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Multi-channel assault on natural supersymmetry at the high luminosity LHC

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Recent clarifications of naturalness in supersymmetry robustly require the presence of four light higgsinos with mass $\sim 100-300$ GeV while gluinos and (top)-squarks may lie in the multi-TeV range, possibly out of LHC reach. We project the high luminosity (300-3000 fb^{-1}) reach of LHC14 via gluino cascade decays and via same-sign diboson production. We compare these to the reach for neutralino pair production $\widetilde{Z}_1\widetilde{Z}_2$ followed by $\widetilde{Z}_2\to\widetilde{Z}_1\ell^+\ell^-$ decay to soft dileptons which recoil against a hard jet. It appears that 3000 fb^{-1} is just about sufficient integrated luminosity to probe naturalness with up to 3% fine-tuning at the 5σ level, thus either discovering natural supersymmetry or else ruling it out.

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The discovery [1, 2] of a very Standard Model (SM)-like Higgs boson at the CERN Large Hadron Collider (LHC) brings with it a puzzle. While chiral symmetry protects fermion masses and gauge symmetry protects gauge boson masses against large quantum corrections, no corresponding protective symmetry exists within the SM to tame the quadratic sensitivity of the Higgs boson mass to new physics at very high scales. The simplest and most elegant protection, known as supersymmetry (SUSY)[3], relates fermions to bosons in exactly the right way to cancel these dangerous corrections. Indirect evidence for softly broken SUSY with weak scale superpartners exists in that 1. the coupling strengths of the strong and electroweak forces, as measured to high precision at the CERN LEP e^+e^- collider at energy scale $\sqrt{s}=m_Z$, enjoy an impressive unification at $Q\simeq 2\times 10^{16}$ GeV when extrapolated to high energies[4]. 2. the top mass, measured to be $m_t\simeq 173.2$ GeV, lies in the range required to trigger a radiatively-induced breakdown of electroweak symmetry[5]. Finally, 3. the light Higgs mass m_h was found to lie at $\simeq 125$ GeV, squarely within the range required by the Minimal Supersymmetric Standard Model (MSSM), where m_h is bounded by $\lesssim 135$ GeV[6]. Expectations were thus heightened for the appearance of supersymmetric matter at LHC with masses not too far above the weak scale as typified by $m_{weak}\simeq m_{W,Z,h}\sim 100$ GeV.

In spite of these impressive success stories, a sense of dismay has emerged due to the lack of evidence for direct production of supersymmetric matter at LHC. Recent analyses of data from the first year of LHC run 2 with $\sqrt{s}=13$ TeV pp collisions and ~ 4 fb^{-1} of integrated luminosity (just 1-2% percent of the design integrated luminosity sample of 300 fb^{-1} even without the high luminosity (HL) upgrade) have resulted in gluino mass bounds as high as $m_{\tilde g}\gtrsim 1.8$ TeV within the context of some simplified models[7]. In addition, the observed value of m_h requires the presence of either TeV-scale highly mixed top squarks or tens of TeV top squarks with just small left-right mixing[8]. Such large sparticle mass values lie far beyond the classic expectations from Barbieri-Giudice[9] (BG) naturalness where $m_{\tilde g}\lesssim 350$ GeV and $m_{\tilde t_1}\lesssim 350$ were expected[10] for fine-tuning no worse than $\sim 3\%$. The situation has led some researchers to proclaim a crisis in physics[11] while stimulating new, non-supersymmetric avenues towards a solution to the gauge hierarchy problem[12].

An alternative response was to scrutinize the validity of the earlier naturalness calculations[13–16]. The simplest, most conservative naturalness measure Δ_{EW}, proposed in Refs. [17, 18], is based on the well-known expression

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2+\Sigma_d^d-(m_{H_u}^2+\Sigma_u^u)\tan^2\beta}{\tan^2\beta-1}-\mu^2 \quad (1)$$

resulting from the minimization of the Higgs potential in the MSSM. Here, $m_{H_u}^2$ and $m_{H_d}^2$ are squared soft SUSY breaking Lagrangian terms, μ is the superpotential Higgsino mass parameter, $\tan\beta=v_u/v_d$ is the ratio of Higgs field vacuum-expectation-values and the $\Sigma_u^u(k)$ and $\Sigma_d^d(j)$ contain an assortment of radiative corrections, the largest of which typically arise from the top squarks. Expressions for the Σ_u^u and Σ_d^d are given in the Appendix of Ref. [18]. The value of Δ_{EW} compares the largest independent contribution on the right-hand-side (RHS) of Eq. (1) to the left-hand-side $m_Z^2/2$. If the RHS terms in Eq. (1) are individually comparable to $m_Z^2/2$, then no unnatural fine-tunings are required to generate $m_Z=91.2$ GeV. The main requirements for low fine-tuning ($\Delta_{EW}\lesssim 30$[1]) are the following.

[1] The onset of fine-tuning for $\Delta_{EW}\gtrsim 30$ is visually displayed in Ref. [19].

- $|\mu| \sim 100-300$ GeV[20–24][2] (where $\mu \gtrsim 100$ GeV is required to accommodate LEP2 limits from chargino pair production searches).
- $m^2_{H_u}$ is driven radiatively to small, and not large, negative values at the weak scale [17, 18].
- The top squark contributions to the radiative corrections $\Sigma^u_u(\tilde{t}_{1,2})$ are minimized for TeV-scale highly mixed top squarks[17]. This latter condition also lifts the Higgs mass to $m_h \sim 125$ GeV. For $\Delta_{EW} \lesssim 30$, the lighter top squarks are bounded by $m_{\tilde{t}_1} \lesssim 2.5$ TeV.
- The gluino mass which feeds into the $\Sigma^u_u(\tilde{t}_{1,2})$ via RG contributions to the stop masses[24] is required to be $m_{\tilde{g}} \lesssim 3-4$ TeV, possibly beyond the reach of LHC.
- First and second generation squark and slepton masses may range as high as 5-20 TeV with little cost to naturalness[18, 19, 25, 28].

SUSY models with these properties have been dubbed radiatively-driven natural SUSY (RNS). The presence of a high degree of fine-tuning generally indicates a pathology or missing element in a physical theory.

It was also found that almost all early estimates based on the BG measure $\Delta_{BG} \equiv max_i|\partial \log m^2_Z/\partial \log p_i|$, where the p_i constitute *independent* fundamental parameters of the theory, were based on application to low energy effective theories where multiple independent soft SUSY breaking terms were introduced to parameterize one's ignorance of hidden sector SUSY breaking. When the underlying correlations among soft terms (that would undoubtedly be present when these are derived from the underlying fundamental theory) are incorporated, it was shown that $\Delta_{BG} \simeq \Delta_{EW}$[13–15].[3] An alternative fine-tuning measure Δ_{HS} based on large log contributions to m_h was introduced[21, 29] which seemed to require three third generation squarks below about 500 GeV[24]. This clearly ignores the possibility of correlated soft terms that result in large cancellations in the Higgs mass. Upon inclusion of all independent contributions to m^2_h, it was found that the large log measure also reduces to the electroweak measure, Δ_{EW} [13, 15].

In light of these clarifications, it should not be surprising that SUSY has not yet emerged at the LHC. Current LHC13 search limits up to $m_{\tilde{g}} \sim 1.8$ TeV[7] probe about half the gluino mass range allowed by natural SUSY, while LHC13 top squark searches – which probe to $m_{\tilde{t}_1} \sim 750$ GeV[30] – explore much less than half the allowed stop mass range. In fact, it has recently been argued that *string landscape* considerations favor the higher range of soft term values so long as the weak scale is maintained at $m_{weak} \equiv m_{W,Z,h} \sim 100$ GeV[31]. In this scenario, the much lighter higgsino-like charginos and neutralino $\widetilde{W}^{\pm}_1$, $\widetilde{Z}_{1,2}$ can be produced at large rates at the LHC but the lightest of these, the $\widetilde{Z}_1$, is assumed to comprise a portion of the dark matter in the universe (along with *e.g.* axions[32]) and thus escapes collider detection. The heavier higgsinos have a relatively small mass gap $m_{\widetilde{W}_1,\widetilde{Z}_2} - m_{\widetilde{Z}_1} \sim 10-20$ GeV and so release only small amounts of visible energy in their decays: thus, they are very difficult to trigger on at the LHC much less observe above QCD backgrounds which produce soft tracks in abundance.[4]

What then are the prospects for future detection of natural SUSY at LHC? The search for gluino pair production always figures prominently on SUSY search menus. In RNS SUSY, gluino pair production will be followed by cascade decays[34] via $\tilde{g} \to t\bar{t}\widetilde{Z}_i$ and $\tilde{g} \to t\bar{b}\widetilde{W}_i$ where now the lightest electroweak-inos (EWinos) $\widetilde{W}^{\pm}_1$ and $\widetilde{Z}_{1,2}$ are the light higgsino-like charginos and neutralinos. Gluino cascade decay events will thus be rich in b-jets, typically four per event, along with isolated leptons, light quark jets and missing E_T ($\not\!\!E_T$). The 5σ reach of LHC14 with 300-3000 fb^{-1} of integrated luminosity has been estimated in Ref. [35] to extend to about $m_{\tilde{g}} \sim 1.7-2.3$ TeV within the context of the mSUGRA/CMSSM model. The overall LHC14 reach for gluino pair production should be very similar for RNS SUSY as compared to the mSUGRA model. These reach projections have been confirmed qualitatively by CMS in Ref. [36] which projects a 5σ LHC14 reach out to $m_{\tilde{g}} \sim 1950$ GeV and by Atlas[37] which projects a 5σ LHC14 reach to $m_{\tilde{g}} \sim 2$ TeV for 300 fb^{-1} and a reach to $m_{\tilde{g}} \sim 2.4$ TeV for 3000 fb^{-1}. The Atlas group also quotes a 2σ (95% CL) exclusion reach to $m_{\tilde{g}} \sim 2.35$ TeV (2.9 TeV) for 300 (3000) fb^{-1}. A distinctive feature of RNS gluino pair production is the presence of a dilepton mass edge in cascade decay events containing an opposite-sign/same flavor (OS/SF) isolated dilepton pair with invariant mass $m(\ell^+\ell^-) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} \sim 10-20$ GeV[38, 39] from $\tilde{g} \to t\bar{t}\widetilde{Z}_2$ decay. The LHC14 reach for $\tilde{g}\tilde{g}$ cascade decays is adapted from the mSUGRA study of Ref. [35] and shown in Fig. 1 in the m_0 vs. $m_{1/2}$ plane of the two-extra-parameter non-universal Higgs model (NUHM2)[40] for $\mu = 150$ GeV, $\tan\beta = 15$,

[2] As in our earlier work, we assume that the dominant contribution to the higgsino mass is the superpotential μ term. A soft SUSY-breaking higgsino mass term is possible if there are no gauge singlets that couple to higgsinos as recently emphasized in Ref. [26]. The authors of Ref. [27] have constructed extended frameworks, with several additional TeV scale fields, to show that it is possible to construct natural models with heavy higgsinos.

[3] For gravity-mediated SUSY breaking, the superpotential μ parameter and the gravitino mass $m_{3/2}$, which sets the visible sector soft terms, are the appropriate parameter choice for the BG measure.

[4] Larger EW-ino mass gaps can occur for models with non-universal gaugino masses where the $SU(2)$ and $U(1)_Y$ gaugino masses become small. See *e.g.* Ref. [33].

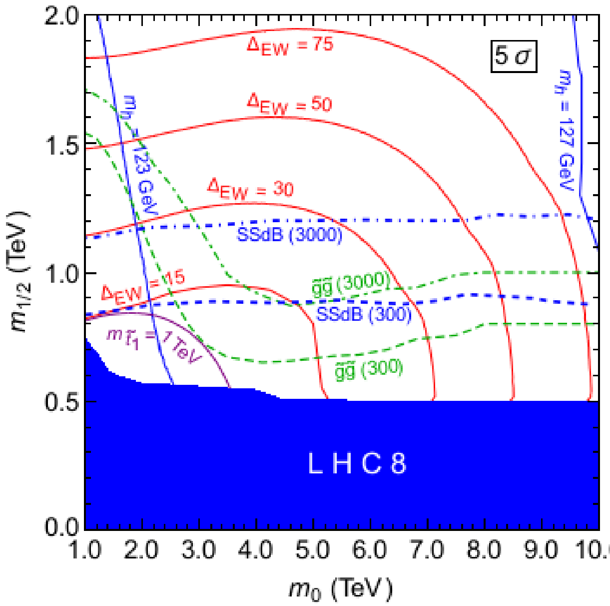

FIG. 1: High luminosity reach of CERN LHC for natural SUSY in the m_0 vs. $m_{1/2}$ plane for $\mu = 150$ GeV, $m_A = 1$ TeV, $\tan\beta = 15$ and $A_0 = -1.6 m_0$ in the NUHM2 model. To aid the reader, we note that $m_{\tilde g} \sim 2.5 m_{1/2}$.

$A_0 = -1.6m_0$ and $m_A = 1$ TeV. Mass spectra were generated using Isajet 7.85[41]. We also show the contours of $m_h = 123$ and 127 GeV along with the current LHC8 mSUGRA bound[42, 43] from 20 fb^{-1}. Throughout, we make the simple and highly motivated assumption of gaugino mass unification as is commonly done in models such as CMSSM/mSUGRA.

A qualitatively new SUSY signature – same sign diboson (SSdB) production[38, 44]– emerges in models with light Higgsinos such as the RNS scenario considered in this paper. This signal arises from wino pair production via $pp \to \widetilde{W}_2 \widetilde{Z}_4$ which is expected to be the largest visible SUSY cross section produced at LHC14 for $m_{\tilde g} \gtrsim 1$ TeV. The winos decay mainly via $\widetilde{W}_2^\pm \to W^\pm \widetilde{Z}_{1,2}$ and $\widetilde{Z}_4 \to W^\pm \widetilde{W}_1^\mp$ so that half these decays yield same sign Ws, more of which are W^+W^+ events since LHC14 is a pp collider. For $W \to \ell \nu_\ell$ decay, then these events yield same-sign dilepton events which are easily distinguished from SS dilepton events arising from $\tilde g \tilde g$ production[45] in that they have minimal accompanying jet activity– just that arising from initial state radiation. Heavy chargino pair production makes a subdominant but significant contribution to the signal.

The SSdB reach along a particular RNS model line was calculated in Ref's [38, 44]. In this work, we extend this reach calculation into the m_0 vs. $m_{1/2}$ plane of Fig. 1 using the hard cuts and background calculations from Ref. [38, 44]. The 5σ LHC14 reach with 3000 fb^{-1} for SSdB production extends well beyond the $\tilde g \tilde g$ reach for $m_0 \gtrsim 3$ TeV and extends to $m_{1/2} \simeq 1.2$ TeV corresponding to $m_{\tilde g} \sim 3$ TeV. A small region with $\Delta_{EW} < 30$ extends out beyond the LHC14 3000 fb^{-1} SSdB reach. Confirmatory signals in the hard- and soft- trilepton and four-lepton channels are also possible [38], but the greatest reach for high-luminosity LHC (HL-LHC) was found to be in the SSdB channel.

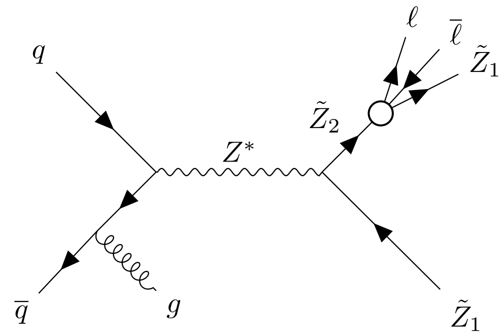

FIG. 2: Feynman diagram for $pp \to \widetilde{Z}_1 \widetilde{Z}_2$ production followed by $\widetilde{Z}_2 \to \ell^+ \ell^- \widetilde{Z}_1$ plus radiation of a gluon jet from the initial state.

While both the $\tilde g \tilde g$ and SSdB signals offer an LHC14 probe for RNS in the $m_{1/2}$ direction, it is desirable to have some probe for Higgsino pair production which would allow exploration in the μ direction of parameter space. Detailed calculations of $pp \to \widetilde{Z}_1 \widetilde{Z}_1 j$ production (where j stands for a QCD jet arising from initial state gluon or quark radiation) – the so-called monojet channel– were performed in Ref. [46–48]. There, it was found that the SUSY signal was typically $\sim 1\%$ of QCD background which arose mainly from Zj production with $Z \to \nu \bar\nu$. Thus, the monojet signal alone does not appear to be a lucrative discovery channel for EWino production at LHC14.

In Ref's [49–51], it was suggested to look at $pp \to \widetilde{Z}_1 \widetilde{Z}_2 j$ production where $\widetilde{Z}_2 \to \ell^+ \ell^- \widetilde{Z}_1$. Here, one triggers on the hard initial state g/q radiation but then requires in addition a soft OS/SF dilepton pair with $m(\ell^+\ell^-) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ (see Fig. 2). The main background occurs from SM di-tau production $pp \to Zj$ where $Z \to \tau^+\tau^- \to \ell^+\ell^- + \not{E}_T$. Using $\not{E}_T$ to reconstruct the di-tau invariant mass, then a cut of $m^2(\tau\tau) < 0$ rejected background much more than signal[50]. A small bump in the OS/SF dilepton invariant mass distribution with $m(\ell^+\ell^-) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ should allow determination of a signal for sufficient integrated luminosity. We have scaled the LHC14 5σ reach of Ref. [50] which is (conservatively) found to extend to $\mu \sim 165$ GeV for 300 fb^{-1} and to $\mu \sim 250$ GeV for 3000 fb^{-1} of integrated luminosity (see Fig. 3).

A panoramic view of the reach of HL-LHC14 for RNS SUSY is presented in Fig. 4 where we show the $m_{1/2}$ vs. μ plane for $m_0 = 5$ TeV, $\tan\beta = 15$ $A_0 = -1.6m_0$ and $m_A = 1$ TeV. The (blue) shaded region labeled LEP2 was excluded long ago by searches for chargino pair produc-

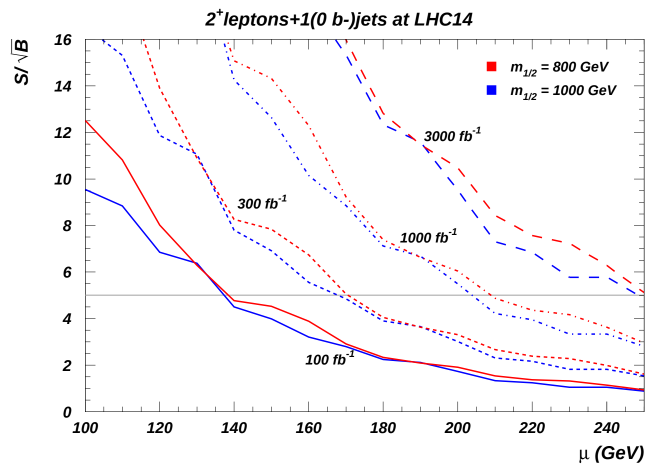

FIG. 3: $S/\sqrt{B}$ from HL-LHC for $pp \to \widetilde{Z}_1\widetilde{Z}_2 j$ followed by $\widetilde{Z}_2 \to \widetilde{Z}_1 \ell^+\ell^-$ decay versus μ, scaled for the luminosity from Ref. [50]. The blue lines are for $m_{1/2} = 1000$ GeV while red lines are for $m_{1/2} = 800$ GeV.

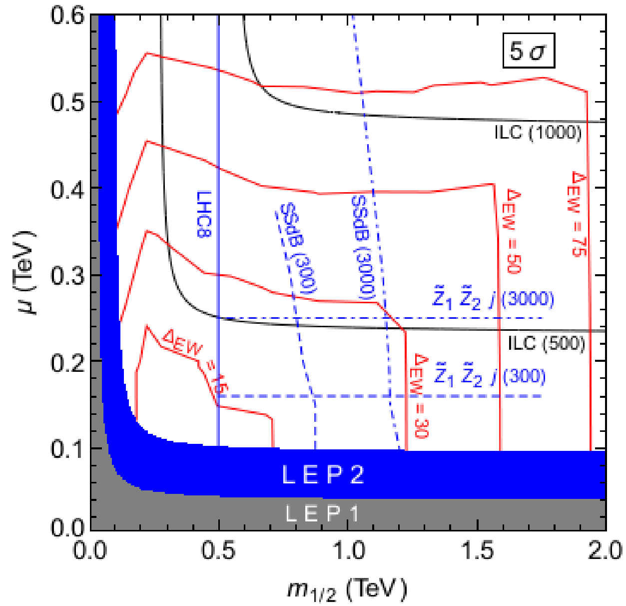

FIG. 4: Plot of Δ_{EW} contours (red) in the $m_{1/2}$ *vs.* μ plane of NUHM2 model for $A_0 = -1.6m_0$ and $m_0 = 5$ TeV and $\tan\beta = 15$. We also show the region excluded by LHC8 gluino pair searches (left of solid blue contour), and the projected region accessible to LHC14 searches via the SSdB channel with 300/3000 fb^{-1} of integrated luminosity (dashed/dot-dashed contours). The LHC14 reach via the $\widetilde{Z}_1\widetilde{Z}_2 j$ channel is also shown, assuming it is insensitive to the choice of $m_{1/2}$ in the low Δ_{EW} region of interest. We also show the reach of various ILC machines for higgsino pair production (black contours). The blue (gray) shaded region is excluded by LEP2 (LEP1) searches for chargino pair production. To aid the reader, we note that $m_{\tilde{g}} \simeq 2.5 m_{1/2}$.

tion at the CERN LEP2 e^+e^- collider which demands $m_{\widetilde{W}_1} > 103.5$ GeV for modestly large $m_{\widetilde{W}_1} - m_{\widetilde{Z}_1}$ mass gaps. The light Higgs mass m_h lies within the $123-127$ GeV range (the expected range of theory accuracy on our m_h calculation) throughout the entire plot. We also show contours of $\Delta_{EW} = 15$, 30, 50 and 75. The $\Delta_{EW} = 30$ contour asymptotically appoaches $\mu \sim 250$ GeV before sharply cutting off around $m_{1/2} \sim 1.2$ TeV wherein the rising top squark masses cause $\Sigma_u^u(\tilde{t}_{1,2})$ to become sufficiently large that the model becomes fine-tuned. We also show the present LHC8 limit for $\tilde{g}\tilde{g}$ production as the vertical line $m_{1/2} \sim 0.5$ TeV[42, 43]. The 5σ reach of LHC14 with 300 (3000) fb^{-1} for the SSdB signal extends to $m_{1/2} \sim 0.8$ (1.2) TeV thus encompassing nearly the entire $\Delta_{EW} < 30$ region (the corresponding 3000 fb^{-1} LHC14 reach for $\tilde{g}\tilde{g}$ extends to $m_{1/2} \sim 1$ TeV). We also show the 300 (3000) fb^{-1} reach of LHC14 for $\widetilde{Z}_1\widetilde{Z}_2 j$ production with $\widetilde{Z}_2 \to \ell^+\ell^-\widetilde{Z}_1$ decay as dashed (dot-dashed) contours at $\mu \sim 160$ (250) GeV, assuming this is relatively insensitive to the precise value of $m_{1/2}$, at least in the interesting region with low Δ_{EW}. Again, nearly the entire $\Delta_{EW} < 30$ region is covered, the exception occuring mainly at smaller $m_{1/2} \sim 0.7-1$ TeV where the $\tilde{g}\tilde{g}$ and SSdB signals should be more robust. Throughout almost all the $\Delta_{EW} < 30$ region, at least two and sometimes all three of the RNS signals $\tilde{g}\tilde{g}$, SSdB and $\widetilde{Z}_1\widetilde{Z}_2 j$ should be accessible, thus offering a degree of confirmation in multiple signal channels. We reiterate that the SSdB signal and the soft dilepton signal from $\widetilde{Z}_1\widetilde{Z}_2 j$ production would both point to the production of light higgsinos characteristic of RNS. For comparison, we also show the reach of ILC with $\sqrt{s} = 0.5$ and 1 TeV. The ILC with $\sqrt{s} \sim 0.6$ TeV should also make a decisive and complementary search for RNS (with $\Delta_{EW} \leq 30$) via the $e^+e^- \to \widetilde{W}_1^+\widetilde{W}_1^-$ and $\widetilde{Z}_1\widetilde{Z}_2$ channels[52].

Summary:

Recent clarification of electroweak naturalness points to SUSY models containing rather light higgsinos $\sim 100-300$ GeV while gluinos and squarks may lie in the 3-4 TeV range while maintaining naturalness at the 3-10% level ($\Delta_{EW} \lesssim 30$). Our extension of HL-LHC SUSY reach estimates for the planned accumulation of

3000 fb^{-1} of data displayed in Fig. 4 shows that nearly all of natural SUSY parameter space will be probed at the 5σ level via $\tilde{g}\tilde{g}$, SSdB and $\widetilde{Z}_1\widetilde{Z}_2 j$ searches. Signals should almost always occur in more than one channel, thus offering strong confirmation of any single-channel signal. The HL-LHC 95% CL exclusion reach typically extends several hundred GeV further in sparticle masses. From this vantage point, HL-LHC should either discover or exclude radiatively-driven natural SUSY. Further confirmation/discovery as well as clear elucidation of the underlying scenario should occur if an e^+e^- collider with $\sqrt{s} \gtrsim 2m(higgsino)$ such as ILC is constructed. In addition, ton-scale noble liquid detectors should detect a higgsino-WIMP signal. [53].

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