Search for low mass BSM particles using h(125)

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on behalf of the CMS Collaboration

DIS2017
University of Birmingham, UK (3-7 April 2017)
The discovered Higgs boson at 125 GeV play a central role in probing physics beyond the Standard Model (BSM)

Many BSM theories predicted several BSM decay modes of h(125)

- Two-Higgs Doublet Models (2HDM)
  - Additional Higgs doublets give rise to 5 Higgs bosons
    - $H^+$, $H^-$, $A$ (CP-odd), $H^0$, $h$ (CP-even)
  - Minimal Supersymmetric Standard Model (MSSM)
    - Type-II 2HDM
    - e.g. $h \rightarrow$ invisible, LFV decays

- Composite Higgs
  - e.g. LFV Higgs decays

- Hidden Valley Model
  - Higgs to dark sector
  - e.g. $h \rightarrow$ invisible

- Higgs Triplet
  - An additional scalar triplet results in charged, doubly-charged, and neutral bosons

- 2HDM+S
  - Two Higgs Doublets with an additional complex singlet (e.g. NMSSM)
    - $CP$-even $(h_1, h_2, h_3)$, $CP$-odd $(a_1, a_2)$, $H^+$, $H^-$
    - e.g. $h \rightarrow$ aa searches

- Electroweak Singlet (EWS)
  - Additional singlet, resulting in 2 CP-even bosons $h, H$
h(125) → invisible
**h(125) → invisible**

- Indirect constraints from LHC couplings
  - no invisible channels included
  - assuming $|\kappa_V| \leq 1$, $B_{BSM} \geq 0$

  \[
  \text{Br}(h \rightarrow \text{BSM}) < 0.34 \text{ (0.39)} \text{ obs (exp)}
  \]

- Br(h→invisible) in the SM, Higgs can only decay via $H \rightarrow ZZ^* \rightarrow 4\nu$ ($\sim 0.1\%$)
  - a hint of new physics e.g. dark matter

- **Direct searches** must be performed in channels where the Higgs recoils against a visible system
  - vector boson fusion (VBF)
  - associated with vector bosons (VH)
  - gluon fusion (ggH)

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VBF $h \to \text{invisible}$

- Signal characteristics: **2 jets large** $\Delta \eta_{jj}$, $M_{jj}$ + **large missing** $E_T$
- Dominant backgrounds from **SM $Z(\nu\nu)/W(\ell\nu)+$jets**
  - lepton control regions in data to normalize MC
- Signal extraction based on counting experiment
  - simultaneous fit in 5 control + signal regions

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**CMS PAS HIG-16-009**

2.3 fb\(^{-1}\) (13 TeV)

<table>
<thead>
<tr>
<th>$\sigma \times B(g)$</th>
<th>[pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed limit</td>
<td>10</td>
</tr>
<tr>
<td>Expected limit</td>
<td>9</td>
</tr>
<tr>
<td>Expected limit (1\sigma)</td>
<td>8</td>
</tr>
<tr>
<td>Expected limit (2\sigma)</td>
<td>7</td>
</tr>
<tr>
<td>$\sigma_{\text{VBF}}$ (SM)</td>
<td>6</td>
</tr>
</tbody>
</table>

95% CL limits

Systematic uncertainties driven by **JES/JER**

Limit on $\sigma \times \text{Br}$ as a function of mass

- assuming SM Higgs cross-section

@125 GeV, Br($h \to \text{invisible}$) < **0.69 (0.62)** obs (exp)*

* Br($h \to \text{invisible}$) < 0.65 (0.49) obs (exp) at 8 TeV
Z(ll)h→invisible

- Clean final state from leptonic Z decay
  - events with **missing** $E_T + 2$ leptons ($e^+e^−/\mu^+\mu^−$)
- Backgrounds dominated by **diboson processes**
  - $ZZ(2l2\nu)$ (70%), $WZ(l\nu ll)$ (25%) from MC
- Signal extraction by fitting **$m_T$ distribution** in 0-, 1-jet categories

$$m_T = \sqrt{2p_T^{\ell\ell} E_T^{\text{miss}} [1 - \cos \Delta\phi(\ell\ell, \vec{p}_T^{\text{miss}})]}$$

Assuming SM Higgs cross-section @125 GeV, $\text{Br}(h\rightarrow\text{invisible}) < 0.86$ (0.70) obs (exp)
Both look for events with **Jet+missing** $E_T$ (VBF veto)

- “fat” jet from $W/Z$ decays hadronically
- “central” jet from a gluon/quark ISR

Dominant backgrounds arise from $W/Z(\nu\nu)+jets$

Signal extracted from fit to Missing $E_T$ spectrum

Upper limits on $\sigma x \text{Br}/\sigma_{\text{SM}}$

for Higgs decaying invisibly @125 GeV
No significant deviations from the SM expectations are observed

- Combination of $h \rightarrow \text{invisible}$ searches performed using **Run-1 dataset** and **2.3 fb}^{-1} of 13 \text{ TeV (2015) data**
  - 95% CL upper limits on $\sigma \times \text{Br}$ relative to SM production is estimated

- VH includes $Z(\ell\ell)$, $Z(bb)$ and $V(jj)H$ channels

\[
\text{Br}(h \rightarrow \text{invisible}) < 0.24 \ (0.23) \ \text{obs} \ (\text{exp}) \ \text{at} \ 125 \ \text{GeV} \ 95\% \ \text{CL}
\]
If dark matter (DM) couples to the Higgs, the following diagrams are possible:

- \( \text{Br}(h \rightarrow \text{invisible}) \) translated into DM-nucleon spin-independent cross section limits as a function of DM mass (if DM mass < \( m_h/2 \))*

Dark Matter Interpretation

CMS PAS HIG-16-016  arXiv:1610.09218

- Assuming scalar, fermion dark matters
- 90% CL to compare with direct detection experiments
  - LUX, PandaX-II, CDMSlite
- CMS limits more stringent for small DM masses

![Graph showing DM mass vs. DM-nucleon cross section with CMS, LUX, PandaX-II, CDMSlite data points and 90% CL limits.]

**DM mass [GeV]**

**DM-nucleon cross section [cm\(^2\)]**

- **CMS**
  - 4.9 fb\(^{-1}\) (7 TeV) + 19.7 fb\(^{-1}\) (8 TeV) + 2.3 fb\(^{-1}\) (13 TeV)
  - B(H \rightarrow \text{inv}) < 0.20

- **90% CL limits**
  - **Scalar DM**
  - **Fermion DM**

**Notes:**

- CMS PAS HIG-16-016
- arXiv:1610.09218
- Assuming scalar, fermion dark matters
- 90% CL to compare with direct detection experiments
  - LUX, PandaX-II, CDMSlite
- CMS limits more stringent for small DM masses
h(125) → aa
Two models interpretation

- **NMSSM**: $h \rightarrow aa \rightarrow 4\mu (2m_\mu \leq m_a \leq 2m_\tau)$
- **Dark SUSY**: $h \rightarrow 2n_1 \rightarrow 2n_D + 2\gamma_D \rightarrow 4\mu (m_h > m_{n1})$

- Mass range of $m_a \in 0.25$ to $3.55$ (8.5) GeV
- Main backgrounds from $bb$, $J/\Psi$ and EWK $pp \rightarrow 4\mu$

- **No excess data is observed**: diagonal signal region: $m_{\mu\mu1} = m_{\mu\mu2}$

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**NMSSM limits**

- 95% CL upper limits as functions of $m_{a1}$ for $m_{h1} = 86, 125, 150$ GeV

observed 1 event w.r.t

$0.74 \pm 0.34$ (stat.) $\pm 0.15$ (syst.) SM background
Dark SUSY Interpretation:

- Predict cold dark matter at ~1TeV scale
- $U(1)_D$ is broken, giving rise to light dark photons ($\gamma_D$)
- $\gamma_D$ weakly couples to SM particles via small kinetic mixing ($\varepsilon$)
- Lightest neutralino ($n_1$) is no longer stable and can decay to a dark neutralino (escape from detection) and a dark photon \[ n_1 \rightarrow n_D + \gamma_D \]

95% CL upper limits on $\sigma(pp \rightarrow h \rightarrow 2\gamma_D + X)Br(h \rightarrow 2\gamma_D + X)$

- Colored contours represent different values of $Br(h \rightarrow 2\gamma_D + X)$ in the range 1-40%
- Assumed $m_{n1} = 10$ GeV, $m_{nD} = 1$ GeV
Reconstructed events with $2\mu$ (good resolution) plus $2\tau$

- combined 5 final states $\rightarrow \mu\mu\tau\tau$, $\mu\mu\tau\tau$, $\mu\mu\tau\tau$, $\mu\mu\tau\tau$ and $\mu\mu\tau\tau$

- Limits set on $\text{Br}(h \rightarrow aa) \times \text{Br}(a \rightarrow \tau\tau)^2$ from an unbinned fit of $m_{\mu\mu}$ distributions with the following relation

$$\frac{\Gamma(a \rightarrow \mu\mu)}{\Gamma(a \rightarrow \tau\tau)} = \frac{m_a^2 \sqrt{1 - (2m_{\mu}/m_a)^2}}{m_{\tau}^2 \sqrt{1 - (2m_{\tau}/m_a)^2}}.$$ 

Upper limits at 95% CL on $h \rightarrow aa$ relative to the SM Higgs production, scaled by $\text{Br}(a \rightarrow \tau\tau)^2$ placed between 4-15% for $m_{\mu\mu} \in 20$ to 62.5 GeV.

CMS PAS HIG-15-011
Focus $ggh \to aa \to 4\tau$

- same-sign di-muon events with large angular separation plus one nearby opposite-sign track ($\mu$+track)

Signal extracted with binned maximum likelihood fit to the 2D distribution of $(m_{\mu\text{track}1}, m_{\mu\text{track}2})$

No excess is observed

- upper limits range from 4.5 pb at $m_{a_1}(m_{h_1}) = 8$ GeV to 10.3 pb at $m_{a_1}(m_{h_1}) = 5$ GeV
Different analysis strategy ($\tau_\mu \tau_\tau$ using HPS algorithm for hadronic tau)
- including ggH, WH, ZH and VBF production modes of h(125)
- higher mass region covered $m_a \in 5-15$ GeV

No excess is found above the SM backgrounds
- upper limits on $\text{Br}(h \rightarrow aa)\text{Br}(a \rightarrow \tau\tau)^2$ are set assuming SM cross-sections for all Higgs production modes
**h → aa → 2μ2b**

- Advantage of the higher rate and lower background contamination in comparison with the 4μ and 4b final states
- **No significant excess is observed**
  - upper limits are set on $\sigma_{ggF} \times \text{Br}(h \rightarrow aa \rightarrow \mu\mu bb)$ with ranging between 4 to 12 fb for $m_{\mu\mu} \in 25$ to 65 GeV
Upper limits from different \( h \to aa \) searches in the context of “2HDM+S”

- Type-1 and Type-2
- Quarkonia decays at 3, 5, 9, 11 GeV
- All results from 8 TeV data
Lepton Flavor Violation
**LFV Higgs Decays**

- Forbidden in the SM, described by **composite Higgs** or **2HDM** models
- LFV Higgs couplings allow $\mu \rightarrow e$, $\tau \rightarrow \mu$, $\tau \rightarrow e$ to proceed via a **virtual Higgs boson**

**Indirect constraints** to branching ratios of $h \rightarrow e\mu$, $h \rightarrow e\tau$, $h \rightarrow \mu\tau$ (theoretical approach described in JHEP 03 (2013) 26)
  - Stringent constraints from $\mu \rightarrow e\gamma$, upper limit at 95% CL $\text{Br}(h \rightarrow \mu e) < O(10^{-8})$
  - Bounds from $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ indirectly provide upper limit at 95% CL $\text{Br}(h \rightarrow \mu\tau)$ and $\text{Br}(h \rightarrow e\tau) < O(10\%)$
**LFV h → eμ, e/μτ**

- Similar signature to the SM h → ττ and h → μμ searches but significant kinematic differences
- Provide direct constraints on the off-diagonal Higgs Yukawa couplings

**h → eμ**

- Very clean but branching ratio strongly constrained!
- 10 channels (barrel/endcap leptons mix with 0-1-2 jets)
- Unbinned likelihood fit to Meμ distribution

**h → eτ and μτ**

- 3 categories (0,1,2 jets) from τ_had and τ_lep
- Large background leads to high systematic uncertainties
- Binned likelihood fit to the distributions of M_{col} (m_h estimated with collinear approx.)

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**Graphs:**

1. **Left:**
   - Data vs. background fit for Meμ distribution.
   - Events / GeV.
   - M_{eμ} [GeV] range from 110 to 160.
   - Data: Black dots.
   - Background fit: Red line.
   - LFV Higgs (B=0.1%): Blue dashed line.

2. **Middle:**
   - CMS Preliminary 2 Jet events.
   - Observed, eμ: Black dots.
   - Background uncertainty: Grey.
   - SM Higgs: Orange.
   - τ: Red.
   - Z: Green.
   - Other: Yellow.
   - Misidentified lepton: Purple.
   - LFV GGF Higgs (BR=100%): Blue.
   - LFV VBF Higgs (BR=100%): Blue.

3. **Right:**
   - CMS Preliminary loose selection events.
   - Data: Black.
   - Bkgd background unc., SM Higgs, τ, Z, τ, τ: Various colors.
   - LFV GGF Higgs (BR=100%): Blue.
   - LFV VBF Higgs (BR=100%): Blue.

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**LFV $h \rightarrow e\mu, e/\mu\tau$**

**CMS PAS HIG-14-040**

\[ \text{Br}(h \rightarrow e\mu) < 0.035\% \]
(0.048\% expected)

\[ \text{Br}(h \rightarrow e\tau) < 0.69\% \]
(0.75\% expected)

No excess is observed
(2.4\(\sigma\) at 8 TeV from $h \rightarrow \mu\tau$ not confirmed but comparable results)

**CMS PAS HIG-16-005**

\[ \text{Br}(h \rightarrow \mu\tau) < 1.20\% \]
(1.62\% expected)
The constraints on $\text{Br}(h \rightarrow e\mu)$, $\text{Br}(h \rightarrow e\tau)$ and $\text{Br}(h \rightarrow \mu\tau)$ can be bounded on the Higgs Yukawa couplings comparing to theoretical numbers:

$$\text{h}\rightarrow e\mu : \sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2} < 5.4 \times 10^{-4} (< 3.6 \times 10^{-6})$$

$$\text{h}\rightarrow e\tau : \sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 0.0024 (< 0.014)$$

$$\text{h}\rightarrow \mu\tau : \sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 0.0032 (< 0.016)$$

* R. Harnik, J. Kopp, and J. Zupan JHEP 03 (2013) 26
Summary

- The discovery of the SM-like Higgs boson opens an era of search for new physics

- $h(125)\to\text{invisible}$ searches at CMS shown the latest results from Run-2 at 13 TeV with 2.3 fb$^{-1}$ and some new results with 12.9 fb$^{-1}$ and their combinations

- $h(125)\to\text{aa}$ searches done in many channels and interpreted results in the context of 2HDM+S

- Direct searches for LFV $h(125)$ decays can constrain $\text{Br}(h\to\text{LFV})$ and set bounds on the off-diagonal Higgs Yukawa couplings

- Stay tuned! a lot more to come!
  - many more BSM results with full 2016 dataset (36 fb$^{-1}$) are on the way
Thanks for your attention!
References

- CMS Public Results
h(125)→invisible searches
- VBF channel: CMS PAS HIG-16-009
- VH channel: CMS PAS HIG-16-008, CMS PAS EXO-16-013
- ggH channel: CMS PAS EXO-12-055, CMS PAS EXO-16-037
- combination: CMS PAS HIG-16-016

h(125)→aa searches
- h→aa→4μ: CMS PAS HIG-16-035
- h→aa→2μ2τ: CMS PAS HIG-15-011
- h→aa→2μ2b: CMS PAS HIG-14-041
- h→aa→4τ: CMS PAS HIG-14-019, CMS PAS HIG-14-022
- combination: CMS PAS HIG-16-015

LFV h(125) decays
- h→μτ: CMS PAS HIG-16-005
- h→eμ,eτ: CMS PAS HIG-14-040

Compact Muon Solenoid (CMS)

**CMS DETECTOR**
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

**STEEL RETURN YOKE**
- 12,500 tonnes

**SILICON TRACKERS**
- Pixel (100x150 μm): ~16 m² ~66M channels
- Microstrips (80x180 μm): ~200m² ~9.6M channels

**SUPERCONDUCTING SOLENOID**
- Niobium titanium coil carrying ~18,000A

**MUON CHAMBERS**
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

**PRESHOWER**
- Silicon strips ~16m² ~137,000 channels

**FORWARD CALORIMETER**
- Steel + Quartz fibres ~2,000 Channels

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
- ~76,000 scintillating PbWO₄ crystals

**HADRÓN CALORIMETER (HCAL)**
- Brass + Plastic scintillator ~7,000 channels
Luminosity 2011-2016

CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2016-10-27 14:12 UTC

- 2010, 7 TeV, 45.0 fb^{-1}
- 2011, 7 TeV, 6.1 fb^{-1}
- 2012, 8 TeV, 23.3 fb^{-1}
- 2015, 13 TeV, 4.2 fb^{-1}
- 2016, 13 TeV, 40.8 fb^{-1}

Date (UTC)
Overview of $h \rightarrow aa$

CMS PAS HIG-16-015

5 April 2017

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LFV Indirect Constraints

- Constraints on flavor violating Higgs couplings to $e$, $\mu$, $\tau$ for a Higgs mass $m_h = 125$ GeV and assuming that the flavor diagonal Yukawa couplings equal the SM values.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Coupling</th>
<th>Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \to e\gamma$</td>
<td>$\sqrt{</td>
<td>Y_{\mu e}</td>
</tr>
<tr>
<td>$\mu \to 3e$</td>
<td>$\sqrt{</td>
<td>Y_{\mu e}</td>
</tr>
<tr>
<td>electron $g-2$</td>
<td>$\text{Re}(Y_{e\mu}Y_{\mu e})$</td>
<td>$-0.019 \ldots 0.026$</td>
</tr>
<tr>
<td>electron EDM</td>
<td>$</td>
<td>\text{Im}(Y_{e\mu}Y_{\mu e})</td>
</tr>
<tr>
<td>$\mu \to e$ conversion</td>
<td>$\sqrt{</td>
<td>Y_{\mu e}</td>
</tr>
<tr>
<td>$M-\bar{M}$ oscillations</td>
<td>$</td>
<td>Y_{\mu e} + Y_{e\mu}^*</td>
</tr>
<tr>
<td>$\tau \to e\gamma$</td>
<td>$\sqrt{</td>
<td>Y_{\tau e}</td>
</tr>
<tr>
<td>$\tau \to 3e$</td>
<td>$\sqrt{</td>
<td>Y_{\tau e}</td>
</tr>
<tr>
<td>electron $g-2$</td>
<td>$\text{Re}(Y_{e\tau}Y_{\tau e})$</td>
<td>$[-2.1 \ldots 2.9] \times 10^{-3}$</td>
</tr>
<tr>
<td>electron EDM</td>
<td>$</td>
<td>\text{Im}(Y_{e\tau}Y_{\tau e})</td>
</tr>
<tr>
<td>$\tau \to \mu\gamma$</td>
<td>$\sqrt{</td>
<td>Y_{\tau \mu}</td>
</tr>
<tr>
<td>$\tau \to 3\mu$</td>
<td>$\sqrt{</td>
<td>Y_{\tau \mu}</td>
</tr>
<tr>
<td>muon $g-2$</td>
<td>$\text{Re}(Y_{\mu\tau}Y_{\tau \mu})$</td>
<td>$(2.7 \pm 0.75) \times 10^{-3}$</td>
</tr>
<tr>
<td>muon EDM</td>
<td>$\text{Im}(Y_{\mu\tau}Y_{\tau \mu})$</td>
<td>$-0.8 \ldots 1.0$</td>
</tr>
<tr>
<td>$\mu \to e\gamma$</td>
<td>$\left(</td>
<td>Y_{\mu e}Y_{e\tau}</td>
</tr>
</tbody>
</table>

\[ \Gamma(H \to \ell^\alpha \ell^\beta) = \frac{m_H}{8\pi} \left(|Y_{\ell \ell \alpha}|^2 + |Y_{\ell \ell \beta}|^2\right), \]

\[ B(H \to \ell^\alpha \ell^\beta) = \frac{\Gamma(H \to \ell^\alpha \ell^\beta)}{\Gamma(H \to \ell^\alpha \ell^\beta) + \Gamma_{SM}}. \]