TAU Identification Improvements for ATLAS Phase-1 Upgrades in L1Calo Trigger System

Srinidhi Budhiraju - Arizona State University
Supervisor: Ralf Gugel, Paul Thompson

Abstract

ATLAS is one of the biggest detectors at the Large Hadron Collider (LHC) at CERN. It is designed to study high-energy particle collisions. Within the detector, there are two levels in the trigger system, Level 1 and High Level Trigger (HLT). The main objective of this project is to study the tau candidate particles in L1Calo to improve the tau identification in the L1Calo trigger system for the phase-1 upgrades in ATLAS. This is done by exploring the matching efficiency algorithm and studying the rCore energy.

CERN Summer Student Program
August 11, 2023

Contents

1 Introduction

In ATLAS, there are two levels in the trigger system, Level 1 and High Level Trigger (HLT). This project is focused on Level 1. The main objective of this project is to study the cTau in L1Calo in order to improve the tau identification in the L1Calo trigger system in for the phase-1 upgrades in ATLAS.

1.1 Taus and Jets

The tau particle, also called the tau lepton, is an elementary particle. Similar to the electron, it has a charge of -1 and a spin of $\frac{1}{2}$. Tau leptons have a lifetime of $2.9 \cdot 10^{-13}$ s and a mass of 1776.86 $\frac{MeV}{c^2}$. Approximately $\frac{2}{3}$ of tau leptons decay hadronically ($\tau \to \nu_\tau q\overline{q}'$) through the week interaction, while the remaining portion undergo leptonic decay ($\tau \to \nu_\tau \overline{\nu_l} l$, $l = e, \mu$), also through the week interaction.

A jet refers to a spray of hadrons and various particles generated through the process of hadronization during high-energy particle collisions. It bears similarities to hadronic tau leptons, but with notable distinctions. Specifically, jets have a larger cone size, encompassing a more extensive area, and they occur much more frequently compared to hadronic tau leptons. For this particular study, the focus is on tau particles, so the ability to effectively discriminate between hadronic tau leptons and jets is of high importance. Doing this significantly reduces the bandwith requirements for data acquisition. Figure 1 shows the tau and jet cones.

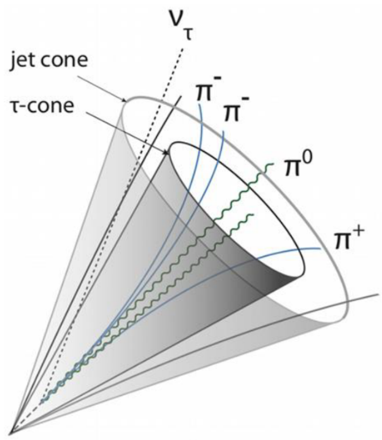

Figure 1: Taus and Jets

1.2 L1Calo - Calorimeter Trigger

The Level-1(L1) trigger system is the first stage of the ATLAS data selection process and it is responsible for rapidly selecting potentially interesting collision events from the vast amount of data produced at the LHC. The Calorimeter Trigger system (L1Calo) is a crucial part of the Level-1 trigger. It relies in information from ATLAS' Liquid Argon (LAr) and scinillating tile (Tile) calorimeters, which are detectors in ATLAS used to measure the energy of particles emerging from the collisions. The L1Calo system rapidly analyzes energy deposits in the calorimeters to identify regions of interest (RoIs). These identified regions are then passed to the next stage of the trigger system for further analysis. Figure 2 shows an overview of L1Calo.

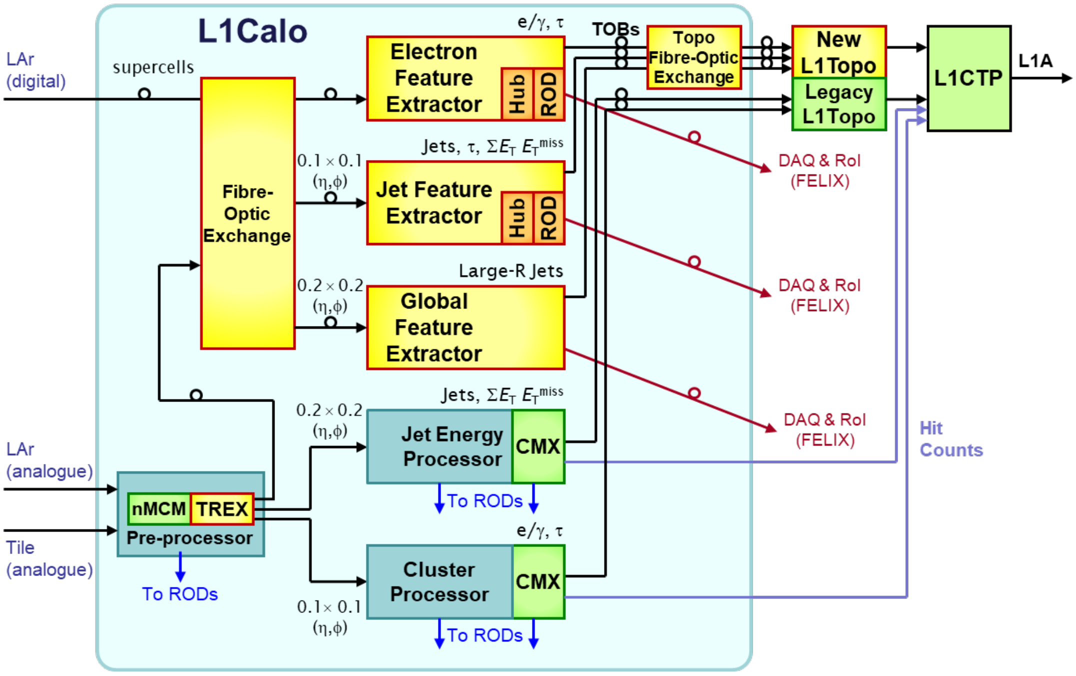

Figure 2: L1Calo Overview (adapted from (Mkrtchyan, 2022))

In the L1Calo phase-1 upgrade, there are three feature extractors identifying such RoIs. These FPGA-based systems aim to extract specific features from the energy deposits in calorimeters to make quick and efficient decisions on whether a collision is interesting and should be further analyzed.

The electron feature extractor(eFEX) is a hardware component that is composed of 24 individual ATCA-based modules that operate independently and in parallel. It employs the full granularity calorimeter data to detect and differentiate electron/photon (EM) and tau-like showers. It utilizes the full depth and spatial information to effectively distinguish them from the jets. Figure 3 shows an eFEX module ("Documentation of the L1Calo algorithm 2 specifications", 2023).

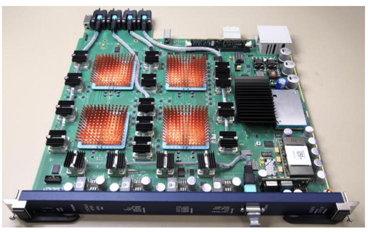

Figure 3: eFEX Module (adapted from (Mkrtchyan, 2022))

The jet feature extractor(jFEX) only utilizes 6 modules since it processes the information at a lower/reduced granularity. It locates jet-like objects, a second flavor of tau, as well as EM candidates outside regions covered by eFEX. It also provides a measurement of the missing transverse energy. Figure 4 shows a jFEX module ("Documentation of the L1Calo algorithm 2 specifications", 2023).

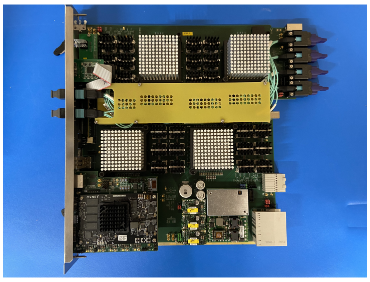

Figure 4: jFEX Module (adapted from (Mkrtchyan, 2022))

The global feature extractor (gFEX) consists of just one single module. It processes data from the whole detector at a coarse granularity. It also identifies jets and measures missing transverse energy, but it is also able to make event-level corrections and identify large-radius jets ("Documentation of the L1Calo algorithm 2 specifications", 2023).

The results from the feature extractors are further processed by the Level-1 topological trigger (L1Topo) by using topological algorithms and a multiplicity trigger. Topological algorithms take into account the spatial relationship or arrangement of the objects identified by the upstream subsystems. These are applied when two or more objects are related to each other. Multiplicity triggers involve triggering based on the number of TOBs detected in a specific region or within certain thresholds (mainly E_T min). For this project, the focus is on the combination of tau candidates provided by the eFEX and jFEX ("Documentation of the L1Calo algorithm 2 specifications", 2023). An L1Topo module is shown in figure 5.

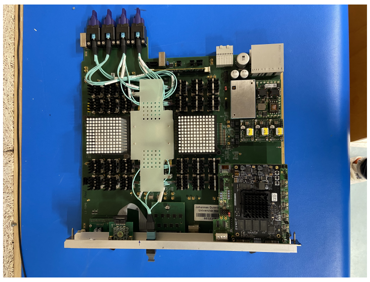

Figure 5: L1Topo

2 Data Sets

The data used for this project comprises samples from ATLAS' "physicsMain" and "zero-bias" streams, as well as simulated $Z \to \tau\tau$ ("signal") and di-jet ("background") monte-carlo samples.

The physics main data set refers to the primary dataset used in high-energy physics experiments to study specific physics processes or phenomena. It typically contains collision events recorded during the main data-taking period of the experiment. These events are the result of the actual collisions created by the LHC.

The zero-bias data set consists of collision events deliberately selected without any specific trigger requirements or biases. These events are randomly chosen, irrespective of the physics processes or the presence of interesting particles. Zero-bias data helps to study the overall performance of the detector, background rates, and other detector-related effects. It also serves as a reference for understanding the efficiency and characteristics of the data taking process.

Background monte carlo data is a simulated dataset that emulates background events that can occur during particle collisions in the detector. Monte carlo simulations are computer-based methods used to model particle interactions and detector responses. The background monte carlo data represents the expected events from known physics processes that produce signatures constituting the background in real data. It is essential for understanding and quantifying the background contribution to the physics analysis and helps to optimize event selection criteria.

Signal monte carlo is another type of simulated dataset, but it models specific physics processes or phenomena that researchers are interested in studying. It represents the events from particles or interactions predicted by the theoretical models beyond the standard model or specific phenomena that are being investigated. The signal monte carlo data is crucial for determining the sensitivity of the experiment to specific signals, calibrating and validating analysis techniques, and assessing the potential for new discoveries.

3 Matching Efficiency

3.1 Definition of Terms

Prior to describing the matching efficiency algorithm, there are several terms to define. First, there are the eTAU and jTAU objects. These represent the tau candidates detected by the eFEX and jFEX respectively. A cTAU (combined tau) object holds the combination of information of the eTAU and jTAU. Like the eTAU, it also represents a potential tau that was detected. A cTAU is constructed from every eTAU and is augmented with information from a matching jTAU if such a match is found.

η is a dimensionless quantity used to describe the pseudorapidity of a particle. Pseudorapidity is a concept that approximates the rapidity of a particle when it is moving at a speed close to the speed of light. Rapidity is a kinematic quantity that is related to the velocity of a particle. In the context of high-energy physics, η is used instead of rapidty because it is more convenient in experimental setups. Pseudorapidity is defined as

$$\eta = -\ln(\tan(\frac{\theta}{2}))$$

where θ is the polar angle of the particle with respect to the beamline in the particle detector (Vidal & Manzano, 2022). ϕ denotes the azimuthal angle of a particle within a detector. It represents the angle in the plane perpendicular to the beamline and is measured relative to a chosen reference direction. Together, η and ϕ provide a way to describe the momentum and direction of particles produced in high-energy collisions.

JIsoEt refers to the isolation of a tau particle. A large jIsoEt value implies that the particle is not very isolated, and a low jIsoEt value implies that the particle is isolated. This is one of the discriminants that are used to used to differentiate between a jet and a tau. Throughout the project, jIsoEt/eET will be used instead of just jIsoEt. This is to reduce the dependence on the overall energy scale of a given detector activity being analyzed.

eET refers to the total transverse energy measured by the eFEX module. In this project, a cut is placed on eET at 12000 MeV. The studies in this project only analyze events that have an energy greater than this cut. This is to reduce background noise from the detector. At low energies, the signal-to-background ratio can become unfavorable, making it more difficult to distinguish the desired signal from random noise.

3.2 Current Matching Algorithm

The purpose of the matching algorithm is to construct τ candidates with higher discrimination power between real leptons and jets compared to relying on eTAU/jTAU candidates alone. To this end, a cut is placed on the isolation (jIsoET/eET) of the detected particle. Currently, the cut is placed at 0.35, meaning that an isolation of less than that value is something that requires further analysis. In the current matching algorith, for each eTAU, a cTAU is created. Then, the algorithm checks if there is a matching jTAU for a given eTAU. This is done by checking if there is an exact match between the eTAU η and ϕ and jTAU η and ϕ values after mapping eTAU coordinates to the reduced granularity of possible jTAU coordinates. If no match is found, then the jIso value is assumed as 0. Otherwise, the jIso is taken from the matching jTAU. This matching prescription is referred to as *full matching* in the following.

3.3 Extended Matching Algorithm

In this project, the matching algorithm was modified so that rather than requiring an exact match between the eTAU η and ϕ and the jTAU η and ϕ, the variables were allowed to differ within a certain threshold, which in this case, was set to 1 (approximately 0.1

x 0.1 in the η x ϕ space. Figures 6 - 9 show the reduction in rate that occurs if the extended matching algorithm is implemented for the physics main, zero-bias, signal and background samples.

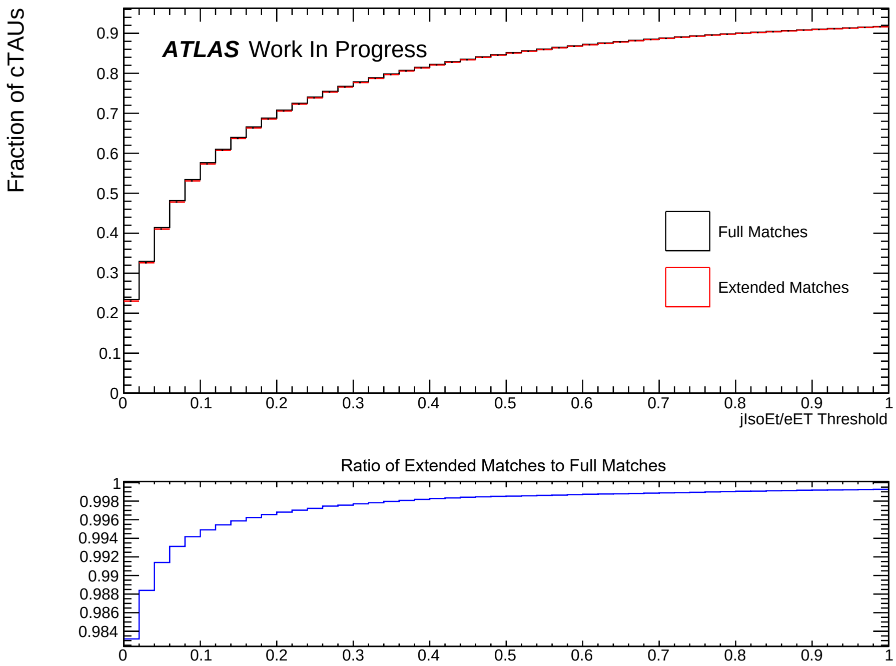

Figure 6: Matching Efficiency for Physics Main Data

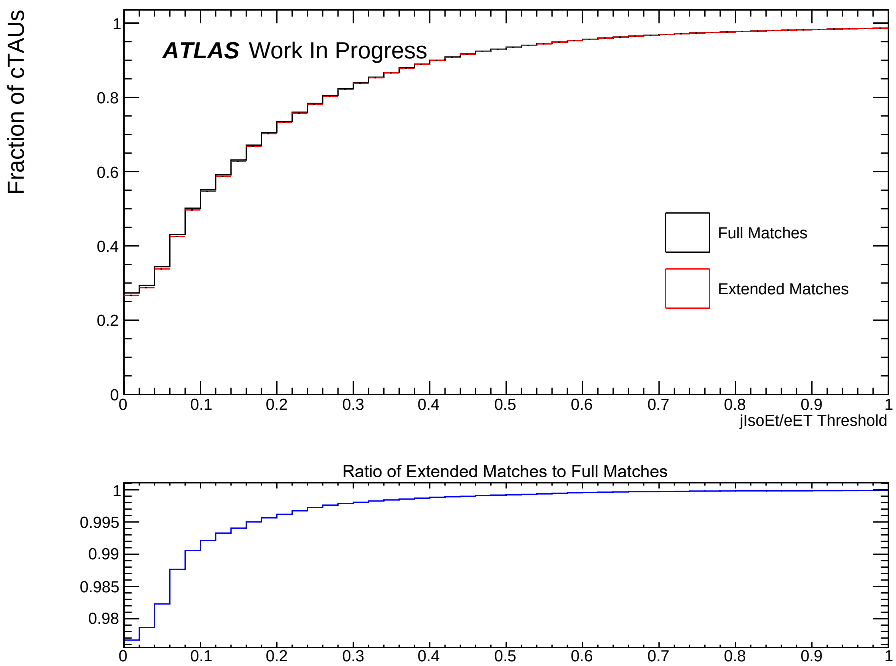

Figure 7: Matching Efficiency for Zero Bias Data

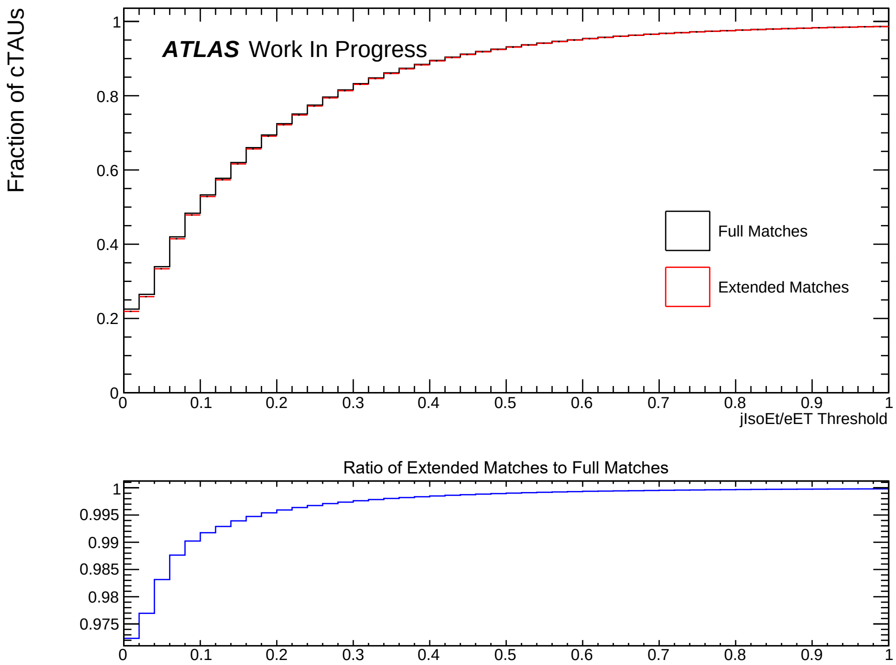

Figure 8: Matching Efficiency for Signal Data

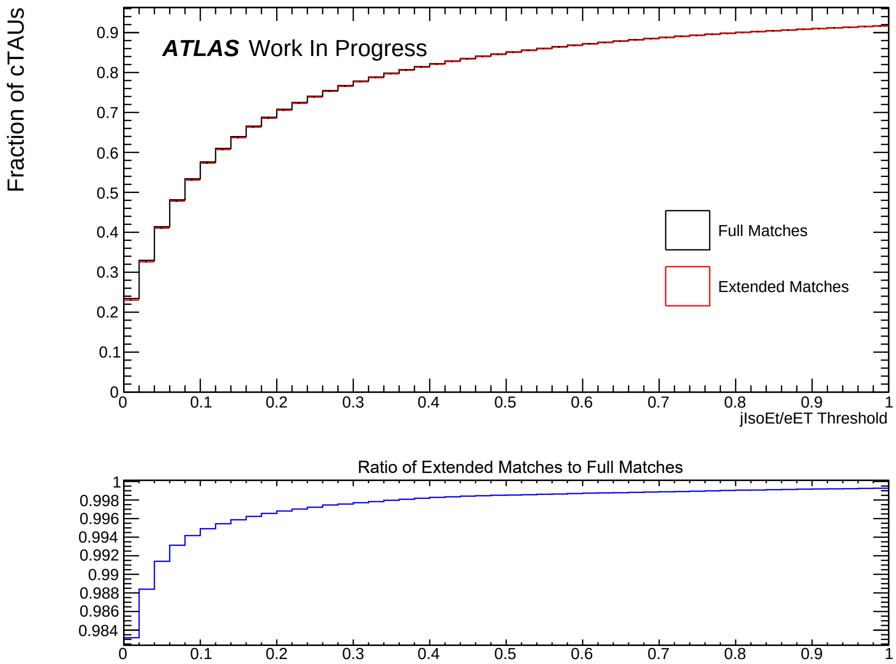

Figure 9: Matching Efficiency for Background Data

In Figures 6 - 9, the plot on the top is the cumulative distribution of the fraction of the cTAUs that have a jIsoEt/eET value that is less than the corresponding x-value. Essentially, it is the efficiency of placing a cut at a particular jIsoEt/eET. This means that if the cut is placed at a high jIsoEt/eET, the efficiency is high. The difference between the

full matches and extended matches shows the rate reduction by implementing the extended matches algorithm. The plot on the bottom shows the ratio of extended matches to the full matches. A high ratio implies a small rate reduction of implementing the extended matches algorithm.
Therefore, the figures show that there is little improvement that can be achieved by implementing the extended matches algorithm. But, something interesting to look at is the cut that should be placed on jIsoEt/eET for the different data sets in order to achieve the same rate reduction. At present, a cut of 0.35 is placed on jIsoEt/eET. In the zero-bias data set, this corresponds to a 87% efficiency or 0.87 fraction of cTAUs that are considered to be potentially interesting. For each data set, a 87% efficiency corresponds to a different cut placed on jIsoEt/eET. The table below summarizes this information.

Physics Main	**Zero Bias**	**Signal**	**Background**
0.61	0.35	0.41	0.59

Table 1: jIsoEt/eET Cut Corresponding to 13% Rate Reduction With Respect to the Rate of eTAU Candidates

4 rCore Studies

4.1 rCore Definition

The second part of this project was to study the rCore property of the eTAU. rCore is computed by taking the ratio of the energy deposited in the 3x2 region around the supercell seed, defined as the rCore core region, to the energy of the 9x2 region around the seed, defined as the rCore environmental region. This ratio essentially measures the concentration of energy near the RoI. Since taus are generally more narrow than jets, enforcing a condition on rCore may be useful ("Documentation of the L1Calo algorithm 2 specifications", 2023).

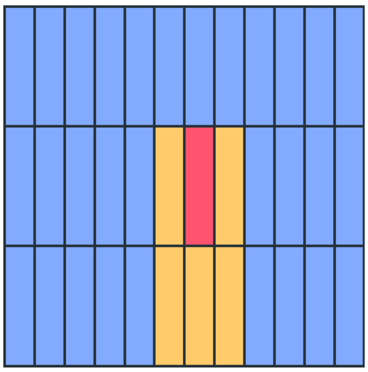

Figure 10: rCore Core Region

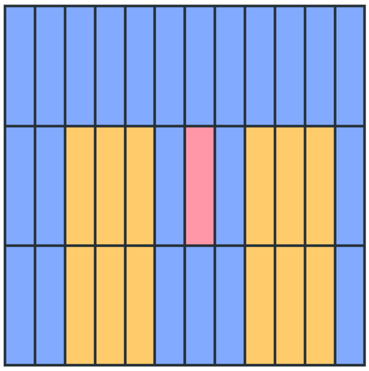

Figure 11: rCore Environment Region

4.2 Methodology

For all of the data sets, 4 different conditions were placed on the rCore property of cTAU. These conditions were 'rCore >= 0', 'rCore >= 1', 'rCore >= 2', 'rCore >= 3'. 'rCore >= 4' implies that there is not restriction placed on the rCore since rCore is always greater than or equal to 0. 'rCore >= 4' is the strongest restriction placed on rCore. Figures 12 - 15 show the rate reduction with different cuts placed on rCore.

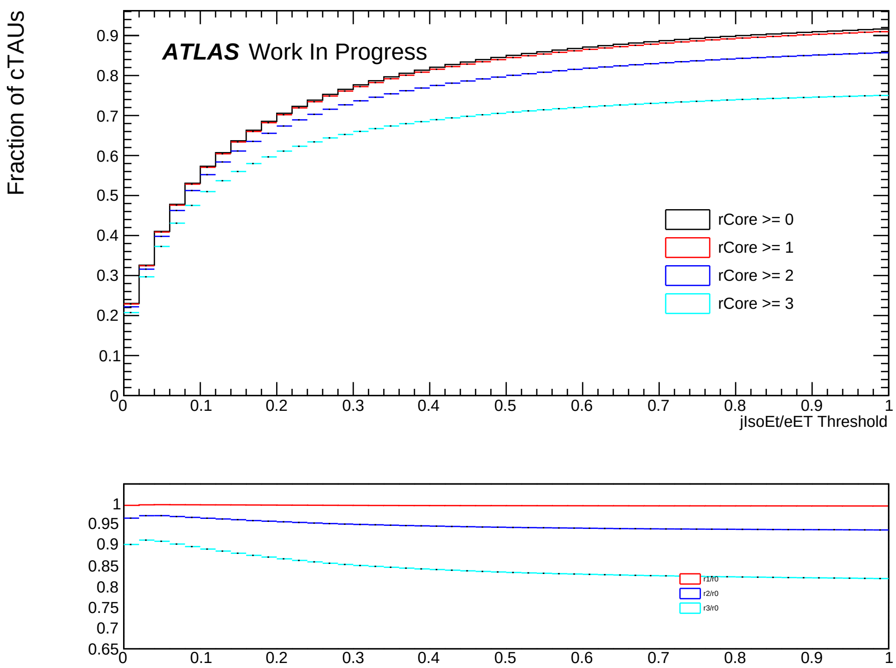

Figure 12: rCore Efficiency for Physics Main Data

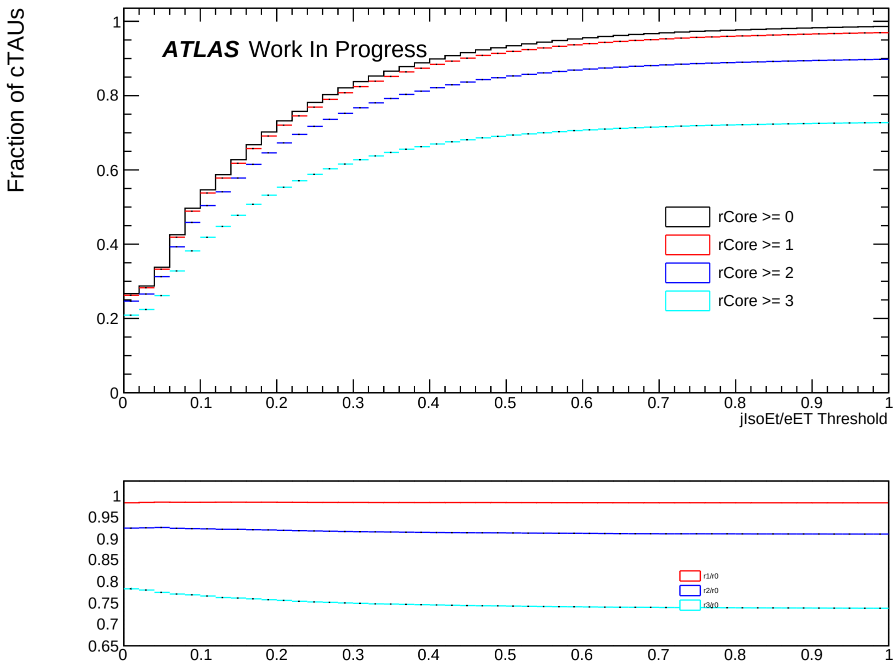

Figure 13: rCore Efficiency for Zero Bias Data

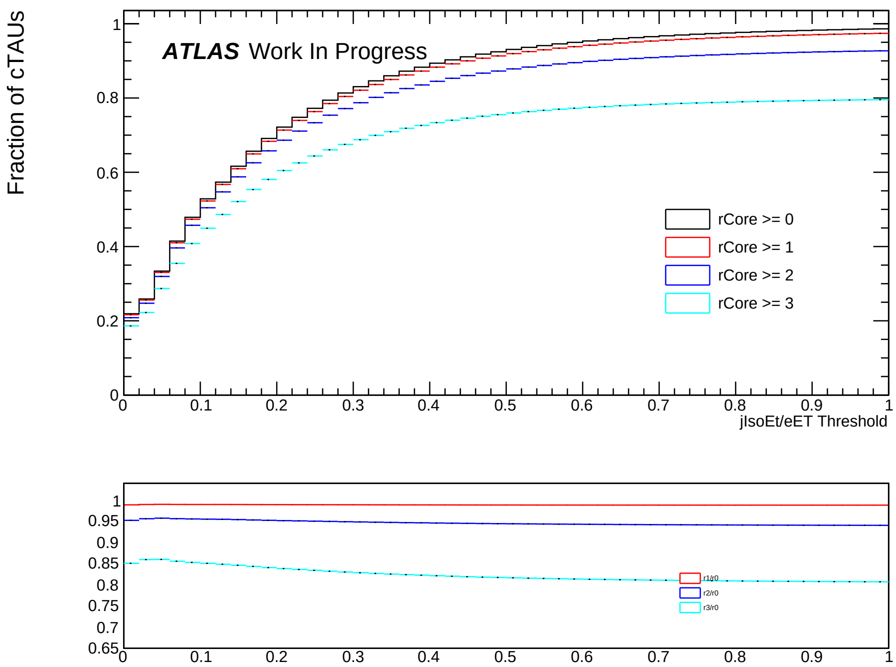

Figure 14: rCore Efficiency for Signal Data

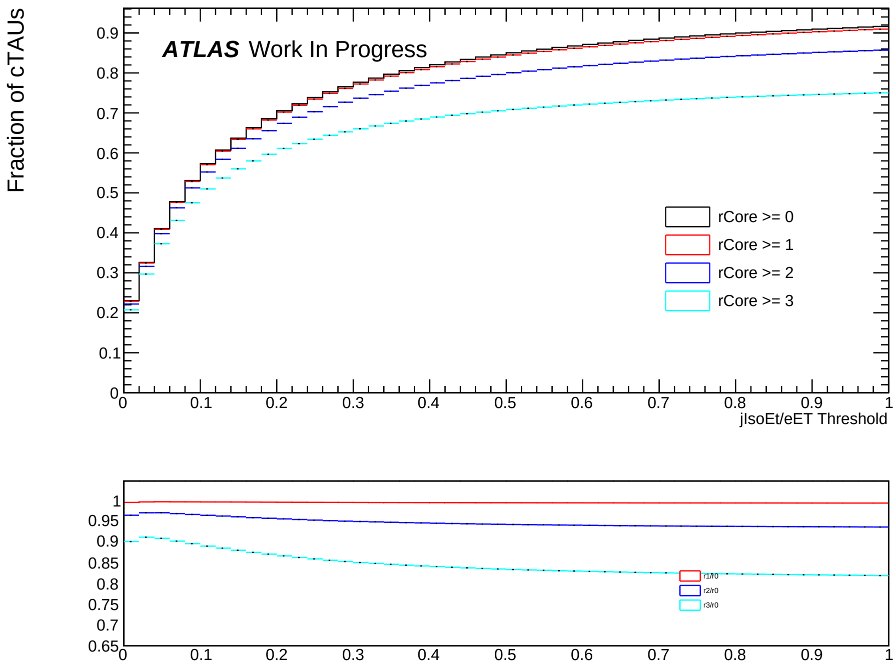

Figure 15: rCore Efficiency for Background Data

In the Figures 12 - 15, the plot on the top is similar to the matching efficiency plots in Figures 6 - 9. The ratio plot on the bottom shows the ratio of each of the restrictions on rCore to no restriction on rCore. It essentially shows how much the rCore is correlated with the jIsoEt/eET. If the two are loosely correlated, combining them may be useful.

It is shown that the rCore property of the cTAU has a significant impact on the rate reduction. In every single plot, as rCore becomes more strict, the rate reduction becomes significantly larger. What's important to notice in these figures is that in both signal and background data, there is a significant rate reduction by restricting rCore. While a large reduction is good for the background data, it's not good for signal. Therefore, the current algorithm and the definition of rCore working points are not ideal.

In addition to that, in the ratio plots, it seems that rCore and jIsoEt/eET are loosely correlated since the ratio plots are relatively flat. This means that combining the information from jIsoEt/eET and rCore is something that would be good to look into.

Similar to the matching efficiency, it would be interesting to see the cut on jIsoEt/eET in addition to a give rCore requirement in order to achieve the same rate reduction determined by placing a cut of 0.35 jIsoEt/eET on rCore >= 0. The summary of that information is shown in the Table 2.

	Physics Main	Zero Bias	Signal	Background
rCore >= 0	0.35	0.35	0.35	0.35
rCore >= 1	0.37	0.39	0.37	0.37
rCore >= 2	0.51	0.71	0.45	0.51
rCore >= 3	-	-	-	-

Table 2: jIsoEt/eET cut at 87% Efficiency

In Table 2, the row for rCore >= 3 is shown to be "-" because with that restriction in place, the algorithm doesn't reach 87% efficiency.

5 Incorporating rCore

5.1 jJet

Previously, the cut had been on jIsoEt/eET. Since it was determined that it may be interesting to incorporate rCore, jJet is considered as an alternative. jJetET is the sum of the tau for energy and its isolation ring. Since eET shouldn't be included in determining the isolation, That value that is used is:

$$\frac{\text{jJetEt}-\text{eET}}{\text{eET}} = \frac{\text{jJetEt}}{\text{eET}} - 1$$

When a jJet is built, its energy is further scaled by an eta dependent factor. In order to get around this, jIsoEt + jET is used in placed of jJetEt. jET is defined as the total transverse energy calculated by jFEX. jIsoEt + jET is essentially the same thing as jJetEt, but without the scaling factor. The value becomes:

$$\frac{\text{jIsoEt}+\text{jET}}{\text{eET}} - 1$$

5.2 Signal and Background Plots

Using this new discriminant, the signal and background cumulative distribution plots were computed for full match and extended match as shown in Figure 16 For convenience the plots using jIsoEt/eET is shown as well in Figure 17.

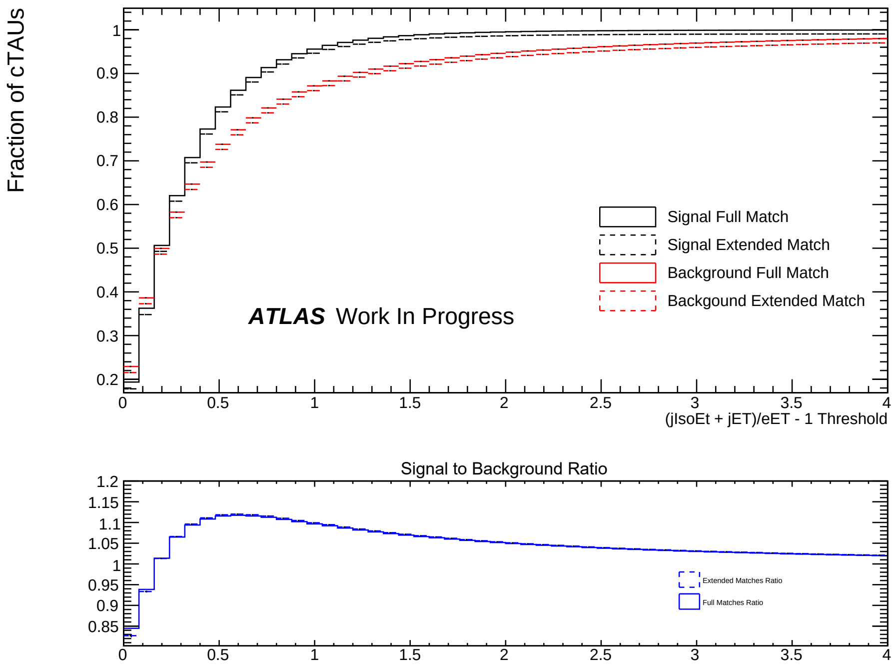

Figure 16: Result of Different Matching Prescriptions for Signal and Background using $\frac{\text{jIsoEt+jET}}{\text{eET}} - 1$

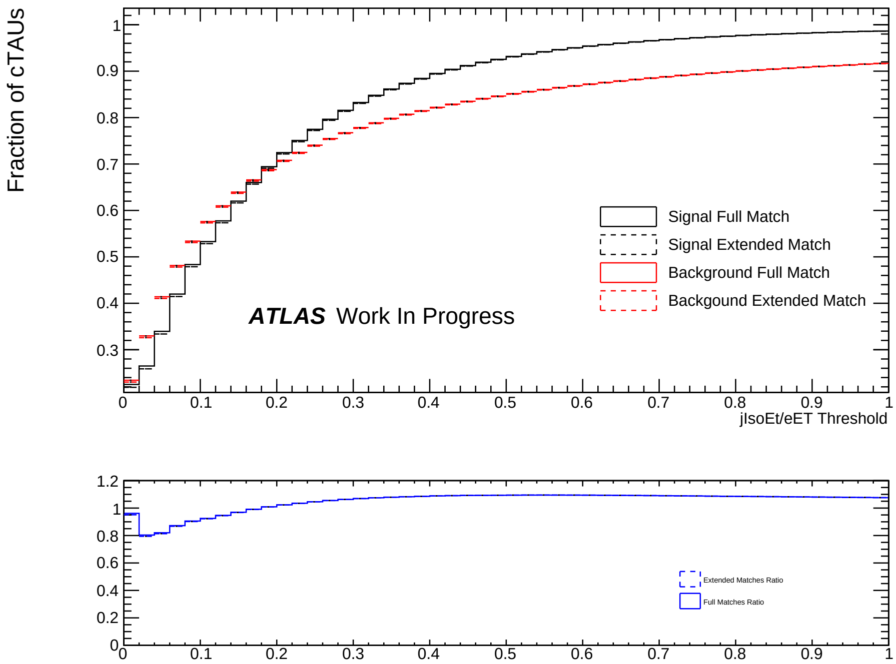

Figure 17: Result of Different Matching Prescriptions for Signal and Background using $\frac{\text{jIsoEt}}{\text{eET}}$

Comparing Figures 16 and 17, there is more of a noticeable difference between the full matches and the extended matches when $\frac{\text{jIsoEt+jET}}{\text{eET}} - 1$ is used as the isolation condition.

6 Results/Further Studies

The results of these studies show that the current tau matching algorithm works quite well and does not need to be modified. It also shows that rCore is an interesting region to study and incorporating that energy may be useful. In the future, it would be good, to further study $\frac{\text{jIsoET+jET}}{\text{eET}} - 1$ and see if tau identification improvements can be made by using this value as the isolation condition.

References

[1] Vidal, X. C., & Manzano, R. C. (2022). Momentum Taking a closer look at LHC. Taking a closer look at LHC - momentum. https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.momentum

[2] Mkrtchyan, T. (2022). *The Phase-I Upgrade of the ATLAS Level-1 Calorimeter Trigger*. ATLAS TDAQ Collaboration.

[3] (2023). *Documentation of the L1Calo algorithm 2 specifications*. The ATLAS L1Calo Collaboration.