Searches for extended scalar sectors in CMS

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Additional Higgs-like scalars

- The observation of a H(125) scalar and measurement of its properties showed compatibility with the SM Higgs boson.
  - But many fundamental open questions still exist

Rich search program by adapting h(125) strategies for higher- and lower-mass scalars, in different production and decay modes.
Indirect constraints from H(125)

- Searches for deviations from the SM in H(125) measurements set constraints on 2HDM / MSSM scenarios
  - Couplings, CP, spin

- Translate 2HDM parameters to couplings and use 3D likelihood scans of parameterizations in \{\lambda_{du}, \lambda_{Vu}, \kappa_{uu}\} or \{\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}\}

**Ratio of couplings for up-vs down-type fermions**

**hMSSM: same Higgs structure as 2HDM Type-II**
Overview of BSM Higgs searches (CMS)

- Direct searches for BSM phenomena

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<td>bbττ</td>
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| X → γγ | |

| X: generic resonance including H |

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<th>H/A → ττ</th>
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| H± | τV |
|    | tb |
| WZ |

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<th>A → Zh</th>
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<td>2μ2τ</td>
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<td>2b2τ</td>
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| Model-independent or specific to 2HDM/NMSSM |

Run1 grand summary: Interpretations into specific 2HDM model -> hMSSM

CMS Preliminary $\leq 5.1$ fb$^{-1}$ (7 TeV) + $\leq 19.7$ fb$^{-1}$ (8 TeV)

Model not strictly applicable

- h(125) (HIG-15-002)
- A/H → bb (arXiv:1506.08329)
- A/H/h → μμ (arXiv:1508.01437)
- A/H/h → ττ (HIG-14-023)
- H → hh (bqq) / A → Zh (llττ) (arXiv:1510.01181)
- H → hh (bγγ) (HIG-13-032)
- H → WW/ZZ (arXiv:1504.00936)

m_A [GeV]
**H → VV (ZZ / WW)**

- Most BSM models allow $H → VV$ decay
- Such searches usually look for
  - $ggH$ and VBF: probes $XVV$ coupling
  - Spin-zero scalar resonance: take into account interference with SM background and $H(125)$
- Several models considered since early Run 2
  - Heavy scalar with SM couplings
  - Electroweak singlet mixing with light scalar
    \[ \Gamma' = \Gamma_{SM} \frac{C^2}{1 - B_{\text{new}}} , \quad C^2 + C'^2 = 1 \]

**$H → ZZ → 2\ell 2\nu$**

**$H → ZZ → 4\ell$**

- ggH, EWS, $B_{\text{new}} = 0$
- 2HDM, Type-II

**CMS-PAS-HIG-15-004**

**CMS-PAS-HIG-16-001**
**H → ZZ → 4l/2l2q/2l2v**

- Search for a high mass scalar resonance with model-independent approach:
  - Scanned Masses: $130 - 3000 \text{ GeV}$, Width: $0 - 30\% m_\chi$
  - $4l$: lowest BR, search in $m_{4l}$
  - $2l2q$: largest BR, search in $m_{ZZ}$, explore boosted and resolved $Z\rightarrow qq$
  - $2l2v$: large BR, signal extraction with $M_T$

\[
M_T^2 = \left( \sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_T^{\text{miss}} + M_Z^2} \right)^2 - (p_T(\ell\ell) + E_T^{\text{miss}})^2
\]

**H → ZZ → 4l**

**H → ZZ → 2l2q**

**H → ZZ → 2l2v**
Combined results $X(H)$ to ZZ to $4l$, $2l2q$ and $2l2v$ final states

No significant excess over SM expectations
- Total cross section limit with VBF / ggF ratio floated and $f(VBF) = 1$

Limits on $\sigma(pp \rightarrow X(H) \rightarrow ZZ)$ as a function of $m_X$ and various widths ($\Gamma = 0, 10, 100$ GeV)

Model independent limits on $\sigma_{prod}$ ($pp \rightarrow H \rightarrow ZZ$):
\( \mathcal{H} \rightarrow \gamma \gamma \)

- Searches for low mass (\( m_{\mathcal{H}} < 125 \text{ GeV} \)) resonances in \( \gamma \gamma \), already since Run1.

- Fit in the di-photon invariant mass [70, 110] GeV
  - Signal model + event categorizations as in standard \( \mathcal{H} \rightarrow \gamma \gamma \) analysis

- **Normalized to SM-like BSM Higgs boson expectation**

- **Unnormalized**

- \( 13 \text{ TeV}: 2.9 \sigma \) local (1.47 \( \sigma \) global) at \( m_{\mathcal{H}} = 95.3 \text{ GeV} \)

- \( 8 \text{ TeV} + 13 \text{ TeV} \) combined: 2.8 \( \sigma \) local (1.3 \( \sigma \) global) for same mass hypothesis
Neutral $A/H/h \rightarrow \tau\tau$

- Favored for exploring MSSM Higgs sector; sensitive at high $\tan\beta$ in MSSM-like models
  - Enhanced coupling to down-type fermions $\rightarrow$ also motivates search for scalar in association with bottom

- 4x2 categories:
  - $e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$ with ‘no b-tag’ and ‘b-tag’

- Signal extraction:
  
  $m_T^{\text{tot}} = \sqrt{m_T^2(l_1, E_T) + m_T^2(l_2, E_T) + m_T^2(h, l_2)}$

\[ \mu\tau_h \text{ in ‘no b-tag’ and ‘b-tag’ categories} \]
**A/H/h → ττ**

Model independent limits on $\sigma_{\text{prod}} \times \text{BR}$:

MSSM interpretation:

$m_{h_{\text{mod+}}}^\text{max}$: $m_h$ modified to $m_h=125$

hMSSM: $m_h=125$ by tuning radiative corrections.
Enhanced b-coupling; complementary to H→ττ for MSSM scenarios

H→bb dominant decay mode → challenging large QCD background → control with >= 3b-tag jets selection

**Limits on tanβ (hMSSM)**

![Graph showing limits on tanβ for hMSSM scenarios](image)

**Constraints on tanβ (flipped scenario)**

![Graph showing constraints on tanβ for flipped scenario](image)
Charged $H^\pm$

- $H^\pm \rightarrow \bar{c} b$ in lepton+jets channel
  - Di-jet mass reconstruction in lepton+jets
  - Set limits on BR($t \rightarrow H^+ b$)

- $H^\pm \rightarrow \tau^\pm \nu$, $\tau$ decay channel in fully hadronic final state

- Two scenarios:
  - Light $H^\pm$: $m_{H^\pm} < m_t - m_b$
  - Heavy $H^\pm$: $m_{H^\pm} > m_t - m_b$
Charged $H^\pm$ cont.

- Charged $H^\pm$ to WZ
  - Narrow-width resonance
  - Limits on $\sigma_{VBF} \times BR(H^\pm \to WZ)$ for $m_{H^\pm}$: [200,2000] GeV

- Doubly-charged Higgs (3 or 4 lepton final states)
  - Limits under various decay hypothesis

- Extend SM with scalar triplet $\phi$

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**Charged Higgs to WZ**

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- Limits on $\sigma_{VBF} \times BR(H^\pm \to WZ)$ for $m_{H^\pm}$: [200,2000] GeV

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Di-Higgs

- HH production
  - SM: $\sigma(13\text{TeV}) = 33.45$ fb
  - SM HH@HLC: not expected to be sensitive

- BSM can increase $\sigma(HH)$
  - $k_\lambda = 10 \rightarrow \sigma_{\text{BSM}} = 10 \times \sigma_{\text{SM}}$

BSM HH production

- Resonant HH: searches for a narrow width resonance (warped extra dimensions, low $\tan\beta$ MSSM, singlet models etc)

- Non-resonant HH enhanced; can be used to study Higgs self-coupling.
Di-Higgs

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  BSM HH production

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HH → (bb) (bb)

- HH system decaying to 4b-jets
  - most sensitive channel to search for HH resonances for $m_X > 350$ GeV

- Boosted techniques; double-b tagging

- Signal region is defined as the elliptical region in $(m_{H1}, m_{H2})$ plane

- Spin0/2 hypotheses tested separately due to different signal efficiency

**Upper limits on cross section for $\sigma (pp \rightarrow X \rightarrow H(bb)H(bb))$**
Resonance mass [GeV]

300
400
500
600
700
800
900

$b b \gamma \gamma \rightarrow HH \rightarrow (X B) X \rightarrow (pp \sigma) (X B) X$

$95\%$ CL upper limits

Observed

Expected

1 std. deviation

Expected

2 std. deviation

Expected

$\lambda = 2$ TeV

$\Lambda_b = 3$ TeV

$\kappa = 0.5$

$\kappa = 1.0$

$\lambda = c_0 = c_2 = 0$

$\kappa_i = 1$

Resonant HH limits on WED models: spin0/spin2

Use BDT to separate signal from overwhelming background

Two signal hypotheses: non-resonant signal (SM+BSM) and resonant signals (all masses, both spins)

Limits on spin-0 and spin-2 signal hypotheses

Resonant HH $\rightarrow (bb) (\gamma\gamma)$

$HH \rightarrow bb\gamma\gamma$: leads the overall sensitivity at the low mass region

NonResonant: Upper limits for BSM models

Bulk radion

Rad. $m_X = 600$ GeV

$gg \rightarrow HH \times 10^5$

$VBF HH \times 10^5$

Grav. $m_X = 300$ GeV

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

CMS-PAS-HIG-17-008

$HH \rightarrow (bb) (\gamma\gamma)$

Classification MVA

Events/(0.04)

$\sqrt s = 13$ TeV

$1$ fb$^{-1}$
- Resonant and non-resonant hh $\rightarrow$ bblvlv
- Train MVA on kin. variables (without $mjj$) to discriminate signal and bkg
  - Multi-signal, multi-categories -> use DeepNN with parameterized Machine Learning
  - Resonant: $mX = 13$ values [260, 900] GeV
  - Non resonant: 32 combinations of $\kappa_\lambda, \kappa_t$
    $$\kappa_\lambda = -20, -5, 0, 1, 2.4, 3.8, 5, 20$$
    $$\kappa_t = 0.5, 1, 1.75, 2.5$$
- Final discriminant: $mjj$ vs MVA
**BSM Higgs to aa**

- Additional singlet + doublet $\rightarrow 7$ Higgs bosons ($h_{1,2,3}, a_{1,2}, H^\pm$) $\rightarrow$ NMMSM

- Low mass resonances searched in exotic decays of $H(125)$: $h \rightarrow aa$

### $h \rightarrow aa \rightarrow 2\mu 2\tau$

![Graph showing $h \rightarrow aa \rightarrow 2\mu 2\tau$ events](image)

### $h \rightarrow aa \rightarrow 2b2\tau$

![Graph showing $h \rightarrow aa \rightarrow 2b2\tau$ events](image)

**$h \rightarrow aa$ summary plot**

(8 TeV + 13 TeV)

- 19.7 fb$^{-1}$ (8 TeV) + 35.9 fb$^{-1}$ (13 TeV)

**95% CL on $\sigma(h \rightarrow aa)/\sigma_{\text{SM}}$**

- 2HDM+S type III
  - $\tan\beta = 5.0$

**$m_a$ (GeV)**

- Expected
- Observed
Summary and outlook

- Rich CMS program to search for new higgs-like scalars covering almost all possible final states
  - Topologies with heavy objects (b quarks, τ leptons) favored
- BSM Higgs searches as powerful tool to test the SM
- Advanced analysis techniques emerge since beginning of Run2:
  - Advanced Multivariate classifiers (DNN)
  - Jet substructure in boosted topologies
  - Sophisticated kinematic observables and selections
- Many more results awaited to exploit full LHC luminosity in 2017+2018!
Back ups
tt A/H $\rightarrow$ tt tt

- Same-sign dileptons
**HH → (bb)(ττ)**

- **HH tag:**
  - invariant mass cut based on $m(ττ)$ and $m(bb)$ resolution
  - BDT discriminant against $t\bar{t}$ in $eτ_h$ and $μτ_h$
- Limit extraction: fitted HH mass (resonant) and MT2 (non-resonant)

**Upper limits on cross section as a function of $k_λ/k_t$**