

**JOINT INSTITUTE FOR NUCLEAR RESEARCH**

**Veksler and Baldin laboratory of High Energy Physics**

FINAL PROJECT REPORT ON THE INTEREST PROGRAMME

**Generation and analysis of events for  
Heavy Ions collisions using the MC  
generator - Terminator 2**

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# Abstract

The Study of heavy-ion collisions can help us unravel the history of the Universe and understand the properties of matter moments after the Big Bang. Quark-Gluon plasma is believed to be formed in the early Universe and can be found in extreme Astrophysical conditions. In this project, we have used the same QGP model to study some heavy ion collisions. Using Therminator 2 we have generated events for Au-Au using hypersurfaces and velocity profiles describing data obtained by RHIC at  $\sqrt{s_{NN}} = 200\text{GeV}$  and at centrality 40%-50%. Then we analysed the femtoscopic correlation function for identical particle pairs like pions ( $\pi^+\pi^+$  and  $\pi^-\pi^-$ ), kaons ( $K^+K^+$  and  $K^-K^-$ ) and protons, Also for non-identical particle pairs pions-kaons ( $\pi^+K^-$  and  $K^+\pi^-$ ), pions-protons ( $\pi^+p$  and  $\pi^-p$ ) and Kaons-protons ( $K^+p$  and  $K^-p$ ).

# Acknowledgement

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A sincere thanks to **JINR INTEREST Team** also, to introduce this program and for providing me and students all around the globe with this opportunity and for the smooth overseeing of the program. Over the course of our project work I have gained immense knowledge which would help us in the coming years.

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# Chapter 1

## Introduction

### 1.1 High Energy Physics

High Energy Physics is one of the vast domains of Physics, intending to determine the most fundamental building blocks of matter and the forces interacting through these particles. Relativistic Heavy Ion Collisions is the part of High Energy Physics which deals with Nuclear Physics of the colliding nucleus of atoms with higher atomic number, at relativistic speeds.

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 the Large Hadron Collider (LHC) at the France-Switzerland border near Geneva. By studying of these collisions, recreate in the laboratory, we can understand nuclear matter state, close to the one that was present shortly after the Big Bang.

### 1.2 Quark-Gluon Plasma

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 [1]. These conditions can then be studied by different methods of analysis; one of them is called Femtoscopic Correlation. Different

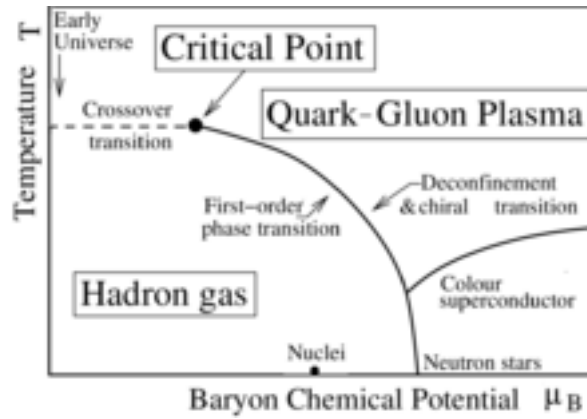


Figure 1.1: Phase diagram of Strong Interacting matter(QGP)

accelerators study the various domains of the QGP to get a better understanding of the early universe. 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.

### 1.3 Heavy Ion Collision

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 [2].

Using statistical mechanics, we can describe matter as a system in thermal equilibrium, with global observables like net charge, temperature, and energy density. The system can display multiple phases of matter when these variables take on

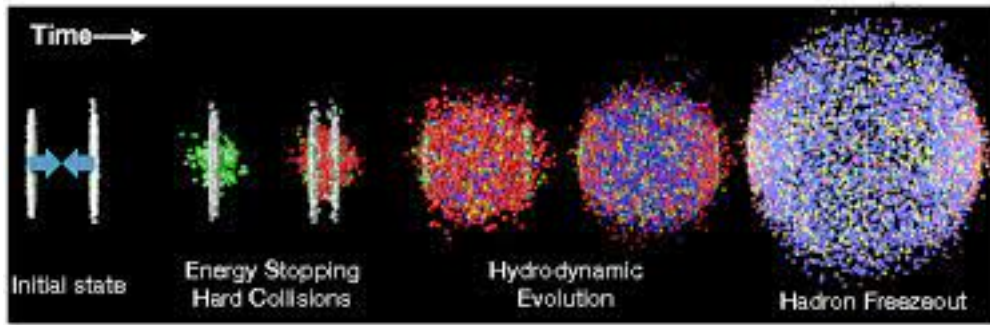


Figure 1.2: Relativistic Heavy-ion collision

changing values. A phase transition from hadronic matter to QGP should occur at high temperatures/densities.

## 1.4 Femtoscopy

Femtoscopy correlation is a technique used in relativistic heavy-ion collisions that can give us an insight of the space-time characteristics of particle production at the femtometer scale ( $10^{-15}$  m) using particle correlations [3]. For identical and non-identical particles, there are two sorts of correlations. The first can be used to investigate the size of two ion collision systems, and the non-identical ones are utilised to investigate the time scale of nucleus fragments created during the collision [4].

The centrality, which is closely related to the impact parameter and represents the size of the overlap region that corresponds to a different number of nucleons that participate in the collision (participants) and those that do not, is another important physical concept used in the analysis of heavy-ion collisions (spectators) [5]. However, because the impact parameter of a collision cannot be directly measured in experiments, but because it is an important metric for event selection and analysis, final state observables such as charged particle multiplicity and energy deposited by spectators are used to define centrality classes based on theoretical model predictions. The centrality class allows us to have an estimate of how many nucleons take part in the collision.

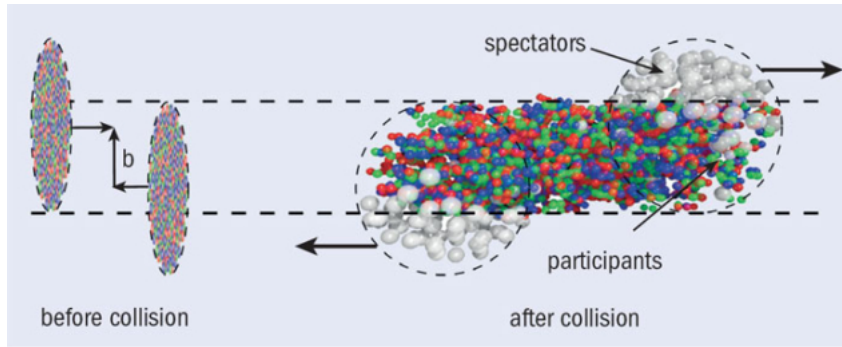


Figure 1.3: Semi-peripheral Heavy-ion collision

### 1.4.1 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 [6]. The correlation function of two particles  $p_1$  and  $p_2$  can be given by the following equation:

$$C(p_1, p_2) = \frac{\mathcal{P}(p_1, p_2)}{\mathcal{P}(p_1)\mathcal{P}(p_2)} \quad (1.1)$$

Here, the numerator represents the measured momentum distribution difference ( $q = p_1 - p_2$ ) of the two particles ( $p_1, p_2$ ) from the same events and the denominator the distribution of two particles taken from different events. The results are normalized so the correlation function tends to 1 when there is no correlation between the particles. The average transverse momentum of the pair will be denoted by  $K_T$ . Calculating this correlation function for different particle pairs was the main objective of this project.



# Chapter 2

## THERMINATOR 2

THERMINATOR 2 [6], **THERMal** heavy **IoN** gener**ATOR** 2, is a Monte Carlo event generator used to study the statistical production of subatomic and elementary particles in relativistic heavy ion collisions. It is written in C++ and using the standard CERN ROOT environment. This not only help us in model applications, but also, the code can be easily adapted for purposes directly linked to experimental data analysis, detector modeling, or estimates for the heavy-ion experiments at RHIC, LHC, SPS, FAIR, or NICA.

It uses a library of standard hypersurfaces and velocity profiles corresponding to Au-Au, Pb-Pb and p-Pb collisions at RHIC and LHC. The package includes the tools for femtoscopic analysis of events. Which can help us carry out analysis of correlation function of HBT radii of the generated events among other auxiliary results. A description of the tasks performed, from the installation of the program to the analysis of the results, is given in the following subsections.

### 2.1 Installation

THERMINATOR 2 uses the ROOT CERN Package, available for various operating systems. However, it is recommended to use Linux. Moreover, a C++ compiler is also needed. For this project, Ubuntu 18.04.5 was installed on a virtual machine, followed by the ROOT environment (the latest version-v6.24.00). A full guide on how to install ROOT is available at the official website [7].

The working and installation, as well as the latest version THERMINATOR 2,

can be found at the official website. The major steps regarding the installation and setup of the program are clearly given in the manual [6], but one must be aware that the last version of THERMINATOR 2 is a decade old and the installation requires some modifications to the code. Once the documentation has been downloaded and unzipped, before compiling using **make** command, add the line **using namespace std;** in the **build/src/therm2\_events.cxx** file after all the function declaration. Also, the 119,123,127 lines of **Makefile** in the main directory in the given form, otherwise it will hinder with the compilation process.

```
$(LD) $(LFLAGS) $* -o $@ to $(LD) $* -o $@ $(LFLAGS)
```

### 2.1.1 Events Generation

To check, if the installation and setup was done properly, one can a test run script called **./runall.sh**. This command run displays all basic functionality of the package, including the femtoscopic analysis, producing the plots with the physical results and more.

In this project, I generated Au-Au collision, using data from the RHIC, using command **./Therm2\_events**. Its important characteristics are the energy of the collision, which is at  $\sqrt{s_{NN}} = 200\text{GeV}$  and the centrality (40%-50%), total 20,000 events were generated and 40 event\*.root files were obtained, containing data of 500 events per file. Other events are available as well. To generate a type of events other than that set by default, one must open the **therminator2/fomodel/lhyquid2dbi** folder and pick the file with the wanted parameters. Copy and paste the name of the file in line 42 of the **fomodel/lhyquid2dbi.ini** file and run the event. A new folder bearing the name of the file will be created.

It is important to generate enough events to obtaining good statistics. The number of events can be increased either by running the same event several times, or directly by modifying the Number of Events line 55 in the **events.ini** file. In this case, I have generated 20,000 events (20,000 - 50,000 events are preferable).

# Chapter 3

## Femtoscopic Analysis using Therminator 2

The THERMINATOR2 package includes a femtoscopic analysis tool called **therm2\_femto** which can be used to calculate the femtoscopic correlation function for identical and non-identical particle pairs [8]. After generating the events as described before, the output was saved in the events folder that contains multiple root files with the name event\*.root with the information obtained from the simulation. These event files can be used to carry our multiple physical analysis. here we will use it to obtains correlation function of the acquired data.

The main source file that performs all the calculation is **therm2\_femto.cxx**. All the physical processes according to the formalism mentioned earlier are defined there and some changes are necessary in order to run the program for different particle pairs. Some of those changes are mentioned in the following sections. The corresponding initialization file is **femto.ini** where some initial parameters are specified, like the type of particle pairs to correlate, number of particles to mix and enable the Coulomb Interactions.

The command to run femtosopic analysis is as following:

```
./Therm2_femto < KTBIN > < Event Directory > < Total number of event files >
```

Where, the transverse momentum bin of the pair ( $k_T$ ), KTBIN has the range from 0 to 3, where each value corresponds to a  $k_T$  value range:

- $k_T = 0$  : (0.15, 0.25) GeV/c
- $k_T = 1$  : (0.25, 0.35) GeV/c
- $k_T = 2$  : (0.35, 0.45) GeV/c
- $k_T = 3$  : (0.45, 0.6) GeV/c

The output files consist of the femto\*.root files that contain the one-dimensional histograms of the numerator and denominator.

### 3.1 Analysis of Generated data

To obtain the correlation function we divided the 1D histograms for the denominator and numerator included on the **femto\*.root** for each  $k_T$  bin. See fig 3.1 below.

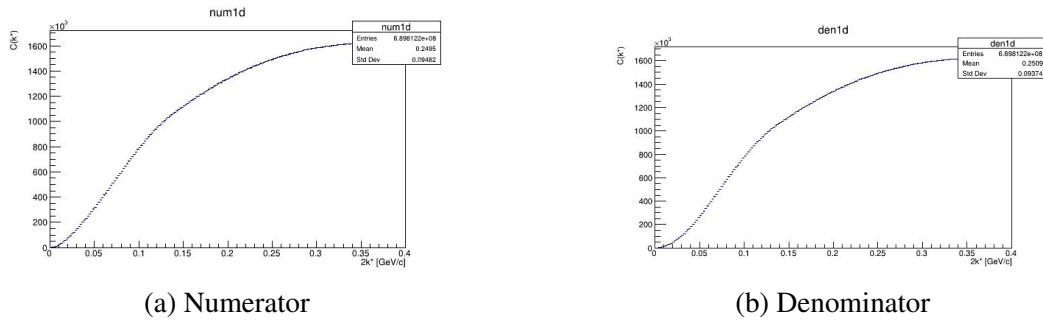


Figure 3.1: One dimensional histograms included in the femto\*.root files (these are from femtopipi0a.root).

The division and graphs were done using a root macro. This division is conducted through the construction of a macro file written in C++ as following:

```
#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 <TDateTime.h>
#include <math.h>
using namespace std;

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

void Correlation(){
tInRootFile = new
TFile("path_of_the_root_file/name_of_the_root_file");
numq = new TH1D(*((TH1D *) tInRootFile->Get("num1d"))); // nominator
denq = new TH1D(*((TH1D *) tInRootFile->Get("den1d"))); // denominator
ratq = new TH1D(*numq);
ratq->Reset("ICE");
ratq->Divide(numq, denq, 1.0, 1.0); // Divison Process
ratq->SetName("Name");
ratq->SetTitle("Title");
ratq->Draw(); // Plotting
}

```

Which can be called using command **root correlation**, keep in mind, that the macro file and the void function must have same name. This code is very basic and can be modified to plot correlation function for all  $k_T$  bin values for a particular particle pair, which is been used in this project and resulting plots can be seen in next sections.

### 3.1.1 Identical Particles

It is possible to obtain the correlation function for both identical particles and non-identical particle pairs. Particles with the same type, mass and charge are referred as identical particles, like the pairs  $\pi^+-\pi^+$ ,  $K^+-K^+$ ,  $p$ - $p$ . Identical particle femtoscopy can be useful to determine the relation between specific space-time information and the source radii. Below are the correlation functions obtained for identical particles.

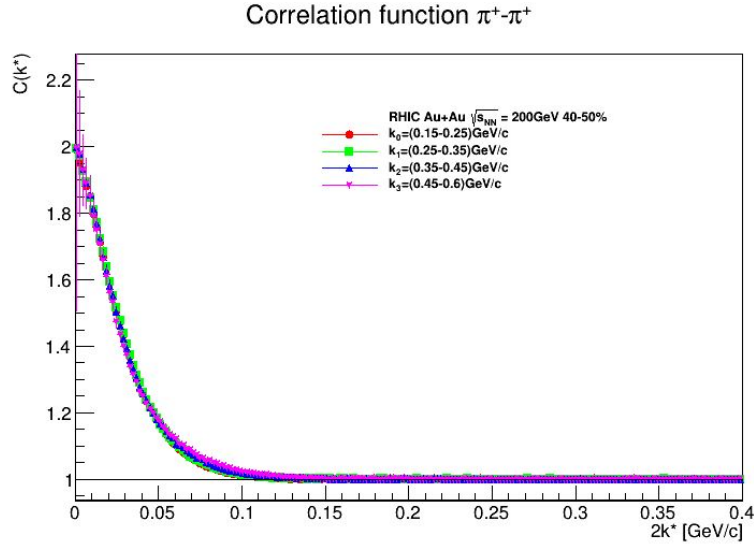


Figure 3.2: Correlation Function for Pion pairs ( $\pi^+-\pi^+$  and  $\pi^--\pi^-$ ) for various  $k_T$  bin values

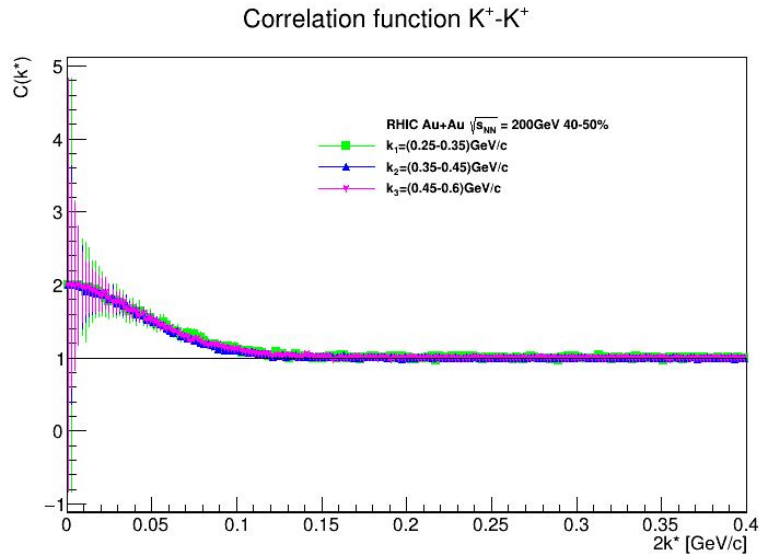


Figure 3.3: Correlation Function for Kaon pairs ( $K^+K^+$  and  $K^-K^-$ ) for various  $k_T$  bin values

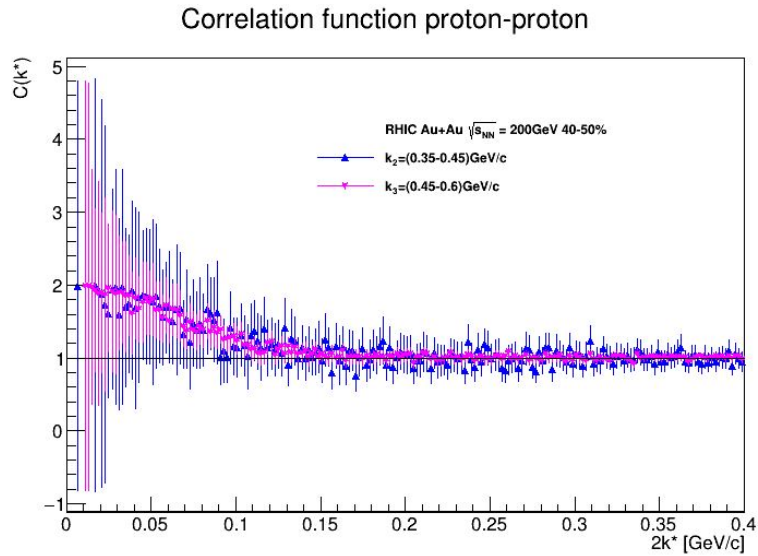


Figure 3.4: Correlation Function for proton pairs ( $pp$ ) for various  $k_T$  bin values

### 3.1.2 Non-identical Particles

For non-identical particles, we have considered particle pairs of different types,  $\pi^+-K^+$ , or different charge like  $K^+-K^-$ . For unlike particles correlation is dominated by Coulomb Interactions [10] which is considered in this analysis, furthermore can be enabled by setting **docoulomb=1** in the **therm2\_femto.cxx** file or can be set in **femto.ini** file.

To analyse non-identical particles using therm2\_femto, we need to make various changes in source code file (**therm2\_femto.cxx**). Below are the changes made for analysis of  $\pi^+K^-$  and  $\pi^-K^+$ .

1. First define the missing PID codes for  $\pi^-$  (#define PINPID -211) and  $K^-$  (#define KNPID -321).
2. the section "Read parameters" we added the missing cases according to the pairs to use: "else if (tPair == "piplus-kminus") pairtype = 3;".
3. In "Pair and particle cuts" we noticed that some of the particles combinations in the "switch(pairtype)" were already defined so we added the ones that were not like the following:

```

case 3:
ptmin1 = PTMIN;

```

```

ptmin2 = PTMIN;
ptmax1 = PTMAX;
ptmax2 = PTMAX;
break ;

```

and at the end of that part add:

```

    else if (pairtype == 3){
partpid = PIPID;
partpid2 = KNPID;
}

```

4. Then in "Save Histograms to file", to save the data on under the given root file, add

```

else if (pairtype == 3)
sprintf(bufs,"%sfemtopi+k-%i%s.root",sEventDir.Data(), nbin ,
onlyprim ? "p" : "a");

```

5. Finally, in "Temporary file" define:

```

    else if (pairtype == 3) {
pionac = -248.519 / 0.197327;
partpid = PIPID;
partpid2 = KNPID;
}

```

6. It is also necessary to change the line 32 in the **femto.ini** file, from the name of the pair we are interested in and that we defined in the "Read Parameters" part.

If after all these changes the desired output is not obtained or an error comes up, we tried commenting a if condition named **if (fabs(mKStarSigned)<0.1)** in "non-identical particle correlation" part. And closed an open file in "save histogram file" section by adding **ofile->Close();** at the end.



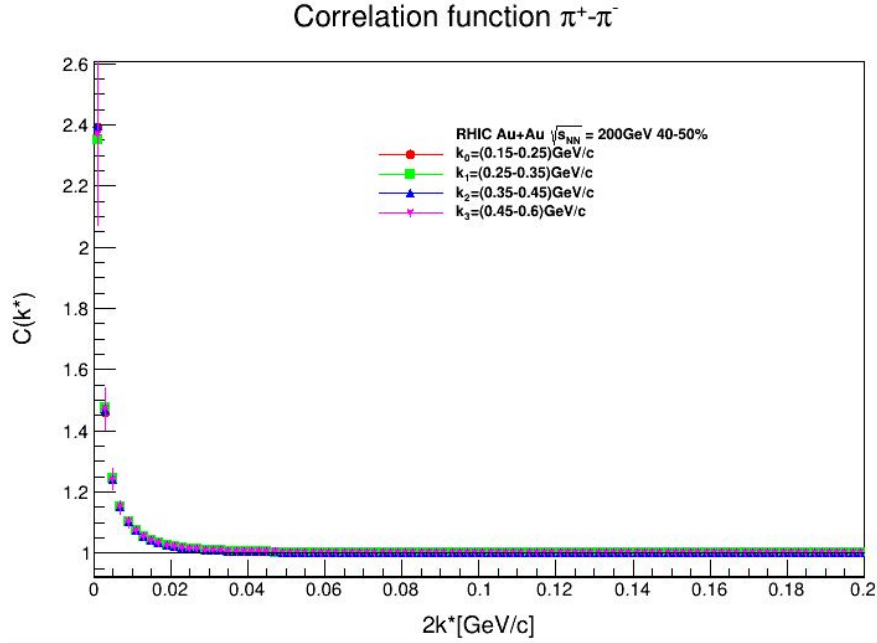


Figure 3.5: Correlation Function for Pion pairs ( $\pi^+\pi^-$  and  $\pi^-\pi^+$ ) for various  $k_T$  bin values

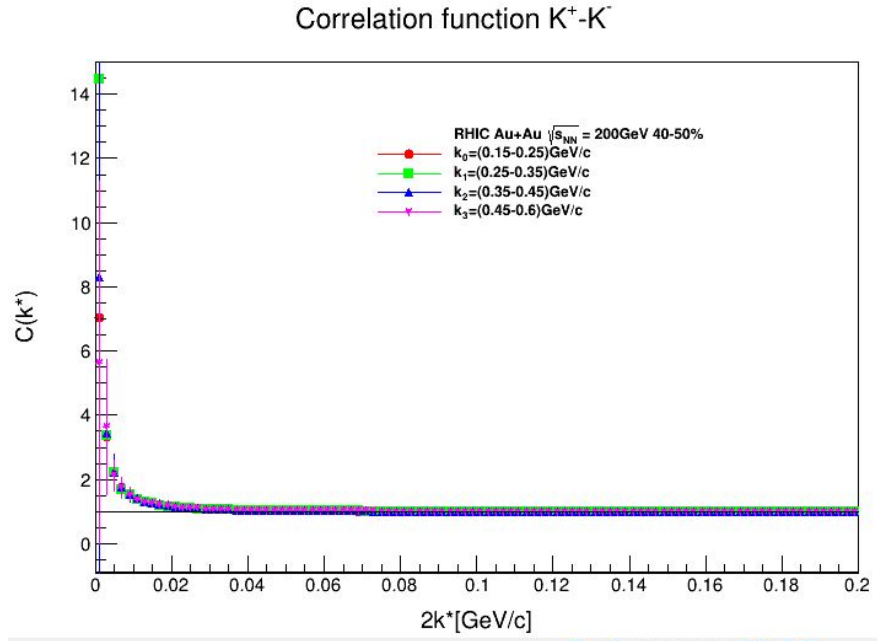


Figure 3.6: Correlation Function for kaon pairs ( $K^+K^-$  and  $K^-K^+$ ) for various  $k_T$  bin values

## 3.2 $\phi$ Meson Observation

The  $\phi$  meson is considered as a good probe to study the QCD matter created in relativistic collisions [12] and according to [11] the  $\phi$  meson may be observed in the correlation for  $K^+K^-$  since it can decay in the channel  $\phi \rightarrow K^+K^-$ . Using

Correlation function  $\pi^+K^-$

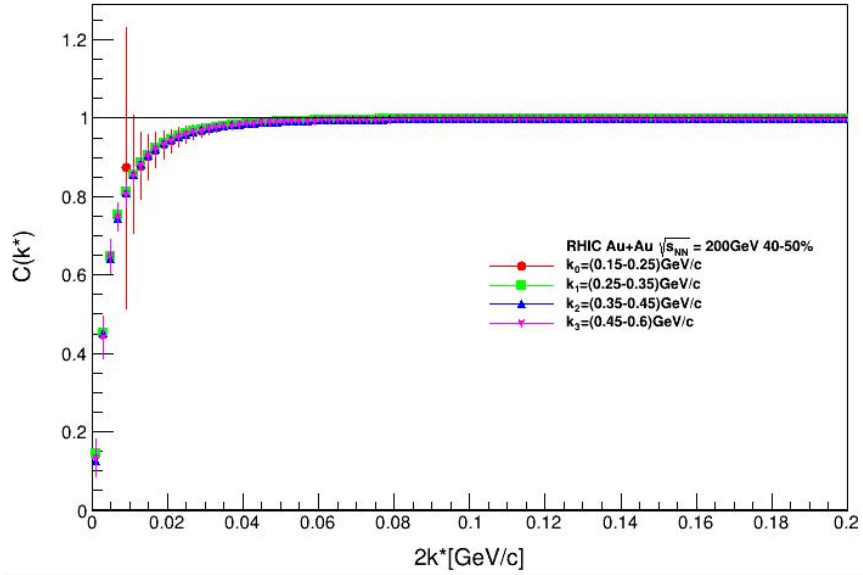


Figure 3.7: Correlation Function for Pion-kaon pairs ( $\pi^+K^-$  and  $\pi^-K^+$ ) for various  $k_T$  bin values

Correlation function  $\pi$ -proton

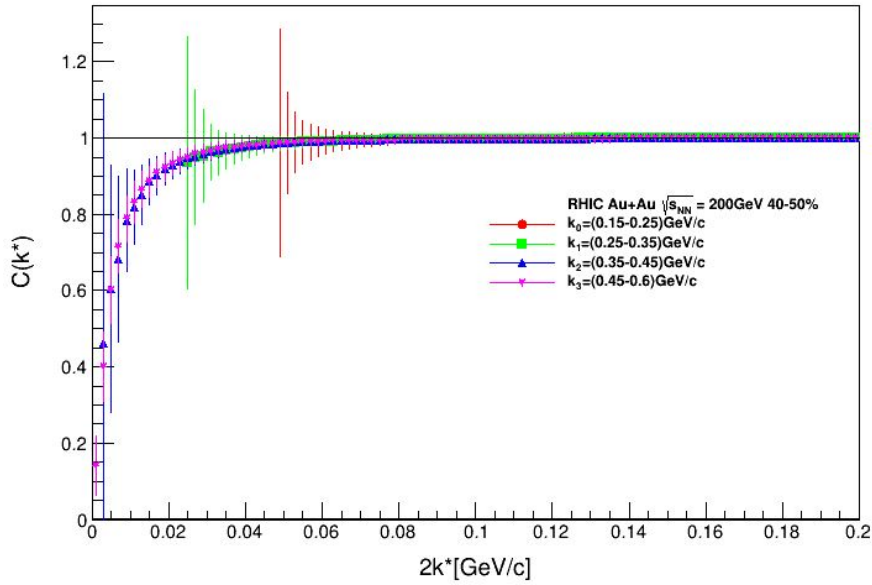


Figure 3.8: Correlation Function for Pion-proton pairs ( $\pi^+p$  and  $\pi^-p$ ) for various  $k_T$  bin values

the version of the code given in the previous section but selecting the histograms "num1dprtrue;1" instead of "num1d;1" and "den1dprtrue;1" instead of "den1d;1", it is possible to observe the  $\phi$  meson peak, as shown in fig 3.10.

Correlation function K-proton

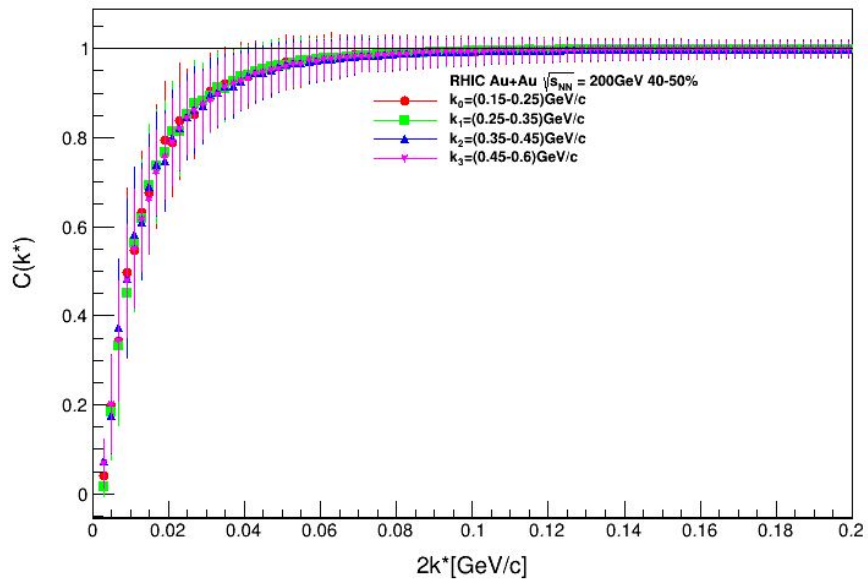


Figure 3.9: Correlation Function for kaon-proton pairs ( $K^+ p$  and  $K^- p$ ) for various  $k_T$  bin values

Correlation function  $K^+ K^-$

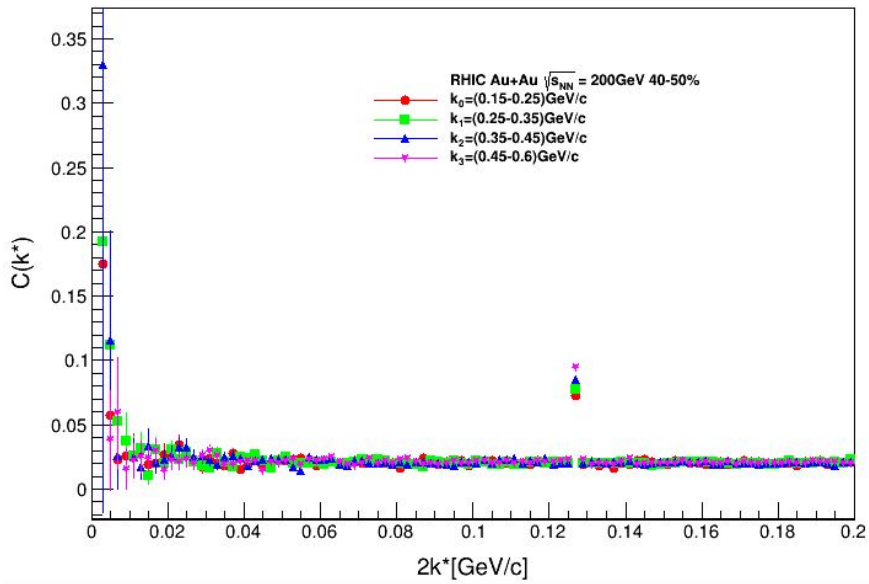


Figure 3.10:  $\phi$  meson peak in  $K^+ K^-$  Correlation Function.

# Chapter 4

## Conclusion

In conclusion, events for Au+Au collisions were generated with Therminator 2 for a centrality class of 40%-50% corresponding to semi-peripheral collisions. Using femtoscopy analysis, the correlation function for identical particle pairs ( $\pi^+\pi^+$ ,  $K^+K^+$  and  $pp$ ) as well as for non-identical particle pairs were obtained. A special remark is made in the case of the  $K^+K^-$  correlation function since it can be used to search for the presence of the  $\phi$  meson.

As a further extension of the project, a deeper analysis could be made comparing the results with the ones produced at other centrality ranges. It also would be interesting to perform the HBT analysis using the code implemented in Therminator 2.

# References

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