Naturalness after the first run of the LHC

Galileo Galilei Institute
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Marco Farina
Cornell University
Naturalness in trouble?

Naturalness is now in trouble, two measurements:

- **top is heavy** \( M_t \approx 173 \text{ GeV} \)
- **Higgs is light** \( M_h \approx 126 \text{ GeV} \)

\[
\delta m_h^2 \approx \delta m_h^2 (\text{top loop}) \approx \frac{12 \lambda_t^2}{(4\pi)^2} \Lambda_{NP}^2 \times \left\{ \frac{1}{\ln M_{Pl}^2 / \Lambda_{NP}^2} \right\}
\]

\[
\delta m_h^2 \lesssim M_h^2 \times \Delta
\]

\[
\Lambda_{NP} \lesssim \sqrt{\Delta} \times \left\{ \begin{array}{c} 400 \text{ GeV} \\ 50 \text{ GeV} \end{array} \right\}
\]
Top partners?

The biggest issue is in the third generation.
Bottom up approach with Higgs+top+top partners:

- Assume mass of the form

  \[ m^2(T_i) = m^2_{0,i} + c_i h^2 + \cdots \]

  Can be spin-0 (SUSY), spin-1/2 (Little Higgs, etc.)

- Cancelling quadratic divergences

  \[ 6y_t^2 = \sum_i g_i (-1)^{F_i} c_i \]
Top partners?

Low-Energy Theorems relate to Higgs couplings:

\[ \mathcal{L}_{h\gamma\gamma} = \frac{2\alpha}{9\pi v} C_\gamma h F_{\mu\nu} F^{\mu\nu} \]

\[ \mathcal{L}_{hgg} = \frac{\alpha_s}{12\pi v} C_g h G_{\mu\nu} G^{\mu\nu} \]

\[ C_\gamma \approx 1 + \frac{3}{4} \sum_f \frac{N_{c,f} Q_f^2 c_f v^2}{m_{0,f}^2 + c_f v^2} + \frac{3}{16} \sum_s \frac{N_{c,s} Q_s^2 c_s v^2}{m_{0,s}^2 + c_s v^2} \]

\[ C_g \approx 1 + 2 \sum_f \frac{C(r_f) c_f v^2}{m_{0,f}^2 + c_f v^2} + \frac{1}{2} \sum_s \frac{C(r_s) c_s v^2}{m_{0,s}^2 + c_s v^2} \]
Top partners

We can now put together (log) FT and Higgs couplings. E.g. spin-1/2 partner
SUSY and the Higgs mass

\[ m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left[ \ln \frac{m_t^2}{m_t^2} + \frac{X_t^2}{m_t^2} \left( 1 - \frac{X_t^2}{12m_t^2} \right) \right] \]

Different ways to get 125 GeV:

- heavy stops
- large stop mixing
- extended scalar sector (NMSSM)

\[ \Delta m_h = \max_i \left| \frac{\partial \ln m_h^2}{\partial \ln p_i} \right| \]

Hall, Pinner, Ruderman
1112.2703
Stops and Naturalness

If too large tuned parameters to get correct EWSB scale

\[ m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left[ \ln \frac{m_t^2}{m_t^2} + \frac{X_t^2}{m_t^2} \left( 1 - \frac{X_t^2}{12m_t^2} \right) \right] \]

\[ \delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2} \left( m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2 \right) \ln \left( \frac{\Lambda}{m_t} \right) \]

Higgs Mass vs. Fine Tuning

Lightest Stop Mass

Hall, Pinner, Ruderman
1112.2703
Stops and Naturalness

\[ m_{\tilde{g}} \lesssim 2m_{\tilde{t}} \]

\( \tilde{g} \rightarrow \tilde{t} \tilde{t}^0 \)

\( \tilde{t} \rightarrow t\chi_1^0 \)

Hall, Pinner, Ruderman

1112.2703
Is the NMSSM the solution?

Add a singlet

\[ W_{NMSSM} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 \]

\[ (m_h^2)_{\text{tree}} \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \]
So far:
- MSSM: stop tuning $\sim 1\%$
- NMSSM: $\sim 5\%$

Why don't we push it further?

$\lambda$-SUSY:
- perturivitiy lost before $\sim 10$ TeV if $\lambda > 2$
- Higgs mass naturally $\sim \lambda v$ up to 350 GeV
Enlarge your $\lambda$

$\lambda$-SUSY:

- perturivity lost before $\sim 10$ TeV if $\lambda > 2$
- Higgs mass naturally $\sim \lambda v$ up to 350 GeV
- observed Higgs mass obtained by mixing with the singlet

Fine Tuning!

Gherghetta et al. 1212.5243
- Mixing with H is \(~\text{few \%}\)

- Can describe the problem with just \((h,s)\)

\[
\begin{pmatrix}
M_{11}^2 & M_{13}^2 \\
M_{31}^2 & M_{33}^2
\end{pmatrix} = \begin{pmatrix}
\lambda^2 v^2 & 2\lambda^2 s v - (2\kappa\kappa s v + \lambda A_{\lambda} v) \\
4\kappa^2 s^2 + A_{\kappa} s + \frac{v^2}{2s} A_{\lambda} \lambda
\end{pmatrix}
\]
Fine tuning

- After fixing Higgs mass and singlet fraction only two free parameters left.

\[ \lambda = 2, \ t\beta = 2, \text{ Singlet Fraction } 10\% \]
- Singlet fraction is a crucial parameter
- Mixing necessary for lowering mass

Large Mixing constrained by data

PRELIMINARY (MF, M. Perelstein, B. Shakya)
Future?

LHC at 14 TeV with 300 fb$^{-1}$

Data from Peskin 1207.2516
Beyond SM vs Naturalness

- **MSSM**: tuning at ~1% or worse
- **NMSSM & $\lambda$-SUSY**: ~5-10%
- **pNGB Higgs**: no sign of strong sector, $m_h$ too light. FT ~few % (FT~$v/f$ and f~few TeV)
- **Top Partners**: ~15%?
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What if there is only the SM?
Is nature natural?

Two (?) roads in front of us:

- **Naturalness**: in trouble.
- **Fine Tuning**: Higgs mass light due to antropic principles.
SM: stability?

- Experimentally now we know \( \lambda \approx 0.13, \ y_t \approx 1 \)
- All SM parameters are measured and beta functions determined
SM: stability

- Second minimum when $\lambda < 0$

$$V = \lambda (|H|^2 - v^2)^2 \approx \frac{\lambda}{4} h^4$$

- Is it a coincidence? A (big) message hiding behind it?

\[\text{Degrassi et al. 1205.6497}\]
Top uncertainties

- Top uncertainties are fully considered? More precise measurements are needed.
Special boundary conditions?

- Are those all hints of special boundary conditions?

\[ \lambda(k_{tr}) \approx 0, \beta_\lambda(k_{tr}) \approx 0 \]

Shaposhnikov, Wetterich 0912.0208

- Sign of some UV-completion before the Planck scale?

\[ \lambda_{\text{eff}} = 4V/h^4 \]

\[ \lambda \text{ in MS} \]

\[ \beta_\lambda \]

\[ M_h = 126 \text{ GeV (dashed)} \]
\[ M_H = 124 \text{ GeV (dotted)} \]
\[ M_t = 173.1 \text{ GeV} \]
\[ \alpha_s(M_Z) = 0.1184 \]

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Degrassi et al. 1205.6497
Special boundary conditions?

- Other boundary conditions are possible?
- EWSB could be generated radiatively. Coleman-Weinberg
- Ruled out in pure SM

\[ M_h = 125.5 \text{ GeV} \]
\[ 3\sigma \text{ bands in} \]
\[ M_t = 173.3 \pm 0.6 \text{ GeV} \]
\[ \alpha_s(M_Z) = 0.1184 \pm 0.0007 \]

Lykken @ MITP Workshop, Mainz
● **Scale invariance**: obvious candidate to forbid quadratic divergence

● Dimensional Regularization is the natural choice

"Classically conformal"

● The Higgs quadratic term is the only one breaking the symmetry. Some non-SUSY extension could enforce the special boundary conditions.

"Classically conformal"

● Even more vanishing? Also \( \lambda=0 \)

Shift symmetry restored.

Bardeen Fermilab-Conf-95-391

Meissner, Nicolai hep-th/0612165

Hebecker, Knochel, Weigand, 1204.2551
More examples

Why should the true cutoff behave like dimensional regularization?

- Conformal invariance at high scales. For example adding a singlet scalar.  
  [Lykken @ MITP Workshop, Mainz, Englert et al. 1301.4224, Heikinheimo et al. 1304.7006]

- Infinite tower of states at Planck scale  
  [Dienes hep-ph/0104274]

- New physics leading to a Veltman throat  
  [Bezrukov et al. 1205.2893]
Is nature natural?

Or maybe there is a third option...

from Strumia talk @ Brookhaven
There is a third (ugly) path:

- **Finite Naturalness**: the SM is valid up to arbitrary scale (i.e. up to Planck scale). We are agnostic about gravity, quadratic divergences are not physical and thus have to ignored.

- However new physics is expected (dark matter, neutrino masses, strong CP problem/axions, etc...)

- Recipe: compute effective potential discarding quadratic divergences and ask the usual \( \delta m_h^2 \lesssim M_h^2 \times \Delta \)
A third (ugly) option

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DISCLAIMER: I don't want to advocate, but to explore its consequences and tests

*MF, D. Pappadopulo, A. Strumia 1303.7244*
The SM satisfies Finite Naturalness

Is the SM "finite natural"?
Logarithmic sensitivity is still present.

P.s. GUTs usually don't satisfy Finite Naturalness
Neutrinos

Three different see-saw models (M used in general as the mass of the new heavy particles):

- **Type-I**: heavy N right handed neutrinos
- **Type-II**: a scalar triplet T, with $Y=1$
- **Type-III**: heavy triplets replace the heavy singlets of type-I

\[
M \lesssim \begin{cases} 
0.7 \times 10^7 \text{GeV} \times 3\sqrt{\Delta} & \text{type I see-saw model,} \\
200 \text{GeV} \times \sqrt{\Delta} & \text{type II see-saw model,} \\
940 \text{GeV} \times \sqrt{\Delta} & \text{type III see-saw model,}
\end{cases}
\]

- Only Type-I could be compatible with Leptogenesis
Another possibility: DM without electroweak interactions.

- Scalar: \[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\left( \partial_{\mu} S \right)^2}{2} - \frac{m_S^2}{2} S^2 - \lambda_{HS} S^2 |H|^2 - \frac{\lambda_S}{4} S^4 \]
Singlet Dark Matter

Another possibility: DM without electroweak interactions.

- Fermion:

\[ \mathcal{L} = \mathcal{L}_{SM} + \frac{(\partial \mu S)^2}{2} + \bar{\psi} i \gamma_5 \psi - \frac{m_S^2}{2} S^2 - \frac{\lambda_S}{4} S^4 - \lambda_{HS} S^2 |H|^2 + \frac{y}{2} S \psi \bar{\psi} + \frac{M_{\psi}}{2} \psi \bar{\psi} + h.c. \]
Finite Naturalness bounds

In general finite naturalness requires new particles around the TeV scale:

- **Neutrinos:** \( M \lesssim \begin{cases} 
0.7 \times 10^7 \text{GeV} \times \sqrt{\Delta} \\
200 \text{GeV} \times \sqrt{\Delta} \\
940 \text{GeV} \times \sqrt{\Delta} 
\end{cases} \)
  
  - type I see-saw model,
  - type II see-saw model,
  - type III see-saw model,

- **Dark Matter:** scalars/fermions \( M \sim 1 \text{ TeV} \)
  with/without EW interactions

- **Axions (KSVZ model):** \( M \lesssim \sqrt{\Delta} \times \begin{cases} 
0.74 \text{ TeV} & \text{if } \Psi = Q \oplus \bar{Q} \\
4.5 \text{ TeV} & \text{if } \Psi = U \oplus \bar{U} \\
9.1 \text{ TeV} & \text{if } \Psi = D \oplus \bar{D} 
\end{cases} \)

- Other models do not have FN bounds
Conclusions I

- **Pessimistic (antropic):** simplest/most popular models tuned to % level.
  Nature is fine tuned, give up!

- **Optimistic:** Nature is Natural!
  Soon we will observe new particles and deviations from SM in Higgs data.

- **Finite Naturalness:** new states could be within reach of LHC and other experiments (dark matter direct detection, etc.).
  We have to rethink concepts taken for granted.
Conclusions II

History repeating?

- **SUSY and MSSM**: CMSSM, PMSSM, BMSSM, NMSSM, RMSSM and so on...
Conclusions II

History repeating?

- **SUSY and MSSM**: CMSSM, PMSSM, BMSSM, NMSSM, RMSSM and so on...

- **Naturalness**: Absolute Naturalness, Technical Naturalness, Finite Naturalness, $!&@!#$ Naturalness...

We hope not.