Searching for a single photon from lightest neutralino decays in R-parity-violating supersymmetry at FASER

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ABSTRACT: In this work, we propose a search for a single photon at FASER and FASER2, produced from decays of bino-like, sub-GeV lightest neutralinos in the theoretical framework of the R-parity-violating (RPV) Minimal Supersymmetric Standard Model (MSSM). We consider a list of representative benchmark scenarios with one or two non-vanishing RPV couplings. The photon has an energy $O(0.1) - O(1)$ TeV. We find a sensitivity reach for RPV couplings beyond the current bounds by orders of magnitude at FASER and FASER2.

KEYWORDS: New Light Particles, Supersymmetry

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1 Introduction

The discovery of a Higgs boson [1, 2] at the Large Hadron Collider (LHC) at CERN, Switzerland, has completed the spectrum of the Standard Model (SM) of particle physics. Despite the huge successes, the SM provides an incomplete description of the Universe. For instance, the observed neutrino oscillations [3–5] require massive neutrinos, in disagreement with the SM. The fine-tuning problem of the Higgs boson — or hierarchy problem [6, 7] — is only resolved beyond the SM (BSM), e.g., by supersymmetry (SUSY) [8, 9]. Furthermore, dark matter and dark energy, as well as baryogenesis in the early Universe are all unexplained within the SM.

Searches for BSM physics have been performed since even prior to the Higgs-boson discovery, on various experimental and observational fronts. These probes include colliders, beam-dump experiments, nuclear- and electron-recoil experiments, and astrophysical observations.

Here, we focus on collider probes for BSM-physics searches. In particular, we study high-energy proton-proton collisions at the LHC, currently aiming to reach a center-of-mass energy of 14 TeV in the near future. The two largest experiments at the LHC — ATLAS [10] and CMS [11] — have hitherto mainly searched for events with large missing energy and/or high $p_T$ objects (jets, leptons, etc.), emphasizing signatures expected to stem from heavy new fields.
Among various signatures, high-energy photons plus missing energy is one interesting example as it is clean with modest SM background, and is predicted in well-motivated theoretical models. One classic example is Gauge-mediated Supersymmetry Breaking (GMSB) models [12]. Given a light and stable gravitino as the lightest supersymmetric particle (LSP), the lightest Minimal Supersymmetric Standard Model (MSSM) superpartner is actually the next-to-lightest supersymmetric particle (NLSP). If the NLSP is neutral, it can be either a neutralino, or a sneutrino. The lightest neutralino can be bino, wino, Higgsino, or a mixture, and can decay to a photon and a non-observable gravitino, either promptly or with a long lifetime; see, e.g., refs. [13–16] for some LHC phenomenology studies. This signature has been searched for at the Tevatron — at CDF and D0 [17, 18] — and at the LHC — at ATLAS [19] and CMS [20].

One additional theory benchmark is a class of models with universal extra dimensions [21]. If the new dimensions are only accessible to gravity, the lightest Kaluza-Klein particle (LKP) can decay to a photon and a gravity excitation. Both the lightest neutralino (assuming R-parity conservation) and the LKP should be pair-produced, and thus lead to the signature of two highly energetic photons plus missing energy at the LHC.

Here, we consider R-parity-violating (RPV) supersymmetry in its minimal form — the RPV Minimal Supersymmetric Standard Model (RPV-MSSM) [22] — with a bino-like lightest neutralino as the LSP (see refs. [23–25] for reviews). The RPV-MSSM is as well-motivated as the R-parity-conserving (RPC) MSSM. It not only solves the hierarchy problem, but also provides a natural solution to the neutrino masses [26–30], as well as a much richer collider phenomenology than the RPC-MSSM. In addition, it can explain various experimental anomalies observed in recent years, such as the $B$-anomalies [31–36], muon $g-2$ [34–36], and the ANITA anomaly [35, 37].

As we discuss in more detail in section 2 below, in the RPV-MSSM, it is possible to have a light neutralino of mass below $10$ GeV, or even massless. Once produced, the neutralino decays via non-vanishing RPV couplings into SM particles. Since these couplings are required by various (low-energy) experiments to be small [24, 38, 39], light LSP neutralinos with mass below the GeV scale are expected to be long-lived; after production at a collider, they travel a macroscopic distance before decaying to SM particles.

Long-lived particles (LLPs) have in recent years received increased attention [40–45]. LLPs are predicted in a wide range of BSM models such as split SUSY, RPV-SUSY, a class of portal-physics models [axion-like particles (ALPs), heavy neutral leptons, a dark Higgs scalar, dark photons], and models of neutral naturalness — which are often related to the non-vanishing neutrino masses or dark matter. In particular, a series of dedicated far-detector programs have been proposed to be operated in the vicinity of LHC interaction points (IPs), mainly aiming to look for LLPs with a proper decay length $c\tau \sim (1 - 100)$ m, or even larger. Some examples currently under discussion include FASER [46, 47], FACET [48], MATHUSLA [40, 49, 50], CODEX-b [51], ANUBIS [52], and MoEDAL-MAPP [53].

FASER has been approved and installed at the LHC TI12 tunnel. It consists of a small cylindrical decay volume of $\sim 0.05$ m$^3$. It is expected to achieve excellent constraining power for a number of theoretical benchmark models such as ALPs [54], dark photons [46], and inelastic dark matter [55]. It is now under operation with the ongoing LHC Run 3. For the
high-luminosity LHC (HL-LHC) period, a larger version of FASER, known as FASER2 [47], is also planned to be installed and running, potentially at the same location or at a collective facility — the Forward Physics Facility (FPF) [56] — hosting various experiments, all in the very forward region of the LHC, including FORMOSA [57] and FLArE [58]. These potential future experiments are all intended to look for various BSM signatures.

Here, we focus on long-lived light neutralinos. They have been studied extensively for various present and future experiments including SHiP [59, 60], ATLAS [59], far detectors at the LHC [61–64], Belle II [65], Super-Kamiokande [66], and future lepton colliders [67, 68]. These works mostly consider the signature of a neutralino decay into a charged lepton plus a meson, induced by $LQ\bar{D}$ operators [69], while the production can result from decays of either mesons, $\tau$ leptons, or $Z$-boson.

In this work, we propose a novel signature associated with very light lightest-neutralino ($\tilde{\chi}_1^0$) decays: A single photon plus missing energy. Such a signature can appear as a result of the radiative decay associated with neutrinos,

$$\tilde{\chi}_1^0 \rightarrow \nu_i + \gamma \text{ or } \bar{\nu}_i + \gamma,$$

arising at the loop level via the RPV couplings $\lambda'_{ijj}$ of the $LQ\bar{D}$ operators or $\lambda_{ijj}$ of the $LLE$ operators. This decay can dominate in certain mass ranges and for certain choices of RPV couplings.\footnote{We note that light long-lived particles (LLPs) decaying to a light neutrino and a photon may explain the MiniBooNE anomaly [70, 71], but given the recent negative results by MicroBooNE [72], and possible SM explanations for the anomaly [73, 74], we do not consider it any further here.}

We consider the lightest neutralino to be produced from rare decays of mesons such as pions and $B$-mesons copiously created at the LHC, and study the probing potential of FASER and FASER2 to these scenarios, for the signature of a single, displaced photon. As discussed in section 5, the background is expected to be negligible.

The paper is organized as follows. We briefly introduce the RPV-MSSM, as well as the light neutralino scenario in the next section. In section 3 we present a list of representative benchmark scenarios, which we investigate in this paper. In section 4 we discuss the experimental setup at FASER and FASER2, and in section 5 we detail our simulation procedure for estimating the sensitivity reach. The results are then presented with a discussion in section 6. We conclude the paper with a summary and an outlook in section 7.

2 Theoretical framework

Here, we discuss the underlying supersymmetric model, as well as details of the light neutralino scenario.

2.1 The R-parity-violating MSSM

Given the $(N = 1)$ supersymmetry algebra, and the MSSM particle content, the most general $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$-invariant, renormalizable superpotential can be written as,

$$W = W_{\text{MSSM}} + W_{\text{LNV}} + W_{\text{BNV}},$$

arising at the loop level via the RPV couplings $\lambda'_{ijj}$ of the $LQ\bar{D}$ operators or $\lambda_{ijj}$ of the $LLE$ operators. This decay can dominate in certain mass ranges and for certain choices of RPV couplings.\footnote{We note that light long-lived particles (LLPs) decaying to a light neutrino and a photon may explain the MiniBooNE anomaly [70, 71], but given the recent negative results by MicroBooNE [72], and possible SM explanations for the anomaly [73, 74], we do not consider it any further here.}
where $W_{\text{MSSM}}$ is the usual MSSM superpotential — see, for instance, ref. [22] — while the terms,

$$W_{\text{LNV}} = \frac{1}{2} \lambda^{ijk} L_i L_j \bar{E}_k + \lambda''^{ijk} L_i Q_j \bar{D}_k + \kappa^i H_u L_i,$$

$$W_{\text{BNV}} = \frac{1}{2} \lambda''''^{ijk} \bar{U}_i \bar{D}_j \bar{D}_k,$$  

(2.2)

violate lepton- and baryon-number, respectively. In the above, $L$ ($Q$), and $E$ ($\bar{U}, \bar{D}$) are the MSSM lepton (quark) SU(2)$_L$-doublet and SU(2)$_L$-singlet chiral superfields, respectively, while $H_u, H_d$ label the SU(2)$_L$-doublet Higgs chiral superfields. We do not show gauge indices explicitly but write the generational ones: $i, j, k = 1, 2, 3$ with a summation implied over repeated indices. The $\lambda$'s are dimensionless coupling parameters, the $\kappa$'s are dimension-one mass parameters.

The combined lepton- and baryon-violation contained in the above terms may cause the proton to decay too quickly [75, 76]. Thus, in the MSSM, all operators in $W_{\text{LNV}} + W_{\text{BNV}}$ are set to zero by invoking a $Z_2$ symmetry called R-parity [77]. This allows $W_{\text{MSSM}}$ while disallowing $W_{\text{RPV}} \equiv W_{\text{LNV}} + W_{\text{BNV}}$. However, the proton can be protected without completely forbidding $W_{\text{RPV}}$. For instance, forbidding $W_{\text{BNV}}$, while keeping $W_{\text{LNV}}$, results in a stable proton. Baryon triality — $B_3$ — is a $Z_3$-symmetry that achieves exactly this [29, 78–80].

Importantly, RPV phenomenology can be starkly different compared to the RPC case [23, 24, 81–83]. The LSP is no longer guaranteed to be stable leading to vastly different final state signatures. The collider phenomenology of RPV models is rich and complex [81, 83], and it is crucial that our SUSY search strategies cover all possibilities. We now discuss in some detail one interesting realization of RPV-SUSY: A very light neutralino.

### 2.2 A very light lightest-neutralino

In principle, any supersymmetric particle can be the LSP in RPV models [83–85]. Here, we restrict ourselves to the case of a neutralino. Potentially important mass bounds come from colliders, dark matter (cosmology), and astrophysics. For collider searches of a stable neutralino, the strongest bound comes from LEP, $m_{\tilde{\chi}^0} \gtrsim 46\,\text{GeV}$ [76]. This is based on chargino searches, and assumes the grand-unified mass relation is satisfied between the electroweak supersymmetry breaking gaugino masses, $M_1 = \frac{3}{2} \tan^2 \theta_W M_2 \approx 0.5 M_2$, with $\theta_W$ the electroweak mixing angle. However, once the relation is dropped, the mass of the lightest neutralino is experimentally unconstrained [86]. Such a scenario typically requires the lightest neutralino to be dominantly bino-like [86, 87].

A stable lightest neutralino is further constrained by dark matter limits. The Lee-Weinberg bound gives $m_{\tilde{\chi}^0} \gtrsim O(10)\,\text{GeV}$ [86, 88–95]. However, in RPV models where the LSP is unstable, this bound does not apply [86].

Then, from our discussion above, if the RPV couplings are small — which is what one expects — the neutralino can be stable on collider scales while unstable on cosmological scales, thus evading all existing constraints. Such a neutralino is allowed to be very light and, in principle, even massless [76, 86]. It is also consistent with astrophysical constraints, such as the cooling of supernovae and white dwarfs, if the sfermions are heavy enough [92, 96, 97].
We next consider the phenomenology of RPV-SUSY scenarios with such light neutralinos as the LSP. If the neutralino is massive enough, and/or the RPV couplings are sizeable, such that the proper decay length of the neutralino is $c\tau \lesssim \mathcal{O}(1)\,\text{m}$, various RPV searches performed at ATLAS and CMS — including those for displaced vertices — apply; see, e.g., refs. [98, 99]. These searches rely on detecting the decay products of the neutralino, which can contain jets and leptons, depending on the dominant RPV couplings. On the other hand, for very light neutralinos, and/or if the RPV couplings are very small, the neutralino LSP is stable on macroscopic scales. Then, the signature is invisible to colliders, just as in the RPC case. Thus, as long as heavier SUSY particles are produced at the LHC, that then cascade-decay down to the neutralino LSP, the RPC searches for large missing transverse momentum apply even to the RPV case.

However, in light of to-date unsuccessful supersymmetry searches, one possibility is that the heavier SUSY spectrum may be inaccessible at the LHC. Very light neutralinos, $m_{\tilde{\chi}^0_1} \lesssim \mathcal{O}(4.5)\,\text{GeV}$, can still be produced in abundance in such a scenario in RPV models through the rare decays of mesons via an $LQ\bar{D}$ operator [59, 87, 100]. These neutralinos would be highly boosted in the forward direction of the momentum of the decaying meson. None of the above search strategies applies in such a case, and the scenario represents a realistic possibility of low-scale SUSY manifesting in a way that would have escaped our searches so far. With the long-lived particle programs at the LHC picking up pace, there is the possibility of filling this gap. If the highly boosted, light neutralino decays with a proper decay length, $c\tau \sim \mathcal{O}(1-100)\,\text{m}$, it may be visible in dedicated far-detector experiments such as FASER. Before we discuss the decay modes of such light neutralinos, we provide, for completeness, the unpolarized decay width of pseudoscalar mesons into a light neutralino and a lepton via an $LQ\bar{D}$ operator, reproduced from ref. [59],

$$
\Gamma \left( M_{ab} \rightarrow \tilde{\chi}^0_1 + l_i \right) = \frac{\lambda^2}{64\pi m^4_{M_{ab}}} \left| G_{S,f} \right|^2 \left( f_{M_{ab}}^S \right)^2 \left( m_{M_{ab}}^2 - m_{\tilde{\chi}^0_1}^2 - m_{l_i}^2 \right),
$$

(2.3)

where $l_i$ denotes a charged lepton $\ell^+_i$ or a neutrino $\nu_i$, depending on whether $M_{ab}$ is charged or neutral, and $\lambda^2$ is the Källén function $\lambda^2(x,y,z) \equiv \sqrt{x^2+y^2+z^2-2xy-2xz-2yz}$. The coupling constants $G_{S,f}$ and the meson decay constant $f_{M_{ab}}^S$ are defined as in ref. [59]. In particular, the $LQ\bar{D}$ coupling $\lambda$ is proportional to $G_{S,f}$. In the above, the charge-conjugated mode is implied.

### 2.3 Neutralino decay

The dominant decay mode of the neutralino is dictated by the relative sizes of the RPV couplings, as well as the neutralino mass [69]. For $m_{\tilde{\chi}^0_1} \lesssim \mathcal{O}(4.5)\,\text{GeV}$, the neutralino can decay into a meson and a lepton via an $LQ\bar{D}$ operator, if kinematically allowed. Similarly, it can decay as $\tilde{\chi}^0_1 \rightarrow \ell^+ \ell^- \nu + \text{c.c.}$ via the $LL\bar{E}$ operators. For operators $L_i Q_j \bar{D}_j$ or $L_i L_j \bar{E}_j$, there is also the possibility for the loop-induced decays,

$$
\tilde{\chi}^0_1 \rightarrow (\gamma + \nu_i, \gamma + \bar{\nu}_i),
$$

(2.4)
which has essentially no kinematic threshold. We show example Feynman diagrams in figure 1. The fermions/sfermions in the loop have generation index $j$. The decay rate is given by [26, 69, 101, 102]:

$$\Gamma(\tilde{\chi}^0_1 \rightarrow \gamma + \nu_i) = \frac{\lambda^2 \alpha^2 m^3_{\tilde{\chi}^0_1}}{512 \pi^3 \cos^2 \theta_W} \left[ \sum_f e_f N_c m_f (4 e_f + 1) \left( 1 + \log \frac{m^2_f}{m^2_{\tilde{f}}} \right) \right]^2,$$

(2.5)

In the above expression, $\lambda$ is the relevant $L_i Q_j \tilde{D}_j$ or $L_i L_j \tilde{E}_j$ coupling, $\alpha$ is the (QED) fine-structure constant, while $\theta_W$ is the electroweak mixing angle. $e_f, N_c$ and $m_f(m_{\tilde{f}})$ are the electric charge in units of $e$, color factor ($3$ for $LQD$, $1$ for $LL\tilde{E}$), and the mass, respectively, of the fermion (sfermion) inside the loop. We note that the above simple formula for the width neglects any mixings in the scalar sector. While this effect — depending on the supersymmetric parameters — may become significant, it introduces several undetermined SUSY-parameters in the expression. At the level of precision of our study, we find it convenient to work with this simplified approximation. The two decay widths in eq. (2.5) are equal as a result of the Majorana nature of the neutralino. The logarithmic function in eq. (2.5), $\log \frac{m^2_f}{m^2_{\tilde{f}}}$, changes only by about a factor of two if we vary $m_{\tilde{f}}$ between $1$ TeV and $100$ TeV. Therefore, in our numerical simulations, we will fix $m_{\tilde{f}}$ at $1$ TeV for the log term, so that we can use $\lambda/m^2_{\tilde{f}}$ as a single combined parameter, without separating $\lambda$ and $m_{\tilde{f}}$.

Despite the loop-suppression, the radiative mode, eq. (2.4), can be relevant for very light neutralinos. The partial width is proportional to $\frac{(m^3_{\tilde{\chi}^0_1} m^2_f)}{m^4_{\tilde{\chi}^0_1}}$, compared to $\frac{(m^5_{\tilde{\chi}^0_1} m^4_f)}{m^8_{\tilde{\chi}^0_1}}$ for the tree-level three-body decay into fermions [26, 81, 101], and can thus be important for small masses. Depending on the generation indices of the dominant RPV coupling(s) and the neutralino mass, it might even be the only kinematically allowed mode. In this paper we focus on the scenario where the neutralino dominantly decays as in eq. (2.4), as this channel has not been considered before in the context of long-lived light neutralino searches. We now present some benchmark scenarios for phenomenological studies.

3 Benchmark scenarios

In order to study the phenomenology of a very light neutralino decaying only via the radiative mode, eq. (2.4), we present some representative benchmark scenarios which we
believe cover all relevant possibilities, and which we investigate in detail in the next section. We list the corresponding parameters in table 1. In each case, we assume the listed couplings are the only non-negligible RPV couplings. The neutralino is produced through the rare decay of the meson $M$ via the coupling $\lambda_{ijk}^P$: $M \to \tilde{\chi}^0_1 + \ell (\nu)$ [59, 87, 100, 103], and then decays in one of the ways discussed in the previous section via the coupling $\lambda_{ijj}^D$.

For benchmark B1, the neutralino is produced via the most abundant mesons at the LHC — pions — in association with muons (neutrinos). This occurs via the coupling $\lambda_{ijj}^P = \lambda'_{211}$. The charged production mode ($\pi^\pm \to \tilde{\chi}^0_1 + \mu^\pm$) is only possible if the mass of the neutralino satisfies the bound,

$$m_{\chi^0_1} < m_{\pi^\pm} - m_{\mu^\pm} \approx 35 \text{ MeV}.$$  

(3.1)

For neutralinos heavier than the above threshold, only the neutral production mode ($\pi^0 \to \tilde{\chi}^0_1 + \nu_\mu$) contributes; however, this mode is suppressed owing to the short lifetime of the neutral pion which translates into a low decay branching fraction into neutralinos. For the benchmark, we choose $m_{\chi^0_1} = 30 \text{ MeV}$; the lightness of the neutralino means that the radiative mode is the only kinematically allowed decay. In principle, with the coupling $\lambda_{ijk}^P = \lambda'_{111}$ instead, a heavier neutralino can be produced in charged pion decays: $\pi^\pm \to \chi^0_1 + e^\pm$, but the severe bound, [38]

$$\lambda'_{111} \lesssim 0.001 \left( \frac{m_{d_R}}{1 \text{ TeV}} \right)^2,$$  

(3.2)

implies this mode can not be probed at the experiments we consider here.

For the decay coupling, we choose $\lambda_{ijj}^D = \lambda''_{333}$. The decay width, eq. (2.5), is roughly proportional to $m_f^2$. Thus, the heavier the fermion in the loop, the shorter the lifetime of the neutralino. For the very light neutralino in B1, we require a heavy fermion in the loop to get testable scenarios at FASER; we expect maximum sensitivity to couplings $\lambda'_{i33}$ or $\lambda_{i33}$.

For the benchmarks B2 and B3, we choose the parameters such that the neutralinos are produced in kaon decays. This time, unlike the pion case, both the charged and neutral modes have comparable contributions. For B2, the neutralino decays only radiatively, as in eq. (2.4). For B3, the decay coupling $\lambda^D = \lambda''_{322}$ also allows for tree-level leptonic decays:

$$\tilde{\chi}^0_1 \to (\nu_\tau, \mu^\pm, \tau^\pm, \nu_\mu) + \text{c.c.}.$$  

(3.3)

However, these are kinematically blocked for $m_{\chi^0_1} \lesssim 2m_\mu$. Thus, we have chosen $m_{\chi^0_1} = 200 \text{ MeV}$. Later, when we present numerical results, we go beyond the strict parameters in the benchmark scenarios and consider plots in the RPV coupling vs. neutralino mass plane. One then has to account for the fact that additional decay modes can open. Note that in B3, we now select a decay coupling that is not third generation in the last two indices, since the neutralino is now heavy enough to avoid a too-small decay width, even for lighter fermions in the loop.

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[2] We note that, in this work, we are neglecting the effects of the suppressed three-body decay that can proceed at one-loop level via an off-shell $Z$, e.g., $\tilde{\chi}^0_1 \to 3\nu$. We thank Florian Domingo for a discussion on this topic.
For the future.

We note in passing the interesting observation that the radiative decay of a neutralino gives us a method of producing significant \( \nu_\tau \) fluxes. These are suppressed in the SM. With FASER\( \nu \) [104, 105] under operation, this may give us an interesting opportunity to detect the neutralino by looking for \( \nu_\tau \) events. However, we leave an investigation in this direction for the future.

### Table 1. Benchmark scenarios considered in this paper. The neutralino is produced through the rare decay of the meson \( M \) via the coupling \( \lambda'_{ijk} \): \( M \to \chi_1^0 + \ell (\nu) \). The neutralino decay is as in eq. (2.4) via the coupling \( \lambda''_{ijl} \). The photon energy in the neutralino rest frame is \( E_\gamma = m_{\chi_1^0}/2 \), but can range from \( \mathcal{O}(0.1) \) to \( \mathcal{O}(1) \) TeV at FASER. In the furthest-to-the-right column, we list the current best bounds on the couplings, see for example, ref. [38].

| Scenario | \( m_{\chi_1^0} \) | Production (\( \lambda'_{ijk} \)) | Decay (\( \lambda''_{ijl} \)) | Current Constraints |
|----------|----------------|---------------------------------|----------------------------|-------------------|
| B1       | 30 MeV         | \( \lambda'_{211} (M = \pi^\pm, \rho^0) \) | \( \lambda''_{333} \) | \( \lambda'_{211} < 0.59 \left( \frac{m_{\chi_1^0}}{1\text{ TeV}} \right) \), \( \lambda''_{333} < 1.04 \) |
| B2       | 75 MeV         | \( \lambda'_{121} (M = K^\pm, K^0_{L/S}) \) | \( \lambda''_{333} \) | \( \lambda''_{121} < 0.59 \left( \frac{m_{\chi_1^0}}{1\text{ TeV}} \right) \), \( \lambda''_{333} < 1.04 \) |
| B3       | 200 MeV        | \( \lambda'_{112} (M = K^\pm, K^0_{L/S}) \) | \( \lambda''_{322} \) | \( \lambda''_{112} < 0.21 \left( \frac{m_{\chi_1^0}}{1\text{ TeV}} \right) \), \( \lambda''_{322} < 0.7 \left( \frac{m_{\chi_1^0}}{1\text{ TeV}} \right) \) |
| B4       | 300 MeV        | \( \lambda'_{221} (M = D^\pm, K^0_{L/S}) \) | \( \lambda''_{333} \) | \( \lambda_{221} < 1.12 \), \( \lambda_{233} < 0.7 \left( \frac{m_{\chi_1^0}}{1\text{ TeV}} \right) \) |
| B5       | 500 MeV        | \( \lambda'_{222} (M = D^0_S) \) | \( \lambda''_{222} \) | \( \lambda_{222} < 1.12 \) |
| B6       | 1 GeV          | \( \lambda'_{113} (M = B^\pm, B^0) \) | \( \lambda''_{333} \) | \( \lambda_{113} < 1.12 \), \( \lambda''_{333} < 1.04 \) |

We have chosen benchmark B4 such that a single coupling leads to production of the neutralinos from both kaons and \( D^\pm \). Since kaons are more abundant at the LHC than \( D \)-mesons, the former production mode contributes more to the neutralino flux. For the selected mass of 300 MeV, there are no other relevant decay modes of the neutralino than the radiative one. But for the coupling vs. mass plot, the neutralino can decay into kaons above the relevant thresholds. The neutralino production through kaons is, of course, blocked for these heavier masses. In addition, for this scenario and the ones below, there can also be three-body decays into two mesons and a lepton, mediated via the \( LQD \) operators; these can become relevant in the very high mass regime, \( m_{\chi_1^0} \gtrsim \mathcal{O}(1.5) \) GeV. These are neglected for simplicity in the present work as their impact for sub-GeV neutralinos — which are the focus of our study — is minor. We will also neglect any Cabibbo-Kobayashi-Maskawa-mixing effects for similar reasons. More details on these effects can be found in ref. [69].

Benchmark B5 is a special case: It requires only a single non-zero RPV coupling \( \lambda'_{222} \) for both production (via \( D^0_S \) mesons) and decay. This is absent in the tree-level neutralino decay case [59], except for an extremely small mass-window of around 4 MeV. For the given mass, \( m_{\chi_1^0} = 500 \) MeV, the neutralino decays only radiatively. But at higher masses, it may decay into \( \eta, \eta', \) or \( \phi \).

Finally, we have chosen benchmark B6 such that the neutralinos are produced via \( B \)-meson decays, thereby allowing the neutralino to be relatively heavy, leading to more energetic photons. The neutralino is produced in association with a \( \tau^\pm (\nu_\tau) \) via the charged (neutral) mode; the two modes have comparable contributions. For \( m_{\chi_1^0} > m_{B^\pm} - m_{\tau^\pm} \), only the neutral mode is kinematically allowed. The radiative mode is the only relevant decay channel.
Before closing the section, we provide a plot in figure 2, showing the decay branching ratios of the lightest neutralino into our signature, $\gamma + (\nu)$, as a function of the neutralino mass, for all the considered benchmark scenarios.

### 4 FASER experiment

The FASER experiment [46, 47] is a cylindrical detector that has recently been installed inside the TI12 tunnel, 480 m from the ATLAS IP along the beam collision axis line of sight. The detector is composed of tracking stations, scintillators, and a calorimeter. The cylinder axis is along the extended beam collision axis. Its decay volume has a radius of 10 cm and a length of 1.5 m. It is currently running during Run 3 of the LHC and is expected to collect data from proton-proton collisions of around $150 \text{ fb}^{-1}$ integrated luminosity. At the front end of FASER, an additional emulsion detector known as FASER$\nu$ [104, 105] has been installed, which is aimed at detecting high-energy neutrinos produced at the ATLAS IP. In this work, we do not study the potential of FASER$\nu$.

A follow-up experiment — FASER2 [47] — is currently slated to be operated during the HL-LHC period. If it is to be installed at the same position as FASER, it will be at a distance of 480 m from the ATLAS IP. Otherwise, it could be one of the experiments to be hosted at the FPF [56], 620 m from the ATLAS IP, also along the beam axis. We expect the difference between 480 m and 620 m distance to the IP to lead to only relatively minor changes in the sensitivity reach, as discussed in ref. [56]. For this study, we work with the geometrical setup of a radius of 1 m and a length of 5 m for the FASER2 decay fiducial volume, and consider it 480 m away from the IP. By the end of Run 5 at the LHC, FASER2 should have collected about $3 \text{ ab}^{-1}$ integrated luminosity of collision data. Similarly, an emulsion detector has been proposed to be installed at the front face of FASER2, known as FASER$\nu$2. We will assume the detector components of FASER2 and hence detection principles and efficiencies are similar to those of FASER, except for the different geometrical acceptances.
In ref. [54], the authors studied axion-like particles (ALPs) at FASER, where the ALPs decay to a pair of photons. They estimated that the calorimeter spatial resolution should be sufficiently good for resolving the two photons with an efficiency of about 50%, and the background should be negligible for diphoton events. Here, our signature includes only one photon. To provide a discussion on the expected background level, we follow the arguments given in ref. [106]. At FASER, the single photons are detected as high-energy deposits in the electromagnetic calorimeter. Other objects may also cause such deposits, e.g., neutrinos interacting deep inside the calorimeter via charged-current interactions. In order to differentiate the photon signal, a pre-shower station has been installed right before the calorimeter [107] which first converts the photon, thereby identifying it. Moreover, during Run 3 of the LHC program, the FASER detector is planned to be upgraded with a high-precision preshower detector. This would allow to distinguish two very closely spaced highly energetic photons [108]. Furthermore, neutrinos and muons coming from the IP can penetrate the 100 m of rock in front of FASER and reach the detector with energies in the TeV scale. These neutrinos could interact with the detector resulting in energetic particles including individual photons. However, these energetic photons are accompanied by tens of charged particles, allowing to veto such events easily with the tracker stations. The muons could radiate high-energy photons as well, mainly via Bremsstrahlung, but the veto stations positioned right in front of the FASER decay volume [107] should enable the rejection of muon-associated events. Finally, neutral pions produced in hadronic showers initiated by muons in the absorber-rock material could also constitute a background for our signal if the two photons produced in their decays cannot be spatially resolved or only one of them is observed. In such a case, requiring an energy threshold for the signal may help since the photons from our signal are expected to be more energetic; see ref. [106] for more details on the point of using energy thresholds. A detailed estimate, however, requires a full simulation of hadronic interactions inside the rock. In this work, we will assume zero background for our signal.

Since the search proposed here with the single-photon signature does not require the usage of the tracker, in principle the tracker volume could be considered as effectively part of the fiducial volume. Taking this into account would allow to enlarge the length of the fiducial volume of FASER and FASER2 by roughly 1 m [107] and 5 m [56], respectively, enhancing the sensitivity reach to some extent. In this work, we only comment on this possibility and choose to stay with the standard benchmark geometries, as given explicitly above.

There are several other past and ongoing experiments that should have sensitivity to a radiatively decaying light neutralino. These include beam-dump experiments such as LSND [109], E613 [110], MiniBooNE [111], E137 [112], and NA64 [113–115], as well as B-factory experiments such as BaBar [116] and Belle II [117, 118]. Typically, each of these experiments is optimized to primarily produce only a certain type of meson, at rates which could be higher than the LHC. Correspondingly, they can probe a subset of

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3 One possible background that we neglect here could come from off-axis muons that can penetrate FASER without passing through the veto stations; estimating such a background would require a detailed simulation. We thank Max Fieg for bringing up this point.

4 We thank Michael Albrow for bringing this to our attention.
the RPV models we have presented here in a somewhat cleaner environment. The LHC has the advantage of producing all types of mesons at significant rates, thus providing a scenario-independent probe. However, given a signal, it could be difficult to disentangle the underlying model(s). Further, given the different center-of-mass energies (and hence the spectra of the produced neutralinos), and the detector layouts, the phase-space region probed by these other experiments may complement that probed by FASER. However, detailed simulations are required to make more precise statements; this is beyond the scope of the present work.

Further, limits coming from searches for heavy neutral leptons can also be relevant for us. We will include these in our plots in section 6.

Finally, we note that our signature could also be probed by FACET — a proposed new subsystem of the CMS experiment. In this study, however, we only focus on FASER and FASER2.

5 Simulation

We now proceed to describe the simulation procedure for estimating the number of signal events in the two experiments. We use the package FORESEE [119] to obtain the neutralino spectrum in the far-forward region, relevant for FASER and FASER2. As mentioned, the dominant sources of the neutralinos are the rare decays of mesons produced at the ATLAS IP:

$$M \rightarrow \tilde{\chi}_1^0 + \ell (\nu) .$$

Direct pair-production of neutralinos, in comparison, is expected to be several orders of magnitude lower [59, 61, 100], and is hence neglected here. We include all possible production modes for the different benchmark scenarios, summing over all meson contributions, to estimate the total number of produced neutralinos over the runtime of the experiment. However, it is necessary but not sufficient for the mother meson to decay into a neutralino: The meson itself may be long-lived, e.g., charged pions and kaons. Thus, we require the meson to decay before hitting any absorber material or leaving the beam pipe; otherwise, the meson could be stopped and the neutralino is no longer boosted in the direction of FASER.

Keeping this in mind, we use FORESEE to determine the neutralino production rate and spectrum from the meson spectrum by specifying the decay branching ratios corresponding to eq. (5.1). The generated spectrum is two-dimensional, in terms of angle and momentum.

We also use FORESEE to compute the probability for the neutralino to decay inside the detector volume. See table 2 for the values corresponding to the detector position and

| Detector | $\mathcal{L}$ | $\sqrt{s}$ | $L$ | $\Delta$ | $R$ |
|----------|-------------|-------------|-----|---------|----|
| FASER    | 150 fb$^{-1}$ | 14 TeV | 480 m | 1.5 m | 10 cm |
| FASER2   | 3000 fb$^{-1}$ | 14 TeV | 480 m | 5 m | 1 m |

Table 2. Integrated luminosities and geometries of the detectors used in the simulations. Here, $\mathcal{L}$, $\sqrt{s}$, $L$, $\Delta$, and $R$ label, respectively, the integrated luminosity, the collider center-of-mass energy, the distance from the IP, the detector length, and the detector radius.
geometry we employ in our simulation for FASER and FASER2. We take into account the full neutralino lifetime, $\tau_{\tilde{\chi}^0_1}$, as well as its kinematics. The former is computed using all possible decay channels of the neutralino (including the decay into pseudoscalar and vector mesons) as a function of its mass and the non-vanishing RPV couplings, cf. the discussion in section 3. However, in the numerical results presented in the next section, we have chosen an explicit signal for detecting the neutralino decay. Although all neutralino decays inside the detector are technically visible, we estimate the signal strength based on the specific radiative mode alone. This is done to avoid the consideration of background events; the decay into a neutrino and a photon gives a clean and unique signature.

Given the neutralino spectra, we estimate the number of decays that occur inside the detector defined by its position and geometry. For the analysis, the simulation takes into account the distance $L$ between the ATLAS IP and the FASER detector, and the acceptance rate $P[\tilde{\chi}^0_1]$ in terms of the neutralino’s three-momentum, its position of production (accounting for the mesons’ lifetimes), as well as the lifetime of the neutralino itself. In our simulation, we do not make any momentum cuts. By further specifying the branching ratio into the radiative mode, the simulation counts the number of signal events passing the selection criteria. Thus, we can finally estimate the number of single-photon neutralino decay observations,

$$N_{\text{obs}}^{\tilde{\chi}^0_1} = P[\tilde{\chi}^0_1] \cdot \text{BR} \left[ \tilde{\chi}^0_1 \rightarrow (\gamma + \nu_i, \gamma + \bar{\nu}_i) \right] \cdot \sum_{\text{mesons}} N_{\text{prod}}^{\tilde{\chi}^0_1}. \quad (5.2)$$

We stress again that we assume zero background, cf. the discussion in section 4. Further, we assume a detector efficiency of 100%.

6 Numerical results

We now present our numerical results. For the sensitivity limits, we require the observation of 3 radiative decays of the lightest neutralino in the detector for an integrated luminosity at the LHC of $150 \text{ fb}^{-1}$ for FASER, and $3000 \text{ fb}^{-1}$ for FASER2. This corresponds to a potential 95% confidence-level exclusion limit under the assumption of vanishing background.

We first show, in figure 3, results for the benchmark scenario B1 of table 1. On the left, we plot the sensitivity in the $\lambda^P/m^2_{\text{SUSY}} = \lambda'_{211}/m^2_{\text{SUSY}}$ versus $\lambda^D/m^2_{\text{SUSY}} = \lambda'_{333}/m^2_{\text{SUSY}}$ plane for a fixed neutralino mass of 30 MeV. In gray we include the low-energy bounds given in table 1, for fixed sfermion masses of 1 TeV (the same choice is taken for the other model-dependent plots in this section). We see that FASER has no new sensitivity for this scenario beyond the low-energy bounds, whereas FASER2 can extend the reach by more than an order of magnitude in $\lambda^P/m^2_{\text{SUSY}}$ or $\lambda^D/m^2_{\text{SUSY}}$ in units of $\text{GeV}^{-2}$. The right plot in figure 3 is model-independent, in that it is valid for any new, neutral long-lived particle (LLP) produced in charged pion decays, which decays with a signature at FASER or FASER2, here specifically with a mass of 10 or 30 MeV. The maximum sensitivity (the minima of the curves) depends on the location of the detector, and also on the momentum distribution of the produced pions and, correspondingly, of the pions’ decay product neutralinos [62]. That is why the minimum of the curve shifts to slightly smaller LLP lifetimes for lighter LLP
Figure 3. Sensitivity reach for FASER (solid lines) and FASER2 (dashed lines) for the benchmark scenario B1, cf. table 1. The left plot shows the sensitivity reach in the production coupling ($\frac{\lambda_{211}}{m_{\text{SUSY}}^2}$) vs. decay coupling ($\frac{\lambda_{333}}{m_{\text{SUSY}}^2}$) plane, for a neutralino mass of 30 MeV. The gray areas are excluded by the low-energy bounds, also given in table 1. The right plot shows the sensitivity reach in $\text{BR}(\pi^{\pm} \to \tilde{\chi}_1^0 + \mu^{\pm}) \times \text{BR}(\tilde{\chi}_1^0 \to \text{signature})$ as a function of the neutralino decay length, $c\tau$, for $m_{\tilde{\chi}_1^0} = 10$ and 30 MeV. The shaded regions correspond to existing constraints from HNL searches.

Figure 4. Sensitivity reach in the neutralino mass-coupling plane for FASER2 for the same physics scenario as in B1 but with variable neutralino mass. The production ($\frac{\lambda_{211}}{m_{\text{SUSY}}^2}$) and decay ($\frac{\lambda_{333}}{m_{\text{SUSY}}^2}$) couplings have been set equal. The gray areas are excluded by the low-energy bounds.
Figure 5. As in figure 3 but for the benchmark scenario B2 with $m_{\tilde{\chi}^0_1} = 75$ MeV, cf. table 1. The right plot shows the sensitivity reach in $\text{BR}(K^\pm \to \tilde{\chi}^0_1 + \mu^\pm) \times \text{BR}(\tilde{\chi}^0_1 \to \text{signature})$ as a function of the neutralino decay length, $c\tau$, for $m_{\tilde{\chi}^0_1} = 75$ and 300 MeV.

masses, which are more boosted. We see that FASER (FASER2) can probe the product of the decay branching fractions of the charged pion into an LLP and a muon and the LLP into the signature, down to a few times $10^{-9}$ ($10^{-12}$). We note that existing searches for heavy neutral leptons (HNLs), $N$, which mix with active neutrinos and are produced from pion decays, may be recast into bounds on the right plot. The leading bounds for HNLs of mass 10 MeV and 30 MeV in $\pi^\pm \to \mu^\pm + N$ decays stem from two peak searches: Ref. [120], and ref. [121], respectively. The former shows a bound of $10^{-5}$ on $\text{BR}(\pi^\pm \to \mu^\pm + N)$ for mass 10 MeV. Ref. [121] presents 90% confidence-level exclusion limits in the mixing-squared vs. mass plane; we convert these into limits on $\text{BR}(\pi^\pm \to \mu^\pm + N)$ [122], obtaining a bound of $6.9 \times 10^{-6}$ for mass 30 MeV. These two bounds are model-independent and are plotted as shaded areas in the right plot of figure 3, using $\text{BR}(\tilde{\chi}^0_1 \to \text{signature}) = 1$. One easily observes that FASER and FASER2 are sensitive to large parts of the parameter space beyond these existing bounds.

Figure 4 shows the sensitivity reach of FASER2 for the benchmark scenario B1 of table 1, but allowing the neutralino mass to vary and fixing $\lambda^P = \lambda^D$. The gray band, as before, indicates the low-energy constraints on the couplings. Since FASER does not provide any new sensitivity reach beyond these low-energy bounds, we do not depict it in the plot. We see a maximum sensitivity is reached for neutralino masses between 10 and 35 MeV. In general, the sensitivity reach in the couplings improves; for instance, as we increase the neutralino mass up to 30 MeV, and again in the region beyond 35 MeV. Heavier neutralinos translate into shorter lifetimes, and hence more decays of the neutralino within the volume of FASER2, cf. eq. (2.5). There is, however, a sharp drop in sensitivity near the neutralino mass, $m_{\tilde{\chi}^0_1} \sim 34$ MeV. This is the threshold for the decay of charged pions to neutralinos accompanied by a muon. The branching fraction of the neutral pion mode, $\pi^0 \to \tilde{\chi}^0_1 + \nu_\mu$, is suppressed by the short lifetime.

In figures 5 and 6 (left), we display the sensitivity plots for benchmark scenario B2. The left plot of figure 5 shows that now both FASER and FASER2 have significant new
reach in the couplings, $\lambda^P$ and $\lambda^D$, for $m_{\tilde{\chi}_1^0} = 75$ MeV. The right plot in figure 5 looks similar to the right plot of figure 3, but it is now a plot of the branching ratio product $\text{BR}(K^\pm \to \tilde{\chi}_1^0 + \mu^\pm) \times \text{BR}(\tilde{\chi}_1^0 \to \text{signature})$ versus the neutralino decay length, $c\tau$, and we have considered heavier LLP masses: 75 and 300 MeV. Similar to B1, we overlap these results with existing bounds from searches for HNLs from kaon two-body decays, $K^\pm \to \mu^\pm + N$. Refs. [123, 124] give the strongest current limits for HNL masses of 75 MeV and 300 MeV. Ref. [123] is a peak search and bounds the HNL mixing-squared with the muon neutrino at $1.3 \times 10^{-5}$ for HNL mass of 75 MeV. Ref. [124] searches for invisible particles and places a limit of $10^{-8}$ on the mixing-squared. We convert these limits into bounds on $\text{BR}(K^\pm \to \mu^\pm + N)$ and obtain $10^{-5}$ and $2.4 \times 10^{-8}$, respectively. We depict these bounds in the right plot of figure 5, using $\text{BR}(\tilde{\chi}_1^0 \to \text{signature}) = 1$. In
Figure 8. As in figure 4 but for the benchmark scenario in B4 while varying the neutralino mass. The sensitivity reach corresponds to FASER (solid line) and FASER2 (dashed line).

particularly, since ref. [124] is a missing-energy search, the limits are valid only for proper decay length larger than 15 m, as explicitly mentioned in the abstract of the paper. We find that FASER and FASER2 can probe the BR-product down to values significantly lower than these current limits.

In the neutralino mass-coupling plane plot of figure 6 (left), we observe that the sensitivity at FASER2 is reduced for lower masses compared to that in benchmark scenario B1, but, unlike the pion case, is robust over the entire higher-mass regime, right up to the kaon mass. This is because even though the charged decay production mode is kinematically forbidden beyond $m_{\tilde{\chi}_1^0} = m_{K^\pm} - m_{\mu^\pm} \approx 390$ MeV — leading to the small bump in the plot at that point — the neutral decay mode has a comparable branching fraction.

The two plots of $\lambda^P/m^2_{\text{SUSY}}$ vs. $\lambda^D m^2_{\text{SUSY}}$ and branching ratio product vs. $c\tau$ for B3 with neutralino mass of 200 MeV, are very similar to figure 5 for B2 and are hence not shown explicitly here. In figure 6 (right), we present the sensitivity plot for scenario B3 for $\lambda_{112} = \lambda^P = \lambda^D = \lambda_{322}$, as a function of the neutralino mass. We note that for $m_{\tilde{\chi}_1^0} \gtrsim 2m_{\mu}$, the decay mode $\tilde{\chi}_1^0 \rightarrow \mu^\pm \bar{\nu}_\mu + \text{c.c.}$ opens up, leading to additional visible events. These are not included in figure 6 (right).

In figures 7 and 8, we show the corresponding plots for the benchmark involving both $D$ and $K$ mesons — scenario B4. One interesting feature in the mass-coupling plane is the kink in the sensitivity curve near the kaon mass, $m_{K^0} \sim 497$ MeV. This is because for $m_{\tilde{\chi}_1^0} \gtrsim m_{K^0}$, the kaon production mode, $K^0/\bar{K}^0 \rightarrow \tilde{\chi}_1^0 + \nu_\mu/\bar{\nu}_\mu$ switches off. Since kaons are more abundant than $D$ mesons at the LHC, this leads to reduced sensitivity beyond this threshold. For larger masses, the neutralino has decay modes into $K^0$ and $K^*0$ plus neutrino opening up at the respective mass thresholds; as before, we only count the photon events as signal. There is an additional interesting feature for this scenario: The sensitivity curve starts to ‘turn back’ in the large coupling, large mass region indicating a drop in sensitivity. This happens as the lifetime of the neutralino becomes too short, decaying well before reaching FASER or FASER2; this effect is made more acute by the additional
Figure 9. The left plot is as in figure 4 but for the single coupling benchmark scenario in B5 while varying the neutralino mass. The right plot shows the sensitivity reach in $\text{BR}(D^\pm \rightarrow \tilde{\chi}_1^0 + \mu^\pm) \times \text{BR}(\tilde{\chi}_1^0 \rightarrow \text{signature})$ as a function of the neutralino decay length, $c\tau$, for $m_{\tilde{\chi}_1^0} = 500$ MeV. The sensitivity reaches correspond to FASER (solid line) and FASER2 (dashed line).

decay modes that open up. To our knowledge, there are no existing searches for HNLs in $D^\pm \rightarrow \mu^\pm + N$ decays; therefore, we do not place any existing bounds in the right plot of figure 7.

Figure 9 shows the sensitivity reach for scenario B5, where only one RPV coupling is switched on (thus, there is no coupling-coupling plane plot). The left plot shows the sensitivity reach of FASER and FASER2 in the mass-coupling plane. Once again, for the plots, we do not consider the additional decay modes into $\eta, \eta'$ or $\phi$ plus neutrino that open up at the respective mass thresholds, for our signature. The large mass, large coupling regime has reduced sensitivity for the same reason stated above. The right plot then contains the sensitivities of FASER and FASER2 to the decay branching fraction product as a function of $c\tau$ for $m_{\tilde{\chi}_1^0} = 500$ MeV. For this plot, as in B4, there is no existing limit that can be obtained from an HNL search in $D^\pm \rightarrow \mu^\pm + N$ decays.

Finally, figures 10 and 11 contain the sensitivity plots for benchmark scenario B6, involving $B$ mesons. We observe in the right plot of figure 10, that the reaches in the branching ratio product are weaker than those in the previous scenarios, because the production rates of the $B$ mesons are orders-of-magnitude smaller than those of the lighter mesons at the LHC. As in the previous two benchmark scenarios, we do not find an existing search for HNLs in $B^\pm \rightarrow \tau^\pm + N$ decays that could be recast into bounds relevant to us, in the BR-product vs. $c\tau$ plane. In figure 11, as before, we see that the sensitivity in the mass-coupling plane is robust across the kinematically allowed mass range since the neutral mode is available even when the charged mode is switched off for $m_{\tilde{\chi}_1^0} \geq m_K^\pm - m_{\tau^\pm}$. This time the drop in sensitivity in the large mass, large coupling region is milder compared to the previous two cases as there are no additional decay modes contributing.
7 Conclusions

We have estimated the sensitivity reach of FASER and FASER2 at the LHC, for a sub-GeV bino-like lightest neutralino decaying to a photon in the context of R-parity-violating supersymmetry. With R-parity broken, the lightest neutralino can be lighter than the GeV scale, or even massless, without violating observational and experimental bounds, as long as it decays. Assuming the lightest neutralino is the lightest supersymmetric particle (LSP), it can be produced from rare meson decays, and can decay to a photon and a neutrino, via certain RPV couplings.

In the sub-GeV mass range, since the RPV couplings are required to be small by existing constraints, the bino-like neutralino is expected to have a long lifetime. Once produced from
mesons’ decays at the LHC, it is highly boosted in the very forward direction. Therefore, we have chosen to focus on the experimental setups of FASER and FASER2 for observing the single-photon signature resulting inside the detector decay volumes.

We have considered several theoretical benchmark scenarios and performed Monte Carlo simulations in order to determine the projected sensitivity reaches at FASER and FASER2. Our study has found that these experiments are sensitive to parameter space beyond the current bounds by orders of magnitude.

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