

# An overview of neV probes of PeV scale physics

## – and of what's in between

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**Abstract.** Low-energy experiments which would identify departures from the Standard Model (SM) rely either on the unexpected observation of symmetry breaking, such as of CP or B, or on an observed significant deviation from a precise SM prediction. We discuss examples of each search strategy, and show that low-energy experiments can open windows on physics far beyond accessible collider energies. We consider how the use of a frequentist analysis framework can redress the impact of theoretical uncertainties in such searches – and how lattice QCD can help control them.

## 1. Context

Direct searches for new physics at the LHC has yielded the discovery of the Higgs boson [1, 2], but no unanticipated, new particles – as yet. On the other hand, observational cosmology, analyzed in the framework of general relativity, tells us that only 4% of the energy density of the universe is in the matter we know [3], so that the SM of particle physics, successful though it is, is probably incomplete. The lack of evidence thus far for new physics and interactions through collider studies at the highest energies motivates broader thinking in the search for new physics. For example, the missing matter could be weakly coupled, making it more challenging if not impossible to identify in a collider environment. Low-energy, precision searches for new physics can also probe this alternative possibility and thus play a key role in the search for new physics. In this contribution we offer a terse overview of the diverse program these experiments comprise.

Generally, there are two distinct search strategies. That is, one can either make null tests of the breaking of SM symmetries, or refine the measurement of quantities which can be computed, or assessed, precisely with the SM. In the former case, one can test, e.g., B-L invariance by searching for  $n\bar{n}$  oscillations or neutrinoless double- $\beta$  decay. Although CP is not a symmetry of the SM, there are nevertheless observables for which the SM prediction is so small that searches at current levels of sensitivity also constitute null tests. Searches for permanent electric dipole moments (EDMs) of the neutron or electron, e.g., or for CP violation in the charm sector, be it through  $D\bar{D}$  mixing or decay rate

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asymmetries, are examples of such tests. There are also a variety of nonzero observables whose value can be tested precisely within the SM. Example of this latter class include (i) parity-violating electron scattering from electrons, protons, or light nuclei, in varying kinematics, (ii) the anomalous magnetic moment of the muon (or electron), and (iii) final-state angular correlations in neutron and nuclear  $\beta$  decay. All these studies probe the possibility of new degrees of freedom, including those which couple so weakly to known matter that they are effectively “hidden”.

## 2. Motivation

The SM leaves many questions unanswered; e.g., it cannot explain the nature of dark matter or dark energy, nor can it explain the magnitude, or even existence, of the cosmic baryon asymmetry (BAU). The BAU itself can be determined by confronting the observed  $^2\text{H}$  abundance with big-bang nucleosynthesis, yielding  $\eta_B \equiv n_{\text{baryon}}/n_{\text{photon}} = (5.96 \pm 0.28) \times 10^{-10}$  [4]. As demonstrated long ago by Sakharov, the particle physics of the early universe can explain this asymmetry if B, C, and CP violation exist in a non-equilibrium environment [5]. Nominally the SM would seem to possess all the conditions required to generate the BAU. However, with the discovery of a Higgs boson of 125 GeV in mass, the phase transition associated with electroweak symmetry breaking is no longer of first order [6], and the SM cannot explain a nonzero BAU. Thus our existence is itself evidence of physics BSM! The mechanism of CP violation in the SM has also been faulted, because an estimate of the BAU (now moot) with a sufficiently light Higgs mass yields a BAU orders of magnitude too small, namely,  $\eta_B < 10^{-26}$  [7]. In the SM nonzero CP-violating effects require the participation of three generations of quarks of differing mass [8]. Consequently, the small value of the computed BAU follows, in part, from the smallness of  $\text{SU}(3)_f$  breaking compared to the electroweak scale. This special way in which CP violation appears in the SM makes it seem that new sources of CP violation are needed to explain the BAU; however, searches for such effects at the  $B$  factories and through improved EDM limits have thus far failed to discover them.

A BAU could potentially be generated in very different ways, and low-energy experiments can help select the underlying mechanism. For example, the discovery of a nonzero EDM at current levels of sensitivity would speak to new CP phases and the possibility of electroweak baryogenesis. The discovery of neutrinoless  $\beta\beta$  decay would tell us that neutrinos are Majorana particles [9], and would make various models of leptogenesis possible [10]. The discovery of  $n\bar{n}$  oscillations would reveal that neutrons are also Majorana particles and would support alternate models for baryogenesis [11]. Finally, the discovery of a dark-matter asymmetry [12] would tell us that DM carries “baryon” number, suggesting that the key to the nature of dark matter and the origin of the BAU could be tied [13, 14]. But only EDMs searches are directly connected to the possibility of new physics at the weak scale.

## 3. Analysis framework

It is natural to think of the SM as the low-energy limit of a more fundamental theory, and to use an effective theory framework to analyze its possible extensions. To illustrate, suppose new physics enters at an energy scale  $E > \Lambda_{\text{BSM}}$ . Then for energies below the new-physics scale  $\Lambda_{\text{BSM}}$  we can extend the SM through the appearance of effective operators of mass dimension  $D > 4$ ; specifically,

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda_i^{D-4}} \mathcal{O}_i^D. \quad (1)$$

Noting the severe empirical constraints on new physics from flavor-changing processes [15–17], it is efficient to impose  $\text{SU}(2)_L \times \text{U}(1)$  gauge invariance on the operator basis. If we assume that an experimental bound is saturated by a single term and that the associated  $c_i$  is of  $\mathcal{O}(1)$ , we can estimate the scale  $\Lambda_i$ ; this indicates the rough energy reach of the experiment. For example, a neutrino mass

of 0.1 eV the expected minimum mass accessible to near future neutrinoless  $\beta\beta$  experiments [18], if generated via the seesaw mechanism implies  $\Lambda_{\text{BSM}} \sim 10^{14-15}$  GeV [19]. Such estimates should be used with care.

### 3.1 The QCD challenge

Estimates of the energy reach of a particular experimental measurement can require non-perturbative QCD input in the form of a hadronic matrix element. In this lattice QCD can play a crucial role. There are examples, however, where lattice QCD calculations are not yet good enough to meet experimental needs. A prominent example of this is the determination of the axial coupling constant of the nucleon  $g_A$ . In this specific case,  $g_A$  can be determined directly from experiment, specifically from the measured angular-correlation coefficients in neutron  $\beta$  decay. The existing lattice-QCD calculations do not agree well with each other. Moreover, the lattice results typically lie some 5–15% below the values from  $\beta$  decay, albeit with much larger errors [20].

## 4. Examples

We now turn to specific examples of low-energy experimental probes of new physics.

### 4.1 Heavy-atom EDMs

Currently, the most stringent experimental EDM limit comes from the study of the diamagnetic atom  $^{199}\text{Hg}$ , for which  $|d| < 3.1 \times 10^{-29}$  e – cm at 95% C.L. [21], a result roughly a thousand times more sensitive than the current experimental limit on the neutron EDM [22]. However, the atom’s electrons shield any nonzero EDM which the nucleus may possess and weaken the constraint thereby placed on the existence of new sources of CP violation. It has become possible to study the EDMs of very heavy atoms, such as  $^{225}\text{Ra}$  [23] or  $^{221/223}\text{Rn}$  [24], that mitigate the cancelling effect of electron shielding through their large  $Z$ , finite nuclear size, and octupole deformation [25]. The evasion of electron shielding in  $^{225}\text{Ra}$  is estimated to be some seven hundred times bigger than that in  $^{199}\text{Hg}$  [26], making these systems excellent candidates for the discovery of a nonzero EDM. Recently the permanent octupole deformation of  $^{224}\text{Ra}$  has been established through Coulomb excitation studies at REX-ISOLDE (CERN) [27]; this makes the nucleus more “rigid” and the computation of the associated Schiff moment more robust [28]. With improved isotope yields, as possible, e.g., through direct production at a proton linac, one expects greatly improved sensitivity to EDMs [24].

### 4.2 Resolving the limits of the $V - A$ law in $\beta$ decay

The possibility of non- $(V - A)$  interactions in  $\beta$  decay can be probed through the angular correlations of the final-state particles. Notably the differential decay rate  $d^3\Gamma/dE_e d\Omega_{e\nu}$  can contain a Fierz interference term  $b$ ; this quantity vanishes at tree-level in the SM but is nonzero if scalar or tensor interactions are present. Adopting an effective operator analysis of  $\beta$ -decay, working in a  $\text{SU}(2)_L \times \text{U}(1)$ -invariant basis in dimension six [29, 30], we have, at the quark level, at low energies [31–33],

$$\mathcal{L}_{\text{CC}} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \left[ \left( 1 + \delta_\beta \right) \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d \right. \quad (2)$$

$$\left. + \epsilon_S \bar{e} (1 - \gamma_5) \nu_e \cdot \bar{u} d + \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_e \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d + \dots + \text{h.c.} \right].$$

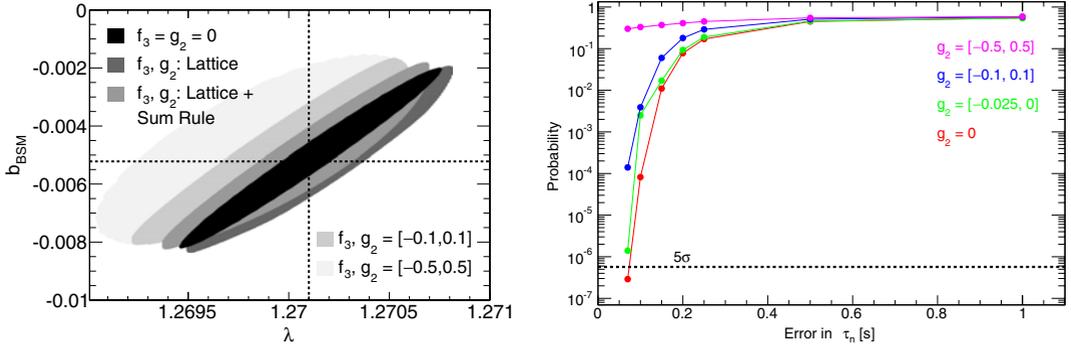
The first term represents the famous  $V - A$  law of the SM, and the others, including the scalar and tensor terms controlled by  $\epsilon_S$  and  $\epsilon_T$ , respectively, reflect the appearance of non-SM physics.

The tree-level coupling  $G_F^{(0)}$  is fixed through the measurement of muon decay and an analysis of its electroweak radiative corrections, and  $\delta_\beta$  reflect those to semi-leptonic transitions. The matching to an effective theory in nucleon degrees of freedom requires the computation of hadronic matrix elements; the result maps to the familiar  $\mathcal{H}_{\text{eff}}$  of Lee and Yang [34] employed in Ref. [35]. We refer to Ref. [36] for a detailed review. In neutron  $\beta$  decay, we have

$$\begin{aligned} \langle p(p') | \bar{u} \gamma^\mu d | n(p) \rangle &\equiv \bar{u}_p(p') \left[ f_1(q^2) \gamma^\mu - i \frac{f_2(q^2)}{M} \sigma^{\mu\nu} q_\nu + \frac{f_3(q^2)}{M} q^\mu \right] u_n(p), \\ \langle p(p') | \bar{u} \gamma^\mu \gamma_5 d | n(p) \rangle &\equiv \bar{u}_p(p') \left[ g_1(q^2) \gamma^\mu \gamma_5 - i \frac{g_2(q^2)}{M} \sigma^{\mu\nu} \gamma_5 q_\nu + \dots \right] u_n(p), \\ \langle p(p') | \bar{u} d | n(p) \rangle &\equiv \bar{u}_p(p') g_S(q^2) u_n(p), \quad \langle p(p') | \bar{u} \sigma_{\mu\nu} d | n(p) \rangle \equiv \bar{u}_p(p') [g_T(q^2) \sigma^{\mu\nu} + \dots] u_n(p), \end{aligned} \quad (3)$$

where  $q \equiv p' - p$  denotes the momentum transfer and  $M$  is the neutron mass. Working at leading order (LO) in the recoil expansion (i.e., neglecting terms of  $\mathcal{O}(\varepsilon/M)$ , where  $|\varepsilon| \ll M$ ) in new physics and at NLO in the SM terms, all  $q^2$  dependence is negligible – and other negligible terms appear as “...” in Eq. (3). Thus we have  $f_1(0) \equiv g_V$ ,  $g_1(0) \equiv g_A$  with  $g_V = 1$  and  $f_2(0) = (\kappa_p - \kappa_n)/2$ , noting  $\kappa_{p(n)}$  is the anomalous magnetic moment of the proton (neutron), in the SM, up to  $\mathcal{O}(\varepsilon/M)$  corrections. The quantities  $f_3(0) \equiv f_3$  and  $g_2(0) \equiv g_2$  are second-class-current contributions, in that they vanish in the SM in the isospin-symmetric limit. Bhattacharya et al. have computed  $g_S(0) = g_S$  and  $g_T(0) = g_T$  in lattice QCD and have shown that their results sharpen the limits on  $\varepsilon_{S,T}$  considerably [32]. Although all the mentioned matrix elements could be computed in lattice QCD, not all of the precise matrix elements needed have been – and we have already noted the problem with  $g_A$ . Consequently, to resolve the limits of the  $V - A$  law in  $\beta$  decay we must fit for SM physics, specifically for  $\lambda \equiv g_A/g_V$ , and BSM physics simultaneously [37]. There are poorly known recoil-order matrix elements, notably  $g_2$  and  $f_3$ ; they enter in recoil order and can mimic the appearance of scalar and tensor effects.

Let us consider the prospects for finding BSM physics through  $b$ ; we can access this quantity either through a measurement of the electron energy spectrum or through its impact on the asymmetry measurements which determine the correlation coefficients  $a$  and  $A$ . Many systematic errors cancel using this latter approach, and we will use it here. We address the analysis problem we have posed in the frequentist  $R$ fit (maximum likelihood) framework adopted by CKMFitter for the analysis of flavor-changing processes for the parameters of the CKM matrix [15, 38]. Most importantly this method provides a means of removing the impact of (SM) theoretical errors on the allowed new-physics phase space. We have used Monte Carlo pseudodata of neutron decay observables to illustrate our implementation of this method [37]. For concreteness we recap our methodology. We employ a pseudodata set of measurements of  $a$  and  $A$  as a function of the electron energy  $E_e$ , along with values of the neutron lifetime. These results, collectively  $\{x_{\text{exp}}\}$ , are to be compared with the theoretical computations of the same quantities, collectively  $\{x_{\text{theo}}(y_{\text{mod}})\}$ , determined by the parameters  $\{y_{\text{mod}}\}$ . A fraction of the set  $\{y_{\text{mod}}\}$  can only be determined from theory; this subset is labelled  $\{y_{\text{calc}}\}$ . The underlying distribution of the  $\{y_{\text{calc}}\}$  parameters is ill-known; the test statistic  $\chi^2$  is thus modified so that the theoretical likelihood does not contribute to the  $\chi^2$ . With this we fit a “New Physics” data set for  $\lambda$  and  $b_{\text{BSM}}$  in which  $\lambda = 1.2701$  and  $b_{\text{BSM}} = -0.00522$  for a value of  $g_T \varepsilon_T = 1.0 \times 10^{-3}$  just below experimental bounds. The results as a function of the theoretical values of  $f_3$  and  $g_2$  are shown in Fig. 1. We see that the best-fit ellipses soften in the presence of the second-class current terms. The method also allows us to construct a test statistic for the validity of the SM; the essential role the neutron lifetime plays in realizing it is shown in Fig. 1. For reference, we note that the lattice-QCD result is determined by an extrapolation from the form factors computed in a  $|\Delta S| = 1$  transition [39], yielding a result at odds with a QCD sum rule calculation [40]. For “Lattice” we use  $f_3 \in (-0.002, 0.016)$  and  $g_2 \in (0.020, 0.066)$ , replacing  $g_2$  with  $g_2 \in (-0.033, 0.066)$  for the union of both. We advocate for a lattice QCD calculation of  $g_2$  and  $f_3$  in neutron decay.



**Figure 1.** Left: illustration of the impact of theoretical certainties (second-class currents) on the search for non- $(V - A)$  currents in neutron  $\beta$ -decay. We show the results of the two-parameter  $(\lambda, b_{\text{BSM}})$  simultaneous fit to the  $\{a, A\}$  New Physics data set. The bands indicate the 68.3% CL allowed regions. Right: an illustration of the essential role the neutron lifetime would play in falsifying the SM. We refer to Ref. [37] for all details.

### 4.3 Spin-independent CP violation in radiative $\beta$ decay

In radiative  $\beta$  decay one can form a T-odd correlation from momenta alone. This is a pseudo-T-odd observable, so that it can be mimicked by final-state interactions (FSI) in the SM. The energy release associated with neutron and nuclear  $\beta$  decay is sufficiently small that only electromagnetic FSI can possibly generate a mimicking effect. These have been computed up to recoil order terms [41], so that we can determine the SM background rather well. The interaction which generates the primary effect comes from the gauging of the Wess-Zumino-Witten term under SM electroweak gauge invariance [42–44]. A direct measurement of this correlation constrains the phase of this interaction from physics BSM, possibly from “strong” hidden sector interactions [45].

## 5. Summary

We believe the analysis framework we have espoused in  $\beta$  decay should benefit the analysis of other low-energy experiments. It should be possible to discover physics BSM through the low energy, precision measurements – the game is afoot!

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