New Exotic BSM Signatures at the LHC

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Prologue:
The Hierarchy problem.
Ginzburg-Landau

\[ F = \left| (\nabla + 2ieA)\Phi \right|^2 + m^2(T)|\Phi|^2 + \lambda|\Phi|^4 + \ldots \]

- Below the critical temperature the mass-squared is negative:

- Photon has become massive: \( m_A \sim e\langle \Phi \rangle \)
What does this have to do with the Higgs Boson?
The Higgs sector of the Standard Model involves the Higgs field and the gauge fields

\[
H, \quad W^a_{\mu}
\]

The Lagrangian for this theory is

\[
\mathcal{L} = \left| (\partial_\mu + ig\sigma^a W^a_{\mu}) H \right|^2 + m^2(T)|H|^2 - \lambda(T)|H|^4 + \ldots
\]

This is just the relativistic non-Abelian version of Ginzburg-Landau.
The Higgs sector of the Standard Model is like a relativistic superconductor!
Ginzburg-Landau is just a phenomenological model, with no explanation of parameters. The macroscopic parameters follow from the detailed microscopic BCS theory (Gor’kov) and there are no surprises.

The order parameter at zero temperature is of the typical scale associated with underlying microscopic parameters.
The Elephant in the Room

We expect the Higgs model is phenomenological, just like G-L. But something totally different seems to be going on.

There is an apparent hierarchy between the model parameters and microscopic parameters:

\[ M_P \sim 10^{16} \langle H \rangle \]

Furthermore, this hierarchy is unprotected: Quantum corrections should lift Higgs mass.
The Elephant in the Room

We expect the Higgs model is phenomenological, just like G-L. But something totally different seems to be going on.

What is the microscopic origin of the weak scale, and why is it so far from other microscopic scales?

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Furthermore, this hierarchy is unprotected: Quantum corrections should lift Higgs mass.
Part 1:

What if $M_P \sim M_H$?

Can be realised if this is an extra-dimensional Planck scale.

Large extra dimensions: Arkani-Hamed, Dimopoulos, Dvali.
Warped Extra Dimensions: Randall-Sundrum.

Any other possibilities?
Linear Dilaton Model

Also found in the continuum limit of the clockwork model, this is a solution to Einstein’s equations for gravity + dilaton (like 5D Brans-Dicke) with the metric:

\[ ds^2 = e^{\frac{4k|y|}{3}} (dx^2 + dy^2) \]

and it offers an extra-dimensional approach to the hierarchy problem very different from RS or LED.

Studied first by Antoniadis, Dimopoulos, Giveon.
In this theory, the Planck scale is:

\[ M_P \sim \sqrt{\frac{M_5^3}{k}} e^{k\pi R} \]

So if all other parameters at the weak scale require:

\[ kR \sim 10 \]

But the mass spectrum is given by:

\[ m_n \sim k \left( 1 + \frac{n^2}{2(kR)^2} \right) \]

Thus the first few states will always be split by %’s, with the relative splitting decreasing for heavier modes.

This splitting is thus a key prediction of the theory.
Most interestingly, due to splittings, signal appears to "oscillate". Thus get extra sensitivity by doing spectral analysis... The "power spectrum" of LHC data!

Can search for continuum spectrum at high energies. BG modelling essential...
Phenomenology

Extract the oscillations, subtract off background:

And then Fourier-transform what’s left over!
As yet, the power spectrum of the LHC has yet to be measured. It may reveal clues to the origin of the weak scale!
Part 2: SUSY, but not as you know her...
\[ t = \tilde{t} + \sqrt{2} \theta \cdot t + \theta^2 F_t \]

Stop. I think we should split up...
But who will look after Higgs?

\[ t = \tilde{t} + \sqrt{2\theta} \cdot t + \theta^2 F_t \]
\[ t = \tilde{t} + i \sqrt{2} \theta \cdot t + \theta^2 F_t \]
• The landscape of top partners:

<table>
<thead>
<tr>
<th></th>
<th>scalar</th>
<th>fermion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>strong direct production</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QCD</td>
<td>SUSY</td>
<td>Composite Higgs/RS</td>
</tr>
<tr>
<td><strong>DY direct production</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EW</td>
<td>folded SUSY</td>
<td>Quirky Little Higgs</td>
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<tr>
<td><strong>Higgs portal direct production</strong></td>
<td></td>
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<tr>
<td>singlet</td>
<td>?</td>
<td>Twin Higgs</td>
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</tbody>
</table>

Mirror Glueballs
Higgs portal observables

Higgs coupling shifts
~ tuning

Table from Curtin and Verhaaren.

• This part: The last box.
Hyperbolic Higgs

• Take two identical copies of the MSSM:

\[ \text{SM}_A \leftrightarrow A \leftrightarrow B \leftrightarrow \text{SM}_B \]

• Take a large D-term with equal and opposite charges for Higgses:

\[
V_H = \frac{g_H^2}{2} \left( |H|^2 - |H_H|^2 \right)^2
\]

This enforces that the scalar potential respects an accidental SU(2,2) symmetry. Not symmetry of theory.
Hyperbolic Higgs

• Remove scalar matter in A, and fermions in B:

\[ \mathcal{L} = \lambda_t \ H \psi_Q \psi_U^c + \text{h.c.} \]

\[ + \lambda_t^2 \left( |H_{\mathcal{H}} \cdot \tilde{Q}_{\mathcal{H}}|^2 + |H_{\mathcal{H}}|^2 |\tilde{U}_{\mathcal{H}}^c|^2 \right) \]

• Quadratic corrections respect the accidental SU(2,2) symmetry:

\[ V_{\mathcal{H}} = -\Lambda^2 \left( |H|^2 - |H_{\mathcal{H}}|^2 \right) + \frac{g_{\mathcal{H}}^2}{2} \left( |H|^2 - |H_{\mathcal{H}}|^2 \right)^2 \]

Thus, at level of one-loop corrections, scalar potential respects an accidental SU(2,2) symmetry.
Hyperbolic Higgs

- In usual “quadratic divergences” parlay:

Quadratic divergences from SM top quark loops cancelled by loops of “Hyperbolic” stop squarks.
Hyperbolic Higgs

- In usual “quadratic divergences” parlay:

\[ \mathcal{L} \sim \lambda_t H \psi_Q \psi_{Uc} + \text{h.c.} + \lambda_t^2 |H|^2 \left( |\tilde{t}_L^H|^2 + |\tilde{t}_R^H|^2 \right) \]

Quadratic divergences from SM top quark loops cancelled by loops of “Hyperbolic” stop squarks.
SM Higgs can decay, through the Higgs portal, to Hyperbolic gluons.

These decay back through Higgs portal. Essentially same as Twin Higgs.

LHC has sensitivity in future.

Curtin, Verhaaren.
Phenomenology

Phenomenology has not been studied, however one aspect could be **radically** different to Twin. If... 

\[ \langle \hat{t}_\mathcal{H} \rangle \neq 0 \]

Then:

- Hyperbolic QCD is broken, so no glueball signatures, no hidden sector hadronisation.
- Longitudinal modes of Hyperbolic Gluons are Top Partners!
- Radial modes of Hyperbolic Stops mix with Higgs, so Higgs becomes, partially, its own top partner!
Summary

The hierarchy problem is here to stay. A handful of ideas has dominated study in the past, but now the LHC has liberated us.

We have now entered an exploratory era, exotic in theory and signature. (See also relaxion.)
Part 3:

What if the weak scale really is far far below the next microscopic scale?
Essentially, it seems like the Universe is just like a Transition Edge Sensor:
The Relaxion

• Radically different take on the hierarchy problem.
• Basic ingredients

\[ \mathcal{L} \sim (M^2 - g\phi)|H|^2 \]

\[-gM^2\phi\]

\[+ f_\pi^3 \lambda_q \langle h \rangle \cos \left( \frac{\phi}{f} \right)\]

In early Universe Relaxion rolls

Once it has rolled far enough, Higgs will develop a small VEV.
Then axion potential turns on and Relaxion stops rolling
The Relaxion

- Cosmological evolution

Relaxion starts at the top of potential. Starts rolling down.

Scans Higgs mass-squared while it rolls, slowly cancelling against large mass-squared.
The Relaxion

• Cosmological evolution

At some point relaxion crosses critical value at which Higgs mass-squared becomes zero.

After this mass-squared becomes negative:
  • Higgs gets a vev
  • Quarks get mass
  • Axion potential turns on
Soon after axion potential turns on (while Higgs vev is still very small), relaxion becomes trapped and stops rolling.

Thus Higgs vev becomes stuck at this finely-tuned point!
The Relaxion

- Cosmological evolution

Soon after axion potential turns on (while Higgs vev is still very small), relaxion becomes trapped and stops rolling. Thus Higgs vev becomes stuck at this finely-tuned point!

Can choose “g” parameter such that field stops when \( \langle h \rangle \) is still very small. This is a parameter choice, not a tuning, since radiatively stable.

\[
\frac{\partial V}{\partial \phi} \sim g M^2 - \frac{f^2 \phi^2}{f} \frac{m_\pi^2}{f} \sin \left( \frac{\phi}{f} \right) = 0
\]
Typically the relaxion is very light and very weakly coupled.

However, if you are willing to lower the microscopic physics scale the relaxion-Higgs mixing can become large enough to observe the light relaxion at colliders.
Supersymmetry

SUSY commutes with SM symmetries, since it extends SM fields to superfields:

\[ t = \tilde{t} + \sqrt{2} \theta \cdot t + \theta^2 F_t \]

With interactions such as

\[ \mathcal{L} \sim \lambda_t h t_L t_R + h.c. + \frac{\lambda_t^2}{2} h^2 (|\tilde{t}_L|^2 + |\tilde{t}_R|^2) \]

And \( \mathcal{L} \sim \tilde{t}^c t \cdot \chi^0 \) which enables decays.
Since 2010 we have been deluged with data.
Now the dust is settling, it’s time to grab the shovel.
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Where haven’t we been digging?
Experimentalists:
• Even if you didn’t have a specific model to compare with, what crazy signature would you search for?
• Where will the big experimental leaps come? Triggering, soft, displaced?

Theorists:
• Where will big improvements in systematics come?
• What rare SM processes have we yet to exploit? Higgs to muons etc.