Jet Measurements with Proton-Proton Collisions at 7 TeV in ALICE

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Jet Measurements with Proton-Proton Collisions at 7 TeV in ALICE

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Senior Project
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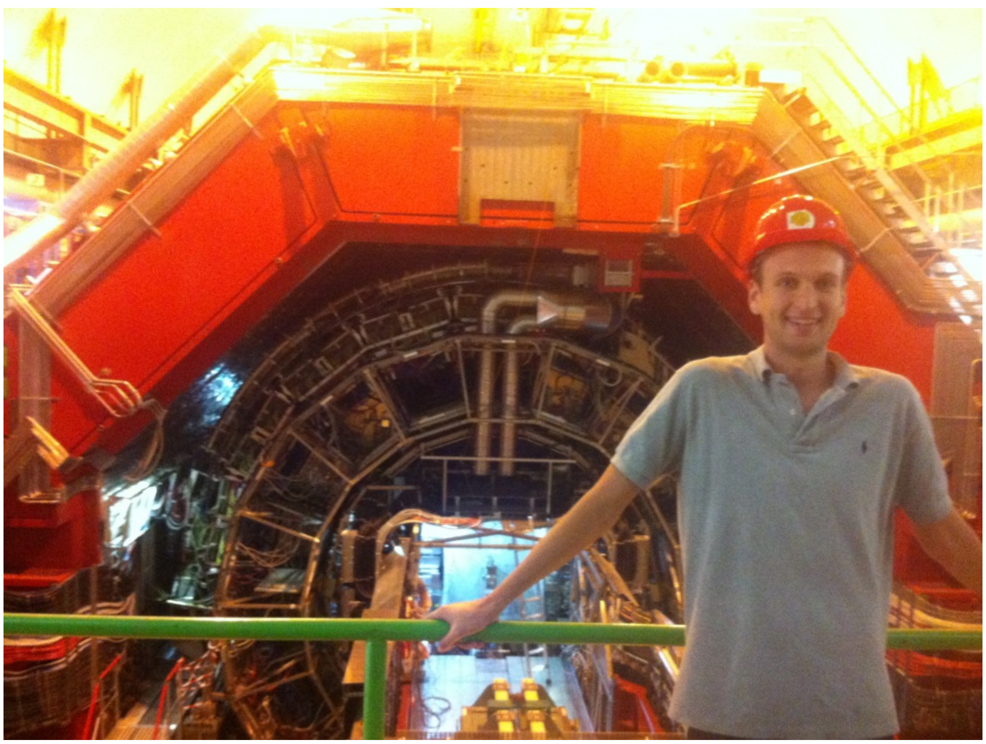

Figure 1: Author Kevin Thompson at the ALICE detector.

Abstract
The CERN Large Hadron Collider (LHC) is the world's largest and most complex particle accelerator, with several experiments making discoveries at the frontiers of particle and nuclear physics. The ALICE experiment at the LHC explores the nature of the early Universe through relativistic nuclear collisions. The properties of the "quark-gluon" plasma of subatomic particles created can be investigated with particle jets, which are produced in the earliest moments of the collision. This paper will provide an overview of the analysis of particle jets in 7 TeV proton-proton collisions, which forms the baseline for understanding jet production in collisions of heavy nuclei. It will cover jet finding methods and their associated biases. Photon contamination via pair production will be outlined and TOF data is prepared for comparison with EMCAL data in an attempt to correct for hardware limitations.

Introduction
The European Organization for Nuclear Research (CERN) completed the Large Hadron Collider (LHC) in 2008. As the name suggests, the LHC collides particles at near light speeds to probe deeper into our knowledge of particle physics. The LHC consists of a seventeen mile circumference tunnel lined with superconducting magnets. When precisely tuned, these magnetic fields are able to stabilize a beam of protons traveling near light speed. To efficiently operate these magnets, they are cooled to 1.85 Kelvin. The Large Hadron Collider has four detectors; this paper utilizes data from A Large Ion Collider Experiment (ALICE), seen in Figure 1. The ALICE detector is able to record the tracks and energies of particles generated in both proton-proton and heavy nucleus (e.g. lead) collisions.

The four detectors at the LHC were designed to answer four fundamental questions:

1. Why do particles have mass?
2. What is the nature of dark matter?
3. Why do we live in a matter dominated universe?
4. What was the state of the universe shortly after the Big Bang?

The ALICE detector largely focuses on the last question.

The purpose of this project is to investigate the production of jets in 7 TeV proton-proton collisions. This work builds on previous investigations by ALICE into jet production at 2.76 TeV [10]. The higher energy level of 7 TeV should yield more jets. ALICE must understand proton-proton collisions before analyzing lead-lead collisions. While the most interesting physics occurs with the higher energy lead-lead collisions, a singular proton-proton collision must be fully understood before attempting to analyze collisions that reproduce the conditions of the Universe after the Big Bang, also known as quark-gluon plasma (QGP). Figure 2 conveys the chaos that occurs during a particle collision. It is important to note that a collision yields thousands of particles and is very difficult to analyze.

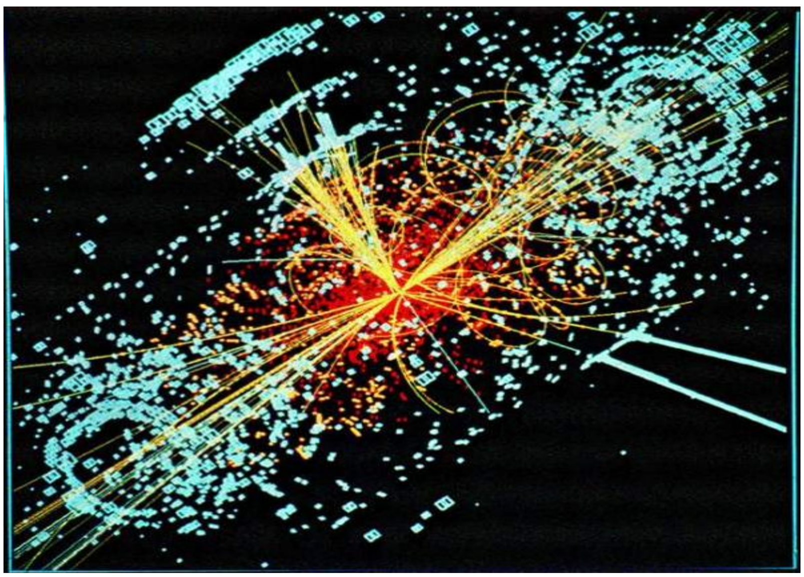

Figure 2: A reconstruction of a high energy particle collision.
Source: http://blogs.library.ucla.edu/sel/files/2013/11/higgs-boson.jpeg

This paper will first provide an overview of particle physics. From there, it will transition into describing jets and jet finding methods. Then the ALICE experiment will be described in detail and results from analyzing ALICE data to extract jet signals will be discussed. Finally, some conclusions and future outlook will be presented.

Particle physics background

Particle physics is the study of the smallest known elements that make up the universe. The purpose of ALICE is to explore the state of the universe shortly after the Big Bang. At this time, the universe was hot and dense. As temperature and pressure rises, materials typically become more fluid and the bonds between particles become weaker. The temperature and pressure of the early universe was so great that not even a proton was stable. Instead, protons were broken into quarks and gluons. This high energy configuration is typically referred to as quark-gluon plasma (QGP). Figure 3 is a phase diagram of nuclear matter. Matter's natural state at current temperatures and pressures is hadronic. Raising temperature and pressure immensely would convert hadronic matter to QGP. One of the reasons for creating QGP in the lab with nuclear collisions is to further investigate the strong nuclear force, which is one of the four fundamental forces: the strong nuclear force, weak nuclear force, electromagnetic force and gravitational force.

Figure 3 shows the phase diagram for nuclear matter in terms of the temperature and baryochemical potential, which is a variable related to density. As the temperature and/or density increase, the quarks and gluons can be released from their bonds inside of nuclei to produce a QGP.

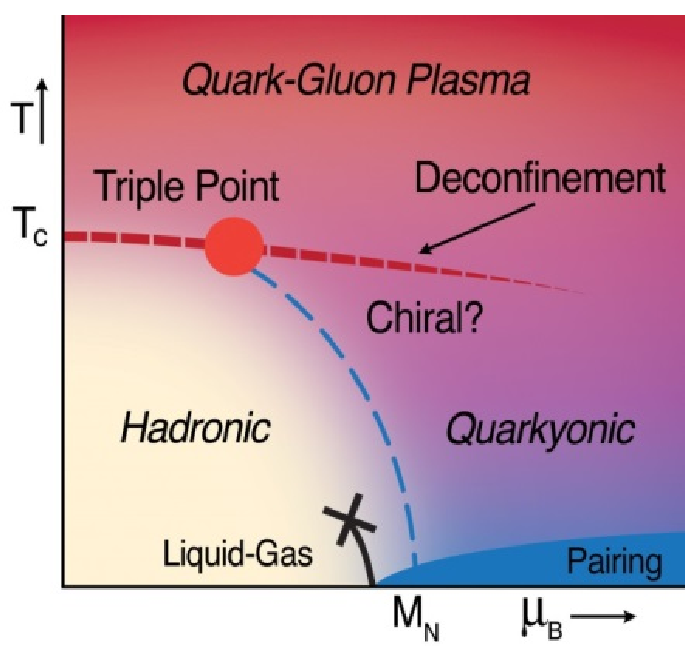

Figure 3: The phase diagram for quark-gluon plasma.
Source: http://quark.phy.bnl.gov/~pisarski/talks/QCDPhaseDiagram.jpg

Standard Model

In the 1930's scientists began compiling all of their discoveries about fundamental particles and the four fundamental forces. By 1970, there was enough information to formulate a Standard Model of particle physics. The goal of the Standard Model is to describe how all matter interacts. Elementary particles make up all matter.

In the Standard Model there are six types of quarks and leptons. There are up, down, charm, strange, top and bottom quarks. Leptons consist of electron, electron neutrino, muon, muon neutrino, tau and tau neutrino. Neutrino leptons are nearly massless and have neutral charge, unlike their counterparts.

There are also four fundamental forces: strong, weak, electromagnetic and gravitational. Strong and weak forces are relatively short range. These forces, quarks and leptons are seen in Figure 4. As its name suggests, the strong force is in fact the strongest force coming in 137 times stronger than the electromagnetic force, 1,000,000 times stronger than the weak force and 6×10^{37} or 60,000,000,000,000,000,000,000,000,000,000,000,000 times stronger than gravity.

Unfortunately, the Standard model is unable to account for the gravitational force at this time. However, at the particle scale, gravity is clearly negligible. The four fundamental forces operate by exchanging force carrier particles, or bosons. The gluon is responsible for the strong force, photons carry the electromagnetic force and the W and Z bosons deliver the weak force. Scientists assume that the predicted graviton will be the boson responsible for gravity. However, it has not been experimentally found. Figure 4 shows a typical visual representation of the particles in the Standard Model.

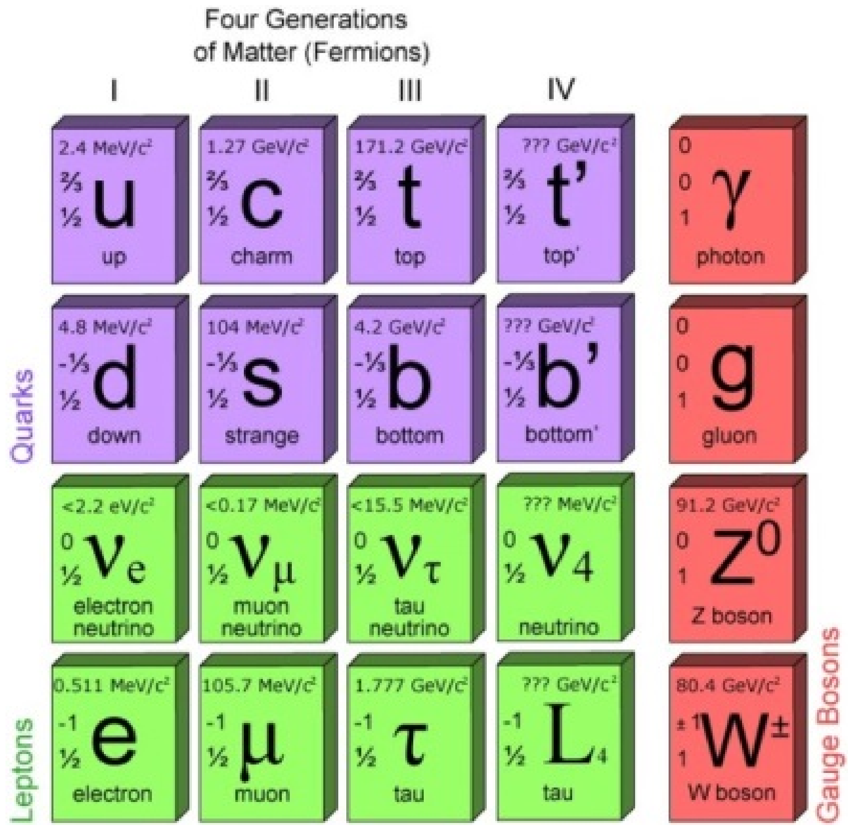

Figure 4: The standard model of physics.
Source: http://www.emmynoethercms.uni-hamburg.de/old_en/research/StandardModel4.jpg

The Standard Model still has room for improvement. It is unable to incorporate gravity and has not been able to answer longstanding questions about dark matter or antimatter. On July 4th, 2012, the LHC found a particle with energy 126 GeV, which has subsequently been confirmed to match the predicted properties of the long-sought Higgs Boson [4]. Two theorists, Francois Englert and Peter Higgs shared the 2012 Nobel Prize in physics for predicting the particle nearly 40 years ago. Future research at the LHC may help complete the Standard Model or find evidence for new physics beyond the Standard Model.

What are jets?

Jets are produced when energy from the colliding particles is converted into new matter. When two billiard balls collide, sound is “created” by transferring the billiard ball’s kinetic energy into sound. Much like this, when two protons collide they transfer some of their energy to produce matter and light. However, the protons are destroyed in the process, whereas the billiard balls, typically, are not. In high energy collisions, hundreds of particles will be produced, some of which come out in the form of “jets”, which are collimated clusters of particles heading in equal and opposite directions, to conserve momentum. These jets are created by the quarks of the original proton. Quarks cannot exist in isolation, so they transform into jets of hadrons. The paths and energies of the jets can be measured to reconstruct what happened during the collision.

A great way to understand what ALICE is trying to accomplish is to relate it to a macroscopic example. Imagine an empty room with white walls. In the center of the room lays a firework. The firework explodes and various jets of colored fire are emitted from it. ALICE scientists enter the room after the smoke has settled and observe scorch marks of various sizes on the once white walls. Their job is to reconstruct the firework and produce a complete history of the explosion. The scientists can use momentum conservation as well as the size and placement of the scorch marks to deduce where the firework was set off.

Experimental Design

The Large Hadron Collider was finished September 10th 2008. It is a 27 kilometer ring of superconducting magnets hundreds of meters underground. It uses magnetic fields to accelerate particle beams in opposing directions to nearly the speed of light. The four detectors (ALICE, ATLAS, CMS and LHCB) are able to observe the products of these collisions.

ALICE, A Large Ion Collider Experiment, is a detector for the LHC. ALICE was built as a heavy-ion detector to explore high density matter created by relativistic nuclear collisions. These high energy collisions create quark-gluon plasma. Understanding QGP is pivotal for our understanding of Quantum Chromo Dynamics (QCD). ALICE also explores proton-proton collisions as a baseline to better understand nuclear collisions.

The LHC accelerates hydrogen and lead atoms. These atoms are stripped of their electrons. The hydrogen atoms effectively become protons in this process. Now that these atoms have positive charges, they can be accelerated to near light speeds. Electromagnets force the particles to collide inside the ALICE detector. ALICE and its hard working scientists use conservation of momentum and energy to reconstruct the interactions during the collision.

Particles can be identified with a “mass spectrometry” approach. ALICE has its own magnetic field and particles have set masses and charges. Charged particles traveling in a magnetic field are bent in a helical spiral. Using the distance deviation and the energy deposited by the particles into the detectors the particles can be identified.

Unfortunately, the particle collisions in ALICE are not an ideal physics problem. There are many complications. There are thousands of particles that result from a high energy collision, not just two or three. During a collision particles typically shoot out in jet formations. In heavy ion collisions these jets typically travel through quark-gluon plasma and lose a significant energy to it. Quark-gluon plasma is a very hot, very dense “particle soup” that can be thought of like molasses. The jet can be imagined as a shotgun shot. The beads will hit the molasses. Depending on their speed and the thickness of the molasses, some may be slowed down or become stuck. Some particles may not make it to the detector or the jet can spread out and hit multiple detector cells. Figure 5 shows a collision occurring asymmetrically in QGP. The asymmetry will yield what appears to be a violation of conservation of momentum. Looking for these fake violations can yield new information about QGP.

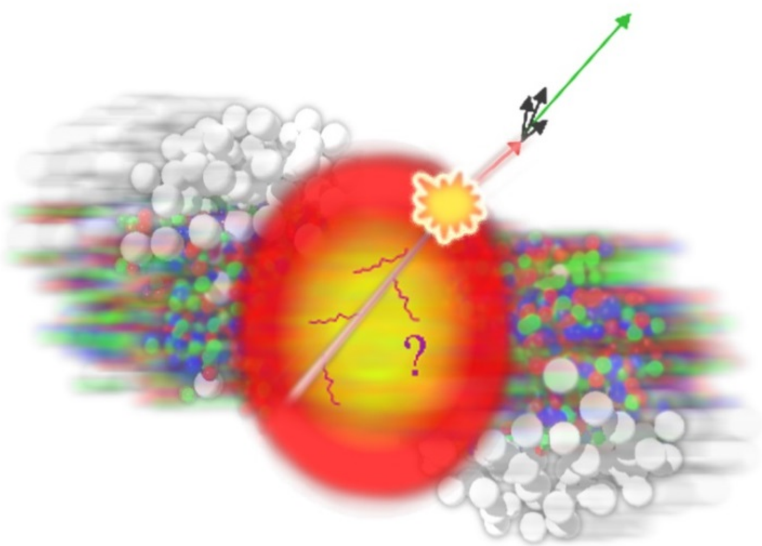

Figure 5: A jet embedded in a particle collision that forms a QGP. Due to the location of the collision, one jet is quenched by the QGP and the other is not before it hits a detector.
Source:http://ph-news.web.cern.ch/sites/ph-news.web.cern.ch/files/jet-quenching.jpg

Fortunately for physicists, these impedances are blessings in disguise. The goal of ALICE is to probe the conditions of the Big Bang. And what better way to do that than to look at what we can't see? When jets lose energy to quark-gluon plasma it reveals information about how the substances interact. Currently, quark-gluon plasma can only exist on the order of femtoseconds. So, one of the best ways to study it is through its manipulations of jets.

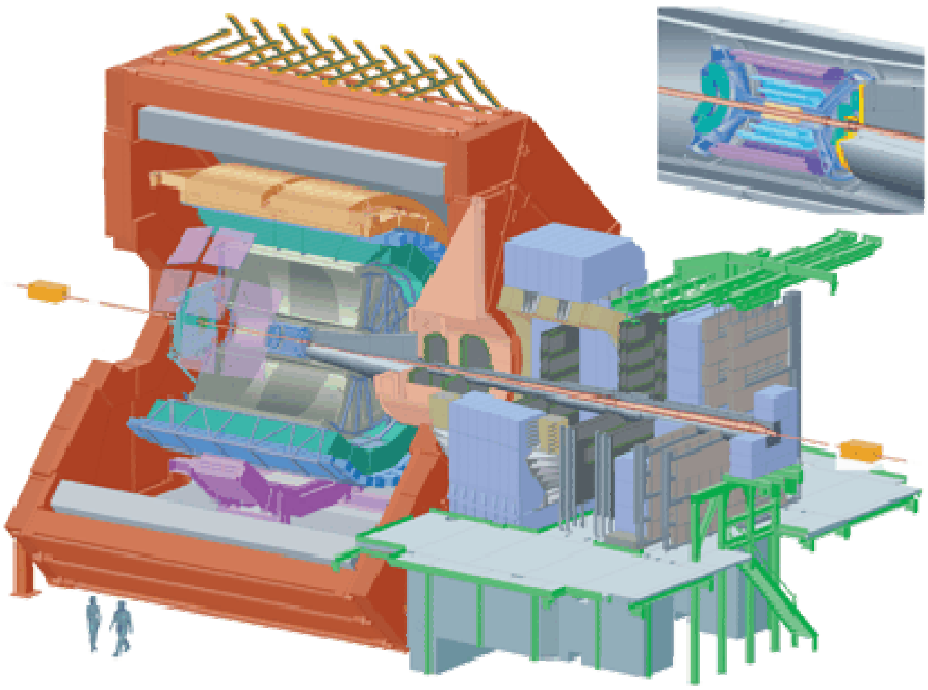

Figure 6: A visual of the ALICE detector.
Source: http://aliweb.cern.ch/secure/system/files/images/alice-images/ALICE-SetUp-2008.gif

ALICE, seen in Figure 1 and 6, is composed of many different sub-detectors designed to measure the particles produced in the collisions in different ways. Three basic classes of detector are tracking detectors, such as the time projection chamber (TPC), the transition radiation detector (TRD) and the inner tracking system (ITS), calorimeters, such as the electromagnetic calorimeter (EMCAL), and specialty detectors such as the time of flight detector (TOF), designed primarily to identify particles. My work is directly associated with the EMCAL, but uses information from the other detectors as well.

The two defining kinematic variables with ALICE data are azimuthal angle, □ (phi) and pseudorapidity, η (eta). Eta is a measure of the velocity or momentum in the beam direction and is a function of the polar angle θ (theta) from the axis that runs through the beam pipe. It is equal to $-ln(tan(\theta/2))$ and is preferred over linear momentum or velocity due to relativistic effects on the particle trajectories. Phi is measured from the horizontal axis while viewing the beam pipe from the open end of ALICE.

The EMCal data is organized in energy clusters corresponding to the energy deposited by a particle in the detector at a given eta and phi. The tracking detector data can also be selected for eta and phi so that tracks can be matched to EMCal clusters to distinguish electrons from photons. Electrons are charged particles so they leave a trail in the TPC, whereas photons are neutral and only deposit energy in the EMCal unless they convert to electron positron pairs.

AliEn

Most people with coding experience have worked with data on a local machine; this is impractical for any work with CERN. Small amounts of data can be loaded on to a local machine to test coding errors. However, to extract meaningful results from an analysis multiple petabytes (1 petabyte = 1 million gigabytes) are required.

AliEn or “ALICE Environment” is a solution to this problem. AliEn is a grid framework that utilizes supercomputing centers all over the globe to analyze the full dataset with code written by a physicist. In order to analyze the data, I wrote algorithms and tested them locally before passing them to the AliEn gridware to process on ALICE data. There are computing centers all over Europe, North America and Asia. Figure 7 shows the vast array of computing centers just in Europe. My particular code was being processed by Japan, Germany and California all at the same time!

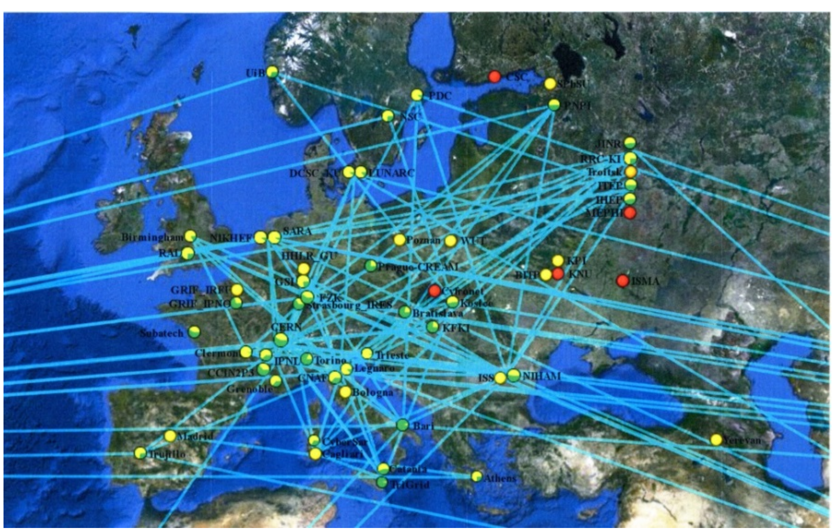

Figure 7: A map of the European computing centers for CERN.
Source: http://niham.nipne.ro/images/monalisa_2030.jpg

Jet Finding Algorithms

FastJet is a highly efficient jet-finding algorithm developed by experts to make extracting the jet signals from high energy collisions easier. As the name suggests FastJet is a fast implementation of multiple recombination algorithms. FastJet's speed is one the key reasons for its wide use. The algorithm takes the data and selectively gathers particle signals into pseudo jets. Along with unheard of speed, it gives the user tools to calculate jet area and it subtracts the background. It even allows the user to access jet substructure [7]. It has already been demonstrated to work with ALICE p-p collision data at 2.76 TeV. Figure 8 shows the inclusive jet spectrum compared to a variety of theoretical predictions published by ALICE. [2]

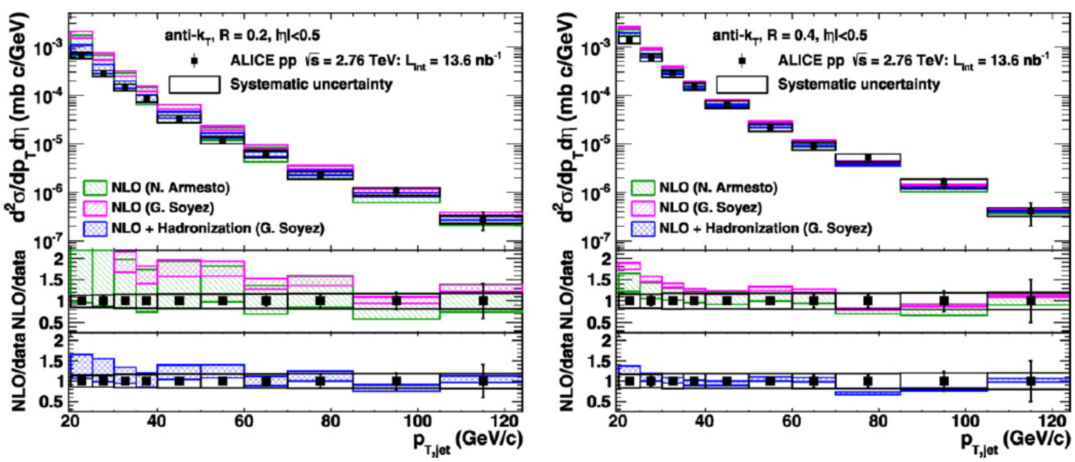

Fig. 3. Upper panels: inclusive differential jet cross sections for $R = 0.2$ (left) and $R = 0.4$ (right). Vertical bars show the statistical error, while boxes show the systematic uncertainty (Table 2). The bands show the NLO pQCD calculations discussed in the text [11,12]. Lower panels: ratio of NLO pQCD calculations to data. Data points are placed at the center of each bin.

Figure 8: Experimental results plotted with three theoretical predictions. [2]

The kt and anti-kt algorithms are available within FastJet to allow one to either collect data that is correlated in momentum (kt) or anti-correlated (anti-kt). By playing these algorithms against each other one can get a better picture of the jets. The kt and anti-kt algorithms are typically favored by theorists and are becoming more popular among experimentalists due to their implementation in FastJet. Before FastJet it was very impractical to run kt and akt due to their large computational load.

For this project our goal was to use the FastJet code implemented for ALICE by the graduate student who produced the ALICE publication on the 2.76 TeV jets.

Jet Investigations

Before blindly proceeding with the analysis tools given to me by CERN, I investigated their attributes to better understand how they work and to identify possible bias. The simplest jet selection method is to define the highest momentum particle in a collision as the center of the "trigger" jet. The remaining particles are then plotted by their angular distance from that trigger. In a collision with back-to-back (momentum conserving) jets, there should be a peak around the trigger particle and another peak 180 degrees away.

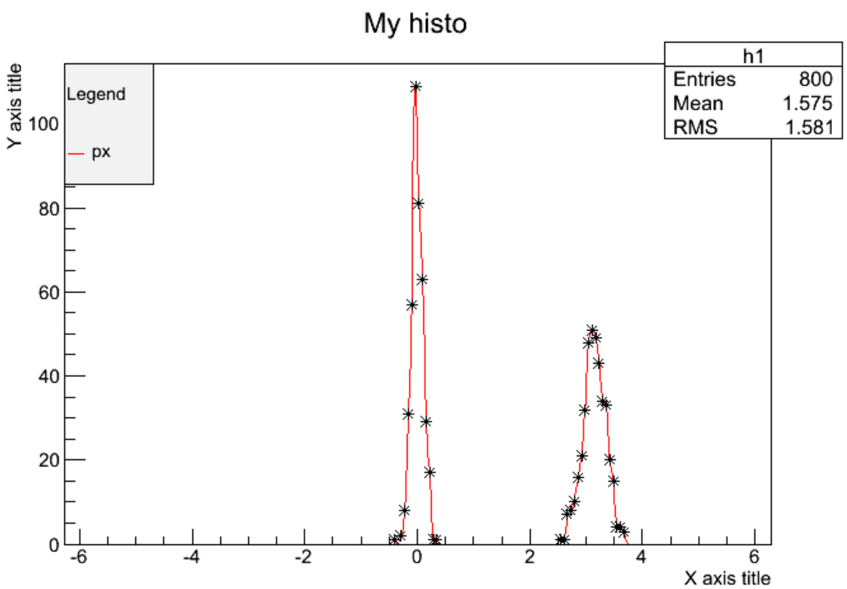

Figure 9: Two peaks from a dijet fragmentation. The x axis is the azimuthal angle difference Δ□ between the trigger particle at □=0 and other particles in the event.

Figure 9 shows a standard plot of a di-jet using simulated data. It may seem that there is a discrepancy from what we might expect. A jet should conserve momentum. However, the two peaks are not symmetrical. What happened? If the energy distributed in the particles on the "away" side of the trigger is distributed differently from the "near" side, the jet will be wider and shorter. In addition, the particles selected for correlation with the trigger particle are subject to a transverse momentum cut to reduce background noise. Just by choosing the highest momentum particle to be the center of the trigger jet, bias is established. Things are more complicated when the jets are embedded in a QGP. The trigger jet prefers those jets produced near the surface, leaving the away side jet to bore through the plasma and lose energy further (see Figure 5). If there is a high momentum particle on the away side, it is likely to lose energy interacting with quark-gluon plasma and not be seen. This is why it is critical to use full jet-finding techniques such as FastJet to avoid the trigger bias of techniques such as azimuthal angle correlations.

Here is the code that was used to generate the simulation and superimpose two transverse jets. The aim is to identify potential biases in the analysis. The software loads some ALICE data from the event tree stored in a file and loops over the events to create histograms of the azimuthal angle correlations like those shown in Figure 9.

```
TFile * file = TFile::Open(fname);
TTree * tree = (TTree*)file->Get("esdTree");

AliESDEvent * esd = new AliESDEvent(); // The signal ESD object is put here
esd->ReadFromTree(tree);

Int_t nev = tree->GetEntries();
for (Int_t iev=0; iev<nev; iev++) { //EVENTS

tree->GetEntry(iev); // Get ESD
Int_t ntrk = esd->GetNumberOfTracks();

for(Int_t irec=0; irec<ntrk; irec++) { //PARTICLES
AliESDtrack * track = esd->GetTrack(irec);
histo4->Fill(x); // fills trigger phi values

for(Int_t irec=0; irec<ntrk; irec++) { //phi0-phi
u = y - track->Phi(); // delta phi
if (u > 0)     { // IF DELTA PHI > 0, PI CHANGER
                    v = u/(2*3.14);
                    w = floor(v);
                    u = u-w*2*3.14;
               }

if (u < 0)    { // IF DELTA PHI < 0, PI CHANGER
                    v= u/(2*3.14);
```

```
                w = floor(v);
                u = u-w*2*3.14;
            }
    histo2->Fill(u); // delta phi
    }
    x = 0; // reset max momentum
    y = 0; // reset max phi
    }

    }
    file->Close();
```

Photon Conversion Contamination

The initial construction of ALICE was complicated by volatile budget constraints. Due to the high cost of an electromagnetic calorimeter (EMCAL), ALICE decided to forego building the detector. The ITS, TPC, TRD and TOF detectors were added and for most of the design and construction period ALICE was planned and built without an EMCAL. However, in the first year of the 21st century, a group of institutions in the United States proposed building the much needed EMCAL. After several years, the ALICE-USA collaboration convinced the U.S. Department of Energy's Office of Science to fund the EMCAL.

ALICE had not anticipated the EMCAL during construction which led to various issues with the EMCAL's design, implementation and functionality. The space constraints meant that only a portion of the full azimuthal angle could be instrumented. Additionally, the EMCAL was installed further from the beam pipe than would be ideal. Several detectors and their support structures lie between the EMCAL and the beam pipe. The increase in material gives rise to a multitude of physics and software issues. One specific issue is photon contamination, which will be discussed in greater detail later in this paper. Due to the spatial and budget constraints the hardware is not as optimized as it could have been. It was hoped that the deficiencies in hardware could be compensated for in software. Unfortunately, software can only do so much. It was my goal to help compensate for hardware design constraints with clever software.

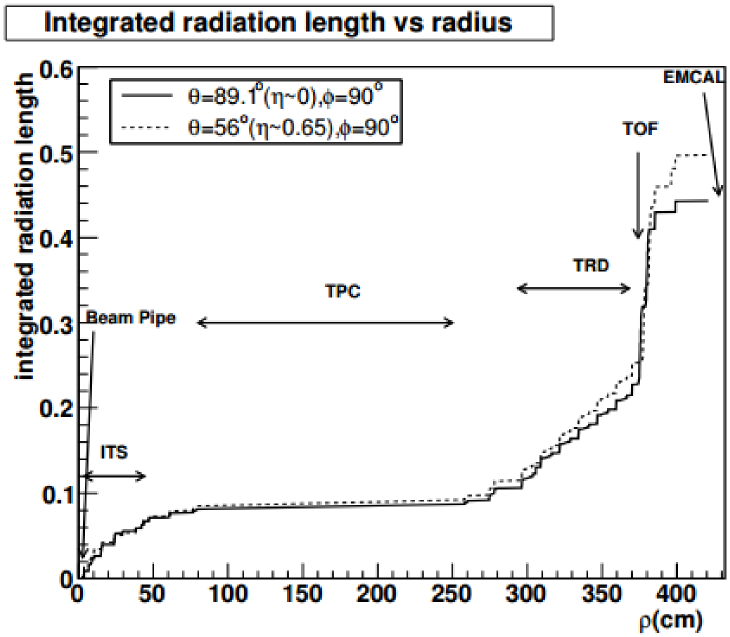

Figure 10: Photon conversion vs. distance from beam pipe.
Source: nucl-ex/1008.0413

Figure 10 illustrates the issue of photon conversion for the TOF and EMCAL detectors. Integrated radiation length is plotted on the y axis as a function of radial distance from the beam pipe. The radiation length is a measure of the probability of photons interacting with material. At approximately 375cm from the beam pipe, nearly half of all photons have undergone pair production through interaction. Under ideal circumstances the TOF and EMCAL detectors would have been built differently to reduce the amount of material ("material budget") in the way. However, they are not moving anytime soon. So, it is up to the software specialists to tackle this problem.

A majority of my work was centered on the issue of photon contamination in the electromagnetic calorimeter. High energy photons can be the catalyst in a phenomenon called pair production. Energy from the photon is converted into mass as an electron and a positron. A positron is the antimatter equivalent of an electron so the reaction conserves charge.

An isolated photon, regardless of energy, cannot cause pair production. It needs an interaction with some material to pair produce. The lower limit of photon energy that can convert is 1.22 MeV, which would leave just enough energy to create the masses of the e+/- pair with 0.511 MeV for each particle. This must hold in all frames; consider a 5 GeV photon. If it interacts with a heavy nucleus with high charge (and therefore large electromagnetic field) the interaction can induce pair production. The e+/- pair carries away the energy of the photon and the recoiling nucleus absorbs the momentum difference.

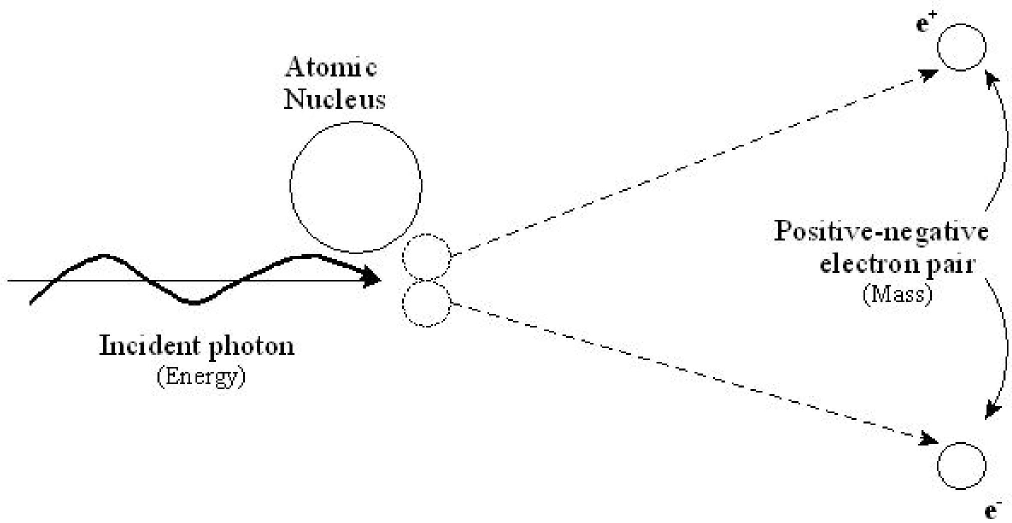

Figure 11: High energy photon pair production
Source: http://ryuc.info/images/pair_production.JPG

Late pair production, seen in figure 11, can corrupt ALICE data. A photon is uncharged; therefore it will pass through the tracking chamber undetected. The tracking chamber uses a particle's electric charge to determine the path of that particle. If the high energy photon decays into a positron and an electron outside of the tracking chamber the electromagnetic calorimeter will record two hits without a corresponding matched track in the TPC instead of a single photon hit. This discrepancy will flaw the data. It was our goal to determine the frequency of these events to determine if it was making a significant impact on the results.

We had to analyze the EMCAL cluster locations that were not matched to a track and try to correlate them with hits in the TOF detector. In order to determine if the questionable cluster is a resultant from pair production, we must determine where and when the clusters occurred.

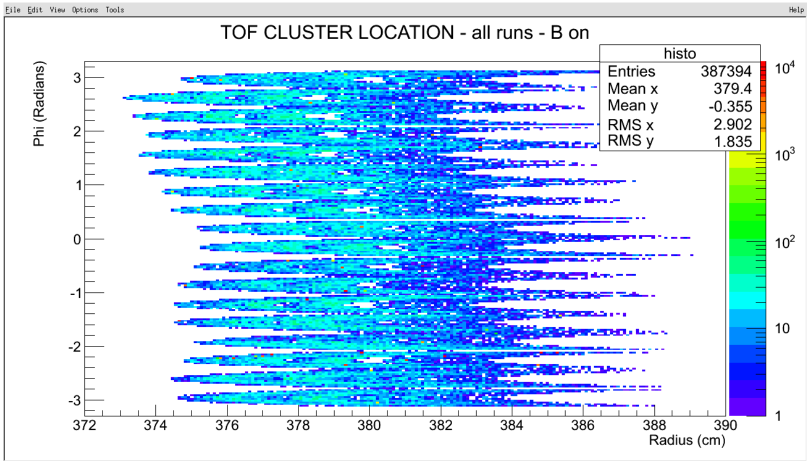

Figure 12: TOF clusters with B field plotted by phi angle in radians vs. radius.

Compared to the EMCAL, the TOF is comprised of larger detector elements that encompass the entire beam pipe. The EMCAL spans from approximately 1.27 radians to 3.14 radians, roughly 110 degrees in phi. Figures 12 and 13 show the TOF cluster locations for two different running conditions – with magnetic field on and off. The sinusoidal patterns in the data illustrate the different cells in the TOF detector. The color corresponds to the number of hits in a particular location. The runs without a magnetic field have more statistics.

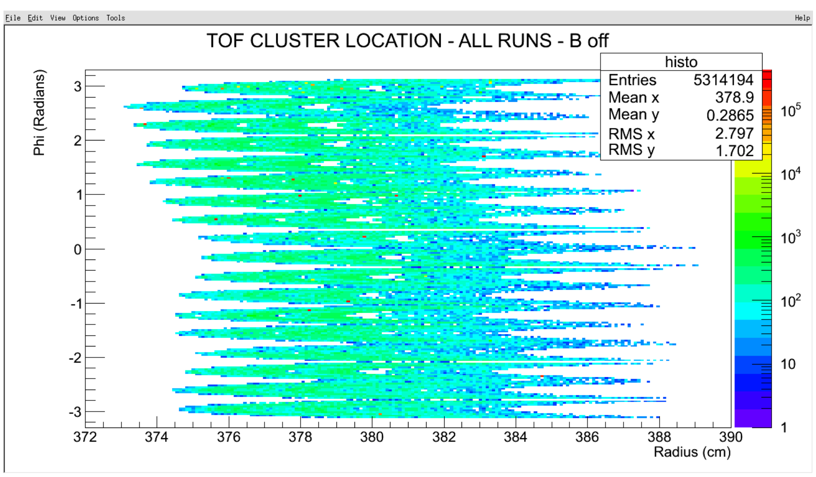

Figure 13: TOF clusters without B field plotted by phi angle in radians vs. radius.

There are two issues to consider when matching TOF clusters to EMCAL clusters: location of pair production and the energy of the particle. The matching of TOF and EMCAL clusters is ongoing and further results will be produced by a subsequent student researcher.

Conclusion

The goal of this project was to analyze ALICE proton-proton collision data to try to extract the inclusive jet spectrum at 7 TeV. In working toward that goal, we investigated the bias in simple jet finding algorithms and explored the techniques used in highly efficient jet finders such as FastJet. We also helped develop algorithms to correct for photon conversion contamination in the EMCAL so that more reliable jet finding results could be produced. Work on finding and correcting for pair production is ongoing. I made significant progress towards identifying TOF clusters. These clusters can be matched with EMCAL clusters to determine the impact of the material on the photon signal in the EMCAL.

Innate human curiosity has always driven the scientific process. However, advances in physics have also produced technological innovation. Of the many innovations to come from CERN's investigation of the Standard Model of particle physics, perhaps the most well-known is the implementation of the World Wide Web. The original purpose of the web was to quickly share data among CERN's scientists. However, now we all benefit from this technology.

My work with CERN has been a rewarding intellectual pursuit. Our innate curiosity has brought nearly every developed nation into collaboration. Working with scientists from different origins, cultures and backgrounds on the same problem is truly humbling.

References

1. "ALICE Collaboration." *ALICE Collaboration*. N.p., n.d. Web. 21 Mar. 2014. <http://aliweb.cern.ch/>.

2. B. Abelev, et al., ALICE Collaboration, "Measurement of the inclusive differential jet cross section in pp collisions at sqrt{s} = 2.76 TeV", Physics Letters B, Volume 722, Issues 4–5, 24 May 2013, Pages 262-272, ISSN 0370-2693, 10.1016/j.physletb.2013.04.026

3. Bellwied, R. et al., ALICE EMCal Collaboration, "ALICE EMCal Physics Performance Report", arXiv:1008.0413 [physics.ins-det]

4. "CERN Accelerating Science." *The Higgs Boson*. N.p., n.d. Web. 12 Mar. 2014. <http://home.web.cern.ch/topics/higgs-boson>.

5. "CERN Accelerating Science." *The Large Hadron Collider*. N.p., n.d. Web. 021 Mar. 2014. <http://home.web.cern.ch/topics/large-hadron-collider>.

6. "CERN Accelerating Science." *The Standard Model*. N.p., n.d. Web. 21 Mar. 2014. <http://home.web.cern.ch/about/physics/standard-model>.

7. "FastJet." *FastJet*. N.p., n.d. Web. 12 Mar. 2014. <http://fastjet.fr/>.

8. "Grid Sites Monitoring Map - ALICE Grid Monitoring with MonALISA." *Grid Sites Monitoring Map - ALICE Grid Monitoring with MonALISA*. N.p., n.d. Web. 21 Mar. 2014. <http://alimonitor.cern.ch/map.jsp>.

9. "Jets at Hadron Colliders (1/3)." *Indico*. N.p., n.d. Web. 21 Mar. 2014. <http://indico.cern.ch/event/115078/>.

10. Ma, R., and P. M. Jacobs. *Analysis Note: Measurement of the Inclusive Differential Jet Cross Section in Pp Collisions at Sqrt(s) = 2.76 TeV*. CERN-PH-EP-ALICE-2012, 12 Mar. 2013. Web.