ANUBIS Workshop
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LLPs from meson decays: reinterpreting searches for ANUBIS

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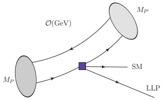
[2302.03216] JHEP05(2023)031

Motivation

Theoretical perspective.

- LLPs (such as HNLs or ALPs) at the GeV scale might be produced in **meson decays**.



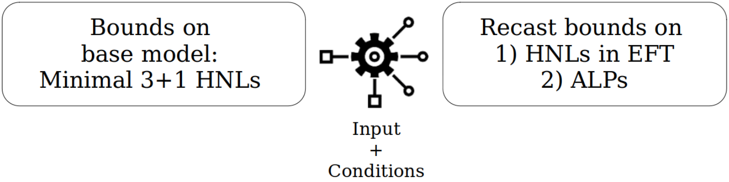
Experimental searches.

- 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.

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

Reinterpretation method

Reinterpretation method



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:

1. LLP **large decay length limit**: $\lambda_{\rm dec} = \beta\gamma c\tau \gg L(\text{IP-detector})$.
2. **Similar kinematics** of LLPs in the different models.

Reinterpretation method

Experiments set exclusion limits based on number of signal events:

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

N_{LLP} : #LLPs produced in meson decays

ε : detector efficiency × acceptance

*Visible final states required by DV searches.

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

$$\varepsilon \propto P\,[\text{decay}] \sim e^{-L/\lambda_{\text{dec}}} \cdot \left(1 - e^{-\Delta L/\lambda_{\text{dec}}}\right)$$
$$\approx \Delta L/\lambda_{\text{dec}} = \Delta L \cdot \Gamma_{\text{tot}}/(\beta\gamma c\hbar)$$

$\lambda_{\text{dec}} = \beta\gamma c\hbar/\Gamma_{\text{tot}}$

Reinterpretation method

N_S in the large decay length limit:

- Base model

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

- Reinterpreted model

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

Considering LLPs have similar kinematics (condition ❷):

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

Base model

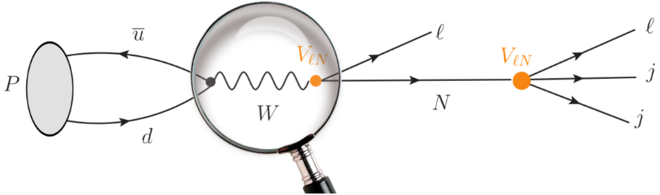
HNLs in the minimal scenario

HNLs in the 3+1 minimal scenario

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

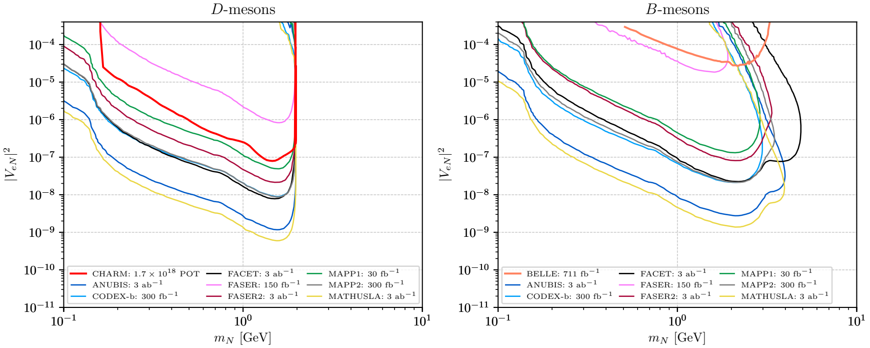
$$\mathcal{L}_{\rm min} = -\frac{g}{\sqrt{2}} V_{\ell N} \, (\bar{\ell}\gamma^\mu N_R^c) \, W_\mu - \frac{g}{2\cos\theta_W} U_{\ell i} V_{\ell N}^* (\overline{N_R^c}\gamma^\mu \nu_{iL}) \, Z_\mu + \text{h.c.}$$

HNL production and decay are governed by $m_N, V_{\ell N}$.



Compute $N_{\rm HNL}$ from meson decays and $\Gamma_{\rm vis}$. Bondarenko et al 1805.08567

Bounds on the 3+1 minimal scenario



- Leading bounds in this mass range come from CHARM and Belle.
- Far detector projections* ($N_S = 3$). de Vries et al 1905.08699

*ANUBIS simulation result using first detector geometry proposal.

Reinterpreted models

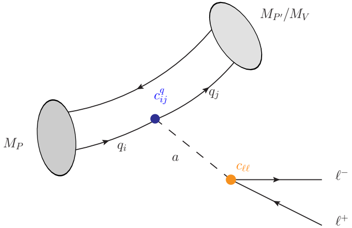
ALPs

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

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



To-do: Compute

- $\Gamma'_{\mathrm{vis}} = \Gamma(a \to \ell^+ \ell^-)$
- $N'_{\mathrm{ALP}} = N_M \cdot \mathrm{BR}(M \to M' + a)$

ALPs in EFT: theoretical input

- ALP decay width:

$$\Gamma\left(a \to \ell^+\ell^-\right) = \frac{{c_{\ell\ell}}^2}{8\pi}\, m_a m_\ell^2 \sqrt{1 - \frac{4m_\ell^2}{m_a^2}}$$

- ALP production in two-body meson decays:

$$\Gamma\left(P \to P'a\right) = f\, \frac{|c_{ij}^q|^2}{64\pi} \left|F_0^{P\to P'}(m_a^2)\right|^2 m_P^3 \left(1 - \frac{m_{P'}^2}{m_P^2}\right)^2 \lambda^{1/2}\left(\frac{m_{P'}^2}{m_P^2}, \frac{m_a^2}{m_P^2}\right)$$

$$\Gamma\left(P \to Va\right) = g\, \frac{|c_{ij}^q|^2}{64\pi} \left|A_0^{P\to V}(m_a^2)\right|^2 m_P^3\, \lambda^{3/2}\left(\frac{m_V^2}{m_P^2}, \frac{m_a^2}{m_P^2}\right)$$

$$\lambda(x,y) = 1 + x^2 + y^2 - 2x - 2y - 2xy$$

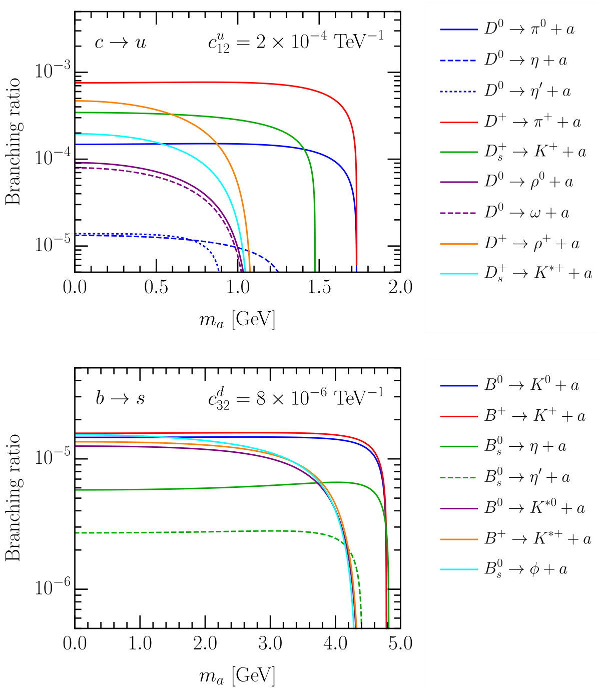
$F_0^{P\to P'}$, $A_0^{P\to V}$: form factors.
f, g: numerical factors.
See section 4.2 [2302.03216]

Bauer et al 2110.10698

ALPs in EFT: Benchmarks

Benchmark	P_{prod}^{ij}	P_{decay}	Production modes	Decay modes
ALP-D	c_{12}^{u}	c_{ee}	$D \to \pi + a$ $D \to \eta^{(\prime)} + a$ $D \to \rho + a$ $D \to \omega + a$ $D_s \to K^{(*)} + a$	$a \to e^+ + e^-$
ALP-B	c_{32}^{d}	c_{ee}	$B \to K^{(*)} + a$ $B_s \to \eta^{(\prime)} + a$ $B_s \to \phi + a$	$a \to e^+ + e^-$

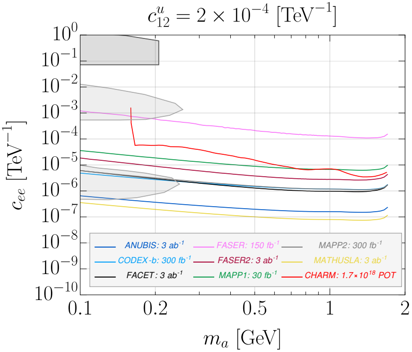
- Experimental limits on the decay BRs of $D^0 \to \pi^0 \nu\bar{\nu}$ and $B \to K\nu\bar{\nu}$ put upper bounds on c_{12}^{u} and c_{32}^{d}.
- Bounds on c_{ee} from E137 and supernovae.



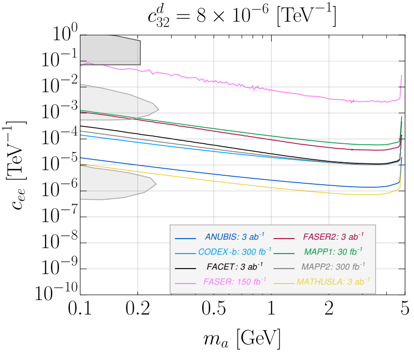
$c \to u$
$c^u_{12} = 2 \times 10^{-4}$ TeV^{-1}
Branching ratio
10^{-3}
10^{-4}
10^{-5}
0.0
0.5
1.0
1.5
2.0
m_a [GeV]
$D^0 \to \pi^0 + a$
$D^0 \to \eta + a$
$D^0 \to \eta' + a$
$D^+ \to \pi^+ + a$
$D^+_s \to K^+ + a$
$D^0 \to \rho^0 + a$
$D^0 \to \omega + a$
$D^+ \to \rho^+ + a$
$D^+_s \to K^{*+} + a$
$b \to s$
$c^d_{32} = 8 \times 10^{-6}$ TeV^{-1}
Branching ratio
10^{-5}
10^{-6}
0.0
1.0
2.0
3.0
4.0
5.0
m_a [GeV]
$B^0 \to K^0 + a$
$B^+ \to K^+ + a$
$B^0_s \to \eta + a$
$B^0_s \to \eta' + a$
$B^0 \to K^{*0} + a$
$B^+ \to K^{*+} + a$
$B^0_s \to \phi + a$

ALPs in EFT

- **ALP-D**



- **ALP-B**



Summary

We propose a reinterpretation method for searches of **LLPs produced in meson decays** ➔ recast sensitivities for ANUBIS.

- 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.

- Applicable to other scenarios:
  ✎ LLPs produced in K or π decays.
  ✎ LLPs decaying into μ, τ or hadrons.

Backup slides

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.

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

Relevant operators at $d = 6$:

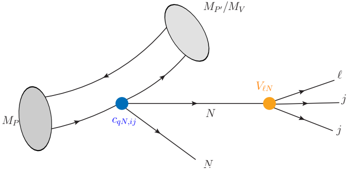
Pair-N_R operators (LNC)	
$\mathcal{O}_{dN}^{V,RR}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{N_R}\gamma^\mu N_R)$
$\mathcal{O}_{uN}^{V,RR}$	$(\overline{u_R}\gamma_\mu u_R)\,(\overline{N_R}\gamma^\mu N_R)$
$\mathcal{O}_{dN}^{V,LR}$	$(\overline{d_L}\gamma_\mu d_L)\,(\overline{N_R}\gamma^\mu N_R)$
$\mathcal{O}_{uN}^{V,LR}$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

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

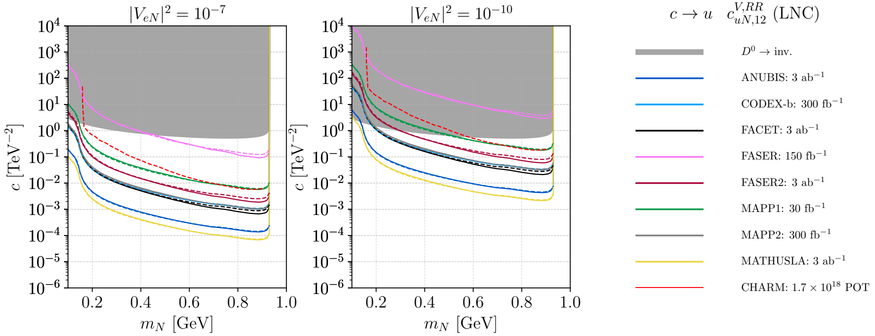
HNL effective portals: Fernández-Martínez et al 2304.06772

HNLs in EFT: pair-N_R operators

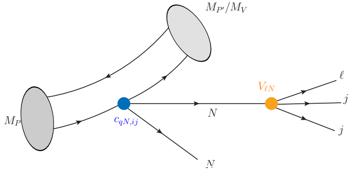


Benchmarks	Production	Decay
2HNL-D1	$c_{uN,12}^{V,RR}$	V_{eN}
2HNL-B1	$c_{dN,31}^{V,RR}$	V_{eN}

- **2HNL-D1**

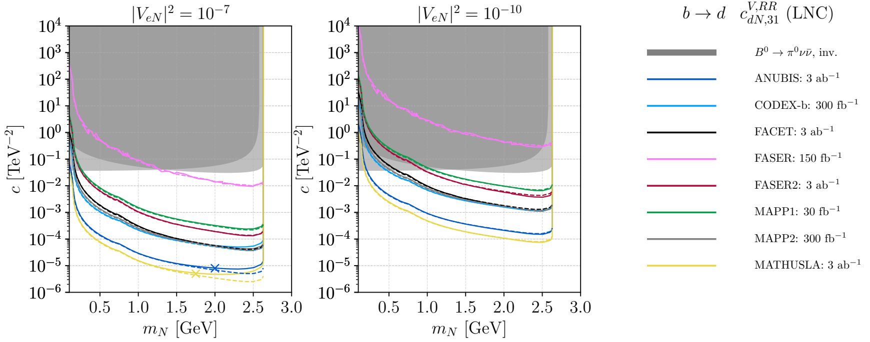


HNLs in EFT: pair-N_R operators



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

- **2HNL-B1**



HNLs in EFT: single-N_R operators

Benchmarks	P^{ij}_{prod}	P^{kl}_{decay}
Leptoquark	$C^{13}_{\text{SRR}} = 4C^{13}_{\text{TRR}}$	$C^{11}_{\text{SRR}} = 4C^{11}_{\text{TRR}}$
VLR	C^{13}_{VLR}	C^{11}_{VLR}

$$v^2 c^X_{udeN,ij} \approx C^{ij}_X$$