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

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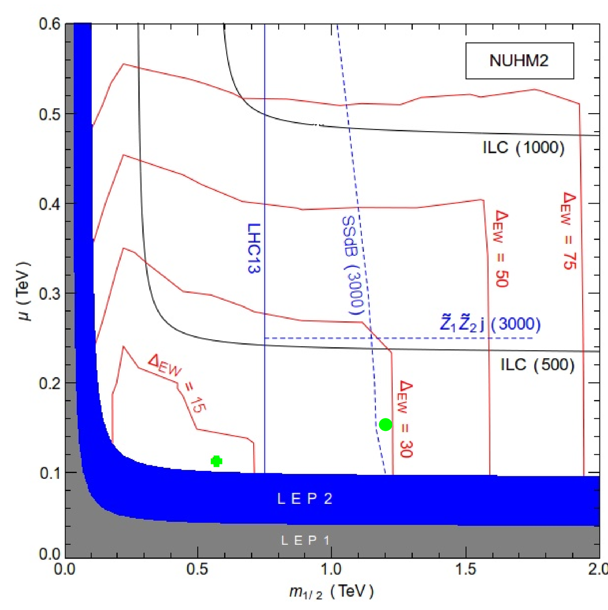
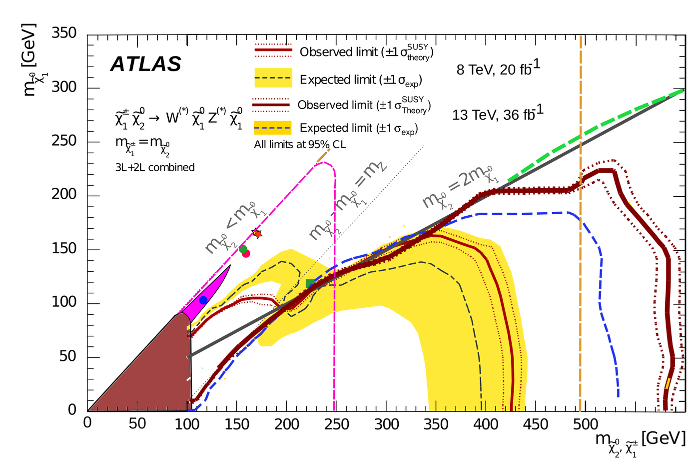
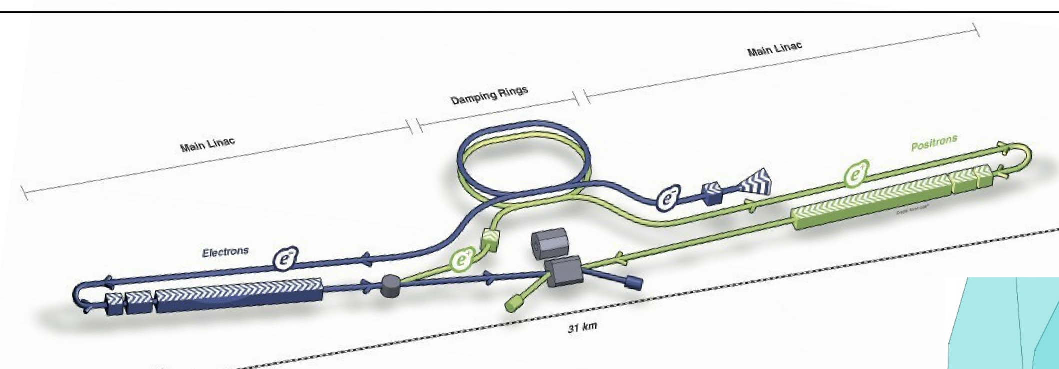
Radiatively driven natural SUSY

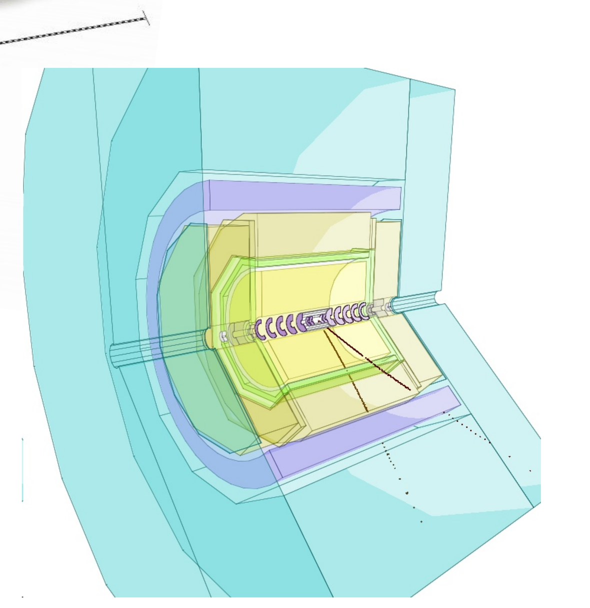
Supersymmetry with radiatively-driven naturalness is especially compelling in that it reconciles electroweak naturalness with (multi-TeV) LHC sparticle mass limits and Higgs boson mass measurements. The most fundamental consequence of radiatively-driven natural SUSY is the prediction of four light higgsinos $\tilde{\chi}_1^{\pm}, \tilde{\chi}_{1,2}^0$ with mass $\sim$ 100 $-$ 300 GeV (the lower the better). Such light higgsinos are difficult (but perhaps not impossible) to see at LHC, but would be easily visible at ILC operating with $\sqrt{s} > 2m$(higgsino). 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, ILC could serve as both a SUSY discovery machine, and a SUSY precision microscope.





We have investigated three natural SUSY benchmark models: two with unified gaugino masses (ILC1 and 2, marked with green symbols above, and red and blue circles left) and one with mirage unification of gaugino masses at an intermediate mass scale between m_{GUT} and m_{weak} (nGMM1 marked with a green circle left). The figures also show current and projected LHC reaches.





ILC and SUSY

- ILC is a power-efficient e^+e^- collider with initial $E_{CMS} = 250$ GeV, "easily" upgradable up to 1000 GeV.
- Colliding point-like objects $\Rightarrow$ initial state known
- EW-production $\Rightarrow$ Low background $\Rightarrow$
  - Thin detectors w/ $\sim 4\pi$ coverage, and No trigger
- Polarised beams.
- Polarised beams + Low background + known in-state + hermetic detectors + energy upgradability: The ideal SUSY environment.

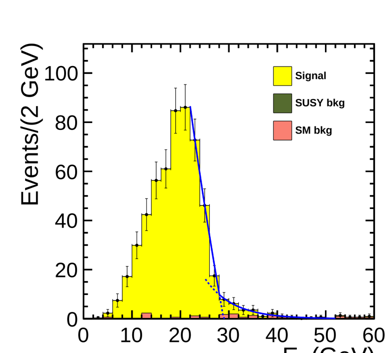
$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\mu^+\mu^-$ in ILD, with full background

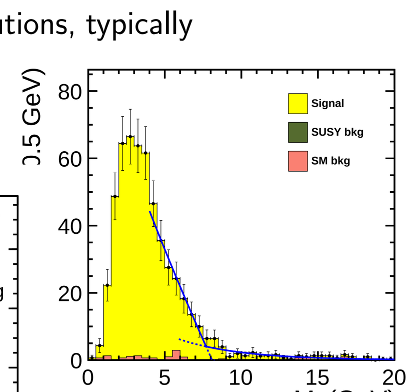
ILC measurements

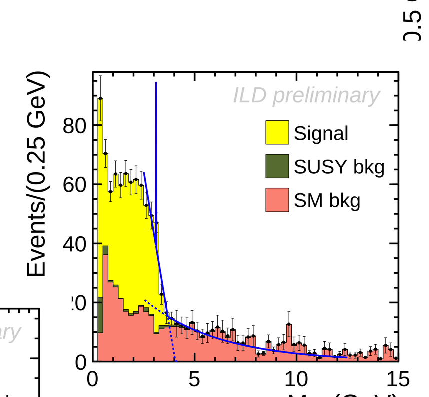
Our calculations implement a detailed ILD detector simulation along with event generation from Whizard of both signal and the full SM.

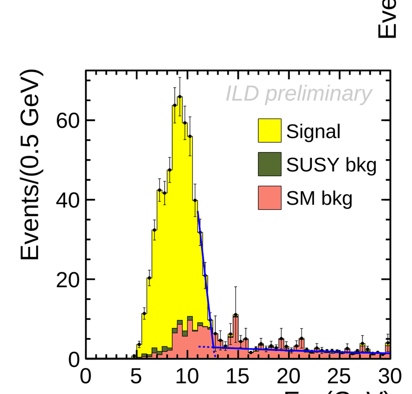
Charginos

By measuring $e^+e^- \to \tilde{\chi}_1^+ + \tilde{\chi}_1^- \to (\ell\nu_\ell\tilde{\chi}_1^0) + (q\bar{q}'\tilde{\chi}_1^0)$ we are able to extract $M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\chi}_1^0}$ via the $m(jj)$ and $E(jj)$ distributions, typically to percent level accuracy. ILC2 shown as an example.









Neutralinos

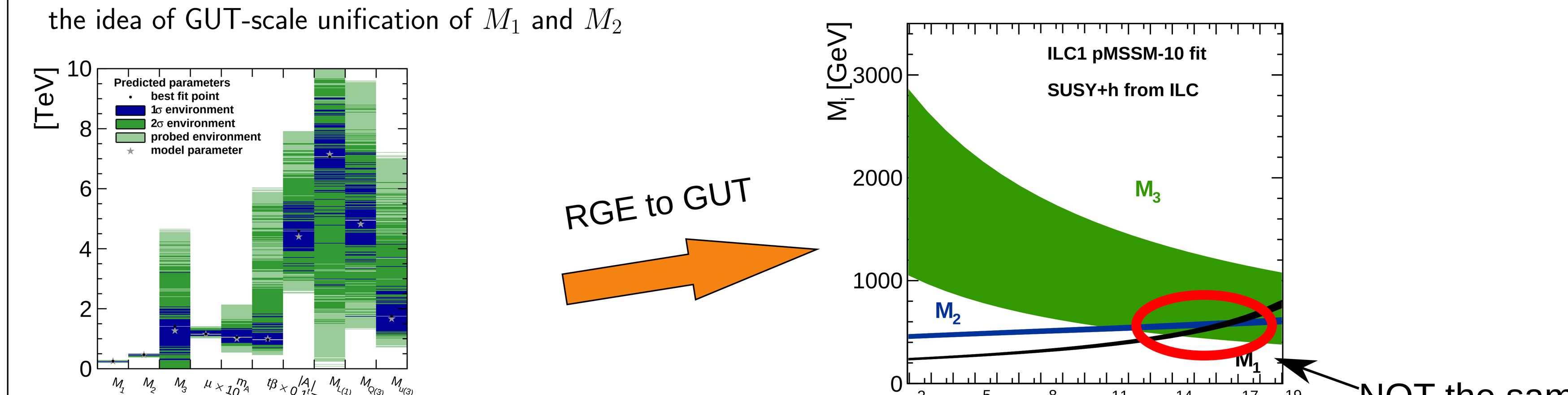
By measuring the dilepton mass and energy distributions from $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0$ followed by $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$, we are able to measure $M_{\tilde{\chi}_1^0}$ and $M_{\tilde{\chi}_2^0}$ to typically percent level accuracy. Here nGMM1 is shown as an example.

After the full ILC program, and depending on model, channel, and polarisation, we find experimentally that

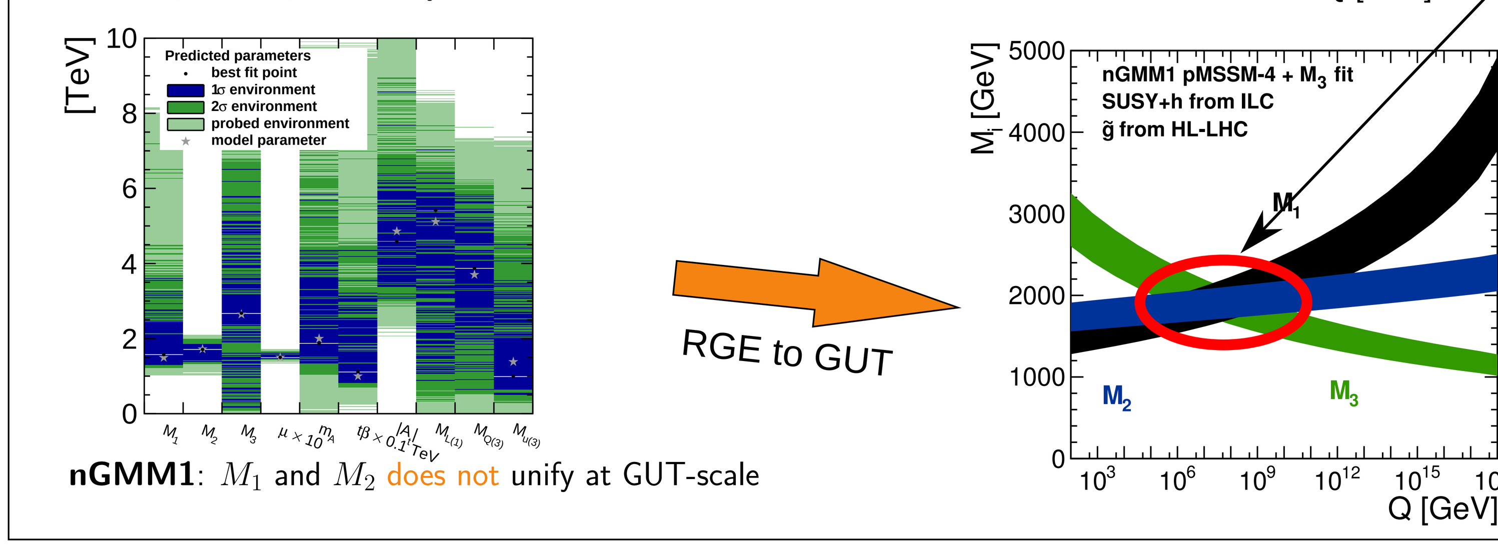
measured $\delta(\text{masses}) = 0.5\text{-}1$ % , $\delta(\sigma \times \text{BR}) = 1\text{-}6\%$

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, or only the four directly involved in the higgsino properties at tree-level. Thanks to the combination of the measured masses, BR:s 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



ILC1: M_1 and M_2 does unify at GUT-scale



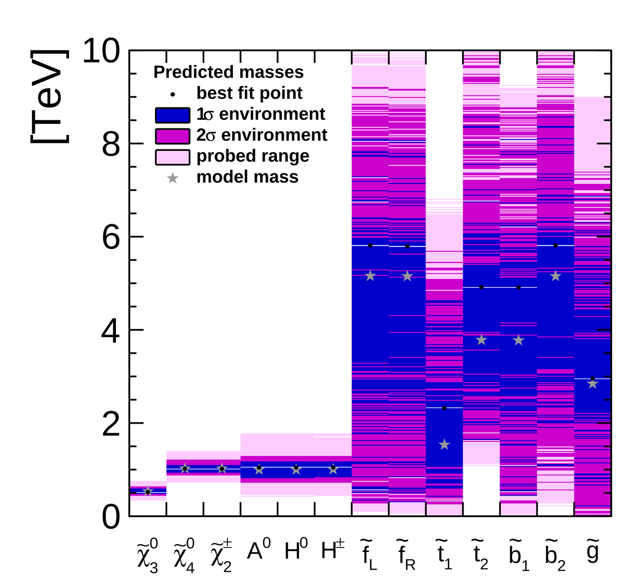
nGMM1: M_1 and M_2 does not unify at GUT-scale

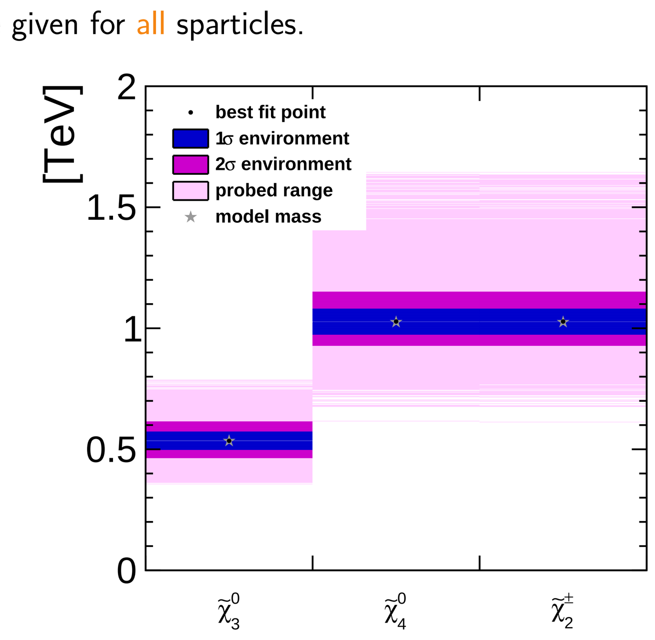
Predict the spectrum

The determined parameters can be used to predict the masses of the yet unobserved sparticles. The figures illustrate the precisions obtained on the pMSSM-10 parameters, or the corresponding pMSSM-4 fit with M$_1$, M$_2$, μ 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

predicted $\delta(\text{masses}) = 1.6$ -3 %

From the 10 parameter fit, both lower and upper limits can be given for all sparticles.





Take-home message

- Light higgsinos motivated by naturalness
- ILC would probe higgsinos complementary to LHC reach
  - Either exclude masses up to $\sqrt{s}/2$=500 GeV for 1 TeV upgrade $\to$ wide coverage of natural SUSY scenarios
  - or discover regardless of mass scale of heavier states
- ILC would measure properties of higgsinos to sub-percent-level precision.
- Precise measurements allow for extracting GUT and weak scale parameters and predicting mass scales of unobserved particles

ILC is *the* SUSY exploration instrument!

More info:

- P. Bambade et al. "The International Linear Collider: A Global Project" (2019), arXiv:1903.01629 [hep-ex]
- T. Behnke et al. "The International Linear Collider Technical Design Report - Volume 1: Executive Summary" (2013), arXiv:1306.6327 [physics.acc-ph].
- S.-L. Lehtinen, "Supersymmetry parameter determination at the International Linear Collider," (2018), PhD Thesis, Hamburg University, DESY-THESIS-2018-035.
- S.-L. Lehtinen et al., "Naturalness and light Higgsinos: why ILC is the right machine for SUSY discovery" (2017), arXiv:1710.02406 [hep-ph]
- K. Fujii et al. "The Potential of the ILC for Discovering New Particles" (2017), arXiv:1702.05333 [hep-ph]