The Hierarchy Problem

1-loop corrections to Higgs mass

\[ \delta m_H^2 \sim \Lambda^2 \]

Virtual effects drag weak scale to \( M_{Pl} \) if no new physics at low scale

\[
m^2_\phi - m^2_{\phi_0} = C_1 \frac{g^2}{16\pi^2} \Lambda^2 + C_2 \frac{g^2}{16\pi^2} m^2_{\text{low}} \log \left( \frac{\Lambda^2}{m^2_{\text{low}}} \right) + C_3 \frac{g^2}{16\pi^2} m^2_{\text{low}}
\]

A (naïve) measure of fine-tuning:
\[ \Delta \sim \frac{\delta m_\phi^2}{m_\phi^2} \]

Guide to new physics scale
\[ \Delta \sim 1 \text{ (no tuning)} \quad \Lambda \sim 500 \text{ GeV} \]
\[ \Delta \sim 10 \text{ (10\% tuning)} \quad \Lambda \sim 1.6 \text{ TeV} \]
\[ \Delta \sim 100 \text{ (1\% tuning)} \quad \Lambda \sim 5 \text{ TeV} \]

Not a no-lose theorem!
Run I Data Well Described by SM Processes

Standard Model Production Cross Section Measurements

<table>
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<th>SM Processes</th>
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<td>Zjj EWK total</td>
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<tr>
<td>W<em>W</em>jj EWK</td>
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<td>ATLAS-CONF-2013-020</td>
</tr>
</tbody>
</table>

LHC pp \( \sqrt{s} = 7 \) TeV

- Theory
- Data
- stat + syst

LHC pp \( \sqrt{s} = 8 \) TeV

- Theory
- Data
- stat + syst

95% CL upper limit
First peek at 13 TeV
What to do?

- Panic!
Naturalness Crisis!

**Is the CNMSSM more natural than the CMSSM?**

Andrew Fowlie

**Implications of naturalness for the heavy Higgs bosons of supersymmetry**

Kyu Jung Baek, Howard Baer, Vernon Barger, Dan Mickelson and Michael Savoy

**What is a Natural SUSY scenario?**

J. Alberto Casas, Jesús M. Moreno, Sandra Robles, Krzysztof Rolbiecki and Bryan Zaldívar

**Natural Supersymmetry in Warped Space**

Ben Heidenreich and Yuichiro Nakai

**EFT naturalness: an effective field theory analysis of Higgs naturalness**

Shaouly Bar-Shalom, Amarjit Soni and Jose Wudka

**Naturalness in low-scale SUSY models and “non-linear” MSSM**

I. Antoniadis, E. M. Babalic, D. M. Ghilencea

**NATURAL SCALARS IN THE NMSSM**

DARIO BUTTAZZO

**Triplet-extended scalar sector and the naturalness problem**

Indrani Chakraborty and Anirban Kundu

**Natural Supersymmetry and Dynamical Flavour with Meta-stable Vacua**

Steven Abel and Moritz McGarrie

**Leaving no stone unturned in the hunt for SUSY naturalness: A Snowmass whitepaper**

H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata

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Maien Y. Binjona, and Stephen F. King
Naturalness Crisis!

Is the CNMSSM more natural than the CMSSM?
Andrew Foulke

Implications of naturalness for the heavy Higgs bosons of supersymmetry
Kyu Jung Bae, Howard Baer, Dan Mickelson

EFT naturalness: an effective
Shao Han

Sophia
April 2014, Volume 53, Issue 1, pp 1-18

Optimistic Naturalism: Scientific Advancement and the Meaning of Life
Date: 28 Sep 2013

Leaving no stone unturned in the hunt for SUSY naturalness: A Snowmass whitepaper
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What is a Natural SUSY?

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[Image of a book cover with the title "Sophia"]
What to do?

- **Panic!**  
  » Re-evaluate measure of naturalness  
  » Extend MSSM  
  » Build new models *(See Cohen)*

- **Hope & Pray!**  
  » 750 GeV DiPhoton excess persists *(See Strumia)*

- **Stay Calm!**  
  » Wait for more data  
  » Should we care?
Evaluating Naturalness

- How is naturalness quantified for SUSY?

\[
\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_{d}^d - (m_{H_u}^2 + \Sigma_{u}^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2
\]

- Traditional (Barbieri-Giudice):

\[
\Delta_{BG} = \max_i |c_i| \equiv \max_i \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2}{\partial a_i} \right|
\]

- High-Scale:

\[
\Delta_{HS} \equiv \max_i |B_i| / (M_Z^2/2)
\]

- Electroweak Scale:

\[
\Delta_{EW} \equiv \max_i |C_i| / (M_Z^2/2)
\]

Generally

\[
\Delta_{EW} \leq \Delta_{BG} \lesssim \Delta_{HS}
\]

B_i contain log Λ dependence

All quantities C_i defined @ weak scale
Naturalness: CMSSM

Clearly a subjective business
Model Building: A Zoo of Natural Ideas

Supersymmetry: MSSM
  CMSSM, NMSSM, pMSSM, XYZ–MSSM

SUSY Beyond MSSM
  RPV, Extended Gauge Sectors, Dirac Gauginos

(Mini–)Split Supersymmetry

Extra Dimensions

Folded Supersymmetry

Maximally Natural Supersymmetry

Little Higgs

Twin Higgs (Neutral Naturalness)

Relaxon

....
SUSY is complex: not a single model but a large framework.

SUSY can be hiding & may only appear at 13 TeV.

SUSY is too big to explore without some assumptions.
CMSSM: $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sgn}(\mu)$

Fit to global data set

See also Mastercode, BayesFITS

Expectations before Run I
Bechtel et al, 1204.4199

Results after Run I
Bechtel et al, 1508.05951
The phenomenological MSSM (pMSSM)
• Most general CP-conserving MSSM
• Minimal Flavor Violation, First 2 sfermion generations are degenerate w/ negligible Yukawas
• No high-scale, SUSY-breaking assumptions!

19 real, weak-scale parameters
• Contains all parameters relevant for collider physics

Provides a more general description of the parameter space

Study 3 model sets:
225k w/ neutralino LSP
10k specialized low fine-tuning neutralino LSP
225k w/ gravitino LSP

Berger, Gainer, JLH, Rizzo, 0812.0980
Cahill-Rowley etal, 1407.4130
pMSSM after LHC Run I

- 19-parameter MSSM with Neutralino LSP
- Consistent with global data set
- Subjected to ~40 LHC Run I SUSY Searches

Fraction of models excluded

- Light Squarks/Gluinos still allowed!
- 2-parameter Simplified Model does NOT provide a good approximation

Simplified Model Limit (ATLAS)
ATLAS Run I Results for the pMSSM

Recent ATLAS analysis
Combines all Run I SUSY searches

Is it live or is it memorex?

ATLAS

pMSSM: \(\tilde{\chi}^0_1\) LSP

\(\sqrt{s}=8\) TeV, 20.3 fb\(^{-1}\)

\(m(\tilde{q})\) vs. \(m(\tilde{g})\)

Fraction of Models Excluded

Aad et al., 1508.06608
pMSSM after LHC Run I

Cahill-Rowley et al., 1407.4130

Aad et al., 1508.06608

Simplified Model Limit (ATLAS)

ATLAS

pMSSM: $\tilde{\chi}_1^0$ LSP

$\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$

$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ [1405.7875]
pMSSM after LHC Run I

Simplified Model Limit (ATLAS)

• Compressed Spectra
  • Stealth SUSY
    – Complicated decay chains
  • Kinematics
    • 2–parameter 
      Simplified Model provides good approximation

Fraction of models excluded

$m_{\chi_0}$ (GeV) LSP mass

$m_{\tilde{g}}$ (GeV) Gluino mass

Cahill-Rowley et al., 1407.4130
First 3.2 fb\(^{-1}\) @ 13 TeV

Slight extension of excluded region over 8 TeV

MET searches included: 2-6 jets, 7-10 jets, 1 lepton, Multi-b, SS/3L, monojet
pMSSM Expectations for 300/3000 fb$^{-1}$

Jets+MET & Stop Searches (ATLAS ECFA & Snowmass Studies)

300 fb$^{-1}$

3 ab$^{-1}$
Low Fine-Tuned pMSSM Model Sample

- Generated specific pMSSM model set with low fine-tuning
- Consistent with global data set
- Barbieri–Giudice formalism

\[ m_h = 126 \pm 3 \text{ GeV} \]
\[ \Omega h^2 = 0.1153 \pm 0.095 \]
Low Fine-Tuning pMSSM after LHC Run I
Coverage of pMSSM Low Fine-Tuning Models

- Jets+MET & Stop Search (ATLAS European Strategy & Snowmass Study)
- 3 ab$^{-1}$ covers entire set!
pMSSM Low Fine-Tuning Sample Spectrum

- Light stop/sbottom
- Suite of light EW gauginos
- Complex stop decays evade SUSY searches
New Search Techniques for Light EW States

- Light EWK multiplets, eg, Higgsinos, have small production $\sigma$’s with large SM backgrounds @ LHC. Constraints only from colored state cascades. What can we do?

  - Mass splittings ($\Delta m$) in multiplets define phenomenology
    - $\Delta m \sim 200$ MeV there is a long-lived charged state (=disappearing track)
    - $\Delta m > \sim$ a few GeV, soft decays visible.
    - In between?

  - Idea: boost system with QCD ISR similar to monojet searches. Look for a soft $\gamma$ from EWK radiation in charged state decay $\sim$ aligned with ‘MET’ /soft decay products due to boost.

Ismail, Izaguirre & Shuve : 1605.00658
Results look promising

Soft $\gamma$ near MET

Hard $j+$ MET used as trigger

In the background $j+Z(\rightarrow \nu \nu)$

Worth detailed study by ATLAS/CMS

Reasonable cross-section/HL-LHC Significance
Warped Geometries: SM in the bulk

- Non-factorizable extra dimension based on AdS$_5$

- $\mathcal{L} = \mathcal{L}_{\text{bulk}} + \mathcal{L}_{\text{branes}}$
  - SM with Higgs, Goldstones + (t, b) on IR brane, transverse gauges in bulk & light fermions near UV brane
  - $\rightarrow$ fermion mass hierarchy.

- Matter closer(further) from TeV brane couples more strongly(weakly) to graviton KK-states

- Essentially no di-lepton events in this set-up!

- Scale of physics on IR-brane

\[ \Lambda_\pi = \bar{M}_P l \varepsilon \quad \text{with} \quad \varepsilon = e^{-kr_c \pi} \]

- Strong constraints from PEWO and FCNC
- Invoke Custodial Symmetry
- $M_1^{\text{Gauge}} > 3-4$ TeV w/ Gravitons even heavier
- $g_1 \rightarrow tt$ best signal @ LHC
Warped Geometries: Brane Localized Kinetic Terms

- Every kinetic term of a 5d Lagrangian can/must have a 4d projection on either brane = BLKT

\[ S_G = \frac{M_5^3}{4} \int d^4x \int r_c d\phi \sqrt{-G} \left\{ R^{(5)} + \left(2\gamma_0 / kr_c\right) \delta(\phi) + \left(2\gamma_\pi / kr_c\right) \delta(\phi - \pi) \right\} R^{(4)} + \ldots \right\}, \]

\[ S_V = \frac{-1}{4} \int d^4x \int r_c d\phi \sqrt{-G} \left\{ F_{AB} F^{AB} + \left(2\delta_0 / kr_c\right) \delta(\phi) + \left(2\delta_\pi / kr_c\right) \delta(\phi - \pi) \right\} F_{\mu\nu} F^{\mu\nu} + \ldots \right\}, \] (2)

- BLKTs reduce the values of the Graviton & Gauge KK couplings
- PEWO/FCNC constraints on the KK states can be mitigated

Davoudiasl et al 0212279, 0305086
Carena et al 0212307
Warped Geometries Example: 750 GeV Graviton KK-state

- **750 GeV G_1 diphoton rate**

\[ \sigma_{\gamma\gamma} = 4.86 \text{ fb} \times \frac{(1 + 2\gamma_0)}{25} \times (5 \text{ TeV}/\Lambda_\pi)^2 \]

- Naturally fits excess w/ IR-physics at few TeV
- **1^{st} KK** should be visible in other channels

<table>
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<tr>
<th>Channel</th>
<th>( \sigma^{13} ) (fb)</th>
<th>( \sigma^{8} ) (fb)</th>
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<tbody>
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<td>( \sigma_{\gamma\gamma} )</td>
<td>5.0</td>
<td>1.18</td>
</tr>
<tr>
<td>( \sigma_{gg} )</td>
<td>40.0</td>
<td>9.44</td>
</tr>
<tr>
<td>( \sigma_{ZZ} )</td>
<td>7.48</td>
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<td>( \sigma_{hh} )</td>
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<td>( \sigma_{bb} )</td>
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<tr>
<td>( \sigma_{tt} )</td>
<td>23.9</td>
<td>5.64</td>
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</table>

- **Gauge 1^{st} KK** \( \sim 566 \text{ GeV} \) very weakly coupled
- `Light’ RS KK states accessible @LHC w/ natural hierarchy solution!
Whither Naturalness?

- The concept of naturalness is subjective
- Naturalness provides a guide for new physics, not a no-lose theorem
- Numerous natural theories still viable
- No need for panic (yet)!
Model Building: A Zoo of Natural Ideas

Supersymmetry: MSSM
CMSSM, NMSSM, pMSSM, XYZ–MSSM

SUSY Beyond MSSM
RPV, Extended Gauge Sectors, Dirac Gauginos

(Mini-)Split Supersymmetry

Extra Dimensions
Folded Supersymmetry

Maximally Natural Supersymmetry

Little Higgs
Twin Higgs (Neutral Naturalness)

Relaxion

Many viable directions that preserve naturalness and are testable at LHC13
Looking forward to more data from Run 2!
Discoveries await!
pMSSM after LHC Run I (Gravitino LSP)

Prompt NLSP decay

Displaced NLSP decay

Neutralino LSP

Cahill-Rowley et al. 1512.asap