A novel experimental search channel for very light Higgses in the Type-I 2HDM

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Abstract

We present a reinterpretation study of existing results from the CMS Collaboration, specifically, searches for light BSM Higgs pairs produced in the chain decay $pp \to H_{SM} \to hh(AA)$ into a variety of final states, in the context of the CP-conserving 2-Higgs Doublet Model (2HDM) Type-I. Through this, we test the LHC sensitivity to a possible new signature, $pp \to H_{SM} \to ZA \to ZZh$, with $ZZ \to jj\mu^+\mu^-$ and $h \to b\bar{b}$. We perform a systematic scan over the 2HDM Type-I parameter space, by taking into account all available theoretical and experimental constraints, in order to find a region with a potentially visible signal. We investigate the significance of it through a full Monte Carlo simulation down to the detector level. We show that such a signal is an alternative promising channel to standard four-body searches for light BSM Higgses at the LHC with an integrated luminosity of $L = 300\ fb^{-1}$.

General Two Higgs Doublets model (2HDM)

2HDM is one of the simplest and well motivated extension of the standard model (SM). The most general $SU(2)_L \times U(1)_Y$ invariant scalar potential can be written as follows :

$$V = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left\{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\}. \quad (1)$$

- Assuming the CP-conservation in the 2HDM and following the hermiticity of the scalar potential, m_{11}^2, m_{22}^2, m_{12}^2, $\lambda_{1,2,3,4}$ and $\lambda_{5,6}$ are real. Invoking $\mathcal{Z}_2$ symmetry implies that $\lambda_6 = \lambda_7 = 0$.
- 5 physical Higgses: two CP-even scalars (h, H with $m_h < m_H$), one CP-odd (A^0) and a charged Higgs pair ($H^\pm$)
- The scalar potential has 10 independent parameters: $m_{11}^2, m_{22}^2, m_{12}^2, v_1, v_2$ and $\lambda_{1,...,5}$
- 2 minimization conditions and the combination $v_1^2 + v_2^2 \Rightarrow$ 7 free parameters: $m_h <\ m_H,\ m_{H^\pm},\ m_A,\ \alpha,\ \tan\beta = \frac{v_2}{v_1}$ and m_{12}^2.

Alignement Limit

- $\cos(\beta-\alpha) \to 0,\ \ h \equiv H_{SM}$; standard hierarchy
  - with decoupling $m_{H^\pm} \sim m_A \sim m_H \gg v$
  - without decoupling: current data do not at all push the model parameters to the decoupling
- $\sin(\beta-\alpha) \to 0,\ \ H \equiv H_{SM}$; inverted hierarchy

Yukawa Coulplings Type-I

One doublet couple to all fermions,

$$\kappa_h^{u,\ d,\ l} = c_\alpha/s_\beta = s_{\beta-\alpha} + \cot\beta\ c_{\beta-\alpha}$$
$$\kappa_H^{u,\ d,\ l} = s_\alpha/s_\beta = c_{\beta-\alpha} - \cot\beta\ s_{\beta-\alpha}$$
$$\kappa_A^{d,\ l} = -\cot\beta,\ \kappa_A^u = \cot\beta$$

with α and β are the mixing angles.

Theo & Exper constraints

There are several theoretical and experimental constraints that must be checked in order to obtain a viable model:

- Unitarity, Perturbativity, Vacuum Stability, EW Precision Observables (S, T and U); `2HDMC`.
- Exclusion limits at 95% Confidence Level (CL) from Higgs searches at colliders (LEP, Tevatron and LHC); `HiggsBounds`.
- Constraints from the Higgs boson signal strength measurements; `HiggsSignal`.
- Constraints of flavour physics observables namely, $B \to X_s\gamma,\ B_{s,d} \to \mu^+\mu^-$ and $\Delta m_{s,d}$; `SuperIso`.

Numerical Analysis

We assume that the heaviest Higgs is the SM-like with mass of 125 GeV, whereas h and A would be lighter than H,

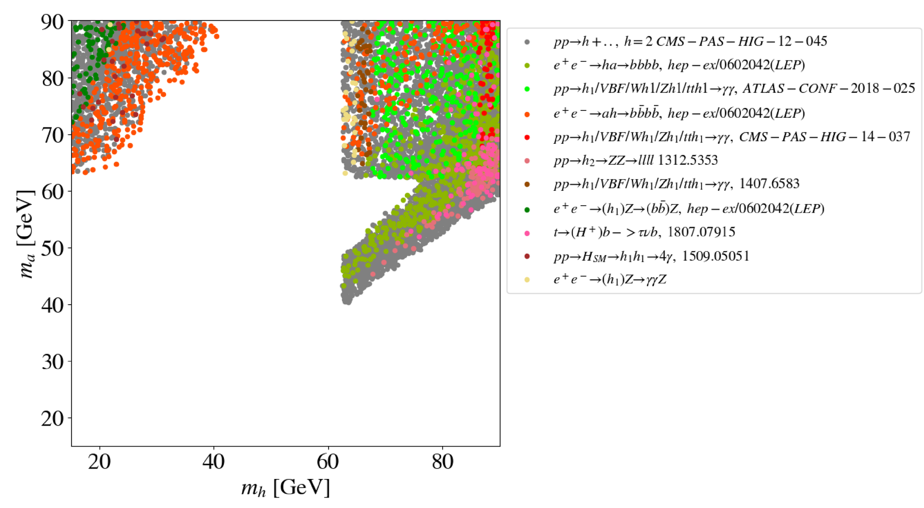


Figure 1:Allowed parameter space in Type-I at 95%C.L vs. searches to which the region are sensitive to.

- Sensitivity in the region with low m_h and high m_A is mainly from LEP searches for processes such as $e^+e^- \to ah \to bbbb$ and $e^+e^- \to (h)Z \to (bb)Z$.
- An update of LHC at Run3 is unlikely to rule out this mass combination (m_h, m_a)

Reinterpretation of exotic Higgs decays in Type-I

CMS search for $pp \to H \to aa \to 2b2\tau$ at $\sqrt{s} = 13$ TeV [1]:

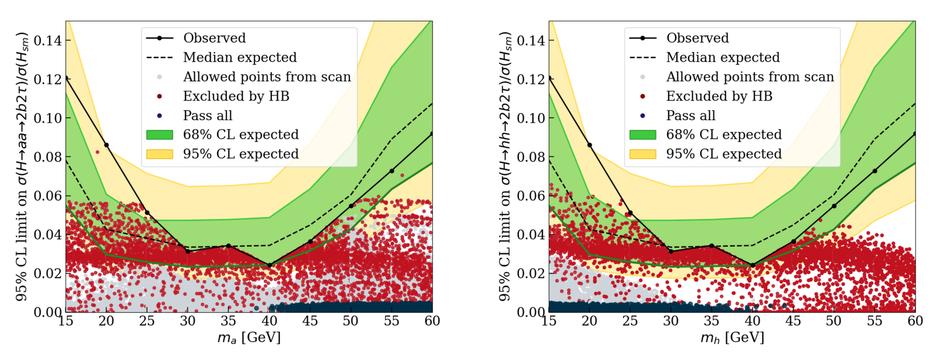


Figure 2:Observed and expected upper limits on $\sigma(H \to aa(hh) \to 2b2\tau)/\sigma_{SM}(H)$ at 95% in 2HDM Type-I

- Recasting the $2b2\tau$ search for $H \to hh$.
- Areas with sensitivity are excluded by previous searches.
- CMS searches at 13 TeV constrain $B(H \to\ BSM) < 0.19$ at 95% C.L.
- Type-I is more constrained by this search than $H \to aa \to 2b2\mu,\ 2\tau2\mu$.

CMS search for $H^\pm \to W^\pm a \to \mu^+\mu^-$ at $\sqrt{s} = 13$ TeV [2]:

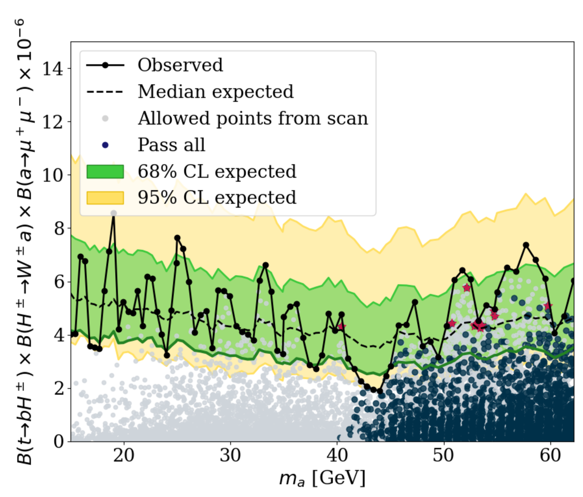


Figure 3:Observed and expected upper limits on $B(t \to H^+b) \to B(H^+ \to W^+a) \times B(a \to \mu^+\mu^-)$[2] at 95% in 2HDM type-I

- Bosonic decay of $H^\pm$ can dominate fermionic channles in BSM when kinematicaly allowed.
- Type-I offers sufficient sensitivity, with an integrated luminosity of 35.9 fb^{-1} (purple stars).

New Signature: $pp \to H_{sm} \to Z^*Z^*h$

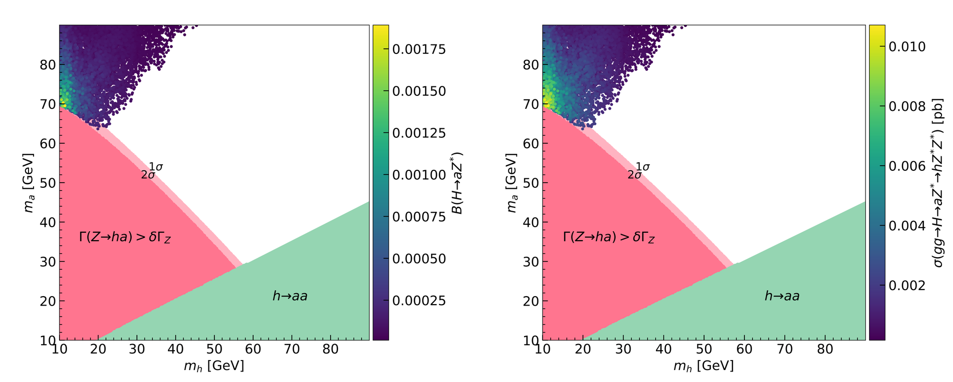
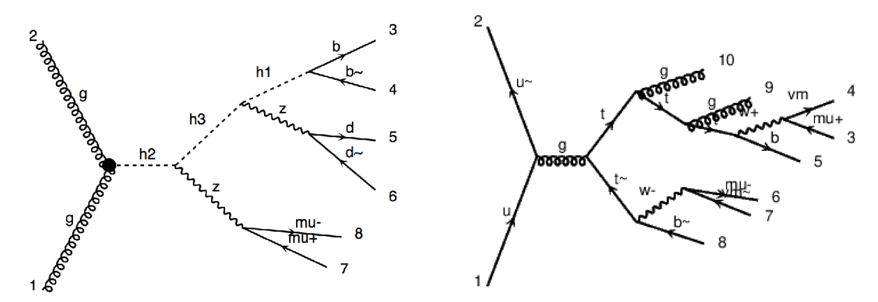


Figure 4:m_a and m_h vs. $\sigma(gg \to H_{sm} \to Z^*a)$ (left panel) and $\sigma(gg \to H_{sm} \to Z^*Z^*h)$ (right panel) at 95% C.L in 2HDM Type-I

- The subsequent decay of a, when the decay chain $H \to aZ^*$ is open, could lead to $a \to Z^*h$ with Z being off-shell and h decaying to fermions and/or $\gamma\gamma$.
- One could look for $Z^*(\to 2\mu)Z^*(\to 2j)h(\to 2b)$ with di-muon trigger & standard $|\eta(\mu)|$.

Signal vs. Background

- Few samples of BPs for the signal given by $H \to aZ^* \to hZ^*Z^* \to \mu^+\mu^-\ jj\ bb$ are considered.
- Background processes with dominant contributions are top pair production in association with 2 initial state radiation (ISR) jets, and ZZ production with additional bb quarks.



`MadGraph-v.9.2.5` is used to generate signal/background events

`PYTHIA8` is used for showering and hadronising parton level events

Applying detector simulation via `Delphes-3.5.0` (CMS card)

Applying cuts and carry out analysis using `MadAnalysis`

Figure 5:Description of the procedure used to generate and analyse MC events.

- QCD corrections are considered through K-factor:
  - NLO QCD correction to $t\bar{t}$ production in association with 2-jets are of the order of -27%.
  - NLO corrections to $gg \to H$ are very large due to the contribution from gg radiation, whereas $\mathrm{K_{NNLO/NLO}}$ is much smaller than $\mathrm{K_{NLO/LO}}$.

Background	Cross section (pb)
$pp \to ZZb\bar{b}_{QCD} \to 6f$	$9.27 \times 10^{-3} \pm 2.4 \times 10^{-5}$
$pp \to ZZb\bar{b}_{QED} \to 6f$	$2.42 \times 10^{-4} \pm 5.5 \times 10^{-7}$
$pp \to ggt\bar{t} \to gg\mu^+\mu^-jj$	2.92 ± 0.008

Table 1:The background cross sections

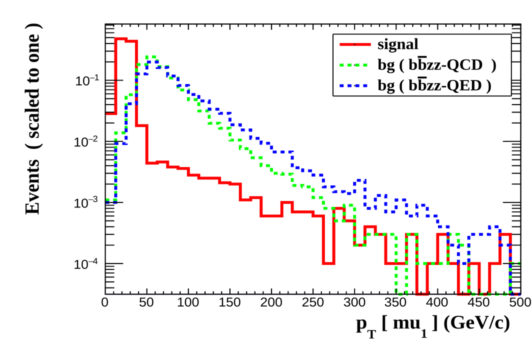


Figure 6:$p_T(\mu_1)$ distribution at parton level

- Triggering on two muons reduces the required momenta to 17 GeV for the muon with higher p_T
- Di-muon trigger increases the acceptance for numerous di-lepton processes and searches for new physics, compared with Isolated and Nonisolated signle muon triggers.

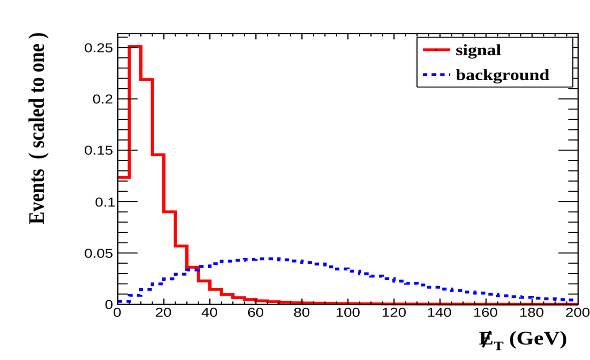


Figure 7:$\not{E}_T$ distributions for the signal (red) and background (blue) at detector level

- $\not{E}_T$ distribution from simulated samples of background events is mainly from di-leptonic decay of tt in association with 2 ISR jets, with $tt \to W^+bW^-\bar{b} \to (\mu^+\nu_\mu b)(\mu^-\bar{\nu}_\mu b)$.
- The observed MET in signal at detector level is from semi-leptonic B-meson decay.

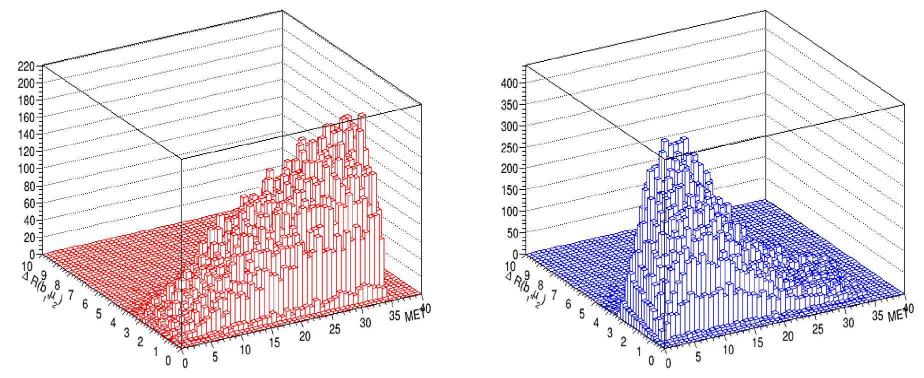


Figure 8:E_T vs. $\Delta R(b_1, \mu 2)$. Signal (blue) and background (red)

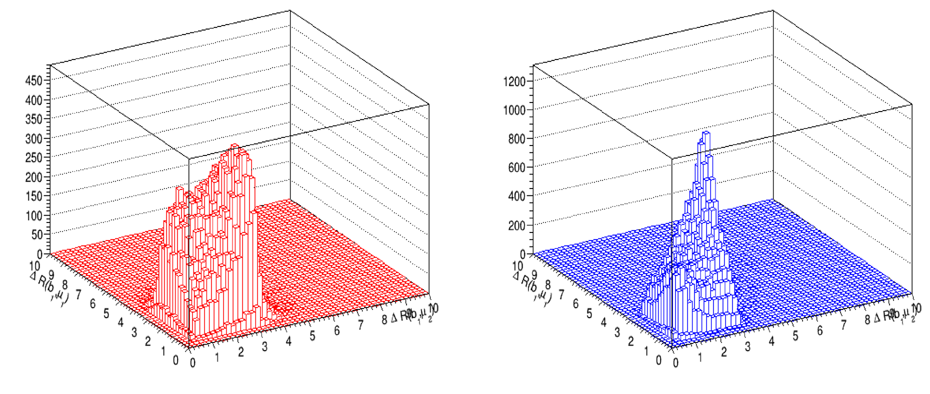


Figure 9:$\Delta R(b_1, \mu_2)$ vs. $\Delta R(b_1, \mu_1)$

- Effective suppression of the reducible background $ggtt$ after applying kinematic cuts.

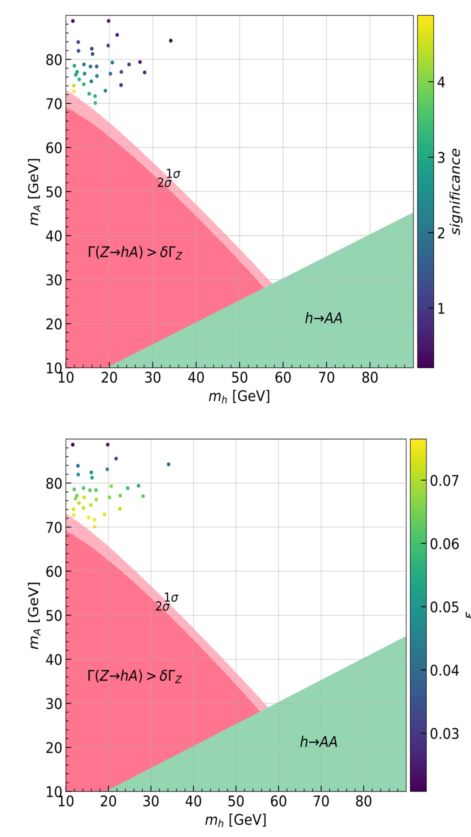


Figure 10:Significance and efficiency (ϵ) of each BP

- Some points on the grid have a significance larger than 3 on the (m_h, m_a) plane for $\mathcal{L} = 300\text{fb}^{-1}$.
- A larger efficiency can be obtained in a parameter space with small m_a.

BP	m_h (GeV)	m_A (GeV)	σ (pb)	k-factor	significance	ϵ
BP1	11.85	72.75	4.82×10^{-4}	2.689	4.88	0.0758
BP2	15.37	72.21	3.28×10^{-4}	2.63	3.20	0.0757
BP3	17.15	76.24	2.54×10^{-4}	2.63	2.29	0.0689
BP4	13.09	75.47	3.538×10^{-4}	2.65	3.31	0.0709
BP5	14.15	74.35	3.458×10^{-4}	2.62	3.29	0.072
BP6	11.96	78.57	3.557×10^{-4}	2.69	2.97	0.062
BP7	12.60	77.17	3.311×10^{-4}	2.66	2.87	0.065
BP9	14.30	76.77	2.423×10^{-4}	2.63	2.31	0.0729
BP10	14.16	78.86	2.572×10^{-4}	2.648	2.11	0.062
BP20	11.83	74.06	4.577×10^{-4}	2.69	4.51	0.073

Table 2:NNLO QCD correction to Higgs production, NLO QCD correction to $t\bar{t}gg$. $\epsilon = \sigma(cuts)/\sigma(no\ cuts)$ and $\mathcal{L} = 300\text{fb}^{-1}$.

Conclusion

1. Most combinations of Type-I for which there is sensitivity for $H \to hh(aa) \to 2b2\tau$ have been excluded by existing searches.
2. $H^\pm \to W^\pm a \to \mu^+\mu^-$ is a channel with good sensitivity for Run 3.
3. There is a good case for looking at Z^*Z^*h in the region with high m_a and small m_h which is expected to be available, once Run3 is turned on. Recall that the searches which have the most sensitivity in that area are from LEP searches.
4. $H_{SM} \to Z^*Z^*h \to \mu^+\mu^-bbjj$ is a promising signature to search for light Higgses, with a suppressed background and a large predicted significance.

References

[1] Albert M Sirunyan et al.
Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two b quarks and two τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Phys. Lett. B, 785:462, 2018.

[2] Albert M Sirunyan et al.
Search for a light charged Higgs boson decaying to a W boson and a CP-odd Higgs boson in final states with $e\mu\mu$ or $\mu\mu\mu$ in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Phys. Rev. Lett., 123(13):131802, 2019.

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