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Studies of granularity of a hadronic calorimeter for tens-of-TeV jets at a 100 TeV pp collider

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Abstract

Jet substructure variables for hadronic jets with transverse momenta in the range from 2.5 TeV to 20 TeV were studied using several designs for the spatial size of calorimeter cells. The studies used the full Geant4 simulation of calorimeter response combined with realistic reconstruction of calorimeter clusters. In most cases, the results indicate that the performance of jet-substructure reconstruction improves with reducing cell size of a hadronic calorimeter from $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ to 0.022×0.022.

Keywords: multi-TeV physics, *pp* collider, future hadron colliders, FCC, SppC

1. Introduction

Particle collisions at energies beyond those attained at the LHC will lead to many challenges for detector technologies. Future circular pp colliders such as the European initiatives, high-energy LHC (HE-LHC) and FCC-hh [1] and the Chinese initiative, SppC [2] will measure high-momentum bosons (W, Z, H) and top quarks with highly-collimated decay products that form jets. Jet substructure techniques are used to identify such boosted particles, and thus can maximize the physics potential of the future colliders.

The reconstruction of jet substructure variables for collimated jets with transverse momenta above 10 TeV requires an appropriate detector design. The most important detector systems for reconstruction of such jets are tracking and calorimetry. Recently, a number of studies [3, 4, 5] have been discussed using various fast simulation tools, such as Delphes [6], in which momenta of particles are smeared to mimic detector response.

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A major step towards the usage of full Geant4 simulation to verify the granularity requirements for calorimeters was made in [7]. These studies have illustrated a significant impact of granularity of electromagnetic (ECAL) and hadronic (HCAL) calorimeters on the cluster separation between two particles. It was concluded that high granularity is essential in resolving two close-by particles for energies above 100 GeV.

This paper takes the next step in understanding this problem in terms of high-level quantities typically used in physics analyses. Similar to the studies presented in [7], this paper is based on a full Geant4 simulation with realistic jet reconstruction.

2. Simulation of detector response

The description of the detector and software used for this study is discussed in [7]. We use the SiFCC detector geometry with a software package that provides a versatile environment for simulations of detector performance, testing new technology options, and event reconstruction techniques for future 100 TeV colliders.

The baseline detector discussed in [7] uses a steel-scintillator hadronic calorimeter with a transverse cell size of 5×5 cm^2, which corresponds to $\Delta\eta \times \Delta\phi = 0.022 \times 0.022$, where η is the pseudorapidity, $\eta \equiv -\ln\tan(\theta/2)$, and ϕ is the azimuthal angle. The depth of the HCAL in the barrel region is 11.25 interaction lengths (λ_I). The HCAL has 64 longitudinal layers in the barrel and the endcap regions.

In addition to the baseline HCAL geometry, several geometry variations were considered. We used the HCAL with transverse cell size of 20×20 cm^2 and 1×1 cm^2. In the terms of $\Delta\eta \times \Delta\phi$, such cell sizes correspond to 0.087×0.087 and 0.0043×0.0043, respectively.

The GEANT4 (version 10.3) [8] simulation of calorimeter response was followed by the full reconstruction of calorimeter clusters formed by the Pandora algorithm [9, 10]. Calorimeter clusters were built from calorimeter hits in the ECAL and HCAL after applying the corresponding sampling fractions. No other corrections are applied. Hadronic jets were reconstructed with the FastJet package [11] using the anti-k_T algorithm [12] with a distance parameter of 0.5.

In the following discussion, we use the simulations of a heavy Z' boson, a hypothetical gauge boson that arises from extensions of the electroweak symmetry of the Standard Model. The Z' bosons were simulated with the masses M = 5, 10, 20 and 40 TeV. The lowest value represents a typical mass that is within the reach of the LHC experiments. The resonance mass of 40 TeV represents the physics reach for a 100 TeV collider. The Z' bosons are forced to decay to two light-flavor quark ($q\bar{q}$), W^+W^- or $t\bar{t}$ final states, where the W bosons and t quarks decay hadronically. In these scenarios, two highly-boosted jets are produced, which are typically back-to-back in the laboratory frame. The typical transverse momenta of the jets are $\simeq M/2$. The main difference between the considered decay modes lies in the different jet substructures. In the case of the $q\bar{q}$ decays, jets do not have any internal structure. In the case of the W^+W^- final state, each jet has two subjets because of the decay $W \to q\bar{q}$. In the case of hadronic top decays, jets have three subjets due to the decay $t \to W^+ b \to q\bar{q}b$. The signal events were generated using the Pythia8 generator with the default settings, ignoring interference with SM processes. The event samples used in this paper are available from the HepSim database [13].

3. Studies of jet properties

We consider several variables that characterize jet substructure using different calorimeter granularities. The question we want to answer is, how closely the reconstructed jet substructure variables reflect the input "truth" values that are reconstructed using particles directly from the PYTHIA8 generator.

In this study we use the jet effective radius and jet splitting scales as benchmark variables to study jet substructure properties. The effective radius is the average of the energy-weighted radial distance δR_i in $\eta - \phi$ space of jet constituents. It is defined as $(1/E)\sum_i e_i \delta R_i$, where E is the energy of the jet and e_i is the energy of a calorimeter constituent cluster i at the distance δR_i from the jet center. The sum runs over all constituents of the jet. This variable has been studied for multi-TeV jets in Ref. [14]. A jet k_T splitting scale [15] is defined as a distance measure used to form jets by the k_T recombination algorithm [16, 17]. This variable has been studied by ATLAS [18], and more recently in the context of 100 TeV physics [14]. The splitting scale is defined as $\sqrt{d_{12}} = \min(p_T^1, p_T^2) \times \delta R_{12}$ [18] at the final stage of the k_T clustering, where two subjets are merged into the final jet.

Figures 1 and 2 show the distributions of the jet effective radius and jet splitting scale for different jet transverse momenta and HCAL granularities. The reconstructed-level distributions disagree significantly with the distributions reconstructed using truth-level particles. The distributions reconstructed with 1×1 cm^2 or 5×5 cm^2 cells are generally closer to the truth-level variables, than the distributions reconstructed using 20×20 cm^2 cells, particularly for resonance masses in the 10-20 TeV range. In these cases, there is not much difference between the 5×5 cm^2 and 1×1 cm^2 cell sizes.

This study confirms the baseline SiFCC detector geometry [7] that uses 5×5 cm^2 HCAL cells, corresponding to $\Delta\eta \times \Delta\phi = 0.022 \times 0.022$. Similar HCAL cell sizes, 0.025×0.025, were recently adopted for the baseline FCC-hh detector [19, 20] planned at CERN. Before the publication [7], such a choice for the HCAL cells was motivated by the studies of jet substructure using a fast detector simulation of boosted jets. In addition to the improvements in physics performance, the smaller HCAL cells reduce the required dynamic range for signal reconstruction [4], and thus can simplify the calorimeter readout.

It should be noted that the ATLAS and CMS detectors use the HCAL cell sizes in the barrel region which are close to $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$. According to this study, such HCAL cell sizes are not optimal in terms of performance for tens-of-TeV jets.

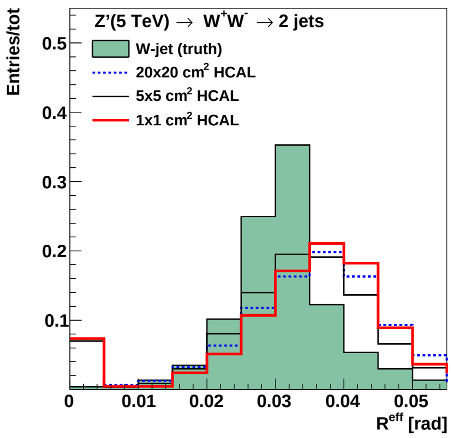
In the following sections we consider several other physics-motivated variables that can shed light on the performance of the HCAL for tens-of-TeV jets.

4. Detector performance with soft drop mass

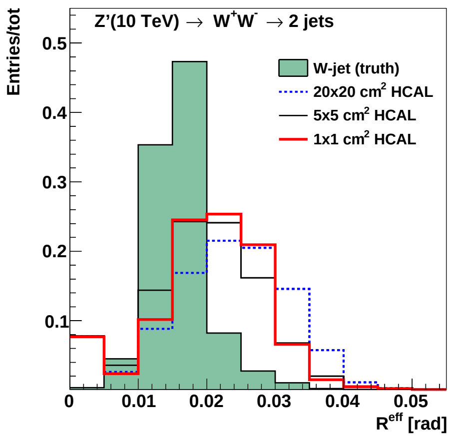
In this section, we use the jet mass computed with a specific algorithm, soft drop declustering, to study the performance with various detector cell sizes and resonance masses.

4.1. The technique of soft drop declustering

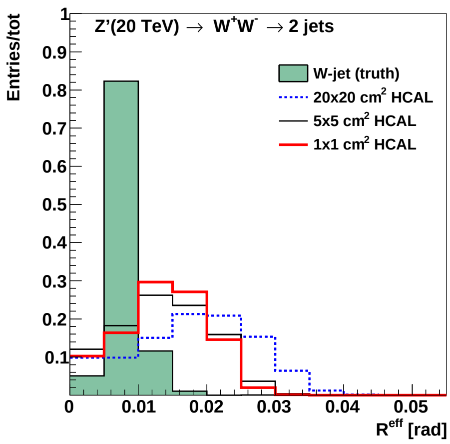
The soft drop declustering [21] is a grooming method that removes soft wide-angle radiation from a jet. The constituents of a jet j_0 are first reclustered using



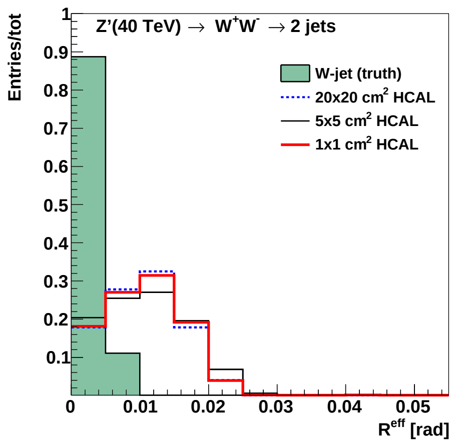
(a) $M(Z') = 5$ TeV



(b) $M(Z') = 10$ TeV

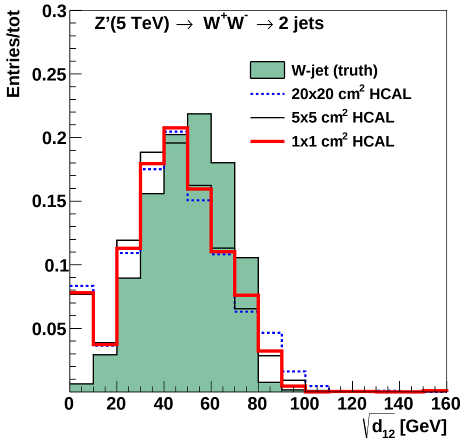


(c) $M(Z') = 20$ TeV

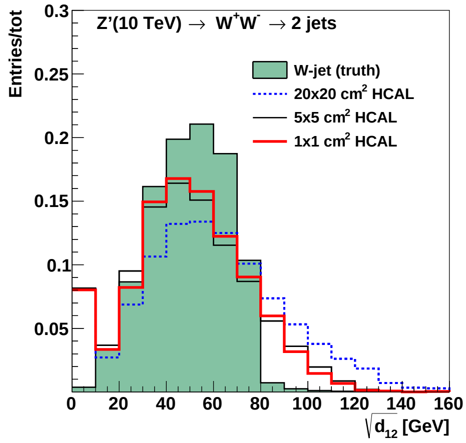


(d) $M(Z') = 40$ TeV

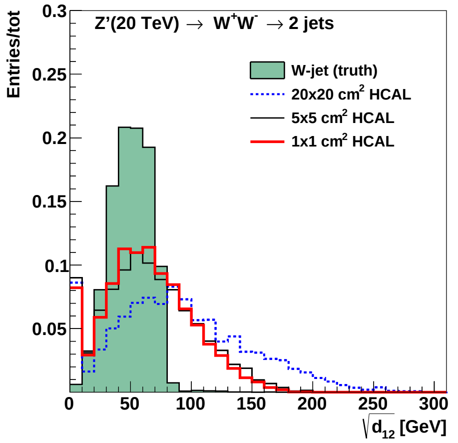
Figure 1: Jet effective radius for different jet transverse momenta and HCAL granularities.



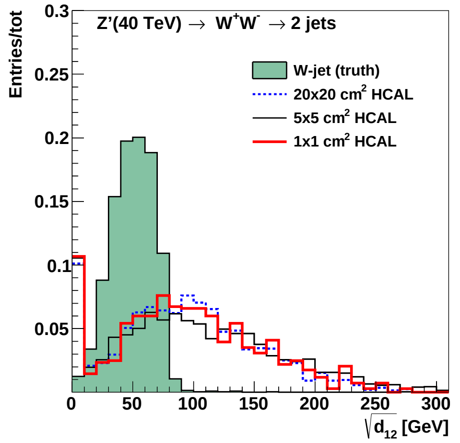
(a) $M(Z') = 5$ TeV



(b) $M(Z') = 10$ TeV



(c) $M(Z') = 20$ TeV



(d) $M(Z') = 40$ TeV

Figure 2: Jet splitting scale for different jet transverse momenta and HCAL granularity.

the Cambridge-Aachen (C/A) algorithm [22, 23]. Then, the jet j_0 is broken into two subjets j_1 and j_2 by undoing the last stage of C/A clustering. If the subjets pass the following soft drop condition, jet j_0 is the final soft-drop jet. Otherwise, the algorithm redefines j_0 to be the subjet with larger p_T (among j_1 and j_2) and iterates the procedure. The condition is,

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}}(\frac{\Delta R_{12}}{R_0})^{\beta}, \tag{1}$$

where p_{T1} and p_{T2} are the transverse momenta of the two subjets, z_{cut} is soft drop threshold, ΔR_{12} is the distance between the two subjets in the rapidity-azimuthal plane (y-ϕ), R_0 is the characteristic radius of the original jet, and β is the angular exponent.

In our study, we compare the HCAL performance for the soft drop mass with $\beta = 0$ and $\beta = 2$. For $\beta = 0$, the soft drop condition depends only on the z_{cut}. For $\beta = 2$, the condition depends on the angular distance between the two subjets and z_{cut} and the algorithm becomes infrared and collinear safe.

4.2. Analysis method

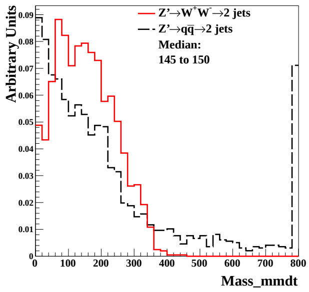
We employ the following method to quantify the detector performance and determine the cell size that gives the best separation between signal and background. For each configuration of detector and resonance mass, we draw the receiver operating characteristic (ROC) curves in which the x-axis is the signal efficiency (ϵ_{sig}) and y-axis is the inverse of the background efficiency ($1/\epsilon_{\text{bkg}}$). In order to scan the efficiencies of soft drop mass cuts, we vary the mass window as follows. We center the initial window on the median of the signal histogram, and increase its width symmetrically left and right in bins of 5 GeV. If one side of the mass window reaches the boundary of the mass histogram, we increase the width on the other side. For each mass window, the corresponding efficiencies ϵ_{sig} and ϵ_{bkg} give a point on the ROC curve.

4.3. Results and conclusion

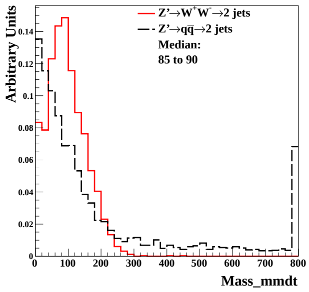
Figures 3, 5, 7 and 9 show the distributions for the soft drop mass for $\beta = 0$ and $\beta = 2$ with different resonance masses and detector cell sizes; the signals considered are the $Z' \to WW$ and $Z' \to t\bar{t}$ processes. Figures 4, 6, 8 and 10 show the corresponding ROC curves for different detector cell sizes and resonance masses.

These studies show that the reconstruction of soft drop mass improves with decreasing HCAL cell sizes. Figures 4 and 6 show that for $\beta = 0$ the smallest detector cell size, 1×1 cm^2, has the best separation power at resonance masses of 5, 10, and 20 TeV when the signal is the $Z' \to WW$ process, and at resonance masses of 10 and 20 TeV when the signal is the $Z' \to t\bar{t}$ process. However, for $\beta = 2$, Figs. 8 and 10 show that the smallest detector cell size does not have improvements in the separation power when compared with larger cell sizes. In fact, the performance for the three cell sizes is similar.

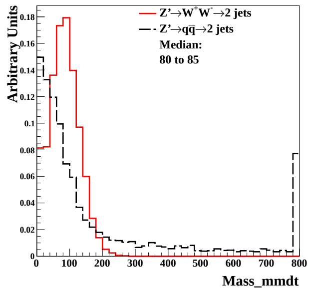
Note that the separation between ROC curves depends on the physics variable and on the boost of the top quarks or the W bosons. For example, the similarity between the ROC curves shown in Fig. 6(a) is due to the insufficient boost of the top quarks. On



(a) 20×20 cm^2

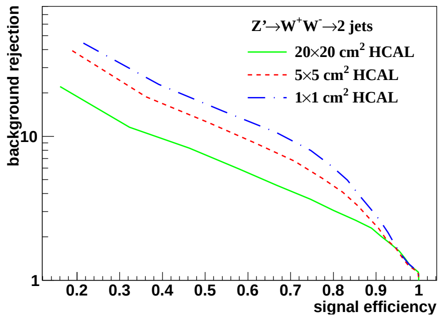


(b) 5×5 cm^2

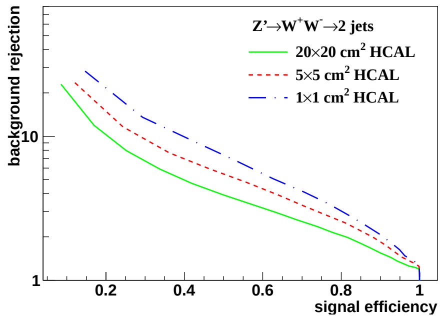


(c) 1×1 cm^2

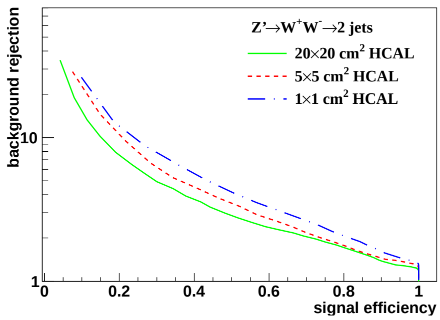
Figure 3: Distributions of soft drop mass for β=0, with $M(Z') = 20$ TeV and three different detector cell sizes: 20×20, 5×5 and 1×1 cm^2. The signal (background) process is $Z' \rightarrow WW$ ($Z' \rightarrow q\bar{q}$).



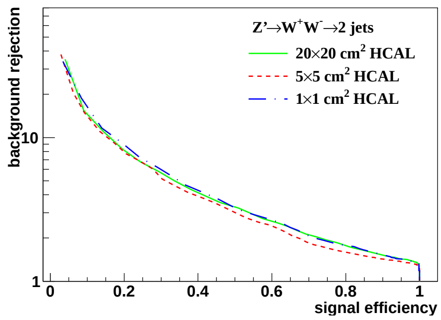
(a) $M(Z') = 5$ TeV



(b) $M(Z') = 10$ TeV

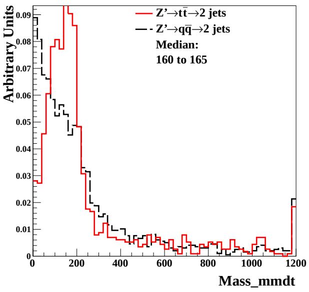


(c) $M(Z') = 20$ TeV

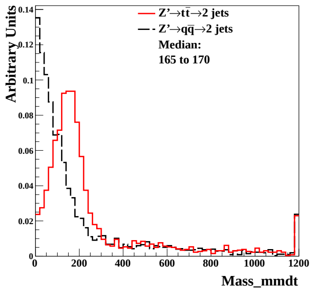


(d) $M(Z') = 40$ TeV

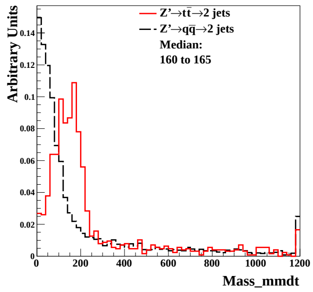
Figure 4: The ROC curves of soft drop mass selection for β=0 with resonance masses of 5, 10, 20 and 40 TeV. Three different detector cell sizes are compared: 20×20, 5×5, and 1×1 cm^2. The signal (background) process is $Z' \rightarrow WW$ ($Z' \rightarrow q\bar{q}$).



(a) 5×5 cm^2

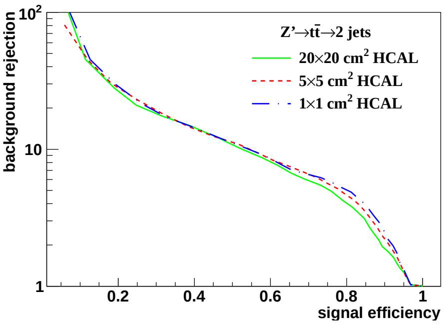


(b) 20×20 cm^2

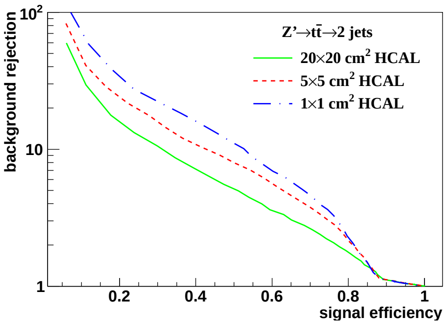


(c) 1×1 cm^2

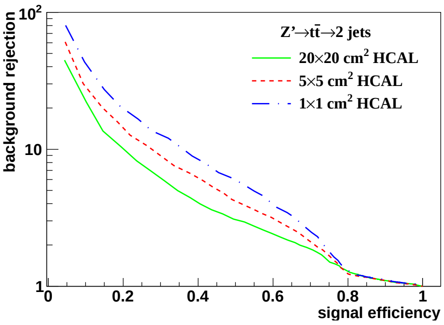
Figure 5: Distributions of soft drop mass for β=0, with $M(Z') = 20$ TeV and three different detector cell sizes: 20×20, 5×5, and 1×1 cm^2. The signal (background) process is $Z' \to t\bar{t}$ ($Z' \to q\bar{q}$).



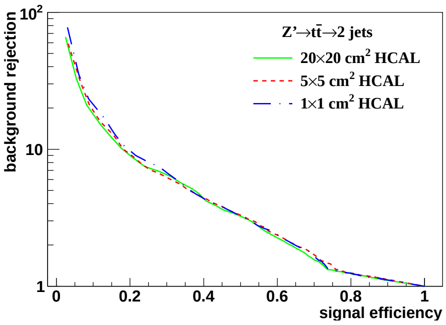
(a) $M(Z') = 5$ TeV



(b) $M(Z') = 10$ TeV

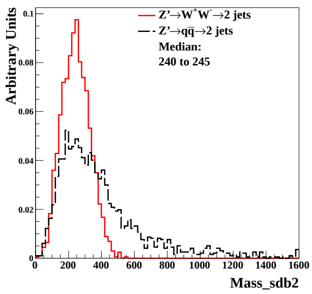


(c) $M(Z') = 20$ TeV

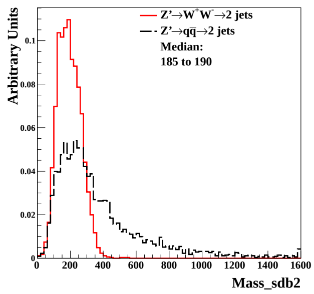


(d) $M(Z') = 40$ TeV

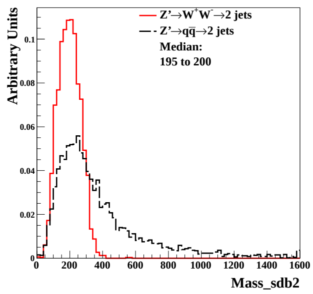
Figure 6: The ROC curves of soft drop mass selection for β=0 with resonance masses of 5, 10, 20 and 40 TeV. Three different detector cell sizes are compared: 20×20, 5×5, and 1×1 cm^2. The signal (background) process is $Z' \to t\bar{t}$ ($Z' \to q\bar{q}$).



(a) 20 × 20 cm^2

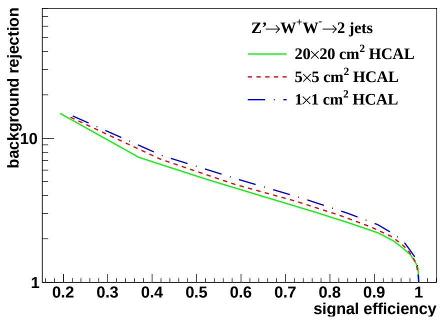


(b) 5 × 5 cm^2

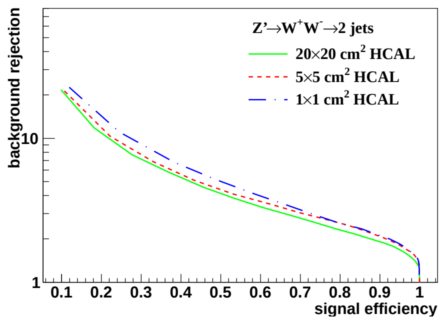


(c) 1 × 1 cm^2

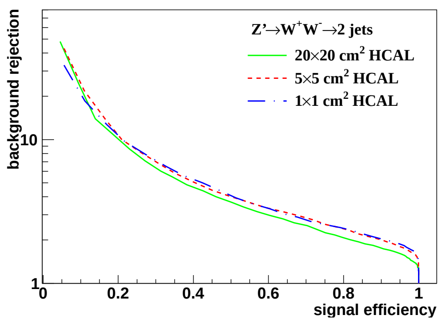
Figure 7: Distributions of soft drop mass for $\beta = 2$, with $M(Z') = 20$ TeV and three different detector cell sizes: 20 × 20, 5 × 5 and 1 × 1 cm^2. The signal (background) process is $Z' \to WW$ ($Z' \to q\bar{q}$).



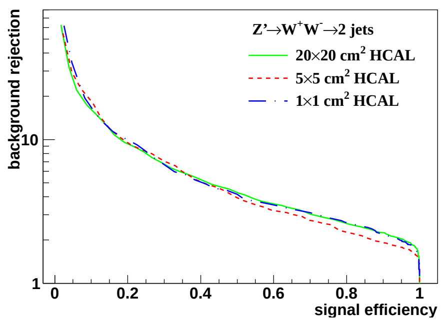
(a) $M(Z') = 5$ TeV



(b) $M(Z') = 10$ TeV

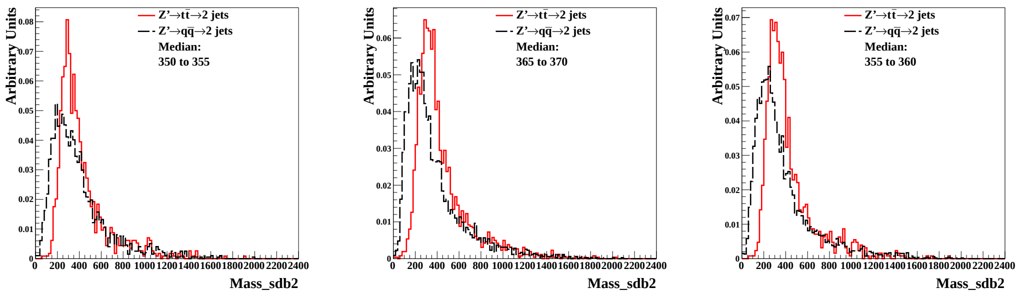


(c) $M(Z') = 20$ TeV



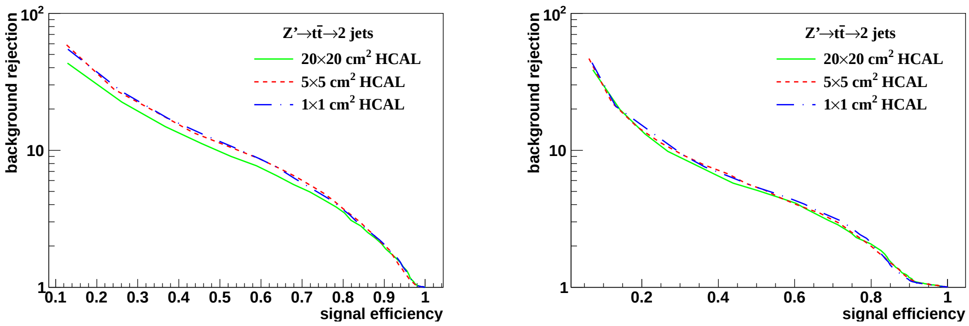
(d) $M(Z') = 40$ TeV

Figure 8: The ROC curves of soft drop mass selection for $\beta = 2$ with resonance masses of 5, 10, 20 and 40 TeV. Three different detector cell sizes are compared: 20 × 20, 5 × 5, and 1 × 1 cm^2. The signal (background) process is $Z' \to WW$ ($Z' \to q\bar{q}$).

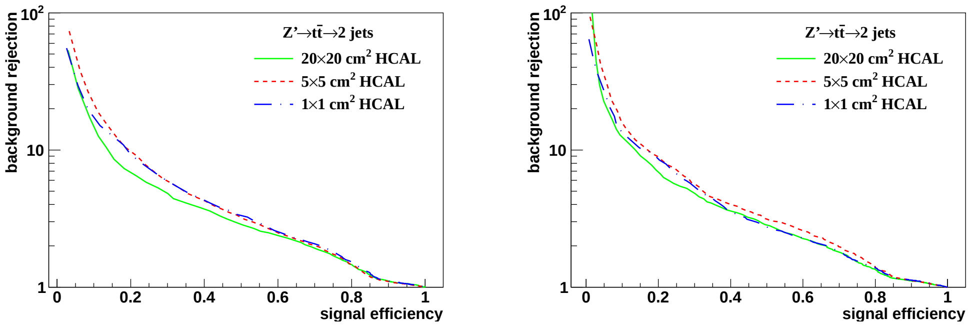


(a) 20×20 cm^2 (b) 5×5 cm^2 (c) 1×1 cm^2

Figure 9: Distributions of soft drop mass for $\beta = 2$, with $M(Z') = 20$ TeV and three different detector cell sizes: 20×20, 5×5, and 1×1 cm^2. The signal (background) process is $Z' \to t\bar{t}$ ($Z' \to q\bar{q}$).



(a) $M(Z') = 5$ TeV (b) $M(Z') = 10$ TeV



(c) $M(Z') = 20$ TeV (d) $M(Z') = 40$ TeV

Figure 10: The ROC curves of soft drop mass selection for $\beta = 2$ with resonance masses of 5, 10, 20 and 40 TeV. Three different detector cell sizes are compared: 20×20, 5×5 and 1×1 cm^2. The signal (background) process is $Z' \to t\bar{t}$ ($Z' \to q\bar{q}$).

the other hand, Fig. 6(d) does not show a difference between the ROC curves because the boost is too high.

We also find that the soft drop mass with $\beta = 0$ has better performance for distinguishing signal from background than with $\beta = 2$. Therefore, we will apply requirements on the soft drop mass with $\beta = 0$ when studying the other jet substructure variables.

5. Detector performance with jet substructure variables

In this section, we use several jet substructure variables to study the performance with various detector cell sizes and resonance masses.

5.1. *N-subjettiness*

The variable N-subjettiness [24], denoted by τ_N, is designed to "count" the number of subjet(s) in a large radius jet in order to separate signal jets from decays of heavy bosons and background jets from QCD processes. τ_N is the p_{T}-weighted angular distance between each jet constituent and the closest subjet axis:

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, ...\Delta R_{N,k}\}, \qquad (2)$$

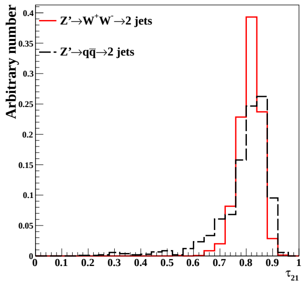
with a normalization factor d_0:

$$d_0 = \sum_k p_{T,k} R_0.$$

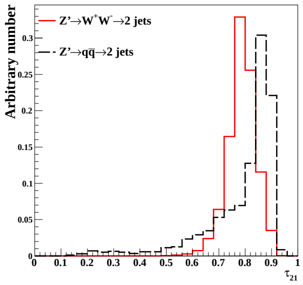
The k index runs over all constituent particles in a given large radius jet, $p_{T,k}$ is the transverse momentum of each individual constituent, $\Delta R_{j,k} = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$ is the distance between the constituent k and the candidate subjet axis j in the $y - \phi$ plane. R_0 is the characteristic jet radius used in the anti-k_t jet algorithm.

This analysis uses the jet reconstruction described in Sect. 2. The subjet axes are obtained by running the exclusive k_t algorithm [25] and reversing the last N clustering steps. Namely, when τ_N is computed, the k_t algorithm is forced to return exactly N jets. If a large radius jet has N subjet(s), its τ_N is smaller than τ_{N-1}. Therefore, in our analysis, the ratios $\tau_{21} \equiv \tau_2/\tau_1$ and $\tau_{32} \equiv \tau_3/\tau_2$ are used to distinguish the one-prong background jets and the two-prong jets from W boson decays or the three-prong jets from top quark decays.

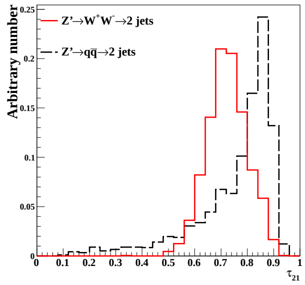
We use the ROC curves described in Sect. 4.2 to analyze the detector performance and determine the cell size that gives the best separation between signal and background processes. Following the suggestion of Ref. [26], the requirement on the soft drop mass with $\beta = 0$ is applied before the study of N-subjettiness. For each detector configuration and resonance mass, the soft drop mass prerequisite window is determined as follows. The window is initialized by the median bin of the soft drop mass histogram from simulated signal events as described in Sect. 4.2. Comparing the adjacent bins, the bin with the larger number of events is included to extend the mass window iteratively. The procedure is repeated until the prerequisite mass window cut reaches a signal efficiency of 75%.



(a) 20 × 20 cm^2

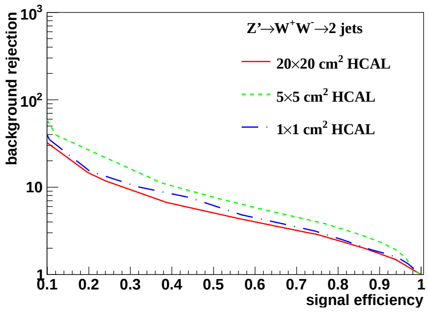


(b) 5 × 5 cm^2

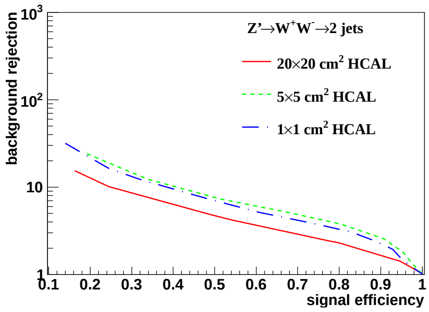


(c) 1 × 1 cm^2

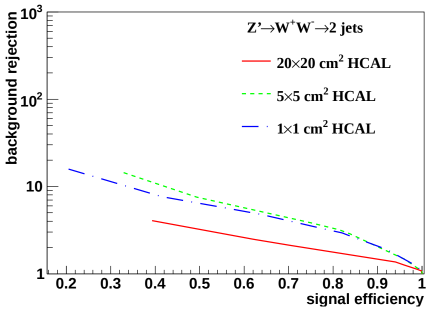
Figure 11: Distributions of τ_{21} for $M(Z') = 20$ TeV for different detector granularities. Cell sizes of 20 × 20, 5 × 5, and 1 × 1 cm^2 are shown here.



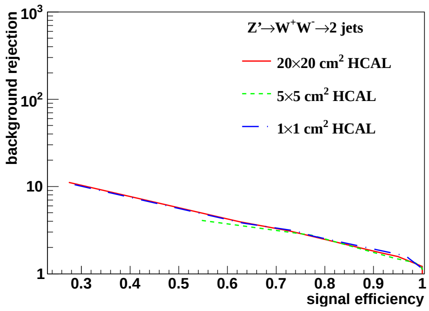
(a) $M(Z') = 5$ TeV



(b) $M(Z') = 10$ TeV



(c) $M(Z') = 20$ TeV



(d) $M(Z') = 40$ TeV

Figure 12: Signal efficiency versus background rejection rate using τ_{21}. Resonance masses of (a) 5 TeV, (b) 10 TeV, (c) 20 TeV and (d) 40 TeV are shown here. In each figure, the three ROC curves correspond to different cell sizes.

With this *a-priori* mass window pre-selection, the signal and background efficiencies of various τ_{21} and τ_{32} window cuts are scanned. Since some of the background distributions have long tails and leak into the signal-dominated region, we use the following method based on the Neyman-Pearson lemma to determine the τ windows. First, we take the ratio of the signal to background τ_{21} (or τ_{32}) histograms. The window is initialized by the bin with the maximum signal to background ratio (S/N). Comparing the adjacent bins, the bin with the larger S/N is included to extend the τ_{21} (or τ_{32}) selection window iteratively. Every window has its corresponding ϵ_{sig} and $1/\epsilon_{\text{bkg}}$ and an ROC curve is mapped out.

Figures 11 and 13 show the distributions of τ_{21} and τ_{32} for $M(Z') = 20$ TeV after applying the requirement on the soft drop mass. The signals considered are the $Z' \to WW$ (for τ_{21}) and $Z' \to t\bar{t}$ (for τ_{32}) processes. Figures 12 and 14 present the ROC curves from different detector cell sizes and resonance masses, respectively. We find that the performance of the 1×1 cm^2 and 5×5 cm^2 cell sizes is similar for both the τ_{21} and the τ_{32} variables, for all resonance masses in the 5-40 TeV range. These smaller cell sizes yield a higher performance than the 20×20 cm^2 cell size when using the τ_{21} variable, for resonance masses of 5, 10 and 20 TeV in the WW final state. In the case of the τ_{32} variable, the results are ambiguous, as the 20×20 cm^2 cell size is more (less) performant for low (high) efficiency selection criteria.

5.2. Energy correlation function

The energy correlation function (ECF) [28] is defined as follows:

$$ECF(N, \beta) = \sum_{i_1<i_2<\ldots.<i_N \in J} \left(\prod_{a=1}^{N} p_{\text{T}ia} \right) \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^{N} R_{i_b i_c} \right)^{\beta}, \qquad (3)$$

where the sum is over all constituents in jet J, p_{T} is the transverse momentum of each constituent, and R_{mn} is the distance between two constituents m and n in the y-ϕ plane. In order to use a dimensionless variable, a parameter r_N is defined:

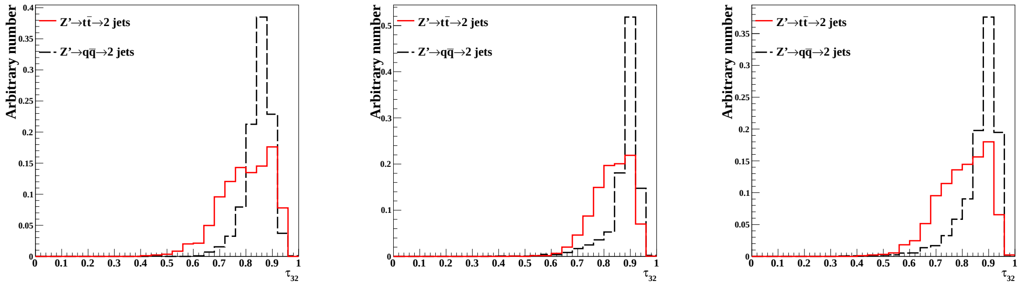
$$r_N^{(\beta)} \equiv \frac{ECF(N+1, \beta)}{ECF(N, \beta)}. \qquad (4)$$

The idea of r_N comes from N-subjettiness τ_N. Both r_N and τ_N are linear in the energy of the soft radiation for a system of N partons accompanied by soft radiation. In general, if the system has N subjets, $ECF(N+1, \beta)$ should be significantly smaller than $ECF(N, \beta)$. Therefore, we can use this feature to distinguish jets with different numbers of subjets. As in Sect. 5.1, the ratio r_N/r_{N-1}, denoted by C_N, (double-ratios of ECFs) is used to study the detector performance:

$$C_N^{(\beta)} \equiv \frac{r_N^{(\beta)}}{r_{N-1}^{(\beta)}} = \frac{ECF(N-1, \beta) ECF(N+1, \beta)}{ECF(N, \beta)^2}. \qquad (5)$$

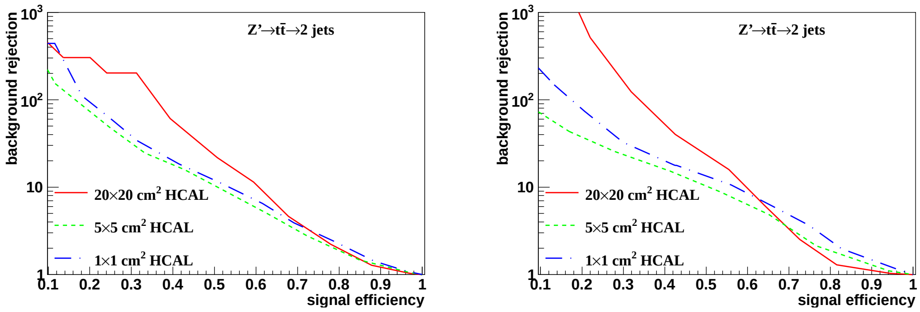
In our analysis, we set $N = 2$ and $\beta = 1$ (C_2^1).

Figure 15 presents the histograms of C_2^1 with $M(Z') = 20$ TeV after making the requirement on the soft drop mass. The signal considered is the $Z' \to WW$ process. Figure 16 shows the ROC curves from different detector cell sizes for each resonance mass. One can see that the 5×5 cm^2 cell size improves upon the 20×20 cm^2 cell size, and either matches or improves upon the 1×1 cm^2 cell size, for all resonance masses.

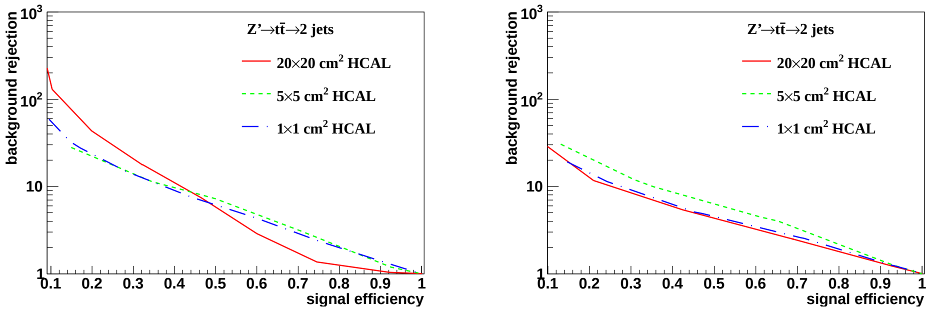


(a) 20×20 cm^2 (b) 5×5 cm^2 (c) 1×1 cm^2

Figure 13: Distributions of τ_{32} for $M(Z') = 20$ TeV for different detector granularities. Cell sizes of 20×20, 5×5, and 1×1 cm^2 are shown here.

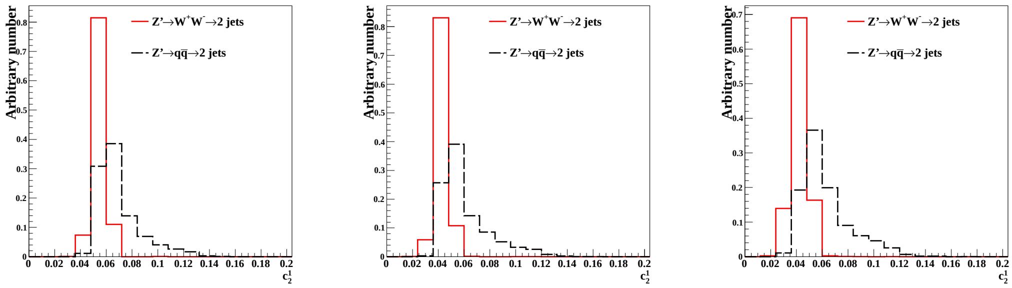


(a) $M(Z') = 5$ TeV (b) $M(Z') = 10$ TeV



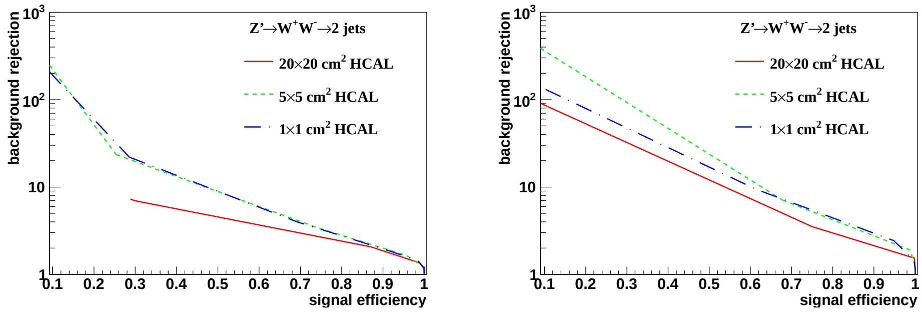
(c) $M(Z') = 20$ TeV (d) $M(Z') = 40$ TeV

Figure 14: Signal efficiency versus background rejection rate using τ_{32}. Resonance masses of (a) 5 TeV, (b) 10 TeV, (c) 20 TeV and (d) 40 TeV are shown here. In each figure, the three ROC curves correspond to different HCAL cell sizes.

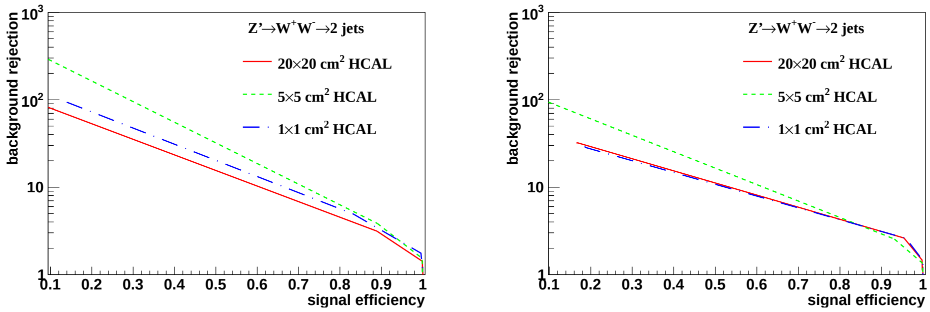


(a) 20 × 20 cm^2 (b) 5 × 5 cm^2 (c) 1 × 1 cm^2

Figure 15: Distributions of C_2^1 with $M(Z') = 20$ TeV for different detector granularities. Cell sizes of 20 × 20, 5 × 5, and 1 × 1 cm^2 are shown here.



(a) $M(Z') = 5$ TeV (b) $M(Z') = 10$ TeV



(c) $M(Z') = 20$ TeV (d) $M(Z') = 40$ TeV

Figure 16: Signal efficiency versus background rejection rate using C_2^1. The resonance masses of (a) 5 TeV, (b) 10 TeV, (c) 20 TeV, and (d) 40 TeV are shown here. In each figure, the three ROC curves correspond to different detector sizes.

6. Conclusions

The studies presented in this paper show that the reconstruction of jet substructure variables for future particle colliders will benefit from small cell sizes of the hadronic calorimeters. This conclusion was obtained using the realistic GEANT4 simulation of calorimeter response combined with reconstruction of calorimeter clusters used as inputs for jet reconstruction. Hadronic calorimeters that use the cell sizes of 20×20 cm^2 ($\Delta\eta \times \Delta\phi = 0.087 \times 0.087$) are least performant for almost every substructure variable considered in this analysis, for jet transverse momenta between 2.5 and 10 TeV. Such cell sizes are similar to those used for the ATLAS and CMS detectors at the LHC. In terms of reconstruction of physics-motivated quantities used for jet substructure studies, the performance of a hadronic calorimeter with $\Delta\eta \times \Delta\phi = 0.022 \times 0.022$ (5×5 cm^2 cell size) is, in most cases, better than for a detector with 0.087×0.087 cells.

Thus this study confirms the HCAL geometry of the SiFCC detector [7], with the $\Delta\eta \times \Delta\phi = 0.022 \times 0.022$ HCAL cells. It also confirms the HCAL design of the baseline FCC-hh [19, 20] detector with $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ HCAL cells.

It interesting to note that, for very boosted jets with transverse momenta close to 20 TeV, further decrease of cell size to $\Delta\eta \times \Delta\phi = 0.0043 \times 0.0043$ did not definitively show a further improvement in performance. This result needs to be understood in terms of various types of simulations and different options for reconstruction of the calorimeter clusters.

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