JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE START PROGRAMME

Particle production and pion-pion femtoscopy in Therminator 2 model

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1 Abstract

Monte Carlo event generators are an essential part of almost all experimental analysis since allows us to compare with theoretical predictions. In this work, we present some basic results on hadron production in Au+Au collisions at RHIC energies of $\sqrt{s_{NN}} = 200$ GeV using the Therminator 2 model. As well as the measurement of the two-particle femtoscopy correlations for $\pi^{+}\pi^{+}$, using the FEMTO-THERMINATOR code included. This can be seen as a tool that allows one to study the properties of the particle-emitting source and information concerning the size and expansion of the system. In addition, the obtention of the HBT radii for a given k_T is presented as an insight into the possible tasks and analysis that can be carried out by this model.

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2 Introduction

High Energy Physics is the field of Physics whose goal is to determine the most fundamental building blocks of matter and the forces interacting through these particles. The concept of "High energy" results from the fact that high energies are needed in order to break these fundamental particles apart to produce new particles which do not exist in the normal state of the matter.

Relativistic Heavy Ion Collisions are the part of High Energy Physics that deals with the Nuclear Physics of colliding nucleus. By studying these collisions we can recreate in the laboratory the properties of nuclear matter in a state close to the one that occurred shortly after the Big Bang.[1]

A way to describe the physics of Relativistic Heavy Ion Collisions is through phenomenological models. These models can be divided into two main categories; microscopic and macroscopic models where one of them takes different things into consideration.

- **Microscopic**
  - Dynamic simulation of the collision process inspired by QCD.
  - Tracking of individual objects.
  - Propagation of individual particles through a cascade of collisions and decays
- **Macroscopic**
  - No consideration of the dynamics of individual objects in detail.
  - Statistical description of multi-particle system

These models are implemented in event generators. Event generators are software libraries that generate high-energy particle physics events. They allow us to compare experimental results with theoretical predictions as well as to make predictions and preparations for future experiments.

3 THERMINATOR 2 Model

THERMINATOR 2 is an extended version of the MC generator THERMINATOR (THERMal heavy IoN generATOR), created to study the statistical production of particles created in relativistic heavy-ion collisions[2]. It implements various thermal models of particle production with single freeze-out. The basic tasks that are carried out by Therminator 2 are the following:

- generation of stable particles and unstable resonances at the chosen hypersurface. The local phase-space density of particles is given by the statistical distribution factors,
- subsequent space-time evolution and decays of hadronic resonances in cascades,
- calculation of various physical observables such as: p_T or m_T spectra, flow coefficients e.g. v_1, v_2, v_4, femtoscopy: two-particle correlation function, HBT radii.

In general, the THERMINATOR model takes a number of parameters to specify collision energy. There are thermodynamic parameters:

- Temperature (T)[MeV]
- Chemical potentials
  - Baryon (μ_B) [MeV]
  - Strangeness (μ_S) [MeV]
  - Third component of isospin (μ_{I_3})[MeV]

And there are geometrical and dynamical parameters:

- mean life time (τ) [fm]
- source size at freeze-out (ρ_{max}) [fm]
- transverse velocity (V_T)

However, in this work, we decided to perform the analysis with one of the hydro-based freezeout models already included in the program using the sets of hypersurfaces that describe the Au+Au data at RHIC.

3.1 Event Generation

To generate events we first selected one of the hypersurfaces and velocity profiles that describe the data of Au+Au collisions at the highest RHIC energy $\sqrt{s_{NN}} = 200GeV$ for different centralities. The *.xml* files containing the hypersurfaces descriptions and parameters are included in the **fomodel/lhyquid2dbi** folder, to run events we selected the *.xml* file corresponding to the type of collision and centrality we are interested in and replaced the name on the **lhhquid2dbi.ini** file. For this project, we worked with Au+Au collisions at the RHIC energy of 200 GeV generating 100,000 events per centrality range.

We then proceed to calculate some basic distributions corresponding to the particle production to check the validity of the model with the data obtained for the STAR experiment[3].

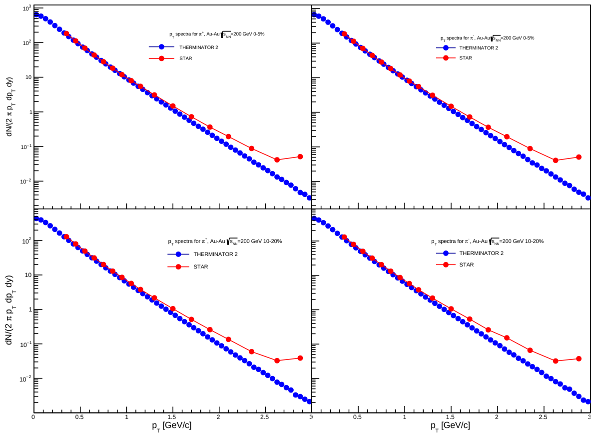


Figure 1: p_T spectra for pions (π^+ and π^-) for different centrality ranges

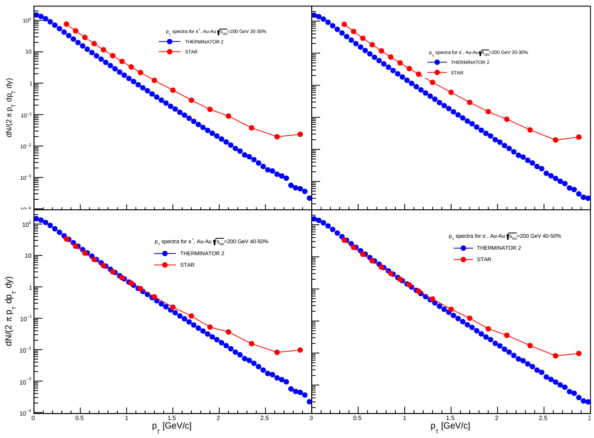


Figure 2: p_T spectra for pions (π^+ and π^-) for different centrality ranges

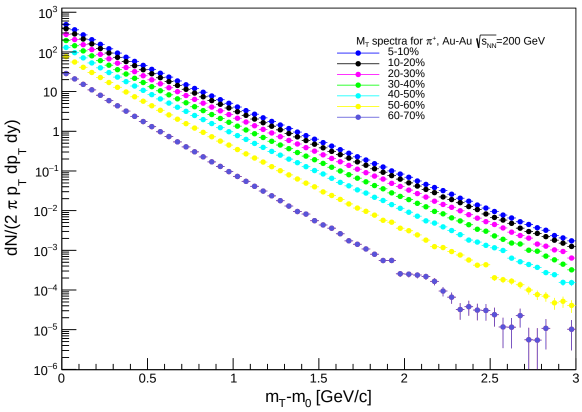


Figure 3: m_T spectra for pions

4 Femtoscopy

Femtoscopy correlation is a technique used in relativistic heavy-ion collisions that can give us an insight into the space-time characteristics of particle production at the *femtometer* scale($10^{-15}m$) using particle correlations.[4]

The femtoscopy method relies on two-particle correlations originating primarily from wave function (anti)symmetrization commonly known as the Quantum Statistics (QS) effect, and whether there can be other sources of correlation like the final state interactions due to Coulomb and Strong interaction between the particle pairs[5][6], these won't be considered in the extend of this work.

There are two types of correlations, for *identical* and *non-identical* particles. While the first can help us to study the size of two ion collision systems, the non-identical ones are used to study the time scale of nucleus fragments produced during the collision[7].

4.1 Correlation Function

The correlation function for two particles is defined as a ratio of the probability of observing two particles with momenta $\mathbf{p_1}$ and $\mathbf{p_2}$ at the same place and time to the product of probabilities of observing such particles independently.

$$C(\mathbf{p_1} \cdot \mathbf{p_2}) = \frac{P(\mathbf{p_1}.\mathbf{p_2})}{P_1(\mathbf{p_1})P_2(\mathbf{p_2})} \tag{1}$$

As mentioned before, the numerator represents the measured momentum distribution difference ($\mathbf{q} = \mathbf{p_1} - \mathbf{p_2}$) of the two particles 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.

For the particles with equal masses we use the notation $q_{inv} = 2|\mathbf{k}*|$, while the average transverse momentum of the pair will be denoted by $\mathbf{k_T}$.

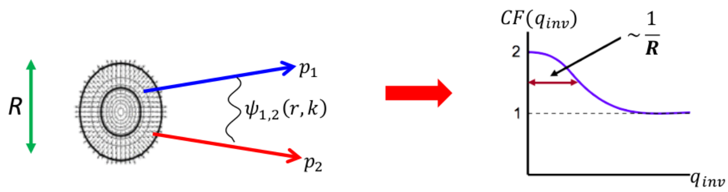


Figure 4: Relationship between the correlation function and the source size

The details from obtaining these correlations for the pairs π^+/π^+ are given in the following sections.

5 Femtoscopy Analysis Using Therminator 2

After generating the events as described before, the event files including the information about the simulation can be used to carry out multiple physical analyses as it was shown previously. Besides the results corresponding to the particle production, we decided to include a brief demonstration of the possibility to use Therminator2 to obtain the femtoscopic correlations for the pair $\pi^+\pi^+$ and how the analysis can be extended to other pairs of particles. A more detailed description of the formalism of the process can be found in [7][5]. We then proceed to calculate the denominator and numerator of the correlation function given by equation 1 for the π^+/π^+ pair in the k_T range from 0.15 to 0.25 GeV and different centrality ranges. It is also possible to obtain the function for other k_T ranges; The arguments necessary to run the code are:

1. $k_T = 0$ corresponds to (0.15-0.25 GeV)
2. $k_T = 1$ to (0.25-0.35 GeV)
3. $k_T = 2$ to (0.35-0.45 GeV)
4. $k_T = 3$ to (0.45-0.60 GeV)

5.1 Identical Particles

As we mentioned before, it is possible to obtain the correlation function for identical particles and non-identical ones. We refers for identical particles as those that are from the same type, mass and charge, like the pairs $\pi^+\pi^+$, K^+K^+, pp. Identical particle femtoscopy can be useful to determine the relation between specific space-time information and the source radii.

In this project we calculated the correlation and the source radii for the pair $\pi^+\pi^+$.

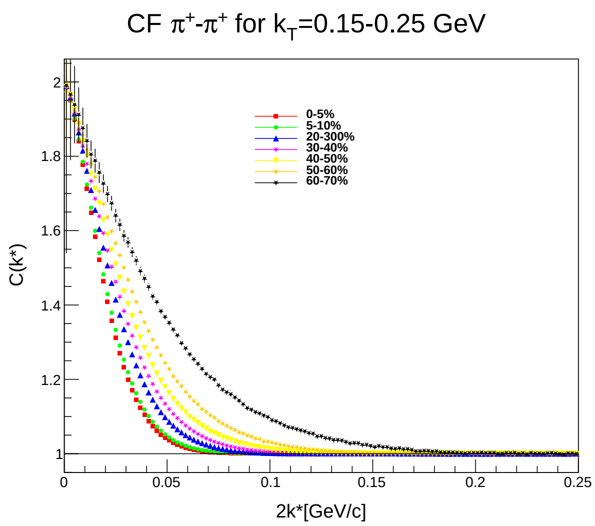


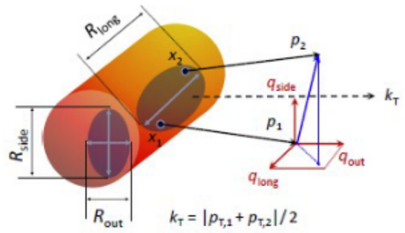
Figure 5: Correlation function for $\pi^+\pi^+$ pairs in a given k_T range

5.2 HBT radii's

The equation 1 can be expressed theoretically as,

$$C(\mathbf{k}^*) = \frac{\int \mathbf{S}(\mathbf{r}^*\mathbf{k}^*)|\mathbf{\Psi}(\mathbf{r}^*\mathbf{k}^*)|^2}{\int \mathbf{S}(\mathbf{r}^*\mathbf{k}^*)} \tag{2}$$

where $\mathbf{r}$ is the relative space-time separation of two particles at the time of generation, $\mathbf{k}$ is half of the pair relative momentum i.e. momentum of the first particle at Pair Rest Frame (PRF) and $\mathbf{S}$ is the source function which corresponds to the probability of the emission of pair of particles and $\mathbf{\Psi}$ is the pair wave function, for the case of two identical particles, $|\mathbf{\Psi}|^2 = 1 + cos(\mathbf{kr})$[8].



The femto code included calculates the $|\mathbf{\Psi}|^2$ for each pion pair and added to the denominator of Eq. 2 in a bin corresponding to the pair's q_{out}, q_{side} and q_{long}. On the other hand, n order to estimate the femtoscopic radii of the system, the source function is assumed to be a three-dimensional ellipsoid with a Gaussian density profile,

$$S(\mathbf{x}, \mathbf{p}) = Nexp\Big(- \frac{x_{out}^2}{4R_{out}^2} - -\frac{x_{side}^2}{4R_{side}^2} - \frac{x_{long}^2}{4R_{long}^2} \Big) \tag{3}$$

where R_{out}, R_{side} and R_{long} correspond to single-particle femtoscopic source radii, in transverse, side and longitudinal directions, respectively, also known as the "HBT radii". And since the source function does not depend on particle momentum. Eq. 2 leads to:

$$C(\mathbf{q}) = 1 + \lambda exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2) \tag{4}$$

where λ is the parameter corresponding to the correlation length. The radii in different directions is extracted by fitting the Eq.(3) to the correlation function. For this we used the **therm2 hbtfit** program to realize the fitting procedure, the results obtained are shown in the next table.

Centrality	λ	R_{out}	R_{side}	R_{long}
0-5%	0.815316 ± 8.62e-04	5.93849 ± 4.52e-03	5.15662 ± 3.91e-03	7.17773 ± 6.11e-03
5-10%	0.808952 ± 9.33e-04	5.68659 ± 4.72e-03	4.92584 ± 4.08e-03	6.87649 ± 6.40e-03
20-30%	0.786331 ±1.27e-03	4.80827 ± 5.62e-03	4.10255 ± 4.76e-03	5.7885 ± 7.58e-03
30-40%	0.773496 ± 1.54e-03	4.36021 ± 6.37e-03	3.67182 ± 5.29e-03	5.18533 ± 8.47e-03
40-50%	0.761305 ± 0.00194069	3.91758 ± 0.00738092	3.24852 ± 5.99e-03	4.5996 ±9.66e-03
50-60%	0.76445 ± 2.31e-03	3.46245 ± 9.16e-03	2.80378 ± 7.27e-03	4 ± 8.05e-04
60-70%	1.04116 ± 5.83e-03	4.35624 ± 5.27e-03	2.34611 ± 1.13e-02	4 ± 1.05e-03

Table 1: $\pi^+\pi^+$ HBT parameters extracted from the fit for a k_T range of (0.15- 0.25)GeV and different centralities for Au+Au collisions at $\sqrt{s_{NN}} = 200$GeV

6 Conclusion and Further Work

In conclusion, events for Au+Au collisions at $\sqrt{s_{NN}} = 200GeV$ were generated with Therminator 2 for different centrality ranges, and some basic particle production observables such as transverse momentum and transverse mass were obtained for some type of particles and compared with previous data obtained from[3]. The model seems to agree reasonably with the p_T spectra.

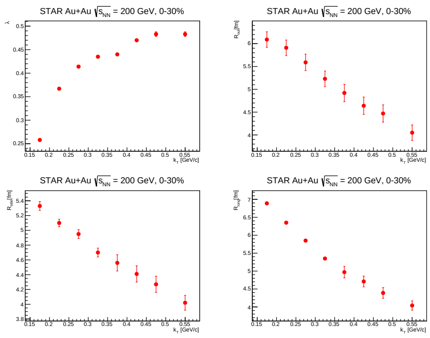


Figure 6: HBT Parameters from STAR at the same beam energy for the 0-30% most central events.

We also used the femtoscopy analysis implemented in Therminator 2, to obtain the correlation function for identical particle pairs, $\pi^+\pi^+$, as well as the HBT fit parameters for a given k_T range. However, the same analysis can be performed for another pair of particles, identical and non-identical ones, yielding a wide variety of interesting results and a more detailed analysis. These results can be used to compare with some of the data obtained in previous works[8], to do so it is necessary to analyze all the k_T ranges. As a further extension of the project, a deeper analysis could be made considering a more theoretical approach as well as the implementation of the corrections such as purity and momentum resolution corrections and the FSI including the Lednicky model. In order to implement the Therminator 2 model in other detectors/experiments, integration in the respective frameworks could be also a task for further work.

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