Generation and analysis of p-Pb collisions with Therminator2

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Abstract

Heavy-ion collisions allow to study matter in regions in extreme conditions. One of these examples is the quark-gluon plasma which formed right after the Big Bang. In this report, The Monte Carlo event generator Therminator 2 is used to generate heavy-ion collisions. The events are generated for proton-lead collisions with beam centre of mass energy of 5.02 TeV. These events are then analyzed and the correlation function for pions ($\pi^+\pi^+$ and $\pi^-\pi^-$) and kaons (K^+K^+ and K^-K^-) is measured.

1 Introduction

When faced with the great unknowns of the universe, physics is one of the tools needed to solve them. In particular, particle physics, with its study of the microscopic world, sheds light on the great mysteries of the cosmos. Research in particle physics has always been in the spotlight, even if sometimes disguised. The ancient Greeks, for instance, tried to explain what the smallest constituent of matter was, as did Democritus when he theorized the existence of infinite types of "atoms" [1]. The first main scientific finding made was John Dalton's discovery of the existence of a single unique type of particle: the atom.

Since then research has made huge advances. It has been discovered that what Dalton called the atom was not the smallest constituent, which was discovered to be made of protons, electrons and neutrons. Even some of those particles were not fundamental: protons and neutrons are made of quarks [2]. Even though we think we have reached an understanding of what the most fundamental particles are our understanding of the world around us is far from complete. There is much we cannot still explain with the knowledge we have and that is why research is crucial.

There are many facilities around the world that carry out research in particle physics through the use of accelerators. These devices enable to generate high energy collisions in which fundamental particles are produced and therefore can be studied. Among these facilities there is CERN (Conseil européen pour la recherche nucléaire). This centre was established to create an international research facility in which scientists with different backgrounds could work alongside one another. The LHC (Large Hadron Collider) consists of a 27-km long tunnel in which hadrons are accelerated.

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: Therminator 2 [3]. The obtained events are then analyzed and the correlation function for pions and kaons is measured.

2 Theory

2.1 The Standard Model

The theory that describes the fundamental particles and forces that make up matter is the Standard Model. It describes three out of the four fundamental forces of nature (electromagnetism, strong and weak interactions but not gravity) and classifies all the fundamental particles. There are two types of elementary particles: fermions and bosons. Fermions have half-integer $\left(\frac{1}{2}\right)$ spin and are further divided into quarks and leptons. Quarks have color charge and participate in strong interactions. These particles are the fundamental constituents of hadrons (i.e. protons and neutrons) and are never found in isolation due to the phenomenon of color confinement [4]. Leptons have no color charge and participate in electroweak interactions. The second type of elementary particles is bosons. These can either be scalar bosons with spin zero, as is the Higgs boson, or Gauge bosons with spin one. In particular, the three Gauge bosons are W^+, W^- and Z that are the vector bosons. Each type of particle then has its antiparticle with same mass but opposite physical charge and spin as shown in figure 1.

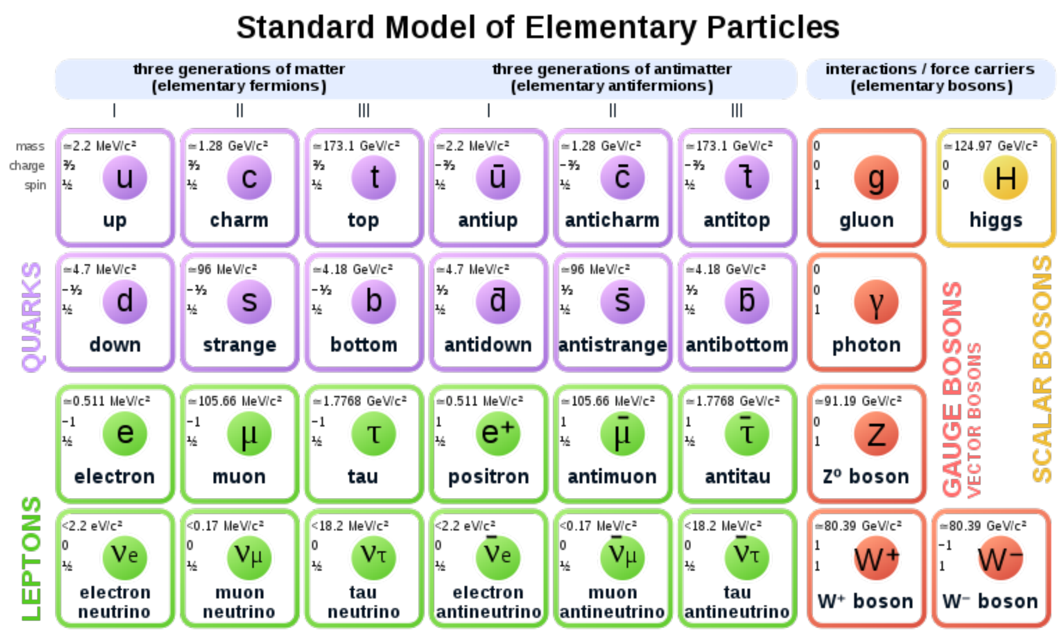

Figure 1: Complete figuration of the Standard Model with all the fundamental particles and their respective antiparticles [5].

2.2 Heavy-ion collisions

The above mentioned particles, interacting with each other, form more complex structures that then create matter as we know it. Atoms are made of protons (two up quarks and one down quark), neutrons (two down quarks and one up quark) and electrons. One particular type of atoms is ions. These are charged atoms (or in alternative molecules). The interaction and properties of these types of particles are crucial steps in the study of modern particle physics. The importance of the study of their collisions lies in the fact that the products of their decays can mirror early Universe conditions. In particular, these processes allow to study matter in extreme conditions such as high densities and pressures. It is widely known that these are the conditions right after the Big Bang, the big explosion that is thought to have given birth to our universe. After each interaction, a particular state of matter, called the Quark Gluon Plasma (QGP) arises. Its name is due to the fact that it is a soup of quarks and gluons, which represents the core from which protons and neutrons are generated. The collisions evolve following definite stages. When two disks (the ions) collide both loose some energy but often are not deviated by large angles. In high energy collisions, the maximum energy is obtained when the two Lorentz

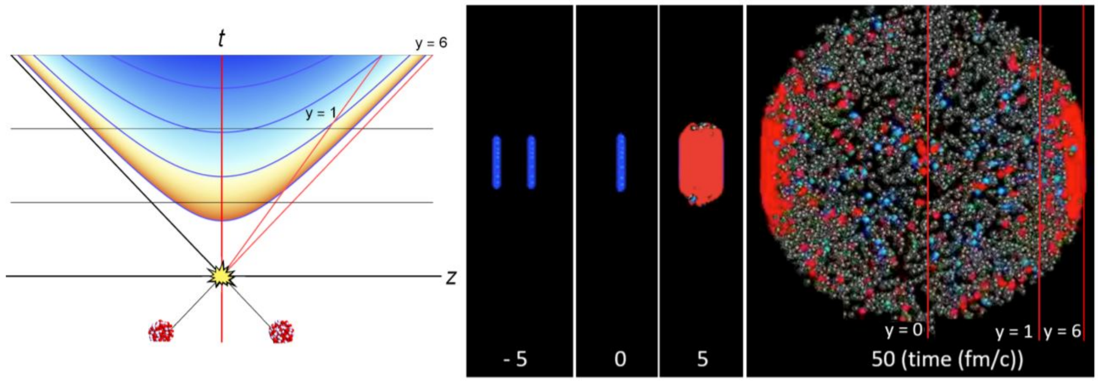

Figure 2: Example of the evolution of heavy ion collisions. On the left, a space-time picture of the collision is shown. The colors represent the temperature of the QGP. Ont the right, a representation of a PbPb collision at 2.76 TeV [6].

contracted nuclei have just collided. Then, the results of the collision, which is gluons and quarks, are encountered in high quantities (in the order of 30000 particles). For this reason, this system is called Quark Gluon Plasma: its constituents cannot be identified as distinct individual hadrons and create a collective medium that behaves as an hydrodynamic fluid. Finally, the particles reach a stage called freeze out in which all mutual interactions cease [6]. An example of these interactions can be found in Figure 2.

3 Femtoscopic analysis

The tool needed to understand and analyze these types of collisions is femtoscopic analysis. This tool allows to measure the space-time characteristics of the collision products and 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 [7].

The correlation function of a pair of particles is defined as:

$$C(p_1, p_2) = \frac{\mathcal{P}(p_1, p_2)}{\mathcal{P}(p_1)\mathcal{P}(p_2)}, \tag{1}$$

in which the numerator is the measured distribution difference $\mathrm{q} = \mathrm{p}_1 - \mathrm{p}_2$ of the three-dimensional momenta of the two particle form the same event and the denominator is the distribution of the two particles being taken from different events. These values are normalized so that the correlation function will tend to 1 when there is no correlation between the particles.

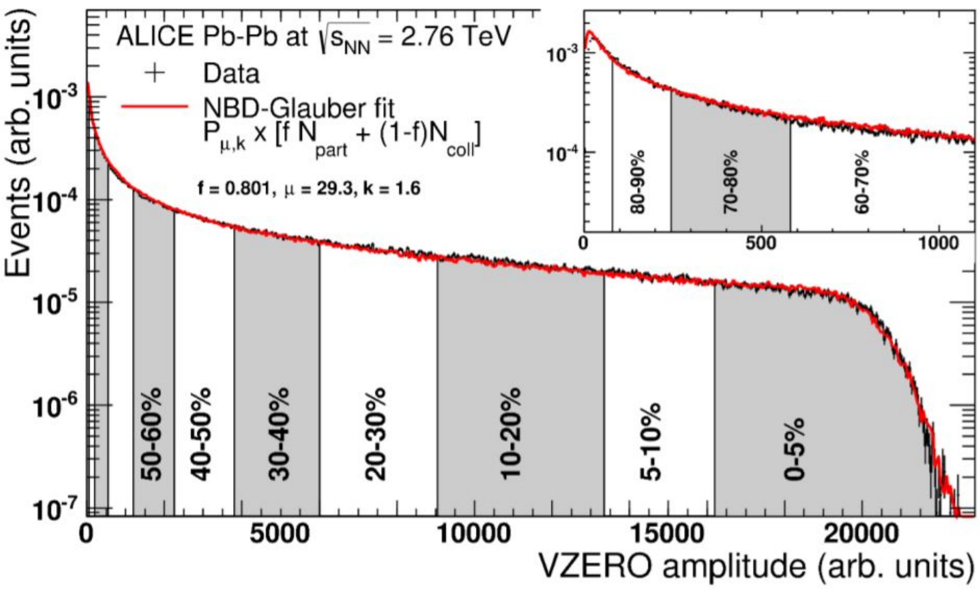

Figure 3: Example of the measurement of the centrality of Pb-Pb collisions at the ALICE detector in the LHC. The centre of mass energy is 2.76 TeV.

4 Package installation and event generation

To generate the events, the package Therminator 2 has to be installed. Therminator is a THERMal and heavy IoA generATOR, whcih studies the statistical properties of heavy ion collisions. First a virtual machine was installed which could support Ubuntu 18. It is crucial to download this version of the software as Ubuntu 20 presented some problems in compiling the package. Then, the Therminator 2 package has to be downloaded following the manual instructions [3]. The website to the download page is: https://therminator2.ifj.edu.pl/. After the completed download of the package some modifications need to be done. In the file build/src/therm2_events.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 correct files were sent by Muhammad Ibrahim. To compile the package after the above mentioned corrections are implemented, the command `make` has to be run in the terminal.

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. Finally, to generate the requested events the command `./therm2_events` has to be run in the terminal. Due to limited computational power, I was specifically sent files of p-Pb collisions thanks to Muhammad Ibrahim.

5 Femtoscopic analysis

To analyze the data and measure the correlation function of the heavy ion collision some of the files have to be modified. To start the default run for the analysis the following command has to be run

```
./therm2_femto <KTBIN> <EVENT DIR> <EVENT FILES>
```

replacing the variables in angle brackets with the appropriate ones. k_T bin 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. To run the full list of events, due to the fact that these were generated in different directories which each contained ten events some code has to be added in the therm2_femto.cxx file on line 717.

```
for(int i=1; i<tEventFiles; i++) {
for(int k=0; k<10; k++){
char Bu[kFileNameMaxChar];
sprintf(Bu,"%slhyquid3v-LHCpPb5020s0.5Ti242t0.60Tf150e%03i/event%03i.root"
,sEventDir.Data(),i,k);
PRINT_DEBUG_1("Adding le:" Bu);
chn->Add(Bu);
chnEv->Add(Bu);}}
```

To create the Correlation function graph after obtaining the numerator and denominator the following code was copied in a C++ file called corr_function.cpp which was provided thanks to Krystian Roslon.

```
TFile* tInRootFile;
TH1D* numq;
TH1D* denq;
TH1D* ratq;
void Correlation Function(){
tInRootFile = new TFile("<PATH OF FILE TO ANALYZE>");
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 KK");
ratq->SetTitle("Correlation Fucntion of KK");
ratq->Draw(); }
```

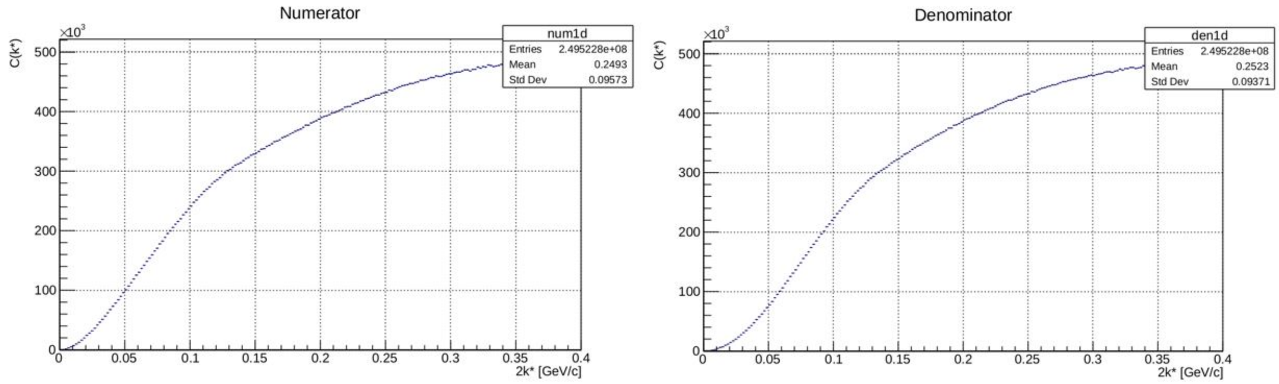

Figure 4: Example of the numerator and denominatr graphs obtained from the analysis of pion pairs and $k_T$bin 0.

To load the .cpp file the command `root` needs to be run, then `.L corr_function.cpp` to load the file, and finally the main function has to be called `corrF()`. The resulting plot is shown in Figure 5.

Finally, to change the type of particle for which the correlation function is measured, in the femto.ini file the PairType line has to be changed from `pion-pion` to `kaon-kaon` paying particular attention not to add any blank spaces. The obtained graph is shown in Figure 6.

6 Conclusion and further analysis

To conclude, events for heavy-ion collisions were generated making use of the Monte Carlo generator Theminator 2. Using femtoscopic analysis of p-Pb collisions, the correlation function for same change pion and kaon pairs are measured. As a further extension of the project, correlation fucntions could be measured for K^+K^- to search for the presence of ϕ mesons.

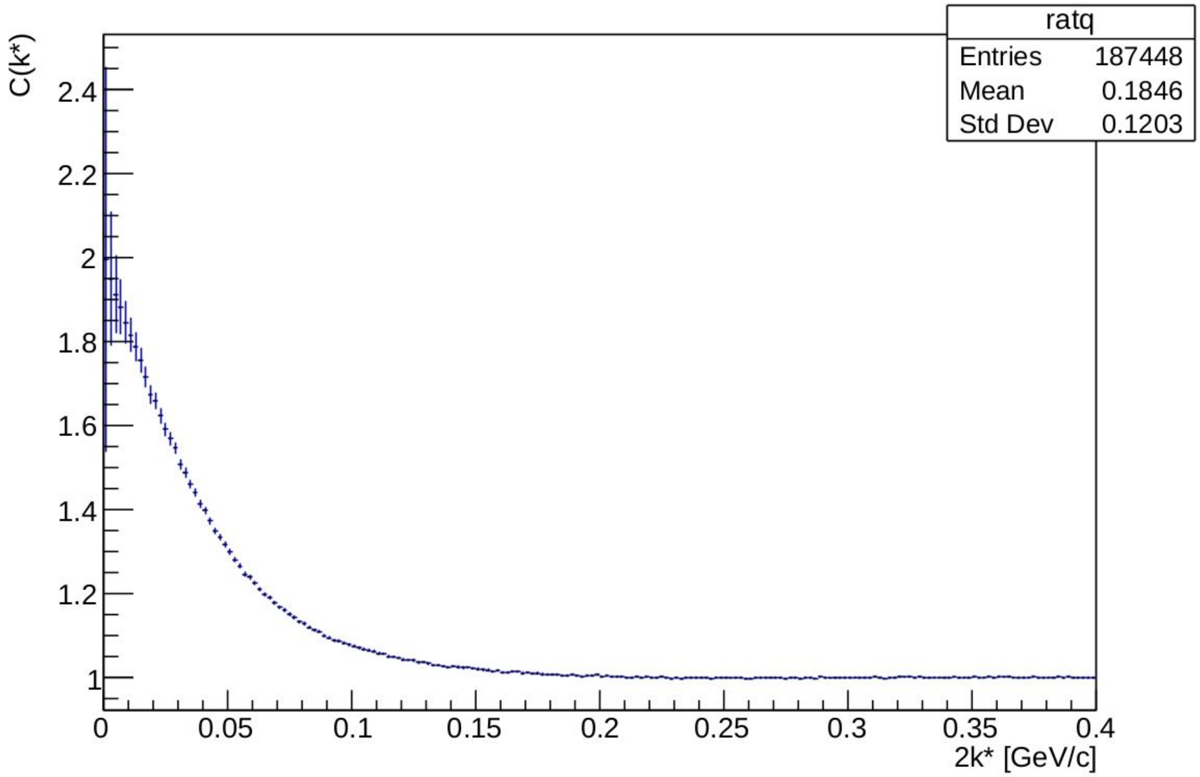

Figure 5: Correlation function for same charge pion pairs in $k_T$bin 0.

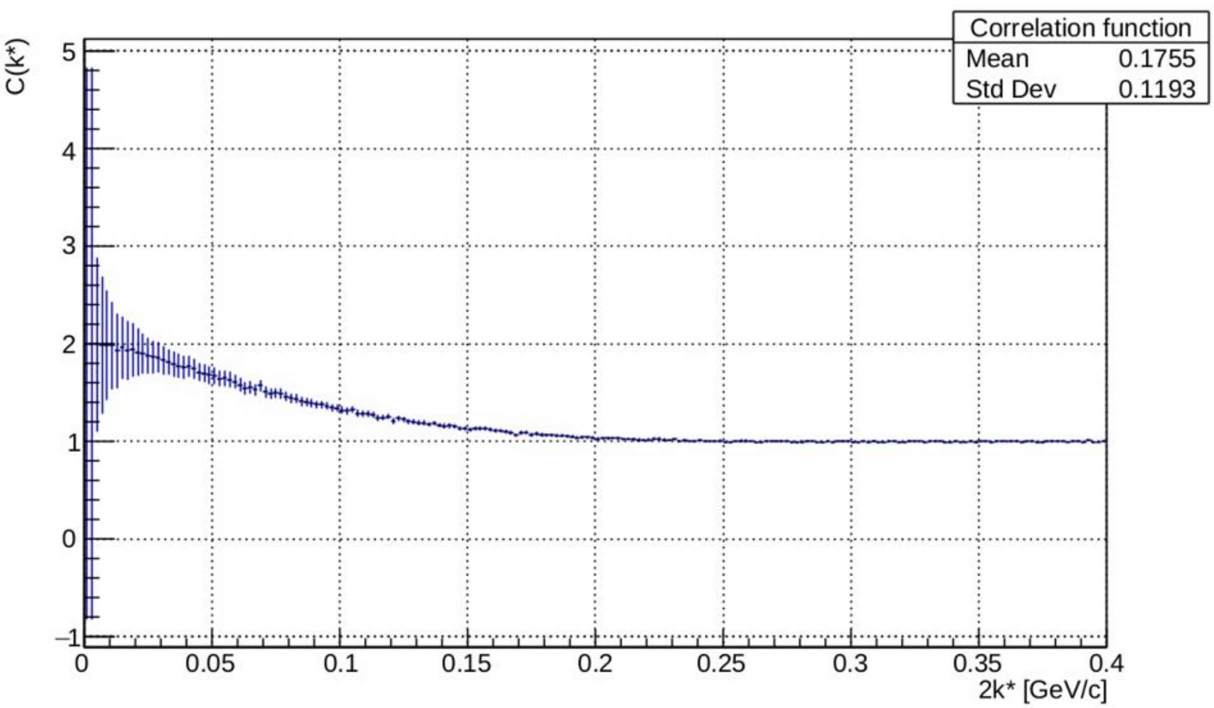

Figure 6: Correlation function for same charge kaon pairs in $\mathrm{k_T}$bin 1.

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