Low Mass Higgs Boson Searches from ATLAS and CMS

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Motivation

• Very narrow Higgs boson width $(\Gamma \sim 4 \text{ MeV}, \Gamma / m_H = O(10^{-5}))$ provides strong sensitivity to new physics $\Rightarrow$ even small couplings of BSM particles to the Higgs boson ($H$) can lead to sizable $B(H \rightarrow \text{BSM})$
  ▪ $O(1\%)$ coupling to a singlet scalar field $s$ can give $B(H \rightarrow ss) = O(10\%)$!

• Non-SM decays of the Higgs boson can be inferred from couplings measurements in the visible Higgs decay channels
  ▪ e.g. ATLAS Run-2 measurement w/ 80 fb$^{-1}$: $B_{\text{BSM}} < 26\%$ (ATLAS-CONF-2018-031)
  ▪ Or, $B_{\text{BSM}}$ can be directly measured by observing $H \rightarrow ss \rightarrow ?? \ldots$

• New scalars are a part of many BSM models
  ▪ While there are many searches for heavy (>125 GeV) BSM particles, possible light BSM particles are not (yet!) well explored at colliders
  ▪ The Higgs boson is a well-motivated portal to other BSM sectors (e.g. 2HDM+S interpretations in this talk) and represents a new tool for further discovery!
H(125) → aa → bbbb

If a pseudoscalar $a$-boson mixes with the Higgs boson and inherits its Yukawa couplings, then $a → bb$ decays would be dominant for $m_a > 2m_b$

Analysis Overview

- Search using Higgs bosons produced in association with a vector boson
  - Final-state leptons provide a signature for trigger and background suppression
- Dominant backgrounds: $t\bar{t}$+jets and $V$+jets
- BDT classifier used as a signal discriminant
• No significant excess over SM prediction is observed

• Limits set as a function of $m_a$ and $c\tau_a$ for

$$\sigma(pp\to VH)\times BR(H\to aa\to bbbb)$$

and compared to the SM inclusive Higgs cross section $\sigma(pp\to VH)$

• In some models, the proper decay length of the $a$-boson is from 10$\mu$m to kilometers
Motivated by models where fermionic decays of the $a$-boson are suppressed ($a \rightarrow \gamma\gamma/gg$ only)

**Analysis Overview**

- Focus on VBF production mode to suppress backgrounds (require $\geq 4$ jets)
- Trigger on di-photons
- Requirements on $p_T^{j1}$, $m_{jj}^{VBF}$, $m_{\gamma\gamma jj}$, $|m_{jj}-m_{\gamma\gamma}|$
- Dominant background is $\gamma\gamma$+jets which is estimated using data-driven methods
- Signal extracted using counts in two uncorrelated observables in (di-)photon ID
• No significant excess over SM prediction is observed

• Limits set on

$$\sigma(pp\rightarrow H) \times \text{BR}(H\rightarrow aa\rightarrow \gamma\gamma gg)$$

as a function of $$m_a$$, normalized to the SM inclusive Higgs cross section $$\sigma(pp\rightarrow H)$$:

$$\sigma(pp\rightarrow H) \times \text{BR}(H\rightarrow aa\rightarrow \gamma\gamma gg): 3.1 - 9.0 \text{ pb}$$
Search for a-boson through $H \rightarrow aa$ or $Z_d$: vector boson of dark sector $U(1)_d$

**Analysis Overview**

- Use combinations of lepton triggers
- Require 2 pairs of same-flavor, opposite-sign leptons ($e/\mu$), Higgs mass window cut on $m(4\ell)$
- Backgrounds: $H \rightarrow ZZ^* \rightarrow 4\ell$ and $ZZ^* \rightarrow 4\ell$
  - Estimated using simulation, validated in background-enriched regions
$H(125) \rightarrow aa/Z_d Z_d \rightarrow \ell\ell\ell\ell$

- No significant excess over SM prediction is observed
- Limits set on $H \rightarrow aa$ and $H \rightarrow Z_d Z_d$ as a function of $m(a)$ and $m(Z_d)$
Motivated by lepton-specific BSM models where $a$-boson decays to muons are sizable (e.g. type-III 2HDM+S)

**Analysis Overview**

- **Signature**: $2\mu + 2$ $b$-tagged jets
- **Single $\mu$ trigger**: $p_T > 24$ to 26 GeV (run-dependent)
- **Main backgrounds**: DY($\mu\mu$) and $t\bar{t}$ production
  - $m_H$ window, $E_T^{\text{miss}} < 60$ GeV to suppress $t\bar{t}$
- **Use a kinematic kit (KF) which exploits the symmetry of $H\rightarrow aa$ decays**
  - $m_{\mu\mu}$ mass resolution is 10x better than $m_{bb}$
  - Fit $b$-jet energies compatible with $m_{\mu\mu} \approx m_{bb}$
  - $2x$ improvement of $m_{bb\mu\mu}$ resolution
• No significant excess over SM prediction is observed

• Limits set for:
  - $\text{BR}(H \rightarrow aa \rightarrow bb\mu\mu)$ as a function of $m_a$, given the SM Higgs cross section:
    $10^{-4} - 10^{-3}$ for $m_a = [20, 60]$ GeV
  - Visible cross section for new physics times branching ratio to the $bb\mu\mu$ final state: $0.1 - 0.73$ pb for $m_a = [18, 62]$ GeV
Analysis Overview

- **Signature:** $2\mu + 2\ b$-tagged jets
- **Di-$\mu$ trigger with $p_T > 17$ and 8 GeV
- **Main backgrounds:** DY($\mu\mu$) and ttbar production
  - $E_T^{\text{miss}} < 60$ GeV to suppress $t\bar{t}$
- **Select events with** $m_{\mu\mu} \approx m_{bb}$ and $m_{bb\mu\mu} \approx m_H$ through a $\chi^2 < 2$ cut with
  - $\chi^2 = (m_{bb} - m_{\mu\mu})^2 / \sigma_{bb}^2 + (m_{bb\mu\mu} - 125 \text{ GeV})^2 / \sigma_H^2$
- **Events categorized by** $b$-tagging quality
  - TL, TM, TT ($T=$tight, $M=$medium, $L=$loose)
• No significant excess over SM prediction is observed
• BR Limits vary from $2 \times 10^{-4}$ to $10^{-3}$ depending on $m_a$

Also derived limits on type-III 2HDM+S considering $b\bar{b}\tau\tau$ signal as $b\bar{b}\mu\mu$ mis-ID
Analysis Overview

- Signature: $2\tau + $ at least one $b$-jet
  - $\tau\tau$ categorized by $e\mu$, $e\tau_h$, $\mu\tau_h$
- Dominant backgrounds: DY($\tau\tau$) and $t\bar{t}$
  - Events with jet$\rightarrow\tau_h$ mis-id (from $W$+jets, top, QCD multijets production) are also significant
- Signal extracted with binned ML fit to $M^{\text{vis}}(\tau\tau)$ to probe $m_a = [15, 60]$ GeV

\[ H(125) \rightarrow aa \rightarrow bb\tau\tau \]
No significant excess over SM prediction is observed.

Combined limits vary from 3% to 12% depending on $m_a$.
Analysis Overview

• Four different final states considered: \( \mu\mu+e\mu, \mu\mu+e\tau_h, \mu\mu+\mu\tau_h, \mu\mu+\tau_h\tau_h \).
  - Events from \( H \rightarrow aa \rightarrow 4\tau \) are considered in the signal
• Dominant backgrounds from events with jet\( \rightarrow \tau_h \) mis-ID
  - Z+jets, WZ+jets, ZZ*\( \rightarrow 2\ell2q \), ttbar, QCD multijets
• Signal extracted w/ unbinned ML fit to \( M^{\text{vis}}(\mu\mu) \) to probe \( m_a = [15.0, 62.5] \) GeV
• No significant excess over SM prediction is observed
• Combined limit for $m_a = 60$ GeV:
$$\sigma \times \text{BR}(H \rightarrow aa \rightarrow \mu\mu\tau\tau) = 1.2 \times 10^{-4} \times \sigma_{\text{SM}}$$
μμ Resonances in μμ+bj

Analysis Overview

• Search for μμ resonances in range $m(\mu\mu) \in [12, 70]$ GeV

• Two signal regions defined:
  - SR1: $\mu\mu + a$ central b-jet + at least one forward jet
  - SR2: $\mu\mu + 2$ central jets ($\geq 1$ b-tag) and no forward jets + $E_T^{miss}$

An excess ($4.2\sigma$ in SR1, $2.9\sigma$ in SR2) of events is seen at 28 GeV in 8 TeV data \( \Rightarrow \) Not confirmed in 13 TeV data analyzed thus far (36 fb$^{-1}$)
**Signature:** $2\tau$ + at least 1 $b$-jet (b) + an additional jet, which can be central (c) or forward (f)

- $\tau\tau$ categorized by $e\tau_h$, $\mu\tau_h$
- $m_T < 40$ GeV to suppress $tt\bar{t}$ production
- $p_T^{\text{miss}}$ consistent with $\tau$ decays

**Search for light pseudoscalar Higgs boson $A(\tau\tau)$**

- $m_T < 40$ GeV to suppress $tt\bar{t}$ production
- $m_T < 60$ GeV to suppress $tt\bar{t}$ production

**2 event jet-based categories:**
- 1b1c, 1b1f
• No significant excess over SM prediction is observed in \( bbA(\tau\tau) \) or \( X(\tau\tau)bj \) searches.
• Limits set on \( \sigma \times \text{BR}(A/X \rightarrow \tau\tau) \) vs \( m_A \) and \( m_X \).
Low mass $X \rightarrow \gamma\gamma$

Search for $X \rightarrow \gamma\gamma$: $m_X = [65, 120]$ GeV

**Analysis Overview**

- **Trigger** on di-photons with luminosity-dependent thresholds
- **Require** two isolated photons that pass a BDT-based identifier
- **A multivariate event classifier** is used to discriminate resonant (X) from continuum di-photon production
  - “Class 0” has highest expected sensitivity, “2” the lowest
- **Background** is modelled by fitting analytic functions to the observed diphoton mass distributions
No significant ($>3\sigma$) excess over SM prediction is observed

- Combined 8+13 TeV results show an excess at $\sim95$ GeV at the level of $2.8\sigma$ local (1.3$\sigma$ global) significance
Search for $X\rightarrow\gamma\gamma$: $m_X = [65,110]$ GeV

**Analysis Overview**

- **Trigger** on di-photons with luminosity-dependent thresholds
- **Require** two well-identified, isolated photons
  - **Split in categories for photon conversions** (CC, UC, UU): CC has more DY background
- **Main backgrounds**: SM $\gamma\gamma/j\gamma/jj$, Z boson (e→γ fakes)
  - Model non-resonant (continuum) and resonant DY backgrounds using data-driven approaches
Low mass $X \rightarrow \gamma \gamma$

- No evidence for significant excess beyond the SM using a narrow-width approximation to interpret the data.
Conclusions and Outlook

ATLAS and CMS performed many searches for exotic decays of the 125 GeV Higgs boson and new low-mass particles decaying to photons and leptons

⇒ Presented in this talk:

- $H(125) \rightarrow aa \rightarrow bbbb$
- $H(125) \rightarrow aa \rightarrow bb\mu\mu$
- $H(125) \rightarrow aa \rightarrow \gamma\gamma jj$
- $H(125) \rightarrow aa \rightarrow bb\tau\tau$
- $H(125) \rightarrow aa/Z(\text{d})Z(\text{d}) \rightarrow \ell\ell\ell\ell$
- $H(125) \rightarrow aa \rightarrow \mu\mu\ell\ell$

No statistically significant excess is observed in any of these searches

⇒ Limits are set on cross section $\times$ branching fraction and interpreted in the context of BSM models such as the 2HDM+S

Proton-proton collisions recently ended with $\sim160 \text{ fb}^{-1}$ delivered to each of ATLAS and CMS, so more data is in hand to be analyzed for many searches

⇒ Stay tuned for more results from Run-II of the LHC
Figure 6: Observed upper limits on $\mathcal{B}(h \rightarrow a_1a_1)$ in the plane of $(m_{a_1}, \tan \beta)$ for type-III 2HDM+S, including $\mu^+\mu^-\tau^+\tau^-$ signal that is misidentified as $\mu^+\mu^-bb$. 