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# Charged Hadron Identification with dE/dx and Time-of-Flight at Future Higgs Factories

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The design of detector concepts has been driven for a long time by requirements on transverse momentum, impact parameter and jet energy resolutions, as well as hermeticity. Only rather recently it has been realised that the ability to idenfity different types of charged hadrons, in particular kaons and protons, could have important applications at Higgs factories like the International Linear Collider (ILC), ranging from improvements in tracking, vertexing and flavour tagging to measurements requiring strangeness-tagging. While detector concepts with gaseous tracking, like a time projection chamber (TPC), can exploit the specific energy loss, all-silicon-based detectors have to rely on fast timing layers in front of or in the first layers of their electromagnetic calorimeters (ECals). This work will review the different options for realising particle identification (PID) for pions, kaons and protons, introduce recently developed reconstruction algorithms and present full detector simulation prospects for physics applications using the example of the International Large Detector (ILD) concept.

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## 1. Introduction

The ILC [1] is a proposed 250 - 500 GeV $e^+e^-$-collider and ILD [2] is one of its detector concepts, shown in Figure 1. It is a multi-purpose detector with a silicon vertex tracker (VTX), a TPC with a silicon envelope (SIT, SET) as central tracking system and a highly granular calorimeter system inside a 3.5 T solenoid and a muon system outside of it. With its forward tracker (FTD) and forward calorimeter system it achieves a high degree of hermeticity. ILD is designed for particle flow [3] and has an asymptotic momentum resolution of $2 \cdot 10^{-5}$ GeV$^{-1}$ and a jet energy resolution of better than 3.5 % above 100 GeV. This work concentrates on the PID capabilities of ILD via measurement of the specific energy loss $dE/dx$ in the TPC and via measurement of the time-of-flight (TOF) in the ECal in full-detector simulation [2]. This work makes use of a large MC production in 2018 [4], which generated, simulated and reconstructed about 500 fb$^{-1}$ of ILC integrated luminosity. This includes the entire Standard Model processes and single particles for calibration and detailed studies.
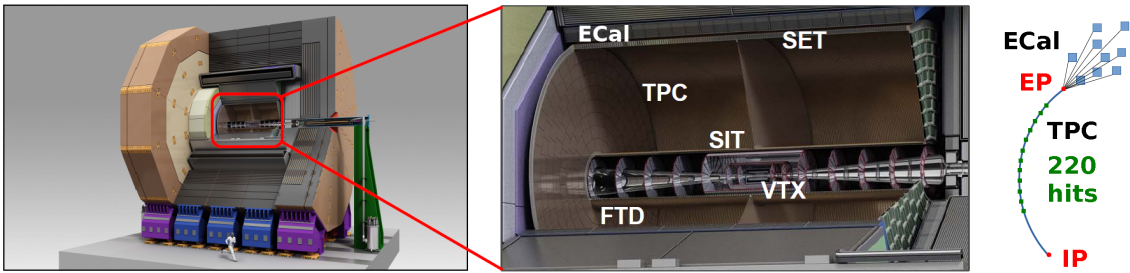


**Figure 1:** Schematic view of ILD, from [2], and scheme of hits in the TPC and the Ecal used for $dE/dx$ and TOF measurements, repectively.

## 2. Specific Energy Loss Measurement $dE/dx$

The ILD TPC provides up to 220 hits per track. The $dE/dx$ estimate for one track is a trimmed truncated mean of the hit $dE/dx$ values, rejecting the 8 % hits with the smallest $dE/dx$ values and 30 % hits with the largest ones. The Bethe-Bloch bands of the five simulated single-particle species are displayed in Figure 2 and are mostly well identifiable. The relative $dE/dx$ resolution in the simulation is about 4.5 %, which was adjusted to reflect the $dE/dx$ resolution measured in test beam experiments, e.g. [5], and meets the aim of ILD to have a $dE/dx$ resolution of 5 % or better. The separation power $S$ is the relative distance between the Bethe-Bloch bands, defined as $S = |\mu_1 - \mu_2|/\sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}}$ with $\mu_i$ and $\sigma_i$ being the mean and width of the band of particle $i$, respectively. Figure 3 shows the $\pi/K$ and $K/p$ separation power. $S > 3$ is achieved for particle momenta between about 2 and 20 GeV in the default detector model IDR-L.

In [6], one example application for PID was investigated, namely its effect on the flavour tag in hadronic W decays. A boosted decision tree (BDT) was trained to separate decays to a d and a u quark from decays to an s and a c quark. Since s and c quarks generate more kaons and kaons with higher momenta than d and u quarks, PID can be used in this separation. The BDT had 20 input variables based on the W-decay system properties, including number, fraction of the jet momentum and leadingness of pions and kaons, which were identified via their $dE/dx$. These input variables were compared to the case when the default vertex-based flavour tag of ILD, LCFIPlus [7], was used as BDT input, as well as to a combination of the two. Figure 4 shows the ROC curves resulting from the BDT training. The $\pi/K$ PID adds independent information, which increases the area-under-the-curve (AUC) by about 4 %-points in the combination. This increase translates for a given purity into an improved effiency, i.e. in increase in available statistics, which is shown in Figure 5. In addition, the reconstruction and analysis were repeated with different values for the $dE/dx$ resolution, demonstrating its impact. For a required purity between 0.9 and 0.99, the efficiency increase is about 10 to
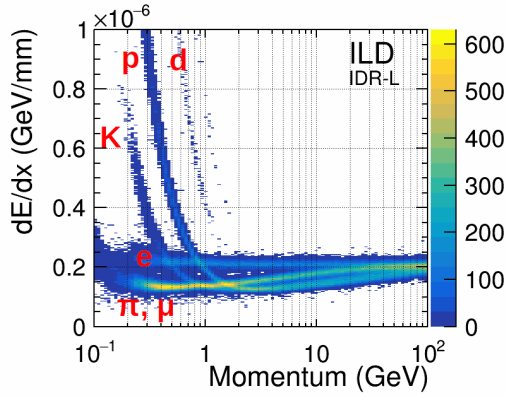
**Figure 2:** Bethe-Bloch curves of single particles. The curves are well separable in most areas, but overlap in some.
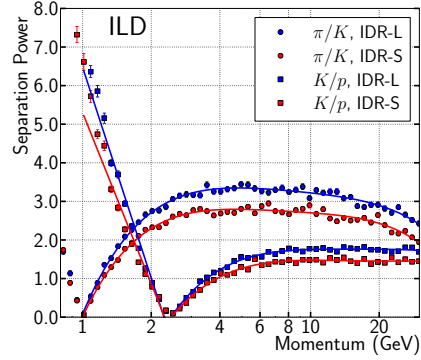


**Figure 3:** Pion-kaon and kaon-proton separation power, for the default and a smaller detector model. The curves are only to guide the eye.
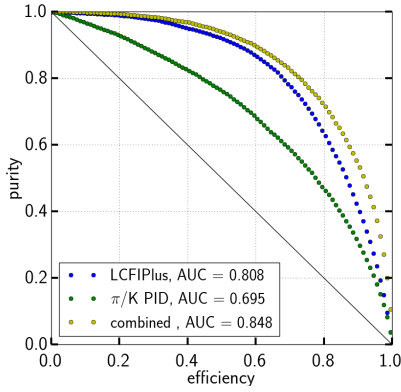


**Figure 4:** BDT result ROC curve for the separation of 1st and 2nd generation hadronic W decays. d$E$/d$x$-based PID is compared to the vertex-based LCFIPlus flavour tag.
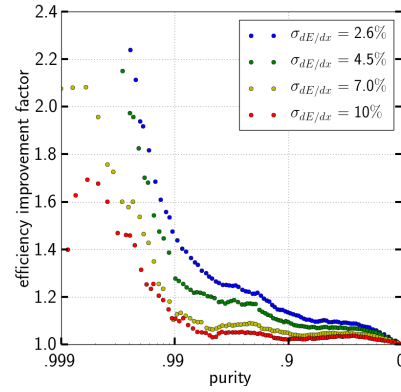


**Figure 5:** Efficiency improvement when adding $\pi$/K PID to the info from LCFIPlus, depending on the requested purity level and on the simulated d$E$/d$x$ resolution.

30 % for the default d$E$/d$x$ resolution. With an enhanced resolution of 2.6 %, this would improve to 15 to 50 %, while a reduced resolution of 7 % or worse would only give an increase of 5 to 10 %. For very high required purities > 0.99, the efficiency increase can be as large as a factor of 2. One possible application of this study is the measurement of the central element of the CKM matrix $V_{\text{cs}}$ without assuming unitarity [8].

## 3. Time-of-Flight Measurement TOF

For the TOF measurement, a timing resolution of 50 ps per channel has been assumed to be achievable for the electromagnetic calorimeter (ECal) and was implemented in the simulation. The TOF estimator for an incident particle is calculated using the first 10 layers of the ECal. The timing values of the one active channel in each layer which is closest to the extrapolated track are projected back to the entry point (EP) into the ECal assuming propagation with the speed of light and then averaged. Together with the track length, the absolute velocity of the particle $\beta$ in units of $c$ is calculated. Possible improvements on this method are being discussed in [9]. This $\beta$ is shown in Figure 6, with bands of pions, kaons and protons which are well separable up to 3 GeV for $\pi$/K and 6 GeV for K/p. The particles used here are from full physics events,
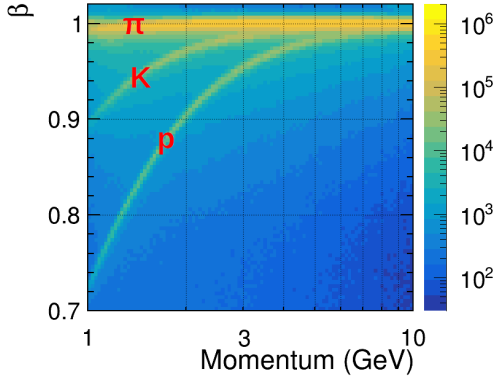
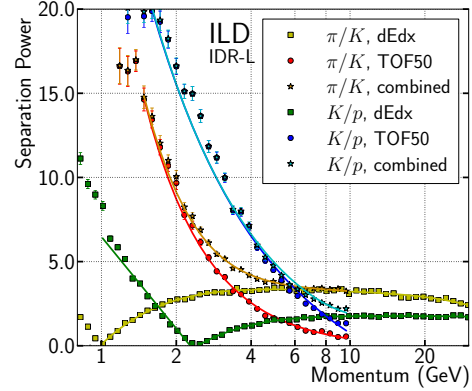**Figure 6:** TOF $\beta$ curves of particles in full physics events.



**Figure 7:** Combined d$E$/d$x$ and TOF separation power for pion/kaon and kaon/proton separation. The curves are only to guide the eye.

which adds considerable background to the bands. The separation power, as defined above, can be calculated and combined with the one from d$E$/d$x$ in quadrature, which are both shown in Figure 7.

## 4. Conclusions

Measurements of dE/dx and TOF provide sensitivity for $\pi/K$ and $K/p$ separation in complementary momentum ranges. In particular TOF excels in the 'blind spots' of d$E$/d$x$ where the Bethe-Bloch bands overlap. Proven performances from beam tests of technological prototypes have been implemented in detailed full-ILD simulations. They show promising application possibilities, like enhanced flavour tagging, and open the door for further studies. This makes PID an invaluable tool to utilize collider data at a future Higgs factory to the best of our possibilities.

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