SUSY Scenarios according to EWSB

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EWSB in MSSM

EWSB can be achieved radiatively:

$$\frac{1}{2}M_Z^2 \simeq -\mu^2(M_Z) - m_{H_u}^2(M_Z)$$

and relates the EW scale to superpartner masses:

$$M_Z^2 \simeq -1.9\mu^2 + 5.9M_3^2 - 1.2m_{H_u}^2 + 1.5m_t^2 - 0.8A_tM_3 + 0.2A_t^2 + \ldots$$

MSSM with boundary conditions at GUT scale

$$\tan \beta = 10$$

We should find superpartners “soon”!
The most common naturalness argument

based on the largest individual contribution to the EW scale; estimated by a variety of probabilistic methods or sensitivity measures, e.g.:

\[
\max_i \left| \frac{\partial \ln M_Z^2}{\partial \ln p_i} \right| \]

R. Barbieri and G. Giudice

Requiring no individual contribution is \( \gg M_Z^2 \):

\[
M_Z^2 \simeq -1.9\mu^2 + 5.9M_3^2 - 1.2m_{H_u}^2 + 1.5m_t^2 - 0.8A_t M_3 + 0.2A_t^2 + \ldots
\]

Expectations:

\[
\text{gluino, stop, chargino} \lesssim \text{few } \times \text{100 GeV}
\]
Naturalness seems to contradict limits

- direct limits:
  - gluino $\gtrsim 2 \text{ TeV}$
  - stop $\gtrsim 1 \text{ TeV}$
  - chargino $\gtrsim 1 \text{ TeV}$

  not universal, depend on assumptions!

- stop masses inferred from the Higgs mass:
  - $m_{\tilde{t}} \gtrsim 7 \text{ TeV}$ for $X_t/m_{\tilde{t}} \simeq 0$
  - $m_{\tilde{t}} \gtrsim 3 \text{ TeV}$ for $X_t/m_{\tilde{t}} \simeq -1$
  - $m_{\tilde{t}} \gtrsim 1 \text{ TeV}$ for $X_t/m_{\tilde{t}} \simeq -2$

only in the MSSM!
The most common naturalness argument

Limits suggest that the LHS is \(~1000\) times smaller than some terms on the RHS:

\[
M_Z^2 \approx -1.9 \mu^2 + 5.9 M_3^2 - 1.2 m_{H_u}^2 + 1.5 m_t^2 - 0.8 A_t M_3 + 0.2 A_t^2 + \ldots
\]

Fine tuning:

In model with parameter \(A \sim 1\) contributing to observable \(X\), in order to get \(X = 0.001\), there has to be something else that cancels the contribution of \(A\) very precisely:

\[
X = A - B
\]

e.g.: \(A = 0.963\)
\(B = 0.962\)

\(B\) has to be tuned to \(A\) at \(~0.1\)% level!
Outline

- SUSY is tuned or special

many
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- Beyond the MSSM
  - Stops are little different
  - Gluino is little different
  - The $\mu$ term is little different

- NMSSM-like models

- Many
  - RD, arXiv:1606.09031
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• SUSY is tuned or special

• Beyond the MSSM
  • Stops are little different
  • Gluino is little different
  • The $\mu$ term is little different

• Simple naturalness argument is too strong requirement
  RD, arXiv:1611.03188
  RD and N. McGinnis, arXiv:1705.01910
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SUSY is tuned or special
SUSY is tuned

accident, anthropic reasoning, bad joke of the creator …

Then the only solid indication for superpartner masses comes from the Higgs mass:

\[ m_{\tilde{t}} \gtrsim 7 \text{ TeV} \quad \text{for } X_t/m_{\tilde{t}} \approx 0 \]

\[ m_{\tilde{t}} \gtrsim 3 \text{ TeV} \quad \text{for } X_t/m_{\tilde{t}} \approx -1 \]

\[ m_{\tilde{t}} \gtrsim 1 \text{ TeV} \quad \text{for } X_t/m_{\tilde{t}} \approx -2 \]

Experiments only started touching the suggested range!
**SUSY breaking scenario is special**

- (Extremely) Low mediation scale

\[ M_Z^2 \approx -1.9 \mu^2 + 5.9 M_3^2 - 1.2 m_{H_u}^2 + 1.5 m_t^2 - 0.8 A_t M_3 + 0.2 A_t^2 + \ldots \]

The coefficient functions \( f(\lambda_t, \alpha_3, \Lambda) \) go to 0 as the mediation scale decreases.

Gluino and stop can even decouple from EWSB.

But, in that limit, understanding of EWSB is gone!
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f(\lambda_t, \alpha_3, \Lambda)

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- Relations - model leads to automatic cancellations

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e.g. Focus point: 0.3 m_0^2 and many others

Seems like a coincidence since coefficients are f(\lambda_t, \alpha_3, \Lambda)!
SUSY is light but we haven’t seen it yet

Possible reasons:

• degenerate/compressed spectra

• unsearched for (or harder to search for) decay modes

• complicated or too many decay modes
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Requires extra mechanism to increase the Higgs mass.
Stops are little different
~2 TeV gluino does not result in more than 10% tuning in EWSB as far as the mediation scale is below ~1000 TeV

However, ~10 TeV stops, suggested by the Higgs mass, feed to $\tilde{m}^2_{H_u}$ very fast:

just 1 decade of RG running results in ~3 TeV contribution to $\tilde{m}^2_{H_u}$ indicating ~0.1% tuning
“Instant” stop masses

In models with vector like families, stop can be a mixture of a state that couples to the Higgs but doesn’t have large soft mass and a state with large soft mass that doesn’t couple to the Higgs:

\[ q, \tilde{u} \quad \text{to} \quad Q, \bar{Q}, U, \bar{U} \]

\[ t, \tilde{t}_{1,2} \]

stops get large soft masses without ever contributing in RG evolution

RD, arXiv:1606.09031
Threshold corrections and 2 loop effects

Assuming universal vectorlike and soft masses, there are just two parameters that determine stop masses (and thus the Higgs mass).

Contributions to $\tilde{m}_{H_u}^2$:

- threshold corrections

$\sim 20\%$ range of soft mass squared results in $< 300$ GeV correction

- two loop effects (gluino and gauge contributions from scalars), small for low mediation scale
MSSM + 1 complete vectorlike family

Relative strength of gauge interactions can be understood from the particle content:

\[ \alpha_G = 0.3, \ M_{\text{SUSY}} = 10 \text{ TeV} \]

All three gauge couplings within:
- 1.5%
- 5%
- 10%

from the measured values.
MSSM + 1 complete vectorlike family

Preferred spectrum:

\[ \alpha_G = 0.3, \ M_G = \text{best fit} \]

Independently points to \( \sim 10 \) TeV scale.
Naturalness argument based on the largest contribution is too strong requirement
Little hierarchy from complexity

In a model with more parameters contributing to $X$:

$$X = A - B - c - d$$

in order to get $X = 0.001$ for randomly chosen $A \sim 1$, no parameter needs to be carefully chosen, e.g.:

- $A = 0.963$
- $B = 0.9$
- $c = 0.06$
- $d = 0.002$

only the first digit of all parameters need to be adjusted no matter what the following digits are

what is a tuned outcome in a model with 2 parameters may be a completely ordinary outcome in a more complex model

RD, arXiv:1611.03188
Minimally specified CMSSM

Assume model parameters of the same order

\[ M_{1/2}, \ m_0, \ \mu, \ -A_0 \approx M_{\text{SUSY}} \]

and vary them in \( \pm 50\% \) range keeping only one digit specifying the departure from \( M_{\text{SUSY}} \), e.g.:

\[
\begin{align*}
M_{1/2} &= 0.6 \, M_{\text{SUSY}} \\
m_0 &= 1.1 \, M_{\text{SUSY}} \\
\mu &= 1.4 \, M_{\text{SUSY}} \\
-A_0 &= 0.9 \, M_{\text{SUSY}} \\
\end{align*}
\]

\[
\begin{align*}
M_{1/2} &= 0.9 \, M_{\text{SUSY}} \\
m_0 &= 1.2 \, M_{\text{SUSY}} \\
\mu &= 0.6 \, M_{\text{SUSY}} \\
-A_0 &= 0.8 \, M_{\text{SUSY}} \\
\end{align*}
\]

\[
\begin{align*}
M_{1/2} &= 0.5 \, M_{\text{SUSY}} \\
m_0 &= 1.1 \, M_{\text{SUSY}} \\
\mu &= 1.5 \, M_{\text{SUSY}} \\
-A_0 &= 0.8 \, M_{\text{SUSY}} \\
\end{align*}
\]
Minimally specified CMSSM

Maximal hierarchy from minimally specified inputs:

RD and N. McGinnis, arXiv:1705.01910

The largest gaps $\sim 0.001$ (fairly uniform away from edges of the distribution)

The smallest outcome that does not depend on specifying parameters with more than 1 digit is indicated by the largest gap found in the distribution. Outcomes smaller than the largest gap are accidental.
Maximal hierarchy from minimally specified inputs:

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\[ m_{\tilde{\tau}} \sim 30 \ M_Z \]

is an ordinary outcome from minimally specified parameters.
Minimally specified CMSSM

For different central values of parameters, the peak of the distribution changes

\[ \mu \approx 2 M_{\text{SUSY}} \quad \mu \approx \sqrt{2} M_{\text{SUSY}} \quad \mu \approx M_{\text{SUSY}} \]

but the maximal gap size remains almost the same.

Prediction for maximal hierarchy is very robust.
Pigeons at Saint Marco

Position of each pigeon in a given time is incredibly tuned,

but finding a pigeon within 1 meter from you is completely ordinary since they come in 1m intervals.
Minimally specified CMSSM

Higgs boson mass from minimally specified inputs:

- Only scenarios with negative $A$-terms can have sufficiently heavy stops to explain the Higgs boson mass.

- $m_{\tilde{t}} \lesssim 30 M_Z$

- $M_{\text{SUSY}} = 3 \text{ TeV}$
- $\tan \beta = 10$

Only scenarios with negative $A$-terms can have sufficiently heavy stops to explain the Higgs boson mass.
Conclusions

It is certain that the old dream, a simple MSSM with all superpartners at the EW scale, is gone;

either SUSY models are different than we thought, or our perception of naturalness must change, or both.
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Theorists can justify and make anything natural in some sense, but only experiment can make something natural by definition:

Natural = existing in or produced by nature

Merriam-Webster dictionary