Developing the KinkFinder for ILD*

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Abstract. This paper presents a study on kink reconstruction for long-lived particle (LLP) searches in the Time Projection Chamber (TPC) of the International Large Detector (ILD) at a future Higgs factory. We develop improved methods to reconstruct kinks' position and associated track momenta, resulting in improved kink mass resolution. We study the perfomance for kinks from long-lived hadron decays inside the TPC.

1 Introduction

Many models of new physics predict charged long-lived particles (LLP). Such charged LLPs may decay to one charged and one or more neutral particles, producing a kinked track. For example, a chargino may decay into a Standard Model (SM) charged particle and a neutralino. The range of a LLP in the laboratory is determined by its lifetime and energy.

A typical collider experiment's tracking detector has a size of one or two metres around the interaction point. In particular, the Time Projection Chamber (TPC) of the International Large Detector (ILD) [1] covers radii between about 33 to 177 cm from the interaction point. It provides quasi-continuous tracking, measuring up to 220 positions along the trajectory of charged particles. This has the potential to efficiently identify kinked tracks, even when the kink angle is very small, or when the daughter track has a very low momentum. The TPC's capabilities are likely to be quite different to those of an all-silicon tracker.

In this study we focus on the reconstruction of kinks produced by the decay of SM hadrons inside ILD's TPC.

2 Analysis setup

2.1 KinkFinder

The KinkFinder [2] is a Marlin [3] processor run in the ILD reconstruction chain. It uses as input the tracks reconstructed by other processors. The KinkFinder considers pairs of tracks with the same charge, dissimilar momenta, and for which the distance between the end of the first track Z^1_{end} and the start of the second track Z^2_{start} is reasonably small (O(cm)). Their distance of closest approach is calculated based on fits of the first or last ten hits of the track to a helix. These helices are extrapolated to ten planes perpendicular to the detector axis z,

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equally spaced between the last hit of the first track and the first hit of the second track. The plane for which the distance between extrapolations is smallest is chosen. The vertex position is taken as the average of the two extrapolated positions in this plane, as shown in Fig. 1.

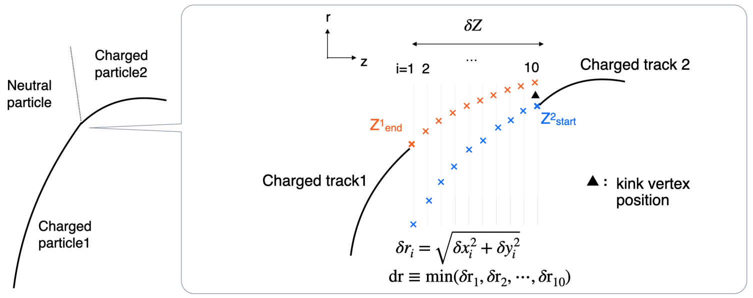


Figure 1: A schematic of the definition of the kink vertex in KinkFinder: the triangle shows the chosen vertex position.

2.2 KinkFinder efficiency

To investigate the performance of the KinkFinder, we study the decay of unstable SM hadrons within the TPC. Kaons with momentum 10 GeV were fully simulated by Geant4 in the default ILD model (ILD_l5_v02 [4]), and reconstructed by the standard ILD analysis chain. We consider events which satisfy the following:

- the Kaon decays well inside the TPC volume.: $r_{in} + 100$ mm $< r < r_{out} - 100$ mm, $|z| < z_{max} - 250$ mm, where r_{in} and r_{out} are the inner and outer radii of the TPC and z_{max} is its half-length, as shown in Fig. 2.
- the Kaon decays to a single charged daughter.

The efficiency is defined in two stages: the fraction of these events in which exactly two tracks are reconstructed, and those in which a kink is also identified. The efficiency of KinkFinder is calculated as a function of the true (Monte Carlo, MC) kink angle. The kink angle is defined as the angle between the parent and daughter directions at the kink, as shown in Fig. 3.

Figure 4 shows that the KinkFinder efficiency is about 80% when the kink angle is between 0.04 and 0.08 rad. However, the efficiency is reduced when the kink angle is smaller or larger than this range. When the kink angle is less than 0.02 rad, the efficiency of reconstructing two tracks decreases: the two particles are reconstructed as a single track. Below 0.04 rad, the efficiency of kink finding reduces, possibly due to requirement of dissimlar track momentum. When the kink angle is larger than 0.08 rad, the tracking efficiency decreases, likely due to the significantly impact parameter of the displaced second track, for which the standard track selection is not optimised.

2.3 Estimation of the kink's parent particle mass

If the mass of the kink's parent particle can be accurately reconstructed, it can help to identify kinks of both BSM and SM origin. Kinks produced by Kaon, π, and Ξ with momentum 10 GeV were studied. These were again simulated and reconstructed in the ILD_l5_v02 model.

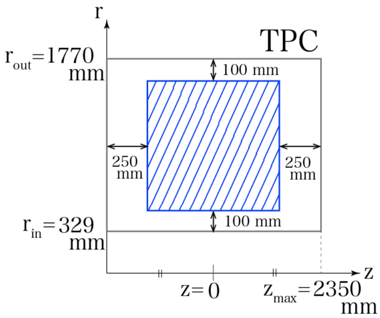


Figure 2: The 2D image for TPC area: The decay point of kaon is required to be within the blue shaded area to select interesting events.

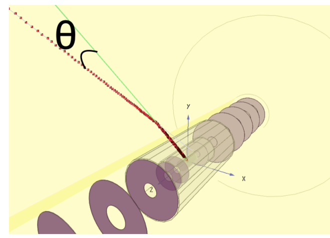


Figure 3: A schematic showing the definition of kink angle θ

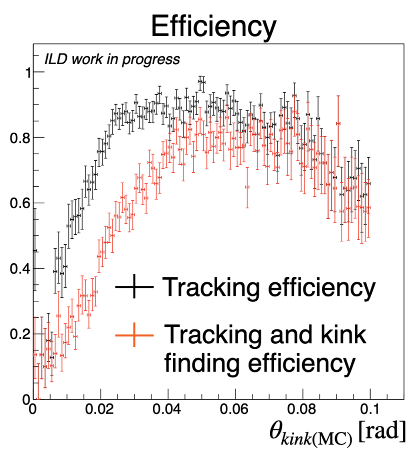


Figure 4: Efficiency dependence on the kink angle: the black points show the tracking efficiency to reconstruct two tracks. The red points show the efficiency to also find a kink, a combination of track and kink finding efficiencies.

2.3.1 Kink mass reconstruction and particle identification

The parent particle's mass, or kink mass m_{kink}, can be derived in terms of the 3-momenta (P) and masses (m) of the parent (par), charged and neutral daughters ($chg\,dau$, $neu\,dau$) using momentum and energy conservation:

$$m_{kink}^2 = \left(\sqrt{P_{chg\,dau}^2 + m_{chg\,dau}^2} + \sqrt{(P_{par} - P_{chg\,dau})^2 + m_{neu\,dau}^2} \right)^2 - P_{par}^2. \tag{1}$$

In the TPC, we can measure the momenta of the parent and charged daughter. Calculating the kink mass requires assumed masses of the charged and neutral daughter particles, $m_{chg\,dau}$, $m_{neu\,dau}$. Several mass hypotheses were considered, as shown in Tab. ??. The mass difference δm is defined as the difference between the calculated and hypothesised parent mass. The hypothesis with the smallest $|\delta m|$ is likely to be the correct hypothesis.

	$m_{\text{charged daughter}}$	$m_{\text{neutral particle}}$
$\pi^{\pm}/K^{\pm} \to \mu^{\pm}\nu$	m_{μ}	0
$K^{\pm} \to \pi^{\pm}\pi^{0}$	m_{π}	m_{π}
$\Sigma^{+}/\Sigma^{-} \to \pi^{\pm}n$	m_{π}	m_{n}
$\Sigma^{+} \to p\pi^{0}$	m_{p}	m_{π}
$\Xi^{-} \to \pi^{\pm}\Lambda$	m_{π}	m_{Λ}

Table 1: Tested kink decays in the standard KinkFinder

2.3.2 How to reconstruct vertex information

An accurate vertex position is essential to accurately reconstruct the kink mass. In standard ILD reconstruction, tracks in the TPC are built from outside to inside. Starting from the outer edge of the TPC, hits are added to a track until the track's χ^2 becomes too large. In the case of a kinked track, a few hits created by the parent track are therefore typically assigned to the daughter track. The vertex is thereby biased to a smaller radius.

We have developed a new method to get more precise and less biased vertex information. We consider TPC hits from both parent and daughter tracks. These are first fitted to a single track by using a full Kalman filter track fit with the KalTest package [5]. For each hit ("cut hit"), the other hits are split into "before" and "after" collections, depending on their position in the original track. Track fits are performed on each collection separately. If the improvement in χ^2 is sufficient, the "cut hit" which results in the smallest total χ^2 (the sum of the two tracks' χ^2) is chosen as the point to separate the two tracks. The "cut hit" is assumed to be at the reconstructed vertex position.

2.3.3 How to reconstruct momentum information

In the KinkFinder, the helix is calculated using the last (first) ten hits of the parent (daughter) track. The momenta are taken from the helix state at the last (first) hit. To improve the method, all hits are used to perform a full Kalman filter track fit for parent and daughter tracks. The momentum of a fitted track at its closest approach to the reconstructed kink vertex is used. The critical difference is getting momenta at a common point in this new method.

2.3.4 Comparison of δm distributions

The δm distributions are estimated in three scenarios: standard KinkFinder, using the true MC vertex position, and using these new methods for momentum and vertex reconstruction, as illustrated in Fig. 5. Figure 6 shows these three methods' resulting δm distributions for Kaon, π, and Ξ decays. In the case of Kaon and π, both the widths of the main peaks and the tails of these distribution are significantly improved. In the case of Ξ, the width of the main peak is also reduced and the mass bias slightly improved. Considering the results of using the true MC vertex, it is clear that futher improvements may be possible.

3 Summary

Kinked tracks are a possible signature of LLPs. In the case of Kaons with momentum 10 GeV, the Kinkfinder efficiency is about 80% when the kink angle is between 0.04 and 0.08 rad. Improved methods to reconstruct the vertex position and track momenta were developed, resulting in improved mass resolution. Future plans include improving the efficiency at small and

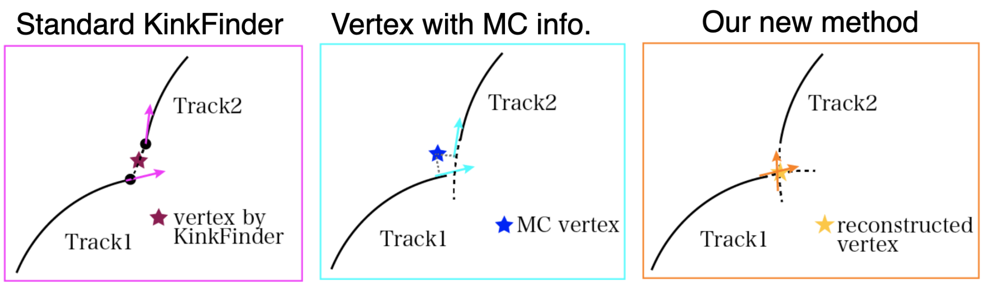
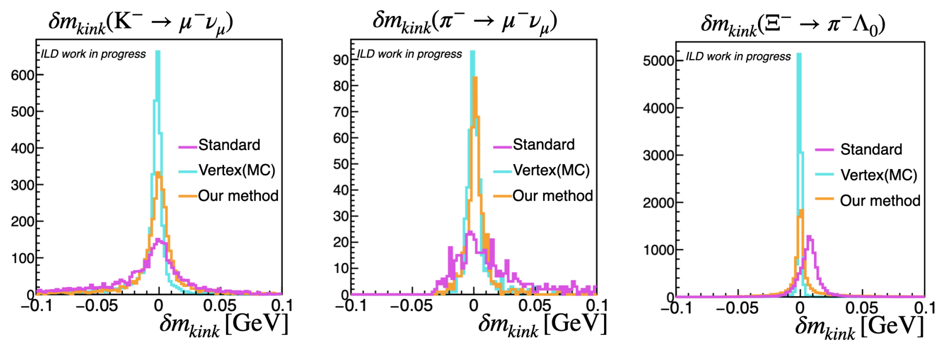


Figure 5: The respective methods to determine momentum and vertex



(a) kaon (b) pion (c) Xi

Figure 6: Mass distributions for Kaon, π, and Ξ using the three methods described in the text. The colors correspond to those of Fig. 5.

large kink angles and kinematic vertex fitting, as well as studying a wider range of momenta and SM and BSM LLPs. Finally, the results will be interpreted in the context of several BSM models.

References

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[4] https://github.com/key4hep/k4geo/blob/main/ILD/compact/ILD_l5_v02

[5] https://github.com/iLCSoft/KalTest