Generation and analysis of events for Au-Au collisionsusing the Monte Carlo generator - Therminator 2

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Abstract

Relativistic heavy-ion collisions create extreme conditions, under which quarks and gluons are in a de-confined phase, the quark-gluon plasma (QGP). This state is thought to have existed immediately after the Big Bang, a long time ago when the temperature was very high. One of the tools developed to probe the Quark-Gluon Plasma is the technique of two-particle correlations in momentum space. Using a Monte Carlo event generators such as Therminator 2 and UrQMD,HIJING,pythia8, it is possible to study particle formation in relativistic heavy ion collisions. This report will describe how Therminator 2 can be used for this purpose. In addition, measurements of femtoscopic correlations were carried out for Au-Au collisions using the freeze-out 2+1 boost-invariant hydrodynamics describing data obtained by RHIC at $\sqrt{s_{NN}} = 200 GeV$ and 0%−5% centrality. This was performed by obtaining the correlation function for the pairs $\pi^+\pi^+$ and $\pi^-\pi^-$.

1. Introduction

Physics, the most fundamental science, aims to understand and describe the world we live in from the largest galaxies to the smallest subatomic particles. Over the centuries scientists developed theories and conducted experiments pushing the boundaries of mankind’s knowledge further and further. During this evolution of our understanding of the principal laws of Nature, four fundamental interactions have been identified: gravitational, electromagnetic, weak, and strong. Gravitation and electromagnetism act potentially over infinite distance and mediate phenomena that we experience in everyday life. In contrast, the weak and strong forces act only over subatomic distances and do not manifest directly on macroscopic scales. This property makes them difficult to study and is the reason why they were discovered relatively recently, about hundred years ago. These four fundamental interactions govern the dynamics of fundamental particles – quarks and leptons. However, the strong interaction, as the name indicates, is the strongest attractive force, with a magnitude more than hundred times greater than the electromagnetic force and 10^{37} greater than gravity. It is the strong force which is responsible for binding quarks and gluons in composite particles called hadrons, such as protons and neutrons, in atomic nuclei. The most commonly accepted theory that describes the strong interaction is the quantum chromodynamics (QCD), established in the beginning of 70s’ of the last century. Being a precise and mathematically elegant quantum chromodynamics, QCD can describe a very wide spectrum of phenomena observed in the experiment and is the basic tool used today by particle physicists. However, many observed properties of strongly interacting matter still remain open questions and collisions of particles at relativistic energies are studied in order to address them. In such collisions we expect to reproduce in the laboratory conditions similar to the ones prevailing at the very beginning of the Universe. In particular, the aim is to create small droplets of strongly interacting matter which we believe have similar properties as the Universe had shortly after the Big Bang. Understanding the processes of the creation and evolution of such systems could map out new frontiers of knowledge.

One of the tools developed to probe the Quark-Gluon Plasma is the technique of two-particle correlations in momentum space, called *femtoscopy*. It is capable of measuring the space scales of the order of single femtometers (10^{-15} m; the size of a nucleon), as well as times of the order of 10^{-23} s. In heavy-ion collisions femtoscopy gives the unique possibility to measure the space-time evolution of the system and provides insight into the collective effects exhibited by the bulk strongly interacting matter. Typically, pion-pion or kaon-kaon correlations are studied in order to determine the source sizes and its evolution time. However, the femtoscopic formalism is not limited only to light mesons and other particles, in particular baryons, can also be studied. In baryon-baryon correlations the femtoscopic formalism can be employed in a novel way to extract the strong interaction parameters, which is known only for a few lightest baryon systems (like proton-proton, proton-neutron, proton-deuteron, etc.). Strong interaction between pairs of more exotic baryons, containing at least one strange quark, is poorly known or not known at all. Therefore, the femtoscopic formalism can be applied to measure these interactions.

2. Correlation function

In 1956 , R. Kamburi-Brown and R. Twiss[1] (HBT method) measured the size of a star using the Bose-Einstein correlation between a pair of photons. This method was first applied in particle physics in 1960 when studying the correlation of a pair of pions in a proton-antiproton collision[2]. The direction of research is called "particle femtoscopy", because the spatial measure of the interaction area of hadrons is one Fermi 1 fm = 10^{-13}cm , 1 femto = 10^{-15}m = 1fm, i.e. a femtometer .

The idea of the method of pulse correlations of particles is based on the possibility to distinguish the particles emitted from different points of the extended source (Fig.1).

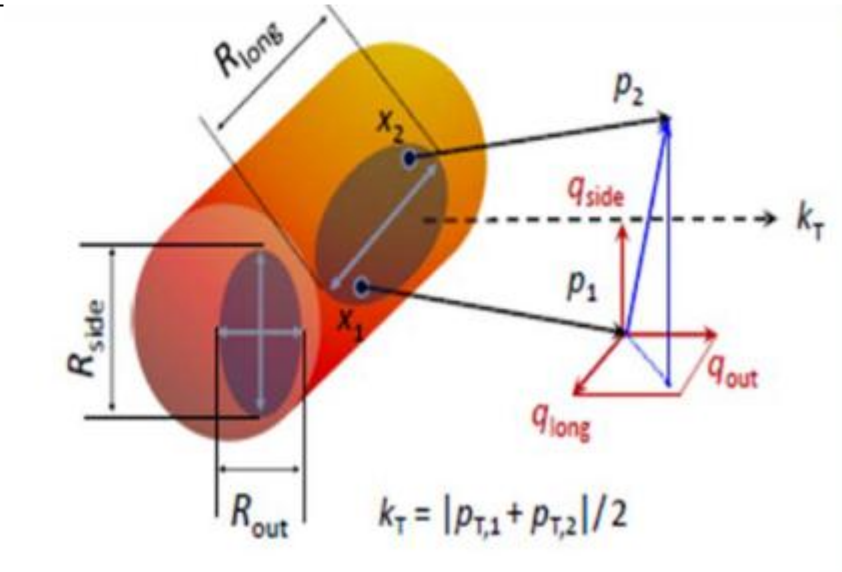

Fig.1. Vectors used in two-particle HBT correlation.

$q = p_1 - p_2$,$k_T = \frac{1}{2}\ p_1 + p_2$

The two-particle momentum correlation function is defined as the normalized ratio of the two-particle distribution to the product of the single-particle distributions:

$$CF\ p_1, p_2\ = \frac{\frac{d^2N}{dp_2dp_2}}{\frac{dN}{dp_1} * \frac{dN}{dp_2}} \tag{1}$$

For $q \to \infty$,correlation function tends to 1. For $q \le 1\ R$, where R is the source size, it is nonzero if there are correlations. Because of the interactions in the final state, for Bose-Einstein identical particles $CF\ q\ < 1$, for Fermi particles $CF\ q\ > 1$.

For 3D parameterization, three projections of the vector q are introduced:

$q_{out} = \frac{q_T k_T}{k_T}$	$q_{side} = \frac{q_L k_T}{k_T}$	$q_{long} = p_{z_1} - p_{z_2}$

Here the denotation is chosen so that the vector q_{long} is parallel to the beam ,q_{out}perpendicular k_T.

In this case [3],

$CF\ \ p_1, p_1\ \ = 1 + \lambda exp$	(2)

where the R_{side} radius determines the geometric size of the source, R_{long} is sensitive to the freeze time, R_{out}/R_{side} is sensitive to the emission time, and λ is sensitive to the correlation intensity.

An example of the measured correlation function is shown in Figure 2.

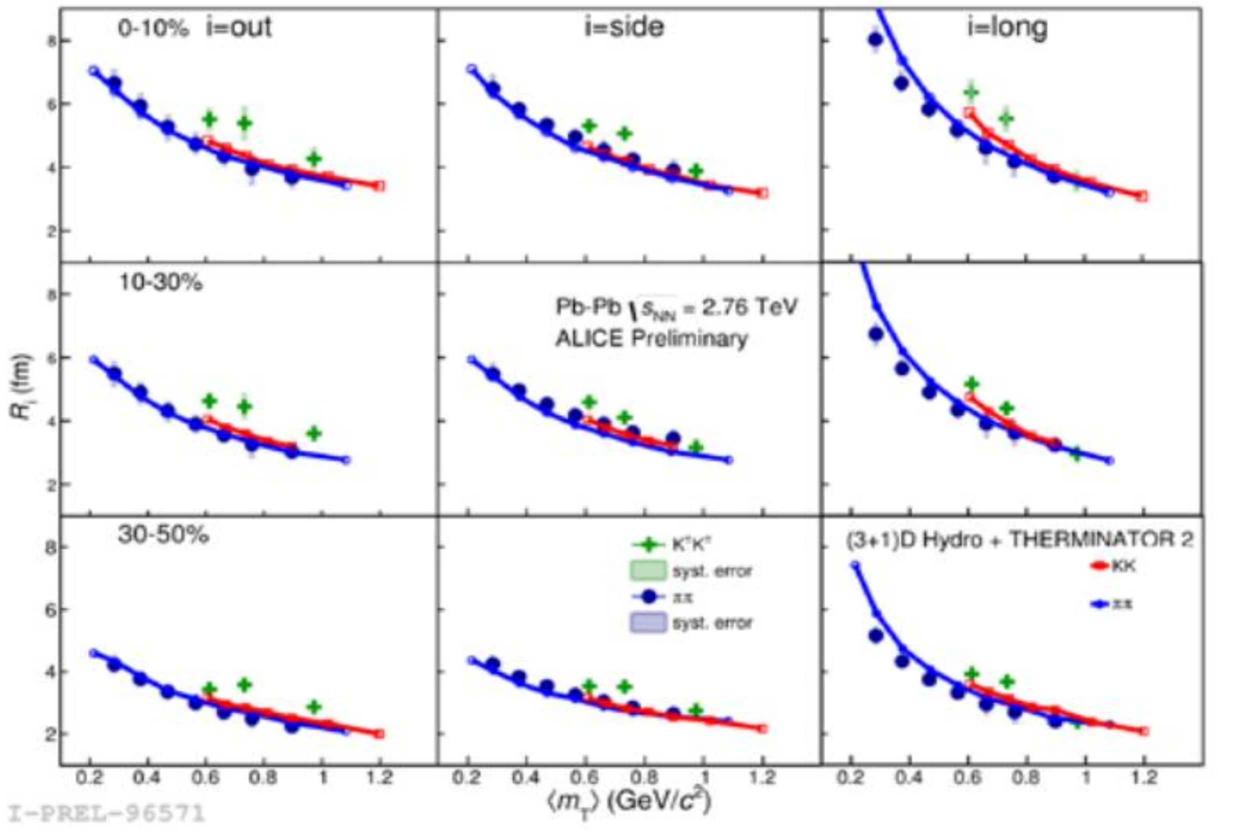

Fig .2. The radii R_{out}, R_{side}, and R_{long} (from left to right) as a function of the transverse mass of the particles $m_T = \sqrt{m^2 + p^2}$ in the ALICE LHC experiment. For pions −circles, for kaons −crosses. Curves –model calculation [4].

3 Therminator 2 and Installing the Therminator 2

THERMINATOR 2[5] is a Monte Carlo generator written in C++ and using the standard CERN ROOT [6] environment. That way, apart from model applications, 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.

TERMINATOR 2 uses the CERN root package accessible for different operating systems. However, it is recommended to use Linux. In addition, a C++compiler is necessary. In this project, Ubuntu 20.04 was installed on a computer, followed by the ROOT environment (the latest version-v6). A full guide on how to install ROOT is available at the official website [6].

The necessary documentation for installing THERMINATOR 2, as well as the latest version, can be found on the official website [7]. The basic steps associated with installing the program are also described on the website, but keep in mind that the latest version of THERMINATOR 2 was released in 2011, and the installation requires some changes in the code. After the completed download of the package some modifications need to be done. In the file ***build/src/therm2events.cxx*** the line *using namespace std*; has to be added. In addition, in the *Makefile* file in the main directory the 119th, 123rd and 127th lines have to be modified to be $(LD) $ˆ−o$@ $(LFLAGS) so that the linking happens properly. The make command must be started in the terminal to compile the package after implementing the above-mentioned fixes.

4. Generation and analysis of events for Au-Au collisions

To generation of events commands used to run events are *./runall.sh* or *./therm2_events*. Open the **fomodel** folder in therminator2_2.0.3 **therminator2**, then open the **lhyquid2dbi** folder. Select the file that you need to run events for and copy the full name of the file. Open lhyquid2dbi.ini file in **fomodel** folder and replace the **.xml** file with the name of the copied file in line **42**. After the completed above steps, To obtain correlations, use the following commands:

./therm2_femto <KTBIN> <EVENTDIR> <EVENTFILES>,

where the parameter KTBIN=0,1,2,3 selects the transverse-momentum bin of the pair, EVENT_DIR is the directory where the event*.root files are stored, and EVENT_FILES is the number of the files to be taken. Parameter FEMTO_INI (optional) is the name configuration file. This parameter is by default is set to *femto.ini*. The PPID parameter (optional) is the system's process ID number used by the shell scripts. By default it is equal to 0.

I used for this project already prepared root files for Au+Au collision at the RHIC with energy of 200 GeV and centrality of 0-5%.

5. Results and Discussion

In this part, I will discuss the analysis made after obtaining root files containing events of AuAu collision. To obtain the correlation function for pion pair, firstly the pair type in line 32 at **femto.ini** file should be changed from pion-pion to kaon-koan. I performed for 50000 events for AuAu at 200 GeV energy of 0-5% centrality.

Pion-Pion correlation functions are defined as the following C++ codes in Root:

```
corralation(){
tInRootFile=new TFile("femtopipi0a.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 ("Corralation");
ratq->SetTitle("The corralation for #pi^{+}#pi^{+} and #pi^{-}#pi^{-} ");
ratq->Draw ();}
```

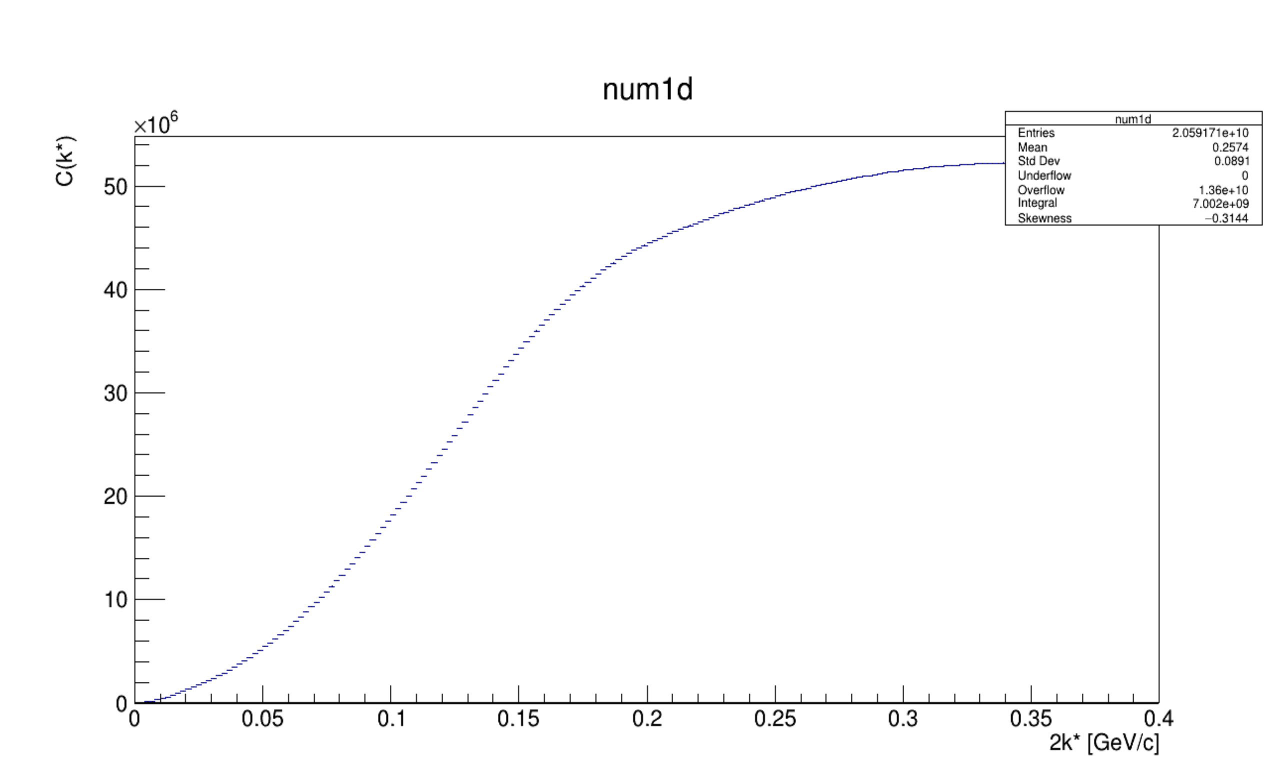

Fig.3. A (q) is a relative momentum distribution containing quantum-statistical correlations

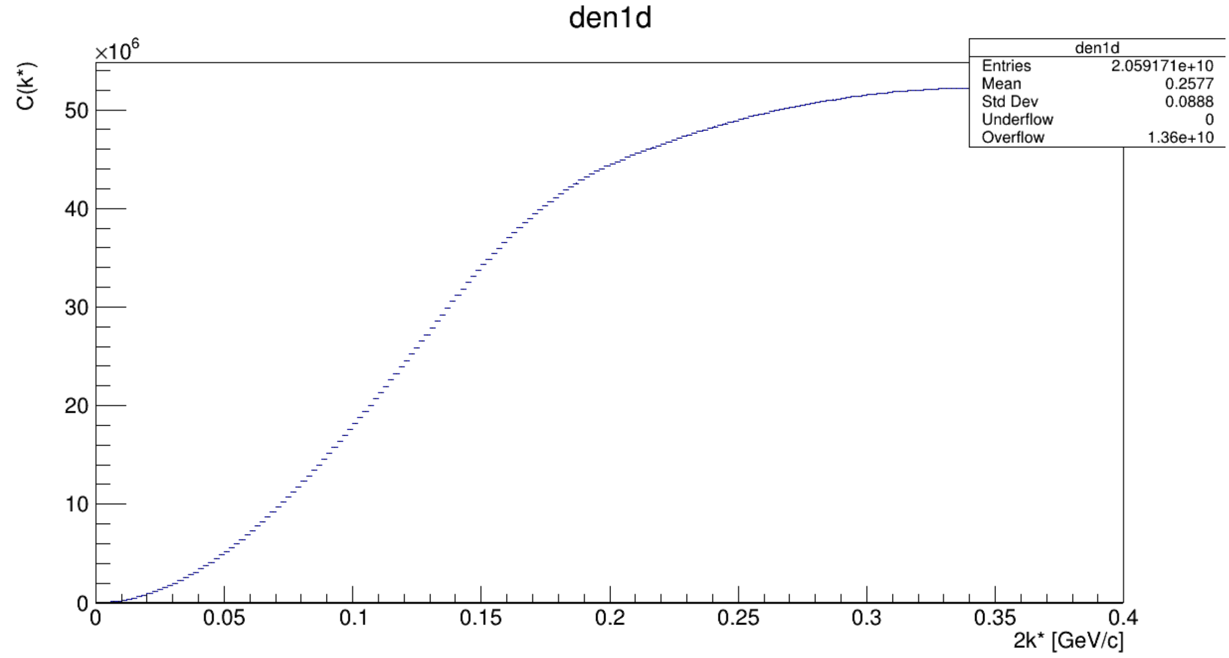

Fig.4 .B(q) is a distribution that does not contain quantum-statistical correlations. (methods: mixing events," rotation " of particles in space, non-identical pairs)

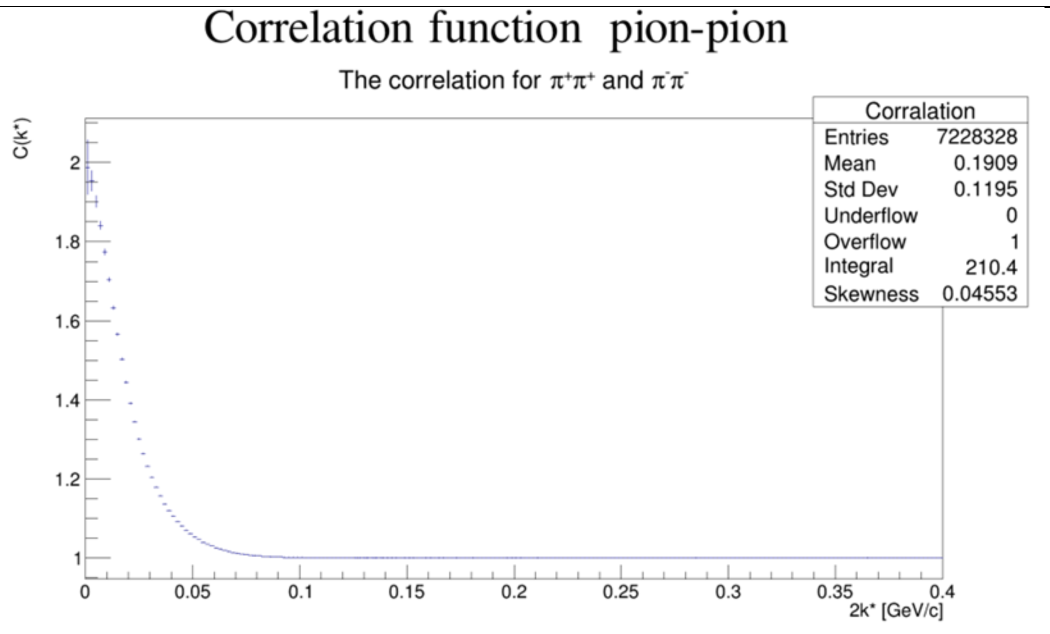

Fig.5. Correlation function for pion-pion pair

6. Conclusion

In conclusion, through the of period of this project: I learned how to use Therminator2 environment and use some commands of C++ programming language. I learned how to use Therminator2 software for events generation of different nucleus-nucleus and proton-nucleus collisions.

Acknowledgments

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