Development of the time-of-flight particle identification for future Higgs factories

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At the latest European strategy update in 2020 it has been highlighted that the next highest-priority collider should be an e^+e^- Higgs factory with a strong focus on precision physics. Particle identification (pID) will be an essential tool for such precision measurements to utilise its clean event environment and push event reconstruction to its full potential. A recent development of the fast-timing Si sensors such as LGADs with a time resolution below 50 ps will allow to enhance precision measurements at the future Higgs factory with an additional separation of $\pi^\pm$, $K^\pm$ and p using the time-of-flight (TOF) technique. In this study we present our latest developments of the TOF pID algorithm with a brief overview of its potential physics applications, discuss its realistic design implementations inside the future Higgs factory detector using the International Large Detector (ILD) as an example and highlight the key role and importance of fast-timing detectors for $\pi^\pm$, $K^\pm$ and p identification.

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1. Introduction

Particle identification is a key component for the precision measurements at future e^+e^- Higgs factories. Right now, TOF is being thoroughly studied as a tool for $\pi^\pm$, $K^\pm$ and p identification below 5 GeV momentum. It would cover the blind regions of overlapping Bethe-Bloch curves for already existing dE/dx (dN/dx) pID in detectors with gaseous tracking, such as ILD [1] or IDEA [2]. In fully Silicon detector designs like SiD [3] or CLD [4] TOF could be the only available pID tool for charged hadrons. TOF pID is based on calculating the velocity $\beta = \frac{v}{c}$ of a particle using precise measurements of the TOF and track length. In combination with the momentum, we can reconstruct the particle's mass:

$$\beta = \frac{\ell_{\text{track}}}{\text{TOF}} \qquad m = \frac{p}{\beta}\sqrt{1-\beta^2} \tag{1}$$

As a first approximation, the momentum of a track can be calculated at the interaction point and the track length can be calculated between the first and the last track hits assuming a perfect helix using simple track parameters:

$$p = p_{\text{IP}} \qquad \ell_{\text{track}} = \frac{|\varphi_{\text{end}} - \varphi_{\text{start}}|}{|\Omega|}\sqrt{1+\tan^2\lambda}, \tag{2}$$

where φ is the azimuthal angle of the momentum of the track, Ω is the curvature of the track and λ is the angle of the track with respect to the plane orthogonal to the beam direction. For a more detailed mathematical description of all track parameters see [5].

A more advanced approach is to calculate the length of individual track segments between neighboring tracker hits using track parameters calculated by a Kalman Filter [6] at every tracker hit, and then sum all segments together. To account for the changing momentum, we can take the square root of the harmonic mean of the squared momentum, which should work better given a non-negligible energy loss of the particle and is mathematically more rigorous for relativistic particles [7]. Equations 3 show how to calculate a track length and harmonic mean momentum using methods described above.

$$p = \sqrt{\langle p^2 \rangle_{HM}} = \sqrt{\sum_{i=0}^{n} \ell_i \Big/ \sum_{i=0}^{n} \frac{\ell_i}{p_i^2}} \qquad \ell_{\text{track}} = \sum_{i=0}^{n} \ell_i = \sum_{i=0}^{n} \sqrt{\left(\frac{\varphi_{i+1} - \varphi_i}{\Omega_i}\right)^2 + (z_{i+1} - z_i)^2} \tag{3}$$

2. Impact of the track length reconstruction

A measurement of a track length is one of the limiting factors for TOF pID. Although, for the high p_T particles in the barrel, the simple helix approximation does a decent job, for the endcap region, where we have the majority ($\sim 2/3$) of our signals, this approach has significant drawbacks. Firstly, it is not designed for tracks with multiple curlers in the tracker. As it uses only two edge points of the track, it will not resolve multiple curlers in-between and will fail to calculate the track length. Secondly, low momentum particles tend to lose more energy in the tracker, thus there will be a significant discrepancy between $p = p_{\text{IP}}$ and $p = p_{\text{ECAL}}$, which makes a thorough calculation of the harmonic mean momentum more relevant. The limitations discussed above motivated the development of a more robust track length algorithm, which is described by equations 3. This algorithm has been recently developed and integrated into iLCSoft [8]. For our study, we used MC samples of the $e^+e^- \rightarrow Z \rightarrow q\bar{q}$ process at 250 GeV collision energy with ILC beam parameters [1]. To assess the performance of the new track length algorithm for the TOF measurement, we have used MC truth information from the closest ECAL hit to the track entry point in the ECAL. Figure 1 shows a comparison of the simplified helix approximation and hit-by-hit iteration methods to calculate track length which is then used for the mass reconstruction of the $\pi^\pm$, $K^\pm$ and p. The dots and error bars in Figure 1 represent mean and standard deviation of the fitted Gaussian in each momentum slice of the underlying 2D histogram. We can see a significant improvement of a new track length method in a relative error, as well as in the bias at high and below 1 GeV momentum. A precise reconstruction of the track length is directly connected with the number of available hits. In the current ILD model, the TPC readout is segmented into 220 radial pad rows, which makes 220 hit points for purely transverse tracks. Fully Si detector designs with a total number of $O(10)$ tracker hits per track might result in worse performance of the TOF pID due to the limitations from the track length resolution.

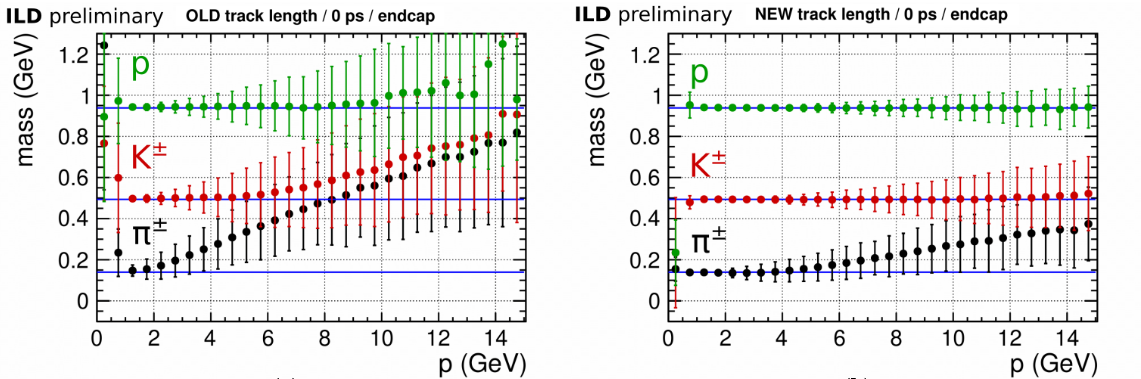

Figure 1: A comparison of the two methods to calculate the track length: (a) a simple helix approximation based on two edge points of the track and (b) the new track length reconstruction algorithm based on the hit-by-hit iteration and sum of individual segments between neighboring hits for mass reconstruction of the $\pi^\pm$, $K^\pm$ and p using the TOF method with a perfect time resolution of a single ECAL hit in the endcap of ILD.

3. Time resolution impact on the pID

We studied the TOF pID performance with different time resolution hypotheses using separation power between $\pi^\pm$ and $K^\pm$, which is defined as:

$$S_{\pi,K} = \frac{|\mu_\pi - \mu_K|}{\sqrt{(\sigma_\pi^2 + \sigma_K^2)/2}}, \tag{4}$$

where μ and σ are the mean and the standard deviation of the fitted Gaussian of the particles' reconstructed mass in a given momentum slice. To simulate time resolution per particle, we used MC truth time information of the closest ECAL hit to the track entry point in the ECAL and smeared it with a Gaussian with a corresponding assumed time resolution value. Figure 2 depicts a degradation of the separation power between $\pi^\pm$ and $K^\pm$ with larger values of the assumed TOF resolution per particle. This plot represents only the barrel region of the ECAL to keep the track length calculation part simple. Even a perfect TOF resolution (0 ps) retains particle identification above 5 GeV momentum very challenging, which indicates other sources of limitation than TOF (track length, momentum). The 10 ps TOF resolution gives a relatively similar result to the perfect time resolution, so 10 ps would be a desirable TOF resolution, while achieving TOF resolution beyond 10 ps would give only a mild improvement and might not be worth the effort for TOF pID purposes due to the technical difficulties on the hardware side. The 30 ps TOF resolution shows a degraded performance and covers only the region up to 3 GeV momentum, which gives a rough requirement for the desired TOF resolution within 10–30 ps for good particle identification.

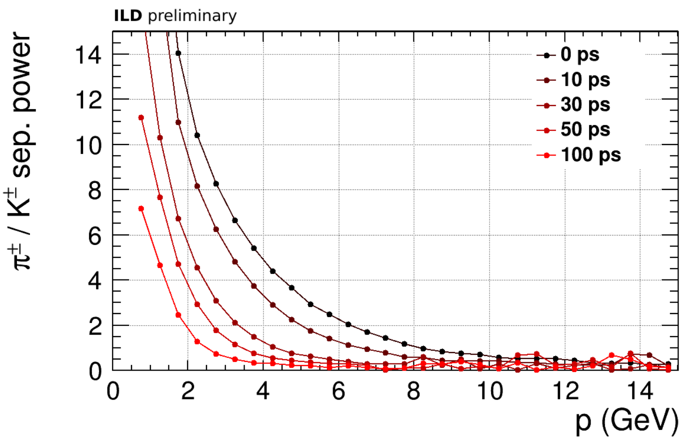

Figure 2: Evolution of separation power between $\pi^{\pm}$ and $K^{\pm}$ using the TOF method assuming different time resolutions per particle using a single ECAL hit in the barrel.

4. Three realistic implementations of time measurement at the ILD

Fast timing Si sensors, which can reach extreme time resolutions of 30 ps per hit, e.g. LGADs [9] are a perfect option for TOF pID, however, fast timing comes with a cost of higher power consumption [10], which puts a constraint on how many sensors we can put in the detector without requiring active cooling or introducing additional dead material, which will deteriorate reconstruction performance, so we have to find a compromise. We have tested three case scenarios how we could implement timing detectors inside ILD:

1. A dedicated fast-timing ECAL layer (30 ps per hit) – equipping only the first ECAL layer might be a feasible option in terms of the power consumption, while also utilizing cutting-edge hit time resolution. Potential drawbacks are having only a single time measurement per track and an additional, inhomogeneous layer in front of the ECAL.
2. Ten ECAL layers with modest timing (100 ps per hit) – while equipping ten layers with fast timing Si sensors might require additional cooling, conventional Si sensors already can reach 100 ps hit time resolution. Utilizing multiple ECAL shower hits, we can improve the final TOF resolution per particle. Later, we might use a more sophisticated algorithm to deduce TOF in the most precise way, but in our current study we use the first ten ECAL layers and in

each layer, take the closest hit to the extrapolated track line inside the ECAL. Each hit time is corrected for the traveled distance inside the ECAL, assuming speed of light and travel distance on a straight line between the track entrance point to the ECAL and the hit position inside the ECAL. Then we average the corrected hit times. The selection of hits is motivated by the fact that charged hadrons tend to leave MIP like "tracks" inside the ECAL region, before they lose too much energy, i.e. before the time, when all useful time information is lost due to stochastic shower development effects.

3. Two strips of Silicon External Tracker (SET), which is a Silicon envelope of the ILD TPC (50 ps per hit) – this option is attractive, as it has no absorber layers in front and uses two time measurements. In the ILD detector model used for this study, SET is foreseen only in the barrel, which limits this comparison only to the barrel region.

The option of a dedicated fast-timing layer can serve as the effective TOF resolution of the particle, which in the end might be comprised of different sources of uncertainty, e.g: resolution of determining the event collision time, intrinsic time resolution of the Si sensors, readout system clock frequency, synchronization among multiple detector components, as well as the time measurement information from multiple independent hits from a shower. Figure 3 presents the TOF resolution of the three approaches. Firstly, the shower effects from a single ECAL layer are negligible. While the SET does not have an inhomogeneous layer in front of it, it still does not provide any visible benefits, compared to the single dedicated ECAL layer, besides the two time measurements, which improves TOF resolution by a factor of $\sqrt{2}$. Secondly, using multiple hits from the deeper layers of the ECAL show similar improvement of the TOF resolution by a factor of $1/\sqrt{N_{\text{hits}}}$. We can observe a small bias of the central peak position and a larger tail towards the larger TOF values, which is mostly caused by the simplistic assumptions of particle propagation in the ECAL. In our case, this effect is small, but it can become larger if we want to include more ECAL hits from the further layers or include more transverse hits per layer. Also, a more realistic simulation of the hit time measurement would introduce additional effects from correlations with the hit energy and digitizer threshold, which could create a more complex pattern than a Gaussian smearing, which is done in this study to simulate different time resolution.

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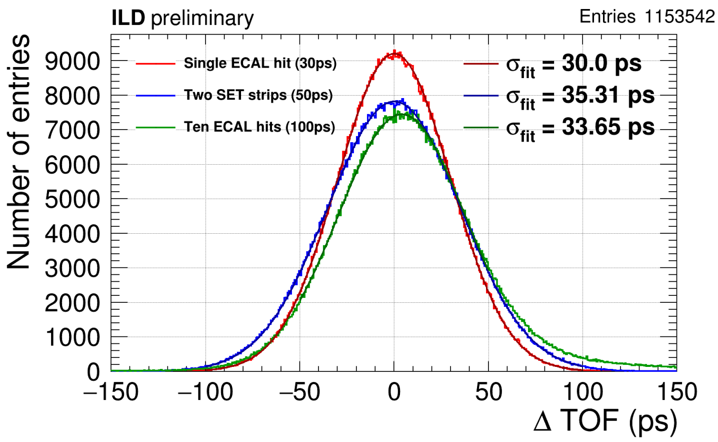

Figure 3: Similar TOF resolutions for three different approaches to measure TOF with the different hit time resolution assumptions in the ILD.

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