Heavy Ion Physics for Dummies

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1 Foreword

This note is made by summer students who worked in HI group in summer 2017 and did various projects. Everything is written by them with our absolutely minor participation.

Sasha, Zvi, Petr, Mirta, Anna, Yakov.

2 Introduction

This is a short introduction to Heavy Ion Physics Lab at Weizmann Institute of Science. It was written by students for students with the purpose of paving the way to those who know nothing about or very little of about this subject. During our stay at Weizmann Institute, we worked on data collected by ATLAS detector. In particular, Alessandro worked on Long-range correlations in Z tagged *pp* collisions at 8 TeV, under the supervision of Prof. Milov; Kushagra studied the Evaluation of charged Hadron Spectra for *p-Pb* collisions at 8 TeV under the supervision of Dr. Balek, while Jovan worked on measuring the Z boson to di-electron cross section for *pp* collisions and compared those results to previously obtained results for *p-Pb* collisions in order to calculate the nuclear modification factor, under the supervision of Mirta Dumančić. We hope you will enjoy this manual and this lab at least as much as we did in our visit.

Contents

3 Heavy Ion Physics Overview

If you decide to study in this lab, you may now wonder what Heavy Ion Physics is all about. Let's start from the beginning. Heavy Ion Physics is interested in studying what happens when two particles collide, i.e. smash one another. These collisions are produced in several colliders all around the World, the biggest among them is the LHC (Large Hadron Collider) at CERN, Geneva, Switzerland. At the moment, our group is analyzing the data collected by the ATLAS Detector. We can collide many different types of particles, for example proton with another proton (*pp* collisions), proton with lead (*p-Pb* collisions) and lead with lead (*Pb-Pb* collisions). It's very likely that each kind of collision will have a very different outcome, but as a rule of thumb you might expect a large shower of many different product particles (leptons, bosons and hadrons). However there is one thing we really care about in Heavy Ion Physics :

The Quark Gluon Plasma (QGP)

Therefore we will focus on it from the very beginning. Then we will discuss how detectors and accelerators work and how ROOT relates to Heavy Ion Physics. Now buckle up and let the journey begin!

4 What's the hottest thing in the universe you can think of?

As you can guess, the answer is QGP. It's temperature is million times more than the temperature at the center of the Sun. In QGP, quarks and gluons become deconfined and make a hot dense medium. But in nature, they interact with each other via *Strong Interaction.* At the time of writing, only four kind of physics interactions have been discovered and investigated in details. These interactions are:

- Gravitational interaction
- Electromagnetic interaction
- Strong Interaction
- Weak Interaction

The theory that describes the strong interaction is now known as Quantum Chromodynamics (QCD). QCD has gluons as spin 1 gauge bosons that mediate the force between quarks. It is modeled based on the simpler theory, Quantum Electrodynamics (QED), which describes electromagnetism. QCD explains two important properties of the strong interaction. At high energies, the interaction is less, and quarks and gluons don't interact much. (Asymptotic Freedom); at low energy the interaction becomes strong and leads to the confinement of color. Because of Asymptotic Freedom, QCD expects that at high temperatures, for which the typical thermal energies of quarks and gluons are large and thus the interactions become weak, ordinary matter made of hadrons undergoes a phase transition to a plasma of quarks and gluons, the quark-gluon plasma.

QGP can be created under either high temperature or high density. As a result we expect QGP was? created in the early Universe, at the center of compact stars and in the initial stage of colliding heavy nuclei at high energies. The last possibility can be experimentally controlled and studied in heavy ion accelerators. High-energy collisions of heavy ions provide an invaluable tool to study puzzles of quark confinement and symmetry breaking in QCD.

5 What's a Jet?

As already mentioned above when we collide particles we can get many different outcomes. Among those jets is one possibility. By looking at Fig.2 you can see that there is a large amount of energy carried by particles in a very localized cone-shaped region of space. That's a jet. Actually Fig.2 displays an event with two back-to-back jets.

What's so special about jets? Some says that when you see a jet you should make a wish, however, since we are physicist we might be interested in measurable quantities. The presence of jets implies a very large transfer of momentum and by momentum conservation we expect to find something as much energetic

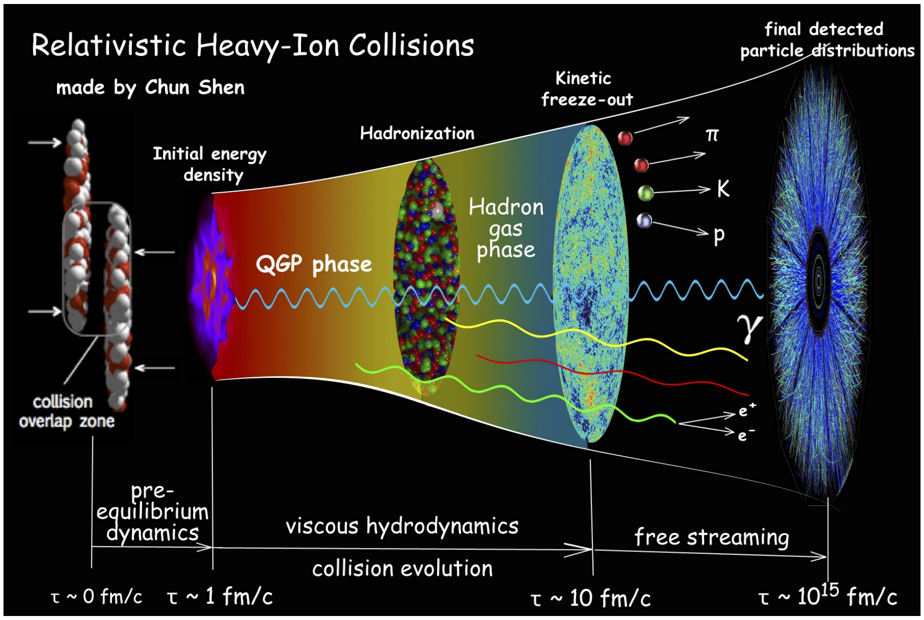

Figure 1: A figure showing the time evolution of an Heavy Ion collision. At approximately $1\frac{fm}{c}$ the hunted QGP phase is produced.

on the other side, for example a Z boson (with a invariant mass around 90 GeV) decaying into two leptons. This is very good place to introduce a very interesting topic : Soft and Hard Processes or Scatterings.
There is no dictionary definition for what is soft and what is hard in Heavy Ion Physics, however I'll try to give to you a general rule of thumb. A hard process is an *"event"* in which there is a large transfer of momentum or energy. Generally speaking this events are also pretty rare, so you will recognize it when you will see one!

6 Some Basics You Really Need To Know

Although this is mainly an experimental lab, all in all we thought you might still be interested in some fundamental basics of this subject and that's why we created this section. We are going to briefly review some of the key concepts in the theory of Heavy Ion physics, such that once you read the following you are going to be able to expand your knowledge by yourself.

6.1 Transverse Momentum a.k.a. p_T

As you may already know, particles inside LHC travels through a tunnel of 27 km of circumference. Their speed is approximately 99.999999 % of the speed

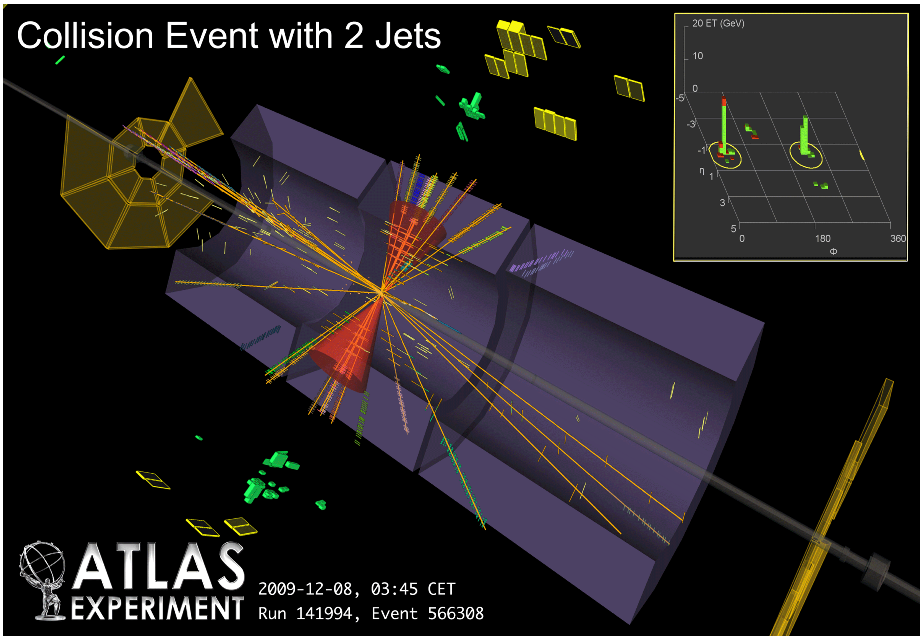

Figure 2: A collision inside the ATLAS detector where the outcome are two back-to-back jets (in red) and other particles. In the top right corner a plot shows the distribution of particles in the $\eta - \phi$ space.

of light, going in circle 11'000 times before the collision. All of this implies a large amount of momentum to be conserved. As you can see from Fig.3 the two particles travel on what is called beamline of the collider. This is actually the z-axis of our coordinate system (Sec.7). Before the collision there is no momentum on any other axis apart from the z-axis, hence all the extra momentum, perpendicular to z, produced on the impact must be conserved and therefore sum up to zero. The momentum perpendicular to the z-axis is often referred as *transverse momentum* a.k.a p_T. In Fig.3 this is represented by the the yellow tracks left by the particles traveling inside the detector.

6.2 Rapidity and Pseudo-Rapidity

As already mentioned in Sec. 6.1, particles travel almost at the speed of light, which means that studying the system with Newtonian Mechanics would not work. In fact, we need to introduce some special quantities which will allow us to study the particles inside the detector.

If you have already met the Theory of Special relativity, you may already know that velocities do not add linearly but they follow *the relativistic compo-*

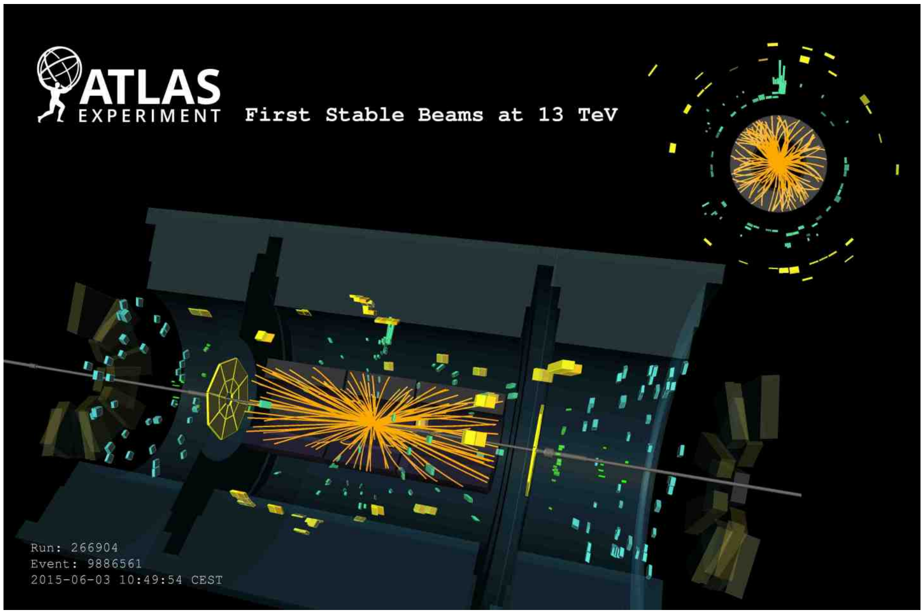

Figure 3: A picture from ATLAS detector during the First Stable Beams collision at 13 TeV. The lines in orange represents the tracks generated by the product particles after the collision. The yellow and green boxes represent the different detectors activated when a particle is detected. In the top right corner the cross-section of the detector is reproduced.

sition of velocities, i.e. :

$$u = \frac{v + u'}{1 + (\frac{vu'}{c^2})}$$

However, working with this formula makes everything much more cumbersome and that's why we want to introduce a quantity which can be added linearly, that is *the rapidity*. This is defined as : *"the hyperbolic angle that differentiates two frames of reference in relative motion, each frame being associated with distance and time coordinates"*. In mathematical terms this becomes:

$$y = \frac{1}{2} \ln \frac{E + p_T c}{E - p_T c}$$

where E is the energy of the particles and p_T is the transverse momentum (Sec. 6.1). The underlying reason for the presence of hyperbolic angles and therefore of the natural log is that a Lorentz boost can be represented as follow :

$$\begin{pmatrix} ct' \\ x \end{pmatrix} = \begin{pmatrix} \cosh y & \sinh y \\ \sinh y & \cosh y \end{pmatrix} \begin{pmatrix} ct \\ x \end{pmatrix}$$

where y is the rapidity.

Another quantity of interest, closely related to the rapidity, is the pseudo-rapidity or η. It is defined as :

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Here θ is the angle between the z-axis and the particle 3-momentum. η often replaces rapidity, in fact, if the mass of the particle is very small or, equivalently, the particle is traveling close to the speed of light, its $E \approx p$ and therefore $\eta \approx y$.

6.3 Vertices on the z-axis

Part of the job of those who study experimental particle physics is to reconstruct the measured tracks with the particles' original locations on the z-axis. Let's have a look at Fig.4! On a first stage, the particles collides along the beamline and from these locations sprays of other particles are ejected. These product particles fly inside the detector's calorimeters and their arrival position is recorded. However since only the last position is known is necessary to back-engineer the process and find the original location on the z-axis, which is called *z vertex*.

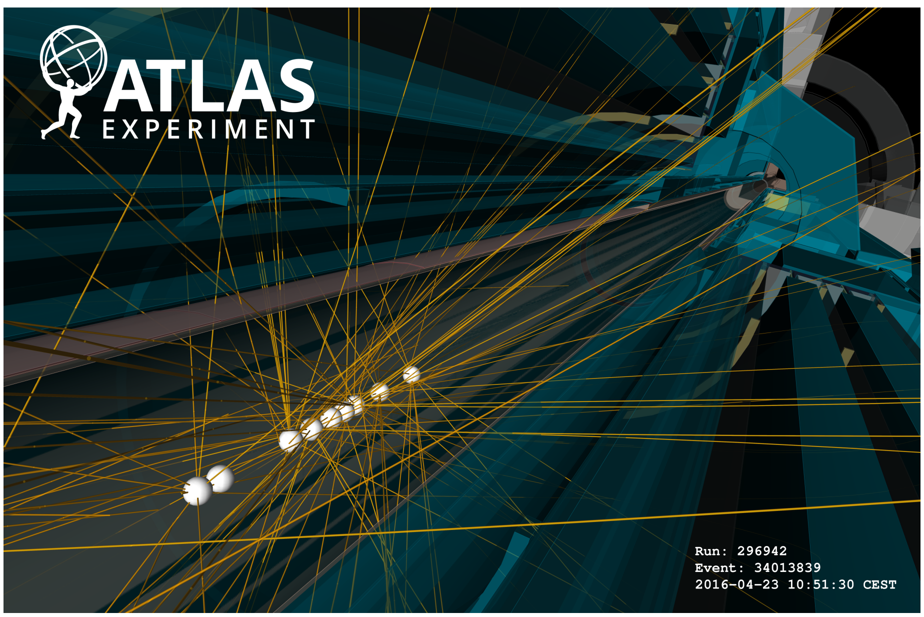

Figure 4: Vertices lie on the beamline, or z-axis of the detector, and from them any other particles in the collision is emitted. The yellow lines represents the tracks of the products particles while the white sphere are their z vertices.

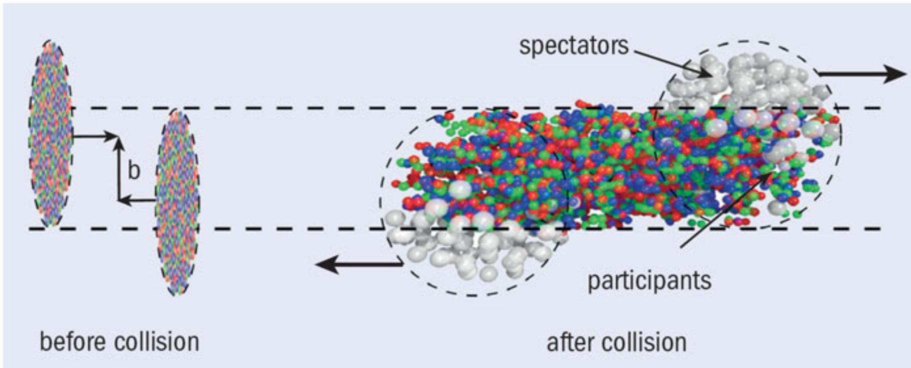

Figure 5: An illustration showing the collision of two Heavy Ions with the presence of participants and spectators particles.

6.4 Centrality

Centrality gives a measure of the "head-on-ness" of our collision. In fact different centralities can produce very different outcomes in particle production. In fact we can approximate colliding particles as a bag of nucleons and depending what fraction of these bags collide, a different number of nucleons will participate in the event. Therefore, as shown in Fig.5, we can distinguish two different categories of particles :

- Participants: Those are the particles which really take part in the collision.
- Spectators : All the other particles which are not directly involved in the impact.

7 Accelerators and Detectors

Generally, detectors follows right-handed coordinate system. The z-axis is the beam axis where particles collide. We measure positions of particles using polar angle θ and azimuthal angle ϕ. Can you think why don't we measure position of particles in Cartesian coordinates?
More on detectors in the appendix. Also check out fig. 6 and 7.

8 ROOT and Heavy Ion Physics

We went over the various features of the detectors and the accelerator, of how particles are produced and what quantity we can measure when we detect them, however, we have never really discussed how we are going to study our data once we record it. Here is where ROOT comes in handy. ROOT Framework is based on very widespread programming language, C++, therefore it supports any

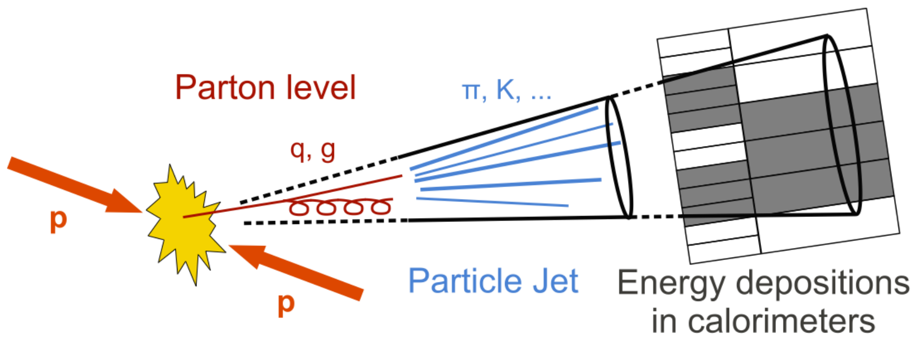

Figure 6: A schematic diagram of a collision and a jet being detected by calorimeter.

of its data structure and code. If you do not have ROOT installed on your computer, don't worry, you can find some reference guides at the end of this manual which will help you going through the process. We will now go over some basics principle of ROOT which will ease your learning process.

8.1 Histograms

The natural visual language of particle physics, in particular Heavy Ion Physics, is the language of Histograms. I will assume that you already know what is an histogram and, in case you don't, you can find many resources online which you can read in the privacy and comfort of your home.
What's the big deal about histograms? Imagine you have a large amount of data, which in our case can either be the raw data coming from the detector or the outcome data we have processed already, that you want a store and analyze. If you decide to use histograms for your goal then this will allow you to see pattern which you could not discover, mainly because the amount of entries you want to record is of the order of 10^6. Histograms allows you also to apply some algebraic structures, for example you can add, subtract and divide histograms. Generally speaking, this is done by ROOT bin by bin, therefore, in order to successfully perform the operation, you will need to have two histograms with the same features, i.e. same number of bins and same axis range. The main histograms libraries in ROOT are `TH1` and `TH2` for 1-D and 2-D histograms respectively. These libraries also include more specific histograms such as `TH1D` histograms with variable bins of type double) and `TH1F(` histograms with fix bins of type float). In case you were wondering, yes, ROOT allows you to fit function with your data and this is generally done by the Fit command, e.g. `histo.Fit("name of the fit")`.

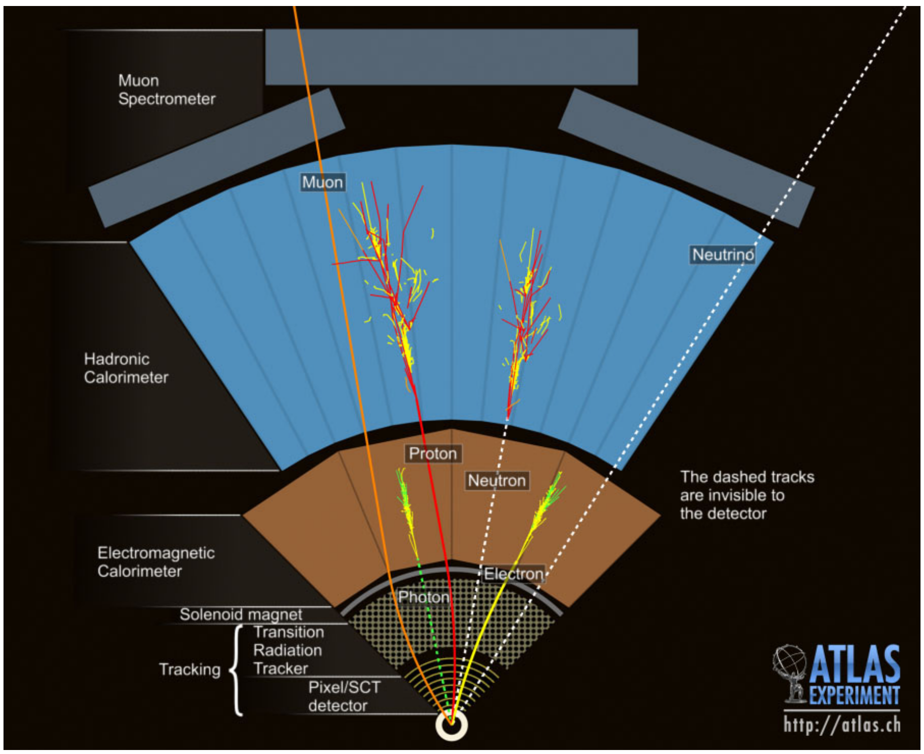

Figure 7: Part of a transverse cross section of the ATLAS detector.

8.2 Plotmanship

Once your data is stored in the histograms it can be plotted by using some libraries available in ROOT such as `TLatex`, `TGraph` and `TCanvas`. A good plotmanship is fundamental to deliver the message you desire hence, you need to spend time on this part of your analysis. Sometimes it might be useful to change the axis range or to rebin your histograms to highlight some hidden features, but it all depends on what you are plotting. Eventually you want to show your results and discuss them either with your supervisor or with some other scientist, hence here is a list of things you should never forget when you produce your plots:

- Each axis needs a label
- The main features of your plot must be clearly visible
- Your axis range must be clearly visible
- Do not plot too much white space
- Do not suppress zero coordinates unless strictly required
- Be careful when using *log* scale
- Include a meaningful legend if necessary

Plotmanship is as important as the data your plot contains, therefore you really should take care of it.

9 Our Projects

The authors of this manual are three student who participated in the Kupcinet-Getz Science Summer School at Weizmann Institute. We were accepted in the Heavy Ion Physics group which guided us throughout our summer projects.

9.1 Alessandro's Project

Alessandro studied Long-range correlations in Z tagged pp collision at 8 TeV during his stay at WIS. While short range correlations allow us to study the mechanisms behind the production of particles, long-range correlations focus on the system of particles as whole. Mathematically speaking this mean that we are interested for $|\Delta\eta|$ in the range of $[2;5]$. The raw data for this project consisted in direct events, which in turn were made of signal and background events, as explained by the following equation.

$$\text{Direct events} = \text{Background events} + \text{Signal events}$$

Usually we would like to clean the Direct events from the Background events in order to find the Signal events. However, since we are studying correlations between particles, things get much more complicated than that, in fact the equation we need to use becomes the following:

$$D * D = S * S - D * M + (M) * (M) - M * M$$

where D represents the direct events, S the signal events and M the mixed events, in fact in this case the background was reproduced by using a Mixed events technique. The big issue with this project is that a large amount of data, including files and histograms, have to be produced and systematically stored, therefore a clear strategy was necessary since the very beginning.

9.2 Kushagra's Project

Kushagra evaluated the charged hadron spectra of p+Pb collisions at 8 TeV recorded with the ATLAS detector in Nov-Dec, 2016. These were the *first* real results of the aforementioned experiment. His task was to combine data from various triggers (Jet, MinBias) and produce a spectra. As a check, he also studied distance of a track from a jet in $\eta - \phi$ space and also plotted ratio of matched tracks (to jets) to all tracks and confirmed that at high p_T all tracks are matched to jets. By comparing p+Pb spectra relative to p+p we can study about QGP since production of hadrons is modified in heavy ion collisions as compared to pp collisions because of energy loss in the hot medium. This would also give us an insight about the initial state effects of the Pb+Pb system.

9.3 Jovan's Project

Jovan studied the production of Z bosons in the di-electron decay channel (decay to an electron and a positron) in *pp* collisions at $\sqrt{s} = 5.02$ TeV which is measured with the ATLAS detector. Studying this decay is useful because the Z boson and electron don't interact with the QGP, so by investigating them we get a better picture of what happened right after the particle collisions. The reason why we don't examine just the Z boson is because it's half-life is too short, so the particle decays before it reaches the detector. The results from *pp* collisions are compared to the previously measured data in the *p-Pb* collisions system at the same energy. Information on the nuclear modification factor R_{pPb}, for Z bosons in *p-Pb* collisions is extracted from the comparison.

10 Appendix

This section was created to gather all the references and all the sources useful to expand your knowledge about Relativistic Heavy Ion Physics and ROOT Framework.

10.1 ROOT references

How to install ROOT on Mac
How to install ROOT on Linux

A beginner's ROOT guide
ROOT users guide
ROOT primer
ROOT workshop 2016 (Nevis)

10.2 Heavy Ion Physics

A short course on Relativistic Heavy Ion Collisions
Chapter 4 of this book

10.3 Accelerators and Detectors

Accelerators and Detectors