Non-SM Decays of the 125 GeV Boson

Survey for the HXSWG

Exotic Decays of the 125 GeV Higgs Boson

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Contains extensive list of references
Outline

- Agenda: Which non-SM decays covered/not covered today?
  - Decays not discussed in our recent review paper

- Motivation: Why might we expect non-SM multi-body $h$ decays?

- Decays with no intrinsic MET (except neutrinos)
  - Promising channels
  - Benchmarks/Simplified Models

- Decays with new sources of MET
  - Complexities
  - Promising channels
    - Low MET vs High MET
  - Benchmarks/Simplified Models
Not Covered In Our Review

\( h \rightarrow Z \gamma ; h \rightarrow \tau \mu \)

- These are actively under study by the experiments
- Benchmarks not needed: parameterize as a Branching Fraction [Br]

Also I will say nothing about \( h \rightarrow \text{invisible} \) today; well-studied.

\( h \rightarrow \text{many visible particles (with or without MET)} \)

- \( h \rightarrow 6 \tau ; h \rightarrow 8 \text{~b} ; h \rightarrow \geq 6 \mu/e \) etc. e.g. in NMSSM
- \( h \rightarrow 2 \text{ triplets of fermions} \) e.g. via RPV SUSY
- \( h \rightarrow \text{many leptons (unclustered)} \)
- \( h \rightarrow \text{complex lepton jets} \)
  - [complex \( \rightarrow \) more than two tracks, possibly including hadrons]
- Needs special discussion all its own – very complicated

\( h \rightarrow \text{long-lived particles decaying in flight} \)

- Needs special discussion all its own – very complicated
h decays
- to at most four visible SM partons
- and involving at least one non-SM particle in intermediate step

Cases With No MET

Cases With MET

\[ \gamma + Z_D \]?
\[ \gamma + a \]?
Motivation

- h decays may serve as window to unknown particles.
  - e.g. discovery of neutrino in beta decay, other neutrinos in muon, tau decay
  - e.g. non-discovery of 4th neutrino, majorons, others in Z decay

- Dark Matter exists;
  - if it is particles, these particles may not carry SU(2) quantum numbers
  - Therefore these particles may have evaded LEP & have mass < 100 GeV
  - So possible that \( h \rightarrow DM \rightarrow \text{invisible decay} \)
    - Difficult to observe for \( Br < 10\% \)
  - If DM part of low mass dark sector ("hidden valley"), then maybe
    - \( h \rightarrow \text{dark sector particles} \rightarrow \text{visible particles, with or without MET} \)
      - Much easier to observe! Can sometimes reach \( Br <<< 10\% \)

- H “Portal” – easy access to dark/hidden sectors/valleys
  - H operator has dimension 1, \( |H|^2 \) is gauge invariant, dimension 2
  - Coupling to “dark” sector involves low dimension operator
Motivation (2)

- 125 GeV $h$ has very narrow width
  - $\Rightarrow$ small interactions with new sector can generate new decays
  - These decays could have had Br $\sim 100\%$; could still have Br $\sim 10\%$.

- Number of $h$ produced is large, so potential to reach Br $\sim 10^{-4}$ or better
  - $10^6$ already produced
  - Approaching $10^8$ in foreseeable future
    - But --- trigger and analysis challenges!
    - 2011-2012 data may still be useful!

- In some theories,
  - $h$ decays are first BSM physics discoverable at LHC
  - Or even the only BSM physics discoverable at LHC14!

- Same searches might turn up new members of scalar sector (e.g. heavy $H$) whose decays are dominated by non-SM final states
What We Don’t Know

What We Know

Invisible?

What We Don’t Know
What We Don’t Know

What We Know

Visible?!

The Challenge

Energy

Interaction

Strength

What We Don’t Know
New particles with $m < m_h$ must be neutral to avoid LEP discovery

- With a small loophole

We consider

- Spin 0 “a” [scalar or pseudo-scalar]
- Spin 1 “$Z_D$” [vector or pseudo-vector]

- Spin $\frac{1}{2} \rightarrow h$ decay to 6 visible fermions or MET
  - e.g. $h \rightarrow$ neutralinos $\rightarrow$ 6 fermions via RPV

Will move from simplest to most complex.

1. $h \rightarrow Z Z_D \rightarrow 4$ SM fermions
2. $h \rightarrow Z_D Z_D \rightarrow 4$ SM fermions
3. $h \rightarrow a a \rightarrow 4$ SM bosons
4. $h \rightarrow a a \rightarrow 4$ SM fermions

Mixed final states possible, e.g. $b b \gamma \gamma$, but not currently sensitive

1 or 2 New Particles
Four e/µ Final State

\[ h \rightarrow Z Z_D \]
- \( Z_D \) produced & decays via kinetic mixing with \( \gamma/Z \)
- 2 parameters: \( Z_D \) mass, \( \epsilon << 1 \)

\( Z_D \) has extremely narrow width

Published ATLAS/CMS ZZ* data allow us to extract limits

**Direct limit**
- \( \text{Br}(h \rightarrow Z X \rightarrow 4\ell) \sim 3 \times 10^{-5} \)

**Including Z decay width to leptons**
- \( \text{Br}(h \rightarrow Z X) \text{Br}(X \rightarrow \ell\ell) \sim 5 \times 10^{-4} \)

Assuming a \( Z_D \) with kinetic mixing
- \( \text{Br}(Z_D \rightarrow \ell\ell) \sim 0.3 \)
- \( \text{Br}(h \rightarrow Z Z_D) \sim 2 \times 10^{-3} \)

\( X \) could also be \( a \) with
\[ \text{Br}(a \rightarrow \mu\mu) \sim (m_\mu/m_\tau)^2 \sim 0.0035 \]

But often need \( m_a < 10 \text{ GeV} \)

Note: no information below 12 GeV
Br’s for $Z_D$ with only kinetic mixing

$\text{Br}(Z_D \rightarrow ee) + \text{Br}(Z_D \rightarrow \mu\mu) > 20\%$ (except at $\rho,\omega$); typically $30\%$
Limit $\varepsilon$ for each $Z_D$ mass

Our recast of CMS; Similar for ATLAS
Four e/μ Final State

\[ h \rightarrow Z_D Z_D \]
- \( Z_D \) produced via mixing of \( h \) with \( h_D \)
- \( Z_D \) decays via mixing with \( \gamma/Z \)

Why doesn’t \( h \rightarrow Z Z^* \) take care of this?
- Incorrectly pair leptons in almost all \( eee\), \( \mu\mu\mu\) events
- Eliminate most \( ee\mu\mu \) events for \( m_\ell < 40 \text{ GeV} \)
- Still we can extract limits (CMS \( h \rightarrow ZZ^* \), ATLAS \( Z^*Z^* \))

Direct limit
- \( \text{Br}(h \rightarrow XX \rightarrow 4\ell) \sim 5 \times 10^{-5} \)
Assuming a \( Z_D \) with kinetic mixing
- \( \text{Br}(h \rightarrow Z_D Z_D) \sim 5 \times 10^{-4} \)

We think ATLAS/CMS could do factor of 2 - 8 better now, especially at low mass
Four $e/\mu$ Final State

$h \to Z_D Z_D$
- $Z_D$ produced via mixing of $h$ with $h_D$
- $Z_D$ decays via mixing with $\gamma/Z$

Unless $Z_D$ is long-lived, $\varepsilon$ does not enter phenomenology

Therefore two parameters:
1. $Z_D$ mass
2. Replace $\theta$ with $\text{Br}(h \to Z_D Z_D)$

3$^{rd}$ parameter: assumed $Z_D$ mixing pure kinetic
- This determines $Z_D$ branching fractions

*However, we think this parameter can be ignored.*
Model: Limit $\text{Br}(h \rightarrow Z_D Z_D) \text{ vs. mass of } Z_D$

$h \rightarrow Z_D Z_D$
- $4\ell ; 2\ell \ 2j ; 4j$
- (rare) final states with neutrinos

Sensitivity from 4 leptons far greater than for any other final states
- Quantified (subject to further study) in our paper

Therefore it is enough to state result from 4 leptons in one model.
- Easy to convert to any other model
  - Just multiply by $[\text{Br}(Z_D \rightarrow \ell\ell)_{\text{new}} / \text{Br}(Z_D \rightarrow \ell\ell)_{\text{old}}]^2$

Recommend:
- **Assume** pure kinetic mixing $\Rightarrow$ Br($Z_D \rightarrow \ell\ell$) determined
- 2 Parameters: Br($h \rightarrow Z_D Z_D$), mass of $Z_D$
Four Photons

\[ h \rightarrow a\ a \]
- \( a \) produced via coupling in scalar effective potential
- \( a \) decays to gluons and/or photons via loop
  - No coupling to fermions

3 parameters \((unlike \ Z_D \rightarrow ff)\)
- \( m_a \)
- \( \text{Br}(h \rightarrow a\ a) \)
- \( \text{Br}(a \rightarrow \gamma\ \gamma) \) – depends on charge/mass of loop particles
  - Colorless particles in loop: \( \text{Br}(a \rightarrow \gamma\ \gamma) = 1 \)
  - Colored particles in loop: \( \text{Br}(a \rightarrow \gamma\ \gamma) < 0.005 \) usually
  - General spectrum: Anything between

Recommend:
- Put limits on \( \text{Br}(h \rightarrow a\ a) \) \([\text{Br}(a \rightarrow \gamma\ \gamma)]^2 \) \((expect\ in\ 10^{-4-5}\ range\ now)\)
- For now, ignore \( \text{Br}(a \rightarrow \gamma\ \gamma) \) ; keep it unspecified. Why?
  - If we take \( \text{Br}(a \rightarrow \gamma\ \gamma) = 1 \), nothing new;
  - But if we take \( \text{Br}(a \rightarrow \gamma\ \gamma) < 0.01 \), no interesting limit until late LHC14 !
  - And it doesn’t matter: 4j, 2j2\( \gamma \) searches maybe relevant only at \( \sim 300(\?) \) fb\(^{-1}\)
An $a$ that couples to fermions

$h \rightarrow a \ a$

- $a$ produced via coupling in scalar effective potential
- $a$ decays mainly to fermions via Yukawa-like couplings

Example: NMSSM -- gets lot of attention, but **where is $S$?**

- $a$ branching fractions similar to comparable-mass $h$
- $a \rightarrow \tau \tau$ small, $\mu \mu$ negligible if $m_a > 2 \ m_b$

Example: More general 2HDM + singlet scalar

- Leptonic, up-type, down-type Br’s may grow/shrink relative to NMSSM
- Can have $a \rightarrow \tau \tau$ large, $\mu \mu$ measurable **even if** $m_a > 2 \ m_b$
Different Branching Fractions for $a$

Should not restrict searches to NMSSM-motivated scenario!

Recommend use of at least two benchmark models:
1. NMSSM-like model
2. Leptonic-dominated quark-suppressed 2DHM+S model
## Current Estimates of Sensitivity

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Projected/Current 2σ Limit on $\text{Br}(F_i)$</th>
<th>Production Mode</th>
<th>quarks allowed</th>
<th>Leptonic 2HDM+S; NMSSM at low $m_a$</th>
<th>quarks suppressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>0.7 [0.2]</td>
<td>Wh</td>
<td>0.8 [0.2]</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>$b\bar{b}\tau\tau$</td>
<td>&gt; 1 [0.15]</td>
<td>VBF</td>
<td>0.1 [1]</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>$b\bar{b}\mu\mu$</td>
<td>$(2 - 7) \cdot 10^{-4}$ [$(0.6 - 2) \cdot 10^{-4}$]</td>
<td>gg</td>
<td>$3 \times 10^{-4}$ [0.2 - 0.8]</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>$\tau\tau\tau\tau$</td>
<td>0.2 - 0.4 [?]</td>
<td>gg</td>
<td>0.005 [?]</td>
<td>0.2 - 0.4 [?]</td>
<td>–</td>
</tr>
<tr>
<td>$\tau\tau\mu\mu$</td>
<td>$(3 - 7) \cdot 10^{-5}$ [?]</td>
<td>gg</td>
<td>$3 \times 10^{-5}$ [?]</td>
<td>0.04 - 0.1 [?]</td>
<td>–</td>
</tr>
<tr>
<td>$\mu\mu\mu\mu$</td>
<td>$1 \cdot 10^{-4}$ [?]</td>
<td>gg</td>
<td>$1 \cdot 10^{-7}$ [?]</td>
<td>$1 \cdot 10^{-5}$ [?]</td>
<td>$m_a &gt; 2m_\tau$</td>
</tr>
</tbody>
</table>

### Notes:
- 14 TeV boosted Wh
- 14 TeV VBF
- 14 TeV gg $\rightarrow$ h
- 8 TeV gg $\rightarrow$ h (from multilepton recast)
- 8 TeV gg $\rightarrow$ h (our analysis proposal)
- Important for $m_a < 2m_\tau$
Summary: Decays Without MET

1. $h \rightarrow Z Z_D \rightarrow 4$ SM fermions
   - Mixing $\epsilon$ vs. $Z_D$ mass

2. $h \rightarrow Z_D Z_D \rightarrow 4$ SM fermions
   - $\text{Br}(h \rightarrow Z_D Z_D)$ vs. $Z_D$ mass

3. $h \rightarrow a a \rightarrow 4$ SM bosons
   - $\text{Br}(h \rightarrow a a)$ vs. $a$ mass
   How best to incorporate $\text{Br}(a \rightarrow \gamma\gamma)$?

4. $h \rightarrow a a \rightarrow 4$ SM fermions
   - NMSSM-like model
   - Model with leptons enhanced, quarks suppressed
   Caution: arbitrary model choices; unwarranted $bb\tau\tau$ pessimism

Lepton/photon collimation, jet merging at low $a$, $Z_D$ mass

Spin $\frac{1}{2} \Rightarrow h$ decay to 6 visible fermions
   - e.g. $h \rightarrow$ neutralinos $\rightarrow 6$ fermions via RPV

Asymmetric Decays (e.g. $h \rightarrow a a'$)

Higher multiplicity: e.g. $8b$, complex lepton jets, etc.

1 or 2 New Particles

Four SM Particles

Mixed final states possible, e.g. $bb\gamma\gamma$

$bbbb$, $bb\mu\mu$, $bb\tau\tau$, $\tau\mu\mu$, $\mu\mu\mu$

4 $e/\mu$

4 photons

$4 \text{ e/}\mu$

$4 \text{ photons}$
Decays with MET

- With MET, the number of processes and parameters grows rapidly
- Any final state can arise from many decay chains
  - Need multiple simplified models

- Low MET vs High MET
  - Very different strategies needed
  - Big differences in sensitivity as masses are varied

- Studies needed!
  - Experimental issues are subtle, so especially need experimental studies!

- Here: focus only on most promising final states
  - 1 or more photons + MET
  - 1 or more lepton pairs + MET
  - No evidence yet that other final states are feasible at high MET
  - Maybe resonant bb + MET at 300 fb$^{-1}$?
Challenges (1)

- Often multiple possible decay chains with different kinematics
  - 
  - Need several simplified models to cover kinematics
  - Typically have 3 or more parameters (multiple masses, Br’s)

- Incomplete List
  - e.g. gauge mediated SUSY

- Hard \( (p_T \sim 40) \) vs. Soft \( (p_T \sim 15) \)
- Resonant vs. non-resonant
- Edge vs. endpoint
- Collimated vs. uncorrelated
Challenges (2)

- High MET: MET is useful in bkgd reduction, but $\gamma/\ell$ soft, inefficient
  - MET-based search, plus soft visible objects to reduce backgrounds
    - Possible kinematic features in the visible objects
- Low MET: harder $\gamma/\ell$, but MET useless; just changes kinematics
  - Visible parton-based search, but with relaxed kinematic constraints

**Example: 4 leptons + MET**

- **High MET:** use VBF + MET search
  - + require 3 soft $\ell$ or + 2 SS $\ell$?
- **Low MET:** use 4-lepton search
  - Require all 4 $\ell$ detectable
  - Do not demand $m_{4\ell} = 125$ GeV
  - Look for resonances or edges in $\ell^+\ell^-$ pairs
    (alternate: use trilepton search, look for $Z_D$ resonance?)

"e.g. SUSY + hidden valley / dark sector"
MET Story Very Incomplete

Not enough studies (by us or by others) to justify strong recommendations

- e.g. no study of $\gamma \gamma + \text{MET}$ where $\gamma \gamma$ is resonant
- Best search techniques are often unclear

Only have preliminary & probably pessimistic estimates of what’s possible.

Even pessimistically, kinematic regimes of nice models exist where MET +

- $2\ell$
- $4\ell$
- $2\gamma$ (and presumably $4\gamma$)

already can be realistically tested with current data

Not clear for MET + $\gamma$
Nothing known for MET + 4b, etc.
Suggested Models For MET Cases

- Search for $h \rightarrow \ell^+ \ell^- + \not{E_T}$, including regimes where the leptons are collimated, and including the cases where there is a resonance in $m_{\ell\ell}$. Benchmark models include $h \rightarrow XY \rightarrow Z_DYY$ or $aYY$, $h \rightarrow XX \rightarrow aa^{(i)}YY$, for $m_a < 2m_\tau$, $h \rightarrow XX \rightarrow Z^*Z^*YY$, where $Y$ is invisible and $Z^*$ is an off-shell $Z$ boson.

- Search for $h \rightarrow \ell^+ \ell^- \ell^+ \ell^- + \not{E_T}$, including regimes where the leptons are collimated, and including the cases where there is a resonance in $m_{\ell\ell}$. Benchmark models include $h \rightarrow XX \rightarrow Z_DZ_DYY$, $h \rightarrow XX \rightarrow aa^{(i)}YY$ for $m_a < 2m_\tau$, $h \rightarrow XX \rightarrow Z^*Z^*YY$, where $Y$ is invisible and $Z^*$ is an off-shell $Z$.

- Search for $h \rightarrow \gamma\gamma + \not{E_T}$, including the cases where there is a resonance in $m_{\gamma\gamma}$. Benchmark models include $h \rightarrow XY \rightarrow aYY$, $h \rightarrow XX \rightarrow aa^{(i)}YY$, $h \rightarrow XX \rightarrow (\gamma Y)(\gamma Y)$, where $Y$ is invisible.

- $h \rightarrow XY \rightarrow \gamma YY$ where $Y$ is invisible, giving $\gamma + \not{E_T}$

**Notes:**
- Occurs in NMSSM
- Also: RPV neutralinos $\rightarrow llY$
- Here $X,Y$ may be scalars or fermions
- $Y$ could be dark matter
Summary

Non-SM decays of h to new particles very well motivated

- We considered low-multiplicity prompt decays of this type
  - Extensive, but by no means a complete survey of non-SM h decays!

- Decays without MET suggest simple benchmark targets
  - $h \rightarrow 2$ spin 1 particles $\rightarrow$ 4 leptons
  - $h \rightarrow 2$ spin 0 particles $\rightarrow$ 4 photons
  - $h \rightarrow 2$ spin 0 particles $\rightarrow$ b/τ/μ final states
    - Need both NMSSM-like model & model with leptons enhanced

- Decays with MET; story less complete
  - Much more complex; poorly studied; many challenges
  - Most promising: photons + MET, leptons + MET; look ahead to b’s + MET
  - Each final state allows various decay chains $\rightarrow$ several simplified models
    - These include NMSSM, RPV SUSY, many dark matter models
# Collimated Objects in $h$ Decays

## Experimental & Theoretical Input on $h$ Decays

- leptons
- photons
- jets

## Production Modes

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Projected/Current 2σ Limit on Br($F_i$)</th>
<th>Production Mode</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>${\mu\mu}{\mu\mu}$</td>
<td>1 \times 10^{-5} (5 \times 10^{-3}) [U]</td>
<td>$G$</td>
<td>CMS [335], $2m_\mu &lt; m_a &lt; 2m_\tau$ (CMS [375] $m_a &lt; 5$ GeV)</td>
</tr>
<tr>
<td>${\mu\mu}X$</td>
<td>1 [U]</td>
<td>$G$</td>
<td>CMS [375], $2m_\mu &lt; m_a &lt; 5$ GeV</td>
</tr>
<tr>
<td>${\mu\mu}E_T$</td>
<td>0.03$^L$ [U]</td>
<td>$W$</td>
<td>Theory study, [52, 53]</td>
</tr>
<tr>
<td>${\mu\mu}{\mu\mu}E_T$</td>
<td>1 \times 10^{-5} (5 \times 10^{-3}) [U]</td>
<td>$G$</td>
<td>CMS [335], $2m_\mu &lt; m_a &lt; 2m_\tau$ (CMS [375] $m_a &lt; 5$ GeV) however, see text for important details</td>
</tr>
<tr>
<td>${\tau\tau}{\mu\mu}$</td>
<td>$(3 - 7) \times 10^{-4}$ $^T$ [U]</td>
<td>$G$</td>
<td>This work, see Sec. 6.2</td>
</tr>
<tr>
<td>${\gamma\gamma}{\gamma\gamma}$</td>
<td>0.01 [U]</td>
<td>$G$</td>
<td>ATLAS [320], $m_a &lt; 400$ MeV</td>
</tr>
<tr>
<td>${\gamma\gamma}E_T$</td>
<td>U[U]</td>
<td>no studies</td>
<td></td>
</tr>
<tr>
<td>${gg}{gg}$</td>
<td>&gt; 1 [0.7$L$]</td>
<td>$W$</td>
<td>boosted $Wh$ [263], $m_a &lt; 30$ GeV</td>
</tr>
<tr>
<td>${bb}{bb}$</td>
<td>0.7$^T$ [0.2$L$]</td>
<td>$W$</td>
<td>boosted $Wh$ [263], $m_a \sim 15$ GeV</td>
</tr>
</tbody>
</table>

### 14 TeV:

- assumes 100 fb$^{-1}$ unless “*”, in which case assumes 300 fb$^{-1}$

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**Matt Strassler**
Benchmark Models: Beyond LO

- Easy for theorists like those on our team to generate BSM benchmark models at LO for experimenters to use.
  - Some of our team are working on this.

- N(N)LO BSM corrections to production are usually unimportant
  - SM corrections are usually sufficient
  - Exception: multi-doublet models where production is not SM even at LO

- But NLO corrections to the decays are beyond us!
  - We do not have branching fractions or differential distributions at NLO

- Need expert help here.
Possible Approach to MET models

- Perhaps a “single-sided” process is most important first target model
  - More MET, fewer objects
    - More like invisible Higgs, less like all-visible
  - Linear in Br, not quadratic
    - Fewer parameters matter

If one can search for \( h \rightarrow \psi'\psi \), where \( \psi \) is invisible, then \( h \rightarrow \psi'\psi' \), \( \psi'\psi'' \) will often be easier

(but not if MET becomes too low!)

(with a on- or off-shell)
FIG. 31: Approximate 95% C.L. upper limit on \((\sigma/\sigma_{SM}) \times \text{Br}(h \to \chi_1 \chi_2 \to \gamma + \not{E}_T)\) from the results of Ref. [355], for \(m_{\chi_1} = (0 \text{ GeV}, 20 \text{ GeV}, 40 \text{ GeV}) < m_{\chi_2}\). Solid lines correspond to 100% photon efficiency, and dashed lines to a (flat) 80% photon efficiency.
2 photons + MET

- Weak limit from GMSB search

Approximate 95% C.L. upper limit on \( (\sigma/\sigma_{SM}) \times Br (h \rightarrow \chi_2\chi_2 \rightarrow 2\gamma + E_T) \)
FIG. 33: Approximate 95% C.L. upper limit on $(\sigma/\sigma_{SM}) \times \text{Br}(h \to 2\gamma + \not{E}_T)$ from the $2\gamma + \not{E}_T$ search in [355]. The solid lines correspond to 100% photon efficiency, and the dashed lines to a (flat) 80% photon efficiency. **Left:** Resonant case, where $h \to aa$, one $a$ decays to $\gamma\gamma$ and the other decays invisibly. **Right:** Cascade case, where $h \to \chi_1\chi_2$, $\chi_2 \to s\chi_1$, $s \to \gamma\gamma$. Here $m_{\chi_1} = 0$ and $m_{\chi_2} = 60$ GeV (although the limit is insensitive to the particular value of $m_{\chi_2}$ as long as it is
FIG. 34: Unit-normalized distributions of $m_T(2\ell, \cancel{E}_T)$. The blue dashed line shows the ATLAS prediction for SM $h \rightarrow WW^*$ events passing all selection criteria in both 7 and 8 TeV data sets [372]. The purple dotted line shows the distribution for the BSM $h \rightarrow 2\ell + \cancel{E}_T$ events arising from $h \rightarrow \chi_2\chi_1$ at the 8 TeV LHC in the benchmark model described in the text.
FIG. 35: Approximate bounds on the branching fraction for \( h \to \chi_2 \chi_2 \), assuming (left) \( \text{Br}(\chi_2 \to a\chi_1) = 1 \), and (right) \( \text{Br}(\chi_2 \to Z_D \chi_1) = 1 \), as a function of \( m_{\chi_1} \), from [335]. Here solid lines indicate \( m_{\chi_2} = 50 \text{ GeV} \) and dotted lines \( m_{\chi_2} = 60 \text{ GeV} \), while red, green, and blue correspond to \( m_{a,Z_D} = 3 \text{ GeV}, 1 \text{ GeV}, \) and \( 0.4 \text{ GeV} \) respectively. We use tree-level results for \( \text{Br}(Z_D \to \mu\mu) \) (see Fig. 13) and a reference \( \text{Br}(a \to \mu\mu) = 0.1 \) (which can occur in Type IV 2HDM+S models, see Fig. 9).
Prioritizing: Partially Visible Decays

Examples which are experimentally “easy” but can’t be reconstructed:

- $\gamma + \text{MET}$
- $l^+ l^- + \text{MET}$ (non-resonant leptons)
- $l^+ l^- l^+ l^- + \text{MET}$ (resonant or non-resonant leptons)
- $\gamma\gamma + \text{MET}, \gamma(\gamma\gamma) + \text{MET}$ (resonant or non-resonant photons)
- …

- If MET is large, pick up in existing invisible searches
- If MET is smaller, pick up in previous visible searches

Quite difficult to prioritize (few theory studies, many possible final states)

- Suggest:
  - Experimentalists: complete first round of invisible & fully-visible searches
  - Theorists: do some studies in coming months
  - Then compare and evaluate the opportunities
Prioritizing: Decays to Unusual Objects

- Unusual Objects means
  - New particles with displaced decays
  - Clusters of new particles with prompt or displaced decays
  - Soft final states

- Many of these searches cannot reconstruct $h$ resonance
  - In this case, can use generic search for unusual objects -- not $h$-specific
  - Or require the jets from VBF or the lepton(s) from $Wh, Zh$

- Only thoroughly studied case is “lepton-jets”
  - Hidden particles with $m < \text{few GeV}$ decaying to lepton pairs, hadron pairs
  - Possibly produced in clusters

- Neither theorists nor experimentalists can study this alone
  - Must communicate and do joint studies
  - Need to plan workshops for later in 2014
Dark Sectors (and/or Hidden Valleys)

Sectors of SM Singlets:
- Very little constrained by previous data!
- Motivated by known BSM:
  - Sterile Neutrinos (for neutrino masses)
  - Dark Matter
- Dark Sector (>1 particle) simple if all particles invisible
  - MET signals only
  - Phenomenologically identical or similar to minimal case of one particle
- (Partially?) Visible Dark Sector (*i.e.* Hidden Valley-type)
  - With multiple particles, visible or partially visible decays often possible
  - If interactions, then rich set of phenomenological signatures available

$h \rightarrow$ invisible

Non-SM Visible $h$ Decays
Non-SM Partly Visible $h$ Decays
Singlets

Rich singlet sector possible, as complex as SM
   (Dark Sector; Twin Higgs; NMSSM; Hidden Valley; Unparticles…)
   ▪ Minimally constrained by previous data!

▪ Few SM particles couple to singlets in renormalizable way
  ▪ U(1) hidden gauge boson V coupling to U(1) hypercharge boson \( F_{\mu \nu} F'_{\mu \nu} \)
  ▪ Scalar S coupling to doublet Higgses \( SH^*H, S^*SH^*H \)

▪ But then S or V can couple to other singlets in renormalizable way
  ▪ E.g. \( S_{\psi \psi} \)

▪ Or additional BSM particles can allow renormalizable couplings
  ▪ E.g. Bino-quark-squark

▪ Other couplings may be induced by strong dynamics in hidden sector

▪ Eventually some metastable singlets may decay back to SM particles
  ▪ This can happen promptly or well-displaced inside the LHC detectors
Singlets

(Dark Sector; Twin Higgs; NMSSM; Hidden Valley; Unparticles…)

- Minimally constrained by previous data!

- Often produced in decay of something heavier

- May be stable \(\rightarrow\) MET

- May decay to SM particle pairs \(\rightarrow\) visible
  - Couplings may be very small \(\rightarrow\)
    - Masses may be small
    - Lifetimes may be long

- May decay to other singlets which in turn…