixing angle

- **On-shell** $s_\mathrm{w}^2 \equiv M_\mathrm{W}^2/M_\mathrm{Z}^2$



- **Effective** $\sin^2\theta_\mathrm{eff}^f \equiv \frac{g_R^f}{2|Q_f|(g_R^f - g_L^f)}$ $\quad (q^2 = M_\mathrm{Z}^2)$

- **Off-shell** effective $\sin^2\theta_\mathrm{eff}^f$ for $q^2 \neq M_\mathrm{Z}^2$
  $\longrightarrow$ Not gauge invariant

- $\overline{\textbf{MS}}$ $\sin^2\bar{\theta}(\mu) \equiv \frac{\bar{g}_R^f(\mu)}{2|Q_f|(\bar{g}_R^f(\mu) - \bar{g}_L^f(\mu))}$

$$\sin^2\theta_\mathrm{eff}^f = s_\mathrm{w}^2(1 + \Delta\kappa)$$

$$\sin^2\theta_\mathrm{eff}^f = \sin^2\bar{\theta}(\mu)(1 + \Delta\bar{\kappa})$$

$\Delta\kappa, \Delta\bar{\kappa}$ = rad.corr., $\quad \Delta\kappa(M_\mathrm{Z}) \ll \Delta\bar{\kappa}$

s_w^2	0.22337
$\sin^2\theta_\mathrm{eff}^f$	0.23153
$\sin^2\bar{\theta}(M_\mathrm{Z})$	0.23121
$\sin^2\bar{\theta}(0)$	0.23857

New physics

Effective field theory: $\mathcal{L}_{\mathsf{BSM}} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}(\Lambda^{-3}) \qquad (\Lambda \gg M_{\mathsf{Z}})$

$$\sin^2\theta^f_{\mathrm{eff}} = s^2_{\mathrm{w}}\Big(1 + \Delta\kappa_{\mathrm{SM}} \underbrace{-\frac{g^2/4}{c^2_{\mathrm{w}} - s^2_{\mathrm{w}}}\bar{c}_{\mathrm{BW}}}_{\propto S \text{ parameter}} \underbrace{-\frac{c^2_{\mathrm{w}}}{c^2_{\mathrm{w}} - s^2_{\mathrm{w}}}\bar{c}_{\mathrm{T}}}_{\propto T \text{ parameter}} - \frac{s^2_{\mathrm{w}}}{2g^f_R}\bar{c}^f_L - \frac{s^2_{\mathrm{w}} g^f_L}{2(g^f_R)^2}\bar{c}^f_R\Big)$$

$$\sin^2\theta^f_{\mathrm{eff}} = \sin^2\bar{\theta}(M_{\mathrm{Z}})\Big(1 + \Delta\bar{\kappa}_{\mathrm{SM}} + \qquad - \frac{s^2_{\mathrm{w}}}{2g^f_R}\bar{c}^f_L - \frac{s^2_{\mathrm{w}} g^f_L}{2(g^f_R)^2}\bar{c}^f_R\Big)$$

$\bar{c}_i = v^2/\Lambda^2\, c_i$

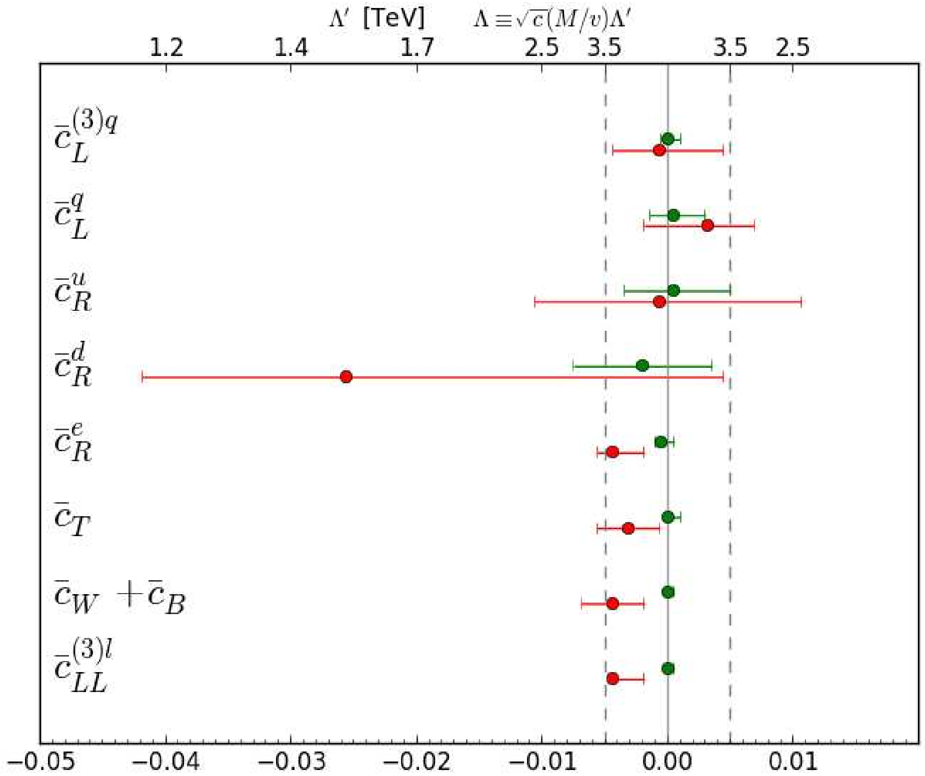
$\mathcal{O}_{\mathrm{T}} = \frac{1}{2}(D_\mu\Phi)^\dagger\Phi\,\Phi^\dagger(D^\mu\Phi) \qquad \mathcal{O}_{\mathrm{BW}} = \Phi^\dagger B_{\mu\nu}W^{\mu\nu}\Phi$

$O^f_{\mathrm{R}} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{f}_{\mathrm{R}}\gamma^\mu f_{\mathrm{R}}) \qquad f = e, \mu\,\tau, b, lq$

$O^F_{\mathrm{L}} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{F}_{\mathrm{L}}\gamma^\mu F_{\mathrm{L}}) \qquad F = \binom{\nu_e}{e}, \binom{\nu_\mu}{\mu}, \binom{\nu_\tau}{\tau}, \binom{u, c}{d, s}, \binom{t}{b}$

New physics reach

Assuming flavor universality:



$\delta \sin^2 \theta^f_{\text{eff}} \sim \pm 10^{-4}$

$\Rightarrow \quad \Lambda \sim 10$ TeV

Significant correlation/ degeneracy between different operators

Pomaral, Riva ’13

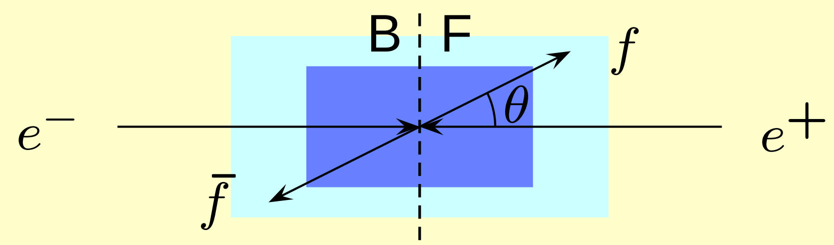
Ellis, Sanz, You ’14

Z-pole asymmetries at e^+e^- colliders

Forward-backward asymmetry:

$$A_{\mathsf{FB}} \equiv \frac{\sigma_{\mathsf{F}} - \sigma_{\mathsf{B}}}{\sigma_{\mathsf{F}} + \sigma_{\mathsf{B}}} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

$$\mathcal{A}_f = \frac{2(1-4\sin^2\theta^f_{\text{eff}})}{1+(1-4\sin^2\theta^f_{\text{eff}})^2} \qquad \sin^2\theta^f_{\text{eff}} = \frac{g^f_R}{2|Q_f|(g^f_R - g^f_L)}$$



Main systematic uncertainties:

- For $f = b$: charge tagging, jet clustering
- For $f = \mu$: calibration of $\sqrt{s}$, muon angle

Left-right asymmetry:

Electron beam polarized with degree P_{e^-}:
$$A_{\mathsf{LR}} = \frac{1}{P_{e^-}}\frac{\sigma_{\mathsf{L}} - \sigma_{\mathsf{R}}}{\sigma_{\mathsf{L}} + \sigma_{\mathsf{R}}} = -\mathcal{A}_\tau$$

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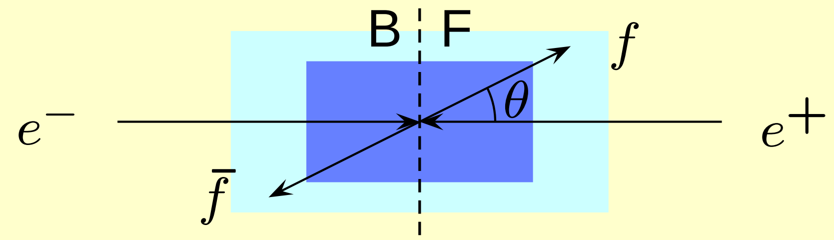

Main systematic uncertainties:

- For $f = b$: charge tagging, jet clustering
- For $f = \mu$: calibration of $\sqrt{s}$, muon angle $\leftarrow$ most robust for future colliders

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Z lineshape

- Deconvolution of initial-state QED radiation:

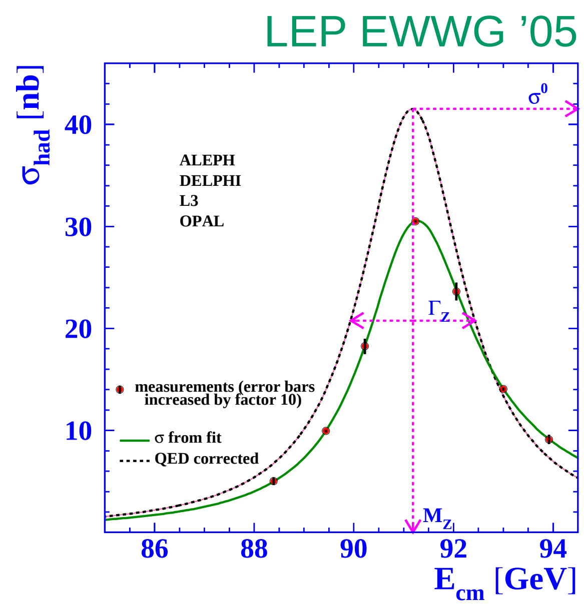
$$\sigma[e^+e^- \to f\bar{f}] = \mathcal{R}_{\text{ini}}(s,s') \otimes \sigma_{\text{hard}}(s')$$

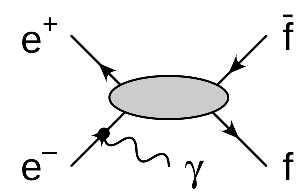
Kureav, Fadin '85
Berends, Burgers, v. Neerven '88
Kniehl, Krawczyk, Kühn, Stuart '88
Beenakker, Berends, v. Neerven '89
Skrzypek '92
Montagna, Nicrosini, Piccinini '97

Soft photons (resummed) + collinear photons

$$\mathcal{R}_{\text{ini}} = \frac{\zeta(1-s'/s)^{\zeta-1}}{\Gamma(1-\zeta)} e^{-\gamma_{\text{E}}\zeta + 3\alpha L/2\pi}$$
$$-\frac{\alpha}{\pi} L \left(1 + \frac{s'}{s}\right) + \alpha^2 L^2 \ldots + \alpha^3 L^3 \ldots$$

$$\zeta = \frac{2\alpha}{\pi}(L-1)$$
$$L = \log \frac{s}{m_{\text{e}}^2}$$





Z lineshape

- Deconvolution of initial-state QED radiation:

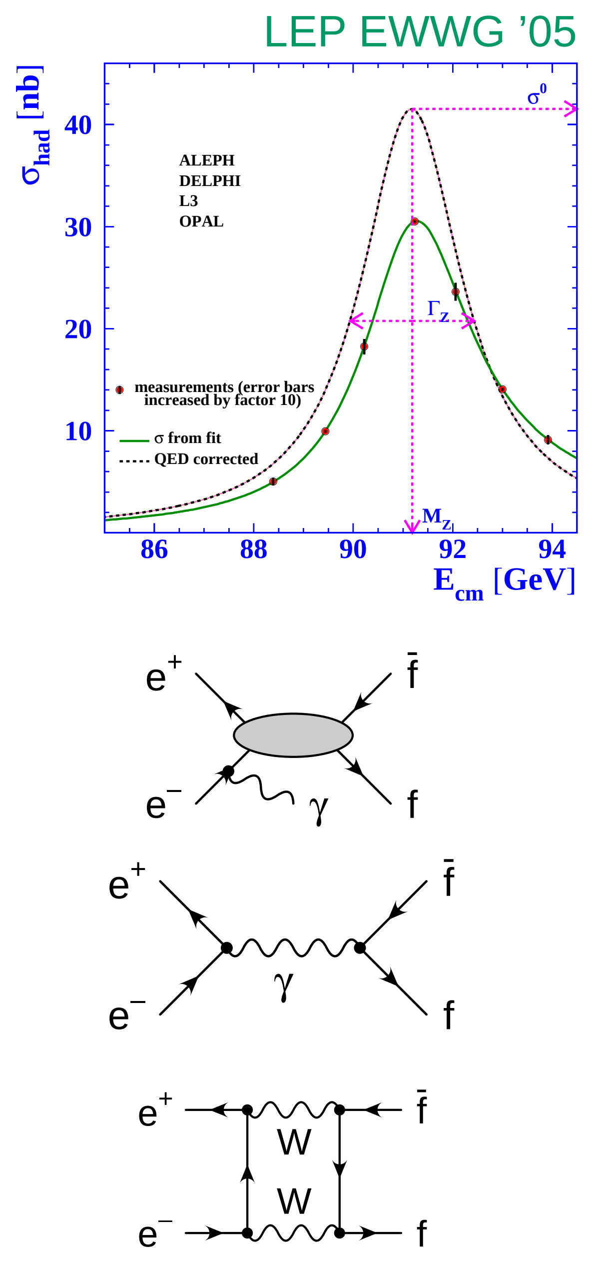
$$\sigma[e^+e^- \to f\bar{f}] = \mathcal{R}_{\rm ini}(s,s') \otimes \sigma_{\rm hard}(s')$$

- Subtraction of γ-exchange, γ–Z interference, box contributions:

$$\sigma_{\rm hard} = \sigma_{\rm Z} + \sigma_\gamma + \sigma_{\gamma \rm Z} + \sigma_{\rm box}$$

- Z-pole contribution:

$$\sigma_{\rm Z} = \frac{R}{(s-\overline{M}_{\rm Z}^2)^2 + \overline{M}_{\rm Z}^2 \overline{\Gamma}_{\rm Z}^2} + \sigma_{\rm non-res}$$



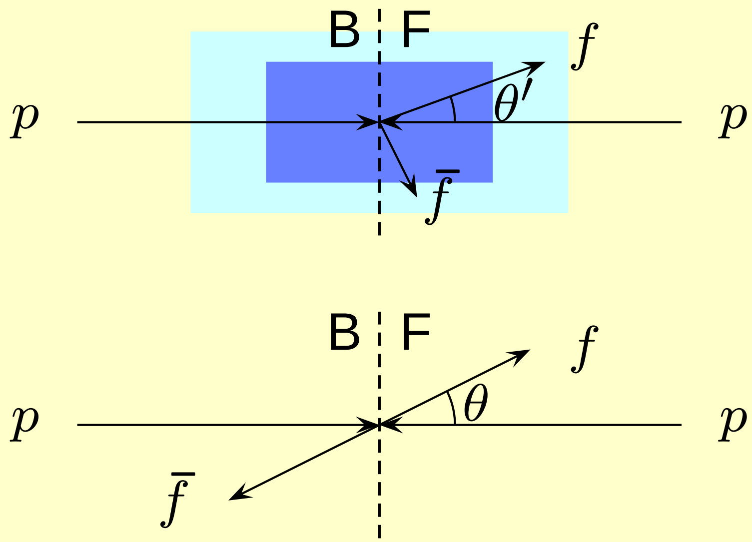
Drell-Yan at hadron colliders

Forward-backward asymmetry: "forward" defined through overall boost

(valence quark typically has higher momentum than sea anti-quark)

lab frame:

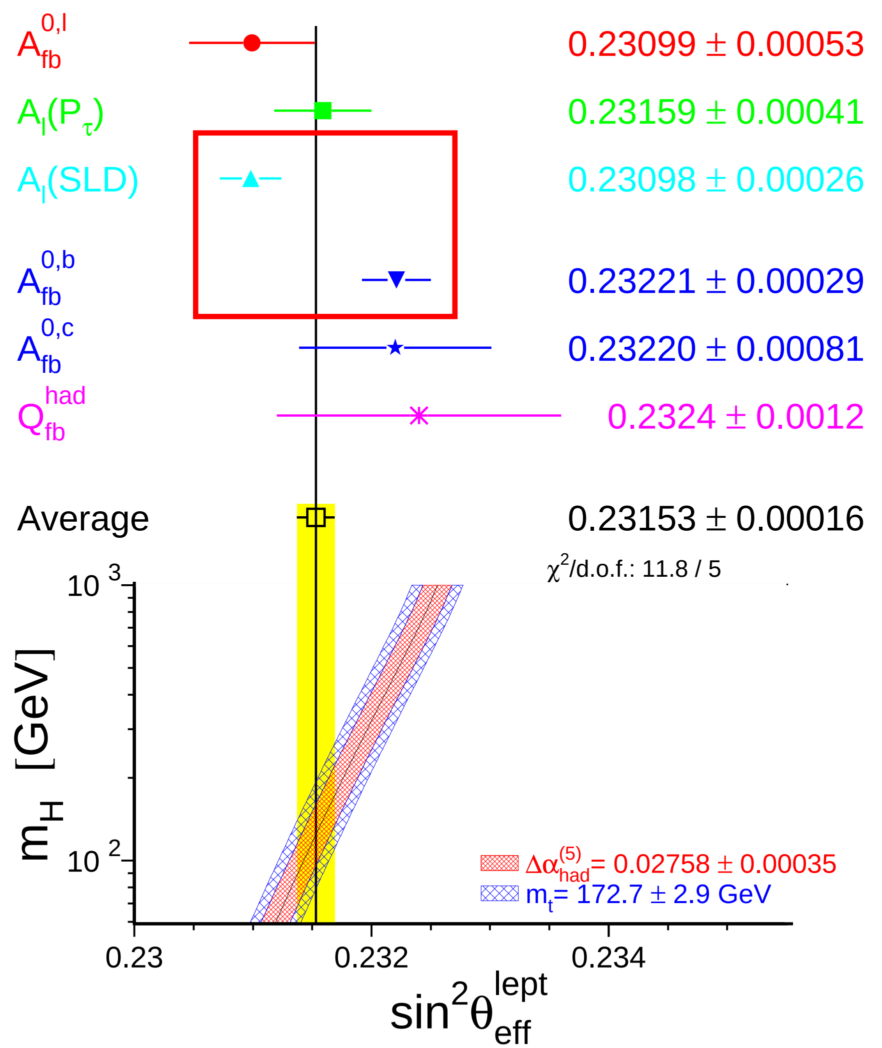
center-of-mass frame:



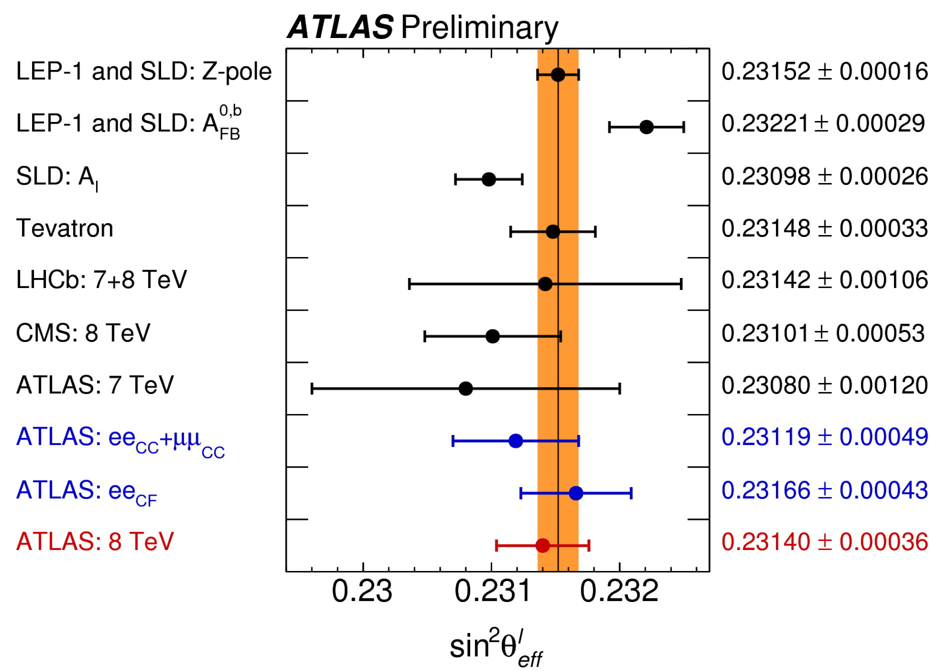
Main systematic uncertainties:

- PDFs
- QCD (QCD$\times$EW) corrections

Current status of $\sin^2\theta^\ell_{\rm eff}$



LEP EWWG '05



ATLAS '18

Future e^+e^- colliders

	Current exp.	CEPC	FCC-ee
M_W [MeV]	15	1	1
Γ_Z [MeV]	2.3	0.5	0.1
$R_\ell = \Gamma_Z^{had}/\Gamma_Z^\ell$ [10^{-3}]	25	2	1
$R_b = \Gamma_Z^b/\Gamma_Z^{had}$ [10^{-5}]	66	4.3	6
$\sin^2\theta_{eff}^\ell$ [10^{-5}]	13*	$<$1	0.5

* naive combination of LEP/SLC/TeV/LHC

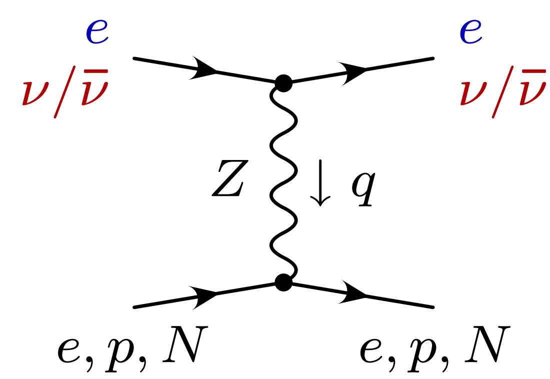
$\longrightarrow$ Improved measurements of several EWPOs necessary to improve global fit

$\longrightarrow$ Will need 3-loop and partial 4-loop SM corrections

Weak mixing angle from low-energy parity violation

- Polarized ee, ep, ed scattering ($Q_W(e)$, $Q_W(p)$, eDIS)
  E158 '05; Qweak '17; JLab Hall A '13
- $\nu N/\bar{\nu} N$ scattering NuTeV '02
- Atomic parity violation ($Q_W(^{133}\text{Cs})$) Wood et al. '97 Guéna, Lintz, Bouchiat '05

$\longrightarrow$ Test of running $\overline{\text{MS}}$ weak mixing angle $\sin^2\bar{\theta}(\mu)$, $\mu^2 \sim |q^2|$



$$g^{ef}_{\text{AV}}\,[\bar{e}\gamma^\mu\gamma_5 e]\,[\bar{f}\gamma_\mu f]$$
$$g^{ef}_{\text{VA}}\,[\bar{e}\gamma^\mu e]\,[\bar{f}\gamma_\mu\gamma_5 f]$$

$$g^{ef}_{\text{AV}} = \frac{1}{2} - 2|Q_f|\sin^2\bar{\theta}(\mu)$$
$$g^{ef}_{\text{VA}} = \frac{1}{2} - 2\sin^2\bar{\theta}(\mu)$$

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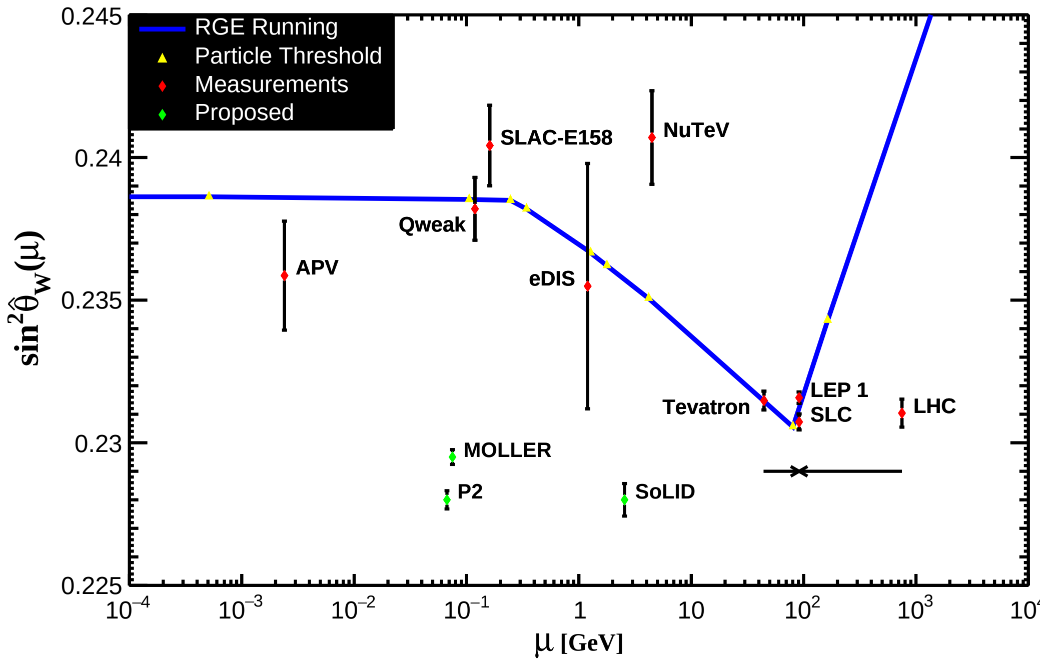
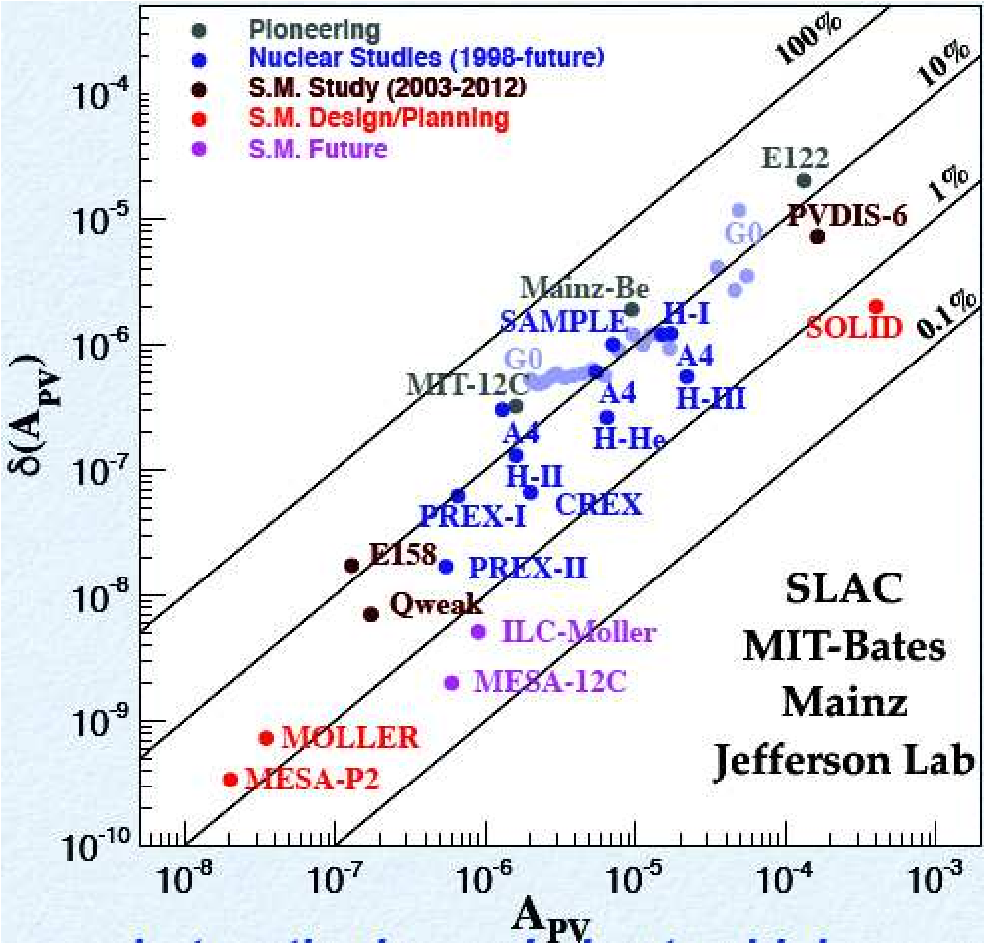
Erler, Ferro-Hernández '17



Polarized electron scattering: experiments



K. Kumar 'PVES 2018

MOLLER experiment at JLab (ee):

$\delta_{\text{exp}} A_{\text{LR}} = 0.73 \times 10^{-9}$ (2.4%)

$\delta_{\text{exp}} \sin^2\theta_W \sim 0.1\%$

Current best ee (SLAC E158):

$\delta_{\text{exp}} A_{\text{LR}} = 14\%$

P2 experiment at MESA (ep):

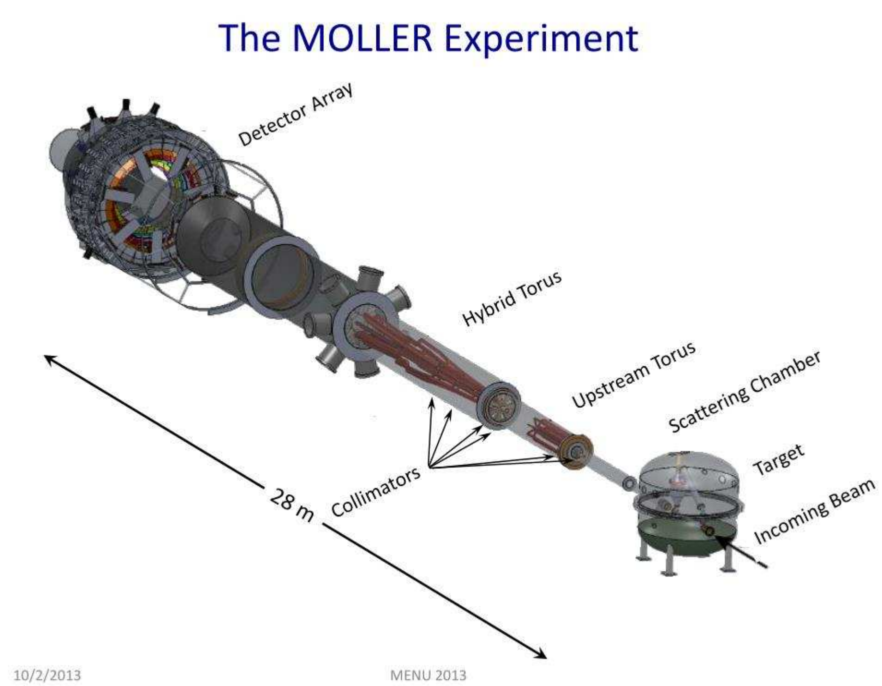
$\delta_{\text{exp}} A_{\text{LR}} = 0.56 \times 10^{-9}$ (1.4%)

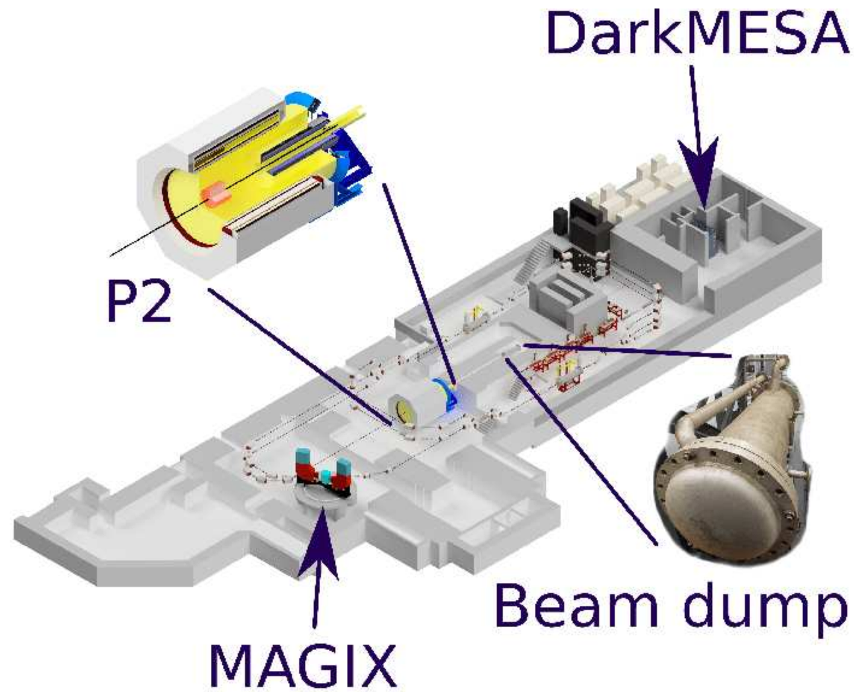
$\delta_{\text{exp}} \sin^2\theta_W \sim 0.1\%$

Current best ep (Qweak):

$\delta_{\text{exp}} A_{\text{LR}} = 8\%$

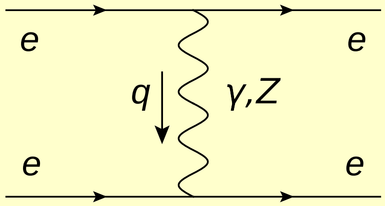
Polarized electron scattering: experiments





Polarized electron scattering

- Polarized e^- on $e^-/p/N$ target
- LR asymmetry for point-like target:

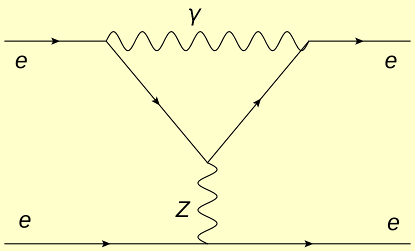


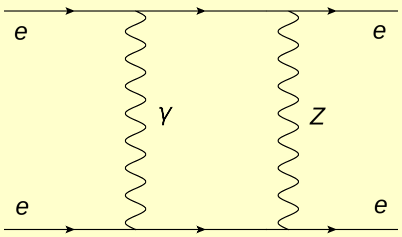
$$A_{\mathrm{LR}}^{ee} = \frac{\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}}}{\sigma_{\mathrm{L}} + \sigma_{\mathrm{R}}} = \frac{G_\mu(-q^2)}{\sqrt{2}\pi\alpha} \frac{1-y}{1+y^4+(1-y)^4} Q_{\mathrm{W}}(e)$$

$$A_{\mathrm{LR}}^{ep} \approx \frac{\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}}}{\sigma_{\mathrm{L}} + \sigma_{\mathrm{R}}} = \frac{G_\mu(-q^2)}{4\sqrt{2}\pi\alpha} Q_{\mathrm{W}}(p)$$

$$y \approx \tfrac{1}{2}(1 - \cos\theta_{\mathrm{CM}})$$

- $Q_W(e) = Q_W(p) = 1 - 4\sin^2\theta_{\mathrm{W}}$
- For low $Q^2 {=} {-q^2}$ proton is approx. point-like, but form factor corrections needed ($Q^2 \sim 0.005\ \mathrm{GeV}^2$ at P2)
- Radiative corrections must be included:
  $1 - 4\sin^2\theta_{\mathrm{W}} \quad \to \quad [1 - 4\kappa(\mu)\sin^2\bar{\theta}(\mu)] + \Delta Q(\mu)$



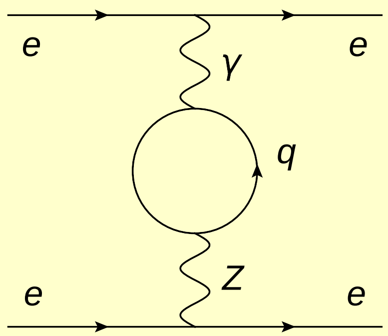


EW corrections to Møller scattering: Hadronic effects

$$A_{\mathsf{LR}} = \frac{\rho G_\mu \, q^2}{\sqrt{\pi}\alpha} \, \frac{-1+y}{1+y^4+(1-y)^4} \Big[1 - 4\kappa(\mu) \sin^2\bar{\theta}(\mu) + \Delta Q(\mu) \Big]$$

- From γ–Z self-energy:

  $\kappa(M_{\mathsf{Z}}) = 1 - \frac{\alpha}{6\pi s^2} \sum_f (I_{3f} Q_f - 2s^2 Q_f^2) \ln \frac{m_f^2}{M_{\mathsf{Z}}^2}$



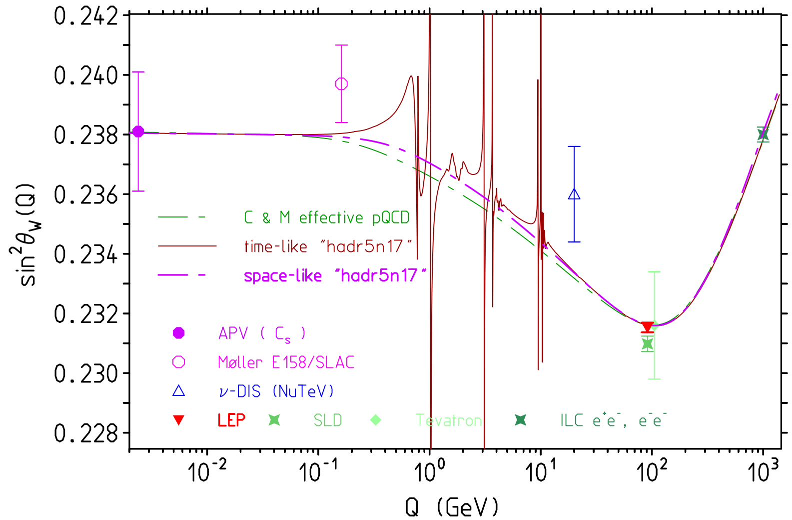
- Sensitivity to m_q: non-perturbative hadron physics
- $\kappa(0)$ is free of $\ln m_f^2$ terms

  $\longrightarrow$ Absorbed into running of $\sin^2\bar{\theta}(\mu)$

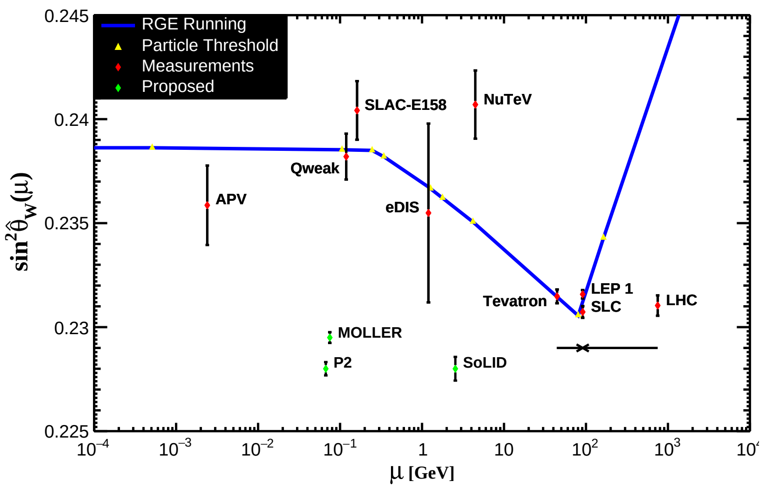
EW corrections to Møller scattering: Hadronic effects

Determination of $\Delta_{\gamma Z} = \sum_f (I_{3f} Q_f - 2s^2 Q_f^2) \ln m_f^2/M_Z^2$:

a) Directly from e^+e^- data using reweighting of different flavors
[SU(3)$_{u,d,s}$ symmetry,
pQCD for u, d, s at c, b thrsh.]
Wetzel '81; Marciano, Sirlin '84
Jegerlehner '86,17



b) Determine "threshold masses"
$\bar{m}_{u,ds,c,b}$ from $\Delta\alpha(q^2)$;
pQCD RG running btw. thresholds
Erler, Ramsey-Musolf '04
Erler, Ferro-Hernández '17



c) Lattice QCD
Ottnad 'PVES 2018

Weak mixing angle measurement at EIC

- Polarized e^- on p for $Q^2 \gg \Lambda_{\mathrm{QCD}}$
- LR asymmetry:

$$A_{\mathrm{LR}}^{ep} \approx \frac{\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}}}{\sigma_{\mathrm{L}} + \sigma_{\mathrm{R}}} = \frac{G_\mu(-q^2)}{4\sqrt{2}\pi\alpha}\left[\frac{F_1^{\gamma Z}}{F_1^{\gamma}} + (1 - 4\sin^2\theta_{\mathrm{W}})\frac{y(1-y)}{1+(1-y)^2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$y = 1 - E_e'/E_e$$

- DIS regime (rather than point-like as at P2):

$$F_1^{\gamma} = \sum_q q_q (f_q + f_{\bar{q}})$$

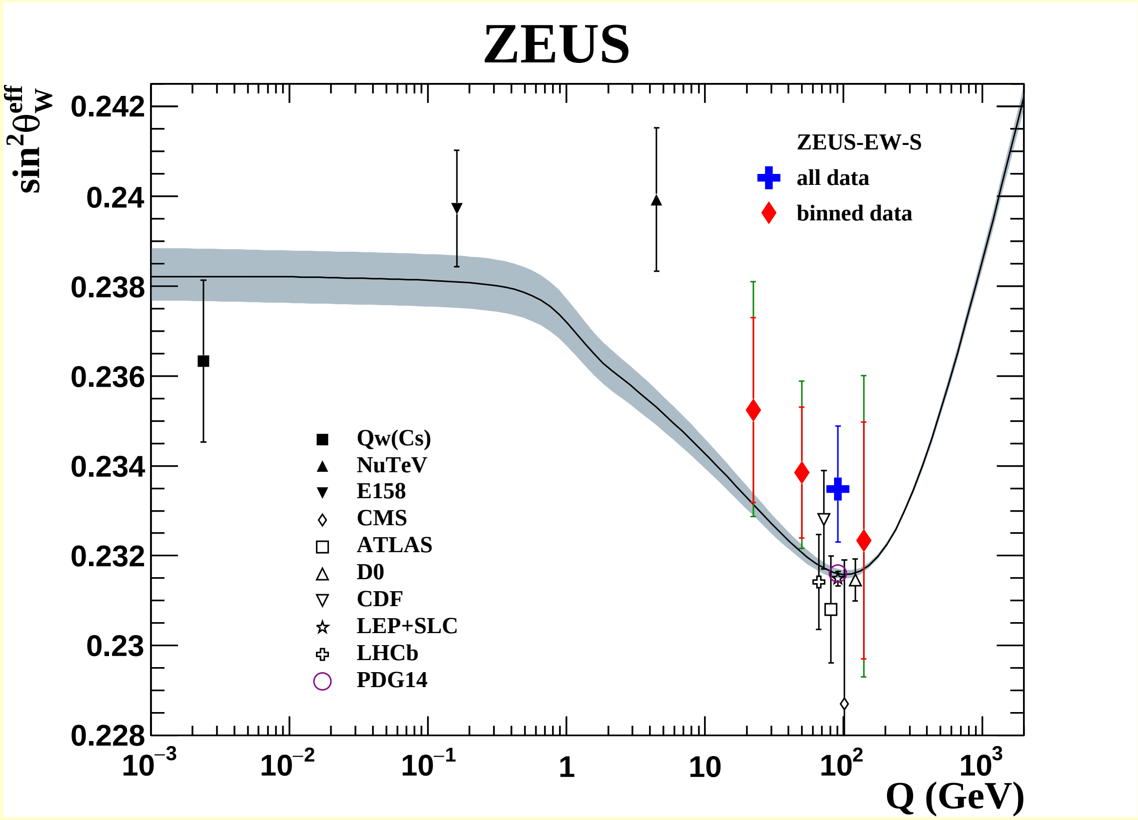
$$F_1^{\gamma Z} = \sum_q q_q\, g_V^q (f_q + f_{\bar{q}})$$

$$F_1^{\gamma Z} = 2\sum_q q_q\, g_A^q (f_q + f_{\bar{q}})$$

$\longrightarrow$ Need precise knowledge of PDFs for $100\ \mathrm{GeV}^2 \lesssim Q^2 \lesssim 5000\ \mathrm{GeV}^2$

Weak mixing angle measurement at EIC

- Polarized e^- on p for $Q^2 \gg \Lambda_{\mathrm{QCD}}$
- Result from HERA (0.3 fb^{-1}):



ZEUS coll. ’16

Weak mixing angle measurement at EIC

- Polarized e^- on d for $Q^2 \gg \Lambda_{\mathrm{QCD}}$
- d is iso-singlet $\longrightarrow$ PDF dependence approximately cancels in LR asymmetry:
- Assuming valence quark dominance and charge symmetry:

$f_u \approx f_d$,
$f_{\bar{u}} \approx f_{\bar{d}} \approx f_{s,c,b} \approx f_{\bar{s},\bar{c},\bar{b}} \approx 0$

$$A_{\mathrm{LR}}^{ep} \approx \frac{G_\mu(-q^2)}{4\sqrt{2}\pi\alpha}\left[\frac{9}{5} - \sin^2\theta_{\mathrm{W}} + \frac{9}{5}(1 - 4\sin^2\theta_{\mathrm{W}})\frac{y(1-y)}{1+(1-y)^2}\right]$$

$\longrightarrow$ Reduced need for precision PDF input

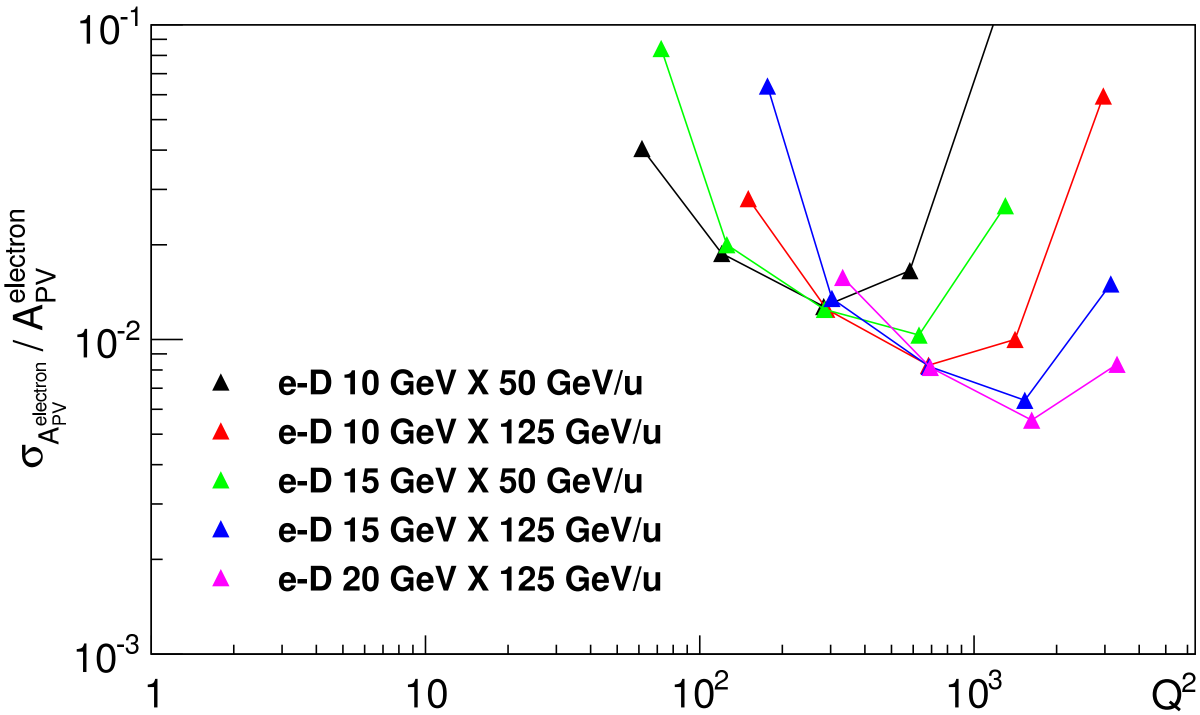
Weak mixing angle measurement at EIC

Simulation with QED and QCD radiative effects (`DJANGOH`), `CTEQ6.1M` PDFs, and detector smearing Zhao, Deshpande, Huang, Kumar, Riordan '16

Assumptions:

- Neglect higher-twist effects and PDF evolution in Q^2 range
- Differential luminosity uncertainty $< 10^{-4}$
- Polarization uncertainty $< 1\%$

$\mathcal{L}_{\text{int}} = 267\ \text{fb}^{-1}$



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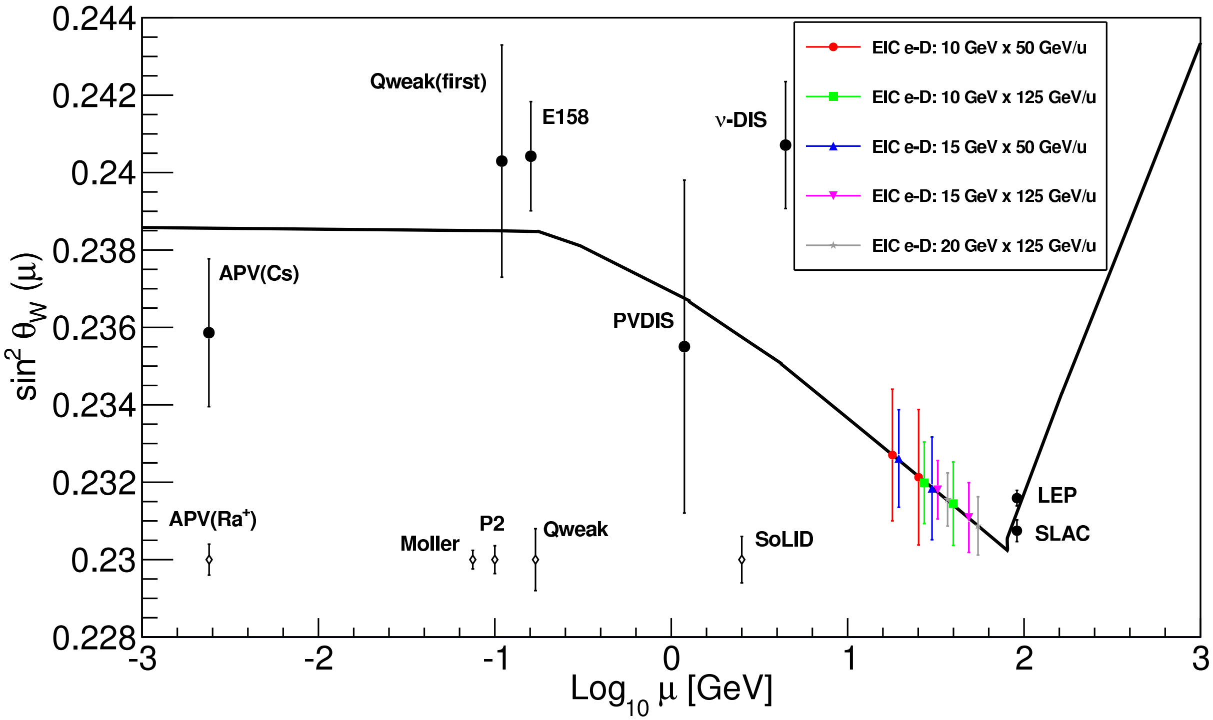
(2 Q^2 bins)



Conclusions

$\oplus$ EIC can determine $\sin^2\bar{\theta}(\mu)$ is poorly explored range
$10\ \text{GeV} \lesssim \mu \lesssim 70\ \text{GeV}$
$\longrightarrow$ Experimentally probe QCD running
$\longrightarrow$ May help to resolve tension between A^b_{FB} and A^e_{LR}

$\ominus$ Precision is lower than at LEP, SLC, LHC, MOLLER, P2
$\longrightarrow$ No improved sensitivity to high-scale new physics

Open questions:

- PDF uncertainties (use EIC ep data as an input)
- Treatment of radiative corrections, non-perturbative corrections?

Backup slides

Z-pole asymmetries

Left-right asymmetry: (using polarization e^- beams)

$$A_{\mathrm{LR}} \equiv \frac{1}{P_{e^-}} \frac{\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}}}{\sigma_{\mathrm{L}} + \sigma_{\mathrm{R}}} = \mathcal{A}_e + \Delta A_{\gamma Z} + \Delta A_\gamma$$

$$\mathcal{A}_f = \frac{2(1 - 4\sin^2\theta^f_{\mathrm{eff}})}{1 + (1 - 4\sin^2\theta^f_{\mathrm{eff}})^2} \qquad \sin^2\theta^f_{\mathrm{eff}} = \frac{g^f_R}{2|Q_f|(g^f_R - g^f_L)}$$

Limited by systematic uncertainty of P_{e^-}

0.5% at SLD, 0.1% possible in future

Karl, List '17

Z-pole asymmetries

Blondel scheme: (if e^- and e^+ polarization available) Blondel '88

Four independent measurements for $P_{e^+}/P_{e^-} = ++, +-, -+, --$

$$A_{\mathrm{LR}} = \sqrt{\frac{(\sigma_{++} + \sigma_{-+} - \sigma_{+-} - \sigma_{--})(-\sigma_{++} + \sigma_{-+} - \sigma_{+-} + \sigma_{--})}{(\sigma_{++} + \sigma_{-+} + \sigma_{+-} + \sigma_{--})(-\sigma_{++} + \sigma_{-+} + \sigma_{+-} - \sigma_{--})}}$$

Note: No need to know $|P_{e^\pm}|$!

Main systematic uncertainties:

- Difference of $|P|$ for $P > 0$ and $P < 0$
- Difference of $\mathcal{L}$ for $P > 0$ and $P < 0$

$\delta A_{\mathrm{LR}} \approx 10^{-4}$ $\Rightarrow$ $\delta \sin^2 \theta^{\ell}_{\mathrm{eff}} \approx 1.3 \times 10^{-5}$ Mönig, Hawkings '99

Theory calculations: Uncertainties

	Experiment	Theory error	Main source
M_{W}	80.379 ± 0.012 MeV	4 MeV	α^3, $\alpha^2\alpha_{\text{s}}$
Γ_Z	2495.2 ± 2.3 MeV	0.4 MeV	α^3, $\alpha^2\alpha_{\text{s}}$, $\alpha\alpha_{\text{s}}^2$
R_ℓ	20.767 ± 0.025	0.005	α^3, $\alpha^2\alpha_{\text{s}}$
R_b	0.21629 ± 0.00066	0.0001	α^3, $\alpha^2\alpha_{\text{s}}$
$\sin^2\theta^\ell_{\text{eff}}$	0.23153 ± 0.00016	4.5×10^{-5}	α^3, $\alpha^2\alpha_{\text{s}}$

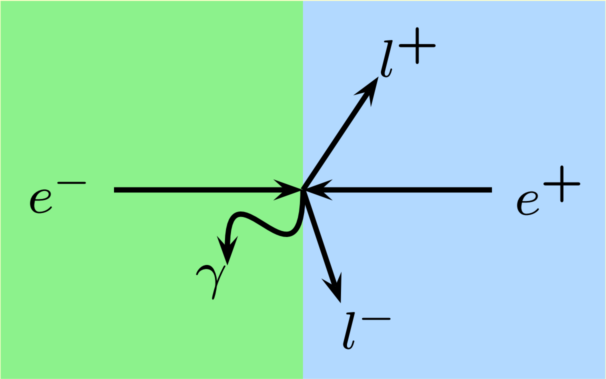
- Theory error estimate is not well defined, ideally $\Delta_{\text{th}} \ll \Delta_{\text{exp}}$
- Common methods:
  - Count prefactors (α, N_c, N_f, ...)
  - Extrapolation of perturbative series
  - Renormalization scale dependence
  - Renormalization scheme dependence

QED radiation in Z asymmetries

QED radiation in principle cancels in asymmetries, e.g. $A_{\mathsf{FB}} = \frac{\sigma_{\mathsf{F}}-\sigma_{\mathsf{B}}}{\sigma_{\mathsf{F}}+\sigma_{\mathsf{B}}}$

Some effects from detector acceptance and cuts

Typical influence $< 10^{-3}$



Implementation of QED effects:

a) Analytical formulae, e.g. `ZFITTER`

Arbuzov, Bardin, Christova, Kalinovskaya, Riemann, Riemann, ...

$\longrightarrow$ exact $\mathcal{O}(\alpha^2)$ ISR/FSR corrections

b) Monte Carlo event generator, e.g. `KORALZ, KKMC` Jadach, Ward, ...

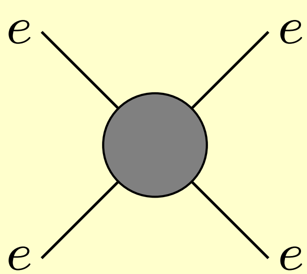
$\longrightarrow$ only $\mathcal{O}(\alpha^2 L)$ accuracy, but more flexible

$$L = \log(s/m_{\mathsf{e}}^2)$$

Sensitivity to new physics scales

4-lepton operator

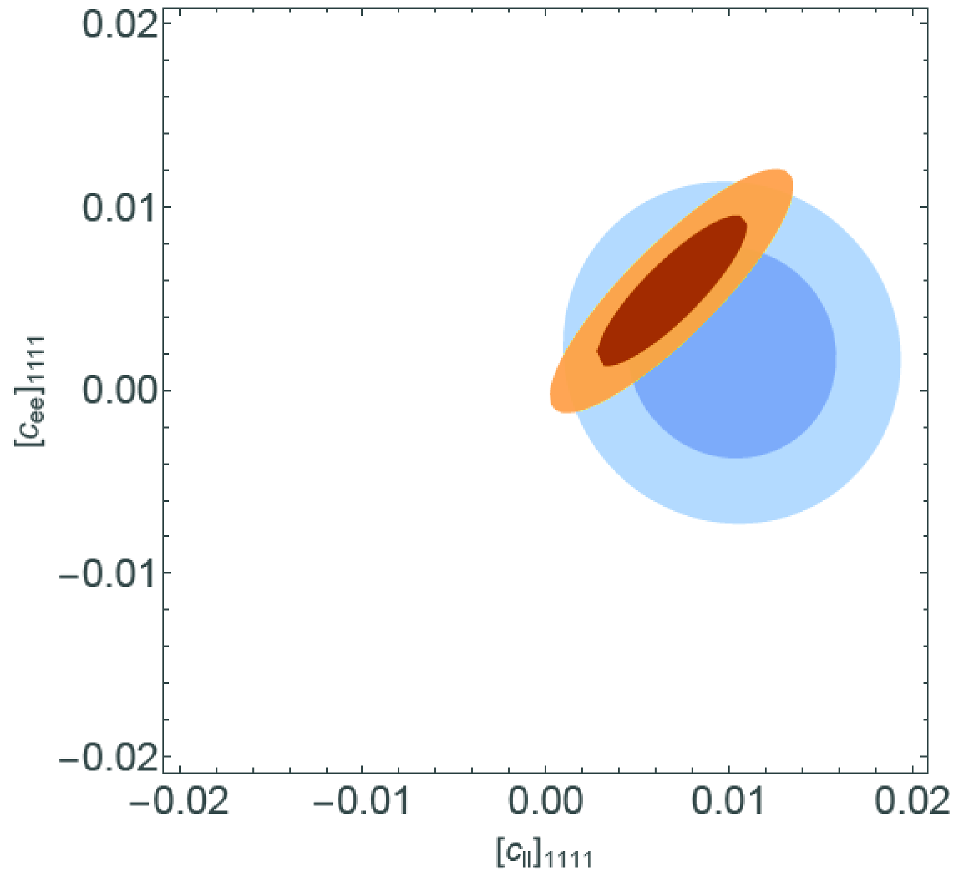
$$\frac{4\pi}{\Lambda^2}\,[\bar{e}\gamma^\mu\gamma_5 e]\;[\bar{e}\gamma_\mu e]$$



E158: $\Lambda \lesssim 17$ TeV

MOLLER: $\Lambda \lesssim 39$ TeV

Erler, Horowitz, Mantry, Souder '14



Falkowski, Gonzalez-Alonso, Mimouni '17
Falkowski et al. '18

$$\frac{c_{ee}}{v^2}\,[\bar{e}\gamma^\mu P_R e]\;[\bar{e}\gamma_\mu P_R e]$$

$$\frac{c_{\ell\ell}}{v^2}\,[\bar{e}\gamma^\mu P_L e]\;[\bar{e}\gamma_\mu P_L e]$$