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 MC generator - Therminator 2

Supervisor:
Mr. Krystian Roslon

Student:
Harshit Choudhary, Delhi Technological University

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ABSTRACT

High Energy nuclear physics deals with the behavior of particles at very energy regimes. The main focus is the study of heavy-ion collisions. The collisions of heavy-ions produce conditions that are reminiscent of the moments after the Big-Bang and also the conditions inside high energy dense nuclear star cores. This high energy state is known as Quark Gluon Plasma (QGP). Studying the QGP with appropriate femtoscopic tools, we can learn a lot about the origins of the universe. We used a Monte-Carlo event generator called THERMINATOR2 to generate these high energy heavy-ion collisions and also analyze them to get femtoscopic correlation function.

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1. INTRODUCTION

1.1 HIGH ENERGY PHYSICS

Traditionally nuclear physics deals with the energy in the domains of order $\varepsilon \sim 0.15$ GeV/fm^3 [1], whereas high energy nuclear physics deals with energy densities of many orders of magnitude higher. Such high energy levels can be achieved via colliding accelerated heavy ions and studying them. Collisions of such magnitude are carried on at two colliders around the world, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) in Upton, New York and Large Hadron Collider at the France-Switzerland border near Geneva.

Both of these particle colliders have carried out various collisions of heavy ions and the aftermath is studied extensively. It has been found out that after the collision, the intra-nuclear particles of the ions like protons and neutrons split up into their constituents and the resulting plasma consists of Quarks and Gluons and is called Quark Gluon Plasma (QGP). This is what is believed to be the conditions that might have existed during the moments after the Big-Bang and is also found in cores of neutron stars. This condition can be imagined as a hot soup of free Quarks and Gluons floating like Plasma governed by the Laws of Hydrodynamics. The QGP is considered to be the primary area of interest when studying about the high energy nuclear physics.

1.1.1 Quark Gluon Plasma (QGP)

In the 1970's it was studied through deep inelastic electron collisions on protons that showed that nucleons are made up of quarks and gluons.[3] The corresponding field theory which explains these quanta is the Quantum Chromodynamics (QCD). This theory suggests that since these particles are strongly bound to each other and thus cannot be studied individually. A quantum number called "color" represents this strong tie. In the physical world all observable particles are colorless, however at high energy densities and temperatures these strong ties among quarks and gluons becomes weak and the colored objects propagate long distances. This is supposed to be the situation in the early universe as well. Heavy ion collisions with the energy in the order of 10-100 A.GeV can also produce QGP for a very small amount of time. These conditions can then be studied by different methods of analysis; one of them is called Femtoscopic Correlation. Different accelerators study the various domains of the QGP to get a better understanding of the early universe.

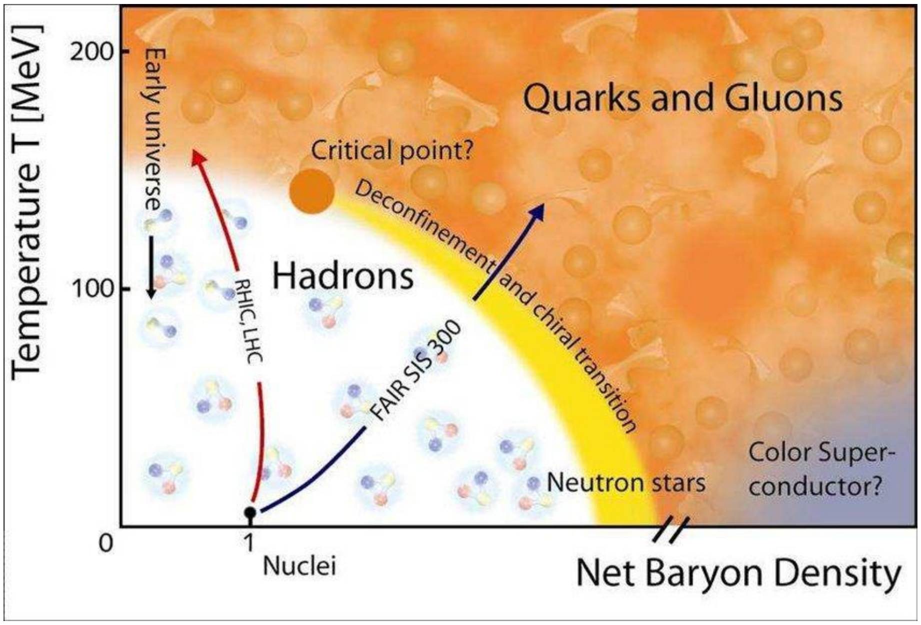

Figure 1: QGP Phase Diagram

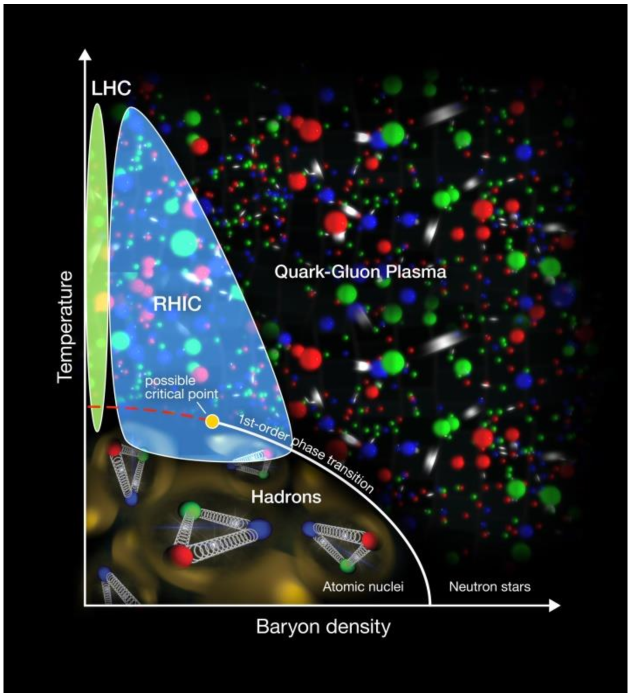

Figure 2: Regions of QGP studied by Heavy Ion Colliders

1.1.2 RHIC and LHC Heavy Ion Collision Results

The Relativistic Heavy Ion Collider (RHIC) aims to study the lower energy domains of the phase diagram; its counterpart the Large Hadron Collider studies the collisions at much higher energy densities. Since QGP produces anti-quarks, experiments at RHIC were able to isolate and characterize nuclei up to anti helium [4]. The data is inferred via the detectors in these colliders, the most prominent being the STAR detector at RHIC along with the PHENIX, PHOBOS and BRAHMS, the latter 3 have completed their operation and the STAR is the only operational detector. STAR is aimed at detection of hadrons and also investigates the proton scattering as a part of additional experiment called PP2PP [5]. Some of important results from RHIC are [9] –

- Elliptical Flow Study
- Study of energy reduction in jets of elementary particles (Jet quenching)
- Analysis of color glass condensate
- The discovery of QGP in 2005

The Large Hadron Collider (LHC) has a huge energy advantage, a factor of 10 over RHIC and was able to carry out measurements with better precision [6]. The experiments at LHC, namely ALICE,ATLAS,CMS,LHCb [7] had excellent vertexing, tracking, particle identification. A major discovery from the LHC experiments is that the particles are not only made of three quarks or one quark-antiquark pair, but there are tetra-, penta- and even hexa-quark states [8]. The discovery of force carrier of Higgs field, the Higgs boson was also made at the LHC in 2012 and subsequently led to Physics Nobel Prize in 2013 [9].

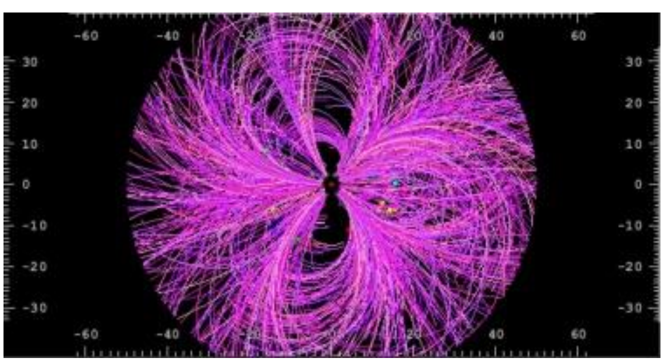

Figure 3: Gold Ion Collisions at RHIC

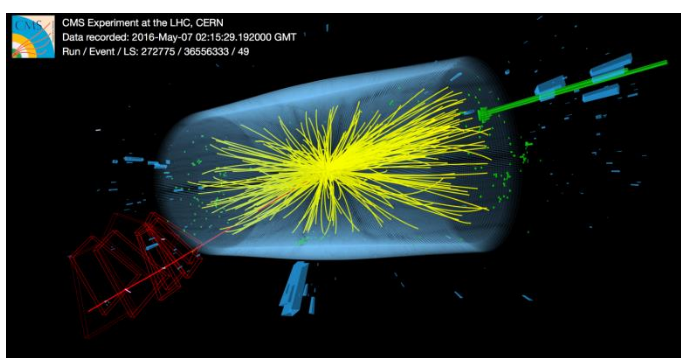

Figure 4: CMS Experiment at LHC

1.2 FEMTOSCOPIC CORRELATION FUNCTION

The femtoscopic correlation function is a probabilistic function which determines how closely the particles are packed in the QGP. The correlation function for two identical particles is given by equation (29) in THERMINATOR2 manual [11].

The correlation function of two particles $p1$ and $p2$ can be given by the following equation

$$C(p1, p2) = \frac{\mathcal{P}(p1, p2)}{\mathcal{P}(p1)\,\mathcal{P}(p2)} \tag{1}$$

Where $\mathcal{P}(p1, p2)$ is the two particle distribution function and $\mathcal{P}(p1)$, $\mathcal{P}(p2)$ are individual distribution functions for each particle.

2. THERMINATOR2

THERMINATOR2 is a Monte Carlo event generator used for generation and analysis of heavy ion collisions. It's written in C++ and uses the CERN ROOT environment [11]. This generator can model many relativistic heavy ion collisions from various experiments conducted at colliders like RHIC and LHC. THERMINATOR2 can work on many freeze out profiles including 2+1 and 3+1 dimensional profiles with near perfect hydrodynamics. The standard package includes a library with hypersurface profiles from Au-Au collisions at RHIC and the Pb-Pb collisions at LHC.

A separate part of THERMINATOR2 package includes the tools for femtoscopic analysis of events called FEMTO-THERMINATOR. This part of code can help us carry out analysis of correlation function of HBT radii of the generated events among other auxiliary results.

2.1 INSTALLATION

The current version of THERMINATOR2 is 2.0.3 which is compatible up to Linux Ubuntu 18.04. The Linux versions after Ubuntu 18.04 are not supported by current THERMINATOR release. The CERN ROOT package can be installed from its official website [12] and the required packages are also to be installed, all of which are specified on the website. The THERMINATOR2 package has some errors which have to be corrected and the corrected package can be accessed in the terminal. Accessing the THERMINATOR2 folder in the terminal and using the **./make** command we can start the compilation and installation. A test run can be run using **./runsall.sh.**

2.2 GENERATION OF EVENTS

After accessing the THERMINATOR2 folder we can generate the events by changing the parameters in the **therm2_events.cxx** file. Here we can choose the type of particles, energy and the centrality at which they collide. The number of collisions can be altered in the **NumberofEvents** parameter in **events.ini** file [11]. After setting up the parameters we can run the **./therm2_events** command in the terminal inside the THERMINATOR2 folder. The time taken to generate events varies according to the type of particles chosen and the centrality of the collision, peripheral collisions will take longer to generate than head on collisions. The generated data is stored as a ROOT file in the events folder in THERMINATOR2.

2.3 ANALYSIS OF GENERATED EVENTS

The THERMINATOR2 package includes a femtoscopic analysis tool called therm2_femto which can be used to calculate the femtoscopic correlation function of the acquired data. After opening the terminal and entering the THERMINTAOR2 folder we have to run the **./therm2_femto** command. This runs the FEMTO_THERMINATOR according to the conditions specified in the **femto.ini** file in THERMINATOR2 folder. The available particles for analysis are Kaons (κ) and Pions (π). After running the femtoscopic analysis the program outputs a ROOT file in the events folder. A root macro available in the THERMINATOR2 can be used to generate transverse-momenta spectra of π^+, κ^+ and protons. The command line for the root macro is [11] –

root -x './macro/figure_distpt.C("./events/ lhyquid2dbi-RHICAuAu200c2030Ti455ti025Tf145/",n)'

Where, n is the number of root files to be analyzed.

3. RESULTS AND DISCUSSIONS

The events generated for this project are **pPb-pPb collisions at 60-70% centrality in the energy range of 5.5 GeV.** The number of events generated is 5,000 and the process took 2 hours and 45 minutes for every 500 events generated. The process took longer due to the collisions being peripheral but it is recommended to generate more than 50,000 events for more stable results.

3.1 CALCULATION OF CORRELATION FUNCTION

The ROOT file obtained after running the therm2_femto command can be opened in the ROOT environment using the **new TBrowser** command and we can view the numerator and denominator of the correlation function as seen in Equation(1). The numerator and denominator graphs are labeled as **num1d** and **den1d** respectively. The correlation function can be obtained by dividing the num1d by den1d, this can be achieved by creating a .cpp file which will carry out the division and give the correlation function as the output. First we need to construct a "Correlation Function.cpp" file and then copy the lines 29-43 in **therm2_hbt.cxx** file along with the following code [13] –

```
TFile* tInRootFile;

TH1D* numq;

TH1D* denq;

TH1D* ratq;

void Correlation Function()

{ tInRootFile = new TFile("path of femtopipi0a.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 PiPi");

ratq->SetTitle("Correlation Fucntion of PiPi");

ratq->Draw(); }
```

Running this file in ROOT environment we can get our ROOT file which contains the correlation function.

Here are the corresponding num1d, den1d and it's correlation function for the π-π collisions.

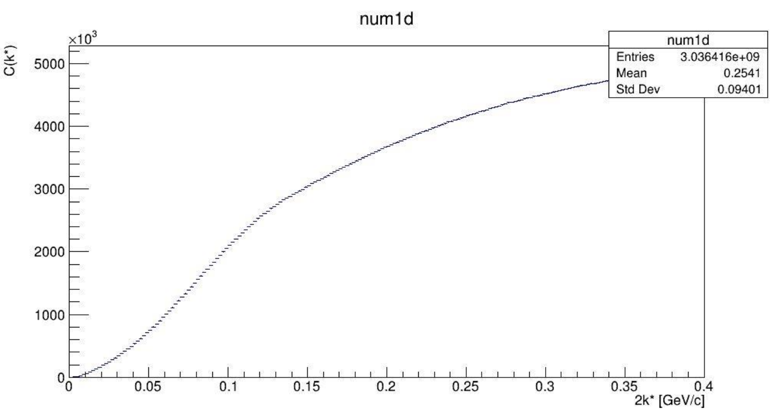

Figure 6.1: Numerator of Correlation Function

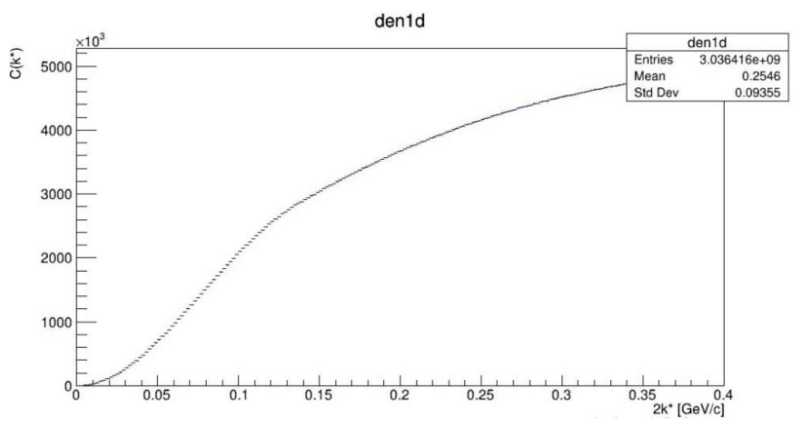

Figure 5.2: Denominator of Correlation Function

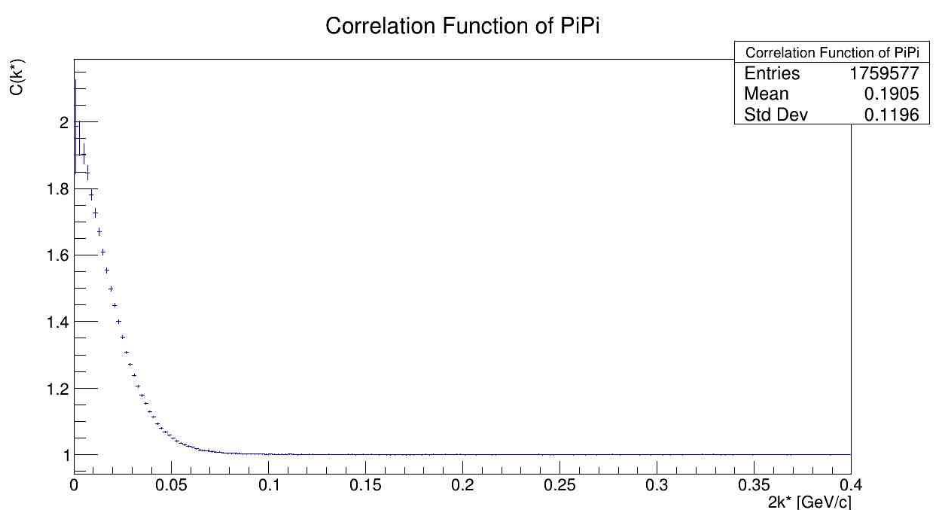

Figure 7: Correlation function for π-π particles

3.2 TRANSVERSE MOMENTUM SPECTRA OF π^+, κ^+, AND PROTONS

The transverse momentum spectra also known as p_T spectra obtained from the ROOT macro clearly shows the particle density at various energy levels.

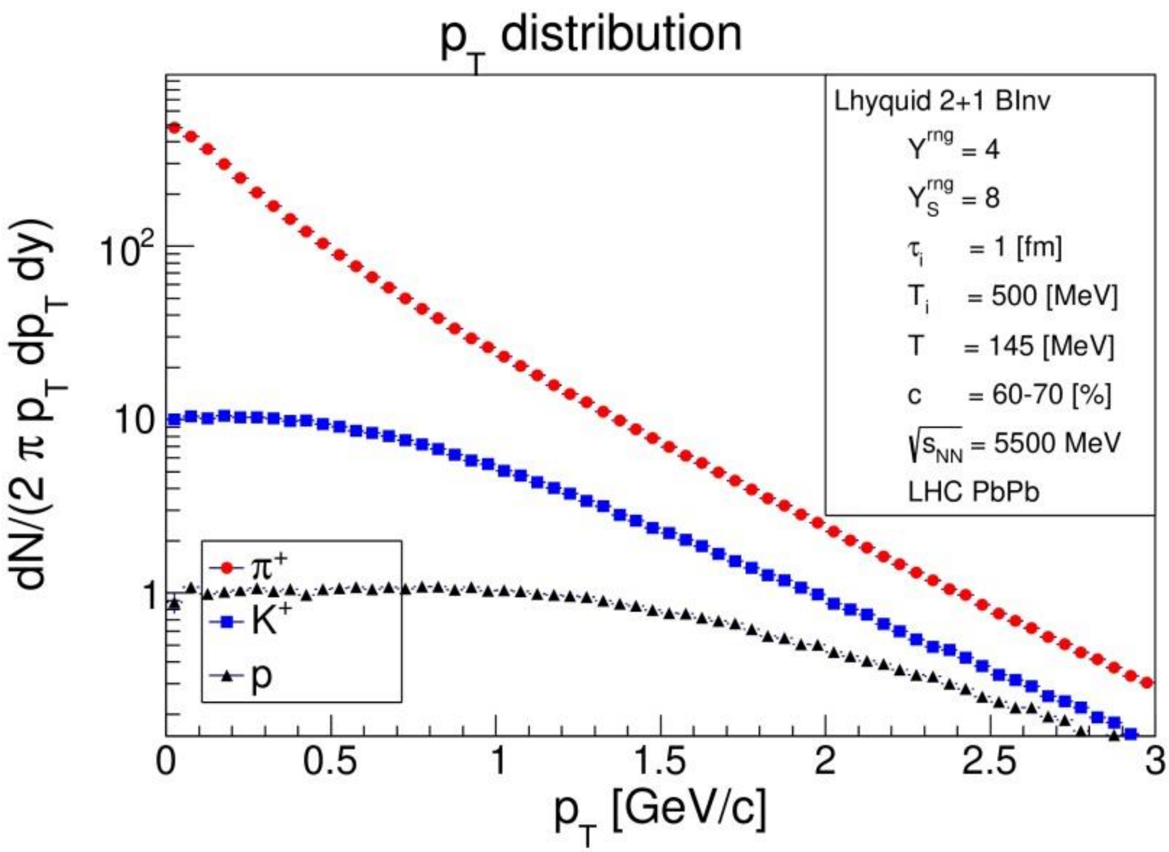

Figure 8: Transverse-momentum spectra of π +, κ+, and protons for Pb+Pb collisions at $\sqrt{sNN}$= 5.5 GeV and the centrality class 60-70%

4. CONCLUSION

I was able to generate the correlation function for the π-π pairs and the transverse momenta graph for the π^+, κ^+, and protons. These graphs would help us study the various regions of the QGP domains and help us grab a better understanding of the particle interactions in QGP state. This project gave me exposure to work in the ROOT environment and also helped me gain a lot of experience with Monte-Carlo Generators.

5. ACKNOWLEDGMENT

I would like to thank my supervisor Mr. Krystian Roslon for helping me out throughout the length of this project, I highly appreciate his assistance. I would also like to thank the Joint Institute of Nuclear Research, Dubna for making me a part of the INTEREST programme and giving me a chance to work on this project. I would like to thank my colleagues Maratbek Shodmonov, Muhammad Ibrahim Abdulhamid Elsayed, Piera Battista, Kashish Agrawal and T.S. Sachin Venkatesh. My special thanks to Muhammad, his research work has been a guiding light for me.

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