JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE INTEREST PROGRAMME

Generation and Analysis of Events for pPb Collisions Using the Monte-Carlo Generator: Therminator2

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Abstract

The collision of heavy ions can help us understand how the universe has been created after the occurrence of Big Bang. Using Therminator2 event generator software we can make a simulation for heavy ions collisions like proton-lead, lead-lead and gold-gold nuclei, depending on previous data obtained by accelerating and colliding ions as in the LHC and RHIC which leads to releasing of particles like pions and kaons at different centrality. In this project analyzed for proton-lead collision at 5.02 Tev depending on data from LHC. We get the correlation function for K^+K^+ and K^-K^- pairs.

Acknowledgement

I would like to express my pleasure working with Mr. Krystian Roslon my supervisor and thanking him too much for his valuable assistance, time and help through the whole program period. I want also to express my gratitude for the INTEREST project team for giving me this great opportunity of learning and gaining new experience.

Contents

1 Introduction

High Energy Physics is the branch of physics that cares about the collision of nuclei at high energies reaching to 13 Tev in the Large Hadron Collider (LHC) at CERN. The main purpose for heavy ions acceleration at the LHC and at Relativistic Heavy Ion Collider (RHIC) is to study Quark-Gluon Plasma (QGP) resulting from heavy nuclei collision.

Quark gluon plasma can be created in form of droplets having low viscosity through ultra-relativistic nuclei collisions [1]. Analyzing these particles that result from heavy ions collision represents a promising way to understand QGP and our universe evolution, in addition to recognizing the dynamics of formation of matter. So it is generally considered that acceleration and collision of these nuclei is a simulation or regeneration for the same events that happened around 14 billion years ago, for sure this helps in discovering the secrets of the early universe.

After about 10^{-5} second of the Big Bang, protons, neutrons and electrons have taken place in the universe. Protons and neutrons are formed by quarks that are strongly coherent via colour force explained by Quantum Chromodynamic (QCD) theory and mediated by gluons. One second after the Big Bang and at a lower temperature, the formation of atoms started by combined protons and neutrons, and electrons [2, 3].

As theoretical models propose that there is a transition from initial hadronic gas phase to QGP phase [4] according to the following phase diagram [3]. This transition can occur at net baryon density and temperatures of approximately 1 GeV/fm and 150 MeV respectively.

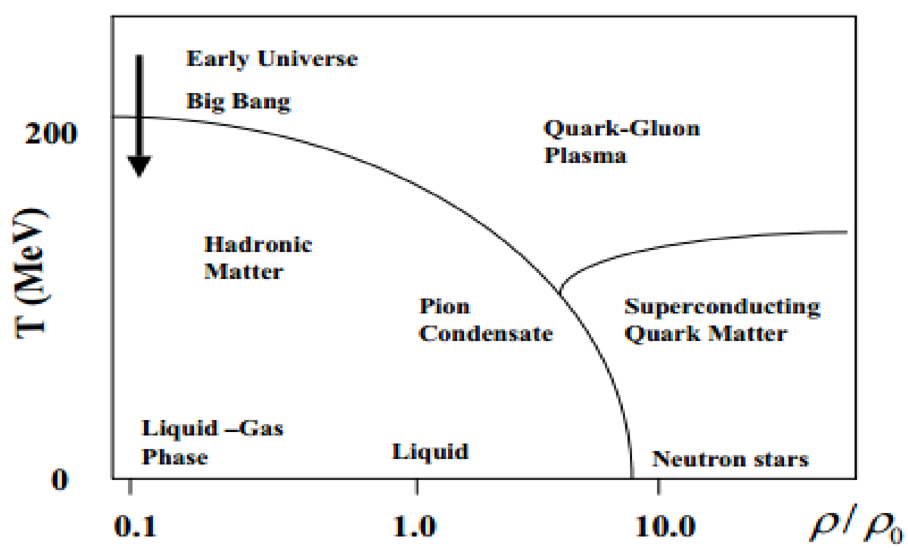

Figure 1: Phase Diagram of the Strong Interacting Matter

1.1 Heavy Ions Collisions

Heavy ions collision enables us to study the behaviour of matter under high density and pressure. At free collision of nuclei, there is no creation of new particles, as they must have the threshold value of energy ranging from small values of Mev to Tev for production of new particles. As the energy of collided particles increase, the number of particles and anti-particles produced will increase too.

Collision type can be classified due to the value of the energy of collided ions. Intermediate heavy ions collision has range of 10 - 100 Mev, while relativistic has a range of 100 Mev - 10 Gev and ultra-relativistic that starts from 10 Gev and upper, at 10 Gev the formation of QGP is possible [2].

The collision evolution of heavy ions is time-scaled as the following figure shows by passing with four stages [1, 5]. Starting from the left which is the initial state before the collision at -5 femtometres/C (as C is the speed of light and is equal to 1 in this case), then we will transfer to collision process in the second stage which is called pre-equilibrium. After that, there will be a hydrodynamic evolution in the third stage due to the collision. Finally, the freezeout stage has some specific conditions that could be related to the thermodynamics of QCD [6].

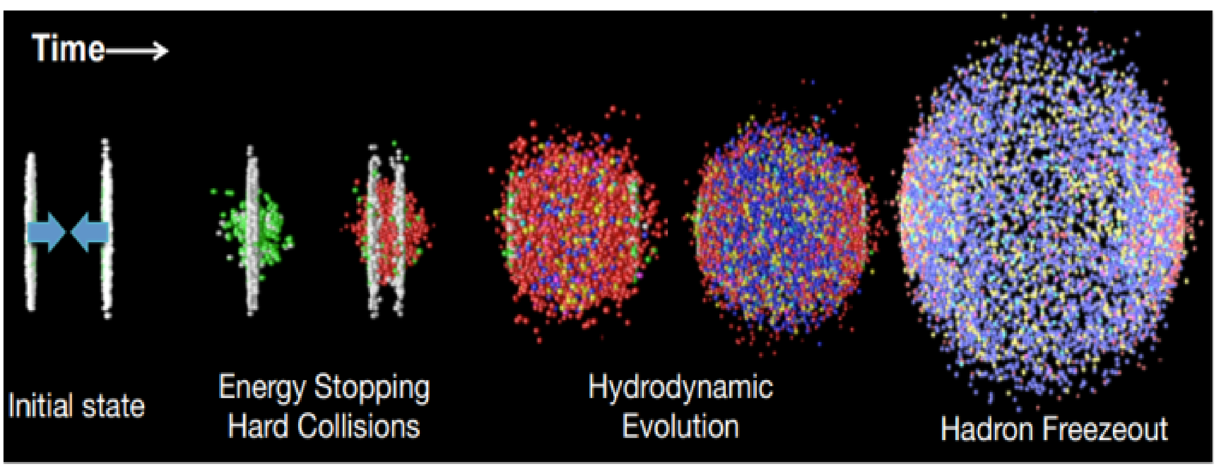

Figure 2: Evolution of heavy ions collision [7]

1.2 Experimental System

A Large Ion Collider Experiment (ALICE) [8] is a detector at the LHC used for studying the formation of quark-gluon plasma. In this part of LHC, the hadrons resulting from a nucleus-nucleus collision like Pb-Pb and p-Pb are studied.

1.2.1 Setup

ALICE detector weighs about 1×10^7 kilograms and has a length of 26 meters, the height of 16 meters and width of 16 meters.

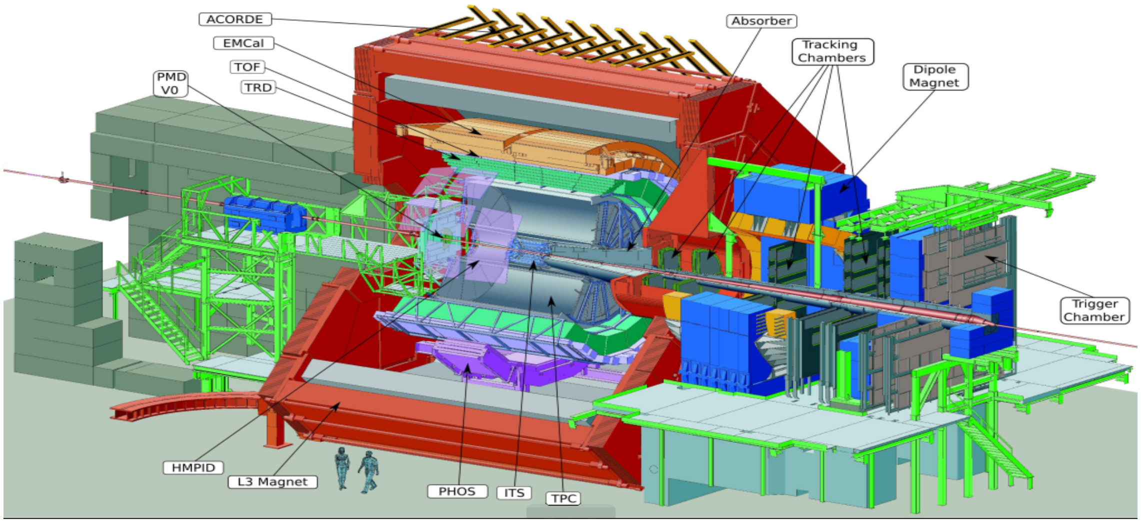

Figure 3: Alice Schematic Diagram

1.2.2 Detector Function and Mechanism

The Detector of ALICE could be divided into three main stages as following [8, 9]:

1. **Tracking Stage**
   The detectors are manufactured from sensitive materials which have the ability to interact with charged particles resulted from the collision. Each charged particle produces an electrical signal that gives information about the charged particle type. The motion of particles and interaction with the detector can be reconstructed using software by collecting these recorded paths of charged particles together.

2. **Calorimeters Stage**
   Calorimeters composed of denser materials like solid-lead glass and argon in its liquid state. They are responsible for particle's losses calibration when they passing through it. Calorimeters can suck the largest number of particles and direct it to deposit all of their energy in the detector.
   There are two types of calorimeters:
   Hadronic: measure the energy of hadronic matter due to their interaction with nuclei.
   Electromagnetic: measure the energy of lighter particles like electrons and photons due to their electrical interaction with charged particles.

3. **Identification of Particles Stage**
   These particle identifiers are used for the increment of the detection accuracy. As the charged particle moves with a specific velocity which calculated angle of Cherenkov radiation released by the particle motion, depending on its velocity which is related to its momentum, the particle mass could be then calculated and it will be easily recognized from its mass.

1.3 Previous Analysis

There is a variety of heavy ions collisions that have been carried out for different nuclei and at different scales of energy using particles accelerators like LHC and RHIC, that used for understanding QCD phase diagram and to study QGP. As shown in the following figures this is a reconstruction of particles created due to the collision of heavy nuclei:

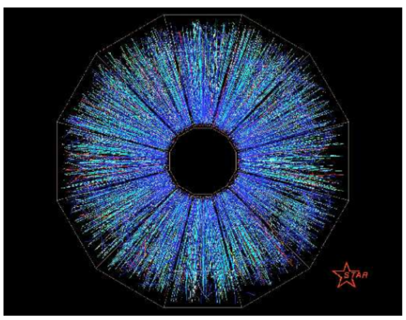

Figure 4: View of Au-Au Collision at Star Experiment

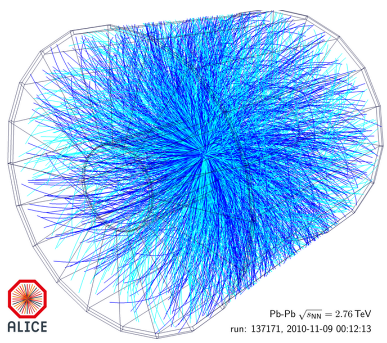

Figure 5: View of Pb-Pb Collision at Alice Experiment

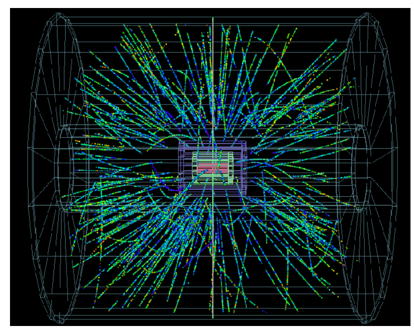

Figure 6: View of p-Pb Collision at Alice Experiment

For proton-lead collision at ALICE [8, 10, 11, 12], it is studied at different centre of mass-energy per nucleons' masses to understand the state of matter at hotter and denser conditions. These are two original papers published by CERN researchers about proton-lead collision at Alice:

1. $\sqrt{snn} = 5.02$ in 2012, to obtain the charged-particle pseudorapidity density for 4 units of pseudorapidity through non single-difractive of p–Pb.

2. $\sqrt{snn} = 5.02$, to measure the transverse momentum of charged particles through non single-difractive of p–Pb.

2 THERMINATOR2

Therminator2 stands for "**THERM**al Heavy **I**o**N** Gener**ATOR**, which is a software program that used for various events generation by the collision of heavy ions like Au and Pb using Mone-Carlo simulation, and depending on previous data from different colliders like the **Large Hadron Collider** (LHC), **Super Proton Synchrotron** (SPS) at CERN, and **Relativistic Heavy Ion Collider** (RHIC) at the USA. It should be mentioned that the only available and latest version of it can be downloaded from theminator2 software main site page [13].

2.1 System Requirements

For making analysis using therminator2, there are some needed requirements for the software to be used like having a linux operating system and CERN ROOT Package. In my case, I used Linux Ubuntu of version 18.04 along with ROOT 6.20 version.

2.2 Setup and Configuration

There is an important manual that has been written by containing all information about the therminator2, in addition to there are two papers about Therminator and Therminator2

2.2.1 Technical Issue in Current Version

The last version of therminator2 was in 2011, that may cause some problems through installing process as we now use more advanced Linux operating systems than the past.
It is important to update this version through following the root terminal instructions at the time of the setup process. This could be made by editing some commands in the latest version's files like **therm2_events.cxx** and **Parser.cxx** in the build folder, using a C++ programming language which is the main language that therminator2 was written in.

2.2.2 Steps of Installing

Based on the manual I have mentioned before. The following steps show how we could install the software correctly:

1. Download Therminator2 from its main site or the edited version using this link.
2. Write in the LINUX terminal the directory of downloaded Therminator2 folder using the cd command, then use the command "make" to compile the program.
3. Follow other steps in the manual to configure that it now works in a correct way.

2.2.3 Configuration

For running the first event, we can use "./runall.sh" or "./therm2_events", which will give us a root file for Au-Au collision.

It is possible to change the centrality and type of nuclei that will collide through the following steps:

1. Open **fomodel** folder in **Therminator2**, then open **lhyquid2dbi** folder.
2. Select the file that you need to run events for and copy the full name of the file.
3. Open **lhyquid2dbi.ini** file in **fomodel** folder and replace the .xml file with the name of the copied file in **line 42**.
4. Use "./runall.sh" or "./therm2_events" to run the new event.

After doing the above steps, there will be a new folder having the same name of xml file we chose directly generated in events folder in Therminator2. In this file, there will be an event***.root file generate at each time we use "./therm2_events" command for the same particles and centrality.

The number of events in one root file generated could be changed from **line 55** in **events.ini** file in **Therminator2**. It is recommended to generate more root files reaching to a whole number of events of 20000 or upper, to use "./therm2_femto" command.

Thanks to Mr. Krystian Roslon, I used for this project already prepared root files for pPb collision at the LHC with energy of 5.02 Tev and centrality of 0-3.4% .

3 Results and Discussion

In this part I will discuss the analysis made after obtaining root files containing events of proton-lead collision. To get the correlation function for kaon pair, firstly the pair type in line 32 at femto.ini file should be changed from pion-pion to kaon-koan. Then I had more than 500 folder containing about 4000 event.root files which must be combined together in one file to use "./therm2_femto" command. There was a problem of emerging all this number root files and renaming them by order from 1 to 4000 to mix particles, with help of Mr. Roslon, the solution was by editing part of "Read event*.root files", line 704 at "therm2_femto.cxx" file in "build/src" folder as following:

```
for(int i=1; i<tEventFiles; i++) {for(int k=0; k<10; k++)
{char Buff[kFileNameMaxChar];
sprintf(Buff,"%slhyquid3v-LHCpPb5020s0.5Ti242t0.60Tf150e%03i/event%03i.root"
,sEventDir.Data(),i,k); PRINT_DEBUG_1("Adding file:"« Buff); chn->Add(Buff);
chnEv->Add(Buff);}}
```

Using "./therm2_femto" command in the following form "./therm2_femto <1> <directory of events files> <number of files=500>" then by pressing enter I got a file called "femtokaka1a.root", that contains all information about K-K pairs resulting after collision.

3.1 Root File Histograms

Now to get the correlation function we transfer to "femtokaka1a.root". It can be opened using command "root femtokaka1a.root" after writing the full directory of the root file using "cd+folder name" in the terminal. After is activated, using "new TBrowser" command we can see various histograms named: cnuma, cdena, num1d, den1d, hbetat and hkt, but we will focus on the third and forth ones, the numerator and denominator histograms shown below.

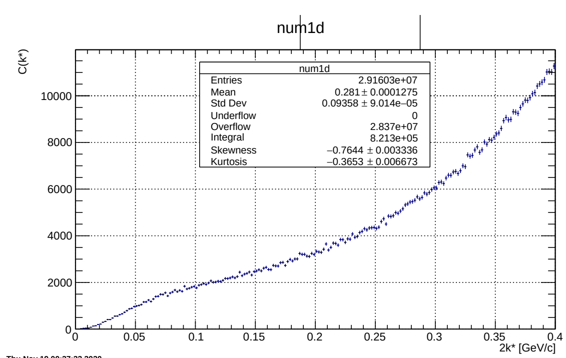

Figure 7: The numerator

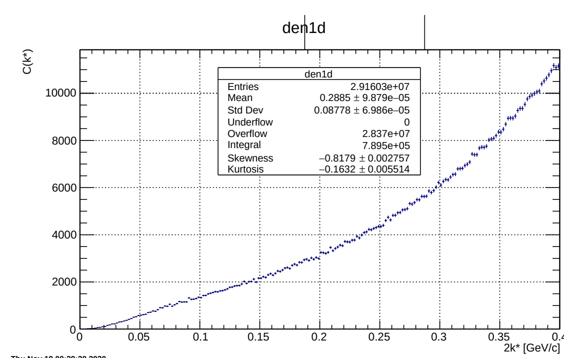

Figure 8: The denumerator

4 Correlation Function

4.1 Kaon-Kaon Pair Correlation

We can get the correlation function by dividing the numerator and denominator histograms, this can be made using ROOT analysis by writing a simple C++ compiler for dividing num1d to den1d. I will be like "therm2_hbfit.cxx" file. By constructing a "Correlation Function.cpp" file and copying lines 29-43 in "therm2_hbfit.cxx" file besides the following code:

```
TFile* tInRootFile;
TH1D* numq;
TH1D* denq;
TH1D* ratq;
void Correlation Function()
{ tInRootFile = new TFile("path of femtokaka1a.root file");
numq = new TH1D(*((TH1D *) tInRootFile->Get("num1d")));
denq = new TH1D(*((TH1D *) tInRootFile->Get("den1d")));
ratq = new TH1D(*numq);
ratq->Reset("ICE");
ratq->Divide(numq, denq, 1.0, 1.0);
ratq->SetName("Correlation Fucntion of KK");
ratq->SetTitle("Correlation Fucntion of KK");
ratq->Draw(); }
```

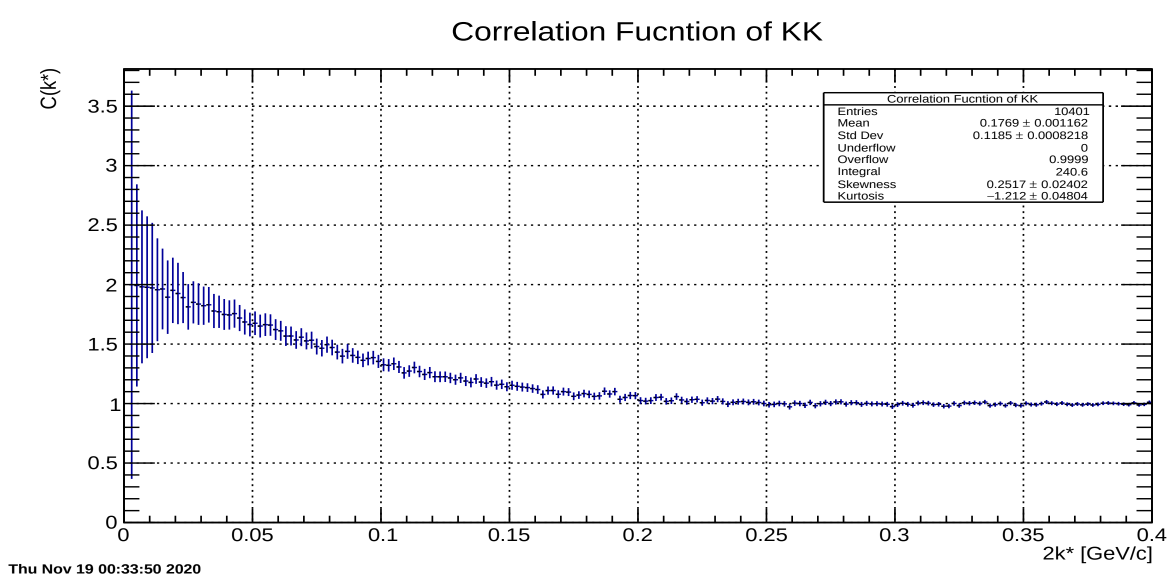

Figure 9: Correlation Function for Kaon-Kaon Pair

4.2 Kaon Femtoscopy Correlation Function

The correlation function is symbolized by $C(\overrightarrow{k^*})$ and as a probabilistic function, it gives an indication of how particles are packed with each others in therms of the distance between their centers. The correlation function of two identical particles is calculated by relation (29) in the manual of therminator2 [13]. For approximation, considering one kaon is surrounded by another group of kaons, in this case the correlation function could express the density of kaons at specific volume.

Assuming there are two particles P_1 and P_2, their correlation is given by the following equation [14]:

$$C(p_1, p_2) = \frac{\mathcal{P}(p_1, p_2)}{\mathcal{P}(p_1)\mathcal{P}(p_2)} \tag{1}$$

Where $\mathcal{P}(p_1)$ and $\mathcal{P}(p_2)$ are the distribution functions for one particle each in the space of rapidity and transverse momentum. $\mathcal{P}(p_1, p_2)$ is two particles distribution.

Relating the results with theoretical calculations, figure (7) representing the numerator of equation (1), while figure (8) is denominator of the same equation. So, to get the correlation function representation we divide the numerator to the denominator that leads to figure (9), the horizontal axis represents the transverse momentum for two kaons, on the other hand vertical axis is for the correlation of the same particles.

5 Conclusion

In conclusion, through the period of this project: first of all, we had a problem with the therminator2 current version and using some commands of C++ programming language like "using namespace std;" we had overcome this setup issue. The second task was knowing some functions of the software starting from choosing the model for the collision, changing the number of events needed in one root file, besides how collision is made using .xml files obtained from previous collisions made at CERN and RICH and I learned how to use therminator2 software for events generation of different nucleus-nucleus and proton-nucleus collisions. The third task was getting the correlation function's histogram for Kaon-Kaon pair based on some basics of ROOT package.

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