Standard Model precision tests from high to low energy

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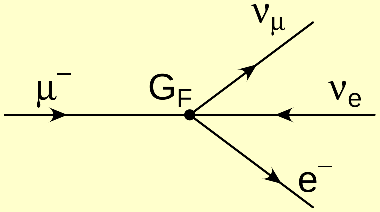
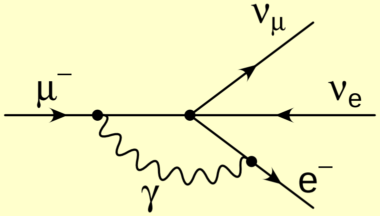
KITP Workshop "Stress-testing the Standard Model at the LHC"
2–3 February 2016

1. Z and W boson physics
2. Low-energy electroweak observables
3. Muon anomalous magnetic moment
4. CP-violation and electric dipole moments
5. Lepton flavor violation

W mass

μ decay in Fermi Model



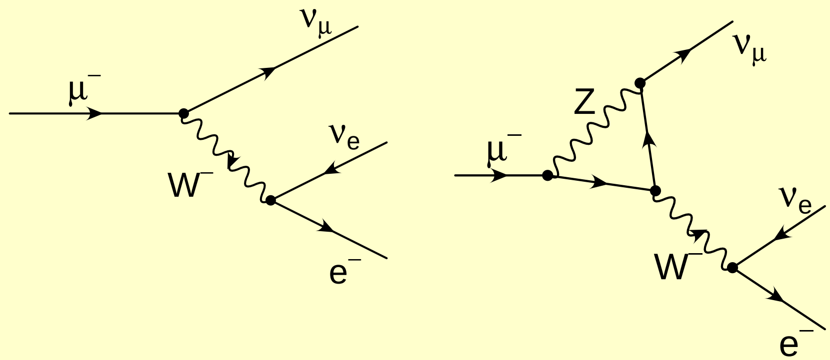


← QED corr. (2-loop)

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

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:

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

- 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:

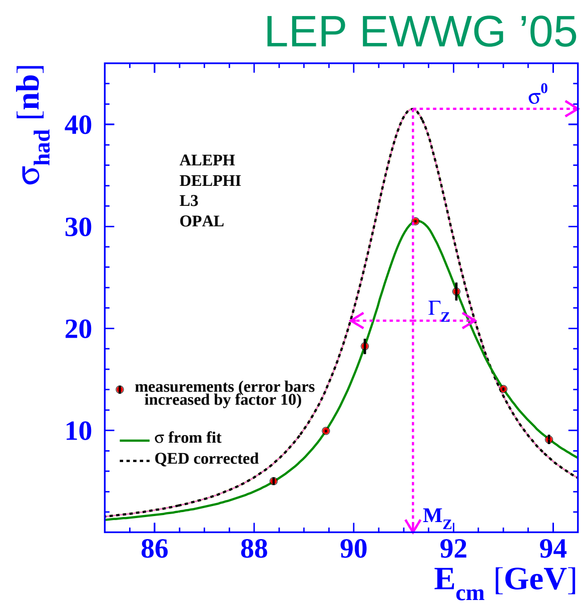
$$\sigma_{\text{Z}} = \frac{R}{(s - \overline{M}_{\text{Z}}^2)^2 + \overline{M}_{\text{Z}}^2 \overline{\Gamma}_{\text{Z}}^2} + \sigma_{\text{non-res}}$$

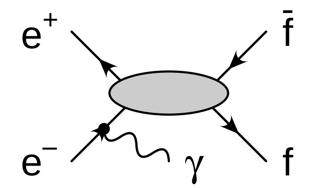
- In experimental analyses:

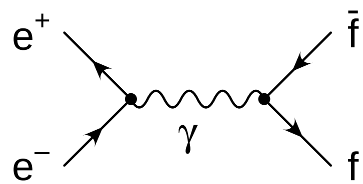
$$\sigma \sim \frac{1}{(s - M_{\text{Z}}^2)^2 + s^2 \Gamma_{\text{Z}}^2 / M_{\text{Z}}^2}$$

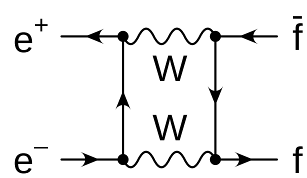
$$\overline{M}_{\text{Z}} = M_{\text{Z}} \Big/ \sqrt{1 + \Gamma_{\text{Z}}^2/M_{\text{Z}}^2} \approx M_{\text{Z}} - 34\text{ MeV}$$

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









Z-pole observables

Effective weak mixing angle:

Z-pole asymmetries:

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

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

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

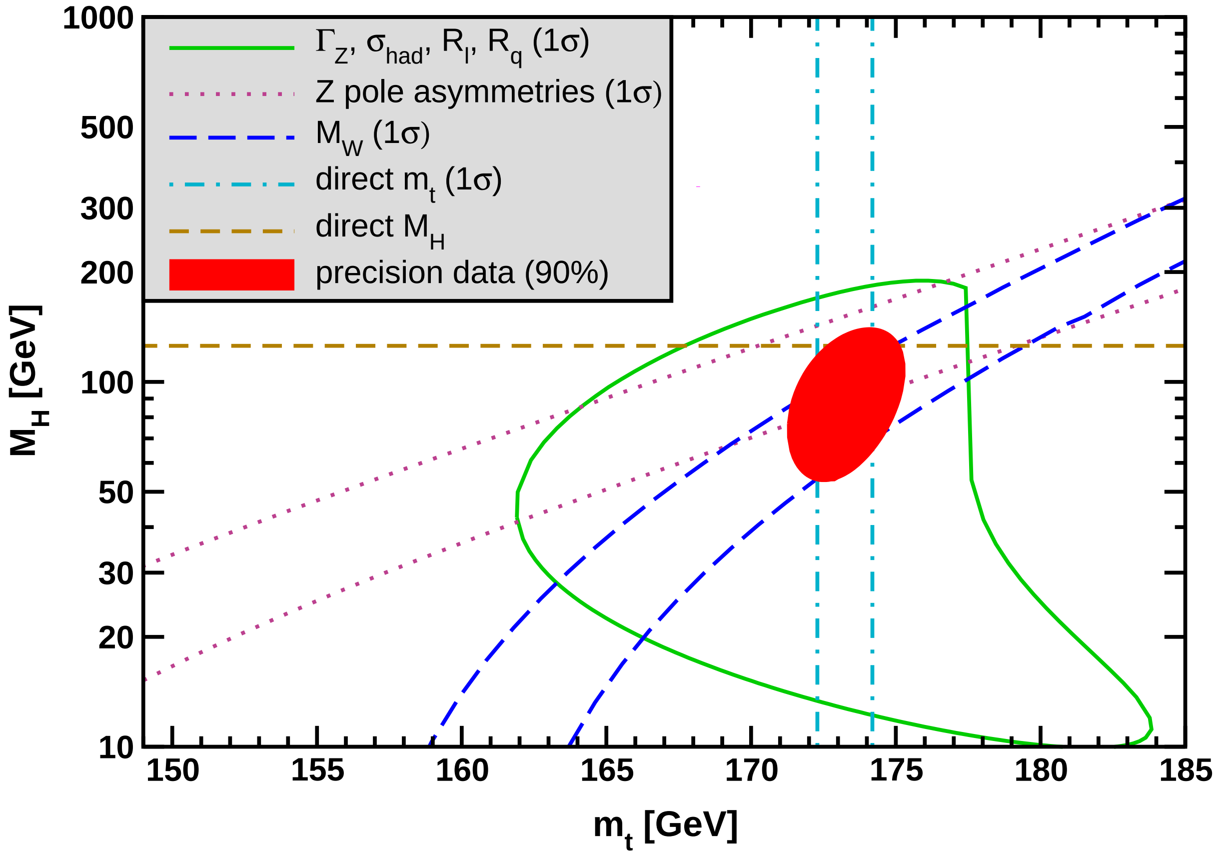
Most precisely measured for $f = \ell$ (also $f = b, c$)

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:

$M_{\rm H} = 125.6 \pm 0.4$ GeV

$m_{\rm t} = 173.24 \pm 0.95$ GeV

Indirect prediction:

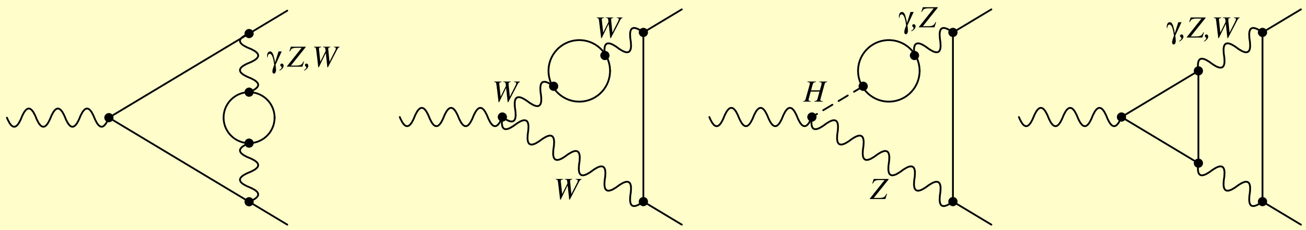
$M_{\rm H} = 123.7 \pm 2.3$ GeV (with LHC BRs)

$M_{\rm H} = 89^{+22}_{-18}$ GeV (w/o LHC data)

$m_{\rm t} = 177.0 \pm 2.1$ GeV

Current status of SM loop results

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



- Complete NNLO corrections (Δr, $\sin^2\theta^\ell_{\text{eff}}$) 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

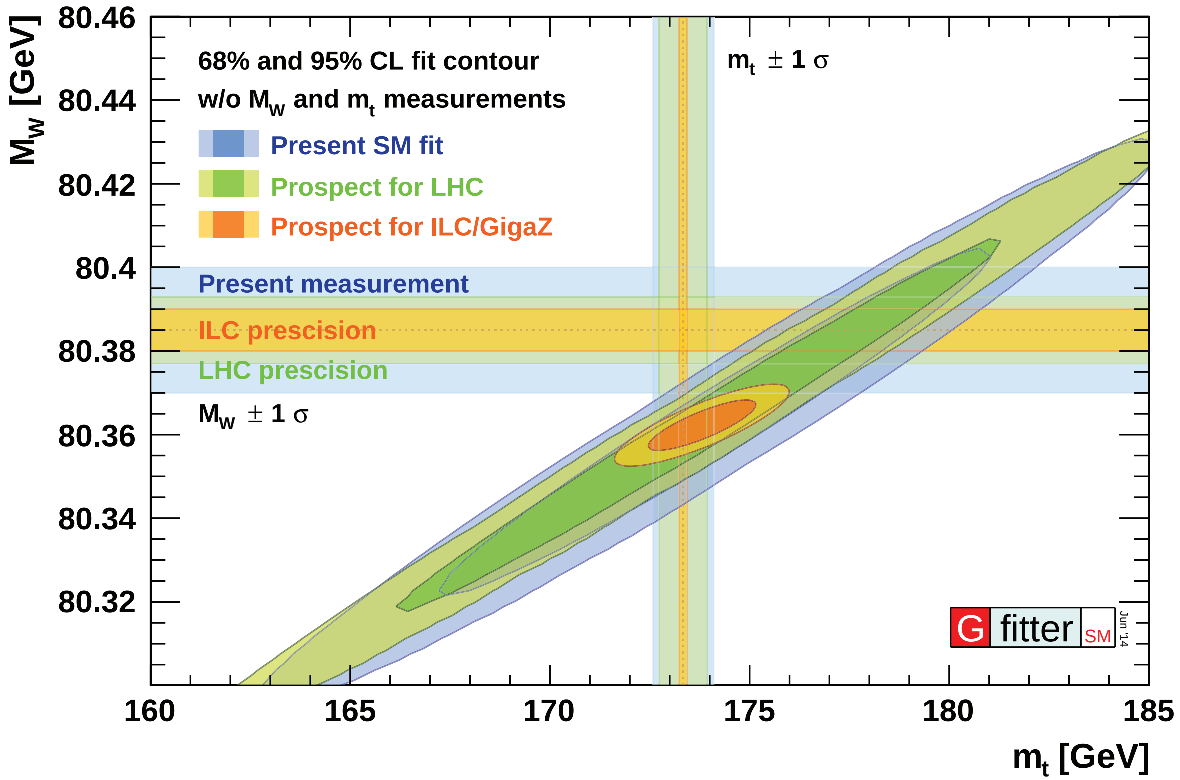
	Experiment	Theory error	Main source
M_W	80.385 ± 0.015 MeV	4 MeV	α^3, $\alpha^2\alpha_s$
Γ_Z	2495.2 ± 2.3 MeV	0.5 MeV	α_{bos}^2, α^3, $\alpha^2\alpha_s$, $\alpha\alpha_s^2$
σ_{had}^0	41540 ± 37 pb	6 pb	α_{bos}^2, α^3, $\alpha^2\alpha_s$
$R_b \equiv \Gamma_Z^b/\Gamma_Z^{had}$	0.21629 ± 0.00066	0.00015	α_{bos}^2, α^3, $\alpha^2\alpha_s$
$\sin^2\theta_{eff}^{\ell}$	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, $\Delta\alpha_{had}$, ...)

W mass measurement at the LHC

Precision target for LHC: $\delta M_{\mathrm{W}} \sim 8\ \mathrm{MeV}$ Snowmass EW group, Baak et al. '13

- Requires improvements in PDF uncertainties (currently $\delta M_{\mathrm{W,PDF}} \gtrsim 10$ MeV)
- Also improvements in **experimental systematics** and **modeling of QED radiation** (state of the art MC programs: `PHOTOS`, `HORACE`)



Gfitter coll. '14

$\longrightarrow$ Will tighten constraints on SM and BSM physics

Drell-Yan at hadron colliders

Meausurement of $\sin^2\theta^\ell_{\text{eff}}$ from A_{FB} for $pp \to Z \to \ell^+\ell^-$

$\longrightarrow$ Check of discrepancy between SLD and LEP

Current errors:

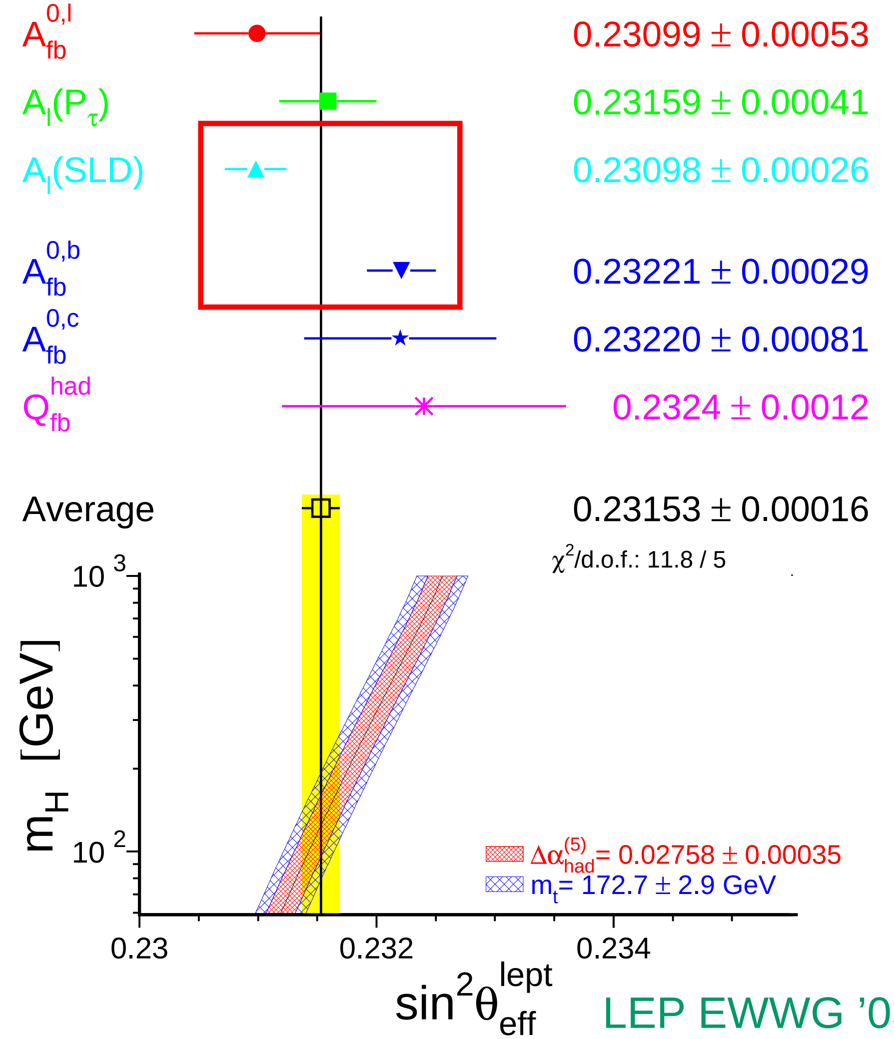
LEP/SLC:	1.6×10^{-4}	2005
ATLAS:	10×10^{-4}	2013
CMS:	32×10^{-4}	2011
CDF:	10×10^{-4}	2014
DØ:	4.7×10^{-4}	2014

Future projection:

LHC: $\lesssim 3.5 \times 10^{-4}$

Snowmass EW group, Baak et al. ’13

CDF: $\sim 4.5 \times 10^{-4}$ Bodek ’14



LEP EWWG ’05

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	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

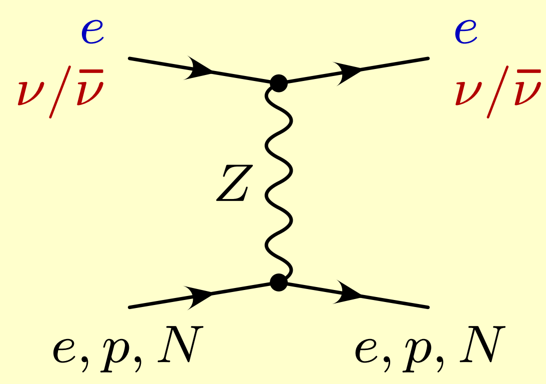
****FCC-ee:** $\delta m_t = 50$ MeV, $\delta\alpha_{\mathrm{s}} = 0.0001$, $\delta M_{\mathrm{Z}} = 0.1$ MeV

also: $\delta(\Delta\alpha) \sim 5\times10^{-5}$

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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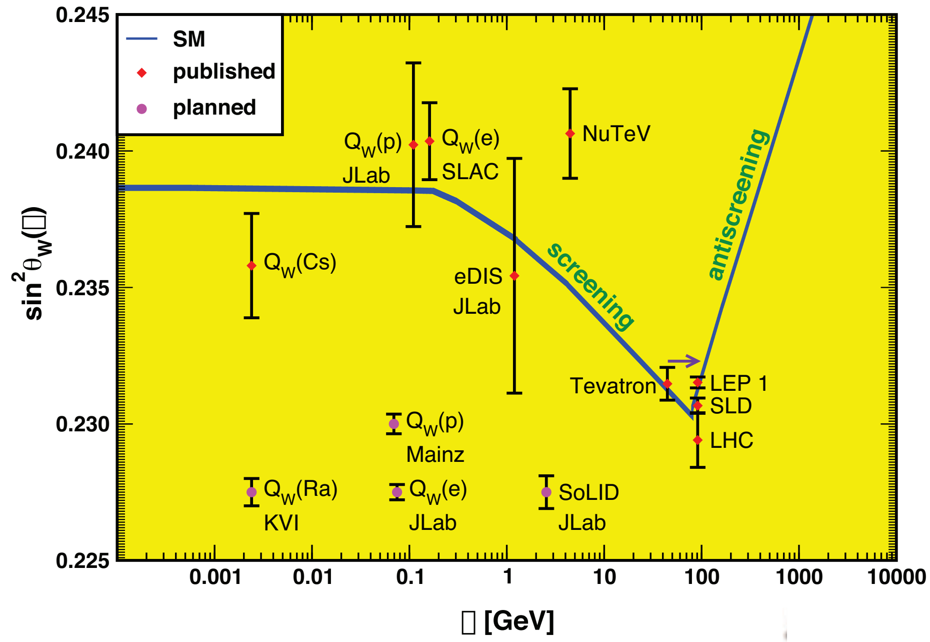
Erler '14



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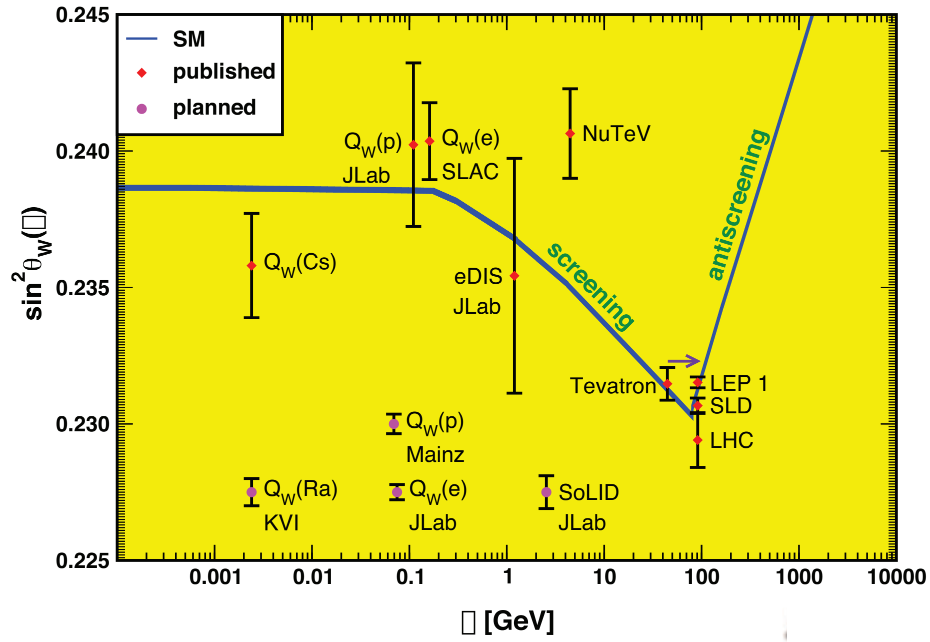
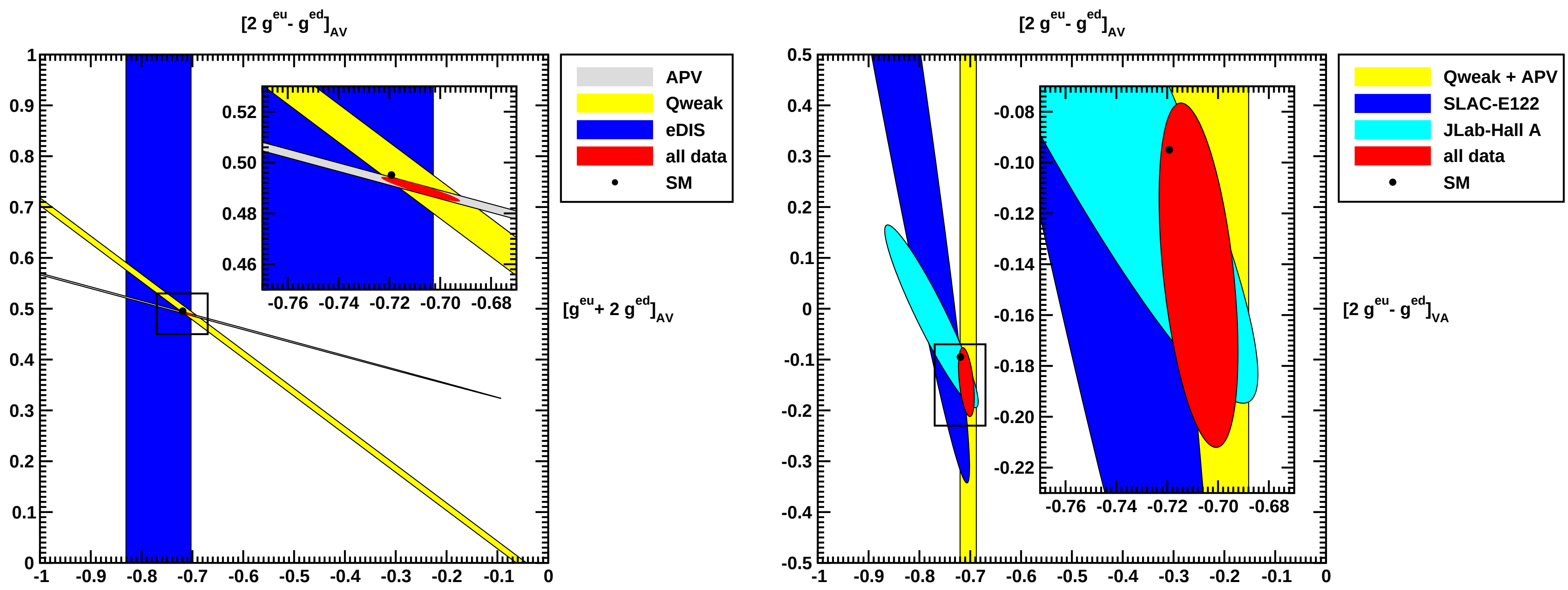
- Future experiments:
  MOLLER (ee), P2, SoLID (ep), Atomic PV in radium

Erler ’14



Independent contact interactions



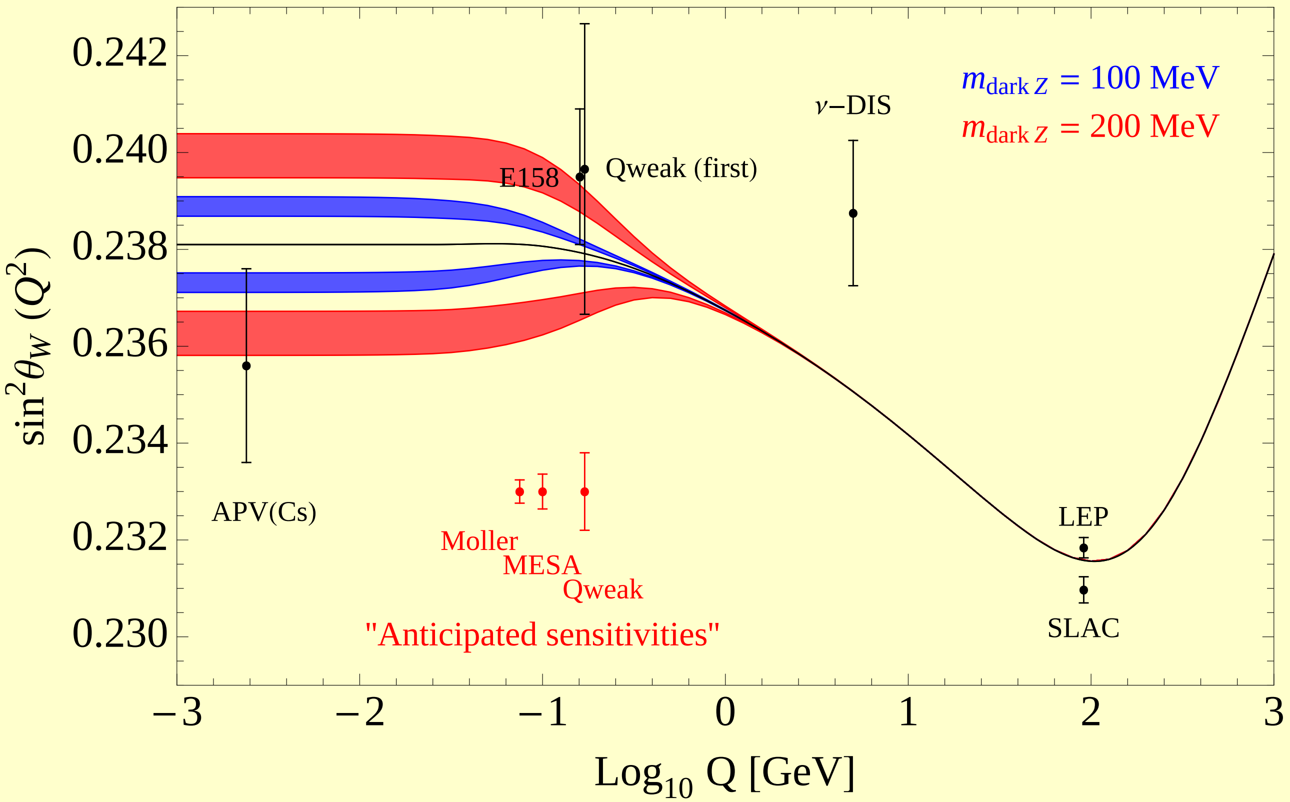
Erler, Horowitz, Mantry, Souder ’14

Dark "photon"

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

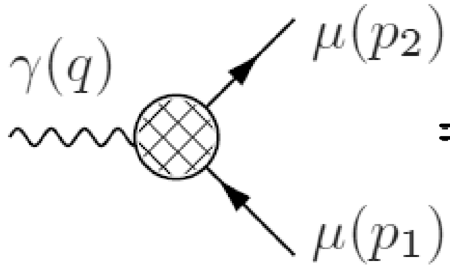
$\longrightarrow$ Can explain $g_\mu - 2$ discrepancy

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



Davoudiasl, Lee, Marciano '14

Muon anomalous magnetic moment

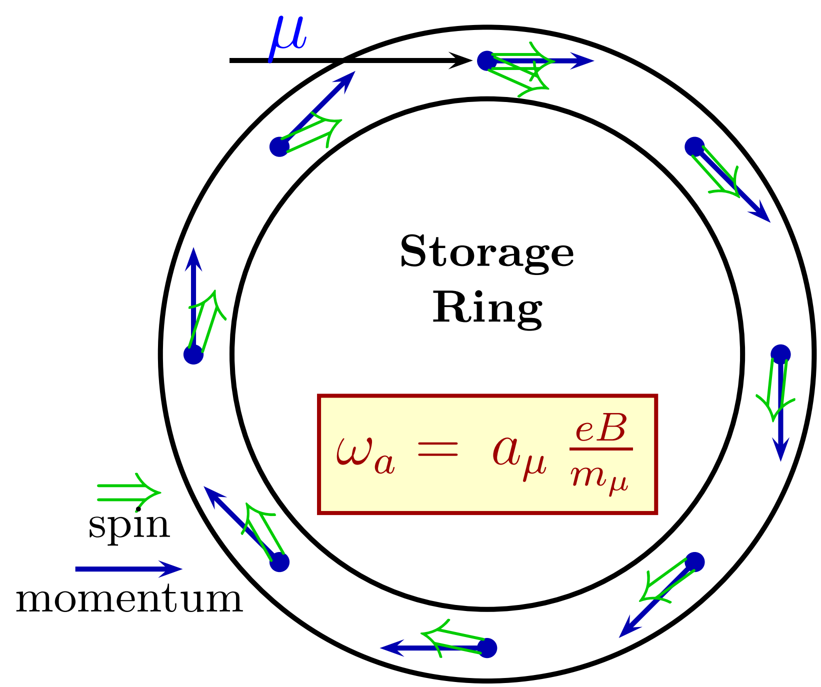


$$= (-ie)\,\bar{u}(p_2)\left[\gamma^\mu F_{\mathsf{E}}(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m_\mu}F_{\mathsf{M}}(q^2)\right]u(p_1)$$

$$a_\mu \equiv \frac{g_\mu - 2}{2} = F_{\mathsf{M}}(0)$$

Measured at BNL g–2 experiment:

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



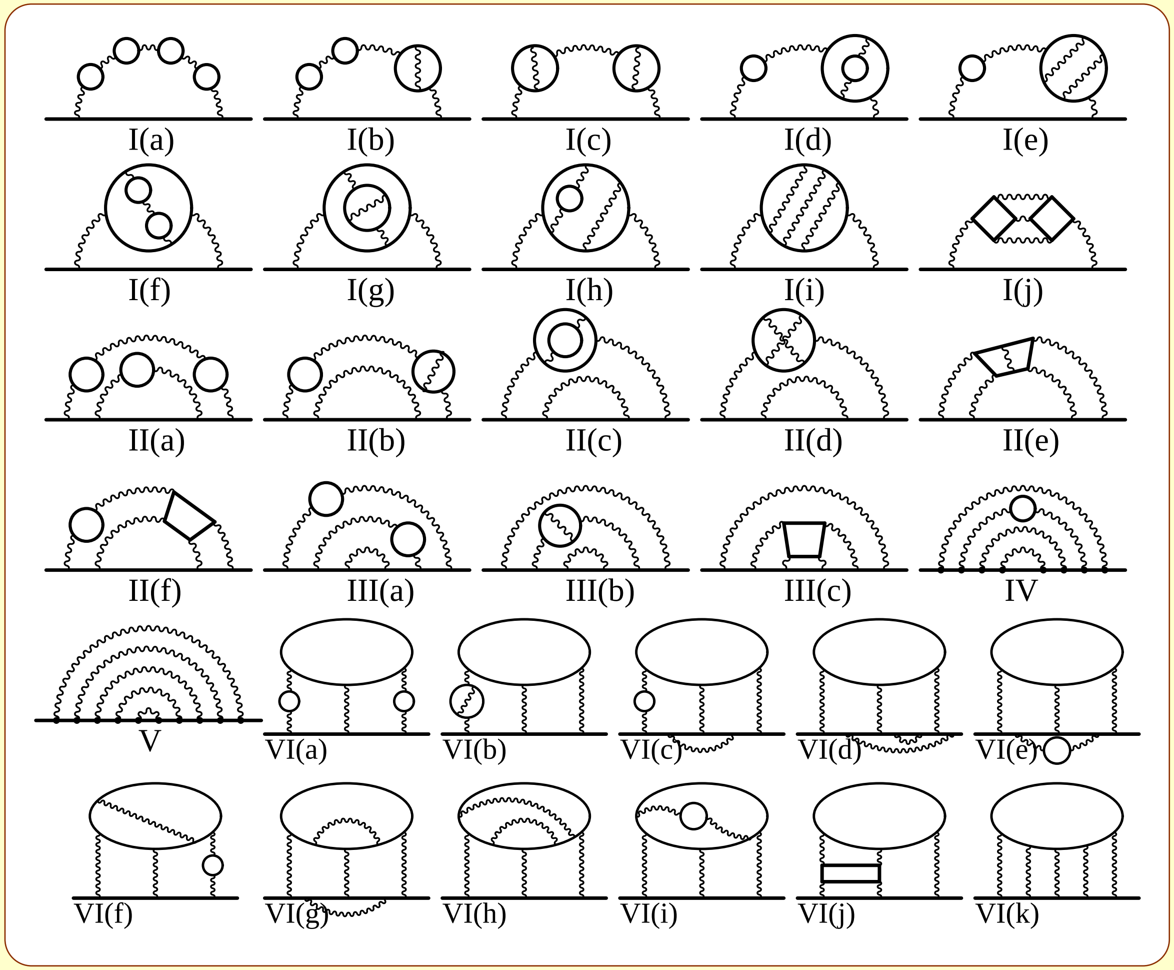
actual precession $\times$ 2

Jegerlehner, Nyfeller ’09

Muon $g-2$: SM theory prediction

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

Aoyama, Hayakawa, Kinoshita, Nio ’12



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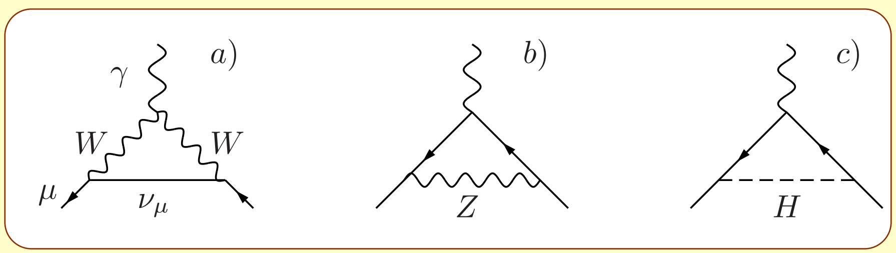
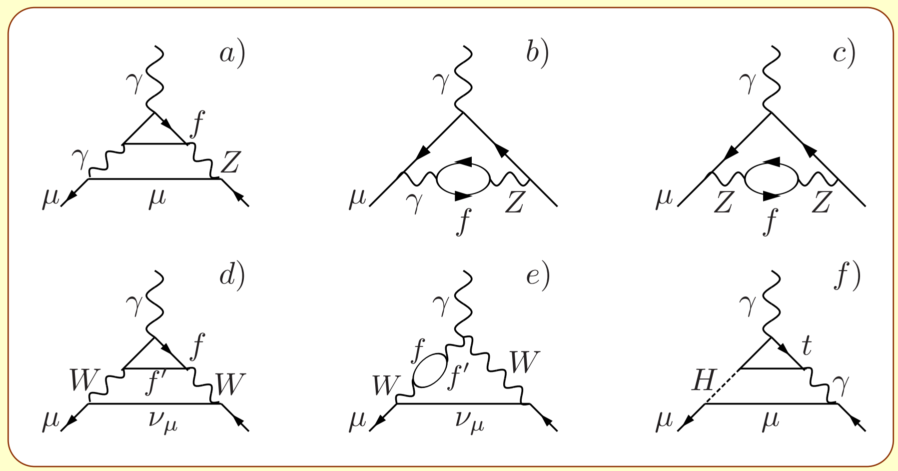
EW $\mathcal{O}(\alpha^2)$	15.3 $\pm$ 0.2

Aoyama, Hayakawa, Kinoshita, Nio ’12

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





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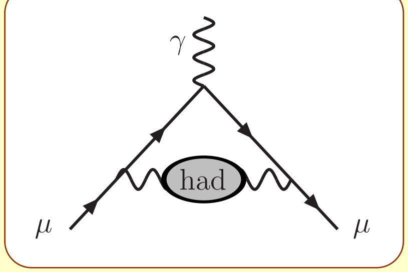
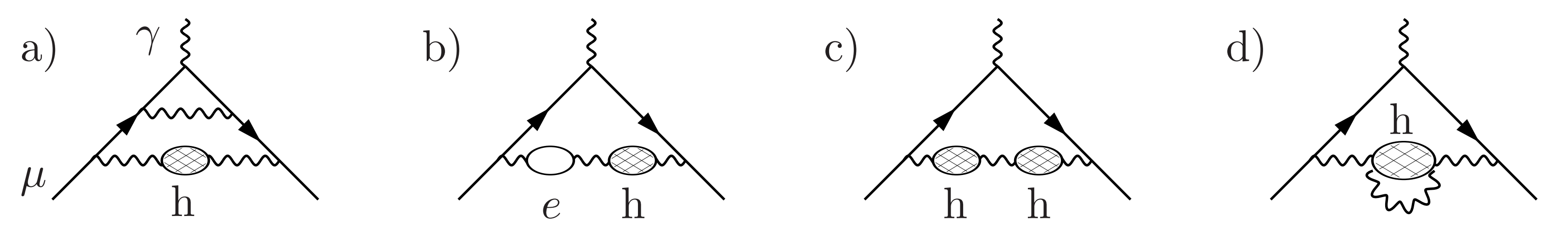
LO had. vac. pol.	687.2 $\pm$ 3.5	Hagiwara et al. ’11 Davier, Hoecker, Malaescu, Zhang ’11 Jegerlehner ’15
NLO	$-$9.93 $\pm$ 0.09	
NNLO	1.23 $\pm$ 0.01	





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	a_μ $[10^{-10}]$
QED $\mathcal{O}(\alpha^5)$	$11\,658\,471.88 \pm 0.01$
EW $\mathcal{O}(\alpha^2)$	15.3 ± 0.2
LO had. vac. pol.	687.2 ± 3.5
NLO	-9.93 ± 0.09
NNLO	1.23 ± 0.01
light-by-light	10.7 ± 3.2

Aoyama, Hayakawa, Kinoshita, Nio ’12

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

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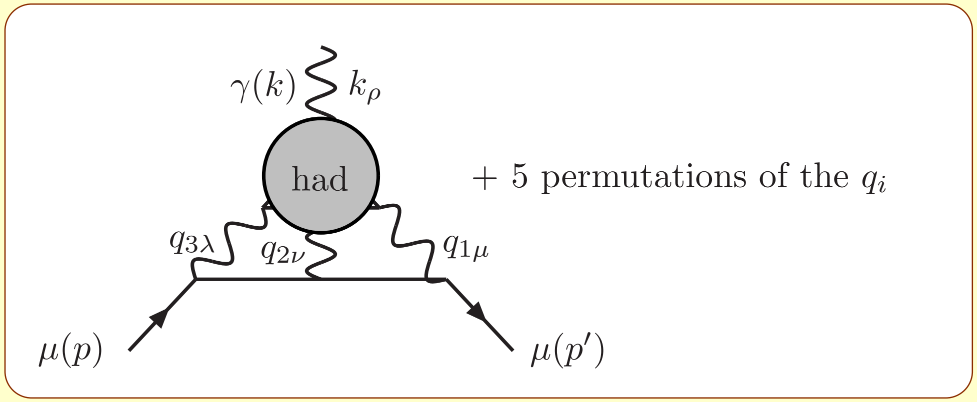
Jegerlehner ’15

Prades, de Rafael, Vainshtein ’09
Nyffeler ’09
Erler, Toledo Sanchez ’06



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LO had. vac. pol.	687.2 $\pm$ 3.5
NLO	$-$9.93 $\pm$ 0.09
NNLO	1.23 $\pm$ 0.01
light-by-light	10.7 $\pm$ 3.2
Total	11 659 176.4 $\pm$ 4.8
Exp	11 659 208.0 $\pm$ 6.3

Aoyama, Hayakawa, Kinoshita, Nio ’12

Czarnecki, Krause, Marciano ’96
Knecht et al. ’02
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Jegerlehner ’15

Prades, de Rafael, Vainshtein ’09
Nyffeler ’09
Erler, Toledo Sanchez ’06

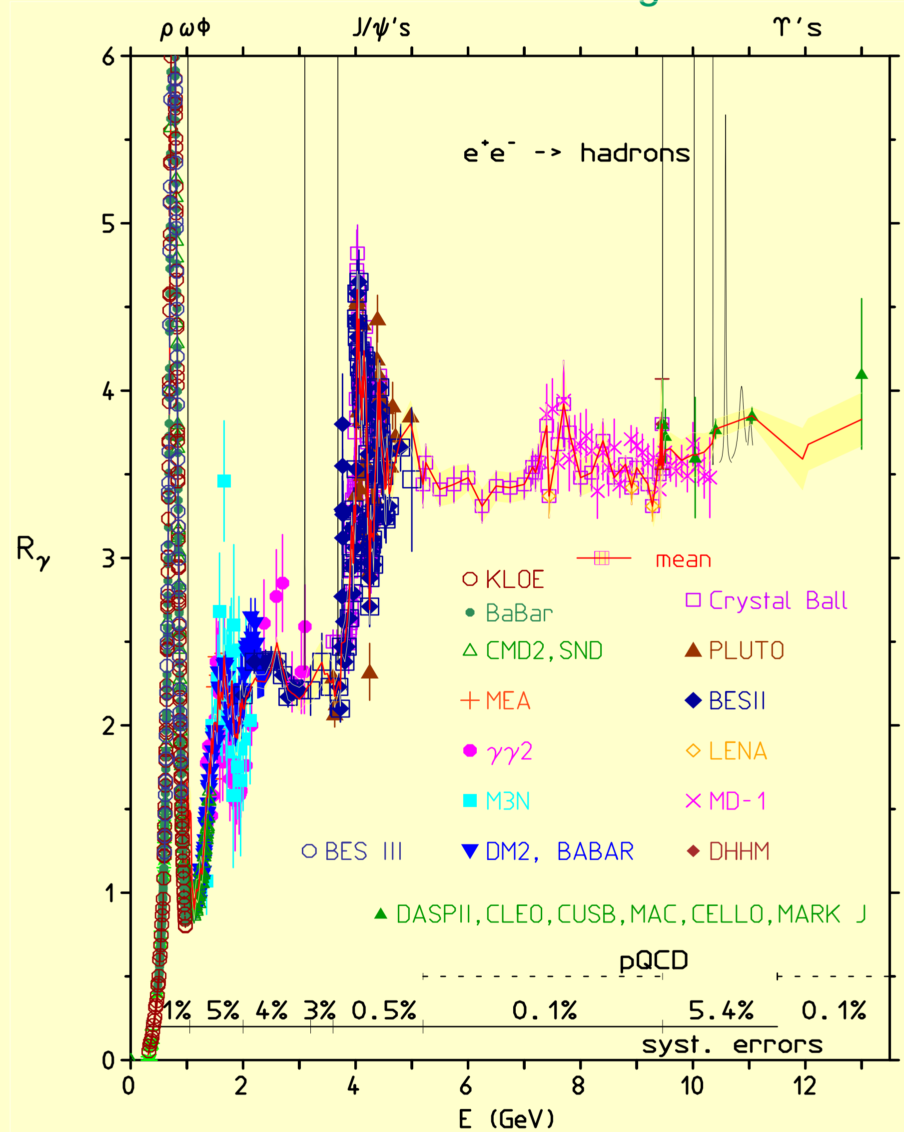
$\longrightarrow$ $>$ 3 standard deviations!

Difficulties with hadronic contributions:

- Had. vac. pol. from e^+e^- and τ decay data (or lattice*)
- Calibration of old e^+e^- experiments
- γ–ρ mixing important for relating e^+e^- and τ data

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

Jegerlehner '15



*Burger et al. '13; Davies et al. '15

†Blum, Chowdhury, Hayakawa, Izubuchi '14

Muon $g-2$: Uncertainties

Difficulties with hadronic contributions:

Jegerlehner, Szafron '11

- Had. vac. pol. from e^+e^- and τ decay data (or lattice*)
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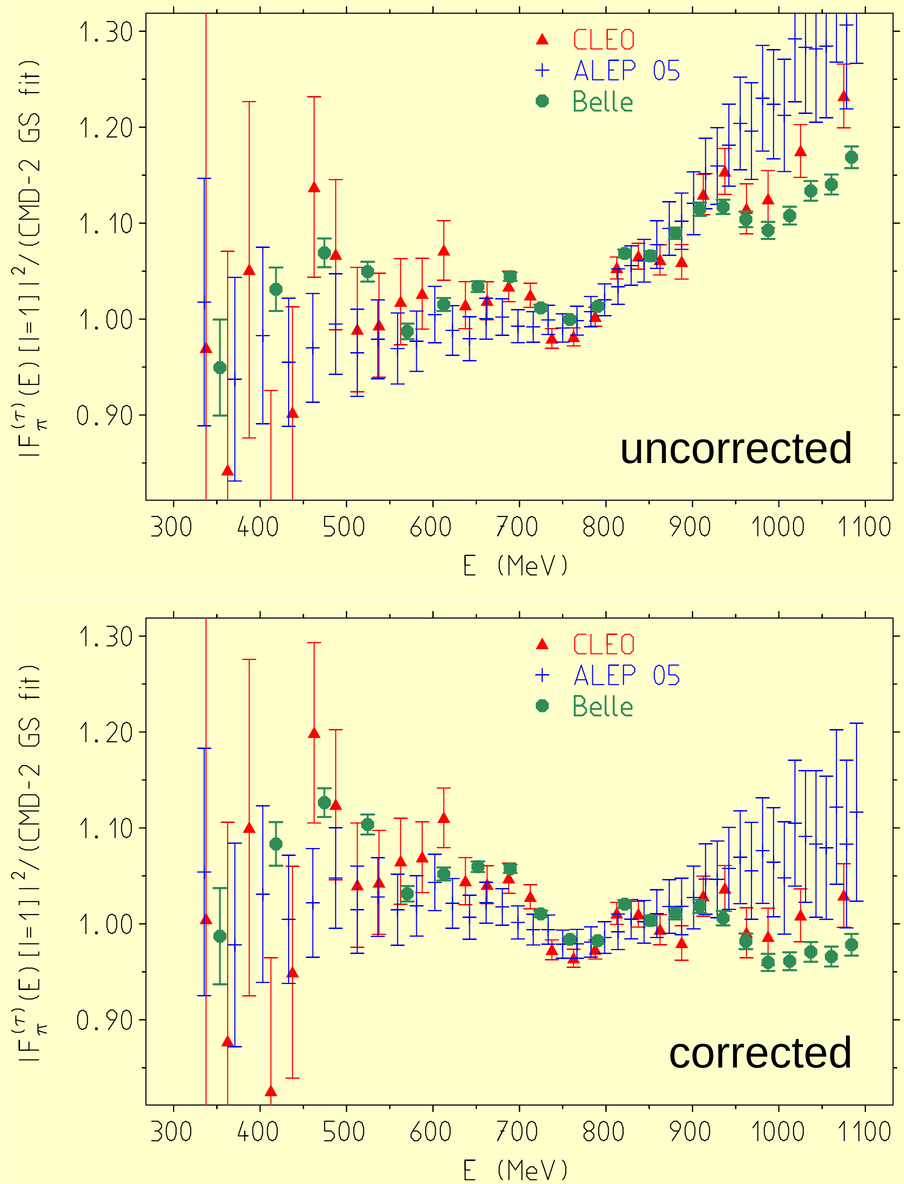

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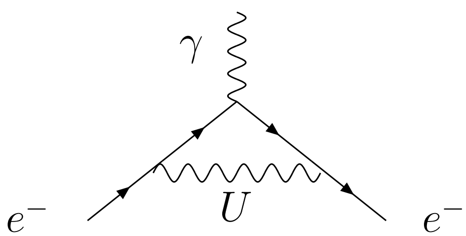
New physics: Dark "photon"

New neutral gauge boson

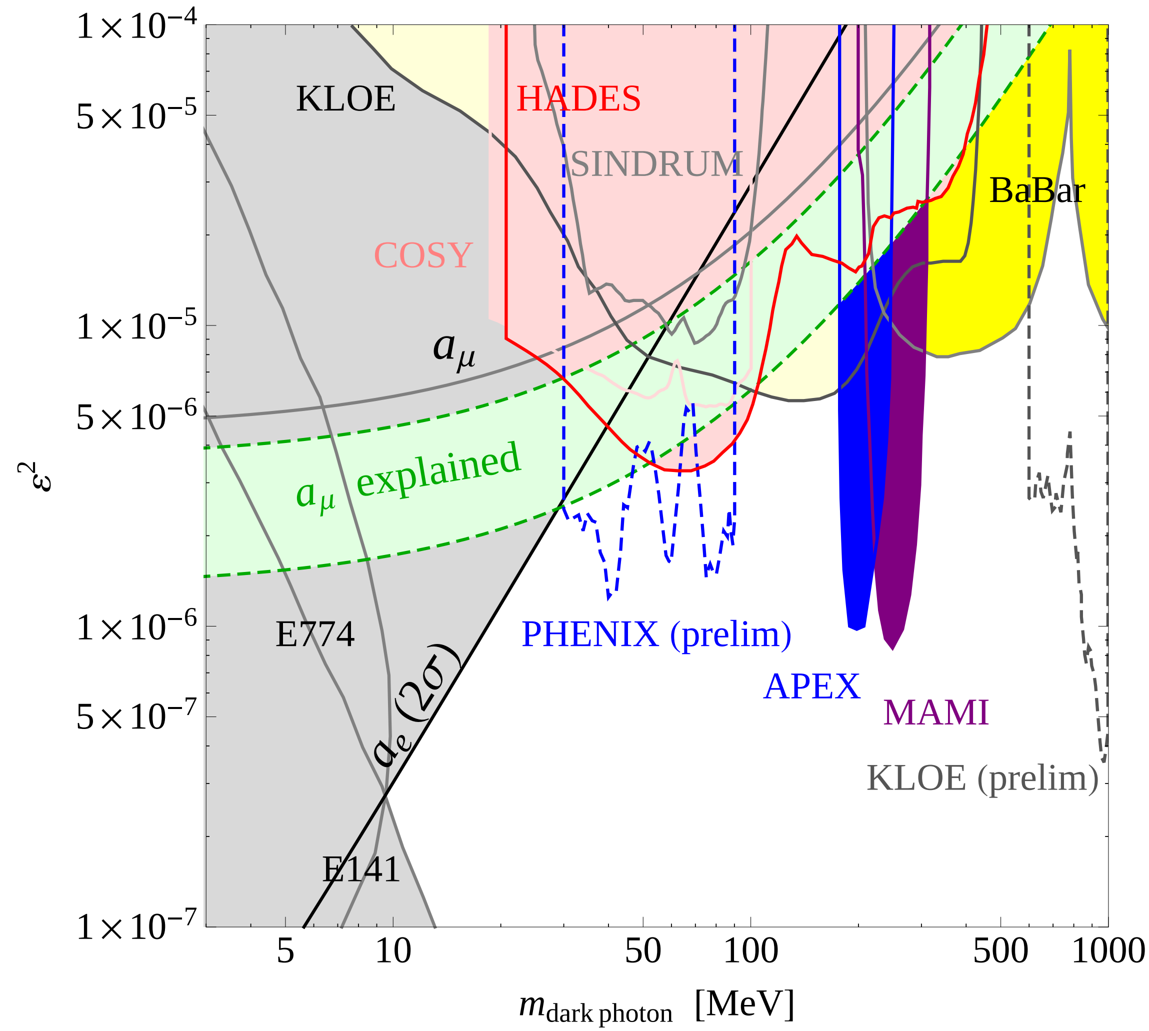
$m_U \sim \mathcal{O}(100\ \text{MeV})$,

which mixes with photon

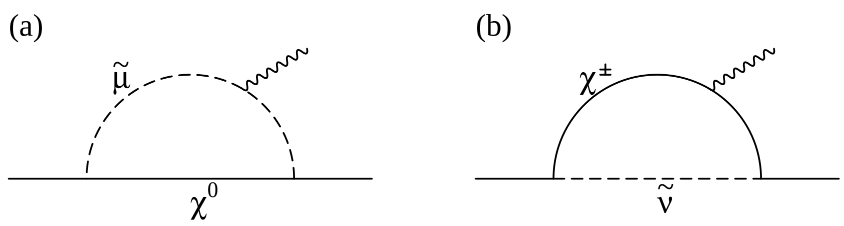
$$\mathcal{L}_{\text{int}} = \frac{\epsilon}{2c_W} B_{\mu\nu} U^{\mu\nu}$$



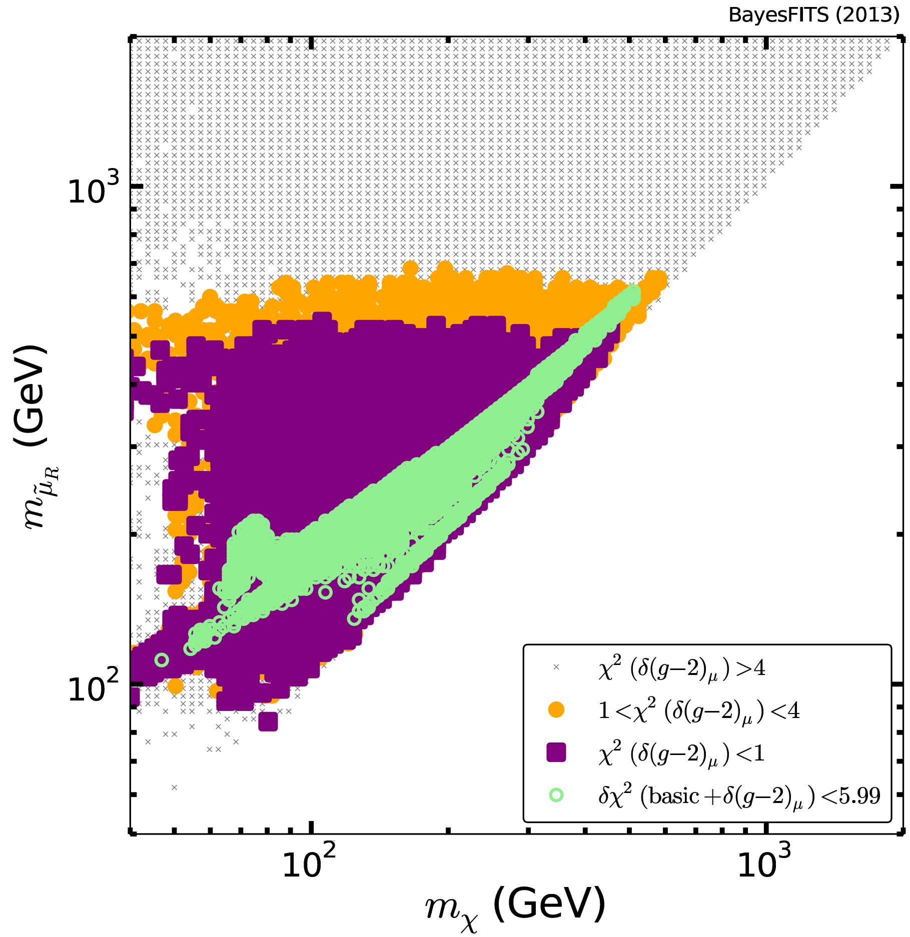
Gninenko, Krasnikov '01
Fayet '07; Pospelov '08
Davoudiasl, Lee, Marciano '14



- Main contribution from slepton–gaugino loops
- Fits $(g_\mu - 2)$ and other constraints for $m_{\mathrm{SUSY}} \sim$ few 100 GeV
- Large $\tan\beta$ helps

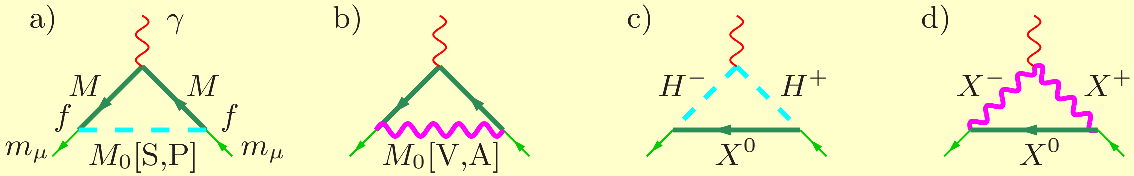


Fowlie et al. '13



New physics: Simplified models

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



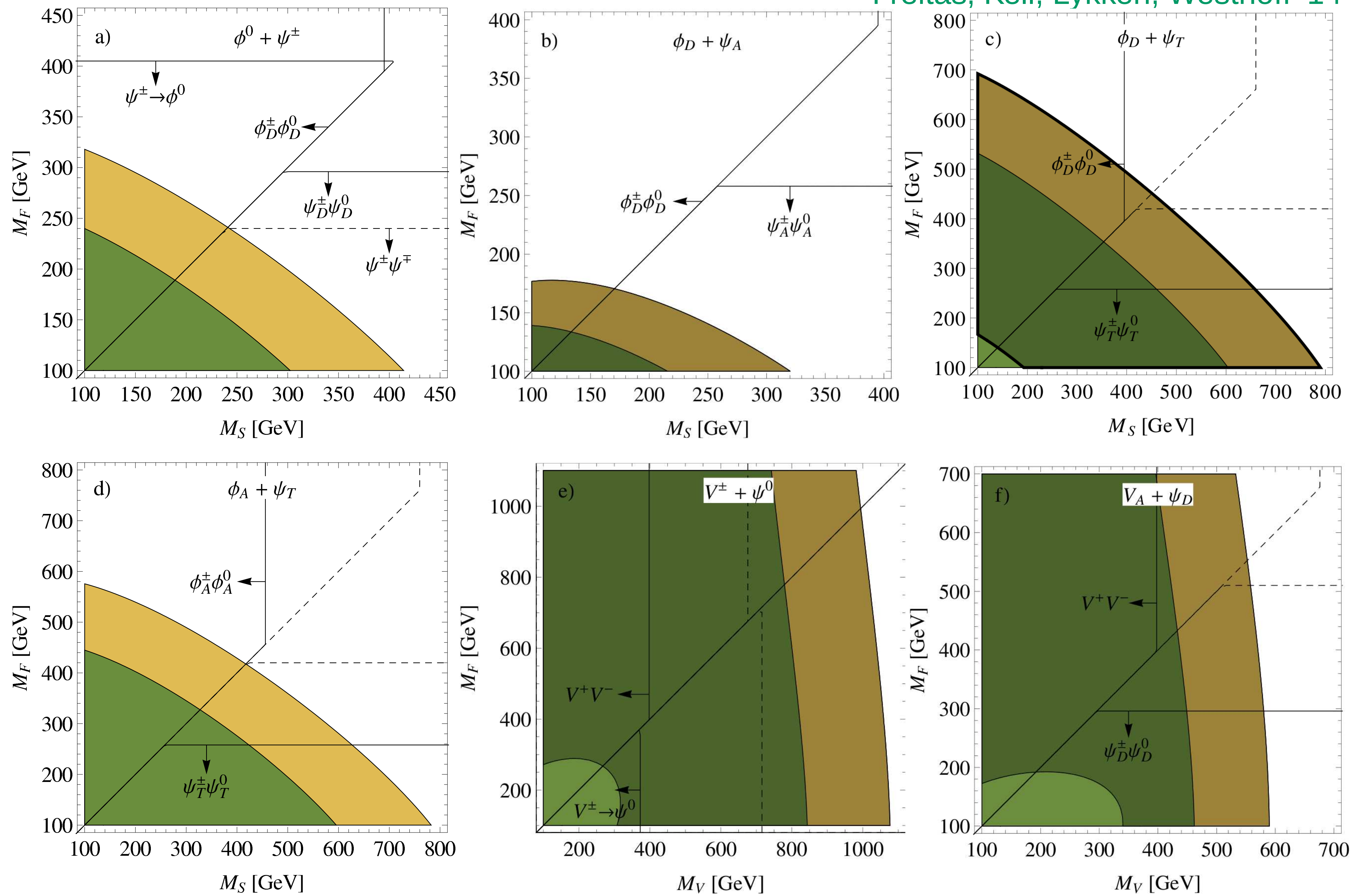
$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (29.3 \pm 8.4) \quad \longrightarrow \begin{cases} m_{\text{NP}} \sim \text{few} \times 100 \text{ GeV} \\ g_{\text{NP}} \sim 1 \end{cases}$$

$\longrightarrow$ 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



CP-violation and electric dipole moments

- Very severe limits on CP violation from from fermion EDMs, d_f, of e and n
- Best limits on d_e from paramagnetic systems (Tl, YbF, ThO):
  $|d_e| < 0.87 \times 10^{-28}\, e\,\mathrm{cm}$ (90% CL)
- Uncertainties from nuclear and multi-electron contributions
- Paramagnetic systems may be influenced by electron EDM
  $$\mathcal{L}_e^{\mathrm{EDM}} = -\frac{i}{2} d_e\, \bar{e}\sigma^{\mu\nu}\gamma_5 e\, F_{\mu\nu}$$
  and (spin-independent) electron-nucleon interactions
  $$\mathcal{L}_{eN}^{\mathrm{NSID}} = -i\frac{G_F}{\sqrt{2}}\,\bar{e}\gamma_5 e\,\bar{N}[C_S^{(0)} + C_S^{(1)}]\tau_3]N$$

  Fits of both contributions lead to weaker limis
  $|d_e| < 5.4 \times 10^{-27}\, e\,\mathrm{cm}$ (95% CL)
  $|C_S| < 4.5 \times 10^{-7}$ (95% CL)

$$C_S = C_S^{(0)} + \frac{Z-N}{Z+N} C_S^{(1)}$$

Dzuba, Flambaum, Harabati '11
Engel, Ramsey-Musolf, von Kolck '13
Chupp, Ramsey-Musolf '14

New sources of CP-violation

- Contributions to d_e and d_n from CKM in SM are very small
- New CP-violation in many models of **flavor** and **extended Higgs sectors**
- 2HDM is good toy model

Two Higgs Doublet Model

Main sources of $\not{C}\!\not{P}$ violation in Higgs sector:

- Mixing between scalar and pseudoscalar from **scalar potential**
- Misalignment between fermion masses and **Yukawa couplings**

Minimal field content to achieve both: add second Higgs doublet

Scalar potential

$$V = \tfrac{1}{2}m_{11}^2\Phi_1^\dagger\Phi_1 + \tfrac{1}{2}m_{22}^2\Phi_2^\dagger\Phi_2 + \tfrac{1}{2}\left(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right)$$
$$+ \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+ \left[\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \tfrac{1}{2}\lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \tfrac{1}{2}\lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right]$$

$$v_1 = \langle\Phi_1\rangle = v\cos\beta, \qquad v_2 = \langle\Phi_2\rangle = v\sin\beta\, e^{i\xi}$$

complex parameters, can be made real by redefining $\Phi_{1,2}$

parameters with physical complex phase

Two Higgs Doublet Model

$\mathbb{Z}_2$ symmetry to avoid FCNC: $\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2$

$\longrightarrow$ Φ_1 and Φ_2 cannot couple to the same fermion F ($F = u, d, \ell$)

May be **softly broken** by m_{12}^2

Scalar potential

$$V = \tfrac{1}{2} m_{11}^2 \Phi_1^\dagger \Phi_1 + \tfrac{1}{2} m_{22}^2 \Phi_2^\dagger \Phi_2 + \tfrac{1}{2}\Big(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}\Big)$$

$$+ \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$

$$+ \Big[\tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \tfrac{1}{2}\lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \tfrac{1}{2}\lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{h.c.}\Big]$$

$v_1 = \langle \Phi_1 \rangle = v \cos\beta, \qquad v_2 = \langle \Phi_2 \rangle = v \sin\beta \, e^{i\xi}$

complex parameters, can be made real by redefining $\Phi_{1,2}$

parameters with physical complex phase

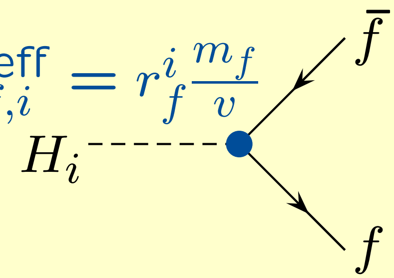
Yukawa couplings

Aligned 2HDM: No $\mathbb{Z}_2$ symmetry, but $y_f^{\Phi_1} \propto y_f^{\Phi_2}$ (3×3 matrices in flavor space) to void FCNC

Pich, Tuzon ’09

$$\mathcal{L}_{\text{Yuk}} = -\frac{1}{v} \sum_i \sum_f r_f^i m_f \, \bar{f}_L f_R H_i + \text{h.c.}$$

$$Y_{f,i}^{\text{eff}} = r_f^i \frac{m_f}{v}$$



$$r^i_{r,d,\ell} = R_{i1} + (R_{i2} + iR_{i3})\zeta_{u,d,\ell}$$

$R =$ mixing matrix of $H_{1,2,3}$

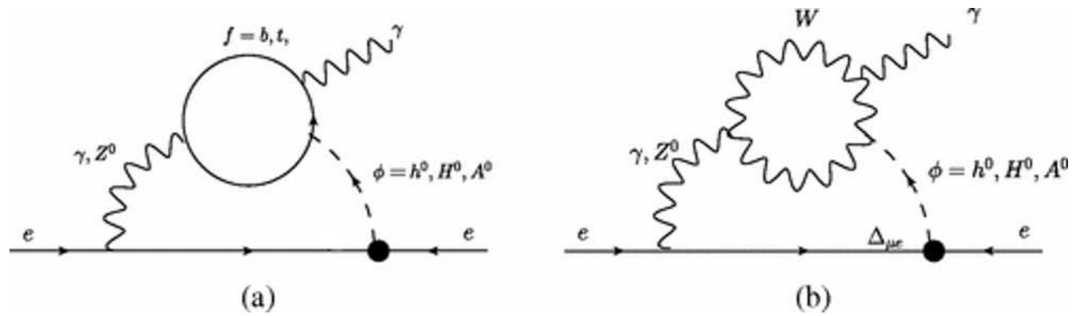
$\zeta_{u,d,\ell} =$ complex $\mathcal{O}(1)$ numbers

→ $\not{C}\not{P}$ in H_1 decays possible also if $R_{13} = 0$ (no scalar–pseudoscalar mixing)

Electric dipole moments in 2HDM

a) Electron EDM: Main contribution from 2-loop Barr-Zee diagrams:

Barr, Zee ’90



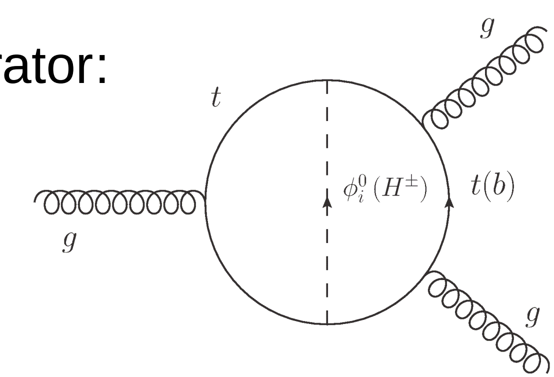
$$\left[\frac{d_e}{e}\right]_t = \frac{\sqrt{2}\alpha G_F v}{6\pi^3}\sum_i \left[f\left(\frac{m_t^2}{m_i^2}\right) \text{Re}\, Y^{\text{eff}}_{e,i}\, \text{Im}\, Y^{\text{eff}}_{t,i} + g\left(\frac{m_t^2}{m_i^2}\right) \text{Im}\, Y^{\text{eff}}_{e,i}\, \text{Re}\, Y^{\text{eff}}_{t,i}\right]$$

$$\left[\frac{d_e}{e}\right]_W = -\frac{\sqrt{2}\alpha G_F}{16\pi^3}\sum_i \left[3f\left(\frac{M_W^2}{m_i^2}\right) + 5g\left(\frac{M_W^2}{m_i^2}\right)\right] \text{Im}\left\{Y^{\text{eff}}_{e,i} v_i\right\}$$

b) Neutron EDM: Main contribution from Weinberg operator:

$$[d_n]_{H^\pm} \propto \text{Im}\{Y^{\text{eff}*}_{t,i} Y^{\text{eff}}_{b,i}\}$$

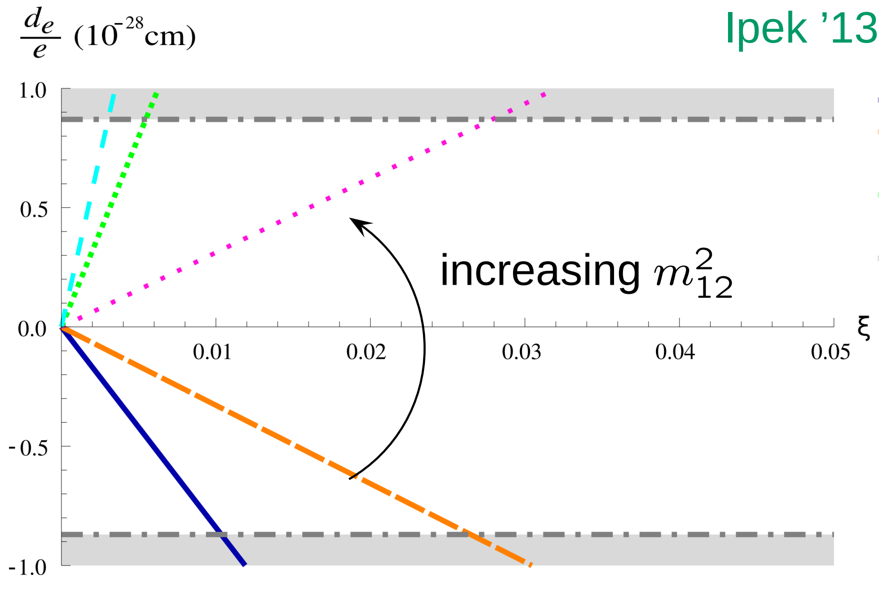
Weinberg ’89



EDM constraints

For $\not{C}\not{P}$ in scalar potential:

Ipek '13



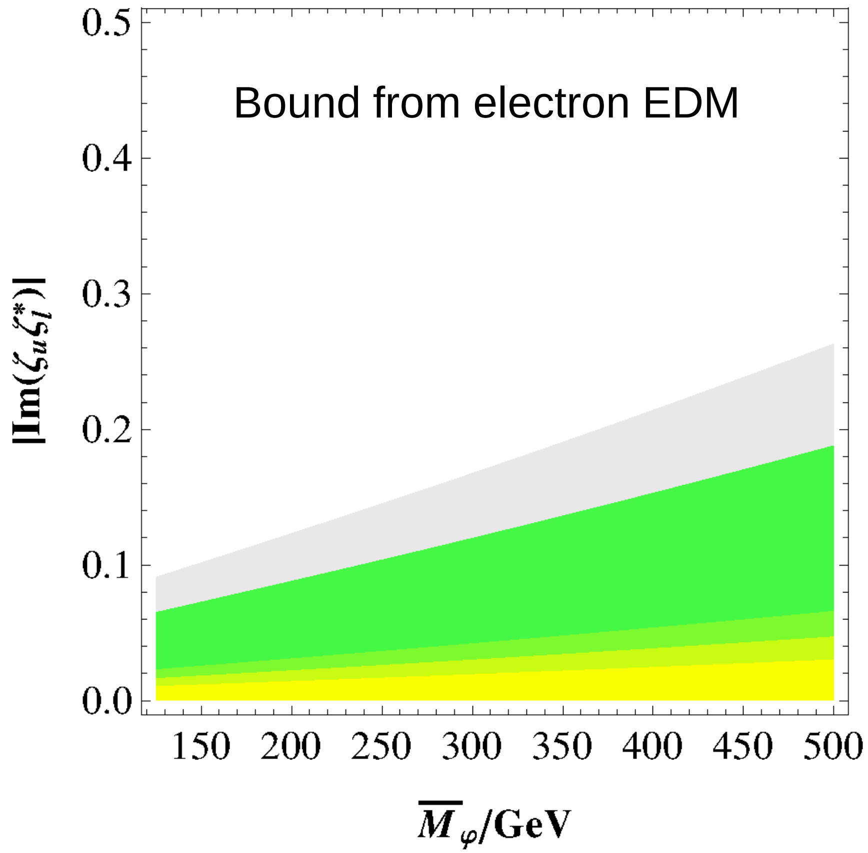
$(m_{2,3} = 400...500$ GeV$, t_\beta = 1, \lambda_6 = 5)$

Cancellation between t and W loop

$\longrightarrow$ $\xi \sim 0.1$ allowed with mild tuning

For $\not{C}\not{P}$ in Yukawa couplings:

Jung, Pich '13

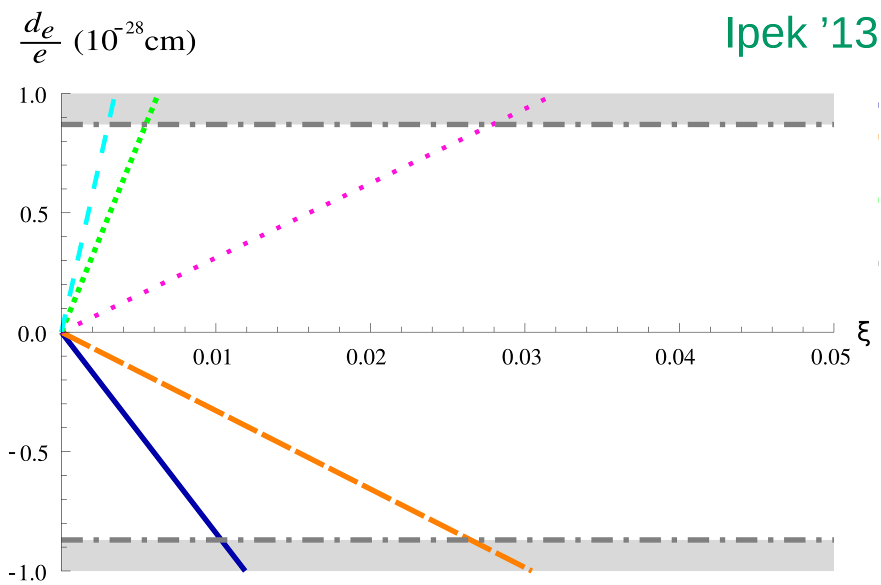


$\longrightarrow$ $\mathcal{O}(0.1)$ CP phases allowed

EDM constraints

For $\not{C}\not{P}$ in scalar potential:

Ipek '13



Curves for different m_{12}^2

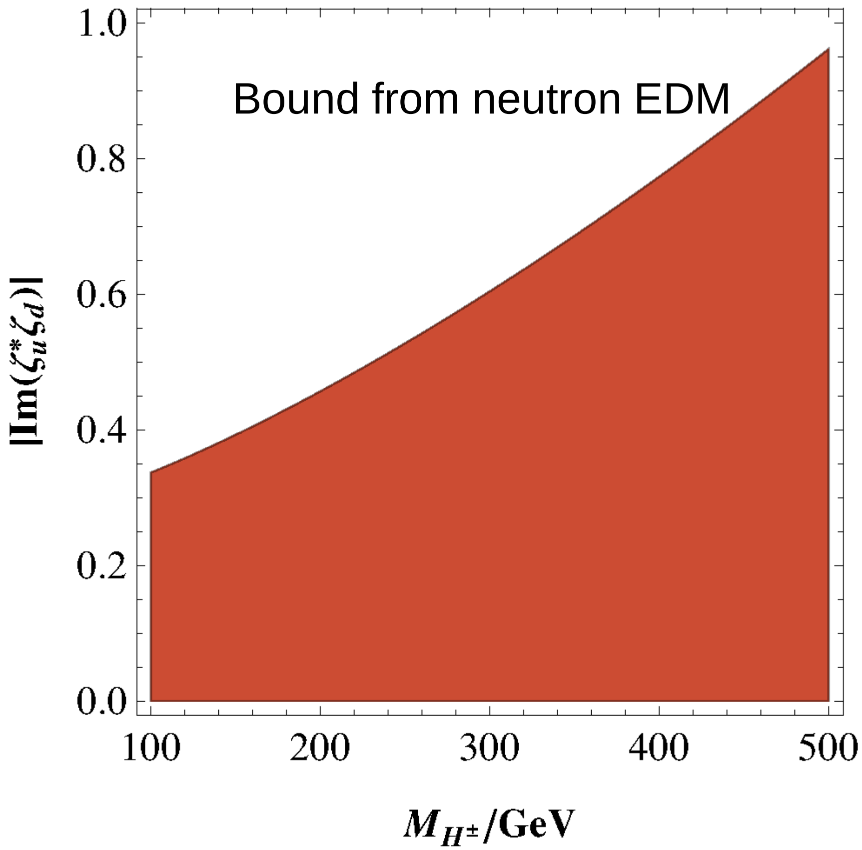
($m_{2,3} = 400...500$ GeV, $t_\beta = 1, \lambda_6 = 5$)

Cancellation between t and W loop

$\longrightarrow$ $\xi \sim 0.1$ allowed with mild tuning

For $\not{C}\not{P}$ in Yukawa couplings:

Jung, Pich '13



$\longrightarrow$ $\mathcal{O}(0.1)$ CP phases allowed

Lepton flavor violation

- Lepton flavor conservation is accidental in SM, due to particle content
  $\longrightarrow$ Very sensitive probe of new physics

- Model-independent description in terms of Dim6 operators:

  $$\mathcal{L}_{\mathsf{LFV}} = \frac{1}{\Lambda^2} \sum_i C_i \mathcal{Q}_i$$

- Same operators contribute to
  $\ell_1^\pm \to \ell_2^\pm \gamma$, $\quad \ell_1^\pm \to \ell_2^\pm \ell_2^\pm \ell_2^\mp$,
  μ–e conversion, and $Z \to \ell_1^\pm \ell_2^\mp$

$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
		$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$\psi^2 \varphi^3$			
$Q_{e\varphi}$		$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$	
$(\bar{L}L)(\bar{L}L)$		$(\bar{L}L)(\bar{Q}Q)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r) \varepsilon_{jk} (\bar{q}^k_s u_t)$
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}^k_s \sigma^{\mu\nu} u_t)$
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$		

Existing constraints

μ–e interactions:

Coeff. $\Lambda = m_Z$	$\mu^+ \to e^+\gamma$ BR$\leq 5.7\cdot10^{-13}$	$Z \to e^\pm\mu^\mp$ BR$\leq 7.5\cdot10^{-7}$	$\mu^+ \to e^+e^-e^+$ BR$\leq 1.0\cdot10^{-12}$
$C_{e\gamma}^{21/12}$	**$2.5\cdot10^{-16}$**		$3.8\cdot10^{-15}$
$C_{eZ}^{21/12}$	**$1.4\cdot10^{-13}$**	$3.9\cdot10^{-8}$	$4.0\cdot10^{-8}$
$C_{\varphi l(1)}^{12}$	$2.6\cdot10^{-10}$	$3.9\cdot10^{-8}$	**$3.5\cdot10^{-11}$**
$C_{\varphi l(3)}^{12}$	$2.5\cdot10^{-10}$	$3.9\cdot10^{-8}$	**$3.5\cdot10^{-11}$**
$C_{\varphi e}^{12}$	$2.5\cdot10^{-10}$	$3.9\cdot10^{-8}$	**$3.7\cdot10^{-11}$**
$C_{e\varphi}^{21/12}$	**$2.8\cdot10^{-8}$**		$8.7\cdot10^{-6}$
$C_{le}^{2111/1112}$	$4.4\cdot10^{-8}$		**$3.1\cdot10^{-11}$**
$C_{le}^{2221/1222}$	**$2.1\cdot10^{-10}$**		
$C_{le}^{2331/1332}$	**$1.2\cdot10^{-11}$**		
C_{ee}^{2111}			**$1.1\cdot10^{-11}$**
C_{ll}^{2111}			**$1.1\cdot10^{-11}$**

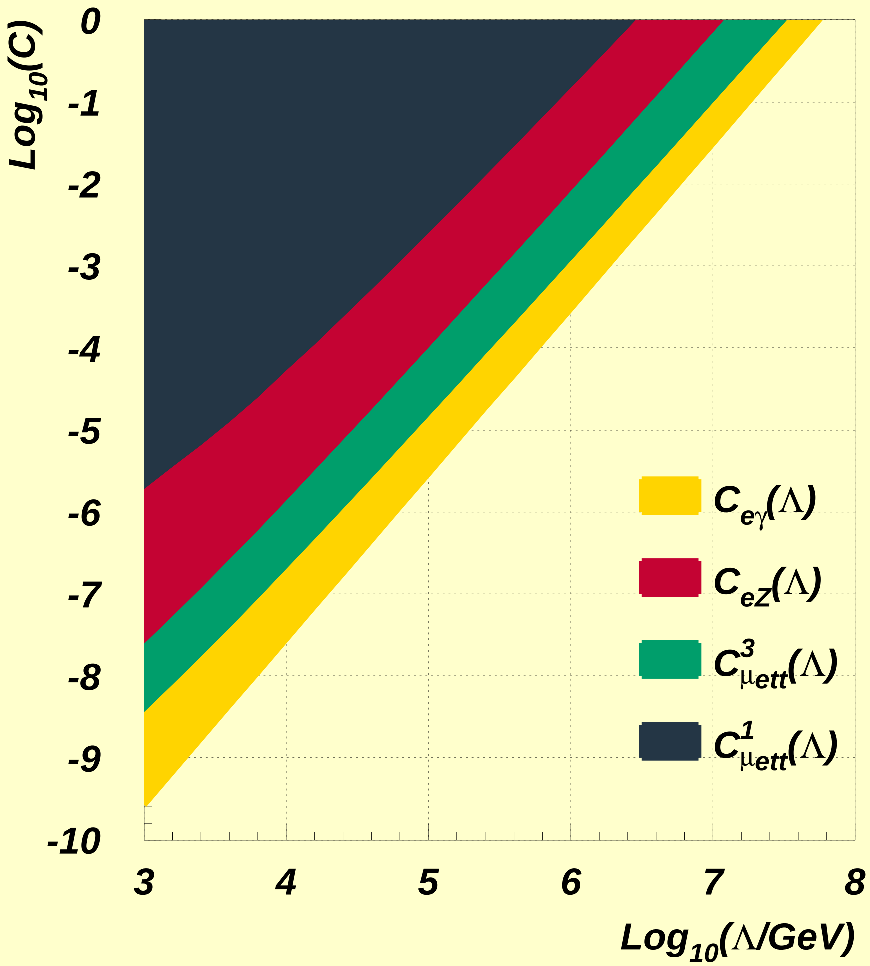
τ–μ interactions:

Coeff. $\Lambda = m_Z$	$\tau^+ \to \mu^+\gamma$ BR$\leq 4.4\cdot10^{-8}$	$Z \to \mu^\pm\tau^\mp$ BR$\leq 1.2\cdot10^{-5}$	$\tau^+ \to \mu^+\mu^-\mu^+$ BR$\leq 2.1\cdot10^{-8}$
$C_{e\gamma}^{32/23}$	**$2.7\cdot10^{-12}$**		$3.8\cdot10^{-11}$
$C_{eZ}^{32/23}$	**$1.5\cdot10^{-9}$**	$1.5\cdot10^{-7}$	$8.7\cdot10^{-7}$
$C_{\varphi l(1)}^{23}$	$1.7\cdot10^{-7}$	$1.5\cdot10^{-7}$	**$1.3\cdot10^{-8}$**
$C_{\varphi l(3)}^{23}$	$1.6\cdot10^{-7}$	$1.5\cdot10^{-7}$	**$1.3\cdot10^{-8}$**
$C_{\varphi e}^{23}$	$1.6\cdot10^{-7}$	$1.5\cdot10^{-7}$	**$1.3\cdot10^{-8}$**
Coeff. $\Lambda = m_Z$		$H \to \mu^\pm\tau^\mp$ BR$\leq 1.8\cdot10^{-2}$	
$C_{e\varphi}^{32/23}$	$1.9\cdot10^{-6}$	**$9.0\cdot10^{-8}$**	$1.6\cdot10^{-5}$
$C_{le}^{3112/2113}$	**$4.8\cdot10^{-4}$**		
$C_{le}^{3222/2223}$	$2.3\cdot10^{-6}$		**$1.1\cdot10^{-8}$**
$C_{le}^{3222/2223}$	**$1.4\cdot10^{-7}$**		
C_{ee}^{3222}			**$4.0\cdot10^{-9}$**
C_{ll}^{3222}			**$4.0\cdot10^{-9}$**

Pruna, Signer '15

Limits for C_i/Λ^2 in GeV^{-2}, matched at scale M_Z

Small LFV effect may be generated at scales $\Lambda \gg M_Z$
$\longrightarrow$ RG running effects become important



Pruna, Signer ’14

Conclusions

- W/Z precision data are stress-testing the SM
  - $\longrightarrow$ Indirect determinations of m_{t} and M_{H}
  - $\longrightarrow$ Strong constraints on new physics $\longrightarrow$ talk by L. Reina
  - $\longrightarrow$ LHC data may help resolve existing discrepancies

- Low-energy precision experiments will become competitive with W/Z-pole data
  - $\longrightarrow$ Unique probes for light new physics
  - $\longrightarrow$ Muon $g-2$ may already hint toward BSM, but hadronic error could be underestimated

- Good control over input parameters m_{t}, M_{W}, α_{s} and $\Delta\alpha_{\mathrm{had}}$ is crucial
  - $\longrightarrow$ Probably limited by theory uncertainties!

- Studies of $\not{C}\!\not{P}$ from EDMs, Higgs and flavor physics are complementary
  - $\longrightarrow$ Improvement of nuclear and atomic theory uncertainties important for future EDM measurements

- FLV provide sensitive tests of high-scale flavor physics