Title: Multi-loop calculations in electroweak physics

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Abstract:

Precision calculations in electroweak physics

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PI Workshop "Radiative Corrections at the Intensity Frontier of Particle Physics"
12–14 June 2017

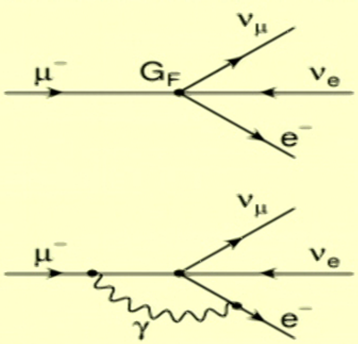
1. Z and W boson physics
2. Future projections
3. Low-energy electroweak observables
4. Muon anomalous magnetic moment

You can shoot a goal from behind with enough precision

Z and W boson physics

W mass

μ decay in Fermi Model

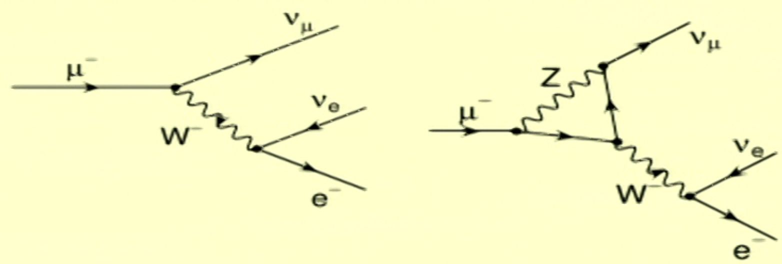


← QED corr. (2-loop)

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

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

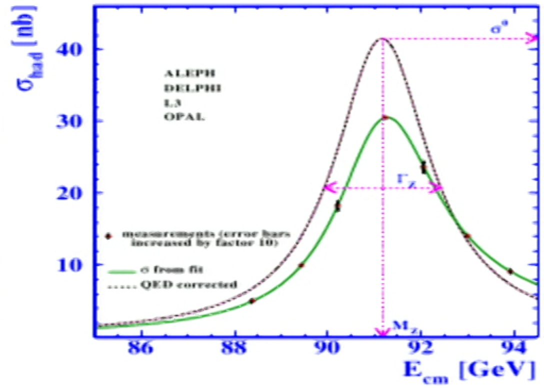
Z-pole observables

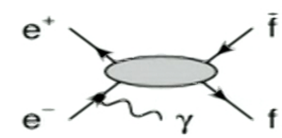
- Deconvolution of initial-state QED radiation:

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

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





Z-pole observables

- Deconvolution of initial-state QED radiation:

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

- 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:

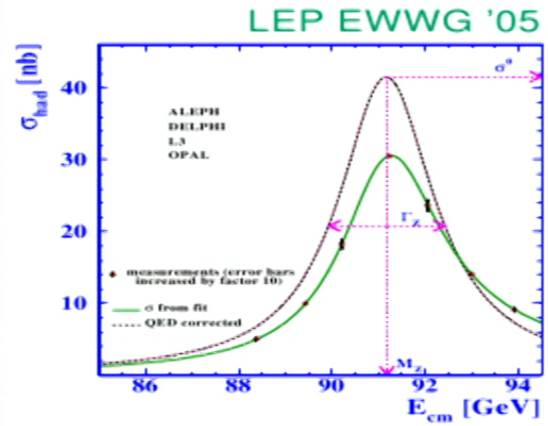
$$\sigma_{\text{Z}} = \frac{R}{(s-\overline{M}_{\text{Z}}^2)^2 + \overline{M}_{\text{Z}}^2\overline{\Gamma}_{\text{Z}}^2} + \sigma_{\text{non-res}}$$

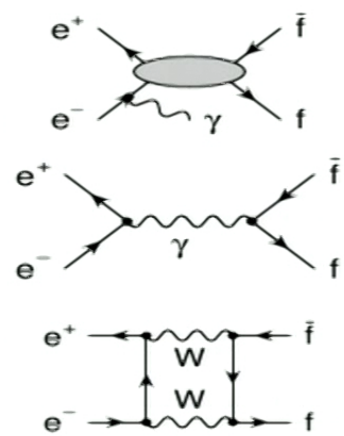
- In experimental analyses:

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

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

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





Z-pole observables

Effective weak mixing angle:

Z-pole asymmetries:

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

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

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

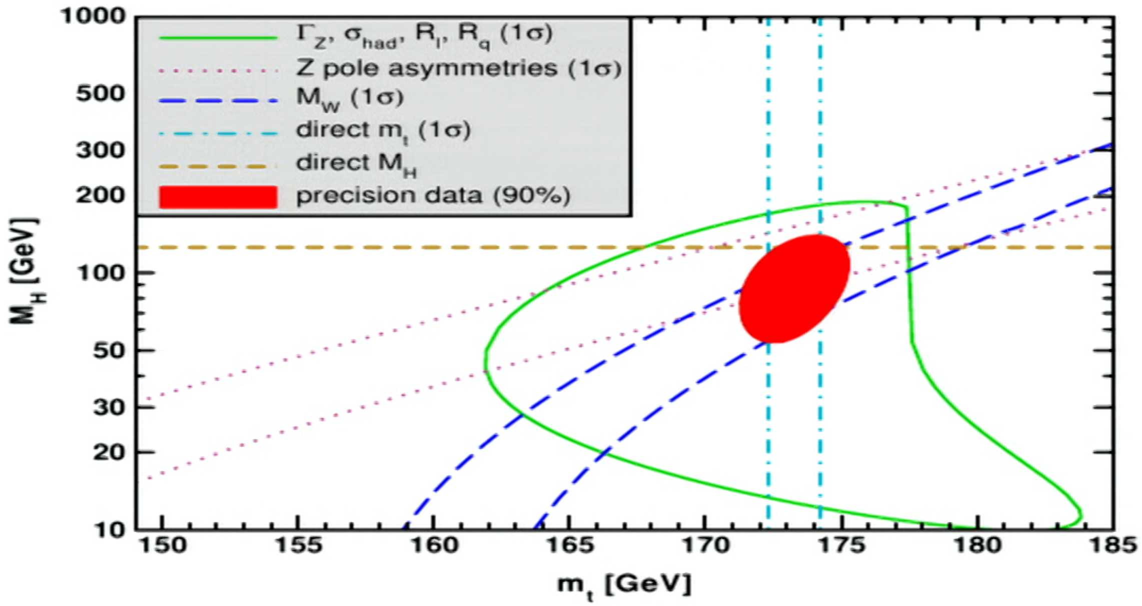
Most precisely measured for $f = \ell$ (also $f = b, c$)

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

Erler '13



Direct measurements:

$M_H = 125.6 \pm 0.4$ GeV

$m_t = 173.24 \pm 0.95$ GeV

Indirect prediction:

$M_H = 123.7 \pm 2.3$ GeV (with LHC BRs)

$M_H = 89^{+22}_{-18}$ GeV (w/o LHC data)

$m_t = 177.0 \pm 2.1$ GeV

Parametrization of new physics

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

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

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

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

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

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

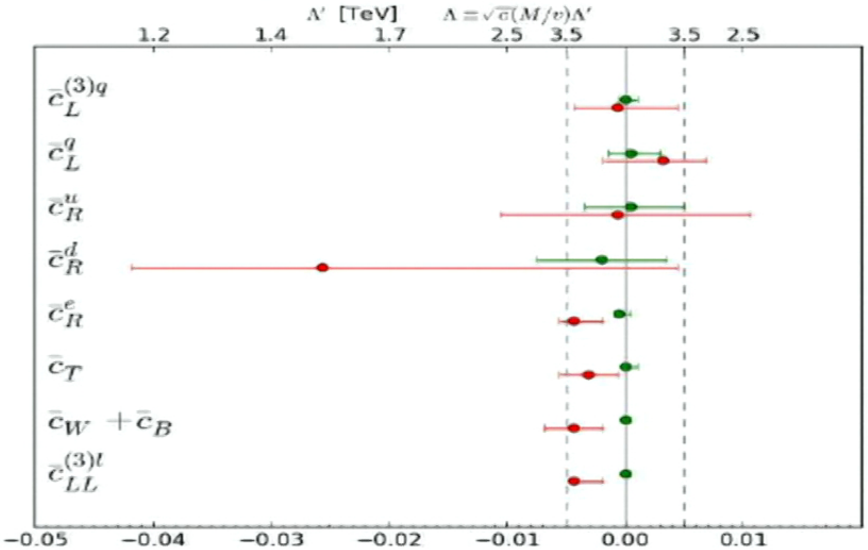
$$O_{\mathsf{L}}^{(3)F} = i(\Phi^\dagger \overleftrightarrow{D}_\mu^a \Phi)(\bar{F}_{\mathsf{L}} \sigma_a \gamma^\mu F_{\mathsf{L}})$$

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:

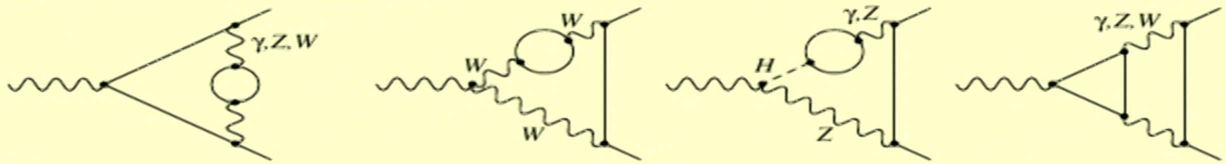


Significant correlation/ degeneracy between different operators

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

Current status of SM loop results

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



- Complete NNLO corrections (Δr, $\sin^2\theta^\ell_{\rm eff}$) 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
- "Fermionic" NNLO corrections (g_{Vf}, g_{Af}) Czarnecki, Kühn '96
  Harlander, Seidensticker, Steinhauser '98
  Freitas '13,14
- Partial 3/4-loop corrections to ρ/T-parameter
  $\mathcal{O}(\alpha_t\alpha_s^2)$, $\mathcal{O}(\alpha_t^2\alpha_s)$, $\mathcal{O}(\alpha_t\alpha_s^3)$ 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

$(\alpha_t \equiv \frac{y_t^2}{4\pi})$

Current uncertainties

	Experiment	Theory error	Main source
M_W	80.385 ± 0.015 MeV	4 MeV	α^3, $\alpha^2\alpha_\mathrm{s}$
Γ_Z	2495.2 ± 2.3 MeV	0.5 MeV	α^2_bos, α^3, $\alpha^2\alpha_\mathrm{s}$, $\alpha\alpha^2_\mathrm{s}$
σ^0_had	41540 ± 37 pb	6 pb	α^2_bos, α^3, $\alpha^2\alpha_\mathrm{s}$
$R_b \equiv \Gamma^b_\mathrm{Z}/\Gamma^\mathrm{had}_\mathrm{Z}$	0.21629 ± 0.00066	0.00015	α^2_bos, α^3, $\alpha^2\alpha_\mathrm{s}$
$\sin^2\theta^\ell_\mathrm{eff}$	0.23153 ± 0.00016	4.5×10^{-5}	α^3, $\alpha^2\alpha_\mathrm{s}$

- Theory error estimate is not well defined, ideally $\Delta_\mathrm{th} \ll \Delta_\mathrm{exp}$
- 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, $\Delta\alpha_\mathrm{had}$, ...)

Renormalization scheme dependence

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

loops $(n+1)$	$\Delta\rho^{\overline{\text{MS}}}_{(n)} \Big/ \left(\frac{3G_F \overline{m}_t^2}{8\sqrt{2}\pi^2}\right)$	$\Delta\rho^{\text{OS}}_{(n)} \Big/ \left(\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\right)$	
2	$-0.193 \left(\frac{\alpha_s}{\pi}\right)$	$-3.970 \left(\frac{\alpha_s}{\pi}\right)$	Djouadi, Verzegnassi '87 Kniehl '90
3	$-2.860 \left(\frac{\alpha_s}{\pi}\right)^2$	$-14.59 \left(\frac{\alpha_s}{\pi}\right)^2$	Avdeev, Fleischer, et al. '94 Chetyrkin, Kühn, Steinhauser '95
4	$-1.680 \left(\frac{\alpha_s}{\pi}\right)^3$	$-93.15 \left(\frac{\alpha_s}{\pi}\right)^3$	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

SM input parameters

- m_t: < 1 GeV precision challenging at hardon colliders — Erler '14
  (b-jet energy scale, hadronization, color reconnection, MC generator, ...)
- M_W: Currently $\delta M_W = 15$ MeV
  Ultimate LHC goal $\delta M_W \sim 5 \ldots 8$ MeV ?
- α_s:
  Most precise determination using Lattice QCD from υ spectroscopy:
  $\alpha_s = 0.1184 \pm 0.0006$ — HPQCD '10
  But e^+e^- event shapes and DIS prefer $\alpha_s \sim 0.114$
  Alekhin, Blümlein, Moch '12; Abbate et al. '11; Gehrmann et al. '13
- $\Delta\alpha_{had}$: Current: $\delta(\Delta\alpha_{had}) \sim 10^{-4}$
  Improvement to $\delta(\Delta\alpha_{had}) \sim 5 \times 10^{-5}$ likely (BES III, Belle II)

Future projections

ILC: High-energy e^+e^- linear collider, running at $\sqrt{s} \approx M_Z$ with 30 fb^{-1}

CEPC: Circular e^+e^- collider, running at $\sqrt{s} \approx M_Z$ with 2×150 fb^{-1}

FCC-ee: Circular e^+e^- collider, running at $\sqrt{s} \approx M_Z$ with $2 \times (> 10)$ ab^{-1}

	Current exp.	ILC	CEPC	FCC-ee	Current perturb.
M_W [MeV]	15	3–4	3	1	4
Γ_Z [MeV]	2.3	0.8	0.5	0.1	0.5
R_b [10^{-5}]	66	14	17	6	15
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	16	1	2.3	0.6	4.5

$\longrightarrow$ Existing theoretical calculations adequate for LEP/SLC/LHC, but not ILC/CEPC/FCC-ee!

Theory and parametric uncertainties

	ILC	FCC-ee	perturb. error with 3-loop†	Param. error ILC*	Param. error FCC-ee**
M_{W} [MeV]	3–5	~ 1	1	2.6	1
Γ_Z [MeV]	~ 1	~ 0.1	$\lesssim 0.2$	0.5	0.06
R_b [10^{-5}]	15	$\lesssim 5$	5–10	< 1	< 1
$\sin^2\theta^{\ell}_{\mathrm{eff}}$ [10^{-5}]	1.3	0.6	1.5	2	2

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_{\mathrm{s}}^2)$, $\mathcal{O}(N_f\alpha^2\alpha_{\mathrm{s}})$, $\mathcal{O}(N_f^2\alpha^2\alpha_{\mathrm{s}})$

(N_f^n = at least n closed fermion loops)

Parametric inputs:

* **ILC:** $\delta m_t = 50$ MeV, $\delta\alpha_{\mathrm{s}} = 0.001$, $\delta M_{\mathrm{Z}} = 2.1$ MeV

****FCC-ee:** $\delta m_t = 50$ MeV, $\delta\alpha_{\mathrm{s}} = 0.0001$, $\delta M_{\mathrm{Z}} = 0.1$ MeV

also: $\delta(\Delta\alpha) \sim 5 \times 10^{-5}$

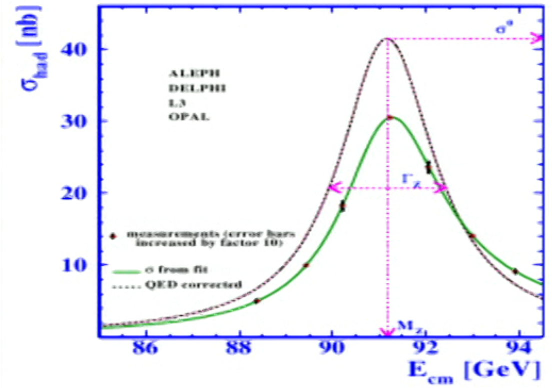
Theory uncertainties in extraction of pseudo-observables 16/27

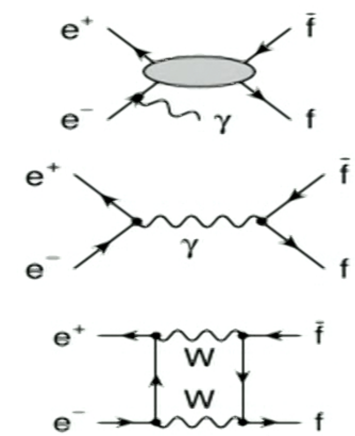
- Subtraction of QED radiation contributions
  - → Known to $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha^3 L^3)$ for **ISR**, $\mathcal{O}(\alpha^2)$ for **FSR** and $\mathcal{O}(\alpha^2 L^2)$ for $\mathbf{A_{FB}}$

    $(L = \log \frac{s}{m_e^2})$ Berends, Burgers, v.Neerven '88
    Kniehl, Krawczyk, Kühn, Stuart '88
    Beenakker, Berends, v.Neerven '89
    Skrzypek '92; Montagna, Nicrosini, Piccinini '97
  - → $\mathcal{O}(0.1\%)$ uncertainty on σ_Z, A_{FB}
  - → Improvement needed for ILC/CEPC/FCC-ee
- Subtaction of non-resonant γ-exchange, γ–Z interf., box contributions, Bhabha scattering

  see, e.g., Bardin, Grünewald, Passarino '99
  - → $\mathcal{O}(0.01\%)$ uncertainty within SM (improvements may be needed)
  - → Sensitivity to some NP beyond EWPO

LEP EWWG '05

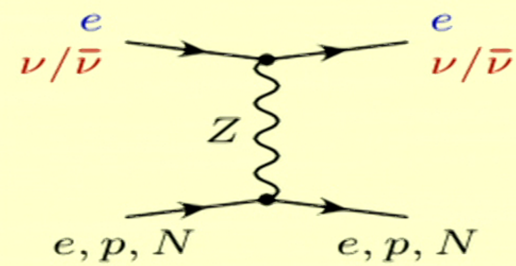




Low-energy electroweak observables

- Polarized ee, ep, ed scattering ($Q_W(e)$, $Q_W(p)$, eDIS)
  E158 '05; Qweak '13; 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 $\sin^2\bar{\theta}(\mu)$



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

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

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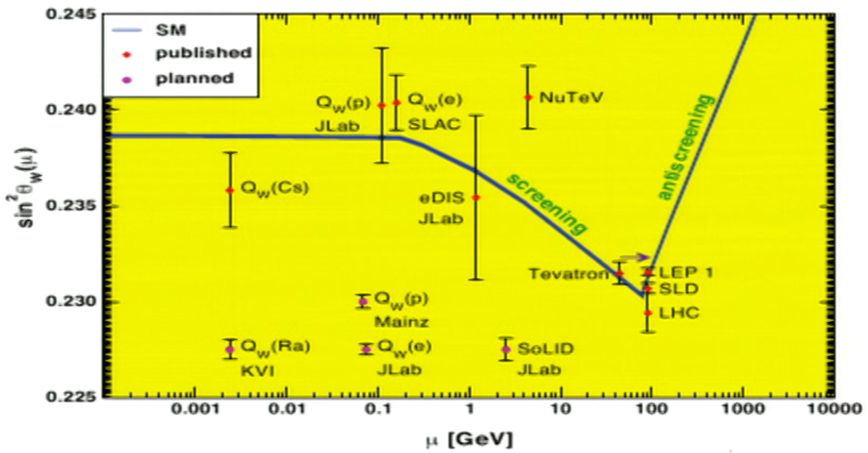
Erler '14



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- Atomic parity violation ($Q_W(^{133}$Cs$)$) Wood et al. '97
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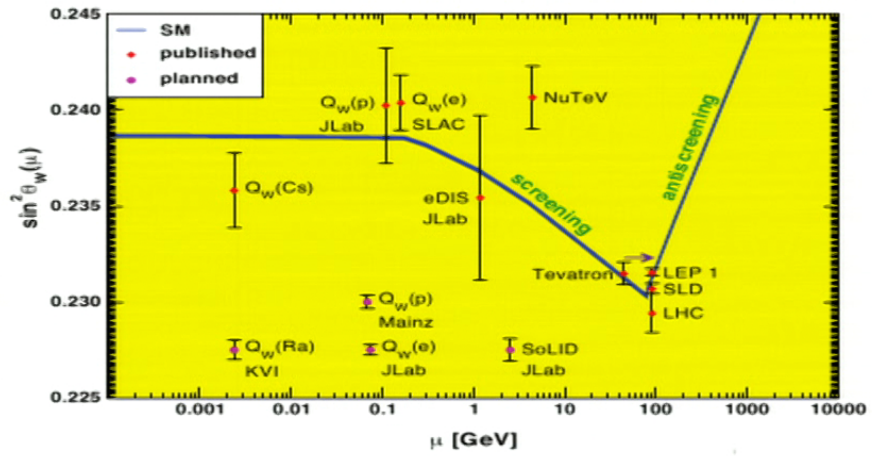
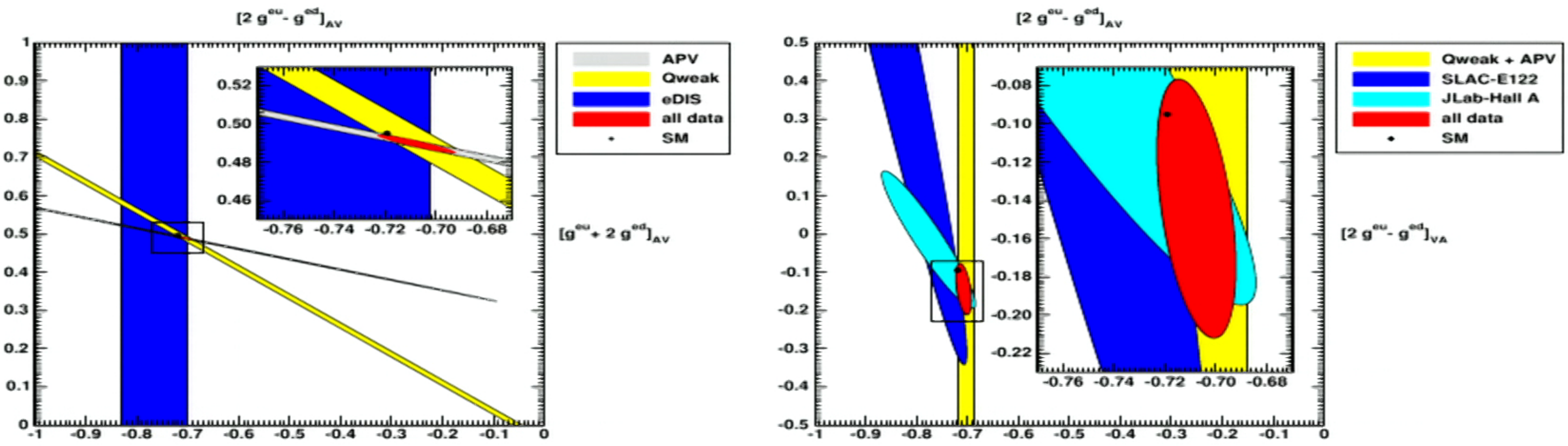
- Future experiments:
  MOLLER (ee), P2, SoLID (ep), Atomic PV in radium

Erler '14



Independent contact interactions



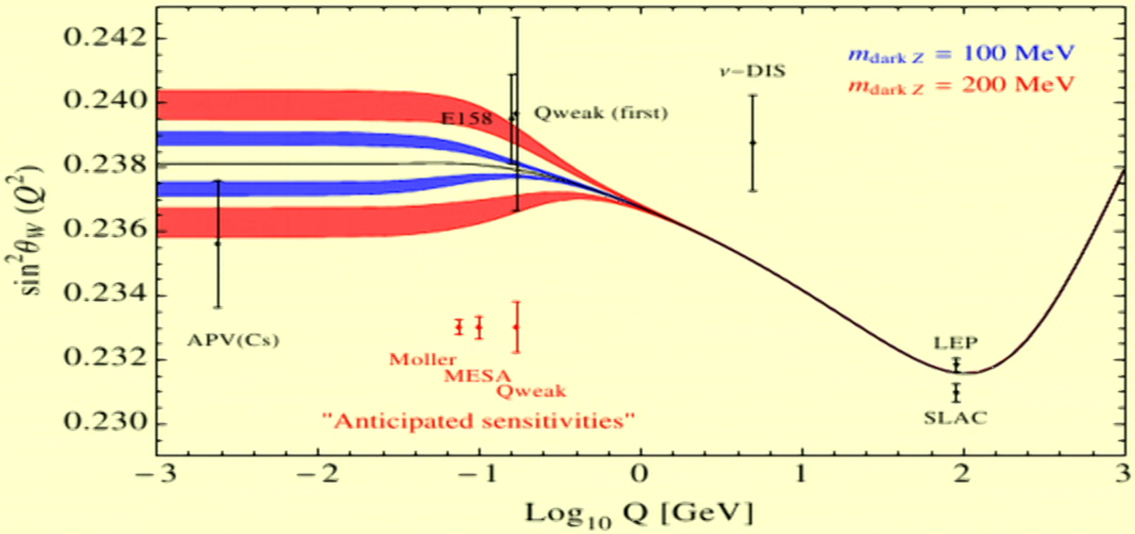
Erler, Horowitz, Mantry, Souder '14

Dark "photon"

New neutral gauge boson with mass $\mathcal{O}(100\text{ MeV})$, which mixes with photon

$\longrightarrow$ Can explain $g_\mu - 2$ discrepancy

$\longrightarrow$ Low-energy precision experiments have highest sensitivity



Davoudiasl, Lee, Marciano '14

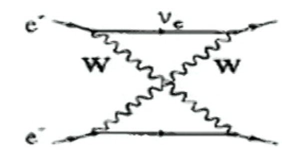
- **Other physics cases?**

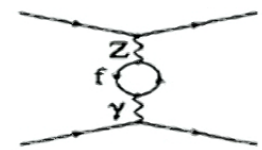
Theory status for low-energy A_{PV}

Electroweak one-loop corrections: Czarnecki, Marciano '96

Large correction to $A_{\mathrm{PV}} = \frac{d\sigma_{\mathrm{L}} - d\sigma_{\mathrm{R}}}{d\sigma_{\mathrm{L}} + d\sigma_{\mathrm{R}}}$:

$\sim 40\%$ for $\sin^2\bar{\theta}(M_Z)$,
$\sim 10\%$ for $\sin^2\bar{\theta}(0)$)





- Tree-level contribution supressed by $1 - 4\sin^2\bar{\theta}(0) \sim 0.045$
- Running $\sin^2\bar{\theta}(M_Z) \to \sin^2\bar{\theta}(0)$:
  Corrections $\sim \ln m_f^2/M_Z^2$
  $\to \sin^2\bar{\theta}(\mu)$ shifted by $\sim 3\%$
- Quark contribution determined by fitting m_q to $\alpha(\mu)$ Erler, Ramsey-Musolf '04

Higher order corrections:

- $\mathcal{O}(\alpha^2_{\mathrm{QED}})$, $\mathcal{O}(\alpha\alpha_s)$ (NLL) and $\mathcal{O}(\alpha\alpha_s^2)$ (NNLL) effects in running of $\sin^2\bar{\theta}(\mu)$
  Erler, Ramsey-Musolf '04

Theory status for low-energy A_{PV}

Higher order corrections:

- **Genuine weak $\mathcal{O}(\alpha^2)$ currently unknown**

  $\longrightarrow$ Leading contributions could be not much smaller than target MOLLER exp. uncertainty (2.4% relative)

- Additional QCD corrections of $\mathcal{O}(\alpha\alpha_s)$ (and NP uncertainties) for ep scattering

  Erler, Kurylov, Ramsey-Musolf '03

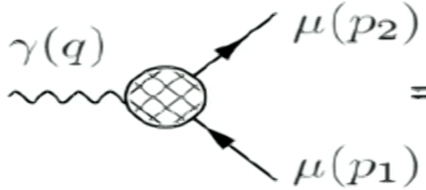
Definition of $\sin^2\bar{\theta}(\mu)$:

- $\overline{\text{MS}}$ $\sin^2\bar{\theta}(\mu)$ is gauge dependent

  (e.g. due to integrating out b/t, c/s at different thresholds)

- Gauge violation may be restored with pinch technique, but cumbersome beyond 1-loop
- More practical: Define $\sin^2\bar{\theta}(\mu)$ in Feynman gauge

Muon anomalous magnetic moment

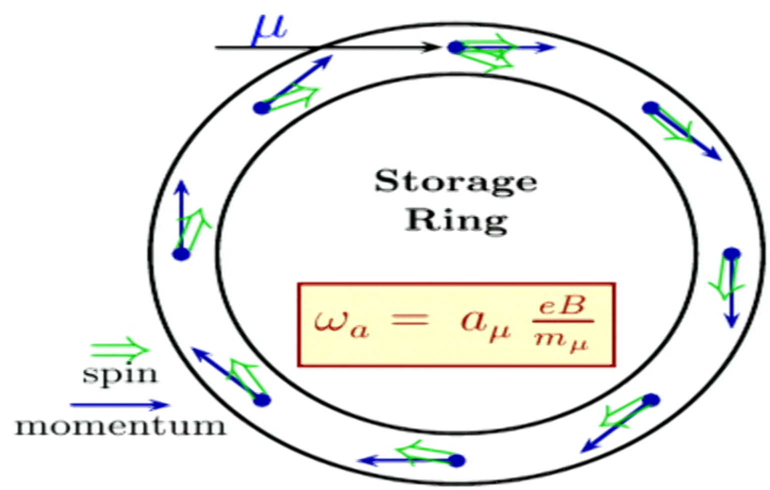


$$= (-ie)\,\bar{u}(p_2)\left[\gamma^\mu F_E(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m_\mu}F_M(q^2)\right]u(p_1)$$

$a_\mu \equiv \frac{g_\mu - 2}{2} = F_M(0)$

Measured at NBL g–2 experiment:

$a_\mu = (11\,659\,208.0 \pm 6.3) \times 10^{-10}$



Jegerlehner, Nyfeller '09

actual precession × 2

Muon $g-2$: SM theory prediction

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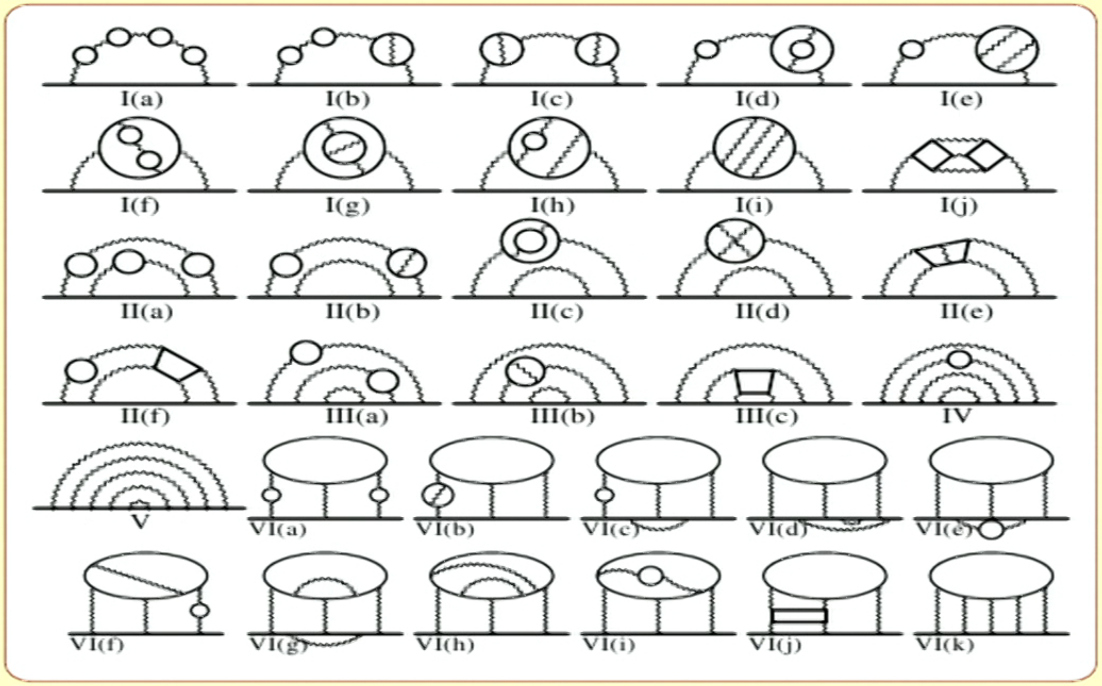
	a_μ [10^{-10}]
QED $\mathcal{O}(\alpha^5)$	11 658 471.88 $\pm$ 0.01

Aoyama, Hayakawa, Kinoshita, Nio '12

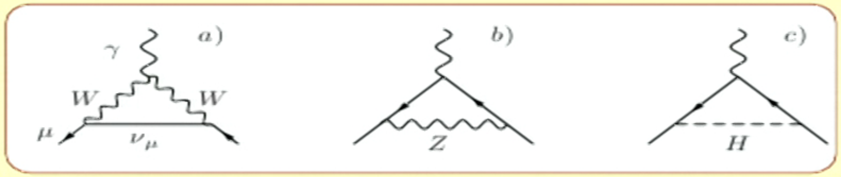


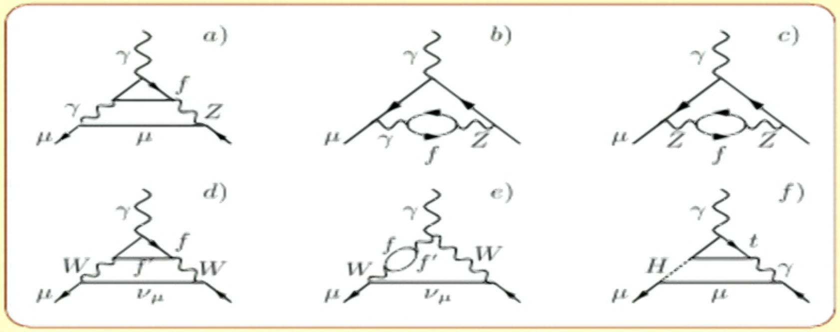
Muon $g-2$: SM theory prediction

	a_μ $[10^{-10}]$
QED $\mathcal{O}(\alpha^5)$	11 658 471.88 $\pm$ 0.01
EW $\mathcal{O}(\alpha^2)$	15.3 $\pm$ 0.2

Aoyama, Hayakawa, Kinoshita, Nio '12

Czarnecki, Krause, Marciano '96
Knecht et al. '02
Czarnecki, Marciano, Vainshtain '03





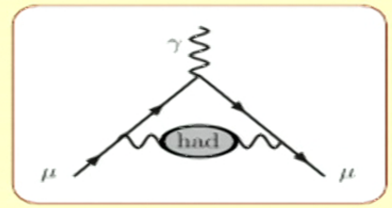
Muon $g-2$: SM theory prediction

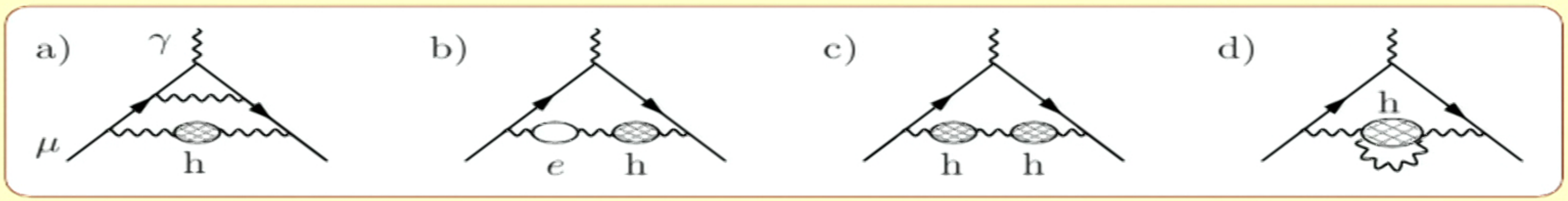
	a_μ $[10^{-10}]$
QED $\mathcal{O}(\alpha^5)$	11 658 471.88 $\pm$ 0.01
EW $\mathcal{O}(\alpha^2)$	15.3 $\pm$ 0.2
LO had. vac. pol.	687.2 $\pm$ 3.5
NLO	-9.93 ± 0.09
NNLO	1.23 $\pm$ 0.01

Aoyama, Hayakawa, Kinoshita, Nio '12

Czarnecki, Krause, Marciano '96
Knecht et al. '02
Czarnecki, Marciano, Vainshtain '03

Hagiwara et al. '11
Davier, Hoecker, Malaescu, Zhang '11
Jegerlehner '15





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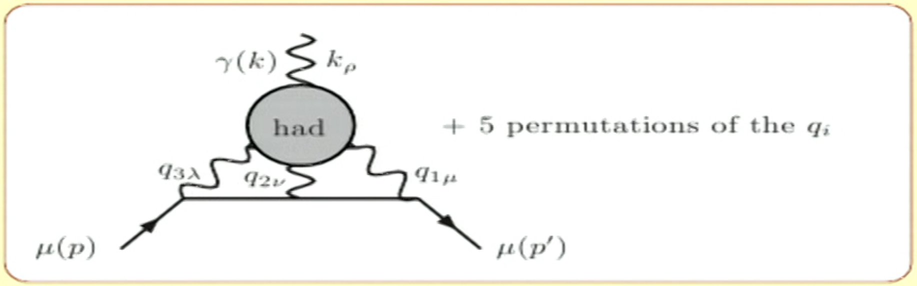
light-by-light	11.6 $\pm$ 4.0	Prades, de Rafael, Vainshtein '09 Nyffeler '09 Erler, Toledo Sanchez '06



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NNLO	1.23 $\pm$ 0.01	
light-by-light	10.7 $\pm$ 3.2	Prades, de Rafael, Vainshtein '09 Nyffeler '09 Erler, Toledo Sanchez '06
Total	11 659 176.4 $\pm$ 4.8	
Exp	11 659 208.0 $\pm$ 6.3	

$\longrightarrow$ $>$ 3 standard deviations!

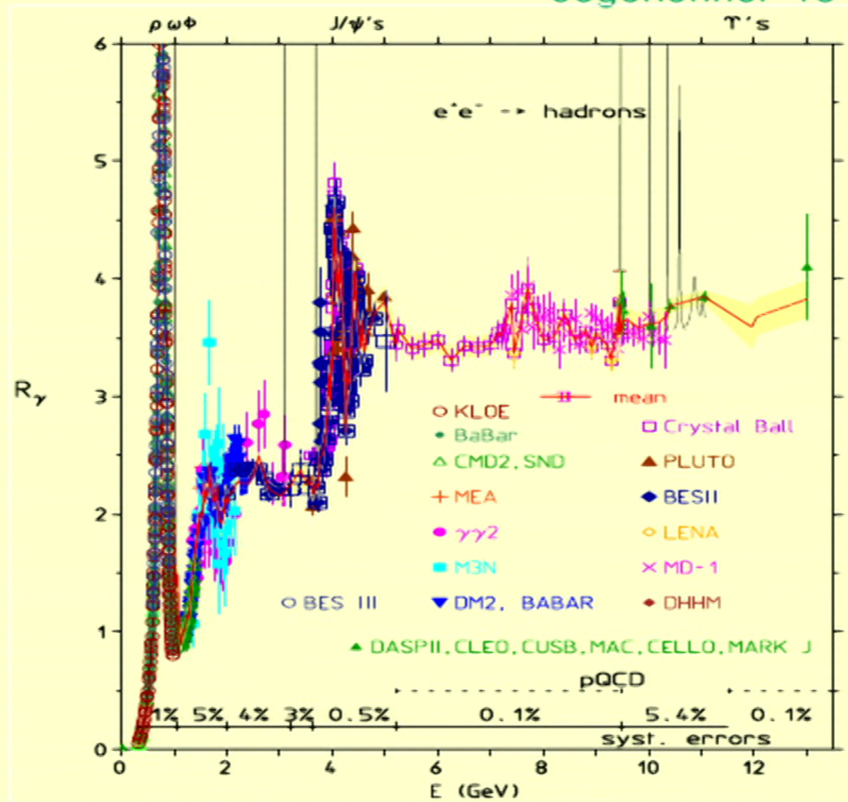
Muon $g-2$: Uncertainties

Difficulties with hadronic contributions:

- Had. vac. pol. from e^+e^- and τ decay data (or lattice†)
- Calibration of old e^+e^- experiments
- $\gamma-\rho$ mixing important for relating e^+e^- and τ data

  Jegerlehner, Szafron '11
- Light-by-light contribution only from hadron models (or lattice*)

Jegerlehner '15



†Blum et al. '15
Chakraborty et al. '16
Della Morte et al. '17

*Blum et al. '16,17

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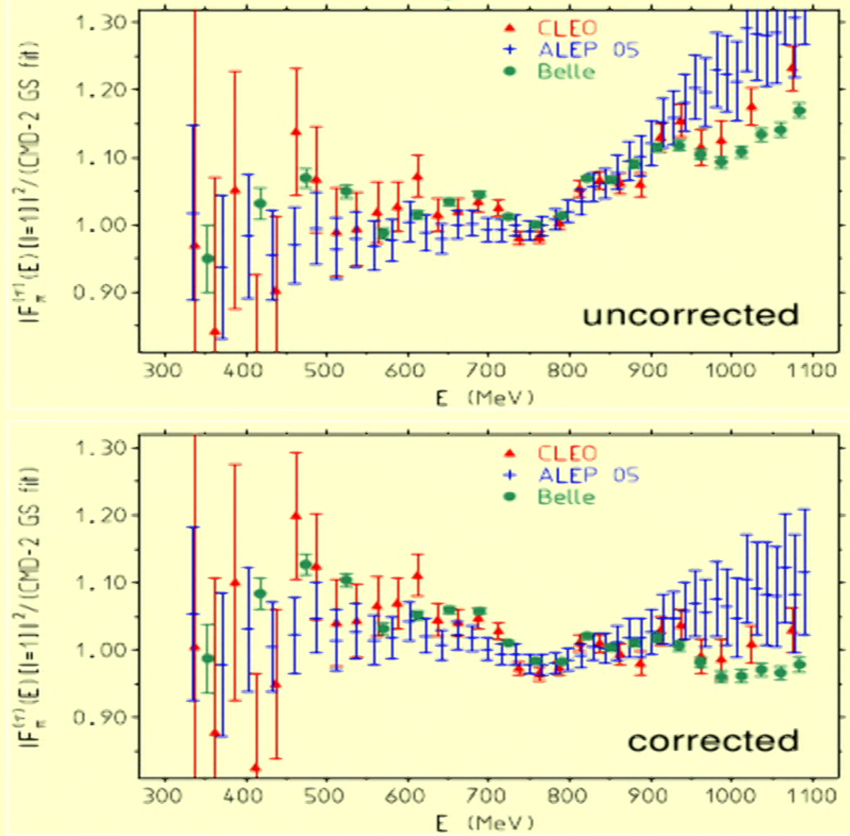


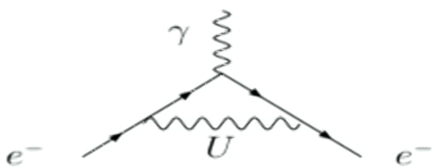
New physics: Dark "photon"

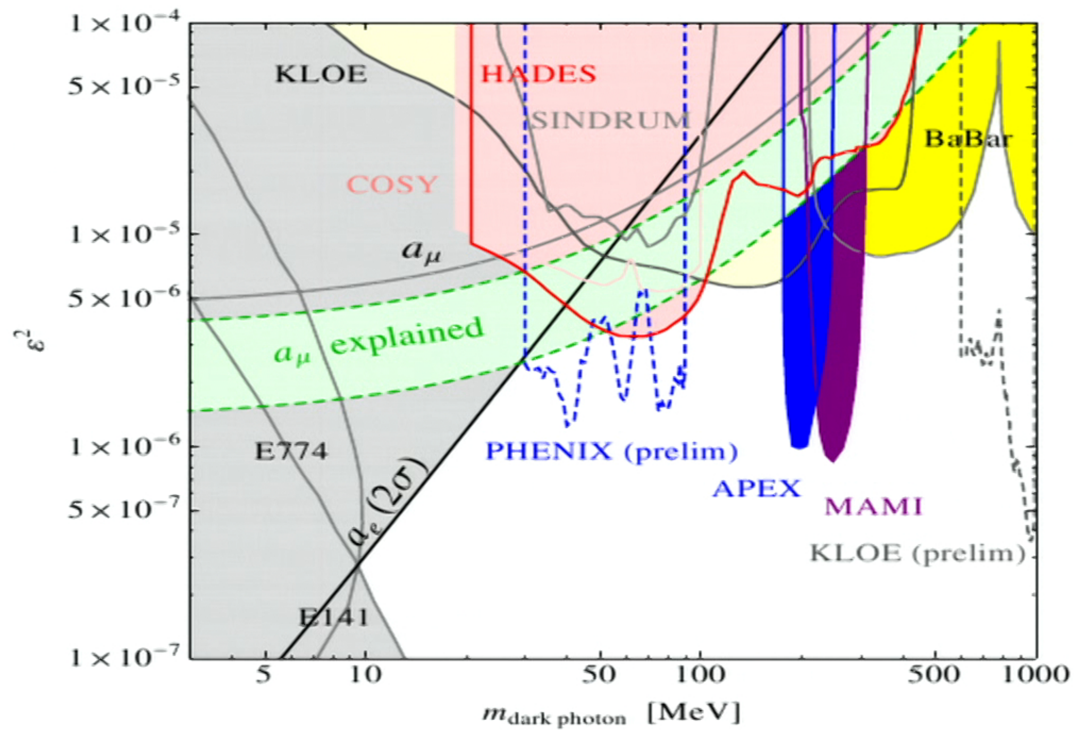
New neutral gauge boson

$m_U \sim \mathcal{O}(100\text{ MeV})$,

which mixes with photon

$$\mathcal{L}_{\text{int}} = \frac{\epsilon}{2c_{\text{w}}} B_{\mu\nu} U^{\mu\nu}$$

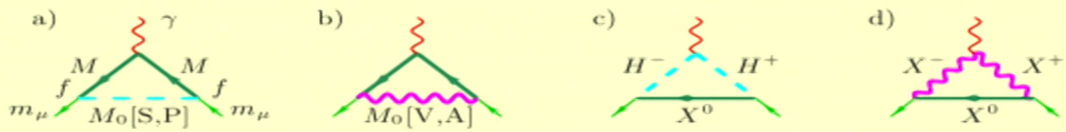




Gninenko, Krasnikov '01
Fayet '07; Pospelov '08
Davoudiasl, Lee, Marciano '14

New physics: Simplified models

Introduce one or two new fields (spin $0, \frac{1}{2}, 1$; SU(2) singlet, doublet, triplet)



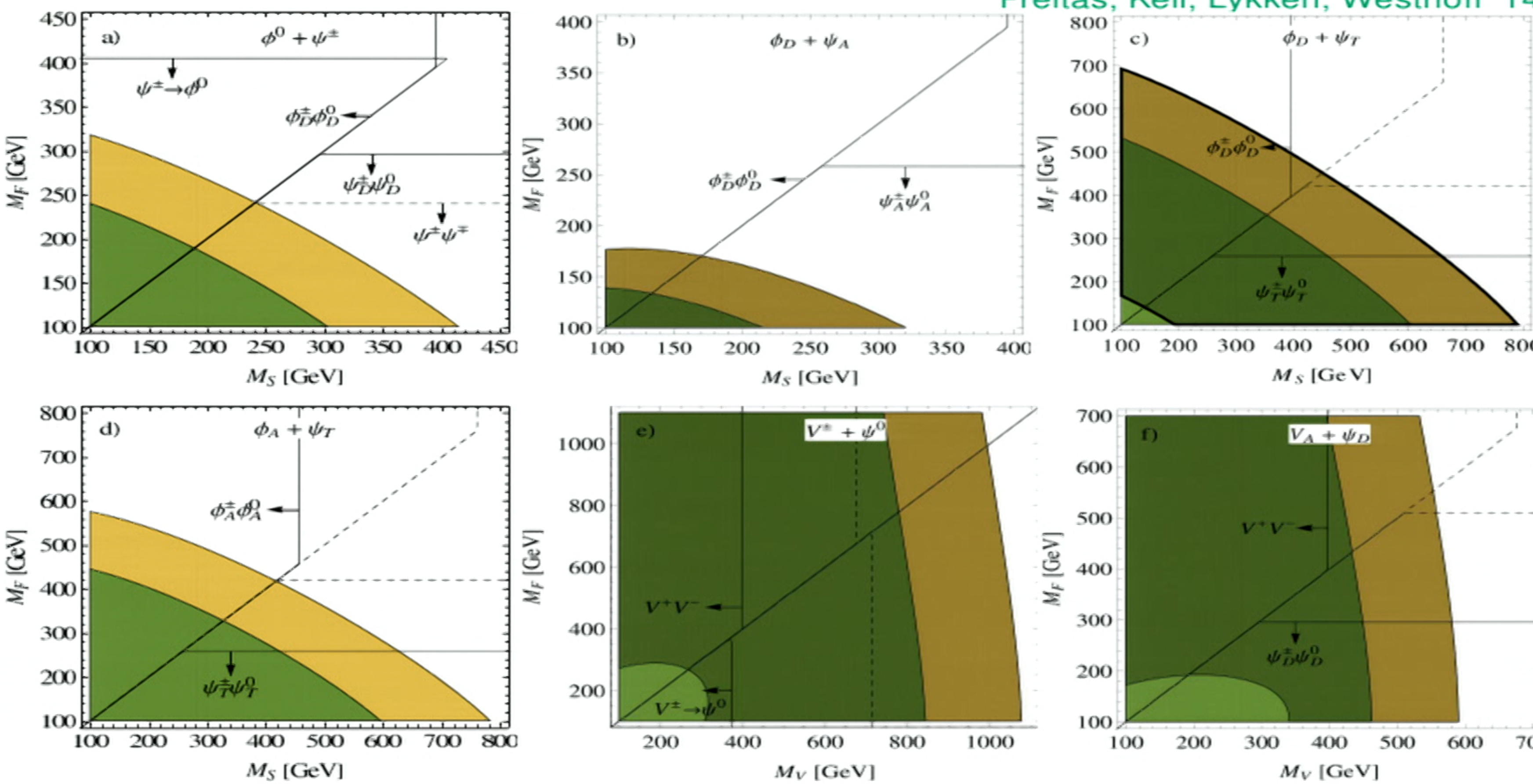
$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (29.3 \pm 8.4) \quad \longrightarrow \begin{cases} m_{\text{NP}} \sim \text{few} \times 100 \text{ GeV} \\ g_{\text{NP}} \sim 1 \end{cases}$$

$\longrightarrow$ Within reach of LHC!

- Identify parameter space that matches Δa_μ at one-loop
- Compare with constraints from LHC searches

Two new fields: Allowed parameter space

Freitas, Kell, Lykken, Westhoff '14



Conclusions

- W/Z precision data may move into the intensity frontier
  - ⟶ Strong constraints on multi-TeV new physics
  - ⟶ Interesting constraints on superweak 10–100 GeV-scale new physics?
- Low-energy precision experiments will become competitive with W/Z-pole data
  - ⟶ Unique probes for light new physics
  - ⟶ Muon $g-2$ may already hint toward BSM, but hadronic error could be underestimated
- Good control over input parameters $m_{\rm t}$, $M_{\rm W}$, $\alpha_{\rm s}$ and $\Delta\alpha_{\rm had}$ is crucial
  - ⟶ Influence of theory uncertainties!
- Open questions:
  - ⟶ Improved higher-order (3-loop) corrections for Z-pole EWPO
  - ⟶ Improved higher-order (2-loop) corrections for low-energy EWPO
  - ⟶ Motivated new physics scenarios at scales $\Lambda \lesssim \sqrt{s}$ for future Z-pole and low-energy precision experiments
  - ⟶ Parametrization of possible low-scale new physics ($\sin^2\bar{\theta}(\mu)$, eff. operators, etc.)