Jets and jet substructure in heavy-ion collisions

Letter of Interest for Snowmass 2021

Authors listed at end[1]

Jet measurements at RHIC and the LHC have established that jets undergo significant modification in heavy-ion collisions relative to jets in proton-proton collisions (see Refs. [1-4] for representative examples). These modifications, referred to as ***jet quenching***, offer a compelling avenue to investigate **the emergence of a strongly coupled system,** the quark-gluon plasma (QGP) [5-7], which is governed by interactions that are asymptotically weak (QCD). A variety of jet quenching observables have been studied in heavy-ion collisions, including the modifications of the inclusive jet and hadron yields, longitudinal and transverse profiles, coincidence rates, angular correlations, and jet substructure. Such measurements have been carried out using untagged jet populations; jets recoiling from jet, photon, Z, and hadron triggers; and heavy-flavor tagged jets. Studies of the jet substructure are notable, since this approach identifies quantities related to hard splittings in parton showers, with good theoretical control [8]. A comprehensive analysis of jet measurements is essential to constrain the nature of jet-medium interactions, including path-length dependence of jet quenching and color coherence effects, and thereby to elucidate emergent properties of QCD displayed by the QGP, such as the nature of the degrees of freedom of the QGP.

In this LOI, we outline several avenues of future study that we believe are key for the advancement of the study of the quark-gluon plasma. This LOI relates primarily to the Energy Frontier Heavy Ions topical group [EF07], with secondary overlap with Precision QCD [EF05] and connections to the Computational Frontier. Moreover, these developments inform the growing field of jets at the EIC, and will influence detector design at the EIC and other upcoming facilities.

Theoretical and experimental innovation

- Development of jet substructure tools designed for the heavy-ion environment, including (i) Study of new jet grooming techniques [9,10,11,13, 23], (ii) New experimental techniques and background subtraction procedures to robustly and

[1] Coordinators: Y. Chen (Yi.Chen@cern.ch), L. Cunqueiro (leticia.cunqueiro.mendez@cern.ch), J. Mulligan (james.mulligan@berkeley.edu), A. Sickles (sickles@illinois.edu)

precisely measure both groomed and ungroomed jet substructure observables at low jet momentum and/or at large jet resolution parameter [12,13]
- Monte Carlo generator development (see Ref. [14,18] for recent examples)
- Development of novel analytical frameworks to study jet observables in heavy-ion collisions (such as Refs. [15,16])
- Study the soft substructure of jets, such as Ref. [17,27], to enhance the sensitivity to medium effects and study hadronization in the QGP.
- Development of jet observables to probe the space-time picture of the quark-gluon plasma (see Refs [24, 25] for first attempts in this direction)
- Direct measurements of jet energy loss (see e.g. Ref [26])
- Accounting for the track-based nature of measurements in heavy-ion collisions in theory calculations [28-30]

Community effort to confront theory and experiment

- Global analyses that simultaneously fit multiple observables, and also improved reporting of systematic uncertainty by experiments, including correlations and potential non-Gaussian tails (see e.g. [18,16])

Profit from current and upcoming facilities

- Exploit higher statistics and enhanced detector capabilities for rare probes such as heavy flavour and EW-tagged jets at LHC Run 3 and Run 4 [31] as well as future running at RHIC with sPHENIX [32] and STAR.
- Measurements of jets in proton-nucleus and light-ion collisions at both RHIC and the LHC in order to understand the onset of jet modifications in the QGP.

Exploration of new applications of innovative tools

- Machine learning is a standard tool in HEP for classification, regression, and generation in jet physics. Its application to jet physics in heavy ion collisions has just begun (see Refs. [19,20]), and further exploration has great potential.
- Quantum computing has been recently applied in nuclear physics and HEP (such as Refs. [21,22]). The exploration of such tools in the context of jet modification in heavy ion collisions may open a phase space for new research in theoretical approaches and experimental applications.

References

1. ALICE Collaboration, “Measurement of jet quenching with semi-inclusive hadron-jet distributions in central Pb-Pb collisions at √sNN = 2.76 TeV,” *J. High Energy Phys.* 2015 no. 9, (2015) 170.
2. ATLAS Collaboration, “Measurement of jet fragmentation in Pb–Pb and pp collisions at √sNN = 5.02 TeV with the ATLAS detector,” *Phys. Rev. C* 98 (2018) 024908.
3. CMS Collaboration, “Measurement of the Splitting Function in pp and Pb–Pb Collisions at √sNN = 5.02 TeV,” *Phys. Rev. Lett.* 120 (Apr, 2018) 142302.
4. STAR Collaboration, J. Adam *et al.*, “Measurement of inclusive charged-particle jet production in Au+Au collisions at √*sNN*=200 GeV,” arXiv:2006.00582 [nucl-ex].
5. G.-Y. Qin and X.-N. Wang, “Jet quenching in high-energy heavy-ion collisions,” *Int. J. Mod. Phys. E* 24 no. 11, (2015) 1530014.
6. J.-P. Blaizot and Y. Mehtar-Tani, “Jet structure in heavy ion collisions,” *Int. J. Mod. Phys. E* 24 no. 11, (2015) 1530012.
7. A. Majumder and M. van Leeuwen, “The theory and phenomenology of perturbative QCD based jet quenching,” *Prog. Part. Nucl. Phys.* 66 no. 1, (2011) 41 – 92.
8. A. J. Larkoski, I. Moult, and B. Nachman, *Jet Substructure at the Large Hadron Collider: A Review of Recent Advances in Theory and Machine Learning*, Physics Reports 841 (2020) 1.
9. F. A. Dreyer, L. Necib, G. Soyez, and J. Thaler, “Recursive Soft Drop”, JHEP 06, 093 (2018)
10. Y. Mehtar-Tani, A. Soto-Ontoso, K. Tywoniuk, Dynamical grooming of QCD jets, Phys. Rev. D 101 (2020) 034004.
11. Andrews et al, “Novel tools and observables for jet physics in heavy-ion collisions”, J.Phys. G 47 (2020) 065102.
12. P. Berta, L. Masetti, D. Miller, and M. Spousta, “Pileup and Underlying Event Mitigation with Iterative Constituent Subtraction,” *JHEP* 08 (2019) 175.
13. J. Mulligan and M. Ploskon, “Identifying groomed jet splittings in heavy-ion collisions,” arXiv:2006.01812 [hep-ph].
14. P.Caucal, E. Iancu, A.H. Mueller, G.Soyez, “A new pQCD based Monte Carlo event generator for jets in the quark-gluon plasma”
15. V. Vaidya and X. Yao, “Transverse Momentum Broadening of a Jet in Quark-Gluon Plasma: An Open Quantum System EFT,” arXiv:2004.11403 [hep-ph].
16. J.-W. Qiu, F. Ringer, N. Sato, and P. Zurita, “Factorization of jet cross sections in heavy-ion collisions,” *Phys. Rev. Lett.* 122 no. 25, (2019) 252301.
17. P. Cal, K. Lee, F. Ringer, W. Waalewijn, “Jet energy drop”, arXiv 2007.12187.
18. JETSCAPE Collaboration, J. Putschke *et al.*, “The JETSCAPE framework,” arXiv:1903.07706 [nucl-th].
19. R. Haake and C. Loizides, “Machine learning based jet momentum reconstruction in heavy-ion collisions”, Phys.Rev.C (2019) 064904.
20. P. Komiske, E. Metodiev and J. Thaler, “An operational definition of quark and gluon jets”, JHEP 11 (2018) 059.
21. C. W. Bauer, W. A. De Jong, B. Nachman, and D. Provasoli, “A quantum algorithm for high energy physics simulations,” arXiv:1904.03196 [hep-ph]
22. A. Wei, P. Naik, A. Harrow and J. Thaler, “Quantum Algorithms for Jet Clustering”, arXiv:1908.0894v2.
23. The BOOST community, Jets and Jet Substructure at Future Colliders Letter of Interest for Snowmass 2021.
24. L. Apolinário, G. Milhano, G. Salam and C. A. Salgado, "Probing the time structure of the quark-gluon plasma with top quarks", Phys.Rev.Lett. 120 (2018) 23, 232301
25. C. Andres, N. Armesto, M. Luzum, C. A. Salgado, and P. Zurita, Eur. Phys. J. C76, 475 (2016)
26. D. Neill, F. Ringer, N. Sato, “Calculating the energy loss of leading jets”, arXiv:2008.09532.
27. P. Cal, D. Neill, F. Ringer, W. Waalewijn, “Calculating the angle between jet axes”, JHEP 04 (2020) 211, arXiv:1911:06840.
28. H.-M. Chang, M. Procura, J. Thaler, and W. J. Waalewijn, “Calculating Track-Based Observables for the LHC”, Phys. Rev. Lett. 111 (2013) 102002.
29. H. Chen, I. Moult, X. Zhang, HX. Zhu, “Rethinking Jets with Energy Correlators: Tracks, Resummation and Analytic Continuation“, arXiv:2004.11381
30. Y.-T. Chien, R. Rahn, S. Schrijnder van Velzen, D. Y. Shao, W. J. Waalewijn, and B. Wu, “Azimuthal angle for boson-jet production in the back-to-back limit”, arXiv:2005.12279.
31. Z. Citron et al. “Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams”, arXiv:1812.06772
32. A. Adare et al. “An Upgrade Proposal from the PHENIX Collaboration”, arXiv:1501.06197

Signatures

L. Apolinário, Laboratory of Instrumentation and Experimental Particle Physics (LIP)
S.A. Bass, Duke University
J. Bielcikova, Nuclear Physics Institute of the Czech Academy of Sciences
H.Bossi, Yale University
Y. Chen, Massachusetts Institute of Technology
T.M. Cormier, Oak Ridge National Laboratory
R. Cruz-Torres, Lawrence Berkeley National Laboratory
L. Cunqueiro, Oak Ridge National Laboratory
D. Derendarz, Institute of Nuclear Physics PAN, Poland
R. Ehlers, Oak Ridge National Laboratory
O. Evdokimov, University of Illinois at Chicago
L. Havener, Yale University
P. M. Jacobs, Lawrence Berkeley National Laboratory
J. Jia, Stony Brook University
C. Klein-Bösing, University of Münster
F. Krizek, Nuclear Physics Institute of the Czech Academy of Sciences
Y. Lai, Lawrence Berkeley National Laboratory
K. Lee, Lawrence Berkeley National Laboratory
M. van Leeuwen, National Institute for Subatomic Physics (Nikhef), Amsterdam, Netherlands
E. Lesser, University of California, Berkeley
C. Loizides, Oak Ridge National Laboratory
J. Mulligan, Lawrence Berkeley National Laboratory
C. Nattrass, University of Tennessee, Knoxville
M. Nguyen, Laboratoire Leprince-Ringuet, École Polytechnique, CNRS
Y. Onel, University of Iowa
D.V. Perepelitsa, University of Colorado Boulder
M.A. Ploskon, Lawrence Berkeley National Laboratory
S. Popescu, Kansas University
J. Putschke, Wayne State University
F. Ringer, Lawrence Berkeley National Laboratory
A. M. Sickles, University of Illinois
M. Spousta, Charles University, Prague
W. Waalewijn, University of Amsterdam