BSM Higgs searches

Adrien Caudron (UCLouvain – CP3) on behalf of CMS experiment

Higgs Hunting 2015
30th July – 1st August 2015
Orsay, France

Outline:
- Search for non-SM h decays
- Search for non-SM h production
- Search for other Higgses
**h → invisible**

- Vector Boson Fusion production of $h →$ best sensitivity [1]
- Combination with $Z(ll)h$ and $Z(bb)h$ [1,2]

$$m_h = 125 \text{ GeV limit on } B(h → \text{invisible})$$
- VBF: 57% (exp. 40%)
- VBF+ZH: 47% (exp. 35%)

Possible reinterpretation in terms of limit on a DM candidate
- spin-independent DM-nucleon cross section in Higgs-portal models comparisons with other DM experiments

From [2], not include latest VBF update

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[1] CMS-PAS-HIG-14-038
h → γ + invisible

More on talk from R. Teixeira De Lima later today (link)

- low-scale SUSY models
  - Gravitino (Ğ) produced by the decay of a Neutralino (χ₁)
    - χ₁ → Ğ+γ
    - m₇ negligible and m₇ ranging from 1 to 120 GeV
  - Two cases:
    - h → Ğ+χ₁ (m₇/2 < m₇ < m₇)
    - h → χ₁χ₁ (m₇ < m₇/2)
- Limit expressed as function of m₇ and cₜ₇

Flavour-violating Higgs processes

- Searches for flavour-violating decay or production of the $h$ boson
  - $h \rightarrow \mu \tau$
  - $t \rightarrow c h$
- Limits on branching ratio at 95% CL
  - $B(h \rightarrow \mu \tau) < 1.51\%$ [1]
  - $B(t \rightarrow c h) < 0.56\%$ [2]
- Probe Higgs Yukawa couplings
  - Better limits than previous analyses for $Y_{\mu \tau}$
  - $\sqrt{|\lambda_{tc}^h|^2 + |\lambda_{ct}^h|^2} < 0.14$

Looking for heavy resonances decaying in pair of $h$ bosons

- $X$ can be reinterpreted as:
  - Spin-0 radion or spin-2 graviton [1,2]
    - In Warped Extra Dimensions models
  - High mass $H$ [3, 4]
SM h boson search for high mass → reinterpreted in terms of BSM models
- Combine $l\nu l\nu$, $l\nu q\bar{q}$, $4l$, $ll\nu\nu$, $llqq$

Probe $m_X$ in [145 - 1000] GeV

Assume SM Higgs-like productions and decays

Reinterpretation in terms of EW singlet extension of SM in terms of model parameters:
- $B_{\text{new}}$: branching fraction of the EW singlet to non-SM decay mode
- $C'$: the scale factors of the couplings with respect to the SM of the high-mass Higgs boson

Only consider cases with $\Gamma_H \leq \Gamma_{\text{SM}}$

Results provided independently for each h decays and production mode (ggh, VBF, $h\to ZZ$, $h\to WW$)

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More on talk from B. Courbon yesterday (link)

- Low mass search [80-110] GeV (new results) [1]
  - Test different signal width up to 10% of the mass
  - Interpretation for spin-0 and spin-2 resonances
  - Limits as function of:
    - $m_X$
    - $m_X$ vs $\Gamma_X$
    - Model dependent $\tan \beta$ vs $\cos(\beta-\alpha)$ at fix $m_X$

[1] CMS-HIG-14-037

Other di-boson search: $X \rightarrow Z \gamma$ (CMS-PAS-HIG-14-031, backup)
A $\rightarrow$ Zh

- Several channels
  - $Z(\ell\ell) h(\tau\tau)$ (new) [1]
  - $Z(\ell\ell) h(bb)$ [2]
  - Multi-leptons and leptons+photons [3]
- Target MSSM like models
  - Model dependent and model independent limits

[1] Paper to be submitted soon, EPS talk
Combination \( H \rightarrow hh \) and \( A \rightarrow Zh \)

- Several channels can be combined for defined BSM models
  - Example: \( H \rightarrow hh + A \rightarrow Zh \)
- Limits derived as function of \( m_A \) vs \( \tan\beta \) and \( \tan\beta \) vs \( \cos(\beta-\alpha) \)

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[1] Paper to be submitted soon, EPS talk
H → ZA, A → ZH

- 2HDM with non-degenerate H and A, $m_h = 125$ GeV, $m_{H^±} = \max(m_H, m_A)$
- Two channels:
  - $Z(\ell\ell)A/H(b\bar{b})$
  - $Z(\ell\ell)A/H(\tau\bar{\tau})$
- Limit as function of $m_H$ and $m_A$ for $\cos(\beta - \alpha) = 0.01$, $\tan\beta = 1.5$
- Limit as function of $\tan\beta$ and $\cos(\beta - \alpha)$ for $m_H = 350$ GeV, $m_A = 150$ GeV
Light Higgses

- 2 analyses in the context of NMSSM:
  - $h_1 + X \rightarrow bb + X$ [1]
    - $30 < m_{h_1} < 100$ GeV
  - $h_{1,2} \rightarrow a_1(\mu\mu)a_1(\mu\mu) + X$ [2]
    - $0.25 < m_{a_1} < 3.55$ GeV and $90 < m_{h_{1,2}} < 150$
- $bbA$ production with $A \rightarrow \tau\tau$ in the context of the 2HDM type II (new) [3]
  - $25 < m_A < 80$ GeV
  - Comparisons with models with different $Y_b$ sign

[1] CMS-PAS-HIG-14-030
[3] Paper to be submitted soon, EPS talk
MSSM $\Phi \rightarrow bb, \tau\tau$

- Search for new resonances in $bb$ and $\tau\tau$ in the context of MSSM
  - $\Phi$ can be $A$, $h$, $H$
  - $\Phi \rightarrow bb$ consider only production with extra $b$'s [1]
    - Sensitive mainly to large $\tan\beta$
  - $\Phi \rightarrow \tau\tau$ consider also $gg\Phi$ production [2]
  - 5 scenarios tested: $m_h^{\text{max}}$, $m_h^{\text{mod}+}$, $m_h^{\text{mod}-}$, light-stop, and light-stau (+ $\tau$-phobic, and low-$m_H$ for $\Phi \rightarrow \tau\tau$)

[2] HIG-14-029, EPS talk
Charged Higgses

- Several channels explored:
  - $tt \rightarrow WbH^\pm b$ ($H^\pm \rightarrow \tau \nu$, cs) [1, 2]
    - $m_{H^\pm} < m_t \rightarrow$ limit on $B(t \rightarrow H^\pm b)$
  - $tH^\pm$ ($H^\pm \rightarrow \tau \nu$, $tb$) [1, 3]
    - $m_t < m_{H^\pm} \rightarrow$ limit on $\sigma \times B$

[1] CMS-PAS-HIG-14-020
Summary

• Discovery of SM Higgs boson enhance interest for this topic
• Wide CMS BSM Higgs search program during Run1
  – Complementary to SM Higgs precision measurements
• Until now → no evidence of new physics in the Higgs sector observed
  – Large phase space explored
  – Limits set on $\sigma \times B$
    • Sensitivity reached O(10 fb) for several analyses
  – Interpretation of the limits in several BSM models (generic 2HDM, MSSM, NMSSM, DM candidate, singlet...)
• Run2 LHC would allow to push further the searches
  – New ideas for final states and models to explore are always welcomed
Backup
**h → invisible (additional information)**

- Vector Boson Fusion production of h → best sensitivity [1]
  - Improvement w.r.t. to [2] due to “parked” data recorded in 2012 and reconstructed in 2013
  - Lower trigger threshold → larger acceptance → improvement on the selection to increase the sensitivity
    - Expected limits on B(h → inv): 0.49% → 0.40%

- Other result: assuming SM Higgs-like particle H → limit on $\sigma \times B(H \rightarrow inv)$ vs $m_H$

![Graph showing $\sigma \times B(H \rightarrow inv)$ vs $m_H$](image1)

**References**

[1] CMS-PAS-HIG-14-038

$h \rightarrow \gamma + \text{invisible (other results)}$

- Results also expressed in function of $m_H$ where $H$ is a SM-like H boson

Figure 6: Expected and observed 95% CL upper limits on $\sigma_{gg \rightarrow H} B$ as a function of the Higgs boson mass with $m_{\chi_1^0} = m_H - 30 \text{GeV}$ in ggH channel (left) and in the ZH channel (right).

$h \rightarrow \mu \tau$ and $t \rightarrow ch$ (additional material)

- Limits on branching ratio at 95% CL by channels and compared to expectation

![Graph showing CMS data for $h \rightarrow \mu \tau$ and $t \rightarrow ch$]

<table>
<thead>
<tr>
<th>Higgs boson decay mode</th>
<th>Obs.</th>
<th>Exp.</th>
<th>68% C.L. range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(h \rightarrow WW^*)$</td>
<td>23.1%</td>
<td>1.58%</td>
<td>(1.02–2.22)%</td>
</tr>
<tr>
<td>$B(h \rightarrow \tau\tau)$</td>
<td>6.15%</td>
<td>7.01%</td>
<td>(3.53–7.74)%</td>
</tr>
<tr>
<td>$B(h \rightarrow ZZ^*)$</td>
<td>2.89%</td>
<td>5.31%</td>
<td>(2.85–6.45)%</td>
</tr>
<tr>
<td>Combined multileptons ($WW^<em>, \tau\tau, ZZ^</em>$)</td>
<td>1.28%</td>
<td>1.17%</td>
<td>(0.85–1.73)%</td>
</tr>
<tr>
<td>$B(h \rightarrow \tau\tau)$</td>
<td>0.23%</td>
<td>0.69%</td>
<td>(0.60–1.17)%</td>
</tr>
<tr>
<td>Combined multileptons + diphotons</td>
<td>0.75%</td>
<td>0.56%</td>
<td>(0.46–0.94)%</td>
</tr>
</tbody>
</table>

[1] CMS-PAS-HIG-14-005
$X \rightarrow hh \rightarrow bbbb, bbyy, \text{ multi-lepton and leptons+photons}$ (other results)

- Looking for heavy resonances decaying in pair of $h$ bosons
- $X$ can be reinterpreted as spin-2 graviton [1,2]
  - In Warped Extra Dimensions models
- High mass $H \rightarrow$ limits on 2HDM models parameter [3]

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SM h boson search for high mass → reinterpreted in terms of BSM models
- Combine $l\nu l\nu, l\nu qq, 4l, ll\nu, llqq$
- Probe $m_X$ in [145 - 1000] GeV
- Assume SM Higgs-like production and decay

Reinterpretation in terms of EW singlet extension of SM in terms of model parameters:
- $B_{\text{new}}$: branching fraction of the EW singlet to non-SM decay mode
- $C'$: the scale factors of the couplings with respect to the SM of the high-mass Higgs boson
- Only consider cases with $\Gamma_H \leq \Gamma_{\text{SM}}$

Results provided independently for each h decays and production mode (ggh, VBF, $h \rightarrow ZZ$, $h \rightarrow WW$)

Search for excess on top of background
- Test different signal width up to 10% of the mass
Range explored: [150-850] GeV
Interpretation for spin-0 and spin-2 resonances
Limits as function of:
- $m_X$ (spin-2 small width, spin-0 large width)
- $\Gamma_X$ for $m_X = 840$ GeV

Search for an excess in $Z(\ell\ell)\gamma$ with $\ell = e, \mu$

Explore mass range [200-500]

Test several $X$ width hypothesis
- Broad width: SM-like $H$ width
- Narrow width: $1\%$ of $m_X$
A → Zh (more results)

- Several channels
  - Z(ll)h(bb) [1]
  - Multi-leptons and leptons+photons [2]
- Target MSSM like models
  - Model dependent and model independent limits

H → ZA, A → ZH (llττ results)

- 2HDM with non-degenerate H and A, $m_H = 125$ GeV, $m_{H^\pm} = \max(m_H, m_A)$
- Two channels:
  - $Z(ll)A/H(bb)$
  - $Z(ll)A/H(\tau\tau)$
- Limit as function of $m_H$ and $m_A$ for $\cos(\beta - \alpha) = 0.01$, $\tan\beta = 1.5$
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Light Higgses (other results)

- \( h_1 + X \to bb + X \) [1] → interpretation of the limits:
  - considering whole NMSSM P4 benchmark with fixed M3~1TeV (gluino mass)
  - Limit on M3 for fixed M1 (bino) and M2 (wino) masses
- \( h \to \gamma_D(\mu\mu)\gamma_D(\mu\mu) + X \) [2] in SUSY model with dark sector
  - \( h=h_{\text{SM}}(125) \)
  - Limit vs \( \epsilon \) (kinetic mixing parameter between SM \( \gamma \) and the dark \( \gamma_D \)) and \( m_{\gamma_D} \)

[1] CMS-PAS-HIG-14-030
MSSM $\Phi \to bb, \tau\tau$ (additional results)

- Search for new resonances in $bb$ and $\tau\tau$ in the context of MSSM
  - $\Phi$ can be $A$, $h$, $H$
  - $\Phi \to bb$ consider only production with extra $b$'s [1]
    - Sensitive mainly to large $\tan\beta$
  - $\Phi \to \tau\tau$ consider also $gg\Phi$ production [2]
  - 5 scenarios tested: $m_h^{max}$, $m_h^{mod+}$, $m_h^{mod-}$, light-stop, and light-stau (+ $\tau$-phobic, and low-$m_H$ for $\Phi \to \tau\tau$)

[2] HIG-14-029, EPS talk
Charged Higgses (more results)

- Several channels explored:
  - $tt \to WbH^\pm b$ ($H^\pm \to \tau\nu, cs$) [1, 2]
    - $m_{H^\pm} < m_t \to$ limit on $B(t \to H^\pm b)$
  - $tH^\pm$ ($H^\pm \to \tau\nu, tb$) [1, 3]
    - $m_t < m_{H^\pm} \to$ limit on $\sigma \times B$

[1] CMS-PAS-HIG-14-020
Doubly charged Higgses $\Phi^{\pm\pm}$

- 6 channels
  - $ee$, $\mu\mu$, $e\mu$, $e\tau$, $\mu\tau$, $\tau\tau$
- Interpretation for 4 benchmark models