Is SUSY still alive?

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What is "SUSY"?

- Low-scale supersymmetry, serving to
  - solve the hierarchy problem
  - predict gauge coupling unification
  - provide a dark matter candidate
  - explain potential anomalies in data: $(g-2)_\mu$, $h \to \gamma\gamma \dots$
- MSSM
- singlet extensions: NMSSM, GNMSSM, ...
- (general Higgs sector extensions)
- (gauge sector extensions)
- (your favourite model)

What is “alive”?

Is SUSY still compatible with present LHC constraints?

Of course.
Even if LHC finds just the Standard Model, this will not rule out SUSY since all SUSY models have a SM-like limit.
SUSY benefits (DM, $(g-2)_\mu \ldots$) may be hard or impossible to obtain though.

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Is SUSY still a plausible solution to the hierarchy problem?

Depends on your personal pain threshold.
Physics which stabilizes the EW scale should show up around the EW scale.
Why would nature conspire to hide its workings from physicists?
“Subtle is the Lord, but malicious He is not”

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Does it make sense to continue working on / looking for SUSY?

Biased personal opinion: It does.
Maybe theorists are overlooking some crucial piece of the puzzle.
Maybe experimentalists have just been unlucky, and SUSY does exist in a strange corner of parameter space (historic precedents exist)

Naturalness and little hierarchy problem in a nutshell

Electroweak scale depends on Higgs-sector soft $\not{S}USY$ terms at tree level:

$$m_Z^2 = -2\,|\mu|^2 - 2\,m_{H_u}^2 + \ldots$$

and on other soft $\not{S}USY$ parameters through loop corrections:

$$\delta m_{H_u}^2 = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q3}^2 + m_{U3}^2 + A_t^2\right) \log \frac{\Lambda}{M_{\not{S}USY}} + \ldots$$

$$\delta m_{Q3,U3}^2 = \frac{2}{3\pi^2} g_3^2\,|M_3|^2\, \log \frac{\Lambda}{M_{\not{S}USY}} + \ldots\,, \quad \delta A_t = -\frac{2}{3\pi^2} g_3^2\, M_3 \log \frac{\Lambda}{M_{\not{S}USY}} + \ldots$$

A "little hierarchy" $m_Z \ll m_{Q3,U3}$ or $m_Z \ll M_3$ is not radiatively stable.

Gluinos and stops can in principle be arbitrarily heavy,
but only at the price of finely tuned large cancellations.

Minimizing fine-tuning in the MSSM: Natural SUSY

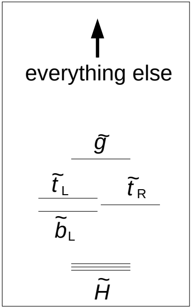
In MSSM, two main indications for a heavy spectrum:

- no superpartners observed at LHC
- $m_{h^0} = 125$ GeV only possible through large loop corrections from heavy (or significantly mixed) stop squarks

“Natural SUSY”

→ Kitano/Nomura ’06, Barbieri/Pappadopulo ’09, Papucci/Ruderman/Weiler ’11; many more since

- higgsinos $\ll 1$ TeV
- stops and LH sbottoms $\lesssim 1$ TeV
- gluinos $\lesssim 1.5$ TeV
- large to maximal stop mixing
- 1st two generation squarks can be heavy
- lower mediation scales preferred



Engineering natural SUSY

Natural SUSY ingredients

- light third generation squarks: "inverted soft mass hierarchy"
- several recent models:
  - approximate $U(2)^3$ flavour symmetry acting on 1st two generations
    $\rightarrow$ Barbieri et al. '12
  - gauged and higgsed SU(3) flavour symmetry + GMSB
    $\rightarrow$ Craig/McCullough/Thaler '12
  - Seiberg duality: 3rd gen. and Higgs fields = composites
    $\rightarrow$ Csaki/Randall/Terning '12
  - heterotic string models: 3rd gen. and Higgs fields = untwisted sector fields
    $\rightarrow$ Krippendorf/Nilles/Ratz/Winkler '12
  - ...
- light higgsinos: typically put in by hand (or ignored)
- not-too-heavy gluinos: typically put in by hand
- large stop mixing: hard to get

Engineering large stop mixing

Loop contributions to lightest Higgs mass maximal for

$$\left|\frac{A_t}{m_{\tilde{t}}}\right| \approx (1.5 \sim 2.5)$$

Generic high-scale models will give

$$A_t \approx -M_3$$

at electroweak scale.
Difficult to get large stop mixing! $\rightarrow$ see e.g. FB/Kraml/Kulkarni '12

Need either A_t large and negative already at mediation scale, or some effect to decrease $m_{\tilde{t}}$ during RG running.

Some proposals:

- very heavy first-gen. squarks decrease $m_{\tilde{t}}$ at two loops $\rightarrow$ Badziak et al. '12
- GMSB with direct messenger-Higgs coupling (leaving μ problem unsolved) $\rightarrow$ Kang/Li/Liu/Tong/Yang '12
  GMSB with direct messenger-Higgs couplings (solving μ problem with a singlet) $\rightarrow$ Craig/Knapen/Shih/Zhao '12
- claimed to follow also from F-theory models $\rightarrow$ Aparicio/Cerdeño/Ibáñez '12

TeV-scale SUSY without naturalness

Original anomaly mediation aka "pure gravity med." $\subset$ "mini-split SUSY"
$\rightarrow$ Giudice/Luty/Murayama/Rattazzi '98

recently: Ibe/Yanagida et al. '11,'12,'13, Arvanitaki/Craig/Dimopoulos/Villadoro '12

Suppose that

- the universe is supersymmetric at a very high scale (e.g. quantum gravity = superstring theory)
- SUSY breaking is gravity mediated, but no tree-level gaugino mass
- nature doesn't care about fine-tuning
- nature wants WIMP dark matter with $\sim$ observed relic density (anthropic argument: structure formation)

Last requirement fixes scalar soft masses at $\sim$ 100 TeV, anomaly-mediated gaugino masses a loop factor lower:
Wino dark matter.
Gauginos could still be observable at LHC.

R-parity violation

R-parity = $\mathbb{Z}_2$ symmetry imposed to forbid dimension-4 B and/or L violation:

$$W \not\supset \mu' \, LH_u + LLE + QLD + UDD$$

Side effect: LSP stable $\Rightarrow$ missing energy signature at LHC

Small breaking of R-parity:
can avoid bounds both from p decay, $n - \bar{n}$ oscillations... and MET searches

Some well-motivated scenarios:

- small R-parity breaking from spontaneous B-L breaking
  $\rightarrow$ Buchmüller/Covi/Hamaguchi/Ibarra/Yanagida '07
  decaying gravitino dark matter, displaced vertices at LHC...
- MFV in R-violating SUSY
  $\Rightarrow$ effective approximate R-parity for first 2 generations
  $\rightarrow$ Nikolidakis/Smith '07; Csáki/Grossman/Heidenreich '11, Francescini/Mohapatra '13, ...
  Complete models rather involved $\rightarrow$ Csáki/Heidenreich '13

Interesting possibilities for keeping ~~SUSY~~ scale relatively low

Singlet extensions

→ countless recent papers ⊃ Arbey, Belanger, Djouadi, Ellwanger, Godbole, Gunion, Jiang, Kraml, Mahmoudi, Slavich, Wymant. . .

$$W = \lambda\, S H_u H_d + \kappa\, S^3 \ (+\ldots)$$

Advantages over minimal SUSY:

- μ problem can be solved
- easier to fit potential anomalies like $h \to \gamma\gamma$ (more free parameters)
- no (or less of an) issue with Higgs mass
  Reason: additional tree-level contributions from λ coupling
  $\Rightarrow$ no heavy stops needed for large loop corrections to m_h^0
  One naturalness issue alleviated

Other naturalness issues remain

- gluinos and 3rd generation squarks should not be too heavy
- but might be harder to find than in MSSM
  see e.g. → Das/Ellwanger/Teixeira '13 → questions to Ulrich

Conclusions: Is SUSY still alive?

Well-known empirical fact: Whenever title = question, the answer is “no”

Conclusions: Is SUSY dead yet?

- No.

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- No.
- Moreover, SUSY won't be killed by LHC
- But SUSY is becoming increasingly unattractive:
  model building more and more guided by the aim of avoiding LHC bounds
- LHC-13 should find a gluino if SUSY has anything to do with naturalness
- Direct stop and sbottom searches, RPV searches also very important
- Searching for 100-300 GeV higgsinos would be nice, but probably not feasible at LHC

F. Zwirner, Moriond summary talk:

"SUSY is too good an idea to be wasted by Nature"

. . . but where is it hiding?