

Flavor-physics benchmarks for tracker-based particle identification at the FCC-ee

Anja Beck^{*} and Eluned Smith

Department of Physics and Laboratory for Nuclear Science, MIT, Cambridge, Massachusetts 02139, USA



(Received 5 December 2025; accepted 19 March 2026; published 28 April 2026)

The correct identification of charged hadrons plays a crucial role in flavor-physics measurements. The final detector configurations at the proposed Future Circular Collider are yet to be determined and this study aims to contribute to this discussion by benchmarking the particle-identification (PID) performance of the proposed CLD and IDEA detectors using fully simulated events. At present, neither detector proposal includes dedicated PID systems, relying instead on information from the tracking subsystems. We estimate the expected level of contamination due to misidentified charged hadrons for b -flavor tagging, rare $b \rightarrow s$ transitions, and s -jet tagging. The PID information provided by silicon trackers, namely time-of-flight and energy-deposit measurements, leads to significant background suppression with high signal efficiency for the low-momentum hadrons considered for same-side b -flavor tagging. In order to improve the contamination in rare decays where momenta are in the medium range, only good timing resolution of 30 ps and below can yield an improvement of one order of magnitude below the level achieved by kinematic criteria alone. Light-quark jet-flavor tagging requires identification of particles with very large momentum, which is not possible using only time-of-flight or energy-deposit information in silicon. Access to the number of clusters in a drift-chamber setup, as proposed for the IDEA detector, however, results in strong background suppression in every case. This suppression can be further improved in some scenarios by time-of-flight resolution of 30–50 ps or better. The PID quality generally exhibits only a small dependence on the cluster-counting efficiency. Whether dedicated PID detectors could further enhance flavor-physics sensitivity should be the subject of future study.

DOI: [10.1103/lnx2-s8wb](https://doi.org/10.1103/lnx2-s8wb)

I. INTRODUCTION

The proposed Future Circular Collider (FCC-ee) is designed to provide electron-positron collisions at different center-of-mass energies in order to determine many parameters of the Standard Model with unprecedented precision [1]. In particular, experiments at the FCC-ee will be able to measure a range of flavor observables with world-leading precision: the clean environment will result in significantly higher selection efficiency and smaller systematic uncertainty on measurements of heavy-flavor decays compared to current LHC experiments while still providing access to the full range of b and c hadrons inaccessible at Belle II as well as access to orders of magnitude more data [2]. Also, the flavor reach in the electroweak sector is expected to improve strongly compared to the ATLAS and CMS

experiments given the simpler environment and better particle identification (PID).

While the focus and specifications of the detectors is yet to be determined, the composition of high-energy physics detectors mostly follows the same principles. A staple feature in all collider experiments is the tracking system enabling one to trace the path of charged particles and their subsequent combination to decay topologies. All modern tracking systems include a silicon vertex tracker sitting close to the interaction region combined with a second tracking subsystem located further away from the interaction point. The popularity of silicon vertex detectors can be attributed to their excellent spatial resolution, practically instant response time, and the required radiation hardness for elements sitting close to the interaction region of particle beams [3]. The hit resolution can be as low as a few micrometers as shown for the novel monolithic active pixel sensor (MAPS) technology to be implemented in a future upgrade of the ALICE detector [4]. Due to its large material budget and/or cost, however, silicon is not a common choice for large-area detectors far from the interaction region in ee colliders. More lightweight solutions are, for example, drift chambers or time projection chambers.

^{*}Contact author: anbeck@mit.edu

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

Besides tracking, particle-physics experiments also need to deduce the particle type. This information can be extracted from the signatures that particles leave when traversing different materials. A calorimeter system is crucial for identifying neutral particles, electrons, muons, and charged hadrons based on the total amount of energy deposited and the spatial extent of the deposition. Any measurements related to flavor properties usually require a more granular distinction of charged hadrons into protons, kaons, or pions. Whereas the tracking system provides the momentum of a particle, additional knowledge of its speed allows direct inference of the mass and hence the identity of the particle. Speed can be measured by clocking the time of flight (TOF) along a known path or via the opening angle of a Cherenkov light cone. Similarly, the relationship between either the energy deposited through ionization or the number of ionization clusters with a particle speed can enable particle identification. Depending on the overall design and specialization of a detector, this can be achieved by dedicated particle-identification systems. It may, however, be convenient and economical to avoid the need for a dedicated subsystem and instead design the tracking system for dual use. Avoiding a dedicated system may also allow for a reduction in the overall material budget of the detector.

This paper presents a study of the charged-hadron identification capabilities of the tracking systems as currently envisioned in the CLD [5] and IDEA [6] detector concepts. The respective tracking detectors and the PID-related quantities obtained from full simulation are presented in Sec. II. Section III outlines the employed particle-identification algorithm. Afterward in Sec. IV, this tool is applied to three flavor-physics examples in order to determine the expected improvement in contamination for varying levels of time-of-flight resolution and cluster-counting efficiency as well as with and without silicon-based dE/dx information. This paper concludes with a discussion and summary in Sec. V.

II. DETECTOR CONCEPTS AND THEIR TRACKING SYSTEMS

The two most mature detector concepts for the FCC-ee are CLD and IDEA. As the name suggests, the *CLIC-like detector* (CLD), described in detail in Ref. [5], was inherited from CLIC studies. Its tracking system is entirely silicon-based and comprises a pixel vertex tracker as well as two more tracking systems which may use pixels or strips. Reference [6] provides a detailed description of the other investigated concept named the *innovative detector for e^+e^- accelerators* (IDEA). The three tracker subsystems of IDEA are a silicon pixel vertex tracker, a high-transparency drift chamber filled with a mix of 90% helium and 10% C_4H_{10} gas inspired by the KLOE and MEG2 experiments, and a wrapper using either silicon strips, MAPS, or low gain avalanche diodes. The results obtained from the IDEA studies in this paper can be directly

transferred to a third maturing detector concept called a *lepton-lepton collider experiment with granular read-out* as they share the same tracking system [7]. All studies described in this paper are performed on simulation of the CLD and IDEA setups using the Key4Hep framework [8].

The silicon trackers in all detector concepts can provide particle identification by measuring the speed of a particle as the ratio of flight distance over time of flight. In this study, the reference points for this measurement are always the first and last recorded hit in any silicon layer. This choice removes uncertainties invoked for particles originating from displaced vertices and does not rely on assumptions regarding the FCC-ee clock resolution. In order to study different values for the time-of-flight precision in the absence of possible improvements due to reconstruction, the true time-of-flight values are smeared using Gaussian distributions. As a consequence, the term *time-of-flight resolution* in this publication always refers to the magnitude of the σ used in the Gaussian to randomly add noise to the total time of flight rather than the timing resolution of an individual pixel. This choice is motivated by the fact that sophisticated tracking algorithms can improve the final time-of-flight resolution for a track significantly relative to the hit-time resolution; see e.g. Ref. [9]. The uncertainty imposed on the flight distance by the finite size of each pixel is naturally included in this study as the hit location is taken from the output of full simulation. Tracking and clustering algorithms can also improve this spatial uncertainty but it is already so small that the impact on the study at hand is negligible. Making our results dependent on the time-of-flight resolution rather than the timing capabilities of the silicon chips, the FCC-ee clock, or reconstruction details also means that the conclusions are portable to different setups as long as the considered absolute time of flight is similar, e.g. using the FCC-ee clock and a single timing layer just before the calorimeter system.

Another useful quantity for particle identification is the energy deposit per traveled distance, dE/dx , in each silicon sensor. The ability of the detector to measure the energy deposit is assumed to be modeled realistically in the simulation and used without additional smearing. Inspired by CMS studies, the dE/dx value per track is determined as the harmonic mean with grade -2 of all recorded hits in silicon layers [10].

Finally, the drift chamber in the IDEA concept also allows for a measurement of the number of primary ionization clusters per traveled distance, dN/dx . Because the number of clusters follows a Poissonian distribution instead of a Landau distribution, dN/dx is preferred over dE/dx , which can also be measured with a drift chamber. The number clusters is not yet available in the IDEA simulation but instead extrapolated based on Garfield simulations and test-beam studies [11] while the traveled distance is taken from the detector Geant4 simulation without modification. The extrapolated value for the number of

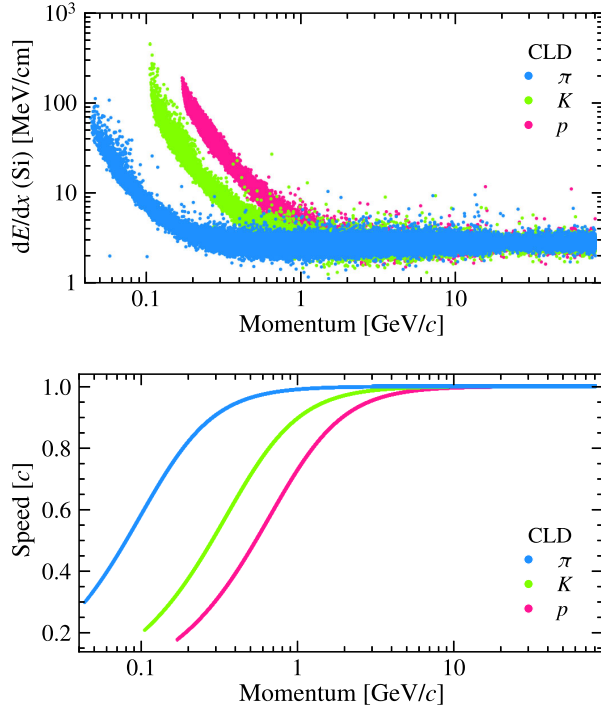


FIG. 1. Input quantities for particle identification using CLD tracking detectors. Top: dE/dx in the silicon sensors, calculated as the harmonic mean of all hits in silicon trackers. Bottom: true speed measured using the time of flight and flight distance between the first and the last hit in silicon trackers.

clusters in each cell is varied according to a Poissonian. The dN/dx value per track is obtained by adding the number of clusters in all cells and dividing by the total distance. In order to study the impact of different cluster-counting efficiencies later on, each cluster is kept or discarded stochastically with a probability corresponding to the chosen efficiency.

Figures 1 and 2 show the dependence of these particle-identification quantities on the momentum for proton, kaon, and pion tracks in the two detector concepts, assuming perfect time-of-flight resolution. Similar figures for nonzero time-of-flight resolution are shown in Fig. 12 in Appendix A. The particles used to make these displays are also used to train the classifiers later and are generated isotropically in space using a particle gun. Because no full tracking algorithm is yet available for the IDEA detector, the generated momentum is used for both IDEA and CLD studies. Given that a momentum resolution well below 1% in the momentum range $p < 100 \text{ GeV}/c^2$ is achievable even for the much more complex events at the LHC [12], this choice has negligible impact on the results.

Tracks sitting outside the acceptance of the silicon detectors are discarded from the study. The gray points in the IDEA figures correspond to tracks with hits in the silicon trackers resulting in valid speed and dE/dx measurements but without hits in the drift chamber. The two main reasons for the lack of dN/dx information are (i) the

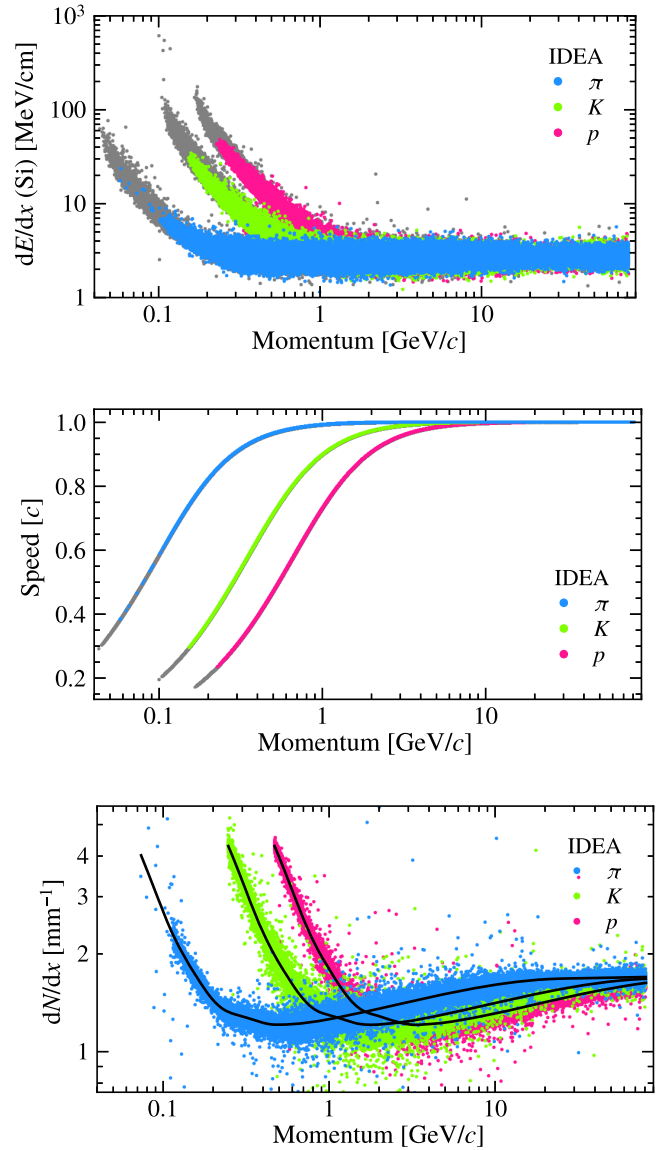


FIG. 2. Input quantities for particle identification using IDEA tracking detectors. Top: dE/dx in the silicon sensors, calculated as the harmonic mean of all hits in silicon trackers. Middle: true speed measured using the time of flight and flight distance between the first and the last hit in silicon trackers. Bottom: dN/dx interpolated from Garfield simulation (black line) with Poissonian variation at the generation stage assuming perfect efficiency (dots).

available interpolation to calculate the dN/dx values is only valid for $\beta\gamma \geq 0.5$ and (ii) the silicon detectors in IDEA and CLD have further acceptance reach toward the beam pipe compared to the drift chamber.

Before describing the study, we want to summarize the limitations of the simulation samples to date. The lack of a reconstruction tool for the IDEA detector requires the use of the true momentum and the true time of flight of the particles, where the latter is smeared with a range of possible resolution values. The spatial resolution, however,

is obtained realistically, i.e. from the simulated hit location. Provided that the FCC-ee environment is very clean and modern reconstruction algorithms are very efficient, these idealizations are likely not far from reality. Additionally, any inverse correlation between spatial and timing resolution, where improving the latter may require a higher material budget if derived from the first and last hits, is not taken into account.

The IDEA simulation does not yet include a realistic drift-chamber response resulting in the need for external simulation and test-beam extrapolations for the number of drift-chamber clusters. In summary, this study sits at the intersection of fast simulation and full simulation. All quantities are calculated on a hit-level basis which is only possible in full simulation. The resolution in the hit location as well as the energy deposit are fully simulated. Only the time-of-flight resolution as well as the cluster-counting efficiency are introduced artificially resembling fast simulation.

III. PARTICLE-IDENTIFICATION ALGORITHM

We employ boosted decision trees (BDTs) to determine the identity of a particle because they are able to capture high-dimensional correlations while providing high interpretability, effectively producing a nontrivial binning scheme across all input variables. The training events are individual particles generated isotropically ensuring full coverage of the angular space. For each charge and species, 100 000 particle-gun events are produced, ensuring sufficient balance between protons, kaons, and pions despite differences in reconstruction efficiency, resulting in a total of 600 000 training particles. The three flavor-physics examples considered later stem from $e^+e^- \rightarrow Z \rightarrow b\bar{b}$ and $e^+e^- \rightarrow Z(\rightarrow \text{anything})H(\rightarrow \text{light quarks})$ events. Given that particle identification relies heavily on the momentum of a particle, the particle-gun training samples are generated in 20 bins of equal content defined based on the momentum distribution of the $e^+e^- \rightarrow ZH$ events considered later. Within each bin, the momenta are distributed uniformly. The ZH events are chosen as they have a broader momentum profile. Figure 3 illustrates the momentum distribution of the charged hadrons for different event types and the particle-gun samples. The particle-gun events are propagated through full Geant4 simulation of both the IDEA and CLD detector concepts [13–17].

The particle-identification algorithm consists of three independent BDTs trained using the XGBOOST algorithm [18] to select protons, kaons, or pions over the other two species based on the momentum and different configuration of dN/dx , silicon-based dE/dx , and speed. For an unseen particle, the species is assigned according to the BDT with the highest output score. The BDT architecture is limited to 1000 trees with at most four layers of depth. The learning rate is set to 0.02. Because the total number of features is very small (two to four depending on the configuration),

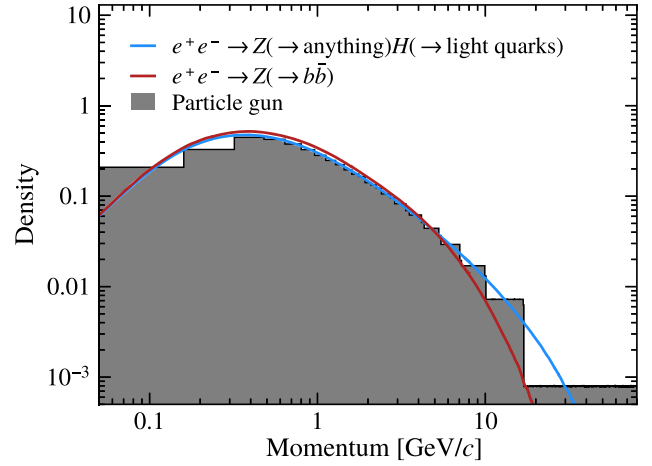


FIG. 3. Generator-level distributions of the charged-hadron momenta in the samples used to study specific flavor measurements and the particle-gun samples employed for training the classifiers.

one very noisy feature can easily lead to overfitting. Three measures are taken to mitigate this problem as much as possible. First, the decision whether and how to split a branch relies on a subset of training samples that is randomly chosen at each node and represents 80% of the total training dataset. Second, a branch only splits if the associated loss reduction exceeds a value of three and there are at least 15 data points in each child. Third, the training stops when the validation loss does not change for 40 iterations. Each BDT is trained on 80% of the particle-gun samples and the remaining 20% are kept for validation. In order to achieve similar magnitudes of the features, the momentum is scaled using $\log(p)$, the speed v is scaled using $-\log(1 - \frac{v}{c})$ and the energy deposit dE/dx is scaled using $\log(dE/dx)$ before training.

The left column of plots in Fig. 4 shows the receiver-operator curves (ROCs) for different time-of-flight resolution (indicated by color) at CLD calculated on the unseen particle-gun validation samples. The solid lines represent BDTs that use the energy deposit in the silicon trackers. For each solid line, there is a corresponding dotted line which represents the same setup but without dE/dx information. For large time-of-flight resolutions, the additional dE/dx input improves the area under the ROC (AUC) notably while it has negligible impact for better time-of-flight resolution. Even the poorest considered time-of-flight resolution of 500 ps leads to AUC values significantly larger than 0.5.

The right column in Fig. 4 shows the same set of plots but for IDEA with a cluster-counting efficiency of 80%. Comparing the solid lines between the CLD (left) and IDEA (right) performance reveals that the additional dN/dx information improves the classification. Note that the black lines representing a scenario without time-of-flight measurement reaches a similar AUC as relying on a

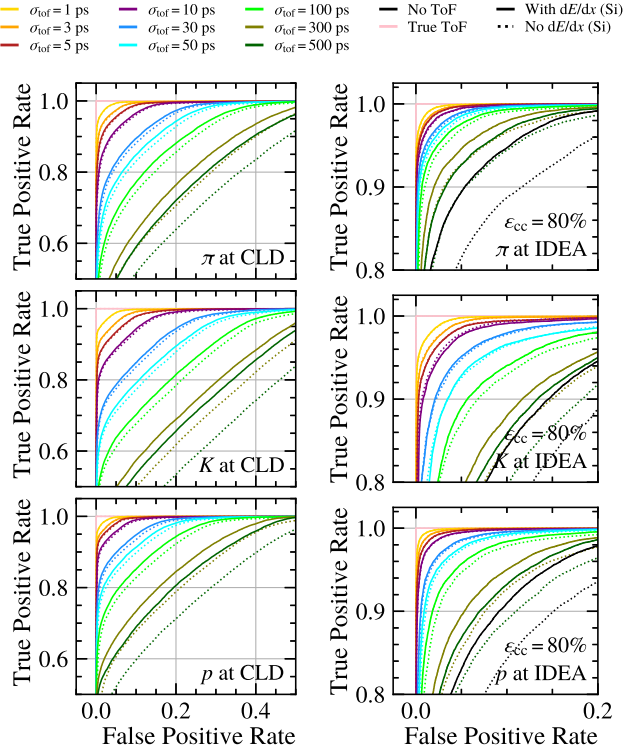


FIG. 4. ROC for the (top) pion, (middle) kaon, and (bottom) proton identification at (left) CLD and (right) IDEA. The colors indicate the TOF resolution and the line style indicates whether the silicon-based dE/dx information was used. A cluster-counting efficiency ϵ_{cc} of 80% is assumed for the drift-chamber reconstruction at IDEA. Note that the axes ranges are different between the CLD and IDEA figures.

time-of-flight measurement of 10 ps for pion identification (purple line in the CLD plot). For all setups, proton and pion identification achieves higher AUCs than kaon identification because in the latter case outliers in both directions lead to misidentification compared to only one direction for protons and pions.

Figure 5 shows the dependence of the AUC on the particle momentum. While identification in the very low momentum regime is close to perfect in almost any setup, the cluster-counting information at IDEA leads to strong particle-identification performance even at higher momenta. The dips in the IDEA AUC scores at medium momentum are a consequence of the crossing between the dN/dx curves as shown in the bottom part of Fig. 2. The two intersections of the kaon-pion and kaon-proton curves are clearly visible as two dips in the kaon identification performance. In the proton (pion) case, the two performance dips merge into one because the distance between the proton-pion and proton-kaon (pion-kaon and pion-proton) curves is smaller. The theoretical dE/dx shapes intersect in the same way which is not visible in Figs. 1 and 2 due to finite resolution and the lack of density information in the scatter plot. Despite the dilution, this effect is slightly visible

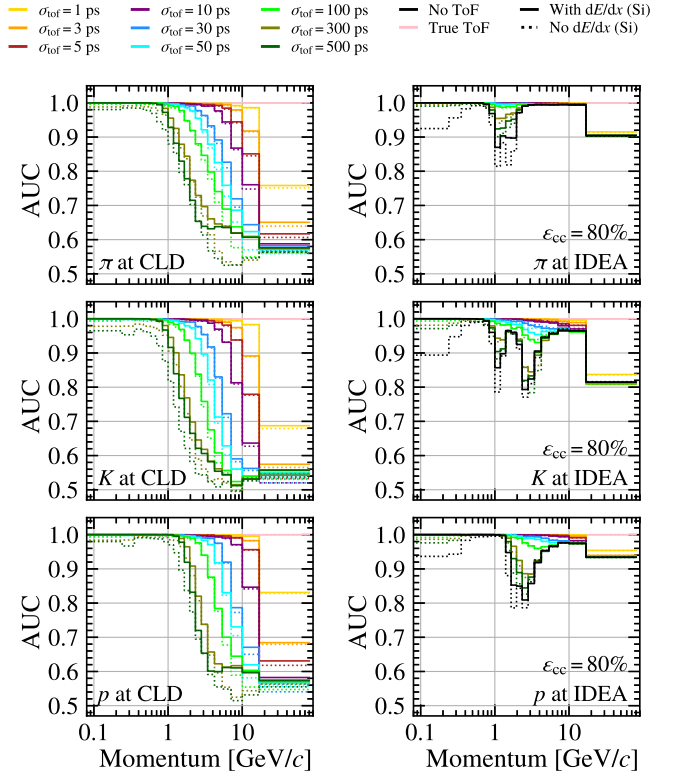


FIG. 5. AUC in different momentum ranges for the (top) pion, (middle) kaon, and (bottom) proton identification at (left) CLD and (right) IDEA. The colors indicate the TOF resolution and the line style indicates whether the silicon-based dE/dx information was used. A cluster-counting efficiency ϵ_{cc} of 80% is assumed for the drift-chamber reconstruction at IDEA.

for CLD and poor time-of-flight resolution. At 500 ps, for example (dark green lines), adding dE/dx information (solid line) on top of pure time-of-flight classification (dotted line) increases the AUC score visibly at low and high momenta while the improvement is only moderate in the 1–3 GeV/c region.

The dependence on the cluster-counting efficiency is generally rather low as the classifier simply learns the additional scaling. Figures 13 and 14 in Appendix B shows the information in Figs. 4 and 5 for cluster-counting efficiencies of 50% and 100%.

To represent the performance of a particle-identification tool, the fraction of misidentified particles, f , is converted into a number of standard deviations, σ , using

$$f_{\sigma} = \Phi^{-1}(1 - f), \quad (1)$$

where Φ is the cumulative distribution function of the normal distribution. We choose not to explicitly quote a separation power, as the BDT responses are non-Gaussian. However, the separation of the BDT discriminator distributions for different particle species can be judged by eye from Figs. 16 and 17 in Appendix C for configurations with

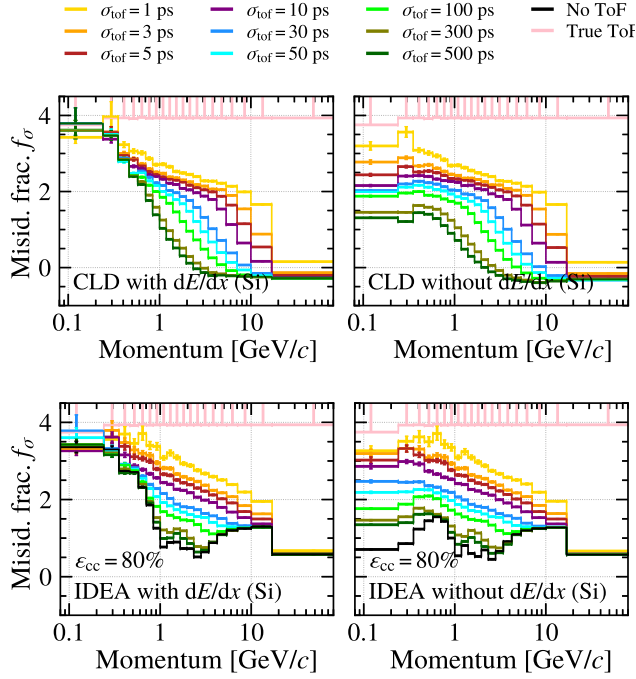


FIG. 6. Fraction of misidentified particles f_σ expressed as a number of standard deviations using Eq. (1) for all particle species combined for different TOF resolution and (left) with and (right) without dE/dx information at (top) CLD (i.e. time-of-flight measurement with or without dE/dx measurement) and (bottom) IDEA (i.e. dN/dx measurement with or without time-of-flight and/or dE/dx measurement). A cluster-counting efficiency ϵ_{cc} of 80% is assumed for IDEA.

a time-of-flight resolution of 30 ps and cluster-counting efficiency of 80%.

The top part of Fig. 6 shows the level of misidentification integrated over the three species for the different configurations tested on CLD (i.e. time-of-flight measurement with or without dE/dx measurement). As expected, the misidentification is low at very low momenta where the distance between the speeds for the different particle types is rather large. Including dE/dx information from the silicon tracker (left plot) improves the differentiation at low momentum regardless of time-of-flight resolution. Note that in case none of the particles in the given bin was misidentified, the lower limit of the 68% confidence level on f_σ , sitting just below 4σ for the available sample size, is shown.

The bottom part of Fig. 6 shows the same set of plots for the IDEA case (i.e. dN/dx measurement with or without time-of-flight and/or dE/dx measurement) with a cluster-counting efficiency of 80%. The dependency on the cluster-counting efficiency is limited; corresponding plots for efficiencies of 50% and 100% can be found in Fig. 15 in Appendix B. The additional dN/dx information generally improves the particle identification significantly, in particular for good to mediocre time-of-flight resolution or very high momenta. Nevertheless, all configurations suffer

a severe deterioration of particle-identification properties at very high momenta caused by the difficult separation in this region as well as the much smaller number of training samples here than in other regions as shown in Fig. 3. The constraints put in place to avoid overfitting prevent very fine binning in this region. Similarly to the CLD case, adding silicon-based dE/dx information improves the performance significantly for low momenta.

The performance of configurations without time-of-flight measurement (black) or with very poor time-of-flight resolution (dark green and olive green) drops between 1 and 3 GeV/c. This behavior is expected and mirrors the shape of the dN/dx curves shown in the bottom plot of Fig. 2. As discussed earlier, this behavior is also reflected in the variation of the AUC score with momentum shown in Fig. 5. The severity of the drop between 1 and 3 GeV/c has a slight dependence on the cluster-counting efficiency; see Appendix B. In the configurations without dE/dx information and with either poor or no time-of-flight information, particle identification is difficult at very low momentum because there are only few training data points but also because the identification relies predominantly or entirely on the dN/dx information which is not available for $\beta\gamma < 0.5$.

Figure 18 in Appendix D shows the contamination in units of standard deviation for each combination of particles separately.

Two additional cross-checks are performed. First, all studies presented in this paper are repeated using a categorical BDT as well as a multilayer perceptron. The classification quality criteria obtained using these alternative methods are indistinguishable from the ones presented in this section obtained using three independent BDTs. Moreover, the results presented hereafter in Sec. IV are also consistent between the three methods. Second, all studies are repeated with all three methods using particle-gun simulation samples with uniformly generated momentum ranging from 0 to 90 GeV/c instead of the realistic spectrum shown in Fig. 3. While the quality measures are nominally different in this case, e.g. the total AUC scores are much lower because there are many more particles with large momenta that are difficult to classify, the observations remain the same. The main difference is an increased sensitivity to the noisy variables because, on average, particles with higher momentum have relatively short time of flight and are hence more affected by a poorer time-of-flight resolution.

All shown results in this work are obtained using the combination of three individual BDTs trained on particle-gun simulation samples with a realistic momentum spectrum; see Fig. 3.

IV. APPLICATION TO EXAMPLE FLAVOR-PHYSICS MEASUREMENTS

This section illustrates the reduction in contamination achieved through tracker-based particle identification for

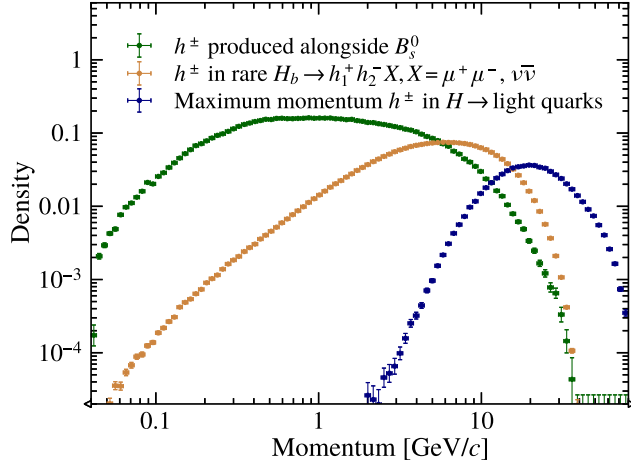


FIG. 7. Momentum distributions of the charged hadrons considered in the three example flavor-physics cases.

three example physics cases. For each example, both CLD and IDEA are considered using configurations with different values for the time-of-flight resolution, the cluster-counting efficiency, and with or without silicon-based dE/dx information. The three examples study (A) the signal and background efficiency for tagging the b flavor of B_s^0 mesons based on *same-side tagging* using the net number of charged kaons produced alongside the B_s^0 meson in the hadronization process, (B) the contamination due to hadron misidentification in fully visible and the semivisible rare decays, and (C) the signal and background efficiency when discriminating s jets against jets from other light quarks based on the charged hadron with the highest momentum in the jet. Figure 7 illustrates how these three examples test vastly different momentum ranges.

A. b -flavor tagging

Neutral b mesons can oscillate between their particle and antiparticle states. Knowledge of the exact meson state at production plays an important role in the flavor sector allowing access to time-dependent and additional CP -violating amplitudes; see e.g. Ref. [19]. The sensitivity is particularly large for B_s^0 decays given the small difference between mass eigenstates.

The FCC-ee running at the Z pole produces $b\bar{b}$ pairs flying back to back in the lab frame. A number of additional, typically lighter, hadrons are produced in the hadronization process. Because the strong force is flavor conserving, the flavor of the b quark can be identified by the lighter hadrons produced alongside. For example, the b quark might hadronize to a $\bar{B}_s^0$ meson with the $\bar{s}$ quark produced via an $s\bar{s}$ pair from the vacuum. The additional s quark must hadronize, too, leading to a negatively charged or neutral kaon. This type of tagging is usually referred to as a *same-side tagger*.

The b quark might also be identified through first identifying the $\bar{b}$ hadron on the other side of the event. This procedure is typically called an *opposite-side tagger* and relies on identifying the $\bar{b}$ hadron based on its decay products. Due to excellent expected mass resolution at the FCC-ee, this is likely possible without employing particle-identification tools. As a consequence, the opposite-side tagger is not investigated here.

Modern b -flavor tagging algorithms employ machine-learning tools to decipher the multidimensional correlations that provide the most efficient tag; see e.g. Refs. [20–23]. Developing such an algorithm for the FCC-ee environment reaches beyond the scope of this study. Instead, the investigations focus on the simplest case, tagging B_s^0 and $\bar{B}_s^0$, using the previously discussed proxy, the net number of kaons. This means that a b hadron is tagged as B_s^0 if it is accompanied by a larger number of K^+ than K^- in its hemisphere and vice versa for the $\bar{B}_s^0$. Accounting for the detector acceptance, this classification would catch 45% of the B_s^0 and $\bar{B}_s^0$ mesons if perfect particle identification were possible.

Figure 8 shows the resulting tagging efficiency to correctly identify a B_s^0 meson in red and corresponding

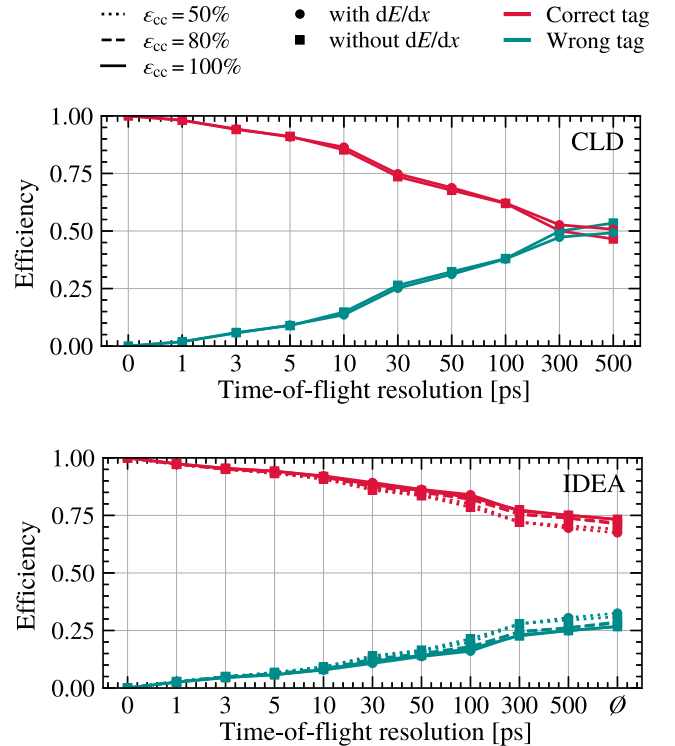


FIG. 8. Efficiency of (mis)tagging B_s^0 mesons by requiring that more K^+ than K^- are produced alongside the $\bar{b}$ meson for (top) CLD and (bottom) IDEA for different time-of-flight resolution (horizontal axis), different cluster-counting efficiencies ϵ_{cc} (IDEA only, distinguished by line style), and with or without using energy-deposit information from the silicon sensors (marker style).

mistag efficiency in green. The efficiencies are calculated with respect to the 45% of B_s^0 with more K^+ than K^- that can be identified this way in order to show the efficiency improvement through particle identification rather than the efficiency of the algorithm. As a consequence of the very low momentum of the considered particles (see Fig. 7), a moderate tagging efficiency can be achieved for time-of-flight resolution below 50 ps at CLD. The addition of dE/dx information is only slightly beneficial for poor time-of-flight resolution. While the trends are fairly similar, IDEA consistently achieves significantly better performance for time-of-flight resolutions in the most realistic range between 30 and 100 ps almost regardless of cluster-counting efficiency.

B. Rare decays

Precision measurements of electroweak-penguin decays of b quarks provide sensitivity to effects at energy scales beyond the direct reach of current or future colliders. Measurements of $b \rightarrow s\ell^+\ell^-$ transitions in different hadronic systems indicate tensions between measurement and prediction [24–44]. Strong suppression of background is crucial to achieve high precision in rare-decay measurements. This is particularly important in angular analyses where the contribution from misidentified rare decays with their unique angular distributions can bias the result. Moreover, this bias is hard to quantify because the background distribution itself is often not well known such that background suppression is the only viable option.

The examples considered in this study are the three hadronic systems $B_s^0 \rightarrow K^+K^-$, $B^0 \rightarrow K^-\pi^+$, and $\Lambda_b^0 \rightarrow pK^-$ either with two muons of opposite charge or a neutrino-antineutrino pair. The b hadrons are produced using Pythia in e^+e^- collisions at the Z pole [45]. They are decayed by the EvtGen package forcing a uniform distribution in the dilepton invariant-mass squared [46]. The compositions of the dihadron spectra are inspired by previous analyses at the photon or J/ψ pole [47–49] with details in Table I in Appendix E. The production fractions used to calculate the contamination are $f_{B^0} = 0.407$, $f_{B_s^0} = 0.101$, and $f_{\Lambda} = 0.075$ [50]. The Λ_b^0 hadronization fraction is an estimate based on the measured hadronization fraction to any b baryon of 0.085 [50] and the assumption that 89% of b baryons are Λ_b^0 baryons, 10% of b baryons are neutral or charged Ξ_b baryons and 1% are other b baryons [51]. The decay branching fractions are set to be equal.

1. Final states with neutrinos

Figure 9 shows how the level of contamination to each of the three semivisible decays changes for different time-of-flight resolution at CLD (top) and different time-of-flight resolution and cluster-counting efficiency at IDEA (bottom, including dN/dx information) in either case with and without the dE/dx measurement. The different colors

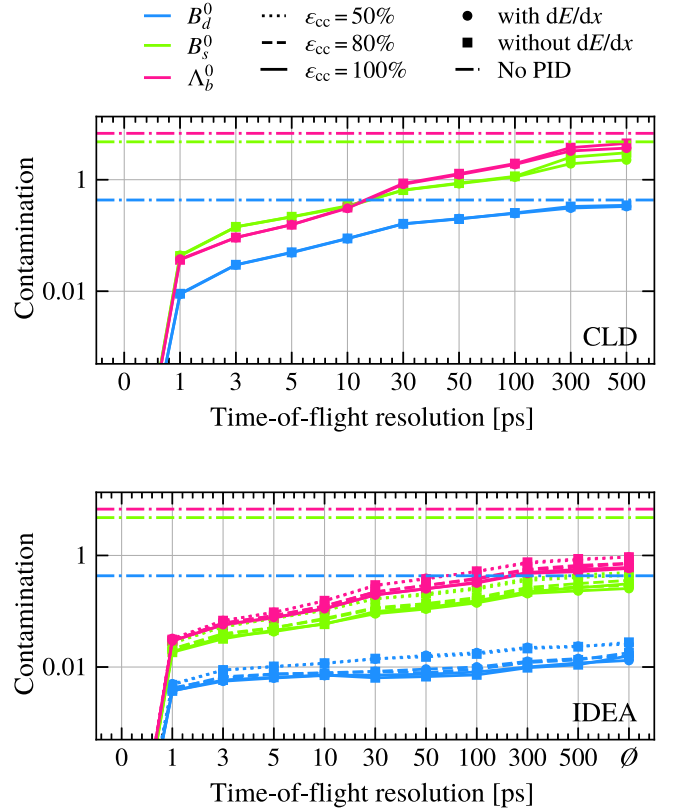


FIG. 9. Level of contamination for the three rare decays with semivisible final states (distinguished by color) at (top) CLD and (bottom) IDEA for different time-of-flight resolution (horizontal axis), different cluster-counting efficiencies ϵ_{cc} (IDEA only, distinguished by line style), and with or without using energy-deposit information from the silicon sensors (marker style).

represent the different decays where the initial differences in contamination between the decays predominantly stems from very different b -hadron hadronization fractions instead of differences in particle identification. A reduction in background at CLD by at least an order of magnitude would require time-of-flight resolution of 30 ps or better depending on the decay. Adding dE/dx information leads to no significant improvement in particle identification. The rightmost points in the IDEA plot (bottom) represent a configuration without time-of-flight measurement revealing that the dN/dx information on its own can reduce the contamination by an order of magnitude with respect to no particle identification (constant, dash-dotted lines). The cluster-counting efficiency as well as including a dE/dx measurement has limited impact. Additional time-of-flight information can improve a purely dN/dx -based classifier by an order of magnitude for resolutions below 10 ps.

All these observations are a consequence of the momentum spectrum shown in Fig. 7 and agree with the discussions in Sec. III. The particles have momenta that are small enough to benefit from moderate time-of-flight resolution (at least 30–50 ps at CLD). At the same time,

many particles have momenta that are large enough to avoid the region of intersecting dN/dx curves such that a dN/dx measurement on its own provides strong classification.

Note that searches of these semivisible final states as discussed in Ref. [52] would focus on an individual dihadron resonance where additional kinematic selections suppress large amounts of misidentified backgrounds. Moreover, the presented numbers are purely based on counting whereas real analyses would likely extract the yields by fitting a suitable variable such as the output of a multivariate classifier to achieve additional separation.

2. Fully visible final states

For fully visible final states, the four-body invariant mass is a helpful discriminator between different b hadrons. When considering, for example, $B_s^0 \rightarrow K^+ K^- \mu^+ \mu^-$ as the signal decay, the four-body invariant mass of true signal candidates accumulates in a peak at the nominal B_s^0 mass. The shape and width of the peak are a consequence of the resolution of the tracking system and reconstruction algorithm. Previous studies of fully visible muonic rare decays using fast simulation of the IDEA detector showed invariant-mass peaks with a full width at half maximum around $10 \text{ MeV}/c^2$ for $B_s^0 \rightarrow \phi(\rightarrow K^+ K^-) \mu^+ \mu^-$ decays [53], $8 \text{ MeV}/c^2$ [54] for $\Lambda_b^0 \rightarrow \Lambda(\rightarrow p \pi^-) \mu^+ \mu^-$ decays, and $4\text{--}5 \text{ MeV}/c^2$ [55] for $\Lambda_c^+ \rightarrow p \mu^+ \mu^-$ decays. Reference [1] provides similar values for other decays. Misidentified backgrounds, on the other hand, appear in very broad smeared-out structures in the signal invariant mass, which are stretched across several GeV/c^2 in the FCC-ee setting. See Fig. 20 and Appendix F for an illustration.

The narrow signal peaks and the wide spread of backgrounds allow one to efficiently select signal and suppress background by focusing on narrow windows around the signal b hadrons (i.e. the B_s^0 mass region in the $KK\mu\mu$ combination for a B_s^0 signal) while vetoing narrow windows around the background b hadrons (i.e. the Λ_b^0 mass region under the $pK\mu\mu$ hypothesis as well as the B^0 mass under the $K\pi\mu\mu$ hypothesis). Because the four-body invariant mass in this study is obtained from the true momenta, different values for the resolution are added artificially by smearing the four-body invariant mass with a Gaussian of predetermined width. The results shown in the main part of this paper use a Gaussian distribution with $\sigma = 5 \text{ MeV}/c^2$ which translates to a conservative full width at half maximum of $11\text{--}12 \text{ MeV}/c^2$. The window for selecting signal and vetoing background peaks is $\pm 10 \text{ MeV}/c^2$ around the nominal peak mass. For this configuration and considering the B_s^0 decay as signal, the chosen kinematic constraints have an efficiency of 73.8%, 0.2%, and 0.1% for the B_s^0 , B^0 , and Λ_b^0 decay, respectively. Figures 21 and 22 in Appendix G show the corresponding

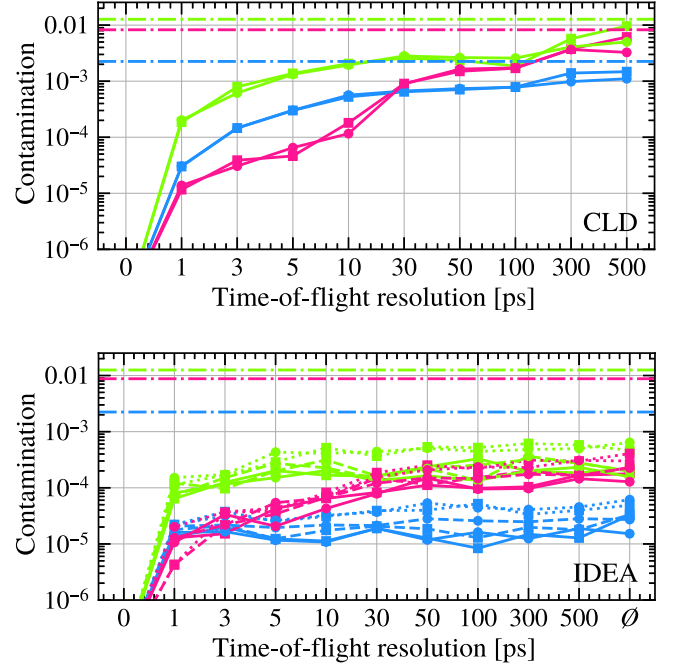


FIG. 10. Level of contamination for the three rare decays with semivisible final states (distinguished by color) at (top) CLD and (bottom) IDEA for different time-of-flight resolution (horizontal axis), different cluster-counting efficiencies ϵ_{cc} (IDEA only, distinguished by line style), and with or without using energy-deposit information from the silicon sensors (marker style).

results for Gaussian widths of $\sigma = 3 \text{ MeV}/c^2$ and $\sigma = 10 \text{ MeV}/c^2$ with appropriately scaled selection windows.

Figure 10 shows the resulting contamination with kinematic selections which suppress backgrounds to below 1%. The improvements achieved through particle identification are of similar magnitude as in the semivisible case. Because the kinematic selections remove different parts of the momentum spectrum for each decay, the trends are slightly different compared to the semivisible example. Note that the strong fluctuations between the different points at very low contamination values are a consequence of the strong background suppression leaving only a small fraction of the 1 000 000 generated decays per species.

The benefit of particle identification for fully visible rare-decay measurements is limited due to the excellent four-body invariant-mass resolution at all FCC-ee detectors leading to almost negligible amounts of background. The practical improvement in contamination, however, might allow for a background-free analysis with negligible associated systematic uncertainty. Because the contribution of new physics can vary across the dimuon invariant-mass squared, q^2 , it has been checked that the level of contamination does not vary significantly across q^2 and is dominated by the different extent of the phase space.

C. s -jet tagging

The FCC-ee provides unique opportunities for measurements involving a Higgs boson decaying to a pair of strange quarks. We study the impact of particle identification on s -jet tagging with simulation samples generated using Pythia assuming e^+e^- collisions at a center-of-mass energy of 240 GeV. Having a collision energy significantly above the ZH threshold maximizes the production cross section [56] and results in a momentum for each boson of around 52 GeV/ c . For the sake of this study, it is assumed that the final-state hadrons can be perfectly assigned to the Higgs or Z boson. Perfect assignment can be achieved either through anticipated advances in reconstruction tools in combination with the cleanliness of e^+e^- events and a nonzero boost of the Z and H bosons or by requiring that the Z boson decays to a dimuon pair, allowing unambiguous assignment of all seen hadrons to the Higgs boson at the cost of significantly reduced sample size.

Other $H \rightarrow q\bar{q}$ and $H \rightarrow gg$ decays present the most problematic backgrounds for $H \rightarrow s\bar{s}$. Taggers identifying jets from heavy quarks are very mature to date relying on high-dimensional information including in particular the long lifetime of b and c hadrons; see e.g. Refs. [57]. Gluon-jet tagging has been explored and often makes use of the significantly increased multiplicity and distinct shape of gluon jets; see e.g. Refs. [58,59], which study $H \rightarrow s\bar{s}$ decays at the FCC-ee and the International Linear Collider. This work focuses on the distinction between s jets and u or d jets. A simple but efficient proxy for the jet flavor in this case is the identity of the highest-momentum hadron as it likely stems from the original quarks produced in the Higgs decay. Based on the simulation produced for these studies, a pion carries most of the momentum in 80% of the u or d jets. Only slightly above 10% of the u or d jets result in a kaon with highest momentum. In s jets, on the other hand, pions and kaons are similarly likely to obtain the largest momentum at a rate of around 46%.

Figure 11 shows the efficiency of selecting events based on whether the particle with the highest momentum was a kaon. Note that the efficiency is calculated relative to the 46% (80%) of the $H \rightarrow s\bar{s}$ ($H \rightarrow u\bar{u}/d\bar{d}$) events where the highest momentum particle was a kaon (pion). Due to the very high momenta shown in Fig. 7, CLD cannot easily distinguish the Higgs jets at realistic time-of-flight resolutions. The dE/dx information does not add discrimination power. The increase in efficiency for signal and background at poor time-of-flight resolution without dE/dx information is a reflection of the training instabilities when considering only two variables with high noise in a BDT. Additional input from cluster counting in the drift chamber at IDEA allows strong distinction between the jet flavors with a slight dependence on the cluster-counting efficiency. The trends described for IDEA agree with existing studies of more sophisticated flavor-tagging tools performed on fast simulation [58].

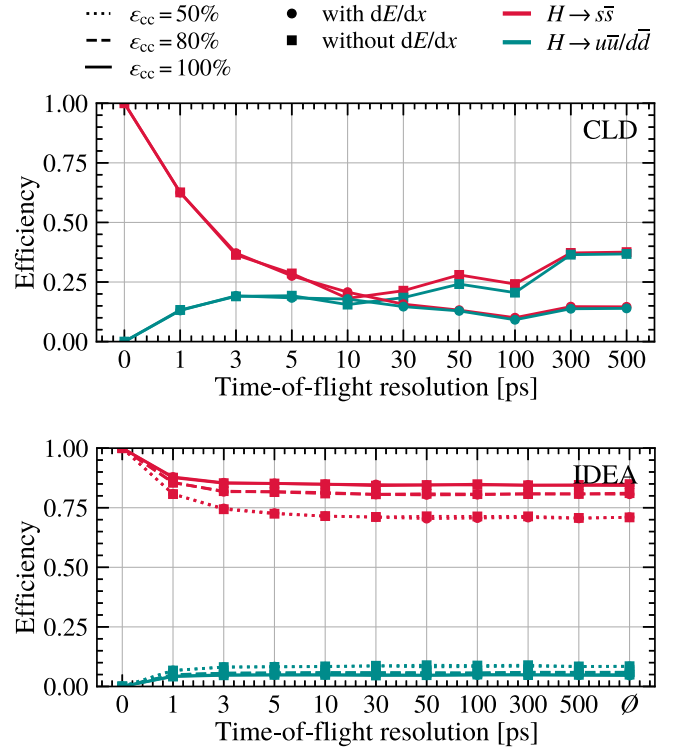


FIG. 11. Efficiency of tagging $H \rightarrow s\bar{s}$ (in red) and $H \rightarrow u\bar{u}/d\bar{d}$ (in green) based on whether the highest-momentum hadron in the jet is a kaon at (top) CLD and (bottom) IDEA for different time-of-flight resolution (horizontal axis), different cluster-counting efficiencies ϵ_{cc} (IDEA only, distinguished by line style), and with or without using energy-deposit information from the silicon sensors (marker style).

V. DISCUSSION

A study of the flavor capabilities of the CLD and IDEA detector concepts at the FCC-ee has been presented. The particle-identification algorithm used is based on three BDTs predicting a likelihood of a charged hadron to be a pion, kaon, or proton. The combination of dN/dx and moderate time-of-flight resolution results in a level of misidentification close to 2σ , i.e. 2%, or better for a given particle combination across almost the entire momentum range appearing in $e^+e^- \rightarrow Z \rightarrow b\bar{b}$ and $e^+e^- \rightarrow ZH$ events; see Sec. III. dE/dx information may be useful at very low momentum.

Three example physics studies are presented covering the low, medium, and high momentum regions. (A) Same-side flavor tagging of B_s^0 mesons relies on identification of very low momentum particles. In this region, good particle identification can be achieved in almost all setups. In a classifier using only time of flight, a resolution of 30 ps or better is necessary to achieve the same performance as a purely dN/dx -based classifier. (B) Charged hadrons from rare b decays sit in an intermediate momentum range. Here, the particles are still slow enough to benefit significantly

from a time-of-flight measurement but require a resolution of at least 30–50 ps for notable improvements. A classifier relying exclusively on time of flight in this case would need perfect time-of-flight resolution in most cases (i.e. 0 ps) to achieve the same performance as a purely dN/dx -based classifier. (C) Tagging $H \rightarrow s\bar{s}$ jets based on the highest momentum hadron in the jet requires particle identification in the momentum range beyond 10 GeV/ c . A measurement of dN/dx in this case leads to solid performance while time of flight only provides useful additional information for vanishing resolution (i.e. 0 ps). It should be noted that the selections used in the three examples are of an illustrative nature and the efficiencies and contaminations optimized for a specific more realistic analysis will differ to an extent.

This and previous studies show that as a consequence of excellent invariant-mass resolution, measurements involving fully reconstructed final states of charged particles do not necessarily require dedicated particle-identification detectors in order to achieve a passable level of background suppression. In fact, these processes would be useful to calibrate a particle-identification tool. Decays of narrow c hadrons, such as $D^0 \rightarrow K^-\pi^+/\pi^+\pi^-/K^+K^-$ or $\Lambda_c^+ \rightarrow pK^-\pi^+$, are excellent calibration channels with expected yields between 10^9 and 10^8 in a total dataset of 6×10^{12} Z bosons [60–62]. Their decay products span a wide range of momenta due to the fact that the c hadron can be produced either directly in the primary vertex or from the decay of a heavier hadron. Any process that cannot be identified based on kinematic criteria requires particle identification. Such processes include in particular decays with unknown final-state configuration as is the case for inclusive decays, like in s -jet and b -flavor tagging, or decays to invisible particles. The need for particle identification also extends to scenarios with insufficient invariant-mass resolution. In this context, investigations of decays involving electrons or neutral particles would provide useful further input.

Due to the lack of reconstruction software for the IDEA detector in this moment, the studies assume perfect reconstruction of the visible event as well as a uniform magnetic field when calculating the time of flight and flight

distance. Neither assumption should have sizable impact on the results presented in this publication. In contrast, the accuracy of the simulated dE/dx values might not yet reflect a realistic level of noise. However, the results of this study indicate that the particle identification does not rely heavily on the silicon-based dE/dx information in real-world examples. More sophisticated machine-learning techniques and in particular specific training samples might improve classification performance in some cases without changing the observations made in this paper. Future investigations may consider realistic simulation of the cluster formation in the drift chamber that cover a potentially more complex cluster-counting efficiency as well as occupancy effects. Similarly, the inclusion of electrons and muons in the identification procedure and an extension of the classifier to calorimeter and muon chamber information could be of interest. Finally, the benefits to flavor-physics analyses in the presence of a dedicated particle-identification system should be ascertained in future studies.

The classifiers used for the presented studies are publicly available in Ref. [63]. Besides the models, the repository also includes a script that provides particle-identification information based on an arbitrary simulation sample for easy use in future studies.

ACKNOWLEDGMENTS

We thank our colleagues in the FCC organization for providing the software and advice, in particular, Jan Eysermans and Brieuc Francois, as well as the participants in the *MIT and friends* FCC-ee meeting series for their discussion of this work. We also acknowledge the U.S. National Science Foundation, whose funding under Award No. 2310073 has helped support this work.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: SPEED SPREAD FOR DIFFERENT TIME-OF-FLIGHT RESOLUTIONS AND CLUSTER-COUNTING EFFICIENCIES

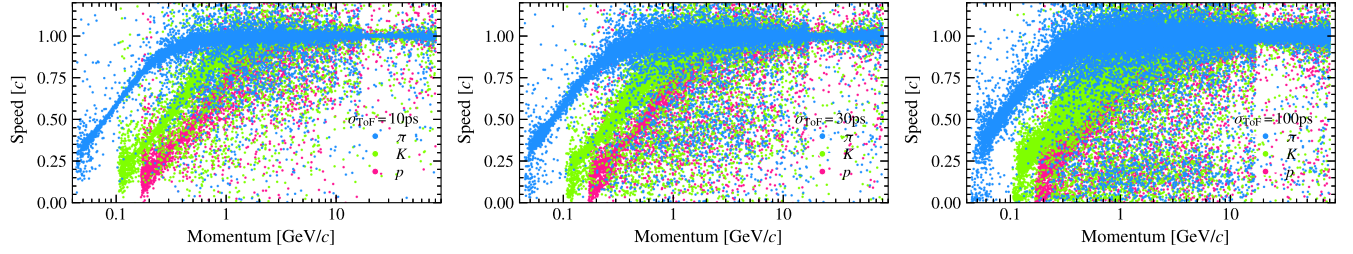


FIG. 12. Spread of the speed-momentum curve for different time-of-flight resolutions. The particles shown are produced in bins; see Fig. 3. The spread in speeds seems to drop abruptly at the bin edges, e.g. between 10 and 11 GeV/c. This is no physical effect but rather a reflection of the sudden change in sample size.

APPENDIX B: PERFORMANCE FIGURES FOR DIFFERENT CLUSTER-COUNTING EFFICIENCIES AT IDEA

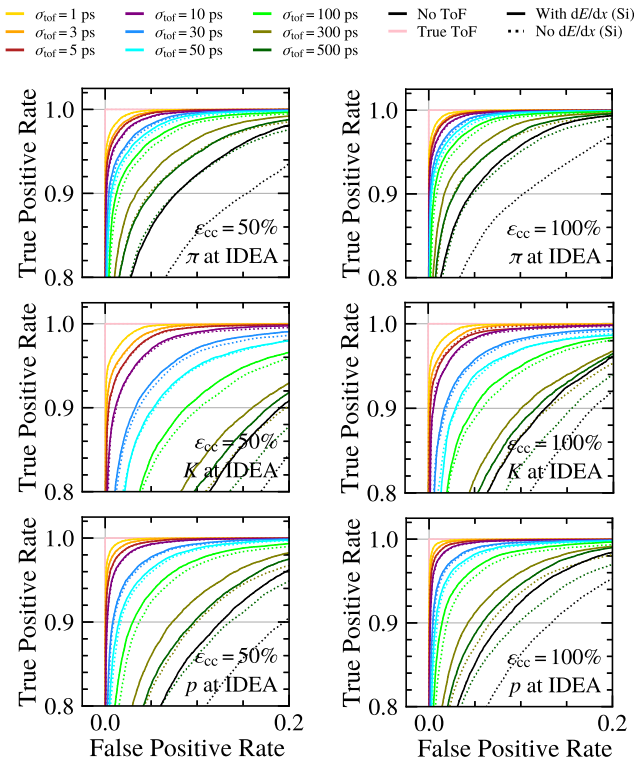


FIG. 13. ROC for the (top) pion, (middle) kaon, and (bottom) proton identification at IDEA with a cluster-counting efficiency ϵ_{cc} of (left) 50% or (right) 100%. The colors indicate the TOF resolution and the line style indicates whether the silicon-based dE/dx information was used.

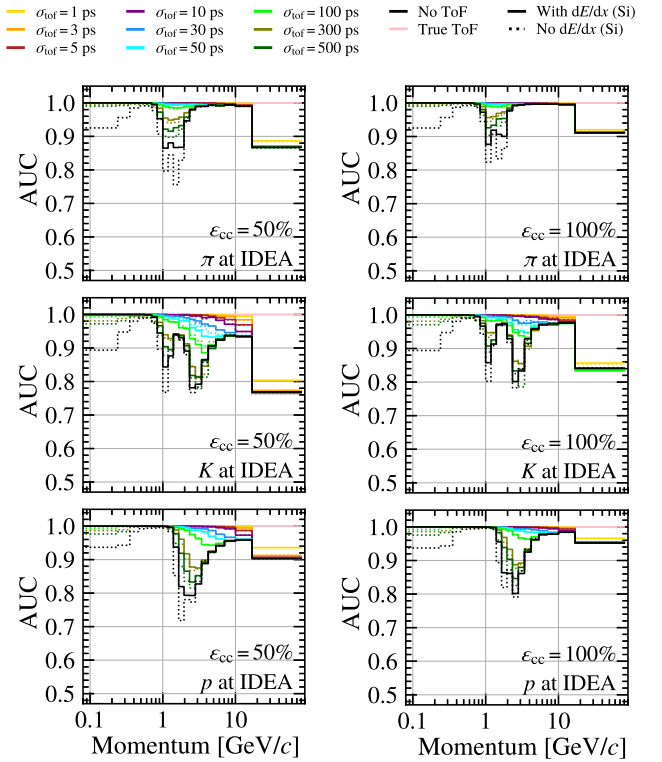


FIG. 14. AUC in different momentum ranges for the (top) pion, (middle) kaon, and (bottom) proton identification at IDEA with a cluster-counting efficiency ϵ_{cc} of (left) 50% or (right) 100%. The colors indicate the TOF resolution and the line style indicates whether the silicon-based dE/dx information was used.

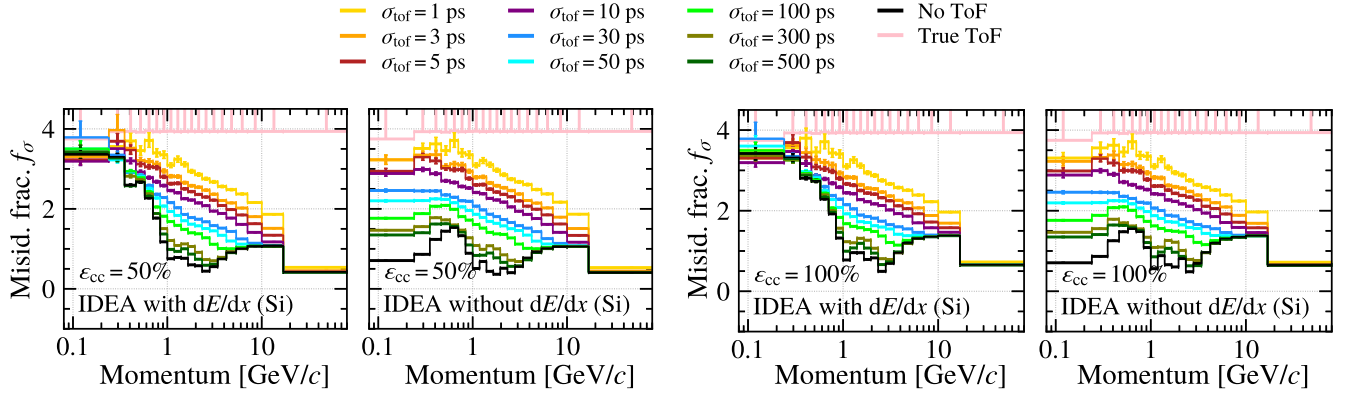


FIG. 15. Fraction of misidentified particles f_σ expressed as a number of standard deviations using Eq. (1) for all particle species combined for different TOF resolution and without and with dE/dx information at IDEA (i.e. dN/dx measurement with or without time-of-flight and/or dE/dx measurement) for a cluster-counting efficiency ϵ_{cc} of (left pair) 50% and (right pair) 100%.

APPENDIX C: BDT OUTPUT SCORES

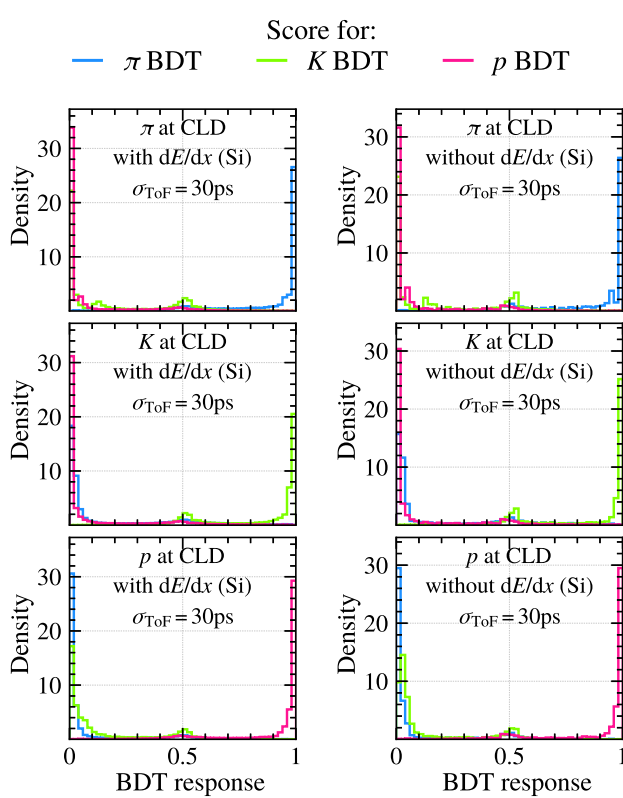


FIG. 16. Distribution of the BDT scores for a true (top) pion, (middle) kaon, and (bottom) proton at CLD for time-of-flight resolution of $\sigma_{TOF} = 30$ ps (left) with and (right) without silicon-based dE/dx measurement at CLD.

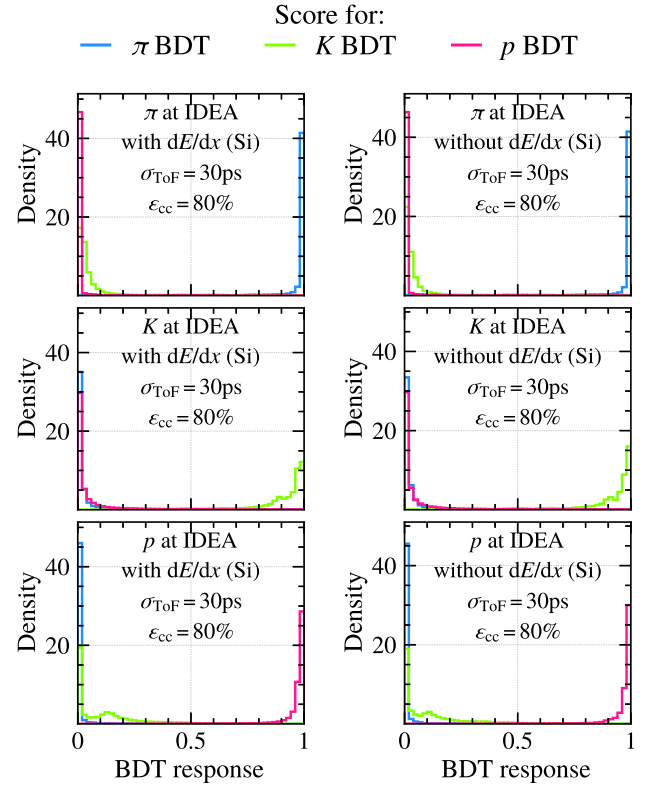


FIG. 17. Distribution of the BDT scores for a true (top) pion, (middle) kaon, and (bottom) proton at IDEA for time-of-flight resolution of $\sigma_{TOF} = 30$ ps, cluster-counting efficiency of $\epsilon_{cc} = 80\%$, (left) with and (right) without silicon-based dE/dx measurement at IDEA.

APPENDIX D: PER-SPECIES SIGNIFICANCE

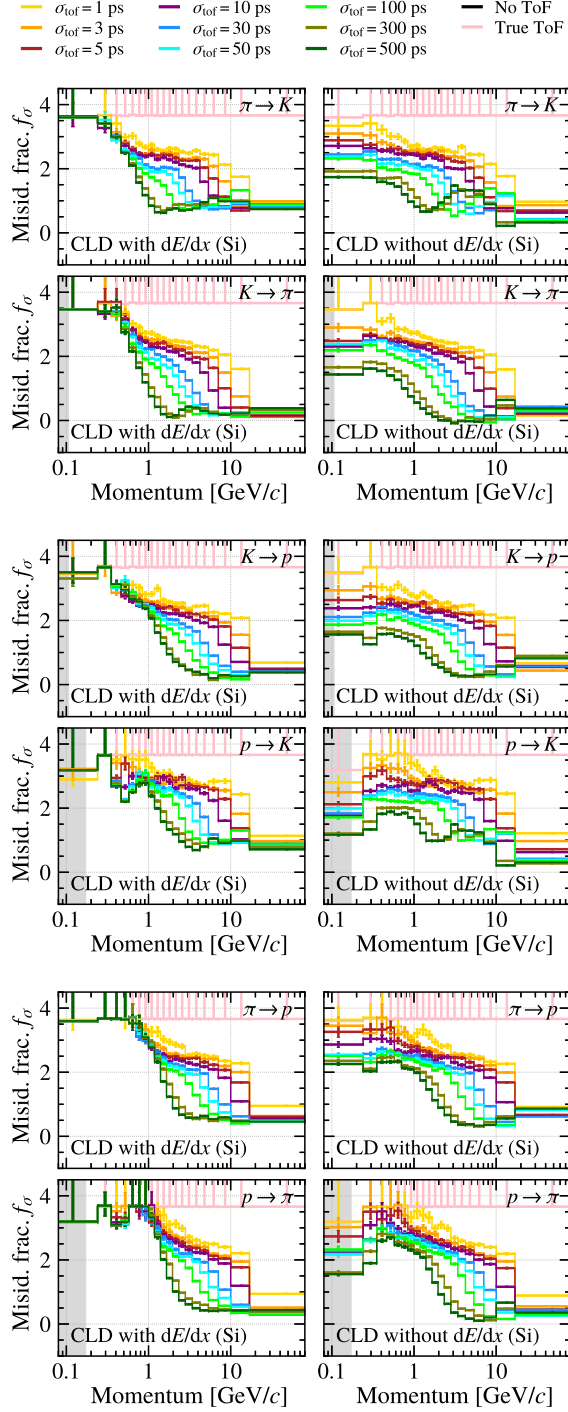


FIG. 18. Fraction of misidentified particles f_σ expressed as a number of standard deviations using Eq. (1) for each combination of hadron species (top, middle, and bottom) for different TOF resolution and with (left) and without (right) dE/dx information at CLD (i.e. time-of-flight measurement with or without dE/dx measurement).

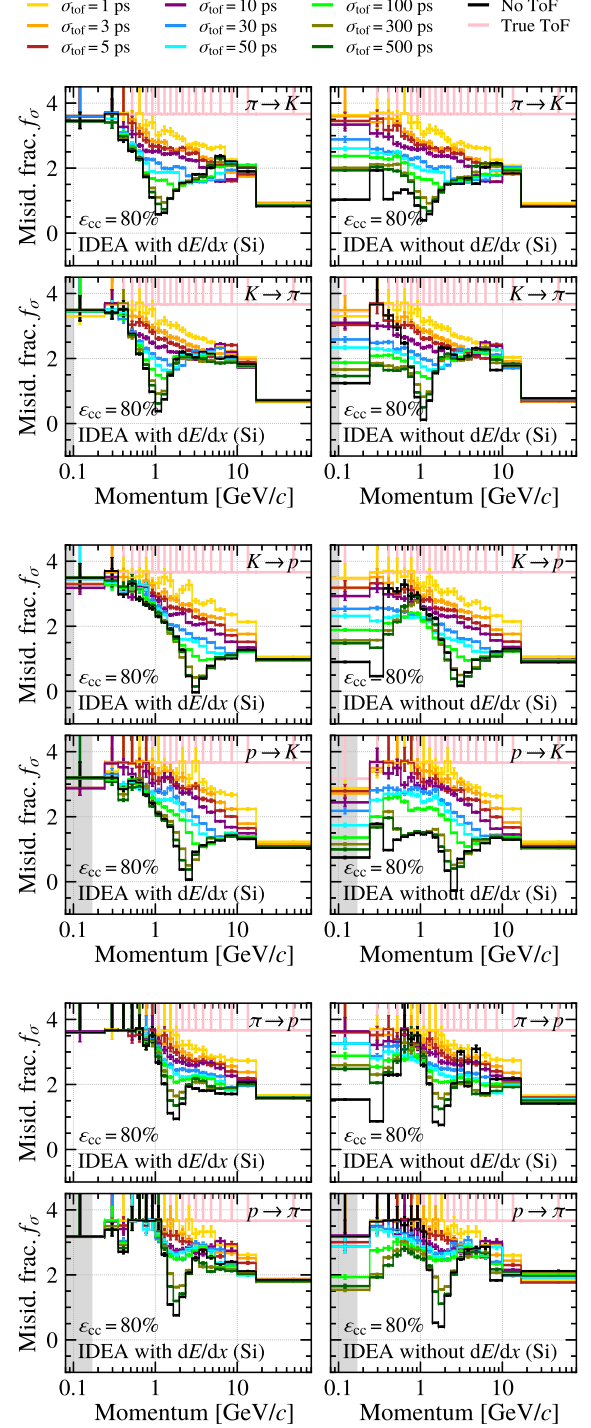


FIG. 19. Fraction of misidentified particles f_σ expressed as a number of standard deviations using Eq. (1) for each combination of hadron species (top, middle, and bottom) for different TOF resolution with (left) and without (right) dE/dx information at IDEA (i.e. dN/dx measurement with or without time-of-flight and/or dE/dx measurement). A cluster-counting efficiency ϵ_{cc} of 80% is assumed.

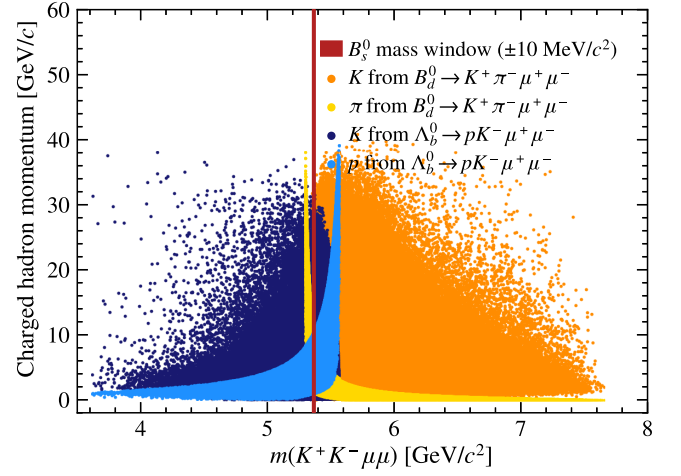
APPENDIX E: DIHADRON SPECTRA

TABLE I. Individual resonances with their relative contribution to the decay rate as simulated in the dihadron spectra of the rare-decay studies.

Hadronic system	Resonance	Contribution
$B_s^0 \rightarrow K^- \pi^+$	$K^{*0}(892)$	0.850
	$K^{*0}(1430)$	0.150
$B_s^0 \rightarrow K^- K^+$	$\phi(1020)$	0.838
	$f_2'(1525)$	0.162
$\Lambda_b^0 \rightarrow p K^-$	$\Lambda(1520)$	0.198
	$\Lambda(1600)$	0.297
	$\Lambda(1800)$	0.348
	$\Lambda(1820)$	0.158

APPENDIX F: MASS SPREAD IN RARE DECAYS

Figure 20 serves to illustrate the wide spread of misidentified rare decays when the signal decay is $B_s^0 \rightarrow K^+ K^- \mu^+ \mu^-$. The horizontal axis shows the value of the four-body invariant mass reconstructed under the KK hypothesis for the dihadron system. The vertical axis corresponds to the momentum of either final-state hadron, such that every decay candidate is represented by two points in the figure. Correctly identified kaons in the B^0 and Λ_b^0 decays are shown as orange and dark blue points, respectively. They accumulate around the B_s^0 mass but have a large spread. The yellow and lighter blue points, on the

FIG. 20. Spread of the four-body invariant mass for different hadron momenta in the case of correctly identified hadrons (red points, kaons from B^0 and Λ_b^0) and misidentified hadrons (yellow and blue points, π from B^0 and p from Λ_b^0).

other hand, correspond to, respectively, the pion and proton from the B^0 and Λ_b^0 decays if they were identified as kaons. Misidentification of a hadron with high momentum results in a four-body invariant mass close to the truth; i.e. the yellow (blue) points accumulate at the B_s^0 (Λ_b^0) mass. If the pion (proton) from a B^0 (Λ_b^0) decay has very low momentum and is misidentified as a kaon, the system artificially gains (loses) energy leading to increasingly high (low) four-body invariant mass. In comparison to the background spread, the signal window of ± 10 GeV/ c^2 is very narrow leading to efficient background suppression.

APPENDIX G: CONTAMINATION FOR DIFFERENT MASS RESOLUTIONS

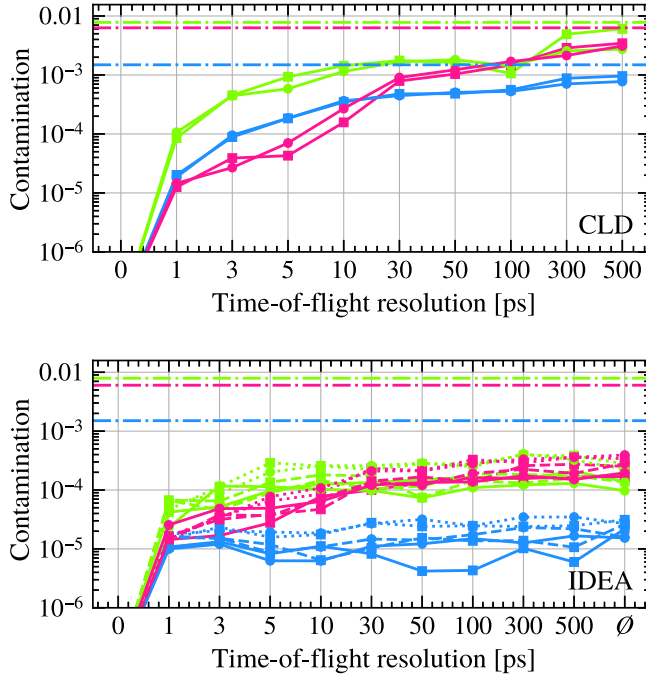


FIG. 21. Level of contamination for the three rare decays with semivisible final states (distinguished by color) at (top) CLD and (bottom) IDEA for different time-of-flight resolution (horizontal axis), different cluster-counting efficiencies ϵ_{cc} (IDEA only, distinguished by line style), and with or without using energy-deposit information from the silicon sensors (marker style).

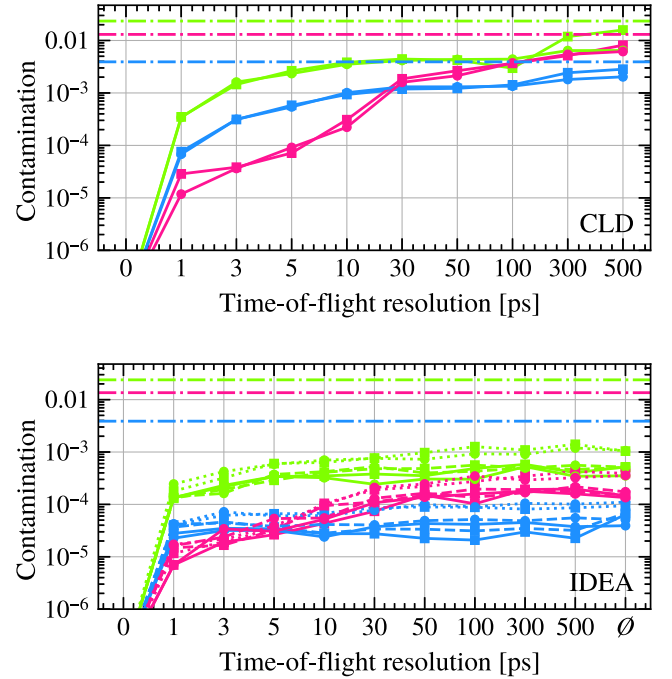


FIG. 22. Level of contamination for the three rare decays with semivisible final states (distinguished by color) at (top) CLD and (bottom) IDEA for different time-of-flight resolution (horizontal axis), different cluster-counting efficiencies ϵ_{cc} (IDEA only, distinguished by line style), and with or without using energy-deposit information from the silicon sensors (marker style).

-
- [1] M. Benedikt *et al.* (FCC Collaboration), Future Circular Collider feasibility study report: Volume 1, physics, experiments, detectors, *Eur. Phys. J. C* **85**, 1468 (2025).
 - [2] W. Altmannshofer *et al.* (Belle-II Collaboration), The Belle II physics book, *Prog. Theor. Exp. Phys.* **2019**, 123C01 (2019); **2020**, 029201(E) (2020).
 - [3] G. Viehhauser *et al.*, *Detectors in Particle Physics: A Modern Introduction* (CRC Press, Abingdon, 2024), 10.1201/9781003287674.
 - [4] R. Ricci (ALICE Collaboration), Study of MAPS silicon detector prototypes for the ALICE inner tracking system upgrade, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1059**, 169000 (2024).
 - [5] N. Bacchetta *et al.*, CLD—A detector concept for the FCC-ee, [arXiv:1911.12230](https://arxiv.org/abs/1911.12230).
 - [6] M. Abbrescia *et al.* (IDEA Study Group), The IDEA detector concept for FCC-ee, [arXiv:2502.21223](https://arxiv.org/abs/2502.21223).
 - [7] J. Pekkanen, ALLEGRO FCC-ee detector concept & noble liquid calorimetry, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1069**, 169921 (2024).
 - [8] G. Ganis, C. Helsens, and V. Völkl, Key4Hep, a framework for future HEP experiments and its use in FCC, *Eur. Phys. J. Plus* **137**, 149 (2022).
 - [9] K. Heijhoff *et al.*, Timing performance of the LHCb VELO Timepix3 Telescope, *J. Instrum.* **15**, P09035 (2020).
 - [10] A. Hayrapetyan *et al.* (CMS Collaboration), Operation and performance of the CMS silicon strip tracker with proton-proton collisions at the CERN LHC, *J. Instrum.* **20**, P08027 (2025).
 - [11] F. Cuna *et al.*, Simulation of particle identification with the cluster counting technique, in *International Workshop on Future Linear Colliders* (2021), [arXiv:2105.07064](https://arxiv.org/abs/2105.07064).
 - [12] Track Momentum Resolution at LHCb in 2024, <https://cds.cern.ch/record/2920248> (2024).

- [13] S. Agostinelli *et al.*, Geant4—A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [14] J. Allison *et al.*, Geant4 developments and applications, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006).
- [15] J. Allison *et al.*, Recent developments in Geant4, *Nucl. Instrum. Methods Phys. Res., Sect. A* **835**, 186 (2016).
- [16] FCC-config: Configuration files for the fcc event-processing chain (2025), <https://github.com/HEP-FCC/FCC-config/tree/main>.
- [17] CLDConfig: Configuration repository for the cld detector model in the Key4Hep stack, <https://github.com/key4hep/CLDConfig> (2025).
- [18] T. Chen and C. Guestrin, Xgboost: A scalable tree boosting system, in *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, KDD '16 (ACM, 2016), pp. 785–794, 10.1145/2939672.2939785.
- [19] R. Aaij *et al.* (LHCb Collaboration), Updated measurement of time-dependent CP -violating observables in $B_s^0 \rightarrow J/\psi K^+ K^-$ decays, *Eur. Phys. J. C* **79**, 706 (2019); **80**, 601(E) (2020).
- [20] R. Aaij *et al.* (LHCb Collaboration), b flavour tagging using charm decays at the LHCb experiment, *J. Instrum.* **10**, P10005 (2015).
- [21] R. Aaij *et al.* (LHCb Collaboration), New algorithms for identifying the flavour of B^0 mesons using pions and protons, *Eur. Phys. J. C* **77**, 238 (2017).
- [22] R. Aaij *et al.* (LHCb Collaboration), A new algorithm for identifying the flavour of B_s^0 mesons at LHCb, *J. Instrum.* **11**, P05010 (2016).
- [23] F. Abudinén *et al.* (Belle-II Collaboration), b -flavor tagging at Belle II, *Eur. Phys. J. C* **82**, 283 (2022).
- [24] A. Hayrapetyan *et al.* (CMS Collaboration), Angular analysis of the $B^0 \rightarrow K^{*0}(892)\mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Lett. B* **864**, 139406 (2025).
- [25] S. Wehle *et al.* (Belle Collaboration), Lepton-flavor-dependent angular analysis of $B \rightarrow K^* \ell^+ \ell^-$, *Phys. Rev. Lett.* **118**, 111801 (2017).
- [26] M. Aaboud *et al.* (ATLAS Collaboration), Angular analysis of $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *J. High Energy Phys.* **10** (2018) 047.
- [27] R. Aaij *et al.* (LHCb Collaboration), Measurement of CP -averaged observables in the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay, *Phys. Rev. Lett.* **125**, 011802 (2020).
- [28] R. Aaij *et al.* (LHCb Collaboration), Differential branching fraction and angular analysis of the decay $B_s^0 \rightarrow \phi \mu^+ \mu^-$, *J. High Energy Phys.* **07** (2013) 084.
- [29] R. Aaij *et al.* (LHCb Collaboration), Angular analysis and differential branching fraction of the decay $B_s^0 \rightarrow \phi \mu^+ \mu^-$, *J. High Energy Phys.* **09** (2015) 179.
- [30] R. Aaij *et al.* (LHCb Collaboration), Branching fraction measurements of the rare $B_s^0 \rightarrow \phi \mu^+ \mu^-$ and $B_s^0 \rightarrow f_2'(1525)\mu^+\mu^-$ decays, *Phys. Rev. Lett.* **127**, 151801 (2021).
- [31] R. Aaij *et al.* (LHCb Collaboration), Differential branching fractions and isospin asymmetries of $B^0 \rightarrow K^{(*)}\mu^+\mu^-$ decays, *J. High Energy Phys.* **06** (2014) 133.
- [32] R. Aaij *et al.* (LHCb Collaboration), Angular analysis of the $B^+ \rightarrow K^{*+}\mu^+\mu^-$ decay, *Phys. Rev. Lett.* **126**, 161802 (2021).
- [33] R. Aaij *et al.* (LHCb Collaboration), Amplitude analysis of the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay, *Phys. Rev. Lett.* **132**, 131801 (2024).
- [34] R. Aaij *et al.* (LHCb Collaboration), Comprehensive analysis of local and nonlocal amplitudes in the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay, *J. High Energy Phys.* **09** (2024) 026.
- [35] A. Hayrapetyan *et al.* (CMS Collaboration), Test of lepton flavor universality in $B^\pm \rightarrow K^\pm \mu^+ \mu^-$ and $B^\pm \rightarrow K^\pm e^+ e^-$ decays in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Rep. Prog. Phys.* **87**, 077802 (2024).
- [36] J. P. Lees *et al.* (BABAR Collaboration), Measurement of branching fractions and rate asymmetries in the rare decays $B \rightarrow K^{(*)} \ell^+ \ell^-$, *Phys. Rev. D* **86**, 032012 (2012).
- [37] S. Choudhury *et al.* (Belle Collaboration), Test of lepton flavor universality and search for lepton flavor violation in $B \rightarrow K \ell \ell$ decays, *J. High Energy Phys.* **03** (2021) 105.
- [38] R. Aaij *et al.* (LHCb Collaboration), Test of lepton universality using $B^+ \rightarrow K^+ \ell^+ \ell^-$ decays, *Phys. Rev. Lett.* **113**, 151601 (2014).
- [39] R. Aaij *et al.* (LHCb Collaboration), Test of lepton universality with $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ decays, *J. High Energy Phys.* **08** (2017) 055.
- [40] R. Aaij *et al.* (LHCb Collaboration), Test of lepton universality using $\Lambda_b^0 \rightarrow p K^- \ell^+ \ell^-$ decays, *J. High Energy Phys.* **05** (2020) 040.
- [41] R. Aaij *et al.* (LHCb Collaboration), Test of lepton universality in beauty-quark decays, *Nat. Phys.* **18**, 277 (2022).
- [42] R. Aaij *et al.* (LHCb Collaboration), Tests of lepton universality using $B^0 \rightarrow K_S^0 \ell^+ \ell^-$ and $B^+ \rightarrow K^{*+} \ell^+ \ell^-$ decays, *Phys. Rev. Lett.* **128**, 191802 (2022).
- [43] R. Aaij *et al.* (LHCb Collaboration), Measurement of lepton universality parameters in $B^+ \rightarrow K^+ \ell^+ \ell^-$ and $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ decays, *Phys. Rev. D* **108**, 032002 (2023).
- [44] R. Aaij *et al.* (LHCb Collaboration), Test of lepton universality in $b \rightarrow s \ell^+ \ell^-$ decays, *Phys. Rev. Lett.* **131**, 051803 (2023).
- [45] T. Sjöstrand *et al.*, An introduction to Pythia 8.2, *Comput. Phys. Commun.* **191**, 159 (2015).
- [46] D. J. Lange, The EvtGen particle decay simulation package, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [47] R. Aaij *et al.* (LHCb Collaboration), Amplitude analysis of the radiative decay $B_s^0 \rightarrow K^+ K^- \gamma$, *J. High Energy Phys.* **08** (2024) 093.
- [48] R. Aaij *et al.* (LHCb Collaboration), Amplitude analysis of the $\Lambda_b^0 \rightarrow p K^- \gamma$ decay, *J. High Energy Phys.* **06** (2024) 098.
- [49] K. Chilikin *et al.* (Belle Collaboration), Observation of a new charged charmoniumlike state in $\bar{B}^0 \rightarrow J/\psi K^- \pi^+$ decays, *Phys. Rev. D* **90**, 112009 (2014).
- [50] Y. S. Amhis *et al.* (HFLAV Collaboration), Averages of b -hadron, c -hadron, and τ -lepton properties as of 2018, *Eur. Phys. J. C* **81**, 226 (2021).
- [51] H.-Y. Jiang and F.-S. Yu, Fragmentation-fraction ratio $f_{\Xi_b}/f_{\Lambda_b^0}$ in b - and c -baryon decays, *Eur. Phys. J. C* **78**, 224 (2018).
- [52] Y. Amhis *et al.*, Prospects for searches of $b \rightarrow s \nu \ell \bar{\nu} \ell$ decays at FCC-ee, *J. High Energy Phys.* **01** (2023) 144.

- [53] T. H. Kwok *et al.*, Time-dependent precision measurement of $B_s^0 \rightarrow \phi \mu^+ \mu^-$ decay at FCC-ee, *Eur. Phys. J. C* **86**, 135 (2026).
- [54] A. Beck, M. Elmarassy, A. Sabbagh, M. Kreps, and E. Smith, Constraints on new physics from decays of polarized Λ_b^0 baryons at the FCC-ee, *Phys. Rev. D* **113**, 055005 (2026).
- [55] A. Di Canto, T. Hacheney, G. Hiller, D. S. Mitzel, S. Monteil, L. Röhrig, and D. Suelmann, New opportunities for rare charm from $Z \rightarrow c\bar{c}$ decays, *Eur. Phys. J. C* **86**, 18 (2026).
- [56] M. Dong *et al.* (CEPC Study Group), CEPC conceptual design report: Volume 2–Physics & detector (2018).
- [57] H. Abidi *et al.*, FCC feasibility studies: Impact of tracker- and calorimeter-detector performance on jet flavor identification and Higgs physics analyses, *Phys. Rev. D* **112**, 052002 (2025).
- [58] F. Bedeschi, L. Gouskos, and M. Selvaggi, Jet flavour tagging for future colliders with fast simulation, *Eur. Phys. J. C* **82**, 646 (2022).
- [59] A. Albert *et al.*, Strange quark as a probe for new physics in the Higgs sector, in *Proceedings of Snowmass 2021* (2022), [arXiv:2203.07535](https://arxiv.org/abs/2203.07535).
- [60] R. Barate *et al.* (ALEPH Collaboration), Study of charm production in Z decays, *Eur. Phys. J. C* **16**, 597 (2000).
- [61] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [62] M. Benedikt *et al.* (FCC Collaboration), Future Circular Collider feasibility study report: Volume 2, accelerators, technical infrastructure and safety, *Eur. Phys. J. Special Topics* **234**, 5713 (2025).
- [63] A. Beck, A tracker-based particle-identification tool for the FCC-ee (2026), <https://github.com/anjabeck/fccee-tracker-pid>.