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Subj: Report on the Habilitation Thesis “Insight into interactions between particles and their production via particle correlations” by Dr Małgorzata Janik

Dr Janik has submitted a Habilitation Thesis “*Insight into interactions between particles and their production via particle correlations*”, which is based on a cycle of 11 thematically related articles in leading refereed journals. Two of them (H1, H2) are review articles with one coauthor where the own contribution of the habilitant is estimated to 50%. Seven articles were published by Dr Janik as a member of the ALICE Collaboration, where she played a decisive role in the publication as member (H3-H5) or chair (H6) of the paper committee or as internal review committee member or chair (H9-H11). Here, her contribution ranged between 15% and 40%, except for H4 and H6, where it was estimated as 60% and 70%, respectively.
Of special importance for this Thesis are the articles H7 and H8 which are published outside the ALICE Collaboration and where her contributions were 50% (one coauthor) and 90% (two coauthors), respectively. The latter publication H8, which resulted from a talk at the Quark Matter conference where she was awarded the best poster prize, may be considered the main innovative work of this Thesis; more details given below.

The Thesis presents a rich body of frontier research work in a well structured and logic manner. It is formulated in very good English language with only a few typos. The Thesis contains two main chapters, an Introduction, a Summary and a Bibliography with 400 entries. The two main chapters are devoted to femtoscopic correlations (chapter 2) and angular correlations (chapter 3), and each of them contains three sections which I will report in detail in the following.

In chapter 1, the Introduction, Dr Janik gives a motivation for the investigation of particle production in proton-proton (pp), proton-Pb and PbPb collision experiments at CERN LHC by underlining their role in developing an understanding of the physics of strongly interacting matter, and in particular for elucidating the formation and properties of the quark-gluon plasma. As it follows from the field of her expertise, the focus of her Thesis is on the ALICE experiment and the physics of two-particle correlations.

The chapter 2 of the Thesis is devoted to “Femtoscopy”, a technique for studying the size of an emitting region by interferometric two-particle correlations in momentum

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space, which was originally developed by Hanbury-Brown and Twiss (HBT) to determine the size of stellar sources in the 1950ies. It was taken over by Koonin (1977) and Pratt et al. (1990) to nuclear physics for studying the size of the collision volume of final state interactions in heavy-ion collisions, based on the similarity of the ratio between the source size and the distance to the observer.
The key quantity is the two-particle correlation function which in Theory is defined with the two-particle wave function and experimentally it is constructed from the measurable momentum-space distribution functions of of particles from the same event and from mixed events. Without going into the formal details, Dr Janik explains that the theoretical correlation function depends on quantum statistical correlations due to the exchange symmetry for fermionic or bosonic identical particles as well as coulombic or strong interactions in the final state. The extraction of this information by comparison of theory and experiment is the subject of the chapter 2 which is divided in three sections, each being based on one publication: 2.1) source sizes (H3), 2.2) space-time emission shifts (H4) and 2. 3) strong interaction (H5).

The main result of section 2.1 is the finding that the femtoscopic radii for pions scale linearly with the cubic root of the charged particle multiplicity density whereby the slope depends on the initial system size from pp over p-Pb to A-A collisions. These results are outlined in H3 where it has been found that the source shape is non-Gaussian and a Lorentzian parametrization for radii in “out” and “long” directions has been given.
The work H3 provides also an analysis of the transverse momentum dependence of source radii for pion pairs from p-Pb collisions, where the particular contribution from Dr Janik was the help she provided to the development of the analysis software of the Warsaw University of Technology group in ALICE. A comparison of the experimental data with results from two theoretical models is provided which both incorporate a fast hydrodynamic expansion of the created medium which is mandatory for A-A collisions, where it signals the onset of collectivity. The model description of the “side” radii in the 0-20% multiplicity range is satisfactory while the “out” radii are overestimated by both models.
In section 2.2, based on the publication H4, space-time emission shifts have been introduced for momentum correlations of non-identical particles between pions and kaons. The rationale behind this is the scaling of flow with particle masses on the one hand and the existence of short-lived resonances decaying into the final state particles as well as rescattering processes between chemical and kinetic freezeout. As a result of the work of the habilitation candidate, both the emission asymmetry and the time delay for kaon production could be quantified in their dependence on the charged particle multiplicity from nonidentical particle correlations.
In the final section 2.3 of the chapter on femtoscopy, Dr Janik uses the formula for femtoscopic correlations in order to infer from measured correlations and assumed information about the source the highly interesting information about kaon-nucleon or antikaon-nucleon interactions. In the paper H5, the author performed a femtoscopic

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analysis of proton-kaon pairs in Pb-Pb collisions and sowed that an attractive Coulomb interaction dominates for small momenta and that a repulsive strong interaction manifests itself in the momentum region of 20-50 MeV/c. The analysis of the real and imaginary part of the scattering length has been performed and showed a good agreement with the world data which thus confirms the validity of the approach that has been introduced in Ref. H5.

The chapter 3 as the second main chapter is devoted to the analysis of angular correlations. To this end, the two-particle correlation function C(Δη,Δφ) is analyzed in the phase space spanned by the difference of azimuthal angles Δφ and the pseudorapidity difference Δη forming a "landscape" which is accessible in the ALICE experiment for different identified particle species: π, K, p, Λ.
In section 3.1, the general shape of this landscape of angular two-particle correlations is discussed. It is a near-side valley and an away-side peak in the Δφ direction. For the two-boson angular correlation function, there is a Bose-Einstein correlation peak at (Δη,Δφ)=(0,0), which is also visible in the Δη-integrated results for the Δφ-dependence of identical pion and kaon pair correlations.
For the proton-proton and antiproton-antiproton correlation, there is a depression at Δφ=0. These experimental results were reported in the publication H6. It was also noticed that the difference in the theoretical modeling by Monte-Carlo (MC) simulations was stemming from the absence of Bose-Einstein correlations in the models. The models failed also to reproduce the depression for like-sign baryon correlations at Δφ=0.
In Ref. H7, the anticorrelation effects in baryon-baryon correlations are studied more in detail and confirmed for pp, ΛΛ and pΛ systems. The MC event generators are listed which do not reproduce the experimental data from the ALICE experiment.
In order to resolve the puzzle, Dr Janik has designed a new MC model (CALM) that allows to focus on the account of conservation laws for momentum, charge, strangeness and baryon number. In Ref. H8 it is demonstrated that a qualitatively correct description of the baryon-baryon correlations can be given in this way. Although the baryon-baryon angular correlation results are not yet fully understood, a significant progress was obtained by this work of the habilitant.
A remark may be in order. Namely, that identical particle effects by the fermion exchange antisymmetry which are not expected in, e.g., the pΛ system on the baryon level of description (where p and Lambda are not identical particles) such effects can be expected on the quark level of description, where protons and Lambdas are consisting of identical (fermionic) up and down quarks.

In section 3.2, Dr Janik applies the method of angular two-particle correlations to the study of pairs formed by a D-mesons and a hadron. In Ref. H9, this is done for pp collisions as a reference and in pA collisions at center of mass energies of 5.02 TeV to check for cold nuclear matter (CNM) effects. In Ref. H10, the same has been done at

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the higher energy of 13 TeV. These experiments show an increase of the near-side peak in D-hadron correlations with increasing transverse momentum of the D-meson. This observation is explained by a higher number of particles in a jet accompanying the fragmentation of a charm quark, valid for the near as well as the away-side peak. Since yields and widths are in agreement in both pp and pPb collisions, no significant CNM effects are observed. There is also no multiplicity or centrality dependence. The extracted correlation functions analysed in H9 and H10 are compatible with measurements at lower energies and agree with the MC simulations.

The final section 3.3. of the habilitation Thesis, Dr Janik considers jet (hadron) – deuteron correlations. Deuteron (d) production in jets can be considered within the coalescence or the statistical hadronisation (nucleation) model of light (anti-) nuclei. A distinct near-side ($\Delta\varphi=0$) and away-side ($\Delta\varphi=\pi$) peak was observed for the d-hadron angular correlations where the hadrons from a jet have transverse momentum exceeding 5 GeV/c. The results are qualitatively well described by PYTHIA+ afterburner model calculations. They are reported in the publication H11 and lead to the conclusion that a significant fraction of deuterons is produced in jets.

Summarizing the results reported in the publications H3-H11 where the particle production in collisions is considered with the method of femtoscopic as well as angular two-particle correlations, this habilitation thesis provides new insights that add to the knowledge on heavy-ion physics as it is comprehensively described in the review papers H1 and H2. There are, however, open questions remaining which concern the comparison of experimental results with simulations in the case of femtoscopic radii extracted from p-Pb collisions as well as for the observation of the same (fermionic) depression of near-side correlations for identical (pp and ΛΛ) as well as non-identical baryons (pΛ). Here, a decisive progress in the understanding has been made by Dr Janik with the design of the MC model CALM based on a simplified picture based on the assumption that hadrons are governed by conservation laws only without other correlation mechanisms.

Beyond the excellent scientific results on the study of two-particle correlations of particles produced in high-energy collisions, that were made possible due to the work of Dr Janik, one has to appreciate the additional service to the community that she has provided. To mention only a few examples of these activities, she is a member of the AEgIS Collaboration at WUT (since 2020), a member of the ALICE Editorial Board (since 2019, two times renewed) and a deputy team leader of the WUT group at ALICE (since 2015).

Dr. Janik has conducted lectures for students as part of the Oslo Winter School program in January 2018 (“Two-particle correlations” and “Jet-quenching in Heavy-ion collisions”) and organized regularly ALICE MasterClass sessions at WUT (7 events in

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2015 – 2023). Such Master classes were held by Dr Janik also at the University of Sarajevo (2018) and at CERN (2021, online).

Dr Janik has demonstrated experience with acquiring research grants such as a NCN Sonata (2016-2019) and a WUT IDUB grant (2022 up to now). She was also participating in as an investigator in 10 other research grants.

A further important aspect of her habilitation is that Dr Janik has supervised the respectable number of 18 Bachelor and 6 Master Theses and is presently supervising two PhD Theses which are planned for defense in 2025 and 2026.

Summarizing, I conclude that the Habilitation Thesis and the scientific activity of Dr Małgorzata Janik fulfil all necessary criteria for promoting her to a habilitated doctor in the physical sciences. I recommend the Thesis to the Faculty for its acceptance.

David Blaschke

Wroclaw, 11.06.2024 Prof. dr hab. Dr h.c. David Blaschke