Experimental state-of-the-art before SQM 2024

Maximiliano Puccio[1,*]

[1]European Organization for Nuclear Research (CERN), Geneva, Switzerland

Abstract. Large conferences like SQM often drive rapid advancements in physics, and this talk was intended to recap the status of the main topics discussed during the event. In these proceedings, the content has been contextualized in light of the discussions and new results presented at SQM 2024.

1 Introduction

Among all the topics discussed in the Strangeness in Quark Matter conference series, this overview is focused on three main subjects: the (circumstantial?) evidence we have of thermalised QCD matter phenomena in small collision systems, the recent headline studies on the properties of the quark gluon plasma (QGP) and of the QCD phase diagram, and the recent advancement on how we can use the "heavy-ion measurement toolkit" to study hadronic physics.

2 Thermalised QCD matter in small systems?

Since the discovery of the quark-gluon plasma in heavy-ions collisions, the question of how small a droplet of QGP can be produced has become a major subject of investigation. This has led to detailed studies of smaller collision systems like proton-proton (pp) and proton-nucleus (p-A) collisions (see [1] for a review). Recently, the field has taken an even further step: investigating whether some fundamental characteristics of a thermalized QGP might already exist in elementary collisions, such as photonuclear collisions, electron-positron (e^-e^+) collisions, or in pp collisions with the lowest multiplicities.

For example, recent results from the ATLAS Collaboration [2] shown in the left panel of Figure 1 indicate that the v_2 of charged particles in high-multiplicity γ-Pb collisions is comparable to that measured in high-multiplicity pp collisions. While this finding is surprising, one could argue that collective behavior naturally emerges in any system when the initial energy transfer is sufficient to produce a large number of charged particles.

However, two recent analyses of the charged particle yields in the "ridge" region of the two-particle angular correlation measurements in pp and e^+e^- collisions present a different perspective, as shown in the right panel of Figure 1. In pp collisions, a significant associated yield is consistently observed, regardless of the multiplicity [3]. In contrast, e^+e^- collisions do not exhibit any significant associated yield [4].

These two results are quite impactful, as they suggest that the presence of a reservoir of color charges – such as a hadron involved in the collision – is necessary to develop signs of collectivity in the form of collective flow.

*e-mail: maximiliano.puccio@cern.ch

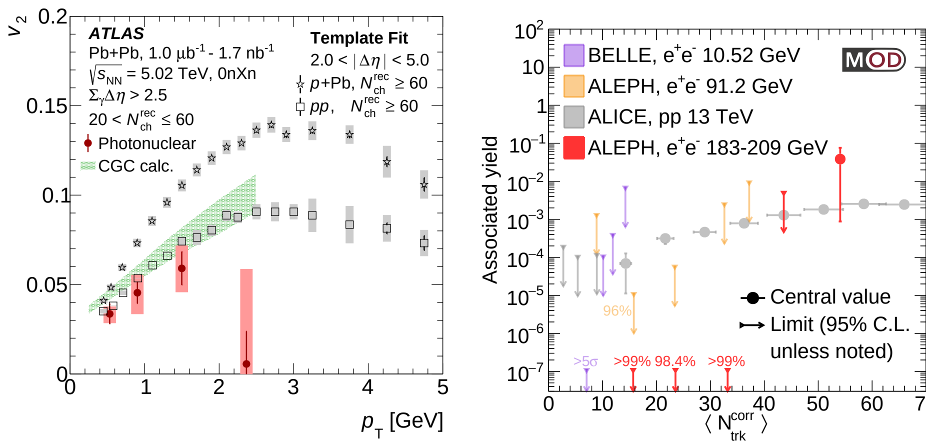
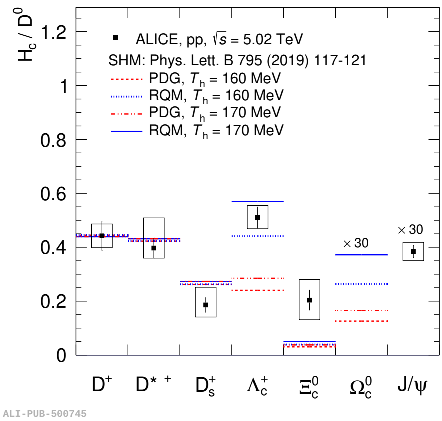


Figure 1. On the left: v_2 for charged particles in γ–Pb (red), pp (black squares), and p–Pb (black stars) collisions measured by the ATLAS Collaboration. The color glass condensate expectation are shown with a green band. Figure from [2]. On the right: charged particles yields associated to the near side peak of two-particle correlations in electron-positron [4] (coloured points) and pp [3] (grey) collisions.

The presence of collective flow is only one piece of evidence pointing to the possible existence of a thermalized, expanding QCD matter droplet in hadronic collisions. If thermalization is achieved, then the particle yields should also distribute according to the predictions of the Statistical Hadronization Model (SHM). It has been observed that the canonical formulation of the SHM describes the yields of light-flavored particles—up to multi-strange baryons—even in low-multiplicity pp collisions within 10–15% accuracy, albeit with a strangeness saturation parameter lower than unity. At the same time, recent versions of PYTHIA that include new hadronization modes with color ropes have achieved similar success in reproducing light-flavor particle yields in small collision systems.

Surprisingly, the SHM predictions are also consistent with the yield ratios of charmed hadrons measured by the ALICE Collaboration [5], as shown in the left panel of Figure 2. Considering that the first measurement of the interaction between D mesons and charged pions – performed by the ALICE Collaboration using femtoscopic techniques [6] – reveals scattering parameters compatible with zero (Figure 2, right panel), and given that any hadronic phase in pp collisions must be extremely short-lived, this suggests that if charm hadrons exhibit thermal yields, these are set at the time of hadronization rather than through subsequent interactions. However, also in the case of the charmed hadrons, modern versions of PYTHIA with new color reconnection schemes are able to describe the measured particle ratios [5].

Measured average particle yields alone are insufficient to distinguish between the string fragmentation and the SHM hadronization scenarios. To differentiate these two distinct hadronization mechanisms, experimental Collaborations have begun measuring various multi-differential observables. Among the most promising ones are the measurements of higher-order moments of the distribution of the number of produced hadrons. Recently, the ALICE Collaboration presented the first measurement of the second-order moment of number of produced multistrange baryon in pp, p–Pb, and Pb–Pb collisions [7]. The second-order moment of the net-Ξ number distribution, normalized by the average yield of Ξ baryons, effectively distinguishes between the PYTHIA and SHM predictions, with the experimental data favoring the SHM scenario across all collision systems, as shown in the left panel of



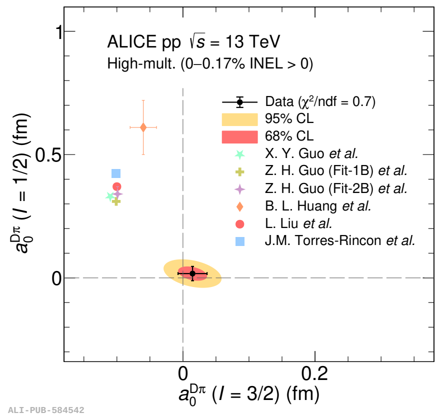


Figure 2. On the left: ratio of the production yield of charm hadrons over neutral D meson yield in pp collisions at $\sqrt{s}$ = 5 TeV. Different implementations of the SHM are shown as colored lines. Figure taken from [5]. On the right: different isospin components of the D-meson pion scattering parameter measured by the ALICE Collaboration [6] and compared to different theoretical calculations. Figure taken from [6].

Figure 3. Similarly, a study by the STAR Collaboration [8] on the higher-order cumulants of the net-proton number distribution in pp collisions at $\sqrt{s}$ = 200 GeV comes to the same conclusion. Additionally, measuring cumulants of the fourth order (C_4) and higher allowed the STAR Collaboration to directly compare their results with Lattice QCD predictions, which are expected to differ from those of the Statistical Hadronization Model (SHM) for cumulants of order higher than the fourth. However, such a comparison with LQCD is complicated by the fact that LQCD only provides predictions for the net-baryon number, whereas experiments measure only the net-proton number. Nonetheless, in both measurements at the LHC and RHIC, continuous trends as a function of multiplicity are observed, and the thermalized system baseline provided by the SHM better describes the experimental data.

3 Exploring the QCD phase diagram

While event-by-event fluctuations of the net-proton number are currently being used to understand if a thermalized QCD medium is created in pp collisions and what is the hadronisation mechanism, over the past decade they have been considered the "holy grail" observable to pinpoint the position of the QCD critical point. A couple of years ago, the STAR Collaboration released results of measurements of higher-order cumulants of the net-proton number as a function of the Au–Au collision energy [9]. These results are shown in the left panel of Figure 4. All theoretical models that do not include a critical point predict a smooth evolution of the normalized fourth-order cumulant of the net-proton number with collision energy. During the conference, an updated measurement was shown, revealing a rather intriguing difference between the C_4/C_2 measurements in central and peripheral collisions in the energy range around $\sqrt{s_{\rm NN}}$ = 20 GeV. How to model the change of baryon number transport at midrapidity and its influence on the fluctuations of the measured number of baryons as a function of collision energy – and how this translates to the reliable definition of a non-critical baseline – remain open points of discussion in this long-awaited search.

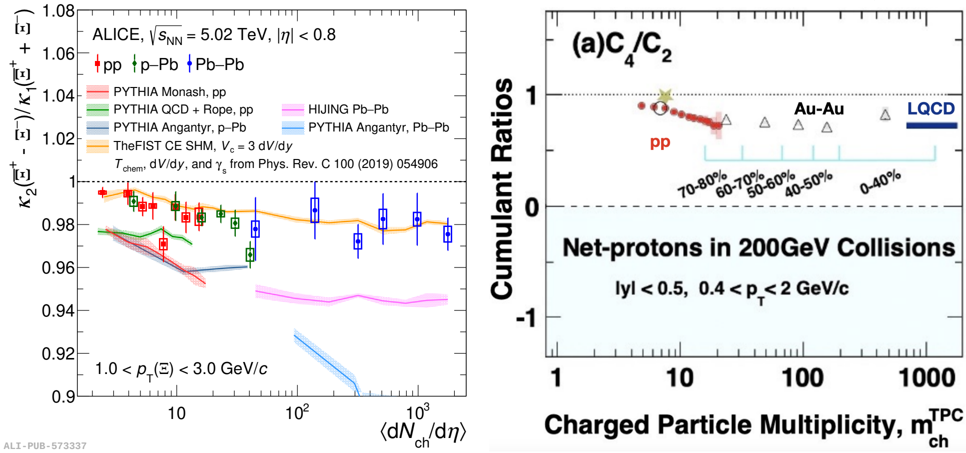


Figure 3. On the left: normalised second-order cumulant of the net-Ξ number as a function of the charged particle multiplicity in pp, p–Pb, and Pb–Pb collisions at the LHC. Figure taken from [7]. On the right: normalised fourth-order cumulant of the net-proton number as a function of charged particle multiplicity in pp and Au–Au collisions at RHIC. Figure adapted from [8].

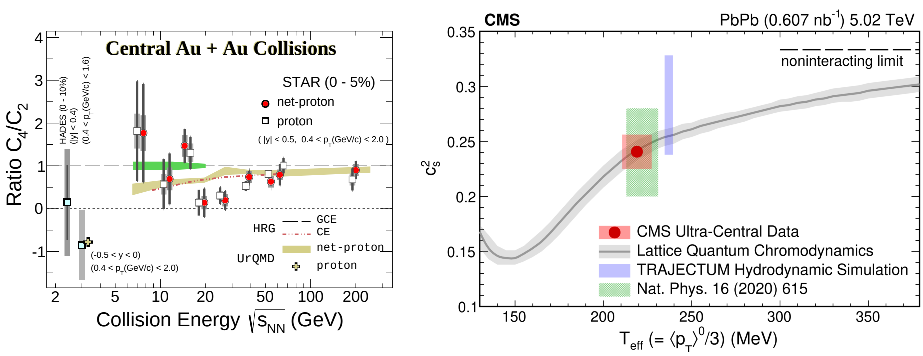


Figure 4. On the left: normalised fourth-order cumulant of the net-proton number as a function of the Au–Au collision energy at RHIC. Figure taken from [9]. On the right: speed of sound as a function of the effective temperature of the expanding QGP. The red point represent the measurement from the CMS Collaboration, while the different coloured bands are model predictions. Figure taken from [10].

While the search for the critical point is the main focus at RHIC, the characterization of the properties of the quark-gluon plasma (QGP) is the primary focus of research in heavy-ion collisions at the LHC. Recently, inspired by a seminal paper [11] on how to relate measured bulk properties of heavy-ion collisions to fundamental properties of the QGP, the CMS Collaboration released the first measurement of the speed of sound in the QGP. This measurement focuses on ultra-central collisions, where fluctuations in the number of partonic interactions lead to an increase in the system's energy density. In such collisions, the average transverse momentum ($\langle p_{\mathrm{T}} \rangle$) of the produced particles and the number of produced charged hadrons (N_{ch}) act as proxies for the temperature and the entropy density, respectively. By utilizing these two proxies, the speed of sound in the QGP has been extracted from the fit to the distribution of $\langle p_{\mathrm{T}} \rangle$ as a function of N_{ch}. The resulting value, which is close to half

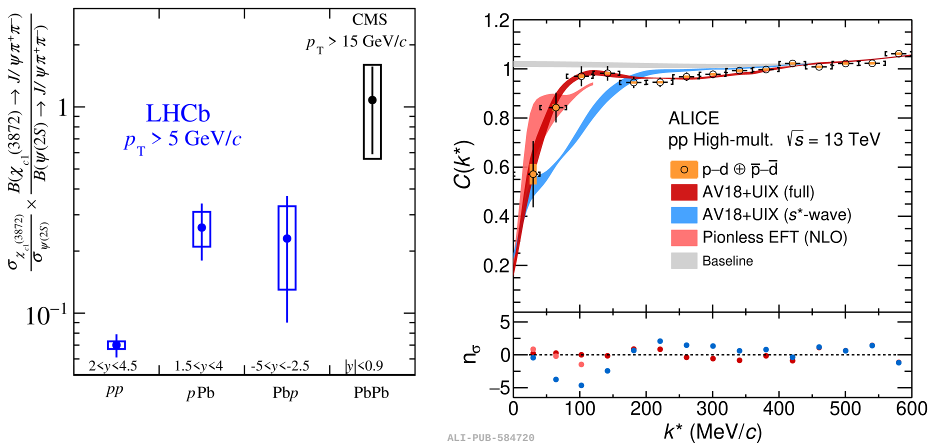


Figure 5. On the left: production cross section of the $\chi_{c1}(3872)$ normalised on the production cross section of the $\psi(2S)$ as a function of system energy. Figure taken from [12]. On the right: femtoscopic correlation function between proton and deuterons. The red-colored band represent the fit with a three-body system calculation. Figure taken from [13].

the speed of light, along with comparisons to theoretical models, is shown in the right panel of Figure 4. During the conference, the ALICE Collaboration also presented a systematic study on the extraction of this quantity, highlighting how the measurement can be influenced by different definitions of centrality estimators and their correlations with the measured $\langle p_T \rangle$ and N_{ch}. However, even in light of this study, no major issues have been found in the CMS measurement.

4 Hadronic structure and interactions

This last section could deserve dedicated proceedings due to the incredible expansion in the number and quality of studies on hadronic structure and hadronic interactions using heavy-ion and heavy-ion-inspired techniques.

In recent years, the study of the production of nuclei and hypernuclei has made headlines, showcasing how we can use their production cross sections in hadronic collisions to study their structure. This was particularly striking when the large wave function of the hypertriton was revealed by measuring its production in small collision systems [14]. Drawing an analogy to nuclear bound states, it was argued almost ten years ago [15] that one could study the structure of the $\chi_{c1}(3872)$ by examining its production in different colliding systems. In the context of these efforts, the LHCb Collaboration recently published the first measurement of the $\chi_{c1}(3872)$ in p–Pb collisions, as shown in the left panel of Figure 5. This measurement indicates that the production of $\chi_{c1}(3872)$ in p–Pb collisions relative to that of the $\psi(2S)$ is more abundant than in pp collisions, following the trend already established by the first measurement of the $\chi_{c1}(3872)$ in Pb–Pb collisions by the CMS Collaboration [16]. Such an enhancement is very similar to that observed for light nuclei; however, it is not easy to reconcile with the measurement of the $\chi_{c1}(3872)/\psi(2S)$ ratio as a function of charged particle multiplicity in pp collisions [17], which is instead decreasing. Future measurements and theoretical developments will be needed to clarify this discrepancy.

However, while the jury is still out in the case of the $\chi_{c1}(3872)$, the CMS Collaboration has established that the $f_0(980)$ is an ordinary meson by measuring its flow in p–Pb collisions and comparing it to that of standard mesons and baryons [18].

Finally, in the study of hadronic interactions, femtoscopic correlations are paving the way to investigate increasingly complex particle systems. For instance, the recent measurement of the correlation between protons and deuterons by the ALICE Collaboration in pp collisions [13] shows that this two-particle correlation cannot be simply explained in terms of a two-body system. Since pp collisions are small systems, the proton interacts with the components of the deuteron, creating a genuine three-body system whose modeling is required to explain the proton-deuteron correlation function, as shown in the right panel of Figure 5. This opens up the possibility of inferring properties of multi-body systems by simply measure two-particle correlations of their constituents. Studying such correlations in large collision systems can be also advantageous, as some interactions may be suppressed, making modeling easier. A first attempt in this direction was made by the STAR Collaboration, which determined the Λ–deuteron scattering parameters by measuring the corresponding two-particle femtoscopic correlation function, as discussed at this conference.

5 Summary: physics at the extremes

In heavy-ion physics, the most extreme hadron collisions ever created by human means are studied. However, we are now pushing further by studying both the extremely high multiplicity region in heavy-ion collisions and the extremely low multiplicity region in pp collisions. Not only that, but we are also pushing observables to their limits. While experimental biases and misleading assumptions can undermine such extreme studies, our field demonstrates a stunning resilience to overcome them and, as demonstrated at this conference, to make lasting contributions to the understanding of QCD matter.

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