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LLP Overview: Theory Perspective

Example models and reinterpretation

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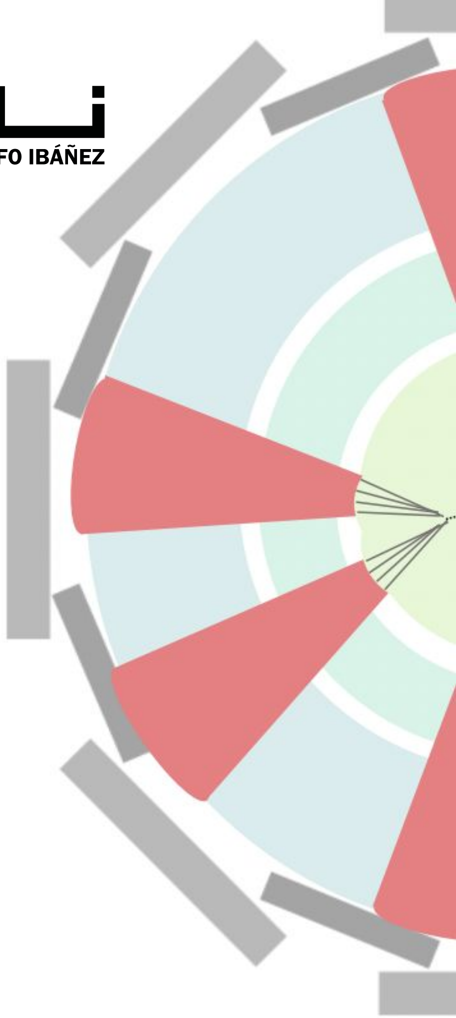


Image from E.Thompson@RAMP Seminar

New physics may be so *feebly* coupled to our Standard Model that their signatures may have been overlooked or miss identified by LHC searches not dedicated to LLPs

LLP?

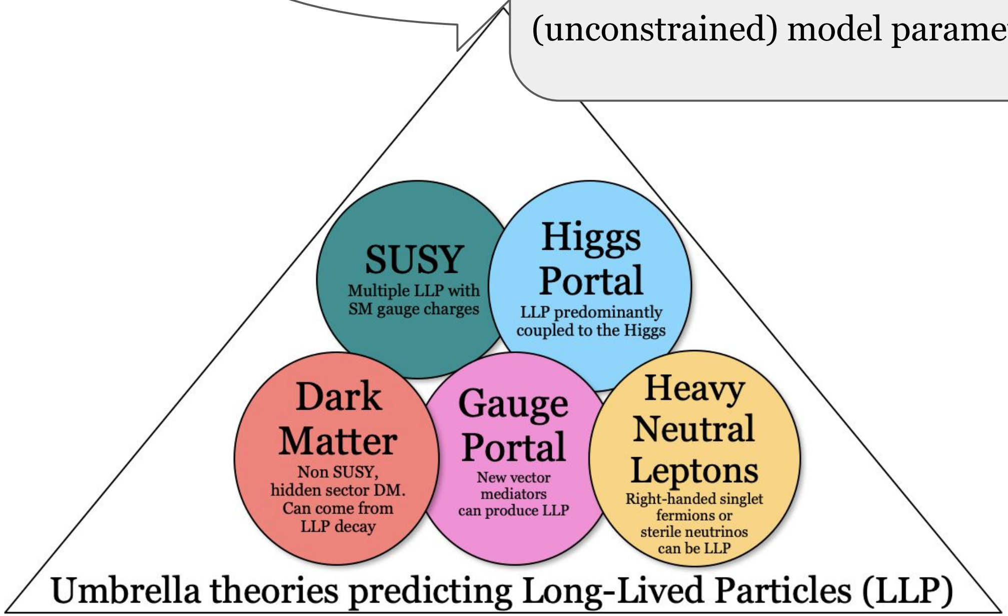
$c\tau \sim \Gamma^{-1} \gtrsim 0.001\ [\mathrm{mm}]$

$$\Gamma \sim c^2 \left(\frac{\Delta m}{\Lambda}\right)^n \Delta m$$

	c^2	$\left(\frac{\Delta m}{\Lambda}\right)^n$	Δm
Three reasons why	Feebly (small) couplings	Large mass hierarchies/ heavy mediators	Small mass difference or "compressed spectra"
Three reasons why is hard	Low rates	Large energies (LHC inaccessible)	Low efficiency (soft particles/limited object reconstruction)

But plenty of reasons why we should look for them (neutrino masses and dark matter) !

Many BSM models predict LLPs with exotic and challenging signatures. Phenomenology needed to accurately characterize them and cover (unconstrained) model parameter space



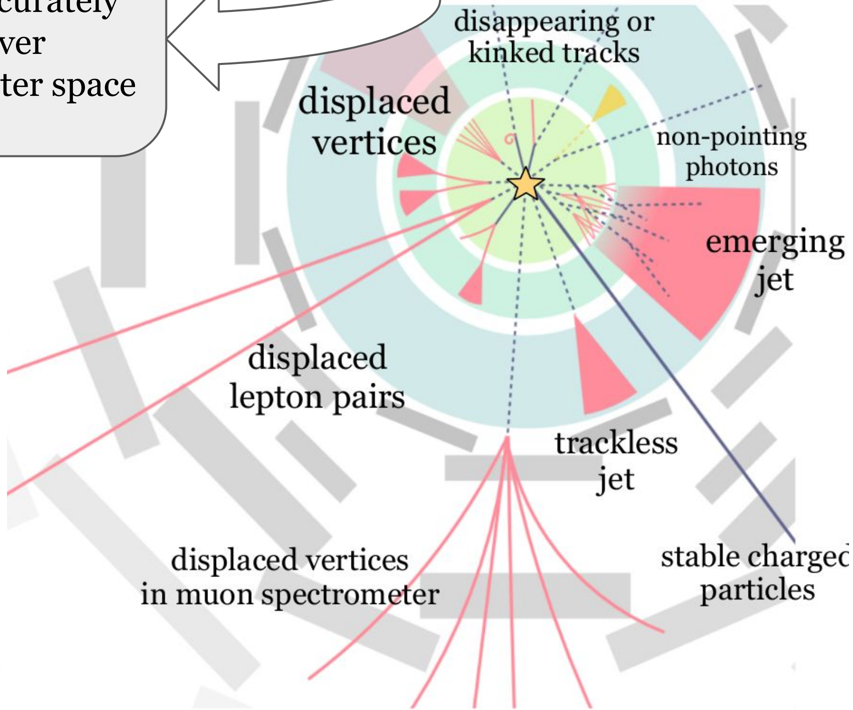


Image by G.Cottin

LLP Image adapted from Heather Russel

See MATHUSLA physics case motivating theoretical models, D. Curtin et al, Rept.Prog.Phys. 82 (2019)

See simplified model classification in LLP Community White Paper, J. Alimena, et al J.Phys.G 47 (2020) 9, 090501

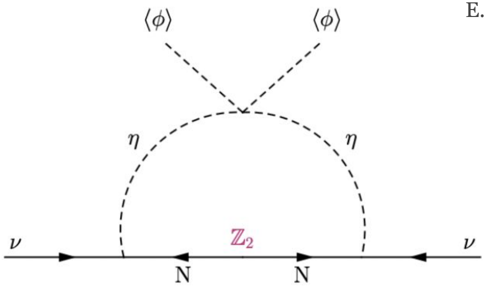
Outline (heavily biased!)

Example models motivated by neutrinos and dark matter 	LLP Production	LLP Decay	LLP Signature	Reinterpreted from/ Forecast for	Proposed LHC detectors/ LHC tunes
Scotogenic	$pp \to \eta^{\pm}\eta^{\mp}, \eta^{\pm}\eta^{0}$	$\eta^{\pm} \to \pi^{\pm}\eta^{0}$	Disappearing track	ATLAS	
Minimal HNL (tau mixing)	$pp \to N\tau$	$N \to u\bar{d}\tau$	Displaced vertex Displaced shower	ATLAS CMS	✓
HNL in EFT (NLEFT)	Meson production @ LHC, i.e. $B^0 \to NN$	Decays via mixing, i.e. $N \to u\bar{d}l$	Displaced decays	Minimal HNL with a new method / AL3X, ANUBIS, CODEX-b, FACET, FASER, MAPP, MATHUSLA	✓
ALPs	Meson production @ LHC, i.e. $D \to \pi + a$	$a \to e^{+} + e^{-}$	Displaced decays	Minimal HNL with a new method / AL3X, ANUBIS, CODEX-b, FACET, FASER, MAPP, MATHUSLA	✓

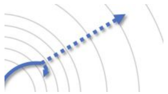
Scotogenic Model

Neutrino masses at 1 loop (small)
DM candidate (real part of scalar doublet)
Predicts long-lived particles! (in the co-annihilation region)

E. Ma, Phys.Rev.D 73 (2006) 077301



Disappearing track signature

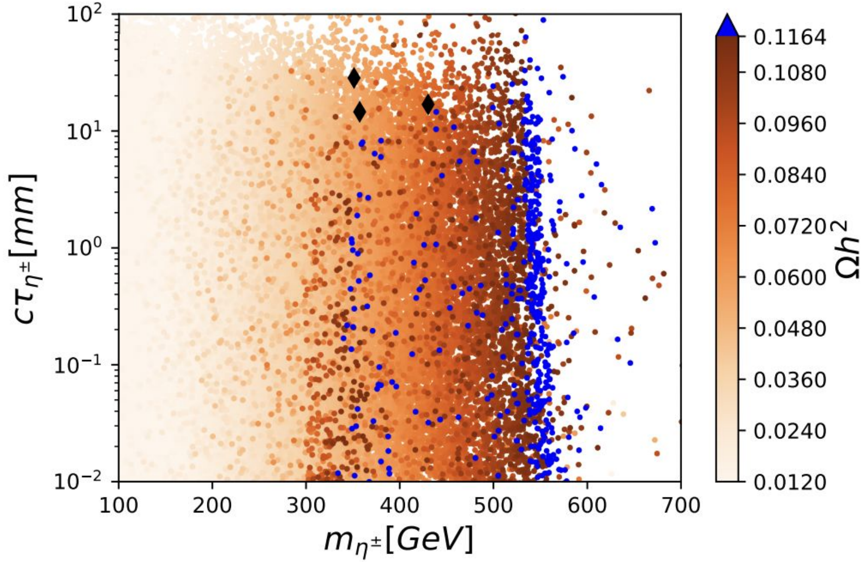


M. Klasen, C. E. Yaguna, et al, JCAP 04, 044 (2013) $m_{N_1} - m_{\eta_R} \sim \mathcal{O}(1)\text{GeV}$

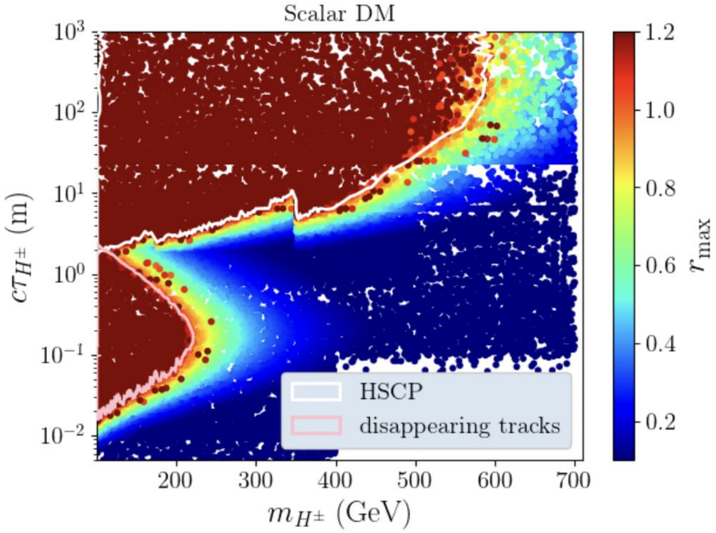
$$m_{\eta^\pm} - m_{\eta_R} = \Delta m_{\eta^\pm} \sim \mathcal{O}(100)\text{MeV}$$

$$\Gamma_{\eta^\pm \to \eta_R \pi^\pm} = \frac{f_\pi^2 g^4}{64\pi m_W^4} \Delta m_{\eta^\pm}^2 \times \sqrt{\Delta m_{\eta^\pm}^2 - m_\pi^2}$$

Ivania M. Ávila, G. Cottin, M. A. Díaz, J.Phys.G 49 (2022) 6, 065001



Constraints in SmodelS2 in G. Alguero et al, JHEP 08 (2022) 068



Minimal HNL model

HNLs (fermionic singlets) motivated by neutrino mass models
HNLs mix with SM neutrinos
Can be automatically long-lived! $\Gamma \sim G_F^2 |V_{lN}|^2 m_N^5$

Seesaw
P. Minkowski, Phys. Lett. 67B (1977)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980)
J. Schechter and J. W. F. Valle, Phys. Rev. D22, 2227 (1980)

Inverse seesaw
R. Mohapatra and J. Valle, Phys. Rev. D34 (1986) 1642

$$\mathcal{L}_{\rm min} = -\frac{g}{\sqrt{2}} V_{\ell N}\, \bar{\ell}\gamma^\mu P_L N\, W^\dagger_\mu - \frac{g}{2\cos\theta_W} U^*_{\ell i} V_{\ell N}\, \overline{\nu_i}\gamma^\mu P_L N\, Z_\mu + \text{h.c.}$$

$m_B < m_N < m_W$

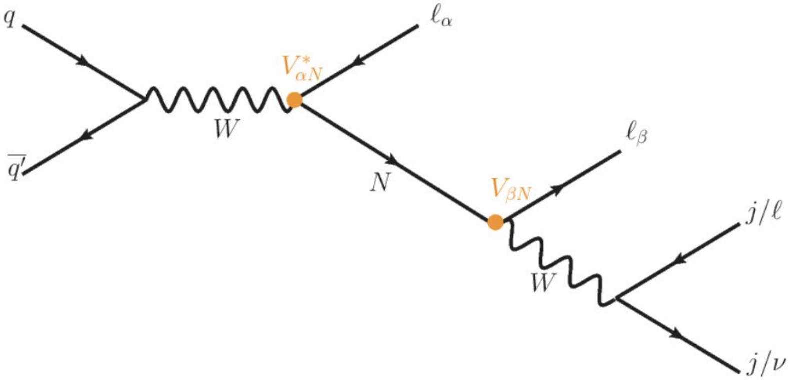
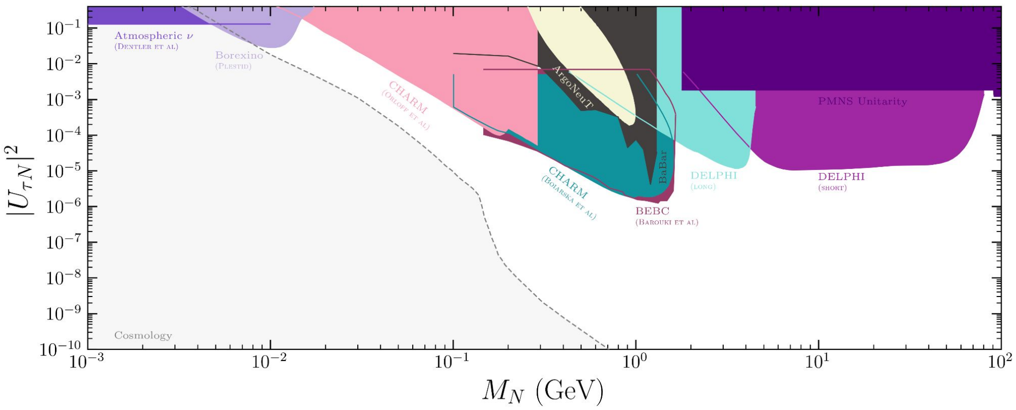


Diagram by R. Beltrán

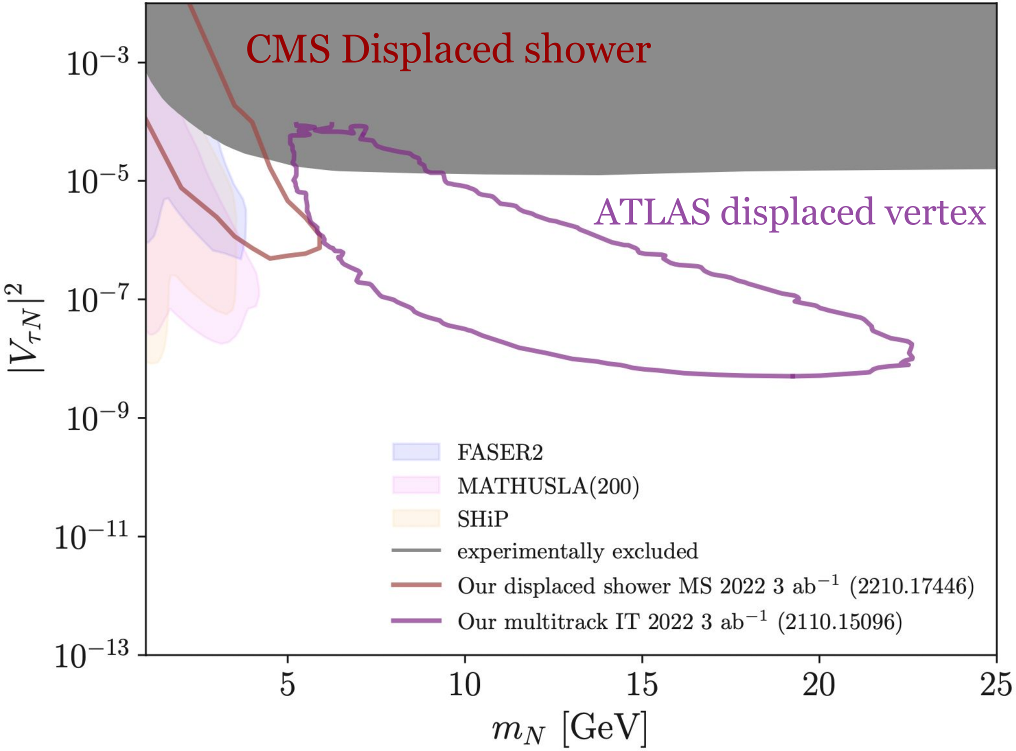
Latest summary of bounds in the tau-sector, see E. Fernandez-Martinez, et. al, 2304.06772

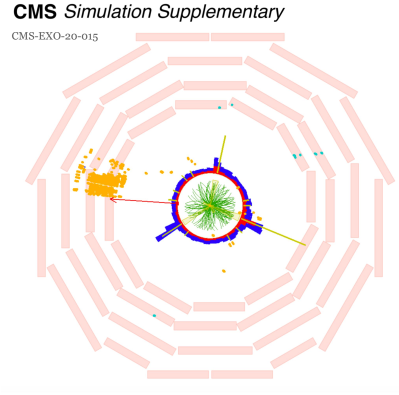


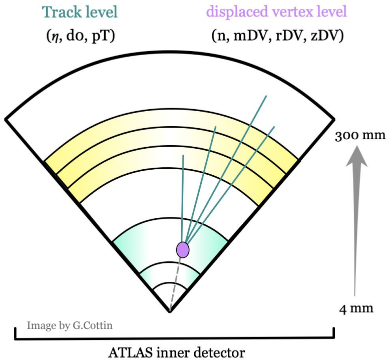
Tau-mixing not covered yet at LHC, what can we do?

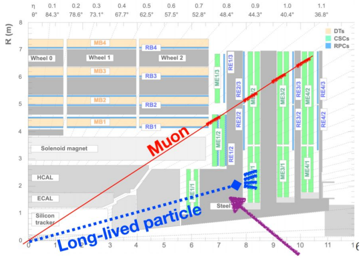
Recast novel searches with current LHC detector subsystems!

G.Cottin, J.C. Helo, M. Hirsch, C. Peña, C. Wang, S. Xie, JHEP 02 (2023) 011









@ 7th LLP Workshop, see talk by Sven Dildick

We reinterpreted a search for a SM Higgs boson decaying to long-lived scalars (which can then decay to taus). Phy. Rev. Lett. 127 (2021)

The search is sensitive to LLPs decaying to taus. Large CMS steel shielding effectively suppresses background.

The unique CMS signature depends on a large cluster of Cathode Strip Chamber (CSC) hits in the muon system (Nhits).

Our reinterpretation relies on the **implementation of a new Delphes module** made specifically for muon system showers from LLP decays (https://github.com/delphes/delphes/pull/103)

Displaced Vertex forecast in
R. Beltrán, et al, JHEP 01 (2022) 044

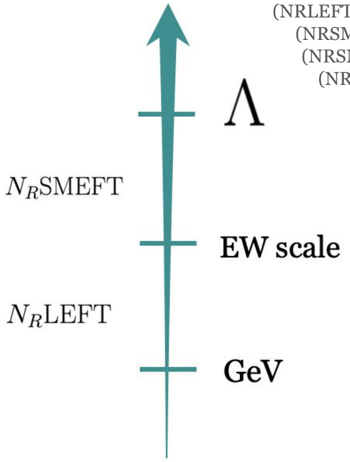
Beyond Minimal HNL

HNL production occurs via meson decays for $m_N < 5$ GeV

We can study them systematically in an EFT approach

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

HNLs in EFT with LLPs at the LHC
(d=5) A. Caputo, et al, JHEP 06 (2017)
(NRLEFT, singleN) Jordy de Vries, et al, JHEP 03 (2021)
(NRSMEFT, single N) G. Cottin, et al, JHEP 09 (2021)
(NRSMEFT, pair N) R. Beltrán, et al, JHEP 01 (2022)
(NRLEFT, pair N) R. Beltrán, et al, JHEP 01 (2023)



F. del Aguila, et al, Phys.Lett.B 670 (2009)
A. Aparici, et al, Phys.Rev.D 80 (2009)
Y. Liao, et al, Phys.Rev.D 96 (2017)

T. Li, et al, JHEP 07 (2020) 152
M. Chala, A. Titov, JHEP 05 (2020) 139

Meson decay via operator, i.e $B^+ \to \pi^+ N N$

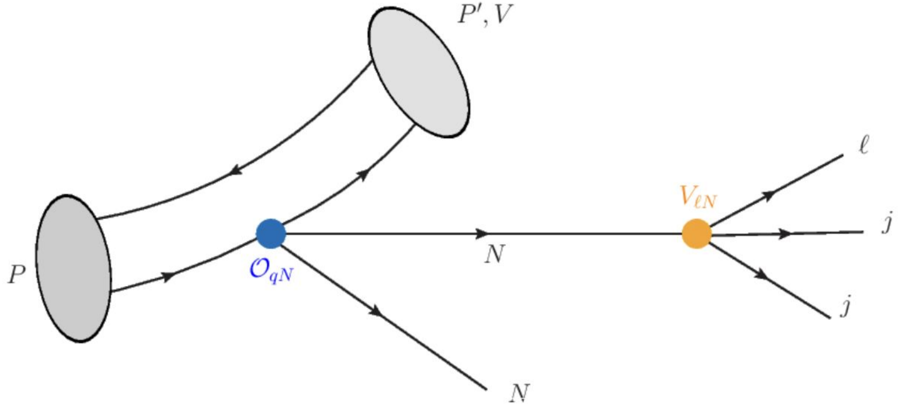


Diagram by R. Beltrán

HNL decays via mixing in K. Bondarenko, et al, JHEP 11 (2018) 032

	2 – body	$P \to P'$	$P \to V$
$c \to u$	D^0	$D^0 \to \pi^0, \eta, \eta'$ $D^+ \to \pi^+$ $D_s^+ \to K^+$	$D^0 \to \rho^0, \omega$ $D^+ \to \rho^+$ $D_s^+ \to K^{\star +}$
$b \to d$	B^0	$B^0 \to \pi^0, \eta, \eta'$ $B^+ \to \pi^+$ $B_s^0 \to \overline{K^0}$	$B^0 \to \rho^0, \omega$ $B^+ \to \rho^+$ $B_s^0 \to \overline{K^{\star 0}}$
$b \to s$	B_s^0	$B_s^0 \to \eta, \eta'$ $B^0 \to K^0$ $B^+ \to K^+$	$B_s^0 \to \phi$ $B^0 \to K^{\star 0}$ $B^+ \to K^{\star +}$

Reinterpretation method

R. Beltrán, G. Cottin, M. Hirsch, A. Titov, Z. S. Wang, JHEP 05 (2023) 031, arXiv:2302.03216

limits from minimal HNL

$$(m_N, |V_{eN}|^2, N_S)$$

Full Monte Carlo simulation (compute decay probabilities at each detector)

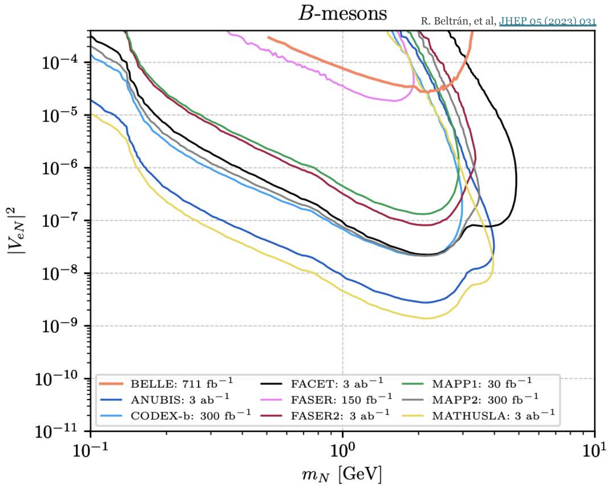
LLP produced from same (or similar) meson *D/B*
lab-frame decay lenght >> distance from IP to detector

reinterpreted limits in EFT (HNL/ALP)

$$(m_N, c, N_S)'/(m_a, c_{ee}, N_S) \quad \Gamma'_{\text{vis.}} \approx \Gamma_{\text{vis.}} \cdot \frac{N_N}{N'_N}\frac{N'_S}{N_S}$$

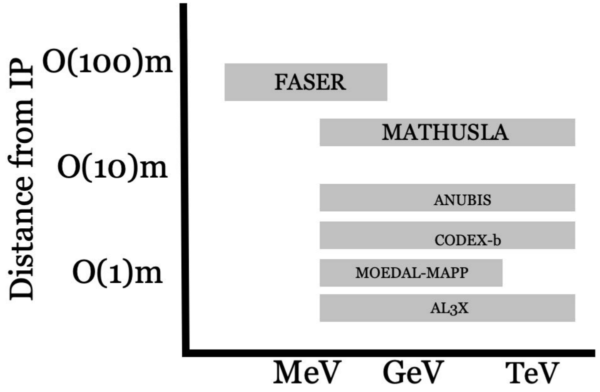
Only theoretical input (LLP production and decay)

$$N_S = N_N \cdot \epsilon \cdot \text{BR}(N \to \text{vis.})$$



$$P[\text{decay}] \approx \Delta L/\lambda_{\text{decay}} = \Delta L \cdot \Gamma_{\text{tot.}}/(\beta\gamma c\hbar)$$

$$N_S = N_N \cdot \Gamma_{\text{tot.}} \cdot \text{BR}(N \to \text{vis.}) \sim N_N \cdot \Gamma_{\text{vis.}}$$



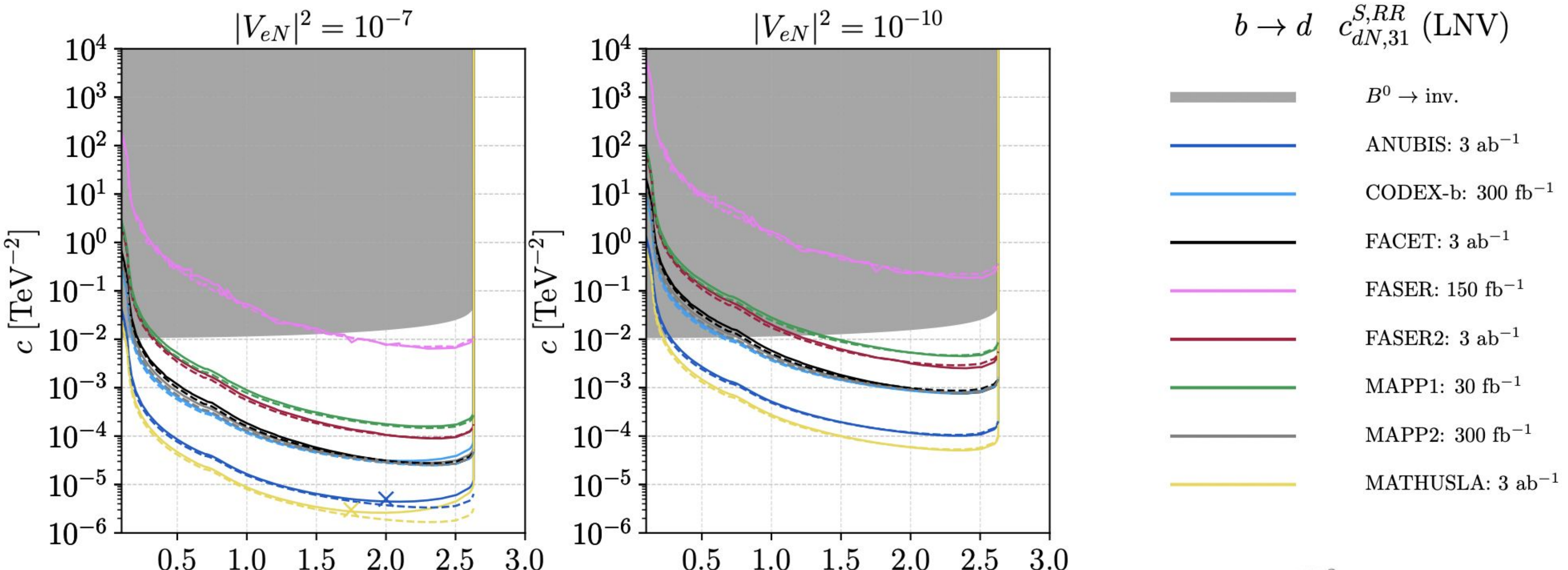
Reinterpretation to N_RLEFT

Full simulation (solid lines) in R. Beltrán, et al, JHEP 01 (2023) 015

Reinterpretation (dashed lines) in R. Beltrán, et al, JHEP 05 (2023) 031

Example operator:

$$\mathcal{O}_{dN}^{S,RR} \quad \Big| \quad \left(\overline{d_L} d_R\right)\left(\overline{N_R^c} N_R\right)$$



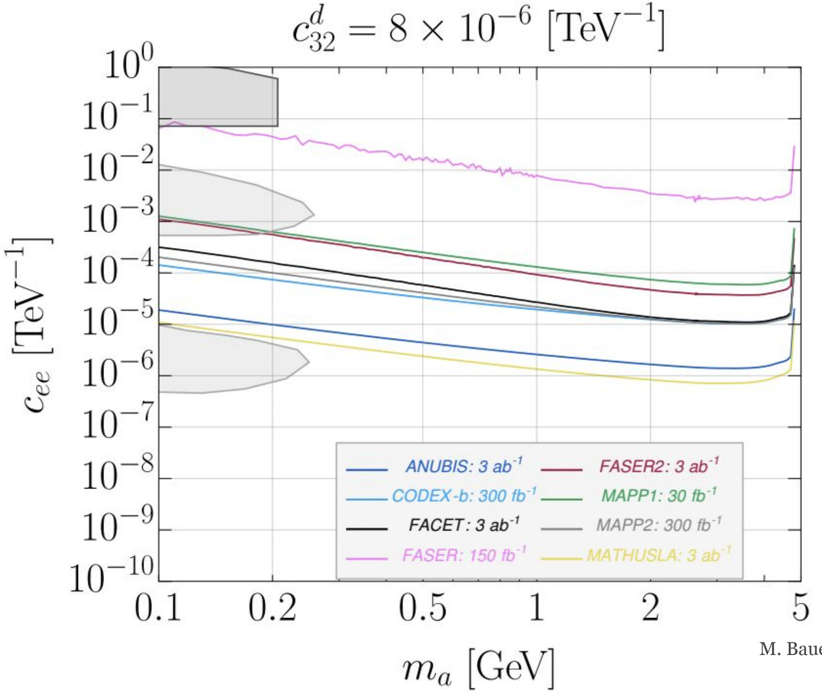
$$c \sim 10^{-4} \xrightarrow{c\ \sim 1/\Lambda^3} \Lambda \lesssim \mathcal{O}(10)\ \text{TeV}$$

Reinterpretation to ALPs

Can be produced through a flavor off-diagonal coupling to quarks, and decay to leptons. Light and weakly coupled ALPs can be long-lived!

Low-energy EFT of ALPs
H. Georgi, et al, Phys.Lett.B 169 (1986)
K. Choi, et al, Phys.Lett.B 181 (1986)

R. Beltrán, et al, JHEP 05 (2023) 031



$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{1}{2}m_a^2\,a^2 + \partial_\mu a\left[\sum_q\sum_{i,j} c^q_{ij}\,\overline{q_i}\gamma^\mu q_j + \sum_l\sum_{\ell,\ell'} c^l_{\ell\ell'}\,\overline{l_\ell}\gamma^\mu l_{\ell'}\right] + \ldots$$

M. Bauer, et al, JHEP 12 (2017) 044

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

Benchmark	$P^{ij}_{\rm prod}$	$P_{\rm decay}$	Production modes	Decay modes
ALP-D	c^u_{12}	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^d_{32}	c_{ee}	$B \to K^{(*)} + a$ $B_s \to \eta^{(\prime)} + a$ $B_s \to \phi + a$	$a \to e^+ + e^-$

Complementary bounds in
M. Bauer, et al, JHEP 09 (2022) 05

Summary and Outlook

Charged and neutral **long-lived particles are predicted in many models motivated by neutrino masses and dark matter.** New exotic LLP signatures are being proposed motivated by dark energy very recently in S. Argyropoulos et al, arXiv:2304.11189)

There is **large discovery potential** at main LHC detectors (ATLAS/CMS) and current and proposed far detectors (i.e FASER/MATHUSLA). New search proposals now include using ProtoDUNE and the CERN SPS very recently in P. Coloma, et al, arXiv:2304.06765

Prospects rely on reinterpretation methods. These can include full simulation, new simulation tools (i.e. CMS displaced showers in the muon system) or Monte Carlo truth/theory input only. All very useful for new models! (similar method at neutrino facilities very recently in B. Batell et al, arXiv:2304.11189)

Still plenty of reasons **why** we should look **hard** for feebly coupled, long-lived physics !