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Subj: Report on the Habilitation Thesis “Strangeness production in proton-proton and heavy ion collisions at SPS energies” by Dr Szymon Puławski

Dr Puławski has submitted a Habilitation Thesis consisting of a Monograph “Strangeness production in proton-proton and heavy ion collisions at SPS energies”, ISBN 978-83-66248-96-0, 2022, Publisher Presscom Sp. Z o.o., which is based on a cycle of thematically related articles: 6 articles in leading refeereed journals as corresponding/main author, 9 articles in postconference publications as first author, 5 articles as chair or member of the editorial board and 32 articles as team member of the NA61/SHINE Collaboration.
Further achievements are listed in the “Summary of Professional Accomplishments”.

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 7 chapters, an Introduction, a Summary and a Bibliography with 142 entries. In my report as an expert in Theoretical Physics, I will referee the chapters 1 and 4 to 7, while sparing the chapters 2 on the expermental setup and 3 on the analysis procedure.

In chapter 1 on the research objective the author motivates the investigation of strangeness production in proton-proton (p+p) and heavy-ion collision (HIC) experiments by their role in understanding the physics of strongly interacting matter, in particular the laws of hadronization, dynamics of heavy-ion collisions and possible signals of the onset of quark deconfinement and the formation of the quark-gluon plasma. He argues that hadrons with a strange quark have a low cross section wth pions and their yields and spectra should not be too much distorted by rescattering effects.

The author motivates the study of p+p collision experiments by their role in providing data that constiitute a reference baseline for “new physics” in HIC. He stresses that on the one hand, there are quualitative differences in the modeling between p+p and A+A collisions, while on the other hand there is a striking consistency of some predictions

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when going from p+p to A+A, however, without going to details of these statements and giving only few references. The author does not discuss here approaches which build predictions for the outcome of HIC on the basis of p+p data like, e.g., the Glauber model.

In a second subsection, Dr Puławski introduces the strangeness enhancement factor *E* and discusses the old concept of strangeness enhancement as a signal for quark-gluon plasma (QGP) for mation in HIC. While indeed a quantitavive discussion of this factor was lacking for many years a p+p reference experiment at CERN SPS energies, the caveats of this quantity as a QGP signal could have been mentioned. Namely, that *E* increases when goind from higher energies at LHC or RHIC to the lower energies at SPS, and that at still lower energies of the GSI-SIS experiments the phenomenon of subthreshold kaon production has been observed as an effect of a dense, purely hadronic environment.
The next subsection is devoted to the discussion of the strangeness-to-entropy ratio, for which the ration of <K+>/<pi+> is a good measure. The statement that this ratio is different in the QGP and in the confined phase of hadronic matter shall motivate it as a signal for QGP formation. But such an interpretation would have required a detailed discussion in which sense the appearance of a “horn structure” observed in HIC as a function of the collision energy dependence would be signalling a transition in the phase structure of the ambient matter.
In the following section devoted to particle production mchanisms, the author mentions resonance formation and decay, string breaking by quark pair creation and statistical hadronization. The details and differentiation between these mechanisms is not sufficiently elucidated, but it is made clear that a detailed, systematic experimental study of strange hadron production from p+p oder p+A to A+A collisions is extremely important. The situation reminds on the phenomenon of color transparency which could have been mentioned in this context as it takes place in the similar energy range as the “horn”.
The chapter on the research objective closes with a section on exotic strange states such as light pentaquarks and multi-strange baryons and their excited states.
This motivation chapter describes the research objective well and touches the main topics except for the Lambda production that is missing. One should note that also the <Lambda>/<pi-> produces a horn effect which mirrors that for <K+>/<pi+>, because K+ and Lambda are produced simultaneously and with a lower threshold than the K+K- pair.

In chapter 4, Dr Puławski presents the main experimental results that he has obtained with the NA61/SHINE experiment regarding strangeness production in p+p and A+A collisions. Separate sections are devoted to the results for spectra and mean multiplicities of Ξ^- , Ξ^0(1530), Ω^- and their antiparticles as produced in p+p collisions. It is an important result for the phenomenology of strageness production to see that at

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higher energies for STAR at RHIC and at LHC, the difference in the mean multiplicities of multistrange baryons and their antiparticles is negligible while at CERN SPS energies this ratio is about 0.5, which allows to infer the baryon chemical potential.
In the final section 4.4 of this chapter the author presents spectra and multiplicities of charges hadrons (pi+, pi-, K+, K-, proton, antiproton) in Be+Be collisions. In view of the discussion of the horn effect, the results for charged kaons and pions are of particular interest. The yields of these particles are a factor 4 higher than in p+p collisions in accordance with the wounded nucleon model (p. 94), but otherwise they show the same energy dependence. While pi+ and pi- are about equally abundant, the K- are roughly a factor 2 less abundant than K+.
It would have been nice, if Dr Puławski would have dwelled a bit on the possible explanation of this observation by the fact that two processes in p+p collisions lead to the creation of a K+ while only one of them creates a K- while the other has the Lambda as a partner state. Because of this larger slope in the energy dependence of the ratio <K+>/<pi+>, the "horn" effect arises for this ratio while the rise of the ratio <K->/<pi-> is too small to produce a horn and thus smoothly joins the QGP asymptotics for this ratio.
To my understanding of this effect, it would be instructive to measure Lambdas and then to show that <K- + Λ>/<pi-> would resemble the similar "horn" feature as the celebrated <K+>/<pi+> ratio.

Chapter 5 discusses the HRG and QGP transition, the onset of deconfinement. In Fig. 5.1. of the monograph the system-size dependence of the energy dependence of the <K+>/<pi+> ratio is shown at mid-rapidity (y ~ 0) and in full phase space. In collisions of heavy ions (Au+Au and Pb+Pb, large systems) the horn structure appears, while in small systems (p+p and Be+Be) it is absent. The author discsses the ratio <K+>/<pi+> as a good measure for strangeness over entropy, which is postulated to be different in hadronic (confined) systems and the QGP. But how exactly should one interprete the horn? How is it related to the onset of deconfinement? Is the onset of deconfinement a matter of the system size or of the collision energy or both? In recent works by Marek Gazdzicki the notion of "onset of fireball" and "onset of deconfinement" has been introduced to which the author, however, does not refer. Does the "horn" have to do with a modification of the production threshold for kaons and Lambdas in a dense hadronic medium (subthreshold kaon production, observed at GSI-SIS)?
Very instructive for understanding the nature of the "horn" effect is to consider the K+/pi+ ratio in the temperature- chemical potential plane together with the parametrized cchemical freeze-out curve, see Fig. 4 of Oeschler et al. nucl-th/0701080 and Fig. 2 of Blaschke et al. ArXiv:2101.10084.

A very intersting observation is that of the "break energy" at √s ~ 8 GeV for the fitted energy dependence of the <K+>/<pi+> ratio in p+p collisions (Fig. 5.3). Can this observation be related to a change in the particle production regimes and with the

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onset of “transparency” in the nucleon-nucleon collisions? Is this break also visible in the Lambda production, i.e. the <Λ>/<pi-> ratio ?

In section 5.2 the author discssed a new baseline for the strangeness enhancement factor that he obtained from the production of Ξ^- and its antiparticle in p+p collisions at SPS energies as one of the main achievents in this Thesis. This factor *E* has two features: a) a linear increase with $\langle N_W \rangle$, i.e. with system size, and b) a dropping slope with increasing collision energy $\sqrt{s}$.
What about the strangeness enhancement as a QGP signal, when the ratio *E* gets enhanced by lowering the collision energies towards the hadronic regime? This should be commented.

In section 5.3 the author presents results for the K/pi ratio in Be+Be collisions from which he cconcludes that there is no horn structure observed and the ratio behaves identical to the case of p+p collisions. Therefore, the Be+Be system can still be considered a sufficiently small system.

In chapter 6, Dr Puławski reports the results of the pentaqark search which culminate in the conclsion that there is no signal over background for a light pentaquark in the mass range 1848 – 1870 MeV/c^2, where NA49 had seen a significant enhancement albeit with a much smaller number of events. This is an important result for the development of phenomenological quark models for multiquark hadrons.

Finally, in chapter 7, Dr Puławski presents a comparison with model calculations of two kinds. In Section 7.1, he compares the measured data with results of transport models: EPOS 1.99, UrQMD 3.4, AMPT 1.26, SMASH 1.6 and PHSD. EPOS describes well the rapidity spectra of the cascade Ξ^- and its antiparticle, while the p_T spectrum is slightly shifted. The K- p_T spectrum is well described by EPOS and SMASH while UrQMD, AMPT and PHSD overestimate. The energy dependence of K+/pi+ is well described by EPOS, UrQMD and SMASH, but AMPT and PHSD overproduce. All models describe the energy dependence of K-/pi- well.
I am wondering why a relatively old version of EPOS has been used since meanwhile EPOS 4.0 is on the market.
In section 7.2 the data for (multi-)strange hadron production are compared with the hadron resonance gas model for different choices of the ensemble (canonical, grand canonical) and strangeness suppression factor γ_S . The best fit is obtained for a strangeness canonical ensemble with fitted γ_S , for which the best χ^2/NDF = 2.8 is obtained.
In comparing results for strangeness production from p+p to A+A collisions, the question of possible universal relations should be discussed. Meanwhile, in partcular at high energy collisions, many unexpected similarities between p+p collisions (naively thought of as a baseline for which no QGP formation would apply) and A+A collisions

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have been uncovered. One example is an interesting similarity of the dependence of the strangeness suppression factor γ_S in p+p and A+A collisions on the initial entropy (temperature) [Castorina, Plumari and Satz, arXiv:1709.02706].

Beyond the excellent scientific results, that were made possible due to the work of Dr Puławski, one has to appreciate that he took responsibilities as a deputy team leader of the Katowice group froom the University of Silesia in the NA61/SHINE experiment and was the Coordinator of different working groups in the experiment, such as for identification of charged hadrons in 2018-2019, for software in 2020-2021 and for bam and beam detectors. He was coordinator of the activities leading to the preparation of the NA61/SHINE experiment after 2020 and is a member of the CERN Physics beyond Collider group. Dr Puławski has also demonstrated experience with acquiring research grants and participating as investigator in collective research grants such as HARMONIA, BEETHOVEN and GRIEG. This is an important aspect of the habilitation as an independent scientist, qualified to lead a scientific group.

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

David Blaschke

Wroclaw, 21.04.2023 Prof. dr hab. Dr h.c. David Blaschke