

1 Development of the time-of-flight particle identification 2 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 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
9 precision measurements at the future Higgs factory with an additional separation of π^\pm , K^\pm and p using the time-of-flight (TOF) technique. In this study we present our latest developments of the TOF particle identification 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 π^\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 π^\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) particle identification in the detectors with gaseous tracking, like ILD [1] or IDEA [2]. In fully Silicon detector designs like SiD [3] or CLD [4] TOF could be the only available particle identification tool. TOF particle identification 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:

$$\beta = \frac{\ell_{\text{track}}}{\text{TOF}} \quad m = \frac{p}{\beta} \sqrt{1 - \beta^2} \quad (1)$$

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:

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

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 refer to [5].

A more advanced approach would be to calculate the length of individual track segments between neighboring tracker hits using track parameters calculated by the 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].

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

2. Impact of the track length reconstruction

A measurement of a track length is one of the limiting factors for TOF particle identification. 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 thorough calculation of the harmonic mean momentum more relevant. The limitations discussed above had motivated a development of a more robust track length algorithm, which is described by

41 equations 3. This algorithm has been recently developed and integrated into the iLCSoft [8]. For
 42 our study, we used MC samples of $e^+e^- \rightarrow Z \rightarrow q\bar{q}$ process at 250 GeV collision energy with
 43 ILC beam parameters. To assess the performance of the new track length algorithm for the TOF
 44 measurement, we have used MC truth information from the closest ECAL hit to the track entry point
 45 in the ECAL. Figure 1 shows a comparison of the simplified helix approximation and hit-by-hit
 46 iteration methods to calculate track length which is then used for the mass reconstruction of the
 47 π^\pm , K^\pm and p . The dots and error bars in Figure 1 represent mean and standard deviation of the
 48 fitted Gaussian in each momentum slice of the underlying 2D histogram. We can see a significant
 49 improvement of a new track length method in a relative error, as well as in the bias at high and
 50 below 1 GeV momentum. Precise reconstruction of the track length is directly connected with the
 51 number of available hits. In the current ILD model TPC readout is segmented into 220 radial pads,
 52 which makes 220 hit points for purely transverse tracks. Fully Si detector designs with $O(10)$ total
 53 number of tracker hits per track might result in worse performance of the TOF particle identification
 54 due to the limitations from the track length resolution.

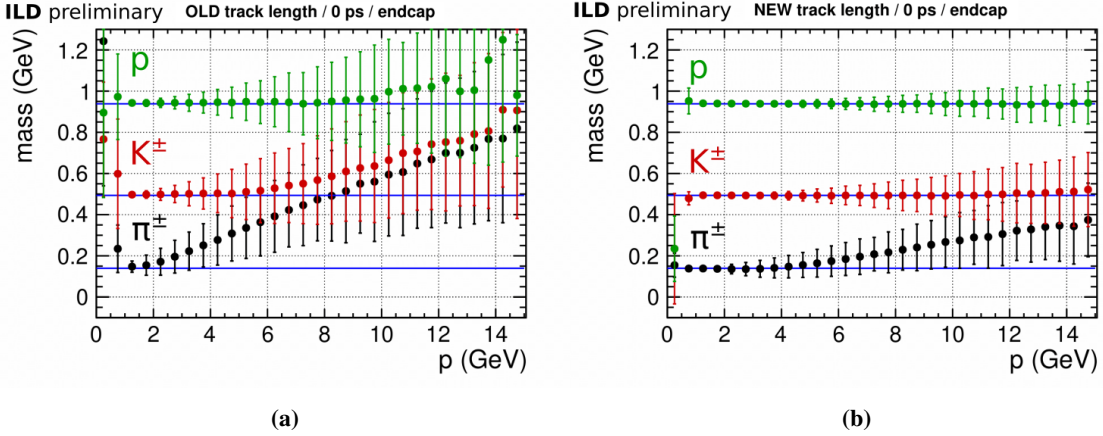


Figure 1: An improvement of the new track length reconstruction algorithm based on the hit-by-hit iteration and sum of individual segments between neighboring hits (b) compared to the simple helix approximation based on two edge points of the track (a) for mass reconstruction of the π^\pm , K^\pm and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

55 3. Time resolution impact on the particle identification

56 We studied the TOF particle identification performance with the different time resolution
 57 hypotheses using separation power between π^\pm and K^\pm , which is defined as:

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

58 where μ and σ are the mean and the standard deviation of the fitted Gaussian of the particles'
 59 reconstructed mass in the momentum slice. To simulate time resolution per particle, we used MC
 60 truth time information of the closest ECAL hit to the track entry point in the ECAL and smeared
 61 it with a Gaussian with a corresponding assumed time resolution value. We can think of it as the

62 effective TOF resolution of the particle, which in the end comes from different sources of uncertainty,
 63 e.g: σ_{t_0} , Si sensor intrinsic time resolution, readout electronic noise and synchronization among
 64 multiple detector components. Figure 2 depicts a degradation of the separation power between π^\pm
 65 and K^\pm with larger values of the assumed TOF resolution per particle. This plot represents only
 66 the barrel region of the ECAL to keep track length calculation part simple. Even a perfect TOF
 67 resolution (0 ps) retains particle identification above 5 GeV momentum very challenging, which
 68 indicates other sources of limitation than TOF (track length, momentum). The 10 ps TOF resolution
 69 gives a relatively similar result to the perfect time resolution, so 10 ps would be a desirable TOF
 70 resolution, while achieving TOF resolution beyond 10 ps would give only mild improvement and
 71 might not be worth the effort for the TOF particle identification purposes due to the technical
 72 difficulties on the hardware side. The 30 ps TOF resolution shows degraded performance and
 73 covers only region up to the 3 GeV momentum, which gives a rough requirement for the desired
 74 TOF resolution within 10–30 ps for good particle identification.

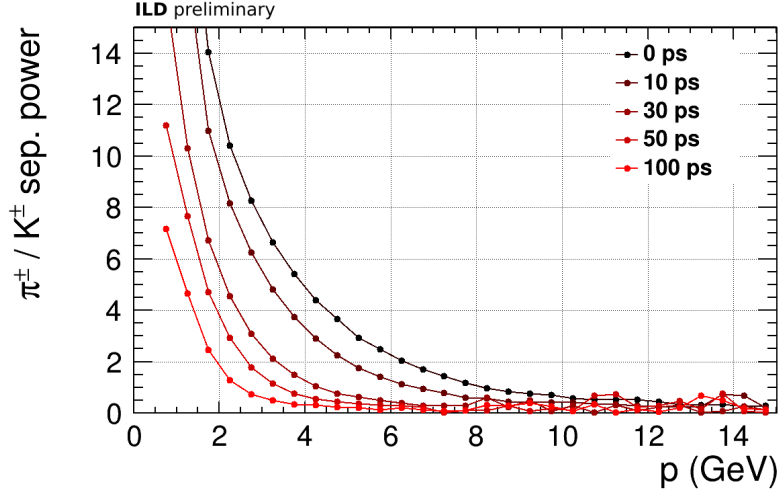


Figure 2: Evolution of separation power between π^\pm and K^\pm using TOF method assuming different time resolution per particle using a single ECAL hit in the barrel.

75 4. Three realistic implementations of time measurement at the ILD

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

- 82 1. A dedicated fast-timing ECAL layer (30 ps per hit) – equipping only the first ECAL layer
 83 might be a feasible option in terms of the power consumption, while also utilizing cutting-
 84 edge hit time resolution. The potential drawbacks that we will always have only a single
 85 time measurement per track and undesired first ECAL absorber layer in front, which might
 86 introduce some shower effects.

- 87 2. Ten ECAL layers with modest timing (100 ps per hit) – while equipping ten layers with fast
88 timing Si sensors might require additional cooling, conventional Si sensors already can reach
89 100 ps hit time resolution. Utilizing multiple ECAL shower hits, we can improve final TOF
90 resolution of the particle. Later, we might use a sophisticated algorithm to deduce TOF in the
91 most precise way, but in our current study we use the first ten ECAL layers and in each layer,
92 take the closest hit to the extrapolated track line inside the ECAL. Each hit time is corrected
93 for the traveled distance inside the ECAL, assuming speed of light and travel distance on a
94 straight line between the track entrance point to the ECAL and the hit position inside the
95 ECAL. Then we average corrected hit times. The selection of hits is motivated by the fact
96 that charged hadrons tend to leave MIP like "tracks" inside the ECAL region, before they
97 lose enough energy, which is before the time, when all useful time information is lost due to
98 stochastic shower development effects.
- 99 3. Two Silicon External Tracker (SET) strips (50 ps per hit) – this option is attractive, as it has
100 no absorber layers in front and uses two time measurements. In the ILD detector model used
101 for this study, SET is foreseen only in the barrel, which limits this comparison only to the
102 barrel region.

103 Figure 3 presents the TOF resolution of the three approaches. Firstly, the shower effects from
104 a single ECAL layer are negligible. Despite SET being in front of the ECAL, it does not provide
105 any benefits, compared to the single dedicated ECAL layer, besides the two time measurements,
106 which improves TOF resolution by a factor of $\sqrt{2}$. Secondly, using multiple hits from the deeper
107 layers of the ECAL show similar improvement of the TOF resolution by a factor of $1/\sqrt{N_{\text{hits}}}$. We
108 can observe small bias of the central peak position and a larger tail towards the larger TOF values,
109 which is mostly caused by simplistic assumptions of particle propagation in the ECAL. In our case,
110 this effect is small, but it can become larger if we would want to include more ECAL hits from
111 the further layers or include more transverse hits per layer. Also, a more realistic simulation of the
112 hit time measurement would introduce additional effects from correlation with the hit energy and
113 digitizer threshold, which could create a more complex pattern than a Gaussian smearing, which is
114 done in this study to simulate different time resolution.

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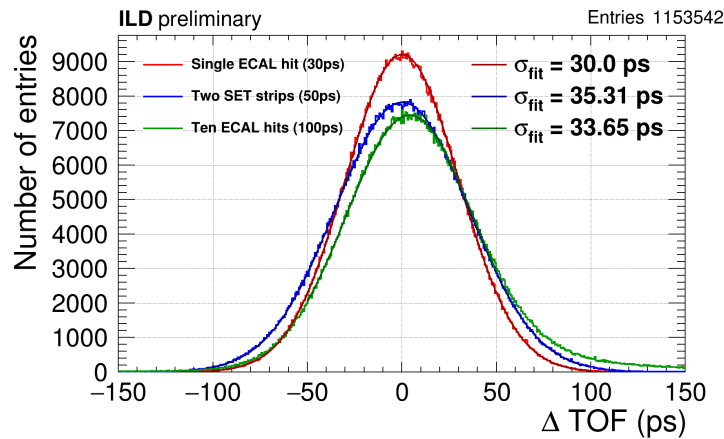


Figure 3: Similar TOF resolutions for three different approaches to measure TOF with the different hit time resolution assumptions in the ILD.

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