



# Long-Lived Particle Reconstruction at CLIC

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## Abstract

Several Beyond Standard Model theories predict the existence of particles whose lifetime is at the millimeter scale. If generated in a high energy collider, these particles could live long enough to travel in the detector tracking system for a few centimeters. Before decaying, they could leave several detectable hits, that can be clustered by the algorithms into a stub track. Hence, the search of long-lived particles (LLPs) is very well-motivated in high energy colliders with high-resolution tracking detectors and robust reconstruction algorithms. The proposed future  $e^+ e^-$  linear collider CLIC provides the perfect environment for the search of these particles, thanks to the lack of QCD-background and its detector low material budget. The presented work tested the CLIC third stage ( $\sqrt{s} = 3$  TeV) reconstruction performances, analyzing simulated stub tracks originating from LLP pair production. In particular, the particles involved were charginos with lifetime  $c\tau \approx 600$  mm and mass  $m \approx 1.5$  TeV. LLP tracks were found to be reconstructable in more than 90% of the cases in the detector central region.

*Summer Student Report 2019*

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## Introduction

The request of searching new physics beyond the Standard Model (SM) is well-supported by the existence of dark matter, neutrino oscillation and other observed phenomena not explained by the theory [1]. Both High-Luminosity LHC and the proposed future colliders are designed to be sensitive to a large set of experimental signatures, that are supposed to be manifestations of the Beyond Standard Model (BSM) physics. Among them there are disappearing tracks, due to particles that decay in between the tracking layers with small phase spaces or small coupling constants. For this reason, these particles are said to be long-lived.

A long-lived particle (LLP) candidate is the chargino ( $\tilde{\chi}_1^\pm$ ), that decays into a neutralino ( $\tilde{\chi}_1^0$ ) and a charged pion with a lifetime  $c\tau$  of about 7.6 mm. The narrow phase space, due to small mass difference between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  ( $\approx 355$  MeV) compared to the chargino mass ( $\approx 1.1$  TeV), causes the chargino to be long-lived and the emitted pion to be very soft.

If the chargino is produced in a collider bunch crossing, it may be long-lived enough to travel in the tracking system for a detectable distance. A stub track is produced whenever the chargino crosses enough tracking layers, before decaying. Therefore, analysis on charged LLPs are generally associated to disappearing tracks searches.

According to preliminary studies [2], the proposed future linear lepton collider CLIC at its third energy stage ( $\sqrt{s} = 3$  TeV) should be sensitive to the thermal higgsino (mass  $m \approx 1$  TeV) discoveries by stub tracks searches: Also for the search of one stub track only (Fig. 1). For this reason the search of LLP signatures at CLIC is very well-motivated.

This work is focused on the analysis of LLP track reconstruction performances, in terms of efficiencies and background discrimination. In Section 1 the description of the CLICdet tracking system is provided, while in Section 2 the employed track reconstruction method is explained. Then, in Sections 3 and 4 the analysis on the tracking performances of simulated events is detailed. Finally, in Section 5 a possible stub track analysis through kinematics cuts selection is reported.

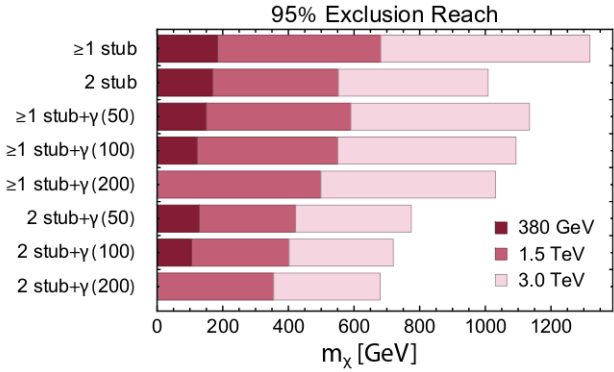


Figure 1: Higgsino search from stub tracks (from [2]). At its third energy stage, CLIC will be sensitive to the thermal higgsino ( $m_{\tilde{\chi}} \approx 1$  TeV).

## 1 CLICdet Tracking System

The CLICdet all-silicon tracking system is divided into two subdetectors: the Vertex and the Tracker. The Vertex detector consists of three barrels in the central region and silicon petals arranged in spirals in each forward ones. The spiral forward disk geometry is designed for a better cooling performance, since the vertex is supposed to be cool down through simple air flow. Thanks to this technique, the detector material budget is restricted, reducing the non-sensitive regions and hence improving the particle detection. On the other hand, the Tracker consists of 6 barrels and 11 endcaps per side (Fig. 2). The whole CLICdet tracking system has a single point resolution at the order of few micrometers.

Assuming a life-time of 7.6 mm and including the expected boost effects at  $\sqrt{s} = 3$  TeV, the chargino would have the life-time distribution illustrated in Figure 3. Therefore, 0.03% of the chargino, produced at  $90^\circ$  polar angle, should cross the three vertex double layers before decaying.

Since the purpose of this study is the analysis of stub tracks reconstruction performances, chargino

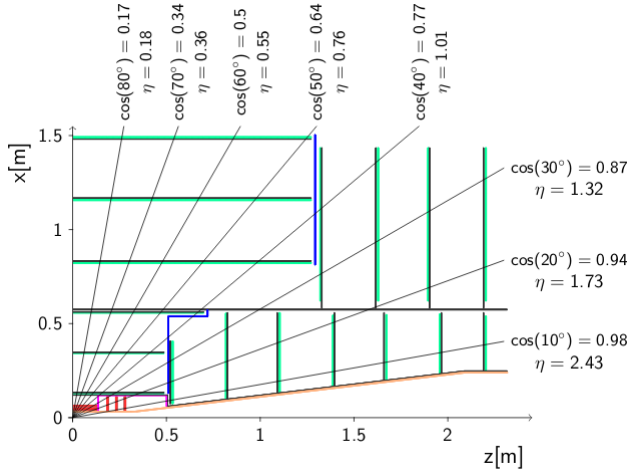


Figure 2: A quarter of the CLICdet tracking system in the  $(x, z)$  plane divided into polar angle slices (from [3]). the Vertex is depicted in red, the Tracker in green.

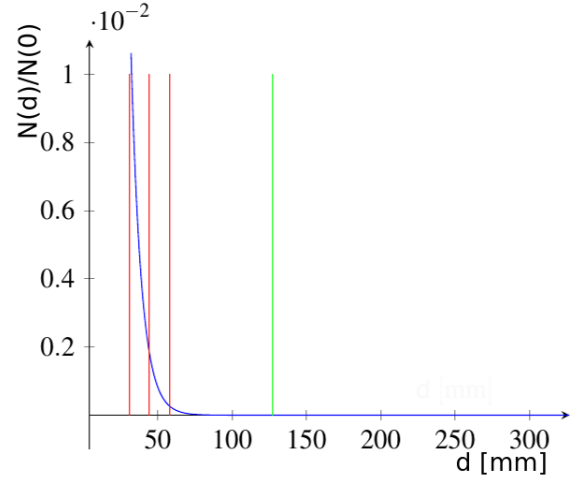


Figure 3: Chargino life-time distribution with the position of the tracking system layers (the Vertex is depicted in red, the Tracker in green), for a polar angle at about  $90^\circ$ .

particles were simulated with a life-time of 600 mm: In this way the probability for a stub track to leave more than 4 hits was incremented and the analysis benefited from an increased statistics. For this reason, if one is interested in what is the impact of this work on the theoretical thermal higgsino, the presented results should be reweighted as to obtain the theoretical life-time parameter.

## 2 Track Reconstruction at CLICdet

Conformal Tracking is the tracking algorithm employed at CLICdet. It performs pattern recognition in the conformal plane, reconstructing particles produced at the interaction point and in displaced points [3]. The former are called *prompt tracks*, while the others *displaced tracks*.

A charged particle passing through pixels layers ionizes their sensitive material, producing in most of the cases a readable electronic signal. A pixel in on state is associated in the simulation software to a hit of a certain position defined by its global coordinates  $(x, y, z)$ . For every bunch crossing several particles are produced. Most of them leave hits in the tracking system. Every hit, projected in  $(x, y)$  plane, is translated by the tracking algorithm into a point of the conformal plane  $(u, v)$  according to the following mapping:

$$u = \frac{x}{x^2 + y^2}, \quad v = \frac{y}{x^2 + y^2}. \quad (1)$$

In this plane, prompt particles bent by the CLICdet solenoidal magnetic field are transformed in straight lines. After this transformation, the reconstruction of particles consists of grouping points aligned along the same straight direction (Fig. 4). In order to reduce the amount of bad-quality tracks, a requirement on the number of hits is applied: A minimum of four hits for prompt tracks and of five hits for displaced tracks is required [3] [4].

Particles are then reconstructed and identified through the PandoraPFA particle flow algorithm, that combines the information on tracks, calorimeter clusters and energy deposit in the muon system [5].

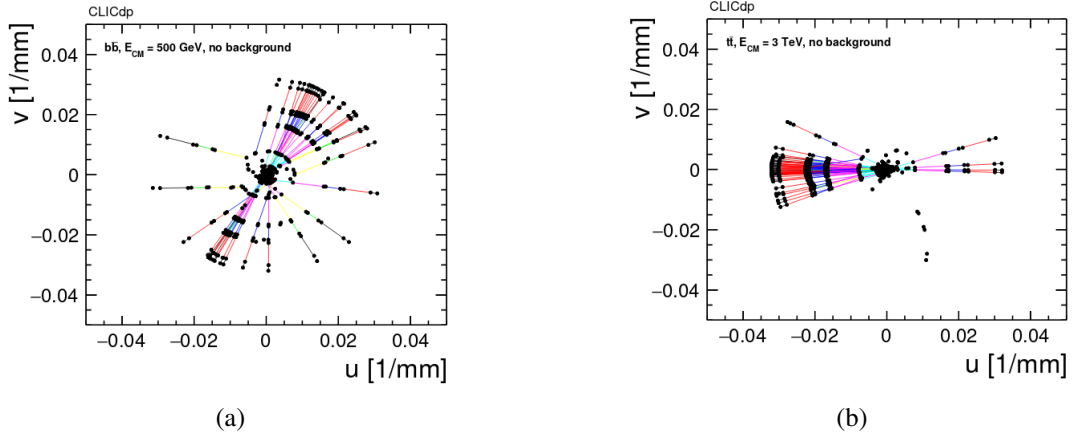


Figure 4: Track candidates reconstructed by the conformal tracking algorithm in CLICdet in the case of a single  $b\bar{b}$  event at 500 GeV center-of-mass energy (a) and a single  $t\bar{t}$  event at 3 TeV (b) [3].

### 3 Simulated Event Sample

The study is based on the analysis of data simulated with Whizard, Pythia6 and GEANT4. Simulation specifications are illustrated in Table 1. The chargino life-time was overestimated for statistical reasons: At the end, the analysis results should be reweighted to the physical chargino life-time distribution.

Two 50000 events data sets have been analyzed: The first one involves only the signal, the second one was overlaid to  $\gamma\gamma \rightarrow$  hadrons beam-induced background events, since it is supposed to be one of the main sources of background to the process. From this point onward, the first data-set will be labeled as *signal-only* sample and the second one as *signal + overlay* sample.

Table 1: Parameters of the simulation.

| Beam characteristics (at $\sqrt{s} = 3$ TeV)          | Physical parameters             |
|-------------------------------------------------------|---------------------------------|
| Beamspectrum [6]                                      | Chargino mass: 1050 GeV         |
| Initial state radiation (ISR)                         | Neutralino mass: 1049.645 GeV   |
| Negative electron beam polarization: $P(e^-) = -80\%$ | Chargino mean life-time: 600 mm |

### 4 Tracking Performances

In the ideal case, all the particles produced in a collision are seen and identified by the detectors. However, the physical detectors cannot completely cover the  $0-360^\circ$  range, because of the beam pipe. For this reason, the detection of a particle is always related to an efficiency parameter, which is the product of the detector acceptance and the detector efficiency. In this work the Tracking detector efficiency was computed counting the reconstructed tracks over all the tracks not eliminated for detector acceptance and with at least 4 hits (reconstructable tracks).

Tracking performances were checked both for the charginos and for the emitted looping pions. In general, reconstructed track parameters and efficiencies revealed good performances of the algorithms.

#### Chargino Reconstruction

Because of their short nature, chargino tracks represent a challenge for the reconstruction algorithm. For the signal-only sample, the algorithm showed good performances in terms of polar and azimuthal

angles (Fig. 5(a) and Fig. 5(b)), while it presented limitations in terms of  $p_T$  (Fig. 5(c)), due to the vertex pixel single point resolution that determines the maximum reconstructable sagitta<sup>1</sup>. This was also demonstrated by the scatter plot between track  $p_T$  residue (difference between reconstructed and simulated values) and number of hits, presented in Figure 5(d): For tracks with few hits, the residue in transverse momentum results in a wider distribution.

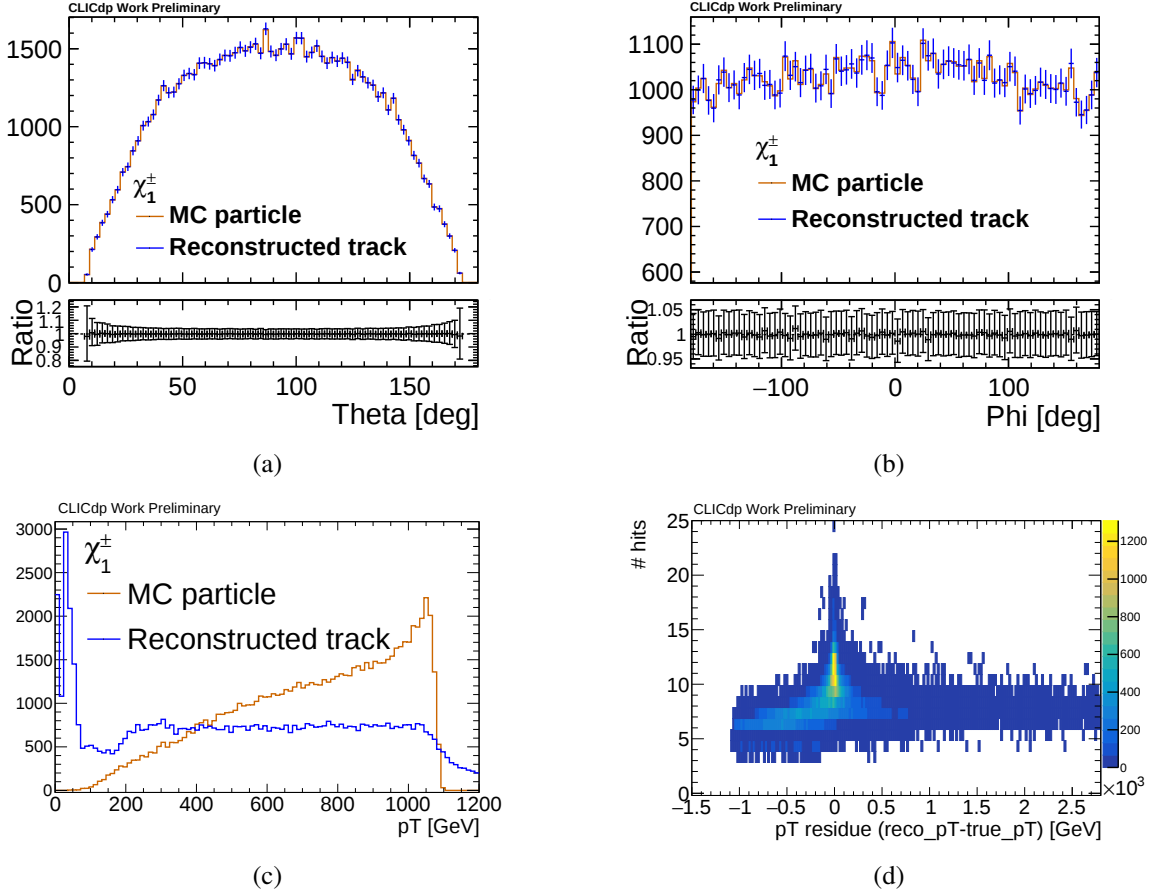


Figure 5: Comparisons between reconstructed and simulated chargino parameters.

The reconstruction efficiency resulted in more than 90% in the central detector region (Fig. 6(a)) and for high transverse momentum ( $p_T$ ) tracks (Fig. 6(b)) for both the data sets.

## Pion Reconstruction

Also pions constitute a challenge for the reconstruction algorithm, since they are soft and hence they loop in the tracking system. A preliminary analysis on pion reconstruction showed an unexpected peak in the central detector region (Fig. 7(a)): A deeper investigation revealed the presence of multiple tracks associated to the same simulated particle, in particular for those produced at about  $90^\circ$  polar angle. Figure 7(b) shows the polar angle distribution, after the selection of the best reconstructed track per simulated particle, i.e. the one with best reconstructed polar angle. The plot in Figure 7(b) still presents an excess of counts in the central region, not yet investigated.

The association of multiple tracks per MC particle occurs mainly in the central polar angle region. This is due to the number of hits that the particle leaves in the detector: The closer the polar angle emission to

<sup>1</sup>Transverse momentum formula  $p_T$  evaluation formula:  $p_T = 0.3B \frac{(d/2)^2 + s^2}{2s}$ , where  $B$  is the magnetic field intensity,  $d$  is the distance between first and last hits on the track and  $s$  the sagitta [7].

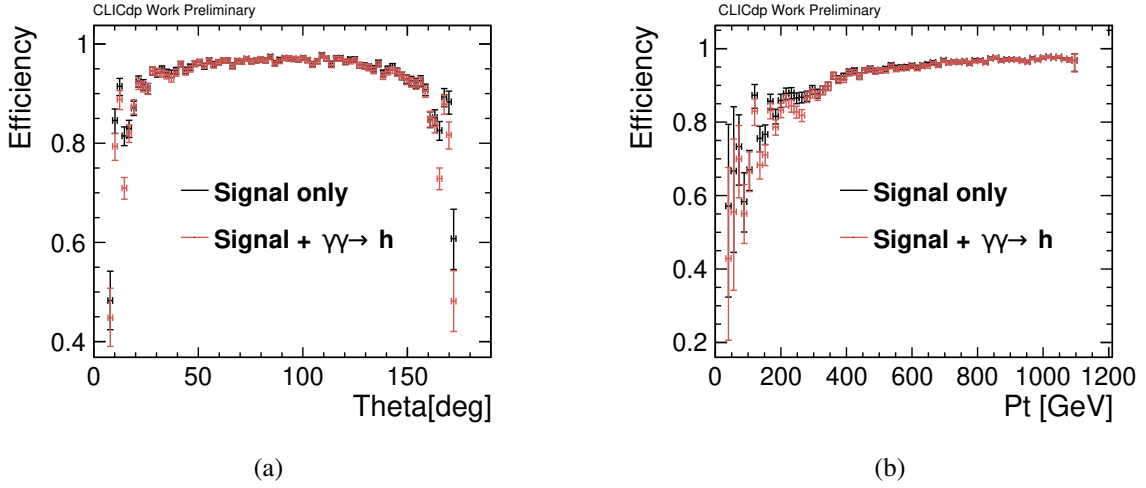


Figure 6: Tracking efficiency as a function of polar angle (a) and transverse momentum (b) (signal-only in black, signal + overlay in red)

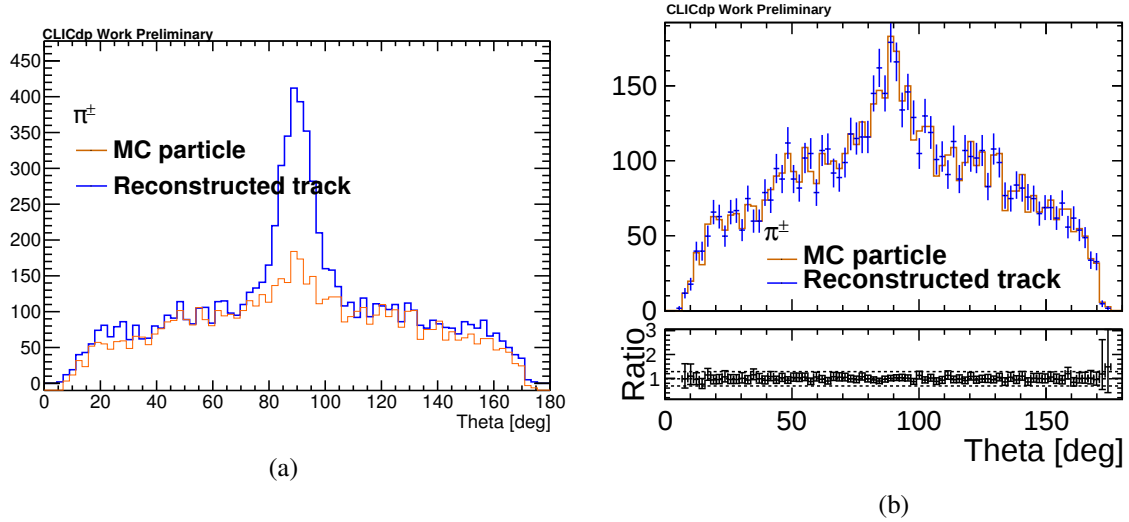


Figure 7: Pion polar angle distribution. (a) shows an excess of counts for the reconstructed tracks in the central detector region: This reveals the presence of duplicates. (b) presents the distribution counting one reconstructed track per MC particle.

$90^\circ$ , the slower the particle in the motion along the  $z$  axis, which allows the trajectory to have more loops in the detector (Fig. 8) and hence to leave more hits in the tracking system region. For a large hit number, the track has high probability to be sliced in pieces, associating multiple tracks to the same simulated particle.

Furthermore, an anticorrelation was found between reconstructed and simulated polar angle (Fig. 9). A possible explanation for this phenomenon, is the pion helix-flipping resulting from the algorithm reconstruction.

The algorithm reconstruction efficiency for pion tracks resulted in more than 6% in the detector central region and for track with higher  $p_T$  for both the data sets. More precisely, the signal + overlay sample presented a reduced reconstruction efficiency for forward detector regions (Fig. 10).

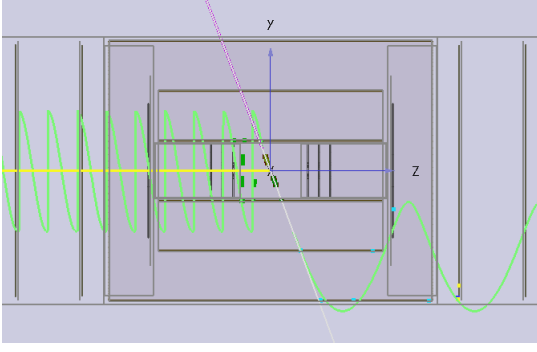


Figure 8: Screenshot of a chargino pair production simulated event. The trajectories of motion of MC decay produced pions are illustrated in green. A  $\approx 90^\circ$  polar angle emission allows the pion to loop more inside the detector region and hence to leave more hits in the tracking system.

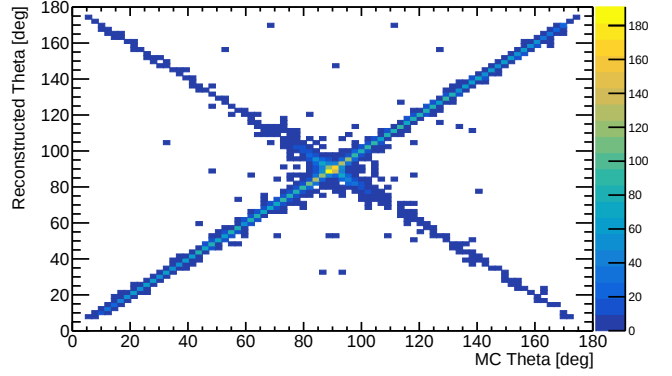
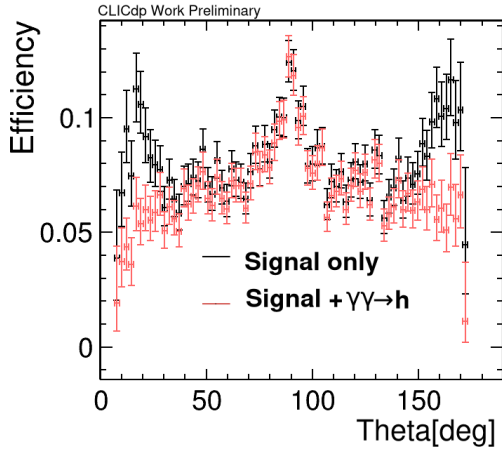
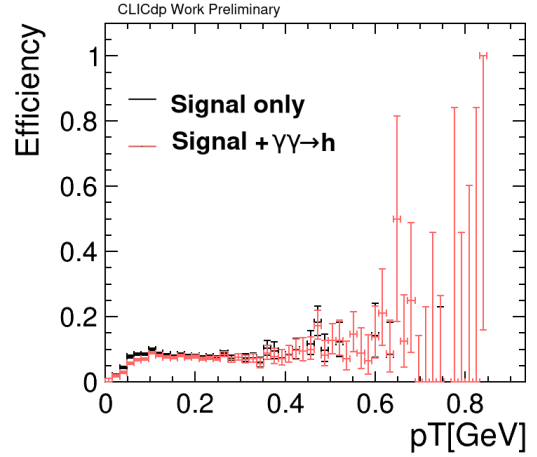


Figure 9: Scatter plot between reconstructed and simulated pion polar angle. Besides the expected correlation between the variables, there is a clear anticorrelation structure. It may be due to pion helix-flipping resulting from the tracking algorithm.



(a)



(b)

Figure 10: Tracking efficiency as a function of polar angle (a) and transverse momentum (b): more than 6% of the tracks in central theta region are reconstructed in both data samples (signal-only in black, signal + overlay in red).

## 5 Analysis

The analysis strategy for long-lived charginos is the creation of a good definition for the stub track candidate (signal selection) and then the study of background events surviving the imposed cuts. The  $\gamma\gamma \rightarrow \text{hadrons}$  background results in many hits in the tracking system, thus it could cause confusion in the pattern recognition. For this reason, the signal + overlay sample was studied: It gives an idea of the background behavior, even if it is not correctly normalized.

### Signal Selection

A good definition of stub track is the one that maximizes the efficiency of recognizing a chargino track and minimizes the number of fakes at the same time. Hence, the signal selection process is based on the

definition of cuts that discard most of the background and least of the signal.

In contrast to most of the background tracks, stub tracks are short, isolated, prompt tracks that are not associated to any calorimeter cluster nor signals in the muon chambers. For this reason, the following variables were investigated:

- *Promptness*:  $\sqrt{D0^2 + Z0^2}$
- No PFO association (particle flow object)<sup>2</sup>
- Kinematics:  $p_T$  requirements
- Isolation:  $\Delta R = \sqrt{\Delta\phi^2 + \Delta\theta^2}$
- Energy deposition:  $\langle dE/dx \rangle$

The plots in Figure 11 illustrate the chargino track distributions in comparison with the  $\gamma\gamma \rightarrow$  hadrons ones, as functions of the parameters enlisted above. At first glance, the most important variables seem to be: the promptness, the lack of associated PFO and the transverse momentum. The proposed cuts are the following:

- $\sqrt{D0^2 + Z0^2} < 0.5$  mm
- No PFO association
- $p_T > 10$  GeV

No cut on energy deposition is proposed, since the analysis for this parameter is based on MC information, and the pixel energy resolution is not known yet.

### Cuts Performances

A study on the efficiency of the cuts of signal + overlay was performed by looking at the polar angle distribution of the survived tracks and the chargino ones at the same time. Figure 12 and Table 2 report the results of this analysis.

The cut with the largest impact is that on the transverse momentum: In particular, the fake stub tracks are characterized by a forward polar angle. Hence, to first approximation, they could be removed by applying a polar angle requirement.

Table 2: Results of efficiency studies in the sample of 50k events of signal + overlay.

| Cut                                    | $\sqrt{D0^2 + Z0^2} < 0.5$ mm | no PFO association | $p_T > 10$ GeV | all cuts |
|----------------------------------------|-------------------------------|--------------------|----------------|----------|
| Number of MC charginos ( $NC$ )        | 81891                         | 81891              | 81891          | 81891    |
| Number of candidates ( $C$ )           | 13784412                      | 3384475            | 105302         | 67928    |
| Candidates that are charginos ( $CC$ ) | 81496                         | 69750              | 79751          | 67756    |
| Efficiency (%) = $\frac{C}{NC} * 100$  | 99.5                          | 85.2               | 97.4           | 82.7     |
| Fake (%) = $\frac{C-CC}{C} * 100$      | 99.4                          | 97.9               | 24.3           | 0.3      |

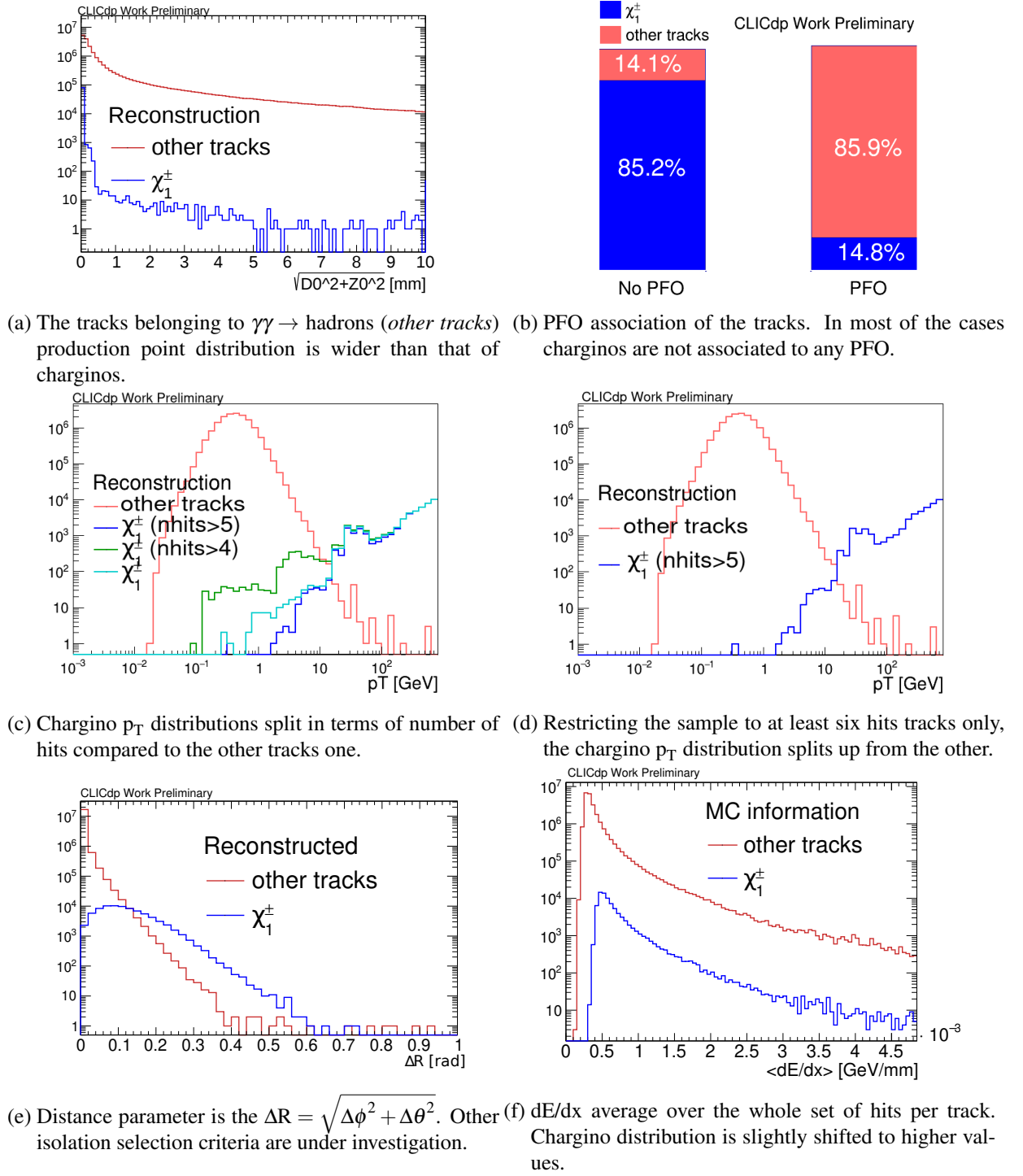


Figure 11: Chargino tracks parameters values in comparison with the tracks generated by the  $\gamma\gamma \rightarrow \text{hadrons}$  (*other tracks*). The normalization of both curves is arbitrary.

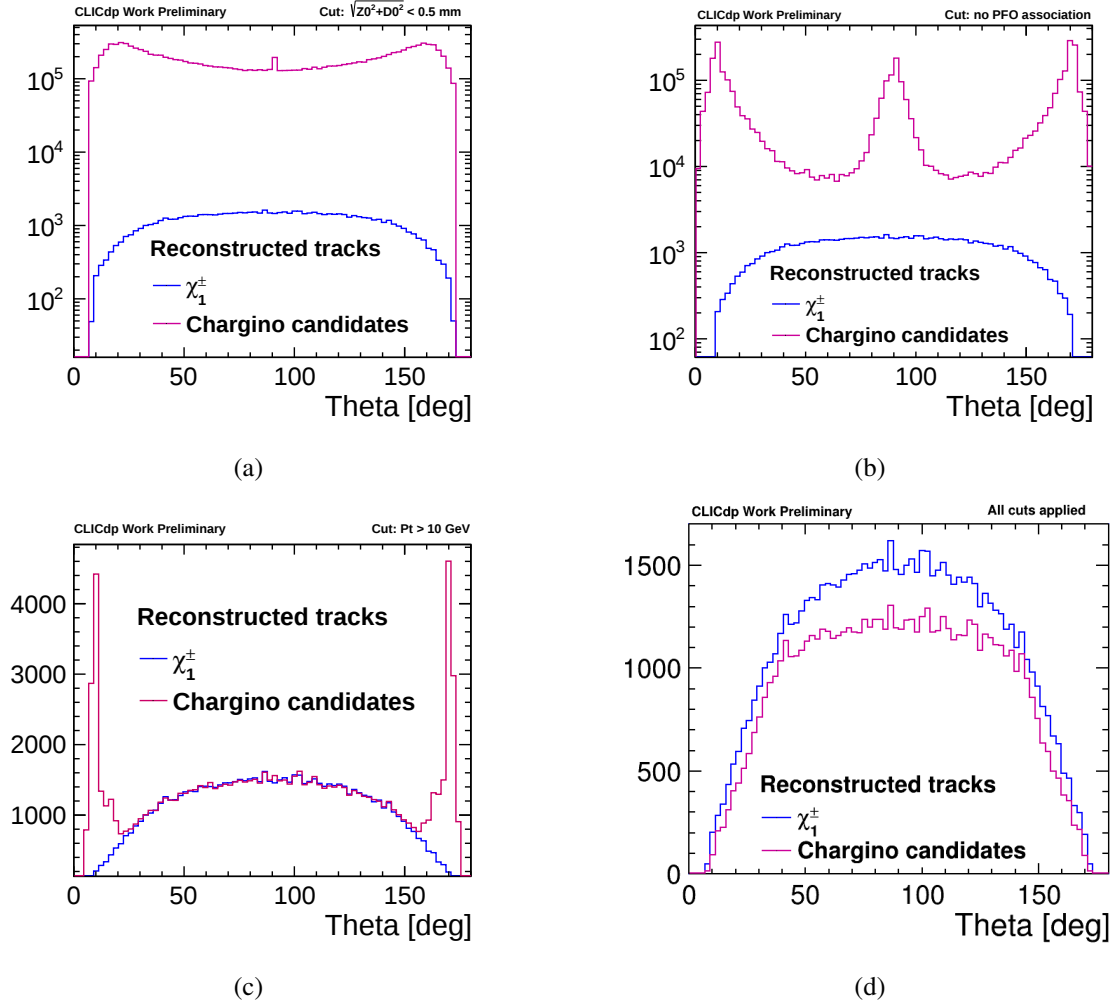


Figure 12: Polar angle distribution of stub tracks candidates, selected with the discussed cuts, compared with that of MC charginos.

## Background

For background studies, a data set of  $125k \ e^- e^+ \rightarrow \nu_e \bar{\nu}_e$  events without initial state radiation were simulated and overlaid to  $\gamma\gamma \rightarrow \text{hadrons}$  tracks. Applying the proposed signal selection cuts on this background-only sample, only 400 tracks were selected. In particular, in Figure 13(a) their mean energy deposition distribution is reported. If the tracking system pixel would allow an analysis of this kind in terms of energy resolution, fake stub tracks could be easily removed by applying a requirement on  $\langle dE/dx \rangle$ . From Figure 13 follows that an effective requirement could be  $\langle dE/dx \rangle > 0.5$  MeV/mm, which would allow to remove most of fake tracks and the minimum of the signal.

## Conclusion

This study has well enforced the motivations for LLP searches at high energy lepton colliders equipped with powerful tracking systems and robust reconstruction algorithms. In particular for CLIC, the tracking

<sup>2</sup>A PFO is an object reconstructed by the Pandora Particle Flow algorithm. For tracks with  $p_T > 1.5$  GeV, a PFO always requires some cluster in the calorimeters.

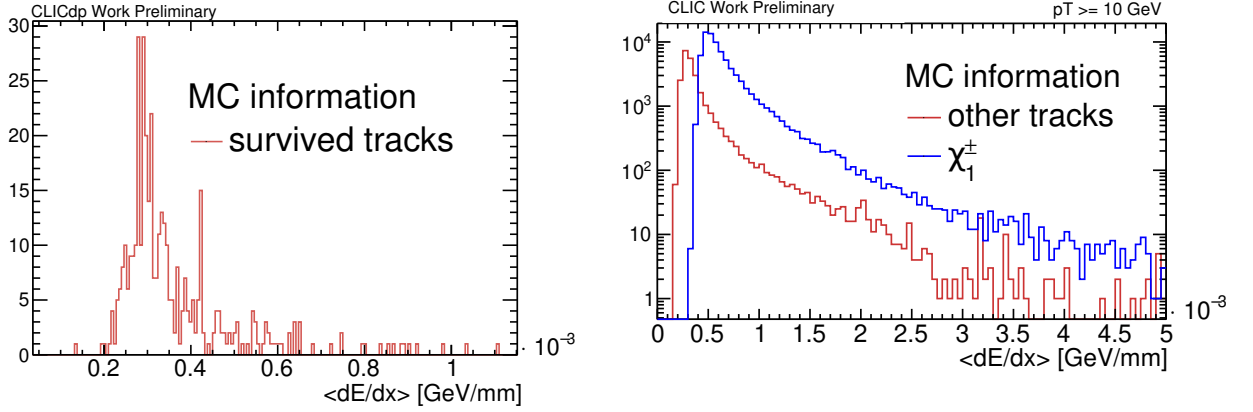
(a) Fake stub tracks  $\langle dE/dx \rangle$  distribution.(b) Same plot of 11(f) with the additional cut on transverse momentum ( $p_T > 10$  GeV).

Figure 13: Fakes in (a) could be removed by requiring a minimum  $\langle dE/dx \rangle$  value, for instance 0.5 MeV/mm, that results to be a good cut also for the chargino selection (b).

reconstruction efficiency resulted in more than 90% in the tracking central region for chargino tracks with a  $c\tau$  of 600 mm.

In order to analyze the discovery power for the thermal higgsino searches the results reported should be reweighted to the physical chargino life-time. This operation would firstly decrease the expected event yield for this signal and then reduce the signal-background discrimination power of the given cuts. Therefore, the stub track selection criteria have to be re-optimised for the reweighted sample. An additional handle for the background suppression is the matching between the chargino stub track and the displaced pion one. Therefore, this should be studied in the future.

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