BSM Higgs status at the LHC

LHCP 2015
St. Petersburg, Russia, 31.08-05.09.2015

Pawel Brückman de Renstrom
on behalf of the ATLAS & CMS Collaborations
(Institute of Nuclear Physics P.A.N., Cracow PL)
Ladies and gentlemen, I think we’ve got it!

Discovery of a Higgs-like particle coupling to gauge bosons
Introduction

\[ m_W = \frac{1}{2} g_W \nu \quad m_H = \sqrt{2 \lambda \nu} \]

- SM Higgs sector is a single free parameter model.
- Fixing the model by measuring the Higgs mass completes the SM scenario.
- The model predicts couplings to all SM particles (\(\sim m\) for fermions, \(\sim m^2\) for bosons)
- Everything else is testing for BSM!
The big picture

ATLAS & CMS combined mass:
PRL 114, 191803 (2015)

ATLAS & CMS combined couplings:

CMS $J^P$: Phys. Rev. D 92, 012004

ATLAS $d\sigma/dx$: arXiv:1508.02507
CMS $d\sigma/dx$: CMS-PAS-HIG-14-028

$m_H = 125.09 \pm 0.24 \text{ GeV}
= 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst) GeV}$

$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07} \text{ (stat)} +^{0.04}_{-0.04} \text{ (expt)} +^{0.03}_{-0.03} \text{ (thbgd)} +^{0.07}_{-0.06} \text{ (thsig)}$
So far the Higgs... looks like SM, sounds like SM, smells like SM.

But:
CONSISTENT with SM ≠ INCOMPATIBLE with BSM

Essential questions:
- Is the 125 GeV Higgs the only one (extended sector)?
- Is it responsible for all the particle mass?
- Is it fundamental?

Need to define models of interest. Most popular are additional EW singlet, 2HDM, NMSSM, composite Higgs, etc.
All allow for SM-like light Higgs phenomenology with smaller or larger coupling modifications.
- Most predict additional (heavier) states in the scalar sector.
**ROADMAP**

Explore the 125 GeV Higgs
- Production rates (ggH, WH, ZH, VBF, ttH, HH, tH, bbH)
- Decay widths (γγ, ZZ, WW, bb, ττ, μμ, Zγ, etc.)
- Couplings to SM particles
- Spin and parity
- LFV, H→αα, H→inv, γ+E, etc.
- Are these consistent with SM?

Explicit search for BSM objects
- Heavy neutral CP-even and CP-odd states (γγ, ZZ, WW, bb, ττ, HH, HZ, tt)
- Heavy charged Higgs (τν, tb, WZ, cs, etc.)
- Any deviations from SM backgrounds?

How much of the BSM scenarios can current data exclude?

*Note: heavily model dependent!*
Explore the 125 GeV Higgs
Mass scaling of Higgs Boson Couplings

- Same production & decay modes as in the SM
- Test the coupling strength and mass dependence at the same time.
- Fairly model independent approach.

\[ \kappa_{f,i} = \frac{m_{f,i}^2}{M^{1+\epsilon}} \]
\[ \kappa_{V,j} = \frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}} , \]

- \( M \) is the “vev parameter” (where \( v = 246 \text{ GeV} \))
- \( \epsilon \) is the “mass scaling parameter”

\[ \text{SM: } \epsilon = 0, M = v \Rightarrow \kappa_f = \kappa_V = 1 \]
Additional Electroweak Singlet

- The simplest extension to the SM Higgs sector involving the addition of one scalar EW singlet field to the doublet Higgs field of the SM, both of which acquire non-zero vacuum expectation values.
- Mixing between the singlet state and the surviving state of the doublet field results in two CP-even Higgs bosons, where $h$ ($H$) is the lighter 125 GeV (heavier) of the pair.

\[ \kappa^2 + \kappa'^2 = 1 \]

\[ \sigma_h = \kappa^2 \times \sigma_{h,\text{SM}} \]

\[ \mu_H = \kappa'^2 (1 - \text{BR}_{H,\text{new}}) \]

$\kappa'^2 < 0.12$ @ 95 CL
Exp: 0.23

ATLAS: arXiv:1509.00672

ATLAS Preliminary

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$\text{fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>4.5-4.7</td>
</tr>
<tr>
<td>8 TeV</td>
<td>20.3</td>
</tr>
</tbody>
</table>

$\text{BR}_{H,\text{new}}$

<table>
<thead>
<tr>
<th>$\Gamma_H/\Gamma_{H,\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.1</td>
</tr>
</tbody>
</table>

Exp. 95% CL: $\kappa'^2 < 0.23$
2HDM Models

- **Generic class implementing a second Higgs doublet.**
  - **Type I:** One doublet couples to vector bosons, the other couples to fermions.
  - **Type II:** One doublet couples to up-type quarks, the other to down-type quarks and leptons: "MSSM -like"

- **Lepton-specific:** couplings to quarks as in the Type I model and to leptons as in Type II.
- **Flipped:** couplings to quarks as in the Type II model and to leptons as in Type I.

\[
\begin{align*}
\tan \beta & \equiv \frac{v_2}{v_1} \\
v_1^2 + v_2^2 &= v^2 \approx (246 \text{ GeV})^2 \\
g_{hVV}^{2\text{HDM}} / g_{hVV}^{\text{SM}} &= \sin(\beta - \alpha) \\
g_{HVV}^{2\text{HDM}} / g_{HVV}^{\text{SM}} &= \cos(\beta - \alpha)
\end{align*}
\]

- "Decoupling": \( A, H^0, H^\pm \) much heavier than the light \( h \).
- Decoupling is not necessary.
  - \( \cos(\beta - \alpha) \rightarrow 0 \) recovers properties of the SM Higgs,

  - "Alignment"
The dominant top and stop radiative corrections to $h$ mass are used to infer effective couplings to $h$ of the mass 125 GeV in the hMSSM model.

The couplings depend exclusively on the $m_A$ and tan($\beta$) parameters and follow from the diagonalization of the light and heavy CP-even Higgs mass matrix:

\[
\begin{align*}
\kappa_V &= \frac{s_d(m_A, \tan \beta) + \tan \beta \cdot s_u(m_A, \tan \beta)}{\sqrt{1 + \tan^2 \beta}} \\
\kappa_u &= s_u(m_A, \tan \beta) \cdot \frac{\sqrt{1 + \tan^2 \beta}}{\tan \beta} \\
\kappa_d &= s_d(m_A, \tan \beta) \cdot \sqrt{1 + \tan^2 \beta},
\end{align*}
\]

Results overlaid with various exclusions from direct searches.

Able to constrain uniformly in wide range of tan($\beta$).

$m_A > 370$ GeV obs. (310 GeV exp.)
Minimal Composite Higgs Models (MCHM) represent a possible explanation for the scalar naturalness problem, wherein the Higgs boson is a composite, pseudo-Nambu-Goldstone boson rather than an elementary particle.

Two variants explored:
1) MCHM4

$$\kappa = \kappa_V = \kappa_F = \sqrt{1 - \xi}$$

2) MCHM5

$$\kappa_V = \sqrt{1 - \xi}$$
$$\kappa_F = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$$

with

$$\xi = \frac{v^2}{f^2}$$

SM corresponds to $f \to \infty$

ATLAS:
arXiv:1509.00672
Invisible Higgs Decays

1) VBF Higgs production with Higgs decaying invisibly. Signature: Two jets with a large pseudorapidity gap and a large invariant dijet mass, together with large E$_{\text{miss}}^T$. [CMS: CMS-PAS-HIG-14-038, ATLAS: arXiv:1508.07869]


3) VH (W or Z), where V->jj and H->inv. Signature: $m_{jj}$ consistent with the V mass, together with large E$_{\text{miss}}^T$. [ATLAS: Eur. Phys. J. C (2015) 75:337].

@ 125 GeV:

- **CMS**: The direct limit from VBF: $\text{BR}_{\text{inv}}<0.5$ @ 95 CL (0.40 exp.)
- When combined with ZH analysis: $\text{BR}_{\text{inv}}<0.47$ @ 95 CL (0.35 exp.)

- **ATLAS**: The combined direct limit: $\text{BR}_{\text{inv}}<0.25$ @ 95 CL (0.27 exp.)
- When combined with the visible modes ($\gamma\gamma, ZZ^*, WW^*, Z\gamma, \tau\tau, \mu\mu, bb$): $\text{BR}_{\text{inv}}<0.23$ @ 95 CL (0.24 exp.)
ATLAS: combined limit \( \text{BR}_{\text{inv}} < 0.22 \) @ 90% CL is converted to couplings to WIMP for either scalar, Majorana fermion or vector particle.

- These are then used to calculate the cross-section for WIMP-nucleon scattering, to be directly compared with direct DM search experiments.
- The main assumption is that Higgs is the only mediator.
- Obvious limit: \( 2m_{\text{WIMP}} < m_H \)

ATLAS: arXiv:1509.00672

\[ \text{ATLAS Preliminary} \]

Vis. & inv. Higgs boson decay channels
\[ \{\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_t, \kappa_{\mu}, \kappa_{g}, \kappa_{\gamma}, \kappa_{Z\gamma}, \text{BR}_{\text{inv}}\} \]
No \( \kappa_{WZ} \) assumption: \( \text{BR}_{\text{inv}} < 0.22 \) at 90% CL
LFV Higgs decays

- LFV highly suppressed in SM due to renormalizability requirement.
- Possibility of sizable LFV predicted in various BSM models (2HDM, composite Higgs, RS, etc.)
- Indirect limits on BR($H \rightarrow \tau \mu$) from searches for $\tau \rightarrow \mu \gamma$ weak $O(10\%)$.

<table>
<thead>
<tr>
<th>Best fit branching fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \tau_e$</td>
</tr>
<tr>
<td>$\mu \tau_{had}$</td>
</tr>
<tr>
<td>$\mu \tau$</td>
</tr>
</tbody>
</table>

- CMS reports an excess of $2.5\sigma$.
- ATLAS (only $\tau_{had}\mu$ channel):
  $\text{BR}(H \rightarrow \tau \mu) \times 1.85\%$ @ 95 CL
  (Best fit: $\text{BR}(H \rightarrow \tau \mu) = (0.77 \pm 0.62)\%$)

- Run 2 has to follow-up!

CMS: PAS HIG-14-005
ATLAS: arXiv:1508.03372

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Explicit search for BSM objects
Heavy $H \rightarrow ZZ/WW$


**$H \rightarrow ZZ$**

4$\ell$, 2$\ell 2\nu$, 2$\ell 2q$ final states

Limits on $\sigma \times \text{BR}(H \rightarrow ZZ)$ for $ggF$ and VBF production.

Limits in the context of 2HDM type II


**$H \rightarrow WW, ZZ$, $WW \rightarrow 4\nu, 4\nuq, ZZ \rightarrow 4\ell, 4\ell 2\nu, 4\ell 2q$**

![Graphs and Plots]

- **ATLAS** graph showing 95% limit on $\sigma_{ggF} \times \text{BR}(H \rightarrow ZZ)$ for $m_H$.
- **CMS** graph showing 95% CL limit on $\sigma_{SM}$ for $m_H$.

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Heavy $H \to ZZ/WW$

**ATLAS:** arXiv:1509.00389

$H \to WW, l\nu l\nu, l\nu qq$. Range 200 - 1500 GeV

Limits in the context of EW singlet Higgs

**CMS:** arXiv:1504.00936

$H \to WW, ZZ$, $WW \to l\nu l\nu, l\nu qq$, $ZZ \to 2l2l$, $2l2q$, $2l2\nu$
$X \rightarrow \gamma \gamma, bb$

ATLAS: PRL 113, 171801 (2014)
CMS: arXiv:1506.02301

$X \rightarrow \gamma \gamma$
- Generic search for $\gamma \gamma$ resonance across a wide range of masses: $m_{\gamma \gamma} < 850$ GeV
- Both narrow and wide resonances considered

$\phi \rightarrow b \bar{b}$
CMS: arXiv:1506.08329
Heavy Higgs produced in association with a b quark

Spin 0 narrow hypothesis (spin 2 very similar)

NEW

CMS, 19.7 fb$^{-1}$ (8 TeV)

CMS, 19.7 fb$^{-1}$ (8 TeV) + 4.9 fb$^{-1}$ (7 TeV)

$m_h^{mod+}$ scenario
$\mu = 200$ GeV
$m_h^{\text{mod+}} \neq 125.3$ GeV

95% CL limit
Expected
$\pm 1\sigma$ expected
$\pm 2\sigma$ expected
Observed
HH or HZ production

- Higgs self coupling already in the SM: \( V = aH^2 + bH^3 + cH^4 \)
- HH Cross-section largely enhanced in BSM models:
  - Composite: factor <3,
  - Singlet models: factor up to 15,
  - 2HDM models: factor up to 50!

- Current experimental limits still far from SM expected rates.

- \( A \rightarrow ZH \) (or \( H \rightarrow ZA \)) with \( H \) being either the heavier or the lighter CP-even state a powerful probe of 2HDM models.
- For \( m_A < 2m_{\text{top}} \) this may be the dominant decay mode of the CP-odd \( A \).
ATLAS combination on hh production

- Both resonant and non-resonant hh production
- Decay channels: $b\bar{b}b\bar{b}, b\bar{b}\tau\tau, b\bar{b}\gamma\gamma, WW\gamma\gamma$
- Limits set for resonant $H \rightarrow hh$: $\sigma(gg\rightarrow H) \times BR(H \rightarrow hh)$ assuming $H$ is narrow ($<1.5\%$).
- Limits on MSSM scenarios on $m_A - \tan(\beta)$ inferred. Here $h_{\text{MSSM}}$ exemplified.

**SM prediction @ 125 GeV:** $9.9 \pm 1.3$ fb

Non-resonant limits on $\sigma$-section [pb]:

<table>
<thead>
<tr>
<th></th>
<th>$\gamma\gamma bb$</th>
<th>$\gamma\gamma WW^*$</th>
<th>$b\bar{b}\tau\tau$</th>
<th>$b\bar{b}b\bar{b}$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.</td>
<td>1.0</td>
<td>6.7</td>
<td>1.3</td>
<td>0.62</td>
<td>0.47</td>
</tr>
<tr>
<td>Obs.</td>
<td>2.2</td>
<td>11</td>
<td>1.6</td>
<td>0.62</td>
<td>0.69</td>
</tr>
</tbody>
</table>

**X\rightarrow HH\rightarrow bb\bar{b}** CMS: arXiv:1503.04114

**X\rightarrow HH\rightarrow \gamma\gamma bb** CMS: CMS-PAS-HIG-13-032
A→Zh, H/A→A/H+Z

A→Zh (Z→ll, νν, h→bb, ττ)

CMS: arXiv:1504.04710

CMS:
arXiv:1503.04114

- A generic search for 2HDM
- Expected irrespective of „alignment“
- H/A → A/H+Z, Z→ll, A/H→bb, ττ
- All combinations of τl and τhad.
- Sensitivity drops rapidly when the ttbar decay channel for the lighter Higgs state opens.
- Highly boosted topologies suffer from reconstruction inefficiencies.
- Interesting exclusions on the cos(β−α)−tan(β) plane possible under given mass assumptions.
MSSM Higgs → ττ

- ATLAS & CMS
- Channels searched:
  - h/H/A → τeτµ (+τµτµ CMS)
  - h/H/A → τlepτhad
  - h/H/A → τhadτhad
- MSSM Higgs couplings to down type quarks and leptons enhanced for large tan(β)
A charged Higgs particle would spectacularly sign BSM. Needed with more than one HD (notably SUSY).

Within MSSM BR($H^+ \to \tau\nu$) remains significant in large range of masses for high $\tan(\beta)$.

For low $\tan(\beta)$ $H^+ \to tb$ dominates for $m_H > m_t$.

$H^+ \to \tau\nu$ saturates the decay for $m_H < m_t$.

Channels searched

- $H^+ \to \tau_{\text{had}}\nu$ (ATLAS, CMS)
- $H^+ \to tb,\tau\nu$ ($t \to l\nu b$) (CMS)
- $H^+ \to cs$ (ATLAS, CMS)
- $H^+ \to WZ$ (ATLAS)

Except for WZ search, $H^+$ tagged together with the accompanying top.
Charged $H^+ \rightarrow \tau\nu$ (had)

- Exclusion limits given in various flavours of 2HDM models:
  - MSSM $m_h^{\text{max}}$
  - MSSM $m_h^{\text{mod}+/\text{mod}-}$
  - MSSM light stau
  - $\tau$-phobic Higgs
  - Low-$M_H$

- Here $m_h^{\text{mod}+}$ exmp.

CMS: CMS PAS HIG-14-020
Charged $H^+ \rightarrow \tau \nu$ (had)

- Exclusion limits given in various flavours of 2HDM models:
  - MSSM $m_{h_{\text{max}}}^{mod}$
  - MSSM $m_{h_{\text{mod}+/^-}}$
  - MSSM light stau
  - $\tau$-phobic Higgs
  - Low-$M_H$

- Here $m_{h_{\text{mod}}}^{mod}$ exmp.

New paper from CMS combining searches in $\tau \nu$ and $tb$ channels has just emerged!

arXiv:1508.07774

Pietro Vischia (Tomorrow afternoon)
Probing for the Georgi-Machacek Higgs Triplet Model (GMHTM) where $H^+$ couples to $ZW$ at tree level.

VBF production of $H^+$ with subsequent decay into a $ZW$ ($llqq$) is searched for.

$240 < m_{H^+} < 700$ GeV exclusion is placed for $S_H=1$ and $BR(H^\pm\to WZ)=100\%$
NMSSM

Introduces an additional Higgs singlet relaxes the constraints resulting from the mass of h^0 being much larger than m_Z (radiative corrections, m_h^{mod+} scenarios)

ATLAS:
EXOT-2013-24
H-→aa-→γγγγ
Signature: ≥3 isolated γ
Search for di-photon resonance (m_{23}).
h_{125}→aa→γγγγ
H→aa→γγγγ 300<m_H<600
Search for m_a <250 GeV
Limits on:
σ/σ_{SM}×BR(h→aa)×BR(a→γγ)^2

CMS:
CMS PAS HIG-14-030
a→bb
SUSY cascade tagged by E_t^{miss}>200GeV and large H_T plus two b-tagged jets.
Limits within the coloured SUSY mass scale of 1TeV.
EXECUTIVE SUMMARY

No BSM excitement in the scalar sector... yet
CONCLUSIONS

- The 125 GeV Higgs looks very SM-like.
- No evidence for BSM phenomena in the scalar sector.
- Large variety of analyses managed to place exclusion limits on various BSM scenarios.
- 8→13 TeV marks an increase of $\sigma_H$ by more than factor two.
- VH, ttH, HH production waiting to be fully explored.
- X-section for production of heavier states increased @13 TeV extending the discovery potential.
- For HL-LHC prospects see: Aleandro NISATI & Jeff RICHMAN

<table>
<thead>
<tr>
<th></th>
<th>$\sigma$(pb) at 13 TeV</th>
<th>$\sigma$(pb) at 8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluon Fusion</td>
<td>43.9</td>
<td>19.27</td>
</tr>
<tr>
<td>Vector Boson Fusion</td>
<td>3.748</td>
<td>1.578</td>
</tr>
<tr>
<td>WH</td>
<td>1.38</td>
<td>.70</td>
</tr>
<tr>
<td>ZH</td>
<td>.87</td>
<td>.42</td>
</tr>
<tr>
<td>ttH</td>
<td>.51</td>
<td>.13</td>
</tr>
<tr>
<td>HH</td>
<td>.034</td>
<td>.008</td>
</tr>
</tbody>
</table>

Run 2 is ongoing. Stay tuned!

THANK YOU.
BONUS MATERIAL
SM Higgs production @ LHC
(~25 fb\(^{-1}\)/exp has been collected till LS1)

- \(~19\text{pb}\) (0.95\text{pb})
- \(~1.5\text{pb}\) (0.07\text{pb})
- \(~1.0\text{pb}\) (0.21\text{pb})
- \(~0.1\text{pb}\) (0.004\text{pb})

Tevatron
Solid: $\tan \beta = 10$, dashed: $\tan \beta = 20$.

$BR(H)$ vs $M_H$ [GeV]

$BR(A)$ vs Mass of $A$ [GeV]

$m_{h^0} = m_{Q}, \tan \beta = 4$

Solid: $\tan \beta = 10$, long dashed: $\tan \beta = 20$, short dashed: $\tan \beta = 30$.

Higher $\tan \beta$ gives more $\tau \nu$. 
Extensive coupling studies

\[
\mu = \frac{\sigma}{\sigma_{\text{SM}}} \quad \kappa_H^2 = \frac{\Gamma_{\text{tot}}}{\Gamma_{\text{SM}}}
\]

\[
\kappa_p^2 = \frac{\sigma}{\sigma_{\text{SM}}} \quad \kappa_d^2 = \frac{\Gamma}{\Gamma_{\text{SM}}}
\]

\[
\lambda_{ab} = \frac{\kappa_a}{\kappa_b} \quad \kappa_g^2 = \frac{\kappa_g}{\kappa_Z} / \kappa_H
\]

- \(\kappa_V, \kappa_f\) common factors for couplings to vector bosons and fermions, respectively.
- Assumption of no BSM loops/width, except for \(\lambda\).
- Interferences allow to resolve signs!

![Graphs and data plots showing coupling studies and assumptions](image)

**Notes:**

- arXiv:1412.8662
- Assumption of no BSM production/no assumptions.
Testing for alternative $J^{CP}$ scenarios using decay kinematics.

**ZZ:** full kinematics available

**WW:** $m_{\ell\ell}$, $p_T^{\ell\ell}$, $\Delta \phi^{\ell\ell}$ and $m_T$

**$\gamma\gamma$:** $\cos(\Theta_{CS}^*)$, $p_T^{\gamma\gamma}$

**Note:** Landau-Yang theorem precludes $J=1$ hypothesis in the presence of $H\to\gamma\gamma$

Exclusions @ 99% CL or better
**Higgs dσ_\text{H}/dx**

**ATLAS:**
- arXiv:1508.02507
- Constraints on Wilson coefficients for anomalous CP-even and CP-odd int. in the EFT (operators ≥ dim6)
- Use H→γγ. dσ/dx:
  - p_T^{γγ}, N_{jets}, m_{jj}, Δϕ_{jj}, p_T^{j1}

**CMS:**
- CMS-PAS-HIG-14-028
- Study of the H→ZZ→4l channel
- Extract fiducial x-sections both inclusive and differential.
- dσ/dx:
  - p_T^H, y^H, N_{jets}, p_T^{j1}, Δy_{Hj1}

### Fiducial cross section H → 4l at 7 TeV

<table>
<thead>
<tr>
<th>Fiducial cross section</th>
<th>Measured</th>
<th>gg → H(HRES) + XH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.56^{+0.47}<em>{-0.44} (stat.) + ^0.21</em>{-0.06} (sys.) + ^0.02_{-0.03} (model) fb</td>
<td>0.93^{+0.10}_{-0.11} fb</td>
</tr>
</tbody>
</table>

### Fiducial cross section H → 4l at 8 TeV

<table>
<thead>
<tr>
<th>Fiducial cross section</th>
<th>Measured</th>
<th>gg → H(HRES) + XH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.11^{+0.41}<em>{-0.35} (stat.) + ^0.14</em>{-0.10} (sys.) + ^0.08_{-0.05} (model) fb</td>
<td>1.15^{+0.12}_{-0.13} fb</td>
</tr>
</tbody>
</table>

### Ratio of fiducial cross sections of H → 4l at 7 and 8 TeV

<table>
<thead>
<tr>
<th>Ratio of fiducial cross sections</th>
<th>Measured</th>
<th>gg → H(HRES) + XH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.51^{+0.27}<em>{-0.40} (stat.) + ^0.13</em>{-0.05} (sys.) + ^0.00_{-0.03} (model) fb</td>
<td>0.805^{+0.003}_{-0.010}</td>
</tr>
</tbody>
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2HDM Models

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$$\tan \beta \equiv \frac{v_2}{v_1}$$

$$v_1^2 + v_2^2 = v^2 \approx (246 \text{ GeV})^2$$

$$\frac{g_{hVV}^{2HDM}}{g_{hVV}^{SM}} = \sin(\beta - \alpha)$$

$$\frac{g_{HVV}^{2HDM}}{g_{HVV}^{SM}} = \cos(\beta - \alpha)$$

<table>
<thead>
<tr>
<th>Coupling scale factor</th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
<th>Type IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_V$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\sin(\beta - \alpha)$</td>
</tr>
<tr>
<td>$\kappa_u$</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>$\kappa_d$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
</tr>
<tr>
<td>$\kappa_l$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
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<td>$\cos(\alpha)/\sin(\beta)$</td>
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</tbody>
</table>
$m_h^\text{max}$: maximize $M_h$ by choosing $A_t$, with other parameters fixed.

$m_h^\text{mod+}$: make $M_h = 125$ GeV by choosing $A_t$, with other parameters fixed.
CMS: Search for $X\rightarrow HH$

**$X\rightarrow HH\rightarrow bbbb$**
- Model independent search
- Using four $b$-tagged jets.
- QCD bkg estimated from data control regions

**$X\rightarrow HH\rightarrow \gamma\gamma bb$**
- Using pairs of $b$-tagged jets and pairs of photons.
- Sensitivity in the range of 260-1100 GeV
- Limits derived for both scalar Radion as well as RS1 $G^*_KK$. 

**CMS-PAS-HIG-13-032**
ATLAS:

arXiv:1506.00285

- Using both pairs of resolved anti-$k_t$ b-tagged jets and trimmed fat anti-$k_t$ jets with two other b-jets.
- Sensitivity in the range of 500-2000 GeV
- Limits derived for both RS $G^*_{KK}$ as well as $H\rightarrow hh$ in the 2HDM models.
- Here 2HDM type II example shown.
- Shaded areas do not provide reliable limits as the width becomes too large.
Zh production

ATLAS:


- $A \rightarrow hZ$, $Z \rightarrow ll$, $h \rightarrow bb, \tau \tau$  
- $h$ denotes here the observed Higgs with mass of 125 GeV  
- $m_A \in (220; 1000)$ GeV  
- 2HDM (type I & II) limits are given for specific choice of $m_A$ or $\cos(\beta - \alpha)$.  
- Here example of 2HDM type II with $m_A = 300$ GeV or $\cos(\beta - \alpha) = 0.10$  
- Assumptions for calculating the limits:  
  $m_A = m_H = m_{H^\pm}$, $m_h = 125$ GeV  
  and $m_{12}^2 = m_A^2 \tan \beta / (1 + \tan^2 \beta)$  
- Blue shaded areas are excluded by $A \rightarrow \tau \tau$ analysis [JHEP 1411 (2014) 056]
HZ production

CMS: arXiv:1504.04710
- $A \rightarrow hZ$, $Z \rightarrow ll$, $h \rightarrow bb$
- $h$ denotes here the observed Higgs with mass of 125 GeV
- 2HDM (type I & II) limits are given for specific choice of $m_A$.
- Here example of 2HDM type II with $m_A=300$ GeV

CMS-PAS-HIG-13-025
- $H \rightarrow hh$ & $A \rightarrow Zh$
- Sensitivity up to 360 GeV
- Limits derived for 2HDM type I & II.
Search for $A \rightarrow Z\gamma$

**CMS PAS HIG-14-031**

- $A \rightarrow Z\gamma$, $Z \rightarrow ll$ (e or $\mu$)
- Model independent
- In particular, probes for composite Higgs models with SU(4) chiral symmetry breaking.
- Sensitivity up to the $tt\bar{t}$ threshold.
ATLAS:
arXiv:1505.01609
H→aa→μμττ
The most stringent limit is placed at 3.5% for m_a = 3.75 GeV. Upper limits are also placed on the production cross section of H→aa from 2.33 pb to 0.72 pb, for fixed m_a = 5 GeV with m_H ranging from 100 GeV to 500 GeV.

NMSSM