

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

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Wave 2

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Abstract

Heavy ion collisions allow us to study matter in regions of extreme energy and matter density. This is the state that the universe is thought to have been in right after the Big Bang, and such environments are hypothesised to make up the cores of neutron stars. Using a Monte Carlo event generator like Therminator 2, one can study the production of particles in relativistic heavy ion collisions. In this report, a description of how Therminator 2 can be used to this end will be provided. In addition, measurements of femtoscopic correlations were carried out for Au-Au collisions using hypersurfaces and velocity profiles describing data obtained by RHIC at $\sqrt{sNN} = 200\text{GeV}$ and 50% – 60% centrality. This was done by obtaining the correlation function for $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs.

1 Introduction

Built on data obtained in the 1950's from cosmic rays irradiating nuclear emulsions in high altitude balloons [1] and the pioneering theoretical work of Fermi [2] and Landau [3], high energy physics is a vibrant field of research. Among others, it allows the study of the state of the universe several microseconds after the Big Bang and densities ten times higher than those found in atomic nuclei. The hypothesis of a new state of matter, Quark Gluon Plasma (QGP) along with the formulation of a theory of the strong interactions - Quantum Chromodynamics (QCD) - led to the building of a series of particle accelerators, among which the most ambitious is the Large Hadron Collider at CERN, able to accelerate particles at energies of several TeV.

The high energies involved in heavy ion collisions cause the particle beams to undergo Lorentz contraction until they become disk-shaped. After the collision, QGP forms in the central region after which it starts to expand and cool down. With the energy dramatically decreasing, hadrons can now form in a process called *hadronization*. All mutual interactions cease when *freeze-out temperature* is reached. To get a grasp of the timescales and parameters involved in these collisions it is useful to look at figures 1 and 2.

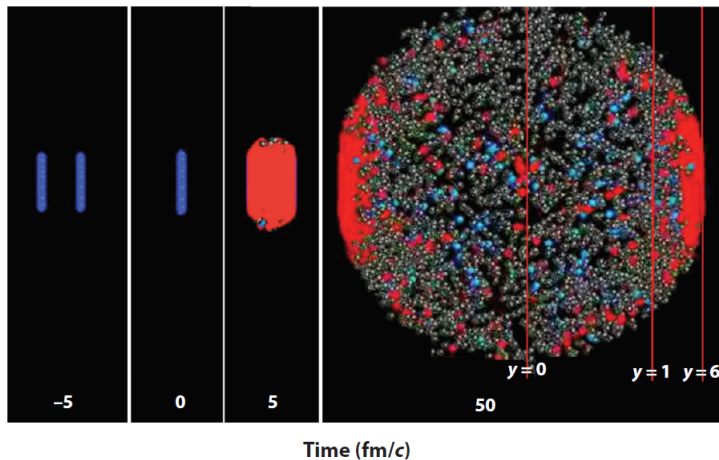


Figure 1: Evolution of a central collision of Pb-Pb nuclei at 2.76 TeV in time (fm/c). The red dots represent the QGP and the blue and grey dots represent hadrons, the hottest regions being correlated with high rapidity y [4].

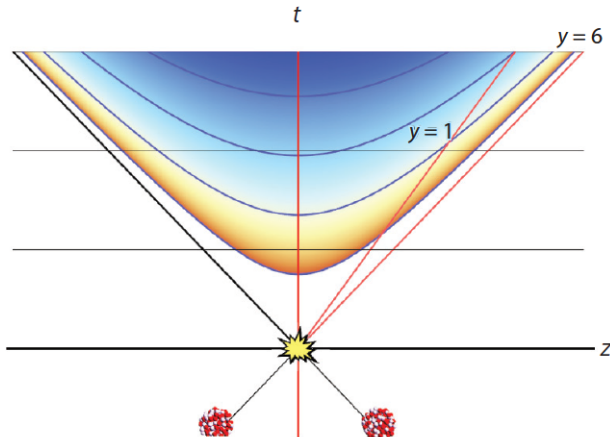


Figure 2: The space-time evolution can also be illustrated with a light-cone diagram. The two colliding beams move along the light cone and collide at $t = 0$. The emerging fragments travel along the light cone, while matter between the fragmentation zone remains in the central region. This matter is in the state of QGP and its evolution is described by relativistic hydrodynamics [1, 5].

2 Femtoscopic analysis and the correlation function

Hadron femtoscopy is responsible with the analysis of particle correlations and measures the space-time characteristic of particle production. Before giving an account of correlation femtoscopy however, it is instructive to look at what Bartke calls the "Geometrical picture of the collision". Also, correlations of identical bosons and identical fermions are underpinned by different physics and such we will only concern ourselves with the bosons. The simplest description is offered by the participant-spectator picture (PSP). PSP assumes that the colliding nuclei move along the same line and the only interacting nuclei are those who overlap, while the others are considered "spectators" [1]. This approximation is justified by the fact that at relativistic energies, the duration of the collisions is significantly shorter compared to other nuclear movement, and such, nuclei outside the overlap area should not experience any effect of the collision and stay cold. A key parameter in this discussion is the *centrality* of the collision and is closely related to the impact parameter b . To a good approximation, centrality can be estimated either by counting the non-interacting nucleons (such that lower centralities lead to fewer interactions) or by

appealing to characteristics of produced particles, like multiplicity. The Glauber model [6] allows the calculation of the number of nucleons involved in the collision for a given centrality and its premises are that nucleons can be treated as hard spheres whose distribution follows a Woods-Saxon potential and that one should neglect any internal motion and correlation between nuclei [1]. A thorough treatment of collision models is beyond the scope of this work, but Glauber’s ideas can be intuitively understood through the following diagrams published for the STAR detector from RHIC.

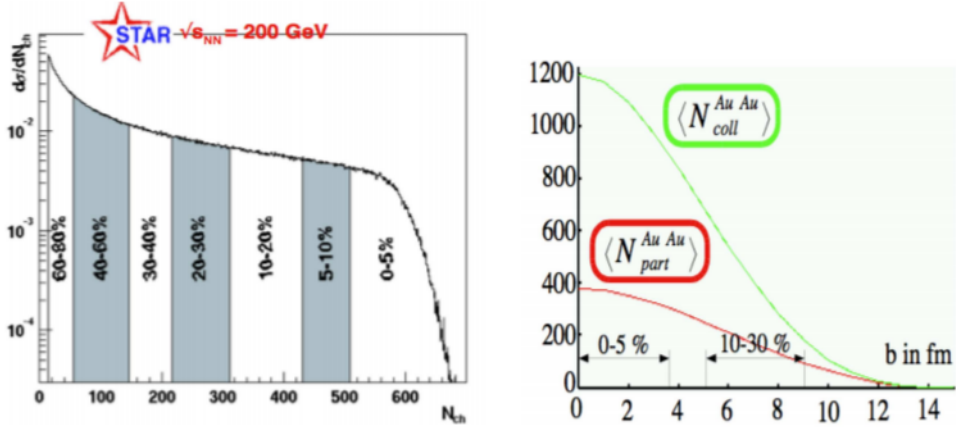


Figure 3: In the left panel, the multiplicity is plotted and the centrality ranges are drawn. One can observe that there is a similarity between the plotted distribution and the Woods-Saxon potential. In the right one, the correlations between the average number of participants, the average number of collisions and the impact parameter are shown. parameter in that centrality class. The range of impact parameter, corresponding to 0–5% and 10–30% centrality is indicated. [7]

The correlation function C is the ratio $C(q) = A(q)/B(q)$, where the numerator is the measured distribution difference $q = p_2 - p_1$ of the 3D momenta of the two particles taken from the same event and the denominator is a reference distribution of pairs of particles taken from distinct events. The numerator and denominator are normalized in the $q = \sqrt{|q|^2 - q_0^2}$ range used so that $C(q) \rightarrow 1$, which means there is no correlation [8]. More detailed descriptions of hadron femtoscopy can be found in chapter 14 at [1] and specifications about how the correlation femtoscopy is implemented in the code at [9].

3 THERMINATOR-2

The "THERMal heavy IoN generATOR 2" is a Monte Carlo event generator used to study the statistical production of subatomic particles in relativistic heavy ion collision [9]. It uses a library of standard hypersurfaces and velocity profiles corresponding to Au-Au, Pb-Pb and p-Pb collisions at RHIC and LHC. Along THERMINATOR, a second code is provided, FEMTO-THERMINATOR, whose role is to analyse the femtoscopic correlations, obtaining information about the spatial evolution of the system. Auxiliary operations are also available, but for the purpose of this paper, the discussion will be limited to the main ones. For further information please see the the THERMINATOR 2 manual [9]. A description of the tasks performed, from the installation of the program to the analysis of the results, is given in the following subsections.

3.1 Installing the Therminator 2 environment

THERMINATOR 2 uses the ROOT CERN Package, available for various operating systems. However, it is recommended to use Linux. Moreover, a C++ compiler is needed. For this project, Ubuntu 20.04 was installed on a virtual machine, followed by the ROOT environment (the latest version-v6.20.04). A full guide on how to install ROOT is available at the official website [10].

The documentation necessary for the installation of THERMINATOR 2, as well as the latest version, can be found at the official website [11]. The main steps regarding the installation of the program are outlined on the website too, but one must be aware that the last version of THERMINATOR 2 is from 2011 and the installation requires some modifications to the code. To this end, once the documentation has been downloaded, add the line *using namespace std;* in the **build/src/therm2_events.cxx** file. Moreover, the 119,123,127 lines of **Makefile** in the main directory were brought to the form

$\$(LD) \quad \hat{\$} -o \quad \$(LFLAGS) ,$

otherwise the linking would not have been done correctly. hindering the installation process.

3.2 Generation of events for Au-Au collisions

The commands used to run events are `./runall.sh` or `./therm2_events`. The event generated by default is created in the subdirectory **therminator2/events/lhyquid2dbi-RHIC AuAu200c2030Ti455ti025Tf145** [9] and the main parameters of the event are found in the name of the file. It is a Au-Au collision, using data from the RHIC. Its main characteristics are the energy of the collision, which takes place at 200GeV and the centrality (20%-30%). 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. Crucial to obtaining good statistics is ensuring that enough events are generated. 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.

3.3 Analysis of the generated data

To implement the femtoscopic formalism and generate the histograms showing the numerator and denominator of the correlation function shown in the figure below, the following command was run:

```
./therm2_femto <KTBIN> <EVENT_DIR> <EVENT_FILES> ,
```

The first parameter can take values from 0 to 3 and selects the transverse momentum bin of the pair, the second parameter specifies the path of the event and the third parameter the number of files in the directory. Setting the particle pairs that are about to be studied is done by changing the *Pair type* to pion-pion or kaon-kaon accordingly in the **femto.ini**

file. For this project, I have studied the $\pi\pi$ pairs, and the *Events to mix* was set to 50. Also, in the same file the Coulomb corrections were eliminated by adding in line 54 *Enable Coulomb Correction = no*. To open the histograms previously created, the command *root* is followed by the name of the file containing them. Then, by running the root command *new TBrowser* one can navigate with the file explorer all the root files.

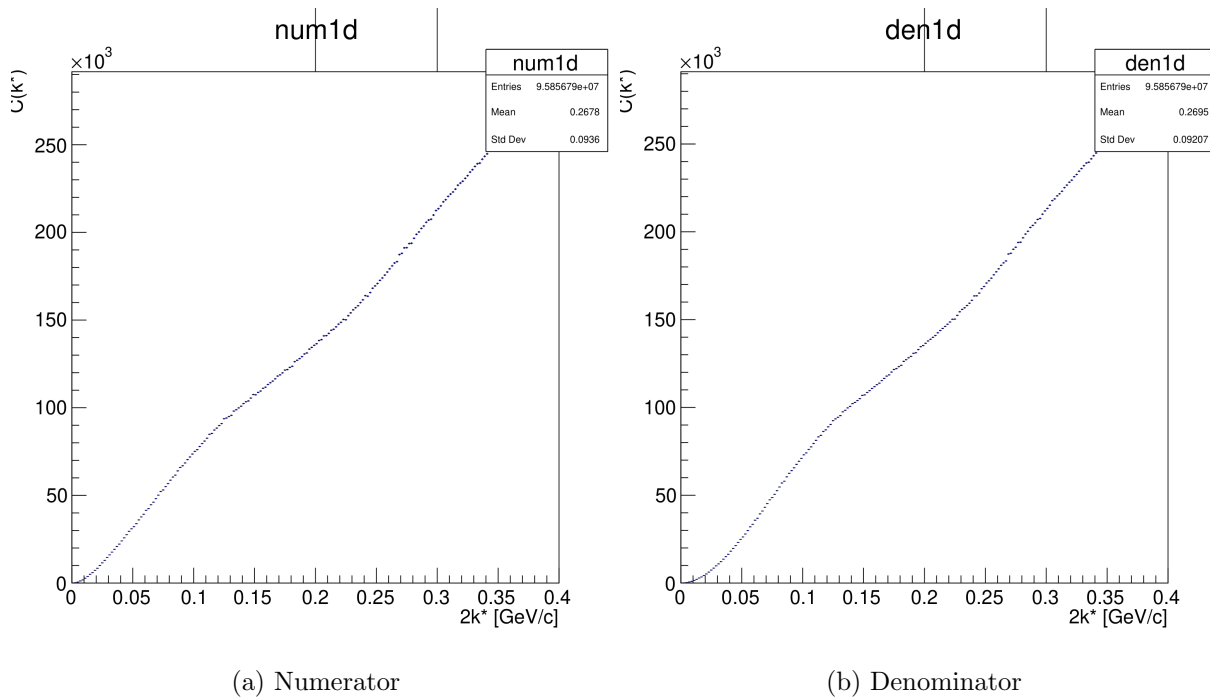


Figure 4: Generated histograms

3.4 Correlation function

The correlation function is obtained by dividing the numerator and denominator. To do this, a new compiler is needed, containing a function that takes the ratio of the histograms. The code was provided to me by Mr. Roslon.

```
// Created by Krystian Roslon on 18.11.2020
#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 corrF() { 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("ratq");
ratq->SetTitle("ratq");
ratq->Draw();}

```

4 Conclusion

The purpose of this report was to describe the steps made to obtain the correlation function for $\pi\pi$ pair production. Initially, the system requirements were outlined followed by

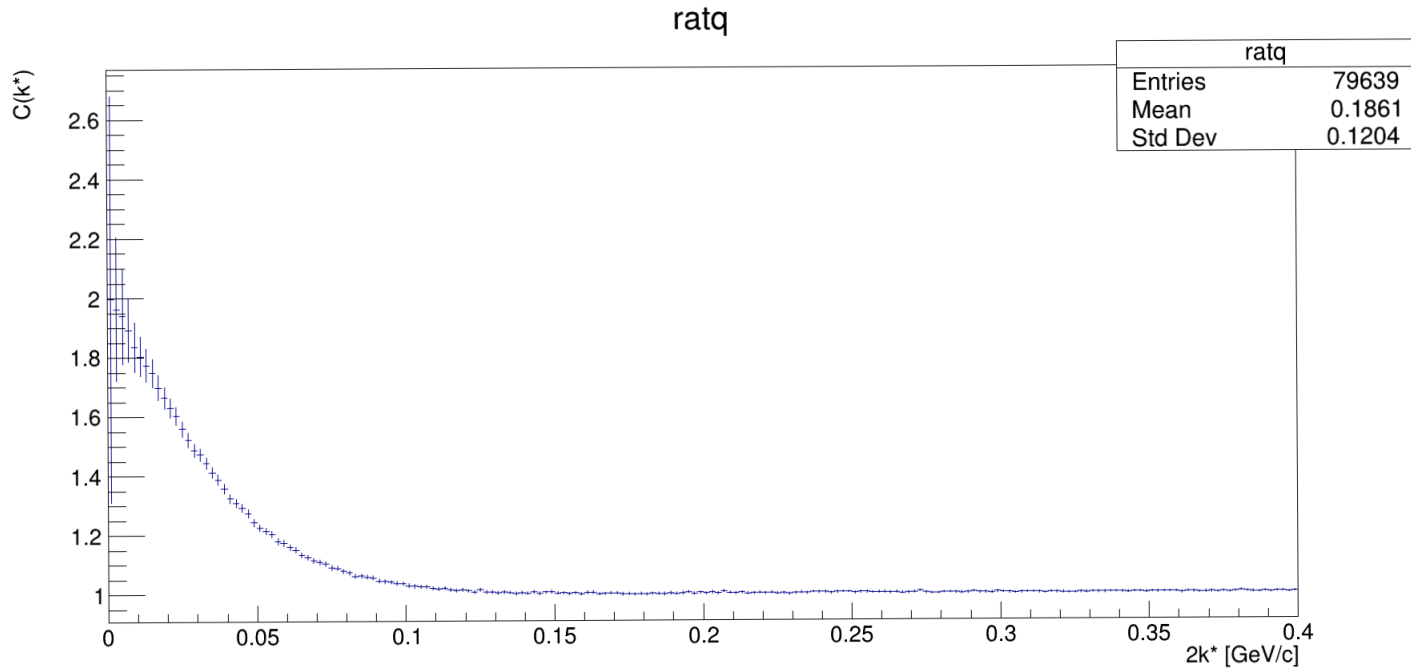


Figure 5: Correlation function of a $\pi\pi$ pair, generated in an Au-Au collision at 50%-60% centrality. One can see how the correlation function almost reaches 2.

instructions on how to install the THERMINATOR2 software. The second task was the generation of events, which was done for a host of Au-Au collisions at RHIC at various centralities. The third task consisted of producing histograms for the numerator and denominator of the correlation function and the fourth assignment was to run a compiler that will give the correlation function.

5 Acknowledgments

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