Soft opposite-sign dilepton plus jet plus MET from light higgsinos at LHC: a Snowmass 2021 EF08 Letter of Intent

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August 18, 2020

Electroweak naturalness in supersymmetric models requires a superpotential μ parameter to be comparable in magnitude to the weak scale while sparticles, which only contribute to the weak scale via loop-suppressed terms, can be much heavier. The resulting little hierarchy with $\mu \sim 100-300$ GeV $\ll m(sparticle)$ is supported by expectations for SUSY from the landscape of string theory vacua. In this situation, only higgssino-like electroweakinos may be accessible to LHC and HL-LHC SUSY searches. We examine aspects of light higgsino pair production reactions for HL-LHC, focussing on $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^0 j$ production followed by $\tilde{\chi}_2 \to \ell^+\ell^-\tilde{\chi}_1^0$ decay. We plot out expected distributions of the soft opposite-sign dilepton plus jet plus MET signature, including p_T and opening angles in order to characterize this promising SUSY discovery channel.

Electroweak naturalness[1, 2] provides the most direct, model-independent and conservative criterion of fine-tuning in SUSY models. It arises from minimization of the MSSM scalar potential in order to determine the Higgs field vacuum expectation values in terms of the SUSY Lagrangian parameters. The minimization condition can be recast as

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \sim -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}). \tag{1}$$

Here, Σ_u^u and Σ_d^d are the one-loop corrections arising from particles and sparticles that couple directly to the Higgs doublets. Over 40 contributions are listed in Ref. [2], of which the largest typically comes from the top-squarks $\Sigma_u^u(\tilde{t}_{1,2})$. The bottom-up notion of electroweak naturalness is the statement that independent contributions to any observable not substantially exceed the value of the observable – then requires μ and $\sqrt{-m_{H_u^2}} \sim m_Z$ while top squarks may inhabit the several TeV range since their contribution contains a loop factor $1/8\pi^2$. The soft term m_{H_d} is comparable to the mass of the heavy physical Higgs fields $A,\ H,\ H^\pm$ but is suppressed by a factor $\tan\beta$ so we can allow heavy Higgs in the several TeV range as well. It has been suggested that in the top-down string landscape picture – which gives the only plausible explanation for the tiny value of the cosmological constant – the soft terms are expected to be statistically selected to as large of values as is possible[8] subject to not-to-large contributions to the calculated value of the weak scale for each phenomenologically viable pocket-universe vacuum value within the greater multiverse[9]. Such a picture gives rise to a little hierarchy where $\mu \sim m_{weak} \ll m(soft)$ where most sparticles other than higgsinos have masses of order the soft SUSY breaking scale $m(soft)$[10, 11].

In this highly motivated scenario,[1] it may well be that only light higgsino-like electroweakinos $\tilde{\chi}_{1,2}^0$ and $\tilde{\chi}_1^\pm$ are readily accessible to LHC or HL-LHC searches. Since the LSP $\tilde{\chi}_1^0$ is a higgsino-like WIMP, it is expected to compose (a portion of) the dark matter and hence escapes LHC detection as missing energy.

[1]While the string landscape provides motivation for the mini-hierarchy between μ and the soft-SUSY breaking terms, we stress that the conclusions from electroweak naturalness have a much broader applicability, and stand independently of the top-down string picture. Electroweak naturalness is compatible with, but independent of, the idea of stringy-naturalness introduced below.

Typical reactions such as $pp \to \tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^0\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ are expected to be very difficult to observe since the visible decay products of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are expected to be very soft[4].

A way forward is to search for $\tilde{\chi}_1^0\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production while recoiling against a hard initial state quark or gluon radiation[5, 6, 7]. In this case, the higgsino decay products are boosted to higher energies and the hard jet or associated MET may be used as a trigger. Indeed, the ATLAS and CMS collaborations have begun searches in these channels for the soft-opposite-sign dilepton plus jet plus MET channel and limits have been placed in the $m_{\tilde{\chi}_2^0}$ vs. $\Delta m \equiv m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ plane. Also, the recent ATLAS analysis using 139 fb^{-1} of data at $\sqrt{s} = 13$ TeV seems to find some excess in this channel with $m(\ell^+\ell^-) \sim 4 - 12$ GeV [**?**].

Given the importance of this channel as a route to discovery of SUSY, we propose for Snowmass 2021 to make detailed distributions of expected $p_T(\ell)$ and $\Delta\phi(\ell^+\ell^-)$ and other distributions without and with initial state radiation. We compare against some prominent SM backgrounds including $t\bar{t}$, $\tau\bar{\tau}j$ and WWj production. The goal here is to fully flesh out characteristics of this discovery channel, and perhaps find improved cuts for discovery of the light higgsinos which are required by electroweak naturalness.

A further goal is to explore theoretical aspects of the $m_{\tilde{\chi}_2^0}$ vs. $\Delta m \equiv m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ discovery plane which is used by experimentalists to display their search limits for this signature. This work has already been largely completed and is available in Ref. [12]. In this work, we wanted to point out the natural and unnatural portions of this discovery plane to guide experimental searches to the most plausible regions of parameter space. For instance, as mass gaps Δm fall below ~ 5 GeV, then the lightest electroweakinos become nearly pure higgsino-like, but also highly unnatural since then gauginos are required to be so heavy as to lead to large Σ_u^u contributions. Also, stringy naturalness based on the landscape favors mass gaps $\Delta m \sim 5 - 10$ GeV. See Ref. [12] for further details.

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