I. Semester report (2025/26/1)

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PhD Program: Particle and Nuclear Physics

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Ph.D. Thesis title: Quantum statistical correlations in high energy physics

Introduction

In the few microseconds following the Big Bang, elementary particles like quarks, and the gluons that carry the strong force between them, were not yet confined inside hadrons [1]. This state of matter is called quark-gluon plasma (QGP). The experimental investigation of the quark-gluon plasma has been made possible by high-energy heavy-ion physics. We can study the properties of the phase-space probability density of particle production (that is, the source function of hadron formation) by measuring Bose-Einstein correlation functions on a femtometer scale [2,3]. This method is called femtoscopy.

In my research I assume that the source emitting the particles has a Lévy shape. The Lévy distribution is a generalization of the Gaussian distribution and includes one additional parameter, the Lévy-index α, describing the shape of the distribution. There are physical arguments supporting the use of the Lévy distribution. One example is the phenomenon called Lévy walk [5], which describes the motion of particles and affects the shape of the correlation function. There are other possible explanations for the deviation from the Gaussian form as well. These include jets, the proximity of the QCD critical point, or event averaging. The Lévy shape has already proven to be successful in several measurements [4,5,6,7]. In addition to experiments, we can also simulate these collisions. It is important to investigate another parameter of the Lévy distribution as well, called the scale parameter and denoted by R, which characterizes the width of the distribution.

In addition to experiments, we can also simulate these collisions. The advantage of simulation is that we can directly access quantities that are not measurable in experiments: the freeze-out spacetime coordinates. Thus, in this case, the source distribution can be studied directly.

Description of research work carried out in current semester

During this semester, I carried out phenomenological studies of kaon and proton source functions using heavy-ion collision events simulated with the EPOS event generator.

First, I would like to briefly summarize the new results I have obtained compared to my MSc thesis. In my thesis, I used an event-by-event method to determine the parameters α and R, while I calculated the uncertainties from the spread of the obtained parameters. In this analysis, I combined N_{events} individual events, then fitted the resulting distributions. Based on this fits, I

determined the mean values and standard deviations of the parameters α and R, and investigated their dependence on transverse mass and centrality. I started my PhD research from this point.

As a first step, I studied the N_{events} dependence of the obtained parameters. I found that above a certain N_{events} value the parameters start to converge. Therefore, instead of the event-by-event method, I switched to an event-averaged approach, i.e. I merged all available events (in a given transverse mass and centrality bin). From the small spread of the parameters obtained for different N_{events} values, I calculated the systematic uncertainty. This method also significantly reduced the runtime, which made it easier to perform various systematic studies.

In the next step, I studied the effects of the cuts applied in the analysis. I found that cuts on pseudorapidity and transverse momentum do not significantly affect the parameter values, while the Q_{LCMS} cuts do. Here, Q_{LCMS} is the three-dimensional spatial separation vector boosted to the Longitudinal Co-Moving System (LCMS). This cut is required to account for the fitting range of the correlation function used in the experimental analysis. This way, particle pairs that have no effect on the correlation function are excluded from the simulation analysis. I also calculated a systematic uncertainty from the Q_{LCMS} cut.

I investigated the dependence of the parameters on the fit range and determined the corresponding systematic uncertainty. In experimental analyses of the correlation function, in addition to the parameters α and R, a third parameter, denoted by λ, is also extracted and can be determined in simulations. I obtained this parameter from the integral of the core–core component of the two-particle source function.

I compared my results for kaons and protons with those obtained for pions. The pion analysis [9] was largely carried out by a collaborator, in which I also participated to a limited extent. I investigated the effects of the pseudorapidity, transverse momentum, and Q_{LCMS} cuts, as well as the dependence on N_{events}. I determined the systematic uncertainties arising from the Q_{LCMS} cut and from the chosen N_{events}.

Some of the main results are shown in the figures below.

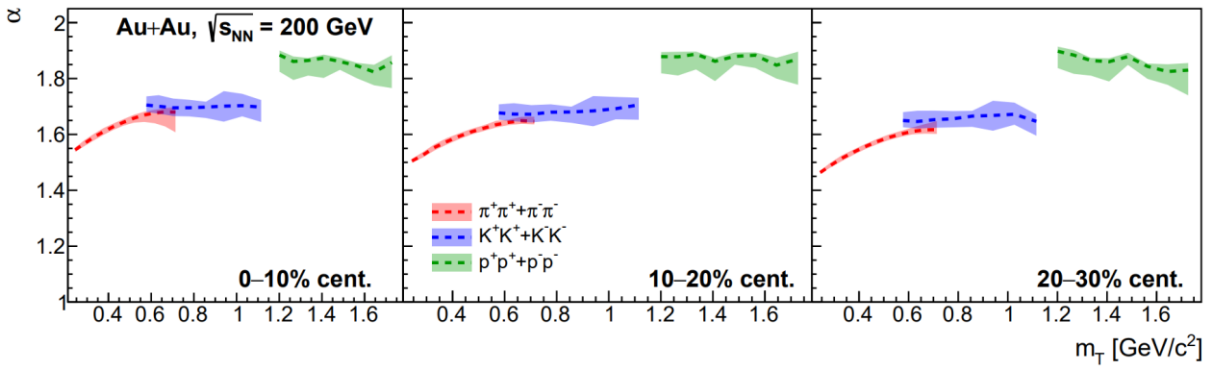

Figure 1: Transverse mass dependence of the parameter α, shown separately for the three centrality classes. The pion results are from Ref. [9].

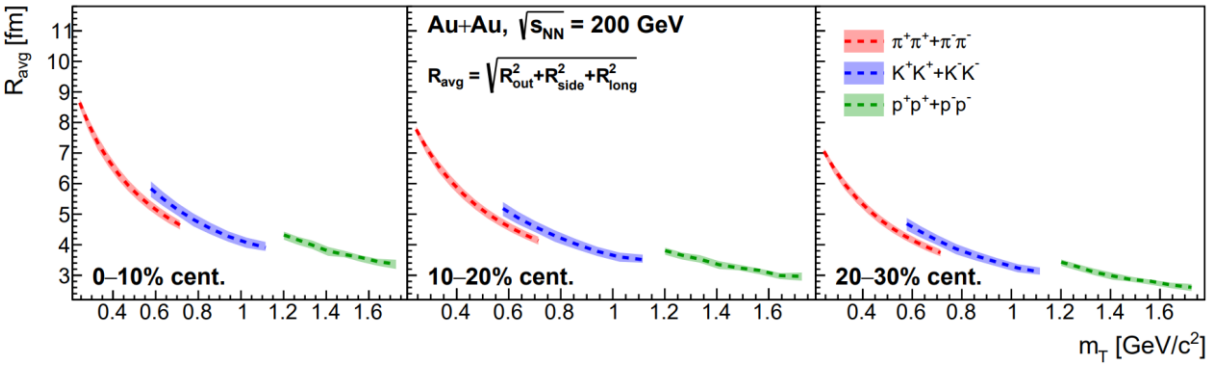

Figure 2: Transverse mass dependence of the parameter R, shown separately for the three centrality classes. The pion results are from Ref. [9].

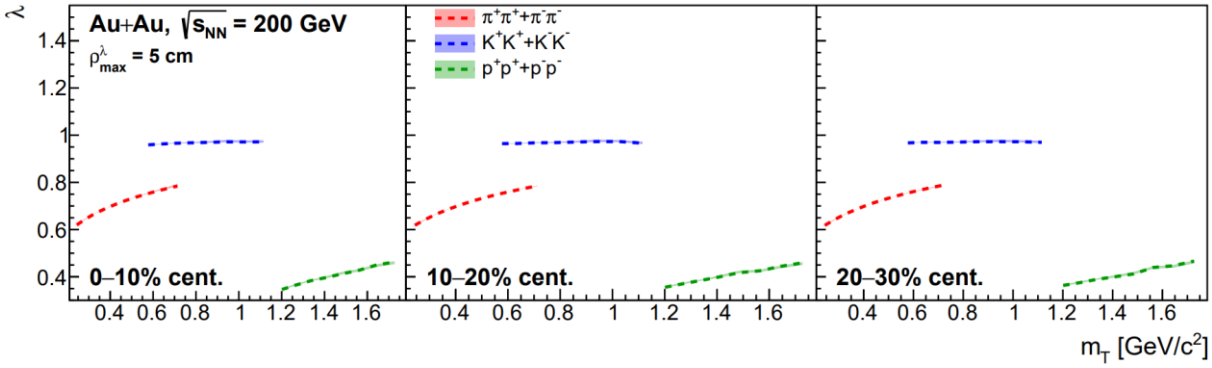

Figure 3: Transverse mass dependence of the parameter λ, shown separately for the three centrality classes. The pion results are from Ref. [9].

Publications

A manuscript entitled *"Three-dimensional sizes and shapes of pion emission in heavy-ion collisions"* has been submitted and is currently under full consideration for publication in *The European Physical Journal C*. The preprint is available on arXiv [9].

Studies in current semester

I took three courses:

- Advanced machine learning lab (FIZ/3/093)
- Experimental methods of particle physics II. (FIZ/2/004E)
- Selected chapters from experimental high energy physics (FIZ/2/117)

Conferences in current semester

The conferences I participated:

- The Day of Femtoscopy, Gyöngyös: I presented my results in a talk.
- The 25th Zimányi School Winter Workshop: I presented my results in both poster and flash talk formats.

Professional activities

I was a member of the local organizing committee of the 25th Zimányi School Winter Workshop.

References

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