EW Naturalness in Light of the LHC Data

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SM Higgs: Lagrangian and Physical Parameters

- The SM Higgs potential has two terms → two parameters:

\[ V = -\frac{\mu^2}{2} h^2 + \frac{\lambda}{4} h^4 \]

- Higgs gets a vacuum expectation value, known from e.g. the W mass:

\[ v = \frac{\mu}{\sqrt{\lambda}} \quad M_W = \frac{g v}{2} = 80.4 \text{ GeV} \rightarrow v = 246 \text{ GeV} \]

- The physical Higgs boson mass is

\[ m_h = \sqrt{2} \mu \]

- Higgs mass at \( \sim 126 \text{ GeV} \) gives

\[ \mu = 88.4 \text{ GeV}, \quad \lambda = 0.13 \]

- Question for this talk: how natural are these values?

- Focus on the mass parameter in this talk; quartic also important
SM Higgs: Renormalization

- Higgs mass parameter receives radiative corrections:

\[-\mu^2 = \mu_{\text{tree}}^2 + \frac{c_X^2}{16\pi^2}\Lambda_X^2 \quad c_X^2 = \kappa_X^2 N_X\]

- \(\kappa_X\) = Higgs-X coupling constant, \(N_X\) = # of d.o.f. in X (X=SM fields)

- Naturalness:

\[\frac{c_X^2}{16\pi^2}\Lambda_X^2 \lesssim \mu^2 \quad \Rightarrow \quad \Lambda_X \lesssim \frac{4\pi\mu}{c_X} \approx \frac{1 \text{ TeV}}{c_X}\]

- Simple measure of unnaturalness:

\[\Delta = \frac{\delta\mu^2}{\mu^2} \quad (\Delta > 1 = \text{fine-tuning})\]

- An alternative measure (usually agree parametrically, but care is needed):

\[\delta\mu^2 = f(p_i), \Delta = \max_i \left| \frac{\partial \log \mu^2}{\partial \log p_i} \right|\]
Natural New Physics Scales

- Hierarchy of SM Higgs couplings

\[ \lambda \sim 1 \quad g \sim 0.5 \quad \lambda \ll 1 \]

\[ \top \quad \text{TOP} \quad g_s \sim 1 \]

\[ \text{HIGGS} \quad \text{SU}(2) \times \text{U}(1) \quad \text{Gauge Bosons} \quad \text{SU}(3) \quad \text{Gluons} \]

\[ \text{1st/2nd Gen. quarks, bottom, leptons} \]

- Cutoff scales required by naturalness are inversely related to the couplings:

\[ \Lambda_X \lesssim \frac{4\pi \mu}{c_X} \approx \frac{1}{c_X} \quad c_X^2 = \kappa_X^2 N_X \]

- Top quark:

\[ c_t = 6 \lambda_t^2 \approx 6 \quad \Lambda_t \lesssim 400 \text{ GeV} \]

- For 1st, 2nd gen. quarks, bottom, leptons, this bound is \(10 \text{ TeV or more}\).
Top Partners

• Are current experimental bounds on new physics consistent with naturalness?

• Bounds depend on the specific nature of new physics

• I will take a bottom-up approach (~simplified model), focusing on the third generation (Higgs+Top+Top Partner)

• I will consider two well-motivated examples:
  • Spin-1/2 top partner (a la Little Higgs)
  • Spin-0 top partner (a la SUSY)
Fermionic Top Partner

[Berger, Hubisz, MP1205.0013]

- **Example 1:** spin-1/2 top partners

- **Realization:** Little Higgs models

\[
\mathcal{L} = -\lambda_1 u_R^\dagger V^\dagger \chi_L - \lambda_2 f U_R^\dagger U_L + \text{h.c.}
\]

- **Global SU(3) symmetry** (softly broken by \(\lambda_2\)) enforces cancellation of quadratic divergence at one-loop:

\[
\delta \mu^2 = -3 \frac{\lambda_i m_T^2}{8\pi^2} \log \frac{\Lambda^2}{m_T^2}.
\]

- **Two-parameter model:** \(m_T\) and \(\alpha = \tan^{-1} \frac{\lambda_1}{\lambda_2}\)
Top Partners: FT vs PEW

- Pre-LHC: Precision electroweak constraints limit $m_T > 500$ GeV

- This corresponds to $\sim 20\%$ tuning

- Note: only top-sector included (i.e. assumes other sources of PEW corrections that appear in full LH models are sufficiently suppressed)
Top Partners: FT vs LHC

- Top partner decays: $T \rightarrow Wb, tZ, th \ (Br \sim 2 : 1 : 1)$

Excluded by CMS $T \rightarrow Wb$

search (recast, 2011 data)

$20\% \ FT$
• Large deviations expected in natural regions of parameter space, due to Higgs “compositeness” (not loops!)

• Current Higgs data already puts better bounds than precision electroweak and direct searches!
Bosonic Top Partners, a.k.a. Stops

- **Example 2:** spin-0 top partners

- A 3-parameter model:

\[
\mathcal{L} = -m_L^2|\tilde{Q}_L|^2 - m_R^2|\tilde{t}_R|^2 + X_t(\tilde{Q}_L H \tilde{t}_R + \text{h.c.})
\]

\[
m_L, m_R, X_t \Rightarrow m_1, m_2, \theta_t
\]

- Same as MSSM with everything but $\tilde{Q}_L, \tilde{t}_R$ "decoupled" at $M > \text{a few TeV}$
  [NB: cannot decouple $\tilde{g}, H$ - come back to it later in the talk!]

- Much recent progress in **top-down models** realizing such spectra in SUSY

- **Fine-tuning:**

\[
\delta m_{H_u}^2 \approx \frac{3g_2^2}{16\pi^2} \left( m_{Q_3}^2 + \tilde{m}_{t_c}^2 + A_t^2 \right) \log \frac{2\Lambda^2}{m_{Q_3}^2 + \tilde{m}_{t_c}^2}
\]

\[
\approx \frac{3}{16\pi^2} \left( y_t^2 \left( \tilde{m}_1^2 + \tilde{m}_2^2 - 2m_t^2 \right) + \frac{(\tilde{m}_2 - \tilde{m}_1)^2}{4v^2 \sin^2\beta} \sin^2 2\theta_t \right) \log \frac{2\Lambda^2}{m_1^2 + \tilde{m}_2^2}
\]

- Fine-tuning is minimal when the "messenger scale" $\Lambda$ is as low as possible
  (model-building issue; probably $\sim 10\text{ TeV}$ is the minimum)
Stops: Fine-Tuning vs Mass

- Optimistically assumed $\Lambda = 10$ TeV; for higher values, rescale by $\log \Lambda$

- Note: SUSY models have an additional issue of generating the required Higgs quartic; this is NOT reflected in these plots
Fine-Tuning vs Higgs Mass

MSSM predicts $m_h = m_Z$ at tree level; needs a large stop contribution to get to 126 GeV fine-tuned at best at $\sim 1\%$ level

However, small non-minimality can alleviate fine-tuning: new F-term (e.g. NMSSM) or D-term (extra gauge groups) contributions to the quartic

NMSSM (extra singlet) only requires 10-20\% tuning

[Hall, Pinner, Ruderman, ’11]
Stops: LHC Bounds

- 560 GeV corresponds to $\sim 15\%$ FT (no mixing, no mass splitting, $\Lambda = 10$ TeV)

- No bounds in “special” (but pretty broad) regions:
  - “Compressed” spectrum ($m_{\tilde{t}} \approx m_{\text{LSP}} + m_t$)
  - “Stealthy stop” ($m_{\tilde{t}} \approx m_t \gg m_{\text{LSP}}$)

- No bounds if R-Parity is violated (for example $\tilde{t} \rightarrow \bar{b}s$, as in MFV-SUSY)
Gluinos and Naturalness

- Rad. corrections to the stop mass also need to be cut off (stop=scalar!)

- Dominated by QCD; cut off by the gluino requires

\[ m_g \lesssim 2m_t \] (Majorana gluinos, as in MSSM)

\[ m_g \lesssim 4m_t \] (Dirac gluinos)

[Brust, Katz, Lawrence, Sundrum, ’11]

[Same plot with an on-shell stop?]
Same-Sign Dilepton Signature of RPV/MFV SUSY

[Berger, MP, Saelim, Tanedo, 1302.2146]

Gluino mass bound: 
\(~800 \text{ GeV}\)

Recast of CMS SSDL+b+MET Search

95% c.l. exclusion limits: CMS SSDL+b jets+MET search

\(\sqrt{s} = 8 \text{ TeV}\)
\(\int L = 10.5 \text{ fb}^{-1}\)
Boosting SSDL RPV Search

Stop decay products
ang. separation

\[ m_{\tilde{g}} = 1.2 \text{ TeV} \]
Naturalness and Higgs Couplings

- **Stop loops** contribute to Higgs couplings to gluons and photons

- **Naive correlation:** more FT ↔ heavier stops ↔ more SM-like hgg; can be violated in the presence of large A-terms (negative contr. to hgg!)
Tree-Level Tuning in SUSY

- So far, we focused on tree vs. loop tuning, which appears in all models.

- In SUSY, there is a separate issue: two distinct tree-level contributions to $m^2$

$$m^2 = -m^2_{H_u} + \mu^2$$

SUSY-breaking soft mass \(\rightarrow\) SUSY-preserving F-term

- Naturalness: $m^2 > \mu^2 \rightarrow$ expect light ($\sim 100$ GeV) Higgsinos

![Diagram showing 95% C.L. upper limit on $m^2$ and expected signals in SUSY models.](image)

- “Minimal” (sort of) spectrum with light sleptons.
Naturalness and Dark Matter Direct Detection (MSSM)

\[ \tilde{\chi}^0 \tilde{\chi}^0 h : \quad (gZ_{\chi^2} - g'Z_{\chi^1})(\cos \alpha Z_{\chi^4} + \sin \alpha Z_{\chi^3}), \]

\[ \tilde{\chi}^0 \tilde{\chi}^0 H : \quad (gZ_{\chi^2} - g'Z_{\chi^1})(\sin \alpha Z_{\chi^4} - \cos \alpha Z_{\chi^3}). \]

"Generic" mixings: \( Z_{\chi i} \sim 1 \)

"Natural" cross section (h exchange only):

\[ \sigma \sim (a \text{ few}) \times 10^{-44} \text{ cm}^2 \]

\[ Z_{\chi i} \ll 1 \] required to get lower x-section!

\[ u\bar{u}h : \frac{\sqrt{2m_u}}{v \cos \beta} \]

\[ d\bar{d}h : \frac{\sqrt{2m_d}}{v \sin \beta} \]

(basically fixed)

[MP, Shakya, 1107.5048]
3.1 Higgsino Fraction Constraint

Our first result concerns the correlation between the direct detection cross section and the Higgsino fraction of the neutralino, defined as

$p = \min(F_H, 1 - F_H)$.

where $F_H$ is the Higgsino fraction. The direct detection cross section limit below a few $\times 10^{-44}$ cm$^2$ puts a constraint on the Higgsino fraction, requiring that it be close to either the "pure gaugino" case or the "pure Higgsino" case. It is convenient to define "neutralino purity" $p_t$ as

$p_t \equiv \min(F_H, 1 - F_H)$.

The bound placed by the XENON1G experiment already rules out essentially all MSSM dark matter models with $p > \frac{1}{2}$. And most models with $p > \frac{1}{3}$, especially for the LSP mass above a few GeV.

The proposed XENON1G upgrade will be able to probe values of $p$ below $10^{-4}$.

A well-known example of such a model is the "well-tempered neutralino" scenario. The fact that this scenario is disfavored by XENON100 has already been noted in Ref. [12].

Color-code: "purity"

Red $p > 0.2$
Orange $0.1 < p < 0.2$
Green $0.01 < p < 0.1$
Cyan $0.001 < p < 0.01$

[Scan: pMSSM, no relic density constraint]

[MP, Shakya, 1107.5048]
Color-code: **EWSB fine-tuning**

- Red \( \Delta < 10 \)
- Green \( 10 < \Delta < 100 \)
- Cyan \( 100 < \Delta < 1000 \)

Lower DD cross section means **MORE FINE-TUNING!**

[Scan: pMSSM, no relic density constraint, gaugino LSP]
Beyond the MSSM

[MP, Shakya, 1208.0833]

NMSSM

lambda-SUSY

Lower DD cross section means MORE FINE-TUNING!
Conclusions

• Current LHC bounds (direct searches) demand fine-tuning only at 10-20% level, in a bottom-up approach

• This applies to spin-0 as well as spin-1/2 top partners

• Even less tuned scenarios are still possible in the spin-0 case: compressed or stealthy spectra, RPV

• Higgs rate measurements are beginning to have interesting implications for naturalness, with much more to come

• Dark matter direct detection bounds are beginning to develop a tension with naturalness, in the (N)MSSM context