Physics Topics for Run 2
(A Postcard from Planet Theory)

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Where We Are Now

• Run 1 a huge success - CONGRATULATIONS!

• Higgs boson discovery completes the verification of the particle content of the SM

• Higgs spin/parity well tested, agrees with SM

• 5 Higgs couplings measured (best at ~10% level), agree with SM

• 100’s of searches for physics beyond the SM, no discovery (some interesting ~2.5-sigma anomalies)
Run 2 Priority: BSM

- LHC Run 2 offers unprecedented opportunities to search for new physics
- Direct searches in the 1-5 TeV mass range, with 10-100 more parton luminosity than run 1
- Precision Higgs as a tool to search for new physics
- New technologies, e.g. boosted top/W/Z/Higgs ID techniques
- Discovery mindset is appropriate!

[figure credit: S. Willocq]
Into the Unknown

• Unlike discoveries of the past ~30 years (W/Z, top, Higgs), theory does not provide robust guidance for BSM searches

• A few big themes ("problems") motivate theoretical extension of the SM

• Many models with no clear frontrunner

• Model-building details affect predicted LHC signatures

• Crucial to pursue a broad range of searches, prioritize discovery over "testing models"

[figure credit: H. Murayama]
Theorists thinking about BSM is motivated by a few deficiencies (real or imagined) of the SM

<table>
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<tr>
<th>BSM Themes</th>
<th>real problem?</th>
<th>TeV scale?</th>
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<tr>
<td>Naturalness</td>
<td>maybe</td>
<td>yes</td>
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<tr>
<td>Origin of EWSB</td>
<td>maybe</td>
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</tr>
<tr>
<td>Dark Matter</td>
<td>yes</td>
<td>maybe</td>
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<tr>
<td>Baryogenesis</td>
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Naturalness

\[ -6\lambda_t^2 \int_0^\Lambda \frac{d^4k}{(2\pi)^4} \frac{1}{k^2} \sim \frac{3\lambda_t^2}{8\pi^2} \Lambda^2 \]

- If no BSM until scale \( \Lambda \), cancellation of “bare” and “radiative” contributions requires, with accuracy \( \sim (m_h/\Lambda)^2 \)

- BSM is required at scale \( \sim 500 \text{ GeV} \), to avoid fine-tuning

- No quantitative lower bound on “acceptable” tuning: simply “yuck factor” \( \sim (\Lambda/500 \text{ GeV})^2 \)

- Does Nature care about fine-tuning? We don’t know.

  - Yes - pions are composite; etc., etc.
  
  - No - cosmological constant but no new physics at \( 10^{-3} \text{ eV} \)
Alternatives to Naturalness

- If fine-tuned, the large hierarchy $m_h \ll \Lambda$ may be explained by other arguments:
  - Anthropic
  - Dynamical (cosmological evolution)

- Naturalness of the weak scale is an experimental question, accessible to the LHC, with profound implications whether or not new physics is discovered.
Electroweak Symmetry Breaking

- In the SM, EWSB happens “because”
  \[ V(H) = -\mu^2|H|^2 + \lambda|H|^4 \]
- But why the minus sign? BSM is required to explain it. (Does Nature care? We don’t know)
- All known explanations require that the hierarchy problem be solved: otherwise large incalculable contributions to Higgs mass
- Possibly important hint: dominant SM radiative correction, due to SM top loops, is negative
- SUSY and Composite/Little Higgs models exploit this to “predict” the minus sign

\[
= -6\lambda^2 \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2}
\]
Natural BSM

- Fundamentally, only two mechanisms are known that can restore naturalness: SUSY and composite Higgs

- Both predict ~"doubling" of the spectrum - plenty of new particles at the "TeV" scale

- Flavor constraints, electron EDMs, Run-1 data all favor "minimal naturalness" - a handful of particles at ~TeV, a bunch more at ~10 TeV

- Minimal TeV spectrum: top partners, gluon partners, maybe W/Z partners
Two priorities for Run 2: high mass frontier and compressed spectra (broad regions remain - not “special”!)

Boosted-object techniques, especially in gluino searches

[see e.g. Berger, MP, Saelim, Spray, ‘11]
“Alternative” Natural SUSY

• Many deviations from the “canonical” model are possible: e.g.
  • Detector-stable stops (astro/cosmo bounds OK if $\tau < 1 \text{ sec}$)
  • Macroscopic stop lifetime/displaced vertex: e.g. $\tilde{t} \rightarrow t + \tilde{G}$
  • R-parity violation: e.g. $\tilde{t} \rightarrow \bar{d}s$
  • RPV with displaced vertices

• None is particularly “exotic”: just different spectra and parameter choices within nSUSY, more-or-less equally motivated

• Many scenarios are already covered, but the search menu still seems heavily biased towards prompt MET

• Careful thought is needed to make sure there are no $O(1)$ gaps in search coverage (same applies to all SUSY searches)
Fermionic Top Partners

- “Canonical” TP well covered in Run 1
- Run 2: Single production becomes important, boosted-object techniques are crucial
- Non-canonical TP: e.g. can forbid all standard decays by “t-parity”
- Possible decay patterns:
  \[ T \rightarrow t\eta, \eta \rightarrow jj \]
  \[ T \rightarrow b\omega^+, \omega^+ \rightarrow jj \]
- Seems rather constrained by RPV gluino and other searches, but more work is needed

Figure 2: Decay scenarios depending on the mass hierarchies. The decay \( T \rightarrow t\eta \) will typically dominate if it is kinematically allowed (scenario 1). If \( m_{\bar{\chi}} > m_T > m_t \), then the decay \( T \rightarrow b\omega^+ \) will dominate if it is allowed (scenario 2). If \( m_T > m_\tau > m_{\bar{\chi}} > m_T \), then cascade decays may be typical.

Scenario 2:
\[ T \rightarrow b\omega^+ \rightarrow jj \]
In this case, the decay to \( \chi \) is assumed not to be kinematically available, in which case the top partner will decay via \( T \rightarrow t\eta \rightarrow t\bar{t} \), \( T \rightarrow b\omega^+ \rightarrow b\bar{b} \). Since \( m_\tau \) receives quadratically divergent contributions to its mass from gauge loops it is normally expected to be heavy.

We therefore consider the region \( m_T > m_{\bar{\chi}} > m_T \), in which case the decay \( T \rightarrow b\omega^+ \) dominates. Again, there is a two-dimensional parameter space in \( m_T, m_{\bar{\chi}} \). The final state is four jets and two bottoms, and so again there will be constraints from multi-jet searches. However, if the \( T, \tau \) mass splitting is small then the \( b \) jets will typically be soft, relaxing the constraints from such searches. This will be discussed in section 3.2.

Scenario 3:
\[ T \rightarrow t\bar{t} \rightarrow t\bar{t} \chi (\chi = \text{stable}) \]
In this scenario, we assume that \( m_\chi < m_T \) in which case the decay \( T \rightarrow t\eta \) will typically dominate and the \( \chi \) is assumed to be stable. There is a two-dimensional parameter space in \( m_T, m_{\bar{\chi}} \). This scenario is similar to classic supersymmetric stop squark production \( \tilde{t} \tilde{t} \rightarrow t\bar{t} \bar{N} \bar{N} \), as we discuss in section 3.3.

2.1 Electroweak Precision Constraints on the Simplified Model
Electroweak precision data place significant constraints on the parameter space of models with fermionic top partners, which need to be taken into account in any discussion of direct searches. Here, we consider the contributions to precision electroweak observables produced by the particles and interactions of the simplified model, Eq. (2.2). These are in a sense “irreducible”, since they follow directly from the structure that gives rise to the LHC signatures of interest to us. It turns out that these contributions are in fact quite small, as we will see in this subsection. Of course, a more complete description of the physics that gives rise to these signatures can be found in the full theoretical framework of supersymmetry.
Higgs Couplings and Top Partners

- Top partners (spin-0 or 1/2) contribute to Higgs couplings via loops.
- Effect can be significant in $hgg$ and $h\gamma\gamma$ couplings, where SM is also one-loop.
- Current bounds rule out TP up to $\sim 300$ GeV, but with no sensitivity to decay channel (e.g. covers the “gaps” in direct stop searches!)
- Increasing Higgs coupling precision may give first hint of TPs.

[see e.g. Farina, MP, Rey-Le Lorier, ‘13]
Neutral Naturalness

- Top partner does not need to be charged under SM gauge groups to solve the (little) hierarchy problem
- Example: “Twin Higgs” models
- Direct searches for colorless TP impossible: cross sections too low
- Rare Higgs decays: into twin sector, then back to SM, typically $4b$ with displaced vertices

[Harnik, Goh, Chacko, ’06]
[figure credit: N. Craig]
Electroweak Phase Transition

- Higgs boson moving through a plasma of quarks acquires a “thermal mass” (much like photon “plasma mass”)
- At high plasma densities, EW symmetry is unbroken!

![Graph of Higgs potential before and after phase transition]

- Right after the Big Bang, the Universe was filled with dense quark plasma, was in unbroken EW phase
- As the Universe expanded and cooled, phase transition to current phase with broken symmetry - EWPT

\[ kT \sim 100 - 1000 \text{ GeV}, \quad T \sim 10^{15} \text{ K}, \quad t \sim 10^{-10} \text{ sec} \]
• It is believed that the observed matter-antimatter asymmetry arose dynamically, very soon (<1 sec) after the Big Bang.

• Many mechanisms proposed; one of the most theoretically attractive is “Electroweak Baryogenesis”, in which the asymmetry is generated during the EWPT.

• It only works if transition is 1-st order (out-of-equilibrium).
First-Order EWPT

- In a 1st-order transition, bubbles of broken ("our") phase are nucleated inside the unbroken-EW phase

- Non-equilibrium process satisfies one of the famous "Sakharov conditions" for generating matter-antimatter asymmetry
EWPT and Higgs Couplings

- In the SM, EWPT is 2nd-order no EW Baryogenesis
- New particles, coupled to Higgs, may change the dynamics and re-open the window for EW Baryogenesis
- However, they will also change the Higgs couplings to gluons, photon, W/Z, and self-coupling
- Run-2 will definitely test the models with colored new particles causing 1-st order EWPT

Example: “RH Stop” model

\[ hgg, h \text{ corrections. (For the case of } h \text{ the correction is always negative, and the plots show its absolute value.) In the shaded region, phase transition into a color-breaking vacuum occurs before the EWPT.} \]

\[ \Delta \kappa_g \geq 17\% \text{ for 1st-order EWPT} \]
Signature Space and Recasts

• Think of each CMS analysis as a “basis vector” in a multi-dimensional space (à la Hilbert)

• Each analysis is optimized to search for some topology/simp. mod./model

• …but has non-trivial sensitivity to many other topologies/models

• Model-builders/hep-ph folks often want to estimate this sensitivity, obtain bounds on their new ideas - “ReCast”

• New tools to simplify/automate this task: ATOM, CheckMate, MadAnalysis

These are very useful - please help the authors implement more analyses!
The top priority for Run 2 is to discover new physics, whether predicted by theorists or not.

In Hilbert space language: is our basis complete? Are there orthogonal signatures that require new searches?

If you can think of such a search, it is already justified: no fancy theory is required!

Just write a simplified model and go for it!

and, Most Importantly...
Bon Voyage!
(and don’t forget to write...)

Standard Model

CMS ATLAS LHC-B
Bon Voyage!

(and don’t forget to write…)

P.S. If you need an espresso, there’s a machine in PSB 438. It’s $0.50 a cup.