Exotic Decays of the Higgs Boson

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with D. Curtin, R. Essig, Z. Surujon, to appear

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Outline

1. Motivation

2. Examples of promising exotic Higgs decays
   I. Higgs decays to scalars
   II. Higgs decays to vectors

3. Summary
We found the Higgs and nothing else

1 TeV

100 GeV

Higgs Precision
Characterize the new state at 125 GeV

Exotic Higgs Decays
h could have large exotic Br!

BSM Searches
BSM → h decays
Treat h like top, W, Z!

Higgs Sibling Searches
Look for H, A, H^+, H^±, ...

125 GeV Higgs

by D. Curtin
A door to new physics

SM Higgs decay width is extremely narrow

\[ \Gamma_{SM} \approx 4.15 \text{ MeV at } m_h = 125 \text{ GeV} \]

tiny couplings to NP \( \sim 0.01 \) can give \( BR(h \to \text{new}) \sim 10\% \)

new physics (NP) easily couple to SM via Higgs

\[ \Rightarrow \text{a rich set of exotic Higgs decays} \]

vast theory literature on (simplified) models exist
Could have many exotic decays in existing and future LHC data

The fit of the SM Higgs couplings can constrain $\text{BR}(h \rightarrow \text{invisible})$ to only $\sim 10\%$ with 3000/fb data at LHC.

plenty of room for exotic decays

imagine $\text{BR}(h \rightarrow \text{new}) = 10\%$, then could have as many exotic higgs decays as:

- LHC Run 1 (25/fb): $\mathcal{O}(50,000)$
- LHC Run 2 (300/fb): $\mathcal{O}(1,000,000)$
- HL-LHC (3000/fb): $\mathcal{O}(10,000,000)$

Dawson et al, 1310.8361
Exotic Higgs decays require dedicated analysis

signal at LHC can be hard to detect

decay products are often very soft, e.g. \( h \rightarrow aa \rightarrow 4j, \ p_T(j) < 30 \ \text{GeV} \)

could easily be missed by other searches

......

some exotic decays have been explicitly looked but there are many many possibilities and discovery potential exists already

systematic efforts are needed
Exotic Decays of the 125 GeV Higgs Boson

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review literature    define simplified model
evaluate potential for discovery   provide benchmarks
inform trigger selection set new constraints by recasting existing searches

Exotic Higgs Decays

Working Group

exotichiggs.physics.sunysb.edu
What decays do we consider?

**Eighteen Decay Channels**

- $h \to \text{MET}$
- $h \to 4j$
- $h \to 4\ell+$MET
- $h \to 2\tau+$MET
- $h \to 4b$
- $h \to 2\gamma 2j$
- $h \to 2\ell+$MET
- $h \to \text{one lepton-jet}$
- $h \to 2b 2\tau$
- $h \to 4\gamma$
- $h \to \gamma+$MET
- $h \to \text{two lepton-jets}$
- $h \to 2b 2\mu$
- $h \to \text{ZZ}_D, Za \to 4\ell$
- $h \to 2\gamma+$MET
- $h \to 2b+\text{MET}$
- $h \to 4\tau, 2\tau 2\mu$
- $h \to \text{Z}_D \text{Z}_D \to 4\ell$
- $h \to 2b+\text{MET}$

**Seven Decay Topologies**

- $h \to 2$
- $h \to 3$
- $h \to 2 \to 3 \to 4$
- $h \to 2 \to (1+3)$
- $h \to 2 \to 4$
- $h \to 2 \to 4 \to 6$
- $h \to 2 \to 6$
Example I:
Higgs Decays to Scalars
Two-Higgs-Doublet-Model (2HDM)

MSSM-like  lepton-specific  flipped

<table>
<thead>
<tr>
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<th>TYPE I</th>
<th>TYPE II</th>
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viable in the “decoupling limit”, where one Higgs is SM-like

see e.g. recent reviews by Craig et al, Branco et al
add one more singlet with small mixing allows

\[ h \rightarrow aa \quad \text{or} \quad h \rightarrow ss \]

where pseudo-scalar \((a)\) and scalar \((s)\) inherit a mixture of 2HDM couplings of \(H_1\) and \(H_2\) to fermions

easily get \(\text{BR} < 10\text{\~}20\%\)

get a rich set of exotic decays
(can be NMSSM Higgs sector; also can be many alternatives)
$a \rightarrow \text{SM}$

$\tan \beta = 5$, TYPE II

$\tan \beta = 5$, TYPE III

$m_a \text{[GeV]}$

$2b \ (>10 \text{ GeV})$

$2\tau \ (>3.4 \text{ GeV})$!
Example: $h \rightarrow aa \rightarrow 2b2\mu$

**Trade-off**

+ easy to trigger in ggF and VBF productions

− small branching fraction

if $\text{BR}(h\rightarrow aa)=10\%$, $\text{BR}(h\rightarrow aa\rightarrow 2b2\mu)=0.00004$ for $\tan \beta=10$, TYPE II; far smaller than $\text{BR}(h\rightarrow aa\rightarrow 4b)$
Example: \( h \rightarrow aa \rightarrow 2b2\mu \)

Max. BR(\( h \rightarrow aa \rightarrow 2b2\mu \)) \( \sim 10^{-2}-10^{-3} \)

for two \( b \)-tags or at least one \( b \)-tag

Curtin, Essig, Surujon, YZ, to appear
Example: $h \rightarrow aa \rightarrow 2b2\mu$

at LHC 14, upper limits on BR can be further improved by a factor of 3~6
Example II: Higgs Decays to Vector Bosons
Kinetic mixing

Standard Model
SU(3)×SU(2)×U(1)

Dark Sector
U(1)_D (massive)

\[\delta L \supset \frac{1}{2} \frac{\epsilon}{\cos \theta_W} \hat{B}_{\mu\nu} \hat{Z}^{\mu\nu}_D\]

Holdom; Galison, Manohar

⇒ introduce \(Z_D\)
In the limit $m_{Z_D} \ll m_Z$, $g_{Z_D}^{\text{ff}}$ is photon-like

$Z_D \rightarrow \text{SM}$

$Z_D$ decays to leptons are sizable
A rich set of exotic Higgs decays

Gopalakrishna et al, 0801.3456
Davoudiasl et al, 1208.2973, 1203.2947, 1304.4935
Example: $h \rightarrow Z \ Z_D$

no public dedicated analysis yet

strong limits coming from the SM $h \rightarrow ZZ^*$ search

can recast those searches to get bound on

$\text{BR}(h \rightarrow ZZ_D) \times \text{BR}(Z_D \rightarrow \ell\ell)$

see also

ATLAS-CONF-2013-013
Example: $h \rightarrow ZZ_D$

at LHC 7+8, max. $\text{Br}(h \rightarrow ZZ_D) \sim 10^{-3}$ are probed even in the non-dedicated search
\( \epsilon \) limits for visible \( Z_D \) decays

non-dedicated search from CMS (ATLAS similar)

dedicated searches at LHC14 (300/fb) may give upper limits on \( \text{BR} \sim 10^{-6} \sim 10^{-4} \)

Davoudiasl et al, 1304.4935

LHC is the only probe for \( \epsilon \) at \( m_{Z_D} > 10 \text{ GeV} \)
Summary

1. Exotic decays of Higgs are well-motivated and deserve explicit searches.

2. Discovery potential exists already in LHC Run 1 for decay channels, $h \rightarrow 2b2\mu$, $h \rightarrow 4\ell$, etc.

3. Even further potential exists in LHC Run 2.