Supersymmetry Phenomenology with Light Higgsinos

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Physics results are obtained in collaboration with,
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SUSY has been an active area of phenomenological research since the early 1980s.

Pierre Fayet was ahead of everyone else.

- Largest possible (space-time) symmetry of the $S$-matrix
- Novel synthesis of bosons and fermions
- Possible connection to gravity (if SUSY is local) and to dark matter (if motivated to keep the proton stable – we impose $R$-parity conservation).

★ SUSY solves the big hierarchy problem. Low scale physics does not have quadratic sensitivity to high scales if the low scale theory is embedded into a bigger framework with a high mass scale, $\Lambda$.

Only reason for superpartners at the TeV scale.

Bonus: Measured gauge couplings at LEP unify in MSSM but not in SM. Is this fortuitous?

Since the scale of superpartners is so crucial, let us take a second look at the arguments that suggest there is new physics at the TeV scale.
Setting the sparticle mass scale

The physical mass of a spin-zero particle has the form (at one-loop),

\[ m_\phi^2 \simeq m_{\phi 0}^2 + C_1 \frac{g^2}{16\pi^2} \Lambda^2 + C_2 \frac{g^2}{16\pi^2} m_{\text{low}}^2 \log \left( \frac{\Lambda^2}{m_{\text{low}}^2} \right) + C_3 \frac{g^2}{16\pi^2} m_{\text{low}}^2. \]

★ $\Lambda^2$ term destabilizes the SM if the SM is generically coupled to very high scale physics; e.g. GUTs.

★ Since $\Lambda^2$ terms are absent in softly broken SUSY, the Higgs sector and also vector boson masses are at most logarithmically sensitive to high scale physics.

In SUSY theories, $m_{\text{low}} = m_{\text{SUSY}}$ and the corrections are

\[ \delta m_h^2 \sim C_2 \frac{g^2}{16\pi^2} m_{\text{SUSY}}^2 \times \log s \sim m_{\text{SUSY}}^2 \] (if the logarithm is 30-40). Since LHC says squarks and gluinos are much heavier than $m_h^2$ or $M_Z^2$ and so requires fine-tuning.

Setting $\delta m_h^2 < m_h^2 \Rightarrow m_{\text{SUSY}}^2 < m_h^2$, and there was much optimism for superpartners at LEP/Tevatron. These were not found.

\[ \Delta \log = \frac{\delta m_h^2}{m_h^2} \] suggested as a measure of fine tuning.
WHAT WENT WRONG?

★ Perhaps $\delta m_h^2 < m_h^2$ is too stringent? Many examples of accidental cancellations in nature of one or two orders of magnitude.

★ Argument applies only to superpartners with large couplings to the EWSB sector (not, e.g. to first generation squarks and gluinos probed at the LHC).

★ Most importantly, once we understand the SUSY breaking mechanism, almost certainly we will find that contributions from the various superpartners are correlated, leading to the possibility of automatic cancellations. Ignoring this, will overestimate the UV sensitivity of any model.

Traditionally, the sensitivity is measured by checking the fractional change in $M_Z^2$ (rather than $m_h^2$) relative to the corresponding change in the independent parameters ($p_i$) of the theory. (Ellis, Enqvist, Nanopoulos, Zwirner, reinvented and explored by Barbieri and Giudice): $\Delta_{BG} = \max_i \frac{p_i}{M_Z^2} \frac{\partial M_Z^2}{\partial p_i}$

\[ \Delta_{\log} \geq \Delta_{BG}, \]

since $\Delta_{\log}$ ignores correlations that we just mentioned.
Electroweak Fine-Tuning

\[
\frac{M_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2, \quad \Sigma_u^u, \Sigma_d^d \text{ are finite radiative corrections.}
\]

Weak scale formula, has no information of high scale physics, so no large logs.\(^a\)

Requiring no large cancellations on the RHS, motivates us to define,

\[
\Delta_{EW} = \max \left( \left| m_{H_u}^2 \right| \frac{\tan^2 \beta}{\tan^2 \beta - 1}, \left| \Sigma_u^u \right| \frac{\tan^2 \beta}{\tan^2 \beta - 1}, \cdots \right). \quad \text{Small } \Delta_{EW} \Rightarrow m_{H_u}^2, \mu^2 \text{ close to } M_Z^2 \text{ as first emphasized by Chan, Chattopadhyay and Nath in 1998.}
\]

\[
\Delta_{EW} \leq \Delta_{BG} \text{ (modulo some technical caveats) because it has no large logs in it. For this reason, Mustafayev and I regard it as a bound on the fine-tuning in a high scale theory rather than a fine-tuning measure. Put differently, } \Delta_{EW} \text{ is the minimum fine-tuning in any theory with a given spectrum, while } \Delta_{BG} \text{ is always the true fine-tuning measure in a high scale theory. (arXiv:1404.1386)}
\]

If SUSY breaking parameters (in some theory) are suitably correlated so that the log \[\frac{\Lambda^2}{m_{SUSY}^2}\] terms essentially cancel, \[\Delta_{BG} \rightarrow \Delta_{EW}.\]

\(^a\)These logs are hidden because I combined \[m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\] into \[m_{H_u}^2\] in the weak scale formula on top of the page.
Why should we care about $\Delta_{EW}$?

★ $\Delta_{EW}$ is essentially determined by the SUSY spectrum.

★ If $\Delta_{EW}$ is large, the underlying theory that leads to the spectrum will be fine-tuned. A small $\Delta_{EW}$ does not imply the theory is not fine-tuned, but leaves open the possibility of finding an underlying theory of SUSY breaking with SSB parameters properly correlated, so that the large logs mostly cancel, giving $\Delta_{BG} \simeq \Delta_{EW}$.

★ Many aspects of the phenomenology depend just on the spectrum, so this can be investigated even without knowledge of the underlying high scale theory.\(^a\)

★ Low $\Delta_{EW} \implies$ low $|\mu|$, but squarks (including stops) may be much heavier.

We think low $|\mu|$ more basic to fine-tuning considerations than light stops.

Quite generally, light higgsinos are a necessary feature of models with low fine-tuning.

\(^a\)Beware though of pheno implications that depend on strong correlations (other than those dictated by fine-tuning considerations) in the spectrum.
Loopholes in the light higgsino argument

★ Assumes the superpotential $\mu$ parameter is independent of SSB parameters.

★ Assumes the higgsino mass indeed comes mostly from $|\mu|$; i.e. no explicit SUSY breaking higgsino mass (This would be a hard SUSY breaking in the presence of singlets that couple to the Higgsinos). Indeed, Nelson and Roy (PRL, 114 (2015) 201802) and S. Martin (arXiv:1506.02105) have constructed models with additional adjoint chiral superfields where the Higgs and higgsino mass parameters are independent.

★ The Higgs boson could be a (pseudo-)Goldstone boson in a theory with global symmetry even if $|\mu|$ is large. Cancellations that give low Higgs mass (and concomitantly low $M_Z^2$) are then a result of a symmetry. (Cohen, Kearney and Luty, PRD 91 (2015) 075004). Origin of global symmetry???

Since there is no reason for a plethora of beyond MSSM fields at the weak scale, we will regard low $\mu$ as a necessary condition for naturalness, and explore its observational implications. Light higgsinos are certainly well-motivated for at least the simplest models.
Realizing Small $\Delta_{EW}$ (and small $\mu$) in a High Scale Model

In the weak scale EWSB condition, in order not to have large cancellations, we clearly need to have $m_{H_u}^2$ (weak) (and also $\mu^2$) close to $M_Z^2$. This is not readily achievable in mSUGRA since $m_{H_u}^2$ typically has a magnitude comparable to other SSB parameters, but is always possible in the NUHM2 model, since $m_{H_u}^2$ is an adjustable parameter. Tune $m_{H_u}^2(\Lambda)$ to get small $m_{H_u}^2$ (weak), and so small $\Delta_{EW}$.

**NUHM2 parameters:** $m_0, m_{1/2}, A_0, \tan \beta + m_{H_u}^2, m_{H_d}^2$

This is not an empty statement. Small $\Delta_{EW}$ cannot be realized in mSUGRA (even in the focus-point region because heavy stops make $\Sigma_{u}^u$ large), and also in many other High Scale models (Baer, Barger, Mickelson, Padeffke-Kirkland). A large value of $\Delta_{EW}$ signals there must be fine-tuning in the theory.

Finally, to get small $\Delta_{EW}$, we also have to ensure that the finite radiative corrections from SUSY particle loops, $\Sigma_{u}^u$, are small. This requires large, negative $A_0$. 

Contributions to $\Sigma_u$ dominantly come from top squark loops.

The $\tilde{t}_2$ contribution is $\propto \left( \ln \frac{m_{\tilde{t}_2}}{m_{\tilde{t}_1}} - 1 \right)$, and so often small.

The $\tilde{t}_1$ contribution suppressed for large $A_t$ values realized for large, negative $A_0$.

Thus, $\Delta_{EW}$ falls sharply for $A_0 \sim -1.6m_0$.

This same range of $A_0$ raises the Higgs mass to 125 GeV!
We are not saying that the NUHM2 model point with small $\Delta_{EW}$ has low fine-tuning. Indeed, the fact that $A_0$ and $m_{H_u}^2$ have to be adjusted to get low $\Delta_{EW}$ says otherwise.

However, if we had a theory of soft-parameters that predicted $A_0 = -1.6 m_0$ and $m_{H_u}^2 = 1.64 m_0^2$ (these correlations yield low $\Delta_{EW}$), it would be a candidate for a theory that is not fine-tuned. In such a theory, $\Delta_{BG}$ would automatically become numerically close to $\Delta_{EW}$ because the large logs would automatically cancel once the fact that the parameters are correlated is incorporated (Mustafayev + XT, arXiv:1404.1386). We do not have such a theory today!!!!

Since this theory has the same spectrum as the RNS scenario, it will have the same phenomenological implications because the phenomenology is mostly determined by the spectrum. The NUHM2 model is a proxy for exploring the phenomenology of this (as yet unknown) theory with low fine-tuning.

Motivation and interpretation for $\Delta_{EW}$ somewhat different from that of Baer and collaborators (PRD 88 (2013) 095013, arXiv:1404.2277), but these differences are unimportant for practical purposes, and do not affect the importance of $\Delta_{EW}$. 

These considerations led us to the radiatively-driven natural SUSY framework for generating spectra with low $\Delta_{EW}$ that may be useful for phenomenological analyses.

In the NUHM2 model, perform a scan over:

- $m_0 = 1 - 7$ TeV; $A_0 = -(1 - 2)m_0$; $\tan \beta = 5 - 50$;
- $\mu = 100 - 300$; $m_A =$ your choice

Find points with $\Delta_{EW} < 30$, consistent with phenomenological constraints.

We then examine the phenomenology of these low $\Delta_{EW}$ RNS scenarios that are obtained from the NUHM2 model.

Underlying philosophy is that if we find an underlying theory of SUSY breaking parameters with low $\Delta_{BG}$ that yields essentially the same spectrum, it will have the same phenomenological implications since these are mostly determined by the spectrum. The NUHM2 model is a proxy for exploring the phenomenology of this (as yet unknown) theory with low fine-tuning.
Four light higgsino-like inos, $\tilde{Z}_{1,2}$, $\tilde{W}_{1}^{\pm}$ with $m_{\bullet} \leq 300$ GeV for $\Delta_{EW}^{-1} \gtrsim 3\%$;

$m_{\tilde{t}_{1}} = 1 - 2$ TeV; $m_{\tilde{t}_{2}} = 2 - 4$ TeV;

$m_{\tilde{g}} = 1 - 5$ TeV (else $\tilde{t}$s becomes too heavy and make $\Sigma_{u}^{u}$ too large); (Resulting bino and wino mass parameters consistent with low $\Delta_{EW}$ is we assume unification.)

Split the generations and choose $m_{0}(1, 2)$ large to ameliorate flavour and $CP$ issues (This is separate from getting small $\Delta_{EW}$).

Large intra-generation splittings among heavy first/second generation squarks leads to large $\Delta_{EW}$ except for specific mass patterns. (PRD 89, 037701 (2014))
Light higgsino-like states $\tilde{W}_{1}^{\pm}$, $\tilde{Z}_2$, $\tilde{Z}_1$ must be present with masses $\sim |\mu| \ll |M_{1,2}|$, and generically small (10-30 GeV) splittings.

If $|M_{1,2}|$ also happens to be comparable to $|\mu|$, large gaugino-higgsino mixing would split the states which would then be relatively easy to access at the LHC via $\tilde{W}_1 \tilde{Z}_2$ production, or at a *LC via $\tilde{W}_1 \tilde{W}_1$, $\tilde{Z}_1 \tilde{Z}_2$ and $\tilde{Z}_2 \tilde{Z}_2$ production. Heavier -inos may also be accessible.

In the generic case, the small mass gap may makes it difficult to see the signals from electroweak higgsino pair production at the LHC because decay products are very soft (even though the cross section is in the pb range for 150 GeV higgsinos).

Monojet/monophoton recoiling against higgsinos also does not work. Can reduce backgrounds by requiring additional soft leptons from higgsino decays.

Gluino pair production, if it is accessible at the LHC, will lead to signals rich in $b$-jets because we have assumed first/second generation squarks are very heavy. However, gluinos may not be accessible.
Light higgsinos at the LHC

★ A novel signal is possible at the LHC if $|M_2| \lesssim 0.8 - 1$ TeV, something that is possible, though not compulsory, for low $\Delta_{EW}$ models.

Decays of the parent $\tilde{W}_2$ and $\tilde{Z}_4$ that lead to $W$ boson pairs with the same sign 50% of the time. Novel same sign dilepton events with hard jet activity only from QCD radiation. (Remember that the decay products of higgsino-like $\tilde{W}_1$ and $\tilde{Z}_2$ are typically expected to be soft.)

This new signal may point to the presence of light higgsinos.
NUHM2: $m_0=5$ TeV, $A_0=-1.6m_0$, $\tan\beta=15$, $\mu=150$ GeV, $m_A=1$ TeV

Hard cuts on $E_T$ and minimum transverse mass $m_T(\ell_{1,2}, E_T)$ are crucial to pull out the signal.
Jet-free Multilepton Signals

In addition to the novel SS dilepton signal without jets, heavy wino production can also lead to observable rates for other interesting signatures.

★ Clean trilepton events from \( pp \rightarrow \tilde{W}_2 \tilde{W}_2, \tilde{W}_2 \tilde{Z}_4 X \rightarrow WZ + E_T \) events.

★ Four lepton signatures that arise because a lepton from the cascade decay of a heavy wino to a light higgsino is also identified (confirmatory channel indicating low \( \mu \)).

★ These signals are in addition to usual jetty signals from gluino production (if gluino production is accessible) where cascade decays would, e.g. lead to OS, SF dilepton events with characteristic dilepton mass edge at \( m_{\ell \ell} \leq m_{\tilde{Z}_2} - m_{\tilde{Z}_1} \). (A small mass difference may also be indicative of a low \( |\mu| \) scenario.)
A Recap of the LHC14 Reach for RNS in terms of $m_{\tilde{g}}$/TeV

<table>
<thead>
<tr>
<th>Int. lum. (fb$^{-1}$)</th>
<th>$\tilde{g}\tilde{g}$</th>
<th>SSdB</th>
<th>$WZ \rightarrow 3\ell$</th>
<th>$4\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>100</td>
<td>1.6</td>
<td>1.6</td>
<td>–</td>
<td>$\sim 1.2$</td>
</tr>
<tr>
<td>300</td>
<td>1.7</td>
<td>2.1</td>
<td>1.4</td>
<td>$\gtrsim 1.4$</td>
</tr>
<tr>
<td>1000</td>
<td>1.9</td>
<td>2.4</td>
<td>1.6</td>
<td>$\gtrsim 1.6$</td>
</tr>
</tbody>
</table>

The canonical gluino signature yields the highest reach only for integrated luminosities up to 100 fb$^{-1}$. For higher integrated luminosities, the SSdB channel yields the best reach. The SSdB signal is a generic characteristic of small $|\mu|$ models. If the SSdB signal is present, there may be confirmatory signals in the $3\ell$ and $4\ell$ channels.

However, these signals and also signals from $t$-squarks may all be inaccessible at LHC13 even if $\Delta_{EW} < 30$. 

Monojet Signals

There has been much talk about detecting natural SUSY via inclusive $\not{E}_T +$ monojet events from $pp \rightarrow \tilde{W}_1 \tilde{W}_1, \tilde{W}_1 \tilde{Z}_{1,2}, \tilde{Z}_{1,2} \tilde{Z}_{1,2} +$ jet production, where the jet comes from QCD radiation.

★ Many analyses done using effective 4-fermion operators. This approximation is invalid because higgsino production dominantly occurs via $s$-channel $Z$ exchange.

★ Although there is an observable rate, even after hard cuts, the signal to background ratio is typically at the percent level. We are pessimistic that the backgrounds can be controlled/measured at the subpercent level needed to extract the signal in the inclusive $\not{E}_T +$ monojet channel. (Baer, Mustafayev, XT arXiv:1401.1162; C. Han et al., arXiv:1310.4274; P. Schwaller and J. Zurita, arXiv:1312.7350; see also Barducci et al., arXiv:1504.02472.)
However, as first noted by G. Giudice, T. Han, K. Wang and L-T. Wang, and elaborated on by Z. Han, G. Kribs, A. Martin and A. Menon that backgrounds may be controllable by identifying soft leptons in events triggered by a hard monojet.

OS/SF dilepton pair with $m_{\ell\ell} < m_{\ell\ell}^{\text{cut}}$ analysis with $m_{\ell\ell}^{\text{cut}}$ as an analysis variable. Alternatively, examine dilepton flavour asymmetry $\frac{N(SF) - N(OF)}{N(SF) + N(OF)}$ in monojet plus OS dilepton events. Normalization systematic better controlled by ratio.

LHC14 reach extends to about $|\mu| = 170$ (200) GeV for integrated luminosity of 300 (1000) fb$^{-1}$. Baer, Mustafayev and XT

Nice that it probes the best motivated $\mu$ range, but not a decisive probe of $\Delta_{EW} < 30$ (3% fine-tuning).
Motivated by the fact that ATLAS and CMS have been able to probe $W^+W^+ \rightarrow W^+W^+$ scattering, Pat Stengel and I considered same sign charged higgsino pair production $pp \rightarrow \tilde{W}_1^\pm \tilde{W}_1^\pm jjX$ in natural SUSY that occurs via $t$-channel exchange of neutralinos. Cho et al. PRD 73 (2006) 054002; Giudice, Han, Wang², PRD 81 (2010) 115001 Also, many VBF studies by the Texas A and M group.

![Image of Feynman diagram](image)

Majorana nature of the exchanged neutralinos is crucial.

To our surprise, we found that the cross section for $pp \rightarrow \tilde{W}_1^\pm \tilde{W}_1^\pm jjX$ production falls off very fast with increasing $m_{1/2}$ even though the chargino mass is not changed.
To understand what was going on, we examined \( W^\pm W^\pm \rightarrow \tilde{W}^\pm_1 \tilde{W}^\pm_1 \).

As \( m_{1/2} \) increases, \( \tilde{W}_1 \) and \( \tilde{Z}_2 \) become increasingly higgsino-like, and the cross section drops off rapidly although \( m_{\tilde{W}_1} \) hardly changes across the figure!

Realized that in the \( M_{1,2} \rightarrow \infty \) limit, the two degenerate neutral higgsinos can be written as one Dirac higgsino (\( \tilde{Z}_D \)) and then, the \( W^+ \tilde{W}_1 \tilde{Z}_D \) coupling has an extra conserved \( U(1) \) charge – the ino number –where \( \tilde{W}_1^+ \) and \( \tilde{W}_1^- \) have equal and opposite charges, as do \( \tilde{Z}_D \) and \( \tilde{Z}_D \). An exact \( U(1) \) symmetry if sfermions decouple. SS higgsino production is suppressed because it does not conserve ino-number.
LHC13 cross section for \( pp \rightarrow \tilde{W}_1^{\pm} \tilde{W}_1^{\pm} jj \) processes

Typically, the SS charged higgsino production cross section is \( \mathcal{O}(10^{-2}) \) fb in natural SUSY, even before any leptonic branching fractions or any analysis cuts!

Same sign higgsino production is not a viable channel at LHC13 if gauginos and squarks are very heavy as expected in natural SUSY. (Stengel + XT, in preparation)
Non-universal Gaugino Masses

Up to now, we have assumed unification of gaugino mass parameters. Then the LHC bound on the gluino forces the EW gauginos to be heavy.

It is, however, possible that $M_{1,2}$ are independent of $M_3 \simeq m_{\tilde{g}}$, and one or the other (or both) is fortuitously small. This does not have an impact on $\Delta_{EW}$ but does impact collider and DM phenomenology.

In particular, if the bino and/or wino is accessible at LHC (and $|\mu|$ is also small as necessary for naturalness) signals from $\tilde{Z}_3$, $\tilde{Z}_4$ and $\tilde{W}_2$ could occur at observable rates, as the mass gap between these states and the higgsinos is typically large.

Multilepton events, $WZ + E_T$ events and $Wh + E_T$ events generic in such scenarios. (LHC collaborations are searching for these!)

DM may all be a well-tempered thermal neutralino if the bino is light, but would have to have other components (axions, perhaps) if $|M_2|$ happens to be small. (See Baer talk)
We have seen that natural SUSY may remain undetectable at LHC13 because gluinos, squarks, binos and winos are too heavy, and higgsino production events are too soft because $\tilde{W}_1 - \tilde{Z}_1$ and $\tilde{Z}_2 - \tilde{Z}_1$ mass gaps are 10-30 GeV in RNS.

Fortunately, the ILC is a higgsino factory!

The cross section for higgsino production exceeds that for Higgs boson production if the higgsinos and Higgs bosons have similar production thresholds.
Even for the small mass gaps expected in natural SUSY, signals from $e^+e^- \rightarrow \tilde{W}_1\tilde{W}_1$ and $\tilde{Z}_2\tilde{Z}_1$ production should be readily detectable at an electron-positron collider if these reactions are kinematically accessible, and we have electron beam longitudinal polarization.

Moreover, the clean environment makes precision measurements of masses possible. Even for a difficult RNS case study with nearly the smallest possible neutralino splitting consistent with $\Delta_{EW} \leq 30$, a study of the dilepton mass and energy spectra from $e^+e^- \rightarrow \tilde{Z}_1\tilde{Z}_2 (\rightarrow \ell\ell\tilde{Z}_1)$ production yields,

$$m_{\tilde{Z}_2} = 158.5 \pm 0.4 \text{ GeV}, \quad m_{\tilde{Z}_1} = 148.8 \pm 0.5 \text{ GeV}.$$ 

Along with cross section measurements, the mass measurements would point to higgsinos as the underlying new physics, and possibly also suggest a link to a natural origin of gauge and Higgs boson masses.

No time for details here, but please see JHEP 1406 (2014) 072.
An overview of the collider reach in RNS

The green region is where the thermal relic density of neutralinos is smaller than 0.12. 
\[ \mu < 170 - 200 \text{ GeV} \] probed via mono-jet + soft dileptons.

There is a large region of parameter space with \( \Delta_{EW} < 30 \) not accessible at LHC14, but kinematically accessible at a 600 GeV \( e^+e^- \) collider which would be a machine that would definitively probe naturalness at the 3% level.

FINAL REMARKS

★ Obituaries of SUSY seem premature. The LHC has run at 60% of its design energy and accumulated $< 10\%$ of the anticipated integrated luminosity.

★ Our original aspirations remain unchanged if we accept that “accidental cancellations” at the few percent level are ubiquitous, and DM may be multi-component. SUSY GUTs remain as promising as ever. Eagerly awaiting LHC13.

★ Viable natural spectra with light higgsinos exist without a need for particles beyond MSSM.

★ Light higgsinos seem necessary for most economic versions of naturalness, and may yield novel LHC signals.

★ Light higgsino scenarios cannot saturate the total CDM; nonetheless, assuming gaugino mass unification, there is enough thermal higgsino DM fraction that will reveal itself in direct and indirect DM searches. Baer talk, and (Baer, Barger, Mickelson, PLB 726 (2013) 330)

★ An $e^+e^-$ collider with $\sqrt{s} \sim 600$ GeV could be a discovery machine for light higgsinos for $\Delta_{EW} \lesssim 30$; i.e. no worse than 3% fine-tuning.
Back up slides
Illustrate how correlations make $\Delta_{BG} \rightarrow \Delta_{EW}$

In a previous study, we had found that the NUHM2 model point (Case A)

$$(m_0, m_{1/2}, A_0, \tan \beta, \mu, m_A) = (2500, 400, -4000, 10, 150, 1000)$$

(mass parameters in GeV), gives $\Delta_{EW} = 11.3$, with $\Delta_{BG} = 3168$.

If these values come from a theory that automatically correlated parameters such that $A_0 = 1.6m_0$ and $m_{H_u}^2 = 1.64m_0^2$, $\Delta_{BG} \rightarrow 257!$

If, in addition, $m_{1/2}$ is also correlated with $m_0$ so that $m_{1/2} = 0.4m_0$, $\Delta_{BG} \rightarrow 15.4$.

We repeated this for a second point (Case B) with

$$(m_0, m_{1/2}, A_0, \tan \beta, \mu, m_A) = (4000, 1000, -4000, 15, 150, 2000)$$

(mass parameters in GeV) and $\Delta_{EW} = 17$ and $\Delta_{BG} = 8553$.

If these values come from a theory that automatically correlated parameters such that $A_0 = 1.6m_0$ and $m_{H_u}^2 = 1.70m_0^2$, $\Delta_{BG} \rightarrow 1123!$

If, in addition, $m_{1/2}$ is also correlated with $m_0$ so that $m_{1/2} = 0.25m_0$, $\Delta_{BG} \rightarrow 55$. 
This table shows what I just told you on the last slide.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Case A</th>
<th>Case B</th>
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<tbody>
<tr>
<td>None</td>
<td>3168</td>
<td>8553</td>
</tr>
<tr>
<td>$A_0 = \xi_A m_0, m_{H_u}^2 = \xi_H m_0^2$</td>
<td>257</td>
<td>1123</td>
</tr>
<tr>
<td>$m_{1/2} = \xi_{1/2} m_0$</td>
<td>15.4</td>
<td>55</td>
</tr>
<tr>
<td>$\Delta_{EW}$</td>
<td>11.3</td>
<td>17</td>
</tr>
</tbody>
</table>

A. Mustafayev and XT, arXiv:1404.1386

Parameter correlations reduce $\Delta_{BG}$ and bring it close to $\Delta_{EW}$. 
CORRELATIONS AMONG HIGH SCALE PARAMETERS CAN LEAD TO AUTOMATIC CANCELLATIONS AMONG THE LOGS, AND THE UNDERLYING META-THEORY WILL NOT BE FINE-TUNED. WE STRESS THAT JUST THE META-THEORY IS NOT FINE-TUNED, AS SHOWN BY THE VALUE OF THE TRUE FINE-TUNING MEASURE $\Delta_{BG}$.

The low value of $\Delta_{EW}$ in the effective theory offers the possibility that the spectrum of this theory will, one day, be derived from such a meta-theory.

I wish I could tell you how this will happen.

The correlations reduce $\Delta_{BG}$ by two orders of magnitude because of automatic cancellations. This means that the calculation of $\Delta_{BG}$ has to be done with a percent level precision; e.g. cannot just use the approximate formulae for one-loop RGE running. We can discuss the technicalities associated with doing so off-line.
Similar result for $E_T$ distribution.

Similar results for mono-photons.