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Review

Phase diagram of strongly interacting matter: the last 20 years at the CERN SPS

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Abstract Twenty years ago, on February 10, 2000, the CERN Director General Luciano Maiani announced: *The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundamental forces between quarks.* This report briefly reviews studies of the phase diagram of strongly interacting matter with relativistic nuclear collisions at the CERN Super Proton Synchrotron which followed the CERN's press release on the quark-gluon plasma discovery. An attempt to formulate priorities for future measurements at the CERN SPS closes the paper. The report is dedicated to David Blaschke who celebrated his 60th birthday in 2019. David's contribution to the studies presented here was very significant.

1 Introduction

The report is organized along Karl Popper's view of scientific method:

$$PS1 \to TT1 \to EE1 \to PS2 \ldots\ , \tag{1}$$

where $PS1$ is an initial problem situation, $TT1$ and $EE1$ stand for tentative theories and error elimination, respectively, and $PS2$ is a resulting new problem situation.

The problem situation emerged after the quark-gluon plasma discovery at the CERN SPS is presented in Section 2. Tentative theories constructed to answer questions motivated by the experimental data are summarized in Section 3. Measurements which were requested to falsify the tentative theories are reviewed in Section 4. A sketch of a new problem situation created by new experimental results closes the paper, Section 5.

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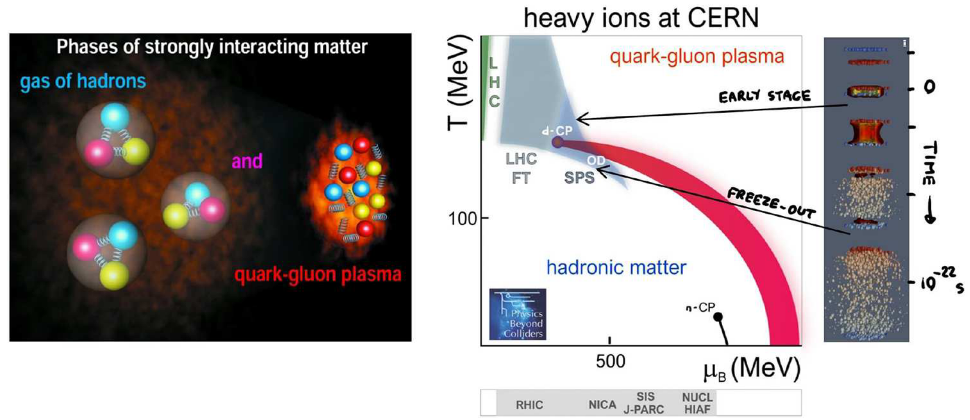

Fig. 1. *Left:* Artistic sketch of the two phases of strongly interaction matter, hadron-resonance gas and quark-gluon plasma. *Middle:* Phase diagram of QCD in temperature T and baryon chemical potential , and the region covered by running or planned experiments [3]. The density range covered by LHC, LHC-FT and SPS experiments is indicated by the shaded areas in the figure. The lower boundary of the grey and blue shaded area follows the chemical freeze-out. The upper boundary relates to the parameters at the early stage of the collisions. The potential deconfinement critical point is labelled with d-CP, the onset of deconfinement with OD. The black line at small temperatures and high densities shows the nuclear liquid-gas transition, also ending in a critical point n-CP. The density range of other experiments is indicated in the bar below the figure. This includes RHIC at BNL, NICA at JINR, SIS100 at FAIR, J-PARC-HI at J-PARC, the Nuclotron at JINR (NUCL), and HIAF at HIRFL. *Right:* Evolution of a heavy-ion collision at high energies. Successive snapshots of a central collision are shown versus time.

2 Problem situation around 2000

On February 10, 2000 the CERN Director General Luciano Maiani said: *The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result veri es an important prediction of the present theory of fundamental forces between quarks. It is also an important step forward in the understanding of the early evolution of the universe. We now have evidence of a new state of matter where quarks and gluons are not con ned. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN's Large Hadron Collider.*

This announcement summarized major achievements [1] of heavy-ion experiments collecting data during the first twenty years of heavy-ion physics at the CERN SPS, for recent review see reference [2]. The measurements were motivated by expectations that matter at very high densities may exist in a state of quasi-free quarks and gluons, the quark-gluon plasma (QGP) and this new state of matter can be created in heavy-ion collisions at sufficiently high collision energies. Moreover, by changing collision energy and nuclear mass number one changes macroscopic parameters of the created matter – its volume, energy, and net baryon number. This allows to move across the phase diagram of strongly interacting matter, see illustration plots in Figure 1.

The experimental search for a quark-gluon plasma in heavy ion collisions at the CERN SPS was shaped by several model predictions of possible QGP signals:

- enhanced production of strange and multi-strange hadrons from the QGP [4],
- suppressed production of charmonium states, in particular J/ψ mesons [5],

– characteristic radiation of photons and dilepton pairs from the QGP [6].

They were confirmed by the experimental data from the CERN SPS experiments, for detail see reference. [2].

This was in fact the moment when the majority of heavy-ion physicists moved to study heavy-ion collisions at much higher energies at the Relativistic Heavy Ion Collider (RHIC) of Brookhaven National Laboratory (BNL) and prepare measurements at the CERN LHC. Rich and precise results obtained during the period of 2000-2010 at RHIC [7–10] and 2009-2020 at LHC [11] provided extensive information on the properties of the QGP. There are no doubts about QGP formation at the early stage of nucleus-nucleus (A+A) collisions at the top SPS, and all the more at RHIC and LHC energies.

The situation after the announcement of the QGP discovery in 2000 at CERN was however rather confusing. Many were pretty sure about its formation in central Pb+Pb collisions at the top SPS energy, but unambiguous evidence of the QGP state was still missing. Questions marks concerning the interpretation of the observed e ects – the strangeness enhancement and J/ψ suppression – started to accumulate, for detail see reference [2].
Needless to say that the Nobel prize for the QGP discovery was not yet awarded. This may be attributed to the difficulty of obtaining unique and quantitative predictions of the expected QGP signals from the theory of strong interactions, QCD.

3 Tentative theories

Difficulties in interpretation of the QGP signatures forced scientists to rethink the QGP-hunt strategy. The emerging new strategy was similar to the one followed by physics studying molecular liquids and gases. In these essentially simpler and familiar cases it is also sometimes difficult to distinguish the properties of a dense gas from those of a liquid. It is much easier to identify the e ects of the liquid-gas transition. Thus, if one believes that the QGP is formed in central Pb+Pb collisions at the top SPS energy one should observe qualitative signals of the *transition* to the QGP at a lower collision energy. Several such signals were predicted within the statistical model of the early stage [12]. Their observation would serve as strong evidence of QGP creation in heavy-ion collisions at high enough collision energies.

These arguments motivated some of us to propose in 1997 the collision energy scan at the CERN SPS with the aim to search for the *onset of decon nement* [13,14]. It was the beginning of the search for the critical structures in heavy-ion collisions, for detail see references [2,15].

Popular model predictions of possible measurable signals were:

– characteristic enhanced production of pions (Fig. 2 (*top left*)) and suppression of the strangeness to pion ratio (Fig. 2 (*top middle*)) [12],

– softening of collective flow of hadrons [16–19], which should be observed in hadron distributions in transverse [16] (Fig. 2 (*bottom*)) and longitudinal momenta [19] as well as azimuthal angle [17,18].

Some years later the workshop *Tracing the onset of decon nement in nucleus-nucleus collisions*, ECT* Trento, April 24–29, 2004, summarized the results from the energy scan programme at the CERN SPS and concluded that future measurements in the SPS energy range are needed [22]. The goal is to search for the deconfinement critical point and study system size dependence of the onset of deconfinement. Possibilities to perform these measurements at the CERN SPS, FAIR SIS300 and RHIC were discussed. The event initiated a series of the *Critical point and onset of*

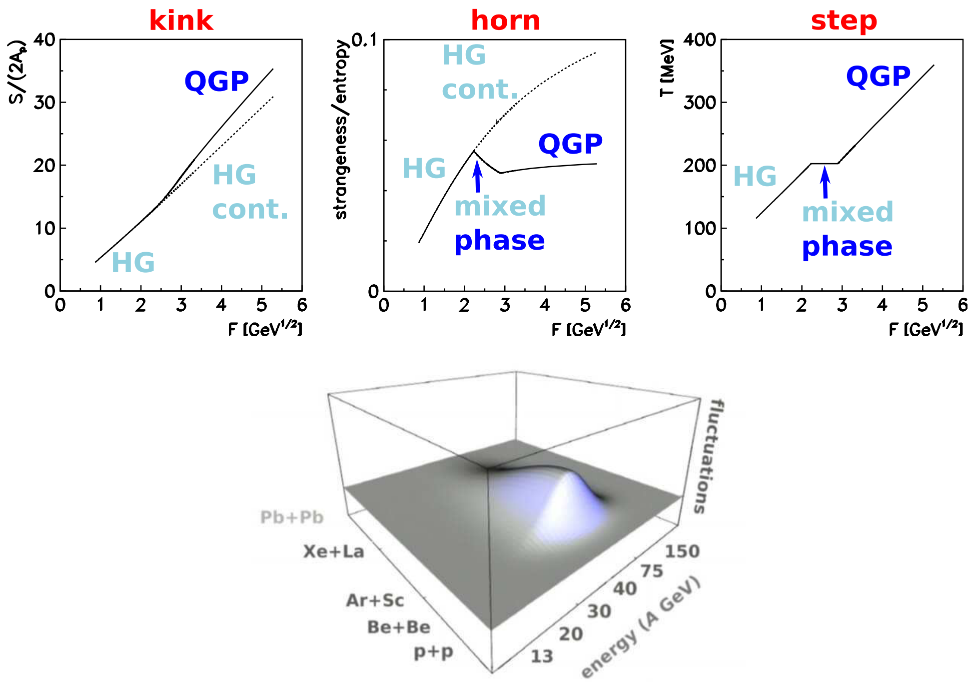

Fig. 2. Sketch of selected model predictions which motivated search for the onset of deconfinement (*top*) and search for the deconfinement critical point (*bottom*) at the CERN SPS (for detail see Refs. [20,21]).

decon nement workshops – where new physics ideas and results as well as needed new measurements are discussed.

The experimental search for the d-CP in A+A collisions at the CERN SPS was shaped by several model predictions (for detail see Ref. [23]) of its potential signals:

- characteristic multiplicity fluctuations of hadrons [23–26],
- enhanced fluctuations of (pion multiplicity)-(transverse momentum) [27].

The signals were expected to have a maximum in the parameter space of collision energy and nuclear mass number of colliding nuclei – *the hill of fluctuations* [28], see Figure 2 (*bottom*).

4 Error elimination

This motivated two experimental programmes at the CERN SPS:

- firstly the beam momentum scan with central Pb+Pb collisions to search for the onset of deconfinement and
- secondly the two dimensional scan in the beam momentum and nuclear mass number of colliding nuclei.

Search for the onset of decon nement. The search for the onset of deconfinement at the CERN SPS started in 1999 with the data taking on Pb+Pb collisions

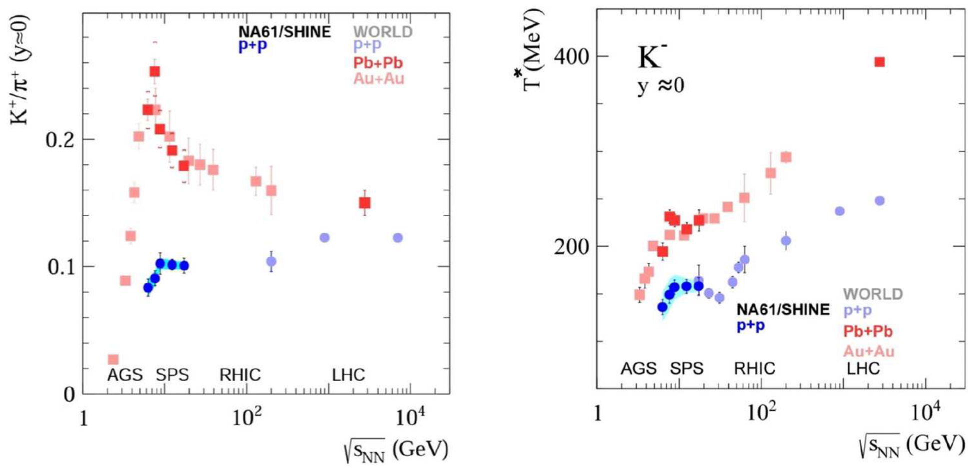

Fig. 3. Examples of results illustrating the observation of the onset-of-deconfinement signals in central Pb+Pb (Au+Au) collisions [29], see text for details and more references.

at $40A$ GeV. The data were registered by NA49, NA45, NA50 and NA57. In 2000 a beam at $80A$ GeV was delivered to NA49 and NA45. The program was completed in 2002 by runs of NA49 and NA60 at 20 and $30A$ GeV. Thus, together with the previously recorded data at $158A$ GeV, NA49 gathered data at five collision energies. Other experiments collected data at two (NA50, NA57) or three (NA45, NA60) energies. In 2010 the beam energy scan programme BES started at RHIC with the aim of covering the low energy range overlapping with the CERN SPS and providing important consistency checks on the measurements.

Results on the collision energy dependence of hadron production in central Pb+Pb collisions from the onset-of-deconfinement search programme at the CERN SPS [30, 31] appeared to be consistent with the predicted signals (for review see Ref. [20]):

- The average number of pions per wounded nucleon, $\langle N \ \rangle/\langle W\rangle$, in low energy Pb+Pb collisions is smaller that this value in p+p reactions. This relation is however changed to the opposite at collision energies larger than $30A$ GeV, the so-called *kink* structure.

- The collision energy dependence of the $\langle K \ \rangle/\langle \ \ \rangle$ ratio shows the so-called *horn* structure. Following a fast rise the ratio passes through a maximum in the SPS range, at approximately $30A$ GeV, and then decreases and settles to a plateau value at higher energies. This plateau was found to continue up to the RHIC and LHC energies.

- The collision energy dependence of the inverse slope parameter of the transverse mass spectra, T^*, of charged kaons shows the so-called *step* structure. Following a fast rise the T^* parameter passes through a stationary region (or even a weak minimum for K), which starts at the low SPS energies, approximately $30A$ GeV, and then enters a domain of a steady increase above the top SPS energy.

Figure 3 shows examples of the most recent plots [29] illustrating the observation of the onset-of-deconfinement signals. As seen data from the RHIC BES I programme (2010-2014) and LHC (see Ref. [29] for references to original experimental papers) confirm the NA49 results and their interpretation.

Search of the d-CP search. The systematic search for the d-CP of strongly interacting matter started in 2009 with the NA61/SHINE [32,33] data taking on p+p

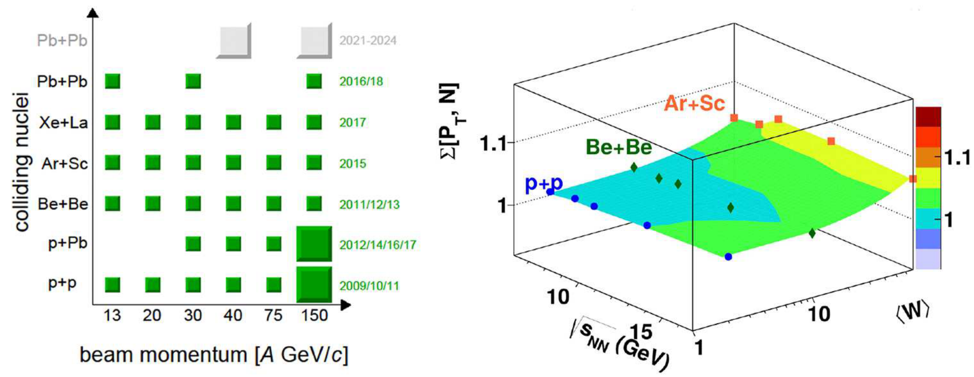

Fig. 4. *Left:* Summary of data recorded by NA61/SHINE at the CERN SPS (*left*) relevant for the search for the deconfinement-CP. *Right:* Results from the NA61/SHINE two dimensional scan of energy and system size for (pion multiplicity)-(transverse momentum) fluctuations in terms of the strongly intensive quantity $[P_T, N]$ [34].

interactions at six beam momenta in the range from 13*A* GeV/*c* to 158*A* GeV/*c*. In the following years data on Be+Be, Ar+Sc, Xe+La and Pb+Pb collisions were recorded, see Figure 4 (*left*) for an overview.

Many experimental results have already been obtained within the d-CP search programmes at SPS, for a recent review see reference [35]. In particular, the hill of fluctuations was expected in the collision momentum - nuclear mass number plane (see Fig. 2 (*bottom*)). Measurements of (pion multiplicity)-(transverse momentum) fluctuations from NA61/SHINE shown in Figure 4 (*right*) do not show this feature [34]. The analysis of the recorded data continues, various fluctuation quantities predicted to be sensitive to d-CP are studied. Thus many new results from the programme are expected in the years to come.

In parallel to the d-CP search at the CERN SPS a search is carried out at BNL RHIC, for recent reviews see references [35,36].

5 Problem situation around 2020

Understanding charm production. Data on charm quark production at the CERN SPS collision energies are very sparse. Systematic results are crucial to understand precise results on charmonia production by NA38, NA50 and NA60 in the context of the onset of deconfinement. Moreover, a collision energy scan in the onset of deconfinement region to measure open and hidden charm production in Pb+Pb collisions and establish the impact of the onset on the heavy quark sector is essential.

This requires high statistics data collected with detectors optimized for open and hidden charm measurements. Charm measurements are planned by NA61/SHINE [37], NA60+ [38] at the CERN SPS, they are considered by MPD [39] at NICA and JHITS [40] at J-PARC-HI MR.

Detailed physics arguments and possible experimental set-ups are presented in references [37,38].

Understanding system size dependence. Measurements of the system size dependence of hadron production properties at di erent collision energies were carried out by NA61/SHINE to search for the d-CP and to establish system size dependence of e ects related to the onset of deconfinement. As a result an unexpected phenomenon has been discovered. Its presentation requires a brief introduction.

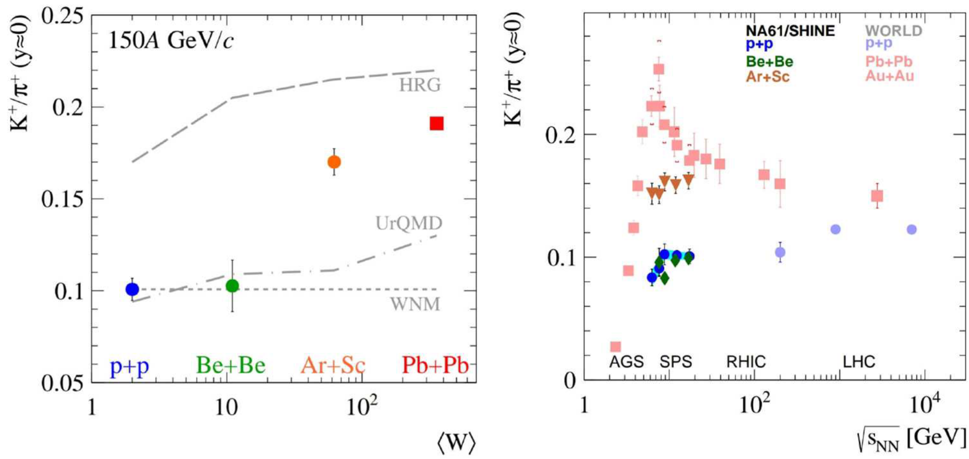

Fig. 5. Measurements of the K /π ratio in p+p, Be+Be, Ar+Sc and Pb+Pb collisions: system size dependence at 150*A* GeV/*c* [44] (*left*) and collision energy dependence [29] (*right*). Predictions of the Wounded Nucleon Model [42] and Hadron-Resonance Gas Model [45] are shown for comparison (*left*).

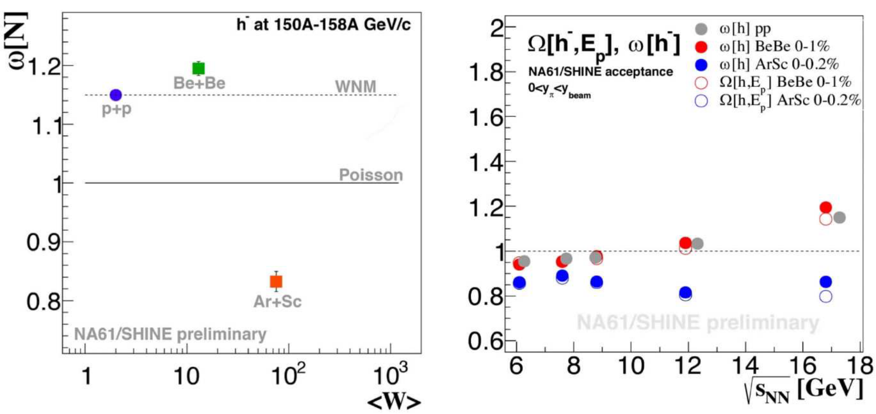

Fig. 6. Measurements of the scaled variance ω of the multiplicity distribution of negatively charged hadrons in inelastic p+p interactions and central Be+Be and Ar+Sc collisions [46]: system size dependence at 150*A* GeV/*c* (*left*) and collision energy dependence (*right*).

There are two models often used to obtain reference predictions concerning the system-size dependence of hadron production properties [41] – the Wounded Nucleon Model (WNM) [42] and the Statistical Model (SM) [43]. For the K / ratio at the CERN SPS energies they are:

– The WNM prediction: the K / ratio is independent of the system size (number of wounded nucleons).

– The SM prediction: in the canonical formulation incorporating global quantum number conservation the K / ratio increases monotonically with the system size and approaches the limit given by the grand canonical approximation of the model. The rate of this increase is the fastest for small systems.

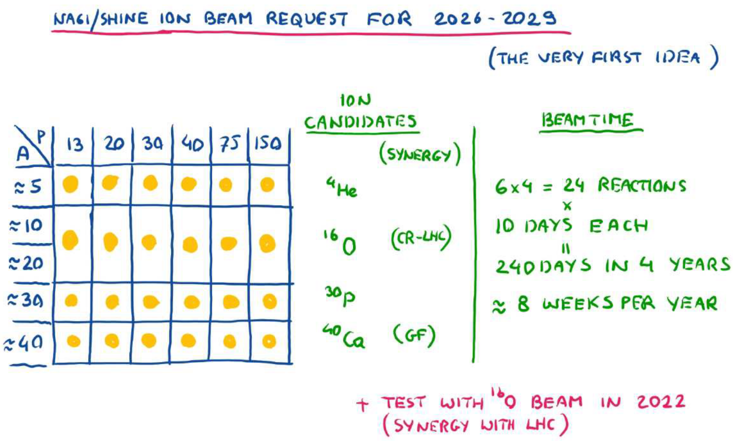

Fig. 7. A first idea on a possible NA61/SHINE beam request for the data taking period after the CERN Long Shutdown 3.

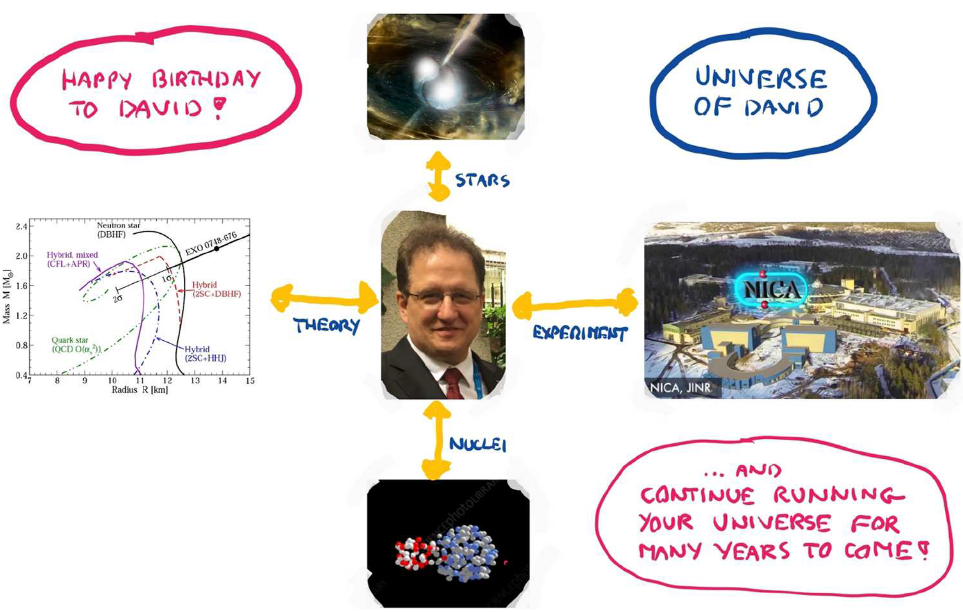

Fig. 8. The *Universe* of David Blaschke.

Figures 5 and 6 show the unexpected result [44,46]. The K / ratio in Figure 5 and the scaled variance of the multiplicity distribution at 150*A* GeV/*c* in Figure 6 are similar in inelastic p+p interactions and in central Be+Be collisions, whereas they are different in central Ar+Sc collisions which are close to central Pb+Pb collisions. Both reference models, WNM and SM (represented here by the Hadron-Resonance Model [45]), qualitatively disagree with the data. The WNM seems to work in the collisions of light nuclei (up to Be+Be) and becomes qualitatively wrong for heavy nuclei (like Pb+Pb). On the contrary, the SM is approximately valid for collisions of heavy nuclei. However, its predictions disagree with the data on p+p to Be+Be collisions.

The rapid change of hadron production properties when moving from Be+Be to Ar+Sc collisions is referred to as the onset of fireball. From Figure 5 (*right*) follows that the increase of the K / ratio depends on the collision energy. On the other hand, the scaled variance ω of the multiplicity distribution shows only weak collision energy dependence (see Fig. 6 (*right*)). The physics behind the onset of fireball is under discussion [45].

NA61/SHINE has started a discussion on possibilities to perform systematic measurements of the e ect by conducting a detailed two dimensional scan with low and medium mass nuclei at the CERN SPS. Figure 7 presents a draft of the beam request for the data taking period after the CERN Long Shutdown 3.

David Blaschke turned 60 in 2019. Over many years David explored synergies between theoretical and experimental physics, between heavy-ion collisions and astroparticle physics, between cultures of many countries, see Figure 8. In particular, David has played an import role in theoretical studies of the onset of deconfinement [47–50]. He was the key organizer of *CPOD 2010* Workshop in JINR, Dubna and *CPOD 2016* Workshop in Wroclaw. Very importantly, David enthusiastically creates the physics programme of NICA – the new heavy-ion facility in JINR, Dubna [51,52]. I wish David to continue running his *Universe* for many years to come.

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References

1. U.W. Heinz, M. Jacob, *Evidence for a New State of Matter: An Assessment of the Results from the CERN Lead Beam Program* (2000), arXiv:nucl-th/0002042
2. M. Gazdzicki, M. Gorenstein, P. Seyboth, *Brief History of the Search for Critical Structures in Heavy-Ion Collisions*, arXiv:2004.02255
3. R. Alemany et al., *Summary Report of Physics Beyond Colliders at CERN*, arXiv:1902.00260
4. J. Rafelski, B. Muller, Phys. Rev. Lett. **48**, 1066 (1982) [Erratum: Phys. Rev. Lett. **56**, 2334 (1986)]
5. T. Matsui, H. Satz, Phys. Lett. B **178**, 416 (1986)
6. E.V. Shuryak, Phys. Rep. **61**, 71 (1980)
7. J. Adams et al. (STAR), Nucl. Phys. A **757**, 102 (2005)
8. K. Adcox et al. (PHENIX), Nucl. Phys. A **757**, 184 (2005)
9. B.B. Back et al., Nucl. Phys. A **757**, 28 (2005)
10. I. Arsene et al. (BRAHMS), Nucl. Phys. A **757**, 1 (2005)
11. K. Aamodt et al. (ALICE), JINST **3**, S08002 (2008)
12. M. Gazdzicki, M.I. Gorenstein, Acta Phys. Polon. B **30**, 2705 (1999)
13. M. Gazdzicki, Pion and strangeness production as signals of QCD phase transition, in *25th International Workshop on Gross Properties of Nuclei and Nuclear Excitation: QCD Phase Transitions (Hirschegg 97)* (1997), pp. 217–223
14. P. Seyboth (NA49) (1997)
15. M. Gazdzicki, J. Phys. G **30**, S161 (2004)

16. M.I. Gorenstein, M. Gazdzicki, K.A. Bugaev, Phys. Lett. B **567**, 175 (2003)
17. L.P. Csernai, D. Rohrich, Phys. Lett. B **458**, 454 (1999)
18. M. Bleicher, H. Stoecker, Phys. Lett. B **526**, 309 (2002)
19. M. Bleicher, High Energ. Phys. (2005) arXiv:hep-ph/0509314
20. M. Gazdzicki, M. Gorenstein, P. Seyboth, Acta Phys. Polon. B **42**, 307 (2011)
21. M. Gazdzicki, P. Seyboth, Acta Phys. Polon. B **47**, 1201 (2016)
22. M. Gazdzicki, P. Seyboth, E. Shuryak, CERN Courier **44**, 40 (2004)
23. A. Bialas, R.C. Hwa, Phys. Lett. B **253**, 436 (1991)
24. N.G. Antoniou, Y.F. Contoyiannis, F.K. Diakonos, A.I. Karanikas, C.N. Ktorides, Nucl. Phys. A **693**, 799 (2001)
25. Y. Hatta, M.A. Stephanov, Phys. Rev. Lett. **91**, 102003 (2003) [Erratum: Phys. Rev. Lett. **91**, 129901 (2003)]
26. N.G. Antoniou, F.K. Diakonos, A.S. Kapoyannis, K.S. Kousouris, Phys. Rev. Lett. **97**, 032002 (2006)
27. M.A. Stephanov, K. Rajagopal, E.V. Shuryak, Phys. Rev. D **60**, 114028 (1999)
28. M. Gazdzicki et al. (NA49-future), PoS **CPOD 2006**, 016 (2006)
29. A. Aduszkiewicz et al., *Proton-Proton Interactions and Onset of Deconfinement* (2019) arXiv:1912.10871
30. S.V. Afanasiev et al. (NA49), Phys. Rev. C **66**, 054902 (2002)
31. C. Alt et al. (NA49), Phys. Rev. C **77**, 024903 (2008)
32. M. Gazdzicki, Z. Fodor, G. Vesztergombi (NA49-future Collaboration), Tech. Rep. [CERN-SPSC-2006-034; SPSC-P-330] (CERN, Geneva 2006) [revised version: https://cds.cern.ch/record/995681 (accessed November 06, 2006, 12:38:20)]
33. N. Abgrall et al. (NA61), JINST **9**, P06005 (2014)
34. M. Gazdzicki (NA61/SHINE), PoS **CPOD 2017**, 012 (2018)
35. T. Czopowicz, Overview of experimental critical point search, in *18th International Conference on Strangeness in Quark Matter* (2020)
36. A. Bzdak, S. Esumi, V. Koch, J. Liao, M. Stephanov, N. Xu, arXiv:1906.00936
37. A. Aduszkiewicz (NA61/SHINE Collaboration), Tech. Rep. [CERN-SPSC-2018-008; SPSC-P-330-ADD-10] (CERN, Geneva 2018). [https://cds.cern.ch/record/2309890]
38. M. Agnello et al. (NA60+), arXiv:1812.07948
39. V. Kekelidze, V. Kolesnikov, R. Lednicky, V. Matveev, A. Sorin, G. Trubnikov, PoS **ICHEP 2018**, 493 (2019)
40. H. Sako (J-PARC-HI), Nucl. Phys. A **982**, 959 (2019)
41. M. Gazdzicki, PoS **CPOD 2013**, 038 (2013)
42. A. Bialas, M. Bleszynski, W. Czyz, Nucl. Phys. B **111**, 461 (1976)
43. J. Rafelski, M. Danos, Phys. Lett. B **97**, 279 (1980)
44. P. Podlaski, Strangeness production at the CERN SPS energies, in *18th International Conference on Strangeness in Quark Matter, 10–15 june, Bari, Italy,* (CERN, 2020)
45. A. Motornenko, V.V. Begun, V. Vovchenko, M.I. Gorenstein, H. Stoecker, Phys. Rev. C **99**, 034909 (2019)
46. A. Seryakov (NA61/SHINE), KnE Energ. Phys. **3**, 170 (2018)
47. A. Andronic et al., Nucl. Phys. A **837**, 65 (2010)
48. D. Blaschke, A. Dubinin, A. Radzhabov, A. Wergieluk, Phys. Rev. D **96**, 094008 (2017)
49. M. Naskret, D. Blaschke, A. Dubinin, Phys. Part. Nucl. **46**, 789 (2015)
50. D. Blaschke, A. Friesen, Y. Ivanov, Y. Kalinovsky, M. Kozhevnikova, S. Liebing, A. Radzhabov, G. Röpke, *QCD Phase Diagram at NICA Energies: K /π Horn E ect and Light Clusters in THESEUS*, arXiv:2004.01159
51. K. Abraamyan et al., Nucl. Instrum. Meth. A **628**, 99 (2011)
52. D. Blaschke, EPJ Web Conf. **138**, 01004 (2017)