Exploring QGP signature in small system: Insights from ALICE in p–Pb and pp collisions

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Abstract. The formation of quark-gluon plasma (QGP) has been confirmed in ultra-relativistic heavy-ion (i.e. Pb-Pb) collisions. Results from small collision systems, such as proton-ion (p–Pb) and proton-proton (pp) collisions at LHC energies, have revealed several notable features: a hardening of the p_{T}-spectra and evidence of radial flow, an enhancement in (multi-)strange hadron production with increasing multiplicity, and non-zero anisotropic flow coefficients. These observations suggest the presence of collective effects, similar to those found in the QGP in heavy-ion collisions. In the searching of QGP formation in small collision systems, in particular, high-multiplicity (HM) p–Pb and pp collisions are essential as their charged-particle multiplicity is comparable to that of peripheral heavy-ion collisions. This proceeding presents the LHC Run 2 results of light-flavour hadron (π, K, p) production in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV with a focus on transverse momenta (p_{T}) spectra, mean transverse momenta ($\langle p_{\mathrm{T}} \rangle$), ratio of p_{T}-spectra and the ratio of the integrated yields of kaon-to-pion and proton-to-pion. The results are compared with that of heavy-ion collisions. The anisotropic flow (v_2) measurement in high-multiplicity p–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV and pp collisions at $\sqrt{s}$ = 13 TeV are also shown and compared with the results from Pb–Pb collisions.

1 Introduction

The heavy-ion collisions (A–A) at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have confirmed the formation of the quark-gluon plasma (QGP), a short-lived new state of nuclear matter where quarks and gluons are deconfined [1]. The production of particles with high transverse momentum (p_{T}) or containing heavy-quarks can be described by perturbative quantum chromodynamics (pQCD). The high-p_{T} partons and heavy quarks lose energy through interacting in the QGP , therefore used as probes of the QGP. On the other-side the production dominated by light-flavour hadrons (π, K, p) at low transverse momentum (p_{T}), created from the soft interactions among the partons, carry useful information of collective behaviour and freeze-out property of the QGP, spatial anisotropy of the collision geometry and anisotropic expansion of medium.

The ALICE experiment characterizes the properties of the QGP medium using heavy-ion collisions (i.e., Pb–Pb, Xe–Xe), while pp collisions are typically used as a reference [2–6]. The collective phenomena such as radial flow, long-range angular correlation and anisotropic

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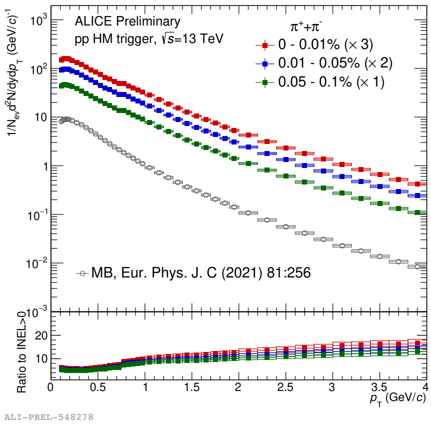
flow [4–9], are typically observed in A–A collisions, where the QGP medium is formed. The recent measurements of light-flavour hadrons production shows mass dependent hardening of the p_T-spectra, an increase in mean transverse momenta ($\langle p_T \rangle$) and an enhancement of baryon-to-meson ratio at intermediate-p_T in small collision systems at large multiplicity depicted similarity with the results in heavy-ion collisions where QGP is formed [4, 10, 11]. The enhancement of strange hadron production in heavy-ion collisions is one of the key signatures of QGP formation. The ratios of (multi-)strange hadrons to non-strange hadrons exhibit a clear trend of smooth increase with multiplicity until reaching saturation. The observation of the smooth evolution of strange to non-strange yield ratios across different collision systems and centere-of-mass energies suggests physics of hadronization follows a mechanism that depends only on the multiplicity. [11, 12]. The origin of strangeness production in small collision systems has been studied through a topological analysis of production towards- and transverse-to-leading particle (a proxy for the jet axis) [13]. Strange hadron production from underlying event (soft scatterings) dominates over hard scattering, and the relative production of strangeness is favoured in transverse-to-leading (i.e. soft scatterings) processes. The measurements of long range angular correlations and non-zero anisotropic flow in heavy-ion collisions are well explained by collective effects of the QGP medium [14]. A similar "ridge"-like structure in angular correlations and non-zero anisotropic flow coefficients has also been observed in p–Pb and pp collisions [15, 16].

The above mentioned observations in small systems (p–Pb, pp) require a comprehensive explanation of the mechanisms behind these phenomena. This proceedings presents the latest measurements from LHC Run 2 data on light-flavour production in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV [17]. The elliptic flow coefficient (v_2) of identified particles in high-multiplicity p–Pb and pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV, respectively, are presented to address the question of a unified description of collective phenomena observed from small to large collision systems.

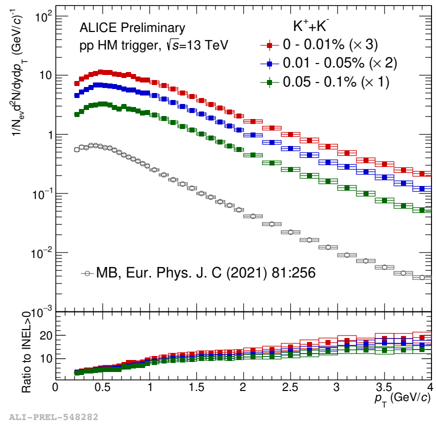
2 Results

The results presented here are based on data samples; of pp collisions at $\sqrt{s}$ = 13 TeV and p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected by the ALICE experiment during the LHC Run 2 data-taking campaign 2015-2018. The minimum bias (MB) trigger requiring hits on both V0A and V0C detectors. The MB events with at least one charged-particle produced in the pseudorapidity region $|\eta| < 1$ are defined as pp inelastic INEL>0 event class. The different V0M multiplicity classes are defined from the sum of all signals in V0M detector (combined signals of V0A and V0C detectors). Different multiplicity classes in pp collision are from the V0M detector signals. For example, the V0M-I and V0M-X multiplicity classes are corresponding to events containing 0–0.92% highest multiplicity and 64.5–100% lowest multiplicity, respectively [11]. For pp collisions at $\sqrt{s}$ = 13 TeV, an additional high-multiplicity (HM) trigger, with a threshold of relative V0M amplitude with respect of average value V0M/$\langle$V0M$\rangle$ > 4.9, is applied, selecting the top 0.1% of the MB events [18].

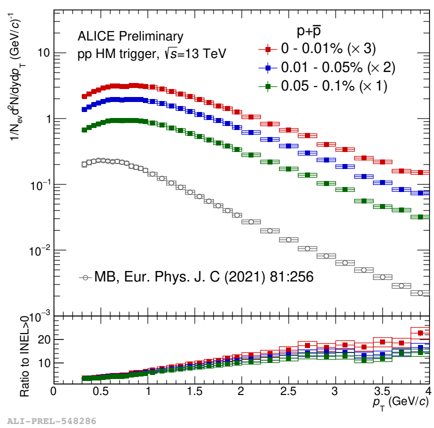
The p_T-differential spectra of the π, K and p for three HM classes, corresponding to the 0-0.01%, 0.01-0.05% and 0.05-0.1% of the MB events of pp collisions at $\sqrt{s}$ = 13 TeV, are shown in Fig. 1 along with the reference MB spectra for the INEL>0 [19]. The bottom panels of the figure show the ratios of the HM spectra to the INEL>0 class. For all three identified hadrons, the ratios exhibit a hardening trend with increasing multiplicity, with the the effect being more pronounced for protons. The observation of hardening of the p_T-spectra with increasing multiplicity, along with mass ordering, is inline with the previously reported results in pp, p–Pb and Pb–Pb collisions where they have been attributed to the hydrodynamical flow [4, 10, 11].



(a) $\pi^+ + \pi^-$



(b) $\mathrm{K}^+ + \mathrm{K}^-$



(c) $\mathrm{p} + \bar{\mathrm{p}}$

Figure 1. p_{T} differential spectra of π, K and p for three different high-multiplicity classes, compared with the reference minimum bias result [19]. The spectra are scaled for better visibility. The ratios to INEL>0 are shown in the bottom panels.

The measurement of mean transverse momentum $\langle p_{\mathrm{T}} \rangle$ as a function of charged-particle multiplicity density $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ for three particles (π, K and p) is shown in Fig. 2. The results are compared with previously reported $\langle p_{\mathrm{T}} \rangle$ measurements in pp collisions at $\sqrt{s}$ = 7 and 13 TeV [11, 20]. A continuously increasing trend of $\langle p_{\mathrm{T}} \rangle$ with increasing of $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ can be observed, with a steeper rise for heavier hadrons. Similar observations have been reported in pp [21] and p–Pb [10] collisions at lower collision energies. The qualitative trend of increasing $\langle p_{\mathrm{T}} \rangle$ with charged-particle multiplicity, along with the mass ordering, is consistent with the results observed in Pb–Pb collisions, though in a different multiplicity region [4]. This observation can be explained by the presence of a stronger radial flow effect at higher multiplicities, which is more pronounced for particles with larger mass, across all three collision systems.

The relative production of different charged particles with transverse momenta can be studied by examining particle ratios across various multiplicity classes. Fig. 3 shows K/π and

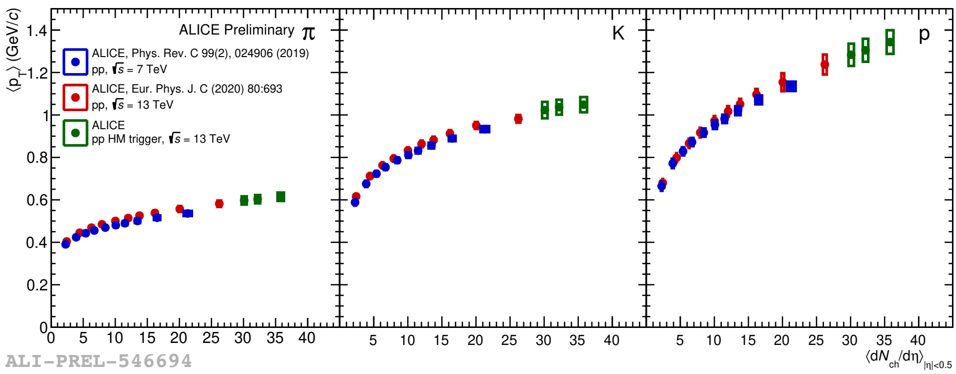


Figure 2. Mean transverse momentum $\langle p_{\mathrm{T}} \rangle$ as a function of charged-particle multiplicity density ($\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$) of π, K and p in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV and compared with results from pp collisions at $\sqrt{s}$ = 7 and 13 TeV [11, 20].

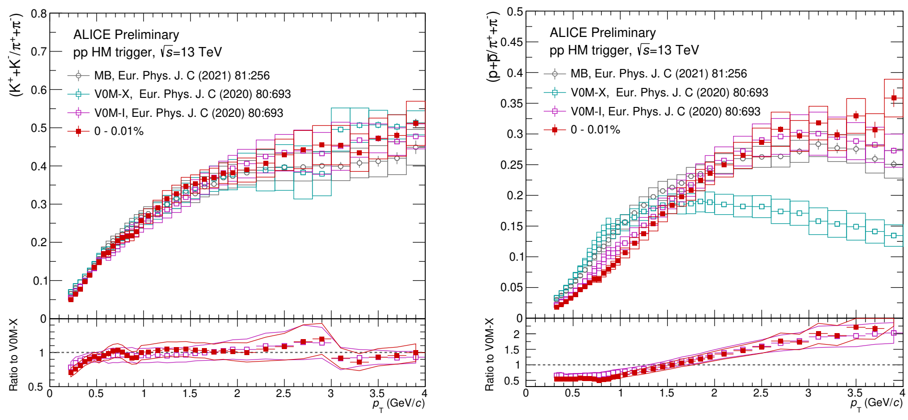


Figure 3. Ratios K/π (left) and p/π (right) of the p_{T}-spectra. The reference results of the V0M and minimum bias classes as shown for comparison [11, 19]. The ratio to V0M-X are shown in the bottom panels.

p/π ratios as a function of p_{T} for the high-multiplicity class 0-0.01%, along with published V0M multiplicity classes and minimum bias results for the same collision system (pp) at $\sqrt{s}$ = 13 TeV [11, 19]. The lower panels of the figure show a comparison of the ratios to the V0M-X class. The K/π ratio shows no significant dependence on multiplicity within the explored p_{T} range. However, the p/π ratio exhibits depletion at low p_{T} ($\sim$ 0.8 GeV/c) and an enhancement with increasing p_{T}, similar to the trend obtained in the V0M-I class. This enhancement of baryon-to-meson ratio has been reported in all three collision systems–pp, p–Pb and Pb–Pb, attributed to radial flow boosting heavier particle at mid p_{T} [20]. A similar pattern of K/π and p/π ratios is also observed in the other high-multiplicity classes, 0.01-0.05% and 0.05-0.1%.

The p_T-integrated particle ratios, kaon- and proton-to-pion, as a function of multiplicity $\langle dN_{ch}/d\eta \rangle$ is shown in Fig. 4 alongside published results from pp, p–Pb and Pb–Pb collisions [4, 6, 10, 11, 20]. The high-multiplicity data points are in good agreement with ratios from the p–Pb and Pb–Pb collisions at similar multiplicities. The ratios exhibit a smooth evolution with increasing charged-particle multiplicity, indicating that the multiplicity is the key driving force of the hadrochemistry, irrespective of the collision energy and colliding system. The increasing trend of K/π ratio with increasing multiplicity could be due to the fact that the strange to non-strange hadron production increases with increasing multiplicity. The small decrease of the p/π ratio with increasing multiplicity supports the hypothesis of antibaryon-baryon annihilation in the hadronic phase, a process which is less significant in low multiplicity or peripheral collisions [22].

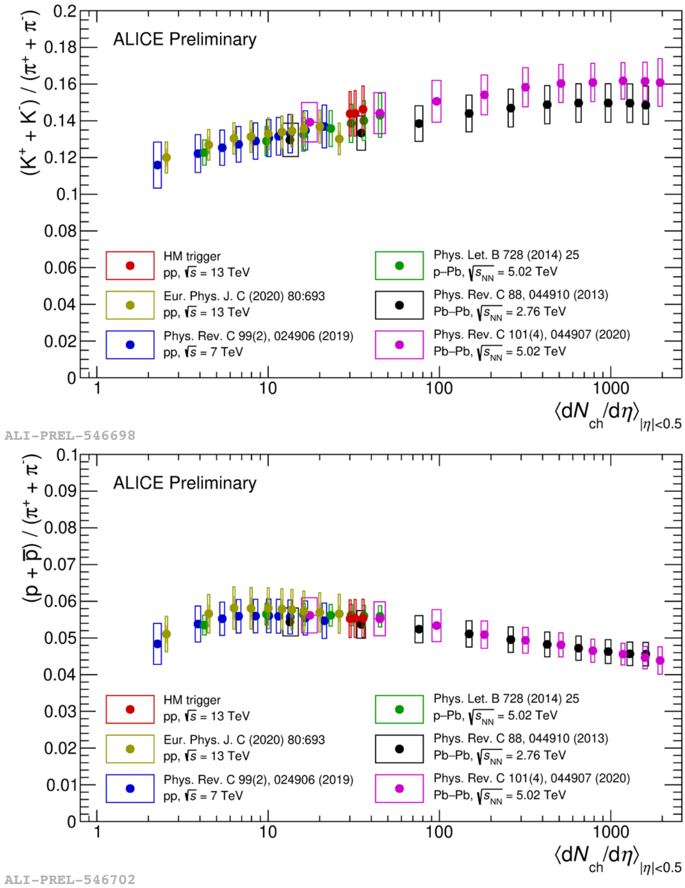


Figure 4. Integrated yield ratios K/π (top) and p/π (bottom)as a function of charged-particle multiplicity density ($\langle dN_{ch}/d\eta \rangle$) for high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV, compared with results from pp, p–Pb and Pb–Pb collisions [4, 6, 10, 11, 20].

The anisotropic dynamic in small collision systems is studied by measuring the elliptic flow coefficient v_2 as a function of p_T in high-multiplicity p–Pb and pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV, respectively, as shown in Fig 5. The figure presents measurement of v_2 for identified mesons ($\pi^{\pm}$, $K^{\pm}$, K^0_s) and baryons (p($\bar{p}$), $\Lambda(\bar{\Lambda})$) up to p_T < 7.5 GeV/c. The behaviour of v_2 with p_T is found similar among all three collision systems: Pb–Pb [23], p–Pb and pp. The coefficient v_2 is found to decrease gradually from Pb–Pb to pp collision systems, which can be attributed to higher anisotropy in larger systems. For $p_T < 2$–3 GeV/c, v_2 of lighter hadrons is larger than heavier ones at the same p_T, which is known as mass ordering of particle species. This behaviour provides significant evidence of collective radial flow, which gives isotropic boost to all particles equally, in addition to the anisotropic expansion of the system. Beyond the low-p_T region, the particles are grouped according to the number of their constituent quarks, known as baryon-meson v_2 grouping. This observation of baryon-meson v_2 grouping at intermediate-p_T in heavy-ion collisions is explained by the hypothesis of particle production via the quark coalescence mechanism [24, 25].

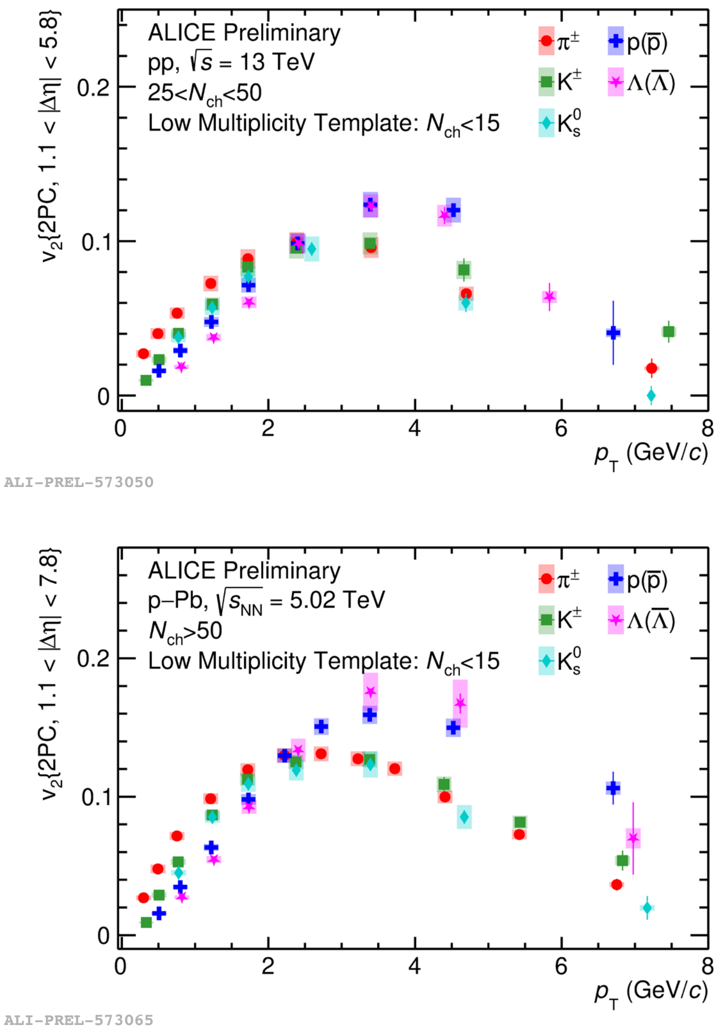


Figure 5. Elliptic flow v_2 as a function of p_T for mesons ($\pi^{\pm}, K^{\pm}, K^0_s$) and baryons ($p(\bar{p}), \Lambda(\bar{\Lambda})$) in high-multiplicity p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (top) and pp collisions at $\sqrt{s} = 13$ TeV (bottom).

3 Conclusions

High-multiplicity p–Pb and pp collisions exhibit shown properties that resemble collective behaviour attributed to the formation of QGP in Pb–Pb collisions. In particular, the transverse momentum spectra of the π, K and p in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV exhibit multiplicity and mass-dependent hardening similar to what is observed in heavy-ion collisions [4, 6]. The mean transverse momentum $\langle p_{\mathrm{T}} \rangle$ increases with multiplicity and its mass-dependent steepness can be attributed to a stronger radial flow effect with increasing multiplicity and particle masses. The ratios K/π and p/π of the p_{T}-spectra confirm a similar trend as observed in the V0M-I multiplicity class of pp collisions at $\sqrt{s}$ = 13 TeV [11]. The ratios of p_{T}-integrated yields of K/π and p/π indicate that hadronchemistry depends on multiplicity only, regardless of collision systems and colliding energies. The elliptic flow coefficient v_2 measured in p–Pb and pp collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV, respectively, exhibit similar features for Pb–Pb but with smaller v_2 values. The mass ordering at low-p_{T} and baryon-meson grouping at intermediate-p_{T} observed in high-multiplicity pp and p–Pb systems are consistent with the elliptic flow measurement in the Pb–Pb collisions. A comprehensive comparison of various observables across different collision systems suggest that collective effects can be commonly present in both small and large systems.

References

[1] W. Busza, K. Rajagopal, W. van der Schee, Heavy Ion Collisions: The Big Picture, and the Big Questions, Ann. Rev. Nucl. Part. Sci. **68**, 339 (2018), [arXiv]1802.04801. 10.1146/annurev-nucl-101917-020852

[2] K. Aamodt et al. (ALICE), The ALICE experiment at the CERN LHC, JINST **3**, S08002 (2008). 10.1088/1748-0221/3/08/S08002

[3] B.B. Abelev et al. (ALICE), Performance of the ALICE Experiment at the CERN LHC, Int. J. Mod. Phys. A **29**, 1430044 (2014), [arXiv]1402.4476. 10.1142/S0217751X14300440

[4] S. Acharya et al. (ALICE), Production of charged pions, kaons, and (anti-)protons in Pb-Pb and inelastic pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys. Rev. C **101**, 044907 (2020), [arXiv]1910.07678. 10.1103/PhysRevC.101.044907

[5] S. Acharya et al. (ALICE), Production of pions, kaons, (anti-)protons and ϕ mesons in Xe–Xe collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.44 TeV, Eur. Phys. J. C **81**, 584 (2021), [arXiv]2101.03100. 10.1140/epjc/s10052-021-09304-4

[6] B. Abelev et al. (ALICE), Centrality dependence of π, K, p production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. C **88**, 044910 (2013), [arXiv]1303.0737. 10.1103/PhysRevC.88.044910

[7] B.B. Abelev et al. (ALICE), Multi-strange baryon production at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Lett. B **728**, 216 (2014), [Erratum: Phys.Lett.B 734, 409–410 (2014)], [arXiv]1307.5543. 10.1016/j.physletb.2014.05.052

[8] G. Aad et al. (ATLAS), Observation of Long-Range Elliptic Azimuthal Anisotropies in $\sqrt{s}$ =13 and 2.76 TeV pp Collisions with the ATLAS Detector, Phys. Rev. Lett. **116**, 172301 (2016), [arXiv]1509.04776. 10.1103/PhysRevLett.116.172301

[9] S. Acharya et al. (ALICE), Investigations of Anisotropic Flow Using Multiparticle Azimuthal Correlations in pp, p-Pb, Xe-Xe, and Pb-Pb Collisions at the LHC, Phys. Rev. Lett. **123**, 142301 (2019), [arXiv]1903.01790. 10.1103/PhysRevLett.123.142301

[10] B.B. Abelev et al. (ALICE), Multiplicity Dependence of Pion, Kaon, Proton and Lambda Production in p-Pb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys. Lett. B **728**, 25 (2014), [arXiv]1307.6796. 10.1016/j.physletb.2013.11.020

[11] S. Acharya et al. (ALICE), Multiplicity dependence of π, K, and p production in pp collisions at $\sqrt{s}$ = 13 TeV, Eur. Phys. J. C **80**, 693 (2020), [arXiv]2003.02394. 10.1140/epjc/s10052-020-8125-1

[12] J. Adam et al. (ALICE), Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions, Nature Phys. **13**, 535 (2017), [arXiv]1606.07424. 10.1038/nphys4111

[13] S. Acharya et al. (ALICE), Investigating strangeness enhancement with multiplicity in pp collisions using angular correlations (2024), [arXiv]2405.14511

[14] J. Adam et al. (ALICE), Anisotropic flow of charged particles in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV, Phys. Rev. Lett. **116**, 132302 (2016), [arXiv]1602.01119. 10.1103/PhysRevLett.116.132302

[15] V. Khachatryan et al. (CMS), Evidence for collectivity in pp collisions at the LHC, Phys. Lett. B **765**, 193 (2017), [arXiv]1606.06198. 10.1016/j.physletb.2016.12.009

[16] S. Acharya et al. (ALICE), Multiplicity and event-scale dependent flow and jet fragmentation in pp collisions at $\sqrt{s}$ = 13 TeV and in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV, JHEP **03**, 092 (2024), [arXiv]2308.16591. 10.1007/JHEP03(2024)092

[17] R.N. Patra, Collective phenomena study in small systems using the bulk of particle production in high-multiplicity pp collisions at $\sqrt{s}$ =13 TeV with ALICE, in *Proceedings of The European Physical Society Conference on High Energy Physics — PoS(EPS-HEP2023)* (2024), Vol. 449, p. 214, [arXiv]2310.20613

[18] S. Acharya et al. (ALICE), Pseudorapidity distributions of charged particles as a function of mid- and forward rapidity multiplicities in pp collisions at $\sqrt{s}$ = 5.02, 7 and 13 TeV, Eur. Phys. J. C **81**, 630 (2021), [arXiv]2009.09434. 10.1140/epjc/s10052-021-09349-5

[19] S. Acharya et al. (ALICE), Production of light-flavor hadrons in pp collisions at $\sqrt{s}$ = 7 and $\sqrt{s}$ = 13 TeV, Eur. Phys. J. C **81**, 256 (2021), [arXiv]2005.11120. 10.1140/epjc/s10052-020-08690-5

[20] S. Acharya et al. (ALICE), Multiplicity dependence of light-flavor hadron production in pp collisions at $\sqrt{s}$ = 7 TeV, Phys. Rev. C **99**, 024906 (2019), [arXiv]1807.11321. 10.1103/PhysRevC.99.024906

[21] S. Chatrchyan et al. (CMS), Study of the Inclusive Production of Charged Pions, Kaons, and Protons in *pp* Collisions at $\sqrt{s}$ = 0.9, 2.76, and 7 TeV, Eur. Phys. J. C **72**, 2164 (2012), [arXiv]1207.4724. 10.1140/epjc/s10052-012-2164-1

[22] J. Steinheimer, J. Aichelin, M. Bleicher, Nonthermal p/π Ratio at LHC as a Consequence of Hadronic Final State Interactions, Phys. Rev. Lett. **110**, 042501 (2013), [arXiv]1203.5302. 10.1103/PhysRevLett.110.042501

[23] S. Acharya et al. (ALICE), Anisotropic flow of identified particles in Pb-Pb collisions at $\sqrt{s}_{\rm NN}$ = 5.02 TeV, JHEP **09**, 006 (2018), [arXiv]1805.04390. 10.1007/JHEP09(2018)006

[24] W. Zhao, C.M. Ko, Y.X. Liu, G.Y. Qin, H. Song, Probing the Partonic Degrees of Freedom in High-Multiplicity $p - Pb$ collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys. Rev. Lett. **125**, 072301 (2020), [arXiv]1911.00826. 10.1103/PhysRevLett.125.072301

[25] Y. Wang, W. Zhao, H. Song, Exploring the partonic collectivity in small systems at the LHC (2023), [arXiv]2401.00913