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Review of the PhD manuscript of Maria Stefaniak entitled "Beam energy scan dependence of elliptic and triangular flow of identified hadrons in the STAR experiment and the EPOS model"

This work has been organized as a cotutelle PhD supervised by Prof. Hanna Zbroszczyk in WUT Warsaw and Prof. Klaus Werner in IMT Atlantique.

Maria Stefaniak presents a comprehensive document describing the scientific context of her studies and her personal work.

The manuscripts starts with a short introduction presenting the interest of studies of the QCD phase diagram at finite net-baryon densities developed by the STAR collaboration and the strategy chosen in this PHD work. The first contribution consists in the analysis of flow harmonics measured for four data sets by the STAR collaboration, recorded at center of mass energies of the pair of colliding nucleons of 27, 35, 54.4 and 200 GeV. This experimental work is complemented by model developments to study the sensitivity of the observables to the Equation of State (EOS) of hadronic matter. Two other tasks performed by Maria Stefaniak are described in Annexes 1 and 2, respectively: a contribution to a software development related to a STAR sub-detector and the implementation in the Rivet software of a code to compare model outputs to STAR data.

Chapter 2 of the manuscript gives a good introduction to all the concepts and tools used for the description of relativistic Heavy Ion collisions. It starts from the basis of Quantum Chromodynamics, then the QCD phase diagram and the Equation of State are introduced. Finally, all kinematic variables are defined.

Chapter 3 addresses the central topic of the PhD: the azimuthal anisotropy of products in heavy-ion collisions which reflects, via pressure gradients, the initial geometrical asymmetry of the system. Using a Fourier decomposition of the azimuthal distributions, the harmonics of the azimuthal distributions (v1,v2,..) can be extracted and compared to models. The interest of these observables for EOS studies, which motivates both the experimental and theoretical work presented in the next chapters is well explained. Maria Stefaniak also reviews in this chapter the existing results obtained by the STAR collaboration, which is used for the discussion of the sensitivity of the different harmonics to the initial geometry and evolution of the expanding system. These results are also used to motivate the new data analysis performed in this PhD work. The last section of this chapter presents the specific method, based on subevent two-particle cumulants, adopted in this PhD to extract flow harmonics.

In Chapter 4, the STAR experimental set-up is described, with emphasis on the Time Projection Chamber, the inner Time Projection Chambers, the Time of Flight and Vertex position Detectors, which are crucial for the reconstruction of protons, antiprotons, charged pions and kaons used in the analysis. This description is kept short and focuses to the measurement principles which are clearly explained.

Chapter 5 presents the analysis steps for selection of protons, antiprotons, charged kaons and charged pions and provides plots which are informative about the quality of the data. The chapter closes with the list of systematic errors affecting the measurement of flow harmonics for $\sqrt{s_{NN}}$=39 GeV. This part is clearly written and reflects a careful study of systematic errors, showing that the main effects are due to the track selection criteria. However, I was expecting the various contributions to be independent, while they seem to have been added linearly. Maybe it would also be useful, for the sake of completeness, to give the values of systematic errors for the other energy points and discuss the origin of the lower systematic errors for kaons w.r.t. to protons and pions.

In Chapter 6, the results obtained by Maria Stefaniak for v2, v3 and v4 at the four energy points are presented and discussed. This chapter starts with a comparison of v2 values with already published STAR data, using the Event Plane method. Consistent results are obtained, however, as a non-expert, I missed some discussion to be convinced by the advantage of using the 2 particle cumulant, considering that error bars are larger for high transverse momenta (pt). Such minor points will be easily clarified during the defense. The results are shown in various projections to emphasize the energy, centrality and pt dependence of the results. The evolution of v2 and v3 with pt shows a mass ordering (lower values for heavier particles) for pt up to 1.5 GeV/c and a difference between proton and antiproton flows. For higher values, all particles except protons follow a scaling according to the number of constituent quarks, while this scaling is observed for protons only at 200 GeV/c. This observation could indicate that the proton flow do not originate fully from the QGP. The difference between proton and antiproton flow at lower energies is studied in detail and possible explanations are explored. Although no conclusive answer can be given, this study demonstrates the power of such differential data to test various theoretical scenarios. In this chapter, Maria Stefaniak demonstrates very good scientific skills and a broad knowledge of her research field.

The last part of the PhD (chapters 7 and 8) deals with the description of the phenomenological EPOS model and the implementation of various EOS, which was realized by Maria Stefaniak. This part reveals her ability for theoretical work and code development. A systematic study of simulations performed with nine different EOS, with different properties, e.g. different locations of the critical points are presented. A comparison to STAR data, including the new results produced in this PhD work is also provided. The limitations of the study are clearly explained: the EPOS model is not yet optimized to describe the particle yields and distributions at lower energies. Improvements are also needed for the treatment of fluctuations of the evoluting system. Nevertheless, this work is very original and useful, as it explores the sensitivity of the various experimental observables to the EOS. The outcome is a small effect on particle distributions and flow harmonics while fluctuations of conserved quantities, like the number of net-protons appear as the best sensitive observable. This result should guide also experimental studies in future.

In summary, taking full advantage of the complementary expertise of the two supervisors of the cotutelle, Maria Stefaniak presented a very comprehensive work, including both data analysis and theoretical activities. Both parts are of high quality and the ensemble is an impressive and original contribution to the study of the QCD phase diagram in the finite net-baryon density region.

Therefore, I warmly recommend that the PhD of Maria Stefaniak be defended.

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