

Review

Heavy-Ion Physics at the CERN SPS H2: NA35, NA49 and NA61/SHINE (With Personal Recollections)

Marek Gazdzicki 

Institute of Physics, Jan Kochanowski University, PL-25-406 Kielce, Poland; marek.gazdzicki@cern.ch

Abstract

This review presents a unified account of the NA35, NA49, and NA61/SHINE experiments, which together form a continuous programme of heavy-ion studies conducted at the H2 beamline of the CERN North Area using the SPS accelerator. The programme, spanning about 40 years, was driven by the search for a high-density state of strongly interacting matter—the quark–gluon plasma (QGP)—and the transitions leading to it. The review focuses on this primary line of research. The highlights of the programme include the observation of the first signal of QGP creation at the top SPS energy in S+S collisions by NA35, evidence for the onset of deconfinement at low SPS energies by NA49, and the establishment by NA61/SHINE of the diagram of high-energy nuclear collisions, featuring transitions between hadron-, string-, and QGP-dominated regimes. This predominantly scientific review is complemented by brief personal recollections related to the discussed topics.

Keywords: heavy-ion physics; quark–gluon plasma; onset of deconfinement; CERN SPS; NA35; NA49; NA61/SHINE

1. NA35: First Hints of QGP

NA35 was the first experiment in the family of heavy-ion experiments conducted at the H2 beamline of the CERN North Area at the SPS. It collected data on collisions of light nuclear beams with various nuclear targets at 60A GeV/c and 200A GeV/c from 1986 to 1992. The main result of NA35 was the observation of enhanced production of strange hadrons in central S+S collisions at 200A GeV/c. This marked the first indication of quark–gluon plasma (QGP) formation at the CERN SPS. During this period, I was a young postdoctoral researcher working on NA35 at universities in Heidelberg, Frankfurt am Main, and Warsaw.

1.1. Background

The origins of the NA35 experiment at CERN can be traced back to a proposal [1] submitted by the GSI-LBL–Heidelberg–Marburg–Warsaw Collaboration to CERN’s Proton Synchrotron and Synchro-Cyclotron Committee on 26 January 1982. The collaboration spokesperson was Reinhard Stock, a charismatic and enthusiastic leader of the streamer chamber heavy-ion experiment at the LBL Bevalac.

The proposal requested measurements of target fragmentation and hadron production in collisions of ^{16}O with target nuclei ranging from ^{40}Ca to ^{206}Pb at the CERN Proton Synchrotron (PS). The requested beam energy range was 9–13A GeV/c, with an anticipated start of data taking in the spring of 1984, requiring 250 h of dedicated PS running time. The ultimate physics goal was the observation of a hypothetical new state of matter, such as



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quark matter or quark–gluon plasma [2,3], with explicit references to the work of Joseph Kapusta and Edward Shuryak included in the proposal.

Although CERN accepted the proposal, accommodating the experiment in the East Hall PS extraction area proved challenging. As a result, CERN management suggested [4] transporting the ion beam from the PS to the Super Proton Synchrotron (SPS) and distributing it to the North and West Halls of the SPS. The maximum SPS ion beam momentum of $200A \text{ GeV}/c$ significantly expanded the programme’s potential. This marked the beginning of CERN’s heavy-ion programme [5] in general, and of NA35 in particular.

1.2. Experiment

The NA35 setup shown in Figure 1 featured a visual tracking detector, a streamer chamber with a sensitive volume of $200 \times 120 \times 70 \text{ cm}^3$, placed in a 1.5 T vertical magnetic field. Downstream, the detector was followed by four calorimeters. Major components of the experiment were inherited from the NA5 and NA24 experiments at the CERN SPS. For a detailed description, see Ref. [6]. An iconic image of a central S+Au collision at $158A \text{ GeV}/c$ is presented in Figure 2.

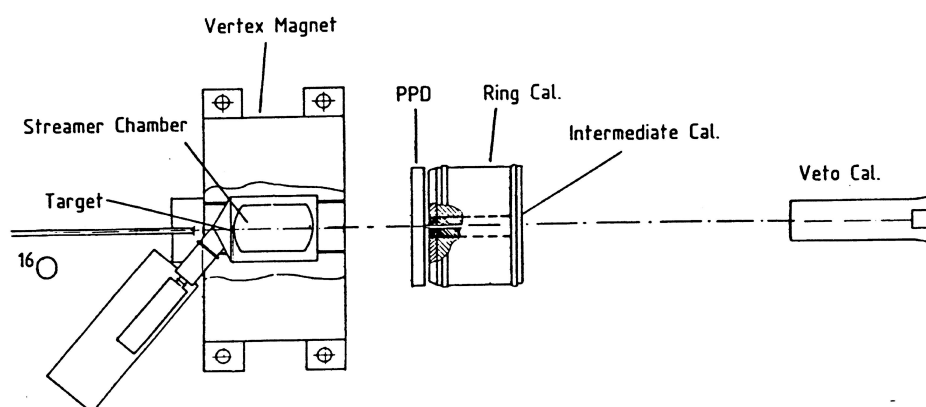


Figure 1. The top view of the NA35 experimental setup [6]; see text for details.

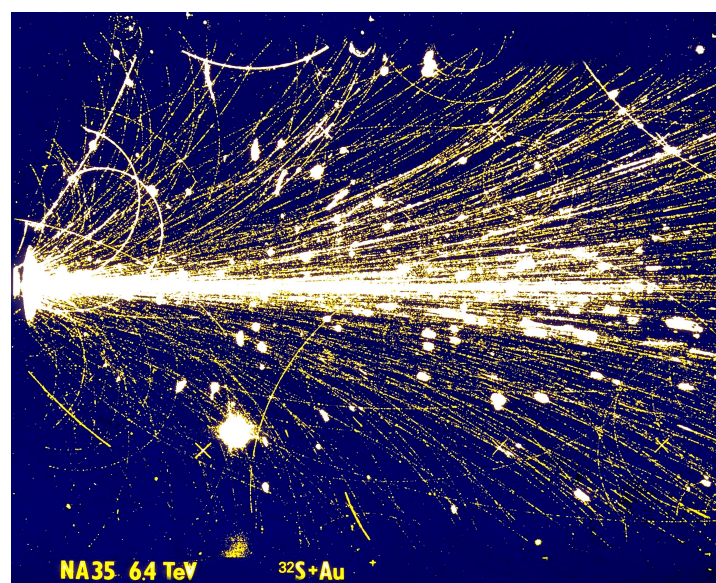


Figure 2. An iconic image of a central S+Au collision at $158A \text{ GeV}/c$ recorded by the NA35 streamer chamber.

NA35 recorded data on collisions of p , d , ^{16}O , and ^{32}S beams at $60A\text{ GeV}/c$ and $200A\text{ GeV}/c$ with S, Ag, and Au targets from 1986 to 1992. In parallel, data with these beams were recorded by NA34 [7], NA36 [8], WA80 [9] and WA85/WA94 [10,11] experiments.

Initially, the collaboration was led by the experiment's initiator, Reinhard Stock. Later, when he shifted his focus to establishing the NA49 experiment, Peter Seyboth, a former leader of the NA5 particle physics experiment at the CERN SPS, took over as spokesperson. Among the many others who contributed to the success of NA35 were Robert Brockmann, Volker Eckardt, John Harris, Grazyna Odyniec, Rainer Renfordt, Andres Sandoval, Herbert Stroebele, and Sigfried Wenig.

1.3. Key Results and Conclusions

The most influential results of NA35 concerned neutral strange hadron production in central S+S collisions at $200A\text{ GeV}/c$ [12]. Owing to the reflection symmetry of the initial state, it was possible to calculate the total mean multiplicity of abundant hadrons carrying strange and antistrange quarks (s and $\bar{s}$), in particular Λ hyperons and K_S^0 mesons. Their yields, relative to negatively charged hadrons (h^- , more than 90% of which are π^- mesons), were approximately twice as large as the corresponding yields in $p+p$ interactions. See Figure 3, taken from Ref. [12], for illustration.

This result indicated substantial production of $s\bar{s}$ pairs, consistent with the predictions of Johann Rafelski and Berndt Müller regarding quark–gluon plasma formation in such collisions [13,14].

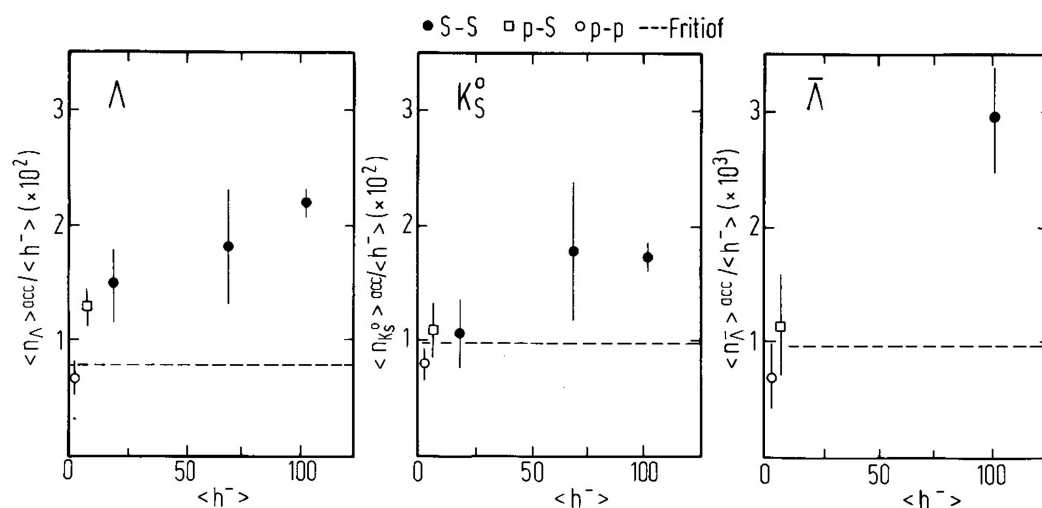


Figure 3. The ratio of the mean multiplicities of strange hadrons within the experimental acceptance to the total negative hadron multiplicity in S+S collisions at $200A\text{ GeV}/c$ is shown for peripheral, intermediate, and central collisions. The two leftmost points represent the corresponding results for $p+p$ and $p+S$ interactions. The predictions of the simple superposition model, Fritiof, are independent of the h^- mean multiplicity. The figure is taken from Ref. [12].

NA35 also achieved other important results, particularly on two-pion correlations [15]. These results demonstrated that the pion–emission source is significantly larger than the size of the colliding nuclei, indicating expansion of the matter created in the early stages of the collisions.

1.4. Memories

I remember being in the beautiful garden of the GSI and TU Darmstadt guest house. While caring for my children, I scanned pages of printouts on fan-fold paper containing histograms and numbers from the final stage of the analysis of Λ and K_S^0 production in S+S

collisions. Eventually, I divided their yields by the h^- yield and, to my shock, found ratios approximately twice as large as those observed in $p+p$ interactions. At that time, I did not believe in the possibility of quark–gluon plasma creation in nucleus–nucleus collisions and was convinced that I had made a mistake. However, subsequent checks by both me and the collaboration revealed no errors.

This discovery transformed me from a QGP skeptic into a believer. I presented the results [16] in 1988 at the Quark Matter conference in Lenox and shortly afterwards at the Hadronic Matter in Collision conference in Tucson, arguing that they were in quantitative agreement with QGP creation. The collaboration’s paper was published in 1990 [12].

2. NA49-1: Event-by-Event Fluctuations and QGP

NA49 is the second experiment in the family of heavy-ion experiments located at the H2 beamline of the CERN North Area at the SPS. The experiment encompassed two distinct physics programmes. The first phase (NA49-1: 1994–1997), presented in this section, focused on the search for anomalies in event-by-event fluctuations in central Pb+Pb collisions at 158A GeV/c, which could signal the creation of quark–gluon plasma (QGP). During this period, I was a scientific associate at the universities of Frankfurt am Main and Warsaw, working on NA49, STAR, and ALICE.

2.1. Background

The NA35 Collaboration initiated the NA49 experiment with a proposal submitted [17] to the Super Proton Synchrotron and LEAR Committee in May 1991, which was approved in September 1991. The proposing institutions included groups from Athens, Berkeley, Darmstadt, Frankfurt am Main, Freiburg, Marburg, Munich, Seattle, Warsaw, and Zagreb. Reinhard Stock served as spokesperson.

The primary aim of NA49 was to search for the deconfinement transition in central Pb+Pb collisions at 158A GeV/c by measuring event-by-event fluctuations of hadron production properties. This goal necessitated a significant upgrade of the NA35 detector to enable large-acceptance measurements of hadron production in high-multiplicity events (up to 1000 charged particles). Building on NA35’s discovery of strangeness enhancement in S+S collisions [12], special emphasis was placed on the identification of charged kaons and pions.

2.2. Experiment

The experimental setup proposed by the NA35 Collaboration, shown in Figure 4 (top), underwent significant changes prior to the construction of the NA49 experiment. The final setup is depicted in Figure 4 (bottom). The main components included four large-volume Time Projection Chambers (TPCs) for tracking and particle identification via energy loss in the TPC gas. Time-of-Flight (ToF) scintillator arrays extended charged-kaon identification down to mid-rapidity. Calorimeters for transverse-energy measurement and central-collision selection using forward energy completed the downstream acceptance. The figure illustrates the different configurations of beam and trigger detectors used for data taking in Pb+Pb (a), $p+p$ (b), and $p+A$ (c) collisions.

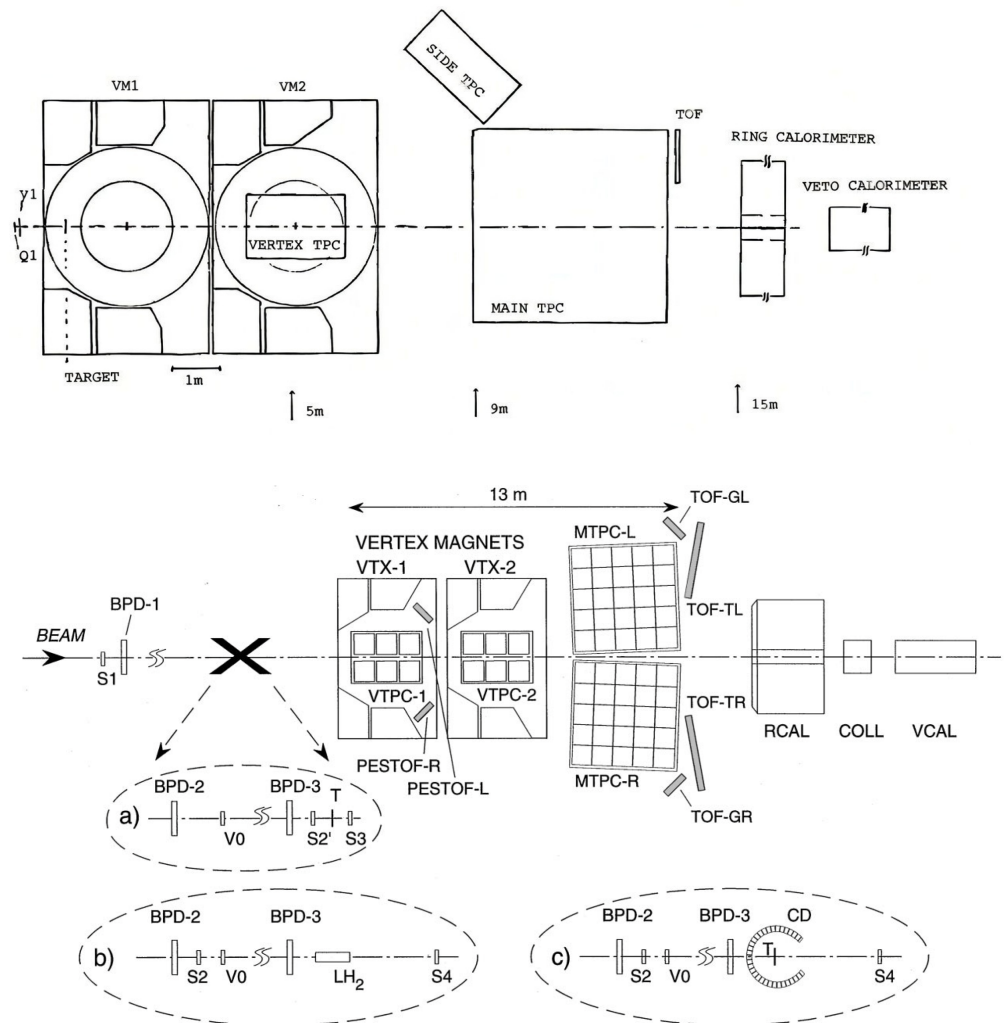


Figure 4. Top: Top view of the NA49 experimental setup as originally proposed by NA35 [17]. Bottom: The setup constructed by the NA49 Collaboration [18]. For further details, see the references above and the text.

In 1995 and 1996, approximately 1.5 million central Pb+Pb collisions at 158A GeV/ c were recorded, fulfilling the original NA49 data-taking plan. In 1997, Reinhard Stock transferred the role of spokesperson to Peter Seyboth. In parallel, data with these beams were recorded by NA44 [19], NA45 [20], NA50 [21], NA52 [22] and WA97/NA57 [23,24] experiments.

2.3. Key Results and Conclusions

The NA49 phase-one results were summarized by the collaboration in 1998 as follows [25]:

The analysis makes use of the unique capability of the NA49 detector to combine the study of particle yields with correlation analysis and physics on the event-by-event level. First results [26–29] shed new light on salient questions concerning the behavior of matter at large energy density. In particular, they show that the transition from collisions of medium-size nuclei (as available in the past) to large-size systems does not lead to a substantial change in observables considered as possible signals of a phase transition, such as the pion-to-baryon and strangeness-to-pion ratios. A significant change in these observables is seen only when comparing nucleon–nucleon interactions with collisions of medium- and large-size nuclei at SPS energy. Our event-by-event analysis of Pb+Pb data does not reveal the appearance of dynamically different new event classes down to the permille level of admixture.

The collaboration concluded [25]: *These results, together with the energy dependence of pion and strangeness production in nucleus–nucleus (A+A) collisions, might indicate that the threshold energy for the creation of a deconfined partonic state (ideally the QGP) was already passed with SPS sulphur beams.* This conclusion marked the beginning of the second phase of NA49, which is discussed below.

2.4. Memories

Measuring and understanding event-by-event fluctuations of hadron production properties, such as the numbers of different hadron species produced in individual events, is a challenging task. I recall returning to Warsaw from a STAR Collaboration meeting in Berkeley. During the long journey and subsequent jet lag, I contemplated the possibility of separating dynamical and geometrical fluctuations in Pb+Pb collisions. Since both types of fluctuations were unknown, the task initially seemed hopeless. Surprisingly, by using a minimal model of the problem, I guessed an analytical solution that later turned out to be correct.

Early the next morning, I rushed to the institute to verify the solution using a simple Monte Carlo simulation (at that time, I had neither a PC nor a laptop at home). The solution passed the numerical check. Shortly thereafter, Staszek Mrowczynski derived an analytical proof of the conjectured solution, and we published the results [30]. This marked the beginning of the strongly intensive quantities [31] approach to fluctuation studies.

I applied the same problem-solving strategy—guessing the analytical solution and asking Staszek to prove it—when proposing a method for fluctuation studies with incomplete hadron identification [32]. The so-called identity method was later significantly developed [33,34] and has since been widely used.

3. NA49-2: Discovery of the Onset of Deconfinement

The second phase of NA49 (NA49-2: 1998–2002), presented here, was devoted to the search for the onset of QGP creation in Pb+Pb collisions by reducing the collision energy. The primary result was the observation of anomalies—referred to as the horn, kink, and step—in the collision-energy dependence of various hadron production properties. These findings suggest that QGP creation begins at low SPS beam momenta, around $30A$ GeV/ c .

During this period, I was a scientific associate at the University of Frankfurt am Main and at CERN, working mostly on NA49.

3.1. Background

In the mid-1990s, numerous results were obtained from collisions of light nuclei at the BNL AGS (beams of Si at $14.6A$ GeV) and the CERN SPS (beams of O and S at $200A$ GeV). Experiments with heavy nuclei (AGS: Au+Au at $11.6A$ GeV; SPS: Pb+Pb at $158A$ GeV) were only just beginning. This period marked the first opportunity to examine the energy dependence of hadron production in nucleus–nucleus collisions at high energies.

Two compilations—one on pion production [35] and another on strangeness production [36]—led to a clear conclusion: the energy dependence of mean hadron multiplicities measured in A+A collisions differs significantly from that observed in $p+p$ interactions. Moreover, the A+A data suggested a notable change in the energy dependence of pion and strangeness yields, located between the top AGS and SPS energies.

Using a statistical approach to strong interactions [37,38], I speculated [39] that this change is related to the onset of deconfinement in the early stage of A+A collisions. Following this conjecture, a quantitative model, the Statistical Model of the Early Stage (SMES) [40], was developed in collaboration with Mark Gorenstein. The SMES assumes the creation of early-stage matter according to the principle of maximum entropy. Depending on the

collision energy, the matter exists in the confined phase ($E \lesssim 30 A \text{ GeV}$), the mixed phase ($30 \lesssim E \lesssim 60 A \text{ GeV}$), or the deconfined phase ($E \gtrsim 60 A \text{ GeV}$). The phase transition is assumed to be of first order.

In 1997, based on these ideas, the NA49 Collaboration proposed studying hadron production in Pb+Pb collisions at 40A GeV [25], marking the beginning of the second phase of the NA49 experiment.

3.2. Experiment

The NA49-2 programme was conducted using essentially the same experimental setup as NA49-1; see Section 2.2. The only modification was to scale the magnetic field in proportion to the beam momentum to ensure kaon identification at mid-rapidity via time-of-flight and specific energy-loss measurements in the TPCs; see Figure 4.

The first 40A GeV Pb beam was delivered to NA49-2 in 1998 as a test. A five-week run at 40A GeV followed in 1999. The success of this initial run at low SPS energy, combined with the promising preliminary results presented by NA49, justified continuation of the programme. In 2000, a beam at 80A GeV was delivered to NA49 for a five-day run. The programme was completed in 2002 with two additional runs: one at 30A GeV (seven days) and another at 20A GeV (seven days). In parallel, data with these beams were recoded by the NA45 [41] and NA60 [42] experiments.

3.3. Key Results and Conclusions

The basic NA49-2 results concerning the onset of deconfinement were published in 2002 [43] and 2008 [44]. These results, focusing on pion and kaon production in central Pb+Pb collisions at 40A GeV, 80A GeV, 158A GeV, and later at 20A GeV and 30A GeV, have together accumulated about 1300 citations.

The collaboration concluded [44]: *A rapid change of the energy dependence is observed around 30A GeV for the yields of pions and kaons as well as for the shape of the transverse mass spectra. The change is compatible with the prediction that the threshold for production of a state of deconfined matter at the early stage of the collisions is located at low SPS energies.*

Following Ref. [44], I briefly report the two most striking results and their relation to the onset of deconfinement, noting that many other results from the beam-energy scan of identified hadron yields, correlations, and fluctuations have also been published.

The $\langle K^+ \rangle / \langle \pi^+ \rangle$ and $E_S = (\langle \Lambda \rangle + 4 \langle K_S^0 \rangle) / \langle \pi \rangle$ ratios are approximately proportional to the total strangeness-to-entropy ratio, which in the SMES model [40] is assumed to remain constant from the early stage to freeze-out. At low collision energies, the strangeness-to-entropy ratio increases steeply with energy owing to the low temperature at the early stage ($T \lesssim T_C$) and the high mass of the strangeness carriers in the confined state (e.g., the kaon mass of 500 MeV).

When the transition to a QGP is crossed ($T \gtrsim T_C$), the mass of the strangeness carriers drops significantly to the strange-quark mass of about 100 MeV. As a result, when $m < T$, the strangeness yield becomes approximately proportional to the entropy, and the strangeness-to-entropy (or pion) ratio becomes independent of energy. This transition leads to a decrease in the energy dependence of the ratio from the larger value for confined matter at T_C to the QGP value. Consequently, the measured non-monotonic energy dependence of the strangeness-to-entropy ratio is followed by saturation at the QGP value. The corresponding anomalous energy dependence of the $\langle K^+ \rangle / \langle \pi^+ \rangle$ and E_S ratios, referred to as the “horn”, is shown in Figure 5 and, within the SMES framework, is a direct consequence of the onset of deconfinement occurring at around 30A GeV.

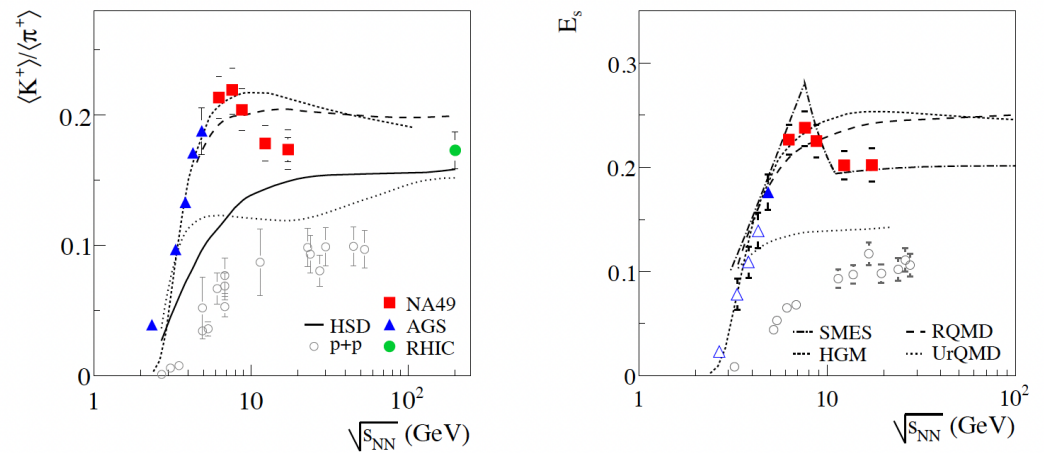


Figure 5. Left: Energy dependence of the $\langle K^+ \rangle / \langle \pi^+ \rangle$ ratio measured in central Pb+Pb and Au+Au collisions (full symbols), compared to the corresponding results from $p+p(\bar{p})$ reactions (open circles). Right: Energy dependence of relative strangeness production as measured by the E_s ratio in central Pb+Pb and Au+Au collisions (full symbols), compared to results from $p+p(\bar{p})$ reactions (open circles). The curves in the figures represent predictions from various models. The plots and caption are taken from Ref. [44], where details and references are provided.

In the mixed-phase region, the early-stage pressure and temperature are independent of the energy density [45]. Consequently, within the SMES model, this results in a weakening of the increase with energy of the inverse slope parameter of transverse mass spectra ($T: 1/m_T dn/dm_T \sim e^{-m_T/T}$) (the “step”) or, equivalently, the mean transverse mass $\langle m_T \rangle$ in the SPS energy range [46].

This qualitative prediction is confirmed by the results shown in Figure 6, where the collision-energy dependence of the T parameter is shown for heavy-ion and $p+p$ collisions (left) and compared with model predictions (right). The hydrodynamic calculations [47] that incorporate the transition between hadronic and deconfined phases (labelled “Hydro+PT” in Figure 6 (right)) describe the data, whereas the other models, having no phase transition, fail to reproduce the experimental results.

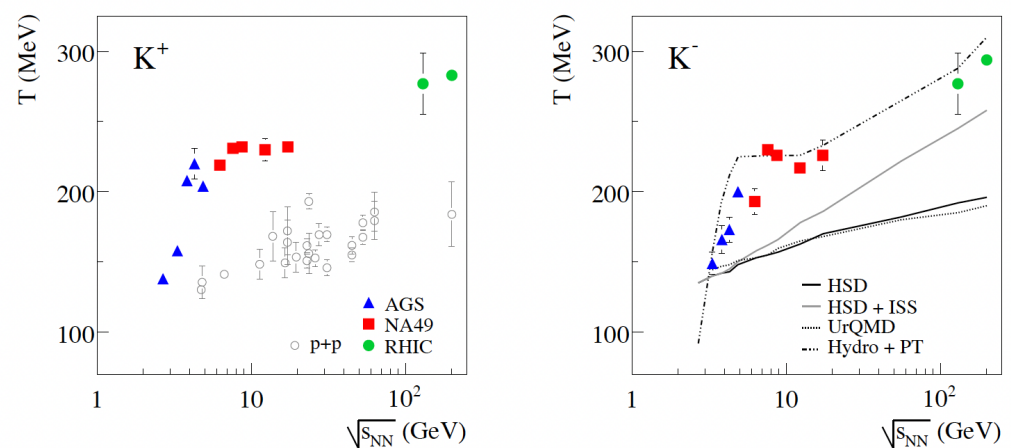


Figure 6. Energy dependence of the inverse slope parameter T of the transverse mass spectra for K^+ (left) and K^- mesons (right) measured at mid-rapidity in central Pb+Pb and Au+Au collisions. The K^+ slope parameters are compared to those from $p+p(\bar{p})$ reactions in the left-hand plot (open circles). The curves in the right-hand plot represent predictions from various models. The plots and caption are taken from Ref. [44], where details and references are provided.

The observation of the predicted signals of deconfinement (the horn, step, and kink; see above and Section 3.4) and the markedly different collision-energy dependence of hadron production properties in central Pb+Pb collisions compared to $p+p$ interactions underscored the need to continue the heavy-ion programme at the CERN SPS and other facilities worldwide. This motivated several initiatives, including NA61/SHINE at the CERN SPS (see the next section), the Beam Energy Scan programme [48] at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, the CBM experiment [49] at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, and the MPD experiment [50] at NICA in Dubna.

A series of workshops titled *Critical Point and Onset of Deconfinement* was established in 2004 by me, Peter Seyboth, and Edward Shuryak at the European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), Trento [51]. During the first workshop in Trento, the search for the critical point of strongly interacting matter was identified as a key objective of these new programmes.

3.4. Memories

I remember walking across the endless car parks of Frankfurter Messe, where the institute was located at the time, contemplating the following puzzle: results on strangeness production indicate that QGP is created in central S+S collisions at the top SPS collision energy. Models suggest that the transition to QGP at $T = T_C$ should result in an entropy increase by a factor of about three. Since the pion number is approximately proportional to the entropy, one would naively expect the number of pions in nucleus–nucleus collisions to increase by ≈ 3 when QGP starts to form. However, experimental data do not show this increase [35]. What could be wrong?

Before entering the office, I found a rather obvious answer: the comparison of entropy between QGP and hadron gas relevant for nucleus–nucleus collisions should be done at fixed collision energy (or, equivalently, fixed energy density), not at fixed temperature. When this approach is applied, the pion number is expected to increase by a factor of $\approx 3^{1/4} \approx 1.3$, rather than 3 [39]. With this correction, the data are consistent with the onset of QGP creation at low SPS energies.

Eager to share the solution with my colleagues, I changed the subject of my talk [52] at the last moment during the Divonne-les-Bains workshop dedicated to Rolf Hagedorn on the occasion of his 75th birthday in June 1994. The following handwritten letter from Rolf Hagedorn reads [53]:

Dear Dr. Gaździcki,

It was a pleasure to listen to your presentation of entropy production in nuclear collisions. It would be interesting to see your interpretation of overproduction in S+S collisions at 200 GeV/c/A confirmed by future data and by independent theoretical estimates of the change of entropy at the phase transition. A lot of work remains to be done before we know there is a (one, may be two?) phase transition and what are the details. Good luck for the future! Yours Rolf Hagedorn

Hagedorn was right: the talk in Divonne-les-Bains marked the first step in a long journey to study the onset of deconfinement in heavy-ion collisions. After 30 years of impressive progress, we have learned a great deal, yet many “details” remain to be established.

4. NA61/SHINE: Diagram of High-Energy Nuclear Collisions

NA61/SHINE is the third and most recent experiment in the family of heavy-ion experiments located at the H2 beamline of the CERN North Area at the SPS. The experiment was approved by the CERN Research Board in 2007. Measurements for strong interaction physics are conducted in parallel with reference measurements for neutrino and cosmic-ray physics. The first phase of the strong interaction programme includes traditional heavy-ion

physics. The part motivated by the quark-gluon plasma-related results of NA35 and NA49 is presented here.

The experiment conducted the world's first systematic scan in the two-dimensional space of laboratory-controlled parameters: the mass of colliding nuclei and collision energy. Results from $p+p$ and Be+Be collisions indicate a transition from hadron production dominated by resonances to that dominated by strings at $\sqrt{s_{NN}} \approx 10$ GeV. Moreover, results at the top SPS energy reveal a transition from string-dominated to quark-gluon plasma-dominated production between Be+Be and Ar+Sc collisions. These findings, combined with results from NA49, STAR, and ALICE, enable the establishment of the diagram of high-energy nuclear collisions.

During this period, I was a professor at Jan Kochanowski University in Kielce and a scientific associate at Goethe University Frankfurt. I was the founder and served as the spokesperson of NA61/SHINE for about 20 years.

4.1. Background

The need for a two-dimensional scan of collision energy and colliding-nuclei masses at the CERN SPS was presented by me at the NA49 Collaboration meeting in March 2003; see Figure 7 showing the scan of the key slide. The idea was based on results from the NA49 energy scan with Pb+Pb collisions, which revealed a markedly different collision energy dependence observed for $p+p$ interactions and central Pb+Pb collisions; see Figure 7. Importantly, the dependence for Pb+Pb collisions aligns with the predictions for the onset of deconfinement at low SPS energies [40].

The proposal for these new measurements was supported by the NA49 spokesperson, Peter Seyboth, and a group of NA49 senior members, including Zoltan Fodor (Budapest), Wojtek Dominik (Warsaw), Rainer Renford (Frankfurt am Main), Herbert Stroebel (Frankfurt am Main), and George Vesztegombi (Budapest).

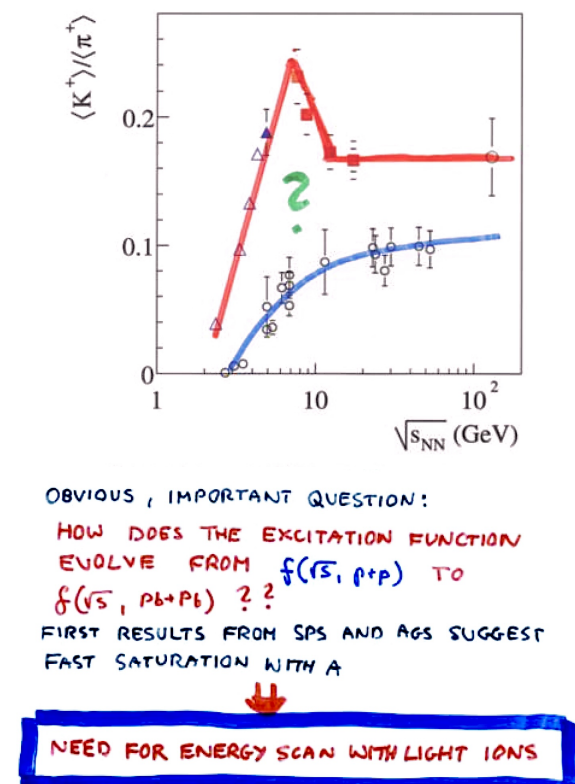


Figure 7. Scanned slide from my presentation at the NA49 Collaboration meeting at CERN in March 2003, which initiated NA61/SHINE [40].

At the Research Board meeting in June 2003, Agnieszka Zalewska, the Board Chair, remarked that a detailed study of the low-energy region would be challenging at RHIC and encouraged the preparation of ideas for further studies of heavy ions at the CERN SPS beyond 2005.

The Expression of Interest, titled “A New Experimental Programme with Nuclei and Proton Beams at the CERN SPS,” was submitted to the SPSC in November 2003 [54], followed by the Letter of Intent in January 2006 [55]. The physics goals included a scan of the mass of colliding nuclei and collision energy, a search for the critical point of strongly interacting matter, and reference measurements for neutrino and cosmic-ray physics. Finally, the proposal, “Study Hadron Production in Hadron-Proton Interactions and Nucleus-Nucleus Collisions at the CERN SPS,” was submitted to the SPSC in November 2006 [56].

The scan programme received significant support from the theory community. Notably, Frank Wilczek, Edward Shuryak, Krishna Rajagopal, and Misha Stephanov sent letters and emails of endorsement. For further details, see the NA61/SHINE website [57].

The new experiment, NA61/SHINE, was approved by the CERN Research Board in February 2007.

4.2. Experiment

The NA49 collaboration transferred ownership of the NA49 detector to NA61/SHINE. Following a successful test in 2006, pilot physics data-taking for the long-baseline neutrino experiment, T2K at J-PARC, began in 2007 [58]. Since then, the detector has been continuously upgraded, with major upgrades implemented during accelerator shutdowns.

Data collection for the 2D scan programme was conducted from 2009 to 2017, utilising an evolving detector setup closely resembling the one presented in Ref. [59]. The Run 3 setup [60] is shown in Figure 8 (*top*). The main components of the tracking system in the large-acceptance hadron spectrometer include a silicon pixel detector (VD) located downstream of the target, followed by four large-volume Time Projection Chambers (TPCs). Two Vertex TPCs (VTPC-1/2) are located within superconducting magnets, with a maximum combined bending power of 9 Tm. The magnetic field was scaled in proportion to the beam momentum to maintain similar rapidity-transverse momentum acceptance at all beam momenta. The main TPCs (MTPC-L/R) and Time-of-Flight (ToF) detectors are located downstream of the magnets. The setup is completed by two forward calorimeters, the Projectile Spectator Detectors (MPSD and FPSD). An event-browser display showing particle tracks produced in an Xe+La collision and recorded by the TPCs is presented in Figure 8 (*bottom*).

Data were recorded for $p+p$ (secondary proton beams), Be+Be (secondary ^7Be beams), Ar+Sc, and Xe+La collisions at $13A\text{ GeV}/c$, $19(20)A\text{ GeV}/c$, $30A\text{ GeV}/c$, $40A\text{ GeV}/c$, $75(80)A\text{ GeV}/c$, and $150(158)A\text{ GeV}/c$, where the number represents the laboratory beam momentum per nucleon. Additionally, data for Pb+Pb collisions were recorded at $13A\text{ GeV}/c$, $30A\text{ GeV}/c$, and $150A\text{ GeV}/c$. The recorded datasets are summarised in Figure 9 (*top*). In parallel, data with ion beams were recorded by the CERN LHC experiments, ALICE [61], ATLAS [62] and CMS [63].

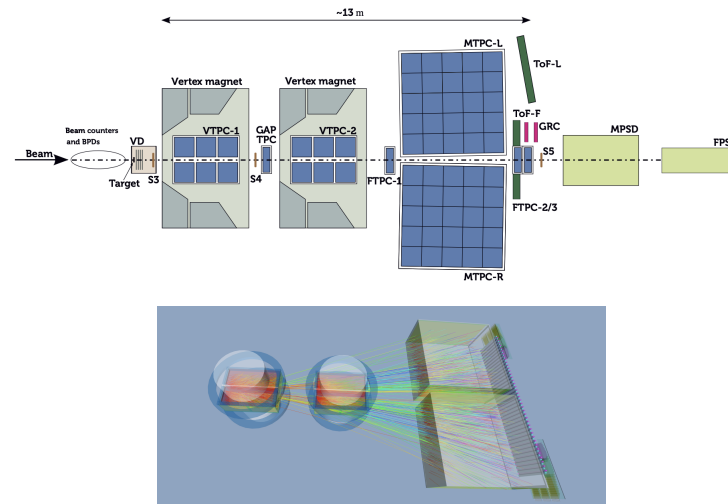


Figure 8. *Top:* The post-LS2 NA61/SHINE detector [60]. *Bottom:* Particle tracks produced in an Xe+La collision and recorded by the NA61/SHINE Time Projection Chambers.

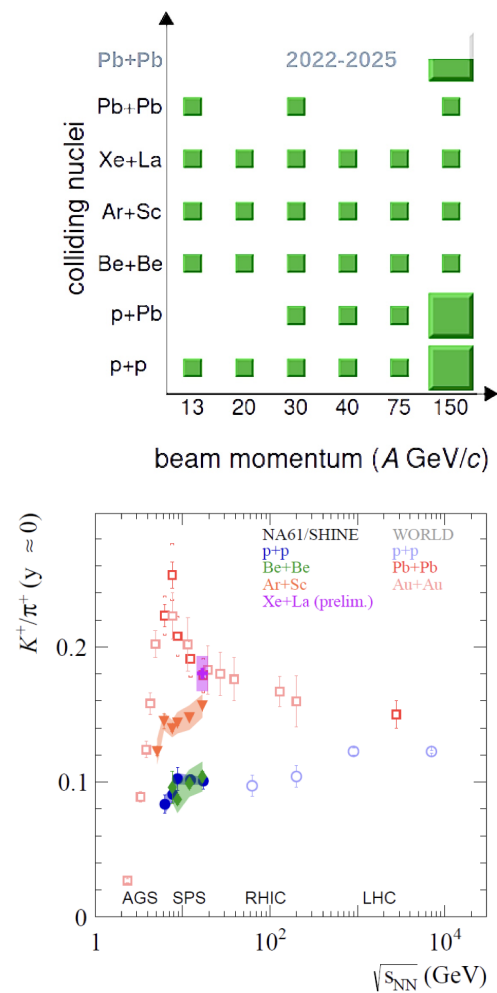


Figure 9. *Top:* Data recorded by NA61/SHINE for its 2D scan programme. *Bottom:* The K^+/π^+ ratio at mid-rapidity as a function of collision energy [64]. NA61/SHINE results are presented alongside a compilation of world data.

4.3. Key Results and Conclusions

Figure 9 (bottom) summarises the collision-energy dependence of the positively charged kaon-to-pion ratio, K^+/π^+ , at mid-rapidity, as measured by NA61/SHINE [64]. The data include $p+p$, Be+Be, Ar+Sc, Xe+La, and Pb+Pb collisions, alongside a compilation of world data.

Firstly precise measurements of $p+p$ interactions revealed a *break* in the $\sqrt{s_{NN}}$ dependence at around 10 GeV [65]. This break was initially interpreted as either a transition from resonance- to string-dominated hadron production or a remnant of the onset of deconfinement observed in Pb+Pb collisions. Subsequent results for central Be+Be collisions [66,67], which surprisingly overlapped with the $p+p$ data, clearly supported the former interpretation. This is because the Statistical Model of the Early Stage (SMES) generalised to collisions of low-mass nuclei [68] predicted that Be+Be collisions would behave similarly to Pb+Pb collisions, rather than resembling $p+p$ interactions.

Thus, it was concluded that the system created in collisions of low-mass nuclei at SPS and below is far from equilibrium. Statistical models cannot approximate its properties. The concepts of the phases of matter, characterised by temperature and chemical potentials, are inapplicable. We had to move beyond the phase diagram of strongly interacting matter to understand the experimental results. This led us to the *diagram of high-energy nuclear collisions* [69].

Then, results from central Ar+Sc collisions [70,71] added another piece to the puzzle. At the top SPS energy, the K^+/π^+ ratio for Ar+Sc collisions matched that of Pb+Pb, but at lower SPS energies, it fell between the $p+p$ and Pb+Pb values, showing no horn. The Xe+La ratio [64] at the top SPS energy was consistent with the Pb+Pb and Ar+Sc ratios. Data for lower energies in Xe+La collisions are expected soon.

The dependence of the K^+/π^+ ratio at the top SPS energy exhibits a rapid change, or *jump*, between collisions of small-mass nuclei ($p+p$ and Be+Be) and those of medium- and large-mass nuclei (Ar+Sc, Xe+La, and Pb+Pb). In contrast, at lower energies, the dependence is continuous. Current models fail to describe these observations, as illustrated in Figure 10, showing the data and the model prediction at 30A (left) and 150A GeV/C (right) as a function of the mean number of wounded nucleons.

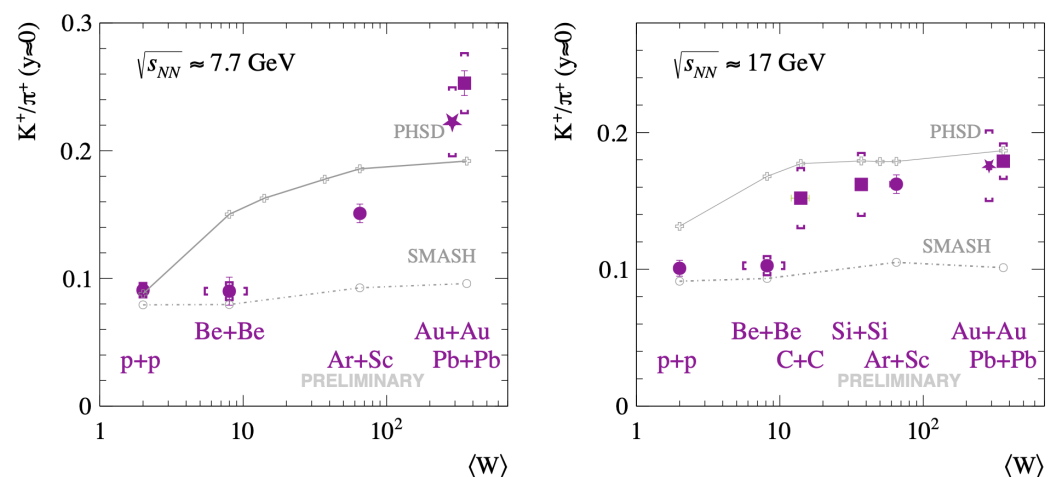


Figure 10. The K^+/π^+ ratio at mid-rapidity measured at $\sqrt{s_{NN}} \approx 7.7$ GeV (left) and $\sqrt{s_{NN}} \approx 17$ GeV (right) is shown as a function of the mean number of wounded nucleons [72]. Experimental results are compared with model predictions.

As mentioned above, the 2D scan of NA61/SHINE led to the development of a concept of the diagram of high-energy nuclear collisions [69]. This diagram depicts the domains dominated by different hadron-production processes in the space of laboratory-controlled

parameters: collision energy and the nuclear mass number of the colliding nuclei. A possible interpretation of the results is given in the diagram shown in Figure 11 (left). The lines indicate the changeover between the resonance, string, and QGP domains, with their approximate locations derived from experimental data; for details, see Ref. [69].

The experimental results suggest that the system created in collisions of high-mass nuclei is close to (local) equilibrium; see, for example, Ref. [73]. In this case, experiments with heavy-ion collisions provide insights into the *phase diagram of strongly interacting matter*. The most widely accepted phase diagram, showing the regions explored by the CERN SPS and LHC experiments, is depicted in Figure 11 (right).

The phase diagram includes the critical point (CP)—the endpoint of the first-order phase transition line, which has properties of a second-order phase transition. A significant objective of the NA61/SHINE 2D scan programme has been the search for the CP. Various experimental strategies, inspired by diverse model predictions, have been pursued; however, no signal has been observed to date. CP-exclusion plots have been produced based on the *intermittency* analysis of particle multiplicity fluctuations [74,75].

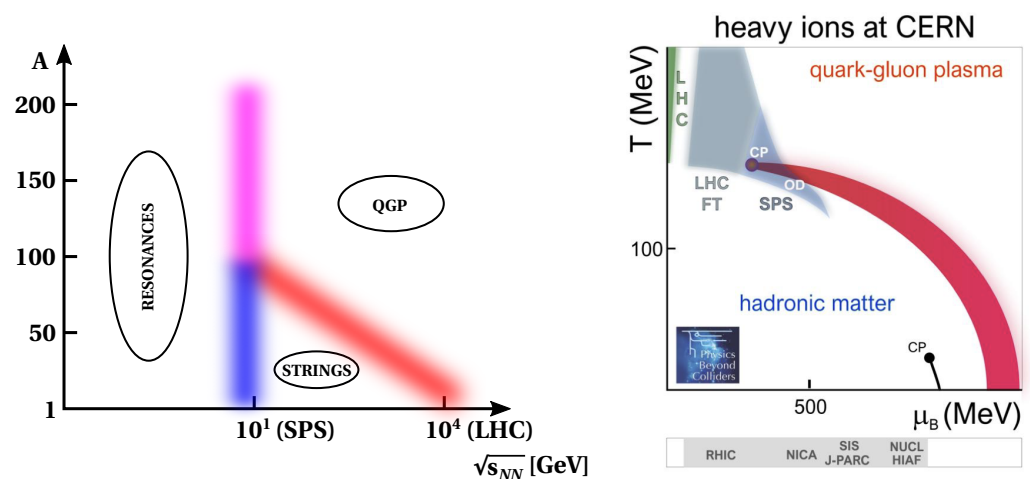


Figure 11. Left: Diagram of high-energy nuclear collisions [69], as suggested by NA61/SHINE and global data. Right: Hypothetical phase diagram of strongly interacting matter, highlighting the domains accessible for experimental studies with heavy-ion collisions at CERN [76]. Up to now, no convincing signal of the critical point (CP on the QGP boundary) has been observed in experiments or demonstrated within QCD. The nuclear liquid-gas critical point (CP at $T \approx 20$ MeV) is well established theoretically and experimentally for symmetric nuclear matter.

During Run 3, NA61/SHINE is collecting high-statistics data on Pb+Pb collisions at the top SPS energy required for systematic measurements of open charm hadrons at the top SPS energy [77]. A detailed 2D scan, essential for studying the transition from string-dominated to resonance-dominated hadron production [72], is planned following CERN's Long Shutdown 3. The idea [78,79] of measuring the correlation between charm and anti-charm hadrons in central Pb+Pb collisions at the top SPS energy is also under consideration [80].

4.4. Memories

Actually, I do not remember when and how the idea of a diagram of high-energy nuclear collisions emerged. Scanning the NA61/SHINE repository of public talks, I found the first sketch of it, in my talk presented at the Workshop on the Standard Model and Beyond in Corfu, September 2017 [81]. We called it the “cross plot”. The current version (Figure 11 (left)) was triggered by the SHINE Open Seminar [82] in Zoom on 21 April 2021. Magda (Kuich) presented a talk entitled “Summary of NA61/SHINE results on the Onset of Fireball” and Edward (Shuryak) followed with the talk “Formation of fireball and clustering

near the (hypothetical) critical point". Clearly, under the pressure of new data and ideas, the diagram will continue to evolve, thereby inspiring future experimental measurements.

Twenty years have passed since the initial idea for the NA61/SHINE 2D scan was formulated, as shown in Figure 7. Data collection for the scan was completed in 2017, and publication of the main results is expected to conclude within the next few years. Several generations of doctoral and postdoctoral researchers contributed to the results presented in Figure 9 (bottom): Antoni (Aduszkiewicz) and Szymon (Pulawski) worked on $p+p$ interactions; Magda (Kuich), Emil (Kaptur), and Szymon on Be+Be collisions; Michel (Naskret), Maciek (Lewicki), and Piotrek (Podlaski) on Ar+Sc collisions; and Sasha (Panova) and Liza (Zharebstova) on Xe+La collisions. Additionally, many contributed to the search for the critical point of strongly interacting matter, with Tobiasz (Czopowicz), Nikos (Davis), Haradhan (Adhikary), and Valeria (Reyna) obtaining the CP exclusion limits.

This period coincided with dramatic global events that also impacted NA61/SHINE: the COVID-19 pandemic, the aggression of Putin's Russia against Ukraine, Trump's chaos and the AI revolution.

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