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Identifying Merged Clusters in the ATLAS Strip Detector

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Abstract. Tracking in high density environments, particularly in high energy jets, plays an important role in many physics analyses at the LHC. In such environments, there is significant degradation of track reconstruction performance. Between runs 1 and 2, ATLAS implemented an algorithm that identifies pixel clusters originating from multiple charged particles (merged clusters), using charge information, resulting in the recovery of much of the lost efficiency. However, no attempt was made in prior work to identify merged clusters in the semiconductor tracker (SCT), which does not measure charge information. In spite of the lack of charge information in SCT, a merged-cluster identification algorithm has been developed in this work. It is based primarily on the difference between the observed cluster width and the expected cluster width, which is derived from track incidence angle. In simulation, allowing merged strip clusters to be shared increases tracking efficiency in dense environments at the cost of an increase in the fake-track rate.

1 Introduction

Charged particle tracking with the ATLAS detector [1] utilizes the ATLAS inner detector, which comprises multiple layers of silicon pixel detectors [2, 3], double sided silicon strip detectors (SCT) [4], and the transition radiation tracker [5]. When charged particles create charge deposits (hits) in adjacent pixels or adjacent strips, the hits are grouped together into clusters. By using the clusters' radial positions and matching clusters on two sides of SCT modules, pixel and strip clusters are interpreted as space-points, and sets of space-points are combined into track-seeds [6]. A collection of track-candidates for the event is generated by extending seeds by adding additional clusters from additional inner detector layers using a combinatorial Kalman filter [7]. The final set of tracks for the event is chosen by the ambiguity solving process, where candidates are scored and rejected if they fail to pass a quality threshold [8]. While ATLAS tracking is robust, pions at mid-rapidity with transverse momentum (p_T) greater than 1 GeV being reconstructed with greater than 90% efficiency and negligible fake rate, performance deteriorates rapidly when particle density approaches the silicon channel segmentation [9, 10]. In high-density environments, such as high p_T jets or three-pronged τ-lepton decays, tracks are likely to share inner-detector hits, which leads to an increased likelihood of track candidate rejection unless care is taken to mitigate this effect.

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Cluster-sharing is not just a track reconstruction effect. Single clusters (both pixel and strip) can be created by multiple generated particles in a single event [10, 11]. These multiple-particle clusters are called 'merged'. This merging leads to a decrease in technical efficiency, where, in the context of three-pronged τ decays, technical efficiency is defined as the proportion of events for which all three reconstructible pions are actually reconstructed [11]. Reconstructible here means that the pion traversed and left charge deposits in at least a minimum number of silicon layers. For example, Ref. [11] shows that, in generator-level reconstructible events with minimal strip cluster sharing, pixel cluster merging leads to a decrease in τ reconstruction efficiency from above 99% at low τ p_{T} to about 80% at a τ p_{T} of about 1 TeV.

In response to this efficiency loss, ATLAS has implemented a neural network to identify merged pixel clusters [10]. For the events referenced in the previous paragraph, when tracks are allowed to share pixel clusters that are identified as merged, the τ reconstruction efficiency once again starts at above 99% at low τ p_{T} but only decreases to about 90% at a τ p_{T} of about 1 TeV.

Currently, there is no similar neural net for identifying merged strip clusters, and tracks may share at most two strip clusters. Allowing more sharing improves technical efficiency because more track-candidates are accepted, but this comes at the cost of increased fake rate. The currently allowed level of sharing was chosen to prevent accepting too many fake tracks [11]. In general, a cluster should be used by the same number of reconstructed tracks as the number of particles that deposited energy in the cluster. Thus a multiple-particle cluster should be allowed to be shared, and a single-particle cluster should not be shared. This paper describes a new algorithm to identify strip clusters created by multiple particles and the effects of using this information in track-candidate ambiguity solving.

2 Identification of Merged Clusters in SCT

The primary inspiration for identifying merged strip clusters is an ATLAS study of δ-rays, which are low-energy electrons knocked out of the silicon lattice from primary particle energy loss [12]. These δ-rays can propagate in the detector, leading to broadened clusters. This study relied on comparing the observed width (W_{o}) of a silicon-detector cluster to the expected width (W_{c}) as calculated using the incidence angle of the track at the cluster in the plane perpendicular to the beam-line, the thickness of the module, and the Lorentz drift angle. Figure 1 illustrates some of the key parameters of this analysis in the case of δ-rays.

The strip pitch of the ATLAS SCT is 80 μm, so W_{o} is a discrete variable in integral multiples of 80 μm. If $0\ \mu\text{m} > W_{\mathrm{c}} - W_{\mathrm{o}} > -80\ \mu\text{m}$, the cluster is as wide as expected; if $-80\ \mu\text{m} > W_{\mathrm{c}} - W_{\mathrm{o}} > -160\ \mu\text{m}$, the cluster is one strip too wide, and so forth. This effect is also illustrated in Fig. 1, where the actual cluster width is shown in green, but the expected cluster width is one strip. One would expect that a cluster coming from one particle would have no extra strip, barring a δ-ray, diffusion, or other sources of charge sharing, while clusters from more than one generated particles (merged clusters) would have at least one extra strip. The effect of cluster merging on the number of extra strips is illustrated in Fig. 2. This plot shows the $W_{\mathrm{c}} - W_{\mathrm{o}}$ distribution for clusters along the tracks of simulated central-pseudorapidity ($\eta = 0$), high-p_{T} three-prong τ decays. The sample of τ's has a uniform distribution of p_{T}'s between 400 GeV and 1 TeV and no pile-up events. The figure is created by looping over all the reconstructed tracks in an event with a nested loop over the clusters associated to the respective tracks. Thus, for example, if a cluster is used by two tracks, it will appear in the figure twice, but with different $W_{\mathrm{c}} - W_{\mathrm{o}}$ values, as W_{c} depends on the independent incidence angles of the tracks. About 80% of merged clusters have at least one extra strip, while about 80% of single-particle clusters do not have an extra strip.

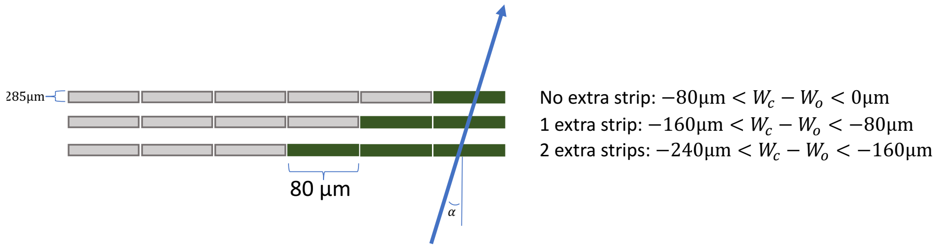

Figure 1. Illustration of a strip cluster with no extra strips (top), one extra strip (middle), and two extra strips (bottom) and of parameters used to determine the presence of extra strips. The blue pointer, indicates the passage of a charged particle through a strip. The observed width, W_o is simply read out from the detector (shown in green). The expected width, W_c, is calculated from the incidence angle of the track at the cluster in the plane perpendicular to the beam-line, α, the Lorentz drift angle, $\lambda_{SCT} = -4°$, and the thickness of the detector $t_{SCT} = 285$ μm. Because the SCT strip pitch is 80 μm, extra strips correspond to $W_c - W_o$ in integral multiples of 80 μm.

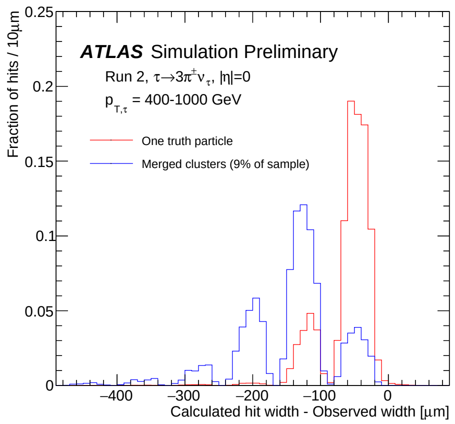

Figure 2. Illustration of $W_c - W_o$ for clusters in a sample of high-p_T three-prong τ decays in the absence of pile-up [14]. The red line is the distribution for single-particle clusters, and the blue line is the distribution for merged clusters. If 0 μm > $W_c - W_o$ > −80 μm, then the cluster is as wide as expected, but if −80 μm > $W_c - W_o$ > −160 μm, then the cluster is one strip too wide, and so forth. It can be seen that about 80% of merged clusters have at least one extra strip, while about 80% of single-particle clusters do not have an extra strip.

Because of this sharp contrast in $W_c - W_o$ between merged and single-particle clusters, this value will be treated as the discriminating cluster-variable. Figure 3, shows receiver operating characteristic (ROC) curves from integrating Fig. 2 from the left. Curves are provided for both 400 GeV τ's and 1 TeV τ's, but the p_T dependence is not strong; though there is more merging at high p_T, $W_c - W_o$ does not depend on the τ p_T. In these three-prong τ decays, a strip cluster with at least one extra strip, i.e. $W_c - W_o \leq -80$ μm, is 85% likely to be merged, and 20% likely to be from a single particle. For reference, the pixel cluster neural network is

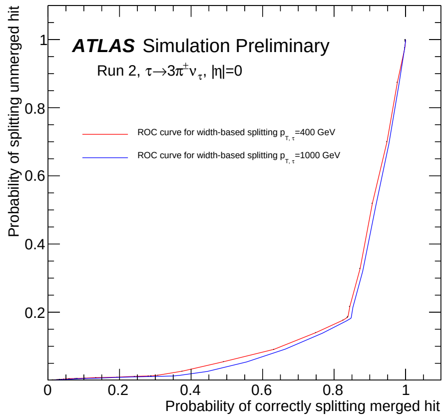

Figure 3. ROC curves illustrating the discriminating power of $W_c - W_o$ alone in three-prong τ decays [14]. Curves are provided for both 400 GeV τ's and 1 TeV τ's, but the p_T dependence is not strong. The kink at about (0.85, 0.2) corresponds to a cut at $W_c - W_o = -80\,\mu$m.

set at a working point where 85–90% of merged clusters are correctly identified, with <10% of single-particle clusters being incorrectly considered merged.

3 Results

To study the effect of identifying merged clusters in the SCT, we have allowed strip clusters to be shared by multiple tracks without penalty if they have at least one extra strip relative to the single track expected width. The change in efficiency for simulated three-prong τ decays is shown in Fig. 4. The green squares represent the default reconstruction efficiency at four different τ p_T values, and an interpolating line is added to guide the eye. The default reconstruction uses the pixel neural network. An event is considered reconstructed if all three of the pions have a reconstructed track matched to a track at generator level [13]. The blue triangles represent the efficiency when the merged strip cluster identification algorithm based on $W_c - W_o$ is implemented. In general, there is a 4–6% relative increase in performance. The red circles show the efficiency when the strip clusters are allowed to be shared based on the clusters' generator-level information, which is essentially a 100% correct to 0% incorrect merging-identification working point. The black inverted triangles show the efficiency when all cluster-sharing penalties are turned off. In this case, most track-candidates are accepted. The pink crosses represent the ideal case: it is the proportion of events where all three pions leave enough inner-detector hits to be reconstructible.

The width-based merging identification approaches the performance of generator-based merging identification, though the performances seem to be increasingly divergent at high τ p_T. Furthermore, the no-penalty case is certainly the most efficient. However, as expected from discussions above, this yields a high rate of duplicate tracks. Here, the rate of duplicates is studied as a proxy for the fake rate; if a single generator level pion is matched to more than one reconstructed track, it is considered to have a duplicate. This duplicate-track effect is illustrated in Fig. 5. The same symbols and colors are used as in Fig. 4. Without a cluster-sharing penalty in the ambiguity solving stage, the duplicate rate approaches 40%. While the

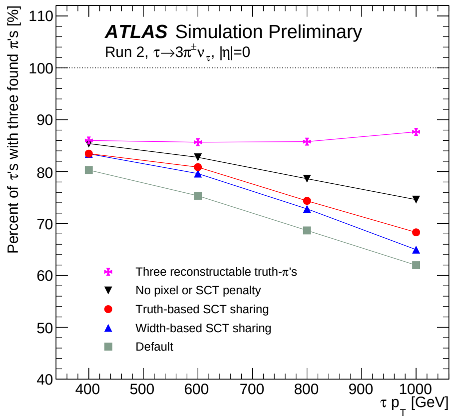

Figure 4. Curves representing the reconstruction efficiency of the pions coming from a three-pronged τ decay as a function of τ p_{T} [14]. An event is considered reconstructed if all three of the pions have a reconstructed track matched to a track at generator level [13]. The different marker styles represent different settings in the ambiguity solving stage. Here, "default" uses the pixel neural network. Additionally, the pink crosses represent the proportion of events in which all three pions leave enough hits to be reconstructible.

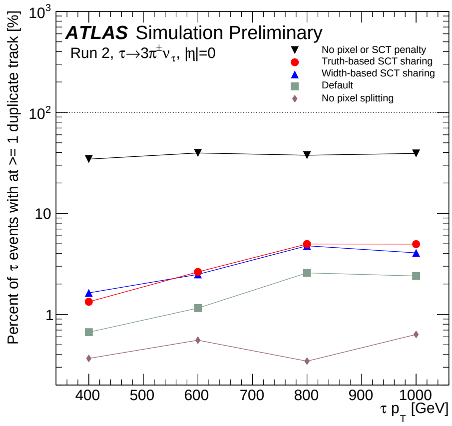

Figure 5. Curves representing the proportion of events with at least one duplicate track as a function of τ p_{T} [14]. An event has a duplicate track if more than one reconstructed track is matched to any π at generator level. The different marker styles represent different settings in the ambiguity solving stage. "Default" uses the pixel neural network.

default case typically stays below 3%, both width-based merging identification and generator-based merging identification stay below 5%.

4 Conclusions and Outlook

Placing a threshold on the difference between a cluster's calculated width and its observed width, $W_c - W_o$, is an effective means of identifying merged strip clusters in simulation of the ATLAS detector. Allowing tracks to share strip clusters which have at least one extra strip based on this metric increases the reconstruction efficiency in dense environments, though there is a simultaneous increase in the duplicate-track rate. Eventually, implementing these changes may improve searches and measurements at the LHC which use tracks inside high p_T τ's and jets.

A possible extension of this work would be to create a neural network similar to that used for pixel clusters. Additional variables have been investigated for their discriminating power in addition to $W_c - W_o$: the cluster layer, the track p_T, the number of pixel clusters on the track designated as merged by the pixel neural network, and the $W_c - W_o$ of the companion cluster on the other side of each double-sided (axial plus stereo) SCT layer. In the clean, central three-prong τ decays considered in this note, the gain in discrimination power by using a neural network with these additional variables was marginal, but it may become more significant in other samples, like jets, and in less central environments.

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