Discovery and Exclusion Potential of Future Colliders for Supersymmetry Signatures

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I. Introduction

The search for supersymmetry (SUSY) is an important part of the LHC physics program given its elegant solutions to questions of Higgs naturalness, gauge coupling unification, Dark Matter, as well as other favorable features. No direct indication of SUSY superpartners has yet been seen at the LHC, and extensive mass limits have been set on simplified models of various superpartners and their decay modes. However, these limits do not cover the full range of theoretically-acceptable masses for superpartners of various models, and are constrained by the 13 TeV center of mass energy (often for strongly-produced processes) or by the integrated luminosity so far collected (often for electroweakly-produced processes). Future colliders with higher energies, larger integrated luminosities, or different production modes can explore interesting regions of phase-space where superpartners may exist.

While there are a number of proposals for future colliders, it's not always obvious which designs would maximize the discovery potential for interesting models of new physics that fall into unique phase-space. The HL-LHC will bring an order of magnitude more data than the current LHC and with it gains in sensitivity, such as for compressed electroweak scenarios [1]. Lepton colliders such as the ILC, CLIC, and LE-FCC would benefit from a cleaner physics environment, with improved sensitivity to some electroweak scenarios at the expense of other strongly-produced scenarios due to the reduced center-of-mass. The sensitivity to higher-mass superpartners would benefit overall from large center-of-mass increases of the HE-LHC and FCC-hh.

This proposal will seek to compare the discovery and exclusion sensitivity of various future colliders for three SUSY scenarios of interest: electroweakinos with compressed mass spectra, electroweakinos in fully-hadronic decay channels, and stops and electroweakinos that decay via R-parity violating couplings. To facilitate the comparison between future colliders, DELPHES-based studies may be pursued. The studies will follow and learn from recent analyses from the ATLAS collaboration, and will attempt to evaluate the accuracy of predictions using current published exclusions. If possible and necessary, upgrade infrastructure from the ATLAS collaboration may be utilized for future LHC predictions.

II. Electroweak Searches with Compressed Mass Spectra

SUSY models with compressed mass spectra between an electroweakino-type lightest SUSY partner (LSP) and next-to-lightest SUSY partner (NLSP) are difficult to probe at the LHC due to the soft decay products, and mass limits are relatively weak compared to models with other LSP types. However, these models are theoretically interesting due to their compatibility with the observed dark-matter density [2], considerations of naturalness [3], and with a possible deviation of the muon's anomalous magnetic moment from SM expectations [1].

A previous comparison of the exclusion predictions for future colliders on the higgsino LSP scenario from the European Strategy Physics Briefing Book [4] can be seen in Fig. 1. A gap exists in the FCC-hh prediction, partially due to the absence of an extrapolation of the soft-lepton A analysis covering Δm (NLSP,LSP) of 2 to 20 GeV. Given uncertainty in the Δm reach of the mono-jet prediction, it is difficult to fully compare the expected performance of FCC-hh and CLIC.

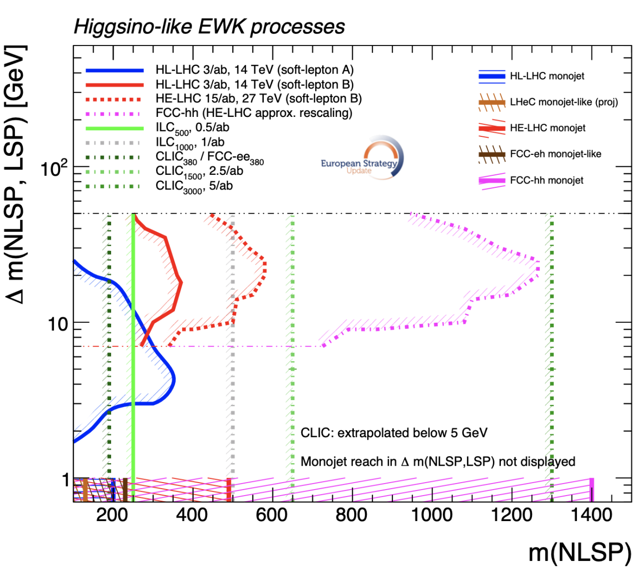

Fig. 1. Predicted exclusion potential of future colliders for Higgsino-like $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ with compressed mass spectra from the European Strategy Physics Briefing Book [4]. Limits are presented as a function of $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ masses, and include predictions for final states with soft leptons or with a mono-jet.

Further investigation of the mono-jet channel can clarify its potential at low Δm, and the inclusion of additional soft or displaced activity could improve the discovery sensitivity to compressed SUSY near $\Delta m = 1$ GeV [5]. Recent developments in compressed searches at the LHC include new techniques in soft-lepton channels [6] and the targetting of VBF production [7]. This proposal will review these recent developments and complete the exclusion predictions in the low-Δm phase space.

III. Electroweak Searches with Fully-Hadronic Final States

Fully-hadronic final states have shown excellent discovery potential and exclusion sensitivity in recent electroweakino searches yet remain underrepresented in future collider predictions. In comparison to leptonic channels, the large hadronic branching ratios for Z and W bosons produced in superpartner decay chains can outweigh the increase in hadronic backgrounds produced at hadron colliders, particularly when probing higher electroweakino masses with higher energies. An example can be seen in the $0\ell b\bar{b}$ search [8] by the ATLAS Collaboration, which is shown in Fig. 2 to set strong mass limits compared to leptonic analyses that use an equivalent 36.1 fb^{-1} dataset when the mass splitting between electroweakinos is substantially large. Furthermore, the analysis can be designed to treat the h, Z, and W bosons inclusively, which drastically reduces the model dependency in its sensitivity without significant loss. Lepton colliders would help reduce the important hadronic backgrounds, at the expense of a reduced center-of-mass energy.

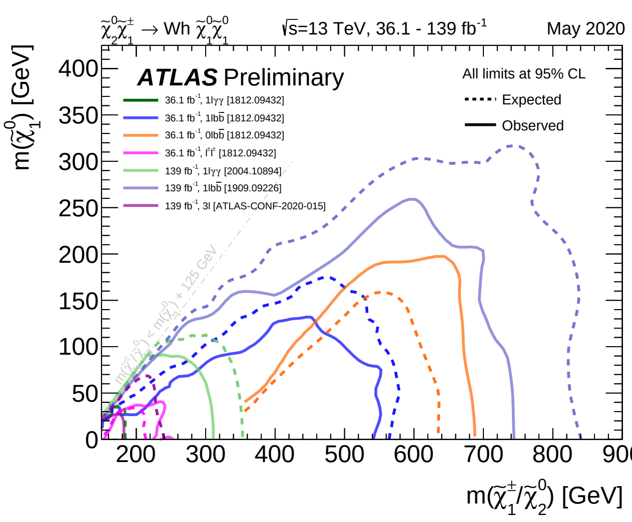

Fig. 2. Summary of 95% CL exclusion limits on $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_1^0$ production from various analyses from the ATLAS Collaboration [9]. All analyses target $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 W$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ decays, and limits are shown as a function of $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ masses with assuming $\mathrm{Br}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h) = 100\%$. The fully hadronic channel $0\ell b\bar{b}$ (orange) is seen to set strong mass limits compared to the other analyses using 36.1 fb^{-1} of data for electroweakinos with a large mass splitting.

The discovery potential of the fully-hadronic channel benefits from recent developments in boosted jet reconstruction and boson tagging exploiting jet substructure, providing powerful handles for identifying boosted h, Z, and W bosons while rejecting the dominant $Z \to \nu\nu$ background. Jet flavor tagging can provide further discrimination, with searches split into zero, two, or four b-jet regions. Understanding and estimating the jet boson tagging, jet substructure, and b-tagging performance at future detectors is important for measuring their potential in the boosted and resolved channels of fully-hadronic searches.

IV. R-Parity Violating Searches with 2 or 3 Leptons

R-parity violating (RPV) searches are of active interest at the LHC but are underrepresented in future collider predictions, which often focus on R-parity-conserving scenarios with missing energy in the final states. In this proposal we plan to investigate both the pair-production of stops and of electroweakinos within a $B-L$ RPV Minimal Supersymmetric Standard Model (MSSM).

In this model, a gauged $U(1)_{B-L}$ extension [10] to the SM allows for a right-handed sneutrino to break the $B-L$ symmetry, introducing L violation at tree level and allowing for RPV decays of the LSP. In a large random scan of the MSSM parameter space, admixture stops were seen to be a possible LSP candidate [11]. They are of additional interest due to their direct effect on the Higgs mass, with naturalness considerations preferring masses up to several TeV. In the $B-L$ RPV model they decay cleanly into a b-quark and a charged lepton of any generation, providing an interesting final-state for comparing future colliders. This stop search was previously performed by ATLAS using 36.1 fb^{-1} of early Run 2 data [12].

In the random MSSM parameter scan, electroweakinos were also seen to be common LSP candidates [13]. The lightest wino-type charginos and neutralinos were seen to be mass degenerate and would both decay via RPV couplings into a heavy boson and a lepton. This allows for unique final states, such as a tri-lepton resonance from a chargino decay into a Z boson and a charged lepton. A tri-lepton search was recently performed by ATLAS using 139 fb^{-1} of Run 2 data [14].

Both the stop and electroweakino searches scanned the possible decay branching ratios into lepton flavor and boson type to limit the dependence on simplified models. This method could be explored in studies with future colliders to provide further insight and context into their predicted sensitivities and exclusions.

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