

Prospects for observing novel photon-induced H^-H^+ production at the high luminosity LHC

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We investigate the production of charged scalar boson pairs H^-H^+ via photon-photon fusion in proton-proton collisions at the High-Luminosity LHC (HL-LHC), High-Energy LHC (HE-LHC), and Future Circular hadron-hadron Collider (FCC-hh). The analysis is performed within the framework of the Two-Higgs-Doublet Model type-III, which predicts large branching ratios for the decay channel $H^\pm \rightarrow \tau^\pm \nu_\tau$, the focus of this work. Motivated by the current excess of events in $\mathcal{BR}(t \rightarrow H^\pm b) \times \mathcal{BR}(H^\pm \rightarrow cb)$ for $M_{H^\pm} = 130$ GeV, we explore charged Higgs boson masses in the range $M_{H^\pm} = 100\text{--}150$ GeV. Using benchmark points (BPs) consistent with current experimental constraints, we evaluate the process $\gamma\gamma \rightarrow H^-H^+ \rightarrow \tau\nu_\tau\tau\nu_\tau \rightarrow e\mu + \cancel{E}_T$ and find *signal significances* $\gtrsim 5\sigma$ across the entire mass range. For the most favored BP with $M_{H^\pm} = 130$ GeV, we predict *significances* of 3σ , 5σ , 8σ with integrated luminosities of 3000, 2300, and 300 fb^{-1} at center-of-mass energies of 14 TeV (HL-LHC), 27 TeV (HE-LHC), and 100 TeV (FCC-hh), respectively.

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I. INTRODUCTION

According to the laws of classical electrodynamics, two intersecting light beams would not deflect, absorb, or disrupt one another. However, effects of quantum electrodynamics allow interactions among photons. Four years ago, the ATLAS collaboration reported the observation of photon-induced W^+W^- production ($\gamma\gamma \rightarrow W^+W^-$) in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV [1]. The measurement was performed by selecting $e\mu$ pairs that come from the decays $WW \rightarrow e\mu\nu_e\nu_\mu$, being in agreement with the theoretical Standard Model (SM) prediction.

Inspired by this observation, herein, we study a charged scalar particle assumed to be slightly more massive than the $W^\pm$ gauge boson, which can be detected by the same method, being a novel process which could be encouraged at future huntings of the High-Luminosity LHC (HL-LHC) [2], High-Energy LHC (HE-LHC) [3] and Future Circular hadron-hadron Collider (FCC-hh) [4]. Such a hypothetical particle, denoted as $H^\pm$, is predicted by several SM extensions and, particularly, in the so-called Two-Higgs-Doublet Model type-III (2HDM-III) [5–10], assuming this theoretical framework henceforth. The charged scalar bosons $H^\pm$ are associated to new degrees of freedom that come from the introduction of a second doublet scalar field to the SM. Interactions of incoming photons in pp collisions for the production of H^-H^+ pairs ($\gamma\gamma \rightarrow H^-H^+$) can provide an invaluable window for the search for such a particle and analyze its features, as well as offer irrefutable proof of physics beyond the Standard Model. In the context of the 2HDM-III, the $\gamma\gamma \rightarrow H^-H^+$ interaction proceeds from trilinear and quartic gauge-scalar boson interactions, as shown in Fig. 1.

In contrast to the production of $\gamma\gamma \rightarrow WW \rightarrow e\mu + \cancel{E}_T$, the generation of events produced in the process

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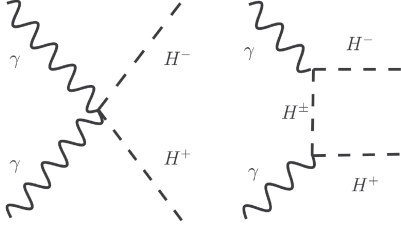


FIG. 1. Feynman diagrams for the production of two charged scalar bosons via photon fusion in pp collisions. There is another diagram similar to the t -channel (not included) in which the four-momenta of the charged scalar bosons are exchanged.

$\gamma\gamma \rightarrow H^-H^+ \rightarrow e\mu + \cancel{E}_T$ is smaller from one to two orders of magnitude, mainly due to the Yukawa coupling $Y_{H^\pm f_i f_j} \propto m_f$ which has a significant impact on the cross section $\sigma(\gamma\gamma \rightarrow H^-H^+ \rightarrow e\mu + \cancel{E}_T)$ [7–9]. Therefore, a larger database is required to study it copiously. Ideal scenarios would certainly be the upcoming super hadron colliders:

- (i) HL-LHC [2]: It is a major upgrade of the LHC, scheduled to begin operation around 2026, maintaining the proton-proton collision energy of 14 TeV in the center-of-mass frame. The primary goal of this upgrade is to increase the integrated luminosity by a factor of ten, reaching up to 3000 fb^{-1} by the year 2035, compared to the expected 300 fb^{-1} from the final phase of the original LHC program.
- (ii) HE-LHC [3]: This machine is a potential future project at CERN, conceived as a 27 TeV pp collider. Designed as a stepping stone toward the 100 TeV Future Circular Collider (FCC), the HE-LHC aims to achieve an integrated luminosity of up to 12000 fb^{-1} , significantly expanding the discovery potential for new physics.
- (iii) FCC-hh [4]: It is a proposed future 100 TeV pp hadron collider, could enable the discovery of rare processes, new interactions, and searches for potential quark substructure.

Thus, in this work, we are interested in analyzing the prospect for hunting the process $\gamma\gamma \rightarrow H^-H^+$ that will produce a final state $e\mu + \cancel{E}_T$, which comes from the decay product of the pair $H^-H^+ \rightarrow \tau\nu_\tau\tau\nu_\tau \rightarrow e\mu + 2\nu_\tau\nu_e\nu_\mu \rightarrow e\mu + \cancel{E}_T$.

In this paper, we show in Sec. II the relevant aspects of the 2HDM-III with a particular emphasis on the interactions $H^\pm f_i \bar{f}_j$. A brief overview of the model parameter space is also included. In Sec. III, we analyze the charged Higgs boson pair production via photon fusion, with their subsequent decays into charged leptons plus missing energy transverse ($\cancel{E}_T$) due to undetected neutrinos. Finally, the conclusions are presented in Sec. IV.

II. THE MODEL

This section presents the relevant aspects of the 2HDM-III. Specifically, we focus on the interactions

involved in the main idea of our research, that is, the interactions $H^\pm \ell \nu_\ell$, $\gamma\gamma H^-H^+$, and γH^-H^+ .

A. Scalar potential

The 2HDM-III includes an additional Higgs doublet with regard to the SM, and it can be written as $\Phi_a^T = (\phi_a^+, \phi_a^0)$ for $a = 1, 2$, with hypercharge $Y = +1$. After the spontaneous symmetry breaking (SSB), they acquire nonzero vacuum expectation values (VEV), which are given by

$$\langle \Phi_a \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_a \end{pmatrix}, \quad a = 1, 2.$$

The most general $SU(2)_L \times U(1)_Y$ invariant scalar potential reads:

$$\begin{aligned} V = & \mu_1^2(\Phi_1^\dagger \Phi_1) + \mu_2^2(\Phi_2^\dagger \Phi_2) - (\mu_{12}^2(\Phi_1^\dagger \Phi_2 + \text{H.c.})) \\ & + \frac{1}{2}\lambda_1(\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\ & + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left(\frac{1}{2}\lambda_5(\Phi_1^\dagger \Phi_2)^2 + \lambda_6(\Phi_1^\dagger \Phi_1) \right. \\ & \left. \times (\Phi_1^\dagger \Phi_2) + \lambda_7(\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{H.c.} \right). \end{aligned} \quad (1)$$

In this research, we assume the potential parameters to be reals, even the VEVs of the Higgs doublets. Therefore, CP symmetry is conserved. Once the scalar potential in Eq. (1) is diagonalized, the mass-eigenstates are generated. The particle spectrum includes two new neutral and two new charged particles—there are contributions to the SM-like Higgs boson mass—whose masses are given by

$$\begin{aligned} M_{H^\pm}^2 = & \frac{\mu_{12}^2}{\sin\beta \cos\beta} - \frac{1}{2}v^2(\lambda_4 + \lambda_5 + \cot\beta\lambda_6 + \tan\beta\lambda_7) \\ M_A^2 = & M_{H^\pm}^2 + \frac{1}{2}v^2(\lambda_4 - \lambda_5), \\ M_{H,h}^2 = & \frac{1}{2}(m_{11} + m_{22} \pm \sqrt{(m_{11} - m_{22})^2 + 4m_{12}^2}), \end{aligned} \quad (2)$$

where $m_{11,12,22}$ are elements of the real part of the mass matrix $\mathbf{M}$,

$$\text{Re}(\mathbf{M}) = \begin{pmatrix} m_{11} & m_{12} \\ m_{12} & m_{22} \end{pmatrix},$$

which are given as follows:

$$\begin{aligned} m_{11} = & M_A^2 \sin^2\beta + v^2(\lambda_1 \cos^2\beta + \lambda_5 \sin^2\beta + 2\lambda_6 \cos^2\beta \sin^2\beta), \\ m_{12} = & -M_A^2 \sin^2\beta \cos^2\beta + v^2[(\lambda_3 + \lambda_4) \sin^2\beta \cos^2\beta \\ & + \lambda_6 \cos^2\beta + \lambda_7 \sin^2\beta], \\ m_{22} = & M_A^2 \cos^2\beta + v^2(\lambda_2 \sin^2\beta + \lambda_5 \cos^2\beta + 2\lambda_7 \sin^2\beta \cos^2\beta). \end{aligned} \quad (3)$$

The angle α is associated to the mass matrix corresponding to the CP -even sector, and it defines the transition from gauge to mass eigenstates as follows:

$$\begin{aligned} H &= \text{Re}(\phi_1^0) \cos \alpha + \text{Re}(\phi_2^0) \sin \alpha, \\ h &= \text{Re}(\phi_1^0) \sin \alpha + \text{Re}(\phi_2^0) \cos \alpha. \end{aligned} \quad (4)$$

Meanwhile, the angle β defines the ratio of the VEVs v_2 and v_1 through $\tan \beta = v_2/v_1$, and it mixes both the charged components of Φ_a and the imaginary part of the neutral components of Φ_a . The above defines the physical charged scalar bosons $H^\pm$, the pseudo-Goldstone boson associated with the W gauge fields, the CP -odd state A , and the pseudo-Goldstone boson related to the Z gauge boson. Their mixings are given by

$$\begin{aligned} G_W^\pm &= \phi_1^\pm \cos \beta + \phi_2^\pm \sin \beta, \\ H^\pm &= -\phi_1^\pm \sin \beta + \phi_2^\pm \cos \beta, \\ G_Z &= \text{Im}(\phi_1^0) \cos \beta + \text{Im}(\phi_2^0) \sin \beta, \\ A &= -\text{Im}(\phi_1^0) \sin \beta + \text{Im}(\phi_2^0) \cos \beta. \end{aligned} \quad (5)$$

From the kinetic term, the interactions $\gamma\gamma H^-H^+$ and γH^-H^+ remain unchanged and are well known [6]. Their explicit forms are as follows:

- (i) $\gamma_\mu \gamma_\nu H^-H^+ = 2ie^2 g_{\mu\nu}$, and
- (ii) $\gamma_\mu H^-(p_1)H^+(p_2) = -ie(p_1 + p_2)_\mu$.

B. Yukawa Lagrangian

We now turn to explore the Yukawa Lagrangian [7,9]. It can be written as follows:

$$\begin{aligned} -\mathcal{L}_Y &= Y_1^u \bar{Q}_L \tilde{\Phi}_1 u_R + Y_2^u \bar{Q}_L \tilde{\Phi}_2 u_R + Y_1^d \bar{Q}_L \Phi_1 d_R \\ &+ Y_2^d \bar{Q}_L \Phi_2 d_R + Y_1^\ell \bar{L}_L \tilde{\Phi}_1 l_R + Y_2^\ell \bar{L}_L \tilde{\Phi}_2 l_R, \end{aligned} \quad (6)$$

where $\tilde{\Phi}_a = i\sigma_2 \Phi_a^*$ ($a = 1, 2$). After SSB, the fermion mass matrices are defined as $M_f = \frac{1}{\sqrt{2}}(v_1 Y_1^f + v_2 Y_2^f)$, $f = u, d, \ell$. We assume both Yukawa matrices to have a four-zero texture form and Hermitians. The sum of the Yukawa matrices inherits its form from the mass matrix as follows:

$$M_f = \begin{pmatrix} 0 & D_f & 0 \\ D_f & C_f & B_f \\ 0 & B_f & A_f \end{pmatrix}. \quad (7)$$

The elements of the fermion mass matrices in Eq. (7) are related to the physical fermion masses m_{f_i} ($i = 1, 2, 3$), via the following invariants:

$$\begin{aligned} \text{Tr}(M_f) &= C_f + A_f = m_{f_1} + m_{f_2} + m_{f_3}, \\ \lambda(M_f) &= C_f A_f - D_f^2 - B_f^2 \\ &= m_{f_1} m_{f_2} + m_{f_1} m_{f_3} + m_{f_2} m_{f_3}, \\ \det(M_f) &= -D_f^2 A_f = m_{f_1} m_{f_2} m_{f_3}. \end{aligned} \quad (8)$$

From Eq. (8), we obtain the relation between the mass matrix elements in its four-zero texture structure and the fermion masses as follows:

$$\begin{aligned} A_f &= m_{f_3} - m_{f_2}, \\ B_f &= m_{f_3} \sqrt{\frac{r_2(r_2 + r_1 - 1)(r_2 + r_2 - 1)}{1 - r_2}}, \\ C_f &= m_{f_3}(r_2 + r_1 + r_2), \\ D_f &= \sqrt{\frac{m_{f_1} m_{f_2}}{1 - r_2}}, \end{aligned} \quad (9)$$

where $r_i = m_{f_i}/m_{f_3}$. Applying a biunitary transformation, the fermion mass matrices are diagonalized. However, the Yukawa matrices generally remain nondiagonal:

$$\bar{M}_f = V_{fL}^\dagger M_f V_{fR} = \frac{1}{\sqrt{2}}(v_1 \tilde{Y}_1^f + v_2 \tilde{Y}_2^f), \quad (10)$$

where $\bar{M}_f = \text{diag}(m_{f_1}, m_{f_2}, m_{f_3})$ and $\tilde{Y}_a^f = V_{fL}^\dagger Y_a^f V_{fR}$. As a consequence, flavor-changing neutral currents will be induced at tree level. The fact that M_f is assumed as Hermitian implies that $V_{fL} = V_{fR} \equiv V_f$. Here, $V_f = \mathcal{O}_f P_f$, where $P_f = \text{diag}\{e^{i\alpha_f}, e^{i\beta_f}, 1\}$ and

$$\mathcal{O}_f = \begin{pmatrix} \sqrt{\frac{m_{f_2} m_{f_3} (A - m_{f_1})}{A(m_{f_2} - m_{f_1})(m_{f_3} - m_{f_1})}} & \sqrt{\frac{m_{f_1} m_{f_3} (m_{f_2} - A)}{A(m_{f_2} - m_{f_1})(m_{f_3} - m_{f_2})}} & \sqrt{\frac{m_{f_1} m_{f_3} (A - m_{f_3})}{A(m_{f_3} - m_{f_1})(m_{f_3} - m_{f_2})}} \\ -\sqrt{\frac{m_{f_1} (m_{f_1} - A)}{(m_{f_2} - m_{f_1})(m_{f_3} - m_{f_1})}} & \sqrt{\frac{m_{f_2} (A - m_{f_2})}{(m_{f_2} - m_{f_1})(m_{f_3} - m_{f_2})}} & \sqrt{\frac{m_{f_3} (m_{f_2} - A)}{(m_{f_2} - m_{f_1})(m_{f_3} - m_{f_2})}} \\ \sqrt{\frac{m_{f_1} (A - m_{f_2})(A - m_{f_3})}{A(m_{f_2} - m_{f_1})(m_{f_3} - m_{f_1})}} & -\sqrt{\frac{m_{f_2} (A - m_{f_1})(m_{f_3} - A)}{A(m_{f_2} - m_{f_1})(m_{f_3} - m_{f_2})}} & \sqrt{\frac{m_{f_3} (A - m_{f_1})(A - m_{f_2})}{A(m_{f_3} - m_{f_1})(m_{f_3} - m_{f_2})}} \end{pmatrix}. \quad (11)$$

A fact of utmost importance is that $V_{u,d}$ must reproduce the measured matrix elements V_{CKM} , which can be obtained through $V_{\text{CKM}} = V_u^\dagger V_d$, as shown in Ref. [10]. From Eq. (10), we obtain the following expression:

$$[\tilde{Y}_a^f]_{ij} = \frac{\sqrt{m_i m_j}}{v} [\chi_a^f]_{ij}, \quad (12)$$

where the parameters χ 's (dimensionless quantities) are responsible for inducing flavor-changing interactions at the tree level. The relevant interactions we are interested in come from Eqs. (6)–(12) and are given by

$$-\mathcal{L}^{H^\pm f \bar{f}} = \frac{\sqrt{2} m_{\ell_j}}{v} \Theta_{ij}^\ell \bar{\nu}_L l_R H^\pm + \text{H.c.}, \quad (13)$$

where

$$\Theta_{ij}^\ell = \left[\mathcal{Z} \frac{m_{\ell_i}}{m_{\ell_j}} \delta_{ij} - \frac{F(\mathcal{Z})}{\sqrt{2}} \sqrt{\frac{m_{\ell_i}}{m_{\ell_j}}} \chi_{ij}^\ell \right], \quad (14)$$

with $F(\mathcal{Z}) = \sqrt{1 + \mathcal{Z}^2}$, and $\mathcal{Z}$ definitions given in Table I for the four kinds of versions. When $\chi_{ij}^\ell \rightarrow 0$, the model reduces to the traditional 2HDM with no flavor violation.

C. Constraints on the 2HDM parameter space

From now on we focus on the particular case of the 2HDM-III type II-like (simply called as throughout the text: 2HDM-III). As seen in Table I, the process studied in this work cannot distinguish the 2HDM-III II-like from the lepton-specific-like. Thus, the analysis performed in this investigation can be applied to both versions. However, it is important to clarify that all versions of 2HDM can be well defined, as shown in Ref. [11].

On the other hand, a comprehensive analysis of the parameter space was reported by one of us in Ref. [12], which was done considering several physical observables, namely: (i) LHC Higgs boson data (and its HL-LHC projection), (ii) Lepton flavor-violating processes (LFVp), and (iii) theoretical constraints, among others. As far as this investigation is concerned, the parameters that have a direct impact on our predictions are $\cos(\alpha - \beta)$, $\mathcal{Z}$, and $\chi_{33}^\ell \equiv \chi_{\tau\nu}$. According to Ref. [12], the allowed region in the $\cos(\alpha - \beta) - \mathcal{Z}$ plane is presented in Fig. 2. The orange points correspond to these allowed by LFVp, while the blue points represent the region that satisfy the projections of Higgs boson data for HL-LHC. The only parameter not studied is $\chi_{\tau\nu}$, which is expected to be of order 1.

TABLE I. Definitions of the $\mathcal{Z}$ parameter for the different model types.

2HDM-III	$\mathcal{Z}$
Type I-like	$-\cot \beta$
Type II-like	$\tan \beta$
Lepton specific-like	$\tan \beta$
Flipped-like	$-\cot \beta$

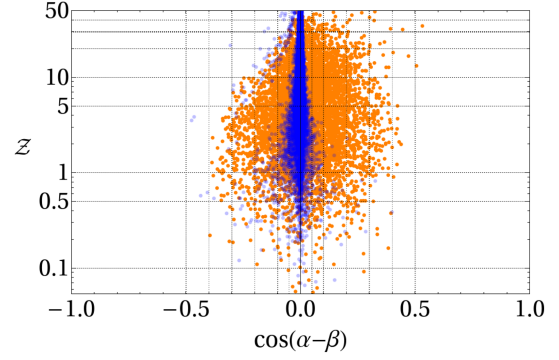


FIG. 2. Parameter space in the $\cos(\alpha - \beta) - \mathcal{Z}$ plane. Blue (orange) points represent the allowed region by projections on Higgs boson data for the HL-LHC (LFVp). Figure taken from [12].

Based on the above, we define three benchmark points (BPs) to be considered in the predictions presented in Sec. III, namely,

- (1) BP1: $\mathcal{Z} = 10$, $\cos(\alpha - \beta) = -0.2$,
- (2) BP2: $\mathcal{Z} = 20$, $\cos(\alpha - \beta) = -0.1$, and
- (3) BP3: $\mathcal{Z} = 2$, $\cos(\alpha - \beta) = 0.1$.

In all the BPs, we set $\chi_{\tau\nu} = 1$ [13,14].

III. COLLIDER ANALYSIS

In this section, we explore the prospects for detecting the process $\gamma\gamma \rightarrow H^- H^+$, for which we use a Monte Carlo generator to obtain a sample of simulated events. We also present the strategy to separate the signal from the background.

Let us first present the signal and the main SM background processes as follows:

- (i) Signal: We are interested in searching for a final state $e\mu + \cancel{E}_T$ coming from the decay of two charged scalar boson produced through photon fusion in pp collisions at the HL-LHC, HE-LHC, and FCC-hh. Feynman diagrams that contribute in the production of a $H^- H^+$ pair with their subsequent decays are shown in Fig. 3.
- (ii) Background: The main SM background processes come from quark-induced WW production ($qq \rightarrow W^- W^+$), and from photon-induced processes, namely, $\gamma\gamma \rightarrow W^+ W^-$ and $\gamma\gamma \rightarrow \ell\ell$ which are reduced by selecting different flavor lepton pairs,

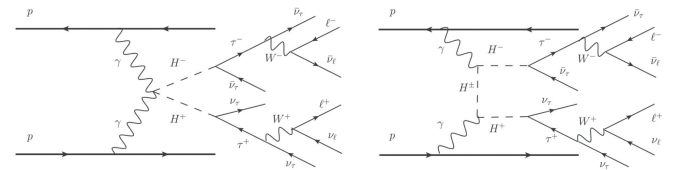


FIG. 3. Feynman diagrams for the production of two charged scalar bosons via photon fusion in pp collisions.

TABLE II. Cross section of the SM background processes at center-of-mass energies of 14 TeV (HL-LHC), 27 TeV (HE-LHC), and 100 TeV (FCC-hh).

Background	14 TeV	27 TeV	100 TeV
$qq \rightarrow WW \rightarrow e\nu_e\mu\nu_\mu$	12.5 fb	64.1 fb	580.6 fb
$\gamma\gamma \rightarrow WW \rightarrow e\nu_e\mu\nu_\mu$	0.52 fb	1.69 fb	9.56 fb
$\gamma\gamma \rightarrow \tau\tau \rightarrow e\nu_e\nu_\tau\mu\nu_\mu\nu_\tau$	32 fb	5160 fb	13297 fb

keeping the contribution of $\gamma\gamma \rightarrow \tau^-\tau^+$ production with lepton τ decays. A numerical cross section of the background processes is presented in Table II.

Motivated by the relatively recent report by ATLAS collaboration [15] on an excess of events at 3σ in the process $\mathcal{BR}(t \rightarrow H^\pm b) \times \mathcal{BR}(H^\pm \rightarrow cb)$ for $M_{H^\pm} = 130$ GeV, we focus on the mass range $M_{H^\pm} \in [100, 150]$ GeV. In Ref. [12] the region of the parameter space that accommodates such an excess is studied. Thus, in this work, we assume that the 2HDM-III satisfies this experimental constraint. We present in Fig. 4 the production cross section of the signal as a function of the charged scalar boson mass $M_{H^\pm}$. For this purpose, we consider a photon center-of-mass energy of 10% of the total that the colliders studied in this work will reach, that is, 700 GeV (HL-LHC), 1350 GeV (HE-LHC), and 5000 GeV (FCC-hh) [16].

For BP1 and BP2 at the HL-LHC, the cross section ranges between ~ 0.1 and 0.01 fb. In contrast, BP3 shows a cross section approximately one order of magnitude lower. Meanwhile, for the HE-LHC, the cross section increases by approximately half an order of magnitude compared to that of the HL-LHC across all three BPs, and for FCC-hh it rises by two orders of magnitude. Numerical cross sections for the three BPs and HL-LHC are presented in Table III.

Concerning our computation scheme, we first implement the model via FeynRules [17] to obtain the UFO files [18] for MadGraph5 [19] which is interfaced with Pythia8 [20] for parton showering, and Delphes [21] for detector response. The default HL-LHC, HE-LHC [22], and FCC-hh [23] cards and NNPDF [24] PDF set were used in the simulations. It is important to note that photon PDF uncertainties play a significant role in photon-induced processes, particularly in proton-proton collisions. These uncertainties can affect $\gamma\gamma$ processes such as $\gamma\gamma \rightarrow H^-H^+$, influencing the cross section—and consequently the *signal significance*—in exclusive processes like $pp \rightarrow p\gamma\gamma p$. The NNPDF PDF set incorporates photon uncertainties derived from a data-driven approach [24], which can reach 10–30%. However, for the upcoming HL-LHC, these uncertainties are expected to decrease to between 5% (optimal scenarios) and 20% (complex cases) [25], thereby improving the results presented in this work. Nevertheless, the photon PDF

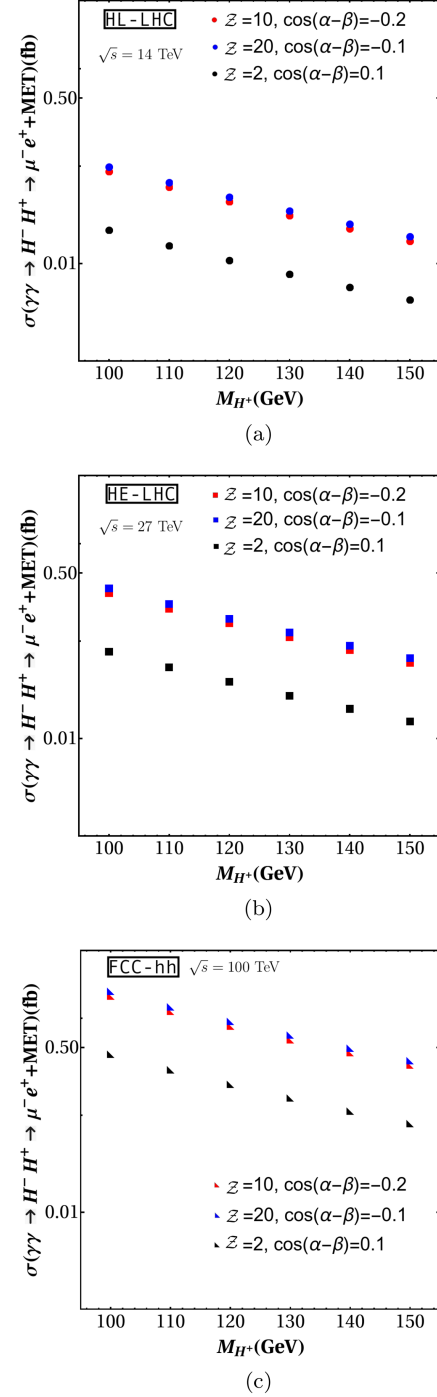


FIG. 4. Production cross section of the signal $\sigma(\gamma\gamma \rightarrow H^-H^+ \rightarrow \tau\nu_\tau\tau\nu_\tau \rightarrow e\mu + \cancel{E}_T)$ as a function of the charged scalar boson mass $M_{H^\pm}$. (a) HL-LHC, (b) HE-LHC, and (c) FCC-hh.

uncertainties may increasingly important at future colliders like the HE-LHC and FCC-hh due to higher probed energy scales, smaller Bjorken- x values, and enhanced photon-induced processes. Future global analyses with HL-LHC data will improve precision, but small- x photon PDFs

TABLE III. Cross section of the signal for the HL-LHC.

BP	$M_{H^\pm}$ (GeV)	Cross section (fb) HL-LHC (14 TeV)
BP1	100	0.087
	130	0.031
	150	0.017
BP2	100	0.098
	130	0.035
	150	0.019
BP3	100	0.022
	130	0.007
	150	0.004

will remain a dominant uncertainty at 100 TeV energies. Collaboration between theory and experiment is critical for progress. Thus, the results presented below for FCC-hh should be interpreted with caution.

On the other hand, in order to isolate the signal from the SM background, we performed a multivariate analysis using *Boosted Decision Trees* [26,27] (BDT),¹ implemented via the XGBoost library [28]. The BDT training is computed using Monte Carlo simulated data. The signal and background processes are scaled to the expected number of events, which is calculated through the cross sections and the integrated luminosity. The BDT selection is optimized for each $M_{H^\pm} \in [100, 150]$ GeV to maximize the *signal significance*, defined as $\mathcal{S} = N_S / \sqrt{N_S + N_B + (\kappa \cdot N_B)^2}$ [29], where N_S and N_B are the number of signal and background candidates, respectively. The factor κ stands for a systematic uncertainty. The ATLAS collaboration reported in Ref. [30] a study on the sensitivity to exclusive WW production in photon scattering at the High Luminosity LHC. In this study, systematic uncertainties of 6% and 3% were considered and compared to the nominal projection. Based on these results, we adopt a systematic uncertainty of $\kappa = 5\%$ as a reasonable estimate.

On the other hand, the main hyperparameters for the training are as follows: (i.) Number of trees $N_{\text{Tree}} = 50$, (ii.) maximum depth of the decision tree $\text{MaxDepth} = 5$, and (iii.) maximum number of leaves $\text{MaxLeaves} = 5$; the remaining parameters are set to their default values. We also compute a Kolmogorov-Smirnov test (KS), and it shows signs of no overtraining: 0.12 for the background and 0.15 for the signal. The BDT classifiers were trained using variables related to the kinematic of the final state particles, including the transverse momentum p_T , pseudorapidity η , transverse masses of charged leptons $M_T(\ell)$

¹We also performed an analysis with neural networks. However, the training time was considerably longer than that in the case of XGBoost. Moreover, neural networks (multilayer perceptron) exhibited a greater demand to control overtraining.

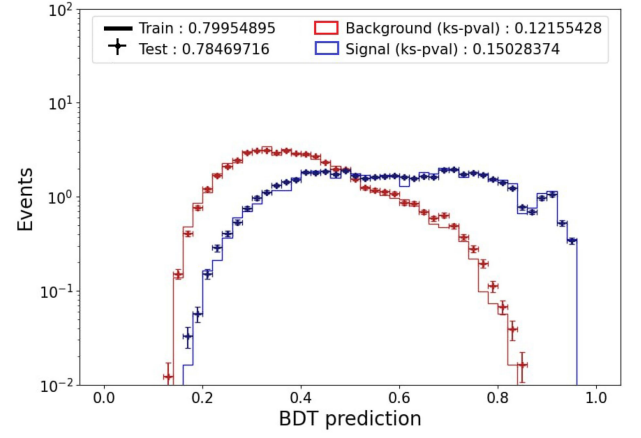


FIG. 5. Discriminant for signal and background data generated by BDT. We consider the BP2 and $M_{H^\pm} = 130$ GeV.

($\ell = e, \mu$), angular distance between the muon and electron ΔR , missing energy transverse $\cancel{E}_T$. Despite having a signal that is difficult to isolate, we are able to highlight it against the background, which is manifested in the discriminant shown in Fig. 5. In this analysis, we use the BP2 and $M_{H^\pm} = 130$ GeV. It is important to mention that we also performed a cut-and-count baseline analysis via MadAnalysis [31] to compare with BDT. However, this method was not effective.

Figure 6 shows the most discriminating characteristics according to BDT. In contrast, it is evident that through

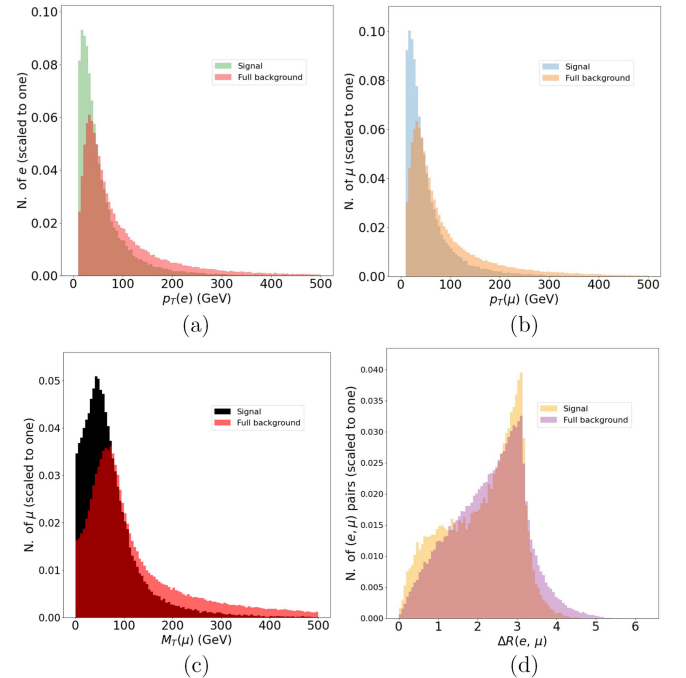


FIG. 6. Normalized distributions: (a) transverse momentum of the electron, (b) transverse momentum of the muon, (c) transverse mass of the muon $M_T(\mu) = \sqrt{2p_\mu^T \cancel{E}_T(1 - \cos \phi_{\mu \cancel{E}_T})}$, and (d) angular distance ΔR between the electron and muon.

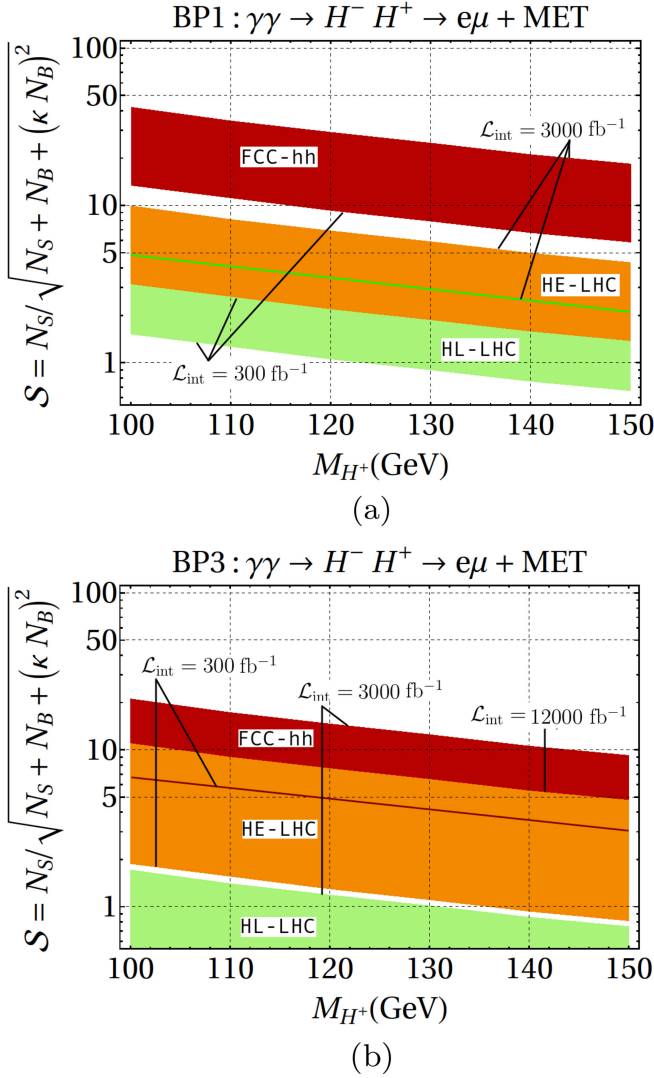


FIG. 7. Signal significance as a function of the charged Higgs boson mass $M_{H^\pm}$ for different intervals of the integrated luminosity $\mathcal{L}_{int}$. (a) BP1 and (b) BP3. For BP2, we obtain similar results (approximately 5% higher) compared to BP1.

“straight” cuts that a significant number of signal events is removed, which considerably reduces the *signal significance*. Based on the previous analysis, we show in Fig. 7 our most important results, i.e., the *signal significance* S , which is presented as a function of the charged Higgs boson mass $M_{H^\pm}$ for several integrated luminosities. From Fig. 7(a), we observe potential evidence at the 3σ level (and a discovery at 5σ) for a pair of H^-H^+ with $M_{H^\pm} = 130$ GeV, requiring an integrated luminosity of $\mathcal{L}_{int} \approx 3000 \text{ fb}^{-1}$ for the HL-LHC ($\mathcal{L}_{int} \approx 1600 \text{ fb}^{-1}$ for the HE-LHC and $\mathcal{L}_{int} \approx \mathcal{O}(10) \text{ fb}^{-1}$ for the FCC-hh). Furthermore, evidence of the signal is predicted for mass intervals $M_{H^\pm} \in [100, 136] \text{ GeV}$ (HL-LHC) and $M_{H^\pm} \in [100, 150] \text{ GeV}$ (HE-LHC), with integrated luminosities of $\mathcal{L}_{int} \in [1000, 3000] \text{ fb}^{-1}$ and $\mathcal{L}_{int} \in [300, 2000] \text{ fb}^{-1}$, respectively.

For BP2, the results are very similar to those of BP1, with significances increasing by approximately 5%. Meanwhile, Fig. 7(b) shows that, for BP3, a *statistical significance* of 1.7σ is obtained for $M_{H^\pm} = 100$ GeV. However, significances of $\gtrsim 5\sigma$ are achievable for the HE-LHC (FCC-hh) with $\mathcal{L}_{int} \in [5000, 12000] \text{ fb}^{-1}$ ($\mathcal{L}_{int} \in [300, 3000] \text{ fb}^{-1}$).

IV. CONCLUSIONS

We have presented an analysis of photon-induced H^-H^+ pair production ($\gamma\gamma \rightarrow H^-H^+$) and explored the prospects for its detection at future proton-proton colliders: HL-LHC, HE-LHC, and FCC-hh. These colliders are ideal scenarios due to their high center-of-mass energies and large accumulated datasets. However, we emphasize that the results for the HE-LHC and FCC-hh should be interpreted cautiously, as photon PDF uncertainties are expected to play a significant role at these machines. This is driven by higher probed energy scales, smaller Bjorken- x values, and the enhanced contribution of photon-induced processes.

Our study is based on the theoretical framework of the Two-Higgs Doublet Model type-III, which predicts the existence of charged scalar bosons $H^\pm$ —the focus of this work. We analyze the final state consisting of an $e\mu$ pair plus missing transverse energy ($\cancel{E}_T$) from undetected neutrinos, originating from the decay of the H^-H^+ pairs. This signature was motivated by the ATLAS collaboration’s detection of W^-W^+ pairs using a similar methodology.

Considering three benchmark points (consistent with experimental constraints) and a mass range of $M_{H^\pm} \in [100, 150] \text{ GeV}$, we obtained promising results that could be tested experimentally. The most favorable scenario is BP2 ($\mathcal{Z} = 10$, $\cos(\alpha - \beta) = -0.2$, $\chi_{\tau\nu} = 1$), where a 5σ discovery of H^-H^+ pairs at the HL-LHC could be achieved for $M_{H^\pm} = 100$ GeV and an integrated luminosity of $\mathcal{L}_{int} \approx 3000 \text{ fb}^{-1}$. Comparable results were found for a modified BP2 scenario ($\mathcal{Z} = 20$, $\cos(\alpha - \beta) = -0.1$, $\chi_{\tau\nu} = 1$). It is important to highlight that we have adopted a conservative value of $\chi_{\tau\nu_i} = 1$, which lacks strong experimental or theoretical constraints. This leaves room for slightly higher *signal significances* than those reported in this work. For BP2 and BP1 with $\mathcal{L}_{int} \gtrsim 1000 \text{ fb}^{-1}$, we predict *significances* of 3σ in the mass ranges 100–136 and 100–130 GeV, respectively. The least favorable case is BP3, which requires luminosities beyond the HL-LHC’s expected reach, yielding only 1.7σ for $M_{H^\pm} = 100$ GeV.

Nevertheless, with improved systematic uncertainties (beyond the $\kappa = 5\%$ assumed here) and better control over photon PDF uncertainties, the HE-LHC and FCC-hh could serve as H^-H^+ pair factories. This would not only allow rediscovery of the process studied here but also open new avenues for probing physics beyond the Standard Model.

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DATA AVAILABILITY

The data that support the findings of this article are openly available at Database [32].

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