Disappearing Tracks in ATLAS Searches for Electroweak Dark Matter

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Surrounding the interaction point at the center of the ATLAS detector, the Inner Detector measures the passage of charged particles and reconstructs their trajectories. It consists of several tracking subsystems: in the barrel, charged particles first cross four layers of the silicon Pixel detector, followed by the silicon-strip Semiconductor Tracker (SCT), and lastly the Transition Radiation Tracker (TRT). As charged particles traverse these layers, they leave localized measurements, known as hits, which are combined to reconstruct their trajectory and momentum. Standard ATLAS track reconstruction requires at least seven silicon hits. The searches discussed in my doctoral project instead focus on particles that decay after traversing only three or four layers of the Pixel detector, producing a short track that disappears before reaching the SCT.

Such signatures can arise in models that introduce new electroweak particles. These particles can form electroweak multiplets containing both charged and neutral states that are nearly mass-degenerate. This occurs, for example, in Minimal Dark Matter and in supersymmetric models. The neutral state can provide a dark matter candidate, while the slightly heavier charged state may be long lived on detector scales. It can therefore travel through several layers of the tracker before decaying into the neutral state and a low-momentum pion. Since the neutral particle escapes the detector and the pion is often too soft to be reconstructed with standard reconstruction techniques, the only visible signature may be the short track left by the charged particle before it decays.

The mass splitting sets the lifetime of the charged state and therefore how far it typically travels through the tracker, making the exact detector signature dependent on the underlying model. Within supersymmetric models, two particularly relevant cases are wino-like and higgsino-like electroweakinos. These scenarios differ in the composition of the charged and neutral states and, as a result, in the mass splitting between them. For a pure wino, the splitting is about 160 MeV, corresponding to a chargino lifetime of about 0.2 ns, while for a pure higgsino the larger splitting of roughly 280 - 350 MeV gives much shorter lifetimes of about 0.03 - 0.05 ns.

While dedicated reconstruction is needed to recover short tracks, or tracklets, the main experimental challenge in disappearing track searches is the suppression and estimation of backgrounds that can mimic the signal. Electrons, muons and hadrons may appear as short tracks after interacting with detector material, while unrelated Pixel hits can be combined into fake tracklets. The latest ATLAS Run-2 disappearing track analysis introduced dedicated tracking techniques to extend the sensitivity to shorter lifetimes. A second-pass reconstruction was used to recover tracklets with as few as three Pixel hits, and a dedicated algorithm was introduced to reconstruct the low-momentum pion from the chargino decay. Improved track-quality requirements, including a veto on calorimeter energy associated with the tracklet, provided additional background rejection. These developments were especially relevant for shorter-lived higgsino-like charginos. I joined this analysis during its final stages, becoming familiar with its strategy and results before moving on to the next disappearing track analysis using Run-3 data.

No significant excess over the Standard Model (SM) expectation was observed. For the mass splittings predicted in the pure-wino and pure-higgsino scenarios, wino-like charginos were excluded up to masses of 670 GeV, while higgsino-like charginos were excluded up to 225 GeV. The much shorter lifetime of the higgsino scenario makes this region particularly challenging for disappearing track searches.

Currently, my work is focused in an analysis that takes a complementary approach, combining disappearing track reconstruction with the specific ionization energy loss, dE/dx, measured in the Pixel detector. It uses the full Run-2 dataset together with the first part of Run 3, collected between 2022 and 2024, and is the first ATLAS search to combine these two techniques. Wino-like particles are more likely to traverse all four Pixel layers before decaying, so their hits can provide not only the disappearing track signature but also information about the particle's ionization. Heavy charged particles can have lower velocities than Standard Model particles of the same momentum and consequently deposit more energy in the silicon, producing an anomalously large dE/dx. Combining these two observables provides additional sensitivity to the wino-like regime, with preliminary studies indicating sensitivity beyond that of the Run-2 disappearing track search at the ~ 0.2 ns wino lifetime.

Looking further ahead, disappearing track searches will eventually have to adapt to a different tracking detector. For the High-Luminosity LHC, the current Inner Detector will be replaced by the all-silicon Inner Tracker (ITk). In the current detector, a particle reaching a radius of about 88.5 mm can already leave three Pixel measurements, while four measurements require it to reach about 122.5 mm. In the ITk barrel, the third and fourth Pixel layers will instead lie at approximately 160 mm and 228 mm. A short-lived particle must therefore survive substantially farther from the interaction point to leave the same number of Pixel measurements. This poses an important question for the future of disappearing track searches: how can the sensitivity gained for very short-lived particles, particularly higgsino-like electroweakinos, be retained with the ITk geometry?