Electroweakino searches at the HL-LHC in the baryon number violating MSSM

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Abstract

The projected reach of direct electroweakino searches at the HL-LHC ($\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$ LHC) in the framework of simplified models with R-parity violating (RPV) operators: $\lambda''_{112}u^c d^c s^c$ and $\lambda''_{113}u^c d^c b^c$, is studied. Four different analysis channels are chosen: $Wh$ mediated $1l + 2b + jets + E_T$, $Wh$ mediated $1l + 2\gamma + jets + E_T$, $WZ$ mediated $3l + jets + E_T$ and $WZ$ mediated $3l + 2b + jets + E_T$ and the projected exclusion/discovery reach of direct wino searches in these channels is analyzed by performing a detailed cut based collider analysis. The projected exclusion contour reaches up to $600 - 700$ GeV for a massless bino-like $\chi_1^0$ from searches in the $Wh$ mediated $1l + 2b + jets + E_T$, $Wh$ mediated $1l + 2\gamma + jets + E_T$ and $WZ$ mediated $3l + jets + E_T$ channels, while the $WZ$ mediated $3l + 2b + jets + E_T$ search channel is found to have a projected exclusion reach up to 600 GeV for $150 \text{ GeV} < M_{\chi_1^0} < 250$ GeV. The baryon number violating simplified scenario considered in this work is found to furnish a weaker projected reach (typically by a factor of $\sim 1/2$) than the R-parity conserving (RPC) case. The projected reach at the HL-LHC in these four channels is also recasted for realistic benchmark scenarios.

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I. Introduction

Supersymmetry (SUSY) \cite{1,2,3,4} has been among the most attractive frameworks for formulating physics beyond the Standard Model. Numerous studies have reported the plausibility of SUSY in resolving various inadequacies within the Standard Model (SM) of particle physics \cite{5,6,7,8} viz the Hierarchy problem \cite{9,10}, gauge coupling unification \cite{11,12,13,14}, existence of a viable Dark Matter (DM) candidate \cite{15,16,17}, naturalness of Higgs mass \cite{18,19}. In adherence to the experimental observations, SUSY has to be broken, and solution to the Hierarchy problem implores the SUSY breaking scale to be $\sim O(\text{TeV})$, thus, bringing the SUSY particles within the potential reach of current and future LHC. The minimal supersymmetric extension of the Standard Model (MSSM) \cite{20,21,22,23,24} has been among the prominent class of nominees considered to address the shortcomings within the SM and in the pursuit of new physics phenomenology. A legion of studies have focused on investigating the current status and future prospects of the MSSM parameter space in light of the LHC Run-I and Run-II results \cite{25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49}. Since the advent of the LHC, the ATLAS and CMS collaborations have performed a multitude of searches to probe the
sparticles using the LHC Run-I and Run-II dataset, however, they are yet to observe a clear signature of physics beyond the SM. Robust lower bounds have been derived on the masses of strongly interacting sparticles. Searches by the ATLAS and CMS collaboration using the LHC $\sqrt{s} = 13$ TeV data collected at $\sim 137$ fb$^{-1}$ of integrated luminosity ($L$) have excluded gluinos ($\tilde{g}$) up to $\sim 2.2$ TeV and $\sim 2.3$ TeV, respectively, for a LSP (lightest SUSY particle) neutralino ($\chi_1^0$) with mass up to $\sim 600$ GeV [50–52] at 95% C.L., however, within the framework of a simplified SUSY scenario. Using the same respective datasets and within a simplified scenario with some specific decay modes and mass hierarchy, ATLAS and CMS have also excluded the stops ($\tilde{t}$) and sbottoms ($\tilde{b}$) up to $\sim 1.2$ TeV for a $M_{\chi_1^0} \sim 400$ GeV at 95% C.L. [52–54]. On the other hand, the electroweakly interacting sparticles viz electroweakinos and sleptons, are rather feebly constrained [55–61].

The MSSM is endowed with an exact symmetry related to the baryon number ($B$), lepton number ($L$) and the spin of the particle ($S$), referred to as $R$-parity ($R_p$)$^2$. $R$-parity conservation (RPC) entails pair production of SUSY particles at colliders and also ensures that the lightest SUSY particle, typically the $\chi_1^0$, is stable and a viable non-baryonic DM candidate. The presence of a stable LSP DM candidate results in missing transverse energy ($E_T$) signatures at the colliders, making the RPC scenarios extensively attractive to be analyzed at the LHC. Consequently, a myriad of studies have addressed the phenomenological implications of $R$-parity conserved scenarios and a non-exhaustive list of such studies can be found in [69–86].

Although the $R$-parity conserved scenarios display a tempting landscape for collider and astrophysical searches, it must be noted that $R$-parity conservation is not fundamentally necessary to obtain a viable SUSY framework. Ensuring the stability of the proton was the prime intent behind introducing $R$-parity conservation (relevant discussions can be found in [87, 88]). However, several studies have also explored the possibility to stabilize the proton without conserving $R$-parity [89–92]. Another strong incentive to consider RPC scenarios is the possibility of a viable DM candidate with a correct DM relic density as discussed previously. In the presence of $R$-parity violation (RPV) (see [93, 94] for reviews), the LSP would undergo decay and would no longer remain a viable DM candidate. However, results from [95–97] indicate that axinos and gravitinos could generate a correct relic abundance in RPV scenarios. Furthermore, the presence of $R$-parity violation has also been shown to ease the amount of fine-tuning

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1 A few phenomenological analysis in this context may be seen in Refs. [62–68].

2 $R_p$ is defined as, $R_p = (-1)^{(3B+L+S/2)}$. The SM particles and their superpartners are have $R_p = +1$ and $R_p = -1$, respectively.
required to obtain a $\sim 125$ GeV Higgs boson in SUSY \cite{98} by weakening the bounds on gluino \cite{99,103} and stop masses \cite{104,105}. Another critical consequence of RPV terms is the successful explanation of the observed pattern of neutrino masses and mixing \cite{106,112}. Within RPV scenarios, lepton number violating couplings can initiate lepton flavor violating processes (viz the scattering of unoscillated $\nu_{\mu}$ into $\tau$) even in the absence of neutrino oscillation \cite{113}. The R-parity framework has also been studied in light of offering a plausible explanation for the $(g-2)_{\mu}$ discrepancy \cite{114}. In addition, the $E_T$ dependent collider search strategies, which are a trademark of RPC scenarios, would be rendered ineffective in the presence of $R$-parity violating terms, and the collider bounds are expected to alter. Thus, the introduction of RPV terms would result in characteristically distinct final states, a study of which would be extremely relevant in the context of collider searches at the LHC\cite{115,116}. Overall, the discussion until now motivates the impulse of probing the sector of RPV MSSM.

The most general, gauge invariant and renormalizable $R$-parity violating terms \cite{20,117} which could be added to the MSSM superpotential ($W_{MSSM}$) are the following (the notation of \cite{118} has been followed):

$$W_{RPV} = W_{MSSM} + \frac{1}{2} \lambda_{ijk} L_i \cdot L_j e^c_k + \frac{1}{2} \lambda'_{ijk} L_i \cdot Q_j d^c_k + \frac{1}{2} \lambda''_{ijk} \epsilon_{\alpha\beta\gamma} u^c_{i\alpha} d^c_{j\beta} e^c_d \mu_i H_u \cdot L_i$$  \hspace{1cm} (1.1)

where, $L$ and $Q$ represents the left handed lepton and quark superfields, respectively, while, $e$, $u$ and $d$ corresponds to the right handed lepton, up-type quark and down-type quark superfields, respectively. $\lambda$, $\lambda'$ and $\lambda''$ are the dimensionless Yukawa couplings while $\epsilon$ is the three dimensional Levi-Civita symbol. Here, $i,j,k$ are the generation indices, $\alpha,\beta,\gamma$ are the flavor indices and $c$ represents charge conjugation.

The collider implications of the lepton number violating RPV couplings: $\lambda_{12k} L_1 \cdot L_2 e^c_k$ ($k \in 1,2$) and $\lambda_{33i} L_i \cdot L_3 e^c_3$ ($i \in 1,2$) have been studied by the ATLAS collaboration through an interpretation in simplified scenarios with wino-like NLSP pair production ($pp \rightarrow \chi^0_2/\chi^+_1 + \chi^+_1$) and higgsino-like NLSP pair production ($pp \rightarrow \chi^0_1/\chi^0_2/\chi^+_1 + \chi^+_1$) in the $WZ$ and $Wh$ mediated 4$l$ ($l$ = electrons ($e$) and muons ($\mu$)) final state \cite{119} using the LHC Run-II data collected at $\mathcal{L} = 36.1$ fb$^{-1}$. Results from \cite{119} exclude a wino-like $\chi^+_1,\chi^0_2$ up to $\sim 1.46$ TeV ($\sim 980$ GeV) for a bino-like $\chi^0_1$ with mass $M_{\chi^0_1} \sim 500$ GeV ($M_{\chi^0_1} \in [400-700]$ GeV) in the presence of $\lambda_{12k} L_1 \cdot L_2 e^c_k$ ($\lambda_{33i} L_i \cdot L_3 e^c_3$) type RPV coupling. The ATLAS collaboration has also probed direct wino production in the context of RPC scenarios and has excluded winos up to $\sim 350$ GeV for a $M_{\chi^0_1} \sim 50$ GeV (at 95% C.L.) from searches in the tri-lepton ($l = e, \mu$) + $E_T$ final state \cite{60} using LHC Run-II data ($\sim 139$ fb$^{-1}$). Similarly, direct wino searches by CMS in
three or more charged $l$ final states in a wino-like RPC scenario, using the LHC Run-II 36 fb$^{-1}$ dataset, has excluded winos up to $\sim 650$ GeV ($WZ$ topology) and $\sim 480$ GeV ($Wh$ topology)\cite{58}. Thus, the $\frac{1}{2}\lambda_{ijk}L_i \cdot L_j e_k^c$ type RPV scenarios imply a more stringent exclusion on the electroweakino sector compared to the RPC scenarios due to harder leptons in the final state. In\cite{120} as well, ATLAS has analyzed the four or more lepton final state in the context of RPV simplified scenario containing $\lambda_{ijk}L_i \cdot L_j e_k^c$ type couplings using the $\sqrt{s} = 8$ TeV LHC data collected at $\sim 20.3$ fb$^{-1}$ integrated luminosity. Results from\cite{120} exclude a wino-like chargino below $\sim 750$ GeV, gluino below $\sim 1350$ GeV and left-handed (right-handed) sleptons below $\sim 490$ GeV (410 GeV), for $M_{\chi_1^0} = 300$ GeV at 95% C.L., within a simplified RPV scenario where the bino-like LSP $\chi_1^0$ can decay only into electrons and muons. If the tau-rich decays are also included, the corresponding exclusion limits get weaker: wino-like chargino ($\lesssim 450$ GeV), gluino ($\lesssim 950$ GeV), left-handed sleptons ($\lesssim 300$ GeV) and right-handed sleptons ($\lesssim 240$ GeV). The CMS collaboration also analyzed the $\sqrt{s} = 8$ TeV LHC data (19.5 fb$^{-1}$) and excluded stops up to $\lesssim 1100$ GeV and $\lesssim 950$ GeV\cite{121} at 95% C.L. in simplified scenarios containing $\lambda_{122}$ and $\lambda_{333}$ type RPV couplings, respectively, for a bino-like $\chi_1^0$ with mass $\sim 400$ GeV. The RPV scenario with $\frac{1}{2}\lambda'_{233}L_2 \cdot Q_3 d_3^c$ type coupling has also been investigated in\cite{121} and has excluded stops with mass between $\sim 550$ GeV and $\sim 700$ GeV for a bino-like $\chi_1^0$ with mass $\sim 500$ GeV at 95% C.L.

Gluino searches in multi-jet final state\cite{122} and the jets plus two same-sign lepton or three lepton final state\cite{123} by the ATLAS collaboration using the LHC $\sqrt{s} = 8$ TeV data ($\sim 20$ fb$^{-1}$) within $\lambda''_{ijk}\epsilon_{\alpha\beta\gamma}u_i^c d_j^c d_k^c$ type RPV simplified scenario has excluded gluinos up to $\lesssim 1100$ GeV and $\lesssim 1050$ GeV, respectively, for $M_{\chi_1^0} \sim 400$ GeV, at 95% C.L. CMS has also searched for the gluinos in multi-jet\cite{124} and same-sign di-lepton plus jets final state\cite{125} using LHC $\sqrt{s} = 8$ TeV data ($\sim 19.5$ fb$^{-1}$) within the framework of $\lambda''_{ijk}\epsilon_{\alpha\beta\gamma}u_i^c d_j^c d_k^c$ type RPV simplified scenarios, and have excluded gluinos below $\lesssim 650$ GeV and $\lesssim 900$ GeV, respectively, at 95% C.L.. The phenomenology of $\lambda''_{ijk}u_i^c d_j^c d_k^c$ type of RPV operators has also been analyzed in\cite{99,126} and the distinct collider signatures emerging in consequence to $\lambda''_{ijk}u_i^c d_j^c d_k^c$ type of RPV coupling has been analyzed in\cite{104,127,128}. At this point, it would be essential to take a look at the analogous exclusion limits in the RPC framework. Searches by the ATLAS and CMS collaborations within RPC scenarios (using the LHC $\sqrt{s} = 8$ TeV, $\sim 20$ fb$^{-1}$ dataset) have excluded gluinos up to $\sim 1400$ GeV\cite{129} and $\sim 1300$ GeV\cite{130}, respectively, for a bino-like $\chi_1^0$ with mass $\sim 400$ GeV at 95% C.L. Using the same dataset, ATLAS and CMS also set lower limits on the mass of squarks ($\lesssim 900$\cite{129}) and stops ($\lesssim 760$\cite{131}), respectively, at 95% C.L.. It is worthwhile to note that the
RPC scenario and the RPV scenario discussed till now imply a comparable exclusion limit on the masses of gluinos and squarks. However, the electroweakino sector of $\lambda^{\nu}_{ijk} \epsilon^{\alpha \beta \gamma} u_i^{\alpha} d_j^{\beta} d_k^{\gamma}$ type RPV models still remain to be explored, and that is precisely the goal of this work.

Our aim is to study the collider constraints on electroweakinos in RPV simplified scenarios with $\lambda^{\nu}_{112} u^c d^c s^c$ and $\lambda^{\nu}_{113} u^c d^c b^c$ type of RPV couplings in context of searches at the future HL-LHC ($\sqrt{s} = 14$ TeV, $L = 3000$ fb$^{-1}$). Here, we have assumed the $\chi_1^0$ to undergo prompt decay. Naively speaking, a $\lambda^{\nu}_{ijk} u_i^c d_j^c d_k^c$ type of RPV scenario, where the LSP would decay into a multijet final state: $\chi_1^0 \rightarrow j_u j_d j_d$ ($j_u = u, c, t$ and $j_d = d, s, b$), would be expected to be amply sensitive to search strategies which considers large jet multiplicity in the final state. However, if the jets produced from the decay of $\chi_1^0$ are highly collimated, then they would evade identification as isolated jets, thereby, altering the reach of collider search strategies. Within simplified RPC scenarios, direct wino searches in the $Wh$ mediated $1l + 2b + \not{E}_T$ and $WZ$ mediated $3l + \not{E}_T$ ($l = e, \mu$) final states furnishes robust bounds on the mass of winos as a function of $M_{\chi_{1}^0}$. In this work, we analyze these collider searches in the context of $\lambda^{\nu}_{112} u^c d^c s^c$ type RPV simplified scenarios$^3$ (in Section II A and Section II C, respectively) and contrast them with the results for RPC scenarios in [132]. Additionally, we also explore the future reach of direct wino searches in the $Wh$ mediated $1l + 2\gamma + \text{jets} + \not{E}_T$ final state (Section II B) and $WZ$ mediated $3l + 2b + \text{jets} + \not{E}_T$ final state (Section II D), respectively characterized by $\lambda^{\nu}_{112} u^c d^c s^c$ and $\lambda^{\nu}_{113} u^c d^c b^c$ type of RPV operators. We have considered final states containing leptons/photons in addition to the multiple jets since they are easier to trigger and offer a cleaner signature. A few benchmark scenarios and their collider implications are discussed in Section III. We conclude in Section IV.

II. COLLIDER ANALYSIS

A simplified SUSY scenario [133] with mass degenerate wino like $\chi_2^0$, $\chi_1^\pm$, and a bino like $\chi_1^0$ is considered in this analysis. We consider the direct production of wino-like $\chi_2^0 \chi_1^\pm$ pair due to its higher production cross-section compared to wino-type neutralino pair ($\chi_2^0 \chi_2^0$) or chargino pair ($\chi_1^\pm \chi_1^\mp$). Furthermore, the wino production cross-section is also roughly $\sim 2$ times larger than the higgsino production rates. Correspondingly, the other SUSY particles namely sleptons, squarks, heavy Higgses and the heavier electroweakinos ($\chi_3^0$, $\chi_4^0$, $\chi_2^\pm$) have been fixed at a higher mass in order to decouple their effects on our

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$^3$ The respective final states feature additional light jets produced from the decay of $\chi_1^0$. 
study.

Direct wino pair production is considered \((pp \rightarrow \chi_2^0 \chi_1^\pm)\) and a detailed collider analysis is performed in multifarious final states originating from the cascade decay of the aforesaid \(\chi_2^0 \chi_1^\pm\) pair. As stated in Section I, our aim is to study the collider ramifications of the baryon number violating RPV operator in simplified MSSM. To reiterate the structure of this paper, we study the implications of \(\lambda''_{112} u^c d^c s^c\) type RPV term in Section II A, II B and II C and \(\lambda''_{113} u^c d^c b^c\) type RPV term in Section II D. In light of these terms, the \(\chi_1^0\) decays into a \(uds\) final state in the initial three cases while the \(\chi_1^0\) decays into a \(udb\) final state in the latter case, resulting in final states with large jet multiplicity. The Feynman diagrams of the signal processes considered in Section II A, II B, II C and II D have been illustrated in Figure 1 (a), (b), (c) and (d), respectively.

In the present work, the signal events have been generated using Pythia-6.4.28 [134, 135], while the MadGraph_aMC@NLO [136] framework has been used to generate the background events at leading
order (LO) parton level in SM. Subsequent showering and hadronization has been performed through \textsc{Pythia-6.4.28}. The background events have been generated by matching up to 3 \textit{jets} (the 3 \textit{jet} matched sample of a background process \textit{bkg} will be represented as \textit{bkg+jets}) except for the \textit{W/Z+jets} background process for which the 4 \textit{jet} matched sample is used. The fast detector response has been simulated using \textsc{Delphes-3.4.1} \cite{137}. The default ATLAS configuration card which comes along with \textsc{Delphes-3.4.1} package has been used in the entirety of this analysis\textsuperscript{4}. For the background processes, we have considered the leading order (LO) cross-sections computed by \textsc{MadGraph} unless stated otherwise. The NLO-NLL order cross-sections (taken from \cite{138, 139}) have been considered for the signal processes (direct wino production: $\sigma^{\text{wino}}_{pp \rightarrow \chi_0^2 \chi_1^\pm}$).

In the following subsections, we present a detailed discussion of the collider search strategy employed to maximize the signal significance in the corresponding search channels and present our results on the projected reach of direct wino searches in these respective search channels at the HL-LHC.

A. Searches in $Wh$ mediated $1l + 2b + jets(N_j \geq 2) + \not{E}_T$ channel

The signal process considered in this subsection is illustrated in Figure 1(a). The $\chi_1^\pm$ and $\chi_2^0$ are assumed to decay into $W\chi_0^0$ and $h\chi_1^0$, respectively, with a branching ratio of 100%, while, the SM branching values for $h \rightarrow b\bar{b}$ ($\sim 57\%$ \cite{140}) and $W \rightarrow l'\nu$ ($\sim 31.7\%$ \cite{140}, \textit{l}' = e, \mu, \tau) have been considered. The cascade decay process culminates in two $\chi_0^0$ along with other SM particles. The RPV operator: $\lambda_{112}^{''} u^c d^c s^c$ implies $\chi_1^0 \rightarrow uds$, resulting in multiple light quark \textit{jets} in the final state. The cascade decay chain eventually results in $Wh$ mediated $1l + 2b + jets + \not{E}_T$ final state.

An event is required to have exactly one isolated lepton ($l = e, \mu$), at least two light \textit{jets} ($N_j \geq 2$), and exactly two \textit{b jets} in the final state. The electron (muon) is considered to be isolated if $\Sigma p_T^{\text{others}}/p_T^l$ is $\leq 0.12$ for electrons and $\leq 0.25$ for muons, where, $\Sigma p_T^{\text{others}}$ is the scalar sum of transverse momenta of charged particles with $p_T \geq 0.5$ GeV (excluding the lepton under consideration) within a cone of radius $\Delta R = 0.5$ centred around the direction of lepton momentum and $p_T^l$ is the transverse momentum of the lepton. Here, $\Delta R$ is defined as: $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$, where, $\Delta \eta$ and $\Delta \phi$ are the differences in pseudorapidity and the azimuthal angle, respectively, between the lepton under consideration and the charged particle. The isolated electron (muon) is required to have $p_T \geq 30$ GeV, while the lighter \textit{jets}

\textsuperscript{4} The \textit{b jet} tagging efficiency has been assumed to be 70\% while the $c \rightarrow b$ ($u, d, s \rightarrow b$) mistag efficiency has been assumed to be 30\% (1\%).
and the \( b \) jets are required to have \( p_T > 20 \) GeV. In addition, the final state leptons and quarks must lie within a pseudorapidity range of \( \leq |\eta| \leq 2.5 \).

The most dominant source of background is \( \ell \bar{\ell} + \text{jets} \). Contributions to the background also arise from \( WZ + \text{jets}, WW + \text{jets} \) and \( ZZ + \text{jets} \) when \( W,Z \) undergoes decay via leptonic decay modes. Additional contributions arise from \( Wh + \text{jets} \) and \( Zb + \text{jets} \) when the \( h \) decays to \( b\bar{b} \) while the \( W/Z \) decays leptonically. Contributions from \( Wb + \text{jets}, Wc + \text{jets} \) (here, the \( c \) jet get mistagged as a \( b \) jet) and \( W + \text{jets} \) are also considered. Here, we have considered the NLO cross-section for \( \ell \bar{\ell} + \text{jets} \), where the NLO cross-section has been computed by multiplying the NLO \( k \) factor (\( k = 1.5 \)) with the LO cross-section obtained from MadGraph\_aMC@NLO. The cross-section of background processes have been listed in Appendix A.

Signal events have been generated for various combinations of \( M_{\chi^0_2} \) (= \( M_{\chi^\pm_1} \)) and \( M_{\chi^0_1} \). \( M_{\chi^0_2} \) has been varied from 200 GeV to 1 TeV with a step size of 25 GeV, while \( M_{\chi^0_1} \) has been varied between 25 GeV to \( M_{\chi^0_2} - 125 \) GeV with a step size of 10 GeV. Three different signal regions are chosen, SR1-A, SR1-B and SR1-C, aimed at maximizing the significance of signal events with small, intermediate and large mass difference, respectively, between the NLSP \( \chi^0_2, \chi^\pm_1 \) and LSP \( \chi^0_1 \). The selection cuts for SR1-A, SR1-B and SR1-C have been chosen by performing a cut based analysis for the three representative benchmark points: BP1-A: \( M_{\chi^0_2} = 200 \) GeV, \( M_{\chi^0_1} = 55 \) GeV, BP1-B: \( M_{\chi^0_2} = 350 \) GeV, \( M_{\chi^0_1} = 165 \) GeV and BP1-C: \( M_{\chi^0_2} = 500 \) GeV, \( M_{\chi^0_1} = 25 \) GeV, respectively. The values of \( \sigma_{\text{wino}}^{pp\to\chi^0_2\chi^\pm_1} \) for BP1-A, BP1-B and BP1-C have been listed in Appendix A. The signal yield (\( S \)) has been computed as follows:

\[
S = \sigma_{\text{wino}}^{pp\to\chi^0_2\chi^\pm_1} \times \mathcal{L} \times \text{Eff.} \times Br(\chi^0_2\chi^\pm_1 \to W_{\chi^0_1}h_{\chi^0_1} \to \ell\nu b\bar{b} + \text{jets})
\]

where, \( \mathcal{L} \) is the integrated luminosity (\( \mathcal{L} = 3000 \) fb\(^{-1} \) for HL-LHC) and \( \text{Eff.} \) represents the efficiency of the signal region\(^5 \).

A variety of kinematic variables have been used to design the optimized signal regions. First and foremost, the invariant mass of the two final state \( b \) jets, \( M_{b_1b_2} \) (\( b_1 \) and \( b_2 \) represents the \( p_T \) ordered leading and sub-leading \( b \) jets in the final state), is used to discriminate the background. For the signal process, the \( b\bar{b} \) pair is produced from the decay of the \( h \) and thereby peaks roughly around \( \sim 110-115 \) GeV. On the other hand, the \( M_{b_1b_2} \) distribution for the most dominant \( \ell \bar{\ell} + \text{jets} \) background has a smoothly falling distribution since the two \( b \) jets are produced from the decay of two different top quarks. The \( M_{b_1b_2} \)

\(^5 \text{Eff. is the ratio of the number of signal events which pass through a certain signal region (IEV) to the total number of generated signal events (NEV); } \text{Eff.} = \frac{\text{IEV}}{\text{NEV}}.\)
distribution for the signal benchmark points and the $t\bar{t} + jets$ background has been shown in Figure 2(a). The distributions for BP1-A, BP1-B and BP1-C in Figure 2 have been illustrated as red, blue and purple solid colors while the $t\bar{t} + jets$ background has been shown in brown color.

The $t\bar{t} + jets$ background also undergoes a considerable reduction upon the application of a lower bound on the contransverse mass ($M_{CT}$) [141, 142], where $M_{CT}$ is defined as,

$$M_{CT} = \sqrt{(E_T^{b1} + E_T^{b2})^2 - |p_T^{b1} - p_T^{b2}|^2}.$$ Here, $p_T^{b_i}$ and $E_T^{b_i}$ are transverse momentum and energy of the $i$-th $b$-jet. The normalized $M_{CT}$ distribution for the signal benchmark points and the $t\bar{t} + jets$ background has been shown in Figure 2 (b).

The invariant mass of the first three $p_T$ ordered light jets, $M_{j1j2j3}$, and the scalar sum of their transverse momenta, $H_T$, are also utilized in performing the cut based analysis. The larger mass difference ($\Delta M$) between $(\chi_2^0, \chi_1^\pm)$ and $\chi_1^0$ in BP1-C results in the $\chi_1^0$ being produced with a relatively larger boost, thereby, producing more collimated light jets from the decay of $\chi_0^0$. As a result, the kinematic variables constructed by using the momenta of the leading light jets ($H_T$ and $M_{j1j2j3}$) peak at a higher value for signal scenarios with large mass difference between the NLSP and the LSP (viz BP1-C) as compared to the cases where the $\chi_2^0$ and $\chi_1^0$ are closer in mass to each other (viz BP1-B and BP1-A).

In addition, the $\Delta R$ between the two final state b jets, $\Delta R_{b_1b_2}$, and the difference between the azimuthal angles of the final state lepton and the $E_T$, $\Delta \phi_{\ell, E_T}$, are also used in constructing the optimized signal regions. The three benchmark points, BP1-A, BP1-B and BP1-C, feature an on-shell $h$ produced from the decay of $\chi_2^0$. For the case of BP1-C, the relatively larger $\Delta M$ between $\chi_2^0$ and $\chi_1^0$ results in a $h$ with relatively larger boost as compared to the case of BP1-A and BP1-B. Thereby, the $b\bar{b}$ pair in the final state of BP1-C is more collimated. As a result, $\Delta R_{b_1b_2}$ in BP1-C peaks at a smaller value ($\Delta R_{b_1b_2} \sim 0.7$) than in BP1-B ($\Delta R_{b_1b_2} \sim 1.4$). Similarly, the $\Delta R_{b_1b_2}$ distribution for BP1-B peaks at a relatively lower value (at $\Delta R_{b_1b_2} \sim 1.1$) than for BP1-A. Furthermore, the $b\bar{b}$ pair which originates from the $t\bar{t} + jets$ background is generated from two different mother particles, and therefore, are widely separated in the azimuthal angle. Consequently, $\Delta R_{b_1b_2}$ for the $t\bar{t} + jets$ background peaks at further larger values ($\Delta R_{b_1b_2} \sim 3$). The normalized $\Delta R_{b_1b_2}$ distribution has been illustrated in Figure 2 (c), where the red, blue and purple solid lines represents BP1-A, BP1-B and BP1-C, respectively, while the brown colored region represents the $t\bar{t} + jets$ background. Additionally, we also consider the azimuthal

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*The cross-section for $t\bar{t} + jets$ process is roughly an order of magnitude higher than the other relevant backgrounds, and, therefore, for the sake of illustrative clarity, we display the kinematic distribution for the $t\bar{t} + jets$ background process only in Figure 2.*
FIG. 2: Normalized distributions of $M_{b_1 b_2}$ (top left), $M_{CT}$ (top right), $\Delta R_{b_1 b_2}$ (bottom left), $\Delta \Phi_{lE_T}$ (bottom right) are shown for BP1-A (red solid line), BP1-B (blue solid line), BP1-C (purple solid line) and the $t \bar{t} + \text{jets}$ background (brown color).

angular separation between the $l$ (produced from $W \rightarrow l \nu$) and $E_T$, represented as $\Delta \phi_{lE_T}$, in performing the cut-based analysis. For BP1-C, $\Delta \phi_{lE_T}$ peaks at a lower value than in BP1-B/BP1-A. The normalized distributions of $\Delta \phi_{lE_T}$ for BP1-A, BP1-B, BP1-C and $t \bar{t} + \text{jets}$ have been shown in Figure 2 (d).

It is to be noted that the top quark dominantly decays into a $bW$ pair and effectively contributes to the background when one of the $W$ boson undergoes leptonic decay while the other $W$ decays hadronically. One obtains two solutions for the z-component of momentum of the neutrino ($p_z^\nu$) produced from the leptonically decaying $W$: $p_z^\nu = (a_1 p_z^l \pm \sqrt{a_3})/a_2$, were, $a_1 = p_x^l E_x + p_y^l E_y + \frac{M_W^2}{2}$, $a_2 = E_{T}^2 - p_z^{l2}$ and
| Cut variables | \( M_{\nu_1} \) (GeV) | \( M_{\nu_2} \) (GeV) | \( \Delta R_{\nu_1\nu_2} \) | \( \Delta \theta_{\nu_1\nu_2} \) (GeV) | \( M_{\nu_3} \) (GeV) |
|---------------|----------------|----------------|----------------|----------------|----------------|
| Selection cuts for SR1-A | 70-130 | \( > 200 \) | \( < 1 \) | \( < 1.25 \) | \( > 190 \) |

**Table I:** Selection cuts corresponding to SR1-A, SR1-B and SR1-C, optimized to maximize the signal significance of signal processes with small, intermediate and large \( \Delta M \) between the NLSP \( \chi^+_1 \), \( \chi^+_2 \) and the LSP \( \chi^0_1 \), respectively, for searches in the \( Wh \) mediated \( 1l + 2b + jets + \text{MET} \) channel at the HL-LHC, are shown. The cut flow table for BP1-A, BP1-B and BP1-C and the relevant backgrounds are also tabulated along with the respective signal significance values.

\[
\alpha_3 = E'^2 \alpha_1^2 - a_2 E'^2 (E^2_{x} + E^2_{y})
\]

with \( p^\nu_{x,y,z} \) representing the \( x\)-, \( y\)-, \( z\)- components of momentum of the lepton, \( E' \) representing the energy of the lepton, and \( E_{x,y} \) represents the \( x\)-component and \( y\)-component of the missing transverse energy. The signal process considered in the current analysis contains two \( b\) jets in the final state, and, coupled with the two possible solutions for \( \phi_{z}^\nu \), results in two different values of
$M_{l \nu_T b_1}$ ($j = 1, 2$) and two values of $M_{l \nu_T b_2}$. Here, $M_{l \nu_T b_i}$ ($i = 1, 2$) represents the invariant mass of the final state lepton, the missing energy and the $b$ jets. The $M_{l \nu_T b_i}$ variable is effective against the $t\bar{t} + jets$ background where the only contribution to $E_T$ comes from the $\nu$ produced by the leptonically decaying $W$. In this regard, we compute all four values of $M_{l \nu_T b_i}$ and choose the combination whose value is closest to the top mass. The invariant mass of the aforesaid combination is represented as $M_{l \nu_T}$, and has been used in performing the cut based analysis.

FIG. 3: The projected discovery and exclusion regions are shown in dark blue and light blue colors, respectively, in the $M_{\chi^0_2-\chi^\pm_1}$ plane. The projection contours have been derived from searches in the $1l+2b+jets+E_T$ final state resulting from the cascade decay of directly produced wino-like $\chi^0_2 \chi^\pm_1$ pair within a simplified model scenario containing $\lambda''_{112u} d s c$ type RPV term. The solid black line represents the current observed limit at 95% C.L. from direct wino searches in the WH mediated $1l+2b+E_T$ final state, in a RPC simplified scenario, derived by ATLAS using the LHC Run-II dataset collected at $\mathcal{L} \sim 139$ fb$^{-1}$ [61]. The light green colored region corresponds to the projected exclusion reach (at 95% C.L.) of HL-LHC, derived by ATLAS, in direct wino searches in the WH mediated $1l+2b+E_T$ final state within a simplified RPC scenario [132]. The brown dashed line represents the condition for on-shell Higgs production ($M_{\chi^0_2-\chi^\pm_1} - M_{\chi^0_1} = 125$ GeV).

The optimized selection cuts corresponding to SR1-A, SR1-B and SR1-C have been shown in Table I. The signal yields for BP1-A, BP1-B and BP1-C, along with the corresponding background yields obtained after successive application of selection cuts listed in SR1-A, SR1-B and SR1-C, respectively, have also been shown in Table I. It should be noted that the signal significances$^7$ tabulated in Table I have been

$^7$ The signal significance is computed as $S/\sqrt{B}$, where $S$ and $B$ are the signal and background yields.
obtained without assuming any systematic uncertainty. SR1-A results in a signal significance of 5.9 for BP1-A, while SR1-B and SR1-C has a signal significance of 2.0 and 4.4 for BP1-B and BP1-C, respectively.

We also derive the projected exclusion limits in the $M_{\chi^0_1} - M_{\chi^0_{2,\chi^\pm_1}}$ plane from direct wino searches at the HL-LHC in the $W\chi$ mediated $1l + 2b + jets + \not{E}_T$ search channel. The value of signal significance is computed for the three optimized signal regions and the maximum among them is considered in deriving the projection regions\(^8\). The projected exclusion and discovery region corresponds to the sector with signal significance $> 2\sigma$ and $> 5\sigma$, respectively. They have been represented in light blue and dark blue colors, respectively, in Figure 3. The brown dashed line in the same figure corresponds to the on-shell mass condition for $h$ production and represents the mass correlation: $M_{\chi^0_2} - M_{\chi^0_1} = 125 \text{ GeV}$. It can be observed from Figure 3 that within the framework of a $\lambda''_{112}u^c d^c s^c$ type RPV simplified scenario, direct wino searches at the HL-LHC in the $W\chi$ mediated $1l + 2b + jets + \not{E}_T$ search channel has a potential exclusion (discovery) reach up to $\sim 630 \text{ GeV}$ ($\sim 450 \text{ GeV}$) for a bino-like $M_{\chi^0_1} \sim 0 \text{ GeV}$.

The ATLAS collaboration has also analyzed the current observed limit ($\sqrt{s} = 13 \text{ TeV}, \mathcal{L} = 139 \text{ fb}^{-1}$) as well as the projected reach of direct wino production at the HL-LHC in the analogous channel for the RPC scenario: $W\chi$ mediated $1l + 2b + \not{E}_T$ final state in [61] and [132], respectively. The current observed limit (at 95% C.L.) reaches up to $M_{\chi^0_{2,\chi^\pm_1}} \sim 720 \text{ GeV}$ for $M_{\chi^0_1} = 100 \text{ GeV}$. The projected exclusion and discovery contour of ATLAS reaches up to $M_{\chi^0_{2,\chi^\pm_1}} \sim 1300 \text{ GeV}$ and $\sim 600 \text{ GeV}$ for a bino like $\chi^0_1$ with mass up to 100 GeV at 95% C.L.. The ATLAS exclusion contour has been shown in light green color in Figure 3. Thus, the projected reach of direct wino searches interpreted in a RPC simplified scenario can get significantly weakened in the presence of $\lambda''_{112}u^c d^c s^c$ type RPV coupling. In the next three subsections, we further study the collider implications of RPV couplings in different final states.

**B. Searches in $W\chi$ mediated $1l + 2\gamma + jets(N_j \geq 2) + \not{E}_T$ channel**

In the current subsection, we consider the process: $pp \rightarrow \chi^\pm_1 \chi^0_2 \rightarrow (W\chi^0_1) (h\chi^0_1) \rightarrow (lvuds) (\gamma\gamma uds)$, which culminates in $1l + 2\gamma + jets + \not{E}_T$ final state (Figure 1(b)). Here, $Br(\chi^\pm_1 \rightarrow W\chi^0_1)$ and $Br(\chi^0_2 \rightarrow h\chi^0_1)$, have been assumed to be 100%. The small branching rate of $h \rightarrow \gamma\gamma$ is a significant drawback for this channel, however, a large photon detection efficiency, sharp di-photon invariant mass peak and a smaller background makes it a promising one. Unlike the $W\chi$ mediated $1l + 2b + jets + \not{E}_T$ channel (discussed in

\(^8\) The same strategy has been followed in all the analyses considered in this work.
Section II A), no HL-LHC projection study has been performed for the analogous RPC scenario channel ($Wh$ mediated $l + 2\gamma + E_T$).

The event selection criteria requires the presence of exactly one isolated lepton ($l = e, \mu$), two photons, and at least two light jets ($N_j > 2$) in the final state. The lepton isolation criteria specified in Section II A is implemented here as well. The final state lepton, jets and photons satisfy the criteria: $|\eta^{l, jet, \gamma}| < 2.5$ and $p_T^{l, jet, \gamma} > 30\,\text{GeV}$ respectively. In addition, we demand that no pair of final state particles must be within $\Delta R < 0.5$ of each other. Furthermore, a $b$-jet veto is applied.

**FIG. 4:** Normalized distribution of $M_{j_1j_2j_3}$ (top left), $H_T$ (top right), $\Delta\phi_{Wh}$ (bottom left) and $M_T^{Wh\gamma}$ (bottom right) are shown for BP2-A (blue solid line), BP2-B (purple solid line), BP2-C (red solid line). The corresponding distributions for $t\bar{t}h + \text{jets}$ and $Wh + \text{jets}$ are also shown in brown and green colored regions.
The selection cuts corresponding to the signal regions: SR2-A, SR2-B and SR2-C designed to maximize the signal significance of BP2-A, BP2-B and BP2-C, respectively, for searches in the Wh mediated \(1l + 2\gamma + \text{jets} + E_T\) channel, are listed. The cut flow table for BP2-A, BP2-B, BP2-C and other relevant backgrounds are also tabulated. The signal significance values have also been listed.

The most dominant contribution to the background comes from the \(tt\bar{t}h + \text{jets}\) and \(W h + \text{jets}\) processes. Sub-dominant contribution to the background arises from \(Zh + \text{jets}\) and \(W/Z + \text{jets}\) processes.

The signal events have been generated by varying \(M_{\chi_2^0} (= M_{\chi_1^\pm})\) in between 200 GeV to 1000 GeV with a step size of 25 GeV, while \(M_{\chi_1^0}\) has been varied between 25 GeV to \(M_{\chi_2^0}\) \(- 125\) GeV, with a step size of 25 GeV. We choose three representative benchmark points, BP2-A: \(M_{\chi_2^0} = 250\) GeV, \(M_{\chi_1^0} = 100\) GeV

\[9\] The \(W/Z + \text{jets}\) process contributes to the background of the \(1l + 2\gamma + \text{jets} + E_T\) signal when the \(W/Z\) decays leptonically and \(\text{jets}\) get faked as photons. In the present analysis, we have assumed a jet \(\rightarrow \gamma\) fake rate of 0.05% \cite{143}.
(small $\Delta M$), BP2-B: $M_{\chi^0_2} = 425$ GeV, $M_{\chi^0_1} = 100$ GeV (intermediate $\Delta M$), and BP2-C: $M_{\chi^0_2} = 600$ GeV, $M_{\chi^0_1} = 150$ GeV (large $\Delta M$), and perform a cut-based collider analysis. The cross-section values for the background processes and the signal benchmark points have been listed in Appendix A.

The kinematic variables used to perform the cut-based analysis are: $M_{\gamma\gamma}$ (invariant mass of the di-photon pair), $M_{j_1j_2j_3}$ (invariant mass of the three leading jets), $H_T$ (scalar sum of transverse momenta of the three leading jets), $\Delta \phi_{Wh}$ (difference in the azimuthal angle of the lepton-$E_T$ system and the $\gamma\gamma$ system (originated from $h$)) and the transverse mass of the $W\gamma_i$ system, $M_{W\gamma i}^T$. Here $M_{W\gamma i}^T (i = 1, 2)$ is defined as $M_{W\gamma i}^T = \sqrt{M_W^2 + |p_{T\gamma_i}|^2 - 2M_{W}E_{T\gamma_i}}$. $M_W$, $E_T$ are the transverse mass, energy and momentum of the leptonically decaying $W$ boson, respectively. $E_{T\gamma_i}$ and $p_{T\gamma_i}$ are the transverse energy and momentum of the $i^{th}$ photon.

The list of selection cuts for these three signal regions along with the cut flow for the three benchmark points have been tabulated in Table II. The total background yield corresponding to the three signal regions, the corresponding signal yields for BP2-A, BP2-B and BP2-C and the signal significances obtained from the cut-based analysis have also been tabulated in Table II. In the current case, SR2-A, SR2-B, SR2-C yield a signal significance of 8.0, 8.5, 2.5 for BP2-A, BP2-B and BP2-C respectively. It is also worthwhile to note the excellent $S/B$ values for the optimixed signal regions. Here, SR2-A, SR2-B and SR2-C results in an exceptional $S/B$ value of 2.89 (for BP2-A), 3.64 (for BP2-B) and 1.18 (for BP2-C), respectively.

The projected $2\sigma$-exclusion (light blue) and discovery regions (dark blue) derived from direct wino searches in the $Wh$ mediated $1l+2\gamma+jets+E_T$ final state at the HL-LHC, have been shown in the $M_{\chi^0_2}-M_{\chi^0_1}$ plane, in Figure 5. The brown dashed line corresponds to the on-shellness condition of $h$: $M_{\chi^0_2,\chi^0_1} - M_{\chi^0_1} = 125$ GeV. It can be observed from Fig. 5 that in the presence of $\lambda''_{112}a^ud^vs^c$ type of RPV operator, direct wino searches at the HL-LHC are projected to exclude winos up to $\sim 700$ GeV at $2\sigma$ and the projected wino discovery reach is up to $\sim 600$ GeV for a massless $\chi^0_1$. 

The normalized distributions of $M_{j_1j_2j_3}$, $H_T$, $\Delta \phi_{Wh}$ and $M_{W\gamma i}^T$ for BP2-A (blue solid line), BP2-B (purple solid line) and BP2-C (red solid line), are represented in Figure 4 (a), (b), (c) and (d), respectively. The normalized distributions of the dominant background processes: $t\bar{t}+jets$ and $Wh+jets$, are also shown as brown and green colored regions, respectively. In analogy with the analysis in Section II A, the normalized distributions of $M_{j_1j_2j_3}$ and $H_T$ for BP2-C is relatively wider and falls smoothly when compared to the analogous distributions for BP2-A and BP2-B. This feature is due to the larger mass splitting between $\chi^0_2$ ($\chi^\pm_1$) and $\chi^0_1$. 

The projected 2$\sigma$-exclusion (light blue) and discovery regions (dark blue) derived from direct wino searches in the $Wh$ mediated $1l+2\gamma+jets+E_T$ final state at the HL-LHC, have been shown in the $M_{\chi^0_2}-M_{\chi^0_1}$ plane, in Figure 5. The brown dashed line corresponds to the on-shellness condition of $h$: $M_{\chi^0_2,\chi^0_1} - M_{\chi^0_1} = 125$ GeV. It can be observed from Fig. 5 that in the presence of $\lambda''_{112}a^ud^vs^c$ type of RPV operator, direct wino searches at the HL-LHC are projected to exclude winos up to $\sim 700$ GeV at $2\sigma$ and the projected wino discovery reach is up to $\sim 600$ GeV for a massless $\chi^0_1$. 

The kinematic variables used to perform the cut-based analysis are: $M_{\gamma\gamma}$ (invariant mass of the di-photon pair), $M_{j_1j_2j_3}$ (invariant mass of the three leading jets), $H_T$ (scalar sum of transverse momenta of the three leading jets), $\Delta \phi_{Wh}$ (difference in the azimuthal angle of the lepton-$E_T$ system and the $\gamma\gamma$ system (originated from $h$)) and the transverse mass of the $W\gamma_i$ system, $M_{W\gamma i}^T (i = 1, 2)$. Here $M_{W\gamma i}^T (i = 1, 2)$ is defined as $M_{W\gamma i}^T = \sqrt{(M_W^W)^2 + 2E_W^W E_{T\gamma_i}^\gamma - 2p_{T\gamma_i}^W p_{T\gamma_i}^\gamma}$. $M_W$, $E_T$ are the transverse mass, energy and momentum of the leptonically decaying $W$ boson, respectively. $E_{T\gamma_i}$ and $p_{T\gamma_i}$ are the transverse energy and momentum of the $i^{th}$ photon.
FIG. 5: The projected exclusion (light blue) and discovery (dark blue) regions in the mass plane of $M_{\chi_0^1}$ vs. $M_{\chi_2^0, \chi_1^\pm}$ in the Wh simplified model with mass degenerate wino like $\chi_1^\pm, \chi_2^0$ and bino like $\chi_0^1$, and with one RPV term ($\lambda''_{112} u^c d^c s^c$). The brown line denotes the line $M_{\chi_0^1, \chi_1^\pm} - M_{\chi_2^0} = 125$ GeV.

C. Searches in the $WZ$ mediated $3l + jets(N_j \geq 2) + \not{E}_T$ channel

A study by the ATLAS collaboration, which probed the future reach of directly produced winos in the $WZ$ mediated $3l + \not{E}_T$ final state at the HL-LHC \([132]\), shows a projected exclusion reach up to $M_{\chi_2^0, \chi_1^\pm} \sim 1150$ GeV for a bino like $M_{\chi_0^1} \sim 100$ GeV at 95% C.L. The future reach of direct wino searches at HL-LHC in the $Wb$ mediated $3l + \not{E}_T$ channel has also been studied by ATLAS in \([144]\). The projected reach excludes winos upto $\sim 650$ GeV for $M_{\chi_0^1} \sim 0$ GeV at 95% C.L.. One of the main reasons behind the weaker reach of Wh mediated $3l + \not{E}_T$ channel compared to the $WZ$ mediated process is the longer cascade decay chain in the former case. This results in a smaller event yield even if one assumes a similar signal region efficiency. In the current subsection, we focus only on the analogous $WZ$ mediated final state reinterpreted in $\lambda''_{112}$ type RPV simplified scenario.

In the presence of a $\lambda''_{112}$ type RPV coupling, the $\chi_0^1$ would decay into $\chi_0^1 \rightarrow uds$ resulting in $WZ$ mediated $3l + jets + \not{E}_T$ final state and the projected exclusions are expected to alter. In the present subsection, we explore this facet and study the projected future reach of $WZ$ mediated $3l + jets + \not{E}_T$ final state at the HL-LHC within the framework of a simplified $\lambda''_{112}$ type RPV scenario. The Feynman diagram of the signal process under consideration is illustrated in Figure 1 (c). The decay chain proceed
FIG. 6: Normalized distributions of $M_{\text{SFOS}}^{ll}$, $M_{\chi_1^0 \chi_2^0}$ and $H_T$, for the signal benchmark points, BP3-A (red solid line), BP3-B (blue solid line) and BP3-C (purple solid line), corresponding to the cascade decay process: $pp \rightarrow \chi_1^\pm \chi_2^0 \rightarrow (\chi_1^\pm \rightarrow W^\pm \rightarrow l\nu)(\chi_2^0 \rightarrow uds) (\chi_1^0 \rightarrow (Z \rightarrow ll)) (\chi_1^0 \rightarrow uds)$, are shown. The brown and green colored distributions represent the most important background processes: $WZ + \text{jets}$ and $ZZ + \text{jets}$, respectively.

An event is required to have exactly three isolated leptons with $p_T > 30$ GeV and at least two light jets with $p_T > 20$ GeV in the final state. Among the three final state leptons, two are required to form a same flavor opposite charge (SFOS) lepton pair with invariant mass in the range of $|M_Z \pm 25$ GeV|. In presence of two different SFOS lepton pairs with invariant mass within $|M_Z \pm 25$ GeV|, the SFOS
pair with invariant mass closest to the Z boson mass is considered to be the correct SFOS pair and their invariant mass is represented as $M_{ll}^{SFOS}$. The lepton isolation criteria discussed in Section II A is applied here as well.

The important sources of background are $WZ + jets$, $ZZ + jets$ and $VVV + jets$ ($V = W, Z$). Potential contribution to background can also arise from $Wh + jets$ and $Zh + jets$ processes, however, their contribution is much lesser when compared to the diboson and triboson backgrounds. Consequently, we ignore the contribution from both, $Wh + jets$ and $Zh + jets$.

The signal events have been generated for various combinations of $M_{\chi_2^0} (= M_{\chi_1^\pm})$ and $M_{\chi_1^0}$. $M_{\chi_2^0,\chi_1^\pm}$ has been varied in between 200 GeV and 1000 GeV with a step size of 25 GeV while $M_{\chi_1^0}$ has been varied from 25 GeV to $M_{\chi_2^0,\chi_1^\pm} - M_Z$ with a step size of 10 GeV. Three representative signal benchmark points with small $\Delta M$ (BP3-A: $M_{\chi_2^0} = M_{\chi_1^\pm} = 400$ GeV, $M_{\chi_1^0} = 175$ GeV), intermediate $\Delta M$ (BP3-B: $M_{\chi_2^0} = M_{\chi_1^\pm} = 600$ GeV, $M_{\chi_1^0} = 325$ GeV) and large $\Delta M$ (BP3-C: $M_{\chi_2^0} = M_{\chi_1^\pm} = 650$ GeV, $M_{\chi_1^0} = 175$ GeV) are chosen. Three optimized signal regions are chosen: SR3-A, SR3-B and SR3-C, with optimized selection cuts which maximize the signal significances of BP3-A, BP3-B and BP3-C, respectively. Appendix A lists the cross-section of the background and signal benchmark points.

The kinematic variables used to perform the cut-based analysis are: invariant mass of the SFOS pair of leptons ($M_{ll}^{SFOS}$), invariant mass of the three leading $p_T$ ordered jets ($M_{j_1j_2j_3}$), the scalar sum of the transverse momenta of the three leading $p_T$ ordered jets ($H_T$) and the missing transverse energy ($E_T$).

$M_{ll}^{SFOS}$, $M_{j_1j_2j_3}$ and $H_T$ are observed to be among the most efficient variables in discriminating the signal from the backgrounds. The normalized distributions of $M_{ll}^{SFOS}$, $M_{j_1j_2j_3}$ and $H_T$ for the signal benchmark points: BP3-A (red solid line), BP3-B (blue solid line) and BP3-C (purple solid line), and the most important background processes: $WZ + jets$ (brown colored region) and $ZZ + jets$ (green colored region), have been illustrated in Figure 6 (a), 6 (b) and 6 (c), respectively. The selection cuts for the respective signal regions are shown in Table III. The signal and background yields obtained upon the successive application of the selection cuts have also been listed in Table III along with the respective values of signal significance.

The future reach of direct wino searches in the $WZ$ mediated $3l + jets + E_T$ final state at HL-LHC is studied. In this context, we evaluate the projected exclusion ($> 2\sigma$) and projected discovery ($> 5\sigma$) contours assuming zero systematic uncertainty in the $M_{\chi_2^0,\chi_1^\pm} - M_{\chi_1^0}$ plane (shown in Figure 7). The light blue colored region and the dark blue colored regions in Figure 7 represents the projected
TABLE III: The selection cuts on $M_{\ell\ell}^{SFOS}$, $E_T$, $M_{j_1j_2j_3}$ and $H_T$ are listed for the three optimized signal regions: SR3-A, SR3-B and SR3-C, optimized to maximize the signal significance in the WZ mediated 3l + jets + $E_T$ final state. The cut flow table showing the signal and background yields upon the successive application of selection cuts is also presented. The maximal value of signal significance obtained from the cut based optimization procedure is also shown.

exclusion and discovery reach, respectively. The brown dashed line represents the mass correlation: $M_{\chi^0_{1}} - M_{\chi^0_{2}} = M_Z$. The projected exclusion region has a reach up to $M_{\chi^0_{1}} - M_{\chi^0_{2}} = 650$ GeV (wino like) for a bino like $M_{\chi^0_{1}} = 100$ GeV, while the projected discovery region has a potential reach up to $M_{\chi^0_{1}} - M_{\chi^0_{2}} = 480$ GeV (wino like) for a bino like $M_{\chi^0_{1}} = 100$ GeV. It is to be noted that within the simplified RPC scenario, the projected exclusion contour (at 95% C.L.) of direct wino searches in the WZ mediated 3l + $E_T$ channel at the HL-LHC reaches up to $\sim 1150$ GeV for a $\chi^0_{1}$ with mass up to $\sim 100$ GeV, as evaluated by ATLAS in [132] (shown as green dashed line in Figure 7). Thus, within the $\chi^0_{112}u^c d^c s^c$ type
FIG. 7: The projected discovery reach (dark blue) and the projected exclusion reach (light blue) from direct wino searches in the $pp \rightarrow \chi_1^\pm \chi_2^0 \rightarrow 3l + \text{jets} + \not{E}_T$ final state at the HL-LHC is shown in the $M_{\chi_2^0, \chi_1^-} - M_{\chi_1^0}$ plane. The solid black and the dashed black line represents the observed limits (at 95% C.L.) derived by ATLAS ($\sqrt{s} = 13$ TeV, $L \sim 139$ fb$^{-1}$) [60] and CMS ($\sqrt{s} = 13$ TeV, $L \sim 36$ fb$^{-1}$) [132], respectively, from direct wino searches in the $WZ$ mediated $3l + \not{E}_T$ channel within a simplified RPC framework. The light green colored region represents the 95% C.L. projected exclusion region derived by ATLAS [132] from direct wino searches in the $3l + \not{E}_T$ final state at the HL-LHC within a simplified RPC framework. The brown dashed line represents the mass correlation: $M_{\chi_1^- \chi_2^0} - M_{\chi_1^0} = M_Z$.

RPV simplified scenario, the projected reach of HL-LHC in direct wino searches in the $3l + \text{jets} + \not{E}_T$ channel is rendered considerably weaker compared to the projected reach of the analogous search in the RPC scenario.

D. Searches in the $WZ$ mediated $3l + 2b + \text{jets}(N_j \geq 2) + \not{E}_T$ channel

In the present subsection, we evaluate the HL-LHC prospects of direct wino searches in the $WZ$ mediated $3l + 2b + \text{jets} + \not{E}_T$ final state, produced from the cascade decay of directly produced wino like mass degenerate $\chi_2^0 \chi_1^\pm$ pair. Owing to the presence of $\lambda''_{113} u'^c d'^c b'^c$ RPV operator, $\chi_1^0$ decays as: $\chi_1^0 \rightarrow udb$. Unlike the previous section, the relevant decay chain proceeds as follows: $pp \rightarrow \chi_1^\pm \chi_2^0 \rightarrow (W\chi_1^0) \left(Z\chi_1^0\right) \rightarrow (lvudb) \ (lludb)$, resulting in $WZ$ mediated $3l + 2b + \text{jets} + \not{E}_T$ final state. Although the channel containing $3l$ in the final state is substantially analysed, $3l + 2b + \text{jets} + \not{E}_T$ final state is not commonly studied in RPC scenario.
FIG. 8: Normalized distributions of $M^{\text{SFO}}_{\ell\ell}$, $\not{E}_T$, and $H_T$ corresponding to the signal benchmark points, BP4-A (red solid line), BP4-B (blue solid line) and BP4-C (purple solid line), in the $3l + 2b + \text{jets} + \not{E}_T$ final state is shown. The respective normalized distributions for the most significant background processes: $t\bar{t}Z$ and $VVV + \text{jets}$ are also displayed as brown and green colored regions, respectively.

The event selection criteria requires the presence of three isolated leptons in the final state along with two $b$ jets and at least two light jets. The final state leptons, $b$ jets and light jets are required to have $p_T > 30$ GeV and the pseudorapidity must lie within a range of $|\eta| \leq 2.5$. Here as well, we demand the presence of at least one SFOS pair out of the final state leptons with invariant mass $M^{\text{SFO}}_{\ell\ell}$ in the range of $M_Z \pm 25$ GeV. In the presence of two such SFOS pairs, the one with invariant mass closest to the $Z$ boson mass is chosen to be the correct one. The background to the $3l + 2b + \text{jets} + \not{E}_T$ final state is
The selection cuts for the three signal regions (SR4-A, SR4-B, and SR4-C) are described in Table IV. These regions are defined by cuts on the missing transverse momentum ($\vec{E}_T$), the transverse mass ($H_T$), and the dilepton mass ($M_{SFOS}^{ll}$). The signal regions are optimized to maximize the signal significance for the wino searches. The signal significance values for BP4-A, BP4-B, and BP4-C are also listed in the table.

Three representative benchmark points: BP4-A ($M_{\chi^0_2}\chi^{\pm}_1 = 250$ GeV, $M_{\chi^0_1} = 135$ GeV), BP4-B ($M_{\chi^0_2}\chi^{\pm}_1 = 600$ GeV, $M_{\chi^0_1} = 205$ GeV) and BP4-C ($M_{\chi^0_2}\chi^{\pm}_1 = 700$ GeV, $M_{\chi^0_1} = 85$ GeV) are chosen according to small, medium and large mass splittings between $\chi^0_2(\chi^{\pm}_1)$ and $\chi^0_1(\chi^{\pm}_1)$. Cut based analysis is performed by optimizing the selection cuts on $M_{ll}^{SFOS}$, $\vec{E}_T$ and $H_T$ to maximize the signal significance.

The normalized distribution of $M_{ll}^{SFOS}$, $\vec{E}_T$ and $H_T$, both for signal and dominant backgrounds have
been illustrated in Figure 8 (a), (b) and (c), respectively. The red, blue and purple solid lines represent
the normalized distributions of BP4-A, BP4-B and BP4-C respectively, while the most dominant back-
grounds: $t\bar{t}Z$ and $VVV + jets$ have been represented by green and brown colored regions respectively.
Since BP4-A features lower mass difference between $\chi_0^2(\chi_1^\pm)$ and $\chi_1^0$ than BP4-B and BP4-C, the light
jets emanating from the decay of less boosted $\chi_1^0$ in BP4-A carry relatively smaller $p_T$ as compared to
the jets produced from the decay $\chi_1^0$ in the other two benchmark points. This in turn shifts the peak of
the $H_T$ distribution towards higher values for BP4-B and BP4-C.

![Diagram](image)

**FIG. 9:** The projected discovery (dark blue colored) and exclusion (light blue colored) regions for direct wino searches in
the $3l + 2b + jets + \slashed{E_T}$ channel at the HL-LHC. The final state is an implication of $\lambda'_{1,3}u'd'b'$ type RPV operator which
implies $\chi_1^0 \rightarrow udb$. The brown line corresponds to $M_{\chi_2^0,\chi_1^\pm} - M_{\chi_1^0} = M_Z$.

The signal and background cross-sections can be seen in Appendix A. The signal significances are
optimized for three signal regions: SR4-A, SR4-B and SR4-C. The list of selection cuts on $M_{ll}^{SFOS}$, $\slashed{E_T}$
and $H_T$ corresponding to the three signal regions have been itemized in Table IV. The cut flow exhibiting
the signal and background yields is also presented in Table IV along with signal significance.

We derive the projected exclusion and discovery contour in the context of HL-LHC, which have been
illustrated in light blue and dark blue colors, respectively, in Figure 9. The brown dashed line corresponds
to the mass correlation: $M_{\chi_1^\pm,\chi_2^0} - M_{\chi_1^0} = M_Z$. The projected exclusion region reaches up to $M_{\chi_1^\pm,\chi_2^0} \sim$
600 GeV for wino like $\chi_1^\pm, \chi_2^0$ and bino like $\chi_1^0$ with mass in the range $\sim [150 − 250]$ GeV.

Thus, we observe that a variety of interesting multiparticle final states can be produced from the
cascade decay of direct wino production on account of the introduction of $R$-parity violating operators, many of which display a strong potential to be excluded and even discovered at the HL-LHC. In the present work, we explored the future prospects of two different types of RPV operator: $\lambda''_{112} x^e d^c s^c$ (in $Wh$ mediated $1l+2b+jets+\not{E}_T$ channel, $Wh$ mediated $1l+2\gamma+jets+\not{E}_T$ channel, $WZ$ mediated $3l+jets+\not{E}_T$ channel) and $\lambda''_{113} u^c d^c c^c$ (in $Wh$ mediated $1l+2b+jets+\not{E}_T$ channel, $Wh$ mediated $1l+2\gamma+jets+\not{E}_T$ channel, $WZ$ mediated $3l+jets+\not{E}_T$ channel) by performing a detailed cut based analysis involving all relevant background processes. We intend to evaluate the implications from various other types of RPV operators on a multitude of search channels in an ongoing work. A more sophisticated analysis of the underlying final state jets and better understanding of the multiparticle backgrounds might help in further improving the future discovery prospects in these channels. Before concluding this work, we briefly discuss the implications from pure higgsino searches and also analyze the projected sensitivity for a few realistic MSSM benchmark points where the neutralinos and charginos are gaugino-higgsino admixtures.

III. BENCHMARK SCENARIOS

We begin our discussion in this section by considering two benchmark points with higgsino-like $\chi_2^0, \chi_3^0, \chi_1^\pm$ and bino-like $\chi_1^0$: BP-$\alpha_H$ \((M_{\chi_3^0,\chi_2^0,\chi_1^\pm} = 450$ GeV, $M_{\chi_1^0} = 150$ GeV) and BP-$\beta_H$ \((M_{\chi_3^0,\chi_2^0,\chi_1^\pm} = 500$ GeV, $M_{\chi_1^0} = 200$ GeV) and contrast their projected detectability at the HL-LHC with their pure wino counterparts: BP-$\alpha_W$ \((M_{\chi_3^0,\chi_1^\pm} = 450$ GeV, $M_{\chi_1^0} = 150$ GeV) and BP-$\beta_W$ \((M_{\chi_3^0,\chi_1^\pm} = 500$ GeV, $M_{\chi_1^0} = 200$ GeV), for the four signal channels considered in this work. BP-$\alpha_W$ and BP-$\beta_W$ fall within the projected exclusion reach of direct wino searches in the $Wh$ mediated $1l+2b+jets+\not{E}_T$ final state (see Figure 3). However, direct higgsino searches in the same search channel results in a signal significance of $\sim 1.56$ and $\sim 0.83$ for their pure-higgsino counterparts BP-$\alpha_H$ and BP-$\beta_H$, respectively, thereby, putting both these benchmark points outside the projected exclusion region. BP-$\alpha_W$ also falls within the projected discovery reach of direct wino searches in the other three search channels (see Figure 5, 7 and 9). However, direct higgsino searches for BP-$\alpha_H$ result in a signal significance of $\sim 2.94$, $\sim 2.30$ and $\sim 1.76$ in $Wh$ mediated $1l+2\gamma+jets+\not{E}_T$, $WZ$ mediated $3l+jets+\not{E}_T$ and $WZ$ mediated $3l+2b+jets+\not{E}_T$ search channels, respectively, and thus, BP-$\alpha_H$ falls within (outside) the projected exclusion (discovery) reach of the aforementioned former two channels and even outside the projected exclusion region of the later search channel. BP-$\beta_W$ also falls within the projected discovery reach of direct wino searches in the $Wh$ mediated $1l+2\gamma+jets+\not{E}_T$ channel, and within the projected exclusion reach in the $WZ$ mediated $3l+jets+\not{E}_T$ channel.
TABLE V: The $\chi^+_1 \chi^0_2$ production cross-section and $\text{Br}(\chi^0_2 \rightarrow Z/ h \chi^0_1)$ are shown against the different $\tan \beta$ values for $\text{BP-} \beta_W$. The respective signal significance values in the 4 analysis channels (3 signal regions in each channel) considered in this work are also listed.

| $\tan \beta$ | $\sigma(\chi^+_1 \chi^0_2)$ (fb) | $\text{Br}(\chi^0_2 \rightarrow Z/ h \chi^0_1)$ (%) | $\text{Br}(\chi^+_1 \rightarrow h \chi^0_1)$ (%) | $\text{Wh}$ mediated $1 + 2b + jets + E_T$ | $\text{Wh}$ mediated $1 + 2\gamma + jets + E_T$ | $\text{WZ}$ mediated $3l + jets + E_T$ | $\text{WZ}$ mediated $3l + 2b + jets + E_T$ |
|-------------|------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 5           | 22.65      | 1.65            | 98.34           | 0.49            | 0.73            | 0.92            | 1.57            |
| 8           | 22.80      | 3.26            | 96.74           | 0.49            | 0.72            | 0.91            | 1.56            |
| 10          | 22.79      | 4.25            | 95.74           | 0.48            | 0.71            | 0.90            | 1.54            |
| 15          | 22.48      | 6.35            | 93.64           | 0.46            | 0.69            | 0.87            | 1.49            |
| 20          | 22.47      | 7.98            | 92.01           | 0.45            | 0.68            | 0.85            | 1.46            |
| 25          | 22.74      | 9.25            | 90.74           | 0.45            | 0.68            | 0.85            | 1.46            |
| 30          | 22.65      | 10.26           | 89.73           | 0.45            | 0.66            | 0.84            | 1.44            |
| 40          | 22.65      | 11.77           | 88.22           | 0.44            | 0.65            | 0.82            | 1.41            |

and $WZ$ mediated $3l + 2b + jets + E_T$. On the contrary, in direct higgsino searches, the signal significance of $\text{BP-} \beta_W$ marginally crosses $2\sigma$ in the $\text{Wh}$ mediated $1l + 2\gamma + jets + E_T$ channel, while registers a value of $\sim 1.66$ and $\sim 1.4$ in the $WZ$ mediated $3l + jets + E_T$ and $WZ$ mediated $3l + 2b + jets + E_T$ channels, respectively. The direct higgsino searches, thus, imply weaker exclusion reach than the analogous wino counterparts, mainly, due to a smaller production cross-section.

In the MSSM, the tree level electroweakino sector is governed by four input parameters: $M_1$ (bino mass parameter), $M_2$ (wino mass parameter), $\mu$ (higgsino mass parameter) and $\tan \beta$ (ratio of vacuum expectation value of the two Higgs doublets). We first consider the case of $\text{BP-} \beta_W$ ($M_1 \sim 200$ GeV, $M_2 \sim 500$ GeV, $\mu \sim 2$ TeV) and study the collider implications of varying $\tan \beta$. In this respect, we consider 8 benchmark points with different values of $\tan \beta \sim 5, 8, 10, 15, 20, 25, 30, 40$ ($M_1, M_2$ and $\mu$ are kept fixed at the aforesaid values) and compute their signal significance in the 4 signal channels considered in this work. In these benchmark points, the sleptons and the squarks have been decoupled by fixing their masses at $\sim 3$ TeV and $\sim 1.5$ TeV, respectively. In the case of $\text{BP-} \beta_W$, $\chi^0_3, \chi^0_4, \chi^\pm_2$ have a dominant higgsino composition with a mass of $\sim 2$ TeV. Being heavier, the direct production cross-section of the chargino-neutralino pairs involving any of these higgsino-like inos is negligible compared to the production cross-section of the wino-like $\chi^\pm_1 \chi^0_2$ pair. Consequently, we only consider the direct production of $\chi^\pm_1 \chi^0_2$ pair while computing the signal significance and ignore the contributions from the other ino pairs. Here,
FIG. 10: The largest signal significance value in a particular signal channel and $\tan \beta$ are shown along the y- and x-axis. The $WZ$ mediated and $Wh$ mediated channels exhibit an opposite behavior with variations in $\tan \beta$. The signal significance values fall and rise with increase in $\tan \beta$ for the $Wh$ mediated and $WZ$ mediated channels, respectively. Here, MET refers to $E_T$.

The signal yield is computed in each of the 4 signal channels by multiplying the $\chi_1^\pm \chi_2^0$ pair production cross-section ($\sigma(\chi_1^\pm \chi_2^0)$) with the branching rates of the relevant cascade decay modes, the integrated luminosity ($\mathcal{L} = 3000 \text{ fb}^{-1}$) and the efficiency of the respective signal regions. In the case of $Wh$ mediated signal channels ($Wh$ mediated $1l+2b+jets+E_T$ and $Wh$ mediated $1l+2\gamma+jets+E_T$), the relevant ino branching modes are: $Br(\chi_2^0 \rightarrow h\chi_1^0)$ and $Br(\chi_1^\pm \rightarrow W\chi_1^0)$, while the relevant ino decay modes in the later two cases ($WZ$ mediated $3l+jets+E_T$ and $WZ$ mediated $3l+2b+jets+E_T$) are: $Br(\chi_2^0 \rightarrow Z\chi_1^0)$ and $Br(\chi_1^\pm \rightarrow W\chi_1^0)$. The SM branching rates are considered for the successive decay of $Z, h$ and $W$ bosons. Prospino [145, 146] is used to compute $\sigma(pp \rightarrow \chi_1^\pm \chi_2^0)$ at NLO while SUSY-HIT [147] is used to compute the ino branching rates. The corresponding ino pair production cross-section and the ino branching rates are dependent on $\tan \beta$ and have been shown in Table V against their respective $\tan \beta$ values. We have also listed the respective signal significance values in the 12 signal regions (4 different analysis channels $\times$ 3 signal regions in each) in Table V.
The coupling of the $Z$ boson with a pair of neutralinos ($\chi_{i,j}^0$) is crucially controlled by the higgsino composition of $\chi_{i,j}^0$, while the $h\chi_{i,j}^0$ couplings are proportional to the gaugino-higgsino admixture in $\chi_{i,j}^0$. As stated earlier, the tree level neutralino mixing matrix is governed by $M_1, M_2, \mu$ and $\tan \beta$. Thereby, the $Z\chi_{i,j}^0$ and $h\chi_{i,j}^0$ couplings are also controlled by the same input parameters at the tree level. In the present case, $\chi_2^0$ is dominantly wino in nature with a small higgsino component (which varies with $\tan \beta$) in all the 8 benchmark points. This makes $\chi_2^0 \to \chi_i^0 h$ as the most preferable decay mode of $\chi_2^0$ with a branching ratio of $\sim 98.34\%$ for $\tan \beta = 5$. However, $Br(\chi_2^0 \to \chi_i^0 h)$ decreases up to $\sim 88.22\%$ upon increasing $\tan \beta$ to 40. Correspondingly, $Br(\chi_2^0 \to \chi_i^0 Z)$ increases from $\sim 1.65\%$ at $\tan \beta = 5$ up to $\sim 11.77\%$ at $\tan \beta = 40$, thus, registering a nearly $\sim 7$ times improvement.

The increase in the branching rate of $\chi_2^0 \to \chi_i^0 Z$ is reflected in the signal significance of $WZ$ mediated analysis (shown along y-axis) of the 4 analysis channels considered (shown in Table V and bottom panel of Figure 10). The signal significance of SR3-A, SR3-B and SR3-C (the optimized signal regions corresponding to $WZ$ mediated $3l+\text{jets}+\not{E}_T$ channel) increases from 0.14, 0.14 and 0.13 (at $\tan \beta = 5$) to 0.98, 1.01 and 0.94, respectively, at $\tan \beta = 40$. A similar increase is also evident in the signal significance of SR4-A, SR4-B and SR4-C (signal regions corresponding to the $WZ$ mediated $3l+2b+\text{jets}+\not{E}_T$ channel) which has a value of 0.001, 0.004 and 0.004, respectively, at $\tan \beta = 5$ while the respective values at $\tan \beta = 40$ are 0.01, 0.03 and 0.03. Equivalently, the signal significance of the $Wh$ mediated signal channels decrease with increasing $\tan \beta$. In Figure 10, we have illustrated the variation of the signal significance (shown along y-axis) of the 4 analysis channels considered in this work with $\tan \beta$ (shown along x-axis) for BP-$\beta_W$. For a particular final state, the largest value of signal significance among the respective 3 signal regions has been considered in Figure 10.

We also analyze additional realistic benchmark scenarios where we vary the higgsino and wino admixtures in the neutralinos and charginos, and study the projected reach of HL-LHC in probing them in the $Wh$ mediated $1l+2b+\text{jets}+\not{E}_T$, $Wh$ mediated $1l+2\gamma+\text{jets}+\not{E}_T$, $WZ$ mediated $3l+\text{jets}+\not{E}_T$ and $WZ$ mediated $3l+2b+\text{jets}+\not{E}_T$ final states. We choose four different benchmark points (BP-$\beta^{10}_W$, BP-$\beta^{30}_W$, BP-$\beta^{50}_W$ and BP-$\beta^{70}_W$) in such a way that $M_{\chi_2^0}$ and $M_{\chi_1^0}$ are always at roughly $\sim 500$ GeV while $M_{\chi_1^0}$ is at roughly $\sim 200$ GeV. We also ensure that $\chi_2^0$ is always bino-like by fixing $M_1$ at 200 GeV. The sleptons, squarks and gluinos are fixed at $\sim 3$ TeV, $\sim 1.5$ TeV and $\sim 4$ TeV, respectively, in order to decouple their effects from the processes of our interest. The value of $\tan \beta$ is fixed to 10. $M_2$ and $\mu$ are varied such that the amount of higgsino component in $\chi_2^0$ is $\sim 10\%$ (BP-$\beta^{10}_W$), $\sim 30\%$ (BP-$\beta^{30}_W$), $\sim 50\%$ (BP-$\beta^{50}_W$) and $\sim 70\%$ (BP-$\beta^{70}_W$). The values of $M_2$ and $\mu$ for these 4 benchmark points along with their electroweakino
| Mass (in GeV) | wino % | higgsino % | Cross-section | Relevant Brs (%) |
|--------------|--------|------------|---------------|-----------------|
| 193.35       | 0.65   | 0.09       | 21.94         | $\chi^{+}_1 \rightarrow \nu Z$ (10.42), $\chi^{0}_1 \rightarrow \nu h$ (15.06), $\chi^{\pm}_1 \rightarrow \nu / \ell$ (9.69), $\chi^{0}_1 \rightarrow \nu / h$ (12.55), $\chi^{+}_1 \rightarrow W Z$ (14.70) |
| 196.95       | 0.92   | 0.12       | 18.91         | $\chi^{+}_1 \rightarrow \nu Z$ (11.62), $\chi^{0}_1 \rightarrow \nu h$ (88.37), $\chi^{\pm}_1 \rightarrow \nu / \ell$ (90.17), $\chi^{0}_1 \rightarrow \nu / h$ (10.60), $\chi^{+}_1 \rightarrow \nu / Z$ (4.09), $\chi^{0}_1 \rightarrow \nu / h$ (19.85), $\chi^{+}_1 \rightarrow W Z$ (24.00) |
| 199.56       | 0.01   | 0.07       | 18.61         | $\chi^{+}_1 \rightarrow \nu Z$ (11.91), $\chi^{0}_1 \rightarrow \nu h$ (88.08), $\chi^{\pm}_1 \rightarrow \nu / \ell$ (88.12), $\chi^{0}_1 \rightarrow \nu / h$ (11.88), $\chi^{+}_1 \rightarrow \nu / Z$ (3.53), $\chi^{0}_1 \rightarrow \nu / h$ (16.85), $\chi^{+}_1 \rightarrow W Z$ (21.20) |
| 202.17       | 1.12   | 0.18       | 18.61         | $\chi^{+}_1 \rightarrow \nu Z$ (11.91), $\chi^{0}_1 \rightarrow \nu h$ (88.08), $\chi^{\pm}_1 \rightarrow \nu / \ell$ (88.12), $\chi^{0}_1 \rightarrow \nu / h$ (11.88), $\chi^{+}_1 \rightarrow \nu / Z$ (3.53), $\chi^{0}_1 \rightarrow \nu / h$ (16.85), $\chi^{+}_1 \rightarrow W Z$ (21.20) |
| 204.78       | 0.01   | 0.07       | 18.61         | $\chi^{+}_1 \rightarrow \nu Z$ (11.91), $\chi^{0}_1 \rightarrow \nu h$ (88.08), $\chi^{\pm}_1 \rightarrow \nu / \ell$ (88.12), $\chi^{0}_1 \rightarrow \nu / h$ (11.88), $\chi^{+}_1 \rightarrow \nu / Z$ (3.53), $\chi^{0}_1 \rightarrow \nu / h$ (16.85), $\chi^{+}_1 \rightarrow W Z$ (21.20) |
| 207.39       | 1.12   | 0.18       | 18.61         | $\chi^{+}_1 \rightarrow \nu Z$ (11.91), $\chi^{0}_1 \rightarrow \nu h$ (88.08), $\chi^{\pm}_1 \rightarrow \nu / \ell$ (88.12), $\chi^{0}_1 \rightarrow \nu / h$ (11.88), $\chi^{+}_1 \rightarrow \nu / Z$ (3.53), $\chi^{0}_1 \rightarrow \nu / h$ (16.85), $\chi^{+}_1 \rightarrow W Z$ (21.20) |

**TABLE VI:** The electroweakino mass spectrum of $BP_{\beta^0W}^0$, $BP_{\beta^0W}^1$, $BP_{\beta^0W}^2$ and $BP_{\beta^0W}^3$ is shown along with the values of $M_2$ and $\mu$. The wino and higgsino composition of the electroweakinos are also listed. The NLO cross-section of directly produced chargino-neutralino pairs and the electroweakino branching fractions which are relevant to the 4 signal channels analyzed in this work are shown. Here, $\chi^{+}_1$ always decays into $W Z$. The signal significance values in the respective analysis channels are also tabulated.
mass spectrum is shown in Table VI. We have also listed the higgsino and wino composition in Table VI.

In the previous case of BP-β_{W}^{10}, the amount of higgsino admixture in \( \chi_{2}^{0} \) was \( \lesssim 1\% \) for \( \tan \beta = 10 \). Also, \( \chi_{3}^{0}, \chi_{4}^{0} \) and \( \chi_{2}^{\pm} \) were much heavier (\( \sim 2 \) TeV) and therefore, the contributions to the signal yield from \( \chi_{2}^{0} \chi_{1}^{\pm}, \chi_{3}^{0} \chi_{1}^{\pm}, \chi_{3}^{0} \chi_{2}^{0} \) and \( \chi_{4}^{0} \chi_{2}^{\pm} \) production processes could be safely ignored due to their small cross-sections. However, in the present case, when we attempt to introduce a finite amount of higgsino admixture in \( \chi_{2}^{0} \) while keeping its mass fixed at \( \sim 500 \) GeV, we are forced to reduce the value of \( \mu \). Consequently, \( \chi_{3}^{0}, \chi_{4}^{0} \) and \( \chi_{2}^{\pm} \) are no more in the \( \sim O(1) \) TeV range. For example, in the case of BP-β_{W}^{10}, where the \( \chi_{2}^{0} \) is composed of higgsinos and winos in the proportion of \( \sim 10\% \) and \( \sim 90\% \), respectively, we are required to choose \( \mu \sim 670 \) GeV. As a result, \( \chi_{3}^{0}, \chi_{4}^{0} \) and \( \chi_{2}^{\pm} \) also become admixtures of winos and higgsinos and have a mass of \( \sim 672.90 \) GeV, \( \sim 693.11 \) GeV and \( \sim 692.73 \) GeV, respectively. Correspondingly, it would be imperative to take into account the contributions from the heavier chargino-neutralino pairs as well. In the present scenario, therefore, contributions to the signal yield can potentially arise from:

\[
pp \rightarrow \chi_{1}^{\pm} \chi_{2}^{0} + \chi_{1}^{+} \chi_{3}^{0} + \chi_{1}^{+} \chi_{4}^{0} + \chi_{2}^{+} \chi_{2}^{0} + \chi_{2}^{+} \chi_{3}^{0} + \chi_{2}^{+} \chi_{4}^{0}. 
\]

The production cross-section of these chargino-neutralino pairs for BP-β_{W}^{10}, BP-β_{W}^{30}, BP-β_{W}^{50} and BP-β_{W}^{70} are listed in Table VI. Here, we have used Prospino-2.1 to compute the cross-sections at NLO. The branching ratios of \( \chi_{i}^{0} \rightarrow Z/h \chi_{1}^{0} \) (\( i = 2, 3, 4 \)) and \( \chi_{j}^{\pm} \rightarrow W \chi_{1}^{0} \) (\( j = 1, 2 \)) are also shown in Table VI where SUSY-HIT has been used to compute them. The signal significance of these 4 benchmark points is computed for (SR1-A, SR1-B, SR1-C), (SR2-A, SR2-B, SR2-C), (SR3-A, SR3-B, SR3-C) and (SR4-A, SR4-B, SR4-C), corresponding to \( Wh \) mediated 1l + 2b + jets + \( E_{T} \), \( Wh \) mediated 1l + 2γ + jets + \( E_{T} \), \( WZ \) mediated 3l + jets + \( E_{T} \) and \( WZ \) mediated 3 + 2b + jets + \( E_{T} \) channels, respectively, and have been listed in Table VI. It can be observed from Table VI that the signal significance of the \( WZ \) mediated channels improve with an increase in the amount of higgsino content in \( \chi_{2}^{0} \). For example, the signal significance of SR3-A and SR4-A increases from \( \sim 0.09 \) and \( \sim 0.03 \) for BP-β_{W}^{10} to \( \sim 0.34 \) and \( \sim 0.58 \) for BP-β_{W}^{70}. This increase is mainly an outcome of the combined effect of an increased \( \chi_{2}^{0}/\chi_{3}^{0} \rightarrow Z \chi_{1}^{0} \) branching rate, an increased \( \sigma(\chi_{3}^{0} \chi_{1}^{\pm}) \) and a lowered \( \sigma(\chi_{2}^{0} \chi_{1}^{\pm}) \). Upon combining the highest signal significance values in each of the analysis channels in quadrature, we obtain a combined signal significance of 2.01, 1.98, 2.33 and 2.12 for BP-β_{W}^{10}, BP-β_{W}^{30}, BP-β_{W}^{50} and BP-β_{W}^{70}, respectively. Before concluding this section, we would like to note that additional contribution to the signal yield may also arise by considering the cascade decay modes of the heavier charginos and neutralinos. For example, in a generic case, the \( \chi_{3}^{0} \) can decay into a \( Z/h \chi_{1}^{0} \) pair and this \( \chi_{2}^{0} \) can further decay into a \( Z/h \chi_{1}^{0} \) pair, resulting in an additional \( Z/h \) bosons in the final state.
multifarious number of such possibilities are potentially feasible, and are outside the scope of this present work. We intend to explore such scenarios on a case by case basis in a future work. In the last section, we provide a detailed summary and conclusion to our results.

IV. SUMMARY AND CONCLUSIONS

In this work, we studied the sensitivity of the future HL-LHC to direct wino searches in a simplified scenario with $\lambda''_{112} u^c d^c s^c$ and $\lambda''_{113} u^c d^c b^c$ type RPV operators. The collider implications of $\lambda''_{112} u^c d^c s^c$ type RPV coupling on direct wino searches in the $Wh$ mediated $1l + 2b + jets(N_j \gtrsim 2) + \not{E}_T$, $Wh$ mediated $1l + 2\gamma + jets(N_j \gtrsim 2) + \not{E}_T$ and $WZ$ mediated $3l + jets(N_j \gtrsim 2) + \not{E}_T$ has been studied in Section II A, II B and II C, respectively, while Section II D examined the projected reach of direct wino searches in the $WZ$ mediated $3l + 2\gamma + jets(N_j \gtrsim 2) + \not{E}_T$ final state, by the virtue of $\lambda''_{113} u^c d^c b^c$ type RPV operator. The direct production of mass degenerate wino type $\chi_1^\pm \chi_0^2$ was considered which eventually underwent cascade decay into bino type $\chi_1^0$ along with the $h, W$ and/or $Z$ bosons. In the presence of $\lambda''_{113} u^c d^c s^c (b^c)$ type RPV operator, the $\chi_1^0$ decays into $\chi_1^0 \rightarrow uds$ ($\chi_1^0 \rightarrow udb$) resulting in jets in the final state.

A detailed collider analysis was performed in the aforesaid channels by taking into account all relevant background samples and by considering a multitude of important kinematic variables. Direct wino searches in the $Wh$ mediated $1l+2b+jets+\not{E}_T$ final state in the context of $\lambda''_{113} u^c d^c s^c$ type RPV scenario exhibited a projected $2\sigma$ exclusion ($5\sigma$ discovery) reach up to $M_{\chi_1^\pm, \chi_0^2} \approx 680$ GeV ($\sim 450$ GeV) for a bino like $\chi_1^0$ with mass up to $\sim 0$ GeV. It is to be noted that the respective reinterpretation within a RPC scenario (studied in [132]) furnishes considerably stringent projections, and the respective 95% C.L. projected exclusion contour reaches up to $M_{\chi_1^\pm, \chi_0^2} \approx 1100$ GeV for bino like $\chi_1^0$ with mass $M_{\chi_1^0} \sim 0$ GeV. The same simplified RPV scenario was also interpreted in terms of searches in the $Wh$ mediated $1l + 2\gamma + jets + \not{E}_T$ final state, and a relatively stronger potential reach was observed. Here, the projected exclusion and discovery contours had reach up to $\sim 700$ GeV and $\sim 600$ GeV, respectively.

As discussed previously in Section II C, the future reach of direct wino searches in the $WZ$ mediated $3l + \not{E}_T$ final state within a RPC framework has been studied in [132], and the projected 95% C.L. exclusion contour reaches up to $\sim 1150$ GeV for a bino like $\chi_1^0$ with mass up to $\sim 0$ GeV. We performed a collider study to derive the projected reach of direct wino searches in the $WZ$ mediated $3l + jets + \not{E}_T$ final state and reinterpreted the projected reach within a $\lambda''_{112} u^c d^c s^c$ type RPV scenario. The projected exclusion and discovery contours displayed a considerably weaker reach as compared to the RPC scenario [132].
The projected $2\sigma$ exclusion contour reached up to $\sim 660$ GeV while the projected $5\sigma$ discovery contour reached up to $\sim 490$ GeV. Similarly, in Section [II D] the projected reach of direct wino searches in the $WZ$ mediated $3l + 2b + jets + \not{E_T}$ final state was reinterpreted to simplified scenario with $\lambda''_{113} u^c d^c b^c$ type RPV coupling. The projected exclusion reach of this search channel reaches up to $\sim 600$ GeV for $M_{\chi_1^0}$ in between $\sim 150$ GeV and $\sim 250$ GeV.

A few benchmark scenarios have been explored in Section [III]. The future reach of direct higgsino production at the HL-LHC in the aforesaid channels was analyzed for BP-$\alpha_{\tilde{H}}$ and BP-$\beta_{\tilde{H}}$. It is observed that the direct higgsino searches furnish weaker projection contours compared to the wino counterparts due to a smaller production rate. Furthermore, the sensitivity of the analysis channels to $\tan \beta$ is also studied. The $WZ$ mediated channels displayed an improvement in signal significance with an increase in $\tan \beta$, will all other MSSM input parameters kept fixed. The implications of a finite wino-higgsino mixing in the heavier ino states on the projected reach of the search channels considered in this work is also analyzed for the case of BP-$\beta_{\tilde{W}}^{10}$, BP-$\beta_{\tilde{W}}^{30}$, BP-$\beta_{\tilde{W}}^{50}$ and BP-$\beta_{\tilde{W}}^{70}$. These benchmark points resulted in a combined signal significance of 2.01, 1.98, 2.33 and 2.12, respectively, thereby, marginally falling within the projected exclusion reach (except for BP-$\beta_{\tilde{W}}^{30}$) of HL-LHC.

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Appendix A: Signal and background cross-sections

| Final state | Process | Cross section (fb) |
|-------------|---------|-------------------|
| $W'h$ mediated | Signal benchmark points | |
| $1l + 2b + jets + R_T$ | BP1-A ($M_{\chi_1^0} = 200$ GeV, $M_{\chi_2^0} = 55$ GeV) | 381 |
| | BP1-B ($M_{\chi_1^0} = 350$ GeV, $M_{\chi_2^0} = 165$ GeV) | 46 |
| | BP1-C ($M_{\chi_1^0} = 500$ GeV, $M_{\chi_2^0} = 25$ GeV) | 10 |
| | $t\bar{t}$ + jets | $9.15 \times 10^4$ |
| | WW + jets | $8.92 \times 10^4$ |
| | WZ + jets | $4.01 \times 10^4$ |
| | ZZ + jets | $1.17 \times 10^4$ |
| | Wh + jets ($h \to b\bar{b}, W \to l'\nu$) | 334 |
| | Zh + jets ($h \to b\bar{b}, Z \to l' l'$) | 54 |
| $1l + 2\gamma + jets$ | BP2-A ($M_{\chi_1^0} = 250$ GeV, $M_{\chi_2^0} = 100$ GeV) | 0.67 |
| | BP2-B ($M_{\chi_1^0} = 425$ GeV, $M_{\chi_2^0} = 100$ GeV) | 0.08 |
| | BP2-C ($M_{\chi_1^0} = 600$ GeV, $M_{\chi_2^0} = 150$ GeV) | 0.02 |
| | $t\bar{t}h$ + jets ($h \to \gamma\gamma$) | 0.82 |
| | Wh + jets ($h \to \gamma\gamma, W \to l'\nu$) | 0.61 |
| | Zh + jets ($h \to \gamma\gamma, Z \to l' l'$) | 0.10 |
| $WZ$ mediated | Signal benchmark points | |
| $3l + jets + R_T$ | BP3-A ($M_{\chi_1^0} = 400$ GeV, $M_{\chi_2^0} = 175$ GeV) | 4.71 |
| | BP3-B ($M_{\chi_1^0} = 600$ GeV, $M_{\chi_2^0} = 325$ GeV) | 0.82 |
| | BP3-C ($M_{\chi_1^0} = 650$ GeV, $M_{\chi_2^0} = 175$ GeV) | 0.56 |
| | WZ + jets | 400880 |
| | ZZ + jets | 11690 |
| | VVV + jets | 799 |
| $WZ$ mediated | Signal benchmark points | |
| $3l + 2b + jets + R_T$ | BP4-A ($M_{\chi_1^0} = 250$ GeV, $M_{\chi_2^0} = 135$ GeV) | 29 |
| | BP4-B ($M_{\chi_1^0} = 600$ GeV, $M_{\chi_2^0} = 205$ GeV) | 0.8 |
| | BP4-C ($M_{\chi_1^0} = 700$ GeV, $M_{\chi_2^0} = 85$ GeV) | 0.4 |
| | $t\bar{t}Z$ | 762 |
| | VVV + jets | 1037 |
| | WZ + jets ($W \to l'\nu, Z \to l' l'$) | 248 |
| | ZZ + jets ($Z \to l' l', Z \to l' l'$) | 319 |

**TABLE VII:** The cross-section of the signal benchmark points and the background processes are shown. The signal cross-sections are at NLO-NLL order (taken from [138, 139]). For the background processes, the LO cross-section values computed by MadGraph\_aMC@NLO have been considered with the exception of $t\bar{t}$ + jets for which the NLO cross-section is considered (the NLO cross-section has been obtained by multiplying the LO cross-section with the $k$ factor ($k \approx 1.5$).)

44