

FCC feasibility studies: Impact of tracker- and calorimeter-detector performance on jet flavor identification and Higgs physics analyses

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The ambitious physics program planned for the Future Circular Collider electron-positron phase imposes stringent constraints on detector performance. This study systematically investigates how different detector configurations impact jet flavor identification and their effects on high-profile physics analyses. Using Higgs boson coupling measurements and searches for invisible Higgs decays as benchmarks, we evaluate the sensitivity of these analyses to variations in tracker and calorimeter detector properties. We examine modifications to single-point resolution, material budget, silicon layer placement, and particle identification capabilities, quantifying their effects on flavor-tagging performance. Additionally, we present the first comprehensive study of Higgs-to-invisible decay detection using full detector simulation, providing insights for optimizing detector designs at lepton colliders.

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I. INTRODUCTION

The Future Circular Collider electron-positron phase (FCC-ee) project [1] aims to explore particle physics frontiers with unprecedented precision. Several detectors have been proposed [2–5], each with specific subdetector configurations and geometries. This study examines how different detector choices impact high-profile analyses, particularly focusing on tracker configurations and their effects on jet flavor identification (jet tagging) and variations in calorimeter properties. We evaluate how these choices influence Higgs boson coupling measurements and Higgs self-coupling analyses. Additionally, we assess various calorimeter properties for detecting invisible Higgs boson decays.

Accurate jet flavor identification represents a cornerstone capability for measuring Higgs boson couplings at the FCC-ee. These algorithms distinguish between fundamental particles produced in high-energy collisions, enabling precise Standard Model (SM) measurements and searches for new physics phenomena. They are essential for the

FCC-ee physics program's core objectives: precision Higgs boson studies, top quark measurements, and searches for physics beyond the SM. Understanding how detector design choices affect these algorithms guides detector optimization and drives technological advancement. Different algorithms [6] for reconstructing track parameters and covariance matrices of charged particles for arbitrary tracking geometries have been developed, including a graph neural network for jet flavor identification. A generalization of this neural network approach to transformer networks has been implemented and is adopted throughout these studies [7] and in [8].

We use the FCC-ee innovative detector for e^+e^- accelerator (IDEA) [2,3] detector prototype as our baseline configuration. We then evaluate various detector configurations, including the addition of a fourth innermost pixel detector layer and removing particle identification capabilities (cluster counting dN/dx and/or time-of-flight measurements). At 240 GeV center-of-mass energy and 10.8 ab^{-1} integrated luminosity, the FCC-ee will produce millions of Higgs bosons primarily through Higgs-strahlung (ZH production). The clean e^+e^- collision environment enables direct measurement of Higgs branching fractions, contrasting with the ratio measurements possible at hadron colliders. Advanced flavor-tagging techniques may enable the first observation of Higgs-charm quark coupling.

Regarding invisible Higgs decays, SM coupling measurements suggest that a non-negligible fraction of the total

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Higgs width could be associated with beyond-the-Standard-Model (BSM) decays [9,10]. While the SM predicts $H \rightarrow ZZ \rightarrow 4\nu$ with $\mathcal{O}(10^{-3})$ branching fraction, the total invisible branching ratio could increase substantially if the Higgs also decays into weakly interacting massive particles [11,12], potentially explaining dark matter. Operating at $\sqrt{s} = 240$ GeV and 365 GeV, the FCC-ee could detect branching ratios below 1 per mille. Current studies examine the ZH process ($Z \rightarrow \bar{l}l$ or $Z \rightarrow q\bar{q}$ where l is a charged lepton and q is a quark, $H \rightarrow \text{invisible}$) using full CLIC-like detector (CLD) [4] simulation.

The organization of this paper reflects our systematic approach to detector optimization. Section II details event generation and simulation across detector configurations. Section III presents extended flavor-tagging performance studies, while Secs. VI and VIII discuss implications for Higgs coupling and self-coupling measurements, respectively. Sections IV and IX examine calorimeter variations and their expected impact on Higgs-to-invisible searches, respectively.

II. EVENT GENERATION, SIMULATION, AND DETECTOR VARIATIONS

A. Sample generation and analysis strategy

Higgs-strahlung events at the FCC-ee Higgs factory ($e^+e^- \rightarrow ZH$) have been generated using Whizard 3.1.2 [13,14] at center-of-mass energy $\sqrt{s} = 240$ GeV and simulated using Delphes [15], as detailed in the following subsections. To conduct comprehensive flavor-tagging performance studies, we produced ten million $e^+e^- \rightarrow Z(\rightarrow \nu\nu)H$ events. These events were evenly distributed among five Higgs decay modes, categorized by jet flavor: bottom (b), charm (c), strange (s), gluon (g), and up/down ($q = u, d$). We specifically combined these decay modes with Z -boson decays to neutrino pairs ($\nu\nu$) to ensure unambiguous assignment of hadronic products to the Higgs-boson decay.

For the fully hadronic analysis, we utilized additional $e^+e^- \rightarrow Z(\rightarrow jj)H(\rightarrow jj)$ samples categorized by final state. These include Z decays to b, c, s , and q quarks, and Higgs decays to b, c, s quarks, gluons (g), tau leptons (τ), Z bosons, $Z\gamma$, and W bosons. The primary backgrounds (WW, ZZ, and Zqq) were generated using Pythia8 [16].

B. IDEA detector concept and Delphes configuration

We employed the official Delphes fast simulation framework enhanced with specialized modules for high-precision particle physics simulations: TrackCovariance [17], TimeOfFlight [18], and ClusterCounting [19]. Our baseline configuration adopts the recent IDEA detector prototype [2,3].

The IDEA conceptual experiment incorporates innovative detector technologies developed in recent years. Its architecture features a silicon inner tracker, encased by a low-mass drift chamber and a silicon wrapper. This inner

detector system operates within a 2T magnetic field generated by an ultrathin superconducting solenoid. A dual-readout calorimeter is positioned beyond the magnet and within its return yoke. For muon detection, the design implements a tracker based on μ -Rwell technology, interleaved within the return yoke material. This same μ -Rwell technology provides an additional preshower layer positioned in front of the calorimeter.

To evaluate the impact on flavor identification performance and Higgs boson measurements at the FCC-ee, we systematically varied detector properties relative to this baseline in both the inner tracking system and the calorimeter components. These variations are described in detail in subsequent sections.

C. Full simulation samples for invisible Higgs analysis

For the Higgs-to-invisible analysis, we generated signal samples consisting of $e^+e^- \rightarrow ZH$ events where the Higgs decays to invisible final states. All samples were produced using Whizard 3.1.2 [13,14] at a center-of-mass energy of $\sqrt{s} = 240$ GeV, with hadronization performed by Pythia 6 [20].

For the $Z(H \rightarrow 4\nu)$ signal samples and other ZH backgrounds, we selected specific Higgs boson decay modes using the unstable feature of Whizard. For ZZ samples, we utilized the “restriction” feature of Whizard to select the desired processes, with the additional constraint that the generated Z resonance must fall within 5 GeV of the SM value. For WW samples, Whizard handled the initial hard scattering, while the subsequent W boson decays were processed by Pythia 6.

Cross sections and branching ratios for the ZH , WW, ZZ, and $Z \rightarrow \tau\tau$ samples were taken directly from Whizard calculations. These samples underwent full detector simulation using the standard CLD detector concept [4], implemented through Geant4 [21] and DD4hep [22]. Event reconstruction was performed using the CLDReconstruction.py and PandoraSettingsCLD [23] configurations from the CLDConfig [24] repository. All simulation and reconstruction processes utilized the 2023-11-23 release of Key4Hep [25].

III. TRACKER DETECTOR PROPERTIES AND PERFORMANCE IMPACT

Having outlined our simulation framework, we now examine how specific tracker properties affect jet flavor identification performance.

A. Methodology for performance assessment

Jet flavor identification algorithms are essential for interpreting complex event signatures and enabling precise measurements at the FCC-ee. While enhanced tracking resolution improves identification accuracy, it often requires additional detector material (e.g., extra silicon

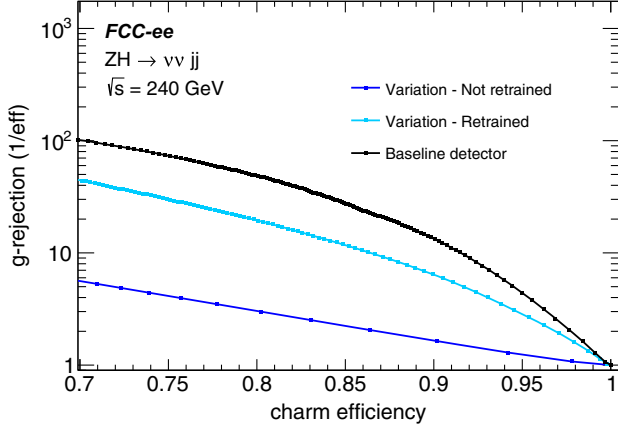


FIG. 1. Rejection of gluon-initiated jets as a function of the charm jet-tagging efficiency for the baseline IDEA detector (black), an alternative IDEA tracker without retraining (blue), and the same alternative tracker with retraining (light blue) of the ParticleNet algorithm. It is clear that training the algorithm on corresponding detector-configuration features is necessary to properly assess performance potential.

layers), which can reduce the rejection efficiency of unwanted flavors. Understanding and optimizing this trade-off is critical for future collider detector designs.

Each detector variation necessitates retraining of jet flavor identification algorithms to ensure fair and meaningful performance assessment. Figure 1 illustrates the receiver operating characteristic (ROC) curves for both the baseline detector and a detector variation, with and without algorithm retraining on samples accounting for such variations.

An algorithm trained on samples simulated with one detector configuration may not perform accurately when evaluated on samples from an alternative configuration. This mismatch can significantly misrepresent the magnitude of performance differences. Performance degradation caused by detector limitations can be largely mitigated by retraining the algorithm on appropriately simulated

samples that include those limitations. Therefore, all tagger performance studies presented herein utilize algorithms trained and evaluated on consistent input samples.

B. Single-point resolution effects

The baseline IDEA detector simulations assume a nominal single-point resolution of $3\ \mu\text{m}$, achievable with a $25 \times 25\ \mu\text{m}^2$ pitch vertex detector [26]. We investigated the impact of varying this resolution by $\pm 65\%$, a direct consequence of hit resolution modifications, and found that it significantly affects the jet flavor identification.

Figure 2 demonstrates that strange-jet rejection is highly sensitive to single-point resolution. Changes in the expected performance exhibit symmetry in the higher charm-efficiency range, with approximately a factor of 2 improvement or degradation in strange-rejection capability depending on resolution changes.

Conversely, the rejection of b -jets for charm tagging shows asymmetric effects, suggesting that asymptotic momentum resolution may have limited relevance at the FCC-ee due to the relatively low transverse momenta ($p_T \leq 50\ \text{GeV}$) of most tracks in jets. As Fig. 2 demonstrates, improved tracker resolution provides minimal benefit for b -jet rejection, which is crucial for $H \rightarrow cc$ analyses. Similar effects are observed when rejecting jets from other flavors while tagging c -jets. For b - and s -tagging, the impacts are considerably smaller, with relative changes in rejection capabilities for other flavors remaining within 10%–20%.

C. Material budget considerations

While improved tracking resolution can enhance identification accuracy, it frequently necessitates additional detector material. We examine how varying the vertex detector material content affects performance, along with the interplay between beam-pipe and vertex-detector material budgets.

Assuming a standard radiation length for silicon of $0.0937\ \text{m}$, we studied the effect of simultaneously varying

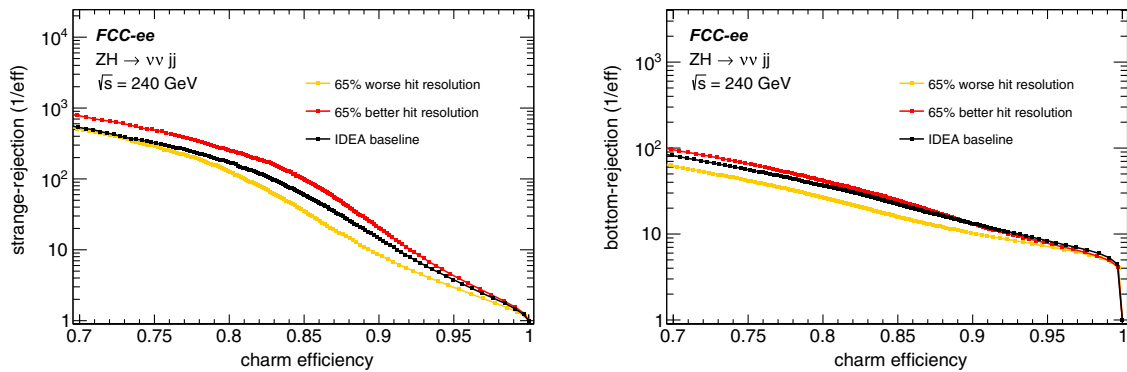


FIG. 2. Rejection of strange-initiated jets (left) and bottom-initiated jets (right) as a function of charm jet tagging efficiency for different hit resolutions.

the radiation length for all silicon layers, equivalent to modifying the material content by $\pm 50\%$. For charm tagging, we observed an asymmetric impact: negative effects from additional material were five times larger than benefits from reduced material. The maximum observed change in strange-jet rejection capability while tagging charm jets was approximately 30%. Such variations had only minor effects on b -jet and strange-jet tagging performance.

These results indicate that while a lighter vertex detector offers minimal performance gains, additional or denser material can substantially degrade performance. For jets with momentum above 70 GeV, as expected, the impact of multiple Coulomb scattering diminishes significantly. Moreover, with substantial increases in beam-pipe material budget, changes in the vertex-detector first layer material budget become secondary concerns.

D. Silicon layer configuration studies

Previous studies [6] demonstrate that an additional innermost silicon layer plays a key role in charm tagging, providing minor improvements in bottom tagging and enhanced background rejection in charm tagging. In the current IDEA baseline detector concept, the beam pipe has been reduced to 1 cm diameter, with the four innermost silicon layers positioned at 1.2, 2, 3.15, and 15 cm from the beam axis. We evaluated the impact on jet flavor tagging of

removing either the second or fourth innermost silicon layer.

Our studies revealed measurable effects on charm-tagging performance, with removal of the second innermost silicon layer producing a more significant impact than removal of the fourth layer. Relative changes in background jet rejection remained within 15%, with similar patterns observed for strange, light quark, and gluon jet rejection while tagging charm jets. While bottom tagging appears more robust against these changes, the effects may amplify when analyzing jets produced at higher momenta, such as in differential measurements.

E. Particle identification capabilities

To characterize flavor-tagging performance enhancements from particle identification (PID) capabilities, we investigated several variations in PID information provided to the algorithm training: baseline PID, complete absence of PID, absence of cluster-counting information, absence of time-of-flight (TOF) measurement, absence of both TOF and cluster-counting information, and baseline PID with improved timing resolution.

Figure 3 demonstrates that timing measurements contribute minimally to strange-jet tagging in this kinematic regime. It has to be noted that the same TOF measurement, combined with the cluster-counting information for the baseline PID detector scenario, has been included in the set

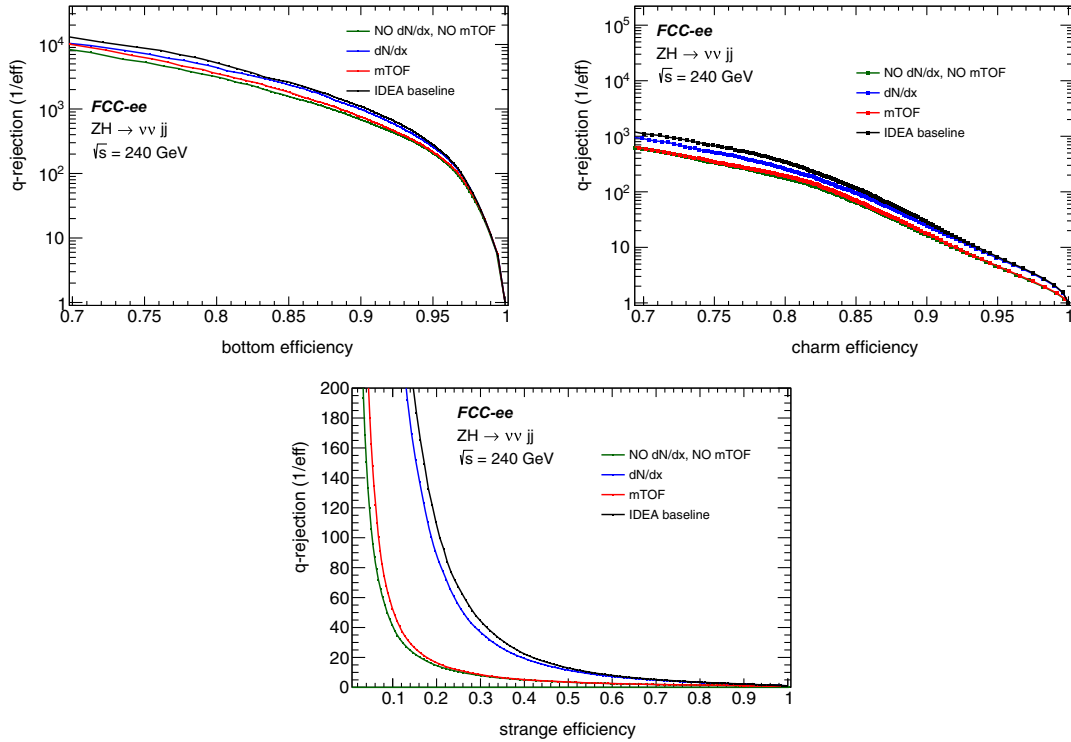


FIG. 3. Rejection of light-initiated jets as a function of jet-tagging efficiency for bottom (upper left), charm (upper right), and strange (lower) jets. Results are shown for the baseline IDEA vertex detector (black), without cluster counting (red), without TOF information (blue), and without both PID components (green).

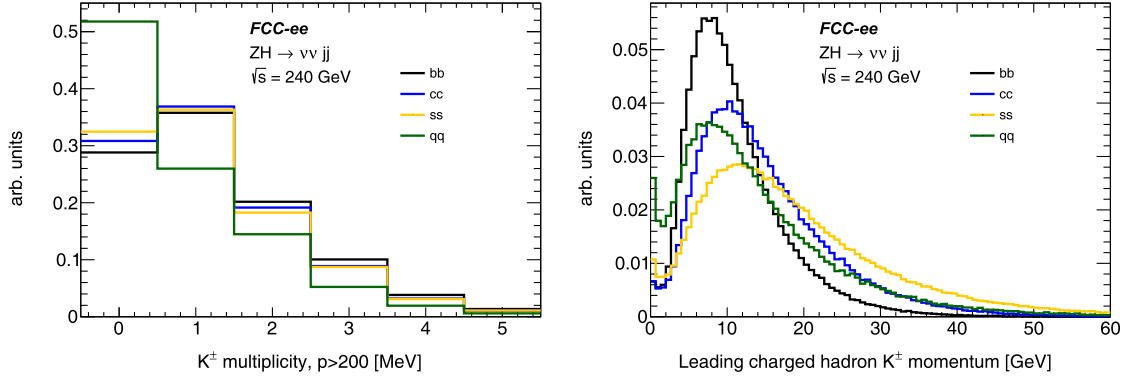


FIG. 4. Multiplicity of kaons with minimum momentum of 200 MeV (left) and momentum distribution of the leading kaon (right) within bottom (black), charm (blue), strange (yellow), and light (green) jets.

of algorithm inputs in order to evaluate the drop in performance caused by the absence of the cluster-counting information. TOF primarily contributes to kaon-pion separation at momenta around 1 GeV [6]. In contrast, TOF measurements demonstrate noticeable effects on charm-jet tagging and significant impacts on bottom-jet tagging, both independently and combined with cluster-counting information.

To establish an upper performance limit achievable with PID information, we implemented truth-matching of particle-flow candidates to Monte Carlo (MC) truth particles.

Figure 4 presents the multiplicity of truth-matched kaons and the momentum distribution of the leading kaon within Higgs-decay jets of different flavors.

We incorporated truth-MC information identifying charged-hadron and charged-lepton particle-flow candidates in a dedicated training. Figure 5 shows the resulting performance improvements. Bottom (charm) jets exhibit a larger fraction of leading charged kaons around 1 GeV than charm (strange) jets, correlating with the hierarchy of performance effects observed in tagger performance.

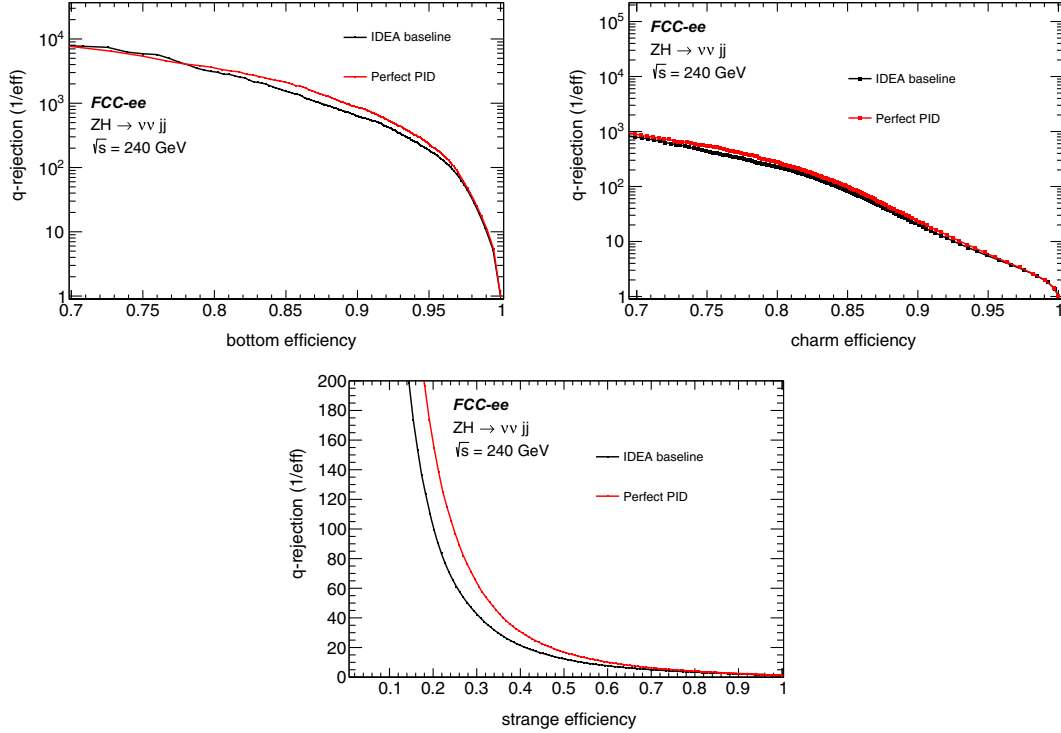


FIG. 5. Light-jet rejection performance for bottom tagging (upper left), charm tagging (upper right), and strange tagging (bottom). Results compare the baseline training (black) with training incorporating truth-MC information for charged-hadron and charged-lepton particle-flow candidates (red).

IV. CALORIMETER PROPERTIES AND DETECTION PERFORMANCE

The nominal energy resolution for the IDEA prototype calorimeters has been assumed from established studies [27]. For the electromagnetic crystal calorimeter, we assume a nominal energy resolution of the form

$$\sqrt{a^2 E^2 + b^2 E + c^2} \quad (1)$$

with $a = 0.005$, $b = 0.03$ and $c = 0.002$.

The nominal energy resolution of the hadronic dual-readout calorimeter is given by

$$\sqrt{d^2 E^2 + e^2 E + f^2} \quad (2)$$

with $d = 0.01$, $e = 0.3$, and $f = 0.05$. The nominal granularity of calorimeters is simulated by means of a cell size of about $6 \times 6 \text{ cm}^2$.

Energy-resolution parameters (a, b, c, d, e, f) are scaled up and down at the same time by a relative 30% to mimic potential degradation and improvement in the calorimeter performance. The nominal cell size is varied by a factor of 2 in order to estimate the potential of a more or less granular calorimetry system.

V. STATISTICAL METHODOLOGY AND LIMIT SETTING

To determine upper limits on the branching ratio (BR) of the process under study, we employed the `xRooFit` toolkit [28], considering only statistical uncertainties. We constructed a likelihood function using signal and background models from simulation, expressing the total probability density function as

$$P(x|\mu) = \mu \cdot S(x) + (1 - \mu) \cdot B(x), \quad (3)$$

where x represents the observable variable (such as recoil mass), $S(x)$ and $B(x)$ are the signal and background components, and μ is the signal strength parameter related to the branching ratio by

$$\mu = \frac{\sigma_{\text{obs}} \cdot \text{BR}}{\sigma_{\text{SM}}}, \quad (4)$$

with σ_{obs} being the observed production cross section and σ_{SM} the SM prediction.

We generated pseudodatasets by sampling the expected signal-plus-background or background-only distributions, incorporating statistical fluctuations consistent with expected event yields. The profile likelihood ratio served as our test statistic:

$$\lambda(\mu) = \frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})}, \quad (5)$$

where $\mathcal{L}(\mu)$ is the likelihood given the signal strength μ , and $\hat{\mu}$ maximizes the likelihood. We evaluated $-2 \ln \lambda(\mu)$ to

compare signal-plus-background and background-only hypotheses, determining its distribution under the background-only hypothesis using asymptotic approximations.

For each detector variation described in previous sections, we performed separate likelihood scans to determine the impact on sensitivity. These scans are conducted by fixing all nuisance parameters to their best-fit values and varying only the signal strength parameter μ . For analyses with multiple channels, we constructed a joint likelihood incorporating all relevant signals and backgrounds, accounting for their respective efficiencies and resolutions. The 95% confidence level (CL) upper limit on the parameter of interest corresponds to the μ value where the cumulative probability exceeds the critical threshold. This methodology is applied consistently across all analyses described in the following sections.

VI. FULLY HADRONIC ZH ANALYSIS AND DETECTOR IMPACT ASSESSMENT

A. Analysis methodology

We have reanalyzed the ZH fully hadronic final state for each retrained flavor tagger, using the expected 68% CL uncertainty on the measured Higgs couplings to bottom, charm, strange quarks, and gluons as metrics to determine the impact of flavor-tagger performance. The analysis methodology follows that described in Ref. [29] and is summarized below.

The exclusive Durham- k_t algorithm is employed for jet clustering, requiring exactly four jets per event corresponding to the hadronic decays of both Z and H bosons. To suppress backgrounds, we apply cuts on angular separation between jets: $15000 < d_{12} < 58000$, $400 < d_{23} < 18000$, and $100 < d_{34} < 6000$, where $d_{ij} = 2 \min(E_i^2, E_j^2)(1 - \cos \theta_{ij})$ between the i th and j th jets. Additionally, we require visible energy and mass greater than 150 GeV, with visible θ within $[0.15, 3.0]$, and at most two leptons with the leading lepton momentum below 20 GeV. Assuming well-measured jet directions and known initial energy in a four-jet system, jet energies are corrected following energy and momentum conservation principles.

Flavor scores from the tagger are used to pair jets and identify Z or H candidates based on dijet masses. Each jet has flavor scores B_i , C_i , S_i , Q_i , and G_i corresponding to the probabilities of the jet being initiated by bottom, charm, strange, up/down quarks, or gluons, respectively. We identify the maximum flavor score for each jet and apply different pairing strategies depending on the pattern of maximum scores:

Case 1—All jets with the same maximum flavor score:

To determine which dijet pair forms the H/Z candidate, we consider all possible jet pairings and compute $\chi_{\text{comb}}^2 = \chi_Z^2 + \chi_{\text{Higgs}}^2$, where $\chi_Z^2 = (m_{Z,\text{reco}} - m_{Z,\text{true}})^2$ and $\chi_{\text{Higgs}}^2 = (m_{H,\text{reco}} - m_{H,\text{true}})^2$. The jet pairing with

minimum χ_{comb}^2 is selected as correct, where $m_{Z/H,\text{reco}}$ are the reconstructed H/Z dijet masses.

Case 2—Pairs with different maximum flavor scores: If combining jets with the same maximum flavor scores yields exactly two pairs with different flavors, the Z candidate is chosen as the pair with minimum $\chi_Z^2 = (m_{lk} - m_{Z,\text{true}})^2$, and the remaining pair is assigned as the H candidate.

Case 3—Two jets with the same maximum flavor score: Two jets with maximum scores from the same flavor are paired, while the flavor of the second pair is determined by examining same-flavor score sums. The flavor of the second pair is chosen as the one that maximizes the same-flavor sum, $\max(\sum_{i,j} B, \sum_{i,j} C, \dots)$. The H/Z candidates are then determined as in Case 1 if both pairs have the same flavor, or as in Case 2 if they have different flavors.

Case 4—Three jets with the same maximum flavor score: Similar to Case 3, the first pair is formed from the jets whose same-flavor sum of scores is greatest. The flavor of the second pair is determined as in Case 3, and the assignment of H/Z candidates follows the approach outlined in Case 3.

Case 5—Four different maximum flavor scores: If each jet has a maximum flavor score from a different flavor, the event is excluded from analysis.

To reject WW and ZZ backgrounds, additional cuts are applied based on the H and Z candidate masses. The final fit is performed in the H and Z mass plane, where $50 \text{ GeV} < m_{Z,\text{reco}} < m_{H,\text{true}}$ and $m_{H,\text{reco}} > m_{Z,\text{true}}$. Events are classified into 60 categories based on the flavor of the H and Z decay products and the sum of flavor scores for the pair forming the Higgs candidate (purity categories).

B. Detector performance impact on physics measurements

While Sec. III demonstrated that tagger performance may be overestimated when evaluated on simulations different from those used in training, this effect has negligible impact at the analysis level. We tested this by applying both the ParticleNet tagger trained on the baseline IDEA simulation and the tagger trained on a simulation with 65% worse single-hit resolution to $Z_{cc}H_{bb}$, $Z_{cc}H_{ss}$, and $Z_{cc}H_{gg}$ signal samples generated with both detector geometries. The Higgs decay tagging efficiency showed no dependence on which tagger was applied, likely due to the robustness of our flavor-tagging strategy. The effects observed in Sec. III are most prominent at lower tagging efficiencies, whereas our analysis ensures high efficiency by using the sum of dijet flavor scores.

Figure 6 illustrates the impact of flavor-tagger performance on likelihood scans and the resulting 68% CL uncertainties for Higgs couplings to bottom, charm, strange

quarks, and gluons. We compare the baseline IDEA detector tagger with variants trained without time-of-flight information (no TOF, only dN/dx), without cluster counting (no dN/dx , only TOF), without both dN/dx and TOF (no PID), and with truth-level particle identification (Truth PID). Notably, detector variations including removal of the innermost silicon layer, displacement of silicon barrel layers, 50% heavier or lighter vertex detector, or 65% better/worse single-hit resolution did not significantly affect Higgs coupling precision, consistent with expectations from the ROC curves shown in Fig. 2.

The Higgs decay flavor reconstruction remains largely unchanged when using a tagger trained without time-of-flight information. This robustness arises from our flavor-tagging technique, which determines H/Z flavor with high efficiency regardless of detector geometry variations, as evidenced by the ROC curves in Fig. 3.

However, removing cluster-counting information from tagger training significantly impacts Higgs coupling measurements. Without cluster counting, the expected uncertainty on $\mu_{H \rightarrow s\bar{s}}$ at 68% CL is 1.5 times worse compared to the baseline uncertainty. These results are consistent with closer inspection of Fig. 3, which shows that light jet rejection as a function of strange-tagging efficiency has a notable impact from the inclusion of cluster-counting information, compared to missing TOF information. Removing cluster-counting information has a smaller impact on the measured μ_{Hbb} and μ_{Hcc} compared to μ_{Hss} . This occurs because light jet rejection is significantly lower at high strange efficiency. In contrast, light jet rejection remains higher at high bottom and charm efficiencies.

C. Jet clustering algorithm comparison

The exclusive Durham- k_t jet clustering algorithm [30] configured in n -jets mode has been the standard approach for jet reconstruction throughout the FCC feasibility studies. However, we identified two key issues: incorrect assignment of jet pairs and poor clustering performance for soft particles in $e^+e^- \rightarrow ZH$ Higgs production when using this algorithm. To address these limitations, we implemented and evaluated the anti- k_t clustering algorithm as an alternative for reconstructing Higgs mass in the fully hadronic 4-jet final state.

We selected the inclusive anti- k_t algorithm as a promising alternative to Durham- k_t because of its infrared and collinear safety properties, which ensure reliable performance when processing soft or closely spaced particles. For our comparative analysis, we used ZH events where the Higgs boson decays to a $b\bar{b}$ pair and the Z boson decays to a $c\bar{c}$ pair, providing a clean fully hadronic 4-jet final state.

For events with more than four jets, we applied an energy recovery algorithm following the procedure outlined in Ref. [31]. This procedure first selects the four highest-energy jets and then merges each remaining soft jet with the hard jet closest in angular separation. After merging,

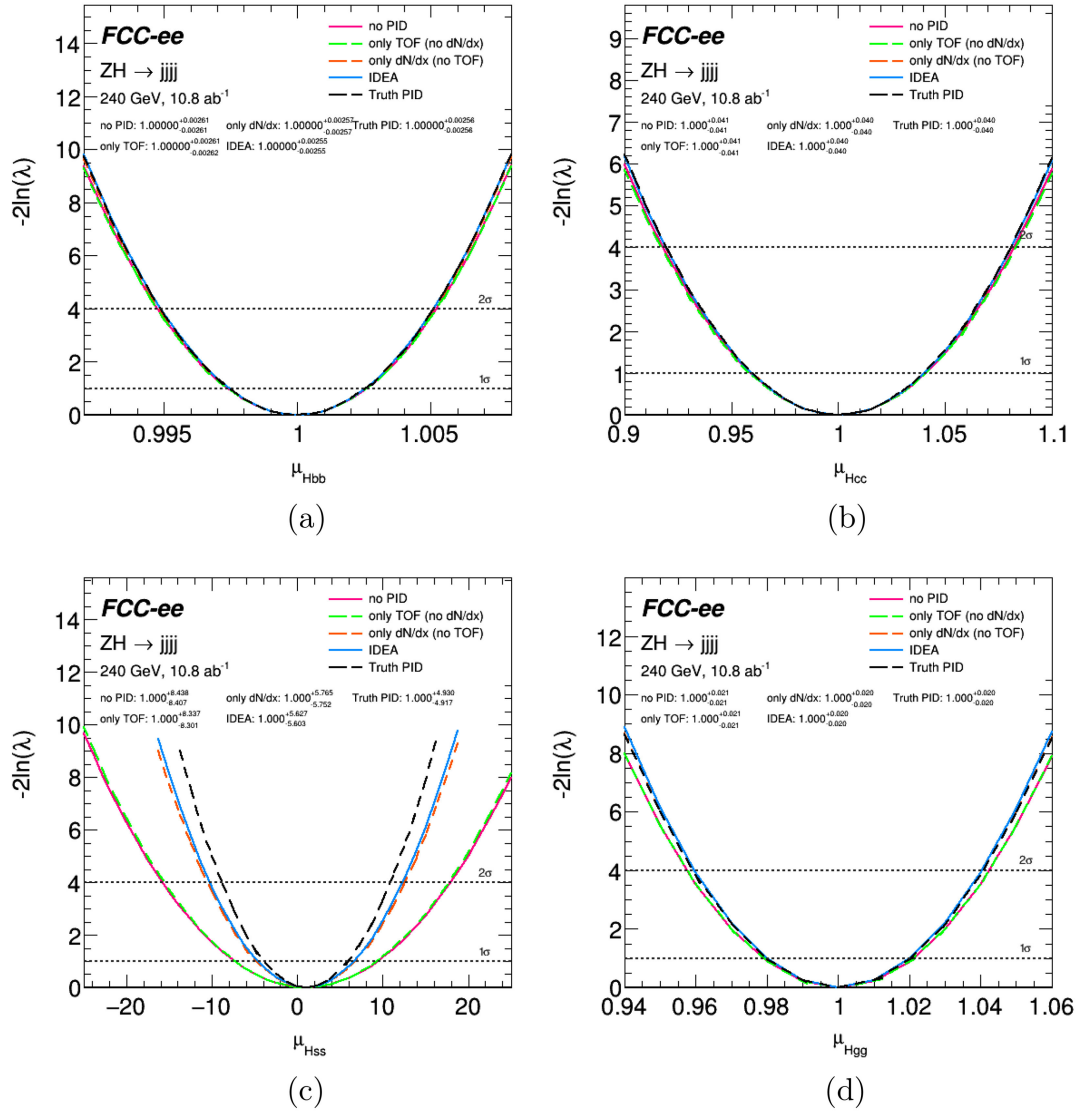


FIG. 6. Impact of flavor-tagger training variations on negative log-likelihood scans for Higgs coupling measurements: (a) μ_{Hbb} . (b) μ_{Hcc} . (c) μ_{Hss} . (d) μ_{Hgg} . The baseline training (IDEA, blue) and training without TOF information (only dN/dx, orange) show similar performance when applied to the ZH fully hadronic analysis. However, removing cluster counting information and keeping the TOF information (no TOF, green) significantly degrades the precision of μ_{Hss} measurement, similar to having no PID information at all (no PID, pink). Truth information (Truth PID, black) modestly improves precision for μ_{Hcc} and μ_{Hss} measurements.

we applied a 10 GeV minimum energy threshold to all jets. We then processed the data using the anti- k_t clustering algorithm with jet radius parameter R varying from 0.4 to 1.0.

Figure 7 presents the reconstructed Higgs-boson mass distributions using different clustering approaches. The anti- k_t algorithm with radius parameter $R = 1.0$ yields a mean Higgs invariant mass of 124.1 GeV, which is closer to the true Higgs mass than the 123.0 GeV mean value obtained with the Durham- k_t algorithm. On the other hand, the Durham- k_t algorithm seems preferable over the other two clustering approaches, since it offers a significantly better resolution of the reconstructed Higgs-boson mass.

The better performance of the $R = 1.0$ configuration, as compared to the $R = 0.4$ one, is likely related to the event topology in e^+e^- collisions at $\sqrt{s} = 240$ GeV, where the relatively low boost of the Higgs boson results in decay products with a relatively wide angular separation compared to high-energy hadron collider environments.

VII. SEMI-LEPTONIC $Z \rightarrow \nu\bar{\nu}$, $H(jj)$ CHANNEL

A. Analysis strategy and particle identification impact

The anticipated precision on the Higgs boson branching fractions to $c\bar{c}$ and $s\bar{s}$ for several particle identification capabilities has been explored using the $Z(\nu\bar{\nu})H(jj)$

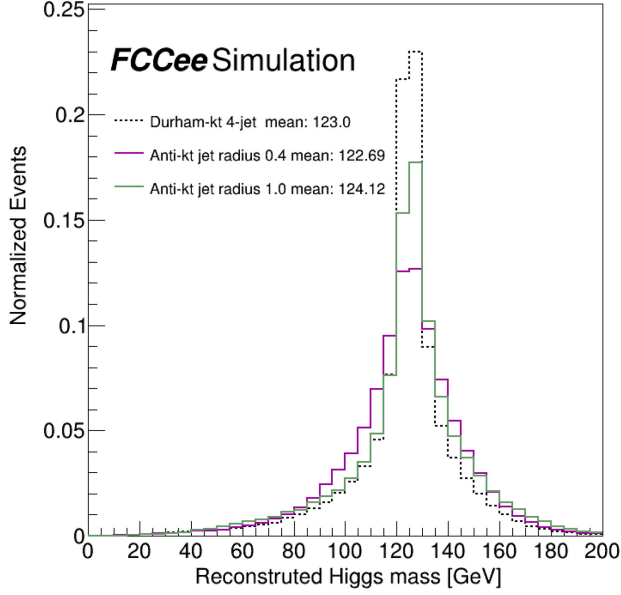


FIG. 7. Comparison of reconstructed Higgs boson mass distributions using the Durham- k_t clustering algorithm configured for exactly four jets and the anti- k_t clustering algorithm with jet radius parameters $R = 0.4$ and $R = 1.0$.

topology. The analysis strategy leverages the flavor-tagging capabilities of the ParticleTransformer tagger in a relatively clean reconstruction environment where the final state consists of only two jets of the same flavor and missing mass from the neutrinos. The analysis is described in detail in [29]. The results are shown in Fig. 8. As anticipated, efficient K/π separation is crucial for tagging strange quarks effectively. Furthermore, cluster counting (dN/dx) provides significant separation power, resulting in higher precision in the relative uncertainty. If only TOF measurements are assumed, the precision of the $H \rightarrow s\bar{s}$ branching fraction measurement severely degrades to values exceeding 300%. The particle identification also contributes to the

$H \rightarrow c\bar{c}$ branching fraction measurement through the decay products of D mesons.

B. Calorimeter performance impact

The identification of di-jet signal events relies on mass resolution (the visible mass), which is influenced by calorimeter performance. Assuming an ideal particle-flow algorithm, visible energy (and mass) resolution is dominated by the neutral hadron resolution, which is primarily driven by the hadronic calorimeter (HCAL) stochastic term. Figure 9 shows the relative loss in precision in $H \rightarrow c\bar{c}, b\bar{b}, s\bar{s}, gg$ decay channels as a function of the HCAL stochastic term, demonstrating that the visible energy (and mass) resolution plays a significant role in the branching fraction measurements, especially for $H \rightarrow c\bar{c}$ and $H \rightarrow s\bar{s}$ decay channels.

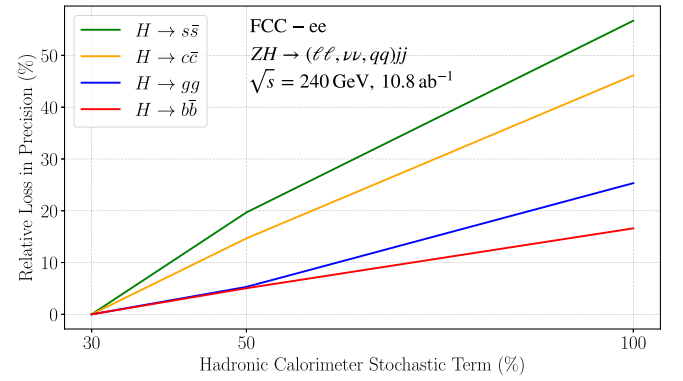


FIG. 9. Expected precision degradation of the branching ratio measurements for the $H \rightarrow c\bar{c}, b\bar{b}, s\bar{s}, gg$ decays as a function of the HCAL stochastic term. To guide the interpretation, the value 30% would correspond to a dual-readout calorimeter as in the baseline IDEA simulation, while 50 and 100% correspond to calorimeters employed at the LHC.

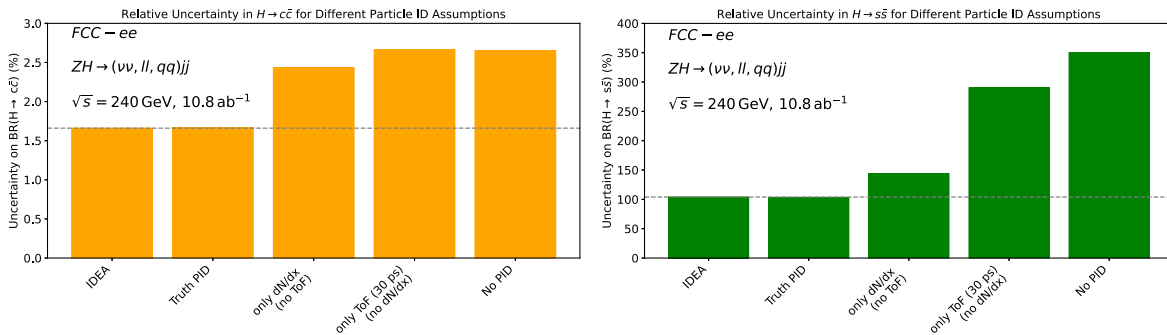


FIG. 8. Relative uncertainty in the $H \rightarrow c\bar{c}$ (left) and $H \rightarrow s\bar{s}$ (right) branching fractions, as expected for several assumptions on particle identification performance.

Additional studies with various tracker assumptions were performed by increasing the beam pipe material, displacing the vertex detector by 500 μm , or varying its resolution by small amounts; however, no significant effect on precision loss was observed.

VIII. HIGGS SELF-COUPLING INTERPRETATION

A. Theoretical framework and motivation

The Higgs self-coupling is a parameter of major interest, as it has a direct impact on the shape of the Higgs potential. It also has a predicted value in the SM, determined by the Higgs mass and vacuum expectation value, to which measurements at colliders can be compared. This parameter is directly accessible through Higgs pair production (HH), a process actively studied at the LHC. It is possible to produce HH at an e^+e^- collider and access the Higgs self-coupling via the Higgs-strahlung process, provided that the e^+e^- center-of-mass energy is large enough. At the 240 GeV phase of FCC-ee, $\sqrt{s}$ is too low to produce HH directly. Instead, the Higgs self-coupling can be indirectly accessed through higher order contributions to single Higgs production processes. In general for e^+e^- colliders, the cross-section for HH starts to become experimentally viable around $\sqrt{s} = 500$ GeV. Current feasibility studies estimate that with $\sqrt{s} = 240$ GeV, a sensitivity to the self-coupling of 49% may be achievable. The recent FCC Feasibility Study reports an expected precision on the Higgs self-coupling of about 28%, including input from the $\sqrt{s} = 240$ GeV and $\sqrt{s} = 365$ GeV runs. When combined with the recent High Luminosity LHC projections [32], the precision on the self-coupling is expected to reach 18% [33].

BSM contributions to the ZH cross section can be parametrized within the SMEFT (SM effective field theory) framework. In our analysis, we used SMEFT in the Warsaw basis [34], and focused on the contribution of the C_ϕ [35,36] operator, which affects the Higgs self-coupling via a dimension-6 operator.

The following equation is used to parametrize the ZH cross section as a function of C_ϕ :

$$\frac{\sigma_{\text{SMEFT}}(C_\phi, \sqrt{s} = 240 \text{ GeV}, \Lambda = 1 \text{ TeV})}{\sigma_{\text{SM,LO}}} = 1 - 0.00699C_\phi(\mu). \quad (6)$$

It is important to note that for single Higgs production processes, contributions of C_ϕ for the ZH process start at the one-loop level. Therefore, this contribution depends on the renormalization scheme choice. In this study, we followed [35,36] where μ is evaluated at 240 GeV. Additionally, in this study, only the cross section of the ZH process is parametrized, while the branching ratios are left at their SM values.

B. Analysis methodology

As described in Sec. VI, the fully hadronic ZH analysis can be used to study various Higgs couplings [29]. For the interpretation described in this section, the same events passing the selections and categorization of the nominal fully hadronic ZH analysis [29] are used, with the ZH cross section parametrized as a function of C_ϕ using Eq. (6).

This parametrization changes the cross section in a linear fashion, up to about 0.7%, hence varying C_ϕ from -1 to 1 . This range of C_ϕ is considered accurate without including higher order terms in its expansion, as including higher powers of C_ϕ returns almost the same cross section variation in this range. Additionally, setting C_ϕ to 0 leaves the cross section unaltered, at its SM value.

C. Detector sensitivity results

We applied this parametrization to all ZH processes and performed likelihood scans for five detector configurations described in Sec. VIB: the default baseline “IDEA,” the “only dN/dx,” the “only TOF,” the “No PID,” and the “Truth PID,” scenarios. The result is shown in Fig. 10.

The constraints on C_ϕ show very similar behavior to the other Higgs coupling scans shown in Fig. 6, as expected since the same events are used for this interpretation and the variation of the cross section from C_ϕ is only up to about 0.7%. The detector variations described in Sec. VIB predominantly impact the coupling of the Higgs to strange quarks, as shown in Fig. 6(c). For the Higgs self-coupling interpretation, all categories are included to maximize sensitivity, among which the Higgs to strange quarks category is subdominant and therefore does not strongly influence the combined C_ϕ constraint across different

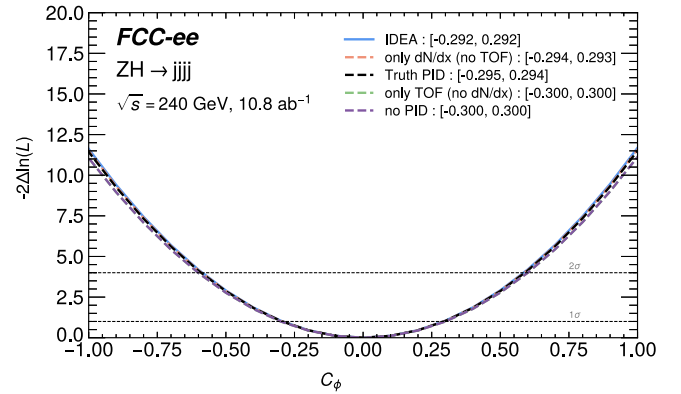


FIG. 10. Negative log-likelihood scan as a function of the SMEFT parameter C_ϕ . We compare the baseline IDEA detector tagger with variants trained without time-of-flight information (no TOF, only dN/dx), without cluster counting (no dN/dx, only TOF), without both dN/dx and TOF (no PID), and with truth-level particle identification (Truth PID). The horizontal lines indicate the 68% and 95% confidence levels, representing one and two standard deviation uncertainties, respectively.

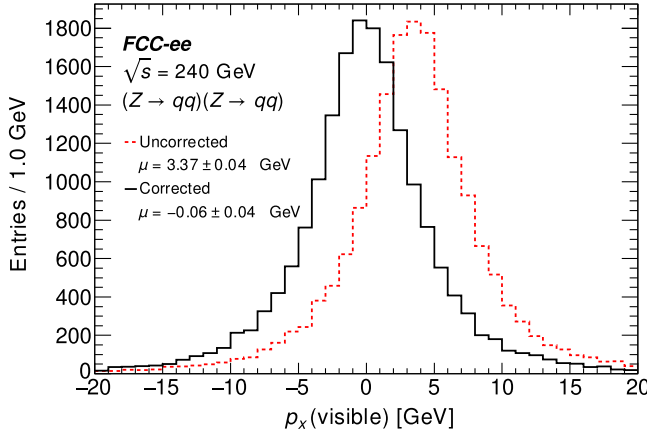


FIG. 11. Total momentum of final-state particles in the x direction for $ZZ \rightarrow qq\bar{q}\bar{q}$ events. The dashed curve shows the distribution before applying the compensating boost, while the solid curve shows the distribution after correction.

detector variations. Recent C_ϕ projections including combinations with and comparisons to HL-LHC projections can be found in [37,38].

IX. HIGGS-TO-INVISIBLE ANALYSIS

A. Analysis strategy and event selection

Invisible Higgs boson decays represent an important probe for physics beyond the SM, with numerous theoretical models predicting contributions beyond the SM process $H \rightarrow ZZ \rightarrow 4\nu$. The clean environment of electron-positron collisions enables reconstruction of unobserved Higgs boson decays through energy-momentum conservation and knowledge of the initial state. Thus, the precision of this measurement is highly sensitive to detector design and simulation accuracy.

We explored the sensitivity to Higgs-to-invisible decays through two complementary approaches. First, we updated

the previous analysis that relied on fast simulation using the IDEA detector [39] and incorporated full simulation using the CLD detector [4]. The direct comparison between the fast and full simulation approaches are shown in Sec. IX E. Secondly, we used fast simulation of the IDEA detector to quantify how the calorimeter property variations, described in Sec. IV, affect the measurement sensitivity.

The event selection mimics what was done in Ref. [39], adapting it to full simulation. First all final-state particles are boosted into the center-of-mass frame. At the FCC, each beam enters the detector at an angle of 0.015 rad with respect to the z -axis in the horizontal plane, resulting in a total crossing angle of 0.030 rad. This configuration imparts a boost to events in the x -direction of $\beta = \sin(\theta/2)$. Figure 11 shows that the total momentum in the x -direction for $ZZ \rightarrow qq\bar{q}\bar{q}$ events is offset from zero by several GeV. Since this offset would affect missing momentum reconstruction, we apply a compensating boost in the x -direction to all final-state particles in fully simulated samples. Since this effect is absent in fast simulation, no correction was applied to those samples.

We selected electrons, muons, and photons using the tight criteria from PandoraPFA [40], requiring leptons to have momentum $p > 10$ GeV and satisfying isolation criteria. For isolation, we calculated the scalar sum p_{cone} of momenta for all particles within a cone of $0.01 < \Delta R < 0.5$ around each lepton, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ and η is pseudorapidity. A lepton is considered isolated if $p_\ell / p_{\text{cone}} > 0.5$.

B. Bremsstrahlung recovery implementation

Electrons traversing detector material emit photons at small angles (bremsstrahlung), producing a substantial low-mass tail in the m_{ee} distribution, as shown by the dashed curve in Fig. 12(a). Since this effect is neither included in the fast simulation nor accounted for in standard CLD reconstruction, it represents a significant

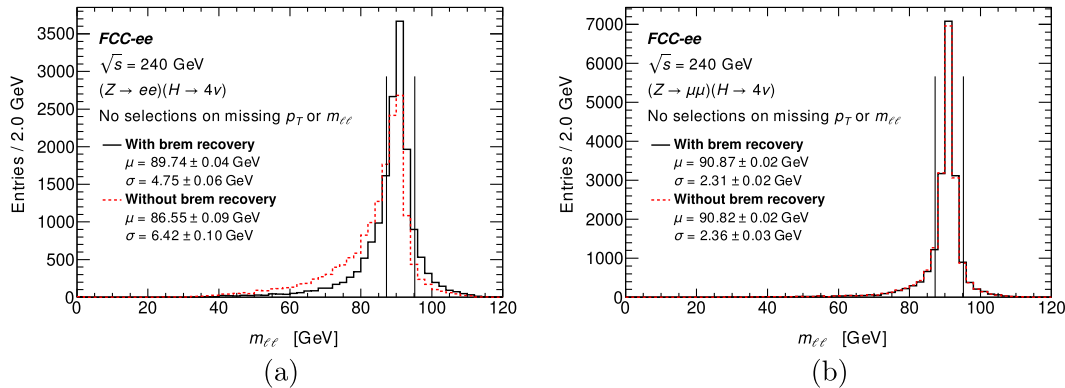


FIG. 12. Dilepton invariant mass for ZH events with the Higgs boson decaying to four neutrinos and the Z boson decaying to (a) electrons and (b) muons. The dashed curves show distributions without bremsstrahlung correction, while solid curves show distributions after applying the correction. Parameters of Gaussian functions fit to the distributions are shown. Vertical lines indicate the acceptance range for analysis selection.

TABLE I. Event selection criteria for the invisibly decaying Higgs boson analysis using full simulation.

Leptons	Tight electrons or muons with $p > 10$ GeV; apply bremsstrahlung recovery	
Channel definition	Exactly two leptons: e^+e^- or $\mu^+\mu^-$	No leptons
Missing p_T	$p_{T,\text{vis}} > 10$ GeV	$p_{T,\text{vis}} > 15$ GeV
Z boson decay	$ m_{\ell\ell} - M_Z < 4$ GeV	$86 \text{ GeV} < m_{\text{vis}} < 105 \text{ GeV}$

source of discrepancy between fast and full simulation. To reduce these differences, we implemented a bremsstrahlung recovery procedure at the analysis level.

Since refitting tracks at the analysis level is not feasible, we instead identified the highest-momentum photon candidate within a 0.05 rad cone around each lepton, then determined whether to add this photon's momentum to the lepton. Simply adding all nearby photons to leptons would degrade resolution, as photon momenta may already be incorporated into lepton tracks depending on where radiation occurred in the detector. Therefore, we trained a neural network (NN) to identify cases where photon addition improves momentum reconstruction.

We classified leptons based on whether adding the photon brings the lepton's momentum closer to or further from the momentum given by MC truth information. Photons that improve momentum reconstruction are classified as “signal” while those that worsen it are labeled “background.” The NN processes five input variables: lepton momentum p_ℓ , the lepton polar angle θ_ℓ , the angle between the lepton and photon, $\Delta\theta(\ell, \gamma)$, the energy of the lepton's calorimeter cluster E_ℓ^{calo} , and the energy of the photon's calorimeter cluster E_γ^{calo} . The NN is implemented using the Deep Neural Network method from TMVA [41] with two hidden layers containing 14 and six nodes, using tanh activation functions for hidden layers and a linear activation function for the output node. The network is trained on the $(Z \rightarrow ee)(H \rightarrow 4\nu)$ signal sample, equally divided between training and test samples. For photons with NN output greater than 0.5, their momentum is added to the associated lepton.

This correction substantially improves the electron pair mass distribution, as shown by the solid curve in Fig. 12(a). The distribution becomes narrower and more symmetric, with the mean shifting closer to the Z boson mass. We applied the same NN to muons, which, despite being less affected by bremsstrahlung, still show slight narrowing of the mass distribution [Fig. 12(b)].

C. Channel definition

The bremsstrahlung recovery procedure is followed by the calculation of the total visible momentum p_{vis} by summing over all final-state particles, excluding photons that the NN determined should not be added to leptons. For backgrounds simulated with fast simulation, we omitted the center-of-mass boost and bremsstrahlung recovery steps, and selected leptons using the provided identification lists.

Three channels are defined based on Z boson decay: electrons, muons, and hadrons. For leptonic channels, we required exactly two same-flavor, opposite-sign leptons, transverse missing momentum $p_{T,\text{vis}} > 10$ GeV, and dilepton mass within 4 GeV of the Z mass ($|m_{\ell\ell} - M_Z| < 4$ GeV). For the hadronic channel, we required no identified leptons, transverse missing momentum $p_{T,\text{vis}} > 15$ GeV, and visible mass between 86 and 105 GeV. Table I summarizes these selection criteria.

For the hadronic channel, we expanded the visible mass selection range compared to the previous fast-simulation analysis [39]. Figure 13 shows the visible mass distribution for the hadronic channel, which peaks significantly above the Z boson mass. This shift likely results from particle flow reconstruction artifacts in PandoraPFA, where neutral clusters near charged hadrons are reconstructed as separate photons despite their momentum being included in the charged hadron's track, effectively double counting energy in the particle summation.

Finally, we calculated the recoil mass from the total visible momentum and nominal collision energy. Figure 14 shows the resulting distributions for all three channels.

D. Resolution comparison between fast and full simulation

Figure 15 compares the transverse momentum resolution for electrons and muons between full simulation and fast simulation for both CLD and IDEA detector

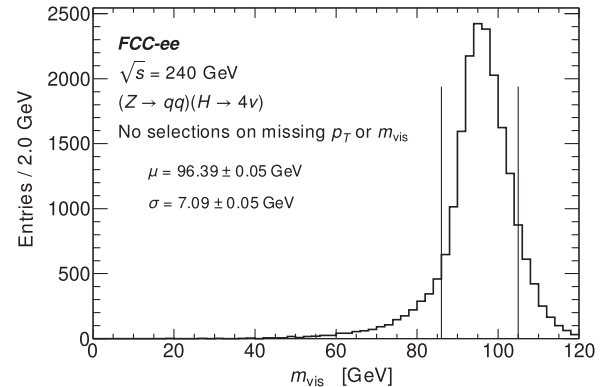


FIG. 13. Invariant mass distribution of all visible particles for ZH events with the Higgs boson decaying to four neutrinos and the Z boson decaying hadronically. The mean and width from a Gaussian fit to the distribution are shown. Vertical lines indicate the acceptance range for analysis selection.

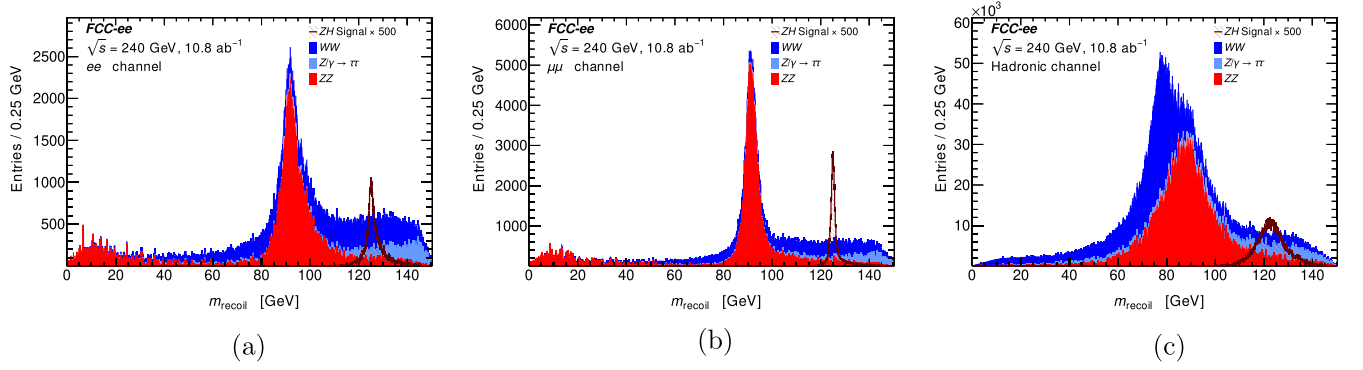


FIG. 14. Reconstructed invisible recoil mass distributions after all selections, normalized to an integrated luminosity of 10.8 ab^{-1} for the (a) ee , (b) $\mu\mu$, and (c) hadronic channels. The signal (red) cross section is scaled up by a factor of 500. The background from other ZH decay modes is negligible and not included in these plots.

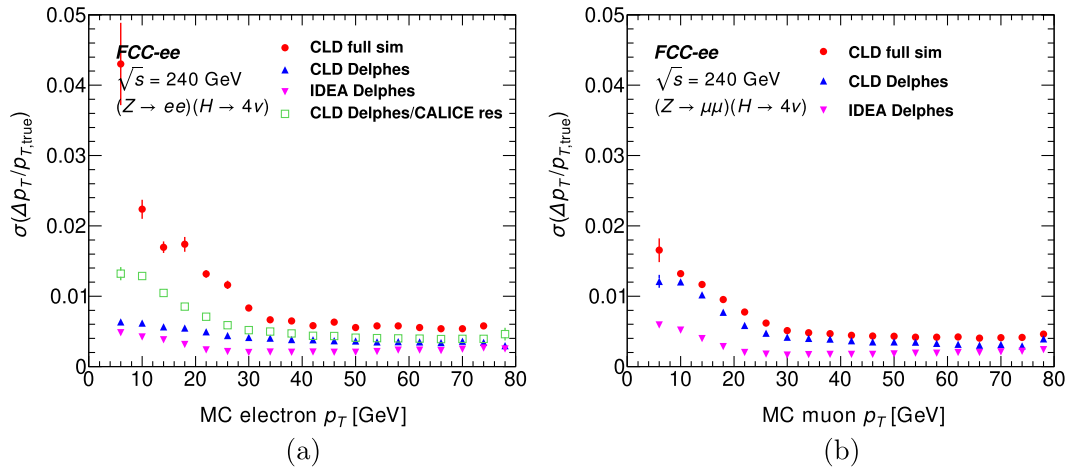


FIG. 15. Relative transverse momentum resolution as a function of transverse momentum for (a) electrons and (b) muons. Within each momentum bin, resolution distributions are fit to Gaussian functions. Results are shown for full simulation (without bremsstrahlung recovery), fast simulation for both CLD and IDEA configurations, and modified CLD fast simulation using a silicon-tungsten CALICE-like [42] calorimeter resolution function.

configurations. For muons, whose momentum resolution is determined almost entirely by tracking performance, the CLD fast simulation closely matches the full simulation results. The IDEA fast simulation shows significantly better muon momentum resolution than CLD, particularly at low momenta, as expected from the lower material budget of its drift chamber-based tracking compared to CLD's all-silicon tracker.

For electrons, however, the CLD fast simulation significantly outperforms full simulation, showing even better resolution than for muons at low momenta. This discrepancy arises because the electromagnetic calorimeter resolution in both CLD and IDEA fast simulation configurations corresponds to a crystal calorimeter ($\sigma_E/E = 0.5\% \oplus 3\%/\sqrt{E} \oplus 0.2\%/E$), while CLD actually employs a silicon-tungsten calorimeter for linear collider experiment (CALICE)-style calorimeter with expected

resolution $\sigma_E/E = 1\% \oplus 16\%/\sqrt{E}$ [27]. If we modify the CLD fast simulation to use the CALICE-like calorimeter resolution [Fig. 15(a)], the results align much more closely with full simulation. This finding highlights the need for caution when using existing fast simulation for applications where electromagnetic calorimeter resolution is critical.

E. Statistical analysis and results

To determine upper limits on the branching ratio (BR_{inv}) of the Higgs boson decaying to invisible final states, we used the statistical methodology explained in Sec. V. Figure 16 presents the resulting limits for each channel, representing an idealized scenario with statistical uncertainties only. The hadronic channel provides the strongest constraint, with an expected limit of 2.8×10^{-3} at 95% CL.

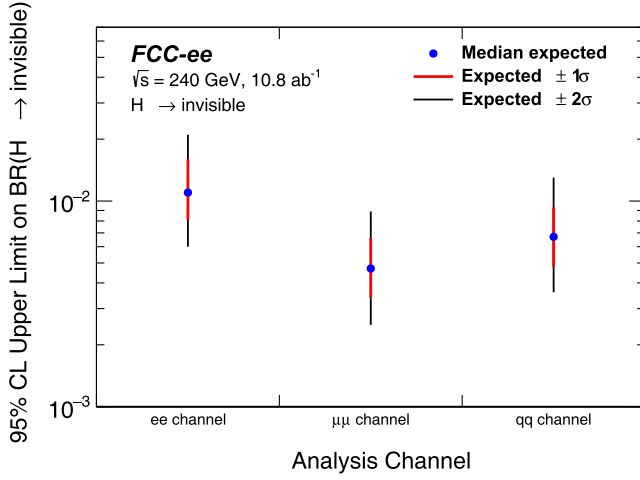


FIG. 16. Expected 95% CL upper limits on the Higgs-to-invisible branching ratio by channel.

F. Detector configuration impact assessment

We propagated variations in calorimeter properties, as described in Sec. IV, through the Higgs-to-invisible analysis [39]. Figure 17 shows the reconstructed invisible recoil mass distributions normalized to corresponding cross sections for the ZH signal in the hadronic channel.

To assess the impact of these detector configurations on sensitivity, we determined the limit on the Higgs-to-invisible branching ratio for each variation. We generated six detector configurations using fast simulation, corresponding to the signal distributions in Fig. 17, while using the nominal detector configuration for backgrounds. We focused exclusively on the hadronic channel due to its significant sensitivity (see Fig. 16) and the presence of two jets in the final state.

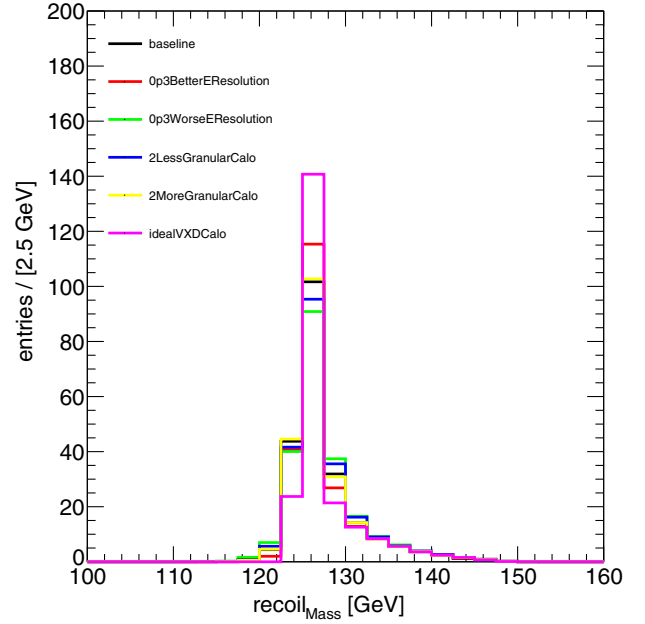


FIG. 17. Reconstructed invisible recoil mass distributions for ZH signal in the hadronic channel, normalized to corresponding cross sections. Comparison includes baseline IDEA calorimeter (black), 30% better relative energy resolution (red), 30% worse relative energy resolution (green), two times more granular calorimeter (yellow), and two times less granular calorimeter (blue).

Figure 18 summarizes the relative changes in expected limits compared to the baseline configuration. Notably, improved energy resolution enhances sensitivity by approximately 9%, while degraded resolution reduces sensitivity by 11%. Increased calorimeter granularity has minimal effect, but reduced granularity degrades sensitivity

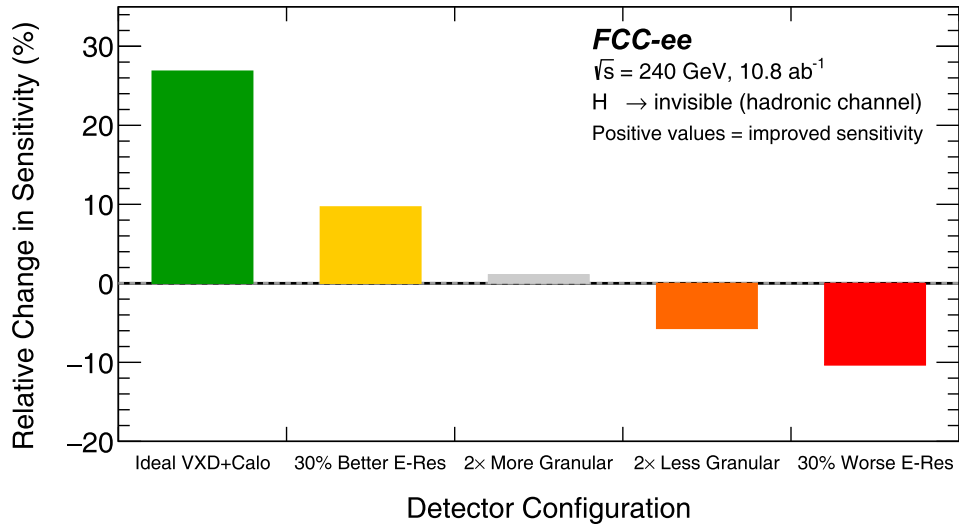


FIG. 18. Relative change in expected 95% CL upper limits on the Higgs-to-invisible branching ratio for different detector configurations compared to baseline (hadronic channel only). Positive values indicate improved sensitivity (lower limits), while negative values indicate decreased sensitivity.

by 7%. The combined effect of an ideal vertex detector and calorimeter improves sensitivity by approximately 27%, demonstrating the potential benefit of detector optimization for this crucial measurement.

X. CONCLUSIONS AND FUTURE DETECTOR OPTIMIZATION

In this comprehensive study, we have systematically assessed the impact of detector design variations on three key physics analyses at the FCC-ee, providing essential insights for optimizing future collider detectors. Our investigation demonstrates that while some physics measurements exhibit remarkable robustness to detector configuration changes, others depend critically on specific detector capabilities.

We have quantified how jet flavor identification performance—essential for precision Higgs physics—exhibits varying sensitivities to different detector parameters. Single-point resolution, material budget, silicon layer placement, and particle identification capabilities all influence flavor-tagging performance, but with different magnitudes and asymmetric effects. Notably, strange-jet rejection shows high sensitivity to tracking resolution, while bottom-jet rejection for charm tagging demonstrates asymmetric behavior suggesting limited relevance of asymptotic momentum resolution at FCC-ee energies. Material budget studies reveal that while lighter vertex detectors offer minimal performance gains, additional or denser material can substantially degrade performance. The removal of intermediate silicon layers produces measurable but manageable effects on charm-tagging performance, with relative changes in background rejection remaining within acceptable limits.

Our particle identification studies demonstrate that cluster-counting capabilities provide the most significant contribution to flavor-tagging performance, particularly for strange-jet identification. Time-of-flight measurements contribute primarily to kaon-pion separation at momenta around 1 GeV and show significant impacts on bottom-jet tagging when combined with cluster-counting information.

When propagating these detector variations through the Higgs coupling measurements in the fully hadronic final state, we observed that the analysis exhibits remarkable robustness to most detector configuration changes. However, the precision of Higgs-strange quark coupling measurements depends critically on cluster-counting capabilities, with the expected uncertainty increasing by a factor of 1.6 when this information is removed from the

flavor-tagger training. Our investigation of alternative jet clustering algorithms further revealed that the Durham- k_t algorithm provides better resolution in the Higgs-mass reconstruction than the anti- k_t algorithm, tested with different radius parameters.

For the first time, we have employed full detector simulation in the study of Higgs-to-invisible decays, enabling direct comparison with fast simulation results and identification of critical detector properties. Our findings demonstrate that electromagnetic calorimeter resolution has substantial impact on this analysis, with a 30% improvement in energy resolution enhancing branching ratio sensitivity by approximately 9%. Calorimeter granularity also affects measurement precision, with reduced granularity degrading sensitivity by about 7%. The comparison between fast and full simulation highlights important discrepancies, particularly for electromagnetic calorimeter modeling, emphasizing the need for careful validation of fast simulation assumptions in precision measurements.

The results presented provide essential guidance for understanding the interdependence between detector design choices and physics performance at the FCC-ee. By quantifying the impact of various detector configurations on key physics measurements, our findings will inform the optimization of detector designs for future experiments at electron-positron colliders. The systematic approach developed here can be extended to other physics processes and detector technologies, helping to maximize both discovery potential and precision measurement capabilities at future facilities.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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