Searches for Higgs boson exotic decays at CMS

By

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On behalf of the CMS Collaboration

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Outline

• Motivation
• MC Simulations and Data
• Signal and Background Models
• Systematics
• Results and Summary
Why low mass?

Is the $h$ (125 GeV) really a SM Higgs boson?

Some BSM theories predict additional low-mass ($< 125$ GeV) scalars/pseudoscalars:

- **General 2HDM:**
  - 2 Higgs doublets (4 types) → 5 Higgs bosons: $h$, $H$, $a$, $H^\pm$
  - In the alignment limit, allows $h \rightarrow aa$ decay
  - $h$ is compatible with a 125 GeV SM-like scalar ($h$ or $H$) + a light Higgs Boson ($a$)

- **2HDM+S:**
  - 2 Higgs doublets + 1 singlet → 7 Higgs bosons: $h_1$, $h_2$, $h_3$, $a_1$, $a_2$, $H^\pm$
  - Allows direct production for $h \rightarrow a_1a_1$
  - Special case NMSSM allowing enhanced coupling to leptons at higher values of $\tan\beta$
  - Compatible with a 125 GeV SM-like scalar ($h_1$ or $h_2$) + a mostly "singlet-like" light Higgs Boson ($a_1$ or $h_1$)
CMS low-mass searches

Exotic decays of Higgs Boson, \( h \ (125) \rightarrow aa \) are searched in various final states

Recent results with 2016 dataset at 35.9 \( fb^{-1} \):

- \( \mu \mu bb \ (20 \rightarrow 62.5 \text{ GeV}) \), CMS PAS HIG-18-003
- \( \mu \mu \tau \tau \ (15 \rightarrow 62.5 \text{ GeV}) \), CMS PAS HIG-17-029
- \( bb\tau \tau \ (15 \rightarrow 60 \text{ GeV}) \), CMS PAS HIG-17-024
- \( \mu \mu \mu \mu \ (0.25 - 8.5 \text{ GeV}) \), CMS PAS HIG-18-003
- \( \tau \tau \tau \tau, \tau \tau \mu \mu \ (4 - 15 \text{ GeV}) \), CMS HIG-18-006
- \( bbbb \ \text{(Ongoing)} \)

Talk covers results of \( \mu \mu bb \) and \( \mu \mu \tau \tau \) final states
CMS low-mass searches

Why $\mu\mu bb$ and $\mu\mu\tau\tau$ final states?

- 4b final state expected to occur with higher number of events but has challenging backgrounds
- 4$\mu$ final state clean but very rare
- $\mu\mu bb$ final state is considered a compromise between 4b and 4$\mu$ states
- Same stands true for $\mu\mu\tau\tau$
- Both the decay channels are expected to provide better sensitivity in the long run [Ref. 01]:
  - $a \rightarrow \mu\mu$ has a clear peak
  - $Br$ depend on the model and model parameters
  - $a \rightarrow bb$ and $a \rightarrow \tau\tau$ have large $Br$ in many parts of the parameter space
  - Particularly very large in the context of the NMSSM [Ref. 02]

Simulated Signal Samples

Model Used
- NMSSMHET used in MadGraph_aMCatNLO, generated signal at LO Mechanism
- Mechanism
  - ggF with $\sigma_{ggF} = 48.58$ pb
  - VBF with $\sigma_{VBF} = 3.78$ pb

Benchmark for the expected yield
- $BR(h \rightarrow aa) = 10\%$
- $BR(h \rightarrow aa \rightarrow \mu\mu bb) = 1.7 \times 10^{-3}$ in 2HDM+S Type 3 \cite{Ref. 03}
- $Br(h \rightarrow aa \rightarrow \mu\mu\tau\tau) = 1 \times 10^{-3}$

$h \rightarrow a a \rightarrow \mu\mu bb$:

Mass range $20 < m_a < 62.5$ GeV

To estimate the contribution from $\mu\mu\tau\tau$ and $\tau\tau bb$, samples with $\mu\mu\tau\tau$ and $\tau\tau bb$ final state were also generated

<table>
<thead>
<tr>
<th>Sample name (Process)</th>
<th>“a” mass (GeV) points Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \rightarrow aa \rightarrow 2\mu 2b$ (ggF)</td>
<td>20, 25, 30, 35, 40, 45, 50, 55, 60</td>
</tr>
<tr>
<td>$h \rightarrow aa \rightarrow 2\mu 2b$ (VBF)</td>
<td>20, 30, 40, 60</td>
</tr>
<tr>
<td>$h \rightarrow aa \rightarrow 2b2\tau$ (ggF)</td>
<td>20, 30, 60</td>
</tr>
<tr>
<td>$h \rightarrow aa \rightarrow 2\mu 2\tau$ (ggF)</td>
<td>20, 30, 60</td>
</tr>
</tbody>
</table>

Similarly simulated signal samples for $h \rightarrow a a \rightarrow \mu\mu\tau\tau$ where generated

Mass range $15 < m_a < 62.5$ GeV

Four final states are considered:
- $\mu\mu + ee, \mu\mu + e\tau_h, \mu\mu + \mu\tau_h$ and $\mu\mu + \tau_h\tau_h$

The $\mu\mu + ee$ and $\mu\mu + \mu\mu$ final states are not considered

- Smaller branching fractions
- Large contribution from the irreducible background of Z boson pair production.
Preselection and Optimization

\[ h \rightarrow aa \rightarrow \mu\mu bb \]

At least one good primary vertex

At least two jets:
- \( p_T > 20/15 \text{ GeV (Optimized)} \)
- \( |\eta| < 2.5 \)
- \( \Delta R(\mu, \text{jet}) > 0.4 \)
- b-tagging CSVv2:
  - One loose/One tight (Optimized)

\[ \chi^2 = \frac{(m_{\mu\mu} - m_{bb})^2}{\sigma_{bb}^2} + \frac{(m_{\mu\mu bb} - 125)^2}{\sigma_h^2} \]

Look for improvements in sensitivity applying optimization cuts on MET and \( \chi^2 \)

Additional Optimization:
- \( E_T^{\text{miss}} < 60 \text{ GeV} \)
- Exploit features in signal such as \( \chi^2 \) with \( \chi^2 < 5 \)

\[ h \rightarrow aa \rightarrow \mu\mu \tau\tau \]

Muons \( p_T > 18/9 \text{ GeV} \)

Electrons from \( \tau \) lepton decays are required to have \( p_T > 7 \text{ GeV} \)

\( \tau_h \) candidates are required to satisfy \( p_T > 18.5 \text{ GeV} \)
Data-MC Distributions and yields

\[ h \rightarrow a a \rightarrow \mu \mu bb \]

For the final state, 14% of the \( h \rightarrow a a \rightarrow 4\tau \) events have at least two muons in the final state.

**Signal and background yields**

<table>
<thead>
<tr>
<th>Process</th>
<th>( \mu^+ \mu^- bb ) selection</th>
<th>Final selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top (tt, single top quark)</td>
<td>33730 ± 120</td>
<td>198 ± 9</td>
</tr>
<tr>
<td>Drell–Yan</td>
<td>5237 ± 77</td>
<td>399 ± 21</td>
</tr>
<tr>
<td>Diboson</td>
<td>51 ± 4</td>
<td>1 ± 0.1</td>
</tr>
<tr>
<td>Total expected background</td>
<td>39015 ± 140</td>
<td>598 ± 23</td>
</tr>
<tr>
<td>Data</td>
<td>36360</td>
<td>610</td>
</tr>
</tbody>
</table>

**Contribution from other signals**

- The \( \mu \tau \tau \) and \( \tau bb \) signals can contribute in our selection:
  - \( \tau bb \) with \( \tau \rightarrow \mu \) decays
  - Leads to a displaced \( \mu \mu \) mass w.r.t the \( \mu bb \) signal: negligible effect on signal yield
  - \( \mu \tau \tau \) with a possibility for \( \tau \)-b misidentification
  - The contribution is small at the benchmark

<table>
<thead>
<tr>
<th>Process</th>
<th>( m_{a_1} = 20 \text{ GeV} )</th>
<th>( m_{a_1} = 40 \text{ GeV} )</th>
<th>( m_{a_1} = 60 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu \tau \tau )</td>
<td>0.017 ± 0.005</td>
<td>0.051 ± 0.009</td>
<td>0.084 ± 0.011</td>
</tr>
<tr>
<td>( \tau bb )</td>
<td>0.304 ± 0.103</td>
<td>0.280 ± 0.086</td>
<td>0.448 ± 0.114</td>
</tr>
</tbody>
</table>

For \( \mu \tau \tau \) final state, 14% of the \( h \rightarrow aa \rightarrow 4\tau \) events have at least two muons in the final state.
Signal Model

- Signal Shape derived from simulation

- Combination of Voigtion and a Crystal ball profiles

\[ S(m_{\mu\mu}|f, p_V, p_{cb}) \equiv f \cdot V(m_{\mu\mu}|p_V) + (1 - f) \cdot CB(m_{\mu\mu}|p_{cb}) \]

- The Voigt profile function is a convolution of Lorentz and Gaussian profiles

- The Crystal ball function has a Gaussian core and a power-law low-end tail

- Resolutions are modelled linearly as a function of dimuon invariant mass:

\[ \sigma_V = \sigma_{V,0} + \alpha m_{\mu\mu}, \]
\[ \sigma_{cb} = \sigma_{cb,0} + \beta m_{\mu\mu}. \]
Background Model

The dimuon mass distributions are parameterized with different polynomials.

The number of degrees of the polynomial required to describe the background in each channel is determined with a Fisher F-test.

<table>
<thead>
<tr>
<th>The TLexc category</th>
<th>$\chi^2$/ndf</th>
<th>F-test probability (&gt; 0.05)</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inv. Poly II</td>
<td>0.87</td>
<td>–</td>
<td>✔</td>
</tr>
<tr>
<td>Inv. Poly III</td>
<td>0.86</td>
<td>0.32</td>
<td>✔</td>
</tr>
<tr>
<td>Inv. Poly IV</td>
<td>0.83</td>
<td>0.90</td>
<td>✔</td>
</tr>
<tr>
<td>Inv. Poly V</td>
<td>0.81</td>
<td>0.03</td>
<td>✗</td>
</tr>
</tbody>
</table>

The best fit output to the data under the background-only hypothesis.

Dark grey and green bands are the 68% CL uncertainty bands for the background model.
Systematics Uncertainties

**Background**
- Uncertainties on the background model are taken into account with the discrete profiling method.

**Signal**
- Signal normalization is affected by various sources of systematic uncertainties:
  - $\sigma_h : \pm 3.6\%$, considered for the limit on BR
  - Luminosity: $\pm 2.5\%$
  - Trigger efficiency: $2\%$
  - Pileup: $\pm 4.6\%$ on the $\sigma_{pp}^{\text{inelastic}}$
  - $\mu$, ID, Iso, HLT scale factors: doubled for $p_T < 20$ GeV
  - JES: $p_T$ and $\eta$ dependent corrections applied on jets and propagated to $E_T^{\text{miss}}$
  - JER
  - Identification, isolation, and reconstruction uncertainties amount to $2\%$ per muon, $2\%$ per electron, and $5\%$ per $\tau_h$ candidate.

- **b-tagging**: different sources affecting the shape calibration are considered and are doubled for low $p_T$ jets.
Expected and observed limits

- Assuming the SM prediction of $\sigma_h$, the results are extracted by fitting the reconstructed dimuon mass distributions.

- Upper limits at 95% CL on the Higgs boson production cross section times branching ratio on $\sigma_h \times B( h \rightarrow a \rightarrow \mu\mu b\bar{b} )$ as well as on the Higgs boson branching ratio.

- Limits are improved by a factor of 2 with respect to Run-I analysis.

- The limits on the branching fraction are reported as $(2-6) \times 10^{-4}$. 

![Graphs showing expected and observed limits](image-url)
Results ( $h \rightarrow a \ a \rightarrow \mu \mu \tau \tau$)

- Expected and observed limits

  - Upper limits at 95% CL on $(\sigma_h / \sigma_{SM}) \times B( h \rightarrow a \ a \rightarrow \mu \mu \tau \tau )$ for the combined final states: $\mu \mu + e\mu, \mu \mu + e\tau_h, mm + \mu \tau_h$, and $\mu \mu + \tau_h \tau_h$

  - Upper limits are set at the 95% confidence level on the branching fraction $B( h \rightarrow aa \rightarrow 2\mu 2\tau )$ for masses of the light pseudoscalar between 15 and 62.5 GeV, and are as low as $1.2 \times 10^{-4}$ for a mass of 60 GeV

  - These are the most stringent limits so far for such a decay channel
Summary

We have just started to extract the physics potential of the 13 TeV dataset!

Extensive program for exotic decays of Higgs boson at CMS is already underway

Search for exotic Higgs decay in $\mu\mu bb$ and $\mu\mu\tau\tau$ final state with 2016 dataset has been presented

- The VBF contribution to the signal is also included and does not have much impact on significance
- For $\mu\mu bb$ final state, contribution from $\mu\mu\tau\tau$ and $bb\tau\tau$ signals is observed to be very small
- No excess is found over the SM backgrounds
- Upper limits are reported on $\text{BR}(h \rightarrow aa \rightarrow \mu\mu bb)$ and $\text{BR}(h \rightarrow aa \rightarrow \mu\mu\tau\tau)$

Present and future Work:
- Whole Run-II data-set analysis in progress
- Improve sensitivity below 20 GeV and to use dedicated tools for low $p_T$ searches

Thank You
Back-Up
Back-Up
Optimization procedure

- Based on simulated background samples
- Started with a loosely selected sample:
  - $p_T^μ > 17(8)$ GeV,
  - $p_T^{jet} > 10$ GeV,
  - $\geq 2$ loose b-jets
- Different FOM’s used to cross check:
  - $s/\sqrt{b}, s/\sqrt{b+(\delta b)^2}, \sqrt{2((s+b)\ln(1+s/b)-s)}$
  - Expected limit based on counting signal and background yields in $|m_{\mu\mu}-m_a| < 5$ GeV
- Tried to have a uniform selection vs. $m_a$
Functions for multipdf

- Different types of polynomials are checked on data in CR
  - RooPolynomial
  - RooBernstein (a particular polynomial with positive definite coefficients)
  - RooArgus
- An inverse polynomial is also introduced \( (1/P_n, \text{ a la Run I}) \)
- An F-test is used to determine the collection of pdfs for each family
- The lowest degree is where the \( \chi^2 / \text{ndf} \) is close to 1
  - Degrees are increased until \( \text{Prob}(-2\Delta \text{NLL}, 1) < 0.05 \)

<table>
<thead>
<tr>
<th>Model</th>
<th>( \chi^2 / \text{ndf} )</th>
<th>F-test probability (&gt; 0.05)</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bernstein II</td>
<td>1.001</td>
<td>-</td>
<td>✓</td>
</tr>
<tr>
<td>Bernstein III</td>
<td>0.948</td>
<td>0.149</td>
<td>✓</td>
</tr>
<tr>
<td>Bernstein IV</td>
<td>0.859</td>
<td>0.017</td>
<td>×</td>
</tr>
</tbody>
</table>

- RooPolynomial and \( 1/P_n \) never gave \( \chi^2 / \text{ndf} \sim 1 \)
General strategy

- **Signal:**
  - Shape is assumed to remain unchanged

- **Background:**
  - Shape is taken from CR, assuming no change in categories

- **Two type of categorizations in signal region:**
  - $\text{MET} < 30 \& 30 < \text{MET} < 60 \rightarrow \text{bkg yield from MC}$
  - B-tagging criterion on Loose b-tagged jet $\rightarrow \text{bkg yield from CR (no MC stat.)}$
    - TT, TMexc (medium, not tight), Tlexc (loose, not medium)

- **Expected limits** are evaluated and compared
Based on simulated background samples

Initially selected loose cuts on signal sample:
- $p_T^{\mu}$ (leading) > 17 GeV
- $p_T^{\mu}$ (sub-leading) > 8 GeV
- $p_T^{\text{jet}}$ (leading/sub-leading) > 10 GeV
- both jets selected with loose $b$-tag discriminant

Variable $s/\sqrt{b + |\delta b|^2}$ used, where $\delta b$ is the statistical uncertainty from MC

B-tag working points are used

Pair of jets in the final state

Various possible permutations
1) Loose-Loose
2) Medium-Loose
3) Tight-Loose
4) Medium-Medium
5) Tight-Medium
6) Tight-Tight

Significance estimated for each permutation for both the taggers (CSVv2 and DeepCSV)
Table 1: Summary of the event selection of the different analyses described in this paper. The quarkonia resonance masses $m_{J/\psi}$, $m_{\psi(2S)}$, $m_{\Upsilon(1S)}$, and $m_{\Upsilon(3S)}$ are taken from Ref. [73].

<table>
<thead>
<tr>
<th>Quadruplet selection</th>
<th>$H \rightarrow ZX \rightarrow 4\ell$ (15 GeV &lt; $m_X$ &lt; 55 GeV)</th>
<th>$H \rightarrow XX \rightarrow 4\ell$ (15 GeV &lt; $m_X$ &lt; 60 GeV)</th>
<th>$H \rightarrow XX \rightarrow 4\mu$ (1 GeV &lt; $m_X$ &lt; 15 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-sign leptons</td>
<td></td>
<td>Leptons in the quadruplet are responsible for firing at least one trigger.</td>
</tr>
<tr>
<td></td>
<td>- Three leading-$p_T$ leptons satisfying $p_T &gt; 20$ GeV, 15 GeV, 10 GeV</td>
<td></td>
<td>In the case of multi-lepton triggers, all leptons of the trigger must match to leptons in the quadruplet</td>
</tr>
<tr>
<td></td>
<td>- At least three muons are required to be reconstructed by combining ID and MS tracks in the $4\mu$ channel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Select best quadruplet (per channel) to be the one with the (sub)leading dilepton mass (second) closest to the Z mass</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $50$ GeV &lt; $m_{12}$ &lt; 106 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $12$ GeV &lt; $m_{34}$ &lt; 115 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $m_{12,34,14,32}$ &gt; 5 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Delta R(\ell, \ell') &gt; 0.10$ (0.20) for same-flavour (different-flavour) leptons in the quadruplet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadruplet ranking</td>
<td>Select first surviving quadruplet from channels, in the order: $4\mu$, 2$e$2$\mu$, 2$\mu$2$e$, 4$e$</td>
<td>Select quadruplet with smallest $\Delta m_{\ell\ell} =</td>
<td>m_{12} - m_{34}</td>
</tr>
<tr>
<td>Event selection</td>
<td>$115$ GeV &lt; $m_{4\ell}$ &lt; 130 GeV</td>
<td>$120$ GeV &lt; $m_{4\ell}$ &lt; 130 GeV</td>
<td>$m_{34}/m_{12} &gt; 0.85$</td>
</tr>
<tr>
<td></td>
<td>Reject event if:</td>
<td></td>
<td>10 GeV &lt; $m_{12,34}$ &lt; 64 GeV</td>
</tr>
<tr>
<td></td>
<td>$(m_{J/\psi} - 0.25$ GeV) &lt; $m_{12,34,14,32}$ &lt; $(m_{\psi(2S)} + 0.30$ GeV), or</td>
<td></td>
<td>$0.88$ GeV &lt; $m_{12,34}$ &lt; 20 GeV</td>
</tr>
<tr>
<td></td>
<td>$(m_{\Upsilon(1S)} - 0.70$ GeV) &lt; $m_{12,34,14,32}$ &lt; $(m_{\Upsilon(2S)} + 0.75$ GeV)</td>
<td></td>
<td>No restriction on alternative pairing</td>
</tr>
<tr>
<td></td>
<td>$5$ GeV &lt; $m_{14,32}$ &lt; 75 GeV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Signal Model

- Signal Shape derived from simulation
- Combination of Voigtion and a Crystal ball profiles

\[ SignalModel \quad S(m_{\mu\mu}, p_v, p_{CB}) \equiv f \cdot V(m_{\mu\mu}, p_v) + (1 - f) \cdot CB(m_{\mu\mu}, p_{CB}) \]

Where, VoigtionFunction \quad V(m_{\mu\mu}, p_v) \equiv V(m_{\mu\mu}, \sigma, \gamma) = G(m_{\mu\mu}, \sigma, m_a) \ast L(m_{\mu\mu}, \gamma, m_a)

\[ G(m_{\mu\mu}, \sigma, m_a) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(m_{\mu\mu} - m_a)^2}{2\sigma^2}} \]

\[ L(m_{\mu\mu}, \gamma, m_a) = \frac{\gamma}{\pi \left( (m_{\mu\mu} - m_a)^2 + \gamma^2 \right)} \]

CrystallBallFunction \quad CB(m_{\mu\mu}, p_{CB}) \equiv CB(m_{\mu\mu}, n, \sigma_{CB}, \alpha, m_a) = N \cdot e^{-\frac{(m_{\mu\mu} - m_a)^2}{2\sigma_{CB}^2}} \quad \text{for} \quad \frac{m_{\mu\mu} - m_a}{\sigma_{CB}} > -\alpha

\[ N \cdot \left( A \left( B - \frac{m_{\mu\mu} - m_a}{\sigma_{CB}} \right)^{-n} \right) \quad \text{for} \quad \frac{m_{\mu\mu} - m_a}{\sigma_{CB}} \leq -\alpha \]