

Probing a 2HDM type-I light Higgs state via $H_{\text{SM}} \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ at the LHC

A. Arhrib,^{1,2,*} S. Moretti^{3,4,†} S. Semmlali^{3,5,‡} C. H. Shepherd-Themistocleous^{5,§} Y. Wang^{6,7,||} and Q. S. Yan^{8,9,¶}

¹*Abdelmalek Essaadi University, Faculty of Sciences and Techniques, Boite Postale 2117 Tétouan, Tanger, Morocco*

²*Department of Physics and Center for Theory and Computation, National Tsing Hua University, Hsinchu, Taiwan 300*

³*School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, United Kingdom*

⁴*Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden*

⁵*Particle Physics Department, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*

⁶*College of Physics and Electronic Information, Inner Mongolia Normal University, Hohhot 010022, People's Republic of China*

⁷*Inner Mongolia Key Laboratory for Physics and Chemistry of Functional Materials, Inner Mongolia Normal University, Hohhot, 010022, China*

⁸*Center for Future High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People's Republic of China*

⁹*School of Physics Sciences, University of Chinese Academy of Sciences, Beijing 100039, People's Republic of China*



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We study the discovery potential for a light Higgs boson via $gg \rightarrow H_{\text{SM-like}} \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ process at the Large Hadron Collider (LHC). Focusing on the 2-Higgs Doublet Model Type-I, which can accommodate light neutral Higgs states, of $\mathcal{O}(100)$ GeV or less in mass, while agreeing with theoretical and up-to-date experimental constraints, we explore the feasibility of a light CP -even Higgs state h via the largely unexplored final state $b\bar{b}\gamma\gamma$ at Run-3 of the LHC. We further propose a few benchmark points for future searches.

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I. INTRODUCTION

The Large Hadron Collider (LHC) holds the promise to deepen our understanding of electro-weak symmetry breaking through its vast Higgs physics programme at Run 3 as well as its future high-luminosity (HL) upgrade. After the Higgs discovery in 2012 [1,2], there has been an extensive, still ongoing at Run 3, effort to measure its properties with high precision [3,4]. This campaign has thus shifted the focus from initial observations to precision measurements. Ultimately, the upcoming HL-LHC datasets will consolidate such a new era of Higgs physics, enabling percent-level precision across most channels, thereby significantly improving our understanding of the Higgs sector.

Simultaneously, there has been a strong push to explore new physics beyond the minimal Higgs framework of the Standard Model (SM). One of the simplest and most extensively studied SM extensions is the 2-Higgs doublet model (2HDM), which introduces an extra Higgs doublet. This framework brings a rich phenomenology, including a wide range of Higgs-fermion interactions and additional new light and heavy Higgs states. It also allows for exotic SM-like Higgs decays to two light (pseudo)scalars, $H_{\text{SM}} \rightarrow aa(hh)$, which then decay into pairs of SM particles, offering a promising avenue to search for beyond the SM (BSM) physics in various final states at the LHC. Present experimental data from the ATLAS and the compact muon solenoid (CMS) collaborations have, respectively, placed upper limits of 12% [3] and 16% [4] at 95% CL on the branching ratio (BR) of non-SM Higgs decays (BR_{BSM}).

Building on these recent experimental searches, we aim to probe the largely unexplored $b\bar{b}\gamma\gamma$ final state in searches for $H \rightarrow aa(hh)$ cascade signals within the sub-62 GeV mass range. Currently, no upper limit exists on $\text{BR}(H \rightarrow aa \rightarrow b\bar{b}\gamma\gamma)$ for $m_a \in [10, 62]$ GeV. However, indirect constraints arise from searches for $H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$. The CMS collaboration reported upper limits on $\sigma(pp \rightarrow H) \times \text{BR}(H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma)$, ranging from 0.80 fb for $m_a = 15$ GeV to 0.26 fb for $m_a = 62$ GeV [5], while the ATLAS collaboration established further limits on

* Contact author: aarhrib@uae.ac.ma

† Contact author: s.moretti@soton.ac.uk, stefano.moretti@physics.uu.se

‡ Contact author: souad.semmlali@soton.ac.uk

§ Contact author: claire.shepherd@stfc.ac.uk

|| Contact author: wangyan@imnu.edu.cn

¶ Contact author: yanqishu@ucas.ac.cn

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$\text{BR}(H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma)$, ranging from 10^{-5} to 0.03, using their full Run 2 dataset with an integrated luminosity of 140 fb^{-1} [6]. A complementary analysis from ATLAS Run 1 searches for $H \rightarrow aa \rightarrow \gamma\gamma jj$ [7] placed additional indirect limits on $\text{BR}(H \rightarrow aa \rightarrow b\bar{b}\gamma\gamma)$. Combining these limits with $\text{BR}_{\text{BSM}} < 0.12$ enables setting indirect bounds on $\text{BR}(H \rightarrow aa(hh) \rightarrow b\bar{b}\gamma\gamma)$. It is noteworthy that processes featuring photon pairs in their final states, such as $H \rightarrow \gamma\gamma\gamma\gamma, \gamma\gamma gg(jj)$, are particularly relevant in models where the light Higgs state decays predominantly to photons and has suppressed fermionic decays (an “almost fermiophobic” scenario), which, in turn, leads to enhanced bosonic decay rates in the 2HDM Type-I [8–14].

In this paper, we cover the final state $b\bar{b}\gamma\gamma$ via the process $\sigma(gg \rightarrow H_{\text{SM}}) \times \text{BR}(H_{\text{SM}} \rightarrow hh \rightarrow b\bar{b}\gamma\gamma)$. This study builds on our previous work [15], where we explored the sensitivity to the 2HDM Type-I parameter space using $H_{\text{SM}} \rightarrow hh \rightarrow b\bar{b}\tau\tau$. By including the $b\bar{b}\gamma\gamma$ final state, we aim to provide a complementary test of the 2HDM framework and to broaden our understanding of potential BSM physics in exotic Higgs decays. Through detailed Monte Carlo (MC) simulations, we assess the feasibility of detecting the process $gg \rightarrow H_{\text{SM}} \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$, during LHC Run 3 (and beyond). Our approach focuses on the distinctive final state in order to identify optimized selection criteria that enhance signal-to-background discrimination and effectively isolate this signature from various background processes, i.e., $t\bar{t}H, ZH, b\bar{b}H$. With this study, we aim to further shed light on the 2HDM Type-I parameter space and explore the possibility of confirming or excluding such a scenario through future LHC data.

This letter is organized as follows. In Sec. II, we provide a brief overview of the 2HDM framework, followed by our simulation setup and analysis in Sec. III, we then conclude in Sec. IV.

II. THE 2HDM TYPE-I

A. Higgs potential

The most general renormalizable Higgs potential of a CP -conserving 2HDM, with a softly broken Z_2 symmetry, is given by [16],

$$\begin{aligned} \mathcal{V} = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.}] \\ & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) \\ & + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \text{H.c.} \right]. \end{aligned} \quad (1)$$

All the squared mass parameters, m_{11}^2, m_{22}^2 , and m_{12}^2 , along with the (dimensionless) quartic couplings λ_{1-5} are assumed to be real valued. Using the potential minimization conditions, m_{11}^2 and m_{22}^2 can be replaced by the vacuum expectation values $v_{1,2}$. At tree level, the quartic couplings

λ_{1-5} can be expressed in terms of the four (physical) Higgs boson masses, the mixing angle α between the CP -even scalars and the angle β , which is defined through $\tan \beta = v_2/v_1$. The Higgs sector can be then described by seven independent parameters,

$$m_H, \quad m_h, \quad m_{H^\pm}, \quad m_A, \quad \alpha, \quad \beta \quad \text{and} \quad m_{12}^2. \quad (2)$$

The presence of an extra Higgs doublet in the Yukawa sector introduces unwanted flavor changing neutral currents (FCNCs). By imposing a Z_2 symmetry, these FCNCs can be suppressed, resulting in four main types of 2HDM, where each is defined by how the Higgs doublets couple to fermions. Here, we focus on the Type-I realization of the 2HDM, where only one of the Higgs doublets couples to all fermions. The neutral Higgs-fermions couplings, $\kappa_{\phi f \bar{f}}$ with $\phi = h, H$, are given by [16],

$$\kappa_{h f \bar{f}} = \cos \alpha / \sin \beta, \quad \kappa_{H f \bar{f}} = \sin \alpha / \sin \beta. \quad (3)$$

B. Theoretical and experimental constraints

The 2HDM parameter space is tested against various constraints. On the theoretical side, all Higgs potential parameters must satisfy unitarity, vacuum stability, and perturbativity conditions. This has been checked using the public code 2HDMC-1.8.0 [17]. On the experimental side, compatibility with EW precision observables (EWPOs) is ensured by requiring the computed S, T , and U values from 2HDMC-1.8.0 to lie within 2σ of the SM fit from [18], while fully accounting for the correlations between the three parameters. Furthermore, constraints from B -physics observables, Higgs searches at lepton and hadron colliders, as well as Higgs signal measurements are checked by SuperIso-v4.1 [19] and HiggsTools-v1.2 [20], respectively.

III. NUMERICAL RESULTS

A. Parameter space

Focusing on the inverted hierarchy, where the heaviest Higgs state is identified as the observed 125 GeV object, we conducted a random scan over the following ranges:

$$\begin{aligned} m_h : & [15, 60] \text{ GeV}, & m_A : & [62, 100] \text{ GeV}, \\ m_{H^\pm} : & [100, 200] \text{ GeV}, & s_{\beta-\alpha} : & [-0.25, -0.05], \\ m_{12}^2 : & 0 - m_h^2 \cos \beta \sin \beta, & t_\beta : & 2 - 25. \end{aligned}$$

The scanned parameter points, which satisfy both theoretical and experimental constraints, are presented in Fig. 1. This figure illustrates the BR of $h \rightarrow b\bar{b}$ as a function of the light Higgs mass (m_h), compared against the overall cross section for the process $gg \rightarrow H \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$. Here, we focus on the main production mechanism of the SM-like Higgs boson (H) at the LHC, which is

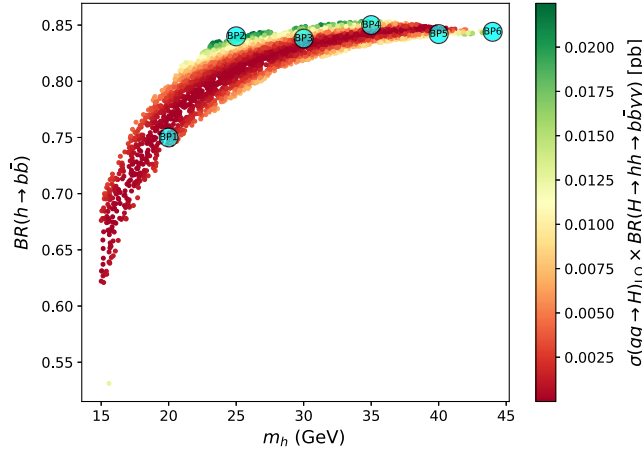


FIG. 1. $\text{BR}(h \rightarrow b\bar{b})$ as a function of m_h vs $\sigma(gg \rightarrow H \rightarrow hh \rightarrow b\bar{b}\gamma\gamma)$. BPs are marked in cyan color.

gluon-gluon fusion. The Higgs production cross section, $\sigma(gg \rightarrow H)$, is computed at leading order (LO) by Sushi [21] at the center-of-mass energy of 14 TeV, whilst the QCD corrections are considered through a K factor [22].

The $h \rightarrow b\bar{b}$ decay has the largest BR, of $\sim 60\%$ – 85% , due to enhanced light Higgs couplings to fermions, while the decay rate of $h \rightarrow \gamma\gamma$ is suppressed, exhibiting a BR below 12% that decreases to approximately 3% for $m_h \gtrsim 30$ GeV. The LO cross section reaches up to 0.02 pb when $\text{BR}(H \rightarrow hh)$ and $\text{BR}(h \rightarrow b\bar{b})$ are at their maximum. Notably, a significant region of the parameter space has been excluded by the recent CMS search for $H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$ [5] at $\sqrt{s} = 13$ TeV, with an integrated luminosity of 132 fb^{-1} . Additionally, further constraints on the parameter space arise from Higgs signal requirements, which restrict here $\text{BR}(H \rightarrow hh)$ to below 4%.

From the parameter points that successfully passed all constraints, several benchmark points were identified to perform a MC simulation. The selected signal samples correspond to a scalar boson mass, m_h , ranging from 20 to 45 GeV in approximately 5 GeV steps to ensure a consistent and systematic exploration of the parameter space as shown in Table I.

B. Signal vs background analysis

The generation of parton-level events for both signal and background processes is performed using MadGraph-v3.4.2 [23]. These events are subsequently passed to PYTHIA8 [24] for parton showering, fragmentation, hadronization, and the decays of heavy-flavor particles. Detector effects are then simulated using Delphes-3.5.0 [25], with a standard CMS card. Finally, events selection and kinematic analysis are carried out using MadAnalysis 5 [26]. The following cuts are applied at parton level for an efficient generation of signal and background events (j here refers to a quark or gluon):

TABLE I. Parameters for BP_{1–6}. All masses are in GeV, with $m_H = 125$ GeV. The LO cross sections $\sigma_{b\bar{b}\gamma\gamma} = \sigma(gg \rightarrow H) \times \text{BR}(H \rightarrow hh \rightarrow b\bar{b}\gamma\gamma)$ for our BPs are given for the collision energy $\sqrt{s} = 14$ TeV. The K factor mentioned above will be used later to compute the final significances.

BP	BP ₁	BP ₂	BP ₃	BP ₄	BP ₅	BP ₆
m_h	20	25	30	35	40	44
$\sin(\beta - \alpha)$	−0.12	−0.07	−0.05	−0.06	−0.077	−0.11
$\tan \beta$	8	13	20	17	14	10
m_A	89	86	87	90	94	99
$m_{H^\pm}$	125	119	109	108	116	145
BRs (%)						
$\text{BR}(H \rightarrow hh)$	0.35	2.4	3.4	3	1.33	2.14
$\text{BR}(h \rightarrow b\bar{b})$	79	83	84	85.2	84.2	84.3
$\text{BR}(h \rightarrow \gamma\gamma)$	6.4	2.9	2.3	2.08	3.17	2.85
Cross section (fb)						
$\sigma_{b\bar{b}\gamma\gamma}^{\text{LO}}$	6.10	20.0	22.0	17.7	12.0	17.4

$$p_T(\gamma[b, j]) > 5[10] \text{ GeV}, |\eta(\gamma, b, j)| < 3.5,$$

$$\Delta R(\gamma, b, j) > 0.3. \quad (4)$$

The major SM background processes are the production of a single Higgs boson in association with a top-quark pair ($t\bar{t}H$), Z boson (ZH), and bottom-quark pair ($b\bar{b}H$), followed by $H \rightarrow \gamma\gamma$. The large contamination from the irreducible background, $pp \rightarrow b\bar{b}\gamma\gamma$, has been also considered. Table II summarizes the LO cross sections for the different background processes, generated at $\sqrt{s} = 14$ TeV.¹

After detector simulation, we require the presence of two final state b jets and two photons in each event that satisfy the following criteria:

$$p_T(b_1/b_2) > 20/20 \text{ GeV}, \quad p_T(\gamma_1/\gamma_2) > 22/14 \text{ GeV}, \\ |\eta(b)| < 2.5, \quad |\eta(\gamma)| < 1.5. \quad (5)$$

In searching for light Higgs bosons in the $\gamma\gamma$ channel, the CMS (high-level) diphoton trigger relies on the presence of two photons where the leading has a p_T threshold of 30 GeV and the subleading one has a $p_T > 18$ GeV [5]. Given the presence of soft final states originating from light Higgs decays, we opted to refine our trigger strategy by focusing exclusively on barrel photons, rather than using an inclusive trigger. For barrel-only photon pairs (i.e., photons within $|\eta| < 1.5$), the trigger thresholds are approximately 22 (14) GeV for the leading (subleading) photon. To further optimize photon candidate identification by rejecting fake photon candidates, we require that the energy deposited in

¹Additional processes such as $pp \rightarrow t\bar{t}h, Zh, b\bar{b}h$ with h being the light Higgs state were also generated. However, their contributions were found to be negligibly small.

TABLE II. LO background cross sections at parton level for the collision energy $\sqrt{s} = 14$ TeV. The K factors mentioned in the text are not included here but will be discussed later.

Process	σ (pb)
$pp \rightarrow t\bar{t}H, t \rightarrow bW^+, \bar{t} \rightarrow \bar{b}W^-, H(\rightarrow \gamma\gamma)$	0.00061
$gg \rightarrow t\bar{t}H, t \rightarrow bW^+, \bar{t} \rightarrow \bar{b}W^-, H(\rightarrow \gamma\gamma)$	0.00046
$pp \rightarrow Z(\rightarrow jj)H(\rightarrow \gamma\gamma), j = j, b, \bar{b}$	0.0007
$pp \rightarrow Z(\rightarrow b\bar{b})H(\rightarrow \gamma\gamma)$	0.00015
$pp \rightarrow b\bar{b}H(\rightarrow \gamma\gamma)$	0.00076
$pp \rightarrow b\bar{b}\gamma\gamma$	4.9

the hadronic calorimeter does not exceed 10% of the energy recorded in the electromagnetic calorimeter. Furthermore, misidentified photons are rejected using the isolation variables $I_{\pm}$, I_0 and I_{γ} , which quantify the calorimetric deposits from charged hadrons, neutral hadrons, and photons, respectively, within a cone of radius $\Delta R = 0.3$ around the photon candidate [27].

For the jets clustering, we adopt anti- k_T algorithm [28] with a jet radius parameter $\Delta R = 0.4$ and $p_T^{\min} = 20$ GeV (for both light and b jets). Requiring exactly two b -tagged jets² in each event with a transverse momentum of $p_T(b) > 20$ GeV imposes a tight condition due to the low p_T values and the limited efficiency of b tagging. This is especially challenging in scenarios with low Higgs masses below 60 GeV, where the resulting b jets typically have lower p_T values. In such cases, the efficiency of b tagging decreases substantially, as b -tagging algorithms are optimized for higher p_T jets [30].

In our previous analysis [15], we explored how such an efficiency varies with different p_T thresholds. We observed that, while alternative pre-selection thresholds [such as $p_T(b_1/b_2) > 20/15$ or $15/10$ GeV] retain more signal events, the 20/20 GeV threshold ultimately offers better event significance, despite a higher loss in signal events. Thus, we require the 20/20 GeV threshold for the current analysis.

To enhance the sensitivity of our analysis and improve the signal-to-background ratio, we examine the reconstructed mass of the entire system ($m_H \equiv m_{b\bar{b}\gamma\gamma}$) alongside other relevant variables, such as the invariant mass of the b jets ($m_{b\bar{b}}$) and diphoton system ($m_{\gamma\gamma}$). In signal events, these variables are expected to be low, as the objects originate from a light Higgs boson, h , meanwhile, background events generated by $t\bar{t}$ and ZH would exhibit large values. This distinction enables an effective separation of signal from background.

In Fig. 2, the reconstructed SM-like Higgs boson mass distribution is consistent with the expected Higgs signal.

²Jets are b tagged with an average efficiency ($\epsilon_{b/b}$) of $\sim 60\%$ [i.e., $\epsilon_{b/b} = 0.85 \times \tanh(0.0025 \times p_T) \times (25.0/(1 + 0.063 \times p_T))$] [29], with p_T being the transverse momentum of the jet.

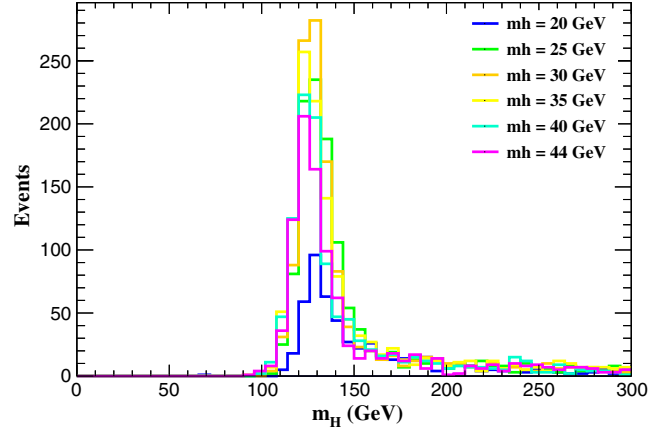


FIG. 2. Distributions of m_H for different BPs are shown at detector level.

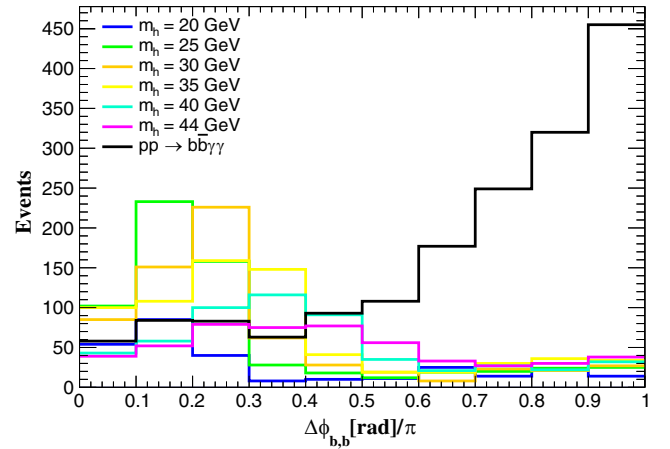
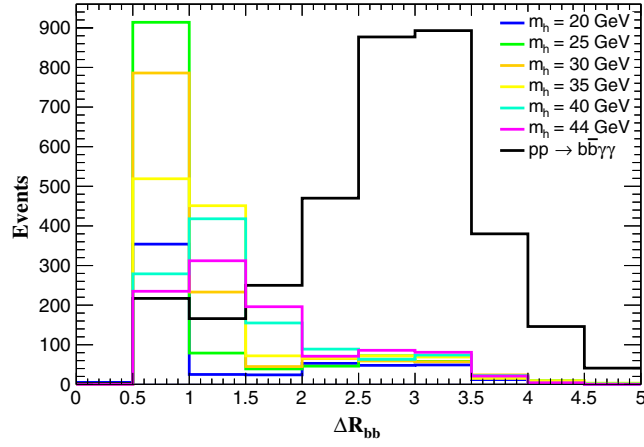


FIG. 3. Opening angles distributions between the two b jets for the signal and the irreducible background $pp \rightarrow b\bar{b}\gamma\gamma$.

Applying a kinematic cut on m_H would then significantly improve the isolation of signal events from background noise, given that signal events, originating from Higgs boson decays, produce a sharp mass peak around 125 GeV, whereas background events, arising from $t\bar{t}$ and ZH , would display a broader distribution at higher masses.

We further explore additional kinematic cuts that can help distinguish the Higgs signal from the substantial contamination of the $pp \rightarrow b\bar{b}\gamma\gamma$ background. Events from the irreducible background tend to exhibit different kinematic properties compared to those originating from a light Higgs state. Jets from Higgs decays typically have small opening angles, whereas those from the irreducible background, which are predominantly emitted back to back, exhibit a larger opening angle, as shown in Fig. 3. Therefore, requiring $\Delta\phi_{b,b}/\pi < 0.6$ would reduce background events.

Similarly, applying a constraint on the angular separation between the b jets further reduces the background contamination. As illustrated in Fig. 4, a cut on the angular


 FIG. 4. ΔR distributions between the two b jets for different BPs and the background process $pp \rightarrow b\bar{b}\gamma\gamma$.

distance, $\Delta R_{bb} < 2.0$, can effectively eliminate a significant portion of background events. Additional cuts on the angular separations between b jets and photons are implemented, along with other kinematic cuts, which we describe in detail below.

In Table III, we present the event rates of the signal after applying our selection criteria. Following the extraction of events containing two photons and two b -tagged jets, we require that $\Delta\phi_{b,b}/\pi < 0.6$, $\Delta R_{bb} < 2.5$, and $\Delta R_{\gamma\gamma} < 2.0$ to reduce the irreducible background. We then impose an additional requirement on the invariant masses of the b -jet ($m_{b\bar{b}}$) and photon ($m_{\gamma\gamma}$) pair to be less than $m_H/2$. This criterion captures the SM-like Higgs boson decaying into two light Higgs bosons, $H \rightarrow hh$, in the signal events. To further enhance the separation between signal and background, we introduce a new variable, $\Delta m_h = (m_{b\bar{b}} - m_{\gamma\gamma})/m_{\gamma\gamma}$, which measures the relative difference between $m_{b\bar{b}}$

 TABLE III. Signal events rates after applying our cutflow for $\mathcal{L} = 300 \text{ fb}^{-1}$.

Signal	BP ₁	BP ₂	BP ₃	BP ₄	BP ₅	BP ₆
m_h (GeV)	20	25	30	35	40	44
NoE	823.5	2700	2970.000	2591	1980	3027
$\gamma\gamma$	172.14	593	635.10	518.87	402.19	600.67
$2b$ -jets	4.75	33.39	38.10	33.06	21.879	30.45
$\Delta\phi_{b,b}/\pi < 0.6$	4.12	31.02	35.76	29.98	16.85	26.58
$\Delta R_{b,b} < 2.0$	3.34	27.83	31.63	26.97	16.85	22.34
$\Delta R_{\gamma,\gamma} < 2.5$	3.34	27.81	31.54	26.9	15.96	19.13
$m_{b\bar{b}} < 62 \text{ GeV}$	3.10	26.83	30.18	25.31	14.85	17.95
$m_{\gamma\gamma} < 62 \text{ GeV}$	3.10	26.83	30.18	25.29	14.81	17.92
$\Delta m_h < 0.25$	1.92	20.68	25.30	21.04	12.45	15.6
$m_H < 150.0 \text{ GeV}$	1.91	20.57	25.15	20.70	12.29	15.35
$\Delta R_{b_1,\gamma_1} < 3.0$	1.43	15.88	20.8	18.21	10.85	14.01
$\Delta R_{b_2,\gamma_2} < 3.2$	1.32	15.20	20.0	17.5	10.57	13.56
$\Delta R_{b_1,\gamma_2} < 2.5$	0.38	6.61	11.2	11.0	7.30	9.65

and $m_{\gamma\gamma}$. Applying a cut of $\Delta m_h < 0.25$ effectively suppresses background events, as there is no intrinsic correlation between $m_{b\bar{b}}$ and $m_{\gamma\gamma}$ in the latter, unlike in signal events, where both $b\bar{b}$ and $\gamma\gamma$ pairs originate from light Higgs bosons of the same mass. We also set a cut on the reconstructed mass of the entire system, consistent with the expectation that the energies of these reconstructed light Higgs bosons are capped at a mass of 125 GeV. Finally, we apply cuts on the angular separations $\Delta R_{b_1,\gamma_1}$, $\Delta R_{b_2,\gamma_2}$, and $\Delta R_{b_1,\gamma_2}$ to remove the remaining background events from $pp \rightarrow b\bar{b}\gamma\gamma$.

Table IV presents the cutflow results for the dominant background processes. Clearly, the mass observables, i.e., $m_{b\bar{b}}$, $m_{\gamma\gamma}$, and Δm_h , alongside the opening angle and the angular separation can greatly suppress the background

 TABLE IV. Backgrounds events rates as a function of our cutflow for $\mathcal{L} = 300 \text{ fb}^{-1}$.

Process	$Z(\rightarrow b\bar{b})H$	$Z(\rightarrow j\bar{j})H$	$pp \rightarrow t\bar{t}H$	$gg \rightarrow t\bar{t}H$	$pp \rightarrow b\bar{b}H$	$pp \rightarrow b\bar{b}\gamma\gamma$
NoE	45.00	210	183	138	228.0	1470000.000
$\gamma\gamma$	12.38	57.52	49.75	37.51	72.24	58767.651
$2b$ -jets	3.05	3.11	19.29	14.66	14.64	5086.199
$\Delta\phi_{b,b}/\pi < 0.6$	2.59	2.84	15.65	11.99	12.82	3348.659
$\Delta R_{b,b} < 2.0$	2.09	2.34	7.57	5.56	10.34	929.040
$\Delta R_{\gamma,\gamma} < 2.5$	1.75	1.95	5.67	4.05	8.78	687.960
$m_{b\bar{b}} < 62 \text{ GeV}$	0.182	0.24	1.26	0.6	0.92	432.180
$m_{\gamma\gamma} < 62 \text{ GeV}$	...	...	0.002	0.003	...	282.240
$\Delta m < 0.25$	...	...	...	...	...	120.540
$m_H < 150.0 \text{ GeV}$	...	...	...	...	...	29.400
$\Delta R_{b_1,\gamma_1} < 3.0$	...	...	...	...	...	8.820
$\Delta R_{b_2,\gamma_2} < 3.2$	...	...	...	...	...	5.88
$\Delta R_{b_1,\gamma_2} < 2.5$	...	...	...	...	...	...

TABLE V. Significances for our signal with $\sqrt{s} = 14$ TeV and $\mathcal{L} = 300 \text{ fb}^{-1}$.

Benchmark points (BP)	BP ₁	BP ₂	BP ₃	BP ₄	BP ₅	BP ₆
m_h (GeV)	20	25	30	35	40	44
Significance (Σ)	0.97	3.98	5.25	5.23	4.26	4.90

events, thereby enhancing the sensitivity to our signal process.³ It is also worth noting that the QCD corrections for the background processes are not included here. Given that our selection criteria already substantially suppress the background events, the QCD corrections to the background would have a negligible effect on the overall sensitivity of our analysis. With background contributions being so limited after selection cuts, we safely neglect them when calculating the significance of the signal.

Table V presents the significance (Σ) values for BP, where $\Sigma = N_S / \sqrt{N_S + N_B} \approx N_S / \sqrt{N_S} \approx \sqrt{N_S}$, where N_S and N_B indicate the event rates of the signal and backgrounds, respectively. Higher order corrections for signal are quantified through K factor ($K \sim 2.4\text{--}2.5$) [22]. One can read from the table that five of our BPs are within the discovery reach at Run 3 of the LHC, with a significance above 3σ . Needless to say, significances at the HL-LHC would be further increased by a factor approximately $\sqrt{10}$, thereby enabling access also to the remaining BP.

IV. CONCLUSIONS

This paper explored the parameter space of the 2HDM Type-I, specifically, within the framework of the so-called inverted mass hierarchy. In this scenario, the heaviest CP -even Higgs state, H , is identified as the SM-like Higgs boson (H_{SM}), while h corresponds to a lighter Higgs state. After taking into account all available theoretical and experimental constraints from standard tools, alongside recent limits from searches for exotic Higgs decays into two lighter (pseudo)scalars, we investigated the final state $b\bar{b}\gamma\gamma$ to search for light Higgs bosons in the

³In the mass range where $m_A > m_h + m_Z$, the decay process $gg \rightarrow A \rightarrow hZ \rightarrow b\bar{b}\gamma\gamma$ can mimic the signal. However, after performing an additional scan across the region $m_A \in [60, 200]$ GeV, we found that applying the specified kinematic cuts would effectively suppress this background, particularly the cuts on $m_{b\bar{b}}$ and Δm_h , as in our study, the $b\bar{b}$ pair originates from a light Higgs resonance, in contrast to the process where $Z \rightarrow b\bar{b}$ and no correlation exists between $m_{b\bar{b}}$ and $m_{\gamma\gamma}$. Moreover, requiring a cut on the reconstructed mass of the full system further reduces noise from this background. In this analysis, we only present results specifically for $m_A \in [60, 90]$ GeV.

decay channel, $H_{\text{SM}} \rightarrow hh$, where the main production mechanism of the SM-like Higgs is gluon fusion.

We have not included some major reducible SM background processes in our analysis, like $pp \rightarrow b\bar{b}jj$, $pp \rightarrow jjjj$, and $pp \rightarrow jj\gamma\gamma$. These processes were omitted based on considerations of b-tagging efficiency and photon mistagging rates. Using these efficiencies and mistagging probabilities, we estimated their contributions to be negligible compared to the dominant backgrounds already considered in our study. It is worth to mention that these SM processes typically have large cross sections and they might contribute to the background via mistagging jets as photons or mistagging light jets as b jets. Estimating such backgrounds demands reliable theoretical calculation and appropriate detector simulations. To circumvent these challenges, experimental groups use the data-driven approaches. For example, these background processes have been taken into account in realistic data analysis as demonstrated in [5–7].

Through a MC analysis of the signal and background processes, exploiting several BPs representative of the parameter space of the chosen BSM framework, we have demonstrated that there is a sensitivity to the overall 2HDM Type-I signal $gg \rightarrow H_{\text{SM}} \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ already at the ongoing Run 3 of the LHC, with full coverage eventually being attained at the HL-LHC. Therefore, this analysis reveals that the 2HDM Type-I offers a viable search avenue for BSM physics with an enlarged Higgs sector with respect to the SM.

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DATA AVAILABILITY

No data were created or analyzed in this study.

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