Snowmass21: Letter of interest

Future collider reach for light DM in the NMSSM via light Higgs searches and direct electroweakino searches*

Rahool Kumar Barman,[1,†] Genevieve Bélanger,[2,‡] Rohini Godbole,[3,§] Dipan Sengupta,[4,¶] and Xerxes Tata[5,**]

[1] *Indian Association for the Cultivation of Science, Jadavpur, Kolkata 700032, India*

[2] *LAPTh, Université Savoie Mont Blanc, CNRS, B.P. 110, F-74941 Annecy Cedex, France*

[3] *Centre for High Energy Physics, Indian Institute of Science, Bangalore 560012, India*

[4] *Department of Physics and Astronomy, University of California, San Diego, 9500 Gilman Drive, La Jolla, USA*

[5] *Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA*

Thematic areas:

☑ EF08: BSM: Model specific explorations

☑ EF10: BSM: Dark Matter at colliders

I. New light particles in the NMSSM

The next to Minimal Supersymmetric Standard Model (NMSSM) offers the possibility of light singlet-like scalar (h_1) and/or pseudoscalar (a_1) Higgs bosons below 122 GeV (and as small as $\sim O(1)$ GeV) while also satisfying the current collider, astrophysical and cosmological constraints with the singlino as a *thermal* dark matter (DM). Being dominantly singlet in nature, the coupling of these light Higgs states to SM particles are considerably suppressed. In the absence of co-annihilation, the NMSSM with a light neutralino dark matter, $M_{\widetilde{\chi}_1^0} \lesssim M_Z/2$, requires the presence of light a_1/h_1 at roughly $\sim 2M_{\widetilde{\chi}_1^0}$ in order to satisfy the measured upper limit on the thermal DM relic density.

A. Light Higgs phenomenology

The currently allowed light neutralino NMSSM parameter space can be probed via direct electroweakino searches at the future LHC, future dark matter detection experiments and Higgs invisible measurements at the future e^+-e^- colliders. In addition to these, the search for light Higgs bosons can also provide complementary probes for discovering/excluding the currently allowed NMSSM parameter region or other BSM scenarios involving light Higgs states at the future colliders. The projected reach of light Higgs searches at the HL-LHC and the HE-LHC in various SM final states, *viz.* $2b2\tau$, $2b2\mu$, 4μ, has been studied in Ref. [1]. However, the projected sensitivities have been derived, in many of the channels, through a scaling of luminosities. On translating these future projections on to the allowed parameter space, it was observed that their discovery potential is not very strong [2].[1] In this regard, dedicated collider analyses and combination of search results in various final states might help in improving the potential reach of light Higgs searches for various benchmark scenarios. One such final state which can have interesting implications at small a_1/h_1 masses is 4τ ($m_{a_1/h_1} \lesssim 10$ GeV). While these collider searches for very light a_1/h_1 bosons are independent of the nature of dark matter, we note that even future direct detection experiments, *e.g.* XENON-nT are not expected to have much sensitivity at these small masses even if the DM attains its (thermal) relic density through resonant anni-

* Contact Email(s):
† psrkb2284@iacs.res.in
‡ belanger@lapth.cnrs.fr
§ rohini@iisc.ac.in
¶ disengupta@physics.ucsd.edu
** tata@phys.hawaii.edu

[1] Note that the projected sensitivity of light Higgs boson searches at the future lepton colliders is stronger than their HL-LHC counterpart by around $\sim 1-2$ orders of magnitude [3, 4].

hilation via a_1/h_1 bosons. The list of studies where the full future potential of light Higgs boson searches (produced from the direct decay of h_{125} or in association with other SM bosons through cascade decay) at the HL/HE-LHC have been explored is rather small. Including the non-traditional a_1/h_1 search modes might open new possibilities for probing the allowed parameter space. We must note that a light a_1/h_1 ($m_{a_1,h_1} \lesssim 122$ GeV) can be also realized in the scenario where the relic density of $\tilde{\chi}_1^0$, computed assuming thermal freeze-out with a standard cosmology, is above the observed DM relic density, and non-thermal mechanisms need to be invoked. Therefore, the searches for the light Higgs bosons may be used to probe the NMSSM parameter space corresponding to such non-standard scenarios as well as the thermal relic scenario. Additionally, our impetus would be to study the complementarity between the future potential of light Higgs boson searches in the traditional and non-traditional final states, projected reach of direct and indirect detection experiments, and the discovery potential of direct electroweakino searches. We also plan to investigate prospects for probing the NMSSM parameter space via searches at BELLE-II for a_1/h_1 (in the $m_{a_1,h_1} \lesssim 2m_b$ region) produced from the decay: $\Upsilon(1s) \to a_1/h_1\gamma$, and a_1/h_1 dominantly decays to $\tau^+\tau^-$ via mixing with the doublet Higgs boson. If the singlet fraction in a_1/h_1 is $\sim 90\%$, then $Br(\Upsilon(1s) \to a_1/h_1\gamma) \times Br(a_1/h_1 \to \tau^+\tau^-)$ is constrained roughly below 5×10^{-5} at 90% CL [5].

B. Direct electroweak ino searches

The work in Ref. [2] shows that the non-standard and non-traditional final states produced from the cascade decay of directly produced electroweakino pairs can have a considerable yield for various allowed parameter space points. In addition to the traditional direct electroweakino search modes, *viz.* WZ or Wh_{125} mediated $3l + \not{E}_{\rm T}$ [6–9], complementary probes can be obtained from search channels like $Vh_{125} + \not{E}_{\rm T}$ or $VV + \not{E}_{\rm T}$ (see for example Ref. [10]) final states. For example, parameter space points with a light bino or singlino-like $\tilde{\chi}_1^0$, and, M_2 ($\sim 200 - 300$ GeV) $< \mu$ ($\sim 400 - 500$ GeV), will have a wino-like $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$ and higgsino-like $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$, $\tilde{\chi}_2^\pm$. In such cases, the production cross-section of $\tilde{\chi}_3^0\tilde{\chi}_2^\pm$ pair at $\sqrt{s} = 14$ TeV can be roughly of $O(10)$ fb. The $\tilde{\chi}_2^\pm$ can decay into $W^\pm\tilde{\chi}_2^0/\tilde{\chi}_1^0$ pair while the $\tilde{\chi}_3^0$ can undergo cascade decay into $Zh_{125} + \not{E}_{\rm T}$ final state, with appreciable branching ratios, resulting in a multi-boson final state. For a cascade branching fraction of $\sim 20\%$, the expected number of events in the $3l + 2b + \not{E}_{\rm T}$ final state at the $\mathcal{L} = 3000$ fb^{-1} HL-LHC would be around $\sim 10^2$. Obviously, a significantly larger event rate will be expected at the proposed high energy LHC where an integrated luminosity of 15 ab^{-1} is projected. While a 5σ discovery is guaranteed via both the WZ and the Wh_{125} mediated trilepton signal at the HE-LHC, signals may be observable also via $Vh_{125} + \not{E}_{\rm T}$ or $VV + \not{E}_{\rm T}$ channels. The presence of these complementary direct search modes may serve to pin down the origin of the new physics.

[1] M. Cepeda et al. *Report from Working Group 2: Higgs Physics at the HL-LHC and HE-LHC*, volume 7, pages 221–584. 12 2019.

[2] R. K. Barman et al. Current bounds and future prospects of light neutralino dark matter in NMSSM. arXiv: 2006.07854.

[3] Z. Liu et al. Exotic decays of the 125 GeV Higgs boson at future e^+e^- lepton colliders. *Chin. Phys. C*, 41(6):063102, 2017.

[4] P. Drechsel et al. Sensitivity of the ILC to light Higgs masses. In *International Workshop on Future Linear Collider*, 1 2018.

[5] W. Love et al. Search for Very Light CP-Odd Higgs Boson in Radiative Decays of Upsilon(S-1). *Phys. Rev. Lett.*, 101:151802, 2008.

[6] Search for electroweak production of charginos and sleptons decaying in final states with two leptons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector. Technical Report ATLAS-CONF-2019-008, CERN, Geneva, Mar 2019.

[7] A.M. Sirunyan et al. Combined search for electroweak production of charginos and neutralinos in proton-proton collisions at $\sqrt{s} = 13$ TeV. *JHEP*, 03:160, 2018.

[8] Search for Supersymmetry at the high luminosity LHC with the ATLAS experiment. Technical Report ATL-PHYS-PUB-2014-010, CERN, Geneva, Jul 2014.

[9] Prospects for searches for staus, charginos and neutralinos at the high luminosity LHC with the ATLAS Detector. Technical Report ATL-PHYS-PUB-2018-048, CERN, Geneva, Dec 2018.

[10] H. Baer et al. LHC luminosity and energy upgrades confront natural supersymmetry models. *Phys. Rev. D*, 98(7):075010, 2018.