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Femtoscopic measurements from STAR to CBM

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Summary. — Femtoscopy is a tool to study the properties of sources that emit particles. This powerful tool uses a two-particle correlation to study the spatio-temporal properties of matter created during heavy ion collisions. This paper reviews the progress in the femtoscopic measurements done by the STAR (Solenoidal Tracker at RHIC) experiment in the context of similar measurements in the future CBM (Compressed Baryonic Matter) experiment experience. The recent Beam Energy Scan II program realized at STAR is very similar to the plans of the CBM collaboration. Both experiments will take data in a similar manner (Fixed Target Experiment) and at similar energies. In this work, I would like to describe how the CBM collaboration can use the experience gained by the STAR experiment to study the properties of strongly interacting matter at high baryonic densities. This included the type of analysis that CBM can do better and the development of the software for femtoscopic analysis.

1. – Femtoscopy

Femtoscopy is a technique used in experimental physics to extract information about the spatial-temporal structure of the matter created during the collisions of two ions. The femtoscopy uses the correlation function to measure the size of the source. The experimental correlation function is a ratio of correlated to uncorrelated pairs of particles. The uncorrelated distribution is usually obtained by the so-called mixing technique (each particle in a pair is from a different event) [1].

Such defined experimental correlation function is compared to the theoretical one:

$$C(q) = \int S(r,q)|\Psi(r,q)|^2 dr \tag{1}$$

In the 1 the C(q) is the correlation function, the q is the momentum difference between two particles, S is the shape of the source (so-called source function), and Ψ is the two-particle wave function that carries information about statistical correlations (for identical particles) and interactions between them (strong and coulomb).

In the experiment, the experimental correlation function is compared to the set of the theoretical correlation functions calculated according to eq. (1). Usually, it is assumed that S has a Gaussian shape. This is the most frequently used femtoscopic technique.

A less popular application of eq. (1) base on the assumption that the S is known, for example, if there are analyzed pairs of particles with known interactions (*e.g.*, protons) and we can precisely measure the S_{pp} pairs we can assume that for similar pairs of particles, *e.g.*, lambdas the source size is similar. In such case, we can put the $S_{\Lambda\Lambda} = S_{pp}$ and get information about interactions between lambdas. Such technique was actually used by STAR collaboration, *e.g.*, to measure $\Lambda - \Lambda$ or $K_s^0 - K_s^0$ interactions [2, 3].

2. – The STAR experiment

The STAR (Solenoidal Tracker at RHIC) is an existing experiment at BNL (Brookhaven National Laboratory). The STAR detector has been taking data since 2000. In the beginning, the STAR was designed to be a collider experiment that would study the properties of QGP produced at the high energy collisions (up to $\sqrt{s_{NN}} = 200\ GeV$ in case of gold-gold collisions). The STAR detector has a barrel-like shape. TPC (Time Projection Chamber detector) and TOF (Time of Flight) are the two most important detectors. The first one is the main tracking detector, which can identify particles at low momenta by measuring their energy losses. At larger moments, the energy losses do not allow distinguishing between different types of particles, and TOF is used.

Later, STAR started the Beam Energy Scan I (BES-I) and BES-II programs. This was an extension of measurements towards lower collision energies. The main goals of such studies were looking for Critical Point (CP), looking for a turning off of the signatures of QGP, and studying the phase transitions from QGP to the hadronic phase [4]. Due to technical reasons, collecting data at the lowest energies of the BES program required significant changes in the STAR detector. The detector was also modified to collect data in Fixed Target mode (FXT). This was made by inserting a thin gold foil into the beam pipe (a target) and upgrading/adding new detectors to the STAR [5].

3. – The CBM experiment

CBM experiment (Compressed Baryonic Matter) is a future experiment that will be a part of FAIR (Facility for Antiproton and Ion Research). CBM will be a Fixed Target experiment designed to measure the collisions up the energy $\sqrt{s_{NN}} \approx 5\ GeV$. The CBM will register collisions with an unprecedented rate of up to 10 MHz. The main detector of CBM is the STS (Silicon Tracking System), which will reconstruct the trajectory of particles; the identification will be done mainly by the TOF (Time of Flight) detector [6].

The CBM was designed to probe the matter at extremely high baryonic densities to help understand the nature of matter at the cores of the neutron stars [7]. The energies of the CBM are comparable to the lowest energies registered by STAR experiment. Therefore, there is an open field of collaboration between both groups of scientists. Actually, the eTOF detector (part of the STAR) is a prototype of the TOF detector that CBM will use [8].

4. – The femtocopy from STAR to CBM

4˙1. *Femtoscopy in STAR.* – STAR collaboration measured the correlation of various types of particles at different energies. This includes the one-dimensional femtoscopy (measure the general size of the source), the three-dimensional (measure the geometrical size of the source and emission time of particles), and azimuthally sensitive measurements (able to measure geometry concerning the reaction plane). Such measurements required

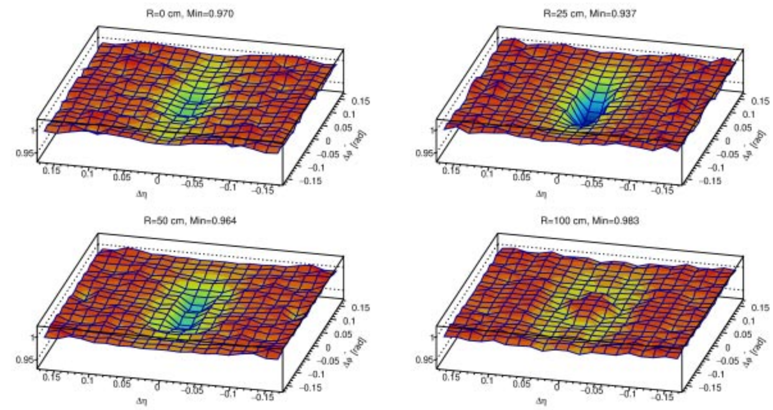

Fig. 1. – The ratio of pairs from the same event to the mixed particle distribution as a function of $\Delta\eta$ and $\Delta\phi^*$ in the simulation of CBM detector [9]. The R value represents the distance between the event vertex and a place where ϕ^* is calculated, and Min represents the minimal value of the normalized ratio. It is visible that at $R = 25$, there is a relatively large fraction of missing pairs of tracks. This area should not be taken into account during the calculation of the correlation function.

the development of sophisticated software. For example, the spherical harmonics decomposition of the correlation function was widely used in measurements of non-identical pairs of particles.

STAR detector has limited momentum resolution. Therefore, methods were developed to take into account detector effects during the measurements, techniques to estimate the systematic uncertainties, etc.

The CBM collaboration will face similar problems; therefore, during preparation, we would like to use the STAR experience in future experiments. This will also be beneficial for STAR collaboration because some of the techniques might be improved by CBM collaboration and used by STAR before the CBM takes data. For example, in fig. 1 is the ratio of correlated to uncorrelated pairs of particles as a function of rapidity difference ($\Delta\eta$) and azimuthal angle between particle's momenta at a given distance ($\Delta\phi^*$) similar variables are used in STAR experiment to remove some detector effects.

4·2. *Femtoscopy in CBM: model predictions.* – STAR experiment provided various sets of data, including the results of femtoscopic measurements or particle productions. Such data allow the theorist to improve their models. Later, such improved models are used by future experiments like CBM to estimate the statistics needed to perform specific measurements. For example, a group of students from WUT worked with the UrQMD model to predict the yields of particles and statistics needed to perform particular types of measurements. Figure 2 contains the expected number of particles at CBM energy range.

4·3. *Femtoscopy in CBM: MC simulations.* – Input from models like UrQMD was used to perform the simulations of the response of the CBM detector. Here, the technique used to remove the two-particle detector effects like splitting (reconstruction of a particle as a pair of tracks) or merging (reconstruction of a particle pair as a single track) was heavily inspired by techniques used by the STAR experiment. To provide more realistic

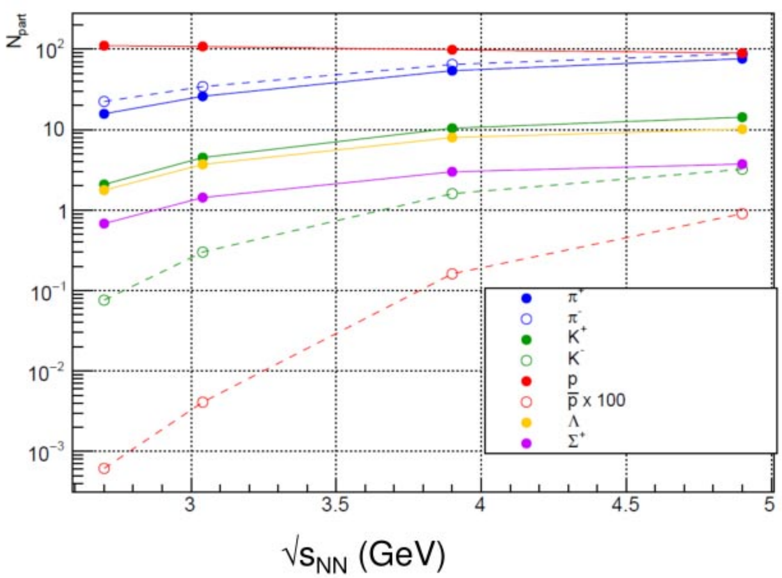

Fig. 2. – Number of particles produced at collisions at CBM energy range. The simulation was performed with the UrQMD model [10].

simulations, we also used the data collected by the STAR experiment. For example, in fig. 3, there is a correlation function of $\pi^- - \pi^-$ pairs with radii taken from data collected by STAR [11]. The theoretical correlation function (blue line) assumes the spherically symmetrical shape of the source, whereas the simulation contains a more realistic non-symmetrical shape of the source measured by STAR.

Current simulations show that the CBM detector will be capable of measuring the correlation of protons and pions. The open question is the capability to measure more exotic particles like hyperons and hypernuclei. The impressive interaction rate and simulations done for non-femtoscopic analysis suggest that CBM might be an excellent tool to study these types of particles [12]; detailed studies of the performance of this detector for femtoscopic measurements are planned for 2024.

4˙4. *Femtoscopy in CBM: Software development*. – The software for femtoscopic analysis HAL (High energy physics Analysis Libraries) was developed for CBM. HAL was heavily inspired by the software used for the STAR experiment. For example, the concept of "readers" was introduced to the HAL. This class translates the event stored in data into a format optimized to a specific type of analysis (like femtoscopy).

HAL was also tested by using the software developed by STAR Collaboration. This test showed that it is possible to perform an efficient, sophisticated analysis of experimental data using HAL. On the other hand, this test showed that there are some missing things in the HAL framework that should be added to make the analysis simpler.

Development of software for CBM, however, is not simply writing a copy of software used by STAR. New features that are not present in currently used software are added. For example, HAL contains an integrated environment for fitting the experimental correlation function with the theoretical one (*e.g.*, screenshot is presented in fig. 4). What

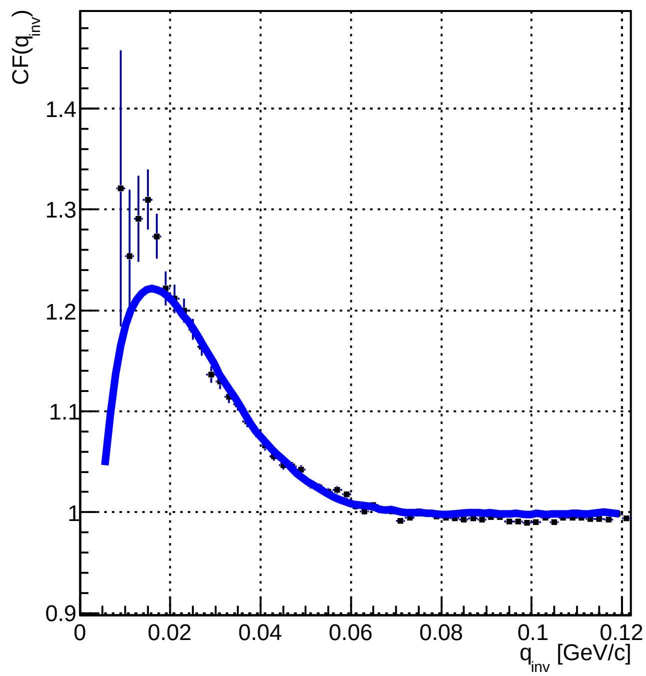

Fig. 3. – The correlation function from simulation of CBM detector response for pairs of negative pions. It can be noticed that the theoretical correlation function poorly describes the experimental one.

is more important, this environment contains a new method that is much more efficient in terms of computing performance than currently used software.

When using the STAR software, we also observed that there are a few missing things that should be added to the future frameworks for the HBT analysis. For example, the representation of results in HAL is much better developed than in STAR - in contrast to old software, HAL does contain not only the results of analysis but also a configuration of analysis - thanks to this, it is possible to check the analysis settings even if original macros to perform the analysis were gone.

5. – Summary

In this paper, we briefly described the plans related to the femtoscopic measurements in the CBM. We showed that this is done with close cooperation with the STAR collaboration.

However, we are planning not only to repeat the STAR measurements but also to improve them by improving/developing existing/new techniques for CBM. We hope that some of these new approaches might be used now in STAR, instead of waiting to get the first data from CBM.

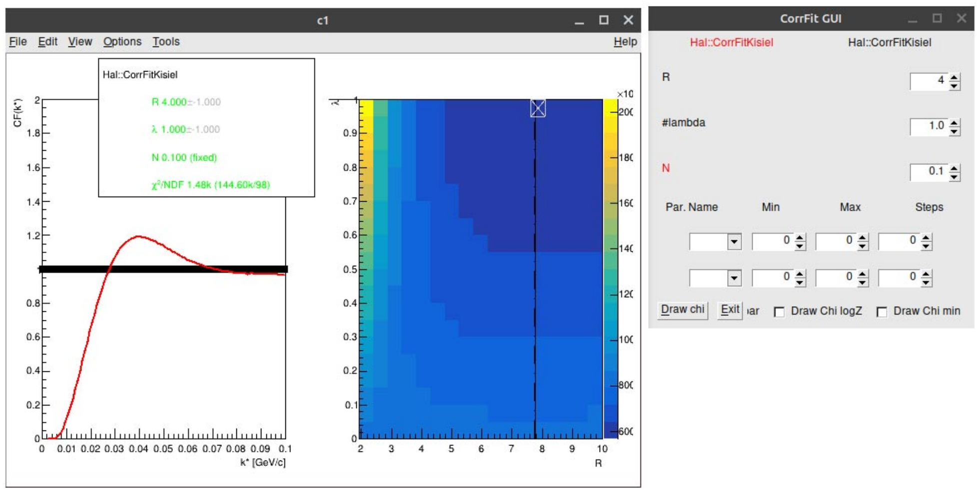

Fig. 4. – The screenshot of the CorrFit module that is used to fit the experimental correlation function. The fitted function is represented as a red line; the fitted function is black. There is also a legend that describes the current parameters of fit, a map of χ^2 value (left plot); on the left, there is also a GUI that can be used to change the parameters of fit or to draw a new χ^2 plot.

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