Precision predictions for low-energy PV observables

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LoopFest XVII

1. Context: Z and W boson precision physics

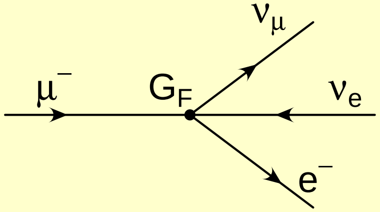
2. Low-energy parity violation

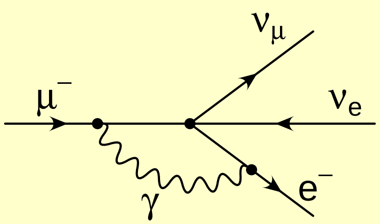
3. Electroweak corrections to Møller scattering
   Du, Freitas, Patel, Ramsey-Musolf, in preparation

Context: Z and W boson precision physics

W mass

μ decay in Fermi Model



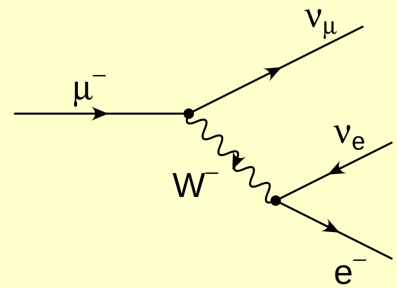


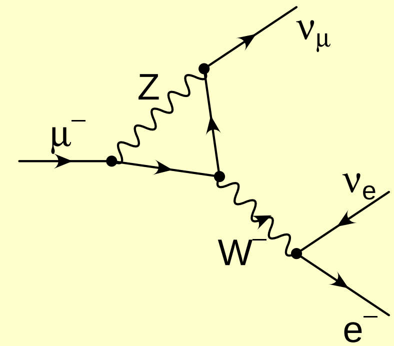
QED corr. (2-loop)

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right)(1 + \Delta q)$$

Ritbergen, Stuart '98
Pak, Czarnecki '08

μ decay in Standard Model





$$\frac{G_F^2}{\sqrt{2}} = \frac{e^2}{8 s_W^2 M_W^2}(1 + \Delta r)$$

electroweak corrections

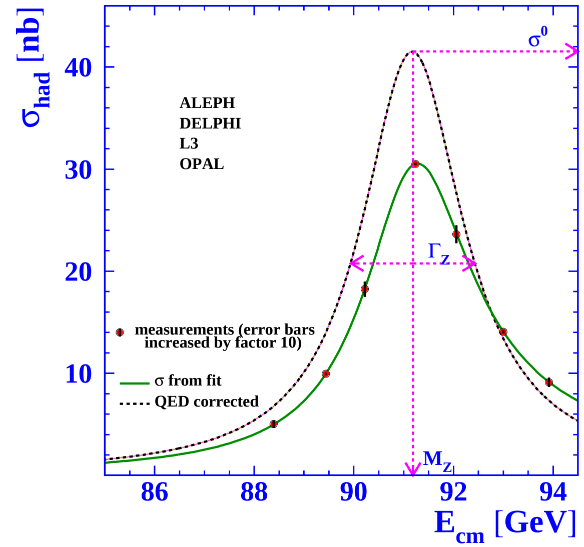
Z-pole observables

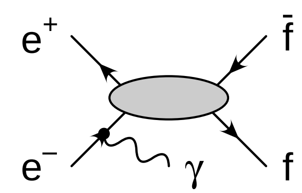
- Deconvolution of initial-state QED radiation:

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

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

LEP EWWG '05





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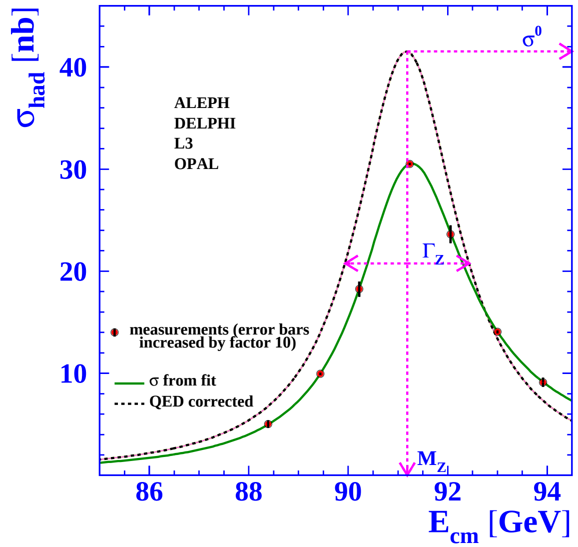
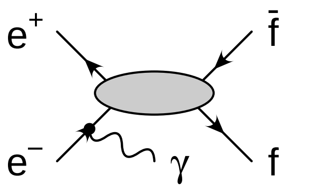
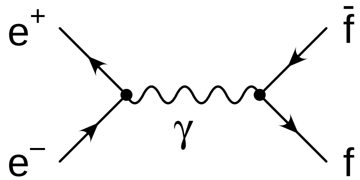
- Subtraction of γ-exchange, γ–Z interference, box contributions:

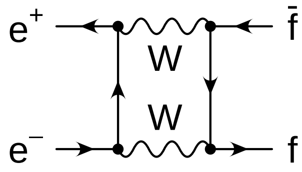
$$\sigma_{\text{hard}} = \sigma_Z + \sigma_\gamma + \sigma_{\gamma Z} + \sigma_{\text{box}}$$

LEP EWWG '05









Z-pole observables

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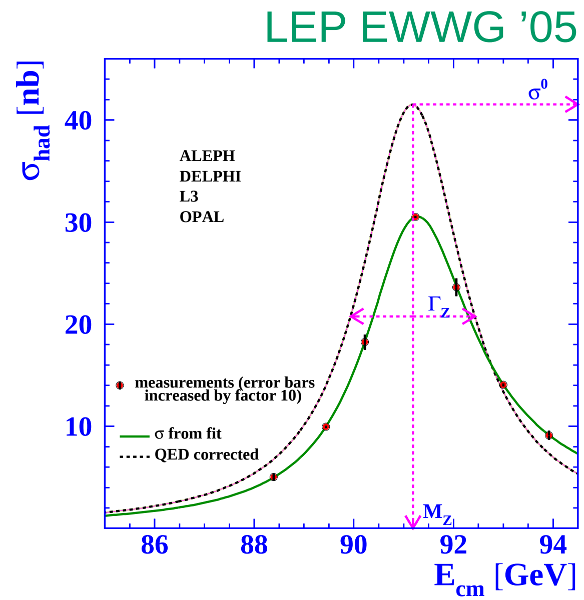
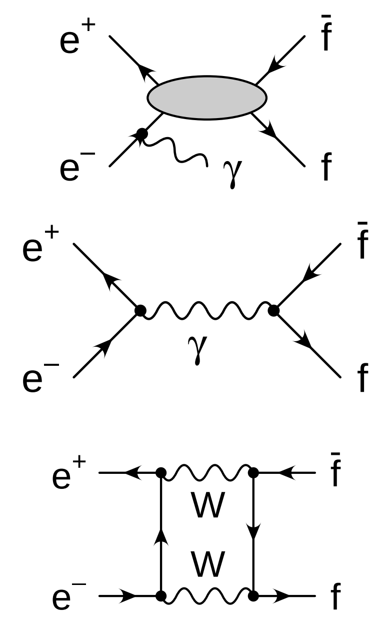
- Subtraction of γ-exchange, γ–Z interference, box contributions:

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

- Z-pole contribution:

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





Z-pole observables

- 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:

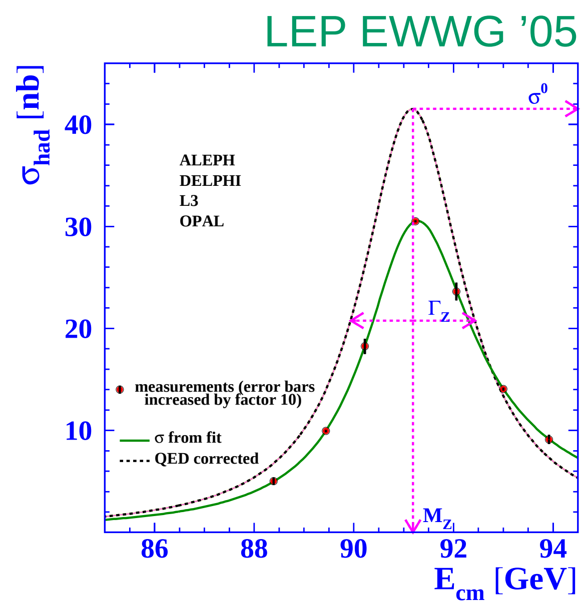
$$\sigma_{\rm Z} = \frac{R}{(s-\overline{M}_{\rm Z}^2)^2 + \overline{M}_{\rm Z}^2\overline{\Gamma}_{\rm Z}^2} + \sigma_{\rm non-res}$$

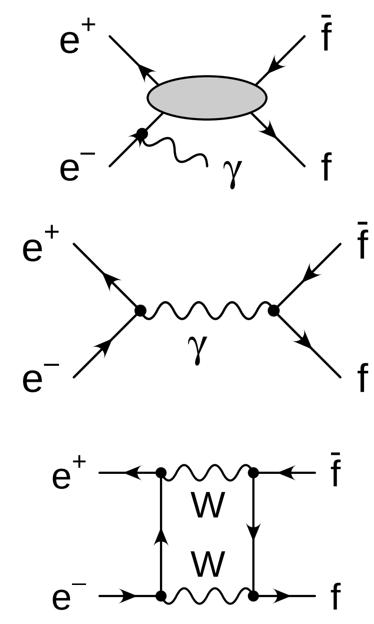
- In experimental analyses:

$$\sigma \sim \frac{1}{(s-M_{\rm Z}^2)^2 + s^2\Gamma_{\rm Z}^2/M_{\rm Z}^2}$$

$$\overline{M}_{\rm Z} = M_{\rm Z}\Big/\sqrt{1+\Gamma_{\rm Z}^2/M_{\rm Z}^2} \approx M_{\rm Z} - 34\ \text{MeV}$$

$$\overline{\Gamma}_{\rm Z} = \Gamma_{\rm Z}\Big/\sqrt{1+\Gamma_{\rm Z}^2/M_{\rm Z}^2} \approx \Gamma_{\rm Z} - 0.9\ \text{MeV}$$





Z-pole observables

Relevant pseudo-observables:

- Total width $\overline{\Gamma}_{\mathrm{Z}}$
- Partial widths $\overline{\Gamma}_f = \Gamma[Z \to f\bar{f}]_{s=\overline{M}_{\mathrm{Z}}^2}$
- Peak cross-section $\sigma^0_{\mathrm{had}} = \sigma_{\mathrm{Z}}(s = \overline{M}^2_{\mathrm{Z}})$
- Branching ratios:

  $R_q = \Gamma_q/\Gamma_{\mathrm{had}}$ ($q = b, c$, probes heavy quark generations)

  $R_\ell = \Gamma_{\mathrm{had}}/\Gamma_\ell$ ($\ell = e, \mu, \tau$)

Z-pole observables

Effective weak mixing angle:

Z-pole asymmetries:

$$A_{\mathrm{FB}}^f \equiv \frac{\sigma(\theta < \frac{\pi}{2}) - \sigma(\theta > \frac{\pi}{2})}{\sigma(\theta < \frac{\pi}{2}) + \sigma(\theta > \frac{\pi}{2})} = \frac{3}{4}\mathcal{A}_e \mathcal{A}_f$$

$$A_{\mathrm{LR}} \equiv \frac{\sigma(\mathcal{P}_e > 0) - \sigma(\mathcal{P}_e < 0)}{\sigma(\mathcal{P}_e > 0) + \sigma(\mathcal{P}_e < 0)} = \mathcal{A}_e$$

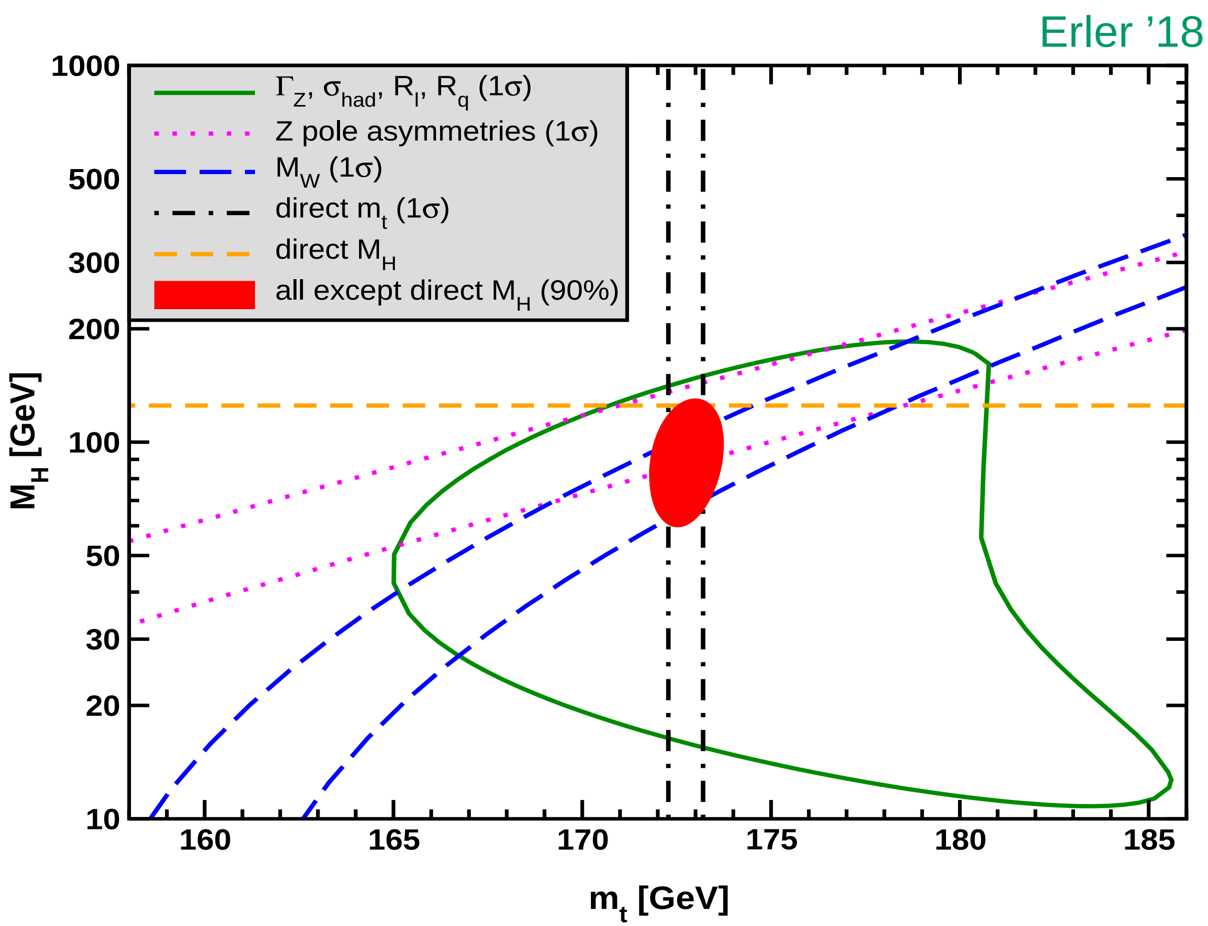
$$\mathcal{A}_f = 2\frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2} = \frac{1 - 4|Q_f|\sin^2\theta_{\mathrm{eff}}^f}{1 - 4|Q_f|\sin^2\theta_{\mathrm{eff}}^f + 8(|Q_f|\sin^2\theta_{\mathrm{eff}}^f)^2}$$

Most precisely measured for $f = \ell$ (also $f = b, c$)

Current status of electroweak precision tests

Standard Model after Higgs discovery:

- Good agreement between measured mass and indirect prediction
- Very good agreement over large number of observables



Direct measurements:

$M_H = 125.14 \pm 0.15$ GeV

$m_t = 172.74 \pm 0.46$ GeV

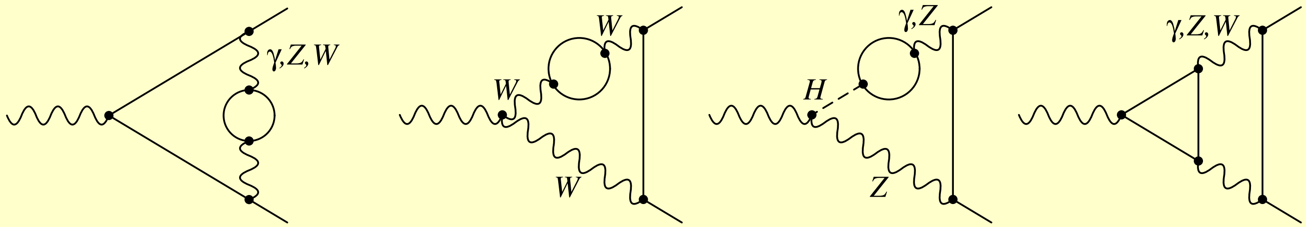
Indirect prediction:

$M_H = 90^{+17}_{-16}$ GeV

$m_t = 176.4 \pm 1.8$ GeV

Current status of SM loop results

Known corrections to Δr, $\sin^2\theta^f_{\rm eff}$, g_{Vf}, g_{Af}:



- Complete NNLO corrections

Freitas, Hollik, Walter, Weiglein '00
Awramik, Czakon '02; Onishchenko, Veretin '02
Awramik, Czakon, Freitas, Weiglein '04; Awramik, Czakon, Freitas '06
Hollik, Meier, Uccirati '05,07; Degrassi, Gambino, Giardino '14
Freitas '13,14; Dubovyk, Freitas, Gluza, Riemann, Usovitsch '16,18

- Partial 3/4-loop corrections to ρ/T-parameter
  $\mathcal{O}(\alpha_{\rm t}\alpha_{\rm s}^2)$, $\mathcal{O}(\alpha_{\rm t}^2\alpha_{\rm s})$, $\mathcal{O}(\alpha_{\rm t}\alpha_{\rm s}^3)$

  $(\alpha_{\rm t} \equiv \frac{y_{\rm t}^2}{4\pi})$

Chetyrkin, Kühn, Steinhauser '95
Faisst, Kühn, Seidensticker, Veretin '03
Boughezal, Tausk, v. d. Bij '05
Schröder, Steinhauser '05; Chetyrkin et al. '06
Boughezal, Czakon '06

Current uncertainties

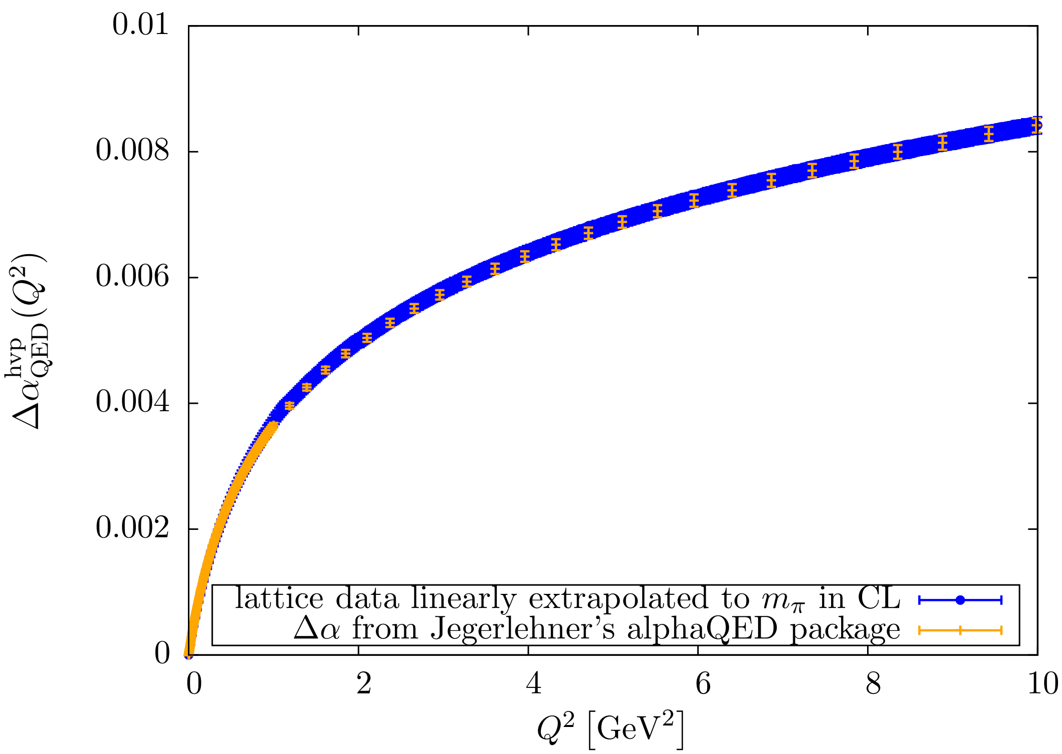
	Experiment	Theory error	Main source
M_W	80.385 ± 0.015 MeV	4 MeV	α^3, $\alpha^2\alpha_s$
Γ_Z	2495.2 ± 2.3 MeV	0.4 MeV	α^3, $\alpha^2\alpha_s$, $\alpha\alpha_s^2$
σ^0_{had}	41540 ± 37 pb	6 pb	α^3, $\alpha^2\alpha_s$
$R_b \equiv \Gamma^b_Z/\Gamma^{had}_Z$	0.21629 ± 0.00066	0.0001	α^3, $\alpha^2\alpha_s$
$\sin^2\theta^\ell_{eff}$	0.23153 ± 0.00016	4.5×10^{-5}	α^3, $\alpha^2\alpha_s$

- Theory error estimate is not well defined, ideally $\Delta_{th} \ll \Delta_{exp}$
- Common methods:
  - Count prefactors (α, N_c, N_f, ...)
  - Extrapolation of perturbative series
  - Renormalization scale dependence
  - Renormalization scheme dependence
- Also parametric error from external inputs (m_t, m_b, α_s, $\Delta\alpha_{had}$, ...)

Shift of finestructure constant

- $\Delta\alpha \equiv 1 - \frac{\alpha(0)}{\alpha(M_Z)} \approx 0.059 = 0.0315_{\text{lept}} + 0.0276_{\text{had}}$
- Hadronic effects from $e^+e^- \to$ had. data
- Last 5 years: new data from BaBar, VEPP, BES
- No significant improvement from including τ data
- Robust precision $\sim 10^{-4}$

Davier et al. '17; Jegerlehner '17
Keshavarzi, Nomura, Teubner '18



Burger, Jansen, Petschlies, Pientka '15

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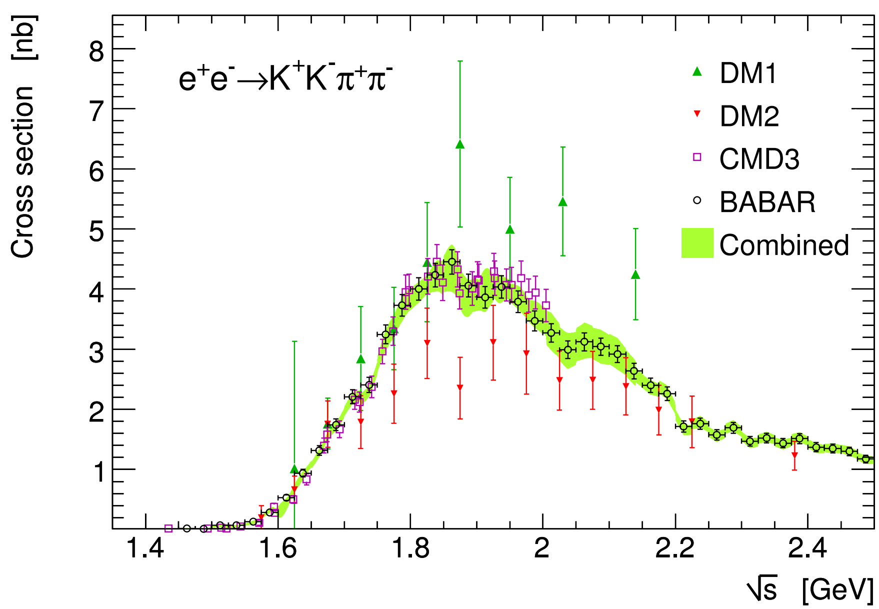
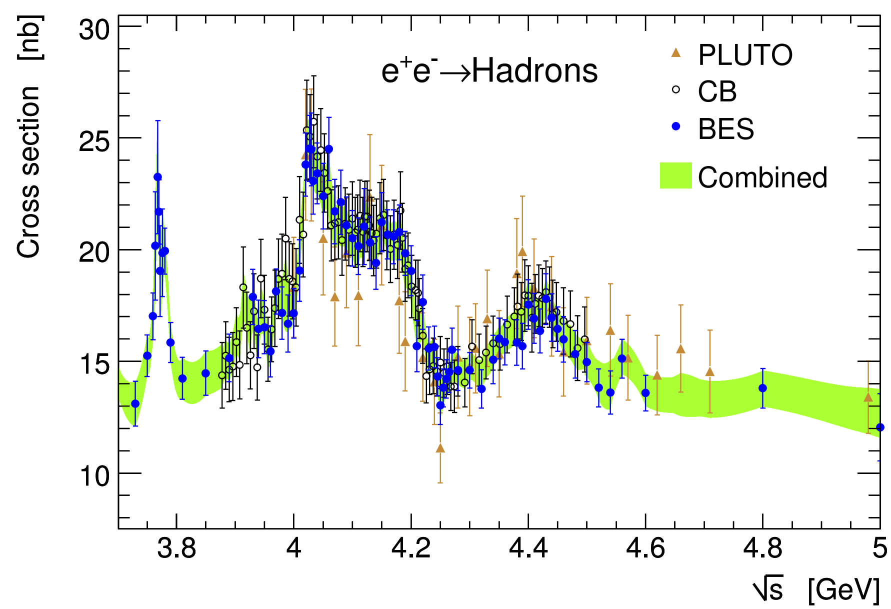


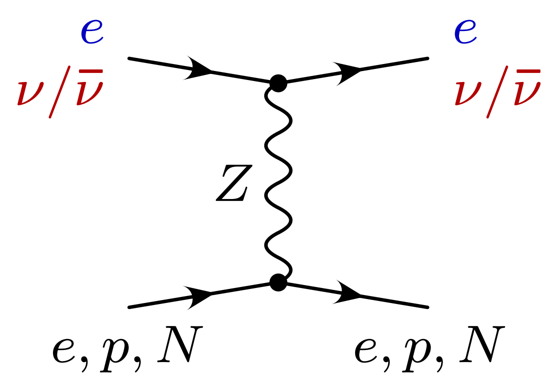


Davier et al. '17

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 $\sin^2\bar{\theta}(\mu)$



$$g^{ef}_{\text{AV}}\,[\bar{e}\gamma^\mu\gamma_5 e]\,[\bar{f}\gamma_\mu f]$$
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$$g^{ef}_{\text{AV}} = \tfrac{1}{2} - 2|Q_f|\sin^2\bar{\theta}(\mu)$$
$$g^{ef}_{\text{VA}} = \tfrac{1}{2} - 2\sin^2\bar{\theta}(\mu)$$

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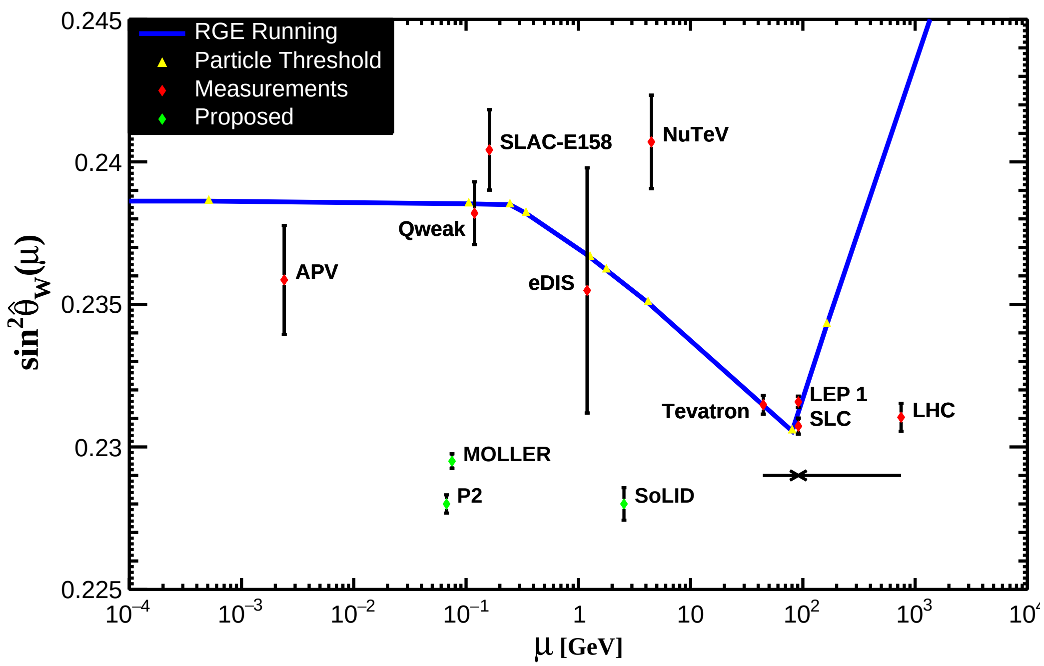
Erler, Ferro-Hernández '17



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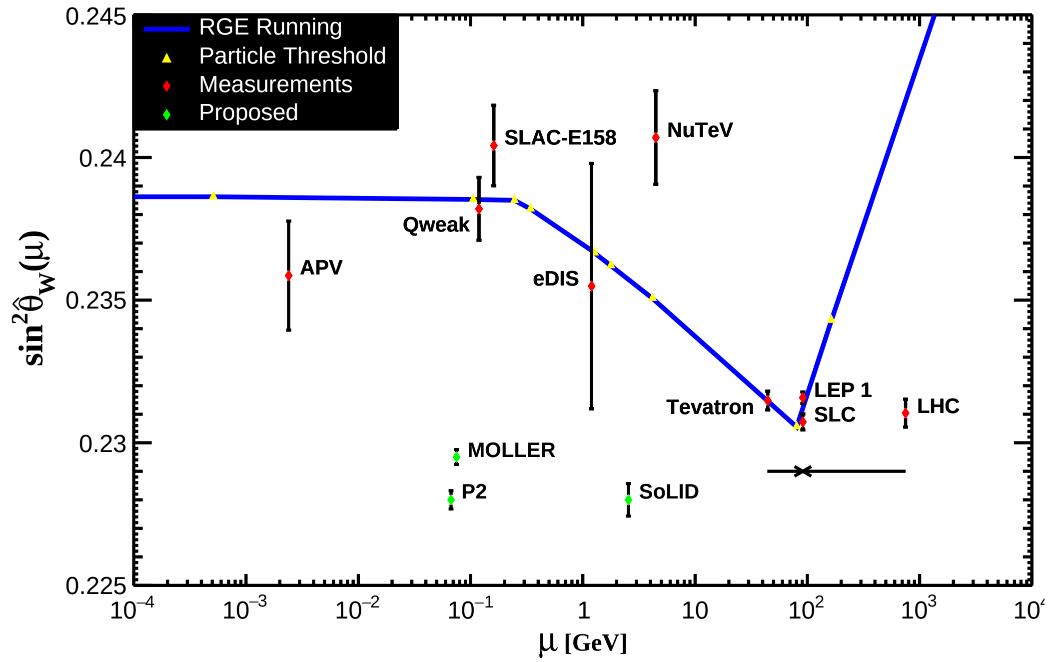
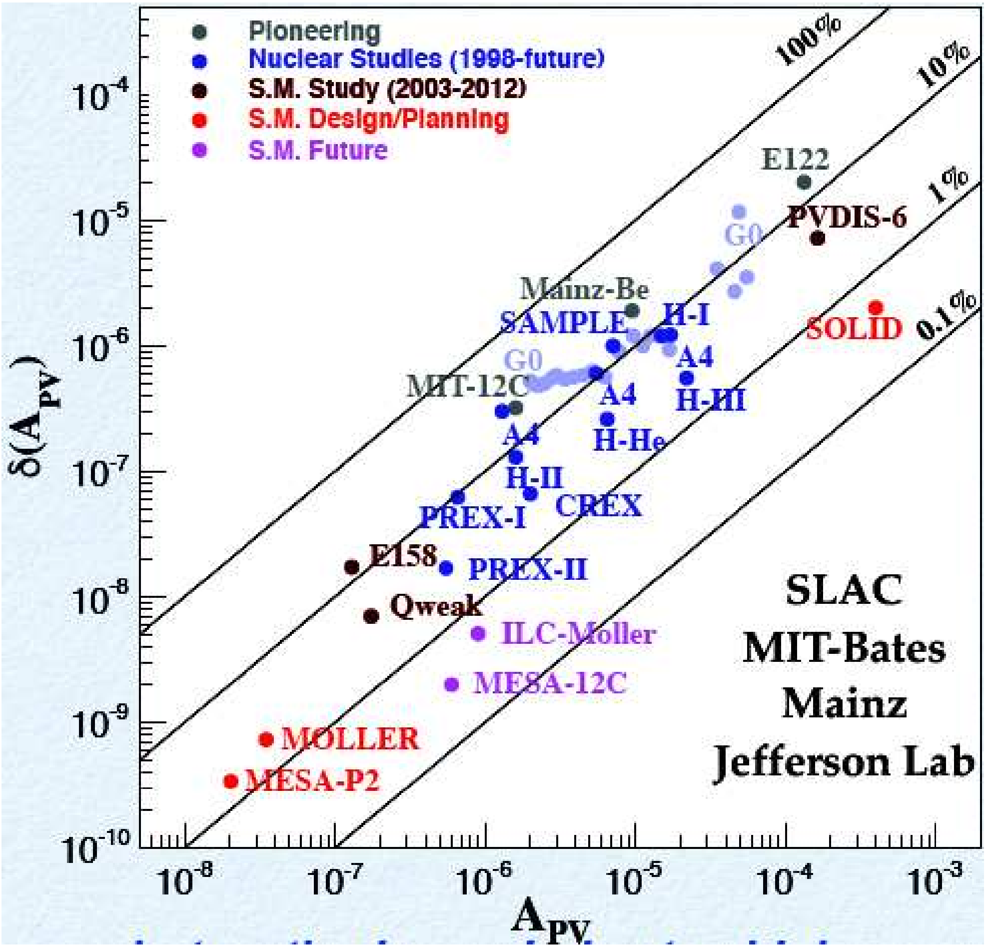
- Future experiments:

  MOLLER (ee), P2, SoLID (ep), Atomic PV in radium

Erler, Ferro-Hernández '17



Tecnical progress



MOLLER experiment at JLab:

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

$\delta_{\text{exp}} A_{\text{LR}} = 2.4\%$

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

Previous ee PV measurement (SLAC E158):

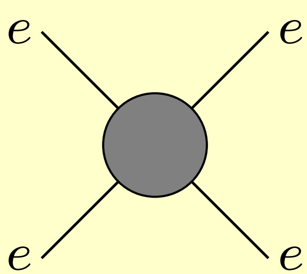
$\delta_{\text{exp}} A_{\text{LR}} = 14\%$

K. Kumar 'PVES 2018

Sensitivity to new physics scales

4-lepton operator

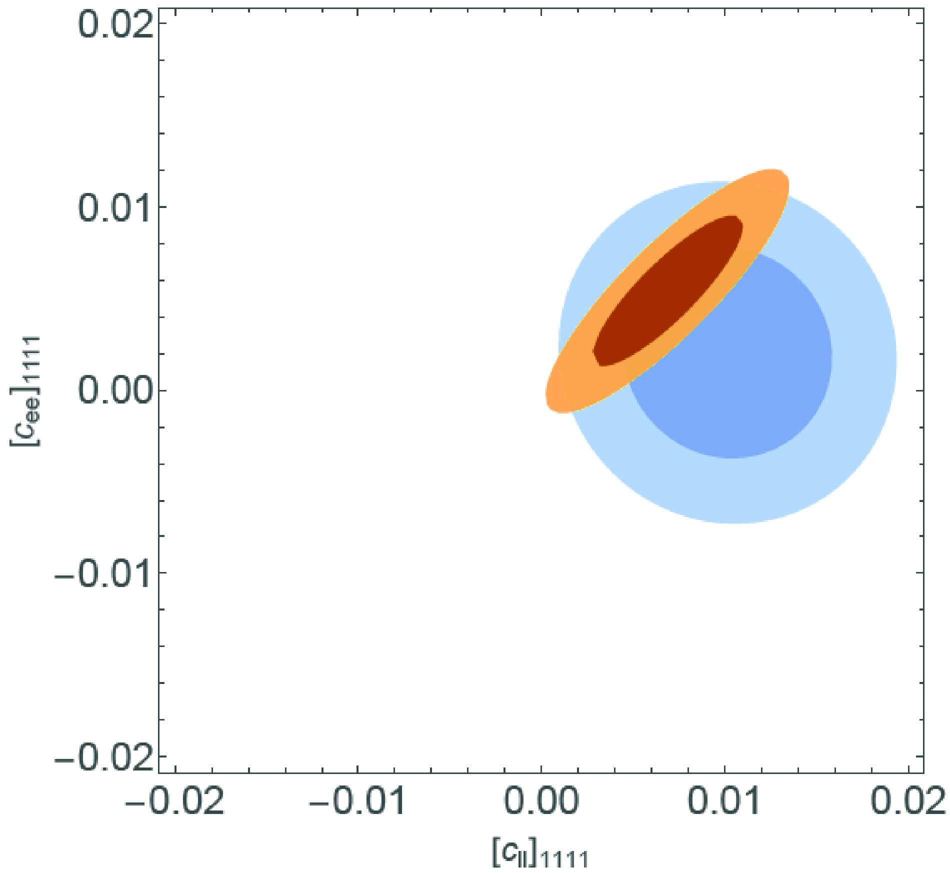
$$\frac{4\pi}{\Lambda^2}\,[\bar{e}\gamma^\mu\gamma_5 e]\,[\bar{e}\gamma_\mu e]$$



E158: $\Lambda \lesssim 17$ TeV

MOLLER: $\Lambda \lesssim 39$ TeV

Erler, Horowitz, Mantry, Souder '14



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

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

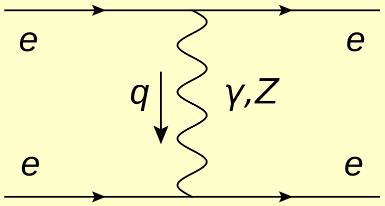
$$\frac{c_{\ell\ell}}{v^2}\,[\bar{e}\gamma^\mu P_L e]\,[\bar{e}\gamma_\mu P_L e]$$

Electroweak corrections to Møller scattering

- $e^- e^-$ PV scattering is very clean channel with minimal hardonic effects
- EW corrections to ee and ep scattering are similar (except box graphs)
- LR asymmetry:

$$A_{\rm LR} = \frac{\sigma_{\rm L} - \sigma_{\rm R}}{\sigma_{\rm L} + \sigma_{\rm R}} = \frac{G_\mu(-q^2)}{\sqrt{2}\pi\alpha} \frac{1-y}{1+y^4+(1-y)^4}(1 - 4\sin^2\theta_{\rm W})$$

$y \approx \frac{1}{2}\cos\theta$

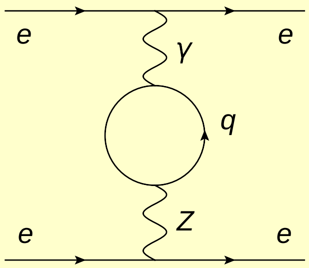


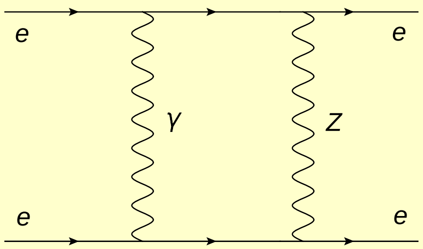
- One-loop correction $\delta_{1l} A_{\rm LR} \sim 40\%$
  $\delta_{1l} \sin^2\theta_{\rm W} \sim 3\%$

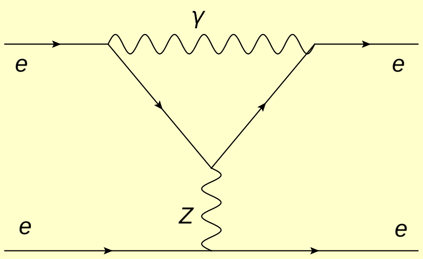
  Czarnecki, Marciano '96

- IR radiation cancels in $A_{\rm LR}$
  $\longrightarrow$ No real emission corrections

- MOLLER exp. target:
  $\delta_{\rm exp} \sin^2\theta_{\rm W} \sim 0.1\%$
  $\longrightarrow$ 2-loop corrections needed

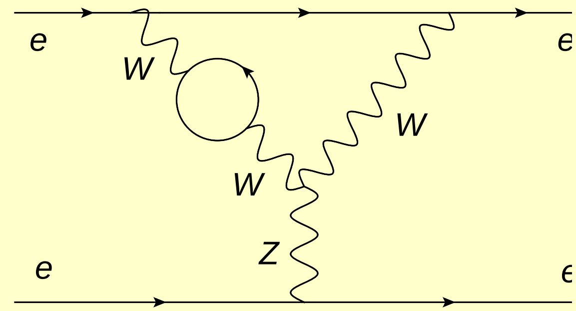




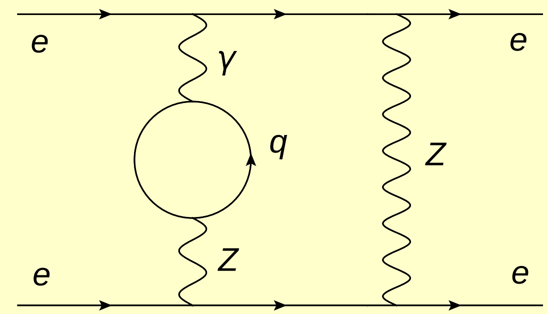


Electroweak corrections to Møller scattering

- As first step: EW 2-loop corrections with closed fermion loops
  $\longrightarrow$ Enhanced by N_f
  $\longrightarrow$ Experience from Z-pole EWPO:
  $\mathcal{O}(\alpha^2_{\mathrm{ferm}}) \,/\, \mathcal{O}(\alpha^2_{\mathrm{bos}}) \gtrsim 5$



- Computer tools to handle many diagrams and large expressions
  - Diagram generation
  - Lorentz and Dirac algebra
  - Integral simplication and expansion
  - Numerical integration of final set of loop functions



EW corrections to Møller scattering: Scales

- At Z pole: $s = M_Z^2 \sim M_W^2 \sim M_H^2 \sim m_t^2 \gg m_f^2 \quad (f \neq t)$
  $\longrightarrow$ Neglect all light fermion masses (except in $\Delta\alpha$)

- Low-energy ee scattering: $|q^2| \sim m_f^2 \ll M_{weak}^2$
  $\longrightarrow$ Expansion in large M_{weak}^2

- Techical realization: expansion by regions — Beneke, Smirnov '97
  $\longrightarrow$ Expansion in integrand, different categories for loop momenta $k_{1,2}$
  $\longrightarrow$ Here only soft+hard regions needed:

  hard–hard: $|k_1| \sim |k_2| \sim M_{weak} \gg Q, m_f \qquad Q = \sqrt{|q^2|}$
  soft–soft: $|k_1| \sim |k_2| \sim Q, m_f \ll M_{weak}$
  soft–hard: $|k_1| \sim Q, m_f \ll |k_2| \sim M_{weak}$ (and permutations)

- Coefficients are simpler integrals:
  hard–hard: 2-loop vacuum
  soft–hard: (1-loop) $\times$ (1-loop)
  soft–soft: 2-loop with fewer masses

- Form of one-loop result: Czarnecki, Marciano '96

$$A_{\rm LR} = \frac{\rho G_\mu q^2}{\sqrt{\pi}\alpha} \frac{-1+y}{1+y^4+(1-y)^4} \Big[1 - 4\kappa(q^2)\,\hat{s}^2(M_{\rm Z}^2) + \text{boxes, QED}\Big]$$

- G_μ absorbs dependence on $\Delta\alpha$

- Corrections to G_μ known at 2-loop — Freitas, Hollik, Walter, Weiglein '00; Awramik, Czakon '02; Onishchenko, Veretin '02

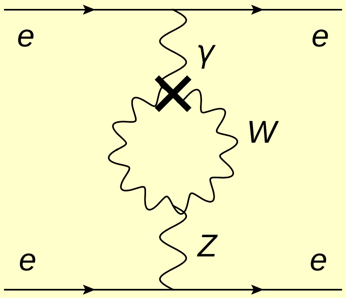
- $\hat{s}^2(M_{\rm Z}^2) \equiv \sin^2\theta_{\rm W}^{\overline{\rm MS}}\big|_{\mu^2=M_{\rm Z}^2}$ numerically close to $\sin^2\theta_{\rm eff}^f$

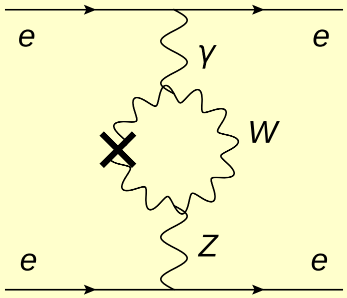
  $\longrightarrow$ Connection to Z-pole EWPOs

- ρ contains remaining renormalization (Z mass)

EW corrections to Møller scattering: Renormalization

- At 2-loop level: need sub-loop renormalization
- Dependence $\Delta\alpha$ re-enters
- Also need renormalization of M_W, but since $\hat{s}^2$ is used as input, M_W is computed from $\hat{s}^2$ and M_Z



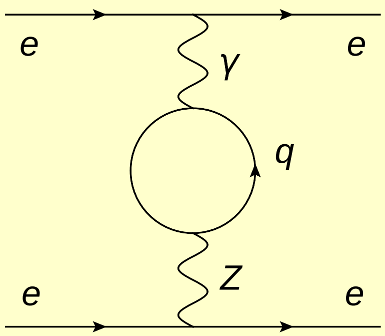


EW corrections to Møller scattering: Hadronic effects

$$A_{\mathrm{LR}} = \frac{\rho G_\mu q^2}{\sqrt{\pi}\alpha} \frac{-1+y}{1+y^4+(1-y)^4}\left[1 - 4\kappa(q^2)\,\hat{s}^2(M_Z^2) + \text{boxes, QED} + \ldots\right]$$

- $\kappa(q^2)$ contains effect of γ–Z self-energy
- $\kappa(q^2) - \kappa(0)$ is small
- At 1-loop: $\kappa(0) = 1 - \frac{\alpha}{6\pi s^2}\Delta_{\gamma Z} + \text{bosonic}$,

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

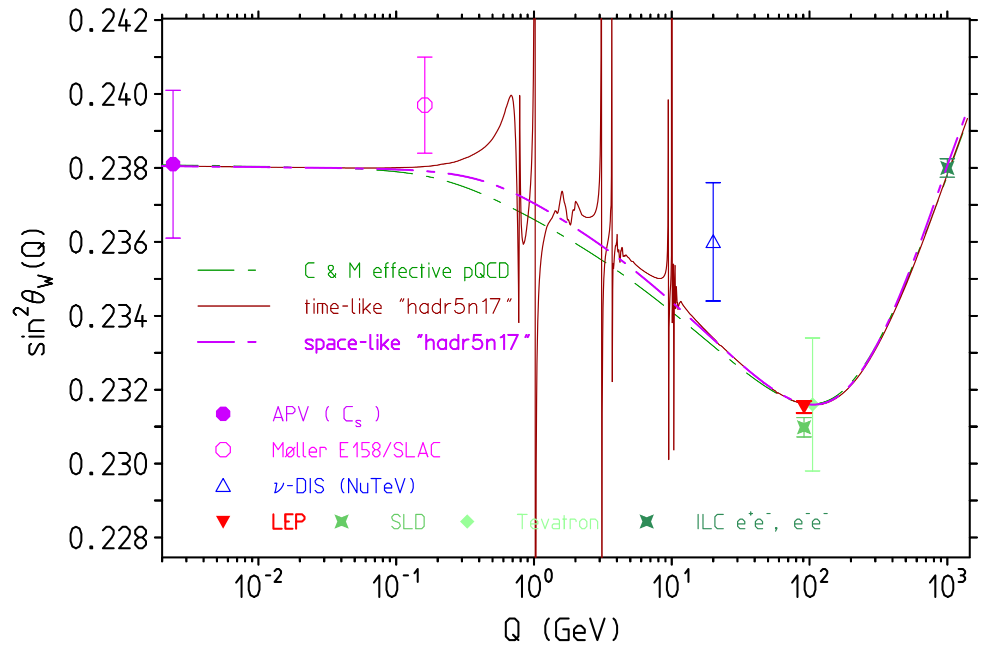


- Sensitivity to m_q: non-perturbative hadron physics
- $\Delta_{\gamma Z}$ described running of $\hat{s}^2(\mu^2)$ from $\mu = M_Z$ to 0

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



EW corrections to Møller scattering: Hadronic effects

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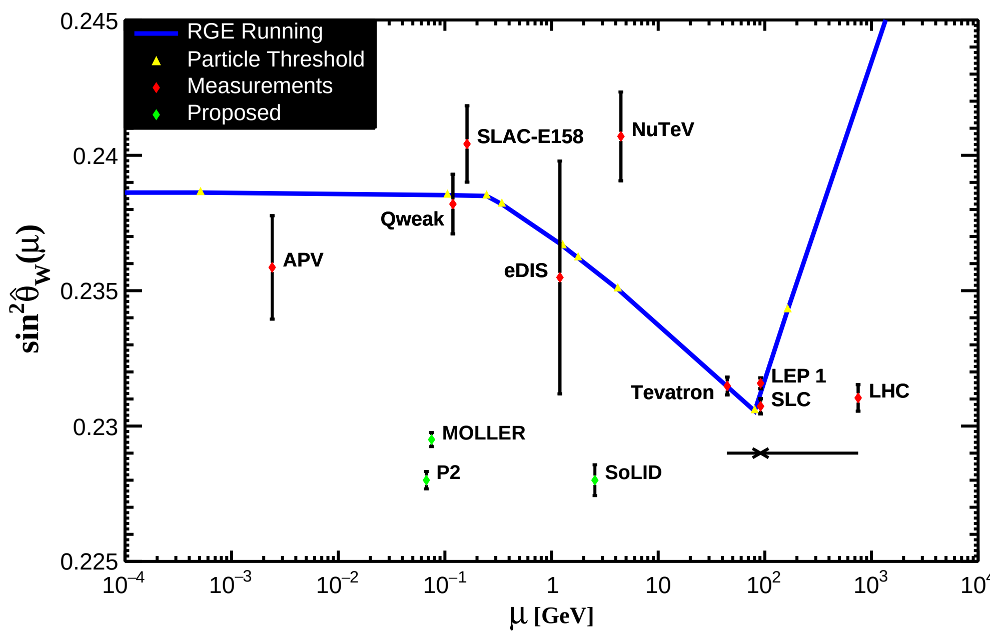
Wetzel '81; Marciano, Sirlin '84
Jegerlehner '86,17

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



EW corrections to Møller scattering: Hadronic effects

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

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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 between thresholds

Erler, Ramsey-Musolf '04
Erler, Ferro-Hernández '17

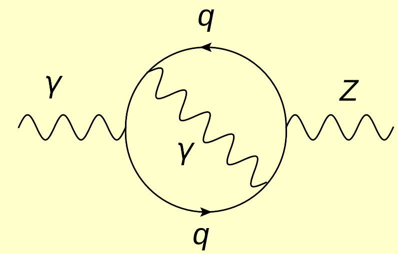
c) Lattice QCD

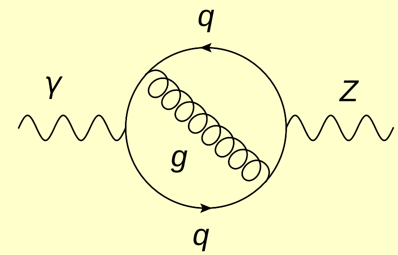
Ottnad 'PVES 2018

EW corrections to Møller scattering: Hadronic effects

Two-loop contributions to γ–Z self-energy:

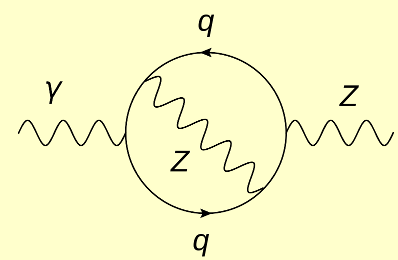
- Quark loops with photon or gluon
  $\longrightarrow$ Already contained in hadronic $\Delta_{\gamma Z}$





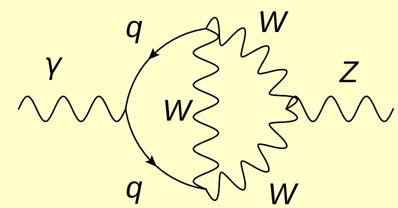
- Quark loops with W/Z boson

- In $\gamma\gamma$ SE:
  $\longrightarrow$ For $\Delta\alpha$ (γ–γ SE) limit $m_q \to 0$ is safe
  due to QED Ward id.



- In γZ SE:
  $\longrightarrow$ Sensitive to low-energy hadron physics

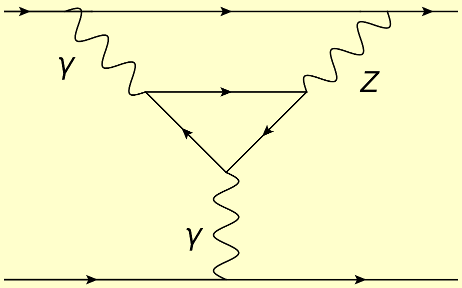
  Perform expansion by regions
  $\longrightarrow$ Factorization into $\Delta_{\gamma Z}^{1-\text{loop}} \times W/Z$-loop
  (except for terms $\propto m_\text{t}^2 \log m_\text{b}^2$)



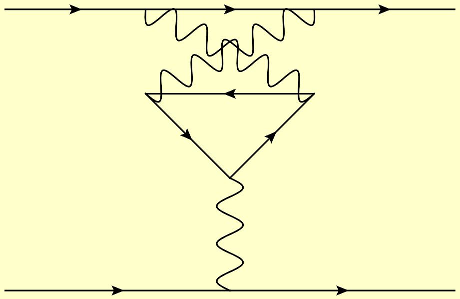
γ_5 and mass regulators

- Vertex diagrams with sub-loop triangles are sensitive to γ_5 problem

- DREG with naively anti-commuting γ_5:
  $\text{Tr}\{\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma_5\} = 0$



- Contributions $\propto \text{Tr}\{\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma_5\}$ are UV finite
  $\longrightarrow$ DREG not needed



- IR singularities from photon propagators
  (in individual diagrams, cancel in sum)
  $\longrightarrow$ Use mass regulator ($m_\gamma \neq 0$) in $D = 4$

Summary

- Sensitivity for Z-pole EWPOs and future low-energy EWPOs requires 2-loop SM corrections

- No fully automated procedure for 2-loop calculations
  $\longrightarrow$ Each process requires new work
  $\longrightarrow$ Combination of analytic and numerical methods
  $\longrightarrow$ Interesting subtleties around definition of input quantities & renormalization

- Evaluation of different methods for including hadronic effects?

$\longrightarrow$ Work is in progress and useful pheno results in few months

Backup slides

Parametrization of new physics

Effective field theory: $\mathcal{L} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}(\Lambda^{-3})$ $(\Lambda \gg M_Z)$

$\mathcal{O}_{\phi 1} = (D_\mu \Phi)^\dagger \Phi\, \Phi^\dagger (D^\mu \Phi)$ $\alpha \Delta T = -\frac{v^2}{2}\frac{c_{\phi 1}}{\Lambda^2}$

$\mathcal{O}_{\rm BW} = \Phi^\dagger B_{\mu\nu} W^{\mu\nu} \Phi$ $\alpha \Delta S = -e^2 v^2 \frac{c_{\rm BW}}{\Lambda^2}$

$O_{\rm LL}^{(3)e} = (\bar{L}^e_{\rm L} \sigma^a \gamma_\mu L^e_{\rm L})(\bar{L}^e_{\rm L} \sigma^a \gamma^\mu L^e_{\rm L})$ $\Delta G_F = -\sqrt{2}\frac{c_{\rm LL}^{(3)e}}{\Lambda^2}$

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

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

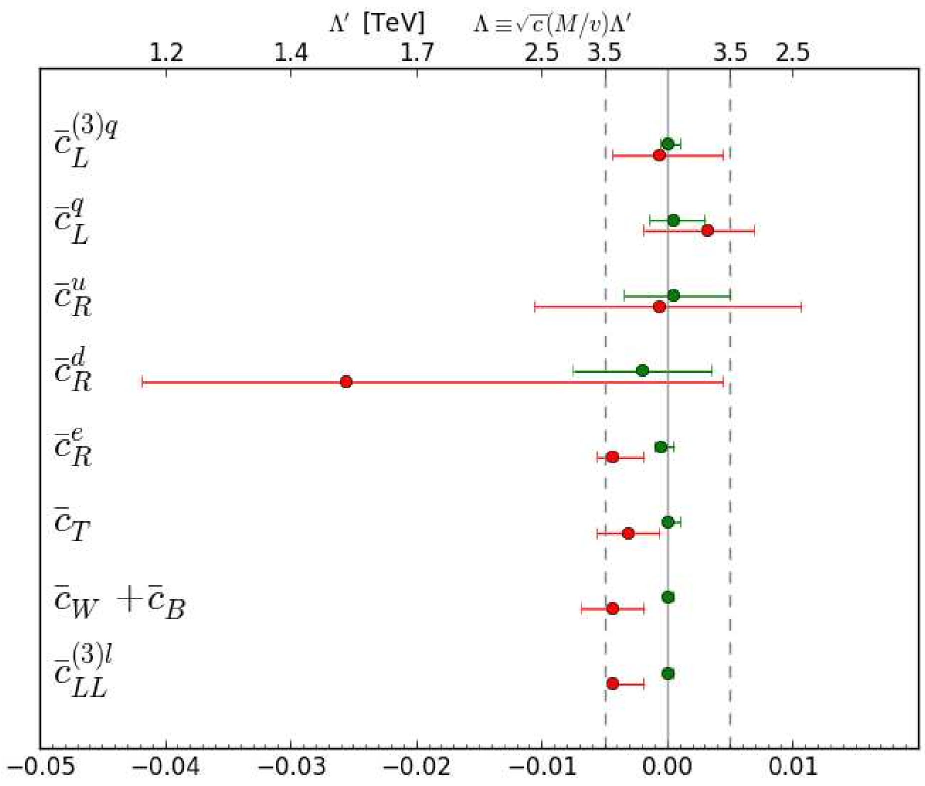
$O_{\rm L}^{(3)F} = i(\Phi^\dagger \overleftrightarrow{D}^a_\mu \Phi)(\bar{F}_{\rm L} \sigma_a \gamma^\mu F_{\rm L})$

More operators than EWPOs

$\longrightarrow$ Some can be constrained by $W \to \ell\nu$, had., $e^+e^- \to W^+W^-$

Current constraints on some dim-6 operators

Assuming flavor universality:



Significant correlation/ degeneracy between different operators

Pomaral, Riva ’13
Ellis, Sanz, You ’14

Renormalization scheme dependence

Use of $\overline{\text{MS}}$ renormalization for m_t reduces h.o. QCD corrections of $\mathcal{O}(\alpha_\text{t}\alpha_\text{s}^n)$:

loops $(n+1)$	$\Delta\rho^{\overline{\text{MS}}}_{(n)} \Big/ \left(\frac{3G_F\overline{m}_\text{t}^2}{8\sqrt{2}\pi^2}\right)$	$\Delta\rho^{\text{OS}}_{(n)} \Big/ \left(\frac{3G_F m_\text{t}^2}{8\sqrt{2}\pi^2}\right)$	
2	$-0.193\left(\frac{\alpha_\text{s}}{\pi}\right)$	$-3.970\left(\frac{\alpha_\text{s}}{\pi}\right)$	Djouadi, Verzegnassi '87 Kniehl '90
3	$-2.860\left(\frac{\alpha_\text{s}}{\pi}\right)^2$	$-14.59\left(\frac{\alpha_\text{s}}{\pi}\right)^2$	Avdeev, Fleischer, et al. '94 Chetyrkin, Kühn, Steinhauser '95
4	$-1.680\left(\frac{\alpha_\text{s}}{\pi}\right)^3$	$-93.15\left(\frac{\alpha_\text{s}}{\pi}\right)^3$	Schröder, Steinhauser '05 Chetyrkin, Faisst, Kühn, et al. '06 Boughezal, Czakon '06

No clear pattern of this kind known for $\mathcal{O}(\alpha^n)$

$\longrightarrow$ Only few results available that allow direct comparison

e.g. Faisst, Kühn, Seidensticker, Veretin '03