Light Leptonic New Physics at the Precision Frontier*

Matthias Le Dall1,a)

1Department of Physics and Astronomy, University of Victoria, Victoria, BC, CANADA.
a)mledall@uvic.ca

Abstract. Precision probes of new physics are often interpreted through their indirect sensitivity to short-distance scales. In this proceedings contribution, we focus on the question of which precision observables, at current sensitivity levels, allow for an interpretation via either short-distance new physics or consistent models of long-distance new physics, weakly coupled to the Standard Model. The electroweak scale is chosen to set the dividing line between these scenarios. In particular, we find that inverse see-saw models of neutrino mass allow for light new physics interpretations of most precision leptonic observables, such as lepton universality, lepton flavor violation, but not for the electron EDM.

Introduction

Despite the success of the Standard Model (SM), there exists strong empirical evidence for new Beyond the Standard Model (BSM) physics. This is required to explain neutrino mass, and dark matter, for example. In particular, since the first evidence of neutrino oscillations, the neutrino sector has been a driving force for BSM searches, where the relative smallness of the neutrino masses [1] compared to that of the charged leptons suggests a novel mass generation mechanism.

In broad terms, and given the lack of new physics discovered by the LHC thus far at the electroweak (EW) scale, it is useful to think in terms of two paradigms for understanding BSM physics. On the one hand we can imagine that new physics lies at energies above the SM energy scale. Typically these are best probed at the energy frontier at collider experiments. On the other hand, one can also imagine new physics being constituted by light degrees of freedom, which are necessarily weakly coupled to the SM. These types of theories are often best tested through precision observables, at the intensity frontier. Interestingly, neutrino masses can be understood equally well within those either paradigms. Indeed, a short-distance origin of light neutrino masses follows from the dimension-5 Weinberg operator $\alpha LLHH/\Lambda_{UV}$ [2], which upon the Higgs developing a vev generates $m_\nu \sim \alpha \langle H \rangle^2 / \Lambda_{UV}$. However, a long-distance origin of neutrino masses can also be understood at the renormalizable level, from the Yukawa coupling $yLHN_\nu$, with new light singlet states $N_\nu$, leading to Dirac neutrino masses, $m_\nu \sim y \langle H \rangle$, provided the coupling $y$ is sufficiently small [3]. Both regimes are of course connected, for example, by adding Majorana masses for $N_\nu$.

This contribution will review some recent work [4], and explore the extent to which classes of low energy precision observables may be unambiguously sensitive to either high or low energy physics. In other words, whether there are classes of observables that can uniquely point to either UV or IR energy scales. We delineate four categories of light new physics theories as follows.

1. The first category couples new neutral states via renormalizable operators. Such theories are exemplified by portal interactions, such as the Higgs or Neutrino portals [5].
2. The second category couples new hidden states through anomaly free currents, such as $B - L$, and require no new charged degrees of freedom.
3. The third category couples new states through anomaly free combinations, but which require non-zero SM charge assignments to satisfy the anomaly cancellation conditions.
4. The last category includes new physics coupled through anomalous interactions.

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We deem new physics as light if the masses are well below \( m_W \), and consistent if they fall into the two first categories, so they do not require extra states above the EW scale. The third category requires additional charged scalars to generate masses for the hidden fields, and charged higgs below the EW scale are heavily constrained and pushed to the UV limit. The last category implies the introduction of a UV cutoff, and the existence of UV scale states [6].

In the next section, a simple neutrino mass model is used to analyze various classes of leptonic precision observables, namely Lepton Flavor Violation (LFV), Lepton Universality (LU), and Lepton Electric Dipole Moments (LEDM). Our conclusion is that they are all sensitive to light physics, except the LEDMs which cannot be generated at the current sensitivity level within this class of models. A larger set of observables, including hadronic observables, has been considered in [4]. A summary is given in Fig. 1.

### The Neutrino Model and Its Precision Constraints

We consider a model of 3 left-handed active neutrinos \( \nu_l \) with \( l = e, \mu, \tau \), along with extra right-handed neutrinos \( N_Ri \), and extra fermion singlets \( N_{SI} \).

\[
- \mathcal{L}_\nu \supset \left( \begin{array}{ccc} 0 & m_D & \mu_D \\ m_D & \epsilon_R & M_D \\ \mu_D & M_D & \epsilon_S \end{array} \right) \left( \begin{array}{c} \nu \\ m_D \\ \mu_D \end{array} \right). \tag{1} 
\]

As a model of light new physics, it falls in category 1 above, utilizing the neutrino portal, and requires no UV completion. In general, the mass entries are not diagonal and contain physical CP-phases, though we simplify the discussion by fine-tuning \( m_D \) and \( \mu_D \) such that they are nearly-diagonal and non-universal, i.e. \( m_{Dl} \sim m_D \delta_{0l} \), similarly for \( \mu_D \). We assume the other matrices to be diagonal and universal, i.e. \( M_{Dl} \sim M_D \delta_{0l} \) and so on for \( \epsilon_R, \epsilon_S \). We also assume the inverse see-saw regime [7][8], where \( m_D \sim \epsilon_S \sim 0 \), and \( \epsilon_S \ll M_D \). At the lowest order in \( m_D / M_D \), we can diagonalize the mass matrix in terms of a unitary transformation \( \mathcal{U} \) parametrized by the mixing angle \( \Theta_l \) between hidden and visible states,

\[
\left( \begin{array}{c} \nu_l \\ N_R \\ N_S \end{array} \right) \simeq \left( \begin{array}{ccc} 1 & \Theta_l & i\Theta_l \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{array} \right) \left( \begin{array}{c} \nu_l \\ N_R \\ N_S \end{array} \right), \quad \Theta_l = \frac{m_D}{\sqrt{2}M_D}. \tag{2} 
\]

In the scenario of one \( N_R \) and one \( N_S \) for each active neutrino flavor, the associated mass spectrum consists of one light active neutrino \( \nu^0 \) and two heavier hidden neutrinos \( N_{S} \) of masses \( m_{\nu} \sim 2\Theta_l^2\epsilon_S \), and \( M_{S} \sim M_D / \epsilon_S/2 \). For a model of light new physics, we take \( m_D, M_D \ll m_W \).

**Lepton Flavor** is weakly violated in the neutrino sector materialized in neutrino oscillations, but is otherwise an accidental symmetry in the charged lepton sector. There are various candidate channels to search for large sources of LFV [9]. We will focus on \( \mu \to e\gamma \) decay and \( \mu \to e \) conversion. The \( \mu \to e\gamma \) decay is measured relative to the total muon decay rate \( 10^{10} \), and is mediated at the one loop level [12][13].

\[
\text{Br}(\mu \to e\gamma) = \frac{\delta^2}{8\pi} \approx \frac{3\alpha}{8\pi} \frac{M_D^4}{m_W^4} \Theta_e^2 \Theta_\mu^2 < 5.7 \cdot 10^{-13}, \quad \delta = \sum \left| U_{\mu i} m_i \right|^2 \tag{3} 
\]

The \( \mu \to e \) conversion channel [14], consists in the lepton flavor oscillation due to nuclear scattering, measured with respect to the muon capture rate \( R_{\mu-e} = \Gamma(\mu-e)/\Gamma_{\text{capture}} \). This channel can be enhanced compared to the previous one thanks to the coherent nature of the low energy scattering. One contributing diagram [15], called photonic, is the same as the on-shell decay except the photon line is connected to the nucleus. Another, the non-photonic box diagram, can be competitive compared to the former due to the small quark masses running in the loop. In the light neutrino regime, the latter dominates, leading to

\[
R_{\mu-e} = \left( \frac{3G_F m_W^2}{4 \sqrt{2} \pi^2} \right)^2 \frac{E_e p_e}{m_e^2} \alpha \beta_{\text{coh}} \simeq 26 \frac{M_D^4}{m_W^4} \Theta_e^2 \Theta_\mu^2 < 7.0 \cdot 10^{-13}, \tag{4} 
\]

where \( E_e p_e / m_e^2 \sim 1 \) and the charge form factor \( |F_{\text{coh}}| \sim 0.5 \). The limit comes from the SINDRUM II experiment using Gold [16], for which the enhancement coherent factor \( \beta_{\text{coh}} \sim 1.6 \cdot 10^6 \).
Lepton Universality tests flavour-independence of the coupling $g_{lH} \bar{l}_y \gamma^\mu v_l W^\mu \nu$. In the SM with massless neutrinos, the coupling $g_{lH} = g \delta_{lH}$ is diagonal. When neutrinos acquire a mass, the flavor states $\nu_l$ become linear superpositions of mass eigenstates $\nu^\mu_l$, and the coupling senses all neutrino species through $g \sum_l U_{li}^* \bar{l}_y \gamma^\mu \nu^\mu_l W^\mu \nu$. Among other variables, the ratio of leptonic tau decays $R_\tau = \Gamma(\tau \rightarrow \mu \nu \nu)/\Gamma(\tau \rightarrow e \nu \nu)$ tests LU, and is measured by BaBar to be \cite{17}

$$R_\tau = \frac{\sum_{i,j} \Gamma(\tau \rightarrow \mu \nu_i \nu_j)}{\sum_{i,j} \Gamma(\tau \rightarrow e \nu_i \nu_j)} = 0.9796 \pm 0.0052,$$

$$\Gamma(\tau \rightarrow e \nu_i \nu_j) = \frac{G_F^2 m^5}{192\pi^2} |U_{\tau i}|^2 |U_{\mu j}|^2 \left( \frac{m^2_{\mu}, m^2_{\nu_j}}{m^2_{\mu} + m^2_{\nu_j}} \right), \quad (5)$$

where $I(x, y)$ is a phase space kinematic function \cite{18}. The deviation of the central value 0.9796 from unity is due to radiative corrections. Ignoring those, we test to which extent the deviation from 1 is due to new physics, i.e. $\Delta R_\tau = 1 - \Gamma(\tau \rightarrow \mu \nu \nu)/\Gamma(\tau \rightarrow e \nu \nu) < 0.0052$.

Electric Dipole Moments are precision probes of CP-violation across a wide range of energy scales \cite{20}. Here, we focus on the electron EDM. In the conventional neutrino see-saw model, it can only arise at the 2 W-loop level \cite{21, 22, 23}, and depends on the neutrino mass square differences $\Delta m^2$ due to the GIM mechanism \cite{24}. As a result, the electron EDM generically scales as $O(e m_{\nu} G^2 \Delta m^2) \sim e \cdot cm \cdot 10^{-45} \Delta m^2 / eV^2$, which is orders of magnitude below the experimental upper limit $d_e \approx 8.7 \times 10^{-29} e \cdot cm$ \cite{25}. It is possible to increase the estimate by using the full mass lagrangian Eq. (1) in a see-saw regime $\epsilon_{R,S} \gg m_D, \mu_D, M_D$, which leads to

$$d_e \sim \left( 5.8 \cdot 10^{-34} e \cdot cm \right) \frac{m^2_D \mu^2_D}{(\epsilon_R + \epsilon_S)} \frac{\epsilon^2_R - \epsilon^2_S}{e GeV^2} \sin(2\eta). \quad (6)$$

In this regime, the active neutrino masses are controlled by the fine tuning of $m_D$ and $\mu_D$, $m_\nu \sim (m^2_D - m^2_\nu)/(\epsilon_R + \epsilon_S)$. Taking $\epsilon^2_R - \epsilon^2_S \approx 100 GeV^2$, and $m_D/\epsilon_S, \mu_D/\epsilon_S \lesssim 0.1$, we find the upper bound $d_e \lesssim 10^{-36} e \cdot cm$, which is still well below the current experimental limit.
Discussion

The results of the above analysis are exhibited in Fig. 1, which shows that the inverse see-saw model provides a viable means of interpreting a range of precision measurements in terms of light new physics. We discussed LFV, LU, and LEDMs, and found that only lepton EDMs cannot be explained within the model, and would instead point to UV physics.

The study can be extended to hadron observables like hadron flavor violation, baryon number violation, hadron EDMs \[4\]. Since the hadronic sector does not allow for renormalizable couplings to neutral states, like the RHN in the lepton sector, there is no equivalent to the portal interactions, and a generic conclusion is that precision hadronic observables tend to test new short-distance physics. Note, however, that hadronic EDMs on the other hand seem to be ambiguous pointers, due to the possibility of an explanation in terms of \(\theta_{QCD}\) which is a marginal coupling and can be generated anywhere above the QCD scale.

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