BSM Higgs,
Experimental report
A. Nikitenko, IC
10th June 2015, Les Houches
First pp collision for physics at 13 TeV

June 3, 2015

No stone to be left unturned to search for BSM physics with Run II

12 Experimentalists from ATLAS+CMS in Les Houches 2015 for BSM Higgs Session 2
BSM Physics with Higgs bosons

- additional Higgs bosons
- non SM decays of $h(125)$
- precise measurements for $h(125)$
  - EFT, CP properties.

$BR_{BSM} < 0.58$ at 95% CL (CMS)
MSSM, 2HDM
Prospects for 2015-2016

• No immediate discovery for with first 5-10 fb\(^{-1}\) is expected.
  – with ~ 5-10 fb\(^{-1}\) at 13 TeV expect to reach 8 TeV/20 fb\(^{-1}\) sensitivity of current 8 TeV analyses and start to explore a new territory

Search for heavy A/H->χχ decays could complement direct searches χχ searches:

Les Houches project:
Apyan Aram (CMS), H\(^+\)->χχ
A. Nikitenko (CMS), A/H->χχ

Long pre-LHC data history of these analyses:
F. Moortgat et al, A. Ketevi et. al
(MSSM) \( H \rightarrow hh \rightarrow \gamma\gamma bb, \tau\tau bb, bbbb \)

**How important is interference with BSM non-resonant di-higgs production?**

- **Di-Higgs boson production in BSM:**
  - Alexandra Oliveira (CMS)
  - Devdatta Majumder (CMS)
  - Chris Pollard (ATLAS)
    - reconstruction of close by b- jets,...
Presentation of limits from heavy Higgs searches in multi-Higgs models

- Example from recent CMS H->ZA, A->ZH analysis (2HDM, m_h=125)

\[ \sigma \times BR \text{ observed limit} \]

**interpretation in 2HDM**
Complementarity between precision measurements of $h_{125}$ and direct searches

alignment scenarios with large $\mu$

Djouadi et.al. arXiv:1307.5205

Ferreira, Guedes, Gunion, Haber, Sampaio, Santos arXiv:1410.1926

$\sin(\beta - \alpha) = 1 \Rightarrow$ SM like limit (alignment)
$k_F = k_V = 1$
$\sin(\beta + \alpha) = 1 \Rightarrow k_D = -1$ ($k_U = k_V = 1$)
"wrong sign" limit; can be excluded with $\sim 5\%$ accuracy on $h \rightarrow \gamma \gamma$ measurement
Open a new mass search region for pp-$\rightarrow$bb$\phi$ and gg-$\rightarrow$$\phi$, $\phi$-$\rightarrow$$\mu$$\mu$, $\tau$$\tau$ analyses

- $\sim 20$ GeV $< m_A < 60$ GeV in 2HDM Type II

- CMS: re-consider public 8 TeV analyses, bbA, A-$\rightarrow$$\mu$$\mu$, $\tau$$\tau$
**Issue 1**

- $\sigma(gg\rightarrow A)$ at low $m_A$ can be much bigger than $\sigma(bbA)$
  - $gg\rightarrow A$ contamination in $b$-tag category can be significant from to two sources:
    - $gg\rightarrow A+$gluon
      - gluon-$bb$
      - gluon is misstaged as $b$-jet

Brown = wrong sign Yukawa cases:
$gg\rightarrow A/bbA$ ratio $\sim 10$ at $m_A=30$ GeV
Blue = normal sign Yukawa cases:
$gg\rightarrow A/bbA$ ratio can be 100 at $m_A=30$ GeV

Proper generation of $gg\rightarrow h+$gluon, gluon-$bb$ is important
Issue 2

- Quite large acceptance uncertainty of \(bbh\) generation with \text{MG5\_aMC@NLO}\ due to \(Q_{sh}\)
  - Selections applied at particle level:
    - \(p_{T\mu_1,2} > 25, 5 \text{ GeV}, |\eta_{\mu_1,2}| < 2.1, 2.4\)
    - \(\geq 1\) b-jet \(p_T > 30 \text{ GeV}, |\eta| < 2.4\)

<table>
<thead>
<tr>
<th>shewer scale, (Q_{sh}) variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
</tr>
</tbody>
</table>

Selection efficiency

- \(2.93 \times 10^{-2}\)
- \(3.33 \times 10^{-2}\)
- \(4.14 \times 10^{-2}\)

Uncert. -12\% +24\%

\(\text{JHEP 10 (2014) 141, Z+\geq 1b}\)

\(\text{JHEP 06 (2012) 126, Z+b}\)
NMSSM, 2HDM+S
Very reach topologies with cross-sections $> \sim 1\ fb$ at 13 TeV!

- Need to set up the list of “hottest” and “doable” topologies for Run II
  - Ulrich Goerlach (CMS)
  - Benoit Courbon (CMS)
    - Final states with photons
      - Camilo Carillo (CMS)
        - Light A/H-$\gamma\gamma$ ($m < 125\ GeV$)
      - David Sabes (CMS)
        - Light scalar bosons in SUSY
          - Nicolas Chanon (CMS)
        - Double Higgs
Search for scalar di-photon resonances, $m_X = [65-600]$ GeV


<table>
<thead>
<tr>
<th>Scenario</th>
<th>$M_{H_1}, M_{H_2}, M_{H_3} = M_{H_1}, M_{h}$</th>
<th>$M_{A_1}, M_{A_2} = M_{A_1}, M_{A}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90.3 GeV, 126.8 GeV</td>
<td>341.3 GeV</td>
</tr>
<tr>
<td></td>
<td>118.5 GeV, 346.7 GeV</td>
<td></td>
</tr>
</tbody>
</table>

**A.1 (Point ID 3877)**

<table>
<thead>
<tr>
<th>Signal Rates</th>
<th>$\sigma(gg\bar{H}_s)$</th>
<th>$\sigma(gg\bar{H}_s)BR(H_s \rightarrow bb)$</th>
<th>$\sigma(gg\bar{H}_s)BR(H_s \rightarrow \tau\tau)$</th>
<th>$\sigma(gg\bar{H}_s)BR(H_s \rightarrow \gamma\gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.37 pb</td>
<td>2.04 pb</td>
<td>204.82 fb</td>
<td>2.74 fb</td>
</tr>
</tbody>
</table>

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<th>$\sigma(gg\bar{A}_s)BR(A_s \rightarrow \gamma\gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>914.07 fb</td>
<td>804.77 fb</td>
<td>84.15 fb</td>
<td>0.36 fb</td>
</tr>
</tbody>
</table>

**Result:** limit on $\sigma \times BR$ in fiducial volume

From talk of Tania Robens at SUSY 2014 (see recent updates in arXiv:1501.02234)

What about the “inverse” scenario, i.e. $m_H = 125.7$ GeV

mainly ruled out by LEP and/or $\chi^2$ fit from HiggsSignals, however, still large number produced due to large $\sigma_{gg \rightarrow h}$

<table>
<thead>
<tr>
<th>$m_h$ [GeV]</th>
<th>$\sin \alpha_{\text{min, exp}}$</th>
<th>$\sin \alpha_{\text{min, 2\sigma}}$</th>
<th>$(\tan \beta)_{\text{max}}$</th>
<th>#gg ~</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>0.82</td>
<td>0.89</td>
<td>9.2</td>
<td>$10^5$</td>
</tr>
<tr>
<td>100</td>
<td>0.86</td>
<td>--</td>
<td>10.1</td>
<td>$10^5$</td>
</tr>
<tr>
<td>90</td>
<td>0.91</td>
<td>--</td>
<td>11.2</td>
<td>$10^5$</td>
</tr>
<tr>
<td>80</td>
<td>0.98</td>
<td>--</td>
<td>12.6</td>
<td>$10^4$</td>
</tr>
<tr>
<td>70</td>
<td>0.99</td>
<td>--</td>
<td>14.4</td>
<td>$10^4$</td>
</tr>
<tr>
<td>60</td>
<td>0.98</td>
<td>$\geq 0.99$</td>
<td>16.8</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>

$\sigma \times BR = (1-\sin^2\alpha)\sigma_{SM} \times BR_{SM} < 12.2$ fb

at $m_h = 100$ GeV

\[ 2m_{\tau} < m_{a_1/h_1} < 2m_b \]

<table>
<thead>
<tr>
<th>D.1 (Point ID 5416)</th>
<th>Scenario</th>
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</thead>
<tbody>
<tr>
<td>( M_{H_s}, M_h, M_H )</td>
<td>9.6 GeV, 124.2 GeV, 793.4 GeV</td>
</tr>
<tr>
<td>( M_{A_s}, M_A )</td>
<td>273.2 GeV, 792.2 GeV</td>
</tr>
<tr>
<td>(</td>
<td>S_{H_1h_1}</td>
</tr>
</tbody>
</table>

\[ 2m_b < m_{a_1/h_1} < 0.5m_{h_{125}} \]

<table>
<thead>
<tr>
<th>D.2 (Point ID 110)</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_{H_s}, M_h, M_H )</td>
<td>112.0 GeV, 126.3 GeV, 1288.2 GeV</td>
</tr>
<tr>
<td>( M_{A_s}, M_A )</td>
<td>61.5 GeV, 1287.4 GeV</td>
</tr>
</tbody>
</table>

\[ \sigma(ggh)\]
\[ 44.28 \text{ pb} \]
\[ \sigma(ggh)\text{BR}(h \rightarrow H_sH_s) \]
\[ 4.22 \text{ pb} \]
\[ \sigma(ggh)\text{BR}(h \rightarrow H_sH_s \rightarrow \tau\tau + \tau\tau) \]
\[ 3.58 \text{ pb} \]
\[ \sigma(ggh)\text{BR}(h \rightarrow H_sH_s \rightarrow \tau\tau + \mu\mu) \]
\[ 31.64 \text{ fb} \]

\[ \mu\mu\tau\tau \]

Assuming \( \text{Br}(a \rightarrow \mu\mu) + \text{Br}(a \rightarrow \tau\tau) = 1 \)
• **h(125)->XX analyses in CMS with 8 TeV data:**
  
  – inspired, in particular by
    
    • Stefano Moretti et. al, arXiv:0805.3505
    • King, Muhlleitner, Nevzorov, Walz arXiv:1211.5074, 1408.1120
    • M. Strassier et. al, arXiv:1312.4992: Exotic decays of $h_{125}$
  
  – **h(125)->AA->4τ, 2m_τ < m_A < 2m_b, approved with 8 TeV**
    • Paper under preparation (HIG-14-019)

  – **h(125)->AA->μμbb, 2m_b < m_A < m_h/2 still to be approved; HIG-14-041**
Higgs and DM
Higgs and DM at LHC

- **Invisible**
  - Latest ATLAS and CMS results on VBF h->invisible

<table>
<thead>
<tr>
<th>ATLAS analysis: VBF h(125)-&gt;invis:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}_{\text{obs}} &lt; 0.29$</td>
</tr>
<tr>
<td>$\text{BR}_{\text{exp}} &lt; 0.35$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CMS analysis: VBF h(125)-&gt;invis:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}_{\text{obs}} &lt; 0.57$</td>
</tr>
<tr>
<td>$\text{BR}_{\text{exp}} &lt; 0.40$</td>
</tr>
</tbody>
</table>

- **Semi-invisible**
  - ATLAS-CONF-2015-001; GMSB, NMSSM: $\gamma(\gamma\gamma)$+MET from VBF h(125)
Higgs and DM at LHC

- **Mono-Higgs:**
  - Linda Carpenter et al.
  - arXiv:1312.2592

- **Les Houches project:**
  - Nicola De Filippis
  - decays \( h \rightarrow 4 \chi \)

- **Other possibility:**
  - MSSM \( h_2(125) \rightarrow h_1 + \text{MET} \)
    - from Felix Yu talk on LHCHXSWG/WG3 Fermilab meeting May 21, 2015

**Relation to \( h \rightarrow 2 \) and \( h \rightarrow 2 \rightarrow 4 \): NMSSM**

- Two-body decay to singlinos (\( h \rightarrow 2 \) decay) suppressed by mixing angles
- Two-body decay to binos (\( h \rightarrow 2 \rightarrow 4 \) decay) suppressed by kinematic threshold
- Asymmetric decay to bino-singlino (\( h \rightarrow 2 \rightarrow 3 \) decay) dominant
- SM-like Higgs is second heaviest CP-even scalar
- Two-body decay to \( h_1 h_2 \) suppressed from PQ limit
Have a good work in Les Houches !
THE END
• Non b-tag category is also dominated by bbH at large $m_A$

<table>
<thead>
<tr>
<th>$m_A$ [GeV]</th>
<th>$m_A=300$ GeV</th>
<th>$m_A=600$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tan \beta$</td>
<td>$20$</td>
<td>$20$</td>
</tr>
<tr>
<td>$\sigma(gg\to A+H)/\sigma(bb\to A+H)$</td>
<td>$0.16$</td>
<td>$0.08$</td>
</tr>
<tr>
<td>$\sigma(gg\to A+H)/\sigma(bb\to A+H) \times (\varepsilon_{gg\to H}/\varepsilon_{bb\to H})^{exp}$</td>
<td>$0.20$</td>
<td>$0.27$</td>
</tr>
</tbody>
</table>
**bbH MC**

- **pp->bbH aMC@NLO vs PY6/8**
  - harder Higgs $p_T$
    - $p_T$ is sensitive to shower scale, $Q_{sh}$ in MG5_aMC@NLO
    - use $Z+b$ data to tune $Q_{sh}$ and apply it to $H+b$
  - (very) different efficiency of the jet veto
    - change of selection strategy for light pseudoscalar $A$ analysis $pp->bbA,A->\tau\tau/\mu\mu$

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**CMS Simulation**

$p\rightarrow bbh, m_h=30$ GeV

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10/06/2015
Signal selection efficiencies MG5_aMC@NLO+PY8 vs PY6 for pp->bbA, A->μμ, $m_a=30$ GeV

| Muon selections | Selection on muon $p_T$, GeV $|\eta| < 2.1$ for both muons | 10 | 15 | 20 |
|-----------------|-------------------------------------------------|----|----|----|
| NLO+PY8         | PY6                                            |    |    |    |
| Muon selections | 0.368                                          | 0.379 | 0.059 | 0.057 | 0.013 | 0.014 |
| $>=1$ b-jet after $\mu$’s sel. $p_T > 30$ GeV, $|\eta| < 2.4$ | 0.104 | 0.106 | 0.280 | 0.379 | 0.558 | 0.731 |
| 1 b-jet no other jets $|\eta| < 4.7$ | 0.628 | 0.751 | 0.643 | 0.722 | 0.553 | 0.640 |

• Huge difference in additional jet veto
  – decided to change a search strategy dropping the jet veto from the selections
Prospects for 2015-2016

- No immediate discovery for Higgs-Exotics channels with first 5-10 fb\(^{-1}\) is expected so far: rare processes, need luminosity
  - with ~ 5-10 fb\(^{-1}\) at 13 TeV expect to reach 8 TeV/20 fb\(^{-1}\) sensitivity of current 8 TeV analyses and start to explore a new territory

J. Stirling 2013

- Light χ’ s are not excluded

MSSM

A/H/H\(^+\)

h(125)->AA, DM, μτ

M. Carrera et al arXiv:1302.7033


Light χ’ s are not excluded

H/A->χχ
Benchmarks and tools used so far by ATLAS and CMS for the interpretation in MSSM and 2HDM

• **MSSM benchmark scenarios**, arXiv:1302.7033:

MSSM Higgs Boson Searches at the LHC:
Benchmark Scenarios after the Discovery of a Higgs-like Particle

M. Carena\textsuperscript{1,2}, S. Heinemeyer\textsuperscript{3}, O. Stål\textsuperscript{4}, C.E.M. Wagner\textsuperscript{2,5} and G. Weiglein\textsuperscript{6}*

– **tools: XS - HIGLU, SusHi, FeynHiggs; BRs: FeynHiggs+HDECAY**

• **2HDM tools (no benchmark scenarios yet)**, arXiv:1312.5571:

LHC Higgs Cross Section Working Group
Interim recommendations for the evaluation of Higgs production cross sections and branching ratios at the LHC in the Two-Higgs-Doublet Model

R. Harlander\textsuperscript{1}, M. Mühlleitner\textsuperscript{2}, J. Rathsman\textsuperscript{3}, M. Spira\textsuperscript{4}, O. Stål\textsuperscript{5}

– **SusHi+FeynHiggs or HIGLU+HDECAY**
\( \phi \rightarrow \tau \tau : \text{“model independent” limits} \)

- Go to MSSM interpretation using inclusive cross section from LHCHXSWG
H$^+\rightarrow\tau\nu$: “model independent” limits and MSSM interpretation

T. Plehn et al., hep-ph/0312286

no cross-sections yet available from LHCHXSWG to close the gap $m_{H^+}$ [160-200] GeV
$\phi \rightarrow \tau \tau$ : interpretation in MSSM benchmark scenarios


Djouadi, Maiani, Polosa, Quevillon, Riquer, arXiv:1502.05653

Large $\mu$: no $H \rightarrow \chi \chi$ decays
What MSSM Higgs boson is discovered, h or H?

**low m_H scenario**

- \( m_t = 173.2 \text{ GeV} \),
- \( M_A = 110 \text{ GeV} \),
- \( M_{\text{SUSY}} = 1500 \text{ GeV} \),
- \( X_t^{\text{OS}} = 2.45 M_{\text{SUSY}} \) (FD)
- \( X_t^{\text{R}} = 2.9 M_{\text{SUSY}} \) (RG)
- \( A_b = A_t = A_e \),
- \( m_{\tilde{g}} = 1500 \text{ GeV} \),
- \( M_{\tilde{t}} = 1000 \text{ GeV} \).

**CMS (unpublished)**

\[ \text{observed} \]

- \( m_{H^+} \neq 125 \pm 3 \text{ GeV} \)

**O. Stal arXiv:1402.6732**

- \( 1 \rightarrow H^+b, H^0 \rightarrow \tau^+\nu \tau^0 \text{jets final state} \)
- \( M_{\text{SUSY}} m_{H^+}^\text{excl} \)
- \( m_{H^+}^\text{obs} \neq 125 \pm 3 \text{ GeV} \)

**Conclusion**

It is the little Higgs boson, h!
A->Zh: the $\sigma \times$ BR limits

- so far 2HDM interpretation is done in the “physics basis,” CP-conserving with input: $m_h, m_{H^0}, m_A, m_{H^+}, \alpha, \tan \beta, m_{12}$
  - additional parameters $\lambda_6, \lambda_7 = 0$ as result of $Z_2$ symmetry ($H_1^0, H_2^0$) and $m_{12}$ is taken as in MSSM: $m_A^2 = m_{12}^2 / (\sin \beta \cos \beta) - \lambda_5 v^2$
  with $\lambda_5 = 0$ as in MSSM

$$V_{2\text{HDM}} = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - \left[ m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]$$

$$+ \frac{1}{2} \lambda_1 |\Phi_1|^4 + \frac{1}{2} \lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 \left( \Phi_1^\dagger \Phi_2 \right) \left( \Phi_2^\dagger \Phi_1 \right)$$

$$+ \left\{ \frac{1}{2} \lambda_5 \left( \Phi_1^\dagger \Phi_2 \right)^2 + \left[ \lambda_6 \left( \Phi_1^\dagger \Phi_1 \right) + \lambda_7 \left( \Phi_2^\dagger \Phi_2 \right) \right] \left( \Phi_1^\dagger \Phi_2 \right) + \text{h.c.} \right\}$$
MSSM: inclusive cross-sections

- New for 13 TeV analyses (S. Liebler, talk on 9th LHCHXSWG workshop Jan 2015):
  - $bb\phi$: add $y_t y_b$ interference term
  - $gg\rightarrow\phi$: change scale ($\mu_F/\mu_R$ from $m_\phi$ to 0.5$m_\phi$) and uncertainty
  - PDF+$\alpha_S$ uncertainty as function of $m_\phi$ (not for every SUSY point)
  - 13/14 TeV root files for Run I benchmark scenarios (Carena et al. 13)
  - Santander matched xs for $pp\rightarrow H^+tb$; new scale setting for 5FS

arXiv:1409.5615

Improved cross-section predictions for heavy charged Higgs boson production at the LHC

Martin Flech1,2, Richard Klees3, Michael Krämer3,4, Michael Spira5, and Maria Ubiali6,7