An experimental overview: collective dynamics

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Abstract. One of the most studied phenomena in heavy-ion physics is the collective emission of particles. Historically, the observation of collectivity in nucleus-nucleus collisions has been viewed as proof of the creation of a strongly interacting medium, as neither independent particle emission nor hadronic interactions alone could account for measurements. Intriguingly, collective particle emission was recently also measured in small collision systems, ranging from proton-proton to even high-multiplicity e^+e^- collisions. In these proceedings, I will elaborate on the current status of the experimental findings regarding collectivity and discuss their implications for the future.

1 Introduction

Collective phenomena has been a staple of heavy-ion collision physics for decades. The successful description of azimuthal particle emission anisotropies in nucleus-nucleus interactions, quantified via fourier expansion coefficients denoted 'flow coefficients', can be achieved using relativistic hydrodynamics simulations that assume the presence of a strongly interacting fluidic matter phase, the quark-gluon plasma (QGP) [1].

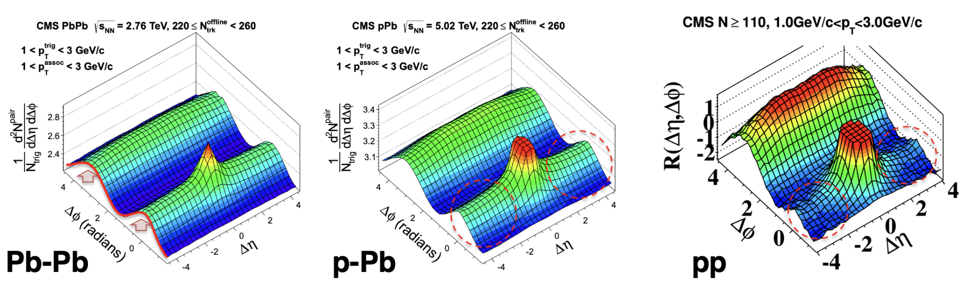

Figure 1. Corrected two-particle correlation functions in Pb-Pb (left), high multiplicity p-Pb (middle) and high-multiplicity pp (right) collisions at the LHC as measured by the CMS collaboration. Adapted from [2, 3].

A defining feature of the anisotropies generated due to hydrodynamical behaviour is that it is delocalized in rapidity, such that they can be probed using two-particle correlation (2PC)

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techniques. Recently, 2PC studies conducted in high-multiplicity proton-proton (pp) and proton-lead (p-Pb) collisions have revealed that long-range correlated particle emission appears even in those collision systems, as seen in Fig. 1. These observations challenged the once-established paradigm that small collision systems serve as a standard, QGP-free QCD baseline [2, 4, 5]. In addition, these findings strengthened the need for understanding the origins of collectivity as well as the conditions in which it first manifests.

2 In-depth study of flow correlations

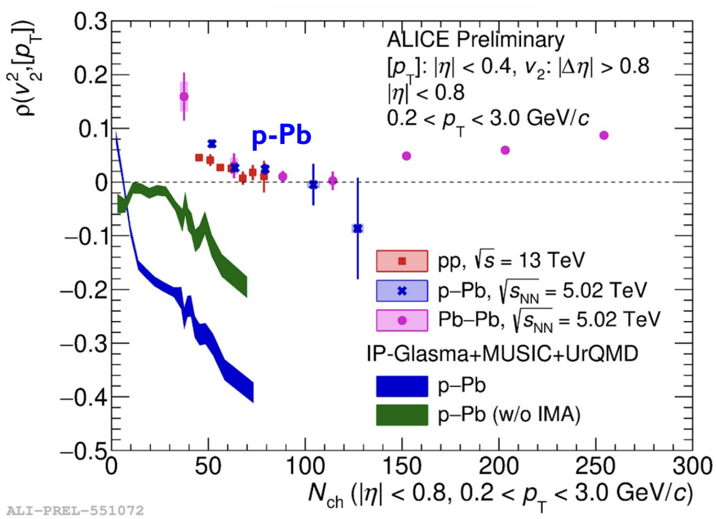

Figure 2. Correlation between elliptic flow coefficient and transverse momentum in pp, p-Pb and Pb-Pb collisions as a function of charged-particle multiplicity density. Continuous bands denote predictions obtained with IP-Glasma + MUSIC + UrQMD with and without Initial Momentum Anisotropy (IMA). Figure from [6]

While flow coefficients serve as a first-order quantification of collective particle emission, they are often not sufficient to disentangle the role of the initial condition versus the hydrodynamical response of the system. That can, however, be achieved by looking at correlations between various flow coefficients as well as with average transverse momenta. One such measurement is shown in Fig. 2, which shows the correlation between the elliptic flow coefficient v_2 and the average transverse momentum as a function of charged-particle multiplicity density in pp, p-Pb and Pb-Pb collisions as measured by the ALICE collaboration. It can be seen that data is not correctly described by state-of-the-art modeling efforts, indicating a possible breakdown of the hydrodynamical expansion picture in proton-lead collisions. This measurement and others shown at QM2023 indicate that not only does the experimental community have a handle on checking for consistent hydrodynamical behaviour, but even that this consistency is not present in small collision systems.

3 Rapidity as a tool for 3D dynamics

Collectivity whose origin is a systemic response to initial geometry is always expected to be very long range in rapidity. As a natural consequence, rapidity is a very important dimen-

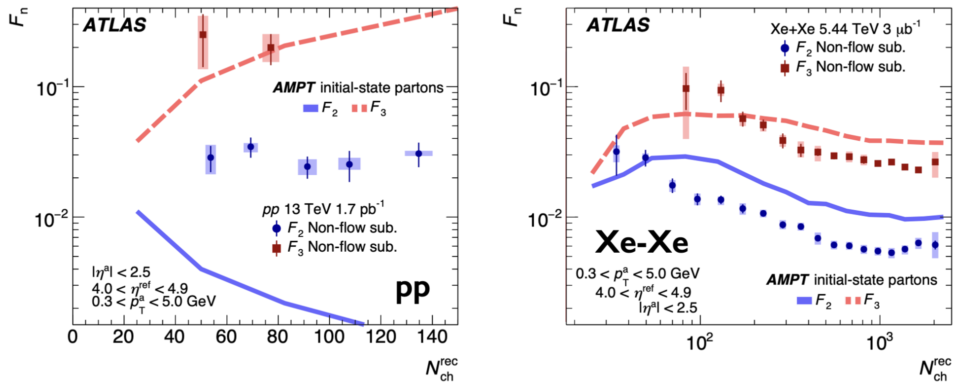

Figure 3. Rapidity decorrelation factor F_n as a function of charged-particle multiplicity density measured in pp (left) and Xe-Xe (right) collisions by the ATLAS collaboration. Continuous curves denote model predictions obtained from AMPT. Figure from [7].

sion that may reveal more about such phenomena, justifying a renewed interest in rapidity-differential measurements in small collision systems. As seen in fig. 3, ATLAS has recently studied flow coefficient decorrelations as a function of pseudorapidity in pp and Xenon-Xenon (Xe-Xe) collisions as a function of charged-particle multiplicity density. Measurements reveal that a strong, multiplicity-independent decorrelation is present in pp collisions, while the decorrelation observed in Xe-Xe is described only qualitatively by the AMPT model. It is theorised that sub-nucleonic structure and fluctuations in longitudinal energy deposition will be required in pp collision modeling to accurately describe these observations.

4 The search for extremes: e^+e^-, γA and lower energies

The observation of long-range collectivity even in pp collisions, as seen in Fig. 1, suggests a fundamental question: exactly under what conditions does collective particle emission appear? To answer that, a number of experimental efforts are currently underway. The STAR collaboration, for instance, has reported a number of interesting observations as part of their Beam Energy Scan (BES) programme. As shown in Fig. 4, the identified particle elliptic flow coefficient v_2 has been observed to switch sign at a collision energy of approximately $\sqrt{s_{\rm NN}} = 3.2$ GeV/c, possibly an indication of spectators blocking in-plane particle emission. Furthermore, at that energy, number-of-constituent-quarks (NCQ) scaling breaks down. While these are clear indications of different dynamics, precise theoretical descriptions of these lower-energy measurements are still lacking.

A number of other intriguing observations were discussed at the QM2023 conference. In particular, while it is known that 2PC analysis in minimum-bias e^+e^- collisions do not show any evidence of long-range collectivity, a specific analysis of high-multiplicity e^+e^- collisions archived from ALEPH has revealed that there may be a hint of a non-zero v_2 present. Considering that these high-multiplicity collisions are more likely to be $e^+e^- \rightarrow W^+W^-$ processes that may hadronize as if they were two colour strings, this could be an indication of the absolute smallest system in which collective behaviour appears and corroborates the picture that models such as *string shoving*, in which colour strings close in phase space interact with

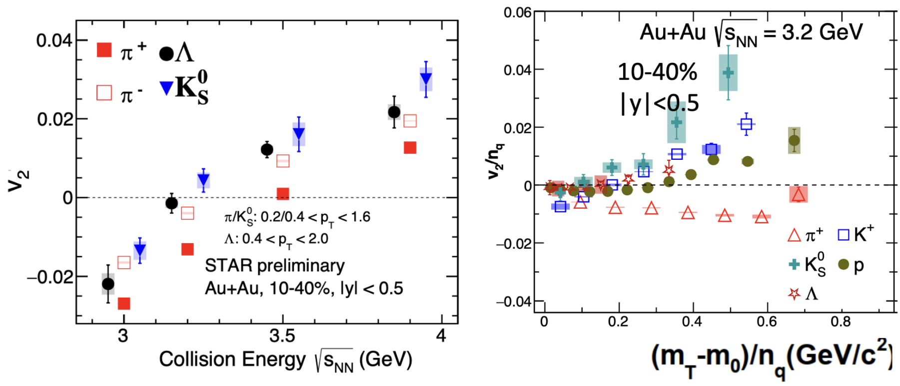

Figure 4. Left: elliptic flow coefficient v_2 as a function of collision energy for charged pions, neutral kaons and Λ baryons. Right: v_2 normalized by the number of constituent quarks n_q as a function of transverse mass per constituent quark. Both measurements are done by the STAR collaboration in semi-central 10-40% Au-Au collisions. Figures from [8].

each other resulting in collective motion, are conceptually correct. Fundamentally, this further increases the importance of extending state-of-the-art event generators such as PYTHIA with string shoving to nucleus-nucleus collisions and presents an enormous opportunity for further advancement of heavy-ion collision phenomenology.

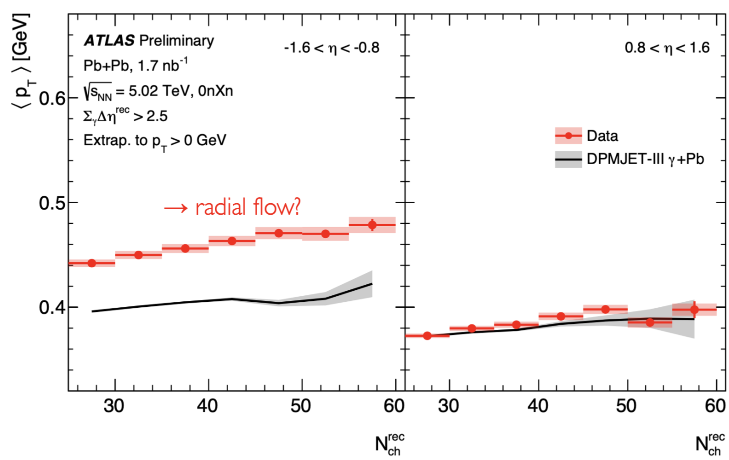

Figure 5. Average transverse momentum as a function of charged-particle multiplicity density in γ-Pb collisions in the lead-going (left) and γ-going (right) direction as measured by the ATLAS collaboration compared to expectations from the DPMJet event generator. Figure from [9].

At LHC energies, very specific event selection criteria can also result in conditions that reveal collectivity in more elementary conditions. In particular, the ATLAS collaboration has been able to isolate photonuclear γ-Pb events by selecting ultra-peripheral collisions and studying these interactions as a function of charged-particle multiplicity. Interestingly, in the lead-going direction, average transverse momenta were observed to be quite pronounced and significantly above DPMJet expectations, as seen in fig. 5, which could be an indication of the presence of radial flow. The ATLAS collaboration is currently characterising γ-Pb events more precisely, studying hallmark signatures of complex QCD dynamics such as relative strangeness production, and results are expected to be made public very soon.

5 Understanding the hard/soft interplay

Among other reasons, correlated particle emission is also thought to be a key consequence of a system that underwent a significant number of strong interactions among uncorrelated particles produced in initial hard scatterings. Crucially, this has implications for the relationship between soft and hard particle emission that can be experimentally checked. While historically the interplay between the soft and hard sectors was studied with e.g. simultaneous analysis of elliptic flow coefficients and nuclear modification factors, new ideas have appeared that consider the possibility that low/high-momentum correlations encode information regarding the origin of collectivity. For instance, the ATLAS collaboration has studied the elliptic flow coefficients of particle emission along a specific *high-multiplicity jet axis*, as opposed to with respect to the laboratory reference frame, as a function of the jet multiplicity. While most of the observed v_2 values are compatible with expectations from the PYTHIA event generator, the values of v_2 measured in extremely high-multiplicity jets are significantly higher than expected, as seen in fig. 6. While this signature is limited to the highest jet multiplicities studied by ATLAS, it is an unexpected finding that will undoubtedly require further modeling effort to be described in full.

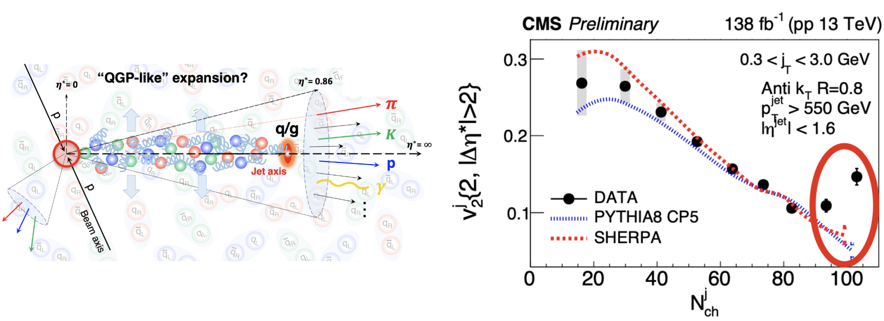

Figure 6. Left: sketch of jet reference frame as used for the elliptic flow coefficient measurement of ATLAS as a function of jet charged-particle multiplicity. Right: elliptic flow coefficient as a function of jet charged-particle multiplicity density compared to predictions from PYTHIA 8 and SHERPA. Figures from [10].

6 Summary and outlook

In conclusion, a number of challenges and new frontiers were evident at QM2023. In broad terms, these can be tentatively classified following the sections in these proceedings:

- **Flow correlations**: while generally the hydrodynamical picture provides a satisfactory description of nucleus-nucleus results, that is not the case in small collision systems. It seems clear, for instance, that a unified description of radial and elliptic flow in those conditions does not appear immediately viable. Flow correlation measurements have shown themselves to be important in disentangling different dynamical origins of flow, and are likely to continue playing a fundamental role.
- **Rapidity and 3D dynamics**: traditional heavy-ion phenomenology employs boost-invariant simulations and compares solely to midrapidity measurements, but deviations from that recipe are now progressively being explored. Also in this case, significant experimental results are forthcoming and present a challenge to theoretical efforts. It is to be expected that full three-dimensional hydrodynamical modeling will have to evolve to reproduce results, as exemplified by ATLAS results shown in these proceedings.
- **Specific regimes and processes**: with the prevalence of collective particle emission in many collision systems, attention has shifted to the minimal conditions necessary for flow-like signatures to appear. First results from lower energies, photonuclear events and specific types of e^+e^- collisions have drawn significant interest and serve as fundamental building blocks for process-based phenomenology such as string shoving to be applied more generally in high-energy particle physics, from the smallest to the largest (nucleus-nucleus) interactions.
- **Soft/hard interplay**: while traditionally the heavy ion 'standard model' consisted of a compartmentalised description of soft (hydrodynamics) and hard (jet quenching physics) sectors, exciting new efforts have revealed that a lot can be learned from studying the interplay between these two fields of study. In addition to the ATLAS result on elliptic flow with respect to high-multiplicity jet axes, other directions also include the use of polarised particle emission to study local medium vorticity, revealing properties about the emitting medium that would be otherwise not accessible.

It is therefore evident that progressively more intricate and revealing measurements of correlated particle flux across various collision systems were carried out in recent years, and as a fortunate consequence, a matching flux of new ideas and concepts has appeared in the community. In the next several years, further news can be expected from a variety of experimental efforts, including the RHIC BES, the LHC and other experiments, continuing to challenge theory and providing ever increasing insights into the behaviour of QCD matter.

References

[1] J.E. Bernhard, J.S. Moreland, S.A. Bass, Nature Phys. **15**, 1113 (2019)
[2] V. Khachatryan et al. (CMS), JHEP **2010** (2010)
[3] S. Chatrchyan et al., Physics Letters B **724**, 213–240 (2013)
[4] B. Abelev et al. (ALICE), Physics Letters B **719**, 29 (2013)
[5] G. Aad et al. (ATLAS), Physical Review Letters **110** (2013)
[6] M. Zhao, These Proceedings (2023)
[7] A. Collaboration, *Measurements of longitudinal flow decorrelations in pp and Xe+Xe collisions with the ATLAS detector* (2023), 2308.16745
[8] Z. Liu, These Proceedings (2023)
[9] S. Das, These Proceedings (2023)
[10] P. Gardner, These Proceedings (2023)