Motivation for e-EDM searches

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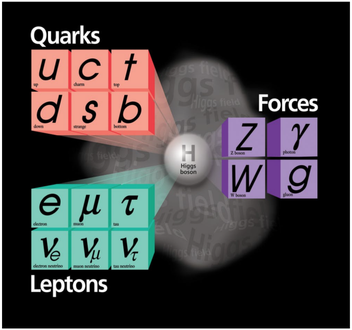
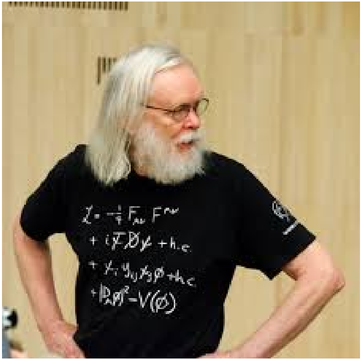
Plan of the lecture

1. **Current status of the Standard Model**
2. **Strategies to look for New Physics at low-energy**
3. **Current status of the EDMs**
4. **EDMs, g-2 and cLFV interrelationship**
5. **Conclusions and future prospects**

The Standard Model (SM) is a remarkably simple Quantum Field Theory (QFT) that describes well all microscopic phenomena that we observe in Nature



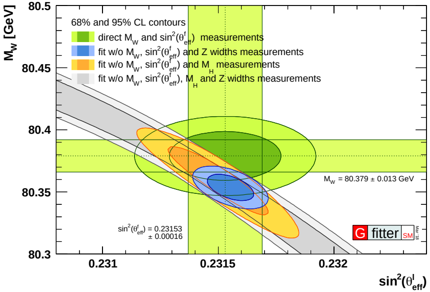
The SM describes fundamental interactions among elementary particles



“This is short enough to write on a T-shirt!”

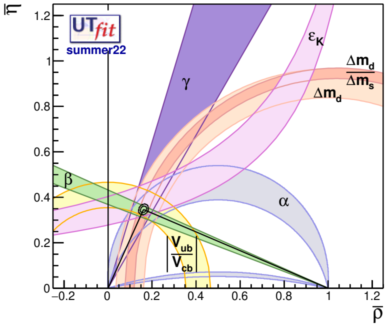
[John Ellis]

The SM legacy



The LEP legacy

- Z-pole observables @ the 0.1% level
- Important constraints on many BSM



The B-factories legacy

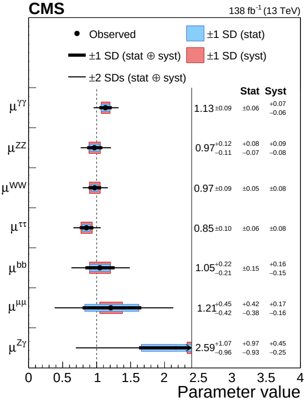
- Confirmation of the CKM mechanism
- Important constraints on many BSM

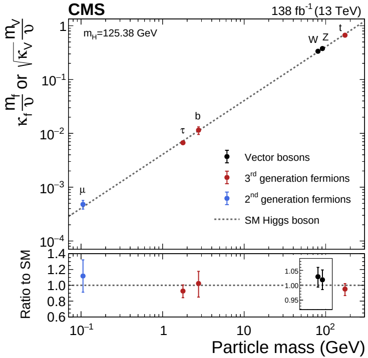
The LHC legacy (so far)

- **Higgs Boson mass** (combined LHC Run 1 + 2 results of ATLAS and CMS)

$$m_H = 124.94 \pm 0.17\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.})\ \mathrm{GeV}$$

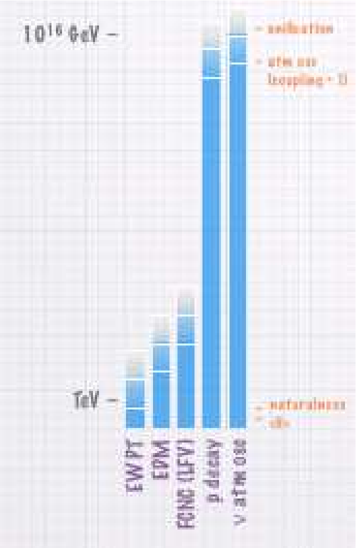
- **Higgs Boson couplings** $\quad \mu_i^f = \dfrac{\sigma_i \times BR^f}{(\sigma_i \times BR^f)_{SM}}$ (signal strengths)





Why do we need New Physics (NP)?

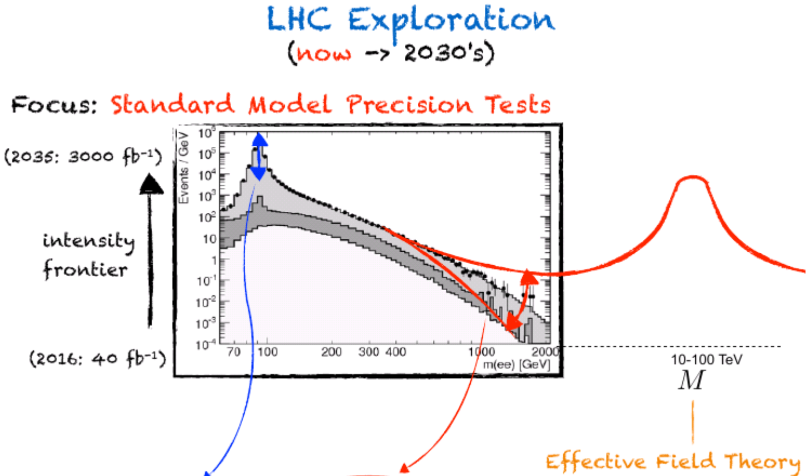
- **Gravity** $\Longrightarrow$ $\Lambda_{\text{Planck}} \sim 10^{18-19}\ \text{GeV}$
- **Neutrino masses** $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}\ \text{GeV}$
- **BAU**: evidence of CPV beyond SM
  - Electroweak Baryogenesis $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim \text{TeV}$
  - Leptogenesis $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}\ \text{GeV}$
- **Dark Matter (WIMP)** $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim \text{TeV}$
- **Hierarchy problem**: $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim \text{TeV}$



SM = effective theory at the EW scale

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d\geq 5} \frac{c_{ij}^{(d)}}{\Lambda_{NP}^{d-4}}\, O_{ij}^{(d)}$$

- $\mathcal{L}_{\text{eff}}^{d=5} = \frac{y_\nu^{ij}}{\Lambda_{\text{see-saw}}} L_i L_j \phi\phi,$
- $\mathcal{L}_{\text{eff}}^{d=6}$ generates FCNC operators



$$\sigma \propto \sum |Amp|^2 \simeq SM^2\left(1 + c_i \frac{E^2}{M^2} + c_i^2 \frac{E^4}{M^4}\right) \leftarrow \mathcal{L}_{eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{M^2}\mathcal{O}_i^{(6)} + \cdot$$

Where to look for New Physics at low-energy?

- **Processes very suppressed or even forbidden in the SM**
- **Processes predicted with high precision in the SM**

....

$0\nu\beta\beta$

CPV in ν osc.

CPV and FCNC in quark sector

Precision EW tests at Z pole

Parity Violating electron scattering (Qweak, ...)

Atomic Parity Violation

β-decays (universality, non V-A, T violation, ...)

EDMs

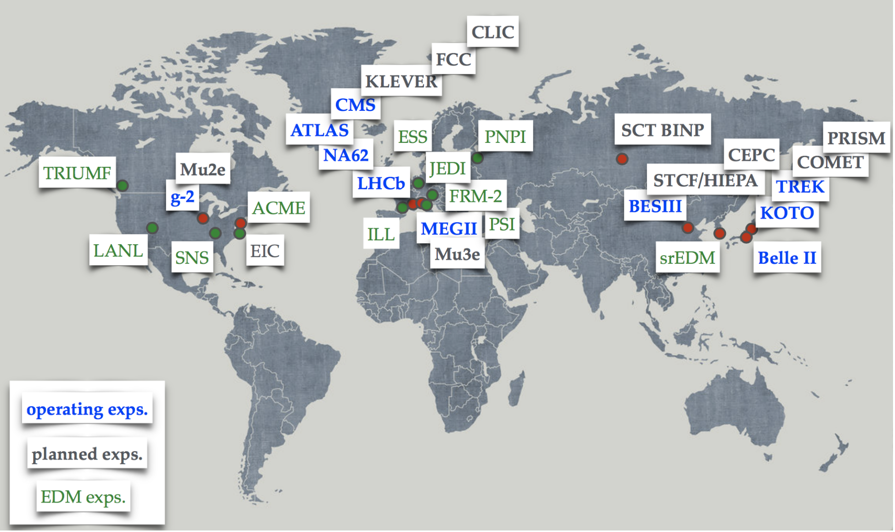
LFV in μ & τ decays

muon g-2

....

High-intensity frontier: A collective effort to determine the NP dynamics

Experimental status



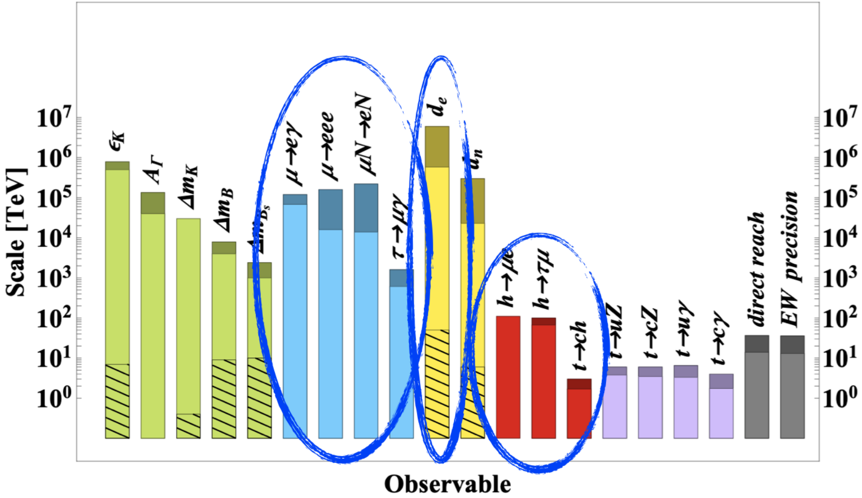
Experimental bounds

Process	Present	Experiment	Future	Experiment
$\mu \to e\gamma$	1.5×10^{-13}	MEG	$\approx 6 \times 10^{-14}$	MEG II
$\mu \to 3e$	1.0×10^{-12}	SINDRUM	$\approx 10^{-16}$	Mu3e
μ^- Au $\to e^-$ Au	7.0×10^{-13}	SINDRUM II	?	
μ^- Ti $\to e^-$ Ti	4.3×10^{-12}	SINDRUM II	?	
μ^- Al $\to e^-$ Al	–		$\approx 10^{-16}$	COMET, MU2e
$\tau \to e\gamma$	3.3×10^{-8}	Belle & BaBar	$\sim 10^{-9}$	Belle II
$\tau \to \mu\gamma$	4.4×10^{-8}	Belle & BaBar	$\sim 10^{-9}$	Belle II
$\tau \to 3e$	2.7×10^{-8}	Belle & BaBar	$\sim 10^{-10}$	Belle II
$\tau \to 3\mu$	2.1×10^{-8}	Belle & BaBar	$\sim 10^{-10}$	Belle II
$d_e(\mathrm{e\ cm})$	1.1×10^{-29}	ACME	$\sim 3 \times 10^{-31}$	ACME III
$d_\mu(\mathrm{e\ cm})$	1.8×10^{-19}	Muon (g-2)	$\sim 10^{-22}$	PSI

Table: Present and future experimental sensitivities for relevant low-energy observables.

- So far, only upper bounds. Still excellent prospects for exp. improvements.
- We can expect a NP signal in all above observables below the current bounds.

Bounds on the NP scale



[Physics Briefing Book, 1910.11775]

Electric and Magnetic dipole moments

- Interaction of a particle with spin $\vec{S}$ with with an electric/magnetic field

$$\mathcal{H} = -\mu \frac{\vec{S}}{|S|} \cdot \vec{B} - d \frac{\vec{S}}{|S|} \cdot \vec{E}$$

Magnetic dipole moment (MDM) μ

Electric dipole moment (EDM) d

- properties under Time Reversal T and Parity P

$$T: \quad \vec{E} \to +\vec{E} \quad \vec{B} \to -\vec{B} \quad \vec{S} \to -\vec{S}$$

$$P: \quad \vec{E} \to -\vec{E} \quad \vec{B} \to +\vec{B} \quad \vec{S} \to +\vec{S}$$

- MDMs are P and T even

- EDMs are P and T odd (CP violating, assuming CPT = locality + Lorentz + spin-statistics)

Relevance of EDMs for particle physics

- Are EDMs relevant for fundamental particle physics ?

  - typical energy resolution in modern EDM experiments

$$\Delta E \sim 10^{-6}\,\text{Hz} \sim 10^{-21}\,\text{eV}$$

  - translates into EDM sensitivity

$$d \sim \frac{\Delta E}{\text{Electric field}} \sim 10^{-25}\,\text{e cm} \qquad \text{for} \qquad \text{Electric field} \sim 10^{4}\,\text{V/cm}$$

  - theoretically inferring scaling of EDMs (see later)

$$d \sim \frac{1}{16\pi^2} \times \frac{1\,\text{MeV}}{\Lambda^2} \quad \longrightarrow \quad \Lambda \gtrsim 1\,\text{TeV}$$

Relativistic generalization of EDMs

- Interaction of a fermion with the photon field

$$-d_f \frac{\vec{S}}{|S|} \cdot \vec{E} \quad \rightarrow \quad d_f \frac{i}{2} (\bar{f} \sigma_{\mu\nu} \gamma_5 f) F^{\mu\nu}$$

$$-\mu_f \frac{\vec{S}}{|S|} \cdot \vec{B} \quad \rightarrow \quad e(\bar{f} \gamma_\mu f) A^\mu + a_f \frac{e}{4m_f} (\bar{f} \sigma_{\mu\nu} f) F^{\mu\nu}$$

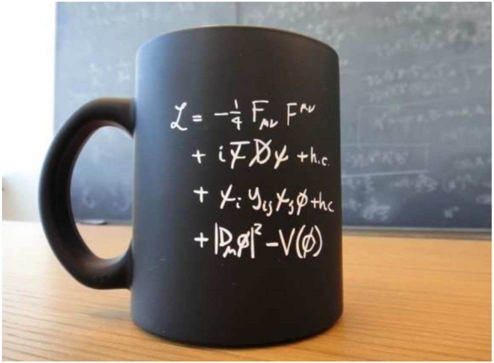
- minimal coupling of fermions with photon gives rise to MDM with gyromagnetic ratio $g = 2$

$$\mu_f = g_f \frac{e}{2m_f} \quad , \quad (g_f - 2) = 2a_f$$

- dimension 5 operators induce an EDM d_f and a MDM a_f

- absent for elementary particles at the classical level, but can be induced by loop corrections

The Standard Model of Particle Physics



CP is violated in nature

$BR(K_L \to \pi^+ \pi^-) \neq 0$

(Cronin, Fitch 1964)

can be accommodated
in the Standard Model
with 3 generations
$\to$ CKM matrix

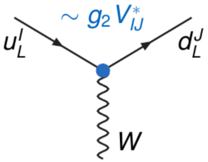
Standard Model
contains another source
of CP violation:
the QCD theta term

more on that later ...

CKM matrix & Jarlskog invariant

parametrizes the misalignment of
up-type quarks and down-type quarks
in flavor space

appears in the weak interactions of
quarks with the W boson (charged current)



$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

unitary 3×3 matrix $\rightarrow$ 3 angles 6 phases

5 phases can be reabsorbed
by redefinition of the quark fields

$$u \rightarrow e^{i\phi_u} u \;, \quad d \rightarrow e^{i\phi_d} d \;, \quad \ldots$$

CKM matrix contains
one physical CP violating phase

Jarlskog invariant

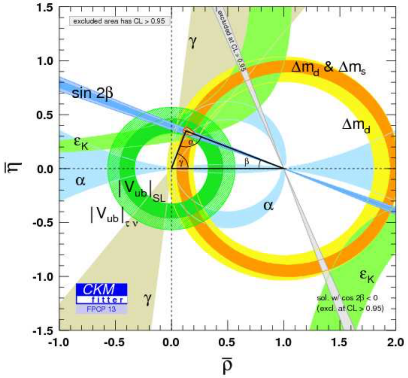
$$\mathrm{Im}[V_{ij} V_{kl} V^*_{i\ell} V^*_{kj}] = J \sum_{mn} \varepsilon_{ikm} \varepsilon_{j\ell n}$$

Unitarity triangle fit (UTfit)

Within the experimental and theoretical uncertainties, the CKM matrix gives a consistent description of all observed flavor and CP violating phenomena

Extraction of the CKM phase from the global fit gives

$$\gamma = 69.7^{+1.3}_{-2.8}$$



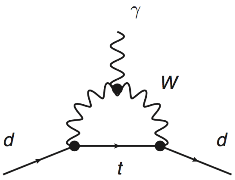
Jarlskog invariant

$$\mathrm{Im}[V_{ij}V_{kl}V^*_{i\ell}V^*_{kj}] = J\sum_{mn}\varepsilon_{ikm}\varepsilon_{j\ell n}$$

Quark EDMs from the CKM matrix

try 1 loop with weak interactions to access the phase of the CKM matrix

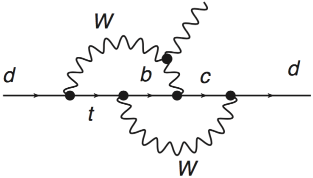
$$d_d \propto \frac{e}{16\pi^2} G_F m_d \mathrm{Im}(V_{td} V_{td}^*) = 0$$



- loop suppressed
- first order in the weak interactions
- helicity suppressed
- pick up a CKM element that contains a CP violating phase
- 1 loop is not sufficient...

Quark EDMs from the CKM matrix

try 2 loops with weak interactions to access the phase of the CKM matrix



$$d_d \propto \frac{e}{(16\pi^2)^2} G_F^2 m_c^2 m_d$$

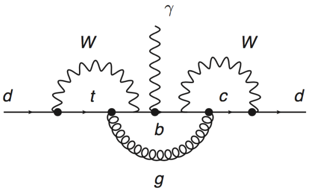
$$\times \mathrm{Im}(V_{td} V_{tb}^* V_{cb} V_{cd}^*) \neq 0$$

- 2 loop suppressed
- second order in the weak interactions
- pick up CKM combination with non-zero CP phase

seems to work!
however when one adds up all 2-loop diagrams one still gets 0...
(Shabalin, 1981)

Quark EDMs from the CKM matrix

first non-vanishing contribution to quark EDMs arises at the 3-loop level



$$d_d \propto \frac{e}{(16\pi^2)^2} \frac{g_s^2}{16\pi^2} G_F^2 m_c^2 m_d$$

$$\times \text{Im}(V_{td} V_{tb}^* V_{cb} V_{cd}^*) \neq 0$$

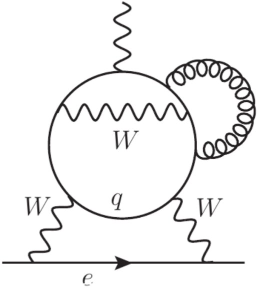
- two electro-weak loops
- one additional gluon loop

$$d_d \simeq 10^{-34} ecm$$

(Khriplovich 1986,
Czarnecki, Krause 1997)

Lepton EDMs from the CKM matrix

for lepton EDMs one needs at least one additional loop
to switch from leptons to quarks and to access the CKM phase
(Khriplovich, Pospelov 1991)



$$d_e \propto \frac{e}{(16\pi^2)^3} \frac{g_s^2}{16\pi^2} G_F^3 m_c^2 m_s^2 m_e$$

$$\times \mathrm{Im}(V_{td} V_{tb^*} V_{cb} V_{cd}^*)$$

- three electro-weak loops
- one additional gluon loop

$$d_e \simeq 10^{-44} ecm$$

(Pospelov, Ritz 2013)

Experimentally accessible EDMs

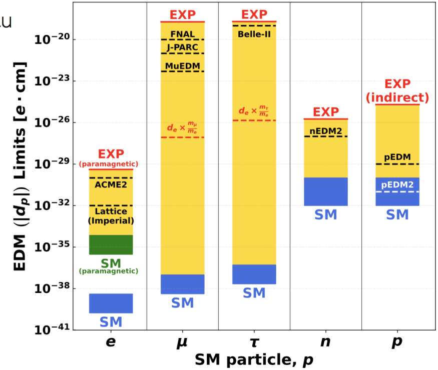
1. EDM of paramagnetic systems: atoms (Tl, Fr, ...) and molecules (ThO, YbF, ...)

2. EDM of diamagnetic atoms (Hg, Ra, Rn, ...)

3. EDM of the neutron, proton, deuteron

4. EDM of the muon/tau

[Courtesy of A. Keshavarzi]



CP violating operators

- CP-odd Lagrangian at the GeV scale

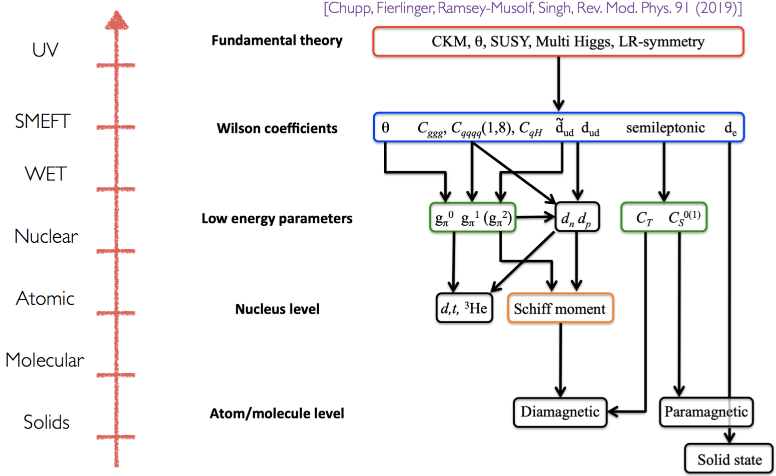
$\frac{g_s^2}{32\pi^2}\bar{\theta}G^A_{\mu\nu}\tilde{G}^{\mu\nu,\,A}$	QCD theta term
$d_f\frac{i}{2}(\bar{f}\sigma_{\mu\nu}\gamma_5 f)F^{\mu\nu}$	EDMs of quarks and leptons
$d_q^c\frac{ig_s}{2}(\bar{q}_\alpha\sigma^{\mu\nu}T^A_{\alpha\beta}\gamma_5 q_\beta)G^A_{\mu\nu}$	chromo EDMs (CEDMs) of quarks
$\frac{w}{3}f^{ABC}G^A_{\mu\nu}\tilde{G}^{\nu\rho,\,B}G^{\mu,\,C}_{\rho}$	Weinberg three gluon operator
$C_{ij}(\bar{f}_i f_i)(\bar{f}_j i\gamma_5 f_j)$	CP violating 4 fermion operators

- terms at dimension 4, dimension 5, dimension 6

From the fundamental theory to EDMs

- Need to predict EDMs of composite systems in terms of CP-violating sources

[Chupp, Fierlinger, Ramsey-Musolf, Singh, Rev. Mod. Phys. 91 (2019)]



EDMs of nucleons

proton and neutron EDMs

high sensitivity to the constituent quark EDMs

additional contributions from CP-odd pion nucleon couplings
(mainly induced by chromo-EDMs)

also the Weinberg 3 gluon operator can contribute

additional contributions from CP-odd 4 fermion operators

e.g. $$d_n \simeq 1.4\,(d_d - \frac{1}{4} d_u) + 1.1\,e\,(\tilde{d}_d + \frac{1}{2}\tilde{d}_u) + e\,22\,\text{MeV}\,w + O(C_{ij}) + \ldots$$

most of the terms have uncertainties of O(1)

EDMs of nucleons

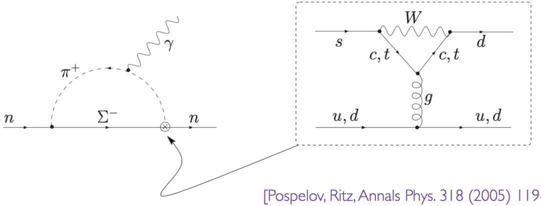
- qEDM is <u>not</u> the dominant source of the CKM-induced EDM of nucleons

  - 4-quark CP-odd operators + chirally enhanced contributions

$$d_N^{(\mathrm{lim})}(\mathcal{J}) \sim e c_n \mathcal{J} G_F^2 m_{\mathrm{had}}^3$$
$$< 10^{-29} e\mathrm{cm} \times c_n \left(\frac{m_{\mathrm{had}}}{300\,\mathrm{MeV}}\right)^3$$

→ $d_N \sim 10^{-(32\div31)}\, e\, cm$

[Khriplovich, Zhitnitsky, Phys. Lett. B 109 (1982)
Gavela, Le Yaouanc, Oliver, Pene, Raynal, Pham, Phys. Lett. B 109 (1982)
McKellar, Choudhury, He, Pakvasa, Phys. Lett. B 197 (1987)
Mannel, Uraltsev, Phys. Rev. D 85 (2012)]



[Pospelov, Ritz, Annals Phys. 318 (2005) 119-169]

Fig. 6. A leading contribution to the neutron EDM in the Standard Model, arising via a four-quark operator generated by a strong penguin, and then a subsequent enhancement via a chiral π^+ loop.

Diamagnetic EDMs

EDMs of diamagnetic atoms (Hg, Ra, Rn, ...)

all electron spins are paired up
suppressed sensitivity to the electron EDM

sensitivity to the EDM of the nucleus,
that is mainly induced by CP-odd pion nucleon couplings,
that in turn depend mainly on the quark chromo-EDMs

additional contributions from CP-odd electron nucleon couplings
(induced by CP-odd 4 fermion contact terms)

e.g. $|d_{Hg}| \simeq 10^{-2}\, d_e + 7 \times 10^{-3}\, e\,(\tilde{d}_u - \tilde{d}_d) + O(C_S) + \ldots$

most of the terms come with uncertainties of $> O(1)$

Diamagnetic EDMs

- EDM of a neutral atom vanishes at LO [Schiff, Phys. Rev. 132 (1963)]

  within a neutral atom (in the non-relativistic limit and treating the nucleus as point-like) the atomic EDM vanishes due to screening of the applied electric field

- Diamagnetic = paired electrons (e.g. ^{199}Hg)

  - Schiff theorem evaded thanks to finite-size of the nucleus
  - atomic EDM is <u>suppressed</u> w.r.t. EDM of the nucleus (by an $(R_{\rm nucl}/R_{\rm atom})^2 \sim$ O(10³) factor)

- Leading contribution arises from Schiff moment $H = 4\pi \vec{S}\cdot\vec{\nabla}\delta^3(\vec{r})$

  - CKM contribution via CP-odd nucleon potential somewhat larger than nucleon EDM one

$$\mathcal{L}_{\rm nuc} = \frac{1}{\sqrt{2}} G_F \eta_{np} \bar{N} N \bar{N} i\gamma_5 N$$

[Flambaum, Khriplovich, Sushkov, Sov. Phys. JETP 60 (1984)
Donoghue, Holstein, Musolf, Phys. Lett. B 196 (1987)
Ginges and V.V. Flambaum, Phys. Rept. 397 (2004)
Ban et al., Phys. Rev. C 82 (2010)]

$$d_{\rm Hg}(\mathcal{J}) \sim -10^{-17}\left(\frac{S(\mathcal{J})}{e{\rm fm}^3}\right) e{\rm cm} \sim 10^{-25}\eta_{np}(\mathcal{J}) e{\rm cm},$$

→ $d_{\rm Hg}(\mathcal{J}) < 10^{-35} e{\rm cm}$

$$\eta_{np}^{(\rm lim)}(\mathcal{J}) \sim c_{\rm Schiff}\, \mathcal{J} G_F m_{\rm had}^2$$

Paramagnetic EDMs

EDMs of paramagnetic systems:
atoms (Tl, Fr, ...) and molecules (YbF, ThO, ...)

contain an unpaired electron
$\rightarrow$ mainly sensitive to the electron EDM that sees an enhanced effective electric field inside the atom/molecule

typical enhancement factor for atoms

$$d_{\text{para}} \sim \frac{10\, Z^3 \alpha_{\text{em}}}{J(J+1/2)(J+1)^2}\, d_e \quad , \qquad \begin{array}{c}\text{J: angular momentum} \\ \text{Z: atomic number}\end{array}$$

for polar molecules the enhancement can be even larger

additional contributions from CP-odd electron nucleon couplings
(induced by CP-odd 4 fermion contact terms)

e.g. $|d_{Tl}| \simeq 585\, d_e + e\, 43\,\text{GeV} \times (C_S^{(0)} - 0.2 C_S^{(1)}) + \ldots$

Paramagnetic EDMs

- Paramagnetic = unpaired electrons (e.g. ThO)

- Receives contributions from both eEDM and semi-leptonic CP-odd operators

$$\mathcal{L}_{CP} = -\frac{i}{2} d_e \bar{e} F\sigma\gamma_5 e - \frac{G_F}{\sqrt{2}} C_{SP} \bar{N} N \bar{e} i \gamma_5 e$$

- C_{SP} does not depend on the spin of the nucleus, coherently enhanced by A (# of nucleons)

- shift of atomic/molecular energy levels (under external E field)

$$\frac{\Delta E}{\mathcal{E}_{\text{ext}}} = f_d (d_e + r C_{SP})$$

- $f_d \simeq \frac{10\, Z^3 \alpha_{\text{em}}}{J(J+1/2)(J+1)^2} \sim O(10^{2\div3})$ enhancement factor due to relativistic violation of Schiff th.

- r : ratio of atomic matrix elements of C_{SP} and d_e operators ($r_{\text{ThO}} = 1.33 \times 10^{-20} e\text{cm}$)

- Equivalent EDM : $d_e^{\text{equiv}} \equiv r C_{SP}$

Paramagnetic EDMs

- CKM-induced C_{SP} contribution dominates w.r.t. the direct contribution from d_e

$$d_e^{\rm equiv}(\mathcal{J}) \sim 10^{-38} e{\rm cm}$$

[Pospelov, Ritz, Phys. Rev. D89 no. 5 (2014)]

- Breakthrough result in 2022

[Ema, Gao, Pospelov, Phys. Rev. Lett. 128 (2022)]

$$G_F C_{SP} \propto \mathcal{J} G_F^3 m_t^2 m_e m_s^{-1} \Lambda_{\rm hadr}^2$$

$$d_e^{\rm equiv} \simeq 1.0 \times 10^{-35}\, e\,{\rm cm}$$

- with O(30%) accuracy

- Equivalent EDM : $d_e^{\rm equiv} \equiv r C_{SP}$

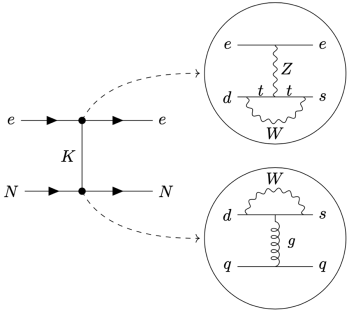
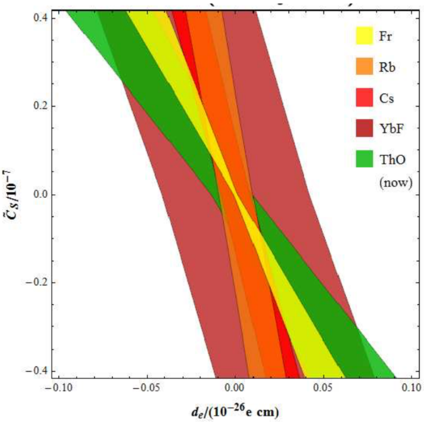


FIG. 1: EW^3 order diagram that dominates in the chiral limit. The top vertex is the CP-odd, P-even $K_S \bar{e} i\gamma_5 e$ generated in EW^2 order, and the bottom vertex is CP-even, P-odd $K_S \bar{N} N$ coupling generated at EW^1 order.

Disentangling contributions to EDMs



different paramagnetic atoms/molecules have different dependence on the electron EDM d_e and the CP-odd electron nucleon interaction C_S.

considering many systems simultaneously allows to bound d_e and C_S separately

QCD theta term

QCD theta term: $\frac{g_s^2}{32\pi^2}\bar{\theta} G\tilde{G}$

the QCD theta term is a dimension 4 operator
$\rightarrow$ not suppressed by any high scale
$\rightarrow$ generically expected to be O(1)

also contributes to the EDMs of hadronic systems

$$d_n \sim e\bar{\theta}\frac{m_u m_d}{m_u + m_d}\frac{1}{m_n^2} \sim \bar{\theta} \times 6 \times 10^{-17} ecm$$

experimental bound on d_n translates into the limit: $\theta \lesssim 10^{-9}$

$\rightarrow$ strong CP problem

QCD theta term

add an axion: a pseudoscalar that couples to $G\tilde{G}$

$$\mathcal{L} = \bar{\theta}\frac{g_s^2}{32\pi^2}G\tilde{G} + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$$

$$= \left(\bar{\theta} + \frac{a}{f_a}\right)\frac{g_s^2}{32\pi^2}G\tilde{G} + \frac{1}{2}\partial_\mu a \partial^\mu a$$

below the QCD scale a potential for the axion is induced

$$V(a) \propto \left(\bar{\theta} + \frac{a}{f_a}\right)^2$$

axion acquires a vev: $\langle a \rangle = -\bar{\theta} f_a$

the $G\tilde{G}$ term vanishes in the vacuum
$\rightarrow$ no contribution anymore to the neutron EDM

EDMs and heavy New Physics

- EDMs are secretly d=6 operators

  - helicity flipping

$$d_f \frac{i}{2}(\bar{f}\sigma_{\mu\nu}\gamma_5 f)F^{\mu\nu} = d_f \frac{i}{2}(\bar{f}_L\sigma_{\mu\nu}f_R - \bar{f}_R\sigma_{\mu\nu}f_L)F^{\mu\nu}$$

  - above the EW scale need to add a Higgs doublet to restore $SU(2)_L$ invariance

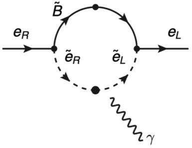
$$\frac{1}{\Lambda^2}H(\bar{f}_L\sigma_{\mu\nu}f_R)F^{\mu\nu} \quad \rightarrow \quad \frac{v}{\Lambda^2}(\bar{f}_L\sigma_{\mu\nu}f_R)F^{\mu\nu} \quad , \quad d_f \sim \frac{v}{\Lambda^2}$$

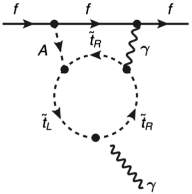
  - typical NP contributions at 1- and 2-loops

$$\frac{|d_e|}{e} \sim \begin{cases} \frac{eg^2}{16\pi^2}\frac{m_e}{\Lambda^2}\sin\phi_{\rm CPV} \sim 10^{-29}\, e\, cm \left(\frac{50\,\text{TeV}}{\Lambda}\right)^2 \sin\phi_{\rm CPV} & \text{(1-loop)} \\ e\left(\frac{g^2}{16\pi^2}\right)^2\frac{m_e}{\Lambda^2}\sin\phi_{\rm CPV} \sim 10^{-29}\, e\, cm \left(\frac{2.5\,\text{TeV}}{\Lambda}\right)^2 \sin\phi_{\rm CPV} & \text{(2-loops)} \end{cases}$$

EDMs and heavy New Physics

- EDMs are secretly d=6 operators





- typical NP contributions at 1- and 2-loops (e.g. from SUSY)

$$\frac{|d_e|}{e} \sim \begin{cases} \dfrac{eg^2}{16\pi^2}\dfrac{m_e}{\Lambda^2}\sin\phi_{\rm CPV} \sim 10^{-29}\, e\, cm \left(\dfrac{50\,\text{TeV}}{\Lambda}\right)^2 \sin\phi_{\rm CPV} & \text{(1-loop)} \\ e\left(\dfrac{g^2}{16\pi^2}\right)^2 \dfrac{m_e}{\Lambda^2}\sin\phi_{\rm CPV} \sim 10^{-29}\, e\, cm \left(\dfrac{2.5\,\text{TeV}}{\Lambda}\right)^2 \sin\phi_{\rm CPV} & \text{(2-loops)} \end{cases}$$

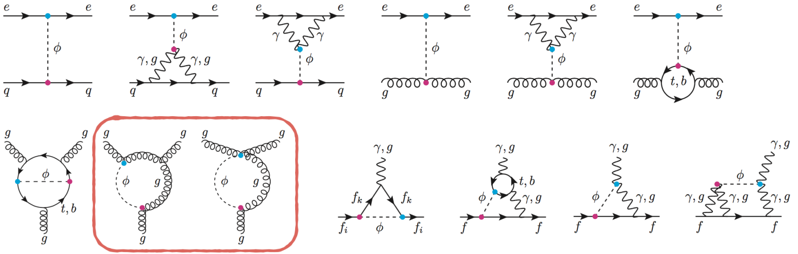
EDMs and light New Physics

- CP-violating axion-like particles (ALPs)

[Marciano, Masiero, Paradisi, Passera, Phys. Rev. D 94 (2016)
Di Luzio, Gröber, Paradisi, Phys. Rev. D 104 (2021)
Di Luzio, Levati, Paradisi, JHEP 02 (2024)]

$$\mathcal{L}_\phi = e^2 \frac{\tilde{C}_\gamma}{\Lambda}\phi F\tilde{F} + g_s^2 \frac{\tilde{C}_g}{\Lambda}\phi G\tilde{G} + i\frac{v}{\Lambda} y_P^{ij}\phi \bar{f}_i \gamma_5 f_j$$
$$+ e^2 \frac{C_\gamma}{\Lambda}\phi FF + g_s^2 \frac{C_g}{\Lambda}\phi GG + \frac{v}{\Lambda} y_S^{ij}\phi \bar{f}_i f_j$$

- different scaling/sensitivity w.r.t. heavy NP + new short-distance contributions to EDMs



Jarlskog invariants

$$C_a \tilde{C}_b, \quad y_S^{ii}\,\tilde{C}_a, \quad y_P^{ii}\,C_a, \quad y_S^{ii}\,y_P^{jj}, \quad y_S^{ik}\,y_{SM}^{kk}\,y_P^{ki}$$

On leptonic dipoles: $\ell \to \ell'\gamma$

- **NP effects are encoded in the effective Lagrangian**

$$\mathcal{L} = e\frac{m_\ell}{2}\left(\bar{\ell}_R\sigma_{\mu\nu}A_{\ell\ell'}\ell'_L + \bar{\ell}'_L\sigma_{\mu\nu}A^\star_{\ell\ell'}\ell_R\right)F^{\mu\nu} \qquad \ell,\ell' = e,\mu,\tau\,,$$

  - **Branching ratios of $\ell \to \ell'\gamma$**

$$\frac{\mathrm{BR}(\ell\to\ell'\gamma)}{\mathrm{BR}(\ell\to\ell'\nu_\ell\bar{\nu}_{\ell'})} = \frac{48\pi^3\alpha}{G_F^2}\left(|A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2\right).$$

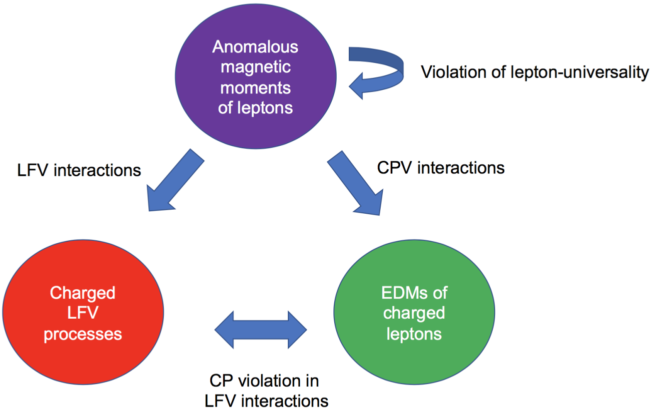
  - **Δa_ℓ and leptonic EDMs**

$$\Delta a_\ell = 2m_\ell^2\,\mathrm{Re}(A_{\ell\ell}), \qquad \frac{d_\ell}{e} = m_\ell\,\mathrm{Im}(A_{\ell\ell})\,.$$

  - **"Naive scaling":** a broad class of NP theories contributes to Δa_ℓ and d_ℓ as

$$\frac{\Delta a_\ell}{\Delta a_{\ell'}} = \frac{m_\ell^2}{m_{\ell'}^2}, \qquad \frac{d_\ell}{d_{\ell'}} = \frac{m_\ell}{m_{\ell'}}\,.$$

Probing NP in the leptonic sector



Model-independent predictions

- $\mathrm{BR}(\ell_i \to \ell_j \gamma)$ **vs.** $(g-2)_\mu$

$$\mathrm{BR}(\mu \to e\gamma) \approx 3 \times 10^{-13} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2$$

$$\mathrm{BR}(\tau \to \mu\gamma) \approx 4 \times 10^{-8} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{\mu\tau}}{10^{-2}}\right)^2$$

- **EDMs vs.** $(g-2)_\mu$

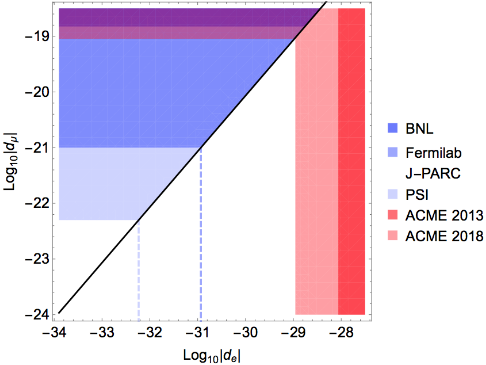
$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 10^{-29} \left(\frac{\phi_e^{CPV}}{10^{-5}}\right) e\,\mathrm{cm}\,,$$

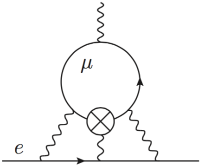
$$d_\mu \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 2 \times 10^{-22}\, \phi_\mu^{CPV}\; e\,\mathrm{cm}\,,$$

- **Main messages:**
  - $\Delta a_\mu \approx (3 \pm 1) \times 10^{-9}$ **requires a nearly flavor and CP conserving NP**
  - **Large effects in the muon EDM** $d_\mu \sim 10^{-22}\, e\,\mathrm{cm}$ **are still allowed!**

[Giudice, P.P., & Passera, '12]

Experimental status of the muon EDM





$$d_\mu \leq 10^{-21}\, e\,\text{cm} \left(\frac{d_e}{10^{-31}\, e\,\text{cm}} \right)$$

[Crivellin, Hoferichter & Schmidt-Wellenburg, '18]

$$d_\mu \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}} \right) 2 \times 10^{-22}\, \phi_\mu^{CPV}\, e\,\text{cm}\,,$$

[Giudice, PP & Passera, '12]

Not only $\mu \to e\gamma$...

- **LFV** operators **@ dim-6**

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2_{\rm LFV}} \mathcal{O}^{\rm dim-6} + \ldots .$$

$$\mathcal{O}^{\rm dim-6} \ni \;\; \bar{\mu}_R \, \sigma^{\mu\nu} \, H \, e_L \, F_{\mu\nu} \, , \;\; (\bar{\mu}_L \gamma^\mu e_L) \left(\bar{f}_L \gamma^\mu f_L\right) \; , \;\; (\bar{\mu}_R e_L) \left(\bar{f}_R f_L\right) \; , \; f = e, u, d$$

- $\ell \to \ell' \gamma$ probe ONLY the dipole-operator (at tree level)
- $\ell_i \to \ell_j \bar{\ell}_k \ell_k$ and $\mu \to e$ in Nuclei probe dipole and 4-fermion operators
- When the dipole-operator is dominant:

$$\mathrm{BR}(\ell_i \to \ell_j \ell_k \bar{\ell}_k) \approx \alpha \times \mathrm{BR}(\ell_i \to \ell_j \gamma)$$
$$\mathrm{CR}(\mu \to e \text{ in N}) \approx \alpha \times \mathrm{BR}(\mu \to e\gamma)$$

$$\frac{\mathrm{BR}(\mu \to 3e)}{3 \times 10^{-15}} \approx \frac{\mathrm{BR}(\mu \to e\gamma)}{5 \times 10^{-13}} \approx \frac{\mathrm{CR}(\mu \to e \text{ in N})}{3 \times 10^{-15}}$$

- **Ratios like** $Br(\mu \to e\gamma)/Br(\tau \to \mu\gamma)$ **probe the NP flavor structure**
- **Ratios like** $Br(\mu \to e\gamma)/Br(\mu \to eee)$ **probe the NP operator at work**

Testing new physics with the electron $g-2$

- **Longstanding muon $g-2$ anomaly**

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP} = (2.51 \pm 0.59) \times 10^{-9}$$

$$\Delta a_\mu \equiv a_\mu^{\rm NP} \approx (a_\mu^{\rm SM})_{weak} \approx \frac{m_\mu^2}{16\pi^2 v^2} \approx 2 \times 10^{-9}$$

- **Testing the muon $g-2$ anomaly through the electron $g-2$**

$$\frac{\Delta a_e}{\Delta a_\mu} = \frac{m_e^2}{m_\mu^2} \qquad \Longleftrightarrow \qquad \Delta a_e = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.7 \times 10^{-13}$$

  - a_e has never played a role in testing NP effects. From $a_e^{\rm SM}(\alpha) = a_e^{\rm EXP}$, we extract α which was is the most precise value of α up to 2018!
  - The situation has now changed thanks to th. and exp. progresses.
  - α can be extracted from atomic physics and a_e used to perform NP tests!

[Giudice, P.P, & Passera, '12]

Testing new physics with the electron $g-2$

- **Status of Δa_e as of 2012**

$$\Delta a_e = a_e^{\rm EXP} - a_e^{\rm SM} = -9.2\,(8.1)\times 10^{-13},$$

$$\delta a_e \times 10^{13}: \quad (0.6)_{\rm QED4},\ \ (0.4)_{\rm QED5},\ \ (0.2)_{\rm HAD},\ \ (7.6)_{\delta\alpha},\ \ (2.8)_{\delta a_e^{\rm EXP}}.$$

  - The errors from QED4 and QED5 will be reduced soon to 0.1×10^{-13} [Kinoshita]
  - We expect a reduction of $\delta a_e^{\rm EXP}$ to a part in 10^{-13} (or better). [Gabrielse]
  - Work is also in progress for a significant reduction of $\delta\alpha$. [Nez]

- **Status of Δa_e as of 2018: 2.4σ discrepancy** [Parker et al., Science, '18]

$$\Delta a_e = a_e^{\rm EXP} - a_e^{\rm SM}(\alpha_{\rm Berkeley}) = -8.8\,(3.6)\times 10^{-13}$$

$$\delta a_e \times 10^{13}: \quad (0.1)_{\rm QED5},\ \ (0.1)_{\rm HAD},\ \ (2.3)_{\delta\alpha},\ \ (2.8)_{\delta a_e^{\rm EXP}}.$$

- **Status of Δa_e as of 2020: 1.6σ discrepancy** [Morel et al., Nature, '20]

$$\Delta a_e = a_e^{\rm EXP} - a_e^{\rm SM}(\alpha_{\rm LKB2020}) = 4.8\,(3.0)\times 10^{-13}$$

$$\delta a_e \times 10^{13}: \quad (0.1)_{\rm QED5},\ \ (0.1)_{\rm HAD},\ \ (0.9)_{\delta\alpha},\ \ (2.8)_{\delta a_e^{\rm EXP}}.$$

- **$\Delta a_e \lesssim 10^{-13}$ is not too far! This will bring a_e to play a pivotal role in probing new physics in the leptonic sector.** [Giudice, P.P, & Passera, '12]

Low-energy vs high-energy frontiers

<u>Complementary</u> (*not* ALTERNATIVE!) approach →
HIGH-PRECISION SMALL/MID-SCALE EXPS.

Low-energy high-precision exps. can exploit :

- many recent ***advances in experimental techniques and technologies*** + **(experimental as well as theoretical)** ***synergies*** with adjacent areas of particle physics (atomic, molecular, optical, nuclear, particle physics)
- the relevant impact of ***quantum mechanical virtual effects*** on physical phenomena → access to the exploration of BSM new physics areas (large energy scales, very feebly coupled new particles, hidden sectors, etc.) difficult to be probed by traditional HE particle physics

<u>SYNERGY</u> between small/mid-scale & large-scale experiments → casting a wider and tighter net for possible effects of BSM physics

Community Planning Exercise: Snowmass 2021 Blum, Winter et al. arXiv:2209.08041v2 ⇒ **2023 P5 (Particle Physics Project Prioritization Panel) Report**

[Masiero]

Conclusions and future prospects

- **Important questions in view of ongoing/future experiments are**:
  - What are the expected deviations from the SM predictions induced by TeV NP?
  - Which observables are not limited by theoretical uncertainties?
  - In which case we can expect a substantial improvement on the experimental side?
  - What will the measurements teach us if deviations from the SM are [not] seen?

- **(Personal) answers**:
  - We can expect any deviation from the SM expectations below the current bounds.
  - LFV processes and leptonic EDMs do not suffer from theoretical limitations and there are still excellent prospects for experimental improvements.
  - FCC-ee and a high-energy Muon Collider are complementary with each other and also with low-energy experiments to probe new physics.

Message: an exciting program is in progress at the low-energy Intensity Frontier which would greatly benefit from the next high-energy frontier program (FCC & MuC)!