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Feature Article

Low-energy precision tests of the standard model: a snapshot

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This brief review describes a class of uniquely crafted particle physics experiments that typically each tackle just one investigation—and they do that very well. The aim of these experiments is to both establish Standard Model parameters and also to provide unique tests in search of new physics. I provide a brief snapshot of many of the current activities, selected with a bias toward low-energy and high precision. These include searches for permanent electric dipole moments, charged lepton flavor violation, tests of the weak interaction, and other broad searches for deviations from very precise Standard Model predictions, such as the muon's anomalous magnetic moment. I highlight what drives these efforts and how they might impact a new Standard Model.

1 Introduction

The physics addressed in this review includes parameter measurements and structural tests of the known Standard Model (SM), and sensitive searches for evidence of new physics. Selective observational deficiencies in the SM such as the baryon asymmetry of the universe (BAU), the origin of dark matter, and the discrepancy between measurement and theory for the muon anomalous magnetic moment, are addressed. There are, as well, theoretical problems with the SM that deserve resolutions and well-considered SM extensions do exist that address both observational and theoretical issues. These include variants of supersymmetric models, universal extra dimensions, little Higgs models, lepto-genesis and baryogenesis mechanisms related to the BAU, and possible new light and weakly interacting particles dubbed dark photons and dark *Z*s. In many models, signals should appear in one or more of the low-energy experimental campaigns presently underway or those planned for the near future.

Typically, specialized low-energy and high-precision experiments provide specific windows into new physics scenarios and they will aid in the interpretation in situations where the LHC will discover new particles. The energy scale reach is generally well matched to the current collider observational window and, in some cases, it extends to the tens of TeV and beyond. The aim of this review is to highlight recent important results from this field, ongoing efforts, and near-future projects. The experiments take place at a variety of labs, both large and small, scattered around the globe. My view is personal (see also, [1]) and I will omit more than I can describe, leaving out important topics that are being covered by other authors in this issue: direct dark matter searches, $0\nu\beta\beta$ decay [2], and quark-flavor physics measurements.

2 A fundamental symmetry test: permanent electric dipole moments

The interaction of a particle or fundamental system having a permanent electric dipole moment (EDM) with an external electric field violates the discrete symmetries of parity (P) and time-reversal (T). Invoking the theoretically sound assumption of CPT conservation implies that a T-violation observation leads to CP violation (CPV). As solid as it might appear, CPT conservation is being vigorously tested by a host of experiments [3], but no violation has been found.

The essential motivation for EDM searches is that a non-zero result would represent a *new* source of CPV, and possibly one that might lead to a plausible electroweak-baryogenisis (EWBG) explanation for the matter-antimatter asymmetry in the universe. The CPV based on the lone phase in the CKM mixing matrix gives rise to differences in decay rates of particles and their anti-particles. The effect is measured in kaon and *B*-meson systems to very high precision owing to many fixed-beam and collider efforts, and indeed next-generation experiments are planned. But the degree of CPV does not explain the BAU; it falls short by many

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Table 1 Selected EDM limits for the electron, Hg atom, neutron and muon. The electron results are based on measurements using polar molecules. In each case, improvements by factors ranging from 10 - 100 are planned or in progress

Type	System	EDM Limit (e-cm)	Ref.
Paramagnetic	YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	[10]
Paramagnetic	ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	[11]
Diamagnetic	^{199}Hg	$d_A = (0.5 \pm 1.5) \times 10^{-29}$	[12]
Nucleon	Neutron	$d_n = (0.2 \pm 1.7) \times 10^{-26}$	[13]
Lepton	Muon	$d_\mu = (-0.1 \pm 0.9) \times 10^{-19}$	[14]

orders of magnitude. EDM searches have intensified lately as hunting grounds for possible new sources of CPV that might give us clues here.

The EDM experimental landscape is based mainly on "tabletop" experiments involving paramagnetic atoms and molecules, diamagnetic atoms, and the neutron (see [4–6]). In a typical experiment, a neutral polarized system is placed in a weak magnetic field B and its spin is tipped at 90 deg with respect to the field to allow it to precess. The precession frequency is measured with a strong electric field alternately aligned parallel and antiparallel with B. Any frequency difference between the two alignments can be attributed to a permanent EDM, denoted d_x in Table 1, where x is the fundamental system being tested. The actual system used may involve enhancements (polar molecules) or suppressions (paramagnetic atoms) of the effective electric field strength. Once the interpretations are factored in properly, the actual sensitivities to the fundamental sources of CPV from the measurements of the electron (d_e), mercury atom (d_A), neutron (d_n) and muon (d_μ) as quoted in Table 1—all consistent with zero—are rather competitive to one another, except for the muon.

Figure 1, Ref [5], is an often displayed hierarchy that illustrates the association of observable EDMs to their possible fundamental CPV sources, which might be chromo-, quark-, lepton-, and semi-leptonic EDMs, or the QCD "theta" parameter, $\Theta_{\rm QCD}$. The diagram demonstrates the complex linkage between what would *cause* a CPV and how it might be *manifest* in different systems at different length scales. Because of the multiple pathways, it will be necessary to study a wide variety of systems to disentangle the origin of any new source of CP violation. We speak here of new sources of CPV, but of course the $\Theta_{\rm QCD}$ term allows for SM CPV in hadronic systems. Current limits from the neutron EDM imply $\Theta_{\rm QCD} < 10^{-10}$; that is, the SM-allowed term appears to be very finely tuned if it is non zero; this is the so-called strong CP problem. If the physical axion exists, then $\Theta_{\rm QCD} = 0$ is allowed, which in turn implies that any non-null EDM results for the neutron (or Hg-199 atom) will point to new CPV sources.

Engel et al. [4] provide a detailed discussion of the complex theoretical issues related to interpreting fundamental sources of CPV from observable EDMs in the different systems listed in Table 1. These includes the complications of non-perturbative strong interaction physics in some of the tested systems. As the Table suggests, one can ascribe an EDM limit on an electron from a measurement using YbF or ThO

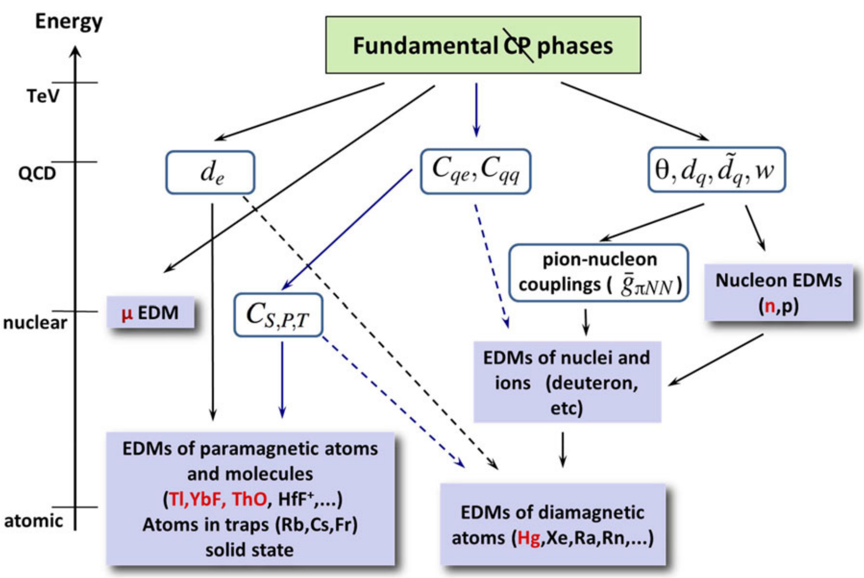

Figure 1 Hierarchy of scales between CP-odd sources and several generic classes of EDM measurements (Figure courtesy A. Ritz, [5])

molecules, but this linkage has theoretical uncertainties and assumptions, which have been recently discussed in Ref. [7].

In general, no simple relation exists between EDM limits and BSM energy scales. But based on general considerations, the current EDM limits imply new physics must lie above the TeV scale, or have CPV phases below $\mathcal{O}(10^{-2})$. The established atomic and polar-molecule measurements continue to improve. A number of next-generation nEDM measurements are being mounted, and a promising storage ring technique has been proposed for charged particles such as the proton, deuteron, and muon [8]. The realization of just some of these efforts should push the probed energy scale above 10 TeV or the CPV phases below the 10^{-4} level [4].

Returning to the idea of non-zero EDMs as a source of EWBG—or, for that matter improved limits and what they might mean for such models—a comprehensive discussion is found in [9]. Generally, for MSSM-based 1-loop models, the current constraints already squeeze down the possibilities for SUSY-based EWBG; but of course, there are knobs to turn in these models to evade such simplified conclusions. At this point, the prudent path is to await the improved EDM experiments and the complementary LHC-14 results.

3 Structure of the weak interaction

The charged weak interaction is believed to have a pure vector minus axial-vector ($V - A$) structure; no scalar or tensor currents are included and none have been observed. It is maximally parity violating, which provides for many convenient studies, as will be illustrated below.

Muons and pions are particularly prolific contributors to studies of the weak interaction. For example, the purely leptonic decay rate establishes the muon Fermi constant, G_μ through the relation

$$\Gamma_\mu = \frac{1}{\tau_\mu} = \frac{G_\mu^2 m_\mu^5}{192\pi^3}\left(1 + \sum_i \Delta q^{(i)}\right) \tag{1}$$

where m_μ is the muon mass and the $\Delta q^{(i)}$ describes phase space and QED corrections. The MuLan Collaboration recently measured τ_μ to 1 ppm precision [15], some 20 times better than previous efforts. This leads to a 0.5 ppm determination of the Fermi constant, G_F, and the connection to the weak interaction coupling g through

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1 + \sum_i r_i\right) \tag{2}$$

where $\sum r_i$ represents higher-order electroweak interaction corrections that are important in global electroweak fits. We have assumed weak universality here; that is, $G_F \equiv G_\mu$. More broadly, it means the lepton couplings to the W of e, μ and τ are identical. This assumption is now known to $\sim 10^{-3}$. Recently, the PEN and PIENU experiments [16, 17] independently measured the decay rate ratio $\pi^+ \to e^+\nu_e$ to $\pi^+ \to \mu^+\nu_\mu$, with the aim, once the analyses are complete, to reach the calculated SM uncertainty of a few times 10^{-4}, where weak-scale new physics might be expected [18].

The purely leptonic charged weak interaction has been tested in experiments at TRIUMF and PSI, see [1]. The precision on the parameters describing the energy and angular distributions of positrons in polarized muon decay [19, 20], and of the longitudinal [21] and transverse [22] polarization of the emitted positron, has been improved by factors of at least 3 and, in most cases, 10. The differential decay rate versus angle and energy can be written in terms of the Michel parameters ρ, η, δ, and $P_\mu\xi$, where P_μ is the polarization. The most general Lorentz invariant, lepton-number conserving interaction has 19 real parameters and allows for possible scalar, vector and tensor interactions among left- and right-handed μ and e. The SM implies that all parameters are identically 0, except $g^V_{LL} = 1$. This reveals itself to be true when $\rho = \delta = 3/4$, $P_\mu\xi = 1$, and $\eta = 0$; and, in the limit $m_e = 0$, the longitudinal polarization $P_L = 1$ and the T-conserving and violating transverse polarization is $P_{T1} = P_{T1} = 0$.

The obtained results from the three collaborations are in excellent agreement with the SM predictions to precision levels close to 10^{-4} in many cases. They are significantly more stringent compared to studies of the same decay parameters in the tau-lepton system. A global analysis [19] of the decay parameters incorporating these new limits constrains new physics, especially in possible departures from a pure V-A structure. For example, strong limits are placed on possible right-handed muon interactions and right-handed electron interactions. In terms of popular Left-Right Symmetric models that introduce a new $V+A$ interaction coupling to right-handed currents, the muon constraints restrict the allowed space of mass and mixing angle of a heavy W_R. However, pp collider and K^0-$\bar{K}^0$ mixing set more stringent lower bounds on W_R-boson masses, and the CKM unitarity tests described next give stronger bounds on W_L-W_R mixing [23]. But, the muon results are purely leptonic; they do not invoke any assumptions of SM couplings nor mixing implications of a W_R based on CKM element values.

The weak-interaction can also be probed in hadronic systems, the simplest being the free neutron, but many nuclear beta decay channels also provide precise information. These studies are complementary to often more sensitive high-energy tests of the same new physics, as described in recent studies, e.g., [24, 25]. They look for exotic couplings, without prejudice for the origin of the underlying theory. We first assemble several pieces of information that are used to test the pure $V - A$ structure and the CKM unitarity of the first row. In the beta decay of polarized neutrons, the angular correlation between the outgoing electron with respect to the neutron spin leads to a determination of the ratio $g_A/g_V \equiv \lambda$, the vector to axial-vector weak coupling constants. The axial coupling is in and of itself important for studies of nucleon spin and various astrophysical processes. Following many years of somewhat inconsistent results on λ, the two most recent experiments PERKEO II and UCNA have established a combined and mutually high-precision result of $\lambda = -1.2755(13)$ [26, 27]. They used sources of cold or ultra-cold neutrons (UCNs), respectively, which made their techniques sufficiently different, adding credibility to the result. The neutron lifetime, τ_n, on the other hand, remains muddled as new techniques have revealed flaws in past efforts. The PDG has had a difficult time sorting through what is worth quoting. In its 2014 compilation [23] τ_n is given as (880.3 ± 1.1) s, a reduction by more than 5 s compared to the 2010 edition. New efforts are planned by several groups using different techniques, a necessary process. The recommended errors for both λ and τ_n are both approximately doubled by the PDG; but, the situation is better now and new efforts hope to improve it further.

The combination of λ and τ_n, together with the very precise Fermi constant, gives a neutron determined value for V_{ud}. However, a much more precise result is obtained from a series of 20 superallowed $0^+ \rightarrow 0^+$ transitions in nuclear beta decays [28]. A 2014 update [29] yields an impressive precision of $V_{ud} = 0.97417(21)$. Alone, this precise result constrains various SM extensions of the weak interaction such as any allowed scalar currents, or the best bound on the energy-dependent Fierz coefficient, b. Together with V_{us} from kaon decay, and the negligible contribution of V_{ub}, leads to the unitarity test: $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99978(55)$, a spectacular success [23, 29]. Finally, in a global comparison of the above quantities, the correlation between λ, τ_n, and V_{ud} now neatly converge as predicted by the ever rugged SM, a situation that just a few years ago was far from realized. The room for exotic couplings is squeezed further. There are no cracks.

We conclude this section with a short discussion of the neutral weak interaction, tested at low energy in the form of the running of $\sin^2 \Theta_W$ [30, 31]. Atomic, neutrino,

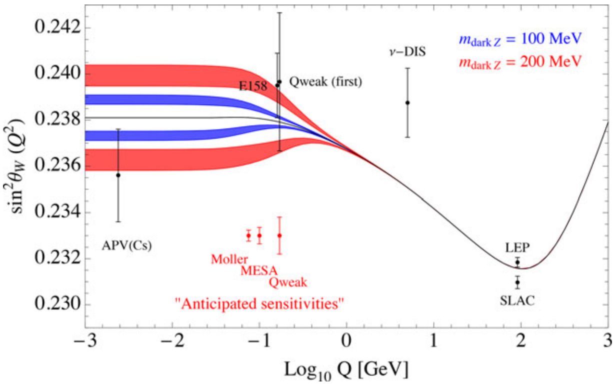

Figure 2 Comparison of published experimental results, and anticipated sensitivities of several proposed efforts, to the Standard Model running (black line) of the weak mixing angle $\sin^2 \Theta_W$ vs energy scale Q. The red and blue bands that depart from the SM represent models with a dark Z of selected mass that is consistent with the muon anomaly in the case with invisible decays; that is, not ruled out by recent experiments that search for decay to lepton pairs. (Figure Ref. [39])

and parity-violating electron scattering (PVES) experiments can explore this quantity at various energy scales, where the SM has firm predictions based on the Z-pole measurements. To date, the measured values confirm the running and generally agree with the SM prediction; the exception is the curious and somewhat controversial neutrino deep-inelastic scattering point [32].

The cleanest system to interpret measures the asymmetry in $e^- e^-$ Møller scattering when the incoming electron beam helicity is reversed, a technique pioneered by E158 at SLAC [33]. The proposed JLab MOLLER experiment [34] plans an impressive uncertainty of 0.1% on $\sin^2 \Theta_W$, which is equivalent to that at the high energy Z pole. PVES in the $e^- p$ system determines the weak charge of the proton, which can similarly be expressed as a measure of $\sin^2 \Theta_W$. The first Q_{WEAK} result [35] agrees with the SM prediction, but their final result based on a ~ 25 times larger data set is undergoing final analysis and not yet unblinded. Mainz $(e^- p)$ [36] and JLab $(e^- q)$ [37] are also planning high-precision measurements. Atomic parity-violating experiments are also underway including studies of single Ra ion trapping [38].

Combined as displayed in Fig. 2, these experiments can provide textbook demonstrations of the consistency of the SM, which relies on the complete electroweak fits for its predictions; thus, they are indirectly related to the new high-precision Higgs mass measurement, the continually improving W mass measurements, the Fermi constant, the fine structure constant, and more. As a test of new physics, one can imagine a scenario

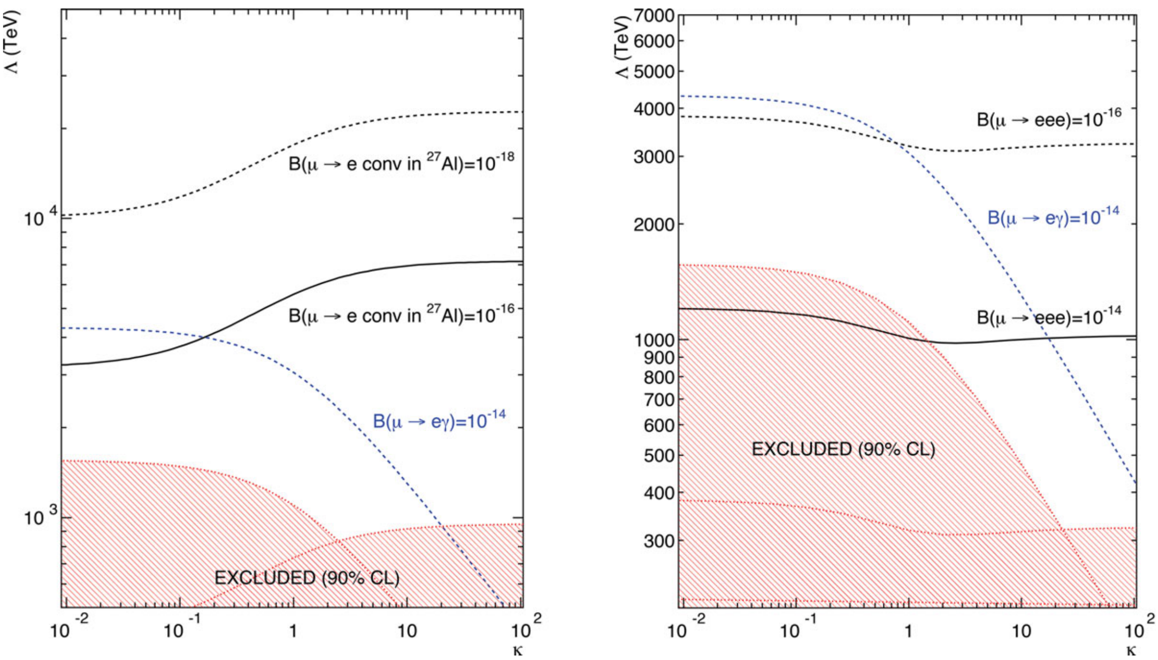

Figure 3 Comparison of the new physics energy scale sensitivity for the $\mu^+ \to e^+\gamma$ versus $\mu^- N \to e^- N$ coherent conversion experiments (left), and to $\mu^+ \to e^+e^-e^+$ (right), at their planned sensitivities vs. κ. (Updated figure courtesy A. de Gouvêa. [40])

where a significant departure from the expected running is observed—as shown in the colored bands in Fig. 2—indicating an unaccounted for exotic process such as a dark Z, which would violate parity. Its impact significantly perturbs $\sin^2\Theta_W$ at lower Q values. The colored bands in Fig. 2 are for the parameter region that can explain the muon $g-2$ anomaly in the invisibly-decaying scenario [39].

4 High-sensitivity tests of new physics with muons

Among the more promising probes of new physics are the high-sensitivity tests of charged lepton flavor violation (cLFV), many of which are carried out at B factories that study tagged hadronic τ decays to muons and electrons. Examples include: $\tau \to eee$, $\tau \to \mu\mu\mu$, $\tau \to e\gamma$, and $\tau \to \mu\gamma$ but many others exist. Impressive sensitivity has been achieved with branching ratios typically at the 10^{-8} level and the future promises order-of-magnitude improvements once Belle-II is operational. A newcomer here is the LHCb experiment, which has already set a competitive limit on $BR(\tau \to \mu\mu\mu)$ of $< 4.6 \times 10^{-8}$, [41]; improved limits will surely continue.

However, it is the low-energy muon reactions (1) $\mu^+ \to e^+\gamma$, (2) $\mu^+ \to e^+e^-e^+$, and (3) the coherent conversion of a muon to an electron in a muonic atom, $\mu^- N \to e^- N$, that have by far the greatest reach in a new physics search, owing to their impressive limits. It has become customary to compare, for example the sensitivity of reactions (1) and (3) using an effective Lagrangian of the form [40]

$$L_{\mathrm{cLFV}} = \frac{M_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

where $\kappa \ll 1$ is a loop-like, photonic dipole operator and $\kappa \gg 1$ represents a point-like contact interaction. The parameter Λ is an effective energy scale that extends for current experimental sensitivity goals to 1000's of TeV—for optimized coupling—well in excess of any collider reach. A similar Lagrangian can be made to look at reactions (1) vs. (2). The sensitivities are shown in Fig. 3 for both cases, along with current exclusions and future experimental goals.

The MEG Collaboration at PSI has studied $\mu^+ \to e^+\gamma$ and established limits on the branching ratio of $< 5.7 \times 10^{-13}$ (90% C.L.) [42]. They have upgrade plans in place to improve by an order of magnitude. In the planning stage are two experiments to search for $\mu^- N \to e^- N$ conversion at single event sensitivities approaching 10^{-17}, a 4 order-of-magnitude improvement over current limits [43]. Mu2e [44] at Fermilab and COMET [45] at J-PARC will each create intense sources of muons inside a superconducting solenoid housing a target and impinged on by an intense proton beam. The negative muons surviving are captured and transported along curved magnetic paths and directed to aluminum targets where, following formation of muonic-Al atoms, the rare possibility of $\mu \to e$ conversion might take place, emitting a 105 MeV electron into a spectrometer. These experiments are indeed quite ambitious as the branching ratios of interest are extraordinarily tiny. See recent reviews: [46, 47].

We reserve to last one of the author's personal projects and one of the strongest hints of new physics now existing, at any energy scale. This is the $> 3\sigma$ deviation between the experimental BNL E821 measurement [48] and the theoretical prediction (see Ref. [49]) for the muon anomalous magnetic moment, $a_\mu \equiv (g-2)/2$. The g-factor of a structureless, point-like, spin-1/2 Dirac particle is exactly equal to 2, apart from the anomalous contributions attributed to quantum fluctuations—loop effects—which is where new physics can arise. The lowest-order QED correction is the exchange of a virtual photon, with $a_\mu(QED-LO) = \alpha/2\pi \approx 1/850$. By now, QED and weak contributions are known to very high precision, much better than an experiment might ever probe. In fact, we rely on the very precise measurement the electron $g-2$ measurements, which together with QED theory, also determine the fine-structure constant [50]. Leading-order hadronic vacuum polarization (HVP) and higher-order hadronic light-by-light (HLbL) scattering are more challenging with a combined uncertainty of 0.42 ppm, slightly better than the final precision of the BNL E821 experiment at 0.54 ppm. A vigorous effort exists now to improve the SM evaluation, focusing on the hadronic terms. Promising tools include lattice efforts, additional measurements of data entering the HVP evaluation, and new discussion of data-driven efforts related to pinning down HLbL terms [51].

On the experimental side, new efforts are being mounted at Fermilab and J-PARC. The FNAL E989 experiment [52] aims at a fourfold or greater reduction in the overall uncertainty. They will reuse the now relocated BNL storage ring, but otherwise rely on a modern update of all instrumentation and a custom high-purity muon beamline. J-PARC E34 aims to match the previous BNL uncertainty. Their approach differs in many technical matters, starting with a low-energy, but ultra-cold muon beam derived by re-accelerating ionized muonium atoms from rest [53]. Both experiments will determine a_μ from three numbers: the precession frequency of the muon spins; the average magnetic field determined from proton NMR; and, the ratio μ_μ/μ_p determined from muonium hyperfine splitting (HFS) measurements and QED theory [54]. An improved HFS experiment is being planned at J-PARC [55]. In both new experiments, order-of-magnitude improvements in the muon EDM limits should come parasitically with $g-2$ data taking.

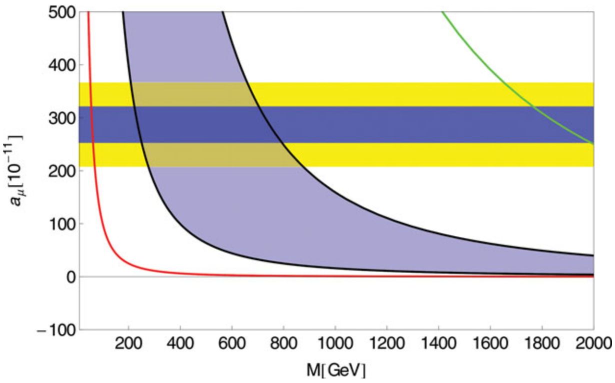

Figure 4 Generic classification of mass scales vs. a_μ contributions from new physics sources. Green line: radiative muon mass generation; Red line: Z', W', universal extra dimensions, or Littlest Higgs models with typical weak-interaction scale coupling; Grey band: unparticles, various extra dimension models, or SUSY models where the coupling is enhanced. The width illustrates a $\tan\beta$ range of $5-50$ for SUSY models. The yellow horizontal band corresponds to the current difference between experiment and theory and the blue band is an improvement with a combined theory and experimental error of 34×10^{-11}. (Figure courtesy D. Stockinger)

The magnetic moment is a flavor- and CP-conserving, chirality-flipping, and loop-induced quantity, which is in contrast to many high-energy collider observables at the LHC and many of the explorations discussed above that might test CP- or flavor-violation. What kind of physics might a non-SM compliant a_μ imply? For many models, this can be illustrated in a general way following a relation discussed in [56] in which new physics (N.P.) contributions will scale as $\delta a_\mu(N.P.) = \mathcal{O}[C(N.P.)] \times (m_\mu/M)^2$ where M is a new physics (N.P.) mass scale and C is a coupling strength, related to any new physics contributions to the muon mass; that is, $C(N.P.) \equiv (\delta m_\mu(N.P.)/m_\mu)$. Stockinger demonstrates how this relation can show that typical new physics models will give very different predictions for a_μ [57]. Figure 4 gives ranges for non-SM contributions for various coupling strengths, C. For muon mass generated by radiative effects, $C(N.P.) = \mathcal{O}(1)$, which indicates that the current a_μ is probing the multi-TeV scale. For $\mathcal{O}(\alpha/4\pi)$ models, one could argue that a_μ is largely incompatible owing to the light implied masses. But for models with enhanced coupling—including SUSY, unparticles and various extra dimensions—the expected mass range corresponds to what can be measured at the LHC, owing to the enhanced coupling, for example from a $\tan\beta$ range of $5-50$ in this plot for SUSY models. The horizontal bands show the current δa_μ limits and an expected combined theory and experimental future sensitivity. What is missing here is the possibility to obtain a large δa_μ from very weakly interacting and very light particles, such as a dark photon or dark Z. This would correspond to another narrow band hugging the vertical axis, crossing the Δa_μ region in the 10 - 100 MeV mass range and having a very small coupling.

We have illustrated in a compact format a significant, but incomplete, list of experimental probes of new physics using low-energy, precision techniques. The most promising discovery potential efforts (i.e, capable of a result with $> 5\,\sigma$ significance) include many of the EDM efforts, the emerging suite of ultra-sensitive cLFV experiments, and $g-2$, which will exceed discovery threshold in the coming years if the central values of theory and experiment are roughly unchanged. If the LHC begins to see signs of new physics during its 14 TeV running, many of the low-energy observables provided by the experimental program described here will be invaluable to help guide and interpret the results; and, that is true for both null observations and positive findings. In the more sobering situation where no new physics emerges from the LHC, then the low-energy, ultra-high-precision probes, will remain vital to explore how to go forward for a long time to come.

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Key words. precision physics, electric dipole moments, muon physics, weak interaction.

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References

[1] T. P. Gorringe and D. W. Hertzog, Prog. Part. Nucl. Phys. (2015). DOI: 10.1016/j.ppnp.2015.06.001
[2] H. A. Tanaka, Ann. Phys. (2015), DOI: 10.1002/andp.201500105
[3] D. Colladay and V. A. Kostelecky, Phys. Rev. **D58**, 116002 (1998).
[4] J. Engel, M. J. Ramsey-Musolf, and U. van Kolck, Prog. Part. Nucl. Phys. **71**, 21–74 (2013).
[5] M. Pospelov and A. Ritz, Annals Phys. **318**, 119–169 (2005).
[6] K. Jungmann, Ann. Phys. **525**(8-9), 550–564 (2013).
[7] T. Chupp and M. Ramsey-Musolf, Phys. Rev. **C91**(3), 035502 (2015).
[8] F. Farley, K. Jungmann, J. Miller, W. Morse, Y. Orlov et al., Phys. Rev. Lett. **93**, 052001 (2004).
[9] D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys. **14**, 125003 (2012).
[10] J. Hudson, D. Kara, I. Smallman, B. Sauer, M. Tarbutt et al., Nature **473**, 493–496 (2011).
[11] J. Baron et al., Science **343**(6168), 269–272 (2014).
[12] W. Griffith, M. Swallows, T. Loftus, M. Romalis, B. Heckel et al., Phys. Rev. Lett. **102**, 101601 (2009).
[13] C. Baker, D. Doyle, P. Geltenbort, K. Green, M. van der Grinten et al., Phys. Rev. Lett. **97**, 131801 (2006).
[14] G. Bennett et al., Phys. Rev. **D80**, 052008 (2009).
[15] V. Tishchenko et al., Phys. Rev. **D87**(5), 052003 (2013).
[16] D. Pocanic et al., AIP Conf. Proc. **1182**, 698–701 (2009).
[17] A. Sher, A. Aguilar-Arevalo, M. Blecher, D. Britton, D. Bryman et al., AIP Conf. Proc. **1560**, 125–127 (2013).
[18] V. Cirigliano and I. Rosell, Phys. Rev. Lett. **99**, 231801 (2007).
[19] A. Hillairet et al., Phys. Rev. **D85**, 092013 (2012).
[20] J. Bueno et al., Phys. Rev. **D84**, 032005 (2011).
[21] R. Prieels, O. Naviliat-Cuncic, P. Knowles, P. Van Hove, X. Morelle et al., Phys. Rev. **D90**(11), 112003 (2014).
[22] N. Danneberg, W. Fetscher, K. Kohler, J. Lang, T. Schweizer et al., Phys. Rev. Lett. **94**, 021802 (2005).
[23] K. Olive et al., Chin. Phys. **C38**, 090001 (2014).
[24] V. Cirigliano, S. Gardner, and B. Holstein, Prog. Part. Nucl. Phys. **71**, 93–118 (2013).

[25] N. Severijns and O. Naviliat-Cuncic, Ann. Rev. Nucl. Part. Sci. **61**, 23–46 (2011).
[26] D. Mund, B. Märkisch, M. Deissenroth, J. Krempel, M. Schumann, H. Abele, A. Petoukhov, and T. Soldner, Phys. Rev. Lett. **110**, 172502 (2013).
[27] M. Mendenhall et al., Phys. Rev. **C87**(3), 032501 (2013).
[28] J. C. Hardy and I. S. Towner, Phys. Rev. C **79**, 055502 (2009).
[29] J. Hardy and I. Towner, Phys. Rev. **C91**(2), 025501 (2015).
[30] K. Kumar, S. Mantry, W. Marciano, and P. Souder, Ann. Rev. Nucl. Part. Sci. **63**, 237–267 (2013).
[31] J. Erler and S. Su, Prog. Part. Nucl. Phys. **71**, 119–149 (2013).
[32] G. Zeller et al., Phys. Rev. Lett. **88**, 091802 (2002).
[33] P. Anthony et al., Phys. Rev. Lett. **95**, 081601 (2005).
[34] J. Benesch et al., (2014).
[35] D. Androic et al., Phys. Rev. Lett. **111**(14), 141803 (2013).
[36] D. Becker, K. Gerz, S. Baunack, K. Kumar, and F. Maas; PoS **Bormio2013**, 024 (2013).
[37] P. Reimer, Nuovo Cim. **C035N04**, 209–213 (2012).
[38] M. Nuñez Portela, J. v. d. Berg, H. Bekker, O. Böll, E. Dijck et al., Hyperfine Interact. **214**(1-3), 157–162 (2013).
[39] H. Davoudiasl, H. S. Lee, and W. J. Marciano, Phys. Rev. **D89**(9), 095006 (2014).
[40] A. de Gouvea and P. Vogel, Prog. Part. Nucl. Phys. **71**, 75–92 (2013).
[41] R. Aaij et al., JHEP **1502**, 121 (2015).
[42] J. Adam et al., Phys. Rev. Lett. **110**, 201801 (2013).
[43] W. H. Bertl et al., Eur. Phys. J. **C47**, 337–346 (2006).
[44] L. Bartoszek et al., Mu2e Technical Design Report: FERMILAB-TM-2594.
[45] Y. Cui et al., COMET Collaboration: KEK-2009-10, 2009.
[46] R. H. Bernstein and P. S. Cooper, Phys. Rept. **532**, 27–64 (2013).
[47] T. Mori and W. Ootani, Prog. Part. Nucl. Phys. **79**, 57–94 (2014).
[48] G. Bennett et al., Phys. Rev. **D73**, 072003 (2006).
[49] T. Blum, A. Denig, I. Logashenko, E. de Rafael, B. Lee Roberts et al., The Muon (g-2) Theory Value: Present and Future: arXiv:1311.2198, 2013.
[50] D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev. Lett. **100**, 120801 (2008).
[51] Benayoun et al., Hadronic contributions to the muon anomalous magnetic moment Workshop: arXiv:1407.4021, 2014.
[52] J. Grange et al., Muon (g-2) Technical Design Report: FERMILAB-FN-0992-E.
[53] H. Iinuma, J. Phys. Conf. Ser. **295**, 012032 (2011).
[54] W. Liu, M. G. Boshier, S. Dhawan, O. van Dyck, P. Egan et al., Phys. Rev. Lett. **82**, 711–714 (1999).
[55] K. Tanaka, M. Aoki, H. Iinuma, Y. Ikedo, K. Ishida et al., JPS Conf. Proc. **2**, 010405 (2014).
[56] A. Czarnecki and W. J. Marciano, Phys. Rev. **D64**, 013014 (2001).
[57] D. Stockinger, private communication.

