# Generation and analysis of events from Au-Au collisions using the Monte Carlo generator - Therminator 2

JOINT INSTITUTE
FOR NUCLEAR RESEARCH

**T.S.Sachin Venkatesh**
Department of Applied Physics
Delhi Technological University

Submitted to:
**Mr.Krystian Roslon**
Joint Institute for Nuclear Research

Final report of the project undertaken through wave 3 of the INTEREST program

## Abstract

Heavy-ion collisions allow us to study matter in regions with extreme conditions. These collisions can help us understand how the universe was created and one of the examples is the quark-gluon plasma which formed right after the Big Bang. QGP is also believed to be present in the core of neutron stars. In this project, heavy-ion collisions were generated for Au-Au using hypersurfaces and velocity profiles describing data obtained by RHIC at 200 GeV and femtoscopic correlation function was carried out for particles at 60-70% centrality. These events were then analyzed and we make use of these produced results to measure the correlation function for pions ($\pi^+$ $\pi^+$ and $\pi^-$ $\pi^-$) and kaons ($K^+$ $K^+$ and $K^-$ $K^-$).

# Contents

# Chapter 1

# Acknowledgements

I would like to heartily thank my supervisor Mr. Krystian Roslon who oversaw and helped me undertake this project, specially during the given times. I take this opportunity to express my deep sense of gratitude for his invaluable guidance, constant encouragement and comments, which has sustained my efforts at all stages of this project work.

A sincere thanks to JINR also, which introduced the INTEREST program for providing me with this opportunity and for the smooth overseeing of the program. Over the course of our project work we gained immense knowledge which would help us in the coming years.

# Chapter 2

# 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's 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 $10^5$ seconds 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 Chromo Dynamics (QCD) theory and mediated by gluons. One second after the Big Bang and at a lower temperature, the formation of atoms started by the freeze out and recombination of protons, neutrons and electrons.

The focus of this report is to present the generation of heavy-ion collisions recreating possible data from the LHC. The events are retrieved through a Monte Carlo generator: Therminator2 [**2**]. The obtained events are then analyzed and the correlation function for pions and kaons is measured.

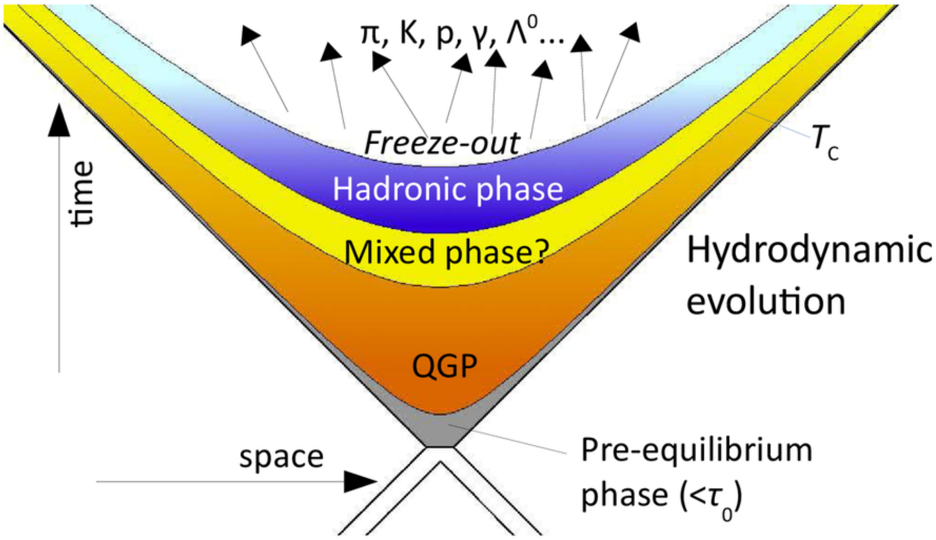

Figure 2.1: The space-time evolution can also be illustrated with a light-cone diagram. The emerging fragments travel along the light cone, while matter between the fragmentation zone remains in the central region. This matter is in the state of QGP.

## 2.1 Heavy Ion 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 above, at 10 GeV the formation of QGP is possible. The collision evolution of heavy ions is shown in the following phase diagram.

## 2.2 Femtoscopic correlation function

The femtoscopic correlation function is a probabilistic function which determines how closely the particles are packed in the QGP[**3**]. The tool needed to understand and analyze these types of collisions is femtoscopic analysis. This allows to measure the space-time characteristics of the collision products and

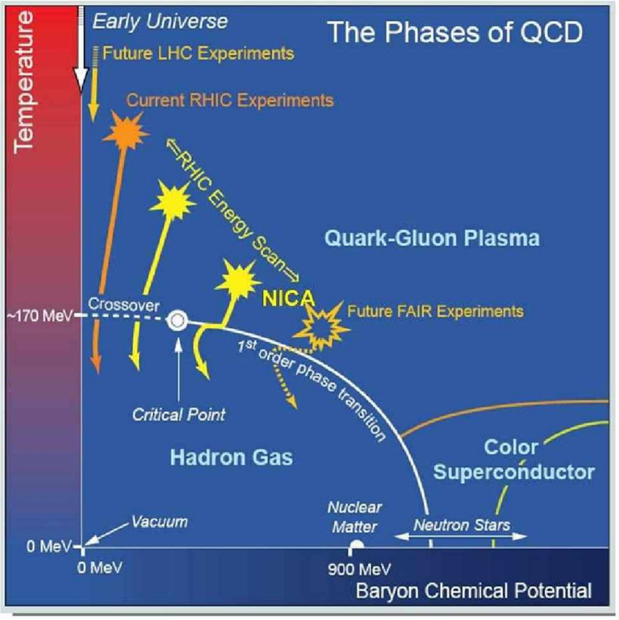

Figure 2.2: Phase diagram of Strong Interacting matter

the particles correlations. One specific quantity which is crucial to discuss is centrality. Heavy ion collisions are described by the quantity called the impact parameter, representing the size of the overlap region which corresponds to a different number of nucleons participants (at least one binary collision) and spectators (no collisions). An estimation of the centrality of a collision will give an estimate of the number of participant nucleons over spectators.

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

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

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

# Chapter 3

# THERMINATOR 2

The ‘THERMal heavy IoN generATOR 2’[**2**] is a Monte Carlo event generator used to study the statistical production of subatomic particles in relativistic heavy ion collisions. It uses a library of standard hypersurfaces and velocity profiles corresponding to Au-Au, Pb-Pb and p-Pb collisions at RHIC and LHC. It’s written in C++ and uses the CERN ROOT environment. 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

## 3.1 Installation

The THERMINATOR 2 although is very useful, it still remains an outdated tool whose support and updates have been ceased. Therefore the latest version of THERMINATOR 2 is compatible upto Ubuntu 18.04. To install this package, CERN’s ROOT package has to be installed first which can be found here []4. After installing ROOT, the THERMINATOR 2 source file has to be compiled, but it has some technical errors which need to be corrected first. After correcting the errors, we simply compile and make the package.

## 3.2 Generation of Au-Au collision events

To generate the required events, firstly the correct freeze-out file has to be chosen. The files can be found in the fomodel/liquid2D.ini folder. Then, the number of required events to generate needs to be changed in the events.ini file. 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. Finally, to generate the requested events the command ./therm2_events has to be run in the terminal. 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.

## 3.3 Analysis of generated events

To analayze 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 $./therm2\_femtocommand$. 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 ($K$) and Pions ($\pi$). After running the femtoscopic analysis the program outputs a ROOT file in the events folder.

To start the default run for the analysis the following command has to be run

$$./therm2\_femto < KTBIN >< EVENTDIR >< EVENTFILES >$$

replacing the variables in angle brackets with the appropriate ones. KTBIN represents the selected transverse momentum bin of the event and can take values 0,1,2 or 3. The default graphs received from these analysis are the numerator and denominator of the correlation function for $\pi^+$ $\pi^+$ and $\pi^-$ $\pi^-$ particles.

# Chapter 4

# Results and Discussion

The events generated for this project were Au-Au collisions at 60-70% centrality in the energy range of 200 GeV[**5**]. The number of events generated were 50,000 and the process varies according to the hardware used to generate the events. It is recommended to generate more than 20,000 events for more stable results.

## 4.1 Numerator and Denominator Histograms

After running the FEMTO_THERMINATOR, we get a root file depending on the KTBIN value used. Since we generated for Pions we get a file named 'femtopipiXa.root' where X is the vaue of KTBIN. Opening this file in ROOT and viewing this file with *new TBrowser* command, we get the numerator and denominator histograms.

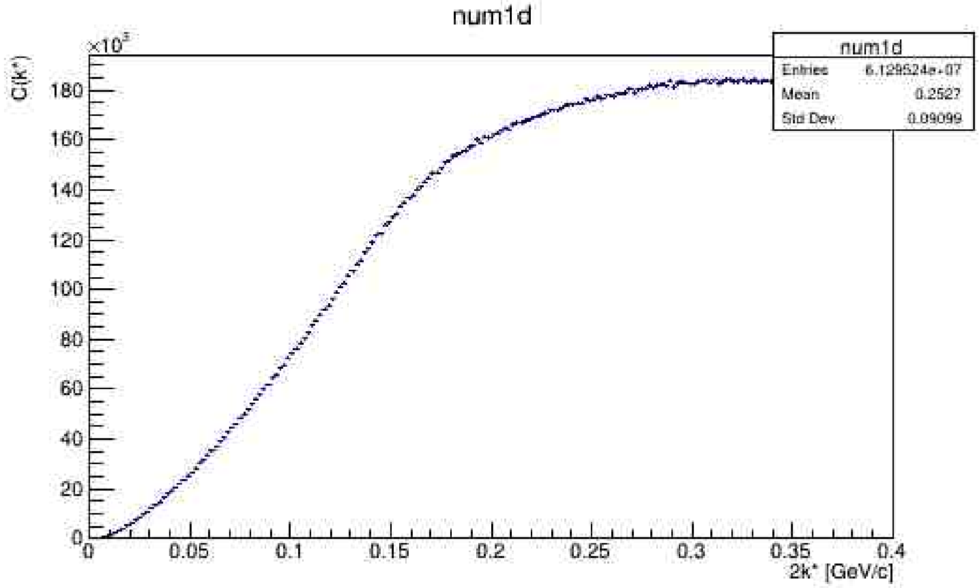

Figure 4.1: Numerator of Correlation Function

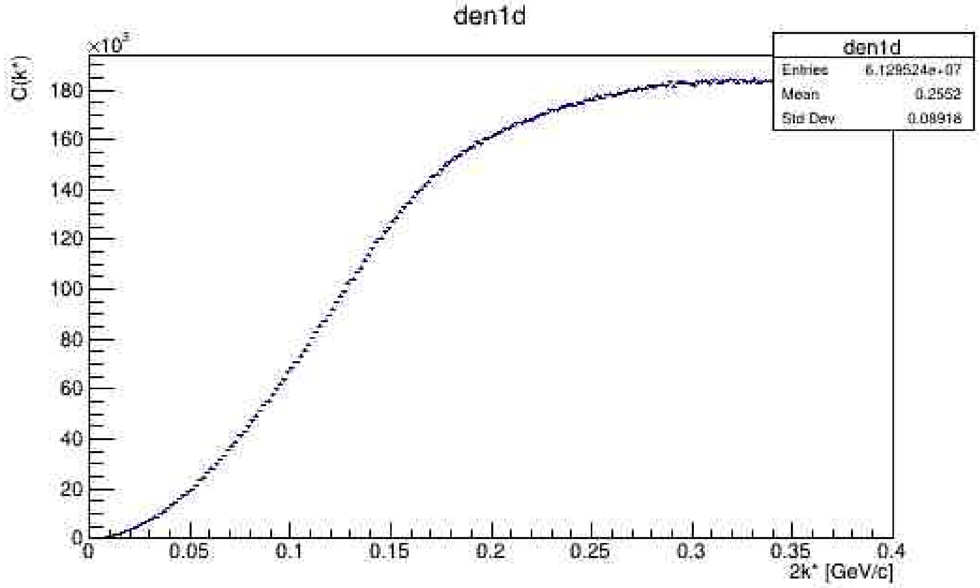

Figure 4.2: Denominator of Correlation Function

## 4.2 Correlation Function calculation

Since the correlation function is calculated separately for every Ktbin and every pair case, we have to write our own code for Correlation Function calculation. An example for calculating CF of KTBIN = 1 is given below which is based off the sample by a fellow participant Muhammad.

```
#include<iostream>
#include<fstream>
#include<sstream>
#include<TH1D.h>
#include<TH3D.h>
#include<TFile.h>
#include<TGraph.h>
#include<TPad.h>
#include<TCanvas.h>
#include<TImage.h>
#include<TMath.h>
#include<TDatime.h>
#include<math.h>

using namespace std;

TFile* tInRootFile;
TH1D* numq;
TH1D* denq;
TH1D* ratq;

void corrfun(){
    tInRootFile = new TFile("femtopipi1a.root");
    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("ratq");
    ratq->SetTitle("Correlation function");
    ratq->Draw();}
```

This gives us the Correlation Function for same charge Pion pairs and we can clearly see that it's value reaches 2 and then starts to fall off rapidly before stabilizing at 1.

We could then use these results to calculate the Bohr's radius and then use that value to manually plot the Correlation Function.

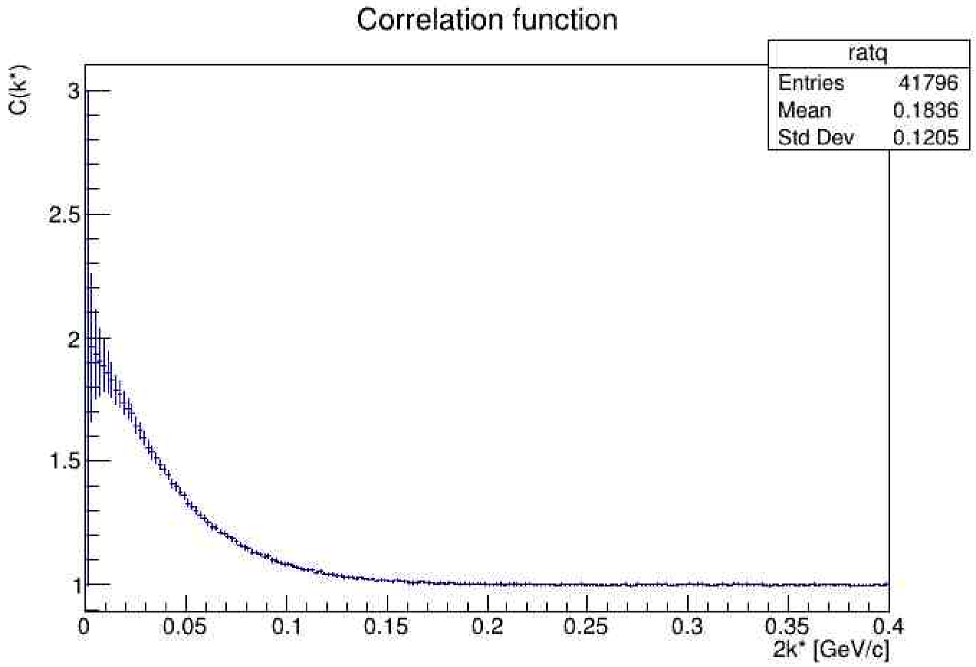

Figure 4.3: Correlation Function for same charge Pion pairs

# Chapter 5

# Conclusions

In conclusion, this project took me through a literature review of Quark Gluon Plasma, the standard model, the early universe and femtoscopy. It also taught me about Monte Carlo generators and their various uses. After learning about one such simulator named THERMINATOR 2, I was able to use that to generate events for Au-Au collisions using the data from LHC and RHIC. The setup and events generation also taught me some troubleshooting and coding in linux and root. In the end, I was able to compile them, produce numerator ann denominator graphs from that ROOT file and use them to generate the Correlation Function. As a further extension of the project, correlation functions could be measured for $\pi^+$ $\pi^-$ to compare and analyse the difference between the different graphs and their characteristics.[**6**]

# Chapter 6

# References

1. Connecting QGP-Heavy Ion Physics to the Early Universe, https://arxiv.org/pdf/1306.2471.pdf
2. THERMINATOR 2 - THERM al heavy I o N gener ATOR version 2, https://therminator2.ifj.edu.pl/
3. Femtoscopic signatures of small QGP droplets in proton-lead collisions at the Large Hadron Collider, https://academiccommons.columbia.edu/doi/10.7916/d8-t50g-tn57
4. ROOT : Data analysis framework, https://root.cern/
5. Anisotropic hydrodynamic modeling of 200 GeV Au-Au collisions, https://arxiv.org/abs/1807.04337
6. Pion-pion, pion-kaon, and kaon-kaon interactions in the one-meson-exchange model, https://academic.oup.com/ptep/article/2014/2/023D04/1533388