

Searching for lepton flavor violating decays of the Higgs boson into $\mu\tau$, $e\tau$, and $e\mu$ final states at FCC-ee

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We investigate the projected sensitivity of the Future Circular Collider in e^+e^- mode (FCC-ee) in probing the lepton flavor violating (LFV) decay of the 125 GeV Higgs boson, $h \rightarrow \mu\tau$, $h \rightarrow e\tau$, and $h \rightarrow e\mu$ at center-of-mass energy of 240 GeV with an integrated luminosity of 5 ab^{-1} . With the clean multilepton final states, we consider the Higgs production modes that contribute to $e^+e^- \rightarrow \ell\ell h$, in particular, the Higgs-strahlung and the vector boson fusion production channels. The 95% confidence level upper limits on branching ratio are found to be 5.94×10^{-4} , 6.28×10^{-4} , and 7.37×10^{-5} for the channels $h \rightarrow \mu\tau$, $h \rightarrow e\tau$, and $h \rightarrow e\mu$, respectively. In addition, we also consider the LFV decay of a new CP-even Higgs boson with mass in the range of 110–200 GeV. The projected FCC-ee sensitivities are then compared to those from low-energy searches for $\ell \rightarrow \ell'\gamma$ decay. We find that the FCC-ee sensitivity for the LFV decays of the Higgs boson in the $e - \tau$ and $\mu - \tau$ channels is superior to the low-energy constraints. However, in the $e - \mu$ case, the low-energy search offers stronger constraints.

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I. INTRODUCTION

The 2012 discovery of the 125 GeV Higgs boson (h) jointly by the ATLAS [1] and CMS [2] Collaborations was a breakthrough in particle physics. It completes the Standard Model (SM) of particle physics, which describes elementary particles and their interactions. Even though the h properties agree very well with the SM predictions [3–5], there are reasons to expect new physics beyond the SM (BSM). Chief indications among them are the massive nature of neutrinos, the existence of dark matter, and the baryon-antibaryon asymmetry of the Universe. These reasons motivate searches for BSM physics, with the Higgs sector offering the possibility to reveal new interactions.

Lepton flavor violating (LFV) decays of the 125 GeV Higgs boson, $h \rightarrow e\mu$, $h \rightarrow e\tau$, $h \rightarrow \mu\tau$, are forbidden in the SM. These decays, if observed, would provide clear evidence for BSM physics. In addition, the LFV decays of h are expected in several BSM frameworks, including the two-Higgs-doublet model (2HDM) [6–11], models with extra dimensions [12–14], models with supersymmetry [15–20], models for neutrino mass generation [21–27], flavor models with Froggatt-Nielsen mechanism [28,29], and models with leptoquarks [30]. Moreover, additional Higgs bosons (H) in BSM models can generically accommodate LFV decays. The LFV decay modes of both the h and H offer a unique opportunity to probe BSM physics at particle colliders such as the Large Hadron Collider (LHC) [31–36].

Existing LHC searches have already placed strong constraints on the LFV decays of the 125 GeV Higgs boson. The CMS Collaboration has set 95% confidence level (CL) upper limits of $\mathcal{B}(h \rightarrow e\mu) < 4.4 \times 10^{-5}$ [37], $\mathcal{B}(h \rightarrow \mu\tau) < 0.15\%$ [38], and $\mathcal{B}(h \rightarrow e\tau) < 0.22\%$ [38]. The ATLAS Collaboration has provided slightly stronger

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upper limits $\mathcal{B}(h \rightarrow e\mu) < 6.2 \times 10^{-5}$ [39], $\mathcal{B}(h \rightarrow \mu\tau) < 0.09\%$ [40], and $\mathcal{B}(h \rightarrow e\tau) < 0.12\%$ [40]. In addition, both CMS and ATLAS have also searched for LFV decays of the additional Higgs boson H . The $H \rightarrow e\mu$ decay mode has been investigated by both CMS and ATLAS in the mass range $110 \leq m_H \leq 160$ GeV [37,39]. In particular, CMS reports a potential excess at $m_H = 146$ GeV with a local (global) significance of 3.8 (2.8) standard deviations (σ). The $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ decays have been searched for by CMS in the mass range of 200–900 GeV with no significant excess reported [41]. Additionally, the $H \rightarrow \mu\tau$ mode has also been investigated by LHCb in the mass range of 45–190 GeV [42].

The planned Future Circular Collider in e^+e^- mode (FCC-ee) offers a clean environment for studying LFV decays of the Higgs boson. At the operating center-of-mass energy of 240 GeV, both the 125 GeV Higgs boson and the additional Higgs boson can be produced via the Higgs-strahlung process, shown in Fig. 1(a). This makes it possible to probe LFV decays in either $q\bar{q}\ell\ell'$ or $\ell\bar{\ell}\ell\ell'$ (four-lepton) final states. Note here that $\ell = e$ or μ . These final states also include contributions from leptonic τ decays. Reference [43], taking advantage of the larger $Z \rightarrow q\bar{q}$ branching ratio, has investigated the FCC-ee reach in the $q\bar{q}\ell\ell'$ final states for a 125 GeV Higgs boson. Even though the four-lepton final states have a lower cross section for the channel with $Z \rightarrow e^+e^-$, they get an additional contribution from the Z -boson fusion process, as shown in

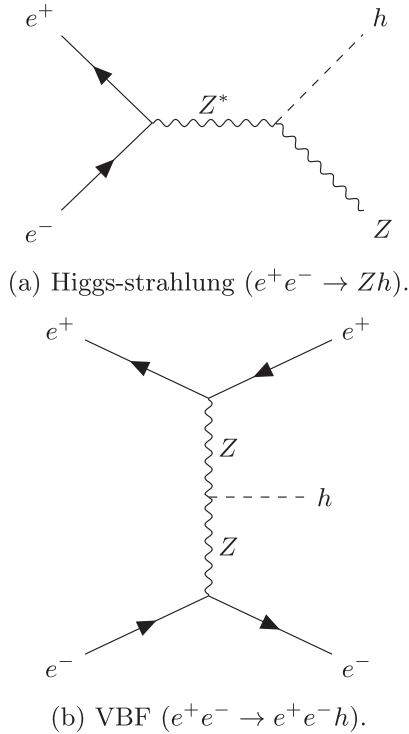


FIG. 1. Higgs boson production modes considered in this analysis. (a) Higgs-strahlung process. (b) VBF.

Fig. 1(b). This extra contribution becomes important for $m_H \gtrsim 150$ GeV, where the Z boson in the Higgs-strahlung process is off shell. In this paper, we study the sensitivity of the FCC-ee to the LFV decays of the Higgs boson. We focus our analysis on the four-lepton final states, which allow us to probe additional Higgs boson masses up to 200 GeV. While not advocating any particular BSM scenario, we interpret our results in the context of the type-III 2HDM. This allows us to compare our FCC-ee projections to low-energy LFV constraints from $\mu \rightarrow e\gamma$ and $\tau \rightarrow \ell\gamma$ decays.

This paper is organized as follows. Section II describes the simulation of signal and background processes. Section III details the reconstruction of the LFV Higgs boson, including collinear mass reconstruction for LFV Higgs decays with τ leptons. The event selection of the three LFV channels, divided into two phase space regions based on the expected mass of the associated lepton pair, is described in Sec. IV. In Sec. V, we present the FCC-ee projected sensitivities to the LFV Higgs decays with an integrated luminosity of 5 ab^{-1} . The obtained sensitivities are then interpreted in the context of the type-III 2HDM and compared to current and future low-energy LFV constraints in Sec. VI. Finally, all findings are summarized in Sec. VII.

II. SIGNAL AND BACKGROUND

The hard scattering part of both the signal and background processes is generated using MadGraph5_aMC@NLO [44] at $\sqrt{s} = 240$ GeV. We then use Pythia8 [45] to handle the final state radiation, the decay of the τ leptons, and the LFV decays of the Higgs bosons. Finally, the detector response is simulated using DELPHES [46] with the Innovative Detector for Electron-positron Accelerator (IDEA) detector card to evaluate the reach of FCC-ee following the design parameters described in Ref. [47]. To reflect the realistic conditions of the collider, the effects of initial state radiation (ISR) and beamstrahlung are also included in the simulation to obtain accurate cross sections, using ISR and beamstrahlung parametrizations for the FCC-ee scenario at $\sqrt{s} = 240$ GeV [48]. The FCC-ee detector is expected to be capable of tracking very soft leptons, with 98% efficiency down to 100 MeV in transverse momentum (p_T) and pseudorapidity (η) coverage up to 2.6 [49]. However, to conservatively estimate detector performance, we impose the following generator-level cuts in MadGraph: lepton $p_T > 1$ GeV, $|\eta| < 2.5$ for all leptons, and a separation requirement of $\Delta R > 0.4$ between the leptons.

A. Signal processes

In this paper, we focus on the final state with four light leptons, $\ell\bar{\ell}\ell\ell'$, where the LFV pair $\ell\ell'$ originates either from the 125 GeV Higgs boson h or the hypothetical CP-even scalar H . The additional lepton pair $\ell\bar{\ell}$ either comes from the Z -boson decay in the Higgs-strahlung (ZH) production mode or from the scattered leptons in the vector boson fusion (VBF) production mode. In our analysis, we

TABLE I. Cross sections of the signal processes. The inclusive $\ell\ell H$ process includes both ZH and VBF contributions, accounting for interference effects, while the exclusive ZH and VBF processes are generated separately. The cross sections are calculated at LO using MadGraph5.

Cross section (fb)			
m_H (GeV)	$ZH, Z \rightarrow \ell\ell$	VBF	$\ell\ell H$
110	18.87	0.735	19.63
120	14.99	0.547	15.47
125	12.99	0.466	13.35
130	10.92	0.395	11.17
140	6.401	0.275	6.471
150	0.653	0.184	0.669
160	9.62×10^{-2}	0.116	0.147
170	3.14×10^{-2}	6.86×10^{-2}	7.01×10^{-2}
180	1.12×10^{-2}	3.70×10^{-2}	3.50×10^{-2}
190	3.76×10^{-3}	1.76×10^{-2}	1.61×10^{-2}
200	1.09×10^{-3}	6.96×10^{-3}	6.25×10^{-3}

consider the inclusive process $e^+e^- \rightarrow \ell^+\ell^-H$, containing both ZH and VBF contributions, as well as their interference effects. To simplify our analysis, we assume the coupling of H to the Z boson is SM-like. Treating the H resonance mass m_H as a free parameter, we study $110 \leq m_H \leq 200$ GeV. Note that, with our assumption, the LFV signal of the h is identical to that of H when $m_H = 125$ GeV.

In our simulation, the signal events $e^+e^- \rightarrow \ell^+\ell^-H$ are generated by MadGraph5 with the H width set to zero, assuming the total width of the H is negligibly small compared to its mass ($\Gamma_H/m_H \ll 1$) and falls well within the detector resolution. The H is then forced to decay via Pythia8 into LFV channels: $H \rightarrow \mu\tau_e$, $H \rightarrow e\tau_\mu$, and $H \rightarrow \mu e$, where τ_ℓ stands for $\tau \rightarrow \ell\nu_\ell\nu_\tau$. Note that the LFV signal processes involving $H \rightarrow \ell\tau$ also contain missing transverse energy (E_T^{miss}). In our analysis, we have generated one million events for each LFV signature.

The cross sections for signal processes at leading order (LO) across the mass range 110–200 GeV are shown in Table I. Separate ZH and VBF samples were generated to illustrate their relative contributions. As shown in Fig. 2, the relative contribution from VBF becomes increasingly important above $m_H \approx 150$ GeV due to the suppression of on-shell ZH near the kinematic limit.

B. SM backgrounds

This study focuses on irreducible SM backgrounds yielding four-lepton final states. Reducible backgrounds involving jet or photon misidentification are expected to be strongly suppressed and are therefore not considered in this analysis. The SM background originates from ZZ production, which contributes to the signal region via the $ZZ \rightarrow \ell\ell\tau\tau$ process, where the τ leptons decay leptonically to

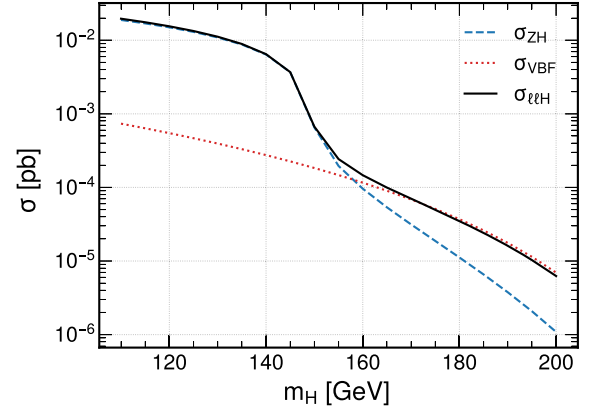


FIG. 2. Cross sections of the inclusive $e^+e^- \rightarrow \ell^+\ell^-H$ (black), exclusive ZH with $Z \rightarrow \ell\ell$ (blue), and VBF (red) processes as a function of m_H . The cross sections are calculated at LO using MadGraph5.

TABLE II. Cross sections of the background processes.

Process	Cross section (fb)
$ZZ \rightarrow \ell\ell\tau\tau$	5.02
Zh ($Z \rightarrow \ell\ell$, $h \rightarrow \tau\tau$)	0.53
$\ell^+\ell^-W^{(*)}W^{(*)}$, $WW^* \rightarrow \ell\ell\nu\bar{\nu}$	0.23

produce the four-lepton signatures. Moreover, there are contributions from the Higgs-strahlung (Zh) production mode where $Z \rightarrow \ell\ell$ and $h \rightarrow \tau\tau$. Additional background arises from electroweak processes (EW) $\ell^+\ell^-W^{(*)}W^{(*)}$, where both $W^{(*)}$ decay to light leptons.

The SM background processes considered in this analysis are summarized as follows:

- (i) Zh with $Z \rightarrow \ell\ell$ and $h \rightarrow \tau\tau$;
- (ii) $ZZ \rightarrow \ell\ell\tau\tau$;
- (iii) EW ($\ell^+\ell^-W^{(*)}W^{(*)}$) with $WW^* \rightarrow \ell\ell\nu\bar{\nu}$.

We have generated ten million events for each background category. The cross sections for these background processes calculated by MadGraph5 at LO are listed in Table II.

III. EVENT RECONSTRUCTION

A. Lepton reconstruction and object definitions

Following the IDEA detector setup, reconstruction for both e and μ is assumed to be perfect at $p_T > 100$ MeV and $|\eta| \leq 2.5$. The τ lepton reconstruction is based on the visible decay products. Note that the lepton transverse momentum is still bounded by $p_T > 1$ GeV from the generator cut.

The missing transverse energy is reconstructed as the negative vector sum of the transverse momenta of all reconstructed particles in the event. Any particles outside the detector acceptance or below the reconstruction

thresholds are not included in this sum, leading to an additional contribution to the E_T^{miss} from those undetected particles.

B. Higgs mass reconstruction

To reconstruct the Higgs mass from its decay products, one needs to know the energy and momentum of all the daughters. However, in the case of $H \rightarrow e\tau_\mu$ and $H \rightarrow \mu\tau_e$, this is impossible since the leptonically decayed τ produces two neutrinos. In this case, we instead reconstruct the collinear mass. Under the collinear approximation, the neutrinos from the τ decay are assumed to be emitted in the same direction as the visible τ decay products. The visible momentum fraction is defined as

$$x_\tau^{\text{vis}} = \frac{p_T^{\tau, \text{vis}}}{p_T^{\tau, \text{vis}} + p_T^{\nu, \text{est}}}, \quad (1)$$

where $p_T^{\nu, \text{est}}$ is the component of $\vec{p}_T^{\text{miss}}$ projected onto the direction of the visible τ candidate. This can be written as

$$p_T^{\nu, \text{est}} = \vec{p}_T^{\text{miss}} \cdot \hat{p}_T^{\tau, \text{vis}}, \quad (2)$$

where $\hat{p}_T^{\tau, \text{vis}}$ is the unit vector in the direction of the visible τ candidate's transverse momentum.

The collinear mass is then reconstructed from the visible invariant mass M_{vis} of the $\tau - \ell$ system (where $\ell = e$ or μ) as

$$M_{\text{col}} = \frac{M_{\text{vis}}}{\sqrt{x_\tau^{\text{vis}}}}. \quad (3)$$

This definition of collinear mass was first proposed in Ref. [50] and was also used in the previous CMS analysis for the same Higgs LFV decay final states in pp collisions at 13 TeV [38].

For the $H \rightarrow \mu e$ channel, the Higgs candidate mass can be reconstructed directly from the invariant mass of the two leptons as

$$M_{\ell\ell} = \sqrt{(E_{\ell_1} + E_{\ell_2})^2 - |\vec{p}_{\ell_1} + \vec{p}_{\ell_2}|^2}. \quad (4)$$

IV. EVENT SELECTION

In this analysis, we focus on three LFV channels: $H \rightarrow \mu\tau_e$, $H \rightarrow e\tau_\mu$, and $H \rightarrow \mu e$. In both the ZH and VBF production modes, the final state is characterized by a pair of opposite-sign and same flavor (OSSF) light leptons ($\ell\bar{\ell}$) produced in association with the H . In the ZH production mode, these associated leptons originate from the Z -boson decay, whereas in the VBF, they represent the scattered leptons. An additional opposite-sign and different

flavor lepton pair ($\ell\ell'$) in the final state arises from the LFV H decay. This results in a four-lepton final state in an asymmetric flavor combination, either $\mu e e e$ or $e \mu \mu \mu$ together with E_T^{miss} from τ decay exclusively in channels $H \rightarrow \mu\tau_e$ and $H \rightarrow e\tau_\mu$. To optimize sensitivity across all mass points for both ZH - and VBF-dominant regions, multiple selection categories are considered, where each category is optimized for an individual production mode. These are discussed in Sec. IV B. As three LFV channels share a similar final state topology except for E_T^{miss} in channels $H \rightarrow \mu\tau_e$ and $H \rightarrow e\tau_\mu$, a common preselection and candidate identification are applied to all three channels, followed by specific selections optimized for each, as detailed in Secs. IV C and IV D.

A. Common preselection

The initial selection requires exactly four leptons with $p_T > 1$ GeV, either in the combinations of $\mu e e e$ or $e \mu \mu \mu$ with charge conservation. Events with additional lepton candidates are discarded. Following the combinatorial logic, all possible four-lepton combinations are listed in Table III.

From the combinations $3\ell + 1\ell'$, the lone lepton (ℓ') is identified as the H candidate denoted as ℓ_H . Then, the same-sign and different flavor lepton to ℓ' is identified as the primary associated lepton (ℓ_A). This assignment is based on the fact that this lepton cannot originate from the same vertex as ℓ_H in an LFV decay without violating charge conservation. The two remaining leptons of the OSSF are treated as ambiguous candidates for the associated pair.

B. Candidate identification

To reconstruct the associated leptons originating either from the Z -boson decay in ZH or from the scattering process in VBF, the identified ℓ_A in the preselection step is paired with one of the two ambiguous leptons. This results in two possible pairs.

For the ZH production mode, the invariant mass of the lepton pair from Z is expected to peak at the Z mass of 91 GeV if the Z boson is produced on shell. For the off-shell Z boson, the distribution extends toward lower masses, with the upper bound determined by the phase space limit at $\sqrt{s} - m_H$. Conversely, the associated leptons in the VBF production mode originate from the

TABLE III. All four-lepton combinations.

ℓ' (first)	ℓ (second)	ℓ (third)	ℓ (fourth)
μ^+	e^+	e^-	e^-
μ^-	e^-	e^+	e^+
e^+	μ^+	μ^-	μ^-
e^-	μ^-	μ^+	μ^+

nonresonant scattering electron pair. This results in a broad continuum in the invariant mass of the associated lepton pair $[M(\ell\ell_A)]$ distribution that also extends toward the lower-mass region, while the upper bound is subject to the same phase space constraints as in the ZH case.

Events are classified into two orthogonal categories based on $M(\ell\ell_A)$:

- (i) The Z -mass category requires $M(\ell\ell_A) \in [81, 101]$ GeV. If multiple pairs satisfy this, the pair with the mass closest to the Z -boson mass is selected.
- (ii) The low-mass category requires $M(\ell\ell_A) \in [21, 81)$ GeV to include contributions from off-shell ZH and soft associated leptons in VBF. In the case of multiple pairs, the one with the highest $M(\ell\ell_A)$ is chosen. This is motivated by the fact that invariant mass distributions for off-shell ZH and VBF processes typically increase toward the phase space limit at $\sqrt{s} - m_H$. A lower bound of 21 GeV is applied to suppress the contribution from backgrounds with a photon as a propagator and low-mass resonance.

To preserve orthogonality between the two categories and avoid double counting, any events containing a lepton pair that satisfies the Z -mass criteria is automatically categorized as Z -mass category, and only the remaining events are considered for the low-mass selection. Once the associated lepton pair is identified, the remaining lepton in the event is automatically assigned to the H candidate.

C. $H \rightarrow \mu\tau_e$ and $H \rightarrow e\tau_\mu$

The final state from H LFV decay consists of one prompt lepton ℓ_{prompt} , one visible decay product of τ , denoted as τ_{vis} , and E_T^{miss} from the neutrinos produced in the τ decay. The prompt lepton from H decay is expected to be energetic, whereas τ_{vis} is expected to be softer. Therefore, the prompt lepton is required to satisfy $p_T(\ell_{\text{prompt}}) > 10$ GeV.

The missing energy from the leptonic decay of the τ is required to be $E_T^{\text{miss}} > 10$ GeV. Additionally, neutrinos from τ decay products are expected to be highly boosted in the same direction as τ_{vis} . To exploit this signal characteristic, an additional requirement is imposed on the azimuthal angle difference between E_T^{miss} and τ_{vis} , requiring that $\Delta\phi(E_T^{\text{miss}}, \tau_{\text{vis}}) < 0.1$. This threshold was optimized by minimizing the expected upper limit, as it suppresses the majority of backgrounds while retaining $> 90\%$ signal. The distributions of $\Delta\phi(E_T^{\text{miss}}, \tau_{\text{vis}})$ are illustrated in Fig. 3.

D. $H \rightarrow \mu e$

Unlike the $H \rightarrow \mu\tau_e$ and $H \rightarrow e\tau_\mu$ cases, the $H \rightarrow \mu e$ channel consists of two prompt leptons without neutrinos from the Higgs decay. Both leptons are then expected to be energetic, leading to the requirement that $p_T(e) > 10$ and $p_T(\mu) > 10$ GeV.

Because of the absence of neutrinos in the signal, we require $E_T^{\text{miss}} < 10$ GeV. Distributions of E_T^{miss} at the preselection level for three channels and backgrounds are presented in Fig. 4. Additionally, Table IV summarizes the cuts on $p_T(\ell)$, E_T^{miss} , and $\Delta\phi(E_T^{\text{miss}}, \tau_{\text{vis}})$ for all three LFV channels.

V. RESULTS

After all selections are applied, H is then reconstructed using the collinear mass method for channels involving τ leptons and the traditional invariant mass method for the $H \rightarrow \mu e$ channel. The prefit distributions of the reconstructed mass are displayed in Fig. 5. In the Z -mass region, the analysis targets signals with on-shell Z -boson decays. However, reconstructing H in this category is precluded for the signal with $m_H > 150$ GeV, as the allowed mass for the associated leptons is constrained by the phase space limit $M(\ell\ell) \leq \sqrt{s} - m_H$. Consequently, the low-mass category

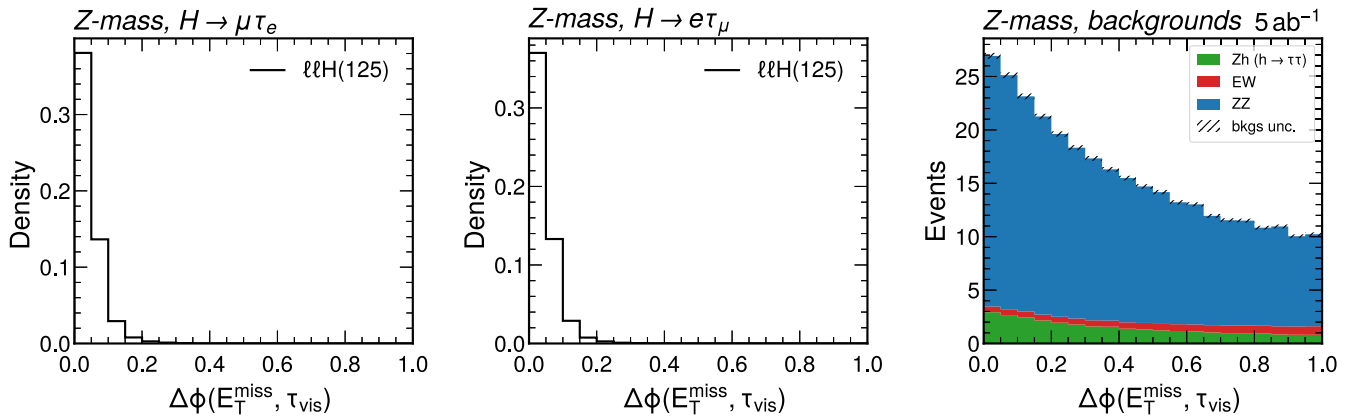


FIG. 3. Distributions of $\Delta\phi(E_T^{\text{miss}}, \tau_{\text{vis}})$ after the candidate identification for signal for the $H \rightarrow \mu\tau_e$ and $H \rightarrow e\tau_\mu$ channels at $m_H = 125$ GeV in Z -mass region. The right figure shows the background normalized to 5 ab^{-1} .

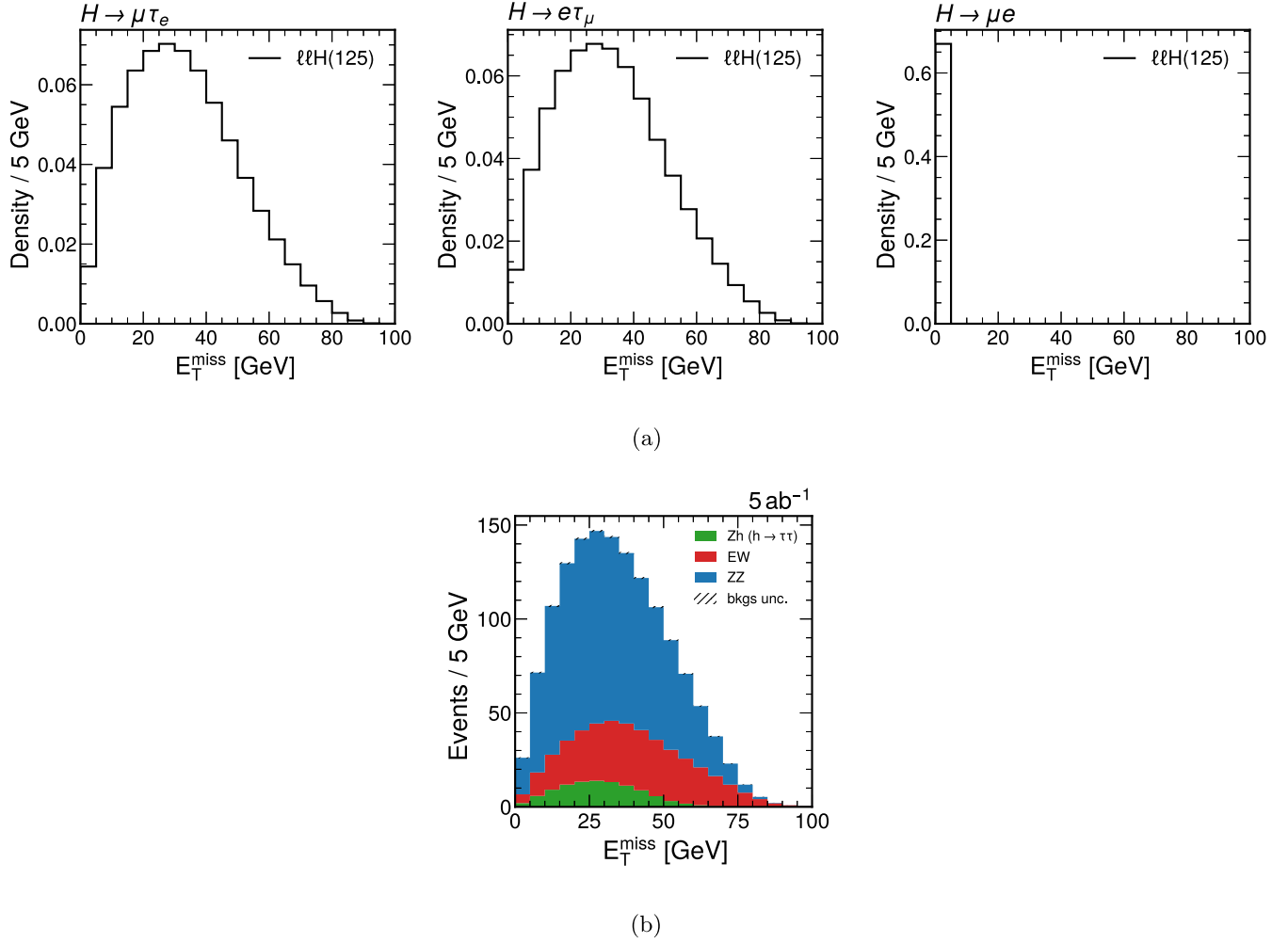


FIG. 4. Preselection distributions of E_T^{miss} for (a) signal at $m_H = 125$ GeV and (b) background normalized to 5 ab^{-1} . Notice the absence of E_T^{miss} in the $e\mu$ channel due to the final state not providing any invisible neutrinos.

is designed specifically to target heavy H in the ZH and the VBF production modes. Note that, in the transition mass range of $150 \leq m_H < 160$ GeV, the signal yields for both categories are significant.

Figure 6 presents the distributions of the reconstructed H for both the expected backgrounds and the signals after all selections. The signal yields are normalized to $\sigma_{\ell\ell H} \times \mathcal{L} \times \mathcal{B}(H \rightarrow \ell\ell')$, assuming an integrated luminosity of $\mathcal{L} = 5 \text{ ab}^{-1}$ and a branching ratio of $\mathcal{B}(H \rightarrow \ell\ell') = 10^{-3}$, with inclusive production cross section $\sigma_{\ell\ell H}$ listed in Table I. For the $H \rightarrow \mu\tau_e$ and $H \rightarrow e\tau_\mu$ channels, an

additional factor of $\mathcal{B}(\tau \rightarrow \ell\nu\bar{\nu}) \approx 0.17$ is applied to account for the leptonic τ decays. Similarly, all SM backgrounds are normalized to 5 ab^{-1} using the cross section provided in Table II. Note that both the integrated luminosity and the collision energy are chosen to align with the Zh production program at FCC-ee, planned for a three-year operation [51].

To mitigate the impact of backgrounds, only the signal and backgrounds around the mass point of interest are considered for the upper limit calculation. The mass window is defined as $|M_{\text{reco}} - m_H| \leq 10 \text{ GeV}$, where M_{reco} is the collinear mass (M_{col}) for $H \rightarrow \mu\tau_e$ and $H \rightarrow e\tau_\mu$ channels and the invariant mass (M_{inv}) for $H \rightarrow \mu e$ channel. The signal efficiencies and the number of events after all selections and the requirement $|M_{\text{reco}} - m_H| \leq 10 \text{ GeV}$ are summarized in Tables V–VII for $H \rightarrow \mu\tau_e$, $H \rightarrow e\tau_\mu$, and $H \rightarrow \mu e$, respectively.

For the $H \rightarrow \mu\tau_e$ and $H \rightarrow e\tau_\mu$ channels, a dominant background arises from $Zh(h \rightarrow \tau\tau)$ production due to similarities in their production modes. However, the

TABLE IV. Selection criteria for three channels.

Selection	$H \rightarrow \mu\tau_e$	$H \rightarrow e\tau_\mu$	$H \rightarrow \mu e$
$p_T(\mu)$	$>10 \text{ GeV}$	$\dots$	$>10 \text{ GeV}$
$p_T(e)$	$\dots$	$>10 \text{ GeV}$	$>10 \text{ GeV}$
E_T^{miss}	$>10 \text{ GeV}$	$>10 \text{ GeV}$	$<10 \text{ GeV}$
$\Delta\phi(E_T^{\text{miss}}, \tau_{\text{vis}})$	<0.1	<0.1	$\dots$

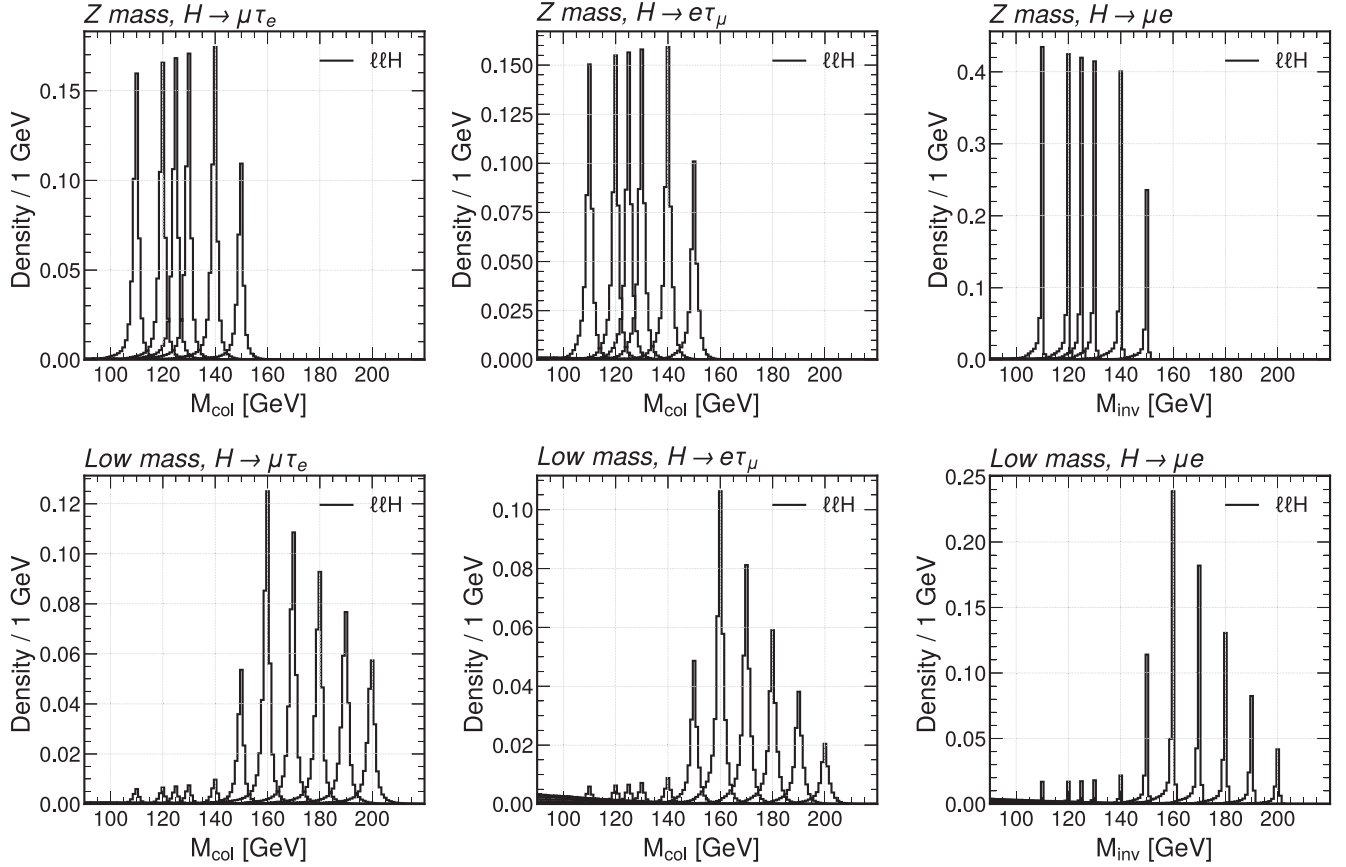


FIG. 5. Reconstructed H mass distributions for three channels after all selections. Signals shown include $m_H = 110\text{--}200$ GeV with 10 GeV increments, in addition to 125 GeV. Notice the absence of signals at $m_H > 150$ GeV in Z-mass categories and small contributions from the VBF production mode in the low-mass category at $m_H < 150$ GeV.

collinear mass method effectively suppresses this background, as the presence of multiple sources of E_T^{miss} makes it highly unlikely for the τ_{vis} to align with the E_T^{miss} in the same way as the signal. As shown in Tables V and VI, the $Zh(h \rightarrow \tau\tau)$ background in the Z-mass region yields approximately two events at $m_H = 110$ GeV, but falls off dramatically to less than 0.1 events for $m_H \geq 140$ GeV. The second largest contribution comes from ZZ production. Although this process has the highest cross section among the SM backgrounds, its reconstructed mass tends to peak around the nominal Z-boson mass. This highly suppresses its contribution to the signal region. In the low-mass region, the prominent backgrounds are ZZ (resulting from lepton mispairing) and EW processes. Despite this, the combined background remains exceptionally low, resulting in fewer than one expected background event (peaking at roughly 0.6 events at 110 GeV) across all m_H .

The $H \rightarrow \mu e$ channel provides the cleanest signal environment, as detailed in Table VII. To mimic the fully visible $\ell\ell\ell\ell'$ final state, all relevant SM backgrounds must inherently contain intrinsic E_T^{miss} . Consequently, applying the $E_T^{\text{miss}} < 10$ GeV condition highly suppresses these backgrounds. This reduces the expected number of

background events to nearly zero across all mass points (with the highest 0.4 events at $m_H = 110$ GeV), while retaining ZH signal efficiencies of up to 58% in the Z-mass region.

The expected upper limits for LFV Higgs decays are calculated using the CMS COMBINE framework [52], employing the HybridNew method with the CL_s criterion and Monte Carlo pseudoexperiments [53]. A joint likelihood is constructed from two counting experiments corresponding to the two event categories. The test statistic $\tilde{q}_\mu$ is defined using the profile likelihood ratio, with nuisance parameters profiled for each tested value of the signal strength μ . For each value of μ , distributions of $\tilde{q}_\mu$ are obtained from pseudodata generated under the signal-plus-background and background-only hypotheses. The expected upper limit at 95% confidence level is determined as the value of μ satisfying the CL_s criterion of 0.05, based on the median of the test statistic $\tilde{q}_\mu$ distribution under the background-only hypothesis. The systematic uncertainties for all processes include the luminosity uncertainty of 2%. Additionally, a conservative 10% uncertainty is assigned to all backgrounds to account for all sources of systematic uncertainties (identification,

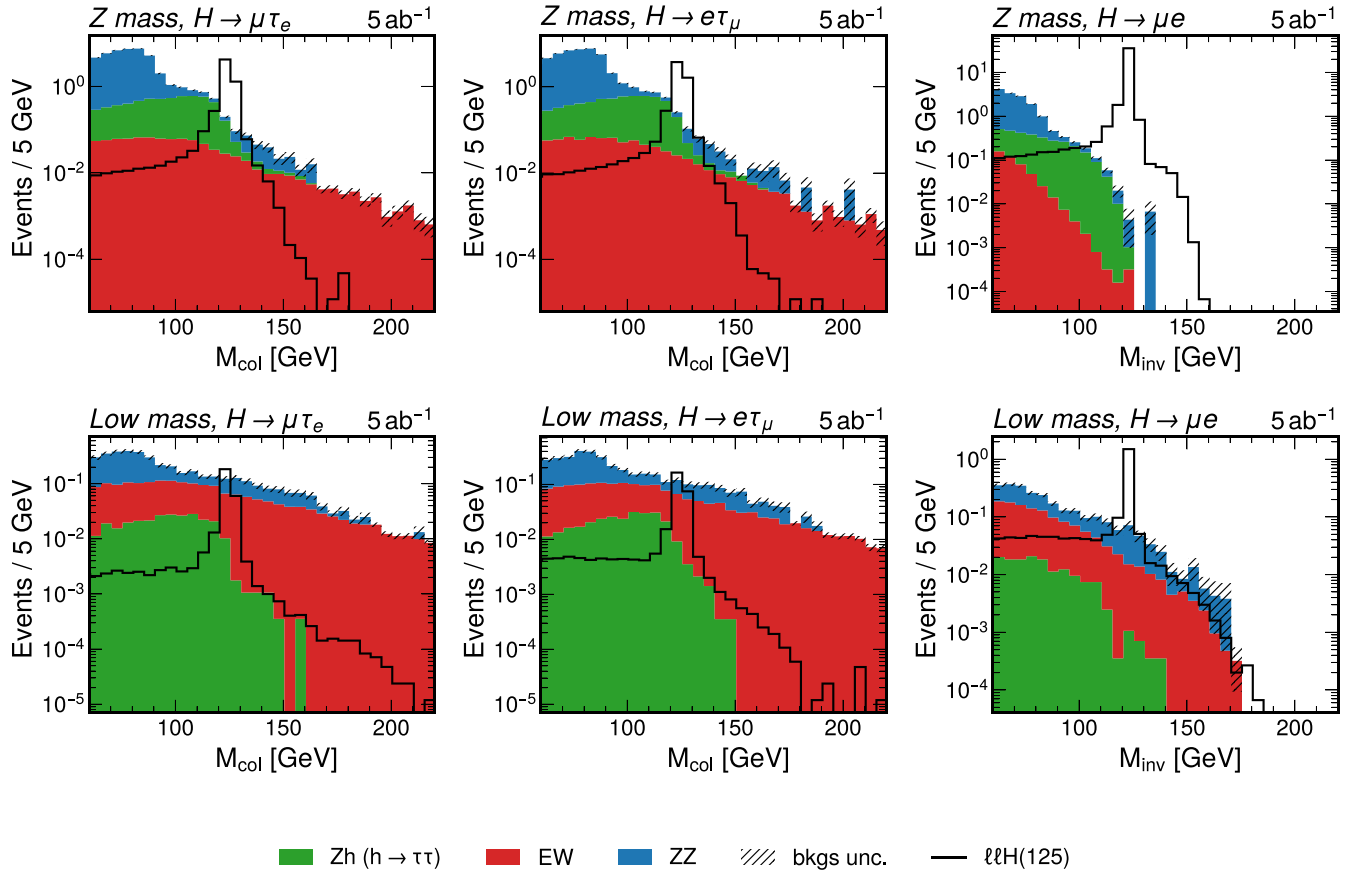


FIG. 6. Distributions of reconstructed H mass for both signal and background processes after all selections. The signal shown is for $m_H = 125$ GeV only.

TABLE V. $H \rightarrow \mu\tau_e$ selection efficiencies and background yields after all selections and $|M_{\text{reco}} - m_H| \leq 10$ GeV are applied. The background yields are normalized to $\mathcal{L} = 5 \text{ ab}^{-1}$.

m_H (GeV)	Z-mass region				Low-mass region			
	Signal		Background		Signal		Background	
	(eff.)		(evt.)		(eff.)		(evt.)	
	$\ell\ell H$	ZZ	Zh ($h \rightarrow \tau\tau$)	EW	$\ell\ell H$	ZZ	Zh ($h \rightarrow \tau\tau$)	EW
110	0.47	0.85	2.04	0.20	0.02	0.21	0.10	0.30
120	0.48	0.35	1.15	0.14	0.02	0.21	0.06	0.27
125	0.49	0.21	0.62	0.11	0.02	0.21	0.04	0.25
130	0.50	0.15	0.21	0.09	0.02	0.21	0.02	0.23
140	0.50	0.11	0.02	0.05	0.03	0.16	0	0.20
150	0.32	0.06	0.01	0.04	0.17	0.13	0	0.17
160	0	0.03	0	0.03	0.40	0.10	0	0.14
170	0	0.01	0	0.02	0.37	0.06	0	0.11
180	0	0	0	0.01	0.33	0.02	0	0.09
190	0	0	0	0.01	0.29	0.01	0	0.07
200	0	0	0	0.01	0.23	0	0	0.05

TABLE VI. $H \rightarrow e\tau_\mu$ selection efficiencies and background yields after all selections and $|M_{\text{reco}} - m_H| \leq 10$ GeV are applied. The background yields are normalized to $\mathcal{L} = 5 \text{ ab}^{-1}$.

m_H (GeV)	Z-mass region				Low-mass region			
	Signal		Background		Signal		Background	
	(eff.)		(evt.)		(eff.)		(evt.)	
	$\ell\ell H$	ZZ	Zh ($h \rightarrow \tau\tau$)	EW	$\ell\ell H$	ZZ	Zh ($h \rightarrow \tau\tau$)	EW
110	0.46	0.82	2.12	0.18	0.02	0.20	0.11	0.26
120	0.47	0.36	1.23	0.12	0.02	0.18	0.07	0.23
125	0.48	0.26	0.70	0.10	0.02	0.18	0.04	0.21
130	0.49	0.19	0.25	0.08	0.02	0.20	0.02	0.20
140	0.49	0.10	0.02	0.05	0.03	0.18	0	0.17
150	0.32	0.04	0.01	0.03	0.16	0.14	0	0.14
160	0	0.02	0	0.02	0.37	0.10	0	0.11
170	0	0.02	0	0.01	0.29	0.06	0	0.09
180	0	0.01	0	0.01	0.22	0.04	0	0.07
190	0	0	0	0.01	0.15	0.01	0	0.05
200	0	0	0	0	0.08	0	0	0.04

TABLE VII. $H \rightarrow \mu e$ selection efficiencies and background yields after all selections and $|M_{\text{reco}} - m_H| \leq 10$ GeV are applied. The background yields are normalized to $\mathcal{L} = 5 \text{ ab}^{-1}$.

m_H (GeV)	Z-mass region				Low-mass region			
	Signal (eff.)		Background (evt.)		Signal (eff.)		Background (evt.)	
	Zh		Zh		Zh		Zh	
	$\ell\ell H$	ZZ	$(h \rightarrow \tau\tau)$	EW	$\ell\ell H$	ZZ	$(h \rightarrow \tau\tau)$	EW
110	0.58	0.09	0.30	0	0.03	0.18	0.02	0.14
120	0.58	0.03	0.06	0	0.02	0.18	0	0.08
125	0.58	0.02	0.01	0	0.02	0.15	0	0.06
130	0.58	0.01	0	0	0.03	0.13	0	0.05
140	0.56	0.01	0	0	0.03	0.05	0	0.03
150	0.34	0	0	0	0.17	0.02	0	0.02
160	0	0	0	0	0.36	0.02	0	0.01
170	0	0	0	0	0.28	0.01	0	0
180	0	0	0	0	0.21	0	0	0
190	0	0	0	0	0.14	0	0	0
200	0	0	0	0	0.07	0	0	0

reconstruction, and theoretical uncertainties). Note that the impact of these systematic uncertainties is small, as the search sensitivity is dominated by statistical uncertainties due to nearly zero expected observed events, especially for higher Higgs masses. For each LFV channel, the Z- and low-mass regions are combined to compute the expected upper limits on the LFV branching ratios $\mathcal{B}(H \rightarrow \mu\tau)$, $\mathcal{B}(H \rightarrow e\tau)$, and $\mathcal{B}(H \rightarrow \mu e)$. The final limits are listed in Table VIII together with the upper limits on the product $\sigma(e^+e^- \rightarrow \ell\ell H) \times \mathcal{B}(H \rightarrow \ell\ell')$ for each LFV channel as a function of m_H .

At $m_H = 125$ GeV, the expected upper limits on $\mathcal{B}(H \rightarrow \ell\ell')$ are found to be 5.94×10^{-4} , 6.28×10^{-4} , and 7.37×10^{-5} for the $H \rightarrow \mu\tau_e$, $H \rightarrow e\tau_\mu$, and $H \rightarrow \mu e$

channels, respectively. These results are complementary to the results obtained from the ZH production mode with $Z \rightarrow q\bar{q}$ decay (equivalent to $e^+e^- \rightarrow q\bar{q}H$) in Ref. [43], which can be combined with our results at $m_H = 125$ GeV to provide stronger constraints. Beyond this 125 GeV limit, the expected upper limits exhibit a mass-dependent trend across the probed 110–200 GeV mass range, as summarized in Table VIII. Generally, as the assumed m_H increases, the upper limits on the branching ratios become less stringent. This behavior is driven by the fall in the total production cross section, which drops from 19 fb at 110 GeV to merely 0.006 fb at 200 GeV. Consequently, the most stringent constraints across all three channels are achieved in the 110–130 GeV m_H region. As evident from the reconstructed mass in Fig. 5 and the cross section in Table I, the highest contribution at $m_H < 150$ GeV comes from the ZH production mode, while the VBF production mode dominates at $m_H > 150$ GeV. As the assumed H mass continues to increase, actual yields from the signal processes become lower than the expected upper limits of the signal event yields, given no observed events due to the vanishingly small production cross section. This leads to the unphysical upper limits on the branching ratios (denoted by asterisks in Table VIII), implying that the assumed integrated luminosity is simply insufficient to constrain the branching ratios in this regime. Notably, across the entire mass range, the $H \rightarrow \mu e$ channel outperforms the $H \rightarrow \mu\tau_e$ and $H \rightarrow e\tau_\mu$ channels by an order of magnitude due to its cleaner final state and the absence of E_T^{miss} from τ decays, allowing for higher background suppression.

VI. CONSTRAINT ON TYPE-III 2HDM

The type-III 2HDM offers a concrete theoretical framework that could accommodate LFV decays of the Higgs boson. The two Higgs doublets are taken to be

TABLE VIII. Summary of LFV limits. The $\mathcal{B}(H \rightarrow \ell\ell')$ is calculated from inclusive $e^+e^- \rightarrow \ell^+\ell^-H$ production mode.

m_H (GeV)	$\mathcal{B}(H \rightarrow \ell\ell')$ $\mu\tau$ $e\tau$ μe			$\sigma(ee \rightarrow \ell\ell H) \times \mathcal{B}(H \rightarrow \ell\ell')$ (ab) $\mu\tau$ $e\tau$ μe		
110.0	5.83×10^{-4}	6.05×10^{-4}	5.08×10^{-5}	11.45	11.88	1.00
120.0	5.86×10^{-4}	6.11×10^{-4}	6.38×10^{-5}	9.07	9.45	0.99
125.0	5.94×10^{-4}	6.28×10^{-4}	7.37×10^{-5}	7.93	8.38	0.98
130.0	5.82×10^{-4}	6.07×10^{-4}	8.79×10^{-5}	6.50	6.79	0.98
140.0	9.80×10^{-4}	9.90×10^{-4}	1.53×10^{-4}	6.34	6.40	0.99
150.0	0.01	0.01	1.75×10^{-3}	6.84	6.91	1.17
160.0	0.06	0.06	0.01	8.27	9.18	1.66
170.0	0.13	0.16	0.03	8.96	11.40	2.10
180.0	0.28	0.43	0.08	9.91	15.14	2.79
190.0	0.72	1.38 ^a	0.26	11.63	22.14	4.17
200.0	2.34 ^a	6.36 ^a	1.25 ^a	14.65	39.73	7.84

^aBranching ratios are unphysical, which are caused by the vanishingly small cross section with respect to those mass points.

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h_1+iG^0}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{h_2+iA}{\sqrt{2}} \end{pmatrix}, \quad (5)$$

where G^+ and G^0 are the would-be Goldstone bosons, $v = 246$ GeV is the electroweak vacuum expectation value, and H^+ and A are the charged Higgs and the pseudoscalar bosons, respectively. The two CP-even neutral scalars h_1 and h_2 mix to form the mass eigenstates

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}. \quad (6)$$

The mixing angle α is constrained by the combined run 1 and run 2 measurements of the 125 GeV Higgs boson properties by ATLAS and CMS, which yields $\sin^2 \alpha \leq 0.0225$ at 95% CL [54–56].

The LFV interactions are parametrized by the Yukawa coupling of the second doublet. In particular, we take

$$\mathcal{L}_{LFV} = \sqrt{2} Y_{ij} \bar{L}_i e_{Rj} H_2. \quad (7)$$

Note that the coupling Y_{ij} and Y_{ji} , for $i \neq j$, leads to the LFV decays $h(H) \rightarrow \ell_i \ell_j$. For simplicity, we will take all components of Y to vanish except for the pair responsible for the LFV decay of interest. In this scenario, the h LFV decay width is given by

$$\Gamma(h \rightarrow \ell \ell') = \frac{\sin^2(\alpha) m_h}{8\pi} (|Y_{\ell \ell'}|^2 + |Y_{\ell' \ell}|^2). \quad (8)$$

The LFV decay width for the H can be obtained from the above equation by a replacement $m_h \rightarrow m_H$ and $\sin \alpha \rightarrow \cos \alpha$.

In the case where the H , A , and H^+ are much heavier than the electroweak scale, our results in the previous section imply $\mathcal{B}(h \rightarrow e\mu) \leq 7.37 \times 10^{-5}$, $\mathcal{B}(h \rightarrow e\tau) \leq 6.28 \times 10^{-4}$, and $\mathcal{B}(h \rightarrow \mu\tau) \leq 5.94 \times 10^{-4}$, respectively. In the context of the type-III 2HDM, the corresponding branching ratios are given by

$$\mathcal{B}(h \rightarrow \ell \ell') = \frac{\Gamma(h \rightarrow \ell \ell')}{\Gamma(h \rightarrow \ell \ell') + \cos^2 \alpha \Gamma_h^{\text{SM}}}, \quad (9)$$

with $\Gamma_h^{\text{SM}} = 4.1$ MeV being the 125 GeV Higgs boson total decay width. Note that the production of h is also suppressed by $\cos^2(\alpha)$. Thus, the upper 95% CL limits on the h LFV branching ratio $\mathcal{B}(h \rightarrow \ell \ell')_{95\%}$ in the previous section translate to

$$\frac{\cos^2 \alpha \Gamma(h \rightarrow \ell \ell')}{\Gamma(h \rightarrow \ell \ell') + \cos^2 \alpha \Gamma_h^{\text{SM}}} \leq \mathcal{B}(h \rightarrow \ell \ell')_{95\%}. \quad (10)$$

Expanding to lowest order in $\sin^2 \alpha$, one gets

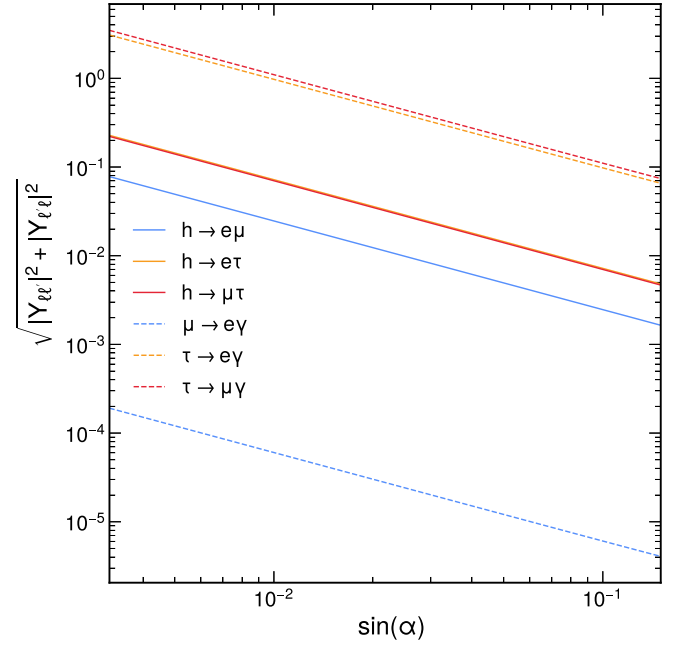


FIG. 7. The projected upper limit on the mixing angle, $\sin \alpha$, and the LFV Yukawa couplings, $Y_{\ell \ell'}$ and $Y_{\ell' \ell}$, from the $h \rightarrow \ell \ell'$ decay channels (solid). For comparison, the corresponding constraints from the low-energy searches $\ell \rightarrow \ell' \gamma$ are also shown (dashed).

$$(|Y_{\ell \ell'}|^2 + |Y_{\ell' \ell}|^2) \sin^2 \alpha \leq \frac{8\pi \Gamma_h^{\text{SM}}}{m_h} \frac{\mathcal{B}(h \rightarrow \ell \ell')_{95\%}}{1 - \mathcal{B}(h \rightarrow \ell \ell')_{95\%}}. \quad (11)$$

Figure 7 shows the corresponding constraints on the $\sin \alpha - \sqrt{|Y_{\ell \ell'}|^2 + |Y_{\ell' \ell}|^2}$ plane from the $h \rightarrow e\mu$ (solid blue), $h \rightarrow e\tau$ (solid orange), and $h \rightarrow \mu\tau$ (solid green) decay channels. For comparison, the corresponding constraints from the low-energy search for $\ell \rightarrow \ell' \gamma$ decays [57–61] are shown by dashed lines.¹ Note that, in the case of $e - \mu$ LFV, there is also a constraint from $\mu \rightarrow e$ conversion in atomic nucleus [63,64]. Such a constraint is comparable to that of $\mu \rightarrow e \gamma$ decay.

Next, we explore the possibility that, in addition to the h , the H could also be around the weak scale, while the H^+ and A are heavier. In this case, our results from the previous section can be interpreted in terms of the LFV decays of the H in the mass range $110 \leq m_H \leq 180$ GeV. In this scenario, the upper limit on the LFV branching ratios is related to

$$|Y_{\ell \ell'}|^2 + |Y_{\ell' \ell}|^2 \leq \tan^2 \alpha \frac{8\pi \Gamma_H^{\text{SM}}}{m_H} \frac{\mathcal{B}(H \rightarrow \ell \ell')_{95\%}}{\sin^2 \alpha - \mathcal{B}(H \rightarrow \ell \ell')_{95\%}}, \quad (12)$$

¹We have used the public PYTHON code provided in Ref. [62] to compute the $\ell \rightarrow \ell' \gamma$ partial decay width.

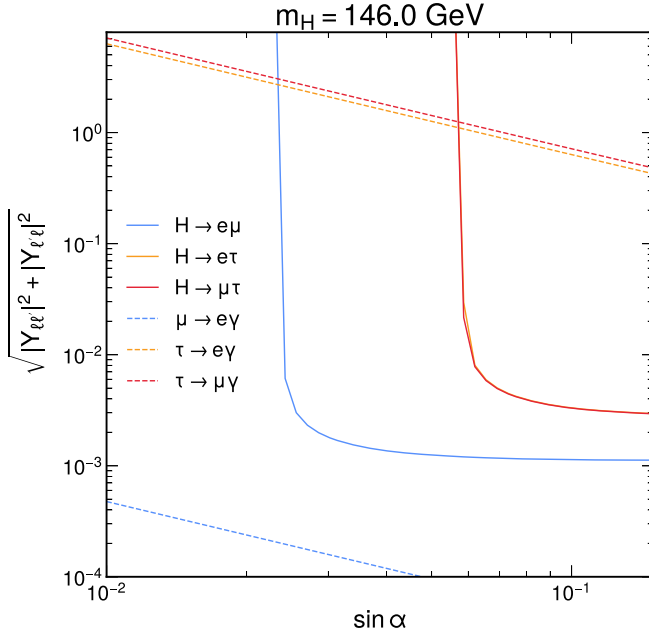


FIG. 8. The projected upper limit on the $\sin \alpha - \sqrt{|Y_{\ell\ell'}|^2 + |Y_{\ell'\ell}|^2}$ plane from the $H \rightarrow \ell\ell'$ decay (solid) and $\ell \rightarrow \ell'\gamma$ decay (dashed) for the $e - \mu$ (blue), $e - \tau$ (orange), and $\mu - \tau$ (red) sectors.

where Γ_H^{SM} is the SM Higgs total decay width at the Higgs mass m_H . Note that from the above equation, one can only obtain meaningful constraints when $\mathcal{B}(H \rightarrow \ell\ell')_{95\%} \leq \sin^2 \alpha$. In the degenerate case where $m_H \simeq m_h$, one needs to take into account the contribution from both Higgses when extracting the upper limits on the LFV Yukawa couplings. Figure 8 shows the upper limits on the $\sin \alpha - \sqrt{|Y_{\ell\ell'}|^2 + |Y_{\ell'\ell}|^2}$ plane for the case $m_H = 146$ GeV. Note that if the lower left corner of the $H \rightarrow \ell\ell'$ constraint is below the corresponding $\ell \rightarrow \ell'\gamma$ constraint, the FCC-ee search is more sensitive for this particular value of m_H . To compare the sensitivity of the FCC-ee and the low-energy searches across the m_H mass range, we follow Ref. [35] in projecting the constraints onto the $\sin(2\alpha)\sqrt{|Y_{\ell\ell'}|^2 + |Y_{\ell'\ell}|^2}$ line. For the FCC-ee constraints, we take the minimum value of such projections. The comparison between the two types of searches for the LFV couplings is shown in Fig. 9.

VII. SUMMARY AND CONCLUSIONS

In this analysis, we have explored the prospects of detecting the LFV decays of H in the $H \rightarrow \mu e$, $H \rightarrow \mu\tau$, and $H \rightarrow e\tau$ channels at the FCC-ee with an integrated luminosity of 5 ab^{-1} at $\sqrt{s} = 240$ GeV. Our analysis focuses on clean four-lepton final states, which require the τ to decay leptonically. For the three LFV channels, both ZH and VBF production modes are considered

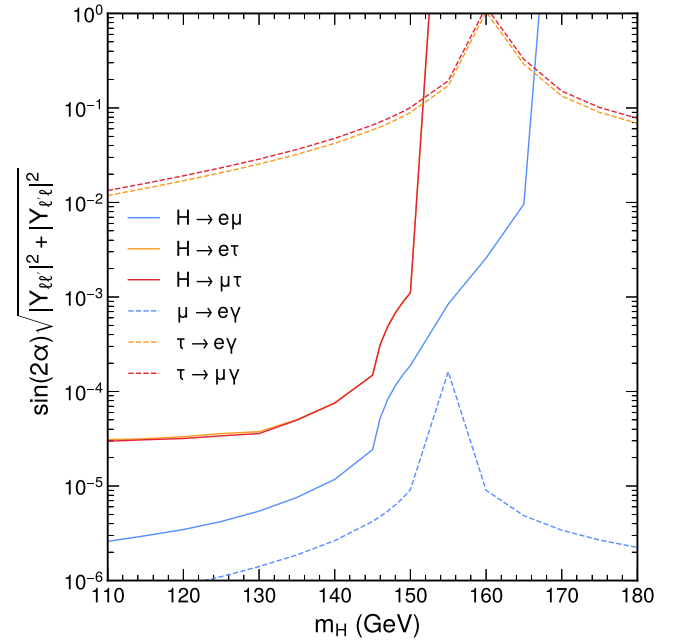


FIG. 9. The comparison between the sensitivities of the FCC-ee (solid) and the low-energy (dashed) searches for LFV decays in the $e - \mu$ (blue), $e - \tau$ (orange), and $\mu - \tau$ (red) sectors in the mass range $110 \leq m_H \leq 180$ GeV.

together via the inclusive process $e^+e^- \rightarrow \ell^+\ell^-H$ to account for the interference effect, as discussed in Sec. II. This allows us to probe H masses up to 190 GeV for the $H \rightarrow \mu e$ and $H \rightarrow \mu\tau$ channels and up to 180 GeV for $H \rightarrow e\tau$ mode. For the Higgs mass in the range 110–200 GeV we have derived the expected 95% CL upper limits on the branching fractions of the LFV Higgs decays, shown in Table VIII. At $m_H = 125$ GeV, the combined limits are found to be $\mathcal{B}(H \rightarrow \mu\tau) < 5.94 \times 10^{-4}$, $\mathcal{B}(H \rightarrow e\tau) < 6.28 \times 10^{-4}$, and $\mathcal{B}(H \rightarrow \mu e) < 7.37 \times 10^{-5}$.

We have also discussed the constraints on BSM models, particularly the type-III 2HDM, given the expected limits on the LFV Higgs decays obtained in this analysis. As shown in Fig. 7, the expected limits of H LFV decays in $e\tau$ and $\mu\tau$ sectors provide better constraints on the mixing angle $\sin \alpha$ and the LFV Yukawa couplings compared to the limit derived from low-energy $\tau \rightarrow \ell\gamma$ searches.

The findings presented in this paper indicate that the FCC-ee detector, proposed for construction and operation, will provide new insights into the study of BSM physics. Still, there are a number of assumptions that have to be made due to the lack of data from the yet-to-be-constructed collider itself, especially the assumptions about systematic uncertainties. Future studies on the expected systematic uncertainties that would apply to future colliders and detectors will provide additional insights and a better estimation of the accuracy for these searches.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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