Physics of small systems experimental overview

Jiayin Sun[1,*]

[1]INFN Sezione di Cagliari, Monserrato, Italy

Abstract. In these proceedings, new experimental results from collisions of small systems are summarized and discussed. Traditionally collisions of small systems are regarded as baselines for large AA collisions. However, recent measurements in collisions of small systems have found signatures of QGP similar to those observed in large systems, which makes the understanding of origin of the observables in small systems much more complex.

1 Introduction

Small collision systems such as pp and pA collisions are traditionally regarded as reference systems for studies of "large" AA collisions where the Quark-Gluon Plasma (QGP) is created. This is because pp collisions provide simple, clean hadronic collisions in vacuum without a QCD medium. On the other hand, pA collisions provide information on cold nuclear matter effects, such as initial state effects in nuclei. Data from these small systems are compared to those from "large" AA systems to extract and quantify effects due to QGP formation.

Surprisingly, many recent measurements in small systems have demonstrated signatures of QGP formation, which were traditionally assumed to be displayed in AA collisions. Among these effects are long-range collective flow [1], the enhanced production in strange light hadrons [2], and an enhancement of baryons over mesons at intermediate transverse momentum [3]. These observations prompted the question of whether a small droplet of QGP is created in small systems. A wealth of recent measurements attempts to further understand the origin of these phenomena in small systems. In these QM23 proceedings, only a few new measurements and findings in small systems are discussed due to the limited space.

2 Initial state

Understanding the initial state of high energy hadron collisions is an important QCD topic and essential for the accurate extraction of the properties of the QGP. The longitudinal structure of nuclei, described by parton distribution functions in nuclei (nPDFs), can be studied in pA and ultraperipheral AA collisions. With many recent measurements from the LHC and other collider experiments, significant progress has been made on constraining the nPDFs with experimental data, especially in the poorly known small Bjorken-x region where effects of nuclear shadowing is expected. At small-x and Q^2, where the gluon density is expected to saturate, the parton distributions can be described by the color-glass condensate (CGC) effective theory.

*e-mail: jiayin.sun@cern.ch

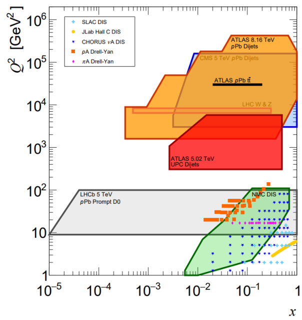

Figure 1. Phase space $x - Q^2$ coverage of selected experimental data [4].

Figure 1 illustrates the x-Q^2 phase space coverage of recent data collected by a few different experiments [4]. Heavy probes, such as measurements with $t\bar{t}$, W and Z bosons and dijets, cover the x range of $10^{-4} < x < 1$ and the large Q^2 range of $10^2 < Q^2 < 10^6$. Nuclear deep-inelastic scattering and Drell-Yan processes at lower energies contribute to the lower right corner of Fig. 1 with low Q^2 and not very low x. Experiments with more forward coverage, such as LHCb, can provide unique access to the small-x region down to $x \sim 10^{-5}$.

The prompt D^0 meson data in 8.16 TeV pPb collisions by LHCb [5] is currently the most precise heavy flavor measurement in pA collisions. Fig. 2 shows the variation of the D^0 nuclear modification factor, $R_{p\text{Pb}}$, as a function of $x_{exp} \equiv 2\frac{\sqrt{p_{\text{T}}^2(D^0)+M^2(D^0)}}{\sqrt{s_{\text{NN}}}}e^{-y^*}$, an experimental proxy to approximate the variation of $R_{p\text{Pb}}$ with x. The data points form a continuous trend from $x \sim 10^{-5}$ to $x \sim 10^{-1}$. The data confirms a significant suppression in the nuclear shadowing region and show a hint of enhancement in the anti-shadowing region.

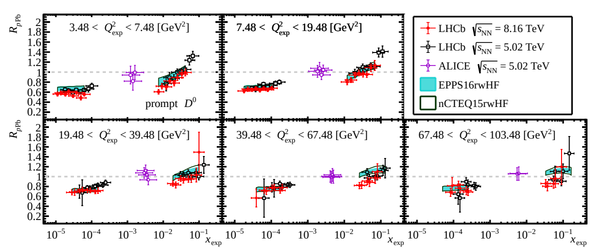

Figure 2. Prompt D^0 nuclear modification factor $R_{p\text{Pb}}$ as a function of x_{exp} in pPb collisions [5].

At low x and Q^2, the direct photon is an ideal probe of gluon nPDF and can allow access to the gluon saturation region. A new direct photon measurement of the $R_{p\text{Pb}}$ ratio by ALICE in midrapidity [6], shown in the left of Fig. 3, is consistent with unity for $12 < p_{\text{T}} < 80$ GeV/c but shows a hint of suppression at $p_{\text{T}} < 15$ GeV/c. To push for small x and Q^2, however, low p_{T} direct photon and light hadron data in the forward rapidity are preferable. Shown on the right of Fig. 3, the LHCb collaboration recently published $R_{p\text{Pb}}$ measurements of light neutral mesons π^0 [7], η and η' [8] that are reconstructed with photons in the forward rapidity. Similar suppression effects that are significantly below unity are observed for the three light meson species. It would be very interesting to extend these measurements to the direct photon.

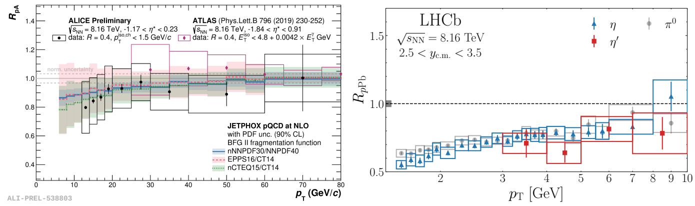

Figure 3. Left: direct photon nuclear modification factor $R_{p\text{Pb}}$ as a function of p_T in midrapidity [6]. Right: π^0, η and η' nuclear modification factor as a function of p_T in forward rapidity [8].

An alternative approach to probe the small-x phenomena is using vector meson photoproduction in ultra-peripheral collisions (UPC). In the left panel of Fig. 4, LHCb recently published a precision measurement of J/ψ photoproduction in UPC PbPb collisions in $2 < y < 4.5$ [9], where the uncertainties of the data are significantly smaller than theoretical uncertainties of nPDF calculations, showing the potential in constraining the gluon nPDF at small-x. CMS [10] (middle panel) and ALICE [11] (right panel) adopt a similar method where coherent J/ψ production is measured in multiple nuclear breakup classes. It resolves an ambiguity of having two possible x values for each data point, thus allows to extract the nuclear gluon suppression factor R_g^{Pb} down to the $x \sim 10^{-5}$ regime.

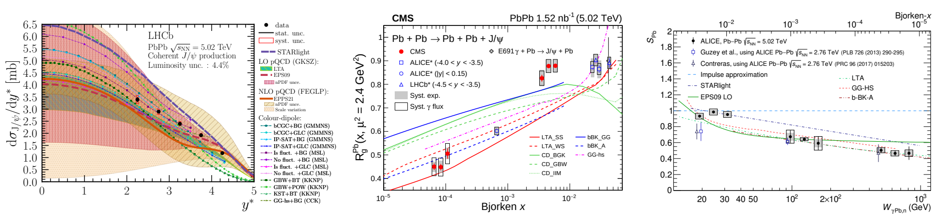

Figure 4. Left: coherent J/ψ cross-section vs. rapidity [9]. Middle and right: nuclear suppression factor as a function of x [10, 11].

3 Hadron production

3.1 Strangeness enhancement

Strangeness enhancement has long been regarded as a signature of QGP creation. Yet ALICE has observed the enhanced production of strange light hadrons in high multiplicity pp and pPb collisions [12] where QGP formation was not expected. The underlying mechanism causing the enhanced strangeness production in small systems is still under investigation. The preliminary results from the STAR collaboration show that K_s and Λ yields in dAu collisions at $\sqrt{s_{NN}} = 200$ GeV increase with growing N_{part} [13]. ALICE measured the probability density function for (multi-)strange particles for the first time [14], offering a unique opportunity to test the connection between charged and strange particle multiplicity production.

Many efforts have been made in search of strangeness enhancement with heavy flavor. In QM22 conference, LHCb reported the observation of enhanced B_s^0/B^0 ratio in high multiplicity pp collisions at 13 TeV [15]. In the left panel of Fig. 5, a new measurement from LHCb at this conference shows a significant increase of D_s^+/D^+ production ratio with increasing event multiplicity in 8.16 TeV pPb collisions [16]. These results may imply the existence of quark coalescence as a common underlying hadronization mechanism for c and b quarks. The right panel of Fig. 5 shows a new observable, prompt Ξ_c^+/Λ_c^+ production ratio measured by LHCb [17], which provides another handle of studying strangeness by examining charm baryons containing an s quark. The data hint at a slightly higher ratio in the backward rapidity, where the average multiplicity is larger than that of the forward, although the uncertainty is too large to allow firm conclusions.

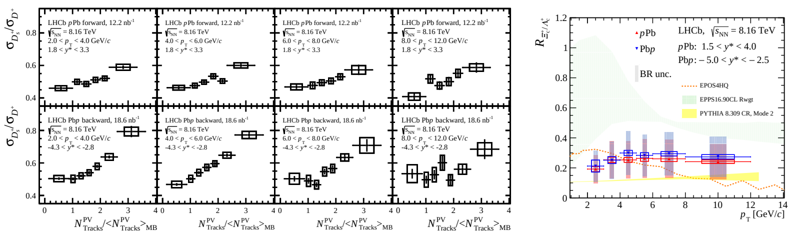

Figure 5. Left: production ratio D_s^+/D^+ vs. event multiplicity in pPb collisions [16]. Right: prompt Ξ_c^+/Λ_c^+ production ratio vs. p_T in pPb collisions [17].

3.2 Heavy flavor hadronization

Recent measurements of charm baryon production in small system raise many open questions on c quark hadronization mechanism in hadronic collisions. One surprise is the violation of fragmentation fractions universality, as ALICE measured a significantly larger fragmentation fraction for charmed baryon Λ_c^+ in pp collisions than values measured in e^+e^- and ep collisions [18]. In the left of Fig. 6, ALICE extends the measurement of fragmentation fractions to all ground state charm hadrons in pp collisions [19] showing significant enhancement of charm baryons Λ_c^+ and $\Xi_c^{0,+}$ with respect to leptonic collisions. In order to describe the data, additional hadronization mechanisms such as quark coalescence needs to be incorporated in model calculations. Quark coalescence requires multiple quarks to overlap in position and velocity, and is expected to make a stronger impact when event multiplicity is larger. A new measurement from ALICE [20] (Fig. 6, right) shows Ξ_c^0/D^0 ratio is slightly enhanced in pPb collisions compared to that in pp collisions.

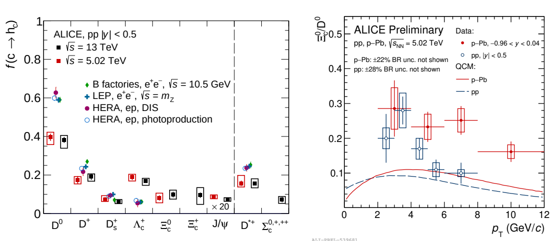

Figure 6. Left: charm hadron fragmentation fractions in pp collisions [19]. Right: Ξ_c^0/D^0 production ratio as a function of p_T [20].

It is useful to look at heavy flavor baryon to meson production ratio as a function of event multiplicity. In the left of Fig. 7, the Λ_c^+/D^0 ratio measured by CMS [21] does not exhibit strong dependence on multiplicity. In contrast, the LHCb Λ_b^0/B^0 ratio [22] shows a clear increasing trend from low to high multiplicity, and is qualitatively consistent with expected characteristics from coalescence.

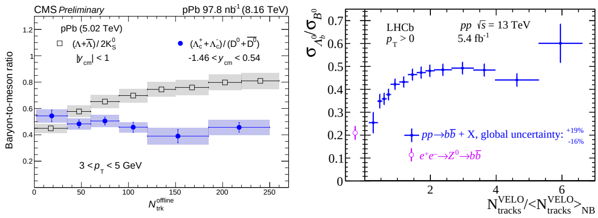

Figure 7. Left: Λ_c^+/D^0 production ratio as a function of event multiplicity [21]. Right: Λ_b^0/B^0 production ratio as a function of event multiplicity [22].

4 Collective flow

The collective flow behavior was considered exclusive to large colliding systems where momentum spatial anisotropy is developed via partonic rescatterings in a hot and dense medium, described successfully by hydrodynamic models. Therefore, the discovery of flow in high multiplicity pp and pA collisions [23], with similar characteristics to those in AA collisions, was surprising. It quickly initiated a hot discussion on whether this can be explained by the possible formation of a tiny droplet of QGP in small systems or by other mechanisms such as initial-state momentum correlations described by CGC.

CMS searches for the minimum system size needed for collectivity to emerge. They study two-particle correlations within a single jet cone [24]. The idea is that collective effects may develop from an initial system of a single energetic parton that subsequently fragments and hadronizes in the vacuum. Fig. 8 shows the correlation functions from all jet multiplicities (left) and the highest (right) jet multiplicity. A hint of a near-side ridge is found in the high jet multiplicity case, although the structure is less distinct than those in pp and pA collisions. The observation cannot be reproduced by MC generators such as Pythia8 and Sherpa, suggesting new QCD effects in the nonperturbative regime.

Among the many notable new results shown at the conference, STAR reports the first measurement of hadron flow in Oxygen-Oxygen collisions [25], a symmetric system of light nuclei that has a multiplicity overlap with pp, pA and AA collisions. The flow-to-eccentricity ratio v_n/ϵ_n is found to be similar to that in ^{3}HeAu collisions. The data also suggests that possible many-nucleon correlations may enhance fluctuations in ultra-central collisions.

5 Summary and outlook

In these proceedings, some new experimental results and progress are summarized although many are left out due to the large amount of new results and the limited space. Small system has become an actively studied area that forms an integral part of QGP research and is no longer regarded solely as a baseline. With LHC data at high center of mass energy of collision, significant progress has been made at constraining nPDFs at small Bjorken-x down to 10^{-5}, although clear signs of gluon saturation is still elusive. Enhanced strangeness production in high event multiplicity is observed with light, charm and beauty hadrons in small

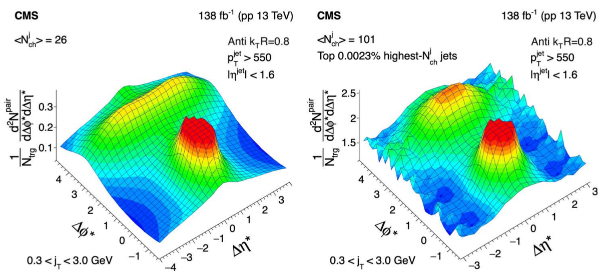

Figure 8. Two-particle angular correlation functions from all jet multiplicity (left) and the highest jet multiplicity (right) [24].

systems. An enhanced beauty baryon production is also reported for Λ_b^0/B^0 ratio in high multiplicity pp collisions, although the charm baryon Λ_c^+/D^0 ratio show no clear dependence on multiplicity, implying a possible different hadronzation mechanism. A hint of near-side ridge is found within high multiplicity single jets, suggesting flow may be developed from a single energetic parton. The ongoing upgrade program at the LHC and the future Electron-Ion Collider will provide greatly improved data to answer these important questions.

References

[1] CMS Collaboration, JHEP **09**, 091 (2010)
[2] ALICE Collaboration, Nature Physics **13**, 535 (2017)
[3] ALICE Collaboration, Phys. Rev. Lett. **127**, 202301 (2021)
[4] Ben Gilbert, presentation in Quark Matter 2023 conference
[5] LHCb Collaboration, Phys. Rev. Lett. **131**, 102301 (2023)
[6] Alice Collaboration, https://alice-figure.web.cern.ch/node/26257
[7] LHCb Collaboration, Phys. Rev. Lett. **131**, 042302 (2023)
[8] LHCb Collaboration, arXiv:2310.17326
[9] LHCb Collaboration, JHEP **06**, 146 (2023)
[10] CMS Collaboration, Phys. Rev. Lett. **131**, 262301 (2023)
[11] Alice Collaboration, JHEP **10** (119 (2023)
[12] Alice Collaboration, Nature Phys. **13** 535 (2017)
[13] Rosi Reed, presentation in Quark Matter 2023 conference
[14] Sara Pucillo, presentation in Quark Matter 2023 conference
[15] LHCb Collaboration, Phys. Rev. Lett. **131**, 061901 (2023)
[16] LHCb Collaboration, arXiv:2311.08490
[17] LHCb Collaboration, arXiv:2305.06711
[18] Alice Collaboration, Phys.Rev.C **107** 064901 (2023)
[19] Alice Collaboration, JHEP **12**, 086 (2023)
[20] Jianhui Zhu, presentation in Quark Matter 2023 conference
[21] CMS Collaboration, CMS-PAS-HIN-21-016
[22] LHCb Collaboration, arXiv:2310.12278
[23] CMS Collaboration, JHEP **09** 091 (2010)
[24] CMS Collaboration, arXiv:2312.17103
[25] Shengli Huang, presentation in Quark Matter 2023 conference