Dynamic range of ATLAS Tile calorimeter for high-p_T jets

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Abstract

This paper presents a study of high-p_T jets in the ATLAS Tile calorimeter (TileCal). The photo-multiplier tubes that are used in the energy detection process of TileCal have a limited dynamic energy range. With the upgrade of the Large Hadron Collider to run collisions at 14 TeV more and more jets will contain particles that will deposit more energy than the TileCal can record. Monte Carlo data was used in a fast simulation (Delphes) and full simulation (Geant4) to better understand how high energy jets are reconstructed when energy readings from cells are truncated. About 4% (1.5%) of jets with $p_T > 3$ TeV and 16% (4.8%) of jets with $p_T > 4$ TeV are affected when cells truncate energy measurements at 1.2 TeV (1.5 TeV). Assuming that cell energy will be truncated at 1.2 and 1.5 TeV, we find that the p_T jet reconstruction of these events are missing energy compared to the truth level jets. Knowing how the dynamic range of the TileCal cells influences jet reconstruction is quite important for run II where many high-p_T will be produced. A similar analysis was done for 100 TeV events to determine dynamic ranges for hadronic calorimeters of a future detector.

1 INRTODUCTION

The Large Hadron Collider (LHC) located at CERN recently upgraded to allow for energy collisions at 14 teraelectron volts (TeV). ATLAS, one of the particle detectors at the LHC, has an energy measuring component called the Tile calorimeter (TileCal). The new high energy events will likely push the limits of the ATLAS detector's ability to measure deposited energy. It is important to understand how TileCal will handle high-p_T jets. A jet is a concentrated cone of particles that result when two particles collide and is illustrated by a cartoon in Fig. 2. The term p_T refers to the transverse momentum, or momentum that is directed perpendicular to the beam line. With LHC upgrade (run 2) we except thousands of jets with $p_T > 3$ TeV, and hundreds of jets with $p_T > 4$ TeV. This means that the TileCal must be able to handle large energy depositions or otherwise jet information will be lost due to measurement saturation or other effects of surpassing the calorimeter limit. This analysis will show how the dynamic range of the TileCal impacts jet p_T reconstruction for high p_T jets. We use Monte Carlo (MC) simulations to study the energy range of TileCal cells and effects of dynamic range truncations.

The ATLAS detector has two calorimeters. The Liquid Argon (LAr) calorimeter system, or electromagnetic calorimeter, measures the energy of electrons, positrons and photons. Outside of the LAr rests TileCal. This hadronic calorimeter's purpose is to detect hadrons and measure jet energy and missing transverse energy. The TileCal is made up of about 10,000 cells which consist of plastic scintillators separated by steel plates. Charged particles that pass through the cell ionizes the plastic. This ionized energy is converted into ultraviolet light by a primary fluor. After passing through a few more fluors and a wavelength shifting fiber the light can finally be converted into electrical signal by use of photomultiplier tubes (PMT) [1]. Each cell is connected to two PMTs. The energy of a cell is determined by summing together the energy readings of that cell's PMTs.

These cells are arranged in three radial layers surrounding the beam line. As seen in Fig. 1 layer A is closest, followed by BC and finally D [2]. The cells within these rings are arranged in such a way that they stack on top of each other with respect to the collision area. The η divisions highlight this feature. Note that η increases by 0.1 up from 0 up to 1.7 resulting in 16 divisions, or "towers." Cells are also divided azimuthally into 64 wedges denoted by ϕ. Cells in layer A have an upper dynamic range of about 1.46 TeV and layers BC and D can measure up to 1.22 TeV. With more high-p_T jets run 2, we expect to start seeing particles that surpass these limits and saturate the cell. When a cell is saturated the energy readout is truncated and jets will appear to have missing energy after reconstruction. We use a full simulation called Geant4 to determine the affect of the TileCal's dynamic energy range. Then Delphes, a fast simulation, is modified to resemble Geant4 which allows us to study high p_T events as well as future detectors.

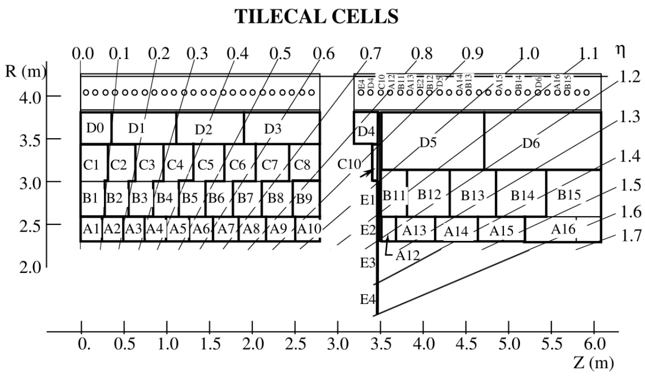


Figure 1: The TileCal consists of three barrels each with three radial layers: A, BC, and D. Each tile is made of steel and scintillating plastic connected to two PMTs.

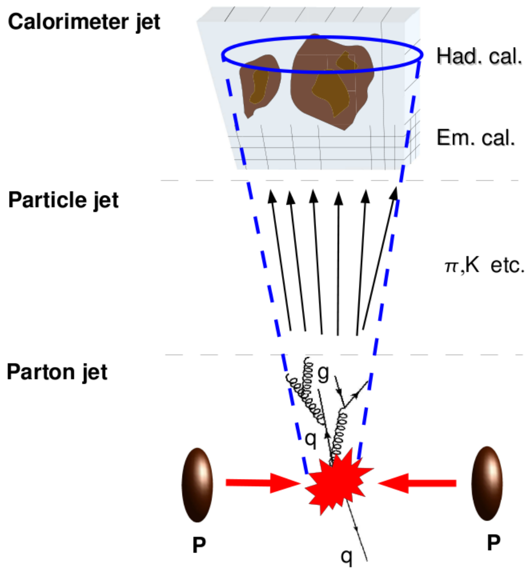


Figure 2: When two high energy protons collide they create a spray of particles. Heavier particles fragment into smaller ones which deposit their energy in one particular region of the calorimeters. This is called a jet.

2 GEANT4: FULL SIMULATION

PYTHIA8 is a program for the generation of high energy physics events. We use it to generate Standard Model, events at 14 TeV which are then processed with the full simulation program based on Geant4. The program creates objects called "truth jets" which contain the true value of the jet's energy, p_T, and position in TileCal. Only truth jets with $\eta < 0.8$ are stored in a separate file for analysis an the rest are discarded. Geant4 also includes information about hits, or a single particle's activity in the detector. We create TileCal cells by adding the energy of each hit to its respective cell. During this process the hit's energy must be correctly calibrated. First an electromagnetic (EM) energy scale is applied to all hits. However, the truth energy of a jet in TileCal is about 20% greater than the EM-scaled energy. To make this conversion additional scaling factors are generated by a random Gaussian distribution with $\mu = 1.2$ and $\sigma = 0.06$. With the cells correctly scaled to the truth energy we can proceed with jet reconstruction. Cells are matched to corresponding truth jets by using

$$dR = \sqrt{(\phi_{cell} - \phi_{jet})^2 + (\eta_{cell} - \eta_{jet})^2} \quad (1)$$

where $dR < 0.4$. Finally, the program checks to see if the cell's energy should be truncated or not. In layer A of the TileCal the upper limit of the cells is 1.46 TeV. Layers BC and D can readout energies up 1.22 TeV. For this study, we examine cuts at 1.2 and 1.5 TeV and both cases are considered for each cell. If a cell's energy is found to have surpassed one of these values, the program sets that cell's energy to either 1.2 TeV of 1.5 TeV respectively. Additionally, the program stores how much energy is lost as a result of the truncation and records how many jets are affected. Running this program over nearly 7000 high-p_T jets we find that 4.17% of jets are affected by a cut of 1.2 TeV. A cut of 1.5 TeV would affect only 1.57% of jets. The shaded area in Figure 3 illustrates which cells would have truncated energy readouts.

The p_T of cells that pass the requirement $dR < 0.4$ are summed together to create reconstructed jets.

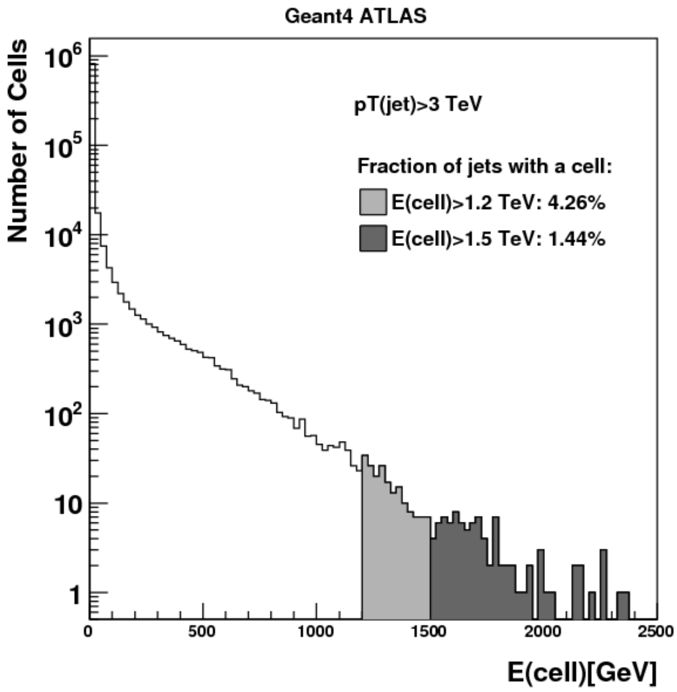


Figure 3: Number of calorimeter cells with respect to the amount of energy deposited in the cell. This analysis uses Geant4 simulated data of 14 TeV events and selecting only jet $p_T > 3$ TeV. The shaded regions show which cells would have truncated energy readings with each respective dynamic range.

Then, to determine how truncated energy readings affect reconstructed jet p_T we use the equation:

$$r = \frac{p_T^{Reco}}{p_T^{Truth}} \tag{2}$$

The normal distribution of equation 2 in Fig. 4 can be seen to center about 0.43 when the cells are allowed to report all the energy they detect. One might except that this distribution should center about 1, since the reconstructed jet p_T should match closely to the truth jet p_T. However, due to the 60% of jet energy deposited in the LAr only a fraction of the total jet p_T reaches the TileCal.

Figure 4 also shows that when cell energy values are saturated, jets shift from higher r values to lower values. This shift is more apparent for the 1.2 TeV cut because more jets are affected in this case. When a cell is limited from reporting the full energy deposited in it, the reconstructed jet necessarily loses some p_T resulting in this shift to lower r values.

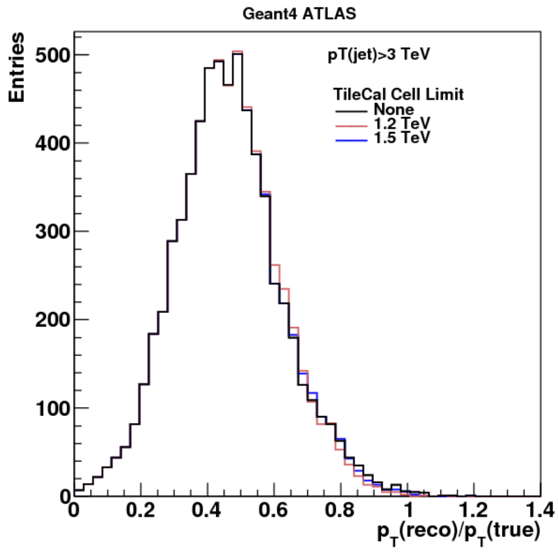


Figure 4: Distribution of reconstructed jet p_T to truth level jet p_T. Note how some jets shift from higher fractions to lowers fractions when a dynamic range limit like 1.2 TeV is introduced.

3 DELPHES: FAST SIMULATION

The usage of a full simulation requires significant process time and cannot easily be used to study different physical processes. Therefore, we adopt a fast simulation, Delphes [3], and tune it to resemble the Geant4 ATLAS full simulation. Delphes already has a geometry that corresponds to 0.1×0.1 cell sizes, which is identical to the ATLAS geometry for A, BC, and D cells. Delphes also includes truth jet information such as p_T, η, and ϕ. However, Delphes differs because it reports reconstructed jet information in the form of "towers," not cells. A tower is the sum of LAr and TileCal cell quantities that all share the same ϕ and η. For example, in Fig. 1 the cells A1, BC1, and D1, along with the corresponding LAr cells, would be considered a single tower entity. From one of these towers Delphes allows us to separate the energy deposition in LAr (Eem) from the deposition in TileCal (Ehad), but not into individual cells. In other words, the depth TileCal is unknown in Delphes. Since this analysis focuses on the dynamic range of cells we must isolate the amount of energy deposited in a single cell from the tower attribute.

To tune Delphes to TileCal, we used Geant4 simulations to determine how energy is deposited in each layer. It has been shown, see Fig. 5, that the energy sharing between the LAr and TileCal is not equal. Rather about 60% of charged particle energy is deposited in TileCal, except for γ and π^0 which are always deposited in LAr. Further tuning requires knowledge of the fraction of a particle's energy that is deposited in each layer of TileCal. A Geant4 simulation found that for high-p_T jets, on average 50% of a jet's energy that makes it to TileCal is detected in layer A, 50% in layer BC, and very little in layer D [4]. Figure 6 shows these results with the error bars showing the RMS values. Using the error bars from this study allows us to use a random Gaussian distribution to simulate the amount of energy deposited in each layer for any given tower. Thus the cell energy is given by

$$CellEnergy = Ehad \times RandomGaussian(\mu, \sigma) \tag{3}$$

with $\mu = 0.5$ and $\sigma = 0.15$. The cell energy is now tuned to either layer A or BC of the Geant4 simulation and can be used in a similar analysis as in the full simulation. We ignore layer D because the study found that a negligible fraction of energy is deposited there. Events at 14 TeV would not produce particles that could saturate cells in layer D.

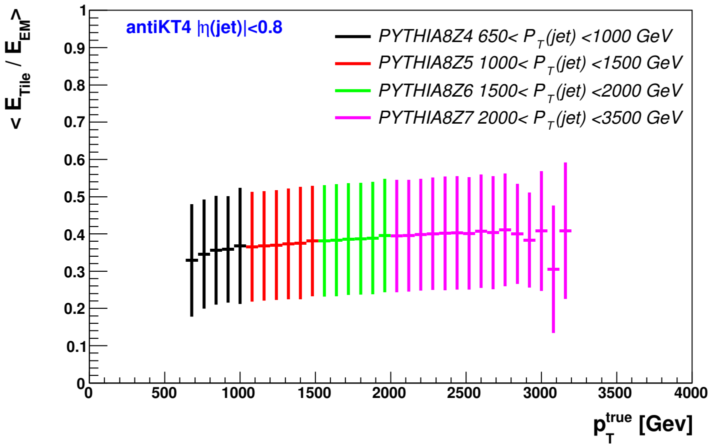
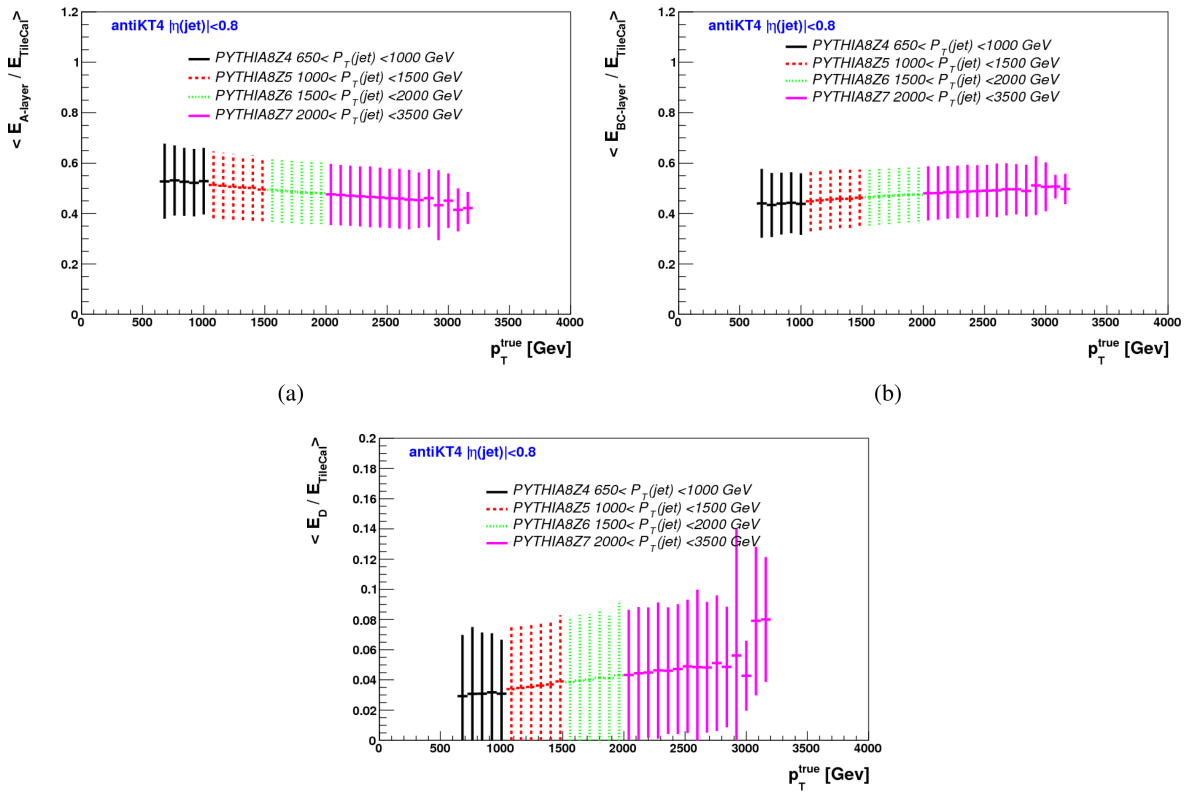


Figure 5: Jet energy fraction at various p_T. Note that for high-p_T jets about 40% of jet energy is found in the TileCal



(a) (b)

(c)

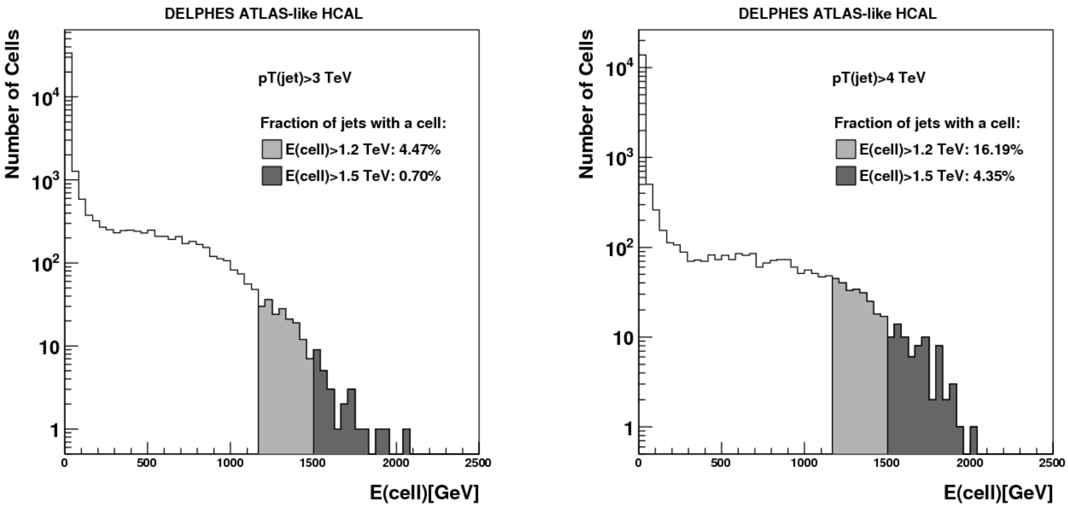
Figure 6: The energy that is deposited in the TileCal is distributed in each layer differently. About 50% of energy is found in layers A (a) and BC (b) and very little in layer D (c).

With Delphes correctly tuned, we proceed to validate the fast simulation by comparing its results to the full simulation at 14 TeV events and passing only jets with $p_T > 3$ TeV and $\eta < 0.8$. The PYTHIA8 simulated data can be found on the HepSim repository with the specifications of 14 TeV, Standard Model, proton-proton collisions. Samples were taken from the file tev14_qcd_pythia8_pt2500. The process to make these events was QCD dijets of $p_T > 2.5$ TeV. The jet construction process uses a radius of 0.4 to be consistent with the full simulation.

We find that at these settings 4.77 % of jets have at least one cell greater than 1.2 TeV and 0.81% of jets have a cell above 1.5 TeV. These values differ only slightly from the full simulation values which is likely the result of random fluctuations from statistical uncertainty. Furthermore, the effect is small so we can concluded that there is good agreement between the simulations regarding the fraction of jets affects. However, Fig. 7(a) appears to have a bump around 500-1000 GeV which is not seen in Fig. 3. We expect this discrepancy is due to the limitation of the fast simulation. As jet p_T increases, a greater fraction of its energy will be deposited deeper into the ATLAS detector. While Geant4 accounts for this phenomenon, Delphes does not. If it did, we could expect more cells shifting to higher energy smoothing out the bump. Nevertheless, the Delphes program can still be used to analyze a wide variety of situations that could not be possible with Geant4. We just must keep in mind that we are under-counting the number of truncated cells. In reality, the energy range problem is probably worse than we present here.

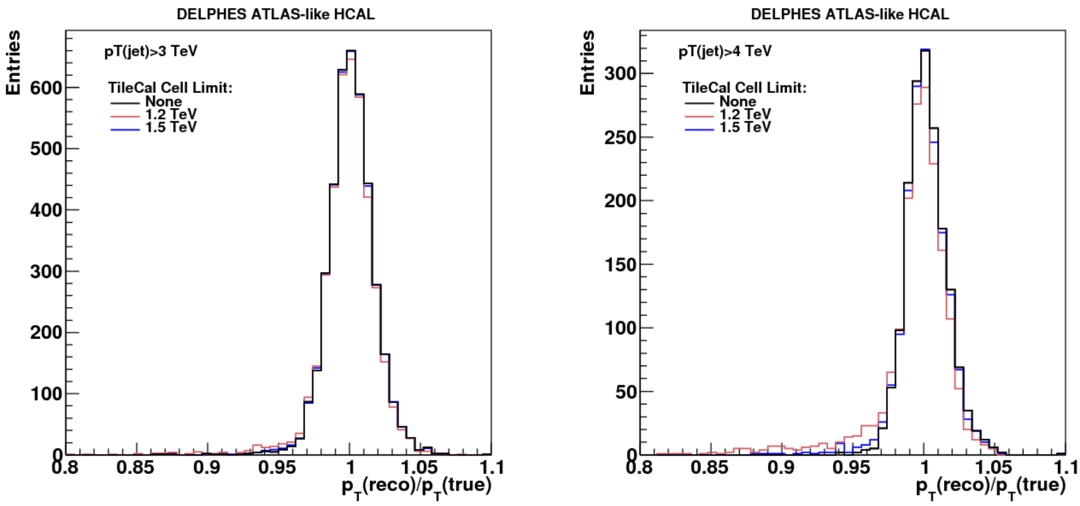
In addition to Delphes potentially under-counting truncated cells, it should be noted that both the full and fast simulations already present an optimistic view of jet p_T reconstruction. This study makes the assumption that when a cell becomes saturated with energy the cell simply reports the maximum value of 1.2 TeV or 1.5 TeV. However, the behavior of these cells around the upper end of their energy range is unclear. It is possible that when a cell becomes overloaded it actually readouts nothing at all: 0 TeV. In this case, a reconstructed jet would be missing large amounts of energy than with truncation assumption, causing the ratio distributions in Fig. 8 to be skewed even more.

Now that the fast and full simulations have been reconciled, we use the fast simulation to perform studies that would require much processing time with Geant4. For example, Fig. 7(b) shows results for jets with $p_T > 4$ TeV. An alarming 16% of jets have a cell energy above 1.2 TeV which results in a number of reconstructed jet that do not match with their truth values. It can be seen in Fig. 8(b) that there are enough of these jets that shift to make the p_T ratio distribution shrink. These changes are important to remember when analyzing data from run 2 that have a significant number of high-p_T jets. Clearly some reconstructed jets will not contain all of the energy they should.



(a) (b)

Figure 7: Energy distributions of cell energy in ATLAS's TileCal for 14 TeV, Standard Model events trimmed to $p_T(jet) > 3$ TeV (a) and $p_T(jet) > 4$ TeV (b).



(a) (b)

Figure 8: Ratio distribution of reconstructed jet p_T to truth jet p_T. Note that when a cell limit is imposed, some reconstructed jets lose p_T.

4 FCC DETECTOR

The Future Circular Collider (FCC) is a proposed 80-100km long ring that would collide particles at 100 TeV. The detector for such a massive experiment like this would need to be able to measure up to very high energies. Using Delphes, we can simulate what the dynamic energy range in such a detector might need to be. We use PYTHIA8 to create 100 TeV, Standard Model events with a jet radius of 0.5. Then the we trim jets at $p_T > 20$ TeV. Since the dynamic range of the future cells are unknown, we applied limits of 5 TeV and 10 TeV as guesses. Figure 9(a) shows the nearly half of all high-p_T jets are affected by a 5 TeV cut but this drops to 5% for a 10 TeV cut. In Fig. 10(a) we can see a relatively large shift of these jets from the original distribution. One solution for this future detector is to make the cells capable of measuring energy up to about 15 TeV where the plots show that very few cells readout that much energy. However, there could be physical limitations with this solution. Another idea is to make the cells smaller so that more of them could fit in the calorimeter. It is proposed to make the η division four times smaller, $\Delta\eta = 0.025$. In this way, four cells would share the energy that a single cell would have to measure in the current model where $\Delta\eta = 0.1$. Figure 9(b) shows the result of such a simulation. There is a decrease in the fraction of jets with a cell above 5 and 10 TeV as expected. The p_T distribution in Fig. 10(b) illustrates that the 10 TeV cut has negligible affects on the reconstructed jets. Thus, as the cells are made smaller the dynamic range necessarily decreases as well.

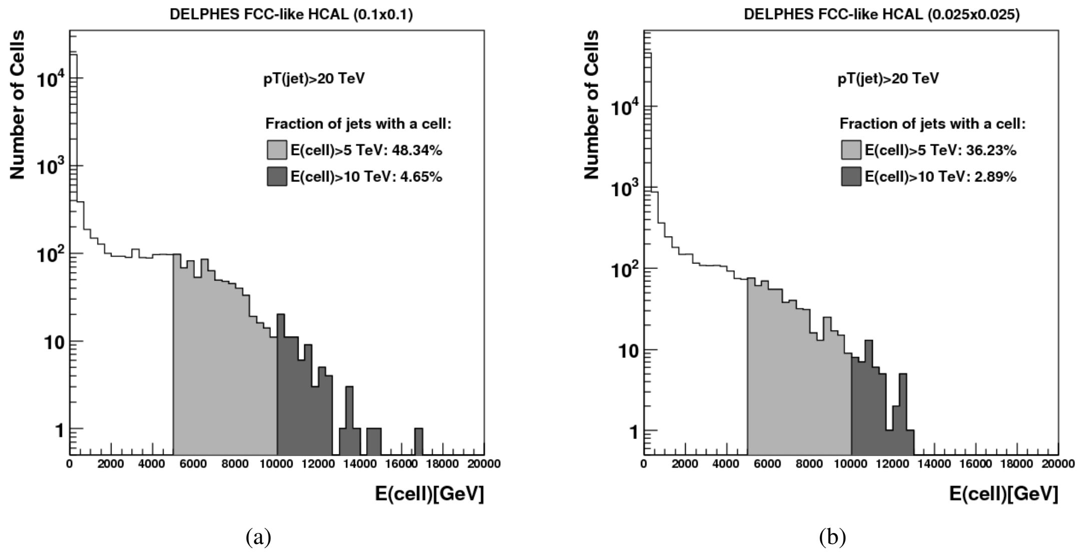


Figure 9: Energy distributions of cell energy in TileCal for a FCC detector using cell sizes of 0.1×0.1 (a) and 0.025×0.025 (b). These figures show the results for Standard Model, 14 TeV events trimmed to $p_T > 20$ TeV.

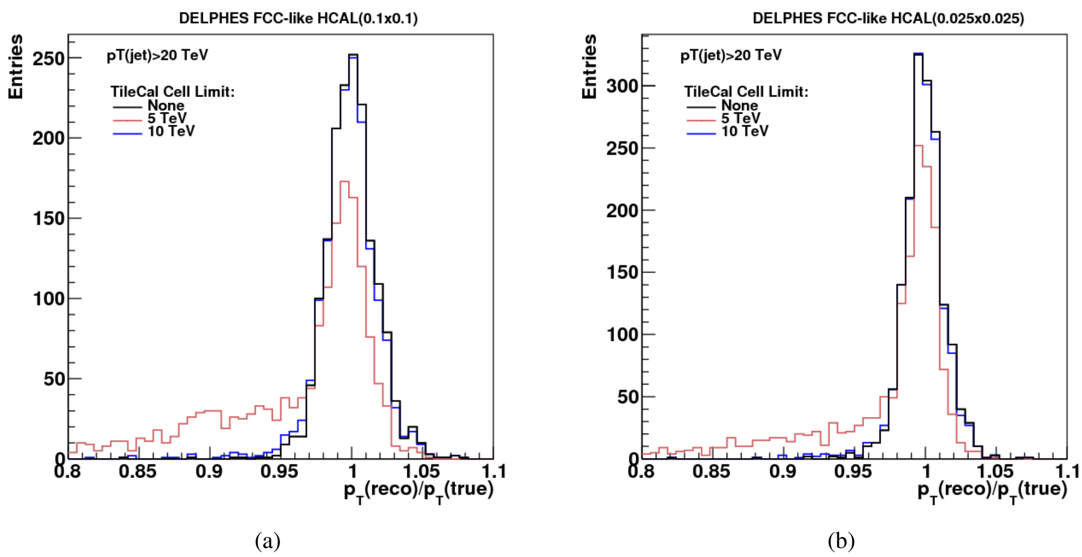


Figure 10: Ratio distribution of reconstructed jet p_T to truth jet p_T. Note that when a cell limit is imposed, some reconstructed jets lose p_T.

5 CONCLUSION

This study uses PYTHIA8 generated data for full and fast detector simulations of the the ATLAS Tile calorimeter. The data is analyzed through the lens of limited cell readout capabilities. We predict in run 2 that about 4-5% (1%) of jets with $p_T > 3$ TeV will lose p_T in reconstruction due to the present TileCal's dynamic range of 1.2 TeV (1.5 TeV). Given that the modified Delphes framework shows similar quantitative behavior to the full simulation, we have used Delphes for the exploration of higher p_T events. For example, 16% jets with $p_T > 4$ TeV exhibit truncated cells at 1.2 TeV. Also, simulated collisions at 100 TeV have shown that smaller η divisions in the TileCal would decrease the required dynamic range needed for good jet reconstruction. This finding is helpful for the planing of a future detector.

This study presents an optimistic view of how p_T will be impacted due to the assumption that cells truncate at their limit. In reality, more energy could be missing. Also, our fast simulation may be undercounting truncated cells because Delphes does not account for the increased energy fraction in TileCal for high-p_T jets. Further research using Geant4 could provide insight on this relation. If this dependency is found, it would be a simple matter to integrate the results into the Delphes program. This would provide more accurate affected jet fractions.

Exotic events present a problem for cell readout ranges too and they would be a good area for further study. Long lived particles decay on average 2 meters from the collision location meaning they are more likely to deposit all other their energy within a concentrated area of TileCal. The cells that see such particles would quickly be saturated and jet reconstruction would be compromised. Investigation of long lived particles should be done to have a better understanding of how the dynamic range of TileCal affects jet reconstruction of exotic events.

In conclusion, here are a few options that might extend the readout range in run 2. One solution is to lower the high-voltage on the PMTs which would allow higher energy readings. Unfortunately, the low-end energy range would shift up as well which might have consequences on the low-end energy spectra and low-noise electronics. Another option would be to flour the plastic scintillator light to beyond the usual specifications. Either way, the dynamic range of TileCal cell does present a problem with jet construction and should be understood prior to data analysis of run 2.

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