BSM Phenomenology at Run 2 and Beyond

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Elementary scalars are quadratically sensitive to physics at higher scales.

Independent of regularization scheme.

Model-building scales aside, gravity attests to presence of a higher scale.

To date, no viable proposals for mitigating sensitivity to physics at the Planck scale without new physics around weak scale.

The hierarchy problem only sharpened with the discovery of an elementary SM-like Higgs (and nothing else so far).
Electroweak naturalness

Supersymmetry

[Susysymmetry breaking
Sparticles $\tilde{m}$

$$\lesssim 4\pi/G$$

Higgs $m_h$

(compositeness, SUSY, turtles)

Global symmetry

[Global symm. breaking
Partner particles $\tilde{m}$

$$\lesssim 4\pi/G$$

Higgs $m_h$

Continuous symmetries $\rightarrow$ partner states w/ SM quantum #s

$$m_h^2 \sim \frac{3y_t^2}{4\pi^2} \tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$$

Totally natural: $\tilde{m} \lesssim 200\text{ GeV}$
The naturalness strategy

This is a *strategy* for new physics near $m_h$, not a *no-lose theorem*, because the theory does not break down if it is unnatural.

But naturalness has often been a very *successful* strategy.

E.g. charged pions

Electromagnetic contribution to the charged pion mass sensitive to the cutoff of the pion EFT.

$$\delta m^2 \sim \frac{3e^2}{16\pi^2} \Lambda^2$$

Naturalness suggests $\Lambda \sim 850$ MeV.

Rho meson (new physics!) enters at 770 MeV.
“Colorful” naturalness

Supersymmetry

Composite/Little Higgs

Simple game for LHC: look for QCD-charged partners.
A physics driver @ LHC

170 of these 226 channels tied to naturalness

ATLAS SUSY Searches* - 95% CL Lower Limits

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ATLAS SUSY Searches* - 95% CL Exclusion

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ATLAS Preliminary [C-H] = (5.0 - 20.3) fb⁻¹

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*Only a selection of available mass limits

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**SUS-12-027** L=9.2 /fb

**SUS-13-013** L=19.5 /fb

**SUS-13-006** L=19.5 /fb

**SUS 13-019** L=19.5 /fb
Direct limits

Supersymmetry

Global symmetry

Where we are: “generically”

~7% tuning level
which rules out LHC is the multijet triggers, which can heavily prescale-away the sign
to account for stop acceptances relative to coloron or hyper
trend suggests that masses near the current limit of 100 GeV might
decay (with a branching ratio
possible to invoke Minimal Flavor Violation (MFV), which suggests that
FIG. 1: Existing constraints on
us to wonder whether the LHC will
inevitable rise of trigger thresholds with instantaneous luminosity an
any stop mass [8–11]. A snapshot of the current situation can be se
resonances at the LHC have failed to reach the sensitivity necessa
and high
the decays of heavier colored superparticles, such as gluinos [33] o
and high
baryonic RPV
improving charm+MET with charm tagging
[Martin '07; LeCompte & Martin '11]

Table:

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<th>Mass [GeV]</th>
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<th>300</th>
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<td>4.7</td>
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Generalize this weakness (stop-scharm mixing)

improving charm+MET with charm tagging

[Mahbubani, Perez, Papucci, Ruderman, Weiler '12]

Live here (stealth)
cascades; tt spin correlations;
tt cross section limit

[Fan, Reece, Ruderman '11; Han, Katz, Krohn, Reece '12; Czakon, Mitov, Papucci, Ruderman, Weiler '14; Martin '11; LeCompte & Martin '11]
Global holes

Search for vector-like top partners assumes decays proceed into SM final states (e.g. bW, tH, tZ)

Cross section large enough that missing energy unnecessary, so less kinematically delicate than SUSY.

But: Many composite and little Higgs models have additional Higgs scalars.

Possible/likely for decays to proceed through additional Higgses, yielding novel final states.

[Kearney, Pierce, Thaler, ‘13]
Run II Direct Reach

Where we’ll be
@ end of LHC:
“generically”

But: we could also have just fallen victim to one of the holes in coverage (compression, stealth, missing decays), or perhaps…
“Neutral” naturalness

5 TeV

[Chacko, Goh, Harnik '05; Barbieri, Gregoire, Hall '05; Chacko, Nomura, Papucci, Perez '05; Falkowski, Pokorski, Schmaltz '06; Chang, Hall, Weiner '06; Burdman, Chacko, Harnik '06; Foot, Volkas '06; Poland, Thaler '08; Harnik, Wizansky '08; Batra, Chacko '08; NC, Englert, McCullough '13; Chacko, Cui, Hong '13; NC, Howe '13; NC, Knapen, Longhi '14; Geller, Telem '14; Burdman, Chacko, Harnik, Lima, Verhaaren '14; NC, Lou, McCullough, Thalapillil '14; NC, Katz, Strassler, Sundrum '15; Barbieri, Greco, Rattazzi, Wulzer '15; Low, Tesi, Wang '15]
An example: Twin Higgs

[Chacko, Goh, Harnik ’05]

\[ L \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B \]

\[ h + \ldots \quad f - \frac{h^2}{2f} + \ldots \]

Higgs is a PNGB of \( \sim \)SU(4), but partner states not charged under the SM.

There are many more theories of this kind [NC, S Knapen, P Longhi]
Twin Signals

• Modest Higgs coupling deviations and invisible branching ratio (~5-10%).

• Displaced decays: Higgs into hidden sector, hidden sector confines, displaced decays via off-shell Higgs.

• Singlet-like heavy Higgs decaying to hh, WW, ZZ, invisible.

Not yet meaningfully constrained; naturalness potentially probed to ~20% level by end of LHC.
Naturalness at future colliders

Three major opportunities

- Uncover UV structure well beyond LHC reach
- Extend reach of LHC for new particles important for naturalness
- Cover holes from LHC with precision Higgs measurements
Precision naturalness

Probing at a Higgs factory:

Look for $\mathcal{O}(\text{loop}^* v/m)$ [SUSY] or $\mathcal{O}(v/f)$ [global] Higgs coupling deviations; precision electroweak corrections.

Where we’ll be @ Higgs factory:

*Sensitive to kinematic holes at LHC.*

~1-2% level
Kinematic naturalness

Probing at 100 TeV:
Look for the light partner states

[Chen, D’Agnolo, Hance, Lou, Wacker]

Where we’ll be @ 100 TeV: “generically”
Kinematic naturalness

Probing at 100 TeV:
...or for the UV physics

Even if light states are hard to find, can directly access heavy resonances
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Thank you!