Search for Higgs Bosons in Extensions of the SM in ATLAS and CMS

S. Bressler
Weizmann Institute of Science

On behalf of the ATLAS and CMS Collaborations
Higgs Bosons in Extensions of the SM

Three main subgroups

- **Neutral** Higgs with *SM-like properties*
  - \( m \not\in [125, 127] \text{ GeV} \) using the SM as a benchmark

- **Neutral** Higgs with *Non-SM properties*
  - Additional scalar \( @ m \not\in [125, 127] \text{ GeV} \)
  - BSM properties of the Higgs \( @ m \in [125, 127] \text{ GeV} \)

- **Charged** scalar (Higgs)

Motivation / optimization / interpretation (if any) in the framework of extensions of the SM

- 2HDM of all types
  - MSSM
  - NMSSM
  - ...

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Neutral Higgs \( m \notin [125, 127] \) GeV: SM-like

“Search for a standard-model-like Higgs boson with a mass in the range 145 to 1000 GeV at the LHC” \texttt{arXiv:1304.0213}

“Search for a high-mass Higgs boson in the \( H \rightarrow WW \rightarrow l\nu l\nu \) decay channel with the ATLAS detector using 21 fb\(^{-1}\) of proton-proton collision data” \texttt{ATLAS-CONF-2013-067}* 

*Interpreted also in the context of non SM Higgs
High mass H: SM-Like

Focus: \( m \in [>140\ \text{GeV}, 1\ \text{TeV}] \)
- Lower range defined by previous exclusions
- Upper range defined by experimental reach

Decay modes:
- Naturally focus on \( H \rightarrow WW \) and \( H \rightarrow ZZ \)

Production modes:
- \( ggF \) & \( VBF \)
- \( VH \) and \( ttH \) are small but also included in some channels

Line-shape model:
- \( m \in [300, 400] \) GeV: running width
  Breit-Wigner propagator
- \( m > 400 \) GeV: complex pole scheme

Data sets:
- \( H \rightarrow WW \): 5 fb\(^{-1} \) @ 7 TeV & 21 fb\(^{-1} \) @ 8 TeV
- \( H \rightarrow ZZ \): 5 fb\(^{-1} \) @ 7 TeV & 5 fb\(^{-1} \) @ 8 TeV

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High mass H: SM-Like

Analysis channels $H\rightarrow WW$
- Fully leptonic: $H\rightarrow WW\rightarrow l\nu l\nu$
- $l = e/\mu$ inc. leptonic $\tau$ decays
- Semi-leptonic: $H\rightarrow WW\rightarrow l\nu qq$

Analysis channels $H\rightarrow ZZ$

<table>
<thead>
<tr>
<th>$H$ decay mode</th>
<th>$H$ production</th>
<th>Exclusive final states</th>
<th>No. of channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ \rightarrow 2\ell 2\ell'$</td>
<td>inclusive</td>
<td>$4e, 4\mu, 2e2\mu$</td>
<td>3</td>
</tr>
<tr>
<td>$ZZ \rightarrow 2\ell 2q$</td>
<td>inclusive</td>
<td>$(ee, \mu\mu) + (T_\ell T_\ell, T_\ell T_\ell, T_\ell T_\ell, T_\ell T_\ell)$</td>
<td>8</td>
</tr>
<tr>
<td>$ZZ \rightarrow 2\ell 2\nu$</td>
<td>untagged</td>
<td>$(ee, \mu\mu) + (jj)_Z + 0, 1, 2$ b-tags</td>
<td>6</td>
</tr>
<tr>
<td>$ZZ \rightarrow 2\ell 2\nu$</td>
<td>VBF tag</td>
<td>$(ee, \mu\mu) + (jj)_VBF$</td>
<td>2</td>
</tr>
</tbody>
</table>

Selection & Signal region definition
- Step 1: Object reconstruction & Event pre-selection
- Step 2: Categorizing / tagging
  - Number of jets
  - Jets topology
  - Number of lepton
  - Lepton flavor
  - ...

arXiv:1304.0213
High mass H: SM-Like - Main results

H→WW→lνlν:
- Full data set
- No H in the range [260,642] GeV

Combined results
- Partial data set
- No H in the range [145,710] GeV

arXiv:1304.0213
Neutral H: Non SM properties - Narrow width

Motivation:
• Models predicting second heavier Higgs (e.g. 2HDM)
• Width narrower than a SM-like Higgs of same mass (over a large parameter space)

Search-channel: $H \rightarrow WW \rightarrow l\nu l\nu$
• Search identical to the SM-like heavy Higgs

Line-shape model:
• Fixed 1 GeV wide Breit-Wigner
No interference with non resonant WW SM background

Results: $\sigma \times \text{BR}(H \rightarrow WW) <$
230 fb for $m = 300$ GeV
32 fb for $m = 600$ GeV
29 fb for $m = 1$ TeV.
Highlights

**Neutral Higgs with SM-like properties**
H→WW→llνν: no Higgs in the mass range [260,642] GeV
H→WW/ZZ: no Higgs in the mass range [145,710] GeV

**Neutral scalar with narrow width**
H→WW→llνν: σ×BR(H→WW) <
  230 fb for m = 300 GeV
  32 fb for m = 600 GeV
  29 fb for m = 1 TeV
Neutral Higgs: Non SM properties

“Search for a Higgs boson decaying into a b-quark pair and produced in association with b quarks in proton-proton collisions at 7 TeV” arXiv:1302.2892

“Search for a light pseudoscalar Higgs boson in the dimuon decay channel in pp collisions at $\sqrt{s} = 7$ TeV” CMS-PAS-HIG-13-010

“Search for flavor changing neutral currents in top quark decays $t \rightarrow cH$, with $H \rightarrow \gamma\gamma$, and limit on the $tcH$ coupling with the ATLAS detector at the LHC” ATLAS-CONF-2013-081

“Search for Higgs bosons in Two-Higgs-Doublet models in the $H \rightarrow WW \rightarrow e\nu\mu\nu$ channel with the ATLAS detector” ATLAS-CONF-2013-027

“Searches for Higgs bosons in pp collisions at $\sqrt{s} = 7$ and 8 TeV in the context of four-generation and fermiophobic models” arXiv:1302.1764

“Search for a fermiophobic Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV” arXiv:1207.1130

“Search for a fermiophobic Higgs boson in the diphoton decay channel with the ATLAS detector” arXiv:1205.0701

“Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in pp collisions at sqrt(s)=7 TeV with the ATLAS detector” arXiv:1211.6956

“Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS” ATLAS-CONF-2013-011

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Neutral H: Non SM properties - Associated production

Theoretical motivation:
- Higgs production in association with b-quarks
- MSSM with large tan β

Search-channel: H→bb ⇒
Final state with ≥ 3b

Signal regions: 3 b-tagged jets
- Fully hadronic: no isolated leptons
- Semi-leptonic: one isolated µ

Search strategy: look for peak in m_{jj} of leading jets

Background:
- Main contribution: QCD with 1 or 2 b-jets
- Modeled using sample with 2 b-tagged jets

Data set: 2.7-4.8 fb-1 @ √s = 7 TeV
- Defined by trigger requirement in attempt to improve the sensitivity to high / medium mass ranges

CMS 2011, L = 4.8 fb⁻¹, √s = 7 TeV

Semileptonic Analysis
Low-Mass Scenario

- Data
- Background
- M_A=120 GeV
- M_A=180 GeV
  (tan β=30)

Data - Background

arXiv:1302.2892
Neutral H: Non SM properties - Associated production: Results

Model independent: $\sigma \times \text{BR}(H \rightarrow bb)$ as a function of $m_H$

Interpretation in MSSM: $m_H^{\text{max}}$ benchmark:

- $M_{\text{SUSY}}$ (soft-SUSY breaking squark mass of 3rd generation) = 1 TeV
- $X_t$ (stop mixing parameter) = $A_t - \mu / \tan^2 \beta = 2M_{\text{SUSY}}$
- $A_t = A_b$ (stop/sbottom trilinear coupling)
- $\mu$ (higgsino mass parameter) = 200 GeV
- $M_2$ (SU(2) gaugino mass parameter) = 200 GeV
- $m_{\text{gluino}} = 800$ GeV
- $M_1 = (5/3)M_2 \sin \theta_W / \cos \theta_W$

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Neutral H: Non SM properties - Light Higgs (<3.5 GeV)

Theoretical motivation:
• Allowed in several BSM models
  NMSSM: \( a_1 \) - the light CP odd
  Dark-SUSY: \( \gamma_D \) - light photon \( n_1 \) & \( n_D \) - neutralinos

Search-channel:
  \( h \rightarrow 2a + X \rightarrow 4\mu + X \)

Signal region: \( \geq 4\mu \)
• 2 Opposite sign pairs with invariant mass consistent within detector resolution

Background: \( b\bar{b} \) & \( J/\psi \)
• No events are observed after the mass selection

Data set: 21 fb\(^{-1}\) @ 8 TeV

CMS-PAS-HIG-13-010
Neutral H: Non SM properties - Light Higgs: Results

Model independent:

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

**NMSSM**

**DarkSUSY**

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**Highlights**

**Neutral Higgs produced in association with b-quarks**
H → bb: Within the MSSM: tanβ ≲ 18 for MA ≈ 100 GeV

**Neutral Light pseudoscalar Higgs:**
h → 2a + X → 4μ + X:
\[ \sigma(pp \rightarrow 2a+X) \times BR(a \rightarrow \mu^+\mu^-)^2 \times \text{acceptance} < 0.25 \text{ fb for } m_a \in [0.5,3.5] \text{ GeV} \]
Neutral H: Non SM properties - FCNC

Theoretical motivation:
- Stringent test of the SM $\rightarrow m_H = 126.8$ GeV
- Allowed in several BSM models
  e.g. 2HDM-III, quark-singlet...

Search-channel:
[t][tbar]→[Wb][Hc]→bcWγγ

Signal regions: 2γ
(selection similar to SM H→γγ)
- Fully hadronic W: no lep.
- Semi-leptonic W: one isolated lepton

Search strategy:
- Looking for ttbar topology:
  based on $M_{jγγ}$ and $M_{jjj} + 1$ b-tag
- Look for peak in $m_{γγ}$

<table>
<thead>
<tr>
<th>Process</th>
<th>SM</th>
<th>QS</th>
<th>2HDM-III</th>
<th>FC-2HDM</th>
<th>MSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \rightarrow uy$</td>
<td>$3.7 \cdot 10^{-16}$</td>
<td>$7.5 \cdot 10^{-9}$</td>
<td>—</td>
<td>—</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow uZ$</td>
<td>$8 \cdot 10^{-17}$</td>
<td>$1.1 \cdot 10^{-4}$</td>
<td>—</td>
<td>—</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow uH$</td>
<td>$2 \cdot 10^{-17}$</td>
<td>$4.1 \cdot 10^{-5}$</td>
<td>$5.5 \cdot 10^{-6}$</td>
<td>—</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>$t \rightarrow cγ$</td>
<td>$4.6 \cdot 10^{-14}$</td>
<td>$7.5 \cdot 10^{-9}$</td>
<td>$\sim 10^{-6}$</td>
<td>$\sim 10^{-9}$</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow cZ$</td>
<td>$1 \cdot 10^{-14}$</td>
<td>$1.1 \cdot 10^{-4}$</td>
<td>$\sim 10^{-7}$</td>
<td>$\sim 10^{-10}$</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow cH$</td>
<td>$3 \cdot 10^{-15}$</td>
<td>$4.1 \cdot 10^{-5}$</td>
<td>$1.5 \cdot 10^{-3}$</td>
<td>$\sim 10^{-5}$</td>
<td>$10^{-5}$</td>
</tr>
</tbody>
</table>

Data sets: 5 fb$^{-1}$ @ 7 TeV & 21 fb$^{-1}$ @ 8 TeV

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Neutral H: Non SM properties - FCNC

**Background:** modeled using side-band techniques

- Fully hadronic: low statistics in the CR ⇒
  generate pseudo-data (~45 events) from smoothed pdf based on Sherpa $\gamma\gamma j$ sample

- Semi-leptonic: very low statistics in the CR ⇒
  use Sherpa $\gamma\gamma j$ sample and replace the low $p_T$ jet with a lepton
SM-Higgs is treated as background

\[ m_H = 126.8 \text{ GeV} \]

\[ \text{BR}(t \rightarrow cH) \leq 0.83 \% \]

(0.53 expected under NULL hypothesis)
“Search for charged Higgs bosons in the $\tau$+jets final state with pp collision data recorded at $\sqrt{s}=8$ TeV with the ATLAS experiment”  \texttt{ATLAS-CONF-2013-090}

“A search for a doubly-charged Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV” \texttt{arXiv:1207.2666}

“Search for a light charged Higgs boson in top quark decays in pp collisions at $\sqrt{s} = 7$ TeV” \texttt{arXiv:1205.5736}
Charged Higgs

Production mechanism:
- $m_H \leq m_t$: $tt$ bar
- $m_H \geq m_t$: $tH$ or $tbH$

Decay modes:
- $H \rightarrow \tau\nu$
- $t \rightarrow Wb \rightarrow qqb$

Signal regions: light (heavy) Higgs
4 (3) jets, 1 $b$-tagged, 1 hadronic $\tau$, large $E_T^{miss}$, ...

Final discriminator

$$m_T = \sqrt{2p_T^{\tau}E_T^{miss}(1 - \cos \Delta \phi_{\tau,miss})}$$

Data set: 20 fb$^{-1}$ @ 8 TeV
Charged Higgs: Results

Model independent:
\[ \text{BR}(H^\pm \rightarrow \tau \nu) = 1 \]

Interpretation in MSSM: \( m_h^{\text{max}} \) benchmark:
- \( M_{\text{SUSY}} \) (soft-SUSY breaking squark mass of 3\textsuperscript{rd} generation) = 1 TeV
- \( X_t \) (stop mixing parameter) = \( A_t - \mu \tan \beta^2 = 2M_{\text{SUSY}} \)
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- \( M_1 = (5/3)M_2 \sin \theta_W / \cos \theta_W \)
Highlights

\[ H^\pm \rightarrow \tau + \text{jets}; \quad \text{BR}(H^\pm \rightarrow \tau \nu) = 1 \]

\[ m_H \in [90,160] \text{ GeV}: \quad \text{Br}(t \rightarrow H^+ b) < 0.24 - 2.1 \% \]

\[ m_H \in [180,600] \text{ GeV}: \quad \sigma(pp \rightarrow H) < 0.017 - 0.9 \text{ pb} \]
Summary

Huge effort by both ATLAS and CMS
  • Different channels
  • Many different final states
  • Many different experimental methods

No deviation from the SM predictions

Model independent limits on many final states
Interpretations within the context of different BSM models

Not all the scenarios are covered
More searches are on-going
At some point nature might cooperate ...
Backup