Studying the timing resolution of FCal1 with a detailed simulation using Geant4

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The ATLAS experiment in the Large Hadron Collider (LHC) has the largest detector in the world. Forward Calorimeter layer one (FCal1) is one of the electromagnetic detectors in ATLAS. It detects the particles that have high pseudorapidity. Because of the special spatial position of FCal1, the timing resolution of FCal1 is very important in determining where the detected particles come from. A study is designed to investigate the timing resolution of current FCal1. This is done by doing simulation based on Geant4 tool kit. The results show that the timing resolution of FCal1 varies at different energy levels, and environmental factor can also affect the resolution. The resolution ranges from 44.34 ± 0.99 ps to 78.55 ± 1.75 ps.

CONTENTS

I. INTRODUCTION

The Large Hadron Collider (LHC) operates at $\sqrt{s} =$ 13 TeV in Run 2. While new physics may be discovered at higher energies and higher luminosity, different experiments and their detectors at the LHC are facing challenges due to an increasing amount of events. To reconstruct an event, it's important to know where the detected particles are coming from.

In the ATLAS experiment, for high p_T particles, the inner detector tells the accurate position where the particles are originally from. However, for particles that have large pseudorapidity, the inner detector, covering $|\eta|$ up to 2.5 [1], is not responsible for the detection. Forward calorimeters (FCal), covering $3.1 < |\eta| < 4.9$ [1], then take the role of telling where the detected particles may come from. According to what particle is being detected, there are two types of calorimeter in ATLAS: the electromagnetic calorimeter and the hadronic calorimeter. FCal contains one module of electromagnetic calorimeter (FCal1) and two modules of hadronic calorimeter (FCal2 and FCal3). FCal1 is placed in front of FCal2 and FCal3 and mainly measures the energy deposited by electron, positron and photon. Once a particle is detected in FCal1, the vertex of the event, which produces the detected particle, can be reconstructed. Therefore, the timing resolution of FCal1 is significant in distinguishing which event the particle may come from. This study investigates the timing resolution of current FCal1 by performing simulation based on the Geant4 toolkit [2].

II. OVERVIEW OF FCAL1

FCal1 is the module closest to the interaction point (IP), from which it is about 5 m away. It is made of copper in the shape of a cylinder with a hole at the center for the passage of a beam pipe. FCal1, as a liquid argon detector, contains a large amount of components that together make FCal1 function. FCal1 module can be thought of as made up of identical unit cells. Each unit cell is parallel to the beam (z) axis, extends the full length of the module, and contains within it one liquid argon electrode. It also contains the absorber material associated with that cell Ref. [3]. Some of the detailed parameters are listed in TABLE I. More parameter information about FCal1 can be found in Ref. [3]. When a particle goes through the liquid argon (lAr) gap, it ionizes the lAr. The electric field between the rod (250 V) and the tube (ground) separates the negative charge and pos-

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itive charge, generating an electrical signal, which takes some time to be read out.

III. OVERVIEW OF SIMULATION

III.1. Simulation toolkit

The simulation is done by using the Geant4 toolkit. Geant4 is a tool kit that can be used to accurately simulate the passage of particles through matter [2]. Geant4 is written and maintained by CERN. C++ is the language that is used to build the toolkit. The general process of simulation includes detector construction, physics specification, and action.

III.2. Simulation design

To study the timing resolution of FCal1, FCal1 is simulated with as much detail as possible, but not with everything. Since the study focuses on FCal1, only the FCal1 is simulated. Other parts of the ATLAS are omitted. However, in order to be more realistic, there are different setups of the detector environment, designed to study how the external factor would affect the timing resolution. A full description of the detector and its environment can be found in Sec. IV. Physics is specified by choosing the physics list. In this study, a Geant4 in-built list, FTFP_BERT is chosen, which is recommended by the Geant4 collaboration for high energy physics. Once the detector and physics are defined, the action of firing particle toward the detector can be simulated. In this study, electrons are chosen to carry energy at 1 TeV and 500 GeV. After the collision between particle and the detector, a signal propagation program engages and calculates the average time of signal readout of that event. At the end of the simulation, ROOT, as the analysis framework, combines all of the timing data and calculates the resolution. There are eight runs in total. Each run has 1000 events (electrons). Each event is simulated individually.

TABLE I. FCal1 Module Parameters[a]

Parameter	size
Module inner radius (mm)	72.3
Module outer radius (mm)	449.4
Module depth (mm)	444.1
Electrode spacing (mm)	7.5
Material	
Rod	Cu
Tube	Cu

[a] Ref. [3]

TABLE II. Material list

Material	Material symbol	source/component
Iron	Fe	G4_Fe
Liquid Argon	lAr	$z = 18$[a]
		$m = 39.95$ g/mole[b]
		$\rho = 1.39$ g/cm[c]
Copper	Cu	G4_Cu
Vacuum		G4_Galactic

[a] Atomic number
[b] Molar mass
[c] Density

IV. DETECTOR SIMULATION DETAIL

To simulate the detector and its working environment, there are two components that need to be specified: the material and the physical volume.

IV.1. Material

All of the materials used in the simulation are either retrieved from the Geant4 material data base directly or constructed manually by specifying the atomic number, molar mass and density. All used materials are listed in TABLE II. Geant4 in-built materials have a "G4_" prefix.

IV.2. Physical volume

Before the detector is simulated, Geant4 requires one to specify the world volume, the top mother volume where the whole simulation runs. In this study, world is a cube with a width of 12 m. For safety purposes, there is a volume called the envelope inside the world volume. The detector is simulated inside the envelope. The material of the world and the envelope is vacuum.

The geometry of the detector is simulated as close as possible to the actual FCal1. In this study, geometry is set up based on Ref. [3]. The detailed simulation of FCal1 is accomplished by simulating different components and then putting them together. The simulated absorber, which has the shape of cylinder with a hole at the center, has the parameters shown in TABLE III. It is made of copper. A view of the simulated absorber is shown in FIG. 1. The absorber is the top mother volume of detector simulation. Therefore, all other components are the daughter volumes of the absorber volume.

The simulation of the electrode is done by simulating the hexagon unit [3]. FIG. 2 and FIG. 3 show the simulated hexagon unit. A hexagon unit has four physical volumes. The top volume is the copper hexagon volume. The lAr gap is the daughter volume of the hexagon. There are two daughter volumes of the lAr gap volume. One is the rod. The other one is the sensitive detector

TABLE III. Simulated Absorber Parameters

Parameter	size
Absorber inner radius (mm)	72.3
Absorber outer radius (mm)	451
Absorber depth (mm)	450

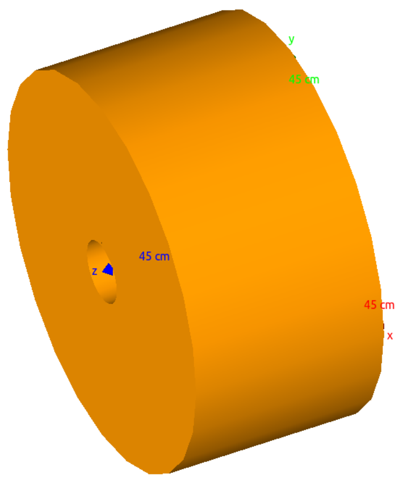


FIG. 1. Absorber simulation

volume, which will be discussed in Sec. V. Parameters of the hexagon volume can be found in TABLE IV.

TABLE IV. Simulated Hexagon Unit Parameters

Parameter	size
Hexagon length (mm)	450
Hexagon in-radius (mm)	3.75
lAr gap outer radius (mm)	2.626
lAr gap inner radius (mm)	2.356
lAr gap depth (mm)	450
Rod radius (mm)	2.356
Rod length (mm)	450

The hexagon units are inserted into the absorber volume according to the arrangement of the actual FCal1, as shown in FIG. 4. The final view of the simulated FCal1 geometry is shown in FIG. 5

In order to make the simulation closer to the actual experimental environment, different setups of the environment are also simulated. FCal1 is not directly exposed to the IP; there is something else sitting in front of it. To simulate this external factor to the detector, disk-shape object (disk) is placed in front of the detector on the side of the IP. Parameters of the disk can be found in TABLE V. The depth of the disk is one radiation length of the chosen material. There are three different placements of the disk(s): one disk placed right in front of the detector, another disk placed 500 mm in font of

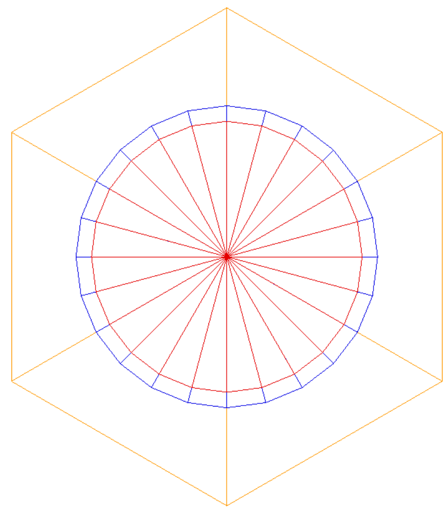


FIG. 2. Hexagon unit simulation (front view)

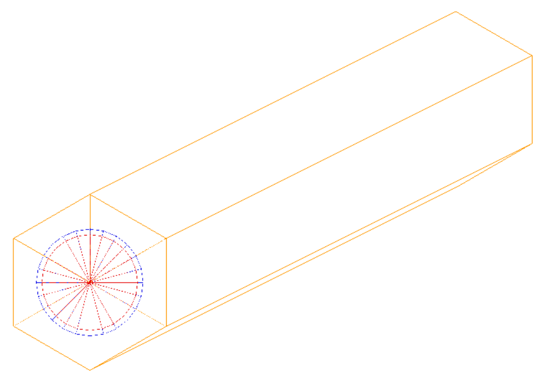


FIG. 3. Hexagon unit simulation (side view)

the detector together with the first disk, and a third disk placed 1000 mm in font of the detector together with the first two disks. A view of the 3-disks setup is shown in FIG. 6. In this simulation of FCal1, the tube is not simulated. The function of the tube is to generate an electric field on the liquid argon gap together with the rod, but the electric field is not simulated. Therefore, the tube is merged into the absorber, which is made of the same material.

TABLE V. Simulated Disk-shape Object Parameters

Parameter	size
Inner radius (mm)	72.3
Outer radius (mm)	451
Depth (mm)	17.57

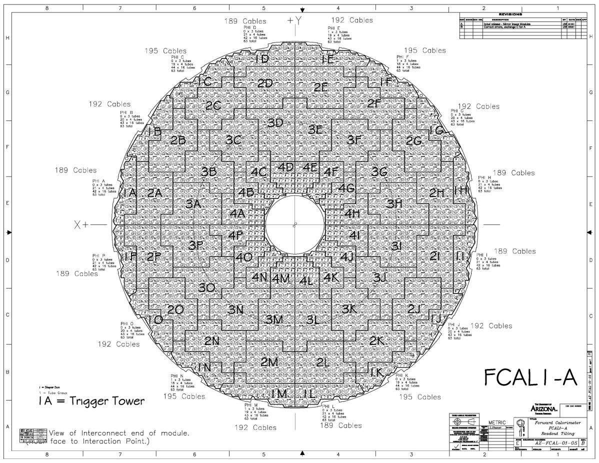


FIG. 4. FCal1-A[a]

[a] Photo credit: Leif Shaver

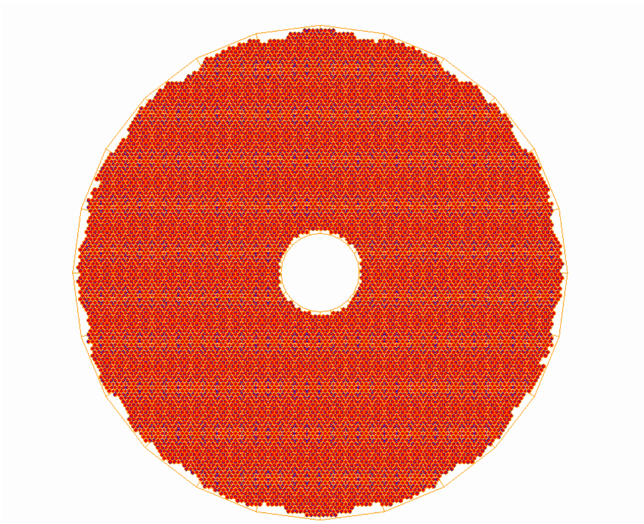


FIG. 5. Simulated FCal1(front view)

V. ACTIONS

After simulating the detector and its environment, one needs to decide what to do at different runtime levels.

V.1. Hit and sensitive detector

In Geant4, a hit is a snapshot of the physical interaction of a track in the sensitive region of a detector [4]. The sensitive region of a simulated FCal1 is the physical volume of sensitive detector. As mention in Sec. IV.2, the sensitive detector is a daughter volume of the lAr gap volume. Each lAr gap volume has 450 sensitive detectors. Parameters of the sensitive detector can be found in TABLE VI. The material of the sensitive detector is also lAr. In other words, every millimeter depth lAr volume works as a sensitive detector. Each sensitive detector has the ability to retrieve and store the information of a hit.

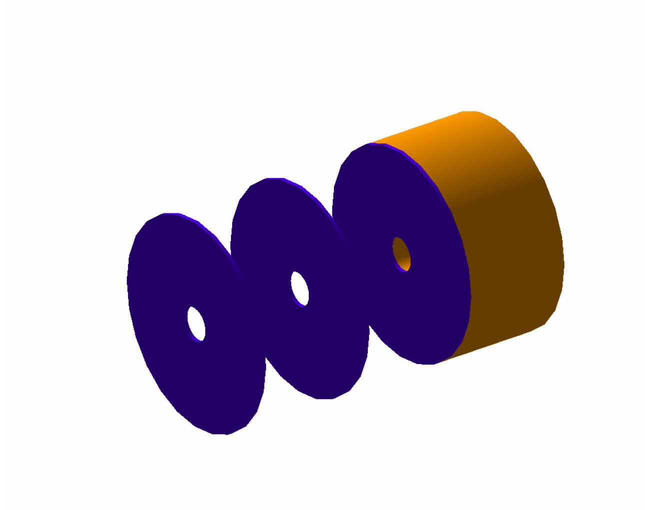


FIG. 6. Simulated FCal1 and Environment (3 disks)

In this study, the position and the deposited energy of all hits in the sensitive detector are recorded.

TABLE VI. Sensitive Detector Parameters

Parameter	size
Inner radius (mm)	2.356
Outer radius (mm)	2.626
Depth (mm)	1

V.2. Event

In this study, an event is firing a high energy electron toward the detector. Energies of 1 TeV and the 500 GeV are used. The incoming electron is fired 4750 mm away from the detector in the z-direction and 20 cm above the z-axis. The electron only has momentum in the z direction, which means it will collide the detector perpendicularly. Once the electron hits the detector, showers develop inside of the detector. Particles that deposit energy in the lAr gap generate hits that will be recorded. After one event, the end of event action calls the signal propagation program to calculate the readout time for all hits and fills the result in histogram. Signal propagation will be discussed in Sec. VI.

V.3. Run

A run includes a collection of events. As discussed in Sec. IV.2, there are different environmental setups: no disk, one disk, two disks, and three disks. Each setup is run at both 1 TeV and 500 GeV, so there are 8 runs in total. At the beginning of each run, ROOT is implemented to create a histogram for the average time of signal readout.

VI. SIGNAL PROPAGATION ANALYSIS

Geant4 simulates how the particles interact with the materials, but it cannot simulate how the actual detector functions. After the simulation of particle interactions, the rest of the simulation needs to be done by other methods. Timing resolution is related to how the detector reads and outputs the information inside of it. Therefore, the signal propagation is simulated and studied.

VI.1. Overview of signal propagation

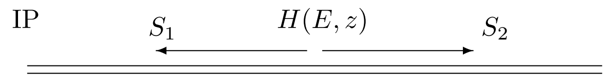
When a high energy particle goes through the lAr gap and ionizes lAr, free electrons move toward the rod due to the electric field and then generate a current pulse on the rod. The drift time of the electrons is 61 ns [3]. Once an electrical signal is generated on the electrode, it divides into two sub-signals equally, and each of them propagate in opposite direction individually. Each of them carries half of the amplitude. According to Ref. [5], because the characteristic impedance of the electrodes, ganged together in parallel at the interconnect, is so low, it is not possible to match them to the readout coax. Hence the triangle current pulse reflects back and forth many times on the electrodes, diminishing in amplitude with each reflection as part of the pulse is transmitted to the cable. The speed of the pulse is $v_{sig} = \frac{c}{\sqrt{1.51}} \approx 2.4 \times 10^8$ m/s, where c is the speed of light.

VI.2. Simulation model and analysis method

The goal of the analysis program is to calculate the average time of readout. The clock for this time starts when the incoming electron hits the detector. The physical propagation of the signals is not simulated in this study. Instead, signal propagation is simulated in terms of a simplified mathematical model. Each hit, $H(E, z)$, in the sensitive detector is consider as an individual signal, where E is the deposited energy of the hit, and z is the z coordinate of the hit. All particles of the shower inside the detector are considered to be traveling at speed of light. Thus, the time before a hit is generated can be calculated using:

$$t_{collision} = \frac{z}{c} \tag{1}$$

The signal on the rod splits into two sub-signals, labeled as S_1 and S_2, as shown in the picture below, each carrying energy $\frac{E}{2}$. If the signals hit the end close to the IP, 10% of the energy being carried is read, and 90% of it remains and keeps propagating. If the signals hit the end away from the IP, nothing is changed, and the whole signal is reflected.



Since the speed of the signal, v_{sig}, is a constant, the readouts of the two bounce signals are periodic. This means that for a hit with known energy and z coordinate, propagation can be modeled by using only the timing parameters. The time for S_1 travels from z to the IP end is

$$t_{s_1} = \frac{z}{v_{sig}} \tag{2}$$

After the fist time S_1 hitting IP end, it always takes

$$t_{round} = \frac{2 \times 450}{v_{sig}} \tag{3}$$

to read S_1 again, where 450 is the depth of the simulated FCal1 module. S_2 always reaches IP end some time after S_1 reaching IP end. This time interval is

$$t_{diff} = \frac{2 \times (450 - z)}{v_{sig}}, \tag{4}$$

where 450 is the depth of the simulated FCal1 module. When the energy readout from the IP end reaches 90% of E, the propagation of the signals is terminated. This is the signal propagation model, but this is not complete. The linear drop pulse behavior due to the drift time need to be considered. The deposited energy of the hit is considered as the amplitude of the pulse. Consequently, it takes 61 ns for the energy pulse to drop back to zero linearly, assuming that a certain amount of energy is read immediately after the pulse being generated. This linear funcion has the form:

$$E_p(t) = at + b, \tag{5}$$

where t is the time, and a and b can be calculated as following:

$$a = -\frac{2E}{61^2} \tag{6a}$$

$$b = -a(t_{collision} + 61), \tag{6b}$$

where 61 is the drift time of the electrons inside lAr. By considering the pulse behavior, the total energy (the amplitude of the current) of the hit does not propagate immediately after the hit has been generated; it takes 61 ns to fully read in all of the energy. While this is a continuous process in actual detector, in the simulation model, it is a discrete process; 61 ns is divided into 10 ps interval. This means that for every 10 ps, a certain amount of energy E_p is read and starts to propagate. E_p is calculated by Eq. 5.

When the signal is read out from the IP end, its time and energy will be recorded. For an event, the energies read out from the IP end within the same timing window are summed together. The timing window in this study is 10 ps. By doing so, the average time of readout for an event can then be calculated:

$$t_{ave} = \frac{\Sigma t_i E_i}{\Sigma E_i}, \tag{7}$$

where t_i and E_i are the time and energy on the i^{th} interval. The same calculation is performed for all events. After doing the calculation for all event, the average time for each event is put into a histogram, as a user defined action.

The signal analysis program is written in C++ and implemented into Geant4 directly. The program will be executed at the end of an event.

VII. RESULT

One histogram is generated after each run. Eight runs are simulated, and therefore there are eight histograms, as shown in FIG. 7 and FIG. 8. The timing resolution is indicated by the standard deviation. A summary of the timing resolution is shown in TABLE. VII.

TABLE VII. Timing resolution

Energy	Number of disk	Resolution (ps)
1 TeV	3 Disks	54.15 ± 1.21
	2 Disks	45.74 ± 1.02
	1 Disk	44.37 ± 0.99
	No Disk	46.32 ± 1.03
500 GeV	3 Disks	78.55 ± 1.75
	2 Disks	56.02 ± 1.25
	1 Disk	44.34 ± 0.99
	No Disk	45.32 ± 1.01

VIII. DISCUSSION

VIII.1. Simulation setup

The simulated absorber is not completely the same as the actual detector. The outer radius is 1.6 mm larger. The reason is that after inserting the simulated hexagon unit into the absorber, there is an offset that requires the extra space to fully contain all of the electrodes. The source of the offset has not been verified, although most likely it may be the initial wrong placement of electrodes. The Molière radius of FCal1 is 17.1 mm [3]. The extra 1.6 mm, approximately 9.4% of the Molière radius, should not lead to the extra significant shower development that would affect the signal readout. Nevertheless, this offset problem should be fixed for a more accurate simulation. The depth of the simulated FCal1 is 450 mm in depth, while the actual FCal1 is 444.1 mm. This difference is due to a wrong initial declaration of the actual value. According to the average shower depth of the detector from the simulation, FIG. 9 and FIG. 10, most of the energy is deposited less than 300 mm inside the detector. Thus, the extra space in depth also has no significant effect on the signal readout.

The detail of the simulated incoming electron is described in Sec. V.2. In this study, the location where the incoming electrons come from is fixed for all simulated events. In the actual experimental environment, an electron with pseudorapidity $3.1 < |\eta| < 4.9$ can be detected, which means that the electron can hit the detector with some angle, though very small with respect to the z-axis. For this reason, this study is not completely generalized. However, since $3.1 < |\eta| < 4.9$ describes a large angle to the transverse plane, the momentum direction is almost parallel to the z-axis, and considering the angle of particles in the simulation should not affect the results significantly.

VIII.2. Results

The results in TABLE. VII show that the timing resolution varies under different circumstances. With three disks, the resolution has the largest value at both 1 TeV and 500 GeV energy. An explanation for this is that after passing through the disks, each of them in one radiation length, part of the energy of the incoming electron is deposited in the disks, which reduces the energy of the electron when it hits the calorimeter. A lower energy means less shower development, which then leads to fewer signals, and gives a larger resolution. This is also the reason why the resolution is generally smaller at 1 TeV with three and two disks than the same setup at 500 GeV. Another explanation is that after passing through the disks, secondary electron may be created and hit the detector. This means that there are two or even more electrons hitting the detector instead of just one. More electrons with different energies increase the resolution. The resolutions at both 1 TeV and 500 GeV with the one disk and no disk setup are close to each other.

VIII.3. Future study

For a future study, all of the current issues, including the placement offset, extra space and incoming electrons momenta, discussed above can be solved and improved. This will give a more accurate and generalized simulation of the detector and detecting process. However, the result should not vary too much from the current result due to the reasons discussed above. A better experimental environment can also be simulated, for example, simulating the end-cap cryostat instead of disks. The signal propagation simulation and analysis can also be improved by optimizing the timing window for both pulse reading and readout reading.

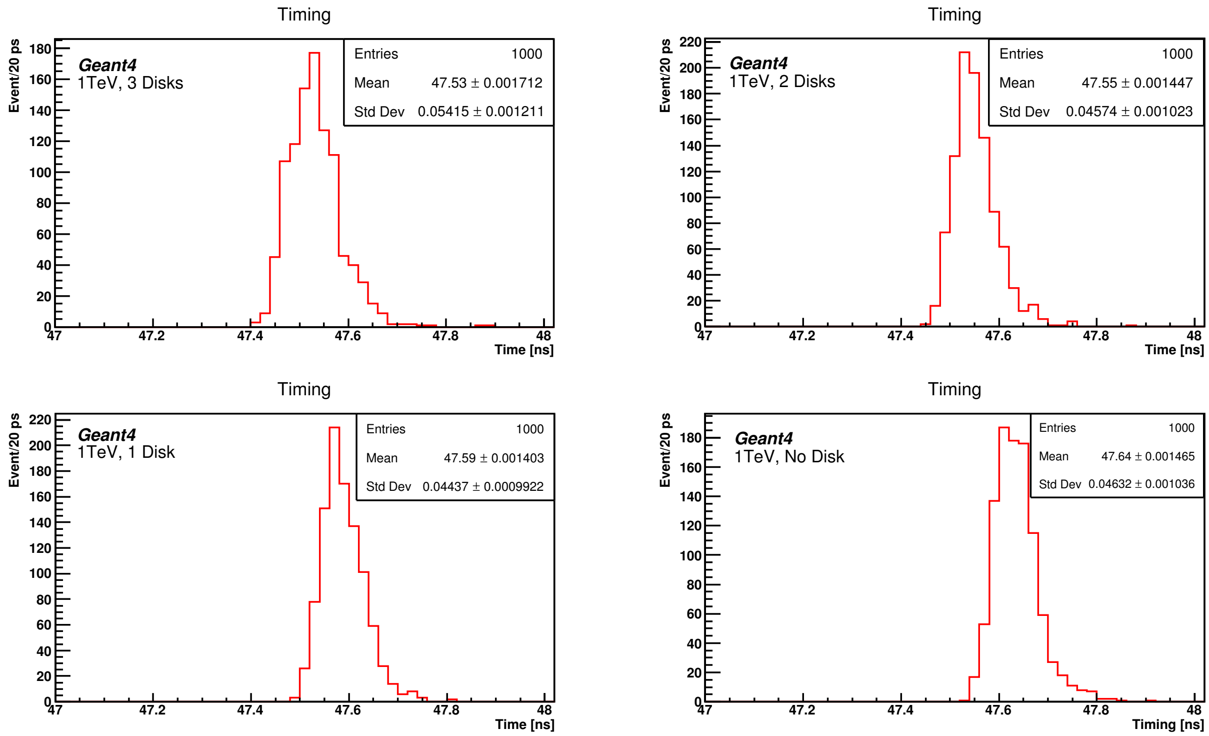


FIG. 7. 1 TeV timing result: histograms of the average time of signal readout.

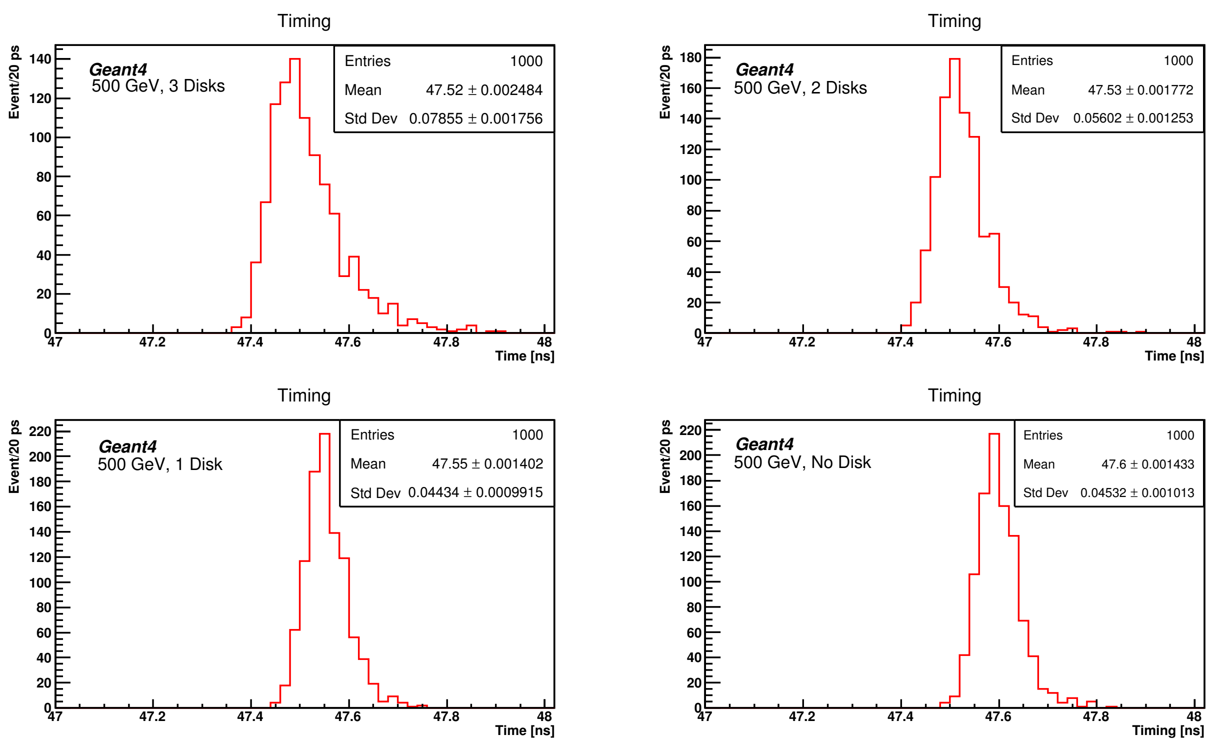


FIG. 8. 500 GeV timing result: histograms of the average time of signal readout.

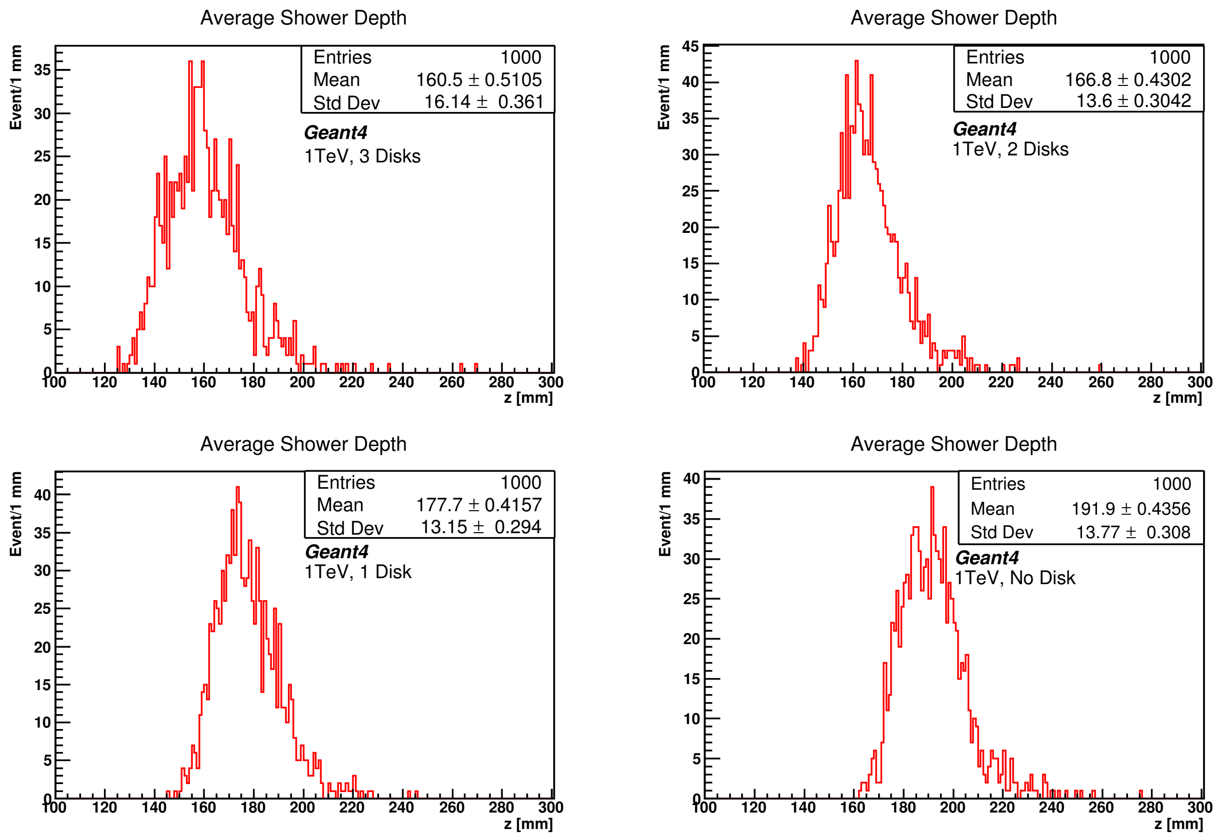


FIG. 9. Average shower depth at 1 TeV

IX. CONCLUSION

A study on the timing resolution of the Forward Calorimeter layer 1 (FCal1) is done by performing simulation based on the Geant4 tool kit. Geant4, a simulation tool kit of particles traveling through matter, is used to simulate the FCal1 and the shower development process. The electron is chosen to hit the detector. An incoming electron interacting with the detector is considered as one event. After an event, a C++ program simulates the signal propagation and analyzes the timing resolution. A run contains 1000 events. At the end of a run, ROOT outputs the results. The incoming electrons are simulated at both 1 TeV and 500 GeV. For the purpose of being more realistic, extra environmental setups are designed; disk-shape objects are simulated and placed in front of the detector on the side of the incoming electrons. Eight different setups are simulated. Thus, there are eight runs in total. The timing resolution of FCal1 at different energy levels varies, and the external factors also have influence on it. The higher the energy is, the less the environment effects on the resolution. The results show that the resolution ranges from 44.34 ± 0.99 ps to 78.55 ± 1.75 ps. While the simulated detector does not have exactly the same geometry and spacial setup as the actual detector, the difference does not make the simulation lose credibility. Future study can be performed by fixing the known issues, making a higher precision ssimulation, and optimizing the analysis program.

ACKNOWLEDGMENTS

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[1] G. Ada *et al.* (The ATLAS Collaboration), JINST **3**, 5 (2008).
[2] Geant4 Collaboration, "Introduction to geant4," (2015).
[3] A. Artamonov *et al.*, JINST **3**, 10 (2008).
[4] Geant4 Collaboration, "Geant4 user's guide for application developer," (2015).

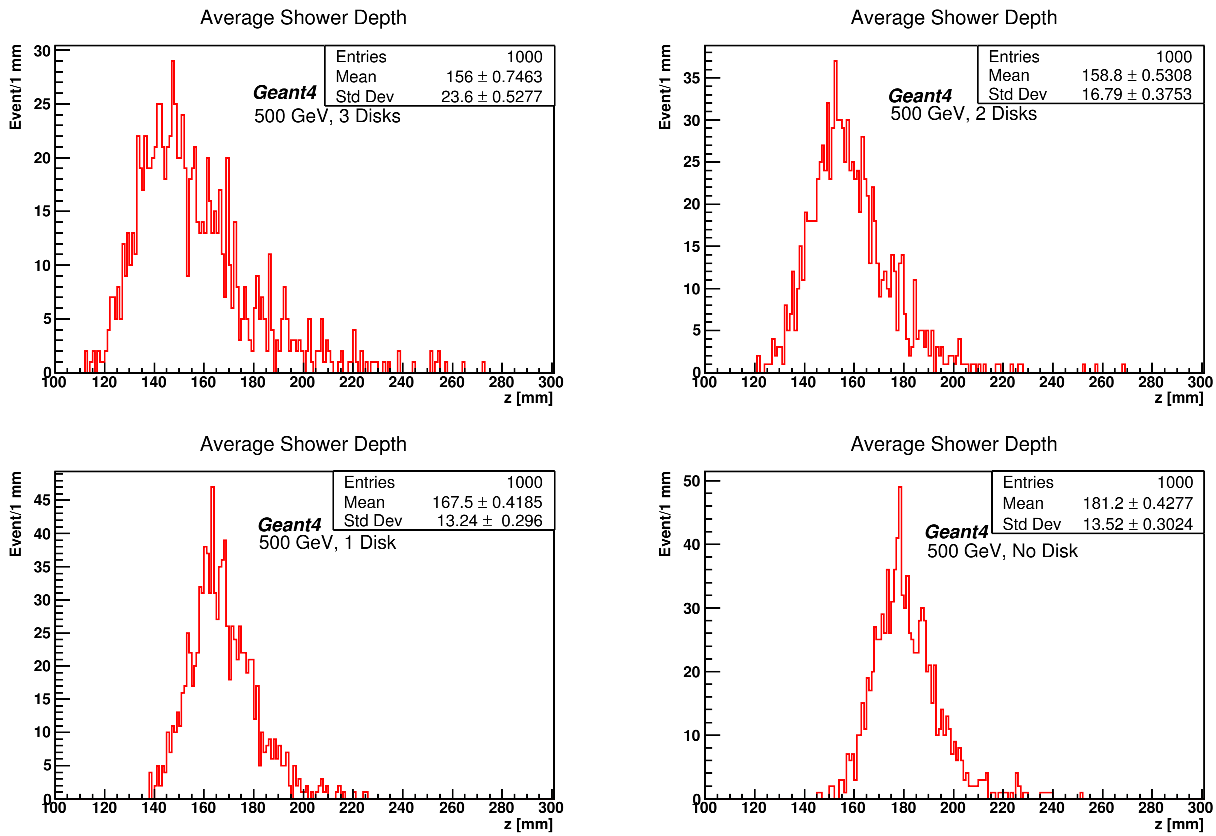

FIG. 10. Average shower depth at 1 TeV

[5] J. Rutherfoord, "Electrode transmission line corrections to the atlas forward calorimeter pulse," (2006), ATLAS Note ATL-LARG-PUB-2006-005, Geneva, CERN.