Probing Leptophobic $\mathrm{U}(1)_{\mathrm{H}}$ Theories at the J-PARC KOTO

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Introduction

The recent results provided by the J-PARC KOTO experiment could not improve the upper limit on the $K_L \to \pi\bar{\nu}\nu$ branching fraction, given by $3.0 \cdot 10^{-9}$ at 90%C.L.. Compared to the SM prediction $\mathrm{Br}(K_L \to \pi^0\bar{\nu}\nu) = 0.34(6) \times 10^{-10}$, it allows a noticeable room for NP which can be investigated from:

$$\begin{aligned} K_L &\to \varphi_R\varphi_I, && \text{followed by} \quad \varphi_R \to \varphi_I + \pi^0; \\ K_L &\to \overline{\nu}_i\nu_j, && \text{followed by} \quad \nu_j \to \nu_i + \pi^0; \\ K_L &\to \pi^0 Z_H, && \text{followed by} \quad Z_H \to \nu + \nu. \end{aligned} \tag{1}$$

KOTO Searches and $U(1)_X$ Theories

$SM \otimes U(1)_X$: We consider two possible operators for $\Delta S = 1$ $s \to d$ transition:

$$\mathcal{O}_V = \left[C_V^L(\overline{s_L}\gamma_\mu d_L) + C_V^R(\overline{s_R}\gamma_\mu d_R)\right] \times J_X^\mu, \quad (2)$$

$$\mathcal{O}_S = \left[C_S^L(\overline{s_R} d_L) + C_S^R(\overline{s_L} d_R)\right] \times J_X, \quad (3)$$

where J_X^μ and J_X denote the missing mass current. In order to generate $\mathcal{O}_V$ type operators from NP, the SM fermions must also be chiral under the new $U(1)_H$ gauge symmetry. Accordingly, there must be at least two important issues to be addressed during the model building step:

(i) It should be anomaly free, what in general can be achieved by the introduction of new chiral fermions;

(ii) It should admit renormalizable Yukawa couplings to all the SM fermions. It will commonly require the introduction of additional Higgs doublets charged under $U(1)_H$.

E_6 Motivated Leptophobic $U(1)_H$

We seek for a general charge assignment of a particle content satisfying the following conditions:

1. The representations define a E_6 $SM \otimes U(1)_H$ subgroup for at least one of the collection of models we construct. It will correspond to extend the SM content with the $SU(2)_L$ neutral lepton singlets n_R and N_L, a pair of d-type quark singlets $D_{L(R)}$, and the lepton doublets $L_{L(R)}$;
2. The h-charges constrain the Yukawa interactions between the SM fermions to those of a type-II 2HDM;
3. $U(1)_H$ is leptophobic over SM leptons.

E_6 Motivated Leptophobic $U(1)_X$

	q_L^i	u_R^i	d_R^i	l_L^i	e_R^i	n_R^i	H_1
$SU(3)_c$	3	3	3	1	1	1	1
$SU(2)$	2	1	1	2	1	1	2
$U(1)_Y$	1/6	2/3	$-1/3$	$-1/2$	-1	0	1/2
$U(1)_H$	$b(1+a)$	$-2b(1+a)$	$b(1+a)$	0	0	$b\left(\pm\sqrt{\frac{a(9+14a)}{2}}-3(1+a)\right)$	0

TABLE I: General charge assignments of the SM fermions under the SM gauge group and the Leptophobic $U(1)_H$ E_6 subgroup.

	H_2	D_L^i	D_R^i	L_L^i	L_R^i	N_L^i	Φ_k	φ
$SU(3)_c$	1	3	3	1	1	1	1	1
$SU(2)$	2	1	1	2	2	1	1	1
$U(1)_Y$	1/2	$-1/3$	$-1/3$	$-1/2$	$-1/2$	0	0	0
$U(1)_H$	$-3b(1+a)$	$-b(2+3a)$	b	ab	$b(3+4a)$	$b\left(\pm\sqrt{\frac{a(9+14a)}{2}}+3(1+a)\right)$	X_k	X_φ

TABLE II: Charge of the new particle content under the SM gauge group and the Leptophobic $U(1)_H$ E_6 subgroup.

Complete Example (a = -6)

$$D_\mu = \partial_\mu - i\left(\frac{g}{\sqrt{2}}(W^+_\mu \mathbb{I}_+ + W^-_\mu \mathbb{I}_-) + e\mathbb{Q}A_\mu + \kappa_Z Z_\mu + \kappa_H Z_{H\mu}\right) \quad (4)$$

The massless photon fixes one angle to zero, such that the above gauge couplings acquire dependence on the new angle $s_\theta = \sin\theta$, in addition to the equivalent weak mixing (Weinberg) angle, $s_w = \sin\theta_W$, i.e.

$$\kappa_H = s_\theta g_Z - c_\theta g_X X, \quad (5a)$$

$$e\mathbb{Q} = s_w g \tau^3 + c_w g_Y Y, \quad (5b)$$

$$\kappa_Z = c_\theta g_Z + s_\theta g_X X, \quad (5c)$$

where $g_Z = \frac{g}{c_w}(\tau_3 - s_w^2\mathbb{Q})$, $c_\theta = \cos\theta$, and $c_w = \cos\theta_W$. In the limit of a decoupled Z_H, i.e. $m^2_{Z_H} \gg m^2_Z$, we have $g_H \gg \overline{g}$, or

$$s_\theta \approx \frac{m_Z^2}{m_{Z_H}^2}\frac{\delta}{\overline{g}}, \quad (6)$$

where $\delta = 2g_X(c_\beta^2 X_{H_1} + s_\beta^2 X_{H_2})$. For light Z_H, $s_\theta \approx \delta/\overline{g}$.

Complete Example

a = -6:

$$\begin{aligned}\mathcal{L} \supset\ & Y_\nu\, \overline{l_L}\tilde{H}_1 n_R + M_n \overline{n_R^c} n_R + Y_{2N}\Phi_2 \overline{n_R} N_L \\ & + Y_L \Phi^\dagger \overline{L_L} L_R + Y_D \Phi^\dagger \overline{D_L} D_R + Y_{lL}\,\varphi_\chi \bar{l}_L L_R + Y_{dD}\,\varphi_\chi \overline{D}_L d_R + \text{h.c.},\end{aligned} \tag{7}$$

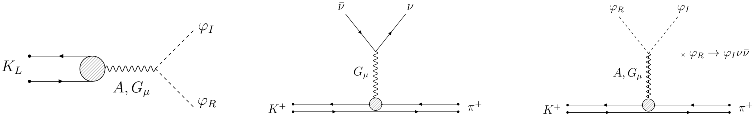
Notice that $c_\beta = v_1/v$ is supposed to modulate neutrino masses.

$$\begin{aligned}V(H_i,\Phi,\varphi) \supset\ & m_\varphi^2|\varphi|^2 + \lambda_\varphi|\varphi|^4 + \lambda_{i\varphi}|\varphi|^2 H_i^\dagger H_i + \lambda_{\Phi\varphi}|\varphi|^2|\Phi|^2 \\ & + \left\{(\lambda_{12\varphi} H_1^\dagger H_2 + \sqrt{2}\mu_{\Phi\varphi}\Phi^\dagger)\varphi^2 + \text{H.c.}\right\}\end{aligned}$$

φ_I: Light DM candidate

$$m_I^2 = m_R^2 - 2\left(\lambda_{12\varphi} v^2 c_\beta s_\beta + 2\mu_{\Phi\varphi} v_\Phi\right), \tag{8}$$

KOTO Searches from Dark Fields

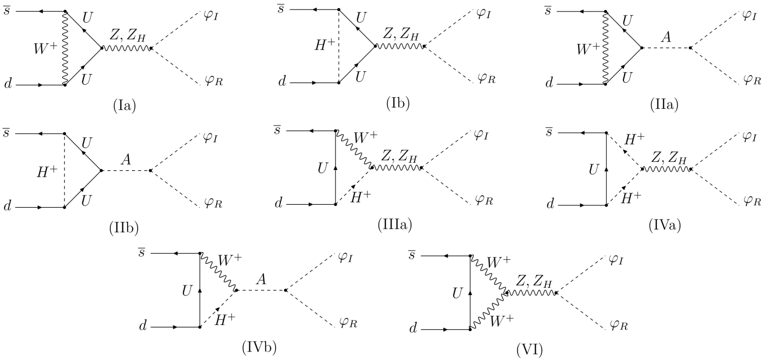


- Rare processes are typically related to $\Delta F = 1, 2$.
- Universal theories: FCNC at tree-level only from mixing between SM and NP;
- For DM theories, i.e. if NP sector is dark (Z_2 odd), the physics of portals will emerge at the loop-level: Need of generalized formulas for penguins, for both vector and pseudo-scalar mediators;

$$i\Gamma_A = g^2 \frac{V_{us}^* V_{ud}}{16\pi^2} A\{a_R[\overline{s_L} d_R] + a_L[\overline{s_R} d_L]\} \qquad (9)$$

$$i\Gamma_G = i g^2 \frac{V_{us}^* V_{ud}}{16\pi^2} z_L^G G_\mu [\bar{s}_L \gamma^\mu d_L]. \qquad (10)$$

$\mathrm{U}(1)_\mathrm{H}$ Phenomenology

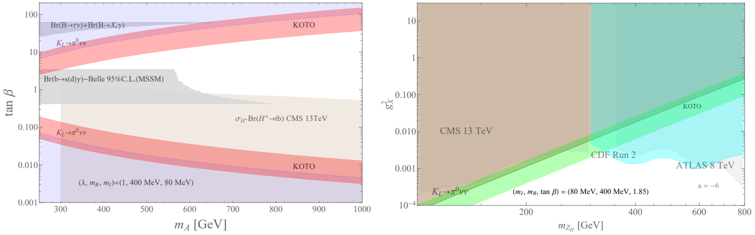


Feynman diagrams for $\mathrm{K_L} \to \varphi_I \varphi_R$.

$U(1)_H$ Phenomenology

i. Pseudo-scalar A only, where Z_H effects are absent and $s_\theta \to 0$. This is close to test 2HDM models;
ii. Z, Z_H only and a decoupled pseudo-scalar. This is close to test $U(1)_X$ theories;
iii. All off-shell A, Z, Z_H contributing. This scenario tests $2HDM_X$, and includes massive neutrinos as the source of missing mass;
iv. Light Z_H resonance mediating fermion production (ν_i).

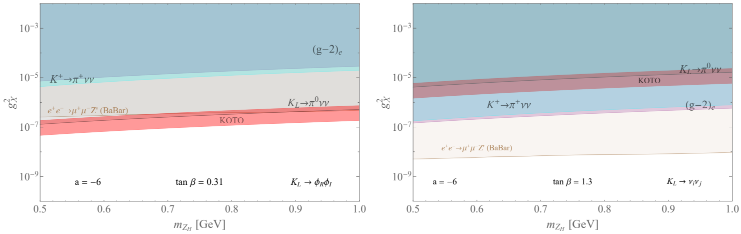
$U(1)_H$ Phenomenology



$K_L \to \varphi_R \varphi_I$ at the EW scale, mediated by (a) pseudo-scalar and (b) $G - Z, Z_H$.

- At the EW scale, the theory would rely on the presence of a light (MeV) scalar among its spectra, which must regulate φ_I abundance;
- DM annihilation from light scalar, s-channel: p-wave, safe from CMB bounds;
- The light scalar would enter in the KOTO physics at the three-body level;

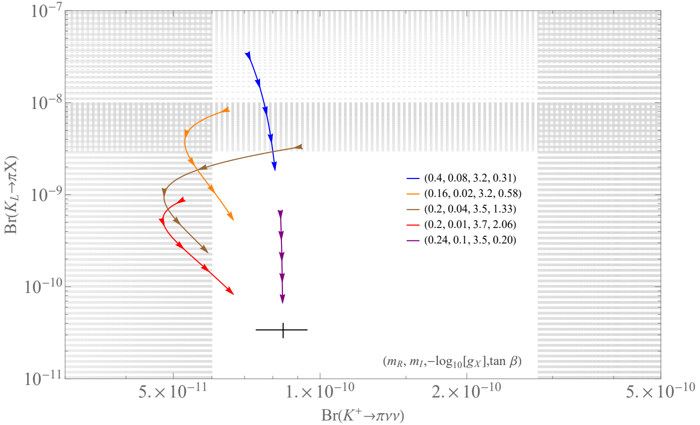
$U(1)_H$ Phenomenology



$K_L \to \varphi_R \varphi_I$ and $K_L \to \nu_i \nu_j$. The red band is affected by the mass-mixing suppression in leptophobic theories.

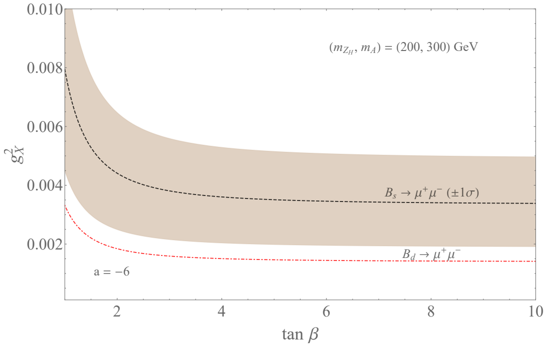
- φ_I abundance regulated by $\varphi_I \varphi_R \to Z_H^* \to SM.$;
- φ_R decayed away at time of recombination: safe from CMB bounds;
- The $\nu_j \to \nu_i \pi$ requires the hierarchy $(M_{\nu_i}, M_{\nu_j}, M_{\nu_k}) = (0.1eV, MeV, M_{\nu_k})$, which can be realized in our setup;

$U(1)_H$ Phenomenology



A correlation plot between $K_L \to \pi X$ and $K^+ \to \pi\bar{\nu}\nu$ in *Model A*, where inelastic scalars contribute to the missing mass. The curves run over $m_{ZH} \in [0.5, 1]$GeV, and correspond to different benchmark points.

$U(1)_H$ Phenomenology



The parameter space $(\tan\beta, g_X^2)$ that brings the SM central value for $Br(B_s \to \mu^+\mu^-)$ to the 1σ standard deviation from the experimental measurement (*Model A*, $a = -6$). The line reproducing the experimental central value of $Br(B_d \to \mu^+\mu^-)$ has also been plotted (red dotted curve).

Inelastic Dark Bosons

From the expansion of $\sigma(\varphi_1\varphi_2 \to Z_H^* \to \bar{l}l)v = a + bv^2$, we find

$$a = \frac{[c_H^A(l)]^2(g_X X_\varphi)^2 m_l^2 (m_1 - m_2)^2[(m_1 + m_2)^2 - 4m_l^2]^{1/2}}{4\pi m_1 m_2 m_H^4 (m_1 + m_2)}. \tag{11}$$

Therefore, the process is purely p-wave either in the elastic framework ($m_1 = m_2$) or in the dark-photon, A', mediation, where $c_H^A = 0$.

Light Inelastic Dark Bosons

Inelastic light (MeV) dark scalars require resonant scalar mediators regulating their annihilation channel.

Conclusions

- We provide a class of type-II 2HDM embedded in leptophobic Abelian theories supplied by a dark sector;
- We provide generalized formulas of loop-corrected $\Delta F = 1$ vertices;
- We probe the physics of vector and pseudo-scalar portals for a particular DM model at the J-PARC KOTO.