BEYOND MINIMAL NATURALNESS

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ME AND PHENO

My first particle physics talk at a conference!
My topic is “Physics Beyond the Standard Model.”
Don’t know how to review the state of BSM in 30 min.

The plan
Revisit why we think naturalness is a guiding principle.

My idiosyncratic take on the naturalness and BSM theory.

What are novel ways naturalness could manifest?

Goal is to motivate observables!
Set the Higgs mass and calculate.

Make predictions.

No conflict with experiment (so far).*

* ignoring a variety of anomalies that are not currently understood...
BRIEF SIDEBAR
DIMENSIONFUL SCALES

Relativity:

Space $\equiv$ Time
Convert meters to seconds with speed of light: $c$.
Mass $\equiv$ Energy
Convert mass to energy with speed of light: $c$. 
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**Quantum Mechanics:**

Energy $\equiv$ $1$/Time

Convert energy to time with Planck's constant: $\hbar$. 
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Large mass scales equivalent to short distance scales.

The LHC is a giant microscope!
END SIDEBAR
REDUCTIONISM
NEW SCALES?

Physics beyond the Standard Model exists!

- dark matter
- matter/anti-matter asymmetry
- neutrino masses
- gravity

Want an explanation for these phenomena?

Need new dimensionful scales.
EFFECTIVE FIELD THEORY

RULES OF THE GAME

Specify symmetries.
Specify matter content.
Write all symmetric terms in Lagrangian.

\[ \mathcal{L} = \ldots \]

CENTRAL QUESTION

Do any symmetries forbid the Higgs mass parameter?

YES
Higgs mass calculable in low energy theory.

NO
Higgs mass sensitive to highest scales in nature.

Answer for Standard Model
Implications

Central Question
Do any symmetries forbid the Higgs mass parameter?

Yes
Higgs mass calculable in low energy theory.
A new symmetry requires new partner particles.

No
Higgs mass sensitive to highest scales in nature.
Other dynamics responsible for light Higgs.

(Avoiding discussion of anthropics on purpose.)

Tim Cohen [University of Oregon]
Symmetry to forbid Higgs mass parameter.
ELECTRON SELF-ENERGY
ELECTRON SELF-ENERGY

**Classical**

\[ \Delta m_e \sim \frac{e^2}{r_e} \]

\[ \frac{\Delta m_e}{m_e} \sim 10^9 \left( \frac{r_{\text{Planck}}}{r_e} \right) \]

“electron radius”
ELECTRON SELF-ENERGY

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QUANTUM

\[ \Delta m_e \sim m_e \frac{e^2}{16\pi^2} \log (m_e r_e) \]

\[ \frac{\Delta m_e}{m_e} \sim 10^{-2} \]

"electron radius"
ELECTRON SELF-ENERGY

\[ \Delta m_e \sim m_e \frac{e^2}{16\pi^2} \log \left( \frac{m_e r_e}{e} \right) \]

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Requires new particle!
WHAT WAS THE SYMMETRY??

A fast and loose argument.
The most famous Lorentz invariant
\[ E^2 = m^2 \]
yields two solutions
\[ E = \pm m \]

Particles and anti-particles!
HIGGS MASS CORRECTIONS

\[ \mathcal{L} \supset y_t H \bar{t} t \quad \Rightarrow \quad m_t = \frac{y_t}{\sqrt{2}} \langle H \rangle \]

Top quark is heaviest particle: largest coupling to Higgs.

\[ \sim \frac{y_t^2}{16 \pi^2} \Lambda^2 |H|^2 \]

Incalculable Higgs mass…
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The cutoff: \( \Lambda \to \infty \)

Incalculable Higgs mass…
Supersymmetry commutes with Standard Model symmetries.

Super-rotations mix particles of different spin, but same charge.

All couplings determined by symmetry properties.
HIGGS MASS CORRECTIONS

\[
\begin{aligned}
H & \rightarrow t \rightarrow H^\dagger \\
\bar{t} & \rightarrow \tilde{t} \rightarrow H^\dagger \\
\end{aligned}
\]

\[\sim \frac{y_t^2}{16 \pi^2} \Lambda^2 |H|^2\]

\[\sim -\frac{y_t^2}{16 \pi^2} \left(\Lambda^2 + c m_{\tilde{t}}^2\right) |H|^2\]
Calculable Higgs mass!
COMPARE TO EXPERIMENT

\[ g \xrightarrow{t_1} \tilde{t}_1 + \ldots \]
TC, Walter Hopkins, Stephanie Majewski and Bryan Ostdiek, arXiv:1804.00111 [hep-ph].
CAN TOP PARTNERS BE NEUTRAL?
DOUBBLE DOWN!
DOUBLE DOWN!
DOUBLE DOWN!

TWO APPROACHES

- Fermionic neutral top partners: Twin Higgs
  Chacko, Goh, Harnik [arXiv:hep-ph/0506256]

- Scalar neutral top patterns: Folded Supersymmetry
  Burdman, Chacko, Goh, Harnik [arXiv:hep-ph/0609152]
THE HYPERBOLIC HIGGS

**Accidental** \( U(2, 2) \)

\[
V = \lambda \left( \left| H_{\mathcal{H}} \right|^2 - \left| H \right|^2 - f^2 \right)^2
\]

\[
\left| H_{\mathcal{H}} \right|^2 - \left| H \right|^2 = \frac{m^2}{\lambda}
\]

Flat-direction
\[ L = (\lambda_t H \psi_Q \psi_{U^c} + \text{h.c.}) + \lambda_t^2 \left( |H_H \cdot \tilde{Q}_H|^2 + |H_H|^2 |\tilde{U}_H^c|^2 \right) \]

\[ \delta V \propto \lambda_t^2 \Lambda^2 \left( |H_H|^2 - |H|^2 \right) \]
A COMPLETE MODEL

Supersymmetry and a compactified extra dimension.

\[ W_{\text{brane}} \]

\[
\begin{array}{c|c|c}
(Q, U^c, D^c, L, E^c) & H & H_{\mathcal{H}} \\
\frac{1}{2}, 0 & & 0, \frac{1}{2} \\
\hline
U(1)_x & \text{MSSM} & \text{MSSM}_{\mathcal{H}} \\
\hline
y = 0 & & y = \pi R \\
\end{array}
\]

\[ \mathbb{Z}_2 \]
FINE TUNING
PLEASE BE PATIENT
PARAMETER SPACE

Hyperbolic mass scale [GeV] vs. Inverse size of extra dimension [GeV]

- Tuning 5%
- 2.5%
- 1%
- 0.5%

$m_h = 125 \pm 5$ GeV
PHENOMENOLOGY

Higgs portal

Top partner vevs

Higgs-top partner mixing

Eaten top partners

Modified dark shower phenomenology
THE OTHER SYMMETRY SOLUTION

What if the Higgs were not an elementary scalar?

Relies on shift symmetry to forbid Higgs mass parameter.

New strong dynamics scale

____________________

Electroweak scale

H

Kaplan, Georgi [1984];
Kaplan, Georgi, Dimopoulous [1984]; …
for a recent review: Bellazzini, Csaki, Serra [arXiv:1401.2457]
THE OTHER SYMMETRY SOLUTION

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COSMOLOGICAL DYNAMICS

Naturalness
Arkani-Hamed, TC, D'Agnolo, Hook, Kim, Pinner [arXiv:1607.06821]
NATURALNESS
For simplicity:
Only variation away from our Standard Model is Higgs mass parameter.

\[-\Lambda_{\text{UV}}^2 \lesssim \left( m_H^2 \right)_i \lesssim \Lambda_{\text{UV}}^2\]
$\Lambda^2_{UV}$

$v = 0$

$v_{us} = 246$ GeV

$v > v_{us}$

$-\Lambda^2_{UV}$

$m^2_H$
Not a multiverse.
No anthropics!

\[ \nu = 0 \]
\[ \nu_{us} = 246 \text{ GeV} \]
\[ \nu > \nu_{us} \]

\[ \Lambda_{\text{UV}}^2 \]
\[ m_H^2 \]
\[ -\Lambda_{\text{UV}}^2 \]

\[ N \text{ COPIES} \]
But why is there energy density in only our sector?!?
THE REHEATON

$S$ reheats the Universe after inflation.

Couples universally to all copies.
MODEL REQUIREMENTS

i) The reheaton is a gauge singlet;

ii) Parametrically lighter than the naturalness cutoff;

iii) Couplings to Higgs bosons of each sector.
CMB Stage IV: future constraint on $N_{\text{eff}} \lesssim 0.02$. Also constrain $\sum m_{\nu_i}$ to SM value.

$\mathcal{L} = \frac{1}{2}m_\phi \phi^2 + a \phi \sum_i |H_i|^2$
OUTLOOK
Stealth SUSY
Fan, Reece, Ruderman [arXiv:1105.5135,1201.4875]; + Krall, Pinner [arXiv:1512.05781]

Dirac Gauginos
Nelson, Fox, Weiner [arXiv:hep-ph/0206096]; Kribs, Martin [arXiv:1203.4821]

Compressed spectra/Auto-concealment
Dimopoulos, Howe, March-Russell, Scoville [arXiv:1412.0805]

The Relaxion
Graham, Kaplan, Rajendran [arXiv:1504.07551]

Clockwork/Linear dilation
Giudice, Kats, McCullough, Torre, Urbano [arXiv:1711.08437]

etc...
Naturalness continues to be strong motivation!

The “experts” do not know what is going on…

The field is ready for your fresh ideas!
ALL THAT MATTERS...

IS THAT WE DISCOVER THE NEW PHYSICS,
NO MATTER HOW HARD NATURE IS WORKING TO TRICK US!