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 – Therminator 2

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Abstract

For a few millionths of a second, shortly after the Big Bang, the universe was filled with particles moving at near light speed, dominated by quarks and gluons. In those first moments of extreme temperature, however, quarks and gluons were bound only weakly, free to move on their own in what's called a **quark-gluon plasma** which can be recreated by collision of heavy ions at high energies. One of the tools used to describe systems created during the high energy collisions is the femtoscopic correlation technique. Using the **Monte Carlo generator – Therminator2**, we have generated events for **Pb - Pb collision modelled according to data obtained by the LHC at $\sqrt{s_{NN}} = 5.5\ TeV$ and at a centrality of 60-70%.** We analysed the femtoscopic correlation function for identical particles such as pions $(\pi^+\pi^+\ and\ \pi^-\pi^-)$ and kaons $(K^+K^+\ and\ K^-K^-)$, and also for non-identical particles such as pions-anti pions $(\pi^+\pi^-)$.

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Introduction

Quark Gluon Plasma

It has been postulated that the early Universe, immediately after the Big Bang, consisted of asymptotically free quarks and gluons. Statistical QCD calculations predict that at high temperature and/or energy **density a system of strongly interacting particles, consisting of quarks and gluons, is formed where the particles would interact fairly weakly due to asymptotic freedom**. Such a phase consisting of (almost) free quarks and gluons is termed as the quark gluon plasma (QGP).[1] They are coupled such that they form a collective medium that expands and flows as a relativistic hydrodynamic fluid with a remarkably low viscosity to entropy density ratio $\eta/s \approx 1/4\pi$, within a time that can be shorter than or of order 1 fm/c in the rest frame of the fluid.[2]

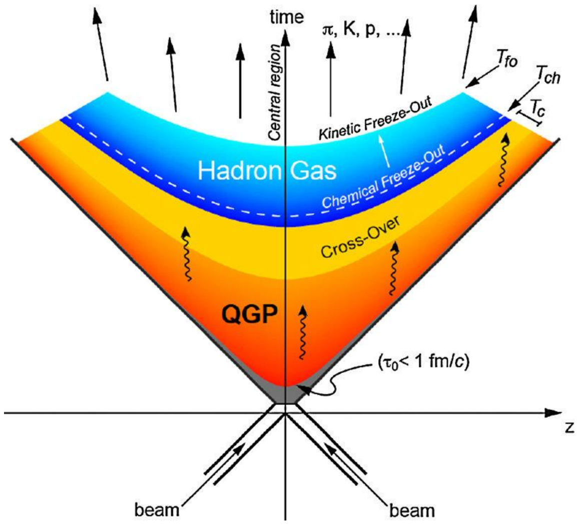

Figure 1.1 – Space Time diagram of QGP Formation [a]

Heavy Ion Collisions

Heavy Ion collisions aim to study the states of matter consisting quarks and gluons, recreating the state of matter right after the Big Bang and before the formation of nucleons. It aims to verify the predictions of the Standard Model consistent with quantum chromodynamics (QCD). QCD calculations predict the presence of weakly interacting system of quarks and gluons due to asymptotic freedom, called Quark-Gluon Plasma (QGP). By colliding two relativistically accelerated heavy ions, it is possible to compress and heat the nuclei to such an extent that their individual protons and neutrons overlap, creating a region of enormously high energy density, where a relatively large number of free quarks and gluons can exist for a brief time.[1]

As the colliding particles recede from each other, a small region of space and time, containing high energy is deposited. **This is the region of hydrodynamic evolution that sees the formation of QGP**. On further expansion and cooling of this plasma, hadronization takes place and after some time, hadronic matter freezes in the hadronic freezeout stage.

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].

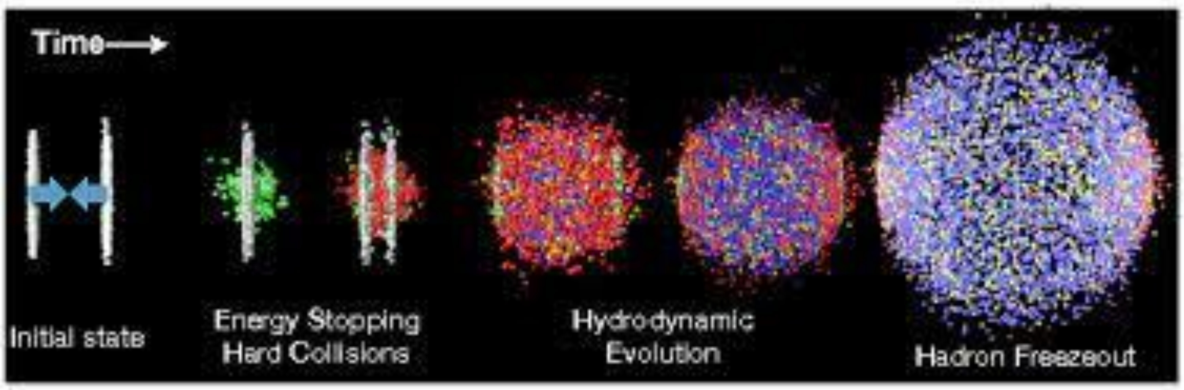

Figure 1.2 - Evolution of heavy ion collisions [1]

Pb-Pb Collisions

Heavy Ion collisions are an integral part of the Linear Hadron Collider (LHC) at CERN for study of QGP matter. The lead isotope accelerated at LHC are $^{208}_{82}\boldsymbol{Pb}$. The LHC acceleration process gradually strips away all of the lead atoms' electrons, leaving a beam composed only of lead nuclei.

In heavy ion reactions, inclusive particle ratios and spectra at low transverse momentum are consistent with simple descriptions by statistical/thermal and hydrodynamical models, where particle ratios are determined during hadronization at or close to the QGP phase boundary ("chemical freeze-out"), whereas particle spectra reflect the conditions somewhat later in the collision, during "kinetic freeze-out".[3]

The Therminator2 generates events at the LHC **Pb+Pb data at $\sqrt{s_{NN}} = 5.5\ TeV$ and centrality of 60-70% having an initial central temperature of 500 MeV, hydrodynamic starting time 100 fm/c and the freeze out temperature at 145 MeV**

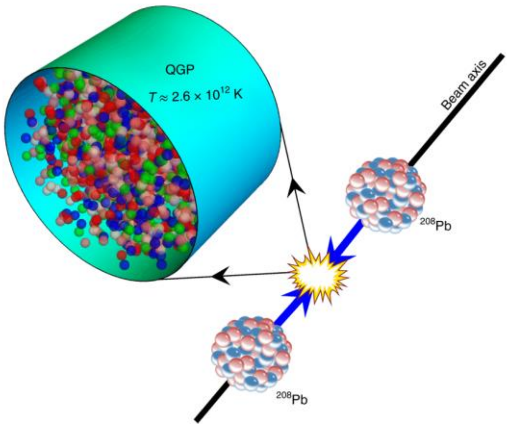

Figure 1.3 – Schematic representation of Pb-Pb collision at the LHC [b]

Femtoscopy

Correlation femtoscopy (commonly referred to as femtoscopy or HBT, Hanbury Brown and Twiss interferometry), measures the space-time characteristics of particle production using particle correlations due to the effects of quantum statistics and strong and Coulomb final-state interactions.[4]

The femtoscopic analysis relies on the correlation of the transverse momentum of a pair of particles in the center of mass system to find information about their production. The observable of interest **$C(\overrightarrow{p_1}, \overrightarrow{p_2})$ is defined as the ratio of the probability of measuring simultaneously two particles with momenta $\overrightarrow{p_1}$ and $\overrightarrow{p_2}$, to the product of the single-particle probabilities:**

$$C(\overrightarrow{p_1}, \overrightarrow{p_2}) = \frac{P(\overrightarrow{p_1}, \overrightarrow{p_2})}{P(\overrightarrow{p_1})P(\overrightarrow{p_2})}$$

The numerator describes the difference in transverse momentum distribution of the two particle p_1 and p_2 from a single event and the denominator describes the transverse momentum distribution of the two particles in separate events. The average transverse momentum of the pair is denoted by k_T.

Femtoscopy also studies of heavy-ion collisions concerns the ratio of radius components in the transverse plane. The strong hydrodynamic flow produces significant positive spacetime correlations during the evolution of the freeze-out hypersurface. This influences the extracted radius parameters of the system in the plane perpendicular to the beam axis. The radius along the pair transverse momentum is reduced by the correlation with respect to the perpendicular one in the transverse plane.[4] This ratio of radius components is important in defining the impact parameter of the collisions, used to calculate the collision centrality.

Therminator2

THERMINATOR 2 – **THERM**al heavy **I**o**N** gener**ATOR** version **2**, is a Monte Carlo event generator that is dedicated to studying the statistical production of particles in relativistic heavy ion collisions.

It is written in C++ and uses the standard CERN ROOT environment such that, apart from model applications, the code can be easily adapted for purposes directly linked to experimental data analysis, detector modelling, or estimates for the heavy-ion experiments at RHIC, LHC, SPS, FAIR, or NICA.[5]

It includes a library of standard sets of hypersurfaces and velocity profiles, which describe the Au+Au data at the highest RHIC energy and the LHC Pb+Pb collisions for various centralities. It has a separate code for FEMTO-THERMINATOR to carry out femtoscopic correlation calculations.

Installing Therminator2

Installing the Therminator2 event generator has certain pre-requisites. Since the Therminator2 uses the standard ROOT environment, the CERN ROOT package should be installed. It also requires a C++ compiler. It is recommended to use a Linux operating system, and for this reason a virtual machine was installed with Ubuntu 18.04.6, and the necessary C++ compiler and ROOT environment was set up. Information relating to the ROOT set up can be found in their official website.[6] The manual for set up of Therminator2 contains most of the information for installing it[5], but some minor modifications to the code are required due to changes in the syntax of code and compilers over the years.

After the Therminator2 package is downloaded and unzipped, add the line **'using namespace std' in the file ./build/src/therm2_events.cxx** after including all the necessary header files. **And in line 119, 123 and 127 of the Makefile**, convert

$(LD) $(LFLAGS) $^ -o $@   to $(LD) $^ -o $@ $(LFLAGS)

so that the C++ codes are linked to the ROOT environment.

After making the above changes, the Therminator2 is installed and compiled successfully using the command **"make".**

Generation of Events

For this project, I was asked to generate Pb-Pb collision events using the hypersurface and velocity profiles anticipated for LHC at $\sqrt{s_{NN}} = 5.5\ TeV$, at a centrality of 60-70% having an initial central temperature of 500 MeV, hydrodynamic starting time 100 fm/c and the freeze out temperature at 145 MeV. The freeze out model used is the **2+1D boost invariant hydrodynamic model**.

Certain changes had to be made in the C++ codes before generating events using the command **"./therm2_events".** These changes had to be made to generate events other than the type set as default. In the file **events.ini** of Therminator2, the number of events generated, in **line 55 was edited to be 1000**. The freeze out model is specified in line 46. In the file **./fomodel/lhyquid2dbi.ini** of Therminator2, the hypersurface, freeze file and event subdirectories were changed to **'LHCPbPb5500c6070Ti500ti100Tf145.xml' in line 41, 42, 46 and 47 respectively.** Also changed the .xml file to "LHCPbPb5500c6070Ti500ti100Tf145.xml" at line 140 of the Makefile of Therminator2.

A new folder with the name of the event will be generated in the events folder of the Therminator2 directory. A total of 20,000 events were generated and 40 event*.root files were created containing 500 events in each file. Obtaining statistically stable results requires a large number of events between 20,000-50,000. Hence 20,000 events were generated.

Femtoscopic Analysis in Therminator2

Therminator2 package includes a separate code for running femtoscopic analysis called **therm2_femto**. It calculates the correlation function for identical and non-identical particle pairs. The generated events are stored in event*.root files contains the information of particle produced in the heavy ion collision. These event files are used to perform the femtoscopic analysis.

The correlation function was calculated for 4 bins of transverse momentum of the particles:

k_T = 0 : 0.15 – 0.25 GeV

k_T = 1 : 0.25 – 0.35 GeV

k_T = 2 : 0.35 – 0.45 GeV

k_T = 3 : 0.45 – 0.6 GeV

The file **./build/src/therm2_femto.cxx** contains the code for all the calculations. The correlation functions are obtained through a numerical implementation of

$$C(\vec{q},\vec{k}) = \frac{\sum_i \sum_{j\neq 1} \delta_\Delta(\vec{q} - \vec{p_i} + \vec{p_j})\delta_\Delta(\vec{k} - \frac{1}{2}(\vec{p_i} + \overrightarrow{p_j}))\left|\Psi(\overrightarrow{k^*},\overrightarrow{r^*})\right|^2}{\sum_i \sum_j \delta_\Delta(\vec{q} - \vec{p_i} + \vec{p_j})\delta_\Delta(\vec{k} - \frac{1}{2}(\vec{p_i} + \overrightarrow{p_j}))}$$

and

$$\Psi = \frac{1}{\sqrt{2}}\left(e^{i\overrightarrow{k^*}\overrightarrow{r^*}} + e^{-i\overrightarrow{k^*}\overrightarrow{r^*}}\right)$$

(No Coulomb effects). As described in the previous sections, particles generated by THERMINATOR2 are grouped into events, as in experiment. In each event every charged pion is combined with every other pion of the same charge. For each pion pair, $|\Psi|^2$ is calculated and added to the numerator in a bin corresponding to the pair's q_{out}, q_{side} and q_{long}. At the same time, 1 is added to the denominator in the corresponding bin. The resulting ratio yields the correlation function.[5]

The analysis was run using the command **"./therm2_femto <k_T bin> <event directory> <number of event files>"**

The calculated correlation functions were stored successfully in femto*.root files containing one dimensional histograms of the numerator and denominator.

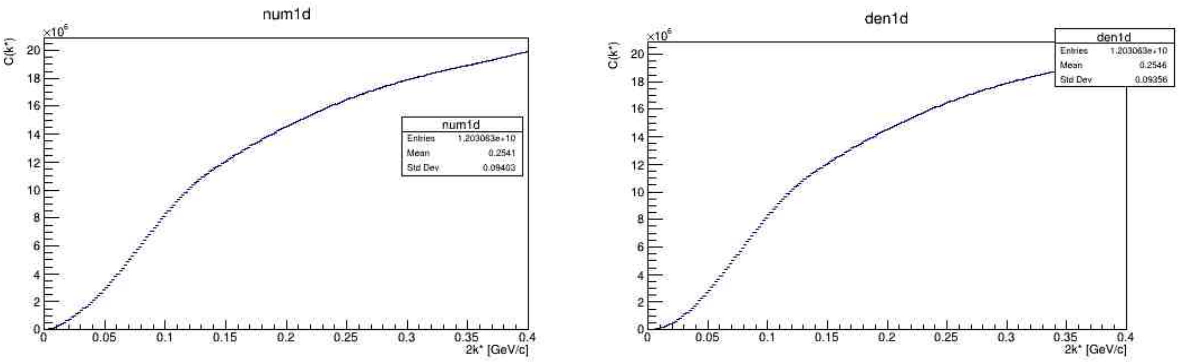

Figure 3.1 – Numerator and denominator of the correlation function for k_T bin = 0

The correlation functions can be calculated by dividing the numerator and denominator obtained in the femtoscopic analysis for each k_T bin. The graph of the correlation function was obtained by creating a root macro file written in C++ as follows:

```
#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* num0;

TH1D* den0;

TH1D* rel0;

TH1D* num1;

TLegend* legend;

void Correlation(){

tInRootFile = new TFile("/home/divya/All/therminator2/events/lhyquid2dbi-LHCPbPb5500c6070Ti500ti100Tf145/femtokpluskminus0a.root");

num0 = new TH1D(((TH1D) tInRootFile->Get("den1dptrue")));

den0 = new TH1D(((TH1D) tInRootFile->Get("num1dntrue")));

rel0 = new TH1D(*num0);

rel0->Reset("ICE");

rel0->Divide(num0, den0, 1.0, 1.0);

rel0->SetName("Kaon Anti Kaon Correlation");

rel0->SetTitle("Correlation function for kaon-anti kaon");

rel0->Draw();

}
```

This is the basic code used. All the k_T bins can be graphed on the same histogram by making further modifications to the code. The macro file and the void function should have the same name. This can be called using the command **"root Correlation.C".**

Analysis of identical particles

No changes had to be made for finding the femtoscopic correlation functions of **identical particles (particles of the same type, mass, charge and particle id)** such as pions $(\pi^+\pi^+ \ and \ \pi^-\pi^-)$ and kaons $(K^+K^+ \ and \ K^-K^-)$. Identical particle femtoscopy can be useful to determine the relation between specific space-time information and the source radii. The correlation functions obtained for identical particles are given below:

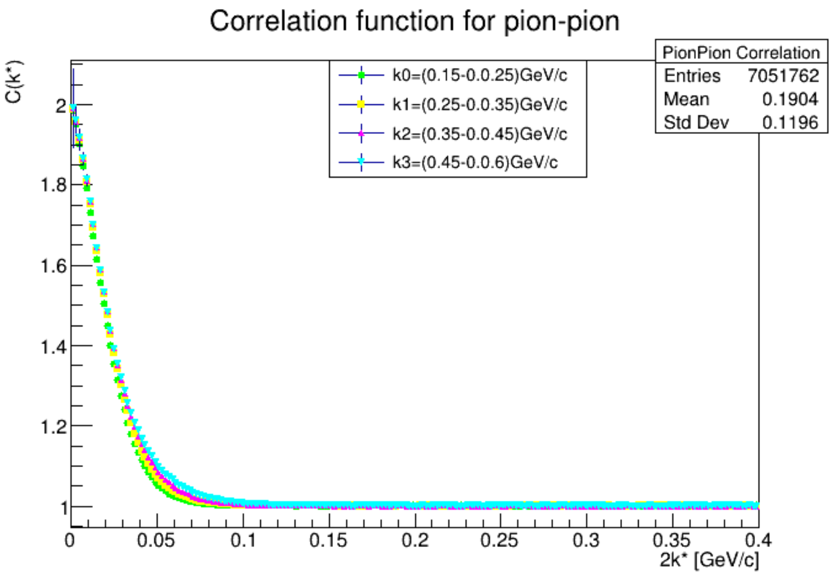

Figure 3.2 – Correlation function for pion pairs ($\pi^+\pi^+$ *and* $\pi^-\pi^-$) for various k_T bins

No graphs were generated for Kaon pairs due to very low number of kaon particle production.

Analysis of non-identical particles

For non-identical particles, femtoscopic analysis was run for pions-anti pions ($\pi^+\pi^-$). For unlike particle correlation functions, the interaction is dominated by Coulomb interactions [7] which is enabled by setting **docoulomb = 1in the ./build/src/therm2_femto.cxx** file. Certain changes had to be made in the C++ code for non-identical particle which are as follows:

- In read parameters section:

  Else if (tPairType == "pionplus-pionminus") pair type = 8;

- In the pair and particle cuts section:

  Case 8:

  ptmin1 = PTMIN

  ptmin2 = PTMIN

  ptmax1 = PTMAX

  ptmax2 = PTMAX

- At the end of pair and particle cuts section:

Else if (pairtype == 8)

partpid = PIPID

partpid2 = -PIPID

- In the save histograms to files section:
  else if (pairtype == 8) sprintf(bufs,”% sfemtopipluspiminus%i%s . root ” , sEventDir.Data( ) , nbin , onlyprim ? ” p ” : ” a ”) ;
- In the InitializeGamow() function:
  else if (pairtype == 8)

  { pionac = 387.5 / 0 .197327;

  partpid = PIPID ;

  partpid2 = -PIPID ; }
- Commented the section - **if (fabs(mKStarSigned)<0.1)** – in the non-identical correlation section of the file
- Closed the file using **ofile->Close ()**; at the end of save histogram file section.

The correlation function obtained for pions-anti pions $(\pi^+\pi^-)$ is

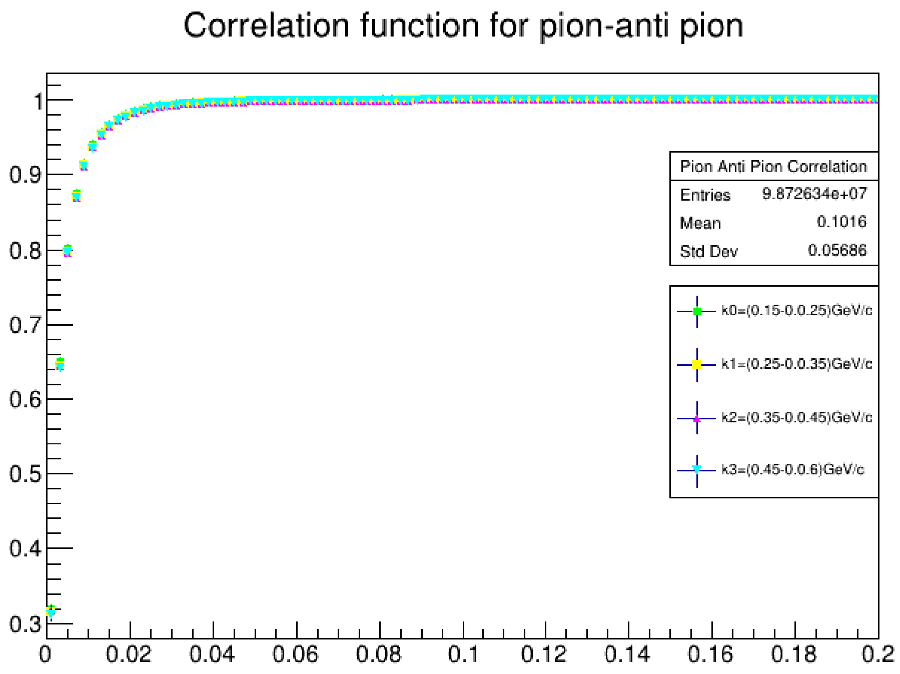

Figure 3.3 – Correlation function for pion-anti pion $(\pi^+\pi^-)$ for various k_T bins

Conclusion

In conclusion, using the Monte Carlo generator – Therminator2, we have generated events for Pb - Pb collision modelled according to data obtained by the LHC at $\sqrt{s_{NN}} = 5.5\ TeV$ and at a centrality of 60-70%. Then we analysed the femtoscopic correlation function for identical particles such as pions $(\pi^+\pi^+\ and\ \pi^-\pi^-)$ and kaons $(K^+K^+\ and\ K^-K^-)$, and also for non-identical particles such as pions-anti pions $(\pi^+\pi^-)$.

References

[1] Nayak, Tapan. (2012). Heavy Ions: Results from the Large Hadron Collider. Pramana. 79. 10.1007/s12043-012-0373-7.

[2] Heavy Ion Collisions: The Big Picture and the Big Questions: Wit Busza, Krishna Rajagopal, Wilke van der Schee. Annual Review of Nuclear and Particle Science 2018 68:1, 339-376

[3] First Results from Pb+Pb Collisions at the LHC: Berndt Müller, Jürgen Schukraft, Bolesław Wysłouch. Annual Review of Nuclear and Particle Science 2012 62:1, 361-386

[4] Kaon femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV: S. Acharya ***et al.*** (ALICE Collaboration). Phys. Rev. C 96, 064613 – Published 21 December 2017

[5] Mikolaj Chojnacki, Adam Kisiel, Wojciech Florkowski, and Wojciech Broniowski. THERMINATOR 2: THERMal heavy IoN generATOR 2. Comput. Phys. Commun., 183:746–773, 2012

[6] https://root.cern/install/

[7] FEMTOSCOPY IN RELATIVISTIC HEAVY ION COLLISIONS: Two Decades of Progress: Michael Annan Lisa Scott Pratt Ron Soltz Urs Wiedemann. Annual Review of Nuclear and Particle Science 2005 55:1, 357-402

[a] Loosely-bound objects produced in nuclear collisions at the LHC - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Colour-online-Space-time-diagram-of-a-heavy-ion-collision-of-two-nuclei-colliding-at_fig7_332366456

[b] Thermodynamics of hot strong-interaction matter from ultrarelativistic nuclear collisions - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Schematic-representation-of-a-Pb-Pb-collision-at-the-LHC-The-great-density-achieved_fig1_340291234