Searches for BSM Higgs bosons at CMS

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Introduction

Where do we look for BSM in the Higgs sector?

After the discovery of the Higgs boson at 125 GeV, we have mainly three handles to use

- Properties for the \( h_{125} \) Higgs boson (see P. Milenovic talk)
- Rare decays: \( Z\gamma, \gamma\gamma^*, \mu\mu \)
- Search for additional Higgs bosons
Searches for neutral Higgs bosons

- In most cases, search is just a reinterpretation of SM analysis
- Assume h(125), add additional boson(s)
- All states contribute to unitarization of $V_L V_L \rightarrow V_L V_L$ and $V_L V_L \rightarrow f \bar{f}$
- Unitarity + custodial symmetry: two constraints to coupling scale factors $\kappa = \frac{g_{\text{meas}}}{g_{\text{SM}}}$

\[ \kappa_v^2 + \kappa_{v'}^2 = 1 \quad \kappa_v \kappa_f + \kappa_{v'} \kappa_{f'} = 1 \]

\[ \kappa_v = \sin \alpha \quad \kappa_{v'} = \cos \alpha \]

- $\kappa_f$ may or may not be the same for all fermions
- One can define benchmarks by setting conditions on the fermion/boson and fermion/fermion relative scale factors

See YR3: arXiv 1307.1347
EWK singlet

- Common scaling factor for all fermions and gauge bosons
- End up with two scalar mixed states with same kinematics as SM but couplings and widths rescaled
- If decays same as SM:
  \[ \sigma'_h = \sin^2 \alpha \sigma_{h,SM} \]
  \[ \sigma'_H = \kappa^2 \sigma_{H,SM} = \cos^2 \alpha \sigma_{H,SM} \]
  \[ \Gamma'_H = \kappa^2 \Gamma_{SM} \]
  → can use the h(126) measured signal strength to put limits on the additional Higgs boson
  Smaller yields, narrower width
- If additional decays are available
  \[ \mu'_H = \kappa^2 (1 - BR_{new}) \]
  \[ \Gamma'_H = \frac{\kappa^2}{(1 - BR_{new})} \Gamma_{SM} \]
  \[ BR_{new} \rightarrow BR \text{ for additional decays} \]
  (like \( H \rightarrow hh \))
First results from EWK singlet searches

CMS PAS HIG-13-014

$H \rightarrow ZZ \rightarrow 2l2\nu$

CMS PAS HIG-13-008

$H \rightarrow WW \rightarrow l\nu qq'$

Direct limit from the 125 Higgs boson

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### 2HDM

- One more degree of freedom: different scaling factor for leptons/bosons, up/down lepton&quarks, leptons/quarks, …
- Free parameters (more general than MSSM)
  - $m_{h'}$, $m_{H'}$, $m_A$, $m_{H^\pm}$, $m_{12}$, $\tan \beta$, $\alpha$
  - Mixing angle for CP-even $h$ and $H$
- All mass eigenstates couple to both $h$ and $H$ in all models, but couplings depend on model

<table>
<thead>
<tr>
<th></th>
<th>Type I</th>
<th>Type II</th>
<th>Lepton-specific</th>
<th>Flipped</th>
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<tbody>
<tr>
<td>$\xi_u$</td>
<td>$\cos \alpha / \sin \beta$</td>
<td>$\cos \alpha / \sin \beta$</td>
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<td>$\xi_h$</td>
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$\kappa_v \sim \sin(\beta - \alpha)$

$\kappa'_v \sim \cos(\beta - \alpha)$

Different scaling for up and down fermions

Different scaling for leptons and quarks

Different scaling for up and down quarks, leptons flipped

See arXiv 1106.0034
Search for $H \rightarrow hh$ and $A \rightarrow Zh$

Exclusive search in multileptons and diphoton + leptons channels

**Multileptons:** require at least three leptons, at most one of which a $\tau_{\text{had}}$

**Diphotons:** exactly two photons and at least one lepton

**$H \rightarrow hh$**

<table>
<thead>
<tr>
<th>$h \rightarrow WW^*$</th>
<th>$h \rightarrow ZZ^*$</th>
<th>$h \rightarrow \tau\tau$</th>
<th>$h \rightarrow bb$</th>
<th>$h \rightarrow \gamma\gamma$</th>
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<td>✓</td>
<td>✓</td>
<td>X</td>
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</tr>
<tr>
<td>h → ZZ*</td>
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<td>h → γγ</td>
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**A → Zh**

<table>
<thead>
<tr>
<th>$Z \rightarrow ll$</th>
<th>$h \rightarrow WW^*$</th>
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CMS PAS HIG-13-025

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2HDM interpretation of $H \rightarrow hh$ and $A \rightarrow Zh$

- Use SuShi + 2HDMC to calculate cross sections and BRs from theory parameters
- Translate limits on $\sigma^*BR$ in limits on $\alpha$ and $\beta$
(N)MSSM searches

- Searches in a specific 2HDM (Type-II)
- Only two free parameters: typically $\tan\beta$ and $m_A$
- Searches in both neutral and charged sector
- Direct search: inclusive and b-tagged
- $\tau$ in both leptonic and hadronic decays

Model-independent limits by separating production modes

CMS Preliminary, $H \rightarrow \tau\tau$, $L = 19.7 \text{ fb}^{-1}$ at 8 TeV

- $m_\Phi = 180$ GeV
- $95\%$ CL
- $68\%$ CL
- $\ast$ Best fit

CMS-HIG-13-021

$m_\Delta < 140 \sim$ excluded

MSSM $m_h^\text{max}$ scenario $M_{\text{SUSY}} = 1$ TeV
NMSSM: extend MSSM by adding a complex singlet field

- Additional CP-even and CP-odd bosons
- Search performed below the $2\tau$ threshold for $a_1$

CMS Prelim. 2012 $\sqrt{s} = 8$ TeV $L_{\text{int}} = 20.65$ fb$^{-1}$

- $H \rightarrow a_1 a_1 \rightarrow 4\mu$

CMS HIG-13-010

NMSSM 95% CL Limits:
- $m_{a_1} = 3.55$ GeV/c$^2$
- $m_{a_1} = 2$ GeV/c$^2$
- $m_{a_1} = 0.25$ GeV/c$^2$
- Prediction with $\sigma(pp \rightarrow h_1) = \sigma_{\text{SM}}(m_{h_1})$, $\sigma(pp \rightarrow h_{1,2}) \times B(h_{1,2} \rightarrow 2a_1) = 0$, $B(h_1 \rightarrow 2a_1) = 0.8\%$ and $B(a_1 \rightarrow 2\mu) = 7.7\%$
• Search of a hh resonant structure in the region 260-1100 GeV

• Search in the $\gamma \gamma$ peak for $m_X < 400$ GeV and in $m_{\gamma\gamma jj}$ for $m_X > 400$ GeV

• $bb \rightarrow$ high BR, $\gamma \gamma \rightarrow$ moderate background and good mass resolution

![Graphs showing $X \rightarrow HH \rightarrow 2\gamma 2b$]
Separate spin-0 and spin-2 hypotheses
- Can search radion and KK decays
- Can also look for 2HDM heavy Higgs decays (planned)

Radion with mass $m_X < 970$ GeV excluded
Conclusions

- Searches for BSM Higgs bosons are a fundamental companion to precision measurements of the h125 properties
- A large part of the SM extensions in the market forsee the existence of additional bosons that contribute to EWSB
- CMS is pursuing both possible approaches to searches:
  - “Model independent” searches for additional scalars or doublets
  - Look for model specific signatures
- The plan is to complete the Run1 analyses and get ready for the next data taking!