Higgs XS WG: Thoughts about LLPs

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The LHC Higgs XS working group is responsible to provide support and recommendations for BSM Higgs related issues.

In particular, the Higgs Exotic Decay sub-group within this group covers $h\rightarrow$LLP decays, together with other three different scenarios.

This talk is going to briefly cover each of them, making emphasis on content that can be helpful for members of the LLP community.
(Semi-)invisible decays are difficult final states due to particles missing detection.

Many possible topologies.

Possibility for already existing analyses to interpret their results for models with “slightly different” final states.
Higgs to semi-invisible decays

- Several final states studied by ATLAS and CMS:
  - $h(\rightarrow \gamma\gamma) + E_T^{\text{miss}}$ [1506.01081, 1306.03948]
  - $h(\rightarrow bb) + E_T^{\text{miss}}$ [1707.01302]
  - Mono-jet analysis [1502.01518].
  - $Zh(\rightarrow \text{invisible})$ [1402.3244, 1711.00431, 1708.09624, 1711.00431]
  - VBF $h(\rightarrow \text{invisible})$ [1508.07869, 1610.09218, CMS-PAS-HIG-17-023]
  - $V(\rightarrow \text{had})h(\rightarrow \text{invisible})$ [1504.04324].

- A handful of interpretations for many BSM models [1312.4992] covered, and more to come!
Leptons Flavor Violating decays of the Higgs boson would be a clear indication of physics BSM.

Most simplistic model for the LFV Higgs decays: a simple off-diagonal Yukawa coupling for $h(125) \rightarrow \ell\ell'$.

Existing results for

- ATLAS and CMS results for $H \rightarrow \mu\tau/e\tau$ both lep-lep and lep-had channels [1604.07730, 1508.03372, HIG-17-001]
- CMS results for $H \rightarrow e\mu$ [HIG-14-040]

H→eμ cross-section values accessible at LHC are already excluded by MEG results (or some level of fine-tuning is needed)
Rare decays of the Higgs boson to a meson and a vector boson give a direct window to the Yukawa couplings.

- Higgs to pseudo-scalar mesons plus SM vector boson [1705.01112]

Can be complimentary to $h \rightarrow Z \alpha$ search with $m_{\text{meson}} \sim m_\alpha$.

- SM Higgs decays with additional radiations to probe CP properties of individual couplings [1610.02025].

- SM Higgs decays with additional radiations to probe light Yukawas [1704.00790]

Complimentary to $h \rightarrow M \gamma$.
Higgs to mesons

Several results published by ATLAS and CMS, and new analyses ongoing.

- $h \rightarrow \phi \gamma$ [1607.03400, 1507.03031].
- $h \rightarrow J/\psi \gamma$, $Y \gamma$ [1501.03276, 1507.03031].
- $h \rightarrow \phi \gamma$, $\rho \gamma$ [1712.02758].

In general far away from being sensitive due to very small branching ratios.
Higgs to light (pseudo-)scalars

- Higgs boson decays to a pair of new spin-zero particles, decaying each to a pair of SM particles.

- Predicted by many theories of physics BSM: NMSSM, Several models of DM [1405.0272, 1712.03974], Neutral Naturalness…

- Recent theory work
  - Higgs exotic decays linking to dark matter [1705.08896]
  - Higgs to axion-like particles $h \rightarrow aa/Z/\gamma a$, $a \rightarrow \gamma\gamma$ [1610.02025]
  - Complementarity in Higgs 2-body and 3-body decays [1609.08127]
Higgs to light (pseudo-)scalars

- Boost in the activity of this group in ATLAS, CMS and LHCb.
  - Searches to cover (almost) every sensitive final state.

- Setting limits on $\sigma/\sigma_{\text{SM}} \times \text{BR}(h \rightarrow 2a \rightarrow \text{XXYY})$.

- Several final states studied by ATLAS:
  - $h \rightarrow 2a \rightarrow 4b$ [1606.08391]
  - $h \rightarrow 2a \rightarrow 2\mu 2\tau$ [1505.01609]
  - $h \rightarrow 2a \rightarrow 2g2\gamma$ [1803.11145]
  - $h \rightarrow 2Zd / ZZd / 2a \rightarrow 4\ell$ [1505.07645, 1802.03388]
  - $h \rightarrow 2a \rightarrow 4\gamma$ [1509.05051]
Higgs to light (pseudo-)scalars

- Boost in the activity of this group in ATLAS, CMS and LHCb.
- Searches to cover (almost) every sensitive final state.
- Setting limits on \( \sigma / \sigma_{\text{SM}} \times \text{BR}(h \rightarrow 2a \rightarrow XXYY) \).
- Several final states studied by CMS:
  - \( h \rightarrow 2a \rightarrow 4\mu \) \([1506.00424]\)
  - \( h \rightarrow 2a \rightarrow 4\tau \) \([1701.02032, 1510.06534]\)
  - \( h \rightarrow 2a \rightarrow 2\mu 2\tau \) \([1701.02032, \text{CMS-HIG-17-029}]\)
  - \( h \rightarrow 2a \rightarrow 2\mu 2b \) \([1701.02032]\)
  - \( h \rightarrow 2a \rightarrow 2b 2\tau \) \([\text{CMS-HIG-17-024}]\)
Higgs to light (pseudo-)scalars

- Boost in the activity of this group in ATLAS, CMS and LHCb.
  - Searches to cover (almost) every sensitive final state.

- Setting limits on $\sigma/\sigma_{SM} \times BR(h \rightarrow 2a \rightarrow XXYY)$.

- Final states studied by LHCb:
  - New search for dimuon resonance for $m_{\mu\mu}$ between 5.5 GeV and 15 GeV.
Fiducial cross sections

- The Exotic Higgs Decay group encourages analysis reinterpretations.
- There is a lot of discussion about this topic → see dedicated workshop earlier this week.
- Efficiencies and fiducial cross sections allow reinterpretation in different models.
- Compute limits on the fiducial cross section using signal efficiencies.

Example: ATLAS $Z_d Z_d$ search:

\[
N^c_{\text{exp}}(m_{\ell\ell}) = N^c_{\text{bkg}} + \sigma^c_{\text{fid}} \times L \times \epsilon_c \times \text{Gaus}(m_{\ell\ell})
\]

\[
\epsilon_c = \frac{N^c_{\text{reco}}}{N^c_{\text{fid}}}
\]

\[
\sigma^c_{\text{fid}} = \sigma_h \times \text{BR}(h \to XX \to 4\ell) \times \frac{\Gamma^c_{4\ell}}{\Gamma_{4\ell}} \times \alpha_c
\]

Reinterpretation on any other model (use acceptance)
Benchmark models

- Theorists and experimentalists (ATLAS, CMS and LHCb) have converged on a set of 2HDM+S models, centralized in our twiki and maintained up-to-date.

- Limits on BR(h→XX→SM) can be reinterpreted into limits on BR(h→XX) for these different models:
  - Type I: all fermions couple to H$_2$
  - Type II: MSSM-like, d$_R$ and e$_R$ couple to H$_1$, u$_R$ to H$_2$
  - Type III: lepton-specific, leptons/quarks couple to H$_1$/H$_2$ respectively
  - Type IV: flipped, with u$_R$, e$_R$ coupling to H$_2$ and d$_R$ to H$_1$
Higgs to long-lived particles

We would like to thank to everyone that is working so hard on the LHC LLP white paper!

Many public results from Run 1 and Run 2 involving LLPs coming from the Higgs boson.

After 3 days of workshop probably no need to go through them in much detail 😊

Displaced jets [1504.03634, 1501.04020, 1705.07332]

Displaced lepton-jets [ATLAS-CONF-2016-042]
Ongoing work and new ideas

From the Higgs Exotic Decay group we are encouraging analyses to **re-interpret** their prompt searches in terms of slightly displaced signatures.

- Probe a region of the phase space “in between” prompt and LL.
- Coordinate the transition between long-lived and prompt searches.

Big effort ongoing to provide final recommendations on the several fronts and feasibility studies for final states not currently being studied.

As it has been done for prompt $h \rightarrow aa$ searches, centralize the different benchmark models and provide recommendations to generate MC, if they don’t exist.
Summary

- Higgs Exotic Decay group works on several fronts involving a 125 GeV Higgs boson decaying to new particles.
- Decays to long-lived particles are becoming more and more promising given the constraints on prompt analyses.
- White paper ongoing, providing recommendations both on the LL models to look at and on the way to present the results.
- Also working to encourage prompt searches to reinterpret their results in terms of slightly long-lived decays when possible.
Backup
Higgs to light (pseudo-)scalars

Efficiencies and fiducial cross sections allow reinterpretation in different models.

A local excess of 3σ at m_{Zd} = 23 GeV for 2l2e channel, no local excess is observed for 2l2μ channel.
Higgs to light (pseudo-)scalars

2HDM+S model with pseudo scalar a-boson
NMSSM-like scenario

\[ \tan \beta = 5, \text{ TYPE II} \]

\[ \sigma^H_{\text{SM}}/\sigma^H_{\text{SM}} \]

ATLAS

13 TeV, 36.1 fb^{-1}

\[ H \rightarrow aa \rightarrow 4\mu \]

Type-II, \( \tan \beta = 5 \)

\[ \text{Observed} \]

\[ \pm 1\sigma \]

\[ \pm 2\sigma \]

\[ \text{Expected} \]

arXiv:1312.4992
Higgs to light (pseudo-)scalars

- **Type I**: all fermions couple to \( H_2 \)
- **Type II**: MSSM-like, \( d_R \) and \( e_R \) couple to \( H_1 \), \( u_R \) to \( H_2 \)
- **Type III**: lepton-specific, leptons/quarks couple to \( H_1/H_2 \) respectively
- **Type IV**: flipped, with \( u_R, e_R \) coupling to \( H_2 \) and \( d_R \) to \( H_1 \)

From LHC Higgs XS WG on Exotic Decays
Higgs to light (pseudo-)scalars

- **Type I**: all fermions couple to $H_2$
- **Type II**: MSSM-like, $d_R$ and $e_R$ couple to $H_1$, $u_R$ to $H_2$
- **Type III**: lepton-specific, leptons/quarks couple to $H_1/H_2$ respectively
- **Type IV**: flipped, with $u_R$, $e_R$ coupling to $H_2$ and $d_R$ to $H_1$

From LHC Higgs XS WG on Exotic Decays

- Type II: $\tan \beta = 0.5$, $\alpha = 0.1$
- Type III: $\tan \beta = 0.5$, $\alpha = -1.4$
- Type IV: $\tan \beta = 0.5$, $\alpha = 0.1$
Higgs to light (pseudo-)scalars

\[ X = Z_d \text{ or } a \]

Hidden Abelian Higgs Model (HAHM)
Assume equal BR to ee and μμ

Results in arXiv:1802.03388