FLASY 2026

12th Workshop on Flavor Symmetries and Consequences in Accelerators and Cosmology

Goldstone Portal to Charged Lepton Flavour Violation

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Motivation: Nambu-Goldstone Bosons

Goldstone's Theorem: Given the spontaneous breaking of a global symmetry, then there is a massless scalar (NGB) for each broken generator

NGBs are among the most important candidates for BSM particles: DM candidates, strong CP problem, etc

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Typically in literature, NGBs come from U(1) symmetries, being (mostly) singlets under the SM gauge group

Therefore... they are very difficult to detect: since they are SM-singlets, they only interact at tree-level with BSM fields

Motivation: NGB interaction with charged-leptons

One of the most relevant signals for detecting NGBs comes from flavour: $\ell_\alpha \to \ell_\beta\ \pi$

These interactions have been analyzed in particular models by computing the correspondent loop diagrams

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Example: Type-I Seesaw with SSB

To generate Majorana neutrino masses we need to break the global U(1), B-L. If B-L SSB → Majoron (NGB)

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Example: Type-I Seesaw

$$\mathcal{L} = y\,\bar{L}\,\tilde{H}\,N + \frac{1}{2}Y\,\phi\,\bar{N}^c\,N + \text{h.c.}\,, \qquad \phi = \frac{1}{\sqrt{2}}\left(v_\phi + \phi^0 + i\,J\right)$$

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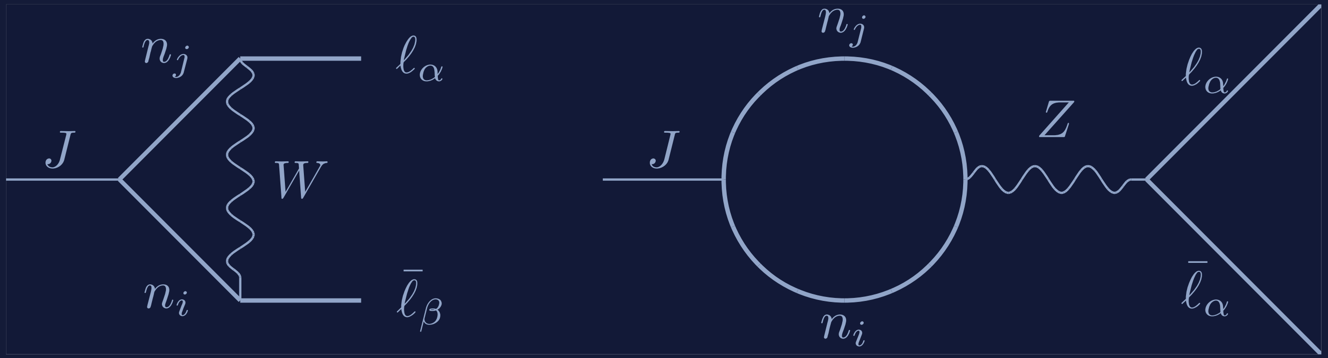

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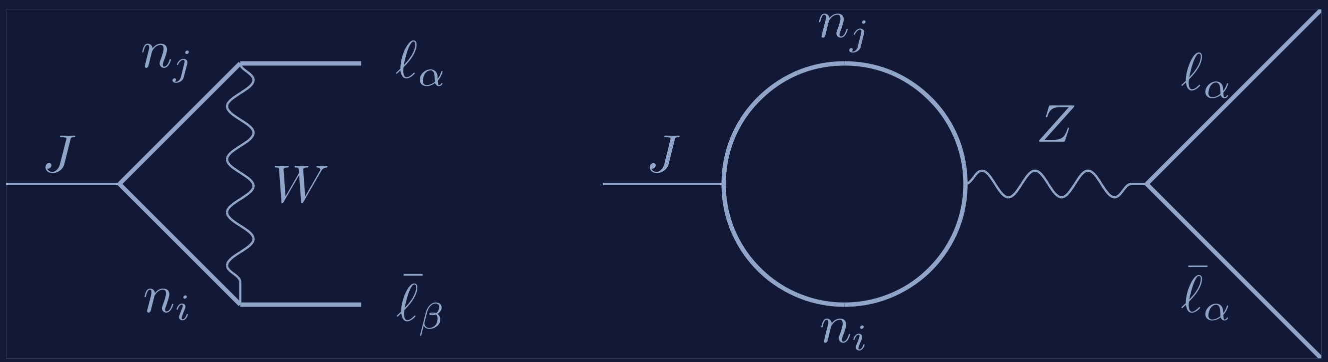

$$\mathcal{L}_{\ell\ell J} \simeq \frac{i J}{16\pi^2 v_H^2 v_\phi}\,\bar{\ell}\left[M_\ell\,\mathrm{Tr}(M_D\,M_D^\dagger)\,\gamma_5 + 2M_\ell\,M_D\,M_D^\dagger\,P_L - 2\,M_D\,M_D^\dagger\,M_\ell P_R\right]\ell$$

C. Garcia-Cely and J. Heeck, arXiv:1701.07209

A. Pilaftsis, arXiv:hep-ph/9308258

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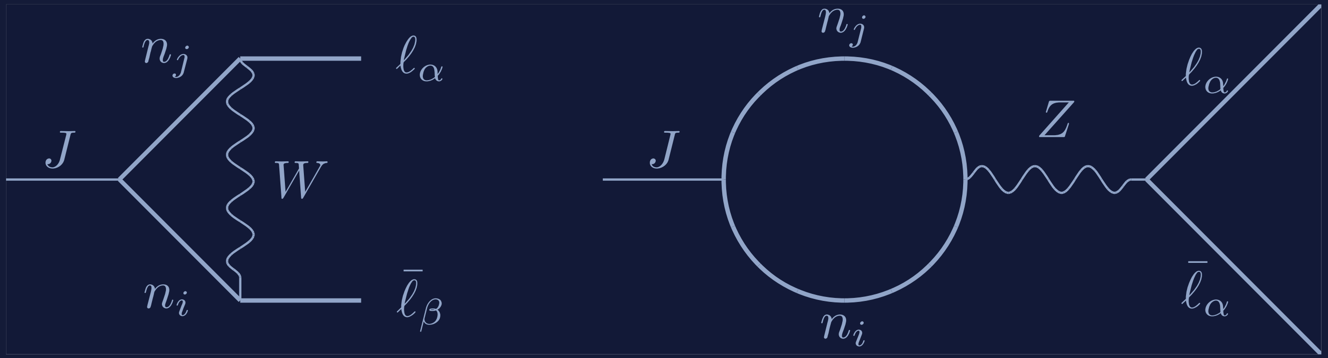

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Distinguish and build models where this interaction becomes relevant

Compare this flavour signal with the traditional $\ell_\alpha \to \ell_\beta\ \gamma$

EFT approach to the coupling

We will consider the NGB associated with the spontaneous breaking of a global U(1) and generated by an SM-singlet

Since the NGB comes from an SM-singlet, it only interacts with charged leptons through higher-dimensional operators

We must distinguish two scenarios

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- **Scenario 1: The U(1) is already broken below the UV cutoff**

  Then the NGB appears as an independent field allowing for the following operators

$$\mathcal{O}_1^{(5)} = c_1^{(5)}\,\pi\,\frac{\bar{L}\,H\,e_R}{\Lambda} \sim \frac{v_H}{\Lambda}$$

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- **Scenario 2: The U(1) still conserved below the UV cutoff**

  The higher-dimensional operators must preserve the global U(1). Hence:

$$\mathcal{O}_1^{(6)} = c_1^{(6)}\,\frac{\bar{L}\,H\,e_R\,\phi\,\phi^*}{\Lambda^2} \sim \frac{v_\phi v_H}{\Lambda^2}$$

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We can compare this interaction with the traditional $\ell_\alpha \to \ell_\beta \gamma$, which arises via

$$\mathcal{O}_\gamma = \frac{c_\gamma}{\Lambda^2}\,\bar{L}\,H\,\sigma_{\mu\nu}\,e_R\,B^{\mu\nu}$$

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$$\mathcal{O}_\gamma = \frac{c_\gamma}{\Lambda^2} \, \bar{L} \, H \, \sigma_{\mu\nu} \, e_R \, B^{\mu\nu}$$

Hence, in models belonging to scenario 1, where

$$\mathcal{O}_1^{(5)} = c_1^{(5)} \, \pi \, \frac{\bar{L} \, H \, e_R}{\Lambda} \sim \frac{v_H}{\Lambda}$$

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we expect $\ell_\alpha \to \ell_\beta \pi$ to dominate over $\ell_\alpha \to \ell_\beta \gamma$

Analytical expression for the coupling

We computed the one-loop NGB coupling to charged leptons in a model-indepedent way (under some assumptions).

A.Herrero-Brocal and A. Vicente, arXiv: 2311.10145

Defining the coupling as

$$\mathcal{L}_{J\ell\ell} = J\,\bar{\ell}_\beta\,\left(S_{\beta\alpha}\,P_L + S^*_{\alpha\beta}\,P_R\right)\,\ell_\alpha$$

we provide a simplified matrix expression for the contribution to S of any possible one-loop diagram.

Given a model, one can identify the one-loop diagrams and couplings, use our general formulae, and obtain a matrix expression for S

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The calculation was focused in the Majoron and assumes Majorana neutrinos, but can be easily generalized for Dirac neutrinos and then valid for any NGB

S.Centelles-Chulià, T.Herbermann, A.Herrero-Brocal and A.Vicente, arXiv:2506.06449

Application: inverse seesaw and the Majoron

The inverse seesaw is defined by the following neutral fermion mass matrix

$$\mathcal{L}_{\rm mass} = \begin{pmatrix} \bar{\nu}_L & \bar{N}^c & \bar{S}^c \end{pmatrix} \begin{pmatrix} 0 & y_N\, v_H/\sqrt{2} & 0 \\ y_N^T\, v_H/\sqrt{2} & 0 & \Lambda \\ 0 & \Lambda & \mu_S \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N \\ S \end{pmatrix} \;,\; \mu_S \,, v_H \ll \Lambda$$

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- **Realization 1**

S. Centelles-Chulià, A. Herrero-Brocal and A.Vicente, arXiv:2404.15415

Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L}$
H	$(\mathbf{2}, \frac{1}{2})$	0
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Phenomenological implications of an enhanced Majoron

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This interaction is constrained by astrophysical and laboratory experiments. The more stringent constrain is given in the $J\ e\ e$ interaction. Assuming Yukawas of order 1,

$v_\phi \gtrsim 10^4\mathrm{TeV}\ \Rightarrow$ Goldstone cLFV allow us to test high scales

We can compare this interaction with the traditional signal $\ell_\alpha \to \ell_\beta\ \gamma$. In the simplified scenario with M degenerate, Yukawas of order 1 and $v_\phi \gtrsim 10^4\mathrm{TeV}$

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$$\mathrm{BR}\,(\mu \to e\gamma) \approx 10^{-23} \qquad \mathrm{BR}^{\mathrm{exp}}\,(\mu \to e\gamma) \lesssim 10^{-13}$$

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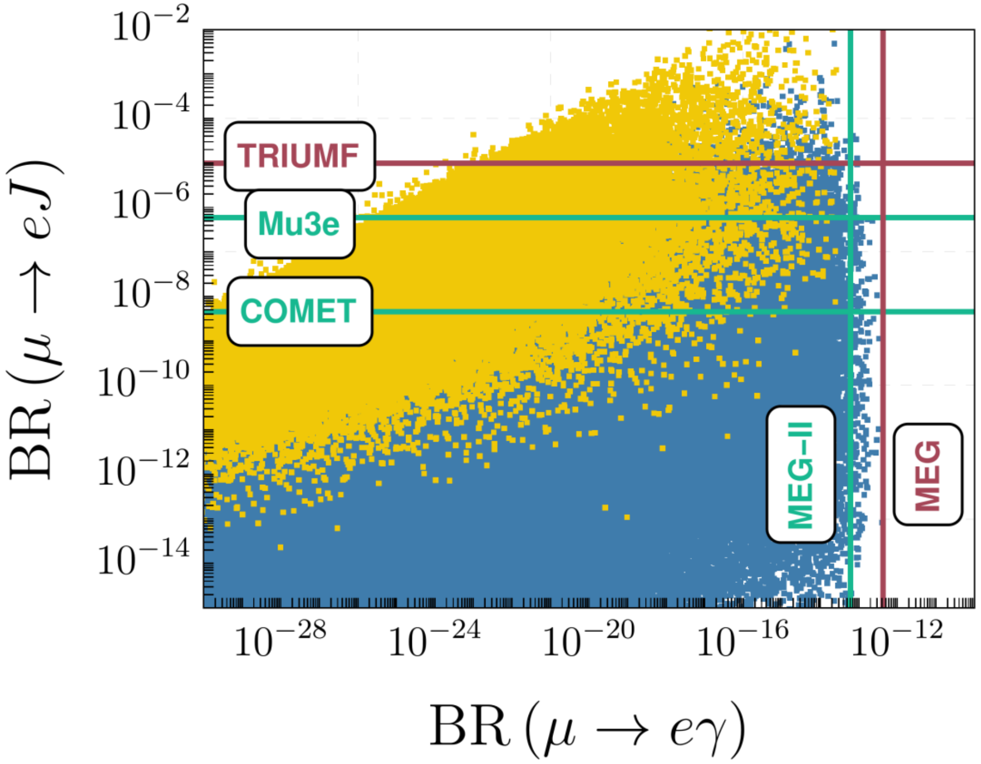

Orange points correspond to $y_N\,,\, Y \sim \mathcal{O}(1)$

Blue points allow for more freedom $y_N\,,\, Y \sim \mathcal{O}(10^{-3} - 1)$

$\mu \to e\ J$ becomes observable above $\mu \to e\ \gamma$ in the most relevant section of the parameter space

$\mu \to e\ \gamma$ requires smaller Yukawas, departing from the main theoretical motivation for low-scale seesaws

Application: Inverse seesaw and the Majoron

- **Realization 2:**

Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L}$
H	$(\mathbf{2}, \frac{1}{2})$	0
σ	$(\mathbf{1}, 0)$	2
L	$(\mathbf{2}, -\frac{1}{2})$	-1
N	$(\mathbf{1}, 0)$	-1
S	$(\mathbf{1}, 0)$	1

$$\mathcal{L}_{\rm mass} = \begin{pmatrix} \bar{\nu}_L & \bar{N}^c & \bar{S}^c \end{pmatrix} \begin{pmatrix} 0 & y_N\, v_H/\sqrt{2} & 0 \\ y_N^T\, v_H/\sqrt{2} & Y^{'}\, v_\phi/\sqrt{2} & M \\ 0 & M^T & Y\, v_\phi/\sqrt{2} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N \\ S \end{pmatrix} \;,\; v_H \,, v_\phi \ll M$$

$\Lambda = M \gg v_\phi \;\Rightarrow$ Scenario 2. Therefore, we expect $\mathcal{L}_{J\ell\ell} \sim \dfrac{v_H\, v_\phi}{\Lambda^2} \sim \dfrac{m_\nu}{v_H}$

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By computing the analytical result for the one-loop coupling

$$\mathcal{L}_{J\ell\ell} = -i\, J\, \frac{v_\phi}{384\,\pi^2} \bar{\ell} \Big\{ 2M_\ell \,\mathrm{Tr}\left(y_N \left[YY' + 2YY^\dagger + 2Y'^\dagger Y' \right] M^{-2} y_N^\dagger \right) \gamma_5 + M_\ell\, y_N \left(5YY^\dagger + 5Y'Y'^\dagger - YY' - Y'^\dagger Y^\dagger \right) M^{-2} y_N^\dagger\, P_L$$
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S. Centelles-Chulià, A. Herrero-Brocal and A.Vicente, arXiv:2404.15415

S.Centelles-Chulià, T.Herbermann, A.Herrero-Brocal and A.Vicente, arXiv:2506.06449

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SUMMARY

- Nambu-Goldstone bosons are one of the best motivated BSM candidates
- Typically, models predicts NGB which are weakly coupled to the SM, making their phenomenology negligible and therefore difficult to detect them
- Here we have developed a general framework to identify NGB with relevant phenomenology
- We applied this general framework to well-motivated models such as low-scale seesaws and we found that for these models one expect to observe $\mu \to e\ J$ over $\mu \to e\ \gamma$.

Thank you!