Snowmass2021 - Letter of Interest

High Density QCD in Small Collision Systems

Coordinators of the LoI:

Wei Li, Rice University, `wl33@rice.edu`

Jacquelyn Noronha-Hostler, University of Illinois at Urbana-Champaign, `jnorhos@illinois.edu`

Dennis V. Perepelitsa, University of Colorado Boulder, `dvp@colorado.edu`

Additional Signatures:

Steffen Bass, Christian Bierlich, Grigorios Chachamis, Yang-Ting Chien, Rainer J. Fries, Charles Gale, Maria V. Garzelli, Frank Geurts, Giuliano Giacalone, Jan Fiete Grosse-Oetringhaus, Ulrich Heinz, Tetsufumi Hirano, Jin Huang, Peter Jacobs, Jiangyong Jia, Roland Katz, Isobel Kolbe, Constantin Loizides, Matthew Luzum, Christina Markert, Aleksas Mazeliauskas, Niseem Magdy Abdelrahman, Mauricio Martinez Guerrero, Guilherme Milhano, Christine Nattrass, Jorge Noronha, Christopher Plumberg, Scott Pratt, Rosi Reed, Radosław Ryblewski, Nihar Ranjan Sahoo, Sevil Salur, Bjoern Schenke, Chun Shen, Matthew Sievert, Anne Sickles, Michael Strickland, Deepa Thomas, Anthony Timmins, Prithwish Tribedy, Julia Velkovska

Abstract: The observation of long-range collective phenomena in small-system collisions, such as *pp* and *p*+A collisions at RHIC and the LHC, with high-multiplicity final states has attracted wide interest in the community. A leading interpretation is that a fluid-like quark-gluon state is formed in these collisions, as it is large nuclear collision systems. However, for the smallest systems, some conceptual challenges remain and thus alternative sources of collective behavior from initial-state gluon saturation effects, motivated by QCD in the high gluon density limit, have been proposed. The analogy to large systems is also challenged by the fact that, while several signatures of quark gluon plasma formation such as collective flow and strangeness enhancement are evident, there has been no definitive measurement of the expected accompanying energy loss. Significant experimental and theoretical efforts have been devoted to the study of high-density QCD in small system collisions, with the goal of understanding the time-scale for the emergence of collectivity and the mechanism for early-time hydrodynamization in large collision systems.

The role of initial- vs. final-state collectivity A reasonable description of the experimental data that exhibit long-range collective phenomena can be achieved for p+Pb collisions [1–3] within a final-state interaction picture in the framework of relativistic hydrodynamics. A small system scan of deformed nuclei recently carried out at RHIC including p+Au, d+Au and ^{3}He+Au collisions, has highlighted the key role of the initial spatial geometry and final-state partonic rescatterings in generating the observed azimuthal anisotropy [4, 5]. The flow magnitude in ultra-central A+A collisions appears to be sensitive even to small spatial deformations of the nuclei [6–8].

However, questions remain about the influence of non-linear effects [9] and sub-nucleonic structure [10–16]. Theoretical approaches still struggle to obtain the correct sign of $c_2\{4\}$ [17] in pp collisions and obtain large Knudsen numbers, which may suggest that a hydrodynamic description of those systems is not complete [18]. These tensions call for deeper studies of how a far-from-equilibrium fluid at these extreme scales may quickly approach hydrodynamic behavior (see recent reviews [19, 20]), including the influence of the initialization of the full energy momentum tensor $T^{\mu\nu}$, insight into hydrodynamic attractors [21–24], effective transport coefficients [22], and Bayesian analyses of collective signatures in small systems. Aspects of the structure of the proton, such as fluctuations in its size [25, 26] and shape [27, 28], may be constrained with further studies. For low multiplicity events, momentum anisotropy arising from gluon saturation in the initial state may also play a role [29], necessitating new efforts and observable [30, 31], to better understand initial and final-state contributions.

A new comprehensive program to scan colliding ion species (e.g., C+C, O+O, Ar+Ar etc.) at RHIC and the LHC by systematically varying the collision system size and geometry at different energies will provide a unique lever arm to disentangle contributions from various mechanisms [9, 32–34]. Studies of polarized beams of small, deformed ions [35] or ultra-central collisions of small deformed ions [15] can further help disentangle hydrodynamic and initial state pictures. Finally, asymmetric collision systems such as Be+Pb(Au), C+Pb(Au) or O+Pb(Au) also provide a unique opportunity to study alpha clustering phenomena in the nuclear structure [36, 37].

High-density QCD in proton-proton collisions Events with high-multiplicity final states in proton-proton collisions are also of intrinsic interest to the QCD community. In this framework, they are connected to the multi-parton interaction (MPI) process. Recent efforts in QCD phenomenological modeling [38] have started to introduce re-interactions of the Lund strings in the MPI process, in an attempt to describe the observed collectivity in pp collisions and make a universal connection to large systems. In this picture, detailed studies of the long-range azimuthal anisotropy in pp collisions at future high-luminosity RHIC and the LHC programs can provide unique insights to quantum fluctuations of proton substructure at very short time scales [27, 28].

Heavy flavor collectivity in small systems Heavy-flavor quarks (charm and bottom) are mainly produced via hard scatterings in the early stages of high energy collisions [39]. Therefore, when compared to the behavior of light-flavor quarks, the study of heavy-flavor quark collectivity provides an additional lever arm to differentiate initial and final-state effects in the collision dynamics. In small systems, heavy flavor hadrons may be more sensitive to possible initial-state gluon saturation effects [40, 41]. Significant elliptic flow (v_2) signals for prompt D^0 and prompt J/ψ mesons in p+Pb collisions and muons from charm hadron decays in pp collisions have been observed [42, 43]. The large v_2 for the J/ψ meson particularly may pose a challenge to the picture of final-state interactions in a QGP-like medium [42, 44], whereas initial state calculations can obtain a large v_2 [40]. The data also indicate that bottom quarks do not exhibit significant collective motion in pp

collisions [43], highlighting the importance of the heavy flavor probes for understanding its origin.

The similarity of the large v_2 for charm in small systems compared to that in large systems, but with a nuclear modification factor $R_{pPb} \sim 1$ for jets and D mesons [45, 46] poses a challenge to theoretical models based on relativistic hydrodynamics. While the magnitude of the v_2 may arise from an interplay between the smaller path lengths and larger eccentricities in these systems [47], additional work employing full event-by-event relativistic viscous hydrodynamics that matches the soft sector is needed to understand the data in pp and p+Pb collisions. Future high-luminosity runs at the LHC, as well as new detector capabilities at RHIC and the LHC, will improve the precision of heavy flavor measurements and open the access to a variety of heavy flavor states, which will provide stringent constraints to dynamics of heavy flavor quarks in small-system collisions.

Medium effects on hard probes in small systems A central complication in the final-state interaction picture is the current lack of a definitive observation of high-p_T parton modification in p+Pb collisions. Experimental measurements of nuclear modification factors are complicated by the presence of multiplicity selection-induced biases [48] or by unrelated physics effects [49] in the large-x region, making this an infeasible avenue in p+Pb collisions. (By contrast, peripheral Pb+Pb events suffer from the opposite bias.) Thus the best bounds on the magnitudes of effects in p+Pb such as energy loss currently come from semi-inclusive measurements, which do not require such selection [50]. However, indirect evidence for the final-state rescattering of high-p_T partons exists via measurements of a non-zero v_2 extending out to $p_\mathrm{T} \approx 50$ GeV [51] and for heavy flavor quarks as described above. Since the partons are propagating in the same physical system being described in a hydrodynamic framework, effects in the hard and soft sectors must be understood together, and the community should strive for a universal description of the produced QCD system.

Data at RHIC and the LHC from small symmetric collisions such as O+O or Ar+Ar can help to resolve this question. Minimum bias collisions are at intermediate multiplicities between central p+A and peripheral A+A, and likewise no multiplicity-based selections are necessary. Rigorous studies have demonstrated that the theoretical baseline for nuclear PDF effects, and the experimental precision, should be sufficient to observe energy loss signatures in these systems [52, 53]. Additional theoretical progress can be made by fully coupling jets to hydrodynamics as has been done in large systems [54], which would help to link the body of data in the hard and soft sectors.

Strangeness enhancement Recent observations of strangeness enhancement in small systems at the LHC [55] confirm that this phenomenon, historically understood to be a signature of quark-gluon plasma formation, is universal across hadronic collision systems at collider energies. Several MC-based [56] and core-corona [57] approaches are able to reproduce the data leading to the idea that small systems may couple a hydrodynamics core to partons in a vacuum or hadronic corona. Further studies that explore flow harmonics, $\langle p_T \rangle$, two freeze-out temperatures [58], or gluon splittings into $s\bar{s}$ pairs [59] are warranted. Theory would be significantly aided with measurements of net-Kaon and/or net-Λ fluctuations across system size.

Other opportunities Additional small systems running at RHIC and the LHC offers several opportunities which are described in other Letters of Interest. These include the new opportunities for extracting parton density modifications in nuclei (nPDFs), nuclear structure, electromagnetic signatures, ultra-peripheral collision (UPC) physics programs, and Beyond the Standard Model (BSM) searches which take advantages of the experimental conditions of heavy ion collisions. Thus the program described here has a valuable synergistic overlap with other physics programs.

References

[1] P. Bozek. “Collective flow in p-Pb and d-Pd collisions at TeV energies”. In: *Phys. Rev.* C85 (2012), p. 014911. DOI: 10.1103/PhysRevC.85.014911. arXiv: 1112.0915 [hep-ph].

[2] I. Kozlov, M. Luzum, G. Denicol, S. Jeon, and C. Gale. “Transverse momentum structure of pair correlations as a signature of collective behavior in small collision systems”. In: (2014). arXiv: 1405.3976 [nucl-th].

[3] R. D. Weller and P. Romatschke. “One fluid to rule them all: viscous hydrodynamic description of event-by-event central p+p, p+Pb and Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV”. In: *Phys. Lett.* B774 (2017), pp. 351–356. DOI: 10.1016/j.physletb.2017.09.077. arXiv: 1701.07145 [nucl-th].

[4] A. Adare et al. “Quadrupole Anisotropy in Dihadron Azimuthal Correlations in Central d+Au Collisions at $\sqrt{s_{_{NN}}}$=200 GeV”. In: *Phys. Rev. Lett.* 111.21 (2013), p. 212301. DOI: 10.1103/PhysRevLett.111.212301. arXiv: 1303.1794 [nucl-ex].

[5] C. Aidala et al. “Creation of quark–gluon plasma droplets with three distinct geometries”. In: *Nature Phys.* 15.3 (2019), pp. 214–220. DOI: 10.1038/s41567-018-0360-0. arXiv: 1805.02973 [nucl-ex].

[6] L. Adamczyk et al. “Azimuthal anisotropy in U+U and Au+Au collisions at RHIC”. In: *Phys. Rev. Lett.* 115.22 (2015), p. 222301. DOI: 10.1103/PhysRevLett.115.222301. arXiv: 1505.07812 [nucl-ex].

[7] G. Giacalone, J. Noronha-Hostler, M. Luzum, and J.-Y. Ollitrault. “Hydrodynamic predictions for 5.44 TeV Xe+Xe collisions”. In: *Phys. Rev.* C97.3 (2018), p. 034904. DOI: 10.1103/PhysRevC.97.034904. arXiv: 1711.08499 [nucl-th].

[8] S. Acharya et al. “Anisotropic flow in Xe-Xe collisions at $\sqrt{s_{\mathrm{NN}}} = \mathbf{5.44}$ TeV”. In: *Phys. Lett. B* 784 (2018), pp. 82–95. DOI: 10.1016/j.physletb.2018.06.059. arXiv: 1805.01832 [nucl-ex].

[9] M. D. Sievert and J. Noronha-Hostler. “CERN Large Hadron Collider system size scan predictions for PbPb, XeXe, ArAr, and OO with relativistic hydrodynamics”. In: *Phys. Rev.* C100.2 (2019), p. 024904. DOI: 10.1103/PhysRevC.100.024904. arXiv: 1901.01319 [nucl-th].

[10] B. Schenke and R. Venugopalan. “Eccentric protons? Sensitivity of flow to system size and shape in p+p, p+Pb and Pb+Pb collisions”. In: *Phys. Rev. Lett.* 113 (2014), p. 102301. DOI: 10.1103/PhysRevLett.113.102301. arXiv: 1405.3605 [nucl-th].

[11] J. Noronha-Hostler, J. Noronha, and M. Gyulassy. “Sensitivity of flow harmonics to subnucleon scale fluctuations in heavy ion collisions”. In: *Phys. Rev.* C93.2 (2016), p. 024909. DOI: 10.1103/PhysRevC.93.024909. arXiv: 1508.02455 [nucl-th].

[12] K. Welsh, J. Singer, and U. W. Heinz. “Initial state fluctuations in collisions between light and heavy ions”. In: *Phys. Rev. C* 94.2 (2016), p. 024919. DOI: 10.1103/PhysRevC.94.024919. arXiv: 1605.09418 [nucl-th].

[13] G. Giacalone, J. Noronha-Hostler, and J.-Y. Ollitrault. "Relative flow fluctuations as a probe of initial state fluctuations". In: *Phys. Rev.* C95.5 (2017), p. 054910. doi: `10.1103/PhysRevC.95.054910`. arXiv: `1702.01730 [nucl-th]`.

[14] J. S. Moreland, J. E. Bernhard, and S. A. Bass. "Bayesian calibration of a hybrid nuclear collision model using p-Pb and Pb-Pb data at energies available at the CERN Large Hadron Collider". In: *Phys. Rev.* C101.2 (2020), p. 024911. doi: `10.1103/PhysRevC.101.024911`. arXiv: `1808.02106 [nucl-th]`.

[15] J. Noronha-Hostler, N. Paladino, S. Rao, M. D. Sievert, and D. E. Wertepny. "Ultracentral Collisions of Small and Deformed Systems at RHIC: UU, dAu, ${}^9BeAu$, ${}^9Be^9Be$, ${}^3He^3He$, and ${}^3HeAu$ Collisions". In: (2019). arXiv: `1905.13323 [hep-ph]`.

[16] B. Schenke, C. Shen, and P. Tribedy. "Running the gamut of high energy nuclear collisions". In: (2020). arXiv: `2005.14682 [nucl-th]`.

[17] W. Zhao, Y. Zhou, H. Xu, W. Deng, and H. Song. "Hydrodynamic collectivity in proton–proton collisions at 13 TeV". In: *Phys. Lett.* B780 (2018), pp. 495–500. doi: `10.1016/j.physletb.2018.03.022`. arXiv: `1801.00271 [nucl-th]`.

[18] H. Niemi and G. Denicol. "How large is the Knudsen number reached in fluid dynamical simulations of ultrarelativistic heavy ion collisions?" In: (Apr. 2014). arXiv: `1404.7327 [nucl-th]`.

[19] P. Romatschke and U. Romatschke. *Relativistic Fluid Dynamics In and Out of Equilibrium*. Cambridge Monographs on Mathematical Physics. Cambridge University Press, May 2019. isbn: 978-1-108-48368-1, 978-1-108-75002-8. doi: `10.1017/9781108651998`. arXiv: `1712.05815 [nucl-th]`.

[20] J. Berges, M. P. Heller, A. Mazeliauskas, and R. Venugopalan. "Thermalization in QCD: theoretical approaches, phenomenological applications, and interdisciplinary connections". In: (2020). arXiv: `2005.12299 [hep-th]`.

[21] M. P. Heller and M. Spalinski. "Hydrodynamics Beyond the Gradient Expansion: Resurgence and Resummation". In: *Phys. Rev. Lett.* 115.7 (2015), p. 072501. doi: `10.1103/PhysRevLett.115.072501`. arXiv: `1503.07514 [hep-th]`.

[22] P. Romatschke. "Relativistic Fluid Dynamics Far From Local Equilibrium". In: *Phys. Rev. Lett.* 120.1 (2018), p. 012301. doi: `10.1103/PhysRevLett.120.012301`. arXiv: `1704.08699 [hep-th]`.

[23] M. Strickland, J. Noronha, and G. Denicol. "Anisotropic nonequilibrium hydrodynamic attractor". In: *Phys. Rev.* D97.3 (2018), p. 036020. doi: `10.1103/PhysRevD.97.036020`. arXiv: `1709.06644 [nucl-th]`.

[24] W. Florkowski, M. P. Heller, and M. Spalinski. "New theories of relativistic hydrodynamics in the LHC era". In: *Rept. Prog. Phys.* 81.4 (2018), p. 046001. doi: `10.1088/1361-6633/aaa091`. arXiv: `1707.02282 [hep-ph]`.

[25] D. McGlinchey, J. L. Nagle, and D. V. Perepelitsa. "Consequences of high-x proton size fluctuations in small collision systems at $\sqrt{s_{NN}} = 200\text{GeV}$". In: *Phys. Rev.* C94 (2016), p. 024915. doi: `10.1103/PhysRevC.94.024915`. arXiv: `1603.06607 [nucl-th]`.

[26] D. Kharzeev, Z. Tu, A. Zhang, and W. Li. “Effect of the fluctuating proton size on the study of the chiral magnetic effect in proton-nucleus collisions”. In: *Phys. Rev.* C97 (2018), p. 024905. DOI: 10.1103/PhysRevC.97.024905. arXiv: 1712.02486 [nucl-th].

[27] H. Mäntysaari and B. Schenke. “Evidence of strong proton shape fluctuations from incoherent diffraction”. In: *Phys. Rev. Lett.* 117.5 (2016), p. 052301. DOI: 10.1103/PhysRevLett.117.052301. arXiv: 1603.04349 [hep-ph].

[28] J. L. Albacete, H. Petersen, and A. Soto-Ontoso. “Symmetric cumulants as a probe of the proton substructure at LHC energies”. In: *Phys. Lett.* B778 (2018), pp. 128–136. DOI: 10.1016/j.physletb.2018.01.011. arXiv: 1707.05592 [hep-ph].

[29] M. Greif, C. Greiner, B. Schenke, S. Schlichting, and Z. Xu. “Importance of initial and final state effects for azimuthal correlations in p+Pb collisions”. In: *Phys. Rev. D* 96.9 (2017), p. 091504. DOI: 10.1103/PhysRevD.96.091504. arXiv: 1708.02076 [hep-ph].

[30] G. Giacalone, B. Schenke, and C. Shen. “Observable signatures of initial state momentum anisotropies in nuclear collisions”. In: (2020). arXiv: 2006.15721 [nucl-th].

[31] C. Shen, J.-F. Paquet, G. S. Denicol, S. Jeon, and C. Gale. “Collectivity and electromagnetic radiation in small systems”. In: *Phys. Rev. C* 95 (2017), p. 014906. DOI: 10.1103/PhysRevC.95.014906. arXiv: 1609.02590 [nucl-th].

[32] Z. Citron et al. “Report from Working Group 5: Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams”. In: *Report on the Physics at the HL-LHC,and Perspectives for the HE-LHC*. Ed. by A. Dainese, M. Mangano, A. B. Meyer, A. Nisati, G. Salam, and M. A. Vesterinen. Vol. 7. Dec. 2019, pp. 1159–1410. DOI: 10.23731/CYRM-2019-007.1159. arXiv: 1812.06772 [hep-ph].

[33] S. Lim, J. Carlson, C. Loizides, D. Lonardoni, J. Lynn, J. Nagle, J. Orjuela Koop, and J. Ouellette. “Exploring New Small System Geometries in Heavy Ion Collisions”. In: *Phys. Rev. C* 99 (2019), p. 044904. DOI: 10.1103/PhysRevC.99.044904. arXiv: 1812.08096 [nucl-th].

[34] S. Huang, Z. Chen, J. Jia, and W. Li. “Disentangling contributions to small-system collectivity via scans of light nucleus-nucleus collisions”. In: *Phys. Rev. C* 101.2 (2020), p. 021901. DOI: 10.1103/PhysRevC.101.021901. arXiv: 1904.10415 [nucl-ex].

[35] P. Bozek and W. Broniowski. “Elliptic Flow in Ultrarelativistic Collisions with Polarized Deuterons”. In: *Phys. Rev. Lett.* 121.20 (2018), p. 202301. DOI: 10.1103/PhysRevLett.121.202301. arXiv: 1808.09840 [nucl-th].

[36] S. Lim, Q. Hu, R. Belmont, K. Hill, J. Nagle, and D. Perepelitsa. “Examination of flow and nonflow factorization methods in small collision systems”. In: *Phys. Rev. C* 100.2 (2019), p. 024908. DOI: 10.1103/PhysRevC.100.024908. arXiv: 1902.11290 [nucl-th].

[37] M. Rybczyński and W. Broniowski. “Glauber Monte Carlo predictions for ultrarelativistic collisions with ^{16}O”. In: *Phys. Rev.* C100.6 (2019), p. 064912. DOI: 10.1103/PhysRevC.100.064912. arXiv: 1910.09489 [hep-ph].

[38] C. Bierlich, G. Gustafson, and L. Lönnblad. “A shoving model for collectivity in hadronic collisions”. In: (Dec. 2016). arXiv: 1612.05132 [hep-ph].

[39] G. D. Moore and D. Teaney. “How much do heavy quarks thermalize in a heavy ion collision?” In: *Phys. Rev. C* 71 (2005), p. 064904. DOI: 10.1103/PhysRevC.71.064904. arXiv: hep-ph/0412346.

[40] C. Zhang, C. Marquet, G.-Y. Qin, S.-Y. Wei, and B.-W. Xiao. “Elliptic Flow of Heavy Quarkonia in *pA* Collisions”. In: *Phys. Rev. Lett.* 122 (2019), p. 172302. DOI: 10.1103/PhysRevLett.122.172302. arXiv: 1901.10320 [hep-ph].

[41] C. Zhang, C. Marquet, G.-Y. Qin, Y. Shi, L. Wang, S.-Y. Wei, and B.-W. Xiao. “Collectivity of heavy mesons in proton-nucleus collisions”. In: *Phys. Rev. D* 102.3 (2020), p. 034010. DOI: 10.1103/PhysRevD.102.034010. arXiv: 2002.09878 [hep-ph].

[42] A. M. Sirunyan et al. “Elliptic flow of charm and strange hadrons in high-multiplicity pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV”. In: *Phys. Rev. Lett.* 121.8 (2018), p. 082301. DOI: 10.1103/PhysRevLett.121.082301. arXiv: 1804.09767 [hep-ex].

[43] G. Aad et al. “Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in *pp* collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”. In: *Phys. Rev. Lett.* 124.8 (2020), p. 082301. DOI: 10.1103/PhysRevLett.124.082301. arXiv: 1909.01650 [nucl-ex].

[44] X. Du and R. Rapp. “In-Medium Charmonium Production in Proton-Nucleus Collisions”. In: *JHEP* 03 (2019), p. 015. DOI: 10.1007/JHEP03(2019)015. arXiv: 1808.10014 [nucl-th].

[45] Y. Xu, S. Cao, G.-Y. Qin, W. Ke, M. Nahrgang, J. Auvinen, and S. A. Bass. “Heavy-flavor dynamics in relativistic p-Pb collisions at $\sqrt{S_{NN}} = 5.02$ TeV”. In: *Nucl. Part. Phys. Proc.* 276-278 (2016), pp. 225–228. DOI: 10.1016/j.nuclphysbps.2016.05.050. arXiv: 1510.07520 [nucl-th].

[46] A. Beraudo, A. De Pace, M. Monteno, M. Nardi, and F. Prino. “Heavy-flavour production in high-energy d-Au and p-Pb collisions”. In: *JHEP* 03 (2016), p. 123. DOI: 10.1007/JHEP03(2016)123. arXiv: 1512.05186 [hep-ph].

[47] R. Katz, C. A. G. Prado, J. Noronha-Hostler, and A. A. P. Suaide. “System size scan of D meson R_{AA} and v_n using PbPb, XeXe, ArAr, and OO collisions at LHC”. In: (2019). arXiv: 1907.03308 [nucl-th].

[48] C. Loizides and A. Morsch. “Absence of jet quenching in peripheral nucleus–nucleus collisions”. In: *Phys. Lett. B* 773 (2017), pp. 408–411. DOI: 10.1016/j.physletb.2017.09.002. arXiv: 1705.08856 [nucl-ex].

[49] M. Alvioli, L. Frankfurt, D. Perepelitsa, and M. Strikman. “Global analysis of color fluctuation effects in proton– and deuteron–nucleus collisions at RHIC and the LHC”. In: *Phys. Rev. D* 98.7 (2018), p. 071502. DOI: 10.1103/PhysRevD.98.071502. arXiv: 1709.04993 [hep-ph].

[50] S. Acharya et al. “Constraints on jet quenching in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by the event-activity dependence of semi-inclusive hadron-jet distributions”. In: *Phys. Lett. B* 783 (2018), pp. 95–113. DOI: 10.1016/j.physletb.2018.05.059. arXiv: 1712.05603 [nucl-ex].

[51] G. Aad et al. “Transverse momentum and process dependent azimuthal anisotropies in $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV p+Pb collisions with the ATLAS detector”. In: *Eur. Phys. J. C* 80.1 (2020), p. 73. DOI: `10.1140/epjc/s10052-020-7624-4`. arXiv: `1910.13978 [nucl-ex]`.

[52] A. Huss, A. Kurkela, A. Mazeliauskas, R. Paatelainen, W. van der Schee, and U. A. Wiedemann. “Predicting parton energy loss in small collision systems”. In: (2020). arXiv: `2007.13758 [hep-ph]`.

[53] A. Huss, A. Kurkela, A. Mazeliauskas, R. Paatelainen, W. van der Schee, and U. A. Wiedemann. “Discovering partonic rescattering in light nucleus collisions”. In: (2020). arXiv: `2007.13754 [hep-ph]`.

[54] Y. Tachibana, N.-B. Chang, and G.-Y. Qin. “Full jet in quark-gluon plasma with hydrodynamic medium response”. In: *Phys. Rev.* C95.4 (2017), p. 044909. DOI: `10.1103/PhysRevC.95.044909`. arXiv: `1701.07951 [nucl-th]`.

[55] J. Adam et al. “Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions”. In: *Nature Phys.* 13 (2017), pp. 535–539. DOI: `10.1038/nphys4111`. arXiv: `1606.07424 [nucl-ex]`.

[56] C. Bierlich and J. R. Christiansen. “Effects of color reconnection on hadron flavor observables”. In: *Phys. Rev.* D92.9 (2015), p. 094010. DOI: `10.1103/PhysRevD.92.094010`. arXiv: `1507.02091 [hep-ph]`.

[57] Y. Kanakubo, Y. Tachibana, and T. Hirano. “Unified description of hadron yield ratios from dynamical core-corona initialization”. In: *Phys. Rev.* C101.2 (2020), p. 024912. DOI: `10.1103/PhysRevC.101.024912`. arXiv: `1910.10556 [nucl-th]`.

[58] R. Bellwied, S. Borsanyi, Z. Fodor, S. D. Katz, and C. Ratti. “Is there a flavor hierarchy in the deconfinement transition of QCD?” In: *Phys. Rev. Lett.* 111 (2013), p. 202302. DOI: `10.1103/PhysRevLett.111.202302`. arXiv: `1305.6297 [hep-lat]`.

[59] M. Martinez, M. D. Sievert, D. E. Wertepny, and J. Noronha-Hostler. “Initial state fluctuations of QCD conserved charges in heavy-ion collisions”. In: (2019). arXiv: `1911.10272 [nucl-th]`.