

Exploring Z' and right-handed neutrinos in the $B - L$ symmetric SM at the Large Hadron Collider

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(Received 13 August 2025; accepted 10 December 2025; published 9 January 2026)

We study the collider phenomenology of the $B - L$ extension of the Standard Model (BLSM), focusing on the production and decay of a heavy neutral gauge boson (Z') at the Large Hadron Collider (LHC). In this framework, the Z' can decay into pairs of heavy right-handed neutrinos (ν_R), which subsequently decay into charged leptons and W bosons. These processes give rise to three distinctive final states: (i) two leptons plus four jets ($2\ell + 4j$), (ii) four leptons plus missing transverse energy ($4\ell + \text{MET}$), and (iii) three leptons plus two jets and MET ($3\ell + 2j + \text{MET}$). To enhance signal sensitivity and suppress Standard Model backgrounds, we employ multivariate analysis techniques based on boosted decision trees (BDTs), as well as selection optimizations using the XGBOOST framework. The classifiers are trained on kinematic observables sensitive to the masses of the Z' and ν_R . We demonstrate that all three final states offer significant discovery potential for both the Z' and heavy ν_R at the High-Luminosity LHC. Our results highlight the testability of the BLSM at current and future collider experiments, and provide a promising avenue for probing the origin of neutrino masses and the baryon asymmetry of the Universe.

DOI: [10.1103/x6dp-4tzs](https://doi.org/10.1103/x6dp-4tzs)

I. INTRODUCTION

The Standard Model (SM) of particle physics has been highly successful in explaining a wide range of phenomena, but it falls short in addressing certain critical issues. Notably, it cannot explain neutrino oscillations, which indicate that neutrinos have mass [1–5], nor the observed baryon asymmetry in the universe, where matter significantly outweighs antimatter. These deficiencies suggest that an extension of the SM is required to account for these phenomena.

One promising extension involves the introduction of right-handed neutrinos (RHN), which can naturally explain the small but nonzero masses of neutrinos through the seesaw

mechanism. Additionally, extending the gauge symmetry of the SM provides a framework to incorporate new physics without fundamentally altering its successful aspects. Specifically, the $B - L$ (baryon minus lepton number) extension of the SM (BLSM) [6–10] offers a minimal and elegant approach to address these shortcomings.

The minimal extension is achieved by augmenting the SM gauge group with an additional $U(1)_{B-L}$ symmetry, leading to the gauge group:

$$G_{B-L} = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}. \quad (1.1)$$

The BLSM extension introduces new particles and interactions that contribute to the SM phenomenology, particularly in the neutrino and baryon sectors.

- (1) Right-handed neutrinos: The model introduces three RHN ν_R^i (where $i = 1, 2, 3$), each with a $B - L$ charge of -1 . These particles do not interact with the SM weak forces but are crucial for generating neutrino masses via the seesaw mechanism.
- (2) New gauge boson Z' : The extension includes an extra gauge boson, denoted as Z' , corresponding to the $B - L$ gauge symmetry. This new force carrier could have observable signatures at high-energy

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colliders such as the LHC, providing a direct test of the extended model.

- (3) Additional scalar field χ : A new scalar field χ , which is a singlet under the SM gauge group but carries a $B - L$ charge of $+2$, is introduced. This scalar plays a crucial role in breaking the $U(1)_{B-L}$ symmetry, analogous to how the Higgs field breaks the electro-weak symmetry in the SM.

In this paper, we investigate the experimental signatures of these new particles, particularly the RHN and the Z' boson, at the Large Hadron Collider (LHC). This question has been addressed previously using different methods and processes, as discussed in [11,12]. However, in this work, we present a distinct computational approach, based on machine learning techniques (XGBOOST, BDT) and consider different production processes, in such a way to justify a fresh investigation of these signatures, not only updating the constraints but also exploring the discovering potential even within a well-studied theoretical framework. The Z' boson, for instance, can manifest as a resonance in dilepton or dijet final states, serving as a potential smoking gun for physics beyond the SM. Similarly, RHNs open up novel decay channels and distinct collider signatures, offering valuable insights into the origin of neutrino masses and the baryon asymmetry of the universe. We emphasize that these signatures not only probe the existence of these particles but also serve as critical tests of the BLSM, seeking to address several fundamental questions in particle physics. Specifically, we examine four distinct signals arising from Z' production at the LHC, where the Z' decays into two RHNs, (ν_R). These decay channels lead to the following final states:

- (i) Two leptons (same sign or opposite sign), four jets.
- (ii) Four leptons and missing energy.
- (iii) Three leptons, two jets, and missing energy.
- (iv) One lepton, multiple jets, and missing energy.

The first three channels arise from the decay of two RHNs into a W boson and a lepton, with the W boson subsequently decaying either into a lepton and ν_L or into quarks. The fourth channel occurs when one RHN decays into a W boson and a lepton, with the W decaying into jets,

while the second RHN decays into a Z boson and ν_L , and the Z decays into two ν_L or two jets.

The decay width of the RHN into a Z boson and ν_L is significantly smaller than its decay into a W boson and a charged lepton. As a result, the production cross section for the fourth channel is substantially lower compared to the other channels. Moreover, this channel suffers from considerable SM background. Therefore, our analysis in the subsequent sections will focus exclusively on the first three channels. We employ boosted decision tree (BDT) techniques [13–16] to optimize the selection criteria and enhance the sensitivity to the Z' and RHN signals, ensuring effective discrimination between potential new physics signatures and SM background processes. In addition, we utilize the XGBOOST algorithm (extreme gradient boosting) [13–16] to further refine the event selection and to identify the most discriminating kinematic variables that separate the signal from the background.

The structure of the paper is as follows: In Sec. II, we present a concise review of the BLSM, with emphasis on the Z' boson and the RHN. We discuss the origin of their masses from the spontaneous breaking of the $B - L$ symmetry and summarize the key interactions relevant to our analysis. This section establishes the theoretical framework for the collider signatures explored in the subsequent sections. Section III outlines the computational methodology, including the application of BDT techniques and the implementation of the XGBOOST algorithm to optimize signal-background discrimination. In Sec. IV, we analyze the four distinct final-state signatures arising from Z' production at the LHC, focusing on their kinematic features and discovery potential. Finally, Sec. V presents our conclusions and discusses future directions.

II. Z' AND ν_R IN THE BLSM

As discussed above, the minimal BLSM is based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$. The Lagrangian for this $B - L$ extension is expressed as follows:

$$\begin{aligned} \mathcal{L}_{B-L} = & i\bar{l}D_\mu\gamma^\mu l + i\bar{e}_R D_\mu\gamma^\mu e_R + i\bar{\nu}_R D_\mu\gamma^\mu \nu_R + i\bar{Q}D_\mu\gamma^\mu Q + i\bar{d}_R D_\mu\gamma^\mu d_R + i\bar{u}_R D_\mu\gamma^\mu u_R \\ & - \frac{1}{4}G_{\mu\nu}^\alpha G^{\mu\nu\alpha} - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}C_{\mu\nu}C^{\mu\nu} + (D_\mu\phi)^\dagger(D_\mu\phi) + (D_\mu\chi)^\dagger(D_\mu\chi) \\ & - m_1^2\phi^\dagger\phi - m_2^2\chi^\dagger\chi - \lambda_1(\phi^\dagger\phi)^2 - \lambda_2(\chi^\dagger\chi)^2 - \lambda_3(\phi^\dagger\phi)(\chi^\dagger\chi) - \lambda_e\bar{l}\phi e_R - \lambda_\nu\bar{l}\tilde{\phi}\nu_R \\ & - \frac{1}{2}\lambda_{\nu_R}\bar{\nu}_R^c\chi\nu_R - \lambda_d\bar{Q}\phi d_R - \lambda_u\bar{Q}\tilde{\phi}u_R + \text{H.c.}, \end{aligned} \quad (2.1)$$

where $C_{\mu\nu} = \partial_\mu C_\nu - \partial_\nu C_\mu$ represents the field strength tensor of the $U(1)_{B-L}$ gauge field. The covariant derivative D_μ is given by

$$D_\mu = \partial_\mu - ig_s T^a G_\mu^a - ig_2 A_\mu^a \tau^a - ig' Y B_\mu - i(\tilde{g}Y + g'' Y_{B-L})C_\mu, \quad \tau^a = \frac{\sigma^a}{2}, \quad \text{and } \sigma^a \text{ are Pauli matrices.} \quad (2.2)$$

TABLE I. The $SU(3)_C \times SU(2)_L \times U(1)_Y$ and $U(1)_{B-L}$ quantum numbers of the particles in the model.

	l	ν_R	e_R	Q	u_R	d_R	ϕ	χ
$SU(3)_C \times SU(2)_L \times U(1)_Y$	$(1, \mathbf{2}, -1/2)$	$(1, \mathbf{1}, 0)$	$(1, \mathbf{1}, -1)$	$(3, \mathbf{2}, 1/6)$	$(3, \mathbf{1}, 2/3)$	$(3, \mathbf{1}, -1/3)$	$(1, \mathbf{2}, 1/2)$	$(1, \mathbf{1}, 0)$
$U(1)_{B-L}$	-1	-1	-1	1/3	1/3	1/3	0	2

Here, g'' , also called g_{B-L} , is the coupling constant of the $U(1)_{B-L}$ gauge group, and Y_{B-L} denotes the $B-L$ quantum numbers of the particles involved, which are listed in Table I.

To analyze the breaking of $B-L$ and electroweak symmetries, we consider the most general Higgs potential that remains invariant under these symmetries. The potential is expressed as

$$V(\phi, \chi) = m_1^2 \phi^\dagger \phi + m_2^2 \chi^\dagger \chi + \lambda_1 (\phi^\dagger \phi)^2 + \lambda_2 (\chi^\dagger \chi)^2 + \lambda_3 (\chi^\dagger \chi)(\phi^\dagger \phi), \quad (2.3)$$

where $\lambda_3 > -2\sqrt{\lambda_1 \lambda_2}$ and $\lambda_1, \lambda_2 \geq 0$ to ensure that the potential is bounded from below. These conditions represent the stability requirements of the potential. Furthermore, to prevent $\langle \phi \rangle = \langle \chi \rangle = 0$ from being a local minimum, we assume that $\lambda_3^2 < 4\lambda_1 \lambda_2$. Similar to the usual Higgs mechanism in the SM, the vacuum expectation values (vevs) v for ϕ and v' for χ can only emerge if the squared mass terms are negative, i.e., $m_1^2 < 0$ and $m_2^2 < 0$.

It is worth noting that the most general kinetic Lagrangian of the BLSM allows for gauge kinetic mixing between $U(1)_Y$ and $U(1)_{B-L}$. This mixing can be absorbed through a redefinition of the covariant derivative where, before the transformation of the gauge coupling matrix, the covariant derivative can be defined as

$$i(D_\mu - \partial_\mu) = g_{YY} Y A_\mu^1 + g_{YB} Y A_\mu^2 + g_{BY} Y_{B-L} A_\mu^1 + g_{BB} Y_{B-L} A_\mu^2, \quad (2.4)$$

where A_μ^1 and A_μ^2 are gauge fields for $U(1)_Y$ and $U(1)_{B-L}$, respectively, so we can use the next transformation to absorb the mixing between $U(1)_Y$ and $U(1)_{B-L}$, and get Eq. (2.2):

$$G = \begin{pmatrix} g_{YY} & g_{YB} \\ g_{BY} & g_{BB} \end{pmatrix} \Rightarrow \tilde{G} = \begin{pmatrix} g' & \tilde{g} \\ 0 & g'' \end{pmatrix}, \quad (2.5)$$

where

$$g' = \frac{g_{YY}g_{BB} - g_{YB}g_{BY}}{\sqrt{g_{BB}^2 + g_{BY}^2}}, \quad g'' \equiv g_{B-L} = \sqrt{g_{BB}^2 + g_{BY}^2},$$

$$\tilde{g} = \frac{g_{YB}g_{BB} + g_{BY}g_{YY}}{\sqrt{g_{BB}^2 + g_{BY}^2}}. \quad (2.6)$$

Here, g' is the $U(1)_Y$ gauge coupling, g_2 the gauge coupling of $SU(2)_L$, and g_s the gauge coupling of $SU(3)_C$; we

assume gauge coupling unification at the grand unified theory scale.

In this basis, after $B-L$ and electroweak symmetry breaking, the masses of the Z and Z' bosons are given by

$$M_Z^2 = \frac{1}{4}(g^2 + g_2^2)v^2, \quad M_{Z'}^2 = 4g''^2 v'^2 + \frac{1}{4}\tilde{g}^2 v^2. \quad (2.7)$$

Furthermore, the mixing angle (θ') between the Z and Z' bosons is given by

$$\tan 2\theta' = \frac{2\tilde{g}\sqrt{g^2 + g_2^2}}{\tilde{g}^2 + 16(\frac{v'}{v})^2 g''^2 - g_2^2 - g^2}. \quad (2.8)$$

From Eq. (2.7), this implies that $v' \gtrsim \mathcal{O}(\text{TeV})$, with v of order SM vev. In models with an extra Abelian gauge symmetry $U(1)_{B-L}$ and kinetic mixing between the hypercharge gauge field B_μ and the new gauge boson B'_μ , the physical coupling of the Z' boson to SM fermions is modified. The effective coupling of Z' to a fermion f is given by [17,18]

$$g_f^{Z'} = g_{B-L} \cdot Q_{B-L}^f + \tilde{g} \cdot Y^f. \quad (2.9)$$

For the benchmark point in Table II and considering charged leptons (e, μ), one gets the effective leptonic coupling

$$Q_{B-L} = -1, \quad Y = -1 \Rightarrow g_\ell^{Z'} = 0.13. \quad (2.10)$$

The cross section for the process $pp \rightarrow Z' \rightarrow \ell^+ \ell^-$ is approximately proportional to

$$\sigma(pp \rightarrow Z') \times \text{BR}(Z' \rightarrow \ell^+ \ell^-) \propto \left(\sum_q |g_q^{Z'}|^2 \right) \cdot \frac{|g_\ell^{Z'}|^2}{\sum_f |g_f^{Z'}|^2}. \quad (2.11)$$

Thus, a smaller $g_\ell^{Z'}$ leads to a suppressed dilepton signal. For $g_\ell^{Z'} = 0.13$, the current LHC bounds (e.g., from ATLAS and CMS Run 2) allow

$$M_{Z'} \gtrsim 2.5\text{--}3 \text{ TeV}. \quad (2.12)$$

TABLE II. Parameters of the benchmark point in the BLSM model.

$M_{Z'}$	$M_{\nu_{R,1}}$	$g'' \equiv g_{B-L}$	$\tilde{g}$
3 TeV	420 GeV	0.42	-0.55

In addition, after the $U(1)_{B-L}$ symmetry breaking [19], the Yukawa interaction term $\lambda_{\nu_R} \bar{\nu}_R^c \nu_R$ generates a mass for the RHN, given by

$$M_R = \frac{1}{2\sqrt{2}} \lambda_{\nu_R} v'. \quad (2.13)$$

Moreover, electroweak symmetry breaking results in the Dirac neutrino mass term

$$m_D = \frac{1}{\sqrt{2}} \lambda_\nu v. \quad (2.14)$$

Thus, the mass matrix for the left- and right-handed neutrinos is

$$\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}. \quad (2.15)$$

Since M_R is proportional to v' and m_D is proportional to v , it follows that $M_R > m_D$. Diagonalizing this mass matrix yields the following masses for the light (ν_L) and heavy (ν_H) neutrinos, respectively:

$$m_{\nu_L} = -m_D M_R^{-1} m_D^T, \quad (2.16)$$

$$m_{\nu_H} = M_R. \quad (2.17)$$

Thus, the $B-L$ gauge symmetry provides a natural framework for the seesaw mechanism. However, the scale of $B-L$ symmetry breaking, v' , remains arbitrary. As in [19], v' is assumed to be of order TeV, making M_R also of that scale.

The Z' boson can be produced in hadron colliders, such as the LHC, through its couplings to quarks. While it can decay into various final states [20–22], we focus on the scenario where the Z' decays into a pair of RHNs. This scenario is particularly interesting because the subsequent decay of the neutrinos into a lepton and a W boson can lead to a final state with two same-sign leptons, when the W boson decays into jets.

The cross section for the process $pp \rightarrow Z' \rightarrow \nu_R \nu_R$ can be expressed as

$$\sigma(pp \rightarrow Z' \rightarrow \nu_R \nu_R) = \int dx_1 dx_2 f_q(x_1, Q^2) f_{\bar{q}}(x_2, Q^2) \hat{\sigma}(\hat{s}), \quad (2.18)$$

where $f_q(x_1, Q^2)$ and $f_{\bar{q}}(x_2, Q^2)$ are the parton distribution functions (PDFs) for the quark and antiquark inside the protons [23,24], evaluated at momentum fractions x_1 and x_2 , and scale Q^2 . The $\hat{\sigma}(\hat{s})$ is the partonic cross section for

$q\bar{q} \rightarrow Z' \rightarrow \nu_R \nu_R$, with $\hat{s} = x_1 x_2 s$ the partonic center-of-mass energy squared, where s is the total hadronic center-of-mass energy squared. The partonic cross section is given by

$$\hat{\sigma}(\hat{s}) = \frac{4\pi^2}{\hat{s}} \frac{\Gamma(Z' \rightarrow q\bar{q}) \Gamma(Z' \rightarrow \nu_R \nu_R)}{(M_{Z'}^2 - \hat{s})^2 + M_{Z'}^2 \Gamma_{Z'}^2}, \quad (2.19)$$

where $M_{Z'}$ and $\Gamma_{Z'}$ are the mass and total decay width of the Z' boson. The partial decay widths of the Z' boson, $\Gamma(Z' \rightarrow q\bar{q})$ and $\Gamma(Z' \rightarrow \nu_R \nu_R)$, are given by

$$\Gamma(Z' \rightarrow q\bar{q}) = \frac{n_q}{72\pi} g'^2 M_{Z'}, \quad (2.20)$$

$$\Gamma(Z' \rightarrow \nu_R \nu_R) = \frac{n_{\nu_R}}{24\pi} g'^2 M_{Z'}, \quad (2.21)$$

where $n_q = 6$, representing the six active quark flavors, as the Z' mass is generally greater than twice the top quark mass, and $n_{\nu_R} = 3$.

Looking at Eq. (2.7), we see that varying the couplings ($g_{B-L} \equiv g', \tilde{g}$) changes the mass $m_{Z'}$, unless one recompensates this by varying the vev v' . From Eqs. (2.9), (2.11), and (2.21), it follows that the total production cross section depends on these couplings through the effective fermion couplings $g_f^{Z'}$ in such a way that the resulting event yield scales approximately as $\sigma(pp \rightarrow Z') \times \text{BR}(Z' \rightarrow \nu_R \nu_R) \propto (g_f^{Z'} g_{B-L})^2$. The statistical significance, proportional to $\frac{S}{\sqrt{S+B}}$ with $S(B)$ denoting the signal (background), thus grows roughly linearly with $|g_f^{\text{eff}}| \simeq |g_f^{Z'} g_{B-L}|$. In the present benchmark, with $g_{B-L} = 0.42$ and $\tilde{g} = -0.55$, the production is dominated by the quark channels producing Z' , due to summing and color factors, while the leptonic branching ratios remain smaller. Moderate variations of $(g_{B-L}, \tilde{g})$ within the phenomenologically allowed region affect the total rate but do not qualitatively change the conclusions.

III. BDT METHOD AND SIGNATURE ANALYSIS

In this study, we focus on the production of a heavy neutral gauge boson, Z' , at the LHC and its subsequent decay into a pair of RHNs (ν_R). Each ν_R further decays into a lepton and a W boson, following the chain

$$pp \rightarrow Z' \rightarrow \nu_R \nu_R, \quad \nu_R \rightarrow \ell W. \quad (3.1)$$

Depending on the decay modes of the W bosons (hadronic or leptonic), different final states arise. We classify the possible signatures into three categories:

- (1) FS1: 2ℓ (same or opposite sign) + 4 jets
- (2) FS2: 4ℓ + MET
- (3) FS3: 3ℓ + 2 jets + MET

In our analysis, we restrict leptons to electrons and muons and consider light jets originating from the hadronization of

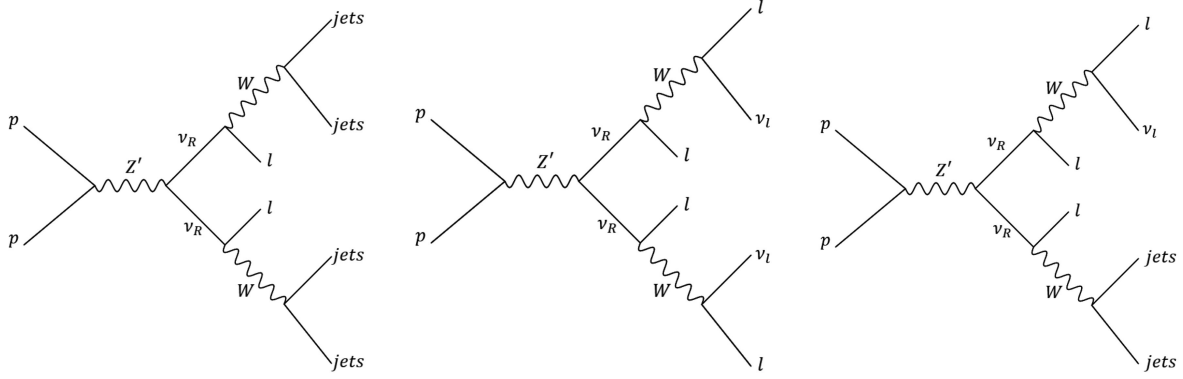


FIG. 1. Representative Feynman diagrams of the processes explored in this study.

u , d , s , and c quarks. The missing transverse energy (MET) arises from neutrinos that escape detection, resulting in an imbalance in the transverse momentum.

Figure 1 illustrates the representative Feynman diagrams corresponding to the three final states discussed above.

In the first final state, where both W bosons decay hadronically, we obtain two same-sign or opposite-sign leptons along with four jets. In the remaining two final states, the W bosons decay fully leptonically and semi-leptonically, respectively. As a result, same-sign charges for whole output leptons are not present, and the final states are characterized by significant MET originating from the undetected neutrinos.

We now discuss the computational setup employed in this study. The BLSM model is implemented in SARAH-4.15.1 [25], which is used to generate the Feynman rules of the model. The resulting model files are then interfaced with SPheno-4.0.5 [26] to compute the particle mass spectra and full numerical value for the model at low energy.

A benchmark point is selected that satisfies current experimental constraints from LHC searches for Z' , RHNs (ν_R), additional Higgs bosons, and measurements of the properties of the observed 125 GeV Higgs boson. The parameters corresponding to the chosen benchmark are listed in Table II.

To evaluate the LHC sensitivity for this benchmark, we simulate proton-proton collisions at a center-of-mass energy of 14 TeV. Event generation for both the signal and background processes is performed using MadGraph5_aMC@NLO [27] with its built-in Pythia event generator for radiation, fragmentation, and hadronization effects, where the BLSM UFO model files are generated via the SARAH framework. Detector effects are simulated using Delphes-3.5 [28], which reconstructs detector-level objects, including leptons, jets, and MET, forming the observable final states.

In classification problems such as distinguishing BLSM signal events from SM backgrounds, traditional cut-based analyses rely on placing thresholds on individual kinematic variables. However, it is often difficult to identify a single variable with strong discriminating power, and such

analyses are limited when the signal-background separation in multidimensional phase space is nonrectangular. In these cases, exploiting correlations among multiple variables becomes essential. To address this, we employ the BDT algorithm to analyze the three LHC signatures.

The BDT algorithm extends the cut-based approach by evaluating multiple variables simultaneously and optimizing a corresponding combination for signal-background classification. Instead of discarding events based on a single cut, the BDT recursively selects the most discriminating variable and cut value at each node, splitting events into branches to build a decision tree. This process continues until misclassification is minimized. We provide the BDT with a set of kinematic variables such as the transverse momenta of final-state objects or the invariant mass of lepton pairs as input. The algorithm learns the correlations among these variables for signal and background events and assigns a score between -1 (background-like) and $+1$ (signal-like). A cut on this BDT score is then used to separate the signal from the background.

In this study, we employ the TMVA framework [29] within ROOT [30] to train a BDT classifier. In the following section, we present a detailed analysis of each of the three final states, including the kinematic variables used for training, their correlations, the model parameters, and the resulting classification performance. The datasets for all final states were randomly divided into independent training (70%) and testing (30%) samples using the TMVA::DataLoader. Overtraining checks were performed through the Kolmogorov-Smirnov (KS) test, which yielded p -values larger than 0.1 in all channels, confirming the absence of overtraining. The classifier performance was quantified by the area under the ROC curve (AUC), showing excellent separation between the signal and the background for all channels: $AUC_{2\ell+4j}^{(OS)} = 0.949$, $AUC_{2\ell+4j}^{(SS)} = 0.963$, $AUC_{4\ell+MET} = 0.986$, and $AUC_{3\ell+2j+MET} = 0.985$.

In addition, we utilize the XGBOOST algorithm, which simultaneously evaluates multiple kinematic variables to

optimize event classification. It constructs decision trees by recursively selecting the most discriminating variables and cut values to separate the signal from the background and iteratively refines these using the gradient boosting framework applied to the input feature set.

IV. Z' AND ν_R SIGNALS AT THE LHC

In this section, we detail the analysis strategy for the three final states resulting from the BLSM benchmark point considered in this study. A point to mention is that all signal and background samples, including processes with possible fake or nonprompt leptons, were generated using the MadGraph5_aMC@NLO—Pythia8—Delphes chain. No data-driven scaling factors were introduced, as the study is purely phenomenological and focuses on the statistical discovery potential at the HL-LHC, rather than on replicating the full complexity of an experimental analysis.

A. FS1: $2\ell + 4j$

1. $2\ell(\text{opposite sign}) + 4j$

The dominant SM backgrounds for this final state are dileptonic $t\bar{t}$ production with two additional jets ($t\bar{t} + 2j$) and the inclusive $2\ell + 4j$ production. Diboson ($VV + 2j$) and triboson (VVV) processes, where V denotes a W or Z

boson, can also contribute to this signature. However, in the BLSM signal, the two leptons originate from the decay of a 420 GeV RHN (ν_R), which is itself produced in the decay of a heavy Z' boson with mass 3 TeV. As a result, the leptons carry large transverse momenta, and the dilepton system exhibits a large invariant mass.

We find that imposing the cuts $p_T^{\ell_1}, p_T^{\ell_2} > 200$ GeV and $M_{\ell\ell} > 250$ GeV significantly reduces the diboson and triboson backgrounds while only marginally affecting the signal efficiency. The $t\bar{t} + 2j$ and $2\ell + 4j$ backgrounds exhibit longer tails in these distributions, resulting in residual contributions after these cuts. For completeness, we can consider the background from $W + j$ s, where the W boson produces one genuine lepton and the other lepton arises from a misidentified jet (fake lepton). We have identified such processes in our simulation, in line with what is done experimentally on the CMS and ATLAS results. We generate the background samples using MadGraph5_aMC@NLO, applying the following parton-level cuts:

$$p_T^{\ell} > 200 \text{ GeV}, \quad p_T^j > 50 \text{ GeV}, \quad M_{\ell\ell} > 250 \text{ GeV}. \quad (4.1)$$

Following parton showering and detector simulation, we apply the following baseline event selection criteria:

$$\begin{aligned} n_{\ell} &= 2, & p_T^{\ell} &> 200 \text{ GeV}, & |\eta^{\ell}| &< 2.5, & M_{\ell\ell} &> 250 \text{ GeV}, \\ n_j &\geq 4, & p_T^j &> 50 \text{ GeV}, & |\eta^j| &< 2.5. \end{aligned} \quad (4.2)$$

Here, n_{ℓ} and n_j represent the number of selected leptons and jets, respectively.

The cross sections for the signal and background processes used in this analysis are summarized in Table III.

To enhance the signal-to-background discrimination, we train a BDT classifier and the XGBOOST model using the following input observables:

- (i) Number of leptons in the event, n_{ℓ} .
- (ii) Electric charges of the leptons, q^{ℓ} .
- (iii) Transverse momenta of leptons and jets, $p_T^{\ell,j}$.
- (iv) Invariant mass of the dilepton system, $M_{\ell\ell}$.
- (v) Invariant masses of dijet combinations, M_{jj} .

TABLE III. Cross sections for the signal and background processes considered in the $2\ell(\text{opposite sign}) + 4j$ final-state analysis.

Process	Cross section (fb)
Signal ($pp \rightarrow Z' \rightarrow 2l + 4j$)	0.18
Background 1 ($t\bar{t}(\text{leptonic}) + 2j$)	23.00
Background 2 ($2\ell + 4j$)	0.67
Background 3 ($W + j$ s + fake lepton)	782.5

(vi) Invariant masses of dijet pairs with either lepton, $M_{\ell jj}$, sensitive to the ν_R mass.

(vii) Invariant mass of the complete $2\ell + 4j$ system, $M_{2\ell 4j}$, sensitive to the Z' mass.

Figure 2 displays the ranking of various features based on their importance in the classification decision, as quantified by the F score—a measure of each variable's relative significance. Among the most important features, we observe that the invariant masses of the jet pairs, $m_{j_{1,3}}$ and $m_{j_{1,2}}$, as well as the transverse momentum of the leading lepton, $p_T^{\ell_1}$, play the most prominent roles.

In Fig. 3, we present the results of the BDT training and testing sample for the signal and background processes. The left panel shows the distribution of the classifier output (BDT score) for signal and background events. We observe that background events predominantly populate the negative side of the distribution, while signal events peak at positive BDT scores, illustrating the separation power of the classifier.

The right panel displays the receiver operating characteristic (ROC) curve, which quantifies the classifier's performance. For a signal efficiency of 80%, the BDT achieves a background rejection rate of approximately 95%. This

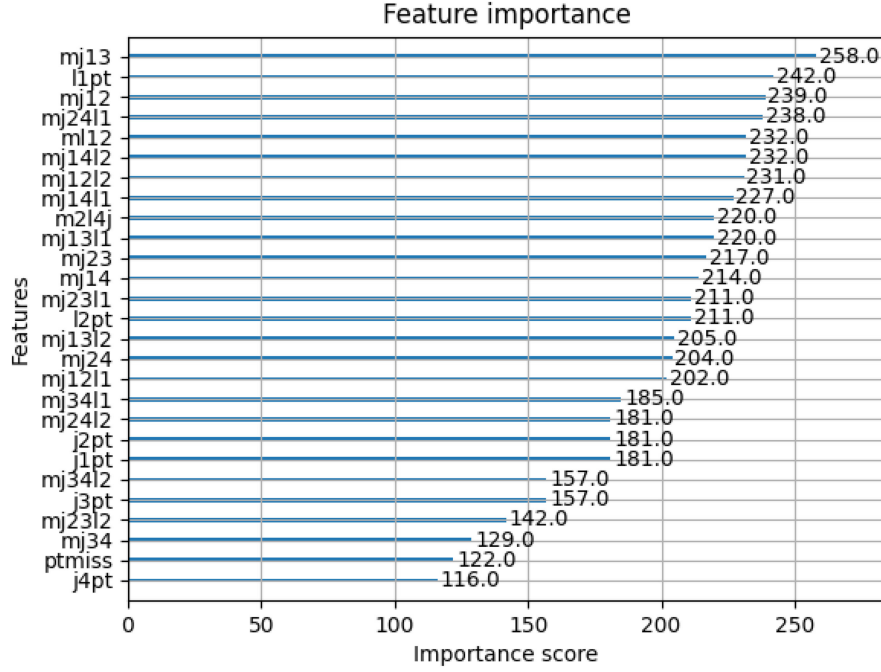


FIG. 2. Ranking of the features used in the XGBOOST model training for the BLSM signal for the $2l(\text{opposite sign}) + 4j$ final state against the background.

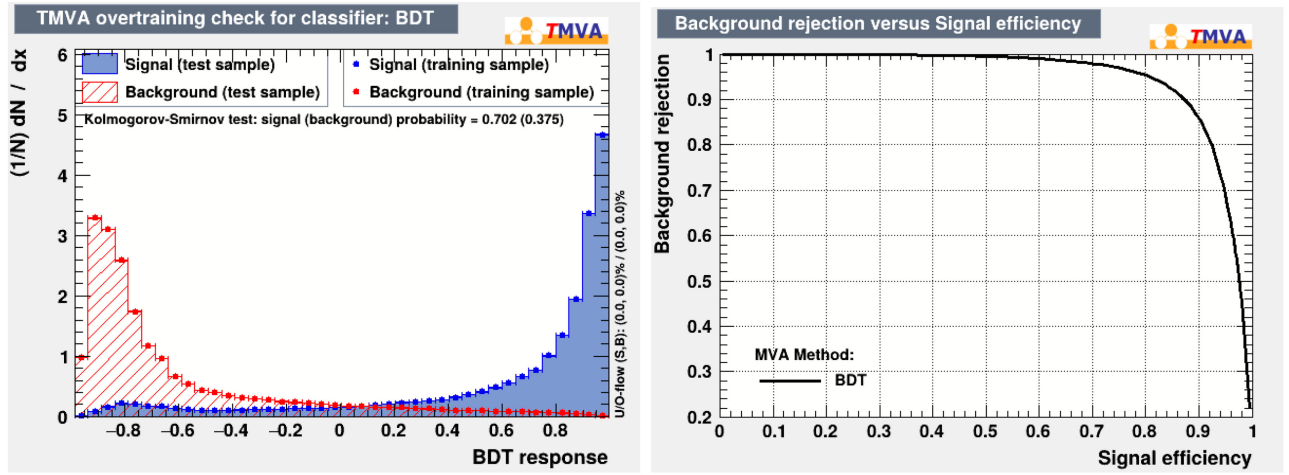


FIG. 3. BDT training performance for the $2\ell(\text{opposite sign}) + 4j$ final state. Left: BDT score distribution for signal and background events (training and test samples). Right: ROC curve showing the background rejection versus signal efficiency. The AUC metric gives 0.949, confirming an excellent ability of the BDT to distinguish the signal from the background.

confirms the effectiveness of the BDT in distinguishing the signal from the background.

To quantify the expected sensitivity at the HL-LHC, we compute the statistical significance defined as $Z_{\text{stat}} = S / \sqrt{S + \sum B}$, where S and $\sum B$ are the expected number of signal and background events passing a given BDT threshold. Actually, in a realistic experimental setting, additional systematic uncertainties arise from several sources, such as the PDFs, the integrated luminosity calibration, and the background modeling (including

misidentification, i.e., fake-lepton rates). These effects typically reduce the nominal statistical significance by a modest amount. A common conservative way to estimate the impact at counting level is to include a fractional background uncertainty ϵ_B in quadrature with the statistical term [31]:

$$Z_{\text{syst}} \simeq \frac{S}{\sqrt{S + \sum B + (\epsilon_B \sum B)^2}}, \quad (4.3)$$

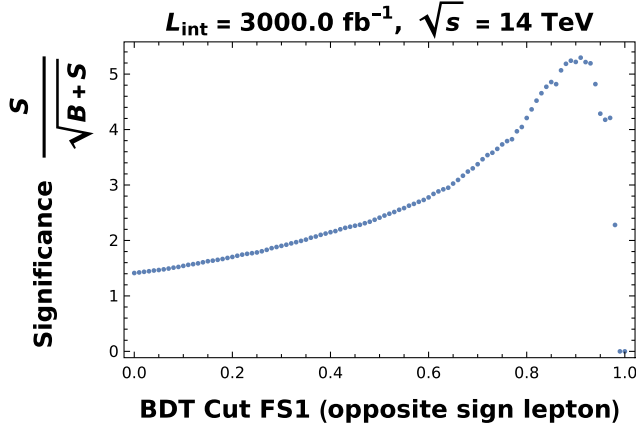


FIG. 4. Variation of the signal significance at the HL-LHC with the BDT threshold on the signal and background events for the final state $2l$ (opposite sign) $+ 4j$.

which provides a robust approximation in the large-sample limit and is conceptually plausible since systematic uncertainties are reported naturally as fractional uncertainties on fundamental inputs [32]. For illustration, adopting a conservative $\epsilon_B = 10\%$ lowers a nominal $Z_{\text{stat}} \sim 3\sigma$ to about $Z_{\text{syst}} \sim 2.7\sigma$, while an exaggerated $\epsilon_B = 20\%$ yields $Z_{\text{syst}} \sim 2.3\sigma$. These shifts do not alter the qualitative conclusions in that the HL-LHC retains sensitivity to the considered benchmark.

In Fig. 4, we show the variation of the significance as a function of the BDT cut value, assuming an integrated luminosity of 3000 fb^{-1} .

Next, we look at the distributions of the variables sensitive to the Z' and ν_R masses. Figure 5 shows the distributions of the invariant masses, M_{2l+4j} and M_{l+2j} , for the signal and the background processes with events passing the BDT threshold. We find that the background is suppressed after the BDT cut, and the signal events peak around the Z' mass of 3 TeV for M_{2l+4j} and the ν_R mass of around 420 GeV for M_{2j+l} .

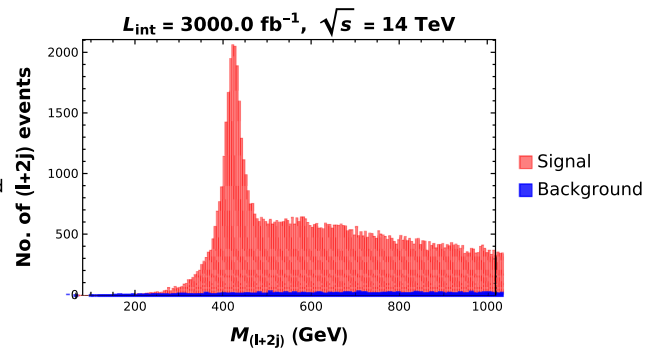
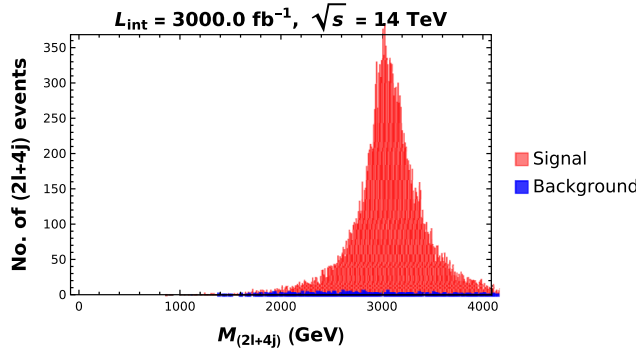


FIG. 5. Background and signal distributions for M_{2l+4j} and M_{2j+l} for events having a BDT score greater than 0.6 for the final state $2l$ (opposite sign) $+ 4j$.

TABLE IV. Cross sections for the signal and background processes considered in the 2ℓ (same sign) $+ 4j$ final-state analysis.

Process	Cross section (fb)
Signal ($pp \rightarrow Z' \rightarrow 2\ell + 4j$)	0.17
Background 1 ($W^\pm W^\pm jj$)	155.7
Background 2 ($t\bar{t}W^\pm$)	0.0083
Background 3 ($W + \text{jets} + \text{fake lepton}$)	782.5

2. 2ℓ (same sign) $+ 4j$

In this section, we consider the final state consisting of two same-sign leptons and four jets. There are three main SM backgrounds for this final state.

The first is same-sign $W^\pm W^\pm$ boson pair production in association with two jets ($W^\pm W^\pm jj$), typically produced via vector boson scattering (VBS).

The second is top quark pair production with an associated W boson ($t\bar{t}W^+$ or $t\bar{t}W^-$), which can yield multiple leptons and jets, including configurations with same-sign leptons.

The third is the $W + \text{jets}$ process, where the W boson decays leptonically to one genuine lepton, and an additional lepton arises from a misidentified jet (fake lepton), resulting in an apparent same-sign lepton pair.

We generate both the signal and background samples using MadGraph5 and apply the same selection cuts used for the 2ℓ (opposite sign) $+ 4j$ analysis. Additionally, the same set of input observables is used to train the BDT for the same-sign case as in the opposite-sign lepton scenario.

The cross sections for the signal and background processes used in this analysis are summarized in Table IV.

Figure 6 shows the ranking of features by their F score, which indicates their relative importance in the classification for the same-sign lepton case. From the plot, we observe that the most important variables are the invariant mass of the lepton pair, $m_{\ell_{1,2}}$, and the missing transverse momentum, p_T^{miss} .

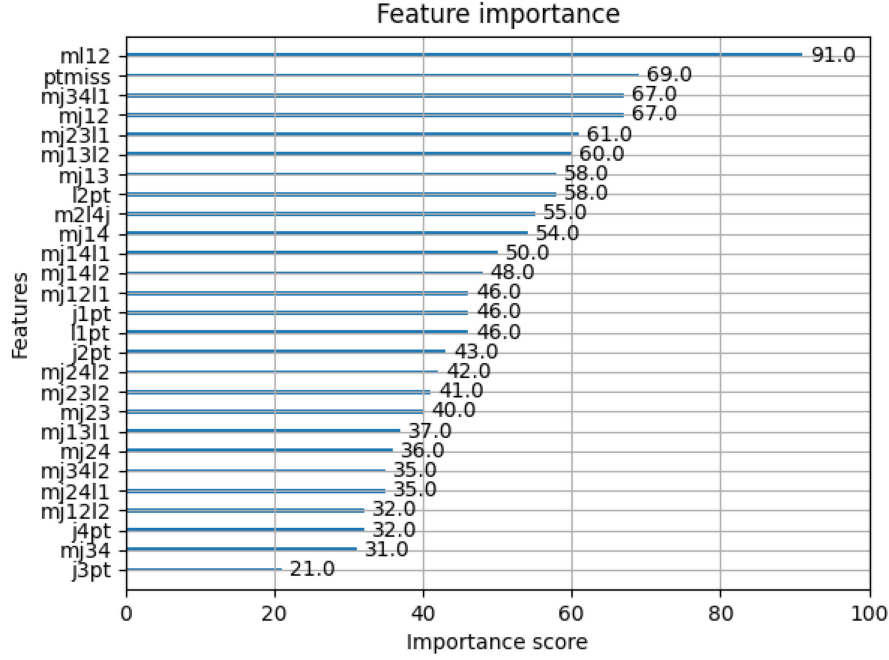


FIG. 6. Ranking of the features used in the xgboost model training for the BLSM signal for the $2\ell(\text{same sign}) + 4j$ final state against the background.

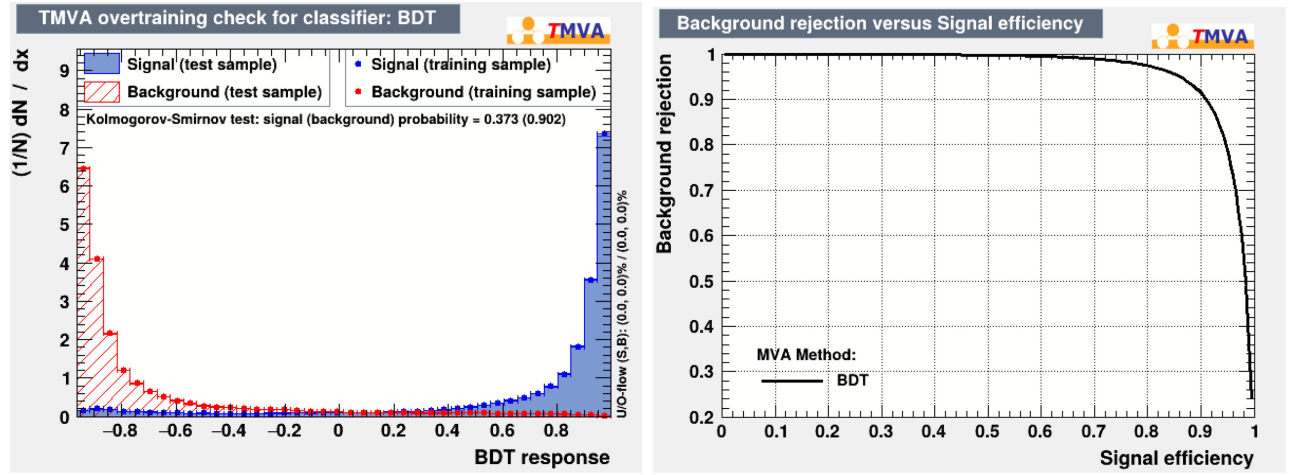


FIG. 7. BDT training performance for the $2\ell(\text{same sign}) + 4j$ final state. Left: BDT score distribution for signal and background events (training and test samples). Right: ROC curve showing background rejection versus signal efficiency. The AUC metric gives 0.963, indicating a strong separation power.

Figure 7 shows the results of the BDT training and testing samples for both the signal and background processes.

In Fig. 8, we show the variation of the signal significance as a function of the BDT cut value, assuming an integrated luminosity of 3000 fb^{-1} .

Finally, in Fig. 9, we present the invariant mass distributions of $M_{2\ell+4j}$ and $M_{\ell+2j}$ for the signal and background events that pass the BDT selection.

B. FS2: $4\ell + \text{MET}$

In this final state, we consider SM backgrounds arising from triboson (VVV) processes, where V denotes a W or Z boson. Specifically, we include the inclusive WWZ , ZZW , and ZZZ production processes as backgrounds. In addition, we include the $t\bar{t}Z$ process as an important background, where the Z boson decays leptonically and the top quarks contribute additional leptons and jets.

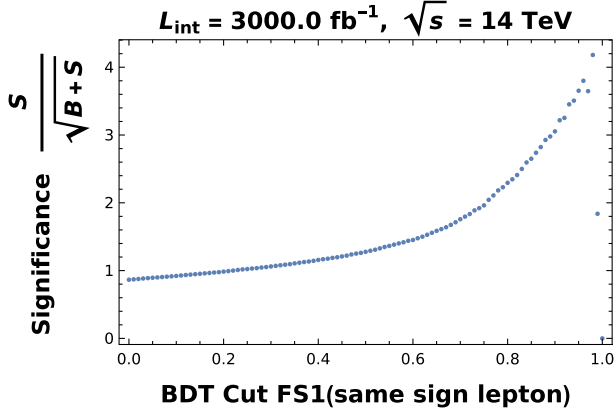


FIG. 8. Variation of the signal significance at the HL-LHC with respect to the BDT threshold for the final state $2\ell(\text{same sign}) + 4j$.

This channel is particularly clean due to the presence of four high- p_T isolated leptons and MET. Consequently, we begin with a cut-based preselection to reduce background contamination. Since the leptons originating from the decay chain of a single ν_R tend to be close to each other in the η - ϕ plane, we apply a tight isolation requirement in our Delphes simulation, using a cone radius of 0.1 for lepton isolation.

We impose the following preselection criteria:

$$n_\ell = 4, \quad p_T^\ell > 50 \text{ GeV}, \quad |\eta^\ell| < 2.5, \quad p_T^{\text{miss}} > 100 \text{ GeV}. \quad (4.4)$$

The cross sections for the signal and background processes used in this analysis are summarized in Table V.

To further enhance the discrimination between the signal and the background, we train a BDT classifier and the SGBOST model using the following set of input observables:

- (i) Transverse momentum of each lepton, p_T^ℓ .
- (ii) Missing transverse energy, E_T^{miss} .
- (iii) Transverse mass of each lepton combined with MET, M_{T^ℓ} .

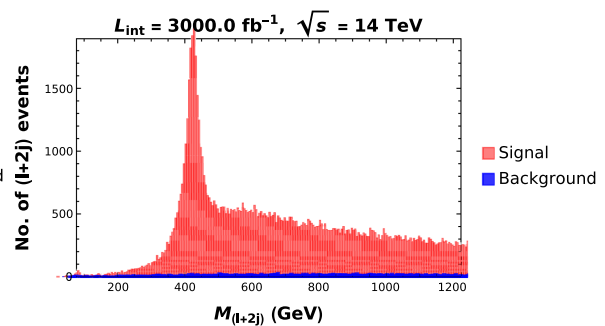
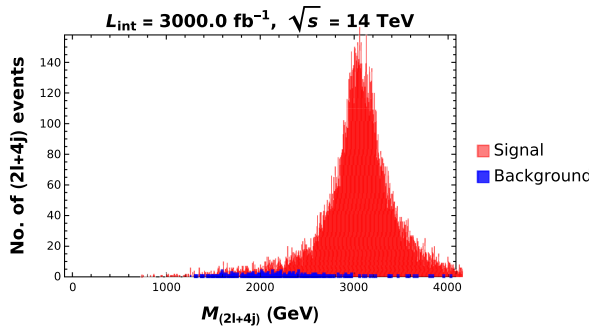


FIG. 9. Signal and background distributions for $M_{2\ell+4j}$ and $M_{\ell+2j}$ for events with a BDT score greater than 0.6 in the final state $2\ell(\text{same sign}) + 4j$.

TABLE V. Cross sections for the signal and background processes considered in the 4ℓ final-state analysis.

Process	Cross section (fb)
Signal ($pp \rightarrow Z' \rightarrow 4\ell + \text{MET}$)	0.11
Background 1 (WWZ)	94.2
Background 2 (ZZW)	30.3
Background 3 (ZZZ)	10.3
Background 4 ($t\bar{t}Z$)	2.15

(iv) Invariant masses of all combinations of lepton pairs, $M_{\ell\ell}$, which are sensitive to the ν_R mass.

(v) Invariant mass of the four-lepton system, $M_{4\ell}$, sensitive to the Z' mass.

Figure 10 shows the ranking of features by their F score, which indicates their relative importance in the classification for the same-sign lepton case. From the plot, we observe that the most important variable is the invariant mass of the lepton pair, $m_{\ell_{i,j}}$.

In Fig. 11, we present the BDT training performance for the $4\ell + \text{MET}$ final state (FS2), analogous to the FS1 case discussed previously. The left panel shows the BDT score distributions for signal and background events. Compared to FS1, the overlap between the signal and background distributions is smaller, indicating improved discriminating power. This enhanced performance is also reflected in the ROC curve shown in the right panel, where we observe that a background rejection of over 98% can be achieved while maintaining a signal efficiency of about 90%.

Similarly to the FS1 case, and in order to quantify the expected sensitivity at the HL-LHC, we compute the statistical significance using the same formula, $S/\sqrt{S + \sum B}$. The variation of the significance with the BDT cut value is shown in Fig. 12.

In Fig. 13, we present the distributions of the invariant masses $M_{4\ell}$ and $M_{2\ell}$ for signal and background events after applying the optimal BDT threshold. We observe a strong suppression of background events due to the BDT cut. Although the presence of neutrinos in the final state leads to significant MET and smears the invariant mass

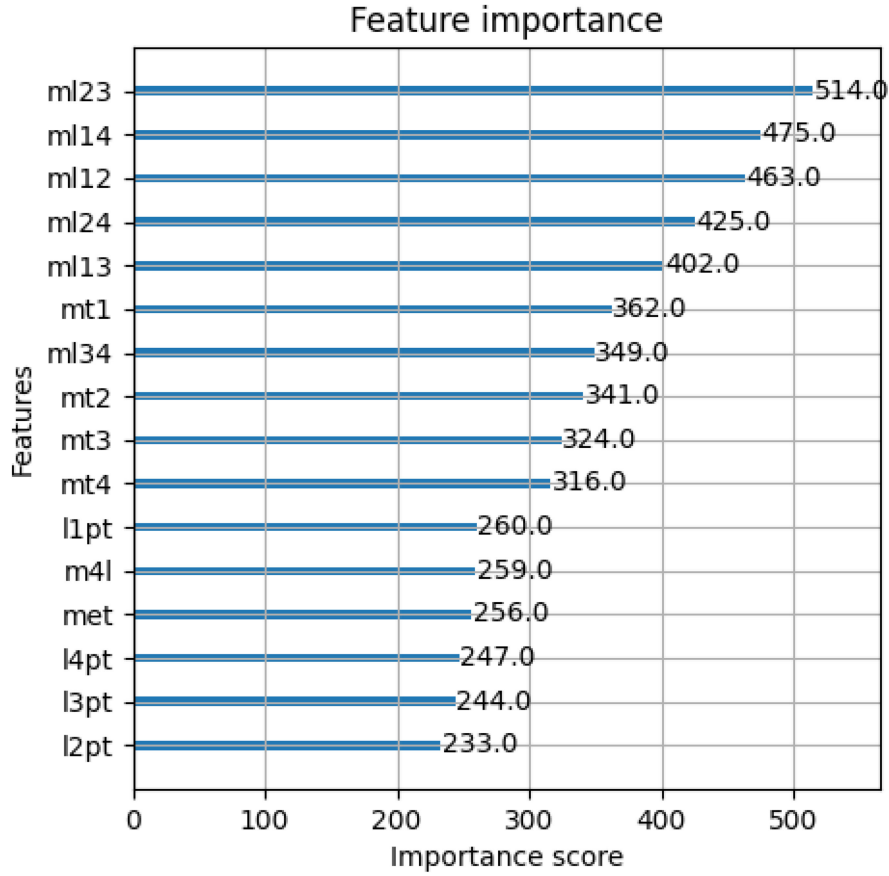


FIG. 10. Ranking of the features used in the XGBOOST model training for the BLSM signal for the $4l + \text{MET}$ final state against the background.

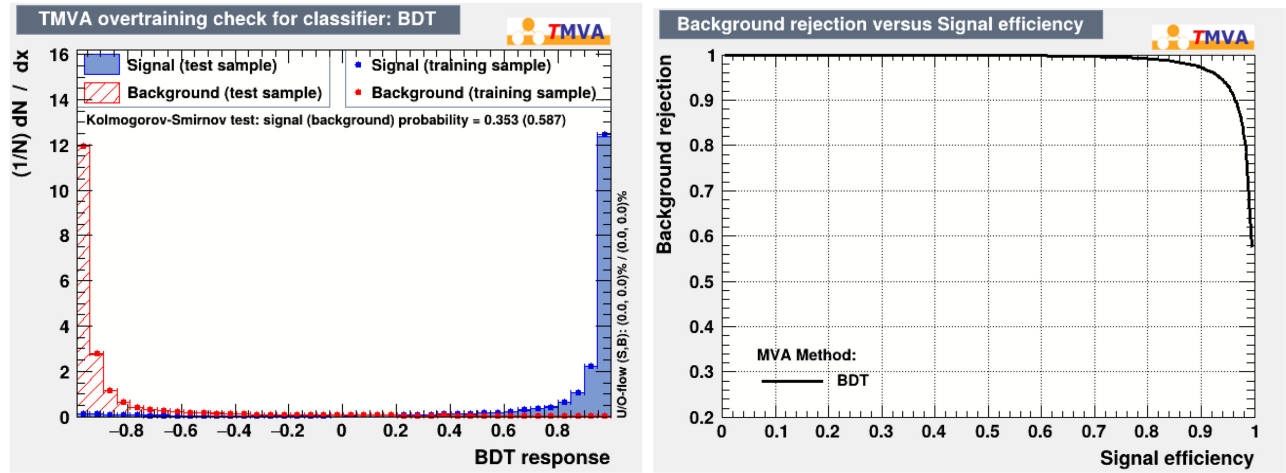


FIG. 11. BDT training performance for the $4\ell + \text{MET}$ final state. Left: distribution of the BDT classifier score for signal and background events (both training and testing samples). Right: ROC curve showing background rejection as a function of signal efficiency. The AUC metric gives 0.986, demonstrating an excellent classification performance.

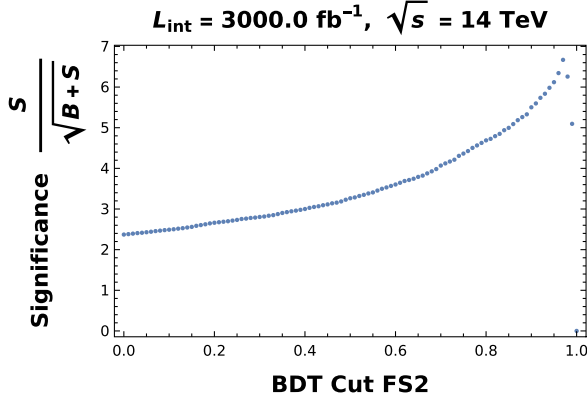


FIG. 12. Variation of the expected signal significance at the HL-LHC with the BDT cut value for the $4\ell + \text{MET}$ final state.

distributions, the signal still exhibits distinctive features: $M_{4\ell}(M_{2\ell})$, sensitive to $Z'(\nu_R)$ mass, shows a peak around 2 TeV (320 GeV) due to MET instead of 3 TeV (420 GeV). These distributions thus retain valuable information about the underlying resonances, even in the absence of sharp peaks.

C. FS3: $3\ell + 2j + \text{MET}$

The final state featuring three leptons, two jets, and MET arises when one of the RHNs decays leptonically and the other semileptonically. Compared to FS1 and FS2, this signature presents a hybrid topology combining both leptonic and hadronic final states, along with significant MET from the neutrinos.

The dominant SM backgrounds include leptonic $WZ + 2j$ production as well as triboson processes such as WWZ , ZZW , and ZZZ . These channels can mimic the signal when the vector bosons decay in configurations that yield three leptons and two jets in the final state. We also consider the process $t\bar{t}W^\pm$ as background, where the associated W boson decays leptonically and both top quarks decay via $t \rightarrow bW \rightarrow b\ell\nu$, leading to a final state with three charged leptons, two b -jets, and significant MET.

As in the earlier analyses, the highly boosted nature of the ν_R due to the heavy Z' (3 TeV) leads to collimated

TABLE VI. Cross sections for the signal and background processes in the $3\ell + 2j + \text{MET}$ final state.

Process	Cross section (fb)
Signal ($pp \rightarrow Z' \rightarrow 3\ell + 2j + \text{MET}$)	0.4
Background 1 ($WZ(\text{leptonic}) + 2j$)	13.98
Background 2 (WWZ)	94.2
Background 3 (ZZW)	30.3
Background 4 (ZZZ)	10.3
Background 5 ($t\bar{t}W^\pm$)	3.9

leptons. We apply a minimum separation cut $\Delta R(\ell, \ell) > 0.1$ to account for this. The signal and background events are generated using MadGraph5_aMC@NLO, applying the following parton-level cuts:

$$p_T^\ell > 50 \text{ GeV}, \quad p_T^j > 50 \text{ GeV}, \quad \Delta R(\ell, \ell) > 0.1. \quad (4.5)$$

Detector effects are included using Delphes, where we further reduce the lepton isolation cone to $\Delta R = 0.1$ to improve lepton reconstruction for boosted decays. After detector simulation, the following event selection criteria are imposed:

$$\begin{aligned} n_\ell &= 3, \quad p_T^\ell > 50 \text{ GeV}, \quad |\eta^\ell| < 2.5, \\ n_j &\geq 2, \quad p_T^j > 50 \text{ GeV}, \quad |\eta^j| < 2.5, \quad p_T^{\text{miss}} > 100 \text{ GeV}. \end{aligned} \quad (4.6)$$

The cross sections of the signal and background processes are listed in Table VI.

To distinguish the signal from the background more effectively, we employ a trained BDT classifier and the XGBOOST model on the following set of kinematic variables:

- (i) Transverse momentum of leptons and jets, $p_T^{\ell,j}$.
- (ii) Invariant masses of lepton and jet pairs, $M_{\ell\ell}$ and M_{jj} .
- (iii) Missing transverse energy, E_T^{miss} .
- (iv) Transverse mass of each lepton with MET, M_T^ℓ .

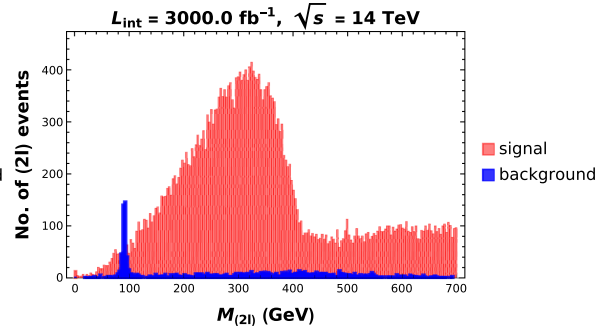
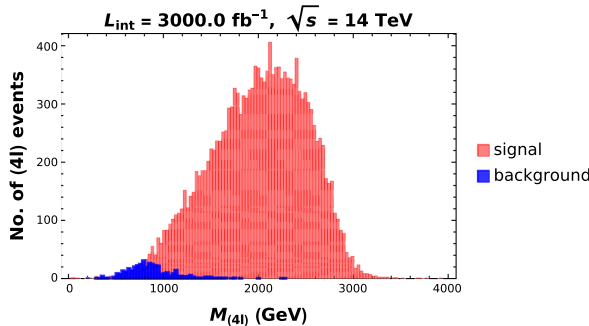


FIG. 13. Distributions of $M_{4\ell}$ (left) and $M_{2\ell}$ (right) for signal and background events with BDT score > 0.6 in the 4ℓ final state.

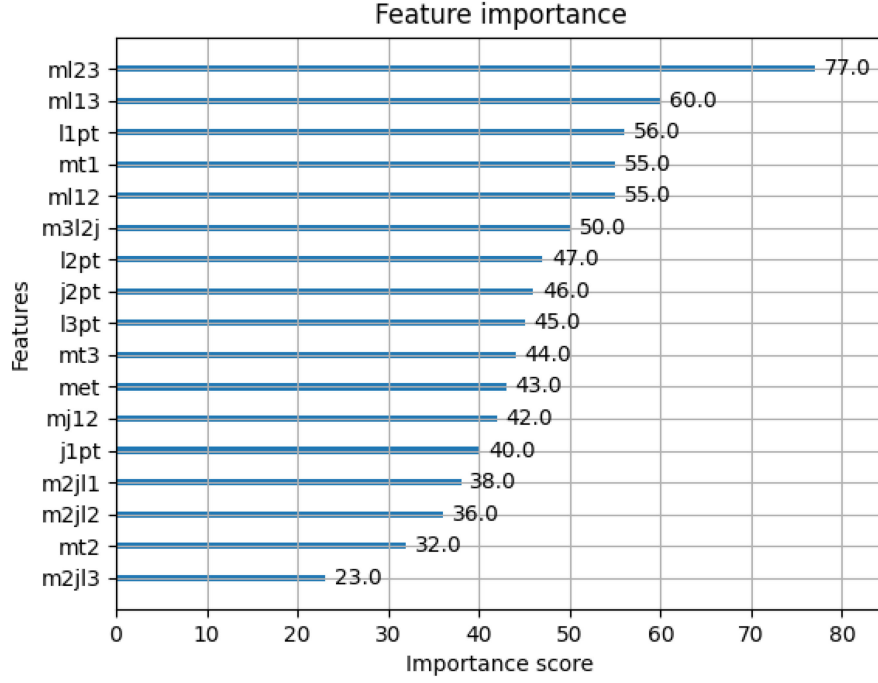


FIG. 14. Ranking of the features used in the XGBOOST model training for the BLSM signal for the $3l + 2j + \text{MET}$ final state against the $WZ(\text{dileptonic}) + 2j$ background.

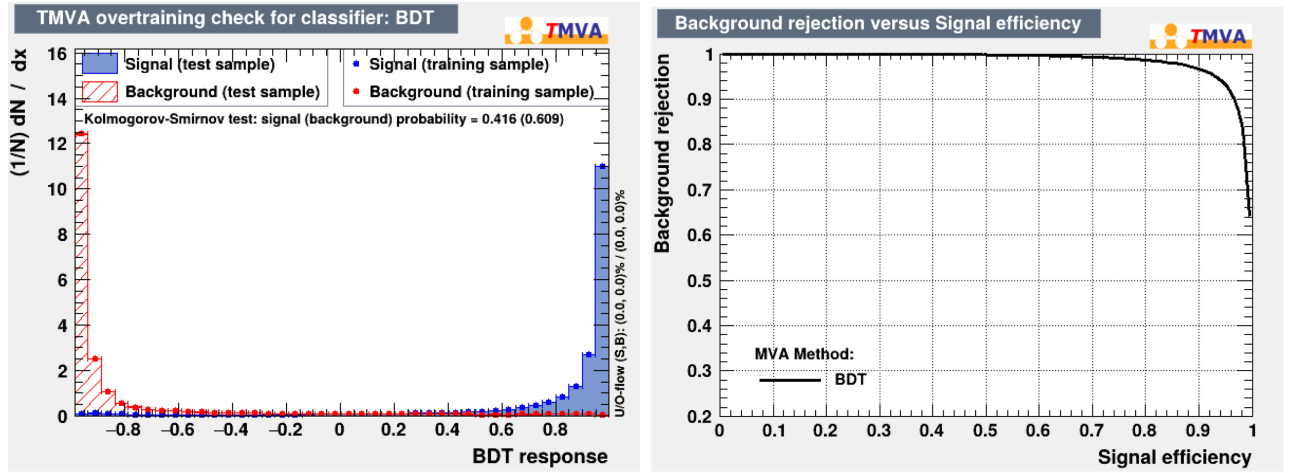


FIG. 15. BDT training performance for the $3\ell + 2j + \text{MET}$ final state. Left: BDT score distribution for signal and background events. Right: ROC curve showing background rejection vs signal efficiency. The AUC metric gives 0.985, confirming a strong discrimination power achieved by the BDT.

- (v) Invariant mass of the full $3\ell + 2j$ system, $M_{3\ell 2j}$, sensitive to $M_{Z'}$.

Figure 14 shows the ranking of various features based on their importance in the classification decision. From the plot, we observe that the most important variables are the invariant masses of the lepton pair $m_{\ell_{2,3}}$ and the jet pair $m_{j_{1,3}}$, along with the transverse momentum of the leading lepton, $p_T^{\ell_1}$.

Figure 15 presents the BDT output for signal and background events. The left panel shows the BDT score

distribution, where the signal is clearly separated from the background. This separation is more pronounced compared to FS1 and FS2. The right panel shows the ROC curve, where for a signal efficiency of 90%, a background rejection exceeding 98% is achieved—demonstrating that FS3 provides the strongest discriminative power among the three channels.

The expected signal significance at the HL-LHC is evaluated as a function of the BDT score threshold using the definition $S/\sqrt{S + \sum B}$. As shown in Fig. 16,

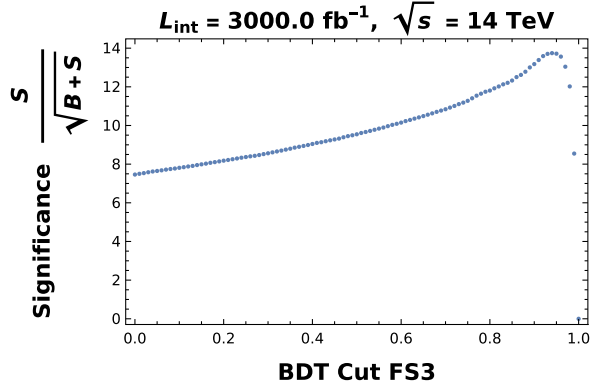


FIG. 16. Expected signal significance at the HL-LHC as a function of the BDT score threshold in the $3\ell + 2j + \text{MET}$ channel.

a significance above 3 can be obtained for BDT scores around 0.6, assuming an integrated luminosity of 3000 fb^{-1} .

Finally, we study the mass-sensitive variables after applying the BDT selection. Figure 17 shows the distributions of $M_{3\ell+2j}$ and $M_{2\ell}$ for the signal and background. Note that $M_{3\ell+2j}(M_{2\ell})$, sensitive to $Z'(\nu_R)$ mass, shows a peak around 2.8 TeV (300 GeV) due to MET instead of 3 TeV (420 GeV), while the backgrounds are heavily suppressed post-BDT selection.

V. CONCLUSIONS

The $B-L$ extension of the SM (BLSM) offers a natural framework for generating small neutrino masses via the inclusion of RHNs. While experimental searches have constrained the masses and couplings of new particles predicted by the BLSM, such as the heavy Z' gauge boson and RHNs, significant regions of parameter space remain viable and unexplored. In this study, we examined the discovery potential of a representative BLSM benchmark at the HL-LHC, focusing on a region consistent with current experimental bounds. We utilized the XGBOOST framework to assess the discriminating power of various kinematic

features and trained a BDT classifier to optimize signal-background separation.

Our analysis considers the production of a Z' boson in proton-proton collisions, followed by its decay into RHNs, which subsequently decay into leptons and W bosons. Depending on the W decay modes, we investigate three final states, combining fully leptonic, semileptonic, and hadronic outputs. For each channel, we perform a detailed background study and apply a multivariate BDT-based classification strategy to enhance sensitivity. The results indicate that, at the HL-LHC with an integrated luminosity of 3000 fb^{-1} , a signal significance exceeding 3σ can be achieved in each of the considered channels. This highlights the effectiveness of the BDT-based approach in probing BLSM signatures. The BDT validation metrics, including large KS p-values and high AUC values (0.95–0.99 across all channels), confirm the robustness of the training and the absence of overtraining in the classification analysis. Our analysis demonstrates that upcoming HL-LHC runs offer promising prospects for discovering new physics predicted by the BLSM. These findings strongly motivate continued experimental efforts to explore this model in future collider searches.

ACKNOWLEDGMENTS

The work of S. K. and K. E. is partially supported by the Science, Technology & Innovation Funding Authority (STDF) under Grant No. 48173. N. C. acknowledges support from the Alexander von Humboldt Foundation and is grateful for the kind hospitality of the Bethe Center for Theoretical Physics at the University of Bonn.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

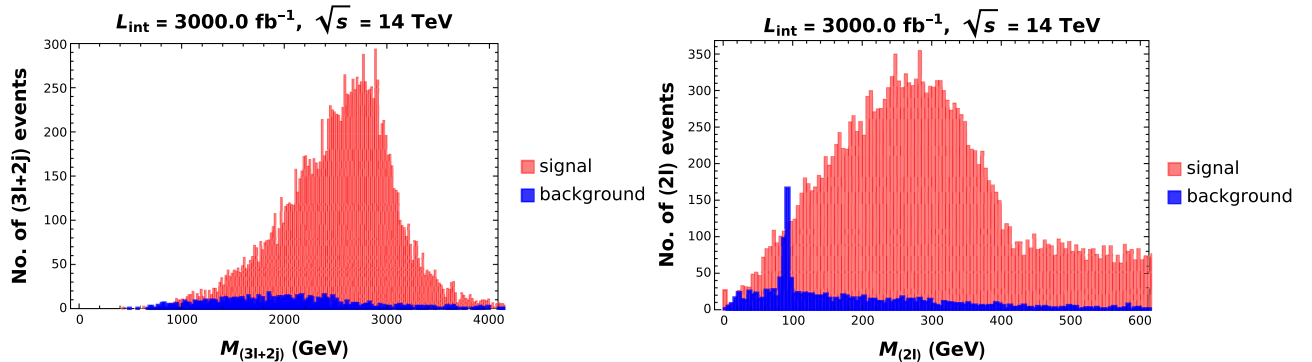


FIG. 17. Distributions of $M_{3\ell+2j}$ (left) and $M_{2\ell}$ (right) for events with BDT score > 0.6 in the $3\ell + 2j$ final state.

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