Searches for additional neutral Higgs bosons at CMS

Dermot Moran (CIEMAT)
On behalf of the CMS collaboration
125 GeV Higgs boson is (so far) consistent with SM predictions

However an extended Higgs sector is strongly motivated
(Hierarchy problem, baryon asymmetry, dark matter/energy...)

Many BSM theories require 2 Higgs doublets \( \phi_1 \) and \( \phi_2 \) (2HDMs)

2 important free parameters: \( \alpha \) and \( \tan \beta \)
(mixing angle of \( h \) and \( H \), and ratio of the VEVs of \( \phi_1 \) and \( \phi_2 \))

MSSM contains Type-2 2HDM
(up-type q couple to \( \phi_2 \), down-type q and \( \ell^\pm \) couple to \( \phi_1 \))
h usually identified as $h(125)$

2 additional neutral Higgs bosons: \(H\) (CP-even) and \(A\) (CP-odd)

Will report on latest neutral Higgs boson searches at CMS

Analyses reported here use 35.9 \(fb^{-1}\) of 2016 data
$H \rightarrow Z(\ell\ell)A(b\bar{b})$

- Largest $Br$ in 2HDM when $\cos(\beta - \alpha) \rightarrow 0$ (SM-like h)
- Main discriminants are $m_{jj}$ (2 b-tagged jets) and $m_{\ell\ell jj}$
- Categorization by lepton flavour (ee and $\mu\mu$)
- $Z+$Jets (largest Bkg) estimated from simulation
- Data-driven estimate of $t\bar{t}$ with $e\mu$ CR
\[ H \rightarrow Z(\ell\ell)A(b\bar{b}) \]

For each signal hypothesis define elliptical SR in \( m_{jj} - m_{\ell\ell jj} \) plane (SR)

Dilation parameter \( \rho \) sets size of ellipse (\( 1\rho \sim 1\sigma \) of signal resolution)

6 elliptical bins defined from \( \rho=0 \) to \( \rho=3 \)

\( \rho \) templates used in final statistical analysis

Dermot Moran (CIEMAT)

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Twisted (Classical) custodial symmetry: $m_H > m_A$ ($m_A > m_H$)

Also sensitive to $A \rightarrow Z(\ell\ell)H(b\bar{b})$
$H \rightarrow \mu \tau$ and $e \tau$

- Lepton flavour violating decays of Higgs allowed in some BSM theories - 4 decay channels considered: $\mu \tau e$, $\mu \tau h$, $e \tau \mu$, $e \tau h$
- Discriminant is collinear mass $M_{Col} = M_{Vis}/\sqrt{x_{vis}^\tau}$ ($x_{vis}^\tau$ estimated assuming $\nu$ are collinear with visible $\tau$ decay)
- Categorization by jet multiplicity (0 and 1 jet)
- Low ($m_H < 450$ GeV) and high mass ($m_H \geq 450$ GeV) selection
- Reducible bkg (Fake $\ell$) estimation from $Z+$Jets and $\ell^+ \tau^-$ data

![Graphs showing observed and expected events vs. $M_{col}$]
$H \rightarrow \mu\tau$ and $e\tau$

Limits set on $\sigma(gg \rightarrow H) \times Br(H \rightarrow \mu\tau)$ and $\sigma(gg \rightarrow H) \times Br(H \rightarrow e\tau)$

![Graph showing limits on $\sigma(gg \rightarrow H) \times Br(H \rightarrow \mu\tau)$ and $\sigma(gg \rightarrow H) \times Br(H \rightarrow e\tau)$ with CMS data for $13$ TeV]
Enhanced when Yukawa coupling of A to down-type fermions is negative - Search for $e\tau_h$ or $\mu\tau_h$ and a b-tag jet

Cut on $D_\zeta$ which quantifies alignment of visible decay products with missing neutrinos

Discriminant is $m_{\tau\tau}$ from $SV_{FIT}$ algorithm

$t\bar{t}$ and $W+Jets$ predictions verified in data CRs while Multijet bkg estimated with $\ell^\pm\tau^\pm$ CR
**bbA***(low mass $A \rightarrow \tau\tau$)**

Limits set on $\sigma(bbA) \times Br(A \rightarrow \tau\tau)$

Representative 2HDMs shown for 2 types of Yukawa couplings (SM-like and wrong-sign)
H → WW

ggF and VBF H with SM width (interference effects considered)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Discriminant</th>
<th>Channels</th>
<th>Categorization</th>
<th>Major bkgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2ℓ2ν</td>
<td>Higgs Visible mass $m_T$</td>
<td>DF &amp; SF $ℓℓ$</td>
<td>based on #jets and tagging of VBF-like events</td>
<td>WW, DY and $t\bar{t}$ from data-driven estimates</td>
</tr>
<tr>
<td>$ℓνq\bar{q}$</td>
<td>Higgs mass $m_{WW}$</td>
<td>$ℓ$, Resolved &amp; Boosted $W_{Had}$</td>
<td>based on MELA and tagging of VBF-like events</td>
<td>$W+Jets$ and $t\bar{t}$ from data-driven estimates</td>
</tr>
</tbody>
</table>

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**Events / bin**

**Data/Bkg**

**m_T [GeV]**

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**Events / 100 GeV**

**Data/Bkg**

**m_{WW} [GeV]**

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Dermot Moran (CIEMAT)
Limits set on $\sigma_{H \rightarrow WW}$ for different $f_{VBF}$

$f_{VBF} = \text{fraction of } \sigma_H \text{ due to VBF}$

Limits set in MSSM benchmark scenarios

Free parameters set so wide range of $m_A - \tan \beta$ is compatible with $h(125)$

*See talk by Dennis Roy yesterday in Searches for New Physics*
And many more final states have been investigated!!

- $H \rightarrow t\bar{t}$
  CMS-PAS-HIG-17-027
- $A \rightarrow Z(\ell^+\ell^-)h(b\bar{b})$
  CMS-PAS-HIG-18-005
- $H \rightarrow \mu^+\mu^-$
  CMS-PAS-HIG-18-010
  arXiv:1907.03152
- $A \rightarrow Z(\ell^+\ell^-)h(\tau^+\tau^-)$
  CMS-PAS-HIG-18-023
- Many $H \rightarrow 2a$ searches
  - Extensions of 2HDM/MSSM with additional scalars
  *See talk by Fengwangdong yesterday

![Graph showing exclusion limits for different Higgs boson decay channels]
Summary

- Latest results using 2016 dataset on searches for additional neutral Higgs bosons at CMS presented
- No evidence for BSM physics observed
- Large areas of parameter space of 2HDMs excluded
- Many new results to come with full Run 2 dataset
  → Almost factor 4 increase in statistics!
Backup
$D_\zeta$ Discriminant

$p_\zeta^{\text{miss}} =$ component of $p_T^{\text{miss}}$ along bisector $\zeta$
$p_\zeta^{\text{vis}} =$ sum of parallel components of $\ell$ and $\tau$ $p_T$

$D_\zeta = p_\zeta^{\text{miss}} - 0.85 p_\zeta^{\text{vis}}$

Remove $t\bar{t}$ and $W+$Jets with $D_\zeta > -40$ GeV