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ANALYSIS OF $\rho^0$ DECAY FROM ULTRA-PERIPHERAL COLLISIONS IN LEAD-LEAD INTERACTIONS AT ALICE

- By 
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- 

A THESIS

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Abstract

This thesis provides analysis for rho meson production during ultra-peripheral collisions at A Large Ion Collider Experiment (ALICE) on the Large Hadron Collider at CERN. It also contains a discussion of the ALICE electromagnetic calorimeter (EMCal) and its uses in pion rejection. An overview of ALICE detectors, focusing on the electromagnetic calorimeter, is provided. Ultra-peripheral collision physics and particle identification for rho meson analysis are discussed. The ALICE trigger system is outlined. The results of rho meson analysis using AliRoot is shown, including uses of the electromagnetic calorimeter for pion identification.
Acknowledgements

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1 CERN, the LHC, and the ALICE Detector

The Large Hadron Collider (LHC) is located along the Swiss-French border on the outskirts of Geneva. In the LHC, counter-circulating beams of particles (protons or fully stripped lead ions) are accelerated to energies of 3.5 TeV for proton beams and 572 TeV for lead ion beams. There are several beam interaction points around the LHC ring. The resulting particle production is investigated at these points by several experiments. This chapter provides a brief description of the sub-detectors comprising the ALICE detector (located in St. Genis Pouilly at P2 in Figure 1. The focus of this thesis is ultra-peripheral rho meson production at ALICE with a look at the ALICE electromagnetic calorimeter for particle identification.
1.1 The LHC, A Brief Introduction

By the early 1990’s, experiments at CERN’s Large Electron-Positron collider (LEP) had completed high statistics studies of the Standard Model. (Hints of potentially interesting physics would keep the LEP operating until 2000.) 200 GeV per nucleon heavy ion fixed target collisions were being studied at both Brookhaven National Lab and CERN. The CERN council convened in December of 1991 to discuss plans for a new particle accelerator, the Large Hadron Collider, with the hope that it could be completed by 1993[2]. Heavy ion collisions with counter-circulating beams were achieved at Brookhaven in 2000. At CERN, construction funds were slow in coming and the first beam was circulated on Sept 10 2008[3]. Damage incurred from grounding problems during a super conducting magnet quench further delayed startup. The first proton-proton collisions occurred on November 23, 2009, first at ATLAS then at CMS in the morning and at ALICE then at LHCb in the evening[4]. The first LHC heavy ion run (involving lead ion collisions) began in November 2010 with lead ion energies of 287 TeV.

For the first part of 2012, the LHC was operating with 3.5 TeV proton collisions. (The 2012 heavy ion run is scheduled to start in early November with a lead ion energy of 655 TeV.)

1.2 ALICE: A Large Ion Collider Experiment

This thesis deals with analysis done using data collected at ALICE (shown in Figure 2). This section gives an overview of the experiment as well as detailed
information on some of its detectors. ALICE lies 150 feet below ground in a large
man-made cavern. The ALICE detector is 52 feet high, 85 feet long, and weighs
over 10,000 tons. It consists of many different kinds of sub-detectors. ALICE was
built and is operated by a large collaboration of 1300 physicists spread across
118 institutes in 35 countries. The collaboration’s main goal is to study strong
interactions at high energy and identify the properties of the quark-gluon plasma
produced during collisions of heavy nuclei. The quark-gluon plasma provides a
look into the early universe. One millionth of a second after the Big Bang [6],
space is believed to have been filled with this plasma as the universe was too hot
for hadronic matter to form.

1.3 The Electromagnetic Calorimeter

![Figure 3: The ALICE Electromagnetic Calorimeter][7]

ALICE’s electromagnetic calorimeter[8] (EMCal) is 5.6m long and covers ap-
approximately 110 degrees of the barrel around ALICE. It is designed to detect the
energy and direction of neutral particles from heavy ion collisions[9]. The EMCal
consists of 10,368 towers constructed of layered lead and polystyrene scintillators.
Towers present a 6cm x 6cm face to the experiment, arranged to approximately
point to the interaction point. Towers are grouped into modules which themselves
are grouped into supermodules. Each of the 8 supermodules contains 288 modules
while two half-sized supermodules each contain 144. For the data collected for
this thesis, the EMCal had 4 supermodules for 2010 Pb-Pb data taking.
When a charged particle hits an EMCal tower, the interaction is determined by the type of particle. Photons interact with the lead atoms and either scatter electrons out or interact with virtual photons from the nucleus and produce electron-positron pairs. These electrons and positrons radiate photons which interact similarly in other lead atoms, causing a cascade effect called a shower. When these charged particles pass through the scintillator material, atoms in the scintillator are excited and photons are produced. These secondary photons are detected by avalanche photodiodes. The number of secondary photons produced is directly proportional to the amount of electron-positron pair production from the initial photon interaction. From the avalanche photodiode signal size one can infer how much energy the initial photon had. When an electron hits the EMCal, it scatters and radiates initial photons, producing the same effect. Both electrons and photons have a fairly high radiation cross section and quickly lose their energy in the calorimeter. They interact in the first layers of the towers. When a charged pion enters the EMCal, it tends to pass through the detector exciting atoms in the scintillator. The photodiode signal is much smaller because it is a single particle causing the excitation rather than a shower of particles. Occasionally a strong nuclear interaction will occur as the pion passes through the calorimeter. In these cases, a larger photodiode signal is observed.

The EMCal is designed for jet reconstruction, neutral pion detection, photon analysis, and charged pion rejection. Jets are groups of closely correlated particles produced by multiple interactions and decays following a collision before the particles enter a detector. The EMCal was specifically designed to study jet quenching[10]. This is energy loss in jets as they pass through quark-gluon plasma. Combining knowledge of charged particles from the time projection chamber with the ability to detect the photons from the decay of short-lived neutral pions in the EMCal, jet quenching studies provide for full jet reconstruction. These neutral pions comprise nearly 90% of the neutral particles coming from an interaction.

The EMCal’s photon measurement capabilities allows the separation of decay photons (photons coming from particle decay) from direct photons (photons coming from the initial interaction). Direct photons are either thermally produced photons or prompt photons. Thermal photons give insight into the temperature of the quark-gluon plasma. Prompt photons give information on hard parton Compton scattering and quark-antiquark annihilation.

The EMCal is also useful in analyzing ultra peripheral collisions. Pions and electrons are difficult to separate in particle identification methods that rely on energy loss in tracking detectors. For collisions where a relatively small number of particles are produced, the EMCal allows the energy of individual tracks to be measured and compared with their momentum. The EMCal cluster energy is divided by the particle’s momentum (times the speed of light) and plotted. Due to the relativistic nature of these electrons and pions, the ratio $E/pc \approx 1$. Electrons, which deposit all of their energy in the EMCal, have a peak around $E/pc = 1$. Pions, which do not deposit all of their energy, have an $E/pc$ ratio of that is less
than 1 (see Figure 4).

![EMCal cluster energy vs particle momentum distributions for pion and electron tracks][11]

Figure 4: EMCal cluster energy vs particle momentum distributions for pion and electron tracks[11]

The EMCal response is tested for charged pions in this thesis. It should prove useful for electron-related studies. Misidentified pions provide a large background for electron measurements in most of the ALICE sub-detectors. For particles such as the J/Psi, which decays into electron-positron pairs 11% of the time, detection depends on good identification of the particle type.

### 1.4 Other Detectors

One of the difficulties inherent in taking data with a particle accelerator like the LHC is seeing what happens close to the beams since there are no detectors present in the beam pipe. The ALICE Inner Tracking System[12] (ITS) helps to determine the location of the primary vertex, the collision point. The Inner Tracking System contains ALICE’s central-most detectors in a barrel just outside the beam line. The ITS is used to reconstruct the primary vertex in particle decays, including charmed particles and hyperon decays, and provides particle identification and tracking of low momentum particles. It also works with the Time Projection Chamber (TPC) to improve measurements of middle and higher momentum particles. The ITS consists of three kinds of detectors: Silicon Pixel Detectors (SPD’s), Silicon Drift Detectors (SDD’s), and Silicon Strip Detectors.
(SSD’s), with two layers of each providing better resolution (see Figure 5).

Figure 5: The ALICE Inner Tracking System[13]

The SPD’s comprise the inner two layers of the ITS and are used for tracking short-lived particles (such as strange, charmed, and bottom particles) in high multiplicity events. The SDD’s are the middle layers of the ITS and provide position information in two dimensions for particles and contribute to particle identification by providing velocity dependent energy loss measurements. This is useful for identifying pions, kaons, protons, and electrons when used in conjunction with other detectors. The SSD’s are the outer two layers of the ITS and, along with the TPC, provides track reconstruction and energy loss measurements.

The Time Projection Chamber[14] (TPC), by far the most important detector in ALICE, is used to provide images of charged particle tracks. Along with other tracking detectors (such as the ITS), the TPC provides charged particle momentum measurements, track separation, particle identification, multiplicity measurements, and vertex determination. The TPC covers a barrel shaped area with a length of 5m and a radius of 2.8m. It can measure the momentum component perpendicular to the beam line \( p_t \) for charged particles in the range from 0.1 GeV/c to 100 GeV/c[15]. The TPC is filled with a gas mixture of 90/10/5 parts neon/carbon dioxide/nitrogen that ionizes when charged particles pass through it. The ionization electrons drift at an average velocity of 2.7 cm/µs along a constant voltage gradient. This gradient, 400 V/cm, is produced by a cathode in the center of the TPC with two anodes at either end cap. The anodes have read-out chambers to detect the drift electrons. Access from the detector barrel to the read-out chambers of the TPC can be turned “on” and “off” by means of a gating grid outside the read-out chambers. This grid consists of wires that are positively charged to deflect incoming electrons when the TPC is not active. The read-out chambers produce a signal that allows the experiment to reconstruct the path that charged particle took through the gas in three dimensions. Two dimensions come from the location of the electron signal in the endcap detector and one dimension from
the drift time. The TPC provides a comprehensive view of the charged particles emerging from a collision.

The Dimuon Spectrometer[16] lies along the beam pipe forward of the experiment. The spectrometer’s main function is to provide identification of muon decay products.

Since there are no detectors in the beam path, ALICE’s Forward Multiplicity Detector[17] (FMD) helps to determine the number of particles that fly off at small angles to the beam pipe. This helps determine the overall distribution of particles produced in collisions, which is essential when reconstructing an event.

The High Momentum Particle Identification Detector[18] (HMPID) provides particle identification at higher momentum than the other detectors in ALICE. The HMPID uses RICH (Ring Imaging CHerenkov) detectors to determine the velocity of the higher momentum particles (up to 5 GeV/c protons or 3 GeV/c kaons) produced during collisions.

The Photon Spectrometer[19] (PHOS) provides high resolution energy measurements for photons. The PHOS is an electromagnetic calorimeter that uses lead tungstate crystals as scintillators.

The Photon Multiplicity Detector[20] (PMD) determines the number of photons produced during a given event. The PMD provides a thermodynamic picture of collisions from the resulting quark-gluon plasma.

The Transition Radiation Detector[21] (TRD) is useful in electron detection for an even larger region than the EMCal. This is useful for studying the decay products from light and heavy vector mesons (D Mesons and B mesons), hadron decay, correlated DD and BB pairs, analysis involving electrons, and in studying jets with high transverse momentum. The TRD makes multiple measurements of energy loss from charged particles passing through its radiator and drift volume.

ALICE’s Time of Flight[22] (TOF) detector measures individual particle’s time of flight from the interaction point of the collision to the detector itself. The TOF provides velocity measurements, allowing for identification of charged particles with intermediate momentum. The combination with various tracking detectors (the TPC and ITS for instance) allows the mass of a particle to be determined via track curvature and momentum. The TOF is particularly useful in distinguishing between pions and heavier charged particles.

The T0[17] detectors are triggering detectors on the beam and provide the fastest indication that a collision has occurred at ALICE. The T0’s also are used to measure the vertex position and assist in estimating the multiplicity of an event.

The two V0[17] detectors on each side of ALICE provide the centrality trigger for the experiment. This allows ALICE to distinguish peripheral from central collisions. The V0 detectors are used to determine the centrality (discussed in the types of collisions section) of interaction events. The V0 detectors additionally provide background rejection capabilities for the dimuon spectrometer. This helps determine whether or not a muon came from the collision, from another interaction, or from a cosmic ray. They also contribute to the rejection of asym-
metric beam-gas events resulting from an imperfect vacuum.

Another detector for measuring particle energy is the Zero Degree Calorimeter (ZDC). The two ZDC’s[23] are located at each end of ALICE on the beam line. These are hadronic calorimeters used in determining particle energy deposited very close to the beam. Their most important function is to determine the energy of spectator nucleons. These are leftover parts of a collided ion that were not directly involved in the collision. This helps determine how much the ions overlapped and contributes to the collision centrality measurement.

Critical to the operation of ALICE is the central trigger processor[24] (CTP). The trigger system divides detectors into two kinds: triggering detectors and read-out detectors. Triggering detectors relay what is happening in the detector to the CTP which determines whether or not there is data worth recording. If there is something of interest, the CTP tells the appropriate read-out detectors to start taking data. A given detector can be triggering, read-out, or both depending on what is required by data acquisition. The trigger system is discussed in detail in Chapter 4.
2 Ultra-Peripheral Collision Physics

Figure 6: An Ultra-Peripheral Collision with relativistic electric fields. Photon-photon and photon-nucleus Interactions are shown.[25]

The Klein-Nystrand model[26] is a widely accepted model of ultra-peripheral collisions (UPC’s). It treats two passing ions as being surrounded by a field of virtual photons that interact to produce particles as shown in Figure 6. This chapter will walk through the mathematics of what happens during hadron-hadron collisions, focusing on ultra-peripheral interactions. It will provide a brief overview of the history of this area of particle physics, discuss particle production during heavy ion interactions and go into detail about the Klein-Nystrand model of UPC’s.
2.1 Observables

Data analysis is based on observables reconstructed from detector data. The transverse momentum, $p_t$, is used rather than the total momentum, $p$, or longitudinal momentum, $p_l$, as $p_t$ is relativistically invariant. The $p_t$ is easier to measure given the barrel design of the experiment. Transverse momentum is the momentum in the direction outwards from and perpendicular to the beam line (as shown in Figure 7a) while longitudinal is along the beam line. The total momentum is simply $p = \sqrt{p_t^2 + p_l^2}$. Mass, momentum, and energy are related according to Einstein’s equation,

$$E^2 = (mc^2)^2 + (pc)^2$$

(2.1)

For UPC rho production, the transverse momentum of the rho particle is small (in fact, for an ideal photoproduced rho, it corresponds to a wavelength larger than the size of the initial heavy ion). A low momentum rho particle takes less energy to produce than a high momentum rho particle, so the particles are more likely to be produced at low energy.

The multiplicity is the number of particles produced during the collision. As expected, peripheral collisions will have a smaller multiplicity than a head-on collision. For example, an ultra-peripheral collision producing a single neutral rho will usually have a multiplicity of two: both pions. More information than just the number of tracks detected is required to be certain of the multiplicity. When a rho particle decays, the pions that result may move in any direction. If the pions pass through gaps in the detectors or move down the beam pipe, they will not be detected. In this case, an event that in reality has a multiplicity of two will appear to have a multiplicity of one or zero.

The observables rapidity and pseudorapidity[28] are often more useful than the longitudinal momentum because of the simple way that they transform between reference frames. The rapidity is defined in terms of the energy and longitudinal
momentum \( (p_t) \) of a particle,

\[
y = \frac{1}{2} \ln \frac{E + p_t}{E - p_t} = \ln \frac{E + p_t}{m_t} = \tanh^{-1} \frac{p_t}{E}
\] (2.2)

The advantage in using rapidity is that its distribution has a simple translation under Lorentz transformations along the z-axis. This means that two identical collisions with different center of mass velocities will have identical rapidity distribution shapes (although the centers of the distribution will be at different values of rapidity).

Pseudorapidity, \( \eta \), (shown in Figure 7b) is the rapidity determined for a particle with a known energy or momentum whose mass is assumed to be zero. In this case, rapidity reduces to a function of the angle the particle’s velocity makes with respect to the beam line, with a pseudorapidity of zero equating to 90 degrees (\( \frac{\pi}{2} \) radians) from the beam and an infinite pseudorapidity being parallel with the beam line. Pseudorapidity is used to discuss detector coverage. The EMCal, for example, covers a pseudorapidity range of \( -0.7 \leq \eta \leq 0.7 \). Pseudorapidity is given by,

\[
\eta = -\ln \tan \frac{\theta}{2}
\] (2.3)

where \( \theta \) is the angle from the beam line in the center of mass frame. Pseudorapidity approximates to rapidity for \( p_t \gg p_t \gg m \).

### 2.2 Types of Collisions

![Figure 8: a: Central, b: Peripheral, and c: Ultra-Peripheral collisions][2]

During hadron-hadron collisions at the LHC, a number of different types of interactions can take place: central, peripheral, and ultra-peripheral. Central collisions (shown in Figure 8a) occur when particles in the beams collide head-on. This type of collision is used in the study of the formation of quark-gluon plasma. Centrality refers to how much of the ions overlap when they collide. It is generally classified as a percentage of all events. Centrality can also be denoted by the collision’s impact parameter, \( b \), the distance of closest approach between the centers.
of the ions. The most central collisions have the 0-5% highest number of nucleons participating in the collision. The number of participants is measured by counting spectator nucleons in the ZDC and corresponds to the highest multiplicities of all events. For the most central events, \( b \approx 0 \). During a central event, the two nuclei will completely break apart. Central interactions are dominated by the strong nuclear force. Central interactions have a high multiplicity, producing many thousands of particles. Table 1 shows the centrality dependence of the multiplicity in the central pseudorapidity region (\(|\eta| < 0.5\)).

Peripheral collisions (shown in Figure 8b) occur when the two ions partially overlap. Peripheral collisions are the 5-80% most central events. The impact parameter for peripheral collisions is given by \( 0 < b < 2R_A \) (where \( R_A \) is the radius of the ion). Peripheral interactions are also dominated by the strong force since the ions pass close enough for a “contact” interaction to take place. Multiplicity is lower for peripheral collisions (as fewer nucleons collide), but still higher than for ultra-peripheral collisions and often larger chunks of the nucleus will remain after the collision, depositing a number of neutrons and protons in the zero degree calorimeter as a result. Table 1 shows that multiplicity is a good indicator of centrality.

This thesis focuses on the third variety of collisions, known as ultra-peripheral collisions (shown in Figure 8c). UPC’s occur when the collision has an impact parameter larger than the combined radii of the ions. UPC events have the lowest multiplicity of all events.

### Table 1: Centrality and Multiplicity

<table>
<thead>
<tr>
<th>Centrality*</th>
<th>( \frac{dN_{ch}}{d\eta} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% - 5%</td>
<td>1601 ± 60</td>
</tr>
<tr>
<td>5% - 10%</td>
<td>1294 ± 49</td>
</tr>
<tr>
<td>10% - 20%</td>
<td>966 ± 37</td>
</tr>
<tr>
<td>20% - 30%</td>
<td>649 ± 23</td>
</tr>
<tr>
<td>30% - 40%</td>
<td>426 ± 15</td>
</tr>
<tr>
<td>40% - 50%</td>
<td>261 ± 9</td>
</tr>
<tr>
<td>50% - 60%</td>
<td>149 ± 6</td>
</tr>
<tr>
<td>60% - 70%</td>
<td>76 ± 4</td>
</tr>
<tr>
<td>70% - 80%</td>
<td>35 ± 2</td>
</tr>
</tbody>
</table>

*Centrality is given as a percentile of multiplicity.
\( \frac{dN_{ch}}{d\eta} \) is the multiplicity within the pseudorapidity range \(|\eta| < 0.5\).

Source: [30]

### 2.3 An introduction to UPC physics

For this thesis, electroweak photon-nucleus interactions are discussed. Photons are emitted by one or both of the ions and produce particles via a phenomenon
known as photoproduction. These interactions have low multiplicity, typically only producing a single particle (such as the rho). The total contents of the detector will be the particle’s decay products.

The study of ultra-peripheral collisions dates back to a paper by Enrico Fermi entitled “On the Theory of Collisions Between Atoms and Elastically Charged Particles”[31]. In this paper, Fermi treats the electromagnetic field produced by a moving charged particle as a virtual photon flux. This flux is equivalent to the number of photons produced by the motion of the particle. As the charge moves, the virtual photons’ energy and density are boosted by the Doppler effect. This then represents both a higher photon flux and higher photon energies.

Weizsäcker and Williams[32] expanded this method in 1934 to include relativistic particles. A relativistic charged particle has a stronger transverse electric field, corresponding to a higher photon flux as it interacts with another charged particle. This model is known as the Weizsäcker-Williams method and contributed to the rise of modern quantum electrodynamics. The Weizsäcker-Williams method has continued to expand thanks to research at particle accelerators around the world. It has particular relevance to the study of ultra-peripheral collisions.

Because UPC’s produce at most a handful of interactions, they are useful in studying the electromagnetic processes that underlie the complex interactions that produce large multiplicities from multiple interactions in more central collisions. They are used in studying nuclear photoexcitation of hadrons at high energies as well.

2.4 The Klein-Nystrand Model of UPC’s

When two nuclei interact in an ultra-peripheral collision, virtual photons are exchanged in their respective electric fields (shown in Figure 9). When this occurs, one of two things can happen. One ion will emit a photon which will interact with the other ion or both ions emit photons that interact with the opposing photon.
Figure 9: UPC with relativistically shifted E fields

The way in which this interaction is studied is referred to as the Klein-Nystrand model of Ultra-peripheral Collisions after Spencer R. Klein of the Lawrence Berkeley National Laboratory and Joakim Nystrand of the University of Bergen. When two ions are accelerated to relativistic speeds, the electric field shifts (see Figure 9) so that it is concentrated perpendicular to the direction of flight. The electric field is modeled as a virtual photon flux, the number of photons per unit area during a collision. The maximum energy of these photons is determined by the Fourier transform of the EM field of the moving ion and is given by,

\[ E_{\text{max}} = \frac{\hbar}{\Delta t} \sim \frac{\gamma \hbar v}{b} \]  

Here, \( \gamma \) is the Lorentz factor: \( \gamma = \sqrt{1 - \frac{v^2}{c^2}} \), \( \Delta t \) is the time over which the interaction takes place (proportional to \( b/\gamma v \)), \( \hbar \) is Planck’s constant divided by \( 2\pi \), \( b \) is the impact parameter, and \( v \) is the velocity of the heavy ion.

The impact parameter, \( b \), is greater than \( R_1 + R_2 \) in a UPC collision. For lead, \( R \approx 9 \text{ fm} \), and \( b > 18 \text{ fm} \).

The virtual photon flux is given by \[ N(\omega, b) = \frac{Z^2 \alpha E^2}{\pi^2 \gamma^2 \hbar^2 \beta^2 c^2} \left( K_1(x)^2 + \frac{1}{\gamma^2} K_0(x)^2 \right) \]  

where \( x = Eb/\gamma \beta \hbar c \), \( Z \) is the ion charge (82 for lead), \( \alpha = 1/137 \), \( \beta = v/c \), \( c \) is the speed of light, and \( K_0 \) and \( K_1 \) are modified Bessel functions. \( K_1(x)^2 \) gives the flux of photons polarized perpendicular to the direction of travel, and \( K_0(x)^2 \) gives the flux for those parallel to the direction of travel.

The viruality, \( q \), given by \( -q^2 < (\hbar/R)^2 \), of these photons indicates that they are “real” enough that there is a high likelihood of interaction. Virtuality corresponds to the momentum which virtual photons have. According to the uncertainty relation \( \Delta x \Delta p \geq \hbar \), \( \Delta x \) corresponds to the distance over which virtual
photons can interact. For a UPC, \( q = \Delta p \geq \frac{\hbar}{b} = \frac{\hbar}{2\pi R_A} \) in order for these virtual photons to interact. If \( q \) allows \( \Delta x = b \), virtual photons can effectively be treated as real photons as they “live” long enough to interact before vanishing again.

Table 2 is a chart of the maximum energies and beam statistics for various particle accelerators. The LHC studies particle interactions at energies more than an order of magnitude greater than any other experiment in the past. In this thesis, my analysis deals with Pb-Pb interactions at the LHC.

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Ions</th>
<th>Max. Energy per nucleon pair(^\dagger)</th>
<th>Luminosity</th>
<th>Max. photon-proton energy(^\dagger)</th>
<th>Max. photon-proton energy(^\dagger)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN SPS</td>
<td>Pb+Pb</td>
<td>17 GeV</td>
<td>-</td>
<td>3.1 GeV</td>
<td>0.8 GeV</td>
</tr>
<tr>
<td>RHIC</td>
<td>Au+Au</td>
<td>200 GeV</td>
<td>4 x 10(^{26}) cm(^{-2}) s(^{-1})</td>
<td>24 GeV</td>
<td>6.0 GeV</td>
</tr>
<tr>
<td>RHIC</td>
<td>p+p</td>
<td>500 GeV</td>
<td>6 x 10(^{30}) cm(^{-2}) s(^{-1})</td>
<td>79 GeV</td>
<td>50 GeV</td>
</tr>
<tr>
<td>LHC</td>
<td>Pb+Pb</td>
<td>5.6 TeV</td>
<td>10(^{27}) cm(^{-2}) s(^{-1})</td>
<td>705 GeV</td>
<td>178 GeV</td>
</tr>
<tr>
<td>LHC</td>
<td>p+p</td>
<td>14 TeV</td>
<td>10(^{34}) cm(^{-2}) s(^{-1})</td>
<td>3130 GeV</td>
<td>1400 GeV</td>
</tr>
<tr>
<td>Tevatron(^*)</td>
<td>p+p</td>
<td>20 TeV</td>
<td>5 x 10(^{34}) cm(^{-2}) s(^{-1})</td>
<td>320 GeV</td>
<td>200 GeV</td>
</tr>
</tbody>
</table>

\(^\dagger\) center of mass energy

Source: \[26\]

For UPC’s, the flux contributes either one or two photons to the interaction depending on the kind of interaction stated above. In a single photon interaction, the single photon flux for a heavy ion UPC is obtained by integrating equation 2.5 over \( b > 2R \). The resulting expression is,

\[
n(E) = \frac{2Z^2\alpha}{\pi\beta^2} [\xi K_0(\xi)K_1(\xi) - \frac{\xi^2}{2}(K_1(\xi)^2 - K_0(\xi)^2)]
\]

(2.6)

where \( \xi = \frac{Eb_{\text{min}}}{\gamma \beta hc} = \frac{2ER}{\gamma \beta hc} \).

For two photon flux, equation 2.6 serves as an approximation when applied to each photon. The orientation of each ion’s electric field must be taken into account for more precise calculations. However, this is outside the scope of this thesis.

### 2.5 Coherence

Photon-photon interactions and photon-nucleon interactions can be coherent or incoherent\([35]\). A coherent interaction happens when the ion as a whole emits or absorbs a photon. This photon has a wavelength longer than or equal to the radius of the ion, and thus the wavelength is too large to see any contribution to the interaction from the individual parts of the nucleus. An incoherent interaction
takes place when individual nucleons or groups of nucleons emit or absorb photons. These photons have a shorter wavelength than those for coherent interactions and can interact with individual nucleons in the other ion.

Due to the photon’s wavelength being at least the radius of the ion, when looking at coherent interactions an ion is seen as a single object. Coherent interactions are produced by a strong electric field acting for a short period of time with the ion as a whole seen as producing the field rather than the individual nucleons. Incoherent interactions are more complicated. The photon wavelength is small enough to see the ion as a conglomeration of protons and neutrons which in turn are seen as quarks and gluons. Each individual nucleon’s contribution to the reaction must be taken into account during an incoherent collision. The majority of rhos in my results are coherent, having a very small momentum. Incoherent rhos are discussed briefly in Chapter 5.

2.6 Heisenberg’s uncertainty principle and the rho meson

The rho particle has a very wide peak in a mass distribution. This is due to Heisenberg’s Uncertainty Principle[36], specifically the relationship between energy and time: \( \Delta t \Delta E \geq h \). Mass and momentum are viewed in terms of their relationship with energy, \( E^2 = (mc^2)^2 + (pc)^2 \). The above uncertainty relation says that the greater the uncertainty in a particle’s lifetime (which is directly proportional to the particle’s lifetime), the more precisely we can know its energy, and vice-versa. Because the rho particle has a very short lifetime, the uncertainty in the energy - and thus the mass - is large.
3 Rho Meson Detection

This chapter will discuss properties of the rho meson and discuss the methods used for their identification in this thesis. This involves an overview of particle identification and calculations (done in AliRoot) used to find the rho peak. The rho particle can be either charged or neutral. This thesis focuses on the neutral rho.

3.1 The Rho Meson

The rho meson is the lightest of the vector mesons. Mesons are quark-antiquark pairs with integer spins. Vector mesons have a spin of 1. The quark composition of the neutral rho is $\frac{u\bar{d} - d\bar{u}}{\sqrt{2}}$. According to the Particle Data Group\cite{pdg}, neutral rho mesons have a mean mass of $0.7685 \pm 0.0011$ GeV/$c^2$ with a mass full width
resonance of $\Gamma = 0.1507 \pm 0.0029$ GeV/c$^2$. The full width resonance is a measure of the “width” that the rho’s mass has due to the Heisenberg Uncertainty Principle. Particles with shorter lifetimes have a greater uncertainty in their rest energy and, thus, in their rest mass.

The $\rho^0$ particle has an extremely short lifetime ($4.4 \times 10^{-24}$ seconds). This short lifetime gives the rho its wide mass resonance[39]. Because at most the rho can travel 1.3 fm from where it was created (assuming a velocity of c), it never makes it far enough from the interaction point to be detected by ALICE and therefore must be detected via its decay products. The $\rho^0$ decays into $\pi^+\pi^-$ pairs with a probability of 98.90 ± 0.16%. This makes it impractical to study any decay channel other than $\pi^+\pi^-$.

### 3.2 Finding Rho Particles

In my identification of potential rho candidates, I assume that all of the tracks detected are pions. These daughter pions should come from a common point of origin on the beam line because rho mesons decay almost immediately. For my analysis, the primary vertex was defined to be within a certain distance of the center of the interaction region: $\pm 2$ cm in x and y and $\pm 5$ cm in z. Those decay vertices that are not on the beam line are most likely due to interaction with gas particles or the detectors. Such non-prompt tracks add to the background and are discarded.

Once the vertex is identified and accepted, I determine the momentum and energy of each pion. I then use the conservation laws of energy and momentum to find the total energy and momentum of the parent particle. From these quantities, I can calculate the parent’s mass using equation 2.1 as shown in Figure 11.

![Figure 11: Rho UPC Event with rho identification calculations](image)

Figure 11 shows an ALICE event display representation of a UPC rho candidate.
event. Each pion’s energy and momentum are calculated (note that the transverse momentum comes from the x and y components of the momentum: \(p_t^2 = p_{1,x}^2 + p_{1,y}^2\)) and the results are used to calculate the invariant mass of the rho candidate.

3.3 A Detailed Look at Particle Identification

The ALICE detector has nearly unparalleled particle identification capabilities. This section provides a look at the major particle identification detectors[41], details of how they operate, and the important quantities analyzed.

One of the most useful quantities for particle identification is the energy loss per unit path length of the particles, written as \(\frac{dE}{dx}\). Different particles have different masses. \(\frac{dE}{dx}\) is velocity dependent. Particles of different mass will have different velocities for the same momentum. This is very useful for separating out electrons, pions, kaons and protons. Generally \(\frac{dE}{dx}\) is plotted versus particle momentum or rigidity. Such plots show clear bands for particles of different masses (see figures below).

Figure 12: Particle identification with the ALICE ITS[42]

The Inner Tracking System uses \(\frac{dE}{dx}\) versus momentum as a method of particle identification. The ITS uses SDD’s and SSD’s (the middle and outer layers of the ITS) to provide up to four samplings per track to get an average \(\frac{dE}{dx}\) calculation. These measurements have a standard deviation of approximately 10-15%. The
ITS can provide pion identification with a minimum $p_t$ of 0.100 GeV/c (see Figure 12).

In the case of the Time Projection Chamber, $\frac{dE}{dx}$ is plotted versus the rigidity of the particles (see Figure 13). The rigidity is used because it is a function of track curvature which allows particles of different charge to be compared on the basis of the two measurable quantities. The TPC has 557568 read-out channels, giving it excellent resolution. It is filled with a gas mixture of 90 parts Neon, 10 parts CO$_2$ and 5 parts N$_2$ that ionizes when particles pass through, allowing it to sample $\frac{dE}{dx}$ many times per track and provide momentum measurements. $\frac{dE}{dx}$ in the TPC is proportional to the number of ions created per unit track length. Each time the particle ionizes an atom in the gas, it loses an amount of energy equal to the ionization energy of the atom. The TPC is useful in identifying all kinds of particles, including antimatter nuclei (see Figure 13).
The Transition Radiation Detector provides electron identification using $\frac{dE}{dx}$ in the drift volume combined with ionization due to photons produced in its radiator. The ALICE TRD can detect electrons above 1 GeV/c via transition radiation: photons are produced when a relativistic particle passes from one medium to another. The TRD uses many layers of alternating media to produce transition photons. These ionize a gas mixture of 85% Xenon and 15% CO$_2$. The charge produced by ionization electrons from passing charged particles and from transition radiation can be used for particle identification. The signal from passing electrons is generally larger than passing pions (see Figure 14).
Particle identification with the Time of Flight (TOF) detector is done using velocity calculated from the path length and time required to traverse this path. Because of the differences in mass between the particles, we will observe different velocities for the same momentum. This provides for excellent particle identification for pions, kaons, and protons (see Figure 15). The TOF has a time resolution of about 80 picoseconds for central lead-lead collisions 120 picoseconds for proton-proton collisions and 202 picoseconds for UPC’s. Due to the excellent resolution of the TOF, electrons, pions, kaons, and protons can be distinguished even in situations of very high multiplicity where a high number of particles could otherwise cause overlap between tracks. The distance from the beam to the TOF and the particle’s path length as measured by the TPC. Most of the error comes from uncertainty in knowing when the event took place. This combined with the measured time of flight gives the particle’s velocity. For an electron with a momentum large enough to be tracked in the TPC, $\beta$ is effectively 1.

Pion identification occurs by measuring the particle momentum from the curvature of particle tracks in the TPC (which is in a known, uniform magnetic field) and the speed of the particle from the TOF. Particles are identified by their mass through the relativistic equation for momentum, $p = mv/\sqrt{1 - v^2/c^2}$ (see Table 3). The five stable particles detected in ALICE are electrons, muons, pions, kaons, and protons.
Table 3: Fundamental Particles by Mass

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>symbol</th>
<th>Mass (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron/Positron</td>
<td>e±</td>
<td>0.005109989 ± 1.3 x 10^{-9}</td>
</tr>
<tr>
<td>Muon</td>
<td>µ±</td>
<td>0.1056584 ± 3.8 x 10^{-6}</td>
</tr>
<tr>
<td>Pion</td>
<td>π±</td>
<td>0.13957 ± 3.5 x 10^{-4}</td>
</tr>
<tr>
<td>Kaon</td>
<td>K±</td>
<td>0.494 ± 1.3 x 10^{-2}</td>
</tr>
<tr>
<td>Proton</td>
<td>p±</td>
<td>0.938272 ± 2.3 x 10^{-5}</td>
</tr>
</tbody>
</table>

Source: [38]

Figure 16: Particle identification with the ALICE HMPID[46]

ALICE is designed for midrange momentum measurements. If the momentum of a particle is too low (below around 0.1 GeV/c), it will not reach the ITS. If it is too high (above around 2 or 3 GeV/c), the particle will pass through everything without interacting enough for a reliable signal. The High Momentum Particle Identification Detector (HMPID) broadens ALICE’s measurement capabilities to include kaons and protons with momentum up to 5 GeV/c. The HMPID uses ring-imaging Cherenkov detectors filled with liquid C_{6}F_{14} to give off light as high momentum particles pass through it. Cherenkov detectors have an index of refraction such that particles entering the medium move faster than the speed of light in that material. The radius of the ring of light produced is related to the velocity of each particle, which combined with knowledge of the momentum from the TPC allows particle identification (see Figure 16).

For UPC’s, we have the luxury of being able to identify each individual track since there is almost always a clear separation between the paths of the two particles. This allows us to identify and assign masses on a particle by particle bases, thus making detailed analysis of each particle possible. In each of these sub-detectors there is a significant overlap in the signal expected from a pion and the signal expected from an electron. This thesis will present the first use of the ALICE EMCal to distinguish pions from electrons in physics events.
Heavy ions in the LHC are circulated in groups called bunches. The time between bunch crossings is much smaller than the time required for read-out of the detector. The experiment must decide in a matter of microseconds following each bunch crossing if data read-out will be triggered. Every action taken during collection by ALICE is governed by one or more triggers. Triggers are set at the Data Acquisition station (DAQ) in the control room and are defined based upon what data is of interest. This section goes into detail on the trigger system at ALICE, both from a hardware and a software standpoint. An overview of the system can be found in Figure 17. Each detector in ALICE can be used as a triggering detector, a read-out detector, or both depending on what types of events are desired by the experiment. Triggering detectors detect that an event has occurred. Messages with this information are sent to the central trigger processor (CTP). The CTP informs the local trigger units (LTU’s) attached to each read-out detector whether or not the read-out for that detector should be triggered. Beyond selecting events to record, triggers are used to provide an initial measurement of event features during data taking. These include event type (central, peripheral, ultra-peripheral) and multiplicity.
4.1 The Central Trigger Processor - CTP

The trigger system at ALICE\cite{48}\cite{49} has a central design. The central trigger processor makes decisions and local trigger units implement those decisions. The CTP receives two timing signals from the LHC: bunch crossing and orbit. Bunch crossing timing is used so that ALICE knows when two bunches will cross in the detector, causing collisions. Orbit timing is used to track oscillations of the bunch orbit from the equilibrium position of the orbit in the LHC ring. This helps ensure that the experiments can keep track of the location of the bunches as they orbit.

There are 60 trigger inputs in the ALICE detector. These are organized into three levels of hardware triggers: Level 0 (L0) with 24 trigger inputs, Level 1 (L1) with 24 inputs, and Level 2 (L2) with 12 inputs. In addition there are 24 busy inputs, one from each read-out detector, in order to tell whether or not a detector is currently busy (being read out). The CTP allows for sub-detectors (such as the SSD, SPD, and SDD in the ITS) to have their own output, allowing for 24 sets of 7 outputs per sub-detector (168 in total).

CTP logic is a set of defined parameters that provide different outputs based upon various inputs. Various detectors act as triggering detectors which tell the CTP that something is happening. Based upon this input, the CTP then decides whether what has occurred in the detector is worth recording. This is based upon which read-out detectors are included in the partition (the group of detectors involved in a given data taking run). If the event is worth recording, then the CTP tells the read-out detectors to take data.

The three trigger levels (L0, L1, and L2) are present to account for the different read-out rates for different detectors. The L0 triggers use faster detectors and have a read-out time of approximately 1.2 microseconds after the event occurs. L1 triggers have a read-out time of 6.5 microseconds and L2 triggers have a read-out time of 88 microseconds. The faster L0 triggers can move on to a new event and continue reading out even while the slower detectors read out previous events.

4.2 Local Trigger Units - LTU’s

The local trigger units serve as interfaces between the CTP and each sub-detector. One of the advantages of using LTU’s to relay the information rather than plugging the detectors directly into the CTP is that it provides modularity to the trigger system. An LTU can be configured for a particular type of detector, but all LTU’s communicate with the CTP in the same manner. In addition to normal data taking, detectors will often perform independent data collection for testing and calibration purposes. During standalone operation, the LTU’s are capable of emulating the CTP for that detector, applying the same logic in data taking.

Data taking is broken into periods where the operating conditions are relatively constant. These data taking periods are called runs. Runs vary anywhere from minutes to several hours in length. During data taking, detectors are grouped into
clusters. Up to six independent clusters can be used in a run and a single detector can belong to multiple clusters. Each cluster is configured for a particular data taking purpose (with the CTP directing the actions that each cluster takes based upon input from read-out detectors).

Triggers use a procedure called past-future protection to minimize multiple interactions in the same read-out event. If events occur too quickly, multiple events can appear in the detector at once and be confused. Past-future protection helps prevent this. Though past-future protection is generally not required for the LHC heavy ion runs, it is very useful during proton-proton collisions which occur at a much higher rate than lead-lead.

4.3 UPC event triggers

Every data run at ALICE uses certain trigger classes depending on which detectors are available and needed. Trigger classes are groups of detector and other hardware triggers that tag the properties of a given event. These classes are represented by text strings in AliRoot (the analysis software for the experiment) that are attached to individual events. There are many L0 and L1 input codes, as well as many more L0 and L1 functions that flag multiple trigger input codes.

Trigger input codes are designed to look at specific conditions in the ALICE detector. The trigger code pertinent to this thesis is CCUP2-B-NOPF-All. This is one of several UPC triggers used at ALICE, and the one used for the LHC 2010 heavy ion run to detect UPC events. The first segment of the code, CCUP2, is a representation of what constitutes a UPC event. For an event to have the CCUP2 label, the SPD must have two hits, the TOF must have two hits, and neither V0 detector can have hits. The V0 detectors are used to find tracks close to the beam line that may miss the SPD and TOF.

The second segment of the trigger code, B, means that the event was produced by beam-beam interactions. NOPF, the third code segment, means that this particular trigger doesn’t use the past-future protection feature of the CTP. As the event rate is low, this is common for trigger classes during lead-lead collisions. Finally, All means that all detectors in the run are considered.

4.4 Data Selection

One of the main difficulties inherent in analyzing complicated data is determining what is unnecessary and applying appropriate filtering. If every event in every run were used, the result would be a sample too large to analyze. In order to get a clean signal, it is necessary to apply certain selection criteria to the data. This process starts with trigger selection of events. Other common data criteria are based on specific detectors and data related quantities.

As described above, this thesis looks at the CCUP2-B-NOPF-All trigger class to cut out all non-UPC events. This trigger class is a conglomeration of several detector related selection criteria involving the SPD, TOF, and ZDC. My analysis
uses two other detector related selection criteria involving the number of locations where evidence of ionization is found along a track in the TPC and ITS in order to determine if a track is worthy of analysis. I require the TPC to have at least 50 clusters out of 159 layers hit and the ITS to have at least three of six layers of the ITS layers hit to qualify a track as acceptable for analysis. These are standard ALICE track quality criteria.

Because we are interested in prompt rho production, the primary vertex for the pion pair must be on the beam line. To this end, we do not consider events that were outside of $|z| > 5 \text{ cm}$, $|x| > 2 \text{ cm}$, and $|y| > 2 \text{ cm}$ from the center of the detector. This ensures that the rho candidates come from near the interaction region.

The observables pertinent to this thesis are the momentum of decay pions and the multiplicity of the events. These selection criteria are determined by the properties of the rho particle, which has a multiplicity of 2 (two pions) and low transverse momentum consistent with a wavelength larger than or equal to the size of the interacting lead nucleus. These criteria are applied last, after distinguishing which events are UPC events, which events fall within the TPC and ITS selection criteria desired, and which events have the appropriate primary vertex. I require a pion momentum greater than 0.05 GeV/c and a multiplicity of 2.
5 Results

This chapter presents and discusses my final results. For a list of data used in producing these results, see Appendix A.

5.1 Invariant Mass and Transverse Momentum

![Invariant Mass Plot](image)

Figure 18: Invariant mass plot: from opposite signed pairs (black). Background can be estimated using like-signed pairs (red)[50]

The black histogram in Figure 18 shows the invariant mass distribution for neutral rho candidates in ultra-peripheral collisions. The red line shows the parent mass from like-signed pairs. Events in Figure 18 were selected to be two track events. We know that the rho meson decays into two pions, thus the multiplicity of any UPC photoproduced rho mesons must be two. As is seen in Figure 18, there is little background relative to the rho signal. The background includes any non-rho candidates that cannot be removed from the data. The distribution of combinatorial background in rho analysis is determined using like-signed pairs. Because conservation of charge dictates that the rho decays into $\pi^+\pi^-$ pairs, those events with $\pi^+\pi^+$ or $\pi^-\pi^-$ cannot come from rho decay. In these events, charged particles (the TPC only tracks charged particles) are lost down the beam line.
Figure 19: $p_t$ spectrum from rho candidates (black) and background estimated from like-signed pairs[51]

Figure 19 shows the transverse momentum spectrum for all two track events where the invariant mass of a parent of the two detected particles would be in the rho mass range \((0.768.5 \pm 0.1507 \text{ GeV/c}^2)\). The majority of rho candidates are at $p_t < 0.1 \text{ GeV/c}$. Like the invariant mass plots, the $p_t$ spectrum is plotted for rho candidates and the combinatorial background is estimated from like-signed pairs. The $p_t$ spectrum clearly demonstrates that the rho particle tends to have low transverse momentum.
5.2 Coherent and Incoherent Rho Production

![Rho Candidate Invariant Mass: two track, low $p_t$ events](image)

Figure 20: Invariant mass plot: from opposite signed pairs (black). Background can be estimated using like-signed pairs (red)[52]

Events in Figure 20 were selected to be two track events with a parent transverse momentum ($p_t$) less than 0.1 GeV/c. The addition of this requirement to the data in Figure 18 produces a very clean rho signal with an almost nonexistent combinatorial background. This plot corresponds to coherent rho production.

Distinguishing between coherent and incoherent rhos is accomplished by calculating the DeBroglie wavelength of the rho mesons for this $p_t$ range. The DeBroglie wavelength is given by:

$$\lambda = \frac{h}{p} = \frac{hc}{pc} \quad (5.1)$$

Where $h$ is Planck’s constant and $c$ is the speed of light. Plugging in $p = p_t = 0.1$ GeV/c, $h = 4.136 \times 10^{-15}$ eV·s, and $c = 2.99 \times 10^8$ m/s, we find that these rho mesons were produced with a wavelength of $\lambda \approx 12.4$ fm. Given that the diameter of the lead nucleus is around 18 fm, this is shown to be on the same scale. Those events with a $p_t$ of 0.068 GeV/c or less have a wavelength of 18 fm or more, thus ensuring that they were coherently produced.
The remaining events in the rho $p_t$ plot in Figure 19 with momenta up to around 1 GeV/c primarily come from non-coherent rho production (rho particles produced by one or more nucleons rather than the lead ion as a whole).

Figure 21 is an invariant mass plot for rho candidates with $0.1 < p_t < 1.0$ GeV/c. As can be seen there is a peak around 0.770 GeV/$c^2$. This indicates incoherent rhos being produced. These incoherent rhos have DeBroglie wavelengths $\lambda \approx 1.24 – 1.2.3 \text{ fm}$, indicating that one or more nucleons produced them as opposed to the lead ion as a whole. Protons have a charge diameter of 1.68 fm, thus showing rhos in this peak are the results of interactions that involved a proton (or a cluster of nucleons for larger $\lambda$).

The broad slope on the left side of the rho peak is likely due to $\omega$ particles. The $\omega$ decays into three pions ($\pi^+\pi^-\pi^0$) and the neutral pion is not accounted for, giving the parent a lower, broader mass than the expected $0.78265 \pm 0.00012$ GeV/$c^2$. Although a larger combinatorial background is present, there is a clear indication of the presence of incoherent rhos in my data. The relative rates between coherent and incoherent rho production is not a focus of this thesis, but it is worth noting that the majority of rho events studied are coherent.
It is useful to compare my own results with those of another experiment. Figure 22 shows the coherent and incoherent rho signals (opposite signed two track events) produced by my analysis compared with rho results at STAR during the 2002 RHIC 200 GeV gold-gold run. The STAR data comes from two track events with $p_t < 0.15$ GeV/c. The results have been normalized to match the coherent peak height. As is seen, the maxima of each data set neatly line up with the rho mass. The asymmetric tail on the left side of the STAR data is matched fairly well by the left side of the incoherent rho plot. This similarity is likely due to the higher $p_t$ cut used in the STAR data.
5.3 Pion Identification with the ALICE Electromagnetic Calorimeter

Table 4: EMCal cluster energy and TPC momentum for pions in UPC events

<table>
<thead>
<tr>
<th>Particle number</th>
<th>EMCal cluster energy (GeV)*</th>
<th>TPC momentum (pc)</th>
<th>E/pc ratio*</th>
<th>TPC e⁻ β</th>
<th>TPC π⁻ β</th>
<th>measured TOF</th>
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<tr>
<td>1</td>
<td>0.483-</td>
<td>0.865-</td>
<td>0.558-</td>
<td>1.000-</td>
<td>0.987-</td>
<td>–</td>
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<td></td>
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<tr>
<td>10</td>
<td>–</td>
<td>0.524-</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>11</td>
<td>–</td>
<td>0.395-</td>
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<td>1.000</td>
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<td>0.968-</td>
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<tr>
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<td></td>
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<td></td>
<td>1.000</td>
<td>0.946</td>
<td>0.924</td>
</tr>
</tbody>
</table>

*Particles without a corresponding signal in a detector are blank.

Source: [55]

All of the particles in Table 4 are expected to be pions from rho decay. Table 4 provides evidence that the EMCal responds as expected to these pions. The ranges presented indicate the experimental uncertainty of each measurement. EMCal cluster energy is compared to the pion momentum for each daughter particle that hits it and produced a signal. Pions have lower values than electrons for this ratio of energy deposited in the EMCal over momentum (times the speed of light) as measured by the TPC. Pions can have values anywhere below 1, while electrons tend to have an E/pc ratio near 1. This is due to pions depositing a random amount of energy in the EMCal while electrons usually deposit all of their energy.
When compared with Figure 4 we can see that the data in the table indicates that the particles being analyzed are indeed pions. Unfortunately, the EMCal coverage was limited to 50 degrees in 2010, having only 4 supermodules. Only the two events shown in Table 4 deposited enough energy in the EMCal to be registered. There were a total of 11 UPC tracks in my data sample that hit the EMCal. The rest were either below the EMCal cluster threshold or struck a gap in the detector and failed to register. Gaps can be caused by dead towers or by physical gaps between towers, modules, and supermodules in the EMCal. The absence of a signal above threshold is consistent with all of these particles being pions as a small EMCal signal would be expected for pions.

Reviewing the electron-pion separation capabilities in the sub-detectors discussed in Chapter 3, the only sub-detector with reasonable resolution in the relevant momentum region is the time of flight detector. Each particle’s $\beta = \frac{v}{c}$ is calculated as if it were an electron or a pion using the measured momentum from the time projection chamber. This is compared to the $\beta$ calculated based upon the time measurement from the TOF and track length from the TPC in order to identify these particles. The relative effectiveness of the EMCal over the TOF for electron-pion separation is clear from Table 4. This result leaves us confident that we can use the EMCal for pion rejection in the future study of $J/\Psi$ decays.
6  Summary and Opportunities for Future Work

I have observed coherent and incoherent rho production in ultra-peripheral collisions in the ALICE detector. I have demonstrated a proof of principle concerning the potential for the use of the ALICE electromagnetic calorimeter for pion identification in ultra-peripheral collisions.

There are many areas still to explore in UPC physics, many of which are happening at ALICE as I write this. Among these are studies of higher mass particles such as J/Psi and Upsilon, performing similar analysis to what I have provided for the $\rho^0$ meson. The study of J/Psi's $e^+e^-$ decay channel is greatly assisted using the EMCal's pion rejection capabilities. Since both the J/psi and Upsilon are significantly more rare than rho mesons, there is always a need for more data. In addition, my own analysis can be expanded to determine a rho meson production cross section and luminosity calculations for the rho meson as well as study rho production in more central events. Further work on the EMCal includes improvement of EMCal cluster identification.
A Appendix A - ALICE Dataset and Accelerator Operating Parameters

The rho analysis is based on ALICE 2010 lead-lead data, specifically LHC10h pass 2 AOD 73 data for run 139465 for Figures 18, 19, 20, 21, and 22 and LHC10h pass 2 ESD data for run 18730 for Table 4. The beams were 3500 GeV Pb-Pb beams with identical conditions (save for the fill schemes) during these runs with the L3 magnet operating at 30,000 Amps, corresponding to a magnetic field of 0.5 T, and the Dipole magnet operating at 6,000 Amps. The beams for run 139465 had 130 interacting bunches with a fill scheme. There were 7 non-interacting bunches per beam. The fill scheme was 500ns_137b_129_130_0_8bpi18inj_JONS. Run 138730’s fill scheme was 500ns_121b_113_114_0_4bpi31inj_JONS with 114 interacting bunches and 7 non-interacting bunches per beam.
B Appendix B - Service Work to the STAR and ALICE Collaborations

In addition to my analysis, it is worth pointing out several other contributions I made to both ALICE and STAR. I spent eight months at ALICE on the LHC and six months at STAR on RHIC. This appendix discusses contributions made to both experiments that were not directly related to this thesis.

B.1 ALICE

During my tenure at ALICE, I was a member of both the ALICE UD Physics working group (which includes the UPC group) and the Electromagnetic Calorimeter group. My work on the EMCal involved training for on-call shifts (though I never sat one) and occasionally assisting Dr. Bjorn Nilsen with work in the ALICE cavern. The latter consisted of geometric measurements of a new supermodule installed during the 2011-2012 technical stop. These measurements are used during calibration of the EMCal supermodules and are used to provide a mathematical representation of the layout of the device.

For my physics working group contribution I compiled a list of UPC events within certain runs as well as assisted Dr. Bjorn Nilsen with detector visualization studies. This consisted of analyzing rho events via the ALICE event display (Alieve), making note of the momentum and energies of particles to see if anything may have been lost either through gaps in the detector or down the beam line. I also gave a presentation at the Nebraska Academy of Science meeting in 2012 outlining my work at ALICE, specifically focusing on rho meson detection.

In addition to my work on the EMCal, I provided a small amount of work regarding Monte Carlo simulations, debugging Alieve, and worked shifts in the ALICE control room for Creighton. I ran my analysis code on Monte-Carlo simulated data, confirming the usefulness rho particle simulations. In addition, I provided Mihai Niculescu with information used to debug the ALICE event display while trying to get it to run on my office computer. This involved following his instructions and providing him with feedback for the combination of Root, AliRoot, and Geant 3 running on my office desktop. Finally I sat seventeen shifts in the ALICE control room. Eleven of these were the Data Quality Management shifts. This shift involved inspecting histograms to ensure that data was being taken appropriately. The other six shifts were Data Acquisition shifts which involved setting up, starting, stopping, and troubleshooting the data acquisition system at ALICE.

B.2 STAR

In addition to my time spent at ALICE, whose data is the focus of this thesis, I spent six months at Brookhaven National Lab working at the STAR experiment.
STAR can be thought of as the predecessor to ALICE in many ways. Prior to the creation of the LHC, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven was the foremost source for heavy ion collider physics in the world.

While at STAR I filled the role of Slow Controls expert. This post, normally filled by a post doc, put me in charge of the control systems of the experiment. STAR uses a hardware control system known as EPICS (Experimental Physics and Industrial Control System) to communicate between the control room and individual components of each detector. Generally these take the form of temperature, current, and voltage readings. When there were problems with this infrastructure (as opposed to problems with the sub-detectors themselves) I would be called to solve them.

My chief duties involved being available 24 hours per day in case problems arose. In addition, I also maintained the software running the channel access system, and occasionally replaced hardware VME boards that had gone bad. EPICS facilitates communication between hardware and software through these VME boards, which are small CPU’s used to apply commands sent from the control room to the hardware of the experiment. Detectors are controlled by Input/Output Controllers (IOC’s) which run VxWorks on RealTime processor boards and in the EPICS environment on Linux boxes. I had to maintain these IOC’s, changing defaults or alarm settings as needed.

In addition to being slow controls expert, I worked three shifts (the equivalent of 21 ALICE shifts) at STAR, two as the shift leader and one as a detector operator.
C Appendix C - ALICE software resources

C.1 ALICE data formats

All ALICE data is analyzed using two types of files: AOD’s and ESD’s. ESD files are more basic and are produced during raw data reconstruction. They take the form of a data tree with each branch being groups of similar data types, and leaves on the branches being histograms containing data relevant to each branch. ESD branches include such data as TPCVertex, Tracks, or caloCluster information as well as several others. The relevant leaves to a branch contain specific data measurements pertinent to that branch. For instance, the Tracks branch of data contains leaves such as track angles, cluster maps, detector signals, as well as others.

ESD’s are organized both by detector and by event. One may look up a quantity specific to a detector such as the EMCal (cluster energy for instance) for all events. In addition, it is known which event each data point belongs to, so that one may look at an event as a whole and perform calculations on it based upon data recorded from all relevant detectors. The data is fairly raw in ESD’s and calculations must be performed in order to transform it into more useful quantities.

AOD files are a second generation of data files, resulting from further processing done on ESD’s. AOD’s also take the form of a data tree. The data for AOD’s is more refined and includes more useful quantities such as (using the tracks branch as an example) track momentum, position, particle identification, charge, and other data relevant to each particle. Where ESD’s have more general data related to the raw data taking, AOD’s are much more condensed and organized. AOD’s are also organized by detector and by event. Both types of files are accessed via classes in AliRoot specifically designed to read these file types.

Finally, ALICE uses a Monte Carlo event generator to simulate certain types of events. The simulator produces ESD’s as if the real detector were taking data, but can be focused on a specific type of event (such as rho events). Monte Carlo data is useful in determining what the detector might be missing. For instance, Monte Carlo data is useful in seeing what percentage of tracks are lost down the beam line during UPC events. In addition, you can test code on Monte Carlo data to make sure that your code performs the analysis that it should.

C.2 ROOT

ROOT is a C++ based data analysis framework[57]. It provides a set of object oriented libraries capable of handling large amounts of data efficiently. This data is handled as a set of objects such as AOD and ESD files in the form of root trees. It is designed for histogramming in multiple dimensions, curve fitting, function evaluation, minimization, graphing, and visualizing data. The scripting language of ROOT is C++, while the analysis framework takes the form of numerous unique
C++ libraries and modules with their own ROOT specific objects.

ROOT is extremely useful in that it was developed specifically by CERN to use in high energy physics analysis. It is made to handle the large amount of data produced by LHC experiments. It is well documented, even providing basic information on C++ for scientists not yet familiar with the programming language. The root website provides numerous tutorials, a user’s guide, examples, and a complete documentation of all ROOT classes.

C.3 AliRoot, AliEn, Geant, and Alieve

AliRoot is based upon ROOT. It contains all basic ROOT modules and incorporates numerous ALICE specific libraries. It was developed by the ALICE collaboration specifically to analyze raw ALICE data, ESD’s, and AOD’s. It is capable of simulating data and analyzing that data as well. AliRoot is used to reconstruct raw data to produce ESD’s and AOD’s. There are AOD and ESD specific modules, each used to retrieve or perform calculations on data specific to these file types. AliRoot is also used to access AliEn, an online environment used for analyzing vast quantities of data. AliRoot is constantly being updated and developed to match the needs of the collaboration (though as a result the documentation leaves something to be desired).

AliEn, or Alice Environment, is an online grid used for distributed computing and efficient data analysis. AliEn uses its own Unix style shell, though limited, understanding only a handful of Linux/Unix commands. AliEn is used to access repositories of ALICE data around the world in order to analyze far more data than could fit on one computer. To run on the Grid, one must establish the appropriate operation environment and from there submit the job to the Grid. These jobs are monitored via an online monitoring system known as Monalisa. Monalisa shows the status of an individual’s jobs as well as any errors that crop up in the course of running. In addition to running jobs on the Grid, AliEn can be used to download data to local machines for testing and small scale analysis purposes.

Geant is a comprehensive simulation program used to describe the passage of elementary particles through matter. It was originally designed for high energy particle physics experiments, though it has found applications in medical and biological experimentation as well. At ALICE it is used in tracking particles through the detector in order to simulate detector responses. It is used to help represent the detector during simulations. It provides a graphical representation of the experimental setup and particle trajectories as well, assisting with event visualization.

The ALICE event display or Alieve is used to visualize both real and simulated events from raw data, ESD’s, and AOD’s. In my work, it proved useful in checking detector accuracy (to see what, if anything, is missed in events). This takes the form of kinks in tracks to indicate secondary decay, checking track mo-
mentum components to make sure momentum was conserved (thus seeing if we missed a particle), and providing track by track analysis of UPC events. Since UPC events are low multiplicity, they can be analyzed in this manner.
References


[37] Alieve, aliroot version 5-02-13-AN. LHC10h run 138730 pass 2 data, 10000138730001.20/AliESDs.root event 6.


[40] Prepared by James Ross using MS paint and Alieve. LHC10h run 138730 pass 2 data, 10000138730001.20/AliESDs.root event 6.


[50] ALICE LHC10h, multiple runs, AOD086 projection on mass axis fromMultiplicity versus mass plots.

[51] ALICE LHC10h, multiple runs, AOD086 projection on mass axis from $p_t$ versus mass plots.

[52] ALICE LHC10h, multiple runs, AOD086 projection on mass axis fromMultiplicity versus mass plots.

[53] Ross, J. Macro: “runUPCanalysis.C” using LHC10h pass 2 AOD073 data


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