The Future of Supersymmetry

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...in recent times, supersymmetry has been getting a lot of bad press
Supersymmetry Bites the Dust
Where Supersymmetry Belongs: In a Coffin
SUSY in the Hospital?
Is Supersymmetry Dead?
“Supersymmetry Dealt a Blow”?
Well that about wraps it up for SUSY?
Truant particles turn the screw on supersymmetry
Supersymmetry takes an arrow to the knee
Is SUSY Dead Yet?
The uncertain future of SUSY
The Future of Supersymmetry

... is rooted in the present
THE CASE FOR SUSY

Aesthetic appeal of SUSY:

• only way of combining spacetime symmetry w. internal symmetry
  ⇒ the only way to combine gravity with other interactions
• only theory which explains differentiation of bosons and fermions
  ⇒ a consequence of the breaking of supersymmetry

Practical appeal of SUSY:

• most natural way of solving hierarchy problem
  ⇒ pairwise cancellation of quadratic divergences
• only theory where a light Higgs boson is predicted naturally
  ⇒ fits the 125 GeV Higgs boson perfectly
• only theory which has a natural dark matter candidate
  ⇒ and also has a ‘solution’ for the cosmological constant
• electroweak symmetry-breaking has a dynamical origin
• only way to get gauge coupling unification with one-step breaking
The Coleman-Mandula no-go theorem

If $\Phi$ is a symmetry group of the S-Matrix, and the following assumptions hold:

1. For any $M$ there are only a finite number of particle types with mass less than $M$,
2. Scattering occurs at almost all energies (except for perhaps some isolated set of energies),
3. The amplitudes for elastic two-body scattering are analytic functions of the scattering angle at almost all energies and angles,

then the generators of $\Phi$ consist of only the generators of the Poincaré group $\mathfrak{g}$, and the generators of internal symmetries.

Haag–Lopuszanski–Sohnius theorem

The only way to evade the restrictions of the Coleman-Mandula theorem is to replace the Lie group of symmetries by a $\mathbb{Z}_2$ graded Lie group

$\Rightarrow$ supersymmetry

$$\{Q_{\alpha}, \bar{Q}_{\beta}\} = 2 (\sigma^\mu)_{\alpha\beta} P_\mu$$
Bosons and Fermions mix freely
⇒ cannot be distinguished

Bosons are Bosons
Fermions are Fermions
⇒ cannot mix with each other

Spin-statistics theorem becomes a low-energy effect
Mass Stabilization Arguments

Standard Model with $f = t$:

$$m_h^2 \approx m_{h0}^2 - \frac{\lambda_f^2}{8\pi^2} N_f \int_0^\Lambda \frac{d^4 p}{p^2} \approx m_{h0}^2 + \frac{\lambda_f^2}{8\pi^2} N_f \Lambda^2$$

$$\mathcal{N}^0 \equiv \frac{m_{h1\text{-loop}}^2}{m_h^2} \sim 10^{30}$$

Supersymmetry with $f = t$:

$$m_h^2 \approx m_{h0}^2 + \frac{\lambda_f^2}{8\pi^2} N_f \left( m_{\tilde{f}}^2 - m_{\tilde{f}}^2 \right) \ln \left( \frac{\Lambda^2}{m_{\tilde{f}}^2} \right)$$

$$m_{\tilde{f}} \lesssim 800 \text{ GeV} \frac{1.0}{\lambda_f} \left[ \frac{3}{N_c^f} \right]^{\frac{1}{2}} \left[ \frac{70}{\ln(\Lambda^2/m_{\tilde{f}}^2)} \right]^{\frac{1}{2}} \left[ \frac{\mathcal{N}_{\text{max}}^0}{100} \right]^{\frac{1}{2}}$$
Light Higgs Boson Arguments

\[ m_{h^0}^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} \sin^2\beta y_t^2 \left[ m_t^2 \ln \left( \frac{m_{t_1} m_{t_2}}{m_t^2} \right) + c_t^2 s_t^2 \left( m_{t_2}^2 - m_{t_1}^2 \right) \ln \left( \frac{m_{t_2}^2}{m_{t_1}^2} \right) \right. \\
\left. + c_t^4 s_t^4 \left( (m_{t_2}^2 - m_{t_1}^2)^2 - \frac{1}{2} (m_{t_2}^4 - m_{t_1}^4) \ln \left( \frac{m_{t_2}^2}{m_{t_1}^2} \right) \right) \right] / m_t^2. \]

91 GeV

113 +... GeV

135 GeV max

Discovery of a 123 – 127 GeV Higgs-like boson vindicates what SUSY has always predicted

\[ h^0, H^0, A^0, H^+, H^- \]

Large stop mass splitting required...
Dark Matter Arguments

Lepton number (L) and baryon number (B) conservation in the Standard Model are purely accidental – they happen because we write the minimum number of possible operators.

Any bigger symmetry, such as a GUT, will automatically violate these U(1) global symmetries and lead to rapid proton decay.

SUSY models lend themselves naturally to a global U(1) R-symmetry. When SUSY breaks, this remains as R-parity

\[ (-)^{L+2S+3B} \]

All SM particles have R-parity +1, all SUSY partners have -1.

\[ \Rightarrow \text{The LSP is stable and weakly interacting} \]

\[ \Rightarrow \text{ideal WIMP for dark matter candidate} \]
Dark matter must be WIMPS.... Bullet Cluster....
Electroweak Symmetry Breaking in SUSY

S.P. Martin

hep-ph/9709256

\[
V = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b H_u^0 H_d^0 + \text{c.c.}) \\
+ \frac{1}{8} (g^2 + g'^2) (|H_u^0|^2 - |H_d^0|^2)^2.
\]

Figure 7.4: RG evolution of scalar and gaugino mass parameters in the MSSM with typical minimal supergravity-inspired boundary conditions imposed at \(Q_0 = 2.5 \times 10^{16} \text{ GeV}\). The parameter \(\mu^2 + m_{H_u}^2\) runs negative, provoking electroweak symmetry breaking.
Gauge Coupling Unification in SUSY

The diagram illustrates the unification of gauge couplings in SUSY (Super Symmetry) with energy scales. The axes are the inverse coupling constant and the energy scale, with SUSY particles indicated.

- $\alpha_1^1(\mu)$ represents the electromagnetic force.
- $\alpha_2^1(\mu)$ represents the weak force.
- $\alpha_3^1(\mu)$ represents the strong force.

The lines intersect at the Grand Unified (GUT) Scale, and the graph shows the absence of supersymmetry at higher energy scales.
Gauge Coupling Unification in SUSY

![Graph showing gauge coupling unification with supersymmetry](image)

- **U(1) E.M. Force**
- **SU(2) Weak Force**
- **SU(3) Strong Force**

**With Supersymmetry**

**SUSY Particles**

**Grand Unified (GUT) Scale**
Dr. Einstein, it seems that the observations made by the British team of the recent solar eclipse in South America support your theory of general relativity.

How would you have felt if your theory had been proven wrong?

Then I would have felt sorry for the Lord. The theory is correct.
The Only Problem...

...we have no experimental evidence at all for SUSY particles

...okay, then they must be heavy...
ATLAS SUSY Searches* - 95% CL Lower Limits (Status: Dec 2012)

**Inclusive searches**
- MSUGRA/CMSM: 0 lep + j's + E_Tmiss
- MSUGRA/CMSM: 0 lep + j's + E_Tmiss
- Pheno model: 0 lep + j's + E_Tmiss
- GMSB (1 NLSP): 2 lep + (8S) + E_Tmiss
- GMSB (2 NLSP): 1 T + 0-1 lep + j's + E_Tmiss
- GMSB (bino NLSP): μ+ + Etmiss
- GMSB (wino NLSP): μ+ + Etmiss
- GMSB (higgsino-bino NLSP): μ+ + Etmiss
- GMSB (higgsino NLSP): Z + jets + E_Tmiss
- Gravitino LSP: μ+ + Etmiss

**3rd gen. s, squarks, gluino med. radiative production**
- 3q Inclusive: b + b' + τ leptons
- 3q Inclusive: t + b' + τ leptons
- 2q Inclusive: Σ + τ leptons

**EW direct**
- Stable Σ R-hadrons: low β, τ (full detector)
- Stable Σ R-hadrons: low β, τ (full detector)
- GMSB: stable Σ
- Long-lived particles
- Higgsino-like: μ + heavy displaced vertex
- LFV: pp -> μ+νX, ν, ν, e+μ resonance
- LFV: pp -> μ+νX, ν, ν, e+μ resonance
- Bilinear RPV CMSM: 1 lep + 7'S + E_Tmiss
- Scalar gluon: 2-jet resonance pair
- WIMP interaction (DS, Dirac): μ+ + Etmiss

**RPV**
- 8 TeV results
- 7 TeV results

**Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.
**Little Hierarchy Problem in 3\(^{rd}\) generation**

\[ m_{\tilde{f}} \lesssim 800 \text{ GeV} \]

\[ \left[ \frac{N_{\text{max}}^0}{100} \right]^\frac{1}{2} \]

<table>
<thead>
<tr>
<th>( N^0 )</th>
<th>Fine tuning level</th>
<th>Max squark mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10%</td>
<td>253 GeV</td>
</tr>
<tr>
<td>100</td>
<td>1%</td>
<td>800 GeV</td>
</tr>
<tr>
<td>1000</td>
<td>0.1%</td>
<td>2.53 TeV</td>
</tr>
<tr>
<td>10 000</td>
<td>0.01%</td>
<td>8 TeV</td>
</tr>
<tr>
<td>100 000</td>
<td>0.001%</td>
<td>25.3 TeV</td>
</tr>
<tr>
<td>1 000 000</td>
<td>0.000 1%</td>
<td>80 TeV</td>
</tr>
</tbody>
</table>

\( N^0 \equiv \frac{m_{h \text{1-loop}}^2}{m_h^2} \)

SUSY around the corner

No reason to panic at this stage
Collider Searches for SUSY: missing pT
Low Energy Searches for SUSY: GIM Violation

\[ \sum_i V_{ib}^* V_{is} f \left( \frac{m_i}{v} \right) \]
Figure 6. Constraints from flavour observables in CMSSM in the plane \((m_{1/2}, m_0)\) for \(\tan \beta = 30\) and \(A_0 = 0\) with the 2011 results. The black line corresponds to the CMS exclusion limit with 1.1 fb\(^{-1}\) of data [38] and the red line to the CMS exclusion limit with 4.4 fb\(^{-1}\) of data [39]. From [37].
Testing Times for Supersymmetry: Looking Under the Lamp Post

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stop mass < 1.5 TeV

cMSSM  NUHM
Collected constraints

- cMSSM
- NUHM

- 'theory' constraints
- 'theory' + indirect
- 'theory' + indirect + direct
- 'theory' + indirect + direct + Higgs mass

LEP bound
Higgs decay constraints

\[
N_{X \bar{X}} = \mathcal{L} \times \sigma(pp \to h^0) \times \mathcal{B}(h^0 \to X \bar{X})
\]

\[
\mu_{X \bar{X}} \equiv \frac{N_{X \bar{X}}}{N_{SM}^{X \bar{X}}} = \frac{\sigma(pp \to h^0)}{\sigma_{SM}(pp \to h^0)} \times \frac{\mathcal{B}(h^0 \to X \bar{X})}{\mathcal{B}_{SM}(h^0 \to X \bar{X})}
\]
The pMSSM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{L(e)_{1,2,3}}$</td>
<td>100 GeV – 4 TeV</td>
</tr>
<tr>
<td>$m_{\tilde{Q}<em>{(q)</em>{1,2}}}$</td>
<td>400 GeV – 4 TeV</td>
</tr>
<tr>
<td>$m_{\tilde{Q}<em>{(q)</em>{3}}}$</td>
<td>200 GeV – 4 TeV</td>
</tr>
<tr>
<td>$</td>
<td>M_1</td>
</tr>
<tr>
<td>$</td>
<td>M_2</td>
</tr>
<tr>
<td>$</td>
<td>\mu</td>
</tr>
<tr>
<td>$M_3$</td>
<td>400 GeV – 4 TeV</td>
</tr>
<tr>
<td>$</td>
<td>A_\text{t,b,r}</td>
</tr>
<tr>
<td>$M_A$</td>
<td>100 GeV – 4 TeV</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>1 - 60</td>
</tr>
<tr>
<td>$m_{3/2}$</td>
<td>1 eV–1 TeV (\tilde{G} L&amp;S)</td>
</tr>
</tbody>
</table>

![Plot](image)
An update of the constraints on the phenomenological MSSM from the new LHC Higgs results

Alexandre Arbey\textsuperscript{a,b,c}, Marco Battaglia\textsuperscript{d,c,*}, Abdelhak Djouadi\textsuperscript{e}, Farvah Mahmoudi\textsuperscript{f,c}

Input values for the Higgs mass and rates used for the study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\gamma\gamma}$</td>
<td>1.71 ± 0.26</td>
<td>ATLAS [3] + CMS [5]</td>
</tr>
<tr>
<td>$\mu_{ZZ}$</td>
<td>0.97 ± 0.26</td>
<td>ATLAS [4] + CMS [6]</td>
</tr>
<tr>
<td>$\mu_{WW}$</td>
<td>0.85 ± 0.23</td>
<td>ATLAS [7] + CMS [6]</td>
</tr>
<tr>
<td>$\mu_{bb}$</td>
<td>1.28 ± 0.45</td>
<td></td>
</tr>
<tr>
<td>$\mu_{\tau\tau}$</td>
<td>0.71 ± 0.42</td>
<td></td>
</tr>
<tr>
<td>$D_{\gamma\gamma}$</td>
<td>1.88 ± 0.46</td>
<td></td>
</tr>
<tr>
<td>$D_{\tau\tau}$</td>
<td>0.79 ± 0.49</td>
<td></td>
</tr>
</tbody>
</table>

SUSY Dark Matter

...but two main classes:

- fermion diagrams: $m_f/M_W$ helicity suppression due to Majorana nature of neutralino

- Gauge boson diagrams: suppressed if neutralino~Bino (this is usually the case when Radiative ElectroWeak Symmetry Breaking is implemented, $|\mu| >> M_1,M_2$)
Cosmological lower bound on $m_\chi$


_upper bound on $\Omega_{CDM} h^2$

curve: analytical approximation for minimal $\Omega_{CDM} h^2$

$\frac{m_\chi [1 - m_b^2/m_\chi^2]^{1/4}}{90 \text{ GeV}} \geq 5.3 \text{ GeV} \left(\frac{m_A}{90 \text{ GeV}}\right)^2$

scatter plot: full calculation
Direct Search:

\[
\begin{align*}
&\text{DAMA/Na} \\
&\text{CoGeNT} \\
&\text{DAMA/I} \\
&\text{SIMPLE (2012)} \\
&\text{XENON10 (2011)} \\
&\text{CRESST-II (2012)} \\
&\text{EDELWEISS (2011/12)} \\
&\text{CDMS (2010/11)} \\
&\text{ZEPLIN-III (2012)} \\
&\text{COUPP (2012)} \\
&\text{XENON100 (2011)} \\
&\text{XENON100 (2012)} \\
&\text{XENON1T (2017)} \\
\end{align*}
\]
Conclusions

• Electroweak-scale SUSY remains the best BSM option
• It was not just around the corner when LHC started
• B factories have also come up with a blank
• No reason to despair yet (recall wait for the Higgs)
• We may have to live with some minor fine-tuning

Thank You