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neutrinos, dark matter & dark energy physics

An EFT approach to possible lepton anomalies

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Status of Lepton experiments

Precision era for neutrino experiments

- Δm^2_{ij} measured at $\mathcal{O}(1\%)$ and $\sin^2(\theta_{ij})$ measured at $\mathcal{O}(5-10\%)$
- δ_{CP} less well known, but dedicated programme including T2K, NOVA, DUNE expected to improve precision

Persistent $(g-2)_\mu$ anomaly

- Improved hadronic vacuum polarisation calculation [1; 2], now $\gtrsim \mathbf{3.5\sigma}$ discrepancy
- Could reach 5σ in a few years at Fermilab if experimental value stays the same

Strong charged lepton flavour violation (CLFV) constraints

- $BR(\mu\to e\gamma) \lesssim 10^{-13}$ most stringent, with $BR(\tau\to\mu\gamma), BR(\tau\to e\gamma) \lesssim 10^{-8}$
- $BR(Z\to \ell_a^\pm \ell_b^\mp) \lesssim 10^{-6}$, $a\neq b$

Recent hints of lepton flavour universality violation (**LFUV**) in the $b\to s\ell^+\ell^-$ channel:

- SM predicts $R_{K^{(*)}} \approx 1$, LHCb finds:

$$R_K[4m_\mu^2, 1.1\text{ GeV}^2] = 0.660^{+0.110}_{-0.070} \pm 0.024; \quad (1a)$$
$$R_K[1\text{ GeV}^2, 6\text{ GeV}^2] = 0.745^{+0.09}_{-0.074} \pm 0.036; \quad (1b)$$
$$R_{K^*}[1.1\text{ GeV}^2, 6\text{ GeV}^2] = 0.685^{+0.113}_{-0.069} \pm 0.047, \quad (1c)$$

giving a combined 4σ deviation from the SM

Effective Field Theory

- Effective field theory (EFT) is a model-independent approach that is especially useful when there are many constraints and the UV completion is unknown
- The Standard Model EFT (SMEFT) Lagrangian can be written up to dimension-6 as

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{C_W}{\Lambda}Q_W + \sum_i \frac{C_i}{\Lambda^2}Q_i + h.c. \quad (2)$$

for Wilson coefficients (WCs) C_i, new physics scale Λ, $d=6$ operators Q_i, and Weinberg operator

$$Q_W = (\overline{l_L^c}\tilde{H}^*)(\tilde{H}^\dagger l_L). \quad (3)$$

- Also useful framework to study a specific model by **matching the model onto WCs**
- Standard procedure: match at tree-level, run at 1-loop: enables systematic selection of leading logarithms
- 1-loop running information contained in anomalous dimension matrix, γ, defined by

$$16\pi^2\frac{dC_i}{d\ln\mu} = \gamma_{ij}C_j. \quad (4)$$

- WCs generated via tree-level matching are $C\sim\mathcal{O}(1)$ for order-1 new physics couplings, while those generated via 1-loop running have size

$$C_{1-loop} \sim \frac{\gamma}{16\pi^2}\log(\Lambda/\mu). \quad (5)$$

Abstract

We use effective field theory to investigate the interplay between precision lepton observables, including charged lepton flavour violation, the $(g-2)_\mu$ anomaly and a 4σ indication of lepton flavour universality violation in B-meson semi-leptonic decays.

R_K and R_{K^*}

The momentum-dependent ratios $R_{K^{(*)}}$ are defined by

$$R_{K^{(*)}}[q^2_{min}, q^2_{max}] = \frac{\int_{q^2_{min}}^{q^2_{max}} dq^2 d\Gamma(B\to K^{(*)}\mu^+\mu^-)/dq^2}{\int_{q^2_{min}}^{q^2_{max}} dq^2 d\Gamma(B\to K^{(*)}e^+e^-)/dq^2} \quad (6)$$

where q^2 is the invariant momentum squared of the final state leptons.

EFT of the type-I seesaw

Type-I seesaw with heavy RH neutrinos permits a general and illuminating EFT description. Can find leading order $d=5,6$ WCs generated by type-I seesaw, then calculate observables. Tree-level Lagrangian (integrate out heavy RH neutrinos) [4]:

$$\mathcal{L}_{tree} = \frac{(Y_\nu^T M^{-1} Y_\nu)_{ab}}{2}Q_{W,ab} + \frac{(Y_\nu^\dagger M^{*-1}M^{-1}Y_\nu)_{ab}}{4}\left(Q^{(1)}_{Hl,ab} - Q^{(3)}_{Hl,ab}\right) + h.c.$$

1. Many WCs generated via **1-loop mixing** of $Q_W, Q_{Hl}^{(1,3)}$

- Compare EFT with calculations made in type-I seesaw models, e.g. with exact $U(1)_L$ symmetry and Dirac masses for sterile neutrinos ('Inverse seesaw'), find:

$$\Gamma(h\to e_k^\pm e_m^\mp) \approx \frac{\lambda^2 m_k^2 v^2 m_h}{(4\pi)^5}\left[Y_\nu^\dagger M^{*-1}M^{-1}\log\left(\frac{|M|}{m_W}\right)Y_\nu\right]^2_{km},$$
$$\Gamma(Z\to e_k^\pm e_m^\mp) \approx \frac{v^2 m_Z^3}{6(4\pi)^5}\left(\frac{17g_2^2+g_1^2}{12}\right)^2\left[Y_\nu^\dagger M^{*-1}M^{-1}\log\left(\frac{|M|}{m_W}\right)Y_\nu\right]^2_{km}$$

agrees at leading order with exact calculations [5; 6]

- Leading order result **computationally simple**

2. 1-loop matching to calculate WCs of EW dipole operators: not generated via mixing $\Rightarrow$ **no leading log enhancement** (cf. Fig. 1), compute

$$C_{e\gamma,ab} = -\frac{ev}{\sqrt{2}}\frac{(Y_\nu^\dagger M^{*-1}M^{-1}Y_\nu)_{ab}y_b}{96\pi^2} - \frac{ev}{\sqrt{2}}\frac{g^2 U^*_{ai}m_i^2 U_{bi}y_b}{256\pi^2 m_W^4} \quad (7)$$

- Hence $C_{e\gamma,ff}<0$, i.e. type-I seesaw worsens $(g-2)_\mu$ anomaly, shown previously in exact computations
- Calculation of $\Gamma(\ell_a\to\ell_b\gamma)$ easily extracted from Eqn. (7) agrees at leading order with literature [7]

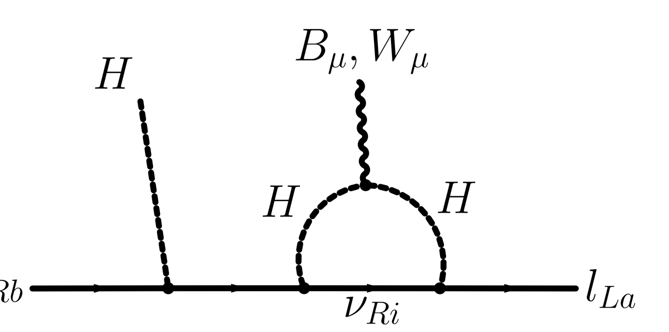

Figure 1: 1-loop matching to calculate C_{eB}, C_{eW} in seesaw EFT.

Type-I seesaw model

- Add n_s right-handed fermions singlet, need $n_s\geq 2$ for at least two non-zero neutrino masses
- Lagrangian for the type-I seesaw is

$$\mathcal{L} \supset \overline{\nu_{Ri}}i\partial\!\!\!/\nu_{Ri} - Y_{\nu,ia}\overline{\nu_{Ri}}\tilde{H}^\dagger l_{La} - \frac{1}{2}\overline{\nu_{Ri}}M_{ij}\nu^c_{Rj} + h.c., \quad (8)$$

- $i,j=1,\ldots,n_s$; can in general make M_{ij} diagonal
- The neutrino mass matrix is given by

$$m_\nu = -\frac{v^2}{2}Y_\nu^T M^{-1}Y_\nu, \quad (9)$$

so $m_\nu\approx 0.1$ eV for $Y_{\nu,ia}\sim 1$ and eigenvalues $|M_i|\approx 10^{15}$ GeV

- Lighter sterile neutrinos (more phenomenologically relevant) achieved by approximate $U(1)_L$ symmetry

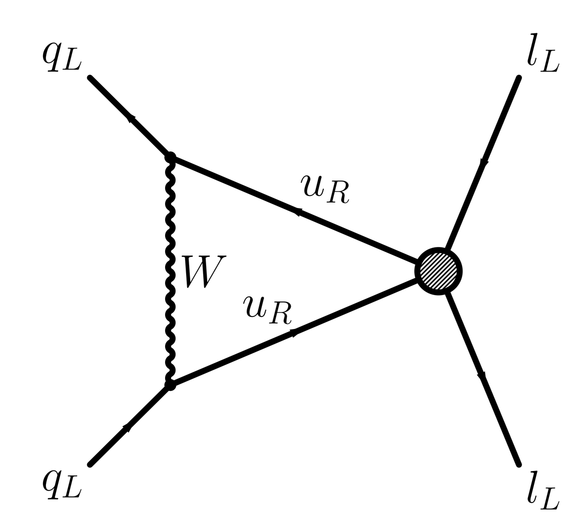

Figure 2: 1-loop contribution to $C_{9,10}$ induced by C_{lu}.

Spurion analysis in type-I seesaw EFT

Consider extended lepton flavour symmetry, $G_L = [SU(3)\times U(1)]_L\times[SU(3)\times U(1)]_R\times[SU(3)\times U(1)]_\nu$, for $n_s=3$, under which the spurions transform as

$$Y_e\sim(\mathbf{3}_1,\overline{\mathbf{3}}_{-1},\mathbf{1}_0);\ Y_\nu\sim(\overline{\mathbf{3}}_{-1},\mathbf{1}_0,\mathbf{3}_1);\ M\sim(\mathbf{1}_0,\mathbf{1}_0,\mathbf{6}_2)$$

The symmetry dictates relations between various WCs:

- $C_{Hl}^{(1,3)} \propto Y_\nu^\dagger M^{*-1}M^{-1}Y_\nu + \mathcal{O}(Y_\nu^4 M^{-2})$, so are proportional at tree-level
- Weinberg WC: $C_W\propto Y_\nu^* M^{-1}Y_\nu^\dagger$
- $C_{eH}, C_{eB}, C_{eW}\propto Y_\nu M^{*-1}M^{-1}Y_\nu^\dagger Y_e + \mathcal{O}(Y_\nu^4 Y_e M^{-2})$, so all suppressed by Y_e
- Y_ν enters in $d=6$ WCs either as $(Y_\nu^\dagger M^{*-1}M^{-1}Y_\nu)$ or $(Y_\nu^\dagger M^{*-1}Y_\nu^* Y_\nu^T M^{-1}Y_\nu)$

Ongoing work: general spurion analysis of lepton observables and relations to each other [8]

EFT of $b\to s\ell\ell$ transitions

1. $b\to s$ anomalies suggest new physics in muons sector: possible **connection to $(g-2)_\mu$ anomaly**?

- Performed basis-independent search for single $d=6$ operator which could explain both anomalies
- Considered effects from tree-level, one-loop and Barr-Zee type two-loop diagrams: showed no operator succeeds
- Difficulties in a combined explanation include:
  - dipole described by tensor operators, $b\to s$ transition by vector operators, only 5/20 Warsaw vector operators mix with tensor
  - $(g-2)_\mu$ is $\Delta F=0$ but $b\to s$ is $\Delta F=1$, so a) relative CKM suppression, and b) few diagram topologies relating them

2. Consider full set of WCs which can contribute at tree-level or 1-loop to these anomalies

- Constraints from observables such as EW precision data
- Previous analyses exist [9; 10], but can be extended in several directions [11]
  - relax top dominance assumption
  - consider operators with electrons as well as muons
  - consider interplay with additional observables, e.g. $(g-2)_\mu$
- E.g. WCs $C_{lu,\alpha\alpha23}, C_{lu,\alpha\alpha33}$ for $\alpha=e,\mu$ contributes at 1-loop to the anomaly with (cf. Fig. 2)

$$C_{9,\alpha} = -C_{10,\alpha} \approx -\frac{m_t^2\log(\Lambda/m_t)}{2e^2\Lambda^2}\left(\frac{y_c}{y_t}\frac{V^*_{cs}}{V^*_{ts}}C_{lu,\alpha\alpha23} + C_{lu,\alpha\alpha33}\right) \quad (10)$$

with constraints from Z-pole data since (cf. Fig. 3)

$$\delta g_L^\alpha \approx \left(\frac{2g_1^2}{3} - 6y_t^2|V_{tb}|^2\right)C_{lu,\alpha\alpha33}\frac{v^2}{32\pi^2\Lambda^2}\log\left(\frac{\Lambda}{m_t}\right). \quad (11)$$

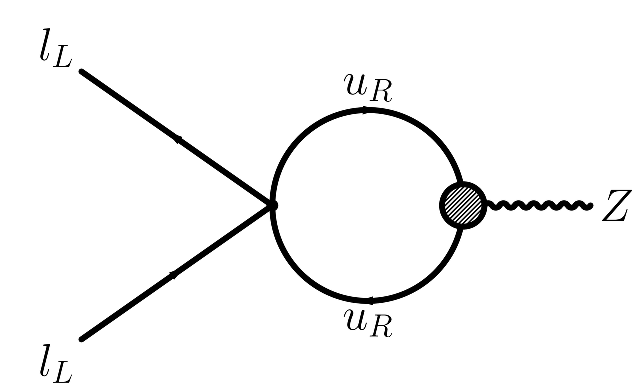

Figure 3: 1-loop correction to $Z\to\ell^+\ell^-$ induced by $C_{eu,\alpha\alpha33}$

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