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# The ILC as a natural SUSY discovery machine and precision microscope: From light higgsinos to tests of unification

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The requirement of electroweak naturalness in simple supersymmetric models motivates the existence of a cluster of four light higgsinos with mass 100-300 GeV. While such light compressed spectra may be challenging to observe at the LHC, future $e^+e^-$ colliders with $\sqrt{s} > 2m_{higgsino}$ would serve as both a SUSY discovery machine and a precision microscope.

We study higgsino pair production signatures at the ILC based on full, `Geant4`-based simulation of the ILD concept. We examine several benchmark scenarios that may or may not be accessible to the HL-LHC searches, with mass differences between the higgsino states between 20 and 4 GeV. Assuming $\sqrt{s}$= 500 GeV and 1000 fb$^{-1}$ of integrated luminosity, the individual higgsino masses can be measured to 1-2% precision in case of the larger mass differences, and still at the level of 5% for the smallest mass difference case. The higgsino mass splittings are sensitive to the electroweak gaugino masses and can allow extraction of gaugino masses to $\sim$ 3-20% (depending on the model). Extrapolation of gaugino masses via renormalization group running can test the hypothesis of gaugino mass unification. We also examine a case with natural generalized mirage mediation where the unification of gaugino masses at an intermediate scale apparently gives rise to a natural SUSY spectrum somewhat beyond the reach of the HL-LHC.

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## 1. Radiatively driven natural SUSY

Supersymmetry with radiatively-driven naturalness [1] is especially compelling in that it reconciles electroweak naturalness with (multi-TeV) LHC sparticle mass limits and Higgs boson mass measurements. The most fundamental consequence of radiatively-driven natural SUSY is the prediction of four light higgsinos $\tilde{\chi}_1^{\pm}$,$\tilde{\chi}_{1,2}^0$ with mass $\sim$ 100 – 300 GeV. Such light higgsinos are difficult (but perhaps not impossible) to see at the LHC, but would be easily visible at the ILC operating with $\sqrt{s} > 2m_{higgsino}$ [2]. In this case, the ILC, initially constructed as a Higgs factory, would turn out to be a higgsino factory! Thus, for this highly motivated scenario, the ILC could serve as both *a SUSY discovery machine, and a SUSY precision microscope*.

We have investigated three natural SUSY models: two with unified gaugino masses ("NUHM2" models) [3], called "ILC1" and "ILC2", and one with mirage unification of gaugino masses at an intermediate mass scale between $m_{GUT}$ and $m_{weak}$ [4], called "nGMM1". The models are indicated in Figure 1 which also show the current or projected limits from LEP, ILC and LHC [5].

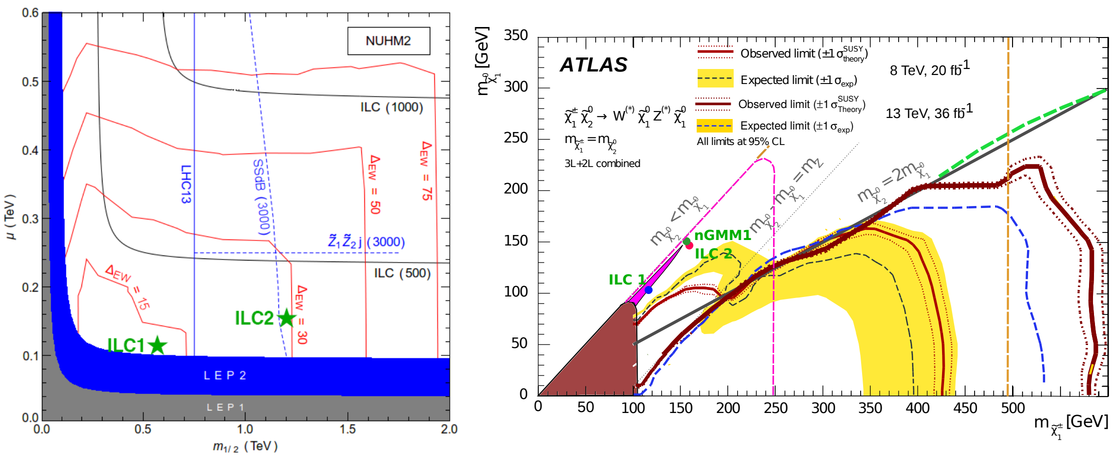


**Figure 1:** Model-parameter space, with our benchmarks indicated. Left: The $m_{1/2}$ vs. $\mu$ plane in the NUHM2 model, with projected LHC and ILC reaches. Right: Discovery or exclusion regions in the $M_{NLSP} - M_{LSP}$ plane for a $\tilde{\chi}_1^{\pm}$. The brown area and the magenta and orange lines show the reaches for $e^+e^-$ colliders (LEP-II, ILC@500, ILC@1000) together with current LHC limits, and HL-LHC projections (green dashed). The magenta area is the ATLAS low $\Delta_m$.exclusion, which however is in a different model.

## 2. The ILC and SUSY

The proposed International Linear Collider (ILC) is a power-efficient $e^+e^-$ collider with initial $E_{CMS}$ = 250 GeV [6, 7]. No other measures than to increase the linac length are needed to upgrade up to 1000 GeV. As an $e^+e^-$ collider, it collides point-like objects, so that the initial state is *known*. The production is electroweak, meaning that background is low, allowing for *trigger-less operation*. It also means that detectors do not need to strive to be radiation hard, and all design consideration can be concentrated on high precision, low material budget and $\sim 4\pi$ *coverage*. Finally, at a linear collider, the beams can be prepared with high and well-known polarisation. The combination of polarised beams, low background, known initial state, hermetic detectors, trigger-less operation, and energy upgradability makes the ILC *the ideal environment to study SUSY*.

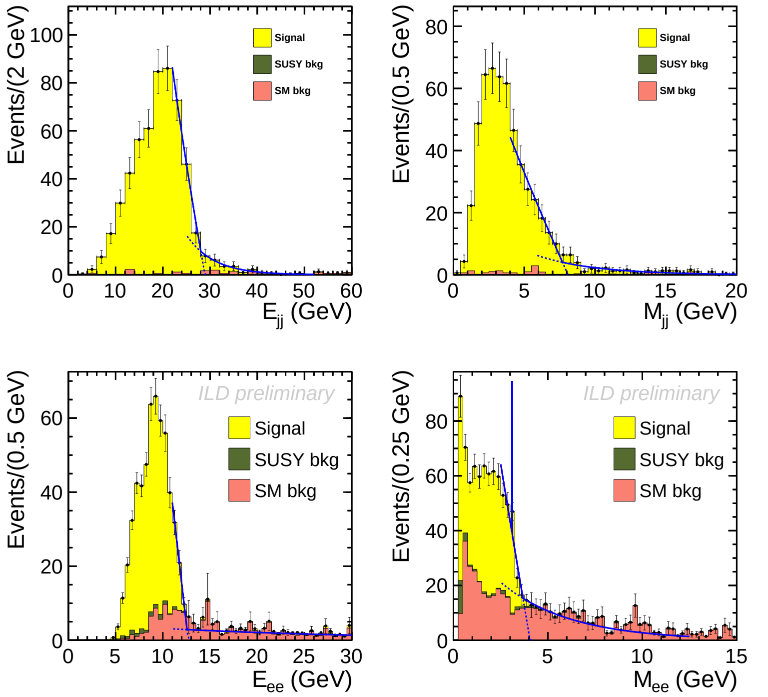


**Figure 2:** Energy and mass distributions for jet-jet in ILC2 ( top, left and right); and for *e-e* in nGMM1. (bottom, left and right)

Our simulation studies of the three models implement a detailed full simulation of the ILD detector at the ILC [8] along with event generation from `Whizard` [9]. Both signal and all Standard Model processes were simulated in this way.

For *charginos*, we study the process $E^+e^- \to \tilde{\chi}_1^+ + \tilde{\chi}_1^- \to (\ell\nu_\ell\tilde{\chi}_1^0)\ +(q\bar{q}'\tilde{\chi}_1^0)$, and we are able to extract $M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\chi}_1^0}$ via the $E_{jj}$ and $M_{jj}$ distributions, typically to percent level accuracy. Figures 2(a) and 2(b) show the resulting distributions for ILC2 as an example. For *neutralinos*, we measure the dilepton energy and mass distributions from $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0$ followed by $\tilde{\chi}_2^0 \to \ell^+\ell^-\ \tilde{\chi}_1^0$. From this, we are able to measure $M_{\tilde{\chi}_1^0}$ and $M_{\tilde{\chi}_2^0}$ to typically percent level accuracy, and here the distributions found in the nGMM1 model is shown as an example in Figures 2(c) and 2(d).

After the full ILC program, and depending on model, channel, and polarisation, we find experimentally measured uncertainties of $\delta$(masses) = 0.5-1 % and $\delta(\sigma \times \mathrm{BR})$ = 1-6%.

## 3. Fit model parameters and evolve to GUT

When these measurements are combined with precision Higgs boson measurements, fits to both weak scale SUSY and high scale SUSY model parameters can be made, either with 10 free MSSM parameters ("pMSSM-10"), or only the four directly involved in the higgsino properties at tree-level ("pMSSM-4") [10]. Thanks to the combination of the measured masses, BRs and Higgs properties, all 10 weak-scale parameters gets constrained, for all three bench-marks. In particular, the bino and wino SUSY breaking masses $M_1$ and $M_2$ - the ones most directly related to the higgsino masses - can be determined at percent level.

The fitted weak-scale parameters can be evolved with the appropriate RGE:s to higher scales. This allows to verify or discard the idea of GUT-scale unification of $M_1$ and $M_2$ The determined parameters can be used to predict the masses of the yet unobserved sparticles. Figure 3 illustrates the precisions obtained on the pMSSM-10 parameters, or the corresponding pMSSM-4 fit with $M_1$, $M_2$, $\mu$ and $\tan\beta$ only, for ILC2. All four parameters can be determined accurately. This results in predictions for the masses of the heavier electroweakinos with a predicted $\delta$(masses) = 1.6 -3 %. From the 10 parameter fit, both lower *and upper* limits can be given for *all* sparticles.

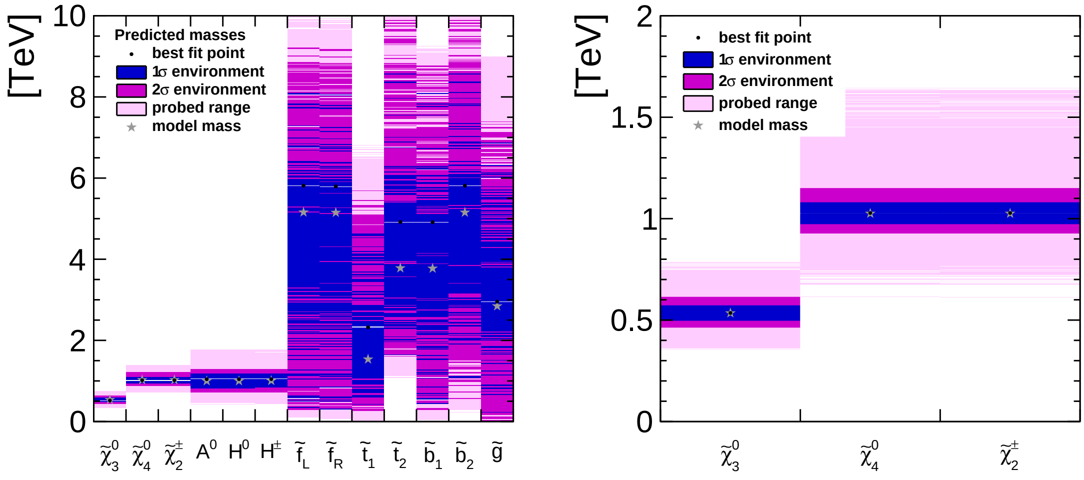


**Figure 3:** Predicted mass ranges from the fit to ILC2. Left: pMSSM-10 fit, Right: pMSSM-4 fit.

## 4. Conclusions

Light higgsinos are motivated by *naturalness*, and the ILC would probe higgsinos in a complementary manner to LHC searches. Studies at the ILC would either exclude masses up to $\sqrt{s}/2$=500 GeV (after a 1 TeV upgrade), or discover natural SUSY, regardless of the mass scale of heavier states. This reach corresponds to a close-to-complete coverage of natural SUSY scenarios. If discovered, experiments at ILC would measure properties of higgsinos to *sub-percent-level* precision. Such precise measurements allow for extracting GUT and weak scale parameters and predicting mass scales of unobserved sparticles. Hence, the ILC is *the* SUSY exploration instrument!

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