BSM Higgs Sectors

FCC Week 2015
Washington, DC

26 March 2015

David Curtin
University of Maryland
BSM Higgs Sectors

**Big Picture Motivations**
- Naturalness
  - SUSY
  - pGB
  - uncolored?
- Electroweak Phase Transition
  - Baryogenesis?
- Higgs Portal
  - Dark Matter?
  - Generic BSM

**IR Models**
- SM+S (mixed/unmixed)
- SM+fermions
- 2HDM
- 2HDM+S
- SILH
- ....

**Observables at Current + Future Colliders**
- producing extra higgs states (incl. superpartners)
- Exotic Higgs Decays
- Electroweak Precision Observables
- Higgs coupling measurements
- Higgs portal direct production of new states
- Higgs self coupling measurements
- Zh cross section measurements

**UV Completions & Rest of Theory**
BSM Higgs Sectors

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1. **1.**
2. **2.**
3. **3.**
BSM Higgs Sectors

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**Lepton Collider:** All about precision.

**100 TeV pp:** Intensity Frontier experiment for Higgs Sector

*Important exception: direct production of heavy higgs siblings, and of course probing the rest of the theory / UV completion!*
Production of Heavy States

The Higgs sector could include more scalar states than just the SM higgs. (e.g. $A/h_2/H^\pm$ in 2HDMs)

These states are produced via DY or variants of SM Higgs production.

Decay to $ff, VV, Vh$. Hard decay products and full reconstruction of intermediate state allow for TeV-reach at HL-LHC, and 5-10 TeV reach at 100 TeV collider.

In SUSY, Higgsinos or EWinos are part of the Higgs sector. Generally similar reach, but invisible particles in decay make compressed spectra very challenging.

No way around a 100 TeV collider to explore at $O(\text{TeV})$ masses!
Exotic Higgs Decays

.. may give first or only probe of new physics:

Tiny higgs width → light BSM particles can couple very weakly (~0.01) and produce sizable Brs (~ 10%)

**Higgs portal:** BSM physics wants to couple to the higgs via low-dimensional operators.

\[
\Delta \mathcal{L} = \frac{\mu}{\Lambda^2} |H|^2 \bar{\psi} \psi \\
\Delta \mathcal{L} = \frac{\zeta}{2} s^2 |H|^2
\]

**Hadron colliders are HIGGS FACTORIES**

HL-LHC makes ~ \(10^7\) Higgses

100 TeV with 3/ab makes ~\(10^8\) Higgses.

Probe **Br(h→conspicuous)** at the \(10^{-8} - 10^{-7}\) level

**Lepton colliders are CLEAN**

Probe **Br(h→arbitrarily stealthy)** at the \(10^{-3}\) level
Precision Observables

Higgs couplings to SM particles

HL-LHC will measure at ~5% level
ILC with high lumi can go to ~0.1%, TLEP few x better.

Many BSM theories give O(1-10%) deviations!

Electroweak Precision Observables

$m_W$, $m_t$, $m_Z$ uncertainty will be greatly reduced by ILC/TLEP

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$S$ (68%)</th>
<th>$f$ (GeV)</th>
<th>$T$ (68%)</th>
<th>$m_{f_L}$ (GeV)</th>
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<tbody>
<tr>
<td>ILC</td>
<td>0.012</td>
<td>1.1 TeV</td>
<td>0.015</td>
<td>890 GeV</td>
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<tr>
<td>CEPC (opt.)</td>
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<td>880 GeV</td>
<td>0.016</td>
<td>870 GeV</td>
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<tr>
<td>CEPC (imp.)</td>
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<td>1.0 TeV</td>
<td>0.011</td>
<td>1.1 GeV</td>
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<tr>
<td>TLEP-Z</td>
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<td>1.1 TeV</td>
<td>0.012</td>
<td>1.0 TeV</td>
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<tr>
<td>TLEP-$t$</td>
<td>0.009</td>
<td>1.3 TeV</td>
<td>0.006</td>
<td>1.5 TeV</td>
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<table>
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<tr>
<th>Experiment</th>
<th>$\kappa_2$ (68%)</th>
<th>$f$ (GeV)</th>
<th>$\kappa_6$ (68%)</th>
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</thead>
<tbody>
<tr>
<td>HL-LHC</td>
<td>3%</td>
<td>1.0 TeV</td>
<td>4%</td>
<td>430 GeV</td>
</tr>
<tr>
<td>ILC500</td>
<td>0.3%</td>
<td>3.1 TeV</td>
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Lepton collider leads the charge, but 100 TeV (or LHC) has good chance of discovering UV physics responsible for deviations!
**Precision Observables**

**hee coupling:** $y_e$ is the smallest coupling in the SM*. Can we probe it?

*Except maybe QCD CP phase

1503.04830 Altmannshofer, Brod, Schmaltz

Dim 6 operators can generate deviations to hee coupling compared to $m_e$, but $y_e^{BSM} \gg y_e^{SM}$ requires tuned cancellation.

Also, Flavor physics consideration in constructing complete model.

Future lepton colliders can probe $y_e^{BSM}$ through higgs production via radiative return: $e^+e^- \rightarrow h\gamma$.

Sensitive to $|y_e^{BSM}/y_e^{SM}| \sim O(10)$

EDM measurements (ACME) constrain CP violation in hee.

Sensitive to $|\text{Im} y_e^{BSM}/y_e^{SM}| \sim O(10^{-2})$

Important to look for large deviations in $y_e^{BSM}/y_e^{SM}$, but precision measurements of $y_e^{SM}$ are likely impossible in the near future.
What if TeV-scale new physics ONLY couples to the Higgs?

100 TeV with 30/ab collider has mass reach of ~ few 100 GeV via VBF $h^* \rightarrow XX$ production.

Shift in $h^3$ coupling. 100 TeV with 30/ab can exclude 10% shift in $\lambda_3$.

This is sensitivity is enough for very meaningful statements about the electroweak phase transition and naturalness.

These could be the only signatures. Mass reach of these probes in relevant models is only a few 100 GeV at a 100 TeV collider.
BSM Higgs Sectors

IR Models
SM + Singlet Scalar

\[ V_{0}^{T=0}(H, S) = -\mu^2 (H^+ H) + \lambda (H^+ H)^2 + \frac{a_1}{2} (H^+ H) S + \frac{a_2}{2} (H^+ H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4. \]

In generality, this scalar mixes with the higgs after EWSB.

- heavy Higgs (sibling) production
- Higgs portal production
- Exotic Higgs Decays
- \( h^3 \) measurement
- \( \sigma(Zh) \) measurement

allowed by:
- CMS heavy higgs search 5+5/fb
- ATLAS light higgs search 5+5/fb
- LEP
- EWPO

Profumo, Ramsey-Musolf, Wainwright, Winslow 1407.5342
SM + Singlet Scalar

\[ V_0^{T=0}(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4. \]

**Difficult case:** unbroken $Z_2$ symmetry $S \rightarrow -S$

- heavy Higgs (sibling) production
- Higgs portal production
- Exotic Higgs Decays
- $h^3$ measurement
- EWPO
- Higgs Couplings
- $\sigma(Zh)$ measurement

**Need large higgs portal couplings for $m_S > m_h/2$**

I409.0005 DC, Meade, Yu
Most commonly consider four discrete types ($\mathbb{Z}_2$ avoids FCNCs). Type II $\supset (N)$MSSM

Generically, Higgs coupling measurements at ILC/TLEP give mass reach $\sim 0.5 - 1$ TeV.

However, corrections can be much smaller in alignment limit → have to do direct searches!

$$\kappa_V \sim 1 - 0.5\% \left( \frac{400 \text{ GeV}}{M_A} \right)^4 \cot^2 \beta$$

$$\kappa_t \sim 1 - \mathcal{O}(10\%) \left( \frac{400 \text{ GeV}}{M_A} \right)^2 \cot^2 \beta$$

$$\kappa_b = \kappa_\tau \sim 1 + \mathcal{O}(10\%) \left( \frac{400 \text{ GeV}}{M_A} \right)^2 .$$

HL-LHC gives $\sim$ TeV mass reach for MSSM (type II).
In MSSM, 100 TeV mass reach is better than 5 TeV.

Exotic Higgs Decays could also reveal light states! Easy to get in 2HDM+S (i.e. NMSSM-like), but also in 2HDM.

Motivates extending NMSSM-like exotic higgs decay searches to full kinematically allowed mass range, and to consider most general Yukawa-ordered $h \rightarrow aa \rightarrow 4f$ decays

1412.4779 DC, Essig, Zhong
1412.3385 Bernon, Gunion, Jiang, Kraml
Strongly Interacting Light Higgs

Low-energy limit of Composite Higgs or RS-like theories. Assume some new ‘strong’ sector is responsible for EWSB.

Generically, can be any BSM higgs sector with a perturbative SM-like higgs dof, up to corrections that depend on the strong coupling scale.

$$\delta g \sim \frac{v^2}{f^2}$$

Lepton colliders are sensitive to $f \sim 1 \text{ TeV}$
(expected effect of higgs mixing/coupling deviations at tree-level), or $f \sim 5 \text{ TeV}$ (generic effect of hadron-zoo at mass scale $\sim f$ on EWPO, but could be subject to cancellations).

$$S \sim \frac{4 \pi v^2}{m^2_\rho} \sim \frac{N v^2}{4 \pi f^2}$$

Can expect to produce EW resonances with similar mass reach as heavy higgs searches, but more model-dependent. (Also top partners, like in SUSY!)

I411.1054 Fan, Reece, Wang
I402.4431 Pappadopulo, Thamm, Torre, Wulzer
BSM Higgs Sectors

Big Picture

Motivations
BSM Higgs Sectors

Big Picture Motivations

Naturalness

See also Nathaniel Craig’s talk!
A calculable theory of the higgs mass requires top partners to stabilize the weak scale beyond $O(500$ GeV).

**Classify such theories by top partner spin and gauge charge.**

This organizes the low-energy signatures of naturalness into a clear pattern.

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hep-ph/0506256 Chacko, Goh, Harnik
hep-ph/0609152 Burdman, Chacko, Goh, Harnik
0812.0843 Cai, Cheng, Terning
1411.7393 Craig, Knapen, Longhi

...
Solutions to the Hierarchy Problem

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**Strong production of top partners**

- **EW DY production of top partners. Interesting decays....**
  - Chacko, DC, Verhaaren [in preparation]

- **Tree-level Higgs coupling shifts of $O(v^2/f^2) \sim$ tuning**

- **Exotic Higgs decays to glueballs of mirror QCD**
  - Chacko, DC, Verhaaren [in preparation]

**Higgs Portal Observables**
# Solutions to the Hierarchy Problem

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## Strong production of top partners

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Higgs Portal Observables
Direct searches for additional Higgs bosons in the MSSM have ~ 1 TeV reach at HL-LHC and ~ 5 TeV reach at 100 TeV (see 2HDM)

Within the MSSM, a 125 GeV Higgs mass requires either very heavy stops (unnatural) or additional tree-level contributions to the Higgs mass:

- **F-terms (NMSSM etc) → extra singlet scalar**
  - Extra Higgs production
  - Exotic Higgs decays!
  - EWPO, etc....

- **D-terms (non-decoupling D-term models) → new gauge group**
  - DY production of BSM gauge bosons at a few TeV!

hep-ph/0309149 Batra, Delgado, Kaplan, Tait

*Of course, a 100 TeV collider has exquisite reach for colored stops....*
Composite Higgs Models

Want Lepton colliders to probe Higgs coupling deviations & EWPO

Want 100 TeV to produce vector resonances of strongly coupled sector (as well as top partners)
Colorless Electroweak Naturalness

Models with uncolored top partners are usually charged under mirror QCD. The mirror sector has dark glueballs for EW-charged partners, and also possibly for SM singlet partners.

These glueballs have < km decay lengths.

0911.5616 Juknevich; 0903.0883 Juknevich, Melnikov, Strassler

The higgs can decay to these glueballs via a top partner loop, which can constitute the discovery signature for uncolored naturalness!

1501.05310 Craig, Katz, Strassler, Sundrum

These glueballs have < km decay lengths.

100 TeV collider to probe ~ 3 TeV uncolored Partners!

⇒ exotic Higgs decays allow the 100 TeV collider to probe ~ 3 TeV uncolored Partners!

(⇒ 1.5 TeV @ HL-LHC)

Chacko, DC, Verhaaren [in preparation]
Singlet Naturalness

Fermionic top partners *without* any SM charge *always* lead to tree-level Higgs coupling shifts. ⇒ Detectable at lepton colliders for partner masses ≲ 1-2 TeV!

What about SM singlet scalar top partners? No theory yet, but can probably write one down....

In that case, would have to rely on *Higgs Portal Observables* at future colliders:
- $h^* \rightarrow SS$ production (100 TeV)
- $\sigma(Zh)$ shift by partner loops (ILC/TLEP)
- *triple higgs coupling shift* by partner loops (100 TeV)

Sensitive to singlet scalar top partners at ~ 300 GeV

If there is a mirror QCD, $h \rightarrow invisible$ decays at lepton colliders *might* be sensitive to ~ 400 GeV

However, the *100 TeV collider* can probably access the UV completion of these models directly.

[in preparation] DC, Saraswat, Sundrum
[in preparation] Cohen, Craig, DC
Big Picture Motivations

*Electroweak Phase Transition*
In the early universe at $T \gg 100 \text{ GeV}$, interactions with the plasma stabilize the Higgs boson at the origin.

Understanding this important part of cosmological history requires understanding the Higgs potential away from our current vacuum.

With some BSM ingredients, the EWPT can be made strongly first order.

This results in bubbles of true vacuum expanding in the universe. The resulting departure from thermodynamic equilibrium can cause Electroweak Baryogenesis if there is a new source of CPV in the plasma.

The Electroweak Phase Transition is very difficult to probe at colliders.
Achieving a strong EWPT

Need to modify the Higgs potential to get barrier:

\[ V_{\text{eff}}(h, T) = V_0(h) + V_0^{CW}(h) + V_T(h, T) \]

**Tree Effects**
Add scalars to modify shape of the Higgs potential at tree-level,

**Loop Effects**
Add particles whose loop interactions reduce the depth of the Higgs potential well,

**Thermal Effects**
Add new **bosons** with large Higgs couplings to the plasma.
Achieving a strong EWPT

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**Loop Effects**
Add particles whose loop interactions reduce the depth of the Higgs potential well,

**Thermal Effects**
Add new bosons with large Higgs couplings to the plasma.

Mass is $< 200$ GeV. Produce directly, modify Higgs couplings.

Cohen, Morrissey, Pierce 1203.2924, DC, Jaiswal, Meade 1203.2932
Carena, Nardini, Quiros, Wagner 1207.6330
Katz, Perelstein 1401.1827
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**Loop Effects**
Add particles whose loop interactions reduce the depth of the Higgs potential well.

**Thermal Effects**
Add new bosons with large Higgs couplings to the plasma.

Do not require very light particles. Can realize this e.g. in SM+S model.

Many parameters, and many potential Higgs sector experimental observables.

**Can a strong EWPT be generally excluded?**

Need to study a model with *minimal signatures* that we can explore completely.

Cohen, Morrissey, Pierce 1203.2924, DC, Jaiswal, Meade 1203.2932
Carena, Nardini, Quiros, Wagner 1207.6330
Katz, Perelstein 1401.1827
Minimal stealthy model for a strong EWPT

\[ V_0 = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2} \mu_S^2 S^2 + \lambda_{HS} |H|^2 S^2 + \frac{1}{4} \lambda_S S^4 \]

Unmixed SM+S. No exotic higgs decays, no higgs-singlet mixing, no EWPO, ....

Two regions with strong EWPT

Only Higgs Portal signatures:
\[ h^* \rightarrow SS \] direct production
Higgs cubic coupling
\[ \sigma(Zh) \] deviation (\( > 0.6\% @ \text{TLEP} \))

100 TeV collider could cover \textit{entire} parameter space.
TLEP (super ILC) can cover \textit{some} of parameter space.
Potential complimentarily!

\[ V(v,0) < V(0,w) \] (tree-level)

Nonperturbative \( \lambda_S \) required
\[ \mu_S^2 > 0 \]

One-Loop Analysis of EWPT breaks down

Two-step EWPT
One-step EWPT

Nonperturbative \( \lambda_S \) required to avoid negative runaways (tree-level)

1409.0005 DC, Patrick Meade, Tien-Tien Yu
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- $\sigma(Zh)$ deviation (> 0.6% @ TLEP)

100 TeV collider could cover entire parameter space.

TLEP (super ILC) can cover some of parameter space.

Potential complimentarily!

I409.0005 DC, Patrick Meade, Tien-Tien Yu
Conclusions
Conclusions

- The Higgs program provides enormous experimental challenges and opportunities.

- The resulting information would allow us to constrain or construct the low-energy Higgs sector, \textit{which could easily be very non-SM-like}!

- This is vital to understand whether nature is \textit{natural}, the \textit{electroweak phase transition / baryogenesis}, and general \textbf{BSM} via the agnostic Higgs portal.

- Both lepton and \textit{100 TeV pp colliders} are vital for this effort!

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