PHENOMENOLOGY OF ADDITIONAL SCALAR BOSONS AT THE LHC

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in collaboration with
Wits HEP Group, HRI India
& Uppsala University, Sweden
The compatibility of LHC Run 1 data with a heavy scalar of mass around 270 GeV

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Abstract

The first run of the LHC with the SM hypothesis being due to the prediction of a heavy scalar and dark matter candidate. This candidate is not the SM Higgs boson and is expected to be produced in association with new physics.

Phenomenological signatures of additional scalar bosons at the LHC

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Abstract In this article we study the search strategies for new scalars beyond the Standard Model (SM) Higgs at the Large Hadron Collider (LHC). We consider an effective model by introducing two hypothetical real scalars, H and χ - a dark matter candidate, where the masses of these scalars are m_H < m_χ < 2m_t and m_χ ≈ m_H/2 with m_t and m_H being the SM Higgs boson and top quark masses, respectively. A distortion in the transverse momentum distributions of H in the intermediate region of the spectrum through the processes pp → H → hχχ could be observed in this model. An additional scalar, S, has been postulated to explain large H → hχχ branching ratios, assuming m_S ≲ m_S ≲ m_H − m_t and m_S > 2m_χ in detail. Furthermore, a scenario of a two Higgs doublet model (2HDM) is introduced and in this scenario the SM is realized.

1 Introduction

The aftermath of the discovery of a Higgs-like scalar [1-6] has been full of activities as intense as the very process of first unraveling its signature at the Large Hadron Collider (LHC). One notices two streams in such activities: (a) experimental efforts to closely examine if details of the behavior of this scalar reveal any discrepancy with predictions of the Standard Model (SM), and (b) theoretical studies on how any trace of new physics, both model-dependent and independent, can be discerned. The ‘new physics’ possibilities in this context often stress on the possible presence of additional scalars that may have participate in electroweak symmetry breaking (EWSB). Based on such expectations
WHAT EXPERIMENTAL DATA TELLS US - LHC AT 7, 8 & 13 TEV
EXCESSES / ANOMALY / FLUCTUATIONS OR CONSISTENCIES !!

• Differential Higgs boson pT spectra: \( h \rightarrow \text{di-photons (yy)} \) and \( h \rightarrow ZZ^* \rightarrow 4l \) [arXiv: 1407.4222, 1408.3226, 1508.07819, CMS-PAS-HIG-14-028]

• Di-Higgs boson resonance searches: Limits on \( H \rightarrow hh \) in different final states with \( bb\tau^+\tau^- \), \( yyWW^* \), \( yybb^- \), \( bb^-bb^- \) and multi-lepton [arXiv: 1509.04670, 1510.01181, 1410.2751, CMS-PAS-HIG-13-032]

• Top associated Higgs boson production - multi-leptons decay channels including measurements on \( h \rightarrow yy \) and \( h \rightarrow bb^- \) decay modes [arXiv: 1409.3122, 1506.05988, 1503.05066, 1408.1682]

• Limits on \( H \rightarrow WW \) and \( ZZ \) decays [arXiv: 1509.00389, 1507.05930, 1504.00936]


• \( H^\pm \) production in association with top (t) and bottom (b)-quarks and decays to \( tb \), considering \( mH^\pm > m_t \), excess observed in wide mass range (200-600 GeV) using multi-jet final states with one electron or muon [arXiv: 1512.03704]
RECENT DI-PHOTON EXCESS
~750 GEV RESONANCE IN RUN 2 ATLAS AND CMS 13 TEV RESULTS
The compatibility of LHC Run 1 data with a heavy scalar of mass around 270 GeV

Stefan von Buddenbrock,1, • Nabarun Chakrabarty,2, • Alan S. Cornell,3, •
Deepak Kar,1, • Mukesh Kumar,3, • Tanumoy Mandal,2, • Bruce
Mellado,1, • Biswarup Mukhopadhyaya,2, • and Robert G. Reed1, •

[arXiv: 1506.00612]
Higgs-Portal

Effective theory approach: introducing a heavy scalar $H$ and a scalar dark matter candidate $X$.

Best Fit results: $m_H = 272 \pm 12 - 9 \text{ GeV}$
Explaining large branching $H \rightarrow h \chi \chi$ by Introducing 'S' - a real singlet scalar.

In result: particle spectrum will be $h, H, \chi$ and $S$ with other SM fermions, bosons.

arXiv: 1603.01208, 1606.01674
The Two Higgs Doublet Model:

A minimal extension to the SM

CP even real bosons \( h, H \)

CP odd boson \( A \)

Charged Higgs boson \( H^\pm \)

\[
\mathcal{V}(\Phi_1, \Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\
+ \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{1}{2} \lambda_5 \left[ (\Phi_1^\dagger \Phi_1)^2 + \text{h.c.} \right] \\
+ \left[ \lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2) \right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right].
\]

Generalised

\[
\mathcal{V}(\Phi_1, \Phi_2, \chi) = \mathcal{V}(\Phi_1, \Phi_2) + \frac{1}{2} m_\chi^2 \chi^2 + \frac{\lambda_{\chi_1}}{2} \Phi_1^\dagger \Phi_1 \chi^2 + \frac{\lambda_{\chi_2}}{2} \Phi_2^\dagger \Phi_2 \chi^2 \\
+ \frac{\lambda_{\chi_3}}{4} (\Phi_1^\dagger \Phi_2 + \text{h.c.}) \chi^2 + \frac{\lambda_{\chi_4}}{8} \chi^4.
\]

\[
\mathcal{V}(\Phi_1, \Phi_2, S) = \mathcal{V}(\Phi_1, \Phi_2) + \frac{1}{2} m_{S_0}^2 S^2 + \frac{\lambda_{S_1}}{2} \Phi_1^\dagger \Phi_1 S^2 + \frac{\lambda_{S_2}}{2} \Phi_2^\dagger \Phi_2 S^2 \\
+ \frac{\lambda_{S_3}}{4} (\Phi_1^\dagger \Phi_2 + \text{h.c.}) S^2 + \frac{\lambda_{S_4}}{4!} S^4 \\
+ \mu_1 \Phi_1^\dagger \Phi_1 S + \mu_2 \Phi_2^\dagger \Phi_2 S + \mu_3 \left[ \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] S + \mu S S^3.
\]
Mass-Matrix, mixing, diagonalisation

\[
\begin{pmatrix}
H_1 \\
H_2 \\
H_3
\end{pmatrix} = R \begin{pmatrix}
\eta_1 \\
\eta_2 \\
\eta_3
\end{pmatrix}
\]

which satisfy

\[
RM^2 R^T = M_{\text{diag}} = \text{diag}(M_1^2, M_2^2, M_3^2).
\]

In our case

\[
\begin{pmatrix}
\rho_1 \\
\rho_2 \\
\varphi
\end{pmatrix} \simeq \begin{pmatrix}
-\sin \alpha & \cos \alpha & \delta_{13} \\
\cos \alpha & \sin \alpha & \delta_{23} \\
\delta_{31} & \delta_{32} & 1
\end{pmatrix} \begin{pmatrix}
h \\
H \\
S
\end{pmatrix}
\]

For phenomenology, we considered

(a) Light Higgs: \( m_h = 125 \text{ GeV} \) (assuming as the SM Higgs),
(b) Heavy Higgs: \( 2m_h < m_H < 2m_t \),
(c) \( CP \)-odd Higgs: \( m_A > (m_H + m_V) \), where \( (V = W^\pm, Z) \),
(d) Charged Higgs: \( (m_H + m_V) < m_{H^\pm} < m_A \),
(e) Additional scalars \( \chi, S \): \( m_\chi < m_h/2 \) and \( m_h \lesssim m_S \lesssim (m_H - m_h) \).

The masses of the physical states \( h \) and \( H \) are

\[
m_{h,H}^2 = \frac{1}{2} \left[ M_{11}^2 + M_{22}^2 \right. \\
\left. \mp \sqrt{(M_{11}^2 - M_{22}^2)^2 + 4 (M_{12}^2)^2} \right],
\]

while the mass of \( S \) is

\[
m_S^2 \simeq m_0^2 + \delta_{13} M_{13}^2 + \delta_{23} M_{23}^2.
\]

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Scalars</th>
<th>Decay modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>D. 1</td>
<td>( h )</td>
<td>( b\bar{b}, \tau^+\tau^-, \mu^+\mu^-, s\bar{s}, c\bar{c}, gg, \gamma\gamma, Z\gamma, W^+W^-, ZZ )</td>
</tr>
<tr>
<td>D. 2</td>
<td>( H )</td>
<td>D. 1, ( hh, SS, Sh )</td>
</tr>
<tr>
<td>D. 3</td>
<td>( A )</td>
<td>D. 1, ( t\bar{t}, Zh, ZH, ZS, W^\pm H^\mp )</td>
</tr>
<tr>
<td>D. 4</td>
<td>( H^\pm )</td>
<td>( W^\pm h, W^\pm H, W^\pm S )</td>
</tr>
<tr>
<td>D. 5</td>
<td>( S )</td>
<td>D. 1, ( \chi\chi )</td>
</tr>
</tbody>
</table>
## Production modes

(a) $gg \rightarrow h, H, A, S,$  
(b) $pp \rightarrow tH^- (\bar{t}H^+), tH^- b + \bar{t}H^+ b, H^+ H^-, H^\pm W^\pm.$

### A List of Searches:

<table>
<thead>
<tr>
<th>Scalar</th>
<th>Production mode</th>
<th>Search channels</th>
</tr>
</thead>
</table>
| $H$    | $gg \rightarrow H, Hjj \ (ggF \ and \ VBF)$ | Direct SM decays as in Table 1  
$\rightarrow SS/\bar{h} \rightarrow 4W \rightarrow 4\ell + $ MET  
$\rightarrow hh \rightarrow \gamma\gamma b\bar{b}, b\bar{b}\tau\tau, 4b, \gamma\gamma WW$ etc.  
$\rightarrow Sh$ where $S \rightarrow \chi\chi \rightarrow \gamma\gamma, \ b\bar{b}, 4\ell + $ MET |
| $H$    | $pp \rightarrow Z(W^\pm)H \ (H \rightarrow SS/\bar{h})$ | $\rightarrow 6(5)\ell + $ MET  
$\rightarrow 4(3)\ell + 2j + $ MET  
$\rightarrow 2(1)\ell + 4j + $ MET |
| $H^\pm$ | $pp \rightarrow t\bar{t}H, (t + \bar{t})H \ (H \rightarrow SS/\bar{h})$ | $\rightarrow 2W + 2Z + $ MET and $b$-jets  
$\rightarrow 6W \rightarrow 3$ same sign leptons + jets and MET |
| $H^\pm$ | $pp \rightarrow tH^\pm \ (H^\pm \rightarrow W^\pm H)$ | $\rightarrow 6W \rightarrow 3$ same sign leptons + jets and MET |
| $H^\pm$ | $pp \rightarrow tbH^\pm \ (H^\pm \rightarrow W^\pm H)$ | Same as above with extra $b$-jet |
| $H^\pm$ | $pp \rightarrow H^\pm H^\mp \ (H^\pm \rightarrow HW^\pm)$ | $\rightarrow 6W \rightarrow 3$ same sign leptons + jets and MET |
| $H^\pm$ | $pp \rightarrow H^\pm W^\mp \ (H^\pm \rightarrow HW^\pm)$ | $\rightarrow 6W \rightarrow 3$ same sign leptons + jets and MET |
| $A$    | $gg \rightarrow A \ (ggF)$ | $\rightarrow t\bar{t}$  
$\rightarrow \gamma\gamma$ |
| $A$    | $gg \rightarrow A \rightarrow ZH \ (H \rightarrow SS/\bar{h})$ | Same as $pp \rightarrow ZH$ above, but with resonance structure over final state objects |
| $A$    | $gg \rightarrow A \rightarrow W^\pm H^\mp (H^\mp \rightarrow W^\mp H)$ | $6W$ signature with resonance structure over final state objects |
Constrain from Run I LHC data on 2HDM-Type I (II):
\[ \cos(\beta - \alpha) \lesssim 0.5(0.2), \ m_H \lesssim 380(\approx 380), \ \tan \beta \lesssim 2(\text{all}) \]

These constraints have been made by considering the decay channels

\[ A/H/h \rightarrow \tau\tau, \ H \rightarrow WW/ZZ, \ A \rightarrow ZH(ll\tau\tau) \]

CMS PAS HIG-16-007
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On-going works:
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- Charged dark matter
- RGE calculations with these new states
- RUN -II LHC ....
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