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

Ulrich Einhaus[a,b,1,*]

[a] *Deutsches Elektronen-Synchrotron, Notkestraße 85, Hamburg, Germany*
[b] *Department of Physics, Universität Hamburg, Hamburg, Germany*
E-mail: ulrich.einhaus@desy.de

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] On behalf of the ILD concept group.
[*] Speaker

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 $2 \cdot 10^{-5}\,\mathrm{GeV}^{-1}$ 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 time-of-flight (TOF) in the ECal in full-detector simulation [2], while PID via measurement of the specific energy loss $\mathrm{d}E/\mathrm{d}x$ in the TPC has been discussed separately [4]. This work makes use of a large MC production in 2018 [5], which generated, simulated and reconstructed about $500\,\mathrm{fb}^{-1}$ of ILC integrated luminosity. This includes the entire Standard Model processes and single particles for calibration and detailed studies.

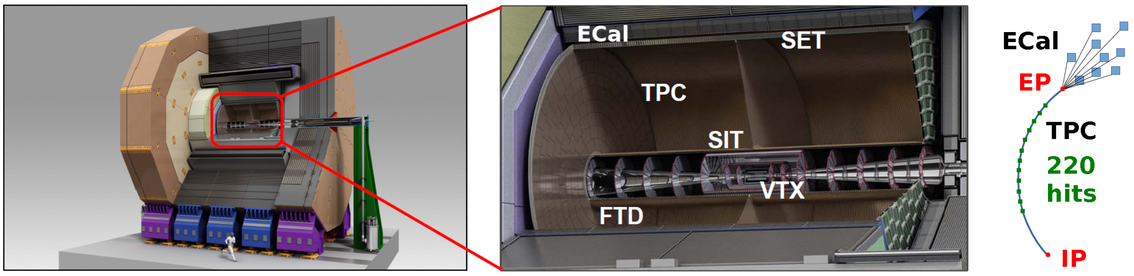

Figure 1: Schematic view of ILD, from [2], and scheme of hits in the TPC and the Ecal used for $\mathrm{d}E/\mathrm{d}x$ and TOF measurements, repectively.

2. 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 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 β in units of c is calculated. This β is shown in Figure 2, with bands of pions, kaons and protons which are well separable up to 3 GeV for π/K and 6 GeV for K/p. The separation power S is the relative distance between the bands, defined as $S = |\mu_1 - \mu_2| / \sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}}$ with μ_i and σ_i being the mean and width of the band of particle i, respectively. This separation power can be calculated and combined with the one from $\mathrm{d}E/\mathrm{d}x$ [4] in quadrature, which is shown in Figure 3.

A possible application of TOF is the measurement of the charged kaon mass [6]. This quantity is known to a precision of $m_K = (493{,}677 \pm 13)$ keV, but the two most precise measurements disagree with each other by 60 keV with individual error bars of about 10 keV [7]. In ILD physics events, the mass m of a particle can be calculated using the reconstructed TOF β and the measured momentum p via $m = p\sqrt{1/\beta^2 - 1}$, which is shown in Figure 4. Here, a timing resolution of 50 ps and only particles with $p < 3$ GeV (upper momentum cut) are used. The kaon peak is well identifiable and is fitted. To reduce background, a particle's $\mathrm{d}E/\mathrm{d}x$ value must be consistent with the kaon hypothesis within 2.5σ (black histogram). In Figure 5 the resulting statistical uncertainty on the fitted kaon mass is shown for an integrated ILC luminosity of $200\,\mathrm{fb}^{-1}$ at 500 GeV. The precision can be optimised wrt. the chosen upper momentum cut and depends on the simulated timing resolution. With a realistic timing resolution of 50 ps, a statistical uncertainty of 30 keV or $6 \cdot 10^{-5}$ can be achieved, which motivates studying systematic effects in the future.

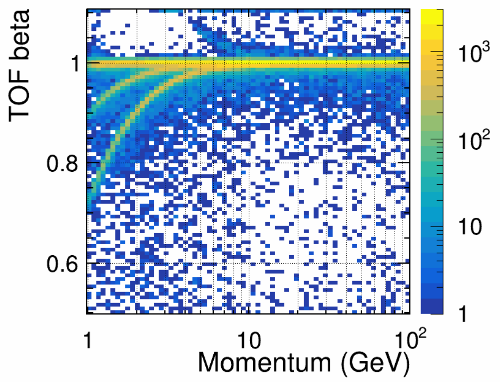

Figure 2: TOF β curves of particles in single particle events.

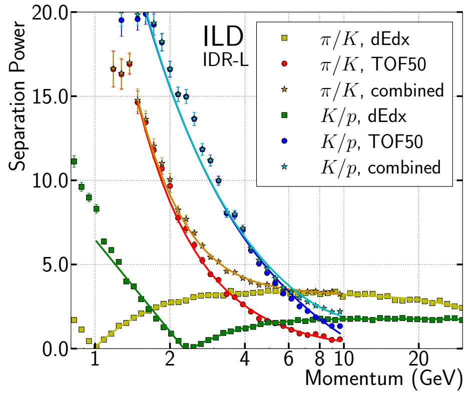

Figure 3: Combined TOF and dE/dx separation power for pion/kaon and kaon/proton separation. For details on dE/dx see [4]. The curves are only to guide the eye.

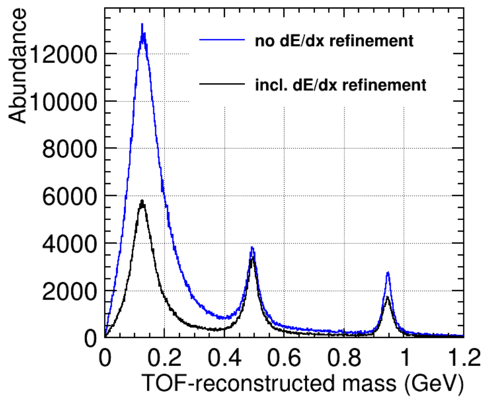

Figure 4: TOF-reconstructed masses in full physics events. Pions, kaons and protons are well separable, and dE/dx refinement can be used to improve kaon selection.

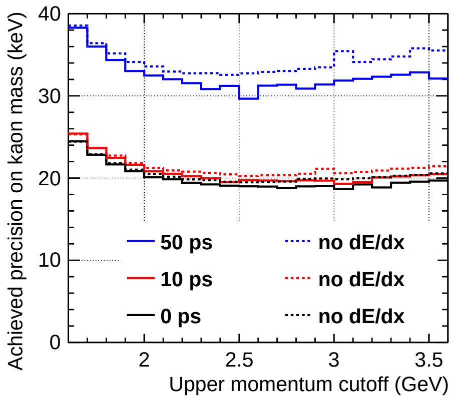

Figure 5: Statistical precision on the kaon mass depending on the simulated TOF timing resolution for 200 fb^{-1} of ILC at 500 GeV.

3. TOF Ongoing Development

The largest systematic uncertainty on a mass measurement comes from the TOF algorithm and is in the order of 10 MeV. Studies are ongoing to improve the algorithm and reduce this bias [8]. The developments will be implemented in a future MC production and include the following aspects. Instead of projecting the measured time of the individual ECal hits to the EP using a propagation velocity c, this velocity can be fitted, compare the example in Figure 6. For extended showers in the ECal, the cluster timing can be calibrated based on the number of cluster hits, which is an effect at the level of 10^{-3}. Since a particle loses energy in the tracker, the reconstructed momentum at the calorimeter EP can be used instead of the one at the IP. This changes the sign of the bias, but reduces its size, as displayed in Figure 7. Here, also 3 TOF algorithms are compared: the default one τ_{avg}, the fit method τ_{fit}, and using only one ECal hit per particle, namely the one closest to the EP, τ_{closest}.

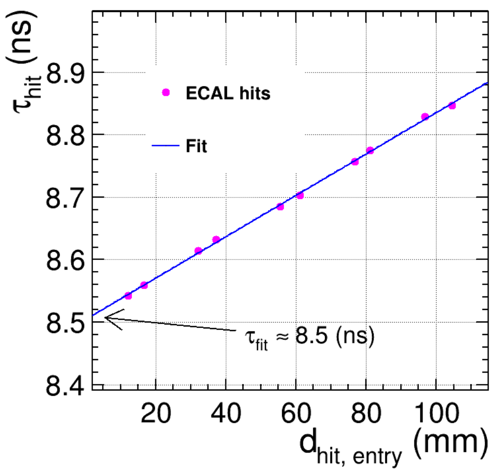

Figure 6: Example of the TOF fit method. Instead of assuming a propagation velocity c in the ECal, this velocity is fitted and gives a TOF estimator at the EP. From [8].

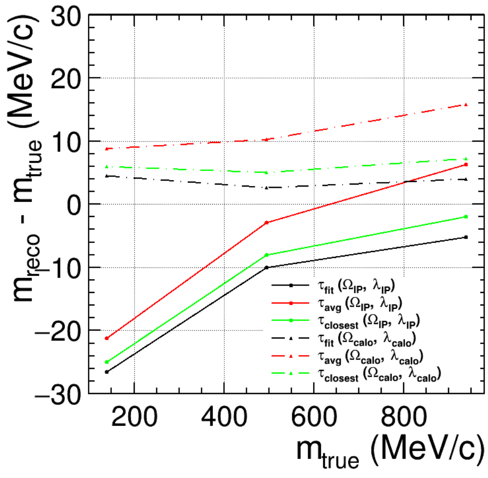

Figure 7: Bias of the reconstructed masses of pions, kaons and protons, depending on the TOF algorithm τ and the reference point for the momentum reconstruction, IP calorimeter EP. From [8].

4. Conclusions

With novel timing technologies, TOF provides a new opportunity for PID at high energy colliders. Measurements of TOF and dE/dx provide sensitivity for π/K and K/p separation in complementary momentum ranges, in particular TOF excels in the 'blind spots' of dE/dx. With TOF, a measurement of the charge kaon mass at the level of better than 10^{-4} is statistically achievable, provided the systematic uncertainties from the TOF measurement and the momentum scale can be kept at the same level. This measurement would help to solve the long-standing disagreement of the kaon mass. Studies are ongoing to improve the systematic precision of the TOF estimator algorithm by making it more realistic. Recent developments improved the bias on the reconstructed hadron mass from several 10 MeV to several MeV.

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