13th LLP Community Workshop
20th June 2023

Reinterpretation of searches for LLPs from meson decays

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In collaboration with
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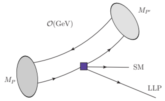
Motivation

Theoretical perspective.

- A variety of models predict the existence of LLP candidates, such as **HNLs** and **ALPs**.
- Diverse production channels: **meson decays** might dominate production of GeV-scale LLPs.



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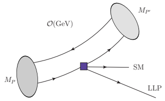

Experimental searches.

- A specific model is typically selected to present the search results.
- Reinterpreting the data to constrain other models often requires detailed analysis information, which may not always be available.

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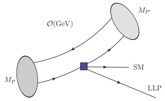

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Is it possible to perform reinterpretation of LLPs from meson decays without running simulation?

Reinterpretation method

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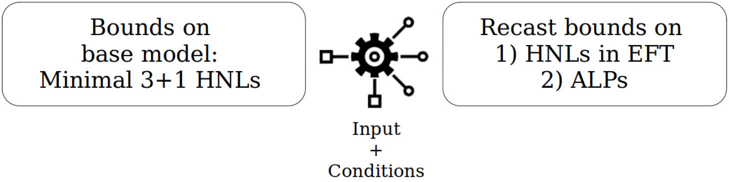


Theoretical input: calculation of production number of LLPs in the model, LLP decay length, BR into final visible states in the detector.

Conditions to be fulfilled:

❶ LLP **large decay length limit**: $\lambda_{\text{dec}} = \beta\gamma c\tau \gg L(\text{IP-detector})$.

❷ **Similar kinematics** of LLPs in the different models.

Reinterpretation method

Experiments set exclusion limits based on number of signal events:

$$N_S = N_{\mathrm{LLP}} \cdot \varepsilon \cdot \mathrm{BR}(\mathrm{LLP} \to \mathrm{vis}^*)$$

N_{LLP} : #LLPs produced in meson decays

ε : detector efficiency $\times$ acceptance

*Visible final states required by DV searches.

Detector acceptance in the limit $\lambda_{\mathrm{dec}} \gg L$ (condition ❶):

$$\varepsilon \propto P\,[\mathrm{decay}] \sim e^{-L/\lambda_{\mathrm{dec}}} \cdot \left(1 - e^{-\Delta L/\lambda_{\mathrm{dec}}}\right)$$

$$\approx \Delta L/\lambda_{\mathrm{dec}} = \Delta L \cdot \Gamma_{\mathrm{tot}}/(\beta\gamma c\hbar)$$

$\lambda_{\mathrm{dec}} = \beta\gamma c\tau \;\;,\quad \tau = \hbar/\Gamma_{\mathrm{tot}}$

Reinterpretation method

N_S in the large decay length limit:

- Base model

$$N_S \propto N_{\rm LLP} \cdot \Gamma_{\rm tot} \cdot {\rm BR}({\rm LLP} \to {\rm vis}) = N_{\rm LLP} \cdot \Gamma_{\rm vis}$$

- Reinterpreted model

$$N'_S \propto N'_{\rm LLP'} \cdot \Gamma'_{\rm vis}$$

Considering LLPs have similar kinematics (condition ❷):

$$\frac{N_S}{N'_S} \approx \frac{N_{\rm LLP}}{N'_{\rm LLP'}} \frac{\Gamma_{\rm vis}}{\Gamma'_{\rm vis}} \xrightarrow{N_S = N'_S} \boxed{\Gamma'_{\rm vis} \approx \Gamma_{\rm vis} \frac{N_{\rm LLP}}{N'_{\rm LLP'}}}$$

Base model

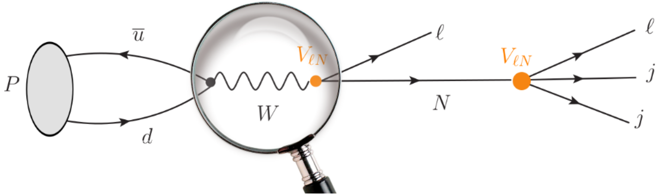
HNLs in the minimal scenario

HNLs in the 3+1 minimal scenario

One HNL, N, that mixes with the active neutrinos ν_ℓ. EW interactions:

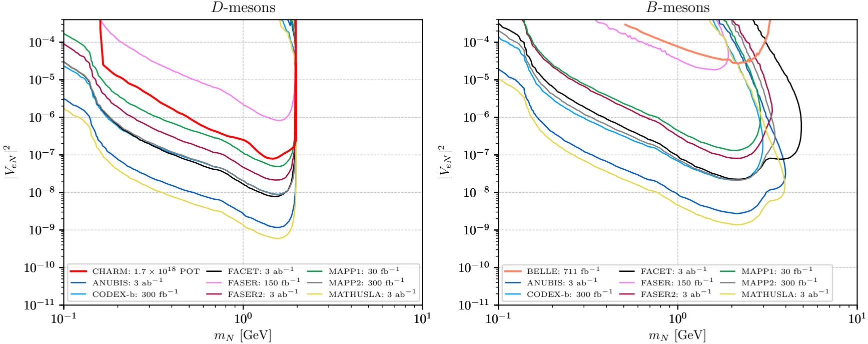
$$\mathcal{L}_{\min} = -\frac{g}{\sqrt{2}} V_{\ell N} \, (\bar{\ell}\gamma^\mu N_R^c) \, W_\mu - \frac{g}{2\cos\theta_W} U_{\ell i} V_{\ell N}^* (\overline{N_R^c}\gamma^\mu \nu_{iL}) \, Z_\mu + \text{h.c.}$$

HNL production and decay are governed by $m_N, V_{\ell N}$.
At energies $\mathcal{O}(\text{GeV})$, HNLs are produced in meson decays.



Bondarenko et al 1805.08567

Bounds on the 3+1 minimal scenario



Exclusion limits for $N_S = 3$.

- Leading bounds from CHARM and Belle on minimal HNLs produced from D- and B-mesons' decays .
- Far detector projections. de Vries et al 1905.08699

Reinterpreted models

I. HNLs in EFT

II. ALPs

RPV-SUSY model. Talk by Martin Schürmann

I. HNLs in EFT

If we extend the SM by GeV-scale HNLs, the suitable framework for describing new physics at low energies (meson decays) is N_RLEFT.

$$\mathcal{L}_{N_R\text{LEFT}} = \mathcal{L}_{\text{ren}} + \sum_{d\geq 5}\sum_i c_i^{(d)}\mathcal{O}_i^{(d)} \qquad\qquad c_i^{(d)} \propto v^{(4-d)}$$

Relevant operators at $d = 6$:

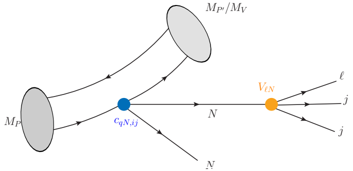
Pair-N_R operators (LNC)	
$\mathcal{O}_{dN}^{V,RR}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{N_R}\gamma^\mu N_R)$
$\mathcal{O}_{uN}^{V,RR}$	$(\overline{u_R}\gamma_\mu u_R)\,(\overline{N_R}\gamma^\mu N_R)$
$\mathcal{O}_{dN}^{V,LR}$	$(\overline{d_L}\gamma_\mu d_L)\,(\overline{N_R}\gamma^\mu N_R)$
$\mathcal{O}_{uN}^{V,LR}$	$(\overline{u_L}\gamma_\mu u_L)\,(\overline{N_R}\gamma^\mu N_R)$

Single-N_R operators (LNC)	
$\mathcal{O}_{udeN}^{V,RR}$	$(\overline{u_R}\gamma_\mu d_R)\,(\overline{e_R}\gamma^\mu N_R)$
$\mathcal{O}_{udeN}^{V,LR}$	$(\overline{u_L}\gamma_\mu d_L)\,(\overline{e_R}\gamma^\mu N_R)$
$\mathcal{O}_{udeN}^{S,RR}$	$(\overline{u_L}d_R)\,(\overline{e_L}N_R)$
$\mathcal{O}_{udeN}^{T,RR}$	$(\overline{u_L}\sigma_{\mu\nu}d_R)\,(\overline{e_L}\sigma^{\mu\nu}N_R)$
$\mathcal{O}_{udeN}^{S,LR}$	$(\overline{u_R}d_L)\,(\overline{e_L}N_R)$

N_RLEFT phenomenology: Beltrán et al 2210.02461, de Vries et al 1905.08699

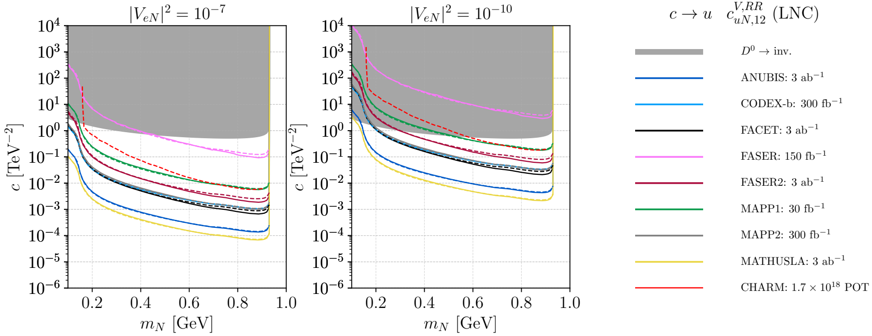
HNL effective portals: Fernández-Martínez et al 2304.06772

I. HNLs in EFT: pair-N_R operators



Benchmarks	Production	Decay
2HNL-D1	$c^{V,RR}_{uN,12}$	V_{eN}
2HNL-B1	$c^{V,RR}_{dN,31}$	V_{eN}

- **2HNL-D1**



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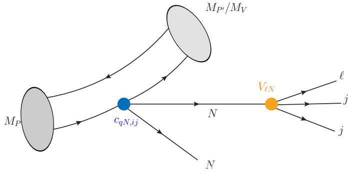

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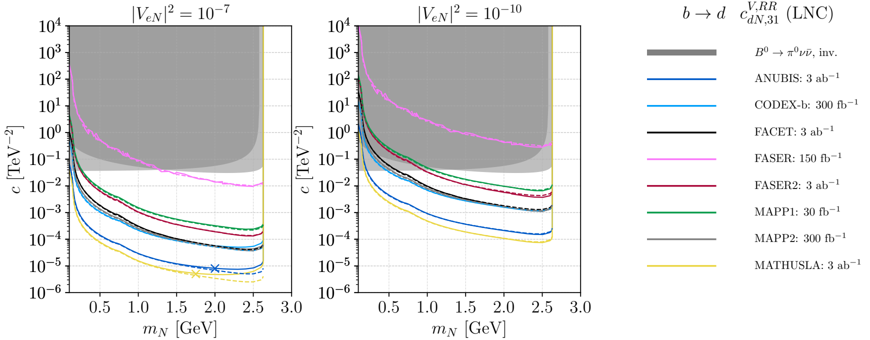
- **2HNL-B1**

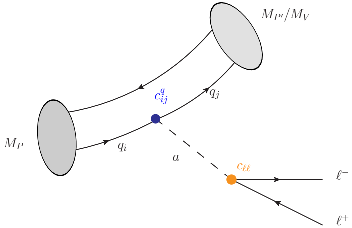


II. ALPs in EFT

ALPs are pseudo-Goldstone bosons associated to a spontaneously broken (approximate) global symmetry.

Low-energy Lagrangian up to $d = 5$: Bauer et al 2012.12272 1708.00443

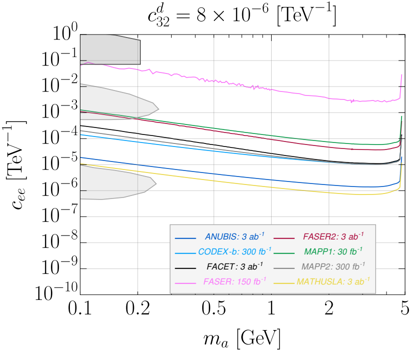
$$\mathcal{L}_{\mathrm{ALP}} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a a^2 + \partial_\mu a \left[\sum_q c_{ij}^q \, \bar{q}_i \gamma^\mu q_j + \sum_\ell \frac{c_{\ell\ell}}{2} \, \bar{\ell} \gamma^\mu \gamma^5 \ell \right]$$



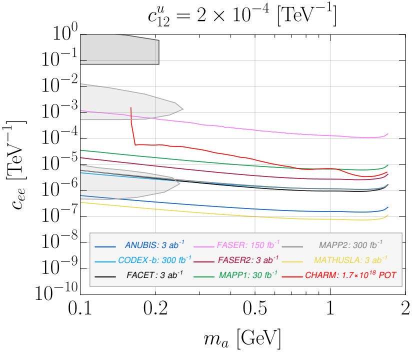
Benchmarks	P_{prod}^{ij}	P_{decay}
ALP-D	c_{12}^u	c_{ee}
ALP-B	c_{32}^d	c_{ee}

II. ALPs in EFT

- **ALP-B**



- **ALP-D**



- Meson decays put upper bounds on the QFV couplings P_{prod}.
- Bounds on P_{decay} from E137 (dark gray) and supernovae (light gray).

Summary

Reinterpretation method for searches of LLPs produced in meson decays.

- No simulation required as long as:
  ❶ LLPs are in the large decay length regime,
  ❷ LLPs possess similar kinematics.
- Advantages: not restricted by LLP spins.
  Drawbacks: prompt-regime bounds cannot be obtained.
- Excellent agreement with the literature for existing limits.
  Recast of two past searches and new projections of far detectors.

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