Search for light Higgs bosons with the CMS experiment

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Extended Higgs sector

- Simplest extensions of the SM: SM +S, 2HDM +s, composite etc
- 2HDM/MSSM: 5 physical Higgs bosons
- NMSSM: 7 physical Higgs bosons
- Composite: h + excited states

**NMSSM, 2HDM+S**
- $h_1, h_2, h_3$
- $a_1, a_2, H^+, H^-$
- 2 doublets, 1 singlet

**MSSM, 2HDM**
- $h, H, A, H^+, H^-$
- 2 doublets

**SM**
- $h$
- 1 doublet

**Next-to-MSSM**
- 3 CP even $h_1, h_2, h_3$
- 2 CP odd $a_1, a_2$
- 2 CP charged $H^+, H^-$

**Minimal Supersymmetric Standard Model, 2 Higgs Doublet Model**
- 2 CP even $(h^0, H^0)$, 1 CP odd $(A^0)$, 2 CP charged $(H^+, H^-)$

**Standard Model**
- 1 CP even $h$
Exotic Higgs decays - *is it even possible?*

if new physics is allowed to modify the loop-induced couplings

\[ \mathcal{BR} (h \rightarrow \text{BSM}) < 20\% @ 95\% \text{ CL} \]
**Exotic Higgs decays assuming**

\[ \mathcal{BR} (h \leftrightarrow \text{BSM}) = 10\% \]

<table>
<thead>
<tr>
<th>Production</th>
<th>( \sigma_{7 \text{ TeV}} ) (pb)</th>
<th>( N^\text{10%}_{\text{ev}}, 5 \text{ fb}^{-1} )</th>
<th>( \sigma_{8 \text{ TeV}} ) (pb)</th>
<th>( N^\text{10%}_{\text{ev}}, 20 \text{ fb}^{-1} )</th>
<th>( \sigma_{14 \text{ TeV}} ) (pb)</th>
<th>( N^\text{10%}_{\text{ev}}, 300 \text{ fb}^{-1} )</th>
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</thead>
<tbody>
<tr>
<td>ggF</td>
<td>15.13</td>
<td>7,600</td>
<td>19.27</td>
<td>38,500</td>
<td>49.85</td>
<td>1.5 \times 10^6</td>
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<tr>
<td>VBF</td>
<td>1.22</td>
<td>610</td>
<td>1.58</td>
<td>3,200</td>
<td>4.18</td>
<td>125,000</td>
</tr>
<tr>
<td>( hW^\pm )</td>
<td>0.58</td>
<td>290</td>
<td>0.70</td>
<td>1,400</td>
<td>1.5</td>
<td>45,000</td>
</tr>
<tr>
<td>( hW^\pm (\ell^\pm \nu) )</td>
<td>0.58 \cdot 0.21</td>
<td>62</td>
<td>0.70 \cdot 0.21</td>
<td>300</td>
<td>1.5 \cdot 0.21</td>
<td>9,600</td>
</tr>
<tr>
<td>( hZ )</td>
<td>0.34</td>
<td>170</td>
<td>0.42</td>
<td>830</td>
<td>0.88</td>
<td>26,500</td>
</tr>
<tr>
<td>( hZ (\ell^+ \ell^-) )</td>
<td>0.34 \cdot 0.067</td>
<td>11</td>
<td>0.42 \cdot 0.067</td>
<td>56</td>
<td>0.88 \cdot 0.067</td>
<td>1,800</td>
</tr>
<tr>
<td>( t\bar{t}h )</td>
<td>0.086</td>
<td>43</td>
<td>0.13</td>
<td>260</td>
<td>0.61</td>
<td>18,300</td>
</tr>
</tbody>
</table>

**Still plenty of room for Exotic Higgs!**
Sensitivity depends on the channel, model and model parameters

In type-III 2HDM and for $\tan \beta > 1$, $a_1$ boson decays to leptons are enhanced, thus $a_1 \rightarrow 2\mu 2\tau$ becomes more sensitive than $a_1 \rightarrow 2\mu 2b$.
\[ h \rightarrow aa \rightarrow 4\mu + X \]

- Motivated by NMSSM and Dark SUSY models
  - **NMSSM**: CP even \( h_{1,2} \) can decay to \( a_1 \): \( h_{1,2} \rightarrow 2a_1, \ a_1 \rightarrow 2\mu \)
  - **Dark SUSY**: \( h \) decays to lightest visible neutralino: \( h \rightarrow 2n_1, \ n_1 \rightarrow \gamma_D + n_D \)
  - Decays of \( \gamma_D \) give \( 4\mu + X \) as spectator particles

- Isolated muon-pairs (from same vertex) with \( m(\mu\mu) < 9 \text{ GeV} \)

- \( a_1 : [0.25, 3.55] \text{ GeV}, \ \gamma_D [0.25, 8.5] \text{ GeV}, \ m(n_1)=10 \text{ GeV}, \ m(n_D) = 1 \text{ GeV} \)

- Main backgrounds: \( b\bar{b}, J/\psi, \text{ EWK} \rightarrow 4\mu \)
  - \( b\bar{b} \): estimated from data (1 di-\( \mu \) pair + 1 “orphan” \( \mu \))
  - \( J/\psi \): mainly from SPS/DPS estimated from data and simulation
$h \rightarrow aa \rightarrow 4\mu + X$

- Signal is extracted from the 2D $m(\mu\mu)_1, m(\mu\mu)_2$
- Leading systematic comes from trigger SF (6%)
- Results for different $h_1/\gamma_D$ masses

CMS Preliminary

35.9 fb$^{-1}$ (13 TeV)

NMSSM 95% CL upper limits:
- $m_{h_1} = 90$ GeV
- $m_{h_1} = 125$ GeV
- $m_{h_1} = 150$ GeV

Reference model:
- $\sigma(pp \rightarrow h_1 \rightarrow 2a_i) = 0.003 \times \sigma_{SM}$
- $\sigma(pp \rightarrow h_1) \times B(h_1 \rightarrow 2a_i) = 0$ for $j \neq i$

$\tan \beta = 20$

$\gamma_D$ couples to SM photons via $\varepsilon$. The lifetime, and thus displacement, of the $\gamma_D$ depends on $m_{\gamma_D}$ and $\varepsilon$. 

CMS Preliminary

35.9 fb$^{-1}$ (13 TeV)

Kinetic mixing parameter $\varepsilon$

CMS

$B(h \rightarrow 2\gamma_D + X)$

$pp \rightarrow h \rightarrow 2n_1 \rightarrow 2\gamma_D + 2n_D \rightarrow 4\mu + X$

$\gamma_D$ couples to SM photons via $\varepsilon$. The lifetime, and thus displacement, of the $\gamma_D$ depends on $m_{\gamma_D}$ and $\varepsilon$. 

CMS Preliminary

35.9 fb$^{-1}$ (13 TeV)
a $\chi^2$ test is employed to select events

Considering ggF and VBF production for $\mathcal{B}(h \rightarrow a_1 a_1) = 10\%$

Probing $m(a_1)$ [20, 62.5] GeV

Requiring 2 isolated muons, 2 b-jets (Tight + Loose/Medium/Tight) and small MET

Categorization is based on b-tag discriminators (TT, TM, TT)

Contamination from $\tau\tau b\bar{b}$ and $\mu\mu\tau\tau$ is negligible/very small
Background modelling with MultiPdf

Best fit to the data for the Tight-Loose category

Type-III 2HDM+S when $\mu\mu\tau\tau$ is misidentified as $\mu\mu bb$
Probing $m(a_1)$ [15, 62.5] GeV.

- for $m(a_1) < 15$ GeV, no sensitivity due to the boost of the $a_1$

- $\mu\mu + (e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h)$ final states, favoured in 2HDM Type III
- muons have excellent mass resolution
- not considering same-flavour (i.e. $ee, \mu\mu$) due to high bkg rate

Signal is extracted from di-muon mass
- Shape is different depending on the origin of the $\mu$

Signal is parametrized with Voigt ($2\mu2\tau$) / Gaussian+polyn ($4\tau$)
Backgrounds: $ZZ \rightarrow 4\ell$ (irreducible), fake leptons/taus (reducible)

- reducible is decreased with b-jet veto

Reducible comes from jets faking leptons (mostly Z+jets, WZ+jets)

- Shape: from data, ZZ enriched w. SS w. relaxed $\tau_h$ isolation

- Yield: from data with 1 or 2 non-isolated $\tau$ weighted with a mis-id probability

Improving previous results by a factor of two

limits as low as $\sim$2 (20)% for Type III (IV)
Three final states: $e\mu$, $e\tau_h$, $\mu\tau_h$ w. at least 1 b-tagged jet w. $p_T > 20$ GeV

Main background is jets faking taus, and it is estimated from data

Signal is extracted from various di-$\tau$(m$^{\text{vis}}_{\tau\tau}$) categories (12 in total)
Reduced sensitivity for $m_{a_1} < 30$ GeV due to low iso eff. of the di-$\tau$ system

Stronger limits on intermediate (low) $\tan\beta$ in 2HDM+S Type III (IV)
Given than $m_{H(125)} \gg m_{a_1}$ & $H(125)$ is produced with small $p_T$

- $a_1$ bosons highly boosted and “back-to-back”
- $\tau$-leptons from the same $a_1$ overlap
  ➞ thus, hard to reconstruct
  ➞ use simple objects i.e. $\mu$ & tracks

**τ decays**

For each $a_1$ decay leg:

- $a_1 \rightarrow \tau_\mu + \tau_e/\mu_{/\text{had}}, 1\text{-prong}$
- Each $\mu$ is required to have exactly 1 nearby charged track
  - form 2 ($\mu$-trk) pair systems
  - each track w. $p_T > 2.5$ GeV and OS wrt $\mu$

$\mu$ decays

Same-Sign $\mu$ with $\Delta R > 2$

⇒ Suppress $t\bar{t}$, DY, Wjet
Probed mass range $a_1$ [4, 15] GeV
Signal extracted from the 2D $\mu$-trk system
Background is 99% multi-jets
→ Estimated from sideband region
Summary

- Models employing exotic light Higgs decays are still viable
- CMS has in place a rich program covering almost full $m_a$ range
  - $m(a_1) < 15$ GeV favours decays to $4\mu/4\tau$ ($a \rightarrow \tau\tau, bb$)
  - Best limits at high masses in general i.e. in type III with large $\tan\beta$ (enhanced couplings to leptons)

Considerable improved results vs Run I

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**2HDM+S type-2**

$\tan\beta = 2.0$

$19.7 \text{ fb}^{-1} (8 \text{ TeV})$ and $35.9 \text{ fb}^{-1} (13 \text{ TeV})$

**2HDM+S type III**

$\tan\beta = 5.0$

$19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 35.9 \text{ fb}^{-1} (13 \text{ TeV})$
Backup
Example: if a new scalar $s$ is coupled:

$$\Delta \mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

(common building block in extended Higgs)

$$\Gamma_{H(125)}^{(SM)} \sim 4.1 \text{ MeV or } \Gamma_H/m_h \sim 3.3 \times 10^{-5}$$

- That means that even small non-standard couplings to $H \rightarrow \text{BSM}$ can give a sizeable effect ie a non-zero $\mathcal{B} \mathcal{R}$ ($H \rightarrow \text{BSM}$)
- Several BSM models allow for such additional decay modes (Higgs portal, 2HDM, 2HDM+S,NMSSM…)

For $\zeta \sim 0.01$, $\mathcal{B} \mathcal{R}$ ($H \rightarrow \text{BSM}$) is $\mathcal{O}(10\%)$ for $m_s < m_H/2$
Higgs Sector in MSSM

**Minimal Supersymmetric Standard Model**
Minimal extension of the SM, introduction 2 Higgs doublets $H_u, H_d$

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5 mass eigenstates:

2 CP even $h^0, H^0$

1 CP odd $A^0$

2 CP charged $H^+, H^-$

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Still, MSSM faces some phenomenological flaws, to which Next-to-MSSM can solve.
Why going to the NMSSM?

- **MSSM**

  \[ m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left[ \ln \frac{m_t^2}{m_t^2} + \frac{X_t^2}{m_t^2} \left( 1 - \frac{X_t^2}{12m_t^2} \right) \right] \]

- **NMSSM: Mixing with singlet**

  \[ m_h^2 \approx \lambda^2 v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\text{rad}} + \Delta_{\text{mix}} \]

  Ellwanger, arXiv 1108.0157

Increases Higgs mass for large values of \( \lambda \)
Why going to the NMSSM?

- NMSSM has one additional singlet

\[
\begin{align*}
H_1 &= S_{1,d} H_d + S_{1,u} H_u + S_{1,s} S \\
H_2 &= S_{2,d} H_d + S_{2,u} H_u + S_{2,s} S \\
H_3 &= S_{3,d} H_d + S_{3,u} H_u + S_{3,s} S
\end{align*}
\]

<table>
<thead>
<tr>
<th></th>
<th>MSSM</th>
<th>NMSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 CP even</td>
<td>2 CP odd</td>
<td>3 CP even</td>
</tr>
</tbody>
</table>

- Pros of NMSSM
  - Increase light Higgs mass
  - Modified couplings to up-/down-type fermions (if \( R_{\gamma\gamma} \neq 1 \))
  - Solves \( \mu \)-Problem (Kim, Nilles Phys. Lett. B 138, 150 (1984))

- Cons
  - More free parameters: couplings \( \lambda, \kappa \)
    - trilinear couplings \( A_\kappa, A_\lambda \)
    - mixing parameter \( \mu_{\text{eff}} = \lambda \langle S \rangle \)
  - (in addition to \( m_0, m_{1/2}, A_0, \tan \beta )\)
Couplings of the neutral scalar and pseudoscalar mass eigenstates in the four types of 2HDM

<table>
<thead>
<tr>
<th>Couplings</th>
<th>I</th>
<th>II</th>
<th>III (Lepton specific)</th>
<th>IV (Flipped)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{VV}$</td>
<td>sin($\beta - \alpha$)</td>
<td>sin($\beta - \alpha$)</td>
<td>sin($\beta - \alpha$)</td>
<td>sin($\beta - \alpha$)</td>
</tr>
<tr>
<td>$g_{tt}$</td>
<td>cos $\alpha$/ sin $\beta$</td>
<td>cos $\alpha$/ sin $\beta$</td>
<td>cos $\alpha$/ sin $\beta$</td>
<td>cos $\alpha$/ sin $\beta$</td>
</tr>
<tr>
<td>$h$</td>
<td>cos $\alpha$/ sin $\beta$ - sin $\alpha$/ cos $\beta$</td>
<td>cos $\alpha$/ sin $\beta$</td>
<td>- sin $\alpha$/ cos $\beta$</td>
<td>cos $\alpha$/ sin $\beta$</td>
</tr>
<tr>
<td>$g_{b\bar{b}}$</td>
<td>cos $\alpha$/ sin $\beta$ - sin $\alpha$/ cos $\beta$</td>
<td>- sin $\alpha$/ cos $\beta$</td>
<td>cos $\alpha$/ sin $\beta$</td>
<td>cos $\alpha$/ sin $\beta$</td>
</tr>
<tr>
<td>$g_{HVV}$</td>
<td>cos($\beta - \alpha$)</td>
<td>cos($\beta - \alpha$)</td>
<td>cos($\beta - \alpha$)</td>
<td>cos($\beta - \alpha$)</td>
</tr>
<tr>
<td>$g_{Ht\bar{t}}$</td>
<td>sin $\alpha$/ sin $\beta$</td>
<td>sin $\alpha$/ sin $\beta$</td>
<td>sin $\alpha$/ sin $\beta$</td>
<td>sin $\alpha$/ sin $\beta$</td>
</tr>
<tr>
<td>$H^0$</td>
<td>sin $\alpha$/ sin $\beta$</td>
<td>cos $\alpha$/ cos $\beta$</td>
<td>sin $\alpha$/ sin $\beta$</td>
<td>cos $\alpha$/ cos $\beta$</td>
</tr>
<tr>
<td>$g_{H^{0}b\bar{b}}$</td>
<td>sin $\alpha$/ sin $\beta$</td>
<td>cos $\alpha$/ cos $\beta$</td>
<td>sin $\alpha$/ sin $\beta$</td>
<td>sin $\alpha$/ sin $\beta$</td>
</tr>
<tr>
<td>$g_{H^{0}t\bar{t}}$</td>
<td>sin $\alpha$/ sin $\beta$</td>
<td>cos $\alpha$/ cos $\beta$</td>
<td>sin $\alpha$/ sin $\beta$</td>
<td>sin $\alpha$/ sin $\beta$</td>
</tr>
<tr>
<td>$g_{AVV}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$g_{At\bar{t}}$</td>
<td>cot $\beta$</td>
<td>cot $\beta$</td>
<td>cot $\beta$</td>
<td>cot $\beta$</td>
</tr>
<tr>
<td>$g_{A\bar{b}\bar{b}}$</td>
<td>- cot $\beta$</td>
<td>tan $\beta$</td>
<td>- cot $\beta$</td>
<td>tan $\beta$</td>
</tr>
<tr>
<td>$g_{A\tau\bar{\tau}}$</td>
<td>- cot $\beta$</td>
<td>tan $\beta$</td>
<td>tan $\beta$</td>
<td>- cot $\beta$</td>
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<table>
<thead>
<tr>
<th></th>
<th>Type-1</th>
<th>Type-2</th>
<th>Type-3 (lepton-specific)</th>
<th>Type-4 (flipped)</th>
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<tbody>
<tr>
<td>Up-type quarks</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
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<td>Down-type quarks</td>
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<td>Charged leptons</td>
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<td>$\Phi_1$</td>
<td>$\Phi_1$</td>
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