Investigating Calibration Procedures for the ATLAS Trigger System

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Introduction

The ATLAS calorimeter is a non-compensating calorimeter that was optimised for measuring electrons and photons. This means that for strongly interacting particles (hadrons), their energy is only partially measured. For example, typically only 70% of a charged pion's energy is measured in the calorimeter. The rest of the energy is invisible, and is released in nuclear reactions, in low energy neutrons, and as heat.

Proton-proton collisions induce hard scattering interactions, producing quarks and gluons. These particles leave jets, which can then be measured by the detector. The energy of jets is also only partially measured.

The ATLAS detector has a two-level trigger system. It consists of a Level 1 (L1) electronics-based trigger system, and the high-level trigger (HLT) system, which is a software-based system. L1 and HLT jets refer to jets that are based off of their respective trigger systems.

The ATLAS hadron calibration procedure uses Monte Carlo simulations to correct for this inefficieny in measuring the energy on average. In addition to simulating the L1 and HLT systems, the Monte Carlo simulations also contain a truth jets; these correspond to the true energy and momentum of the particles. In order to improve the energy resolution, variables indicating the type of dominant interactions for a given jet can be used. One of these variables is the electromagnetic fraction defined as the energy deposited in the calorimeter divided by the total energy of the particle.

If we only consider pions (the lightest hadrons), a jet contains typically 30% of neutral, negatively or positively charged pions. Unlike the charged pions, the neutral pions decay dominantly into two photons and therefore their energy is fully measured in the calorimeter. Consequently, jets with a high neutral pion content have a high response and a large energy deposit in the electromagnetic calorimeter which contains the photons from the pion decay. The jet response r is defined as the ratio between the p_T of two types of jets. For example, the HLT-truth response is the ratio of HLT jet p_T to the truth jet p_T. The jet resolution can be improved by studying r as a function of the EM fraction.

The goal of this project is to investigate if these kinds of calibrations can be also used in the ATLAS trigger system. During the project, the main datasets used were Run 2 data and Monte Carlo simulation data. A Run 3 dataset was also considered, but was abandoned due to a lack of available statistics. All data analysis was done using RDataFrame.

Methodology

The various datasets used contain L1 trigger, high-level trigger (HLT), truth, and/or reconstructed jets. These jets are classified by their transverse momentum[1] p_T, their angle ϕ, pseudorapidity η, and (usually) their energy E. Each of these quantities are stored in separate branches, but are linked such that the j^{th} entries in the branches correspond to the same particle(s). The branches are also ordered in descending p_T, so the leading and subleading jets are accessible.

In principle, the leading jets should match up, but this is not necessarily the case in practice. For example, the L1 jets have worse resolution than the HLT jets, and so the leading L1 jet may instead correspond to the subleading HLT jet. In order to account for this, one can instead look into the η and ϕ branches to match the jets via their direction.

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} \tag{1}$$

The quantity ΔR, defined by equation (1) above, is a measure of directional agreement between the two jets; $\Delta\phi$ and $\Delta\eta$ are the differences in the ϕ and η values between the two branches. When the matching code is implemented, we set ΔR_{cut} equal to some threshold value and so two jets are considered to be matched if ΔR is below this threshold. For this project, the threshold was set at 0.3.

The code used for this direction matching works with four-momentum variables, not with the p_T, η, ϕ, and E branches. Thus, a constructor must be used to map (p_T, η, ϕ, E) to a (E, $\boldsymbol{p}$) four-vector. This, however, has another complication in that certain jets (primarily the L1 jets) do not have an E branch. The energy can be calculated to be $E = p_T cosh(\eta)$ if the mass of the particle is negligible compared to its momentum (for details, see the *Appendix*).

Di-Jet Asymmetry

The first phase to evaluate the energy resolution was to look at the di-jet asymmetry A, defined as

$$A = \frac{p_{T,1} - p_{T,2}}{p_{T,\,avg}}, \tag{2}$$

where $p_{T,1}$ and $p_{T,2}$ denote the leading and subleading jet p_T respectively, and $p_{T,\,avg}$ is their average.

Asymmetry histograms were made for both the HLT and L1 jets with various cuts on the HLT p_T range. The L1 jets typically displayed a large asymmetry and have worse resolution than the HLT jets. When the jet data was displayed, there were many instances of the leading L1 jet being in saturation ($p_{T,1} \sim 1000$ counts) and the subleading L1 jet being lower than expected. This would result in a larger asymmetry, and filtering out the leading L1 jets with $p_T > 1000$ does resolve this issue. *Figure 1* shows histograms for the HLT and L1 symmetries with and without this p_T filter on L1.

[1] The L1 jets have transverse energy E_T instead, but $E_T \approx p_T$; see the *Appendix* for further details.

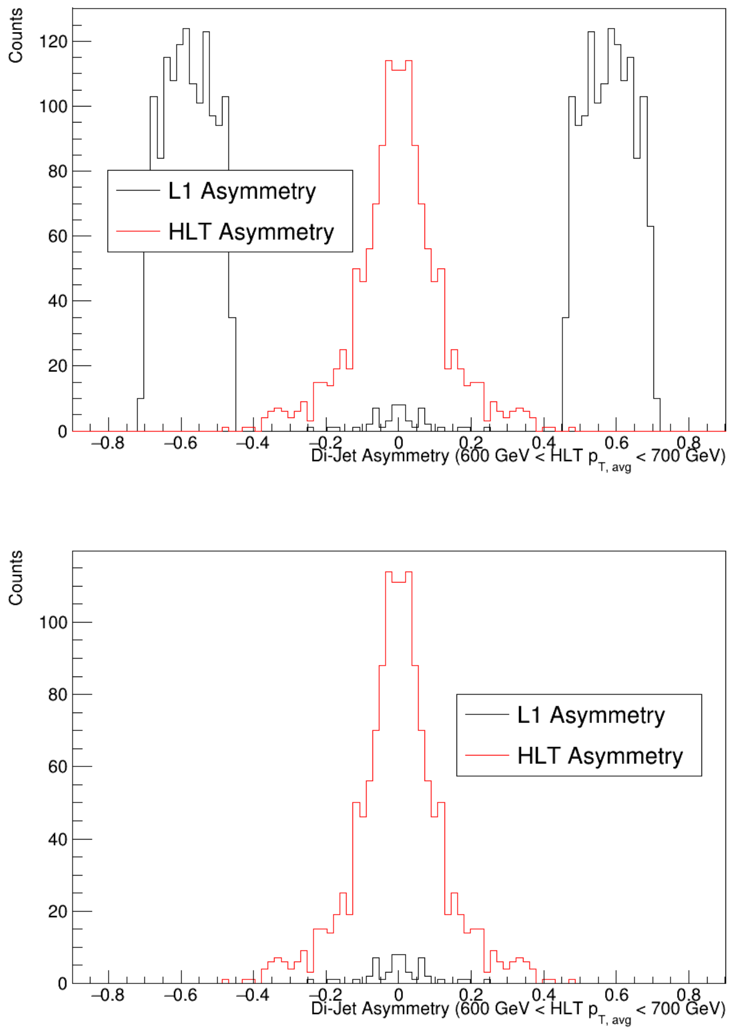

Figure 1: *A di-jet asymmetry histogram with all jets (top), and with the saturated lead L1 jets filtered out. Both histograms have a cut with* $p_{T,avg}$ *between 600 and 700 GeV.*

This saturation issue was unexpected, especially since it emerged at relatively low HLT p_T (500 − 600 GeV). In order to test for a directional dependence in the saturation, 2D histograms of the ϕ and η branches were made. If, in the histograms where only saturated values were present, a strong peak was observed, this could indicate that L1 saturation is due to particles passing through that area of the detector. These histograms were made using the lead L1 jets and all matched L1 jets (the direction matching is done between the L1 and HLT jets). When looking at all jets, both histograms are quite uniform. As shown in *Figure 2*, there is no directional influence on the saturation. The cause of this saturation is still unknown.

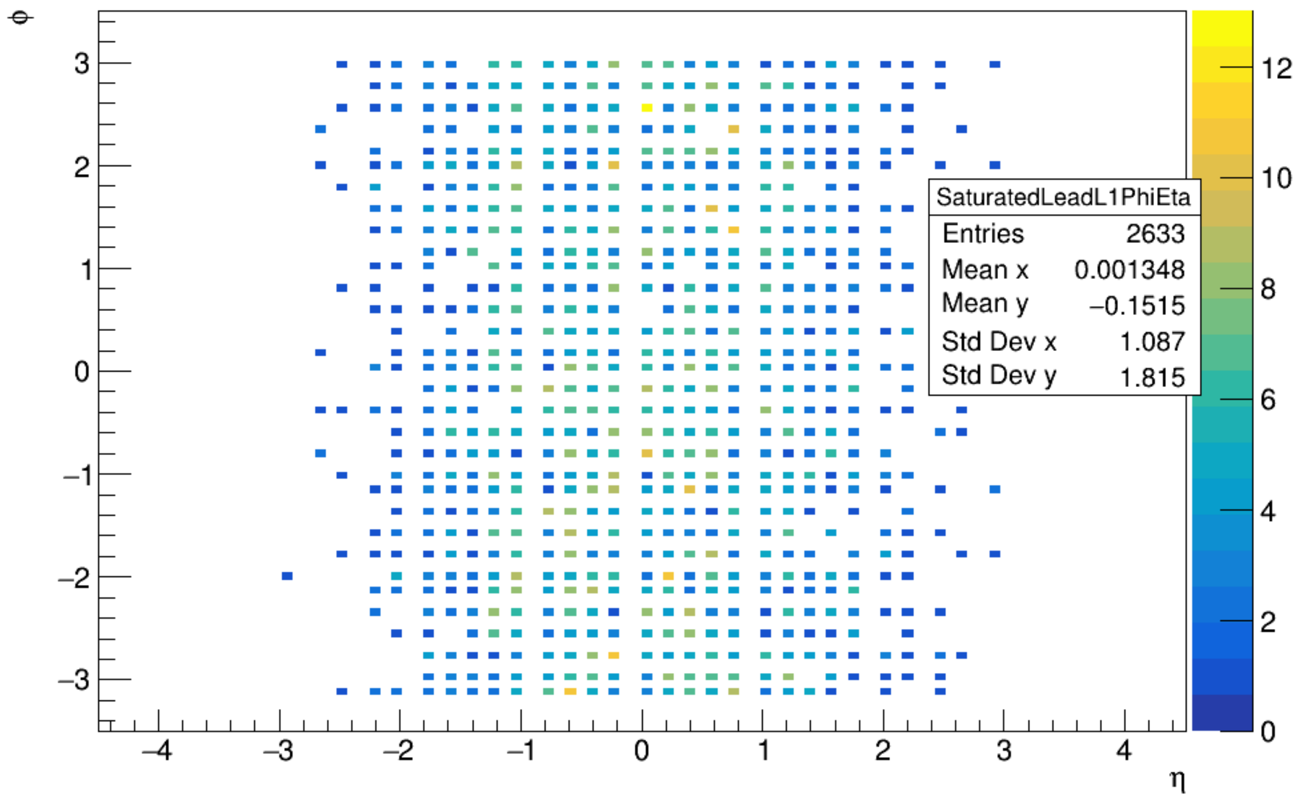

Figure 2: *Lead L1 ϕ vs. η* histogram corresponding to lead p_T in saturation.

The lead L1-HLT response r was also plotted against the lead HLT p_T, as shown in *Figure 3*. Note that r is around 0.5, indicating that indeed the L1 jet p_T counts are measured in counts, where one count is 0.5 GeV. The top line that is shown is due to the L1 jet being in saturation. As before, this saturation appears even at relatively low HLT p_T values.

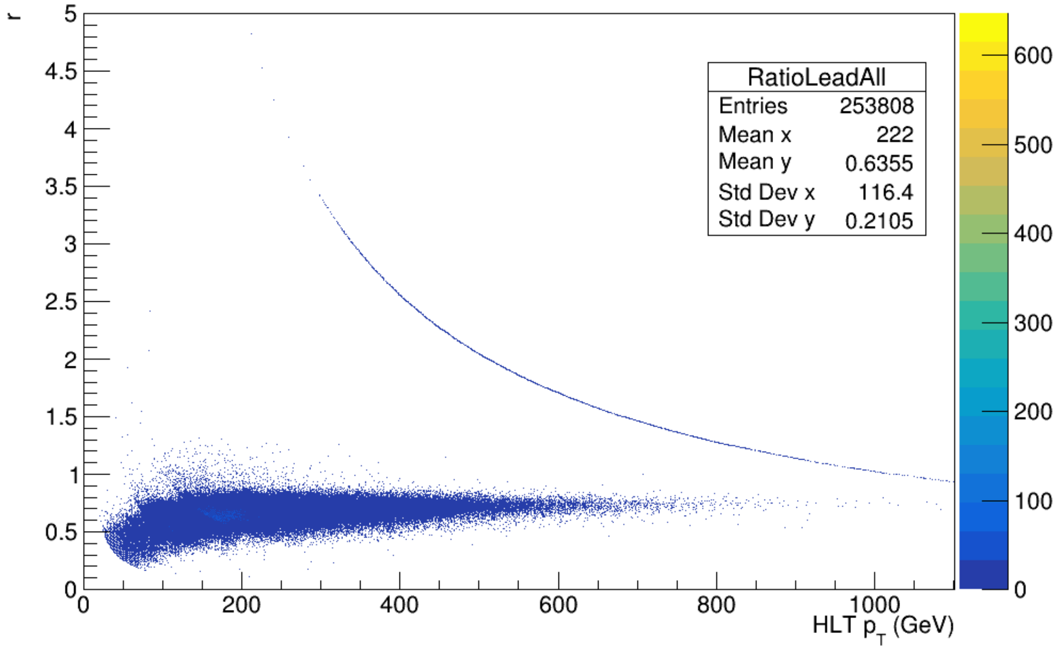

Figure 3: *The L1-HLT response vs. the lead HLT* p_T.

EM Fraction Plots

The main phase of the project was focused on the EM fraction. As a preliminary study, the reconstructed-truth response was plotted against the truth p_T (the reconstructed and truth jets are matched beforehand). *Figure 4* shows a histogram and its x-profile. Note that the profile is approximately 1 at higher p_T; there is a low p_T bias due to asking for a 20 GeV cut. Hence, cutting at $p_{T,\,Truth} = 30$ should work as expected.

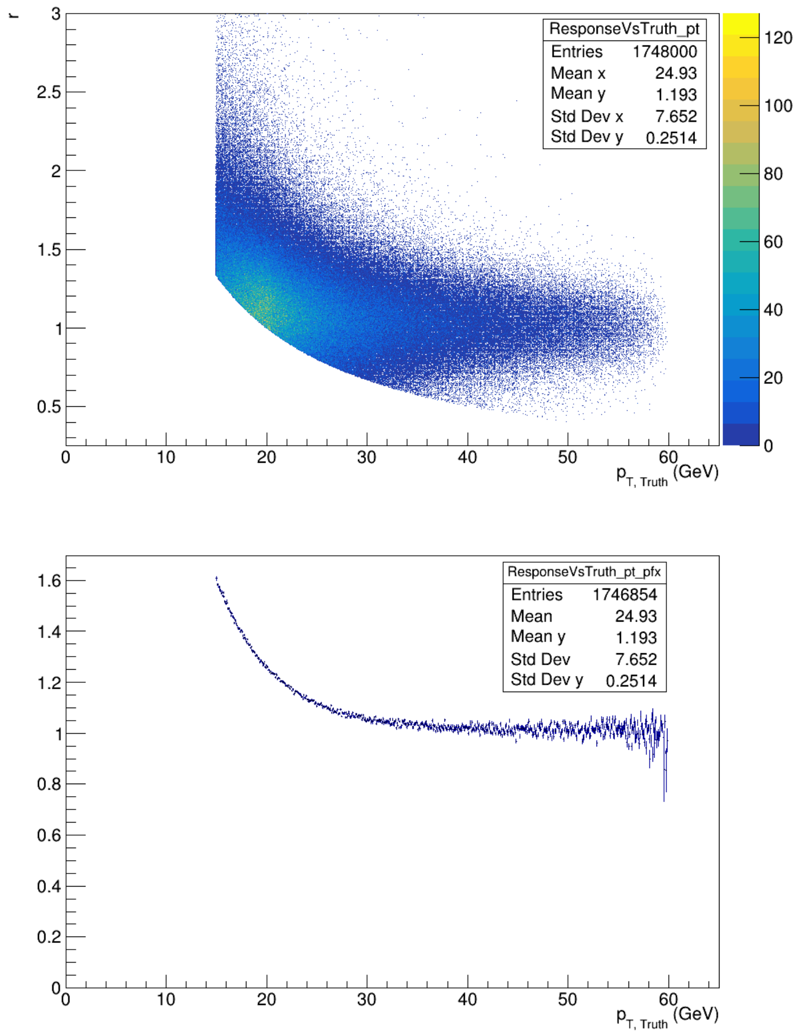

Figure 4: *A histogram of r vs. $p_{T,Truth}$ (top), and its profile (bottom).*

The final set of histograms plotted the HLT-truth response against the EM fraction as well as the L1-truth response against the EM fraction. The Monte Carlo simulation data contains the EM fraction corresponding to the HLT jets, but not one for the L1 jets. The hope is that the HLT EM fraction is an accurate approximation for the L1 EM fraction.

In order to make these plots, the jets were matched, and the EM fraction should be matched as well. Since the EM fraction is based on the HLT jets, the matched HLT jet p_T values can be compared to all HLT p_T values, and can collect the indices in latter branch corresponding to an equality between values in the two branches. Then, the matched EM fraction would be the EM fraction values corresponding to these indices. Unfortunately, due to time constraints, this was not successfully implemented.

Appendix

The transverse energy E_T of a particle is defined in terms of its mass m and transverse momentum p_T as

$$E_T = \sqrt{m^2 + p_T^2}. \tag{3}$$

If $m \ll p_T$, then $E_T \approx p_T$.

In order to show that $E \approx p_T \cosh(\eta)$, first recall the invariant mass of a particle:

$$m^2 = E^2 - p^2. \tag{4}$$

If the mass is negligible, then (4) becomes

$$E = |\boldsymbol{p}| \tag{5}$$

The momentum components in Cartesian coordinates can be expressed in terms of p_T, η, and ϕ via

$$p_x = p_T cos(\phi),$$

$$p_y = p_T sin(\phi),$$

$$p_z = p_T sinh(\eta).$$

Using these expressions in (5):

$$E = \sqrt{p_T^2 cos^2(\phi) + p_T^2 sin^2(\phi) + p_T^2 sinh^2(\eta)}$$

$$= p_T \sqrt{1 + sinh^2(\eta)}$$

$$\Rightarrow E = p_T cosh(\eta).$$

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