Searches for BSM Higgs bosons, Higgs rare and BSM decays, and di-Higgs production

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on behalf of the ATLAS & CMS collaborations

LHCP 2018 - Bologna June 4-9
Challenging the SM

searching for another Higgs boson

April 2018

CMS Preliminary

Observation of HH would indicate BSM effect

One fb line

W/Z

Top

Higgs

7 TeV CMS measurement (L = 5.0 fb⁻¹)
8 TeV CMS measurement (L = 19.6 fb⁻¹)
13 TeV CMS measurement (L = 36.9 fb⁻¹)
Theory prediction

7,8,13 TeV : 5.2σ (4.3σ exp) (arXiv:1804.02610)

Observed ttH

M.D'Alfonso (MIT)
Theory motivations

Extended phenomenology from theoretical models \((\text{Higgs SM sector + scalar, doublet, triplet } \ldots)\)

→ Direct searches @ collider complementary to indirect constraints \((b\rightarrow s \gamma, g-2)\) and connected to BSM (i.e. dark matter)

**Scalar singlet**

They are not charged under the SM symmetries

Direct production of light scalar or from the \(h_{125}\) decay

- 2HDM + scalar
- theories for light Dark Matter with scalar mediator

**doublet**

Two-Higgs Doublet Models (2HDM) extend the SM by adding one Higgs doublets, lead to 5 Higgs bosons \(H^+, H^-\), \(A\) (CP-odd), \(H\) and \(h\) (CP-even)

4 types according to couplings of two Higgs doublets with fermion sector:

- **Type-I:** only one doublet couples to fermions
- **Type-II:** up vs. down
- **Lepton Specific:** quark vs lepton
- **Flipped Coupling:** \(b\) enhanced \(\tau\) suppressed

**triplet**

Fermiophobic \(H^\pm, H^{\pm\pm}\) bosons appear in Higgs sectors extended by a scalar triplet \(\Phi\)

- couplings to \(W\) and \(Z\) bosons at tree level
- e.g. Georgi-Machacek (GM) model

6/4/18
Introduction into Exotic Higgs Sector

Full coverage of a broad mX range is crucial to maximize the sensitivity to different models

→ Extended phenomenology from theoretical models (higgs SM sector + *scalar, doublet, triplet* …)

→ Direct searches @ collider complementary to indirect constraints (b->s γ , g-2) and connected to BSM ( i.e. dark matter )

→ Multiple analysis techniques
  i.e. boosted objects, soft triggers, high $p_T$ btagging, mva …

→ General enhancement of production xsection from PDF at 13TeV
  i.e. exploit different production modes: gluon fusion, VBF, bb/tt radiation, W/Z associated

Light resonances
$h_{125} \rightarrow aa, H^\pm \rightarrow cs, cb, \tau\nu,
A \rightarrow \tau\tau, H \rightarrow \gamma\gamma$

Heavy resonances
$H, A, H^\pm, H^{\pm\pm}$

125 GeV
Exotics decay
(invisible, Flavor Violating
Semi-invisible, long lived)

??

Mass (GeV)

No golden channel
important to cast a wide net

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**Experimental handles**

MET triggers suffers threshold dictated by the rate

Multivariate techniques are exploited to find rare signals on top of bkg

Boosted W/Z and Top became standard candles

Charm tagging giving results.

Low and high pT bTagging play a key role to suppress the ttbar background.

Run 2 major upgrade of the L1 trigger system increases the $\tau_h$ collection efficiency.
Since the extraction of the quantum field theory, it is the quantum theory of unknown dynamics. Additional Higgs like scalars are revealed by M. D’Alfonso et al. [arxiv:1504.04630].

Indirect constraints in BSM model imposed by \( m_{h_{125}} \), low \( \tan \beta \), high mass generally unexplored. One analysis dominates in one case but not a general statement.

\( \tan \beta \)
\( m_A \) [GeV]

\( H \rightarrow \tau \tau \)
Higgs → $3^{rd}$ generation fermion

BSM scenarios leading search channels:

- A/H→bb : CMS arxiv:1805.12191

$h_{125}$ : established *ad-hoc* hierarchical Yukawa couplings $\propto m_f$

Not imposed by a fundamental symmetry → searches exist in other decay modes

A/H→$\mu\mu$, $H^\pm$→cs,cb
Significant interference between the \( gg \to tt \) production and \( A/H \to tt \).

- 1 e/\( \mu \) + >=4jets + MET
- Discriminating variable: invariant mass of the top pair

**ATLAS Simulation**

\( s = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

Parton level; before selection

\( m_H = 500 \text{ GeV}, \tan \beta = 0.68 \)

**Upper Limits on Scalar H, pseudo-scalar (A) for Type-II 2HDM**

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \), all limits at 95% CL

\( \text{Obs.} \quad \text{Exp.} \pm 1\sigma/2\sigma \quad \text{Signal Samples} \)
**Same Sign leptons**
signature helps to kill the overwhelming background. O(100) search regions binned in $N_j$, $N_b$, $H_T$, MET, $m_T$, and lepton $p_T$.

*Statistics limited, expect continued progress in future.*
Unique Coupling to down-type fermion

QCD multijet is the main background

- Three subranges to reduce bias from the choice of the background model
- Signal shape for different signal hypothesis
(b)tH^\pm \rightarrow (b)ttb

TTbar + HF production the major background. Analysis categorized in jet and bjet multiplicity. MVA discriminant used to separate the small signal respect to the background.
Hadronic tau final state

Signal extraction w/

\[ m_h^2 = 2 \cdot p_T^{\tau^+} |\vec{E}_T| \left(1 - \cos \Delta \phi (\vec{E}_T, \tau^h)\right) \]

\[ \tau^h \rightarrow \nu \]

CMS-PAS-HIG-16-031
ATLAS-CONF-16-088

MSSM: Higgs + doublet

\( \tau_{h} \rightarrow \nu \)

MSSM Mh \text{mod+}

\( \tau_{h} \rightarrow \nu \)

\( \tau_{h} \rightarrow \nu \)

\( m_h^\text{MSSM} \geq 125 \pm 3 \text{ GeV} \)

associated production

CMS Preliminary

\( \text{Data} \)

\( \text{MSSM} \)

\( \text{CMS} \)

\( 12.9 \text{ fb}^{-1} (13 \text{ TeV}) \)

\( \text{Data} \)

\( \text{MSSM} \)

\( \text{CMS} \)

\( 12.9 \text{ fb}^{-1} (13 \text{ TeV}) \)

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\( \text{Data} \)

\( \text{MSSM} \)

\( 12.9 \text{ fb}^{-1} (13 \text{ TeV}) \)
### Heavy Higgs → dibosons

<table>
<thead>
<tr>
<th></th>
<th>W⁺</th>
<th>Z</th>
<th>γ</th>
<th>H/A/h₁₂₅</th>
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</thead>
<tbody>
<tr>
<td><strong>W⁺</strong></td>
<td></td>
<td>Z⁺ → W⁻ W⁺</td>
<td>H⁺⁺ → W⁻ W⁺</td>
<td>CMS-PAS-SMP-17-004</td>
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<tr>
<td></td>
<td>WW → 2l2ν</td>
<td>ZZ → 2l2q, 2l2ν, 4l</td>
<td>ZZ → 2l2q, 2l2ν, 4l</td>
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<td>ATLAS-HIGG-2016-31</td>
<td>ATLAS-H17-012,2016 36fb</td>
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<td><strong>Z</strong></td>
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<td>ATLAS EXOT-2016-28</td>
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<td>CMS-H16-027,2016</td>
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<td></td>
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<tr>
<td>γ</td>
<td>W/Z/h⁺⁺(→qqq) +γ</td>
<td>Zγ → (2l,2q)+γ</td>
<td>γγ</td>
<td></td>
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<tr>
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<td>CMS-EXO-17-005, 2016 36fb</td>
<td>CMS-EXO-17-005, 2016 36fb</td>
<td>CMS-EXO-16-027,2016 36fb</td>
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<td></td>
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<td>ATLAS-HIGG-2016-19</td>
<td>ATLAS-Prec 775 (2017) 105</td>
<td></td>
</tr>
<tr>
<td>H/A/h₁₂₅</td>
<td>W/Z(→lν,2l,2ν)+h₁₂₅→bb</td>
<td>Z(→2l)+H/A(→bb)</td>
<td>h₁₂₅UPPORT</td>
<td></td>
</tr>
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<td></td>
<td>B2G-17-004</td>
<td>CMS-H16-010 ,2015 (**)</td>
<td>CMS-EXO-17-005, 2016 36fb</td>
<td></td>
</tr>
</tbody>
</table>

In this talk

Bump hunting on dibosons mass spectrum

(*) also mass X→γγ 8-125 TeV HIG-14-037
(**) also Z(→2l)+H/A(→ττ) 8TeV HIG-14-034
**H→ZZ→2l2q, 2l2ν, 4l**

**4l**
ggH, VBF

**Lowest BR**
Low reducible background
Clear Bump Hunt

**2l2ν**
ggH, VBF
Signal extraction w/

\[ M_2^2 = \left( \sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_T^{miss} + M_Z^2} \right)^2 - \left( E_T(\ell\ell) + E_T^{miss} \right)^2 \]

Limits as function of MH and Γ

**2l2q**  **Largest BR**
explored both the boosted and resolved Z→qq
ggH, VBF

Search over Mzz and

\[ D_{Zj} = \left[ 1 + \frac{P_{Zj}(XX \rightarrow 2\ell\ell | \Delta M_{ZZ})}{P_{X \rightarrow 2\ell\ell}(X \rightarrow 2\ell\ell | \Delta M_{ZZ})} \right]^{-1} \]
Resonant $\mathcal{A} \rightarrow W/Z h_{125} \rightarrow \ell \ell b b, \ell \nu b b, \nu \nu b b$

Result on the gluon fusion and associated production

arxiv:1804.01126

Resonant $\mathcal{A} \rightarrow Z H \rightarrow \ell \ell b b$
Three leptons search, with two OS on Z

\[ M_T(WZ) = \sqrt{(E_T^Z + E_T^W)^2 - (p_T^Z + p_T^W)^2} \]

Sensitivity on NP mainly comes from bins at large energy

H. Georgi and M. Machacek
Higgs + SU(2) triplet

\[ H^{\pm\pm} \rightarrow W^\pm W^\pm \]

Same sign leptons

CMS-PAS-HIG-16-036

Both statistics limited, expect continued progress in future.


Di Higgs production

SM cross section @ 13 TeV

\[ 33.53^{+4.3\%\text{(scale)}}_{-6.0\%\text{(\alpha_s)}} \pm 2.3\%\text{(PDF)} \pm 2.1\% \text{ fb} \]

not accessible with the Run2 data

BSM effects lead to:

- the presence of resonant hh process.
- the enhancement of the non-resonant hh production cross section and the modification of the kinematics of the decays.

Very different theoretical motivation, but similar experimental signature.

One H\( \rightarrow \)bb or H\( \rightarrow \)WW decay required to keep BR high enough
Resolved

4 AK4jets:

B-jet triggers

4 btag jets:
  ATLAS: $\epsilon \geq 70\%$ WP
  CMS: new DeepCSV

CMS:
  fit function form taken from mbb-X sidebands
ATLAS:
  • 2b2j sample to model the 4b,
  • normalisation factor and kinematic corrections in control regions in m2jlead–m2jsubl plane

Boosted

Two large cone jets:
  ATLAS R=1.0
  CMS R=0.8

High pT FatJet trigger

ATLAS:
  btag R=0.2 track jets
  1or2 btag jets per large-R jet

CMS:
  double btagged
  SDmass and n-subjettiness

Probe mass $> 1$TeV

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Probe mass up to $\sim 1$TeV

M.D'Alfonso (MIT)
### Di Higgs

**bbVV**: high BR, large irreducible tt

**bbγγ and bbττ** with similar sensitivity at low mass

**WWγγ**→ studied by ATLAS

<table>
<thead>
<tr>
<th>Channel</th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbVV</td>
<td>$&lt;79$</td>
<td>JHEP 01 (2018) 054</td>
</tr>
<tr>
<td>bb bb</td>
<td>$&lt;342$</td>
<td>$&lt;13$ arxiv:1804.06174</td>
</tr>
<tr>
<td>bb γγ</td>
<td>$&lt;23.6$</td>
<td>arxiv:1806.00408</td>
</tr>
<tr>
<td>WW γγ</td>
<td>$&lt;230$</td>
<td>paper in preparation</td>
</tr>
</tbody>
</table>

ATLAS new (36 fb):

**bb γγ (WW γγ)** Observed 95% limits on $\sigma$ ranging from 1.14 to 0.12 pb (40 to 6.1 pb)

Complementarity of the channels in different mass ranges → much gain from a combination

Tested anomalous trilinear and BSM Higgs couplings as well.
Rare $h_{125}$ boson decay

SM-like Higgs @ 125 is narrow

But room for BSM

$B_{BSM} < 0.34$ (0.39) obs (exp) ATLAS + CMS combined

$125$ GeV

Exotics decay

(Invisible, Flavor Violating
Semi-invisible, long lived)
Rare $h_{125} \rightarrow \mu\mu$ decay

Most sensitive category is in the VBF channel

Less than 3 sigma away from SM

Rare $h_{125}$ boson decay

$\text{Statistics limited, expect continued progress in future.}$

$125 \text{ GeV (first, second generation ... )}$

$h_{125} \to Q\gamma$ clean probe for higgs quark coupling of 1st/2nd generation

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>$13\text{TeV}(36 /\text{fb}), 8\text{TeV}$</th>
<th>$\sigma/\sigma_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{125} \to Z\gamma$ (ATLAS) JHEP 10 (2017) 112</td>
<td>&lt; 6.6</td>
<td></td>
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<td>$H_{125} \to Z\gamma$ (CMS) PAS-HIG-17-007</td>
<td>&lt; 8</td>
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<tr>
<td>$H_{125} \to \gamma^*\gamma$ (CMS) PAS-HIG-17-007</td>
<td>&lt; 4</td>
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<tr>
<td>$H_{125} \to \rho \gamma$ (ATLAS) arxiv:1712.02758</td>
<td>&lt; 52</td>
<td></td>
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<tr>
<td>$H_{125} \to \phi \gamma$ (ATLAS) arxiv:1712.02758</td>
<td>&lt; 208</td>
<td></td>
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<tr>
<td>$H_{125} \to j/\psi \gamma$ (CMS) Phys. Lett. B 753 (2016) 341</td>
<td>&lt; 540</td>
<td></td>
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<tr>
<td>$H_{125} \to j/\psi \gamma$ (ATLAS) Phys. Rev. Lett. 114, 121801 (2015)</td>
<td>&lt; 540</td>
<td></td>
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<tr>
<td>$H_{125} \to Y\gamma$ (ATLAS) Phys. Rev. Lett. 114, 121801 (2015)</td>
<td>&lt; $10^5$</td>
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</table>

Dedicated talk by Andrew Haas

M.D’Alfonso (MIT)
$h_{125} \rightarrow aa$ decay

$H \rightarrow \bar{e}_5, c_6, t_7, A \rightarrow \tau, H \rightarrow \gamma\gamma$

125 GeV
(first, second generation ... )

$H, A, H^+, H^{±}$

$\rightarrow a$, $\rightarrow a \rightarrow fermions$

$h_{125} \rightarrow a \rightarrow 4\mu$

CMS 13TeV, 2.3 /fb $\text{HIG-16-035}$

ATLAS $\text{arxiv:1802.03388}$

$h_{125} \rightarrow a \rightarrow 2\mu 2\tau$

CMS $\text{arxiv:1805.04865}$

ATLAS $\text{arxiv:1505.01609}$

$h_{125} \rightarrow a \rightarrow 4\tau$

JHEP 10 (2017) 076

$h_{125} \rightarrow a \rightarrow 2b 2\tau$

$\text{arxiv:1805.10191}$

$h_{125} \rightarrow a \rightarrow 2\mu 2b$

JHEP 10 (2017) 076

$h_{125} \rightarrow a \rightarrow 4\gamma$


$\text{arxiv:1803.11145}$ (w/ VBF tag)

$\text{arxiv:1606.08391}$ (w/ W tag)

$\text{arxiv:1803.11145}$

M.D'Alfonso (MIT)
Rare $h_{125}$ boson decay

$125$ GeV
(Flavor Violating, Invisible,.. )

Lepton/quark flavor violating

Invisible Higgs

$\chi$ gives MET signature
SM invisible width = 0.1% $\Gamma(h_{125})$
from $h_{125}$ -> ZZ -> $\nu\nu\nu\nu$

$BR(H \rightarrow \tau \mu) < 1.43\% < 0.25\%$
$BR(H \rightarrow \tau e) < 1.04\% < 0.61\%$
$BR(H \rightarrow e \mu) < 0.036\%$

Dedicated talk by G. Zevi
Invisible Higgs

Gluon fusion

W/Z + H

VBF

Dedicated talk by Andrew Haas

High pT recoiling jet
Largest $\sigma$
Lowest S/B

Z→ OS/SF leptons close to Mz
Smallest BR, Higher S/B

Dijet system with
Large rapidity gap $\Delta\eta(j_1,j_2)$
Large dijet mass $M(j_1,j_2)$

V→ qq resolved or boosted

CMS-PAS-HIG-17-023
ATLAS arxiv:1708.09624
Summary

A rich program of searches for Higgs bosons in the context of models beyond the SM being pursued since Run-1

Direct search of new physics exploits:
→ Production of extra higgs decaying in Standard Model particles
→ Exotic decays of the $h_{125}$

BSM Higgs bosons are still hiding
More decay channels being explored, more statistics to come
→ So far analyzed mainly (36 fb-1), expected new results with 5 times large Run2 dataset!