Electromagnetic Calorimeter Calibration: Getting Rid of the Trash

A Senior Project

presented to

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Bachelor of Science

by

Jacob P. Gamble

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Abstract

The ALICE experiment at CERN is focused on studying relativistic heavy ion collisions and one of ALICE's primary detectors is an electromagnetic calorimeter (EMCal.) This paper describes one method of calibration of the detector. To eliminate background from photons that convert to $e^{\pm}$ pairs, geometric and timing cuts are made to associate hits in the ALICE time-of-flight (TOF) detector and EMCal.

Introduction

At the European Counsel for Nuclear Research [otherwise known as CERN (the Conseil Européen pour la Recherche Nucléaire)] there are four major experiments. Each experiment (as its own collaboration) is dedicated to investigation of the origins of force, mass, and particles that came into being during the early formation of the universe. By colliding particles at speeds nearing the speed of light, scientists are able to replicate conditions similar to that of the Big Bang.

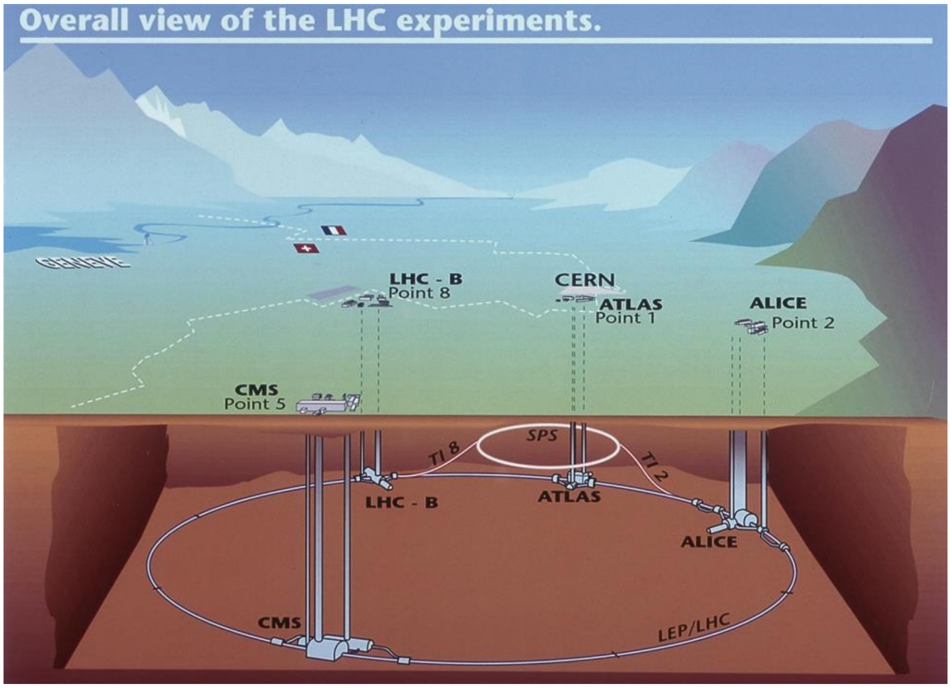

Figure 1: Schematic overview of the location of each associated experiment at CERN LHC Source: *http://www.atlas.ch/photos/detector-site-surface.html*

The aim of this project is to identify and eliminate known photon backgrounds from the nuclear collision data collected by the ALICE (A Large Ion Colliding Experiment) detector at the CERN LHC so that we can better investigate the fundamental theory of the strong nuclear force. Unlike the other experiments, the data collected at ALICE is focused on heavy-ion collisions. Alice's strength is its detailed particle id capability, stemming from the suite of specialized detectors (see Figure 2) surrounding the collision zone. The EMCal is designed to measure photons, some of which are convert to $e^{\pm}$ pairs, by sampling of the energy deposited by these particles when they produce an electromagnetic shower in the detector.

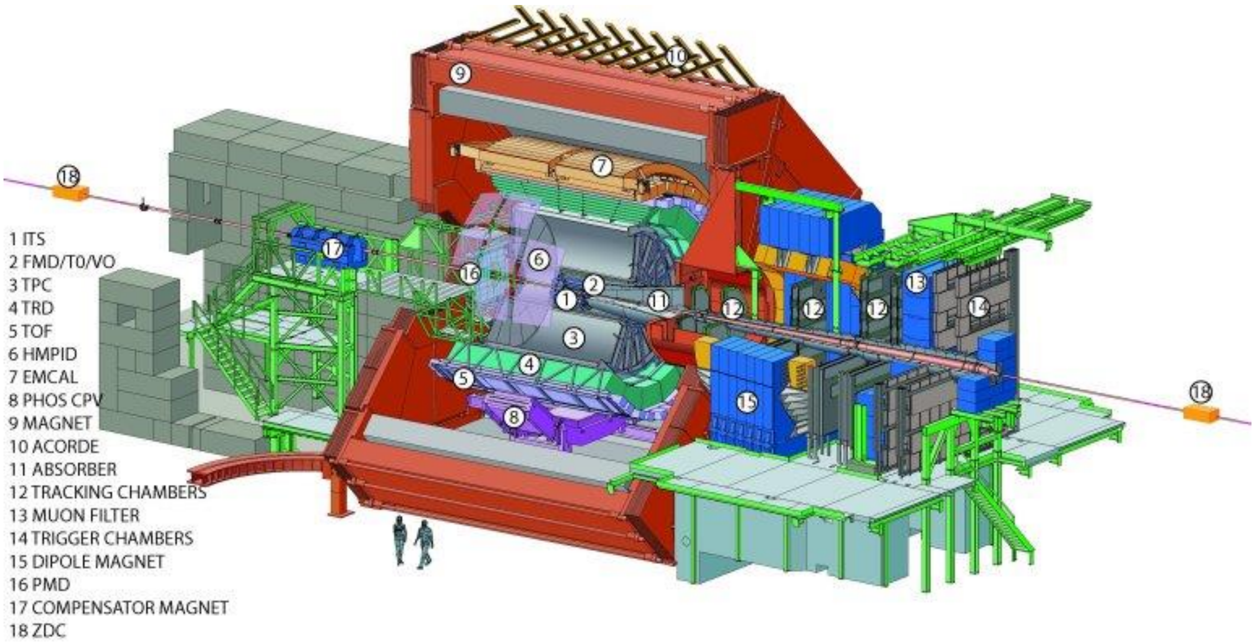

Figure 2: Schematic of ALICE experiment. Source: *http://aliceinfo.cern.ch/Public/en/Chapter2/Chap2InsideAlice-en.html*

ALICE is particularly interested in investigating Strong Force interactions among quarks and gluons. To study this interaction, ALICE works backwards from the post-collision aftermath to reconstruct the collision effectively thereby studying how each particle has interacted with the other and how the environment/universe settled into normal nuclear matter called hadrons (protons, neutrons, etc.) following its initially dense, energetic state of quark gluon plasma or QGP.

Experimental Design

The LHC and ALICE

Protons (ionized Hydrogen) and Lead ions stripped of their electrons, are injected into a linear accelerator from their respective sources and a series of electric and magnetic fields from boosters and synchrotrons (counter-circulating circular accelerators) bring these particles to energy. (Figure 3) Once at injection energy the particles are injected into the main beamline of the Large Hadron Collider (LHC) a 17-mile circumference tunnel under the Franco-Swiss border. The beams are made to collide at four interaction points where the four experiments ALICE, ATLAS, CMS and LHCb lie.

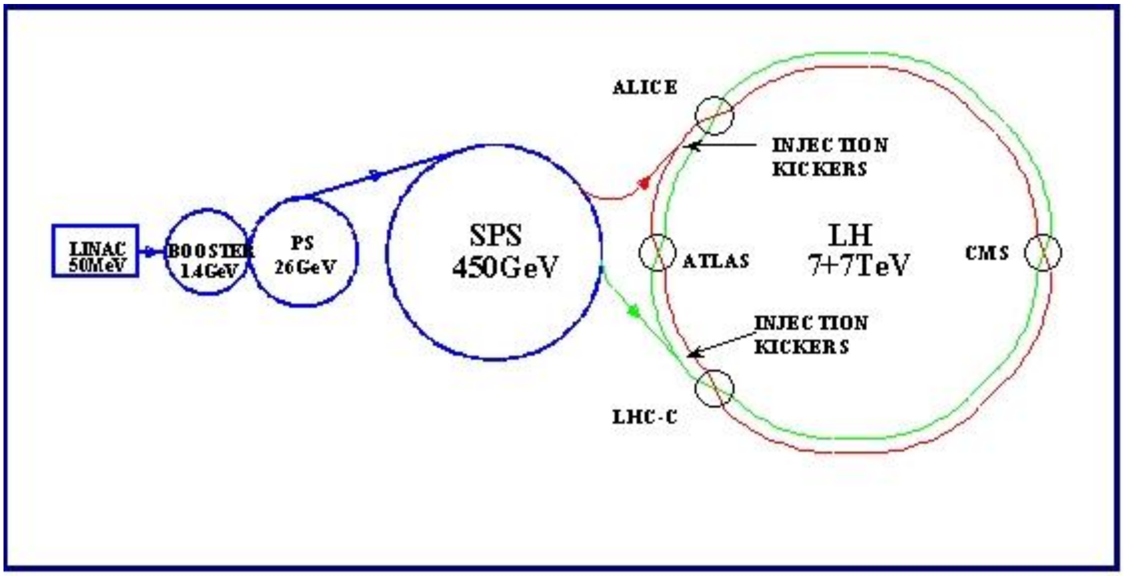

Figure 3: Schematic Overview of Injection Process and Experimental Beam Interaction Points Source: http://www.atlas-canada.ca/lhc_history_pic_Page_3_Image_0001.jpg

As the beams arrive at ALICE, the ALICE crew in the Control Room watches the detectors for errors to ensure the best data collection possible during their small window of opportunity to collect data. Each fill (the period in which a stable beam is held steadily) may vary in length, leaving every second of measurement important. Scientists use particle identification and event reconstruction based on collected signals from each detector to look for interesting physics observables in the data set.

ALICE uses a composition of layered sub-detectors (see Figure 2) each varying in measurement methodology. The three basic types of detectors are trackers, calorimeters, and specialized detectors. Tracking detectors are designed to measure the trail/path of the particle's trajectory as it travels through the experimental apparatus. This is typically done using a measurement of the ionization trail through a material or at the end points. Calorimeters are designed to absorb some if not all of the particle's energy. Specialty detectors are designed specifically for particle identification and can vary in measurement methodology. A great example of a specialty detector is the time-of-flight (TOF) detector. The TOF uses a combination of time-of-arrival measurements with the distance traveled to the determine velocity. This can be combined with the momentum measured from the curvature of particle trajectory in the tracking detectors is used to determine the particle's mass. This observed curvature of trajectory and measured momentum is seen in part to the magnetic field of 0.25 Tesla provided by the big orange solenoid at ALICE [Figure four.]

Figure 4: (Top) Picture of ALICE Detector with camera flash on to illustrate where each particle detector is located and to check their respective alignment. Source: *http://aliceinfo.cern.ch/Public/en/Chapter2/Chap2InsideAlice-en.html*

For example, a particle with a momentum of 400 MeV/c and charge of +1e coming out of a collision at ALICE we can expect a radius of 3.3337 m using the relationship between the radius of curvature and magnetic field, where m is mass, v is velocity, q is charge, and B is magnetic field.. This is a fairly average momentum for a particle coming from a collision.

The momentum can be calculated from the radius of curvature using

$$\frac{mv^2}{r} = qvB \rightarrow r = \frac{mv}{Bq} \tag{1}$$

with the variables as described above. This is used with the relativistic formula for the relationship between energy, momentum and mass

$$E^2 = p^2c^2 + m^2c^4 \tag{2}$$

to determine the correlated mass of the particle based on the energy deposited into the detector and the measured momenta associated with the particle.

The innermost tracking systems at ALICE; the TPC, ITS, and TRD are fantastic examples of the tracking systems mentioned above. In practice these tracking detectors can also be used to measure decay points of neutral particles to help associate daughter and parent particles. The Electromagnetic Calorimeter absorbs the energy deposited by a particle and the energy signatures measured on these detecting elements can be used as well to associate daughter and parent particles.

Photons are often seen as a source of background for both physics-focused as well as calibration-focused collisions. While the source of most of the photons is the collision itself, all that the detectors know is that an energy was registered and should be taken into account as a registered particle. Many of the photons come from the decays of neutral pions. These photons sometimes convert to $e^{\pm}$ pairs in the detector material, producing signals that are hard to correlate with their parent particles. To understand how to eliminate the background photons, it is important to first understand the primary process from which the photons interact with the detector during Pair Production. Photons are not detected directly by tracking detectors because they carry no electric charge.

Pair-Production occurs in situations where the energy of the photon from the collision is greater than double that of an electron's rest energy and the photon is close to the nucleus of the atoms in the detector. The minimum photon energy needed for this interaction can be seen in that

$$\mathrm{E}_{\gamma}{}^{min} = 2\,\mathrm{m}_{\mathrm{electron}}\mathrm{c}^2\,\left(1 + \frac{m_{electron}}{M_{nucleus}}\right) \qquad (3)$$

where the minimum amount of energy is related to the ratio of electron-nucleus mass and the resting energy of the electron. It is in this interaction on the detector's surface, which a photon interacts with the strong electric field of the nucleus and converts into an electron-positron pair, hence where the process receives its name. This type of interaction usually concerns high energy photons on the order of MeV (gamma radiation.)

Since photons have neutral charge they leave no signature trajectory in the tracking detectors. With calorimeters, particle measurements correspond directly to either energy deposit (from which we can relate event timing) or momentum (geometry from which the event occurred) the measurements of the photons have to be measured directly with calorimeters otherwise reconstruction is necessary based on indirect measurements of daughter particles coming from the conversion process.

Particle energy signatures will overlap with those of other particles, making it difficult to discern particle from particle. At ALICE we sue the Electromagnetic Calorimeter or EMCAL to measure photons and match other particles with tracks in the tracking detectors.

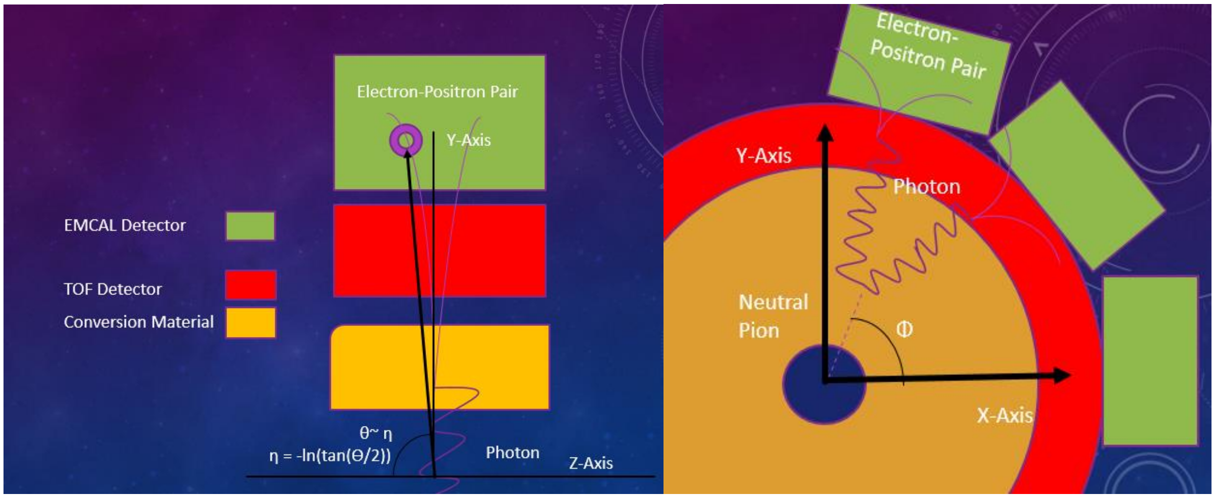

Figure 5: Illustrated photon-material conversion from a single and double Pair-Production to illustrate pseudorapidity (η) and phi (φ).

To help identify the particle energy signature a momentum vector can be measured in either Cartesian or Polar coordinates to help correlate the identified energy signature to the associated particle identity. Given that the particles come out of the collision in jets, it is most convenient to use the following three variable: pseudorapidity (denoted by eta, η), phi (φ), and transverse momentum, P_T. Pseudorapidity or

$$\eta = -\ln(\tan(\frac{\theta}{2})) \qquad (4)$$

it can be further defined as the angular spacing away from the z-axis. By using this relationship based on θ, is the angle measured up from the beam axis (taken to be the z-axis,) and phi, which is the azimuthal angle measured in the up from the positive x-axis. We are able to pass these values of pseudorapidity to find the momentum vector of the particle in question.

EMCAL Calibration

All detectors at ALICE have independent data recording systems in place that allow for a purer set of data reconstruction. At ALICE they have a dedicated set of data collection processes for each detector that must be watched independently by a data collection process manager. A dedicated person is put in place to watch this manager and to ensure that data quality is up to par. Once the data is collected and pushed to the storage manager, it can be access by offline users for full analysis.

Data from all detectors must be combined and in our case we need to correlate and compare the data sets from the TOF and the EMCAL relative to that of the measured collision times (Figure 10.) Based on the time of arrival between the detectors we can determine the mass of the particle and the likelihood of particle species.

We can measure the photons directly from the collision using the Electromagnetic Calorimeter (EMCAL) at the edge of the experiment or we can measure them indirectly by correlating electron-positron pairs and/or neutral pions to the photons themselves.

Mapping the first signal on each track (Figure 6) we are able to examine the origin of the track signals. This will help us identify where photons have converted to $e^{\pm}$ pairs. By inspection, it can be seen that the majority of tracks begin at the ITS which is the closest detector to the collision point. Then as we progress outward from the collision point the number of track origins mapped decreases both in part to the number of daughter particle tracks decreasing and for radii occurring after 190 cm away from the beamline having less than the number of points necessary to be considered a good track. Since there are support structures for detectors that cause an electron-positron conversions further than 190 cm we can't expect to see these tracks in the TPC but they may possibly be detected by the EMCal and the TOF.

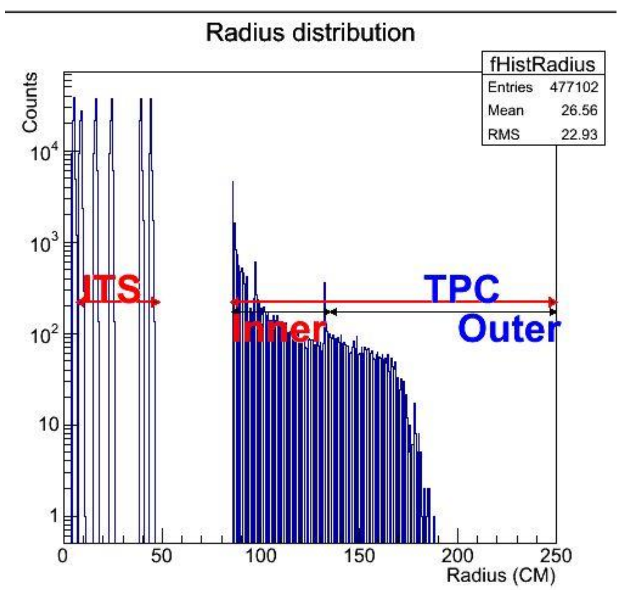

Figure 6: Distribution of Registered Particle Track Origins for the ITS and TPC

Material Budget

Figure 7 shows how a photon as it travels through the ALICE detector systems, encounters a greater and greater probability of interacting with the support structure of the detector subsystems leading to pair production. Considering that the majority of photon-conversions hall after the TPC and before the EMCal, it is important to correlate the TOF and EMCal data sets so that we will be able to eliminate background signals.

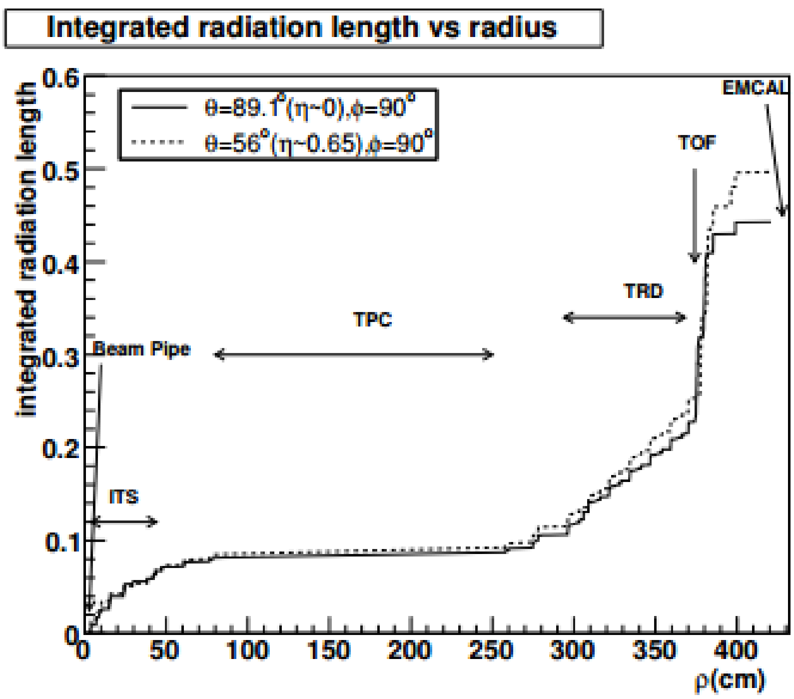

Figure 7: Figure showing probability of photon conversion as the photon moves away from the collision vertex.

Another part for consideration is that it is not uncommon to see two separate calorimeter hits on the EMCal (from the electron-positron pair) without a corresponding track from the tracking systems. Making the reconstruction of the events even more important in understanding the correlation of particle-track matching between detectors.

Geometric Correlation

To correct the unmatched clusters in the EMCal we can geometrically inspect the relation of detector collision points. Looking at the energy deposited into the detector and its geometric spacing denoted as following

$$\Delta R = \sqrt{\varphi^2 + \eta^2} \quad (5)$$

we can match EMCal clusters as possibly coming from the same particle, not previously observed in the tracking detectors. Associating these EMCal and TOF hits that are unmatched to the TPC, we are able to include TOF clusters in reconstruction that are usually discarded from the reconstruction data set.

Figure 8 shows examples of TOF and EMCal clusters in (η and φ) from two examples events, one with high occupancy (let) and one with low occupancy (right.) The purple circles indicate probable good matches, whereas the red arrow shows two clusters with large ΔR that are not well-matched.

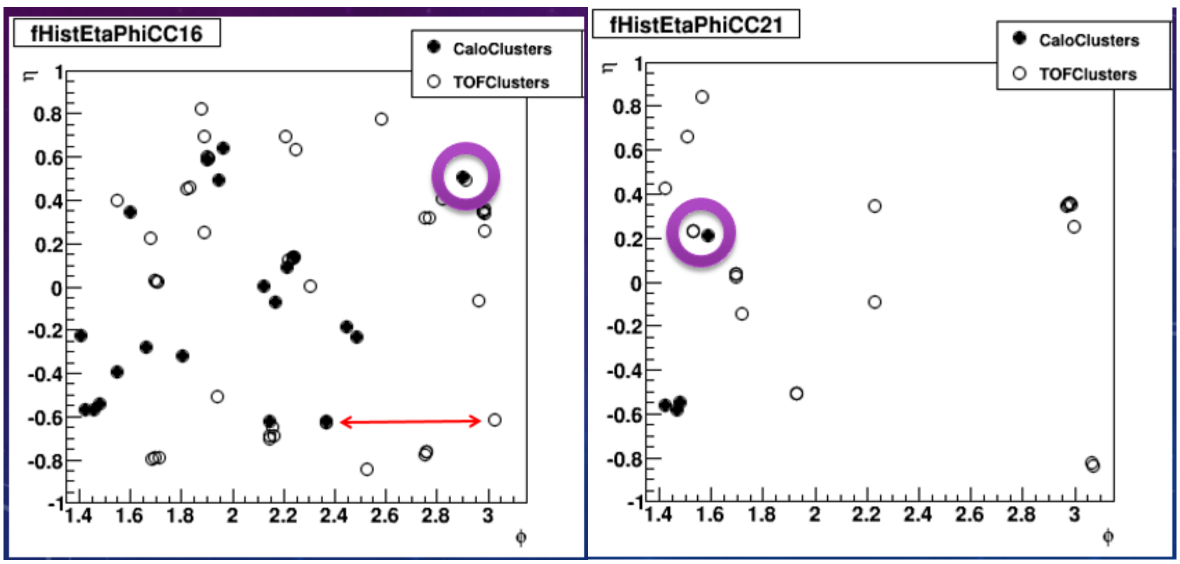

Figure 8: Example events with TOF and EMCal cluster locations in eta and phi.

Timing

Using kinematics and graphical analysis we were able to determine that faster particles (photons) were more likely to appear in the TOF detector between 12 ns and 15 ns after the collision. Whereas the heavier particles will arrive between 109 and 137 ns. Time measurements are made possible through the relationship of transverse momentum and velocity

$$v_e = \frac{-1}{2}\left(\frac{p_t}{m_e c}\right)^2 + \frac{1}{2}\sqrt{\left(\frac{p_t}{m_e c}\right)^4 + 4c\left(\frac{p_t}{m_e c}\right)^2} \qquad (6)$$

where p_t denotes the transverse momentum and m_e denotes the mass of the electron. Upon finding the velocity and passing the value to the kinematic equation [$t = x/v$] to find the time of arrival, with the value of x being

$$x = R\sin(2\tan^{-1}(e^{-\eta})) \qquad (7)$$

where R is defined as found above and eta is the pseudorapidity.

Collecting the output values of time of arrivals to the detector and organizing them based on their associated values of eta (Table 1), we use those values to confirm the particle species and employ Equation 10 to confirm the associated measured energy deposited at the detector is equal to the anticipated particle energy/mass.

	*Δ*ToA (ns) η = 0.7	*Δ*ToA (ns) η=0	TOF ToA (ns) η=0	TOF ToA (ns) η=0.7	EMCal ToA (ns) η= 0	EMCal ToA (ns) η=0.7
$P_{Electron}$ = 400 MeV/c	8.07	101	277	220	378	301
P_{Pion} = 400 MeV/c	2.13E04	2.68E04	7.31E04	5.82E04	9.98E04	7.95E04
$P_{Electron}$ = 1000 MeV/c	3.23	40.5	111	88.2	151	120
P_{Pion} = 1000 MeV/c	853	1.07E04	2.92E04	2.33E04	3.99E04	3.18E04
$P_{Electron}$ = 5000 MeV/c	6.46	8.11	22.1	17.6	30.2	24.1
P_{Pion} = 5000 MeV/c	171	214E03	5.85E03	4.66E03	7.99E03	6.36E03
Photon	3.65	4.58	9.97	12.5	13.6	17.1

Table 1: This table shows the values of different particle time of arrivals (ToA) based on η, mass, and transverse momentum.

The different values of arrival times is further seen in Figure 9 where we can see the pile up of particle arrivals. And it can also be seen that the arrival times correspond nearly directly to the table above validating the associated particle identification procedure.

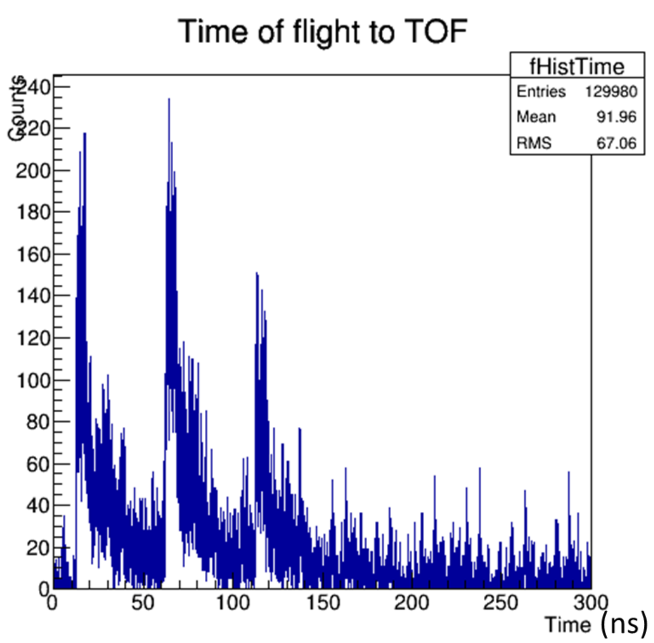

Figure 9: This diagram illustrates TOF arrival times in nanoseconds for different particles.

Conclusion

Refitting ΔR distribution to better fit the resolution of the EMCAL detector will allow us to investigate further opportunities to maximize TOF reconstruction points of produced $e^{\pm}$ pairs in the EMCAL and further correlate the unmatched tracks in the TPC.

Further resolving our timing cuts and combining our energy and geometric resolution meathodologies to match TPC to TOF and EMCal clusters, it is anticapated that we will be able to make further advancements in TOF EMCal event reconstructions.

References

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