Exotic decays of SM & BSM Higgs bosons

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UC Santa Cruz

Higgs couplings 2019
Oxford University
October 3, 2019
Exotic Higgs signatures & open problems in particle physics
Exotic Higgs signatures & open problems in particle physics

1. Origin of flavor hierarchies
   Higgs flavor violating decays (and productions)

2. Origin of DM
   Possible existence of a dark sector
   Higgs decays to dark particles

3. Higgs hierarchy problem
   SUSY; neutral naturalness; ...
   Heavy Higgs decays to new particles

Origin of neutrino masses;
Origin of baryon anti-baryon asymmetry;
...

A broad topic. Apology for the omissions…
In the SM, the Higgs couplings to fermions are highly hierarchical. Experimentally, we do not yet know if the Higgs gives mass to all quarks and leptons! The couplings to light generation quarks/leptons are still very much un-known (hee (BR \sim 5 \times 10^{-9}), hmumu (BR \sim 2 \times 10^{-4}), hcc (BR \sim 3\%), hss (BR \sim 2 \times 10^{-4}), \ldots)
Higgs and flavor

In the SM, the Higgs couplings to fermions are highly hierarchical.

Experimentally, we do not yet know if the Higgs gives mass to all quarks and leptons!

The couplings to **light generation quarks/leptons** are still very much un-known
(hee (BR ~ 5*10^{-9}), hmumu (BR ~ 2*10^{-4}), hcc (BR ~ 3%), hss (BR ~ 2*10^{-4}), …)

**Flavor puzzle:**
what is the origin of the large hierarchies between quark and lepton masses, as well as mixing angles?

- Is the 3rd generation special?
- Is there an approximate U(2) symmetry in Nature?
- Breaking of flavor universality?

\[ \frac{Y_{hcc}}{Y_{htt}} \not= \frac{m_c}{m_t} \]
New flavorful structures

Models with an extended Higgs sector that
- break flavor universality
- naturally generate (some) mass hierarchies
  can be consistent with low energy flavor measurements
New flavorful structures

Models with an extended Higgs sector that
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can be consistent with low energy flavor measurements

Example

\[ \mathcal{L} = \bar{t} Y f H + \bar{t} Y' f H' \]

125 Higgs (h) Additional Higgses (H, A, H⁺)

\[ \mathcal{M} = v Y + v' Y' \]

\[ (\mathcal{M}_0 + \Delta \mathcal{M}) \]

(alogous structure in the quark sector)

- Hierarchies obtained through \( v \gg v' \)
- Flavor constraints under control thanks to an approximate U(2) symmetry
- New Higgs exotic decays (flavor violating decays)

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927;
see also Ghosh, Gupta, Perez, 1508.01501

see also talk by G.G.Ross
New flavorful signatures

Experimental bounds are mild

No bound beyond LEP for $\tan \beta \leq 12$

Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398
New flavorful signatures

Experimental bounds are mild

![Graph showing experimental bounds for tanβ ≤ 12!](image)

No bound beyond LEP for tanβ ≤ 12!

Plenty of new signatures for the additional Higgs bosons...

Quark-quark fusion:

- $pp \rightarrow H \rightarrow cc$
- $pp \rightarrow H \rightarrow tc$

Top-Higgs production:

- $pp \rightarrow t(c)H, \ H \rightarrow tc$
- $pp \rightarrow t(c)H, \ H \rightarrow cc$
- $pp \rightarrow t(c)H, \ H \rightarrow \tau \mu$

Charged Higgs:

- $pp \rightarrow H^{\pm} \rightarrow Wh$
- $pp \rightarrow H^{\pm} \rightarrow cs, \ cb$
- $pp \rightarrow tH^{\pm}, \ H^{\pm} \rightarrow cs, \ cb$

...and of the SM-like Higgs

- $pp \rightarrow h \rightarrow \tau \mu$

Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

S.Gori
(Thermal) dark matter

The DM mass scale

MeV  GeV  TeV

Dark sectors

Thermal DM  WIMPs

axions, sterile neutrinos

Machos
(Thermal) dark matter

The DM mass scale

- MeV
- GeV
- TeV

Dark sectors

Thermal DM

WIMPs

Annihilate through weak interactions

Annihilate through new interactions

Lee-Weinberg bound (~ few GeV)

Neutral under the SM interactions.

Need for new particles in addition to DM: dark sector

Machos

axions, sterile neutrinos

S.Gori
(Thermal) dark matter

The DM mass scale

MeV                      GeV                        TeV

- Thermal DM
- Axions, sterile neutrinos
- WIMPs
- Machos

Neutral under the SM interactions. Annihilate through **new interactions**

Need for new particles in addition to DM

- **dark sector**

- Weaker bounds

S.Gori
A typical signature: Higgs exotic decays

We can write down only a limited set of renormalizable operators connecting SM particles to dark particles:

\[ B_{\mu\nu}F'_{\mu\nu}, \ |H|^2|S|^2, \ HLN \]

dark photon, dark Higgs, dark neutrino
A typical signature: Higgs exotic decays

We can write down only a **limited set of renormalizable operators** connecting SM particles to dark particles:

\[ B_{\mu\nu}F'_{\mu\nu}, \ |H|^2|S|^2, \ HLN \]

**Typical signatures:**

- Multi-(resonant) leptons
- Multi-(resonant) leptons + MET
- Multi-quark/lepton resonances, typically involving heavy flavor
- (Multi) lepton + MET

Easy to obtain sizable branching ratios (SM Higgs width is tiny!)

Crucial to cast a wide net of searches!
Higgs invisible signatures

\[ h \to \text{dark particles} \to \text{MET} \]

BR Higgs decay to invisible particles (DM?)
is constrained to be \(< \sim 25\%\)
Higgs invisible signatures

\[ h \rightarrow \text{dark particles} \rightarrow \text{MET} \]

BR Higgs decay to invisible particles (DM?)
is constrained to be \(< 25\%\)

This result fully constrains purely Higgs-mediated DM models!
Characterizing prompt visible channels

For a comprehensive list of 2-body decays leading to prompt signatures + present/future LHC bounds:

Exotic decays of the 125 GeV Higgs boson

David Curtin,^{1,a} Rouven Essig,^{1,b} Stefania Gori,^{2,3,4,c} Prerit Jaiswal,^{5,d} Andrey Katz,^{6,e} Tao Liu,^{7,f} Zhen Liu,^{8,g} David McKeen,^{9,10,h} Jessie Shelton,^{6,i} Matthew Strassler,^{6,j} Ze’ev Surujon,^{1,k} Brock Tweedie,^{8,11,l} and Yi-Ming Zhong^{1,m}
## Characterizing prompt visible channels

$h \rightarrow$ dark particle  dark particle $\rightarrow$ visible

<table>
<thead>
<tr>
<th>Decay Topologies</th>
<th>Decay mode $\mathcal{F}_i$</th>
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<tbody>
<tr>
<td>$h \rightarrow 2$</td>
<td>$h \rightarrow E_T$</td>
</tr>
<tr>
<td>$h \rightarrow 2 \rightarrow 3$</td>
<td>$h \rightarrow \gamma + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \rightarrow (b\bar{b}) + E_T$</td>
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<td>$h \rightarrow 2 \rightarrow (1+3)$</td>
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<tr>
<td>$h \rightarrow 2 \rightarrow 4 \rightarrow 6$</td>
<td>$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-) + E_T$</td>
</tr>
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<td></td>
<td>$h \rightarrow (\ell^+\ell^-) + E_T + X$</td>
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<tr>
<td>$h \rightarrow 2 \rightarrow 6$</td>
<td>$h \rightarrow \ell^+\ell^-\ell^+\ell^- + E_T$</td>
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From Z. Liu
Characterizing prompt visible channels

$h \rightarrow$ dark particle  dark particle $\rightarrow$ visible

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Great reach at the LHC/future hadron colliders (clean signatures)

From Z. Liu
**Characterizing prompt visible channels**

\[ h \to \text{dark particle} \text{ dark particle} \to \text{visible} \]

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Great reach at the LHC/future hadron colliders (clean signatures)

Background limited signatures (hadronic/with MET). Interplay with future e^+e^- colliders

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From Z. Liu

S.Gori
Decays to long-lived particles

Depending on the strength of the interaction between the dark sector and the SM, the dark sector particle can be long-lived.

Nothing so exotic. We have plenty of long-lived particles in the SM.

\[ h \rightarrow XX (+ \text{MET}), \ X = \text{long-lived} \]

Challenging decays to search for.

Low trigger thresholds needed and/or sub-leading Higgs production modes.
Decays to long-lived particles

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Challenging decays to search for. Low trigger thresholds needed and/or sub-leading Higgs production modes.

A few searches have been already performed. For example:

- Vh → XX, X → bb
- h → XX, X → μμ

Many more opportunities!
Many models that can (at least partially) address the hierarchy problem contain several Higgs bosons:

- **SUSY**: MSSM: 2 charged scalars, 1 pseudoscalar, 2 scalars; NMSSM: …
- **Neutral naturalness models**: fraternal twin Higgs: 2 scalars; …
The hierarchy problem & new Higgs bosons

Many models that can (at least partially) address the hierarchy problem contain several Higgs bosons:

- **SUSY**: MSSM: 2 charged scalars, 1 pseudoscalar, 2 scalars; NMSSM: …
- **Neutral naturalness models**: fraternal twin Higgs: 2 scalars; …

+ several additional new particles:
  stops, sleptons, charginos, neutralinos, …; twin tops, twin Z, glue-balls, …

Some of these particles are relatively hidden to experimental searches for direct production. Examples: staus, glue-balls, …

Can these particles be copiously produced from the decay of the new Higgs bosons?
The heavy H portal to SUSY EW particles

Extensive literature. What are the most promising channels? A couple of examples...

SG, Liu, Shakya, 1811.11918

More room to study exotic SUSY signatures of H, especially in extended SUSY models

+ “Higgs to higgs decays”. e.g. $H \to hA$, …
Twin Higgs exotic decays

\[ V = \lambda (|H_A|^2 + |H_B|^2) - m^2 (|H_A|^2 + |H_B|^2) + \kappa (|H_A|^4 + |H_B|^4) + \bar{\mu}^2 |H_A|^2 + \rho |H_A|^4 \]

\[ |\langle H_A \rangle|^2 + |\langle H_B \rangle|^2 = f^2 \]

A typical spectrum:

- \( H_{\text{twin}} \)
- Twin tops
- Twin W, Z
- SM Higgs
- Twin bottoms
- Twin taus
- Twin neutrinos
- Glueballs
Twin Higgs exotic decays

\[ V = \lambda (|H_A|^2 + |H_B|^2)^2 - m^2 (|H_A|^2 + |H_B|^2) + \kappa (|H_A|^4 + |H_B|^4) + \tilde{\mu}^2 |H_A|^2 + \rho |H_A|^4 \]

\[ |\langle H_A \rangle|^2 + |\langle H_B \rangle|^2 = f^2 \]

Twin particles undertake cascade decays to (typically) long lived glue-balls

A typical spectrum:
- \( H_{\text{twin}} \)
- Twin tops
- Twin W, Z
- SM Higgs
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- Twin taus
- Twin neutrinos
- Glue-balls

N.Craig

S.Gori
Prompt vs. long-lived decays

Prospects for the HL-LHC

Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315
Prompt vs. long-lived decays

Prospects for the HL-LHC

125 GeV Higgs coupling measurements

Twin Higgs mass [GeV]

Twin Higgs → ZZ, hh (prompt)

Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315
Prospects for the HL-LHC

Twin Higgs

Glue-ball.
O++ mixes with the 125 GeV Higgs and decays typically displaced.

Theory: more work to be done to compute rates!

Prospects for the HL-LHC

Twin Higgs \rightarrow \text{glue-balls: (long lived)}
CMS inner tracker analysis;
ATLAS muon spectrometer analysis

125 GeV Higgs coupling measurements

Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315
Conclusions & outlook

The most important open problems in particle physics motivate models that naturally predict exotic decays of the 125 GeV Higgs / additional Higgs bosons.

- Higgs flavor violating decays.
- 125 GeV Higgs decay to light dark particle.
- Heavy Higgs bosons decaying to SUSY/twin particles.

Many experimental opportunities to discover exotic signatures.
### Flavor non universality

Comparing to the other flavor structures...

<table>
<thead>
<tr>
<th>Flavorful 2HDM</th>
<th>W,Z, H _V</th>
<th>up quarks</th>
<th>down quarks</th>
<th>leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>2HDM type 1</td>
<td>C_{\beta-\alpha}</td>
<td>1 \frac{s_\alpha}{t_\beta c_\beta}</td>
<td>1 \frac{s_\alpha}{t_\beta c_\beta}</td>
<td>1 \frac{s_\alpha}{t_\beta c_\beta}</td>
</tr>
<tr>
<td>2HDM type 2</td>
<td>C_{\beta-\alpha}</td>
<td>1 \frac{s_\alpha}{t_\beta c_\beta}</td>
<td>t_\beta \frac{c_\alpha}{s_\beta}</td>
<td>t_\beta \frac{c_\alpha}{s_\beta}</td>
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In the flavorful 2HDM there are additional corrections to the \( \kappa \)'s of the order of \( O(m_c / m_t), O(m_s / m_b), O(m_\mu / m_\tau) \)
Production & decays of the scalar H

bH typically suppressed, if compared to Type II 2HDMs

The branching ratio to the "golden" channel, $\tau \tau$, is suppressed
Production & decays of the scalar $H^\pm$

s-channel production (quark-quark fusion) is the dominant one

The branching ratio to the "golden" channels, $tb$, $\tau v$, are suppressed

Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398
Higgs width and exotic decays

The SM Higgs width is tiny: \(~4\,\text{MeV}\) (and challenging to measure directly at hadron colliders)

If a BSM theory contains light dark particles, \textit{sizable branching ratios for the Higgs decaying into dark particles} is a generic prediction

Example:

\[
\frac{\xi}{2} |S|^2 |H|^2
\]

Value of \(\xi\) needed for the corresponding BR
Glue-balls in twin Higgs

$$g_s^B(\Lambda) = g_s^A(\Lambda) + \delta g$$

$$y_b \left( H_A b_A^l b_A^r + \delta y_b H_B b_B^l b_B^r \right)$$

Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315
Displaced vs. prompt searches

Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315