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# LLP overview: theory perspective

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I comment on selected example models predicting Long-Lived Particles (LLPs) motivated by neutrino masses and dark matter. Sensitivity prospects at the Large Hadron Collider (LHC) main detectors (ATLAS and CMS) and current/future proposed far detectors (such as FASER or MATHUSLA) are provided. Some of these projections include novel reinterpretation efforts, which are highlighted as well.

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## 1. Introduction

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 [1]. One can identify three main reasons as to why this can happen when looking (generally) at the total decay width of a particle. In order to have small decay widths or macroscopic decay distances (starting from microns to several meters) couplings can be small, which can lead to small rates at the LHC. Secondly, we can have large mass hierarchies or very heavy off-shell mediators, perhaps too heavy to be accessible for LHC energies. Thirdly, small mass differences in the decay chain would lead to low reconstruction efficiencies due to the "compressed spectra".

Nevertheless, many well motivated theories predict LLPs [2] with exotic and challenging signatures such as displaced vertices or disappearing tracks [3]. Phenomenological projections are needed to accurately characterize these model signatures and to cover unconstrained model parameter space. Here we focus on the phenomenology of the Scotogenic model [4], which tackles both the generation of small neutrino masses and dark matter (from a one-loop seesaw mechanism), models predicting Axion-like particles (ALPs) [5–7] as well as models with Heavy Neutral Leptons (see for reviews [8–11] ), also motivated by neutrino masses.

## 2. Model prospects: Scotogenic and minimal Heavy Neutral Leptons

The Scotogenic model [4] predicts three new right-handed fermion singlets and a scalar doublet. The dark matter candidate can correspond to either a scalar or a fermion. When considering the real part of the doublet as scalar dark matter ($\eta_R$) produced via standard thermal freeze-out, long-lived particles can arise [14] in the coannihilation region [15][1]. The charged component of the doublet ($\eta^\pm$) can be a long-lived particle that decays to the dark matter and a (soft) pion when the mass difference is $m_{\eta^\pm} - m_{\eta_R} \sim \mathcal{O}(100)$ MeV. Interestingly, the prediction of long-lived particles can happen in a region of parameter space where the dark matter relic abundance is fully satisfied for dark matter masses below 500 GeV [14]. This model scenario was also recently constrained by the SModelS collaboration [16] by reinterpreting a disappearing charged track search, which could exclude masses of the new charged scalar up to about 200 GeV for decay distances of 10s of centimetres.

In the minimal Heavy Neutral Lepton (HNL) model, the Standard Model is extended with only one right-handed singlet fermion or a HNL, which can be a long-lived particle for low mixings with the SM neutrinos and $\sim$ GeV scale masses[2]. A recent summary of experimental bounds can be found in [17] for different mixings $|V_{lN}|^2$, with $l = e, \mu, \tau$. Mixings with $\tau$ leptons are far less constrain at the LHC than mixings with electrons or muons. This motivates novel strategies to efficiently access $\tau$-mixing within the LHC detector's subsystems.

In ref. [21] we reinterpret a novel CMS search for a "displaced shower" in the CMS muon system [22] to HNLs decaying to $\tau$ leptons. We use public reinterpretation material and instructions

[1]The LLP phenomenology of the Scotogenic model with a fermionic dark matter candidate was studied in [12] considering freeze-in, and in [13] for freeze-out.

[2]For simplicity, in the minimal HNL model the HNL mass and mixing are considered independent parameters (they can be related in a model dependent way via for example the see-saw [18, 19] or inverse see-saw [20] relations).



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provided by CMS in the original search – sensitive to LLPs decaying hadronically– as well as implement a new DELPHES module [23] to simulate the clusters of hits in the CMS cathode strip chamber (CSC) of the CMS muon detector (which form the displaced shower). We are able to access HNL masses between 1 and 6 GeV, complementary to prospects with displaced vertices in the tau-sector [24–27]. See figure 1.

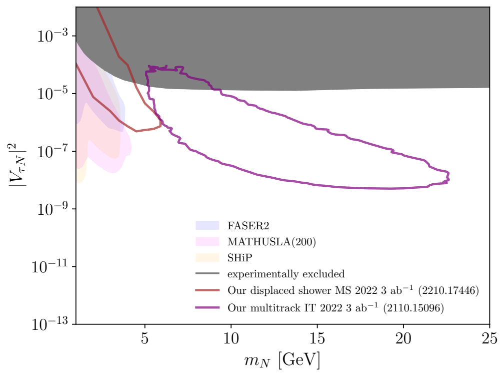


**Figure 1:** Projected sensitivity to HNL mixing in the tau sector with a displaced shower signature in the CMS muon system [21] and with a multitrack displaced search in the inner trackers [24].

## 3. Reinterpretation method beyond minimal Heavy Neutral Leptons

Beyond the minimal HNL model and to study lighter HNLs (below 5 GeV), we can consider the low-energy effective field theory of the Standard Model extended with HNLs (which has had plenty of attention in recent years, see ref. [10] and references therein for an overview on HNLs and EFT, and refs. [24, 28–31] for HNLs in EFT with LLPs at the LHC). Within this so-called $N_R$-LEFT framework, we consider dimension 6 operators that induce the decay of mesons to HNLs. The HNLs can then decay via standard mixing [32]. In order to provide sensitivity prospects at future LLP far detectors, we make use of a new reinterpretation method [33] which can be potentially useful to any LLP produced in meson decays.

The method goes as follows[3]. We start with the minimal HNL model from the *already* known sensitivity curves for a certain experiment. For each mass value on this curve, there is a corresponding mixing angle (or coupling) for which the predicted signal event number ($N_s$), the total production number of the HNL from decays of a specific meson ($N_N$), as well as the visible decay width ($\Gamma_{\text{vis.}}$) are all known or calculable. There are two assumptions to get the reinterpreted limits (primed ’ quantities) : i) that in the reinterpreted model, the LLP is produced from the same type of meson (to ensure the same kinematics) and ii) that the HNLs are long-lived compared to the detector distance from the interaction point. This is so we can work in the linear regime for the exponential decay distribution, and so the (unknown) detector acceptance × efficiencies would be simply proportional to the total decay width of the HNL. Therefore we have: $N_S = N_N \cdot \Gamma_{\text{tot.}} \cdot \text{BR}(N \to \text{vis.}) \sim N_N \cdot \Gamma_{\text{vis.}}$. Then we can compute the new reinterpreted quantities relying on theoretical input only (LLP production and decay): $\Gamma'_{\text{vis.}} \approx \Gamma_{\text{vis.}} \frac{N_N}{N'_N} \frac{N'_s}{N_s}$.

[3]We note that a similar method at neutrino facilities was also recently proposed in [34].

Figure 2 (left) shows the results of the reinterpretation method for one example operator inducing the decays of neutral $B$ mesons to pairs of HNLs. We show constraints in the plane of the wilson coefficient as a function of mass for several LLP detector experiments. In this case we can compare the results of the method (dashed lines) with the full simulation (from previous work in ref [31]). We have very good agreement except when the HNLs are not long-lived enough in the lab frame, compared to the distance of MATHUSLA from the CMS interaction point (the reinterpreted bounds for ANUBIS and MATHUSLA are slightly too strong, represented with x on the figure).

Finally, we show we can also use this method to constrain long-lived Axion-like particles which can be produced from mesons. ALPs can be produced through flavour off-diagonal coupling couplings to quarks and decay to two electrons. These can be long-lived for small couplings and light masses. The right side of fig. 2 shows bounds obtained with our reinterpretation method for a fixed production coefficient, and as a function of the $c_{ee}$ coupling and ALP mass.

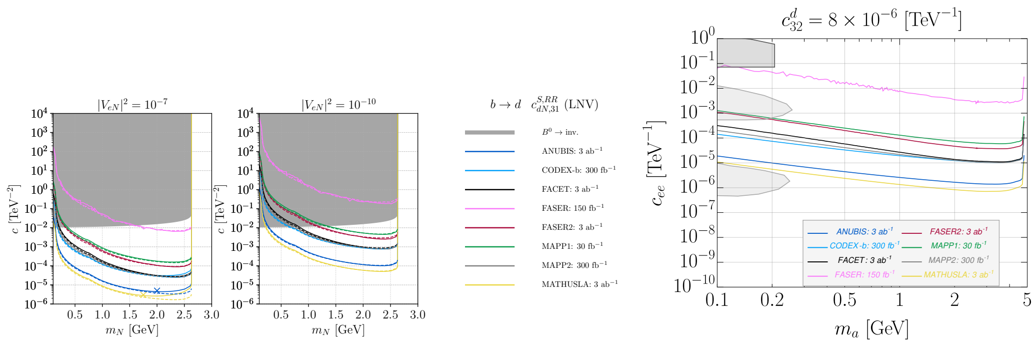


**Figure 2:** Reinterpreted bounds with the method presented on HNLs (dashed lines, left panel) and axion-like particles (solid lines, right panel) [21].

## 4. Summary and outlook

Charged and neutral long-lived particles are predicted in many models motivated by neutrino masses and dark matter. There is large discovery potential at the main LHC detectors (ATLAS/CMS) and current and proposed far detectors (FASER/MATHUSLA). Prospects rely on reinterpretation methods. These can include new simulation tools (i.e. CMS displaced showers in the muon system) or Monte Carlo truth/theory input only (i.e. reinterpretation method beyond minimal HNLs). These probe to be very useful for constraining new models predicting feebly coupled, long-lived physics.

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