The left-right supersymmetric option at a high-energy upgrade of the LHC

Mariana Frank,1,∗ Benjamin Fuks,2,† Katri Huitu,3,‡ Subhadeep Mondal,3,§ Santosh Kumar Rai,4,¶ and Harri Waltari5,∗∗

1Department of Physics, Concordia University, 7141 Sherbrooke St. West, Montreal, QC, Canada H4B 1R6
2Sorbonne Université, CNRS, Laboratoire de Physique Théorique et Hautes Énergies, LPTHE, F-75005 Paris, France, & Institut Universitaire de France, 103 boulevard Saint-Michel, 75005 Paris, France
3Department of Physics and, Helsinki Institute of Physics, P. O. Box 64, FI-00014 University of Helsinki, Finland
4Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, HBNI, Chhatnag Road, Jhusi, Prayagraj 211019, India
5Department of Physics and Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom, & Department of Particle Physics, Rutherford Appleton Laboratory, Didcot OX11 0QX, United Kingdom

(Dated: March 20, 2020)

We investigate the possibility that a minimal realization of left-right supersymmetry can be reachable at a high-energy upgrade of the LHC, expected to operate at a center-of-mass energy of 27 TeV. This minimal scenario has a relatively light SU(2)R doubly-charged Higgs boson, which could decay dominantly into tau-lepton pairs. We explore the associated signals comprised of at least three hadronically-decaying taus, or with at least two hadronic taus and one same-sign-same-flavor charged lepton pair. Our analysis shows that the former signature is challenging to use for getting handles on the signal due to the large corresponding background, and that the latter one can lead to a handful of new physics events in an almost background-free environment. We find that the first signal is more promising and likely to be observed at an early stage of the operations of a 27 TeV upgrade of the LHC.

I. INTRODUCTION

During the last years of operation at the Large Hadron Collider (LHC), no significant deviation from the Standard Model (SM) predictions has been found. Still, the SM as it stands is incomplete as it fails to explain, for instance, neutrino masses, dark matter and the baryon-antibaryon asymmetry of the Universe. However, new particles and interactions have failed (so far) to materialize at the LHC. Of all the candidates for physics beyond the SM, weak scale supersymmetry [1, 2] is amongst the most promising ones. It associates one partner of opposite statistics with each of the SM degrees of freedom and unifies the Poincaré symmetry with the internal gauge symmetries. This setup leads to an elegant solution to the divergences in L-loop corrections [14–16], or by spontaneous R-parity breaking [17]. The most appealing option consists of the second one, in which loop corrections stabilize the

gauge symmetry group [6–8]. In the supersymmetric context, in which both supersymmetry and left-right motivations are combined, the same extended gauge symmetry reason leads additionally to the automatic absence of any R-parity-violating interaction. This therefore prevents the proton from being unstable and guarantees a viable dark matter candidate as the LSP. However, the simplest left-right supersymmetric realizations often predict upper bounds for particle masses that do not easily agree with the latest non-observations of any hint for new physics in LHC data, at least when tree-level calculations are in order. Already the first proposal for a left-right supersymmetric (LRSUSY) model hence suggested an SU(2)R charged gauge boson with a mass satisfying mW_R ≲ 1 TeV [9], which is today largely ruled out by the results of the LHC experiments [10, 11]. This has consequently led to the development of LRSUSY models featuring an extended Higgs sector, so that the SU(2)R boson masses could be pushed to a higher scale [12].

In this case, left-right symmetry breaking is often minimally built through SU(2)_R scalar triplets featuring two neutral, one singly-charged and one doubly-charged Higgs degrees of freedom. At tree-level, the latter generally acquires a vacuum expectation value (VEV) at the global minimum of the potential that corresponds to a configuration that is lower in energy than the one in which only the neutral states develop a VEV. This problem can be cured by invoking large contributions either from non-renormalizable operators [6, 8, 13] or through loop corrections [14–16], or by spontaneous R-parity breaking [17]. The most appealing option consists of the second one, in which loop corrections stabilize the
charge-conserving vacuum [16]. In this setup, the model turns out to be quite predictable, at least for what concern the properties of the $W_R$ boson (and in particular its mass).

On different grounds, imposing a dark matter candidate with the right features, that for instance leads to a relic density in agreement with Planck data, further restricts the possibilities for the particle spectrum as the LSP has to lie within some mass range below 1 TeV [18, 19]. With this phenomenologically constrained version of LRSUSY at hand, we investigate in this work whether the future high-luminosity phase of the LHC (HL-LHC) or its proposed 27 TeV energy upgrade, the so-called high-energy LHC (HE-LHC) [20], could observe or rule out the model once and for all.

The rest of this work is organized as follows. In Sec. II, we briefly describe our theoretical framework, detailing in particular how a LRSUSY discovery at the HL-LHC could not happen. In Sec. III, we focus on this most pessimistic case and design a set of representative benchmark scenarios. We then demonstrate how the HE-LHC could provide handles on the model. We summarize and conclude in Sec. IV.

II. LEFT-RIGHT SUPERSYMMETRY

Left-right symmetric models [3–5] are based on the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The matter sector is defined by three families of left- and right-handed quark and lepton supermultiplets,

\[
\begin{align*}
Q_L &= \begin{pmatrix} u_L^T \cr 3_3 \end{pmatrix}, \\
Q_R &= \begin{pmatrix} d_R^T \cr 3_3 \end{pmatrix}, \\
L_L &= \begin{pmatrix} e_L^T \cr 1_1 \end{pmatrix}, \\
L_R &= \begin{pmatrix} e_R^T \cr 1_1 \end{pmatrix},
\end{align*}
\]

where we include in our notation the representations of the various fields under the LRSUSY gauge group, with the $U(1)_{B-L}$ charge given as a subscript. Compared with the usual Minimal Supersymmetric Standard Model (MSSM), the spectrum features a right-handed neutrino field $N$ (as part of the $SU(2)_R$ lepton doublet $L_R$), so that Dirac neutrino mass term are allowed in the superpotential. The Higgs sector of the model is quite rich and includes an $SU(2)_R$ Higgs triplet to break the $SU(2)_R \times U(1)_{B-L}$ symmetry, its $SU(2)_L$ counterpart to preserve left-right parity, as well as a pair of $SU(2)_L \times SU(2)_R$ Higgs bidoublets that are required to generate all SM fermion masses. Neutrino masses are hence generated through a combination of the Type-II [21–25] and Type I [22, 26–31] seesaw mechanisms, after the breaking of the left-right symmetry. The Higgs sector moreover includes an extra gauge singlet that allows for the shift of the left-right symmetry breaking scale well beyond the TeV regime. The Higgs superfield content and the associated representations under the LRSUSY gauge group are hence summarized as

\[\Phi_a = \left( \frac{\phi_{a1}^+}{\phi_{a2}^0} \phi_{a3}^0 \phi_{a2}^- \right) \sim (1, 2, 2^*)_{0},\]

\[\Delta_L = \left( \frac{\lambda_L^0}{\lambda_L^0} \right) \sim (1, 3, 1)_{-2},\]

\[\delta_L = \left( \frac{\delta_L^0}{\delta_L^0} \right) \sim (1, 3, 1)_{2},\]

\[\Delta_R = \left( \frac{\lambda_R^0}{\lambda_R^0} \right) \sim (1, 1, 3)_{-2},\]

\[\delta_R = \left( \frac{\delta_R^0}{\delta_R^0} \right) \sim (1, 1, 3)_{2},\]

\[S \sim (1, 1, 1)_{0}.
\]

The model Lagrangian includes, on top of usual gauge-invariant kinetic terms for all fields, supersymmetric interaction terms originating from the superpotential $W$ and a soft supersymmetry-breaking Lagrangian. The superpotential reads

\[W = Q_L^T Y_Q^{(i)} Q_R + L_L^T Y_L^{(i)} L_R + L_L^T h_{LL} \delta L L_L + L_R^T h_{RR} \delta R R_R + \lambda_L S \, Tr[\Delta_L \delta L] + \lambda_R S \, Tr[\Delta_R \delta R] + \lambda_S S \, Tr[\tau_2 \Phi_1^T \tau_2 \Phi_2] + \lambda_{S'} S' \, Tr[\tau_2 \Phi_1^T \tau_2 \Phi_2] \]

where the Yukawa couplings $Y_Q, L$ and $h_{LL, RR}$ are $3 \times 3$ matrices in the flavor space, and the $\lambda$ and $\xi_F$ parameters are associated with the various Higgs(ino) self-interactions. Moreover, in our notation, $\tau_2$ denotes the second Pauli matrix and we omit all indices for clarity. We derive from the form of the superpotential the corresponding soft terms, to which one should add scalar and gaugino mass terms. Further details of the model can be found in refs. [18, 32].

The LRSUSY spectrum is largely determined by the scale of the left-right symmetry breaking. While current experimental limits imply that this scale has to lie in the multi-TeV range, it must at the same time satisfy an upper limit, so that $\langle \Delta_R^0 \rangle \sim v_R \in [10, 15]$ TeV when all other parameters are held fixed [16]. Larger $v_R$ values would indeed destabilize the charge-conserving vacuum configuration, as the scalar potential terms

\[\left| \xi_F + \lambda_L Tr[\Delta_L \delta L] + \lambda_R Tr[\Delta_R \delta R] + \lambda_S Tr[\tau_2 \Phi_1^T \tau_2 \Phi_2] + \lambda_{S'} Tr[\tau_2 \Phi_1^T \tau_2 \Phi_2] + 3 \lambda_S S'^2 \right|^2 \]

would lift the energy of the corresponding ground state. However, if $v_R$ and $\langle S \rangle = v_S / \sqrt{2}$ are of the same order of magnitude and $\lambda_R$ and $\lambda_S$ are of opposite signs, this contribution can be kept small. In this small part of the parameter space, one may have values of $v_R$ clearly greater.
than 15 TeV, so that one gets a decoupling limit in which many particles become heavy due to the large $v_R$ and $v_S$ VEVs, unless one invokes unforeseen fine-tuning effects. In this limit, the $SU(2)_R$ gauge sector is easily beyond the reach of the LHC, so that the light part of the entire LRSUSY spectrum may only include an $SU(2)_R$ doubly-charged Higgs state, as its mass is loop-suppressed relatively to the scale of left-right symmetry breaking, in addition to the LSP, the dark matter candidate.

In the following, we assume that the LSP belongs to the bidoublet higgsino state, so that extra neutralinos and charginos are expected to be not too heavy as well. In this setup, a relic density in agreement with the observations can be achieved if the higgsino spectrum lies below 1 TeV. The only HL-LHC handle on the model is then comprised of a signature made of a multi-leptonic system and missing energy that emerges from resonant higgsino production (via the $SU(2)_R$ gauge sector) [19]. Other cosmologically-favored options could feature the lightest right-handed sneutrino as a dark matter candidate. The spectrum does not significantly differ here from the higgsino dark matter case, as to explain the non-observation of any signal in the direct detection experiments and to avoid dark matter over-abundance, one needs to rely on the existence of co-annihilation channels [19]. This leads to a spectrum including a rather light sneutrino in addition to a set of light higgsino states. If the $W_R$ gauge boson is too heavy to be produced at the LHC, the sneutrino signal will only emerge through multi-leptonic higgsino cascade decays, as in the former higgsino dark matter case. If the $W_R$ boson lies instead within the reach of the HL-LHC, we should expect multi-leptonic signals to originate from its decays into sleptons [18].

The light doubly-charged Higgs state could then be the best probe of the model, as suggested by recent studies on the sensitivity of future colliders in the framework of Type-II seesaw models [33, 34]. However, in LRSUSY and in contrast with Type-II seesaw scenarios, the couplings of the Higgs triplet are not determined by the neutrino masses and mixings, as the neutrino mass generation mechanism is comprised of a combination of Type-I and Type-II seesaws. This means that the $SU(2)_R$ doubly-charged Higgs boson could dominantly decay into a pair of same-sign tau leptons, taming the sensitivity of the usually considered same-sign electron or muon channels. In addition, as the doubly-charged Higgs state belongs to an $SU(2)_R$ triplet and not an $SU(2)_L$ triplet as in the Type-II case, the production mechanisms are different.

In the rest of this work, we focus on such LRSUSY scenarios in which the Yukawa couplings responsible for the neutrino masses obey the same generational hierarchy as for the other SM fermions, i.e., the coupling to the third generation is the largest. The $SU(2)_R$ doubly-charged Higgs boson then features a main decay mode into tau leptons, and it could be light without violating any LHC constraint. Moreover, the lightest superpartners are the neutral and charged bidoublet higgsinos, the lightest one being neutral and a viable dark matter candidate. Such an LRSUSY configuration would be experimentally the most challenging to observe, and therefore deserves the present dedicated study.

### III. COLLIDER PHENOMENOLOGY

#### III.1. Generalities

As detailed in the previous section, the class of LR-SUSY scenarios that we consider focuses on setups in which the $SU(2)_R$ doubly-charged Higgs boson ($H_1^{±±}$) is relatively light [18, 19]. In the minimal version of the model, its mass cannot be much larger than 1 TeV [16, 35]. The $H_1^{±±}$ boson can thus in principle be reachable at the 14 TeV LHC, even without the need of a very high luminosity. Currently, the most stringent mass limits impose that $m_{H_1^{±±}} \gtrsim 800 \text{ GeV}$. 

$$m_{H_1^{±±}} \gtrsim 800 \text{ GeV}. \quad (5)$$

This however requires dominant $H_1^{±±}$ decays into same-sign electron and/or muon pairs. Conversely, the constraints become much weaker as soon as the $H_1^{±±}$ state dominantly decays into a pair of tau leptons [37],

$$m_{H_1^{±±}} \gtrsim 500 \text{ GeV}. \quad (6)$$

Under these circumstances, even HL-LHC operations are unlikely to be effective in probing heavier $H_1^{±±}$ bosons, especially if their mass gets close to 1 TeV. This is the type of complicated scenarios that we are interested in this work. We hence aim at estimating the prospects of a potential high-energy upgrade of the LHC at a center-of-mass energy of 27 TeV to probe scenarios in which $H_1^{±±} \rightarrow \tau^± \tau^±$ is the dominant decay mode.

We consider the all-hadronic channel for which no dedicated study exists. In our analysis, we first design a signal region SR1 targeting a signature arising from the production of a pair of $H_1^{±±}$ bosons decaying each into a di-tau system. In other words, we focus on a final state featuring four hadronic tau leptons $\tau_h$. We however only select events in which three hadronic taus have been reconstructed, which guarantees both sufficient signal rates after accounting for imperfect tau reconstruction, and a not too overwhelming SM background. Moreover, we additionally require some missing transverse energy as it would stem from the tau decays.

Furthermore, we also explore how the subleading $H_1^{±±}$ branching ratio into same-sign electron or muon pairs could be used to get an extra handle on the signal, as the corresponding signature is cleaner to reconstruct. We define a second signal region SR2 in which one selects events featuring a same-sign lepton (i.e., electron or muon) pair and a di-tau system.

We therefore consider the following two signal regions,

**SR1:** At least $3\tau_h$, some $E_T$;  
**SR2:** At least $2\tau_h$, 1 same-sign lepton pair, some $E_T$. 


In order to generate signal events at the HE-LHC for given benchmark scenarios, we make use of the LRSUSY model implementation in the SARAH package \[16, 38\]. This allows for both the computation of the particle spectrum and branching ratios through SPHENO 3 \[39\], and for the translation of the model into the UFO format \[40\] so that hard-scattering event generation could be achieved with MG5\_AMC@NLO \[41\]. For both signal and background, we convolute leading-order matrix elements with the NNPDF 2.3 set of parton distribution functions \[42\] and match the resulting events with the parton showering and hadronization infrastructure of PYTHIA 8 \[43\]. Subsequently, we implement the simulation of the detector response with DELPHES 3 \[44\], that relies on the anti-\textit{k}_T algorithm \[45\] as implemented in the FASTJET package \[46\] for event reconstruction, and use the default ATLAS detector parameterization. For a better description of the background, we merge multipartonic matrix elements according to the MLM procedure \[47\], unless stated otherwise. Finally, in order to obtain cosmologically-favored benchmark scenarios (see Sec. III.2), we estimate the dark matter properties of our scenarios with the MadDM package \[48\].

### III.2. Benchmark scenarios

In order to assess the sensitivity of the HE-LHC to the considered class of LRSUSY scenarios, we select three representative benchmark configurations BP1, BP2 and BP3 featuring a different SU(2)_R doubly-charged Higgs boson mass. The LSP is enforced to be part of the higgsino bidoublets and its mass and properties are constrained to lead to a cosmologically viable dark matter candidate. Its relic density is required to agree with latest Planck data \[49\], which can be achieved thanks to multiple co-annihilation processes among the six nearly mass-degenerate higgsino-like neutralino and chargino states \[19\]. The light part of the benchmark scenario spectra is presented in Table I, together with the relevant branching ratios of the H^{±±}_1 state.

### III.3. SR1: Investigating the triple-tau signature

Our SR1 signal region focuses on events featuring at least three reconstructed hadronic tau leptons and missing energy. SM backgrounds can arise from QCD multi-jet processes and single boson production in association with jets (V+jets, with V ≡ W^{±±}, Z) when light jets are mis-tagged as hadronic taus. We study, in our analysis, the dependence of the results on the tau mis-tagging rate, that is allowed to vary between 1% and 2%. This choice stems from the absence of any realistic mis-tagging rate expectation for a potential future proton-proton collider at a center-of-mass energy of 27 TeV \[26\], and has been inspired by LHC capabilities for a tau-tagging efficiency of 70% \[50, 51\]. Moreover, one expects subleading background contributions originating from Zh, hh, VV and VVV production in association with jets. For each component of the background and all signal samples, the tau-tagging performances are included in the evaluation of the rates presented in the following.

In order to avoid excessive multi-jet and V+jets background event generation (to get numerical Monte Carlo uncertainties under control after accounting for the small mis-tagging rates), we make use of the properties of the signal in which quite hard tau jets with a large transverse momentum are required to fake the hadronic activity defined as the sum of the transverse momenta of all reconstructed jets to satisfy |\mathbf{p}_T| > 40 GeV.

In the multi-jet case, we increase this selection criterion to |\mathbf{p}_T| > 150 GeV for the three hardest jets and impose that the hadronic activity defined as the sum of the transverse momenta of all reconstructed jets is greater than 1200 GeV. In practice, we separately generate hard-scattering events for the pp → jjj and pp → jjjj sub-processes and match them with parton showers, the di-jet case being ignored given the need for the events selected in our analysis to feature at least three hard jets faking tau leptons. Whilst in principle the overlap between the tri-jet and tetra-jet samples should be removed by an appropriate merging procedure, we instead directly com-

| mass (GeV) | BP1 | BP2 | BP3 |
|-----------|-----|-----|-----|
| m_{W_R}   | 6550.5 | 7486.2 | 7486.2 |
| m_{Z'}    | 10993.2 | 12563.6 | 12563.6 |
| m_{H^±±}  | 875.0 | 1016.4 | 780.9 |
| m_{χ^0_1} | 878.4 | 803.7 | 770.1 |
| m_{χ^0_2} | 889.7 | 812.1 | 777.7 |
| m_{χ^0_3} | 893.0 | 815.3 | 780.7 |
| m_{χ^0_4} | 895.6 | 817.6 | 782.9 |
| m_{χ^0_5} | 1032.2 | 1043.5 | 1048.0 |
| m_{χ^0_6} | 886.4 | 809.3 | 775.1 |
| m_{χ^±_1} | 893.5 | 815.7 | 781.2 |
| m_{χ^±_2} | 7413.2 | 8412.9 | 5619.2 |
| \text{BR}(H^±± \rightarrow τ^±τ^±) | 0.92 | 0.92 | 0.92 |
| \text{BR}(H^±± \rightarrow ℓ^±ℓ^±) | 0.08 | 0.08 | 0.08 |

TABLE I. Relevant masses defining our three benchmark scenarios, given in GeV, and H^{±±}_1 branching ratios. The table includes the masses of the W_R and Z' extra gauge bosons, the one of the H^{±±}_1 state, those of the lightest neutralino χ^0_i (with i = 1, 2, 3, 4), singly-charged charginos χ^±_i (with i = 1, 2) and doubly-charged chargino χ^{±±}_1.
bining those two samples for simplicity. This is expected to yield a (conservative) over-estimation of the multi-jet background.

For $V+$jets event generation, we similarly separately consider the $V+jj$ and $V+jjj$ subprocesses and conservatively directly combine them. The overlap between the two samples is however expected to be small, as any extra radiation originating from a $V+jj$ final state is generally soft. All other background components are treated as described in Sec. III.1.

In the considered SR1 signal region, one preselects events by requiring that they feature at least three hadronic tau ($\tau_i$ (or jets faking taus) with a transverse momentum

$$p_T(\tau_i) > 150 \text{ GeV}. \quad (7)$$

We moreover veto the presence of any charged lepton with a $p_T$ greater than 20 GeV and of any $b$-tagged jet with a $p_T$ greater than 25 GeV. Moreover, any system comprised of any two hadronic tau ($\tau_i, \tau_j$) must have an invariant mass satisfying

$$m_{\tau_i\tau_j} > 200 \text{ GeV for } i,j = 1,2,3. \quad (8)$$

After this preselection, we impose that the scalar sum of the transverse momentum of the three leading taus (including the potential jets faking taus) satisfies

$$H_T = \sum_{i=1}^{3} p_T(\tau_i) > 1200 \text{ GeV}, \quad (9)$$

and require that the missing transverse energy fulfills

$$E_T > 150 \text{ GeV}. \quad (10)$$

Finally, in order to ensure a better rejection of the multi-jet background, we require the event sphericity $S$ [52], computed from the three selected taus, to be larger than 0.3,

$$S > 0.3. \quad (11)$$

The corresponding cut-flow is provided, for the three benchmark points and all the components of the background, in Table II. As the tau-jets arising from the on-shell decays of weak gauge and Higgs bosons are typically softer than in the case of our signal, the corresponding multi-boson backgrounds are drastically rejected already by our preselection cuts. The dominant background components are therefore driven by jets faking hadronic tau leptons. These can however be significantly reduced by the three extra cuts of Eq. (9), Eq. (10) and Eq. (11), for a moderate signal efficiency of about 50%. As shown in Table III, about 6 ab$^{-1}$, 12.4 ab$^{-1}$ and 3.7 ab$^{-1}$ of data would be needed for a 3$\sigma$ statistical significance in the BP1, BP2 and BP3 cases, respectively, three luminosities that are well within the reach of the HE-LHC, which is indeed expected to collect a luminosity as high as 15 ab$^{-1}$.

Given the low sensitivity of the previously described cut-based analysis, we implement a complementarily multi-variate analysis based on a boosted decision tree (BDT). We first preselect events as described in the cut-and-count analysis and impose the $H_T$ selection of Eq. (9). We then rely on seven variables as inputs for our BDT classifier, namely the invariant mass of any system made of any pair of two of the three leading taus $m_{\tau_i\tau_j}$ (with $i,j = 1,2,3$), the missing transverse energy $E_T$, and the three variables that are used in the cut-based analysis.

| Process     | Generator | Preselection | $H_T > 1200 \text{ GeV}$ | $E_T > 150 \text{ GeV}$ | $S > 0.3$ |
|-------------|-----------|--------------|---------------------------|-------------------------|-----------|
| BP1         | 0.251     | 0.020        | 0.013                     | 0.010                   | 0.006     |
| BP2         | 0.125     | 0.011        | 0.008                     | 0.007                   | 0.004     |
| BP3         | 0.430     | 0.031        | 0.017                     | 0.014                   | 0.008     |

| Process     | Scenario | Cut-and-count | Multivariate |
|-------------|----------|---------------|--------------|
| BP1         |          | 6.0           | 1.95         |
| BP2         |          | 12.38         | 3.91         |
| BP3         |          | 3.66          | 1.14         |

TABLE II. Cross sections, in fb, for the three benchmark signals and the different components of the SM background at various stages of the SR1 analysis. We present generator-level total rates (second column), as well as the reminding cross sections after the preselection (third column) and the various analysis cuts of Eq. (9), Eq. (10) and Eq. (11) (last three columns). We consider a 70% tau-tagging efficiency for a mis-tagging rate of 1%. Results for a mis-tagging rate of 2% are given between parentheses (where relevant).

TABLE III. Required luminosities, in ab$^{-1}$, to obtain a 3$\sigma$ statistical significance with our cut-and-count (second column) and multi-variate (third column) analysis, for the three considered benchmark scenarios.
the effective mass \( M_{\text{eff}} \) defined as

\[
M_{\text{eff}} = \sum_{i=1,3} p_T(\tau_i) + E_T, \tag{12}
\]

the angular separation in azimuth between the missing transverse momentum \( p_T \) and the leading tau \( \Delta \phi(p_T, p_T(\tau_1)) \) and the sphericity \( S \). We extract the HE-LHC sensitivity by using the XGBOOST toolkit [53], employing the gradient boosting method with a number of 1000 trees, a maximum depth of 4 and a learning rate of 0.01. Our training set includes 80% of the generated events, the remaining events being then used for testing purposes. Moreover, we have verified that our results were not affected by the addition of an extra variable to the list of BDT inputs, both in the context of basic quantities like the transverse momentum of any of the three leading taus or their azimuthal separation, and in the context of more complex observables like the planarity \( \Delta \) [52], the missing energy significance \( E_T/\sqrt{\not{E}_T} \), the \( E_T/M_{\text{eff}} \) ratio, or the relative \( p_T \) of the third tau with respect to the two leading ones \( y_{23} \),

\[
y_{23} = \frac{p_T^2(\tau_3)}{[p_T(\tau_1) + p_T(\tau_2)]^2}. \tag{13}
\]

Including any extra variable on top of the seven above-mentioned ones has indeed only been found to increase the correlations. While the relative relevance of the variables varies from benchmark to benchmark, the level of correlations is maintained in each case to a low level, as illustrated in Fig. 1 for the BP1 scenario.

As evident from Fig. 2 for the BP1 scenario, our BDT classifier is quite efficient in identifying signal events whilst rejecting background events, as signal efficiencies larger than 80% can be obtained together with high background rejection rates. In the upper panel of the figure, we present the receiver operating characteristic (ROC) curve of the algorithm. The area under the curve (AUC) is a good indicator of the algorithm effectiveness as it should approach 1 for well-performing methods. It is found to be of about 0.92 for the BP1 scenario, whilst similar results are obtained for the BP2 and BP3 scenarios, with AUC of 0.88 and 0.82 respectively. In the lower panel of Fig. 2, we present the signal and background distributions (in the case of the BP1 scenario) according to the BDT classifier, which reinforces the illustration of its good discriminating power. This largely impacts the sensitivity of the HE-LHC to the model, the resulting significance factors being importantly improved relatively to the cut-based analysis. This is complementarily demonstrated in Table III in which the HE-LHC luminosity needed to reach a 3\( \sigma \) statistical significance is presented for each of our three representative scenarios. In all three cases, this luminosity is found three times smaller than for the cut-based analysis.
The cuts of the SR2

\textbf{TABLE IV.} Fiducial signal cross sections after imposing all the three chosen benchmark points, after imposing the SR2.

| Benchmark | SR2 cross section (fb) |
|-----------|------------------------|
| BP1       | 0.003                  |
| BP2       | 0.002                  |
| BP3       | 0.005                  |

The same-flavor lepton pair originating from the p as two same-sign electrons or muons with taus with a transverse momentum p\_T ensures that there is not much background surviving the selection. In our SR2 analysis, we select events containing at least two hadronic taus with a transverse momentum p\_T > 150 GeV, as well as two same-sign electrons or muons with p\_T > 50 GeV. We moreover veto the presence of b-jets and constrain the invariant mass of the system made of the two hardest taus to be larger than 200 GeV. With these criteria, all the SM background is rendered negligible, for the signal rates presented in Table IV in the context of the three considered benchmark scenarios. We equivalently obtain an almost background-free environment for a handful of signal events for the expected 15 ab\(^{-1}\) luminosity of the HE-LHC.

As a consequence, the SR2 analysis may provide a complementary handle on the signal, relatively to the SR1 one, with an enormous advantage in the fact that the doubly-charged Higgs-boson mass can be reconstructed from the analysis of the properties of the pair of same-sign leptons (that moreover consists in a smoking gun signal for a doubly-charged Higgs boson). This mass reconstruction can be quite precise despite the detector effects, as illustrated in Fig. 3. In this figure, we present the invariant-mass spectrum of the di-lepton-pair for all three benchmark scenarios. In each case, the distribution exhibits a clear peak located right at the doubly-charged Higgs-boson mass.

Apart from the two signal regions defined in this work, one can also build an analysis targeting a signature stemming from the production of multiple higgsino states. Altogether, the considered class of scenarios features spectra in which four neutralino and two chargino states are nearly mass degenerate and sitting at the lighter part of the LRSUSY model particle spectrum. However, as a consequence, any SM jets and/or leptons that may arise from higgsino production and decay is expected to be too soft to be detected. The standard probe to such scenarios consists thus of the monojet channel, that is at least promising in MSSM-like scenarios. In this last case, higgsino masses of 500 GeV can be reached at the HE-LHC [54]. Owing to a richer higgsino sector in the LRSUSY framework, one can expect a larger signal cross section for a fixed mass, so that heavier higgsino states could conversely be probed. However, the lower limit on the higgsino mass so that we could obtain a viable dark matter candidate is of about 700 GeV [19]. The corresponding monojet rates have been found to be substantially too low to lead to any observable signal with 15 ab\(^{-1}\) of HE-LHC luminosity.

\section*{IV. SUMMARY AND CONCLUSION}

We have analyzed the sensitivity of a high-energy upgrade of the LHC expected to operate at a center-of-mass energy of 27 TeV (\textit{i.e.}, the HE-LHC) to a class of left-right supersymmetric scenarios favored by dark matter, with a relic density as measured by the Planck collaboration originating from the co-annihilations of multiple higgsino states of about 700 GeV. In a minimal LR-SUSY setup where the stabilization of the vacuum occurs through radiative corrections, the doubly-charged Higgs-boson mass is loop-suppressed relatively to the rest of the SU(2)\(_R\) sector, so that we expect it to be the first manifestation of the model at colliders. As previous experimental limits on this state are obtained by assuming a pair-production mode followed by a decay into a same-sign pair of electrons or muons, we focus on the still phe-

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Distribution in the invariant mass of the same-sign-same-flavor lepton pair originating from the H\(_{\pm}^+\pm\) decay for the three chosen benchmark points, after imposing the SR2 selection.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.6\textwidth]{figure3.png}
\caption{Distribution in the invariant mass of the same-sign-same-flavor lepton pair originating from the H\(_{\pm}^+\pm\) decay for the three chosen benchmark points, after imposing the SR2 selection.}
\end{figure}
nomenologically viable option where the doubly-charged Higgs boson decays almost exclusively into tau leptons. We explore this possibility and estimate the chances to observe such an LRSUSY scenario at the HE-LHC.

We consider in particular two signatures, namely a first one where the pair-produced doubly-charged Higgs states decay into tau leptons, and a second one in which one of them is assumed to decay into an electron or a muon pair. For the former case, we focus on the production of at least three hard hadronic tau leptons. The SM background is mostly comprised of multi-jet and vector-boson-plus-jets events in which QCD jets are faking tau leptons. We have implemented a series of cuts which not only lead to a good significance at high luminosities, but that can also serve as a basis for a multi-variate analysis relying on boosted decision trees. In this case, three times less luminosity could be required to observe a 3$\sigma$ signal (which would occur thus at an early HE-LHC stage). For our latter analysis, we position ourselves in an almost background-free environment by investigating a di-tau plus same-sign di-lepton signature. Whereas signal cross sections are expected to be small, the large HE-LHC luminosity makes this analysis a nice complementary handle on the previously considered LRSUSY signal. Moreover, the presence of the two first or second generation leptons guarantees the reconstruction of the doubly-charged Higgs boson mass. In contrast, any signal that could arise from the large number of light higgsino states has been found not to give any hope for a discovery, as the corresponding monojet cross sections are way too small.

In summary, in the minimal left-right supersymmetry setup in which one relies on radiative corrections to stabilize the vacuum configuration, we expect the first signal of new physics to arise from the doubly-charged Higgs boson. However, it may hidden as decaying mainly into a pair of same-sign tau leptons. We have shown that at the HE-LHC, we may see a signal for doubly-charged Higgs boson masses ranging up to around 1 TeV, this upper limit being theoretically motivated as it requires to push the left-right symmetry breaking scale in a way that is only possible in a very small part of the parameter space. In addition to the doubly-charged Higgs boson, the model includes a dark matter candidate that cannot be too heavy. The latter will however hardly provide any clear signal without the help of the $SU(2)_R$ gauge sector, as shown in previous work.

If the doubly-charged Higgs boson fails to materialize at the HE-LHC, we may conclude that the LRSUSY vacuum has likely to be stabilized by some other mechanism than by loop corrections. Models employing an even larger Higgs sector or those breaking the $R$-parity spontaneously may have a tree-level contribution to the doubly-charged Higgs boson mass, which could thus be larger.

**ACKNOWLEDGEMENTS**

MF thanks NSERC for support through grant number SAP105354. SKR acknowledges financial support from the Department of Atomic Energy, Government of India, for the Regional Centre for Accelerator-based Particle Physics (RECAPP), Harish-Chandra Research Institute. HW acknowledges the support from Magnus Ehrnrooth Foundation and STFC Rutherford International Fellowship (funded through MSCA-COFUND-FP, grant number 665593).

[1] H. P. Nilles, Phys.Rept. **110**, 1 (1984).
[2] H. E. Haber and G. L. Kane, Phys.Rept. **117**, 75 (1985), UM-HE-TH-83-17, SCIPP-85-47.
[3] J. C. Pati and A. Salam, Phys. Rev. **D10**, 275 (1974), [Erratum: Phys. Rev.D11,703(1975)].
[4] R. N. Mohapatra and J. C. Pati, Phys. Rev. **D11**, 566 (1975).
[5] R. N. Mohapatra and J. C. Pati, Phys. Rev. **D11**, 2558 (1975).
[6] R. N. Mohapatra and A. Rasin, Phys. Rev. Lett. **76**, 3490 (1996), arXiv:hep-ph/9511391 [hep-ph].
[7] R. Kuchimanchi, Phys. Rev. Lett. **76**, 3486 (1996), arXiv:hep-ph/9511376 [hep-ph].
[8] R. N. Mohapatra and A. Rasin, Phys. Rev. **D54**, 5835 (1996), arXiv:hep-ph/9604445 [hep-ph].
[9] M. Cvetic and J. C. Pati, Phys. Lett. **135B**, 57 (1984).
[10] A. M. Sirunyan et al. (CMS), Phys. Lett. **B769**, 520 (2017), [Erratum: Phys. Lett.B772,882(2017)], arXiv:1611.03568 [hep-ex].
[11] M. Aaboud et al. (ATLAS), Phys. Rev. **D96**, 052004 (2017), arXiv:1703.09127 [hep-ex].
[12] M. Cvetic, Phys. Lett. **164B**, 55 (1985).
[13] C. S. Aulakh, A. Melfo, and G. Senjanovic, Phys. Rev. **D57**, 4174 (1998), arXiv:hep-ph/9707256 [hep-ph].
[14] K. S. Babu and R. N. Mohapatra, Phys. Lett. **B668**, 404 (2008), arXiv:0807.0481 [hep-ph].
[15] M. Frank and B. Korutlu, Phys. Rev. **D83**, 073007 (2011), arXiv:1101.3601 [hep-ph].
[16] L. Basso, B. Fuks, M. E. Krauss, and W. Porod, JHEP **07**, 147 (2015), arXiv:1503.08211 [hep-ph].
[17] R. Kuchimanchi and R. N. Mohapatra, Phys. Rev. **D48**, 4352 (1993), arXiv:hep-ph/9306290 [hep-ph].
[18] M. Frank, B. Fuks, K. Huitu, S. K. Rai, and H. Waltari, JHEP **05**, 015 (2017), arXiv:1702.02112 [hep-ph].
[19] A. Chatterjee, M. Frank, B. Fuks, K. Huitu, S. Mondal, S. K. Rai, and H. Waltari, Phys. Rev. **D99**, 035017 (2019), arXiv:1810.03891 [hep-ph].
[20] A. Abada et al. (FCC), Eur. Phys. J. ST **228**, 1109 (2019).
[21] M. Magg and C. Wetterich, Phys. Lett. **94B**, 61 (1980).
[22] J. Schechter and J. W. F. Valle, Phys. Rev. **D22**, 2227 (1980).
[23] T. P. Cheng and L.-F. Li, Phys. Rev. **D22**, 2860 (1980).
[24] R. N. Mohapatra and G. Senjanovic, Phys. Rev. D23, 165 (1981).
[25] G. Lazarides, Q. Shafi, and C. Wetterich, Nucl. Phys. B181, 287 (1981).
[26] P. Minkowski, Phys. Lett. 67B, 421 (1977).
[27] T. Yanagida, Proceedings: Workshop on the Unified Theories and the Baryon Number in the Universe: Tsukuba, Japan, February 13-14, 1979, Conf. Proc. C7902131, 95 (1979).
[28] M. Gell-Mann, P. Ramond, and R. Slansky, Supergravity Workshop Stony Brook, New York, September 27-28, 1979, Conf. Proc. C790927, 315 (1979), arXiv:1306.4669 [hep-th].
[29] S. L. Glashow, Cargese Summer Institute: Quarks and Leptons Cargese, France, July 9-29, 1979, NATO Sci. Ser. B 61, 687 (1980).
[30] R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980), [,231(1979)].
[31] R. E. Shrock, Phys. Rev. D24, 1232 (1981).
[32] A. Alloul, M. Frank, B. Fuks, and M. Rausch de Traubenberg, JHEP 10, 033 (2013), arXiv:1307.5073 [hep-ph].
[33] T. B. de Melo, F. S. Queiroz, and Y. Villamizar, Int. J. Mod. Phys. A34, 1950157 (2019), arXiv:1909.07429 [hep-ph].
[34] R. Padhan, D. Das, M. Mitra, and A. Kumar Nayak, (2019), arXiv:1909.10495 [hep-ph].
[35] K. S. Babu and A. Patra, Phys. Rev. D93, 055030 (2016), arXiv:1412.8714 [hep-ph].
[36] M. Aaboud et al. (ATLAS), Eur. Phys. J. C78, 199 (2018), arXiv:1710.09748 [hep-ex].
[37] C. Collaboration (CMS), (2017).
[38] F. Staub, Comput. Phys. Commun. 185, 1773 (2014), arXiv:1309.7223 [hep-ph].
[39] W. Porod and F. Staub, Comput. Phys. Commun. 183, 2458 (2012), arXiv:1104.1573 [hep-ph].
[40] C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer, and T. Reiter, Comput. Phys. Commun. 183, 1201 (2012), arXiv:1108.2040 [hep-ph].
[41] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, JHEP 07, 079 (2014), arXiv:1405.0301 [hep-ph].
[42] R. D. Ball et al. (NNPDF), JHEP 04, 040 (2015), arXiv:1410.8849 [hep-ph].
[43] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaitre, A. Mertens, and M. Selvaggi (DELPHES 3), JHEP 02, 057 (2014), arXiv:1307.6346 [hep-ex].
[44] M. Cacciari, G. P. Salam, and G. Soyez, JHEP 04, 063 (2008), arXiv:0802.1189 [hep-ph].
[45] M. Cacciari, G. P. Salam, and G. Soyez, Eur. Phys. J. C72, 1896 (2012), arXiv:1111.6007 [hep-ph].
[46] M. L. Mangano, M. Moretti, F. Piccinini, and M. Trecani, JHEP 01, 013, arXiv:hep-ph/0611229 [hep-ph].
[47] F. Ambrogi, C. Arina, M. Backovic, J. Heisig, F. Maltoni, L. Mantani, O. Mattelaer, and G. Mohlabeng, (2018), arXiv:1804.00944 [hep-ph].
[48] P. A. R. Ade et al. (Planck), Astron. Astrophys. 594, A13 (2016), arXiv:1502.01589 [astro-ph.CO].
[49] The ATLAS collaboration, ATL-PHYS-PUB-2019-033.
[50] A. M. Sirunyan et al. (CMS), JINST 13, P10005 (2018), arXiv:1809.02816 [hep-ex].
[51] C. Chen, Phys. Rev. D85, 034007 (2012), arXiv:1112.2567 [hep-ph].
[52] T. Chen and C. Guestrin, (2016), 10.1145/2939672.2939785, arXiv:1603.02754 [cs.LG].
[53] T. Han, S. Mukhopadhyay, and X. Wang, Phys. Rev. D98, 035026 (2018), arXiv:1805.00015 [hep-ph].