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Subject: Review of the doctoral dissertation of Daniela Ruggiano, M.Sc. entitles: Exploring the baryon correlation puzzle via multiplicity-dependent two-particle angular correlations in pp, pPb and PbPb collisions at the LHC energies"

The dissertation of Daniela Ruggiano is focused on the problem of angular correlation studies in collisions at ultra-relativistic heavy-ion collisions (HIC). This topic has very important implications in understanding baryogenesis and several features of heavy-ion collision and QGP dynamics (for example the origin of collectivity in small systems). The physics of the thesis is addressed with the technique of correlation function measurements, expressed as a function of relative azimuthal angle and pseudo-rapidity, performed with the ALICE detector at CERN.

This topic is of high relevance for the scientific community. It represents one of the major physics topics discussed in major conferences. In this respect, the thesis is of high relevance to the field.

Before going presenting my comment on the work by D. Ruggiano, first I would like to provide a summary and critical assessment for each chapter in the dissertation.

In ***Chapter 2,*** after a very general introduction on the focus of the thesis work (in **Chapter 1**), the author presents a general overview of the standard model of particles and interactions, of the physics of QGP, the method of heavy-ion collisions to study the QGP and how hadronization is expected to occur according to models. I found it very well written and complete, with a nice overview of observables such as collective flow (elliptic, direct, radial). The problem of the "emergence" of collectivity is then presented in a clear way as one of the important aspects of the thesis.

Comments and suggestions: as the author mentions in the chapter, QGP formation is expected to occur also at high densities. I would suggest mentioning the existence of research of neutron stars where a QGP-Hadron phase transition may occur in their core at high densities and zero-temperature. This is a topic under the attention of several physicists, with also possible implications on the emission of gravitational waves from neutron star binary mergers or in the emission of supernova electron antineutrinos during the formation of the core of proto-neutron stars. Adding a couple of sentences about these astrophysical and astro-particle implications of hadron-QGP phase transitions may pedagogically enrich the chapter.

Chapter 3 is dedicated to Monte Carlo models. After a general overview, with a description of all different phases (initial hard scattering with perturbative phase, transition to the non-perturbative phase, hadronization, resonance decays etc.), the author focuses on the MC models that are specifically used in the thesis work, with their special links to the phenomenon of minijets that are important for the work on the author in this thesis: PYTHIA, EPOS, DPMJET, HIJING, AMPT and CALM.

Comments and Suggestions: The chapter is necessarily technical, but it has the merit of highlighting in which aspect each of these models is relevant for the work presented in the thesis, especially as far as minijets and their relevance to angular correlations are concerned. This is a preferable approach as compared to the other option of presenting the MC models in the middle of the data analysis when they are

used. The author succeeds, in this way, to help the reader in understanding the main ingredients that characterize models in view of the final goal of the author. In this respect, my assessment of this chapter is very positive. I have only some minor suggestions to improve its readability:

- Fig. 3.1 may be better explained with some more text (labels) written on it. The different phases of MC event generators are described in the text, but it is not immediate to connect the description to the different lines in the figure. Adding some arrows and labels, clearly showing the hard scattering starting point, followed by the other stages of MC generation, would help the reader.
- Fig. 3.6 has a quite short caption. Maybe some more words in the caption to explain the comparison between the two different approaches would help the reader.
- I would recommend the author to check if there are more recent references about recent versions of PYTHIA and EPOS. I noticed that the ones provided in the bibliography are quite old (with some exception).

Chapter 4 presents how two-particle angular correlations are constructed. The first part of the chapter is nicely pedagogical, as it describes the correlation function and its rescaled version, with also an explanation of the reason why this multiplicity rescaling is important. Then, all possible sources of correlations and how they manifest on the three-dimensional plots are explained.

Comments and suggestions: This part of thesis is very useful and well written. The explanation of phenomena affecting the general shape of the correlation function is very good. I also have some minor suggestions:

- On Fig. 4.3, it looks like there is a mistake in the vertical axis label. If I correctly understand the goal of the figure, the left panel shows S, the central panel shows B and the right panel shows C. At present, all of them are labeled as C.
- In the text of subsection 4.3.1, it would be good to point to the figures when presenting how to construct S and B.
- Section 4.4.1. The author may consider the possibility of adding a reference to the work on EMCIC (Energy and Momentum Conservation Induced Correlations) at the STAR collaboration (Chajecki and Lisa Phys.Rev.C78:064903). Even if the paper addresses the effects on Femtoscopy, I think it may complete the references on the topic.
- Fig. 4.7. For more clarity, the Delta-phi axis may be labelled “Delta-phi (rad)”, as the away-side peak shows up at about delta-phi = 3.14 (π).
- Section 4.4.3. I would suggest the author to explain that the FSI and QS effects are the basis of Femtoscopy when expressed as function of invariant mass. Even if it is not the main topic of the thesis, I think it is useful to put the reader in the more general context of particle-particle correlations. Also, effects of Femtoscopy appear on two-particle angular correlations, as the author shows and mentions on Chapter 8 and Chapter 9.

Chapter 5 is the part of the thesis where the author explains the problem of the Baryon correlation puzzle, a very famous and important phenomenon observed in pp collisions with the ALICE detectors. This is one of the main motivations of the work done by Daniela Ruggiano in the following chapters. There is a historic presentation of the puzzle, with clearly described figures to show how p-p and anti_p-anti-p (like-sign protons) behave differently than like-sign mesons (with well explained differences between pions and kaons).

Comments and suggestions: The author presents nicely and in a complete manner the existing literature on attempts to explain the puzzle, directly pointing to the not yet understood mechanism for baryon production. Then, in subsection 5.4, the main goal of the thesis is presented with a nice link to the open problems described in this chapter. I consider the chapter very well written, and I do not have any special suggestions.

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Chapter 6 presents the ALICE experiment at LHC. It is very well written and clearly organized. Even if the ALICE experiment is already very well known, I appreciated the efforts of the student to provide a personal view of the detector description and its methods to identify the large number of particles produced t LHC energies.

Comments and suggestions: The chapter is personally one of the best syntheses I have read about ALICE technology and its direct link to observables. I have no suggestions to provide.

In ***Chapter 7***, the author describes the performed data analysis, starting from how centrality events are isolated, how particle identification is performed and how tracks for correlation measurements and event-mixing procedures are selected. The author focuses on correlations between like-sign and unlike-sign mesons (pions and kaons) and between protons and their anti-particles (like-sign and unlike-sign proton correlations), as a specific case of baryon correlation study. The analysis is done on pp, pPb and PbPb collisions.

The chapter reports the techniques used in the data analysis to select different centrality in events, to isolate specific tracks of interest and identify particles. The technical details to identify "good" pairs (getting rid of merging and splitting) is well explained and not difficult to follow. In subsection 7.6, the concept of purity in data analysis is presented and its p_T dependence is shown with simulations filtered on ALICE for pp, pPb and PbPb collisions. Detector efficiency and response is studied, leading to detector-corrected Signal and Background distributions from which the correlation function can be evaluated and scaled to the multiplicity, as it was previously explained in chapter 4.

Comments and suggestions: The explanation of the observed effects is complete and very clear, even in the most technical details. I have no special suggestions, and I would not modify anything in this chapter.

Chapter 8 and 9 are the main core of the results obtained by the author if the thesis. I appreciated very much the organization in Part 1 and Part 2, which makes the reading of this final part of the thesis even more clear and pleasant for the reader.

While Chapter 9 reports the large system AA case (with PbPb collisions), Chapter 8 is first focused on the case where a small system is used in the collisions, namely pp and pPb collisions.

Part I – Chapter 8.

In this part of the thesis, the "smaller" collision systems are studied, namely p-p at at $\sqrt{s_{NN}} = 13$ TeV and p–Pb data at $\sqrt{s_{NN}} = 5.02$ TeV. Building on the methodological work of Chapters 4–7, it shows a very important and original systematics of correlation functions for like-sign and unlike-sign meson and baryon (proton) correlations. Many of the figures are original as the author declares, as they are submitted for publications. The impressive amount of work that is shown clarifies several aspects of the physical effects observed in the near-side and away-side bumps. The author explains the difference between a correlation function constructed as a bare ratio between probabilities and the one obtained from multiplicity rescaled analyses. The methods are nicely and rigorously validated with MC simulations and many quality control tools in the data analysis.

By looking at the obtained results, the case of pion-pion and kaon-kaon correlations is linked to known effects of minijets, resonance decays, and well-known quantum-statistical / final-state-interaction effects. The evolution of the away-side ridge with the multiplicity shows that the mixed-event background and rescaled-cumulant formalism are under excellent control.

The first nice and original result that I can see is the observation of the like-sign-proton anticorrelation which is confirmed at 13 TeV, after having been first observed at 7 TeV. This confirms the presence of the baryon puzzle which is one of the focuses of the thesis. The dependence of the effect on multiplicity is discussed critically by the author, pointing to the need to improve models of baryon production mechanisms. These are certainly new findings and deserve publication. Also, the observation of a depletion $(\Delta\eta, \Delta\varphi) \approx (0,0)$ region in the highest multiplicity bins for p-anti(p) correlation is a new result that points to

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how one can better understand the strong potential between these pairs of particle-antiparticle species. The author also nicely explains the observed differences between pp and pPb collisions, with critical evaluation of possible effects induced by soft background or nuclear-shadowing effects rather than a fundamental change in the baryon-suppression mechanism.

Comment and suggestions: I evaluate this chapter as Excellent. The narrative is clear and complete. The chapter is full of interesting results that deserve publication, and it also prepares the reader to the following chapter 9, where heavier systems are studied and where more collective effects and the presence of the QGP may play an important role in the game. The comparison to model prediction is also well done and discussed. I do not have any special suggestions or recommendation except, maybe, a simple table to list the values and error bars of the amplitude of near-side peak and baryon dip versus multiplicity, observed in the correlation functions. It may help the reader to have a general compact overview of the results. But it is really a very minor suggestion.

Part II – Chapter 9

Finally, Chapter 9 extends the correlation analysis into the domain of Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, where QGP formation may play a key role in understanding the baryon correlation puzzle as well as other findings of this work. The author investigates on whether the like-sign baryon anticorrelation found in small systems still exists inside a hot and dense medium where hadron production phenomena occur. ***This is another new and important point of this thesis work***, with respect to the existing literature.

The investigation is again conducted looking at both the correlation functions and the rescaled ones, by ***maintaining the same rigorous logics of the previous chapter***. The procedures include the comparison to Montecarlo models which help understanding the methodologies and the missing components in the models themselves.

The observation of the anticorrelation in like-sign pp correlations also in heavy-ion collisions is a ***new result and it is analyzed and interpreted in great details***. The critical comments about the influence of flow make the analysis and the interpretation even more intriguing and pointing to new work to be done in the future.

Chapter 10 presents an overall comparison of results in all three collision systems under study. The reader has the opportunity of having a clear summary of all obtained results. ***The author clearly and exhaustively explains all the effects of minijets and flow for all like-sign and unlike-sign correlations for pions, kaons and protons***. ***This chapter is rich of clarity and well organized*** to lead the reader to the conclusions of the work presented in the following Chapter 11.

Chapter 11 is the conclusion where the author presents the obtained results, with comments, self-criticism and interpretation. It also contains a narrative list of "original" contributions of the analysis to the field, with ***results that are observed for the first time in the study of ultra-relativistic collisions***. Among them, I would mention:

- the use of rescaled angular correlations in ALICE data (previously done only in STAR data), with a very serious analysis of the multiplicities and of the methodology itself, performed also with the aid of MC models
- the extended comparison of angular correlations between small, intermediate and large systems (pp, pPb and PbPb). The striking observation of almost the same results across different systems, shows that the mechanisms are independent of system size. Small effects of QGP formation seem to be observed in PbPb collisions.
- The observation of the anticorrelation for like-sign baryon pairs also in the PbPb collisions, as evidence of the need for more work to understand the baryon correlation puzzle.

The author has done an excellent job that will further stimulate other studies both from an experimental and a theoretical point of view. These may include improvements of MC models with missing mechanisms by

directly looking at the experimental results of this thesis, as well as extension of particle-particle correlations analyses to other particle species while investigating on the proton composition of jets, which may one new hypotheses of interpretation of the baryon correlation puzzle.

The methods, experimental and theoretical (in the comparison between models and data), presented by the author, are fully appropriate and in line with what is recognized as scientifically sound in the field. They also contain elements of novelty that enrich the work.

I believe that the thesis deserves maximum attention by the scientific community at large, possibly with publication of the results.

I strongly recommend the award of the Ph.D. title to Daniela Ruggiano.

Sincerely yours,

Giuseppe Verde

Done in Catania, on May 5th, 2025

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