Measuring neutrino dynamics through light higgsinos and sneutrinos

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Outline

Today I shall discuss

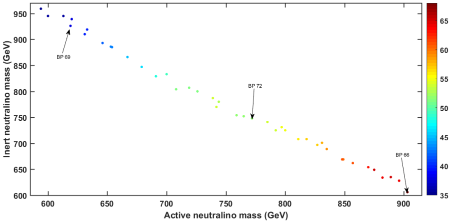
- light higgsinos and some ways to search them
- light higgsinos in the presence of a sneutrino LSP
- prospects of measuring neutrino dynamics in such a case at the ILC

The main part is based on 2109.06802, but I'll mention some results from 2007.10966, 2104.07347. My coauthors in these works have been Shaaban Khalil, Yi Liu, Stefano Moretti and Diana Rojas-Ciofalo.

Light higgsinos is a scenario testable at the ILC

- It is well known that electroweak symmetry breaking in MSSM leads to the tree-level condition
$$\frac{1}{2}m_Z^2 = -\frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{\tan^2\beta - 1} - |\mu|^2$$
- As μ is a supersymmetric parameter and the soft masses are SUSY breaking, a priori these should not be at the same scale
- If there are no significant cancellations, μ should not be too much above the electroweak scale, which would potentially make higgsinos light enough to be produced at the ILC

The light higgsino scenario can be saved by nonstandard DM or second DM candidate



- If the higgsino is the LSP, it is well known that the relic density bound is saturated around $m_{\tilde{H}} \simeq 1$ TeV, lighter masses lead to underabundance
- It is possible to have light higgsinos as the LSP if there is a second dark matter candidate, say axions or inert higgsinos (E6 inspired example in 2007.10966)
- It is also possible to saturate the relic density if there is a DM candidate not belonging to the MSSM, one example being singlet sneutrinos

A Higgsino-like LSP with small mass splittings is easier to find with the ILC

- Light higgsinos can be searched at the LHC in the multileptons + MET channel, but you need ISR to trigger the event and to boost the soft leptons, the reach is somewhat limited
- At ILC you can probe smaller mass splittings (even so soft leptons that they do not reach calorimeters) in the monophoton channel, similar idea has been used at LEP (*e.g.* hep-ex/0406019)
- At LHC this is impossible because the partonic $\sqrt{s}$ is not fixed

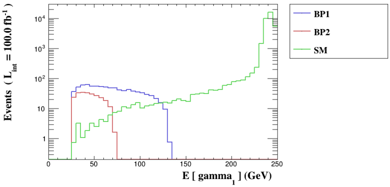


Figure: Figure from 2104.07347

NMSSM with right-handed neutrinos leads to an electroweak scale seesaw

The superpotential

$$
\begin{aligned}
W &= Y_u Q H_u U^c + Y_d Q H_d D^c + Y_\ell L H_d E^c + Y_\nu L H_u N^c \\
&\quad + \lambda S H_u H_d + \lambda_N S N^c N^c + \frac{\kappa}{3} S^3
\end{aligned}
$$

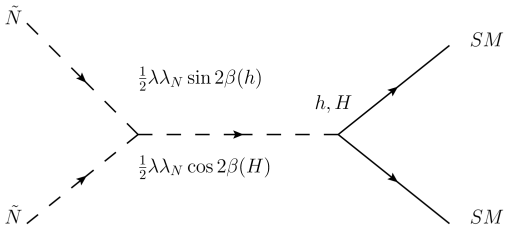
- The NMSSM solves the μ-problem by introducing a singlet, whose scalar component gets a VEV $\Rightarrow \mu_{\text{eff}} = \lambda\langle S\rangle$
- The NMSSM still lacks a mechanism for neutrino masses, but extending the model with RH neutrinos solves this problem
- The singlet generates a mass term for RH neutrinos, too $\Rightarrow$ expect both higgsinos and RH neutrinos to be at the electroweak scale $\Rightarrow$ tiny neutrino Yukawa couplings needed ($\mathcal{O}(10^{-7})$)

The singlet makes the RH sneutrino a viable thermal dark matter candidate

Much of the important physics is captured in the scalar potential term

$$V = |\lambda H_u H_d + \lambda_N \tilde{N}^2 + \kappa S^2|^2 + \ldots$$

- The cross terms generate a three-point coupling between the neutral Higgses and RH sneutrino pairs
- If the RH sneutrino is the LSP, this allows the sneutrino to annihilate efficiently through the (heavy) Higgs portal if λ, λ_N are large enough



We try to measure neutrino Yukawa couplings when sneutrino is the LSP

Setup: Right-sneutrino LSP, light higgsinos so that higgsino pair production possible, right-neutrinos so light that $\tilde{\chi}^0 \to \tilde{N}N$ kinematically open, look at $e^+e^- \to \tilde{\chi}^+\tilde{\chi}^-$

- If sneutrinos are heavier than higgsinos, their decays lead to displaced vertices (see 2012.14034)
- If, however the charged higgsinos are heavier, the visible decay proportional to neutrino Yukawas ($\tilde{\chi}^\pm \to \ell^\pm \tilde{N}$) has to compete with the three-body decay ($\tilde{\chi}^\pm \to W^{*\pm}\tilde{\chi}^0 \to \tilde{\chi}^0 \ell\nu/q\overline{q}'$)
- The tiny Yukawa couplings make the decay rare even with favourable kinematics, but on the other hand the existence of the second decay mode provides a standard of comparison
- The width of the three-body decay is computable, if we assume that only the W-boson contributes
- If $\tilde{\chi}^0 \to \tilde{N}N$ is kinematically open, it dominates over all other decay modes ($\tilde{N}\nu$), the right-neutrino decay to ℓjj provides an additional handle

The overall process of determining Yukawa couplings

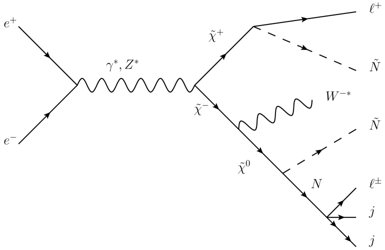
See a signal of the two-body process $\Rightarrow$ Determine the branching ratio (initial number of event before cuts & chargino production cross section) $\Rightarrow$ Use three-body decay width to compute two-body decay width $\Rightarrow$ Relate this to Yukawa couplings

The difficult parts:

- finding the signal
- inverting the cuts

It is easier to find the signal at an e^+e^- collider

We look at a two leptons, two jets and missing transverse momentum topology.



The features that allow to distinguish the signal from the background:

- The two-body decay has fixed kinematics so E_ℓ is within a narrow range (at LHC not true as lab frame $\neq$ CM frame)
- The RH neutrino leads to a lepton and two jets having an invariant mass near m_N
- The two LSPs give a substantial amount of $\not{p}_T$

With ILC design energy and luminosity you would get at least evidence of the rare decay

Cut	BP1	BP2	BP3	Background
Initial	87.0	139	116	2357000
b-jet veto	84.2	137	115	377200
Same-sign dilept	17.8	26.0	20.6	1140
$N(j) = 2$	8.66	12.3	8.69	440
$p_T(j_1) < 70$ GeV	8.66	12.0	8.35	182
$p_T(\ell_1) > 30$ GeV	7.87	10.2	8.11	153
$p_T(\ell_2) < 40$ GeV	7.87	10.2	8.11	114
$H_T < 100$ GeV	7.87	10.2	8.00	87.7
$E(\ell_1) \in [60, 120]$ GeV	7.87	9.33	7.65	42.2
$\Delta\Phi_{0,\pi}$ >2.5	7.70	8.08	6.14 9	20.0
$\not{E}_T \in [50, 100]$ GeV	6.82	5.99	4.06	10.5
$M(\ell_1\ell_2) < 80$ GeV	5.60	5.71	3.94	5.9
$M(j_1j_2\ell_2) < 110(100)$ GeV	5.51	5.71	3.94	3.3(2.5)
$M(j_1j_2\ell_2) > 90(80)$ GeV	3.67	3.48	2.43	1.1(0.64)

Most cut efficiencies can be estimated in a data-driven way

- In order to estimate Yukawa couplings, we need to figure out how many initial events we had
- Selection efficiencies can be rather well estimated from other types of events, as can b-tagging efficiencies
- Some selection efficiencies can be estimated from the main decay mode of the chargino (*e.g.* H_T or jet momenta)
- In general when "data-driven" estimates were available, they agreed with our simulated cuts to within 10–15%
- Some cuts need to be simulated, nevertheless one can expect that the statistical uncertainty dominates due to the small event rate
- Fortunately the two-body decay width is proportional to $|y_\nu|^2$, so the relative error of the Yukawa coupling is smaller than for the decay rate
- At least you can estimate the order of magnitude for the Yukawa coupling and show that it is consistent with what you expect

Summary

- The ILC can probe the light higgsino scenario also in the kinematical regions difficult for the LHC
- Higgsino-sneutrino couplings can lead to visible decays that contain information about the neutrino mass generation mechanism
- Finding the rare two-body decay is easier with the fixed (partonic) CM energy
- ILC could possibly probe other neutrino mass generation mechanisms through sneutrinos — this is for future work