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Review of Ph. D. Thesis "Beam Energy Scan dependence of elliptic and triangular flow of identified hadrons in the STAR experiment and the EPOS model" delivered by M.Sc. Eng. Maria Stefaniak

The main aim of the study is the search for physics quantities sensitive to the profile of the equation of state (EoS) of the QCD matter in the region of high temperatures and non-negligible baryochemical potential (μ_B), in particular to the position of the critical point (CP) of transition between the hadron gas and QGP phases. For that purpose the Author investigated the coefficients of mostly directed and triangular flow (i.e. weights of 2./3. harmonics of the azimuthal distribution w.r.t. reaction plane) of most abundant hadrons (p, $\bar{p}$, π^+, π^-, K^+, K^-) emitted from the collisions of Au+Au at available energies of the nucleon-nucleon system $\sqrt{s_{NN}} \in \{27, 39, 54.4, 200\}$ GeV. These coefficients were extracted as function of collision centrality and transverse momentum. This data was made available in course of the "BES II" campaign of the beam energy scan of the collisions measured by the STAR apparatus installed at the RHIC, Brookhaven (USA). The profiles of flow coefficient were obtained using the *2-particle cumulant* approach for the first time in STAR. This method is not burdened with uncertainties due to reaction plane finding, thus is considered as more precise than the latter approach. In addition Mrs. Stefaniak, in collaboration with the group of theorists developing the EPOS transport model, embedded different variants of the EoS into the simulations, and obtained predictions of the flow coefficients, which were further compared to the experimental profiles.

The Thesis begins with the Abstract and Table of Contents followed by the opening. In the introductory physics **Chapter (# 2)** the main ingredents of the Standard Model are discussed. Next, the QCD phase diagram is considered including possible variants of transitions between hadron gas and quark-gluon plasma (QGP), the signatures of the latter phase, and the possible CP. The phase diagram shown in Fig. 2.6 would, however, be more complete if the liquid-gas phase transition at Fermi energies was added, together with a possible chiral restoration line (or region). In the further step, the basic features of EoS are discussed, including energy density and pressure dependence on temperature, and an extension of pressure towards larger μ_B in terms of Taylor expansion, followed by the introduction of shear (η) and bulk viscosity. The subsection 2.2.4 on the Monte Carlo Generators is short, but the Author can be mostly absolved, as large part of Chapter 7 is devoted to description of the EPOS transport model. Nevertheless it would be good to provide some basic consideration of features of various transport models (not limited to EPOS), and a bit of discussion what is the difference between EPOS and the others (e.g. UrQMD, PHSD, AMPT, vHLLE etc.), and what possible systematic bias could be introduced by deciding to use just EPOS. Also, some statements are given without reference, e.g.: $k = 0.87$ GeV/fm in Eq. 2.1, the stated correctness of description of the charmonium and bottomonium masses, or the claim on p. 12 that the local equilibrium is reached after 1 fm/c.

In the next subsection (2.3) the Author introduces the basic features of the relativistic heavy-ion collisions: correlation of collision centrality with multiplicity of charged hadrons, difference between the reaction and participant plane, eccentricity of the initial transverse overlap of nuclei, and kinematic variables. Being armed in these observables, the Author passes to **Chapter 3**, solely devoted to the azimuthal anisotropy. The consideration starts with sketching the subsequent phases of the flow buildup. Next, the Author demonstrates the need to minimize the side effect of the non-flow contribution to flow, by requiring the minimal distance between two particles in terms of $\Delta\eta$. The further part of this chapter is devoted to patterns of subsequent flow harmonics, and their relations to features of the matter: compressibility and phase type, but also the event-based fluctuations. A presentation of the p_T–dependence of the elliptic flow is a good starting point for discussion of the possible parton-based mechanism of flow. The beam energy dependence of integrated elliptic flow is linked to predicted changing of the shear viscosity over entropy (η/s).

Here some comments should be made. As the evolution of pressure is supported by the evolution of transverse energy (Fig 3.2) the relation between these two quantities should be pointed out. The captions of Figs. 3.2, 3.3 and 3.8 should state, which colliding system and energy, and if relevant – the results of which transport model were shown in the plots, whereas the "left panel of Fig. 3.3" (referred on p. 27) is not present. Also in several places (Figs. 3.3, 3.9, 3.13, 3.14) the hadron type is not specified. Regarding "*v_n is expected to be proportional to the number of charged hadrons N_{ch}*" – this proportionality of at least v_2 should be inverse, as shown on Fig. 6.7.

An aspect of flow coalescence is discussed in Sect. 3.3. Assuming the hadrons coalesce from their constituent quarks, the flow should scale with their number ("*NCQ–scaling*"). Indeed, as shown in Fig. 3.15, such scaling was observed at $\sqrt{s_{NN}} = 200$ GeV. Looking ahead, the Author's analysis confirms it (Fig. 6.6). Mrs. Stefaniak presents also the overall findings on v_2 and v_3 from previous experiments, spanning wide range of energies from $\sqrt{s_{NN}} = 7.7$ GeV up to 2.76 TeV, that shows a muted beam dependence of the NCQ-scaling for higher p_T and holding of this scaling at lower beam energies. The Author discusses a small surplus in elliptic flow of matter over antimatter (except π) arising toward lower beam energies. She puts forward 3 hypotheses aiming to explain this effect: viscous corrections, mean field potentials of different signs, and differentiation between primary and produced protons.

One ought to point out that Figs. 3.16 and 3.17 were interchanged. The claim "*v_3 is more sensitive to viscous damping*" should be referenced and explained. Also, the stated explanation that the rise of $v_{2,3,4}$ with beam energy is due to increase of temperature (p. 43) should be supported by reference or reasoning, as the thermal motion is different from the collective one. The symbol for a viscous coefficient on p. 43 is missing, and if the Author meant β'' (caption of Fig. 3.19 states $\beta'' \sim \eta s$), this term should be introduced beforehand. Regarding the 1st hypothesis for matter-antimatter differences, the Author should point out, which quantities are suspected to be sensitive to these differences.

The methods of flow extraction are described in Sect. 3.4. Mrs. Stefaniak moves to the Cumulant Method, but also parameterizes the non-flow contributions and event-based flow fluctuations. The Author also distinguishes between the flow of referenced particles and that of particles of interest. Further on, an additional weighting is applied for compensating inhomogeneous efficiencies across the device. However, in my opinion this subsection should be more referenced and is burdened with several deficits related to description and language. It is not commented, why the v_n is not considered as function of (pseudo)rapidity in addition to that of p_T. Regarding "*Ψ_R cannot be measured experimentally*": it can be measured within the Q vector method, but with considerable uncertainties. Eq. 3.10 uses Ψ but this angle is not explained (reaction plane was noted before as Ψ_R, not Ψ). Similarly, Ψ_n in Eq. 3.12 is referred to Fig. 3.24, but in this figure only Ψ_R (not Ψ_n) is shown. Places 3.10 and 3.11 contain 2 equations each, so should be vertically stacked. Regarding "*v_n^0 is the driven by the average overlap region geometry component*": one should show more precisely, what is v_n^0, e.g. if it was just the contribution of flow from the initial geometry, why is it predefined as a centroid of the Gaussian distribution (left Eq. in 3.11)? Also stating $v_n\{2\}$ as being defined by Eq. 3.17

is misleading: this equation is not a definition but a result of derivation (c.f. Eq. 17a in N. Borghini et al., PRC 64, 054901). The paragraph 3.4.2 mentions "*diagonal and off-diagonal contributions of* $|Q_n|^2$", but hitherto Q_n was not presented as a matrix.

Chapter 4 of the Thesis is devoted to the RHIC accelerator and the STAR apparatus. The paths of proton and ion beam within RHIC are traced, and then the Author focuses on the subsequent devices of STAR, covering their geometry and detection methods. Here one should point out the involvement of Mrs. Stefaniak in the development of the iTPC in terms of the software development, as is also documented in **Appendix B**. Two particle identification (PID) methods are shown: (1) based on energy loss dependency on momentum, (2) based on time-of-flight. Then, in **Chapter 5** the Author describes the data analysis, starting from the gross properties of data samples, moving into the event selection procedure. It's important to stress that the data volume and energy range (Fig. 5.2) is impressive and points to large amount of analysis Mrs. Stefaniak did to get her results. By correlating the multiplicities of events per bunch crossing detected in TPC and TOF, the pileup effect is quenched, and by inspecting the z-th component of vertex the noise events are minimized. Turning to the track selection, the Author considers the track-vertex distance of closest approach (DCA) and minimum number of hits accepted as track members. After that, the combination of methods assigns hadron types to tracks.

A few remarks should be made. First, the tracking algorythms should be mentioned (e.g. Kalman Filter?) What is the track geometry hypothesis, (e.g. helix?). Regarding Fig. 5.2, the panel named "right" is placed below. Points described in caption as "green", are black. Regarding the v_Z distribution in Fig. 5.3 (left), the wide pedestal should be commented. The tracks with DCA around 0 cm were characterized as ones with high chance of not originating from resonance decays. But this is true only for weak and electromagnetic decays (Λ, K^0_s, ...), and not strong ones (Δ, ϕ, …). If PID is found by a "combination of methods", it should be explained or at least outlined. The labelling of axes in Fig 5.7 is not informative: please explain the meaning of variables.

In the next step the Author describe the necessary acceptance corrections as function of the track topology and event centrality, which she applied to the data with help of weighting the entries. The tracking efficiency, studied via the Monte Carlo simulations, was found to be on the level of 1% for all the investigated hadron types, and thus was not applied. Mrs. Stefaniak also verified several sources of systematic errors. The largest contribution to flow for the data at $\sqrt{s_{NN}} = 39$ GeV stemmed from DCA variations and was at $\leq 4.5\%$ level for v_2 and $\leq 10\%$ level for v_3. The analysis results were further plotted with corridors of these errors.

A presentation of flow results in **Chapter 6** begins from comparisons to previous analysis of p_T –dependences of v_2 in 3 centrality bins of 6 types of hadrons emitted at $\sqrt{s_{NN}} = 39$ GeV. Despite different methods, a degree of overall of agreement is impressive. It's also important that the Author plotted the profiles of differences. Next, Mrs. Stepaniak presents the flow results from $\sqrt{s_{NN}} = 200$ GeV, and finds out that regarding v_2 and v_3 flow harmonics, the difference between hadrons and antihadrons is negligible. The p_T–dependence of three harmonics: $v_{2,3,4}$ shows an overall anticorrelation of flow strength with No. of constituent quarks (n_q) at $p_T \lesssim 1.5$ GeV, and correlation at higher p_T. This prompts Mrs. Stepaniak to consider the v_n flow dependence on *transverse kinetic energy* (KE_T; energy without p_Z component), but v_n divided by $n_q^{n/2}$, and KE_T divided by n_q. In this representation all the experimental profiles were found to nearly lie on the same curve, which is an impressive finding. It supports the interpretation that the flow at $\sqrt{s_{NN}} = 200$ GeV builds up in the partonic phase. In the next step the Author displays the flow dependencies at lower beam energies: $\sqrt{s_{NN}} \in \{27, 39, 54\}$ GeV, and due to differences in flow between the matter and antimatter, Mrs. Stefaniak traces the hadrons individually. The p_T and centrality dependencies of v_2 and v_3 coefficients, shown in Figs. 6.7 – 6.12 constitute the large body of results, and the Author should be congratulated for this impressive analysis.

In general, all across the beam energies and hadron types, the v_2 coefficients rise with p_T and centrality toward saturation (and slight drop at peripheral collisions), whereas the v_3 coefficient rises with p_T but seems not to depend on centrality within the uncertainties. The level of this saturation of v_2 at higher p_T keeps the mass hierarchy (perhaps meson/baryon one), therefore Mrs. Stefaniak moves into inspecting the flow in scaled variables (v_N over $n_q^{n/2}$ as function of KE_T over n_q). This inspection shows that also at studied energies lower than 200 GeV (of $\sqrt{s_{NN}}$) the n_q–scaling still approximately holds, with a notable deviation of protons. In addition, Mrs. Stefaniak traces the disparity in flow between matter and antimatter. It is particularly visible for p–$\bar{p}$ difference of v_2's , but deviations in p_T profile are also seen for v_3. As shown in Fig. 6.17, after averaging over phase space and centralities – this disparity rises with dropping beam energy, again especially for protons. Here one should point out that the references to Figs. 6.13, 14, 15 and 16 are absent in the relevant text. Again, the statement that the v_2 drop at peripheral collisions is dominated by the viscous effects should be referenced.

Two subsequent **Chapters** (**7** and **8**) are devoted to the EPOS transport model, the default implementation of EoS (Chapter 7) and its development by introducing several scenarios (8). The subsequent stages of the collision treatment are described: initial non-thermalised phase, division between the core and corona region, hydrodynamical evolution of the QGP phase, hadronization and hadron rescattering. The sketches 7.1 – 7.8 are very illustrative in explanation of the approaches to the non-theorists, and much of the formalism is described. However, some terms in equations should be clarified. E.g. α appears in Eq. 7.1 as α_0 and α'. s_0 under Eq. 7.3 is not introduced, as well as $x^{+/-}$ in Eq. 7.7 and β in Eq. 7.12. The latter equation starts with an unknown " Σ^2 " term (maybe some quantity was omitted?) Also under Eq. 7.13 some term is omitted, and indices 1 and 2 appear without explanation.

Since initially EPOS was designed for $\mu_B \approx 0$, a model upgrade proposed by the BEST Collaboration is presented, where the EoS is extended towards CP and its neigbourhood. The Ising-based model is applied with a mapping scheme onto the QCD diagram. Here, however Equations 7.26-28 arouse some confusion, also with respect to references [168, 169]. The Θ, σ, R parameters are not explained, and on the other hand the stated α / β are not seen in Eqs. 7.26-28. In papers [168,9] β appears as exponent of R in equation corresponding to 7.26, σ in Eq. 7.27 equals to $\beta \cdot \delta$ in [168,9] and both β and δ are said to be critical exponents of given values [169]. g in $g(\Theta)$ is also not explained.

Mrs Stefaniak modified the EPOS code to flexibilize the inputting of EoS-related information. To make an informed guess on the temperature region where CP has changes to be located, the Author fits the p_T distribution of emitted π^+ with Hagedorn-Tsallis formula. However, here I don't see how the normalization parameter A is identified as the *inverse slope*. Next, the Author probes the possible EoS variants with 8 scenarios, and for each one she simulates the Au+Au collisions as in experiment. An inspection of 10 hadron yields (Fig. 7.8), reveals a moderate agreement (factor 2), where pion yields are overpredicted, but also each antimatter particle (the latter the Author should state) – regardless from the EoS variant. Having investigated the p_T–dependence of elliptic flow, Mrs. Stefaniak rightly finds this observable as insensitive to the EoS variants. However, it is the **moments of net proton number** distribution at $\sqrt{s_{NN}} \in \{7.7, 27\}$ GeV which she finds **responsive to the scenario changes**, especially at lower average multiplicities, although an increase of simulated events would be beneficial.

Despite the mentioned issues, my general opinion is that the bulk of experimental work and simulations (some already published in peer-reviewed journals) is a decent physics analysis. In consequence, I find that the considered Ph.D. Thesis of MSc. Maria Stefaniak **fulfills the requirements of the Act on Academic Degrees and Academic Title regarding the degree of Doctor of Philosophy**. **Therefore I request the Council of Physical Sciences for admission of MSc. Stefaniak to the next stages of the doctoral procedure**.

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