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Long-lived NMSSM : Analysing some long-lived NSLP signatures in the NMSSM

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The Next to Minimal Supersymmetric Standard Model (NMSSM) with singlino-like neutralino as the lightest supersymmetric particle (LSP) can open up possibilities for long-lived electroweakinos. We identify such regions in the NMSSM parameter space where the next to lightest supersymmetric particle (NLSP) is a long-lived bino-like electroweakino, consistent with dark matter direct detection and collider constraints. These long-lived NLSPs can appear as displaced vertex signatures in the cascade decay of directly produced chargino-neutralino pairs at the high luminosity LHC (HL-LHC). We study the prospects of observing such scenarios at the HL-LHC through track based analysis. We show that the discovery reach of the HL-LHC on the eletroweakino parameter space can be improved through focused long-lived particle searches.

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1. Introduction

The existence of the dark matter (DM) [1], matter-antimatter asymmetry, and non-zero neutrino masses [2], as well as theoretical considerations like hierarchy problem, all point to the existence of new physics beyond that in the Standard Model (SM). Among the extensions of the SM, those involving supersymmetry (SUSY) still remain one of the most appealing. Depending on exact realization, SUSY presents a number of viable DM candidates, the lightest neutralino ($\widetilde{\chi}_1^0$), which is stable in a R-parity conserving scenario, being one of them. Within the MSSM, relic density compliant regions require either heavy DM or rely on a co-annihilation mechanism, which demands a small mass splitting between DM and its co-annihilating partner. Such small mass gaps can lead to long-lived particles (LLP), which can then be investigated, for example, by looking for displaced vertices or heavy stable charged particles. Similar LLPs can also be realized in a singlet extension of the MSSM, the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [3–5] which remedies the drawbacks like "μ-problem".

Such extended sectors can open up exciting possibilities for DM phenomenology and the experimental searches for it at the colliders. In this work, we revisit the neutralino sector of the NMSSM, focusing on the LSP with a significant singlino fraction [6–9]. The singlino has suppressed couplings with the rest of the SUSY spectrum and thus can lead to a long-lived NLSP neutralino. We investigate this possibility through displaced vertex search, relying on tracks originating from the decay of the long-lived NLSP at the HL-LHC. It should be noted that the region of the LLP parameter space in the NMSSM has two distinct features. First, the LLPs result from suppressed couplings and not small mass differences; second, a large part of the LLP parameter space corresponds to over-abundant relic density i.e $\Omega_{DM}^{obs.}h^2 > 0.122$.

2. Details of parameter space and its features

Our primary focus in the analysis is the region in the parameter space of the R-parity conserving NMSSM, featuring a long-lived neutralino. In the limit $\lambda \to 0$ (for a fixed μ), the singlet-like scalar, singlet-like pseudoscalar, and the singlino can no longer interact with the MSSM sector. This consideration can lead to the possibility of a pure singlino-like neutralino LSP ($\widetilde{\chi}_1^0$) with a tree level mass $\sim 2\kappa v_S$ and a bilo-like NLSP ($\widetilde{\chi}_2^0$). There are no tree-level couplings between the bino and singlino which can further be suppressed with a small mass difference between LSP and NLSP. In such scenarios, the bino-like $\widetilde{\chi}_2^0$ can be LLP. The heavier neutralinos $\widetilde{\chi}_3^0, \widetilde{\chi}_4^0, \widetilde{\chi}_5^0$, and charginos $\widetilde{\chi}_1^\pm, \widetilde{\chi}_2^\pm$ can be either higgsino-like, wino-like, or admixtures of both and decay promptly. In this analysis, we consider a moderately mixed scenario with $\mu < M_2$ which implies a relatively large higgsino admixture in $\widetilde{\chi}_3^0, \widetilde{\chi}_4^0$, and $\widetilde{\chi}_1^\pm$. We utilize the `NMSSMTools-5.5.3` [10, 11] package to perform a random scan over the following parameter space.

$$\begin{aligned} &10^{-5} < \lambda < 0.1,\ \left|\frac{\kappa}{\lambda}\right| \leq 0.15,\ M_1 = (150, 550)\text{ GeV}, M_2 = (2000, 3000)\text{ GeV},\\ &M_3 = (3000, 10000)\text{ GeV}, \mu = (500, 1000)\text{ GeV},\ \tan\beta = (1, 40),\\ &A_\lambda = (-100, 10000)\text{ GeV},\ A_\kappa = (-1000, 100)\text{ GeV}, A_t = (-10, 10)\text{ TeV} \end{aligned} \tag{1}$$

H_1 is required to be consistent with the Higgs mass constraints [12] and Higgs signal strength constraints coming from the LHC [13–18]. The heavier CP-even Higgs bosons H_2, H_3 and the

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CP-odd Higgs bosons A_1, A_2 can be an admixture of singlet and doublet components and can be constrained by heavy Higgs searches at the LHC. The constraints from heavy Higgs searches are subject to the doublet content and get weaker with increasing singlet admixture. Furthermore, the NMSSM parameter space of our interest is also constrained by limits from LEP searches [19–21], flavor physics [22–24], direct [25–27] and indirect [28] detection experiments and direct electroweakino searches at the LHC.

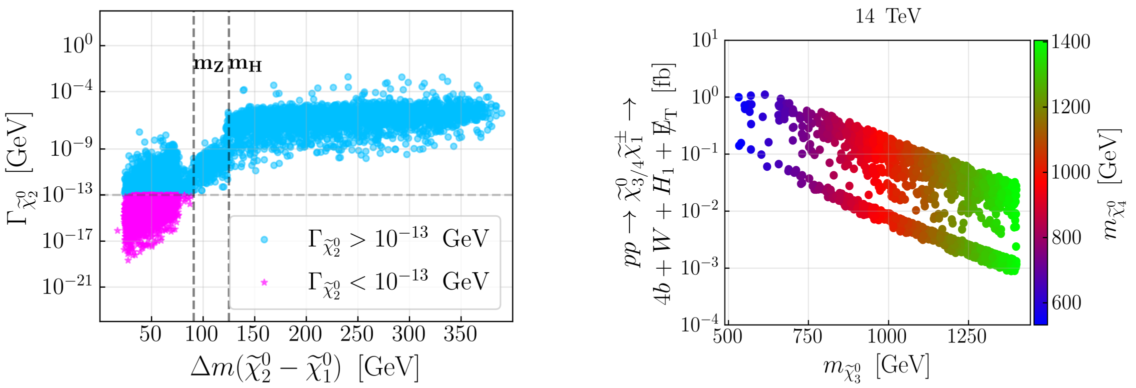

Figure 1: *Left panel:* Allowed points in the parameter space are presented in the plane of mass difference $\Delta m(\tilde{\chi}_2^0 - \tilde{\chi}_1^0)$ vs. the decay width of $\tilde{\chi}_2^0$, $\Gamma_{\tilde{\chi}_2^0}$. Points with $\Gamma_{\tilde{\chi}_2^0} \leq 10^{-13}$ GeV and $\Gamma_{\tilde{\chi}_2^0} > 10^{-13}$ GeV are illustrated in pink and cyan colors, respectively. *Right panel:* Leading order cross-section for the process $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_3^0/\tilde{\chi}_4^0 \to (\tilde{\chi}_1^\pm \to \tilde{\chi}_2^0 + W^\pm, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + b\bar{b})(\tilde{\chi}_3^0/\tilde{\chi}_4^0 \to \tilde{\chi}_2^0 + H_1, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + b\bar{b}) \to 4b + WH_1 + \not{E}_T$ at $\sqrt{s} = 14$ TeV for the allowed parameter space with $\Gamma_{\tilde{\chi}_2^0} < 10^{-13}$ GeV.

In Fig. 1 left, we present the decay width of $\tilde{\chi}_2^0$ ($\Gamma_{\tilde{\chi}_2^0}$) as a function of the mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$, $\Delta m(\tilde{\chi}_2^0 - \tilde{\chi}_1^0)$. We concentrate on the region highlighted by pink with $\Gamma_{\tilde{\chi}_2^0} \leq 10^{-13}$ which corresponds to $\Delta m(\tilde{\chi}_2^0 - \tilde{\chi}_1^0) < m_Z$. A decay width of $\Gamma \sim 10^{-13}$ GeV roughly translates to $c\tau \sim \mathcal{O}(0.1)$ mm. In this region, only three body decays of $\tilde{\chi}_2^0$ are viable [29] *viz* $\tilde{\chi}_1^0 + b\bar{b}/\tau^+\tau^-$ with BR~0.6. The higgsino-like $\tilde{\chi}_3^0, \tilde{\chi}_4^0$ mostly decays through the intermediate bino-like $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0/\tilde{\chi}_4^0 \to \tilde{\chi}_2^0 + H_1/Z$ with BR~0.9. Most notably, the mass difference is still large enough to produce energetic final states in $\tilde{\chi}_2^0$ decays. Such configurations are not possible in MSSM with neutralino LSP and are a unique feature of the NMSSM scenario we consider.

3. Discovery potential of LLP decays at the HL-LHC

Directly produced chargino-neutralino pairs at the HL-LHC can lead to interesting final state topologies containing the long-lived NLSP in addition to several promptly decaying particles. Cross-section for one such typical cascade decay chain is shown in the right plot of Fig. 1. We choose allowed benchmark points with mass $M_{\tilde{\chi}_3^0} \sim 750$ GeV and perform a search in $b\bar{b}$ channel which has a cross-section of ~ 1 fb at $\sqrt{s} = 14$ GeV. Since the $\tilde{\chi}_2^0$ is long-lived, the final states contain displaced b-jets along with $W + Z/H_1 + \not{E}_T$. This motivates us to use lepton triggers from the prompt H_1/W decays i.e 1(2) e/mu with $p_T > 30(20)$ GeV and $\not{E}_T > 50$ GeV. As the momentum resolution at the tracker is better than the energy resolution at the calorimeters for charged tracks [30], we restrict our analysis to the tracker.

The two LLP candidates from the two $\widetilde{\chi}_2^0$ can lead to two displaced secondary vertices (DSV), which produce tracks with a large transverse impact parameter, $d_0 > 2$ mm at the collider, as shown in the left plot of Fig. 2. Such large d_0 tracks can also originate in case of $t\bar{t}$ production from long-lived mesons like K_s^0, Λ, D etc. produced from decay of b hadrons. In an ideal scenario, tracks that arise from the same secondary vertex are expected to share a common point of origin $\{x_0, y_0, z_0\}$. Correspondingly, we allocate tracks with $|d_0| < 2$ mm whose point of origins satisfy $\{|\Delta x| < 1$ mm, $|\Delta y| < 1$ mm, $|\Delta z| < 1$ mm$\}$ to a DSV. Imposing the requirement for at least one DSV reduces the background effectively as shown in the right plot of Fig. 2.

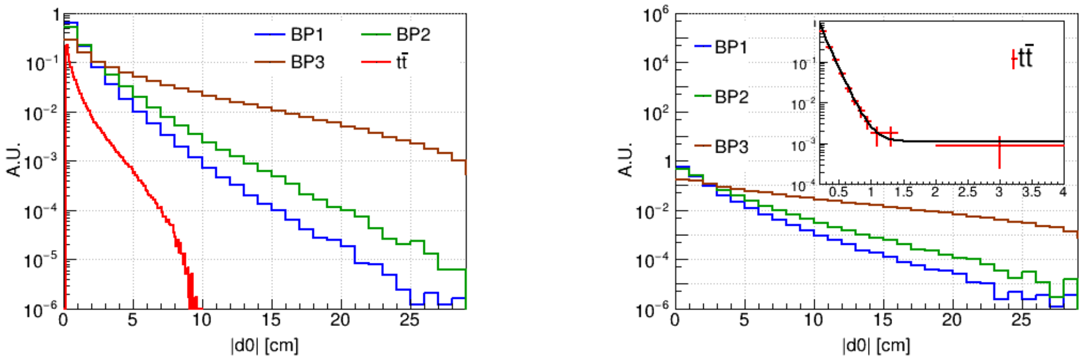

Figure 2: Distribution of transverse impact parameter $|d_0|$ for all tracks with $p_T > 1$ GeV and $|\eta| < 4$ corresponding to 3 signal benchmarks (BP1, BP2, BP3) and $t\bar{t}$ background, at the HL-LHC. *Left panel:* Events pass the trigger choice $n_\ell = 1$. *Right panel:* Events pass the trigger choice $n_\ell = 1$ and have at least one displaced secondary vertex.

Tracks originating far from the center of the detector tend to have higher values of d_0 whose reconstruction has low efficiency. Hence, without solely relying on d_0 to eliminate the background, we construct a few variables *viz* the track multiplicity of two DSVs, the radial distance of the DSV from the primary vertex, and the sum of transverse momenta of all the displaced tracks associated with DSVs. Using these discriminators, we observe that even for tracks with $d_0 < 1$ cm, one can perform an LLP search of displaced vertices with completely suppressed background at HL-LHC.

4. Outlook and conclusion

LLPs can open up novel ways to search for new particles. These can occur in SUSY extension of the SM like NMSSM, especially in the electroweakino sector with a comparatively large mass difference, unlike in MSSM. This special region appears for the case of neutralino spectrum as given $m_{\text{singlino}} < m_{\text{bino}} < m_{\text{higgsinos}}$ with LSP and NLSP mass difference less than m_Z. This allows three-body decays of NLSP like $\widetilde{\chi}_1^0 + b\bar{b}/\tau^+\tau^-/jj/\gamma$ with ≥ 1 mm decay length in the allowed parameter space. We study the projected sensitivity of these long-lived channels in direct electroweakino production $pp \to \widetilde{\chi}_3^0/\widetilde{\chi}_4^0\widetilde{\chi}_1^\pm$ at HL-LHC with $\sqrt{s} = 14$ TeV. We use lepton triggers for baseline selection of events and reconstruct DSVs from the displaced tracks to contaminate the background. Properties of DSV tracks like impact factor, track multiplicity, and HT of tracks can be used to achieve a background-free scenario.

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