Opportunities and Future directions for Heavy-Ions:

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The high-luminosity upgrade of the LHC (HL-LHC) provides an excellent platform for advancing QCD studies in heavy-ion collisions. Rare probes such as boosted top quarks and W bosons [1], alongside novel jet observables [2,3], offer unprecedented opportunities to investigate the formation and evolution of the Quark-Gluon Plasma (QGP).

Emerging frameworks incorporating temporal variables into QCD emission [4] descriptions enable direct correlations between jet evolution and the QGP's time-dependent properties. By embedding space-time dimensions into jet re-clustering algorithms and substructure analyses, these approaches allow the extraction of the QGP's evolving characteristics. Semi-leptonic decays of boosted top quarks and hadronic decays of W bosons provide complementary delayed probes relative to the QGP's lifetime, enhancing sensitivity to its later stages. These tools pave the way for deeper understanding into jet-medium interactions and the properties of this strongly coupled fluid.

As the LHC heavy-ion program approaches its target Pb-Pb integrated luminosity of 13 nb^{-1} by 2031, the potential to extend this to 26 nb^{-1} by the end of Run 5 presents a strategic opportunity. Including lighter ions in the remaining heavy-ion running time might present significant advantages with respect to additional Pb-Pb statistics. Lighter ions offer a controlled environment for studying QGP properties at varying nuclear densities, reducing geometric and background biases inherent in central Pb-Pb collisions. This provides a more precise baseline for disentangling the role of initial spatial anisotropies in QGP formation.

Presently, the observation of collectivity-like behaviour in proton-lead and high-multiplicity proton-proton collisions—manifested through azimuthal anisotropy without the energy loss effects typically associated with a QGP—poses significant challenges. Connecting jet evolution with QGP properties through the space-time structure of parton cascades, supported by tomographic analyses via boosted objects, will clarify whether these collective phenomena arise from genuine QGP signatures or alternative mechanisms. Also in this respect, the variation of system size and density afforded by a lighter ion programme could serve as ideal laboratory.

The FCC-ee collider offers a complementary platform for advancing QCD studies. Recent findings suggest that exploring the space-time structure of QCD processes could provide new insights into hadronization mechanisms [5,6], offering an access window to QCD confinement. Furthermore, studying QCD radiation in a clean electron-positron environment, free from medium effects, would establish critical benchmarks for interpreting results from heavy-ion collisions.

[1] L. Apolinário, J. G. Milhano, C. A. Salgado, G. Salam, Phys.Rev.Lett. 120 (2018) 23, 232301
[2] L. Apolinário, A. Cordeiro, K. Zapp, Eur.Phys.J.C 81 (2021) 6, 561
[3] L. Apolinário, P. Guerrero-Rodríguez, K. Zapp, Eur.Phys.J.C 84 (2024) 7, 672
[4] C. Andrés, L. Apolinário, N. Armesto, A. Cordeiro, F. Dominguez, J. G. Milhano, arXiv: 2409.13536
[5] Y-T. Chien, A. Deshpande M. M. Mondal, G. Sterman, Phys.Rev.D 105 (2022) 5, L051502
[6] L. Apolinário, R. Elayavalli, N. Olavo, Phys. Rev. D (2025) XXX