EPJ Web of Conferences **364**, 10009 (2026) https://doi.org/10.1051/epjconf/202636410009
Quark Matter 2025

Comprehensive study of jet substructure using a multi-stage jet evolution framework

Chathuranga Sirimanna[1,*] and *Yasuki* Tachibana[2] for the JETSCAPE Collaboration

[1]Department of Physics, Duke University, Durham, NC 27708, USA
[2]Akita International University, Yuwa, Akita-city 010-1292, Japan

Abstract. We present a comprehensive study of jet substructure modifications in heavy-ion collisions using the JETSCAPE framework. Our approach utilizes the multi-stage jet energy loss description, which includes suppression of jet-medium interaction at high virtuality, reflecting the virtuality dependence of the process. The parameters used in our simulations are tuned to reproduce hadron R_{AA} and inclusive jet R_{AA}, particularly in the high-p_T region at 5.02 TeV. Using these simulations, we analyze key observables such as Soft Drop observables, jet mass, and fragmentation functions. Our results show good agreement with current experimental data, highlighting the model's reliability. This study provides a solid baseline for further detailed investigations of jet structures in heavy-ion collisions, offering insights into jet-medium interactions and their effects on jet evolution.

1 Introduction

Jets, collimated sprays of hadrons originating from the fragmentation of hard-scattered quarks and gluons, play a central role in the study of ultra-relativistic heavy-ion collisions. In such collisions at RHIC and the LHC, the formation of a hot, dense, and strongly interacting quark–gluon plasma (QGP) provides a unique environment to explore the properties of QCD matter under extreme conditions. Because jets are produced at early times and traverse the medium, they act as penetrating probes that carry information about both the perturbative stages of parton shower evolution and the non-perturbative dynamics of hadronization and medium response. Their internal structure encodes a wealth of information, but in practice this is often masked by backgrounds such as soft, wide-angle radiation, the underlying event, and pileup contributions in high-multiplicity environments. Disentangling the hard jet signal from these sources of contamination remains a key challenge.

To address this, jet grooming techniques have been developed and widely adopted in both proton–proton and heavy-ion analyses [1–3]. Among these, the Soft Drop algorithm and related recursive declustering methods have emerged as especially powerful tools. By systematically removing soft, large-angle constituents from jets, grooming suppresses contamination and reduces sensitivity to poorly controlled non-perturbative effects. This not only sharpens the connection between experimental observables and first-principles QCD calculations but also enables precision tests of parton shower dynamics and medium-induced modifications. Groomed observables such as the momentum-sharing fraction z_g, the groomed jet radius r_g,

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[*] e-mail: chathuranga.sirimanna@duke.edu

and the groomed jet mass m_g provide clean, theoretically interpretable handles for probing both vacuum jet physics and jet–medium interactions.

Photon–jet correlations provide an additional advantage in isolating partonic effects. Since the photon escapes the medium without strong interaction, its momentum serves as a calibrated measure of the initial parton kinematics. Moreover, photon-triggered jets are predominantly quark-initiated, in contrast to the gluon-enriched composition of inclusive jet samples. This distinction makes photon–jet systems particularly valuable for disentangling quark and gluon substructure and understanding how parton flavor influences jet–medium interactions.

In this work, we present a systematic analysis of both inclusive and photon-triggered jets, with a focus on their substructure modifications in heavy-ion collisions. To further separate medium and parton-type effects, we perform controlled studies using monoenergetic quark and gluon jets simulated within the JETSCAPE framework. By comparing these results with inclusive and photon-triggered samples, we aim to clarify the roles of quark–gluon composition, jet energy scale, and medium-induced dynamics in shaping groomed jet observables. This multi-faceted approach provides new insight into how different jet samples probe the QGP and strengthens the connection between experimental measurements and theoretical modeling.

2 Simulations with JETSCAPE framework

In this study, the JETSCAPE framework [4–6] is employed to generate both monoenergetic jet events, where a single parton with a fixed initial energy showers in vacuum or medium, and prompt photon events, consisting exclusively of photons produced in the initial hard scattering. The bulk medium in $\sqrt{s_{NN}} = 5.02$ TeV Pb–Pb collisions is modeled using pre-generated event-by-event 2+1D VISHNU [7] hydrodynamic profiles with TRENTo [8] initial conditions. The hard scattering is simulated with PYTHIA, and all partons undergo energy loss through medium-modified partonic showers. For p–p collisions, the MATTER [9, 10] vacuum shower with the PP19 tune [11] is used, while Pb–Pb collisions are simulated with the multistage MATTER+LBT [12, 13] framework with the AA22 tune [14]. Final-state partons are hadronized using the Lund string model in PYTHIA.

3 Results and Discussion

In this study, we analyze monoenergetic, photon-triggered, and inclusive jets in both $p-p$ and $Pb-Pb$ collision systems within the JETSCAPE framework to investigate hard jet substructure and its medium modifications. For the purposes of this proceedings contribution, we focus specifically on the ratios of the groomed jet radius (r_g) and groomed jet mass (m_g) distributions, which provide complementary information on angular and momentum-space jet dynamics. A more detailed discussion, including comparisons with experimental data and systematic studies, can be found in Refs. [5, 6, 15].

The groomed jet radius r_g, defined as the angular separation between the two branches of the first hard splitting identified by the Soft Drop procedure, offers a direct probe of the angular structure of jets. This observable is particularly sensitive to differences between quark- and gluon-initiated jets, with quark jets typically appearing narrower, as well as to medium-induced effects such as jet broadening, color decoherence, and modifications of parton branching patterns in heavy-ion collisions. Figure 1 shows the ratios of r_g distributions between $Pb-Pb$ and $p-p$ systems. In the left panel, comparing quark and gluon jets, we observe that quark jets undergo noticeable broadening in the medium, while gluon jets show little or no modification. In the right panel, comparing inclusive and photon-triggered jets, the inclusive sample exhibits negligible modification, consistent with its gluon-dominated composition. Photon-triggered jets, however, show a small but visible modification, in line with their quark-jet dominance and their stronger sensitivity to medium effects.

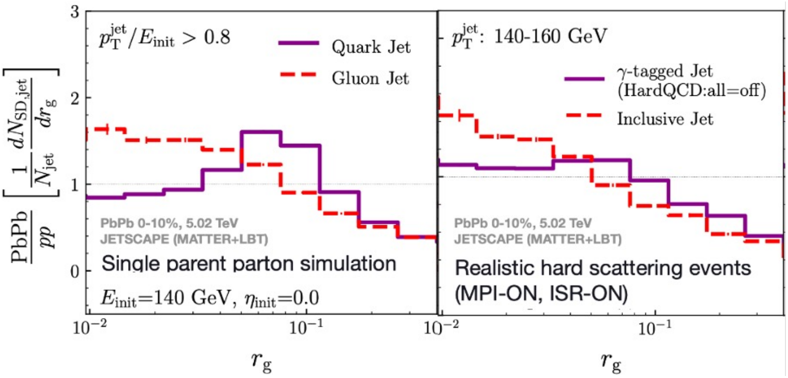

Figure 1. *Pb − Pb* to *p − p* ratio of r_g distributions for monoenergetic quark and gluon jets at E_{init} = 140 GeV (left), and for inclusive and photon-triggered jets with p_T^{jet} = 140–160 GeV (right).

The groomed jet mass m_g, defined as the invariant mass of the constituents that survive Soft Drop grooming, provides complementary information on the energy distribution and splitting dynamics within jets. This observable is sensitive to both the parton flavor—since gluon jets generally produce larger masses due to their higher color factor—and to medium-induced phenomena such as additional soft radiation and parton energy loss. Figure 2 presents the ratios of m_g distributions between $Pb-Pb$ and $p-p$ collisions. In the left panel, comparing quark and gluon jets, we find that quark jets experience a moderate increase in groomed mass, while gluon jets remain largely unaffected by the medium. In the right panel, inclusive jets again show minimal modification, consistent with their gluon-rich composition, whereas photon-triggered jets exhibit a slight but discernible enhancement of m_g, signaling medium-induced modifications to quark-initiated jets.

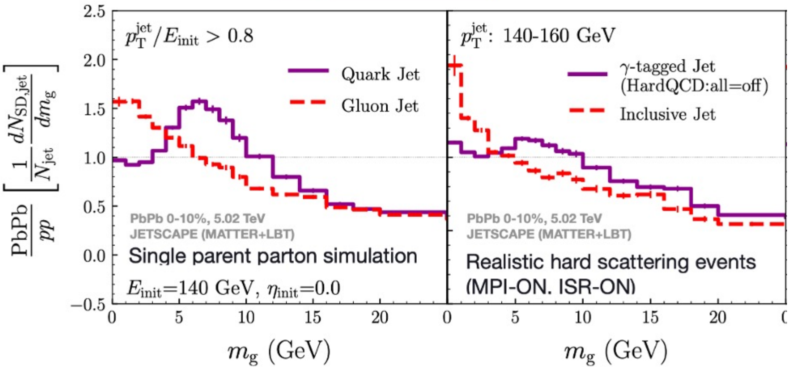

Figure 2. *Pb − Pb* to *p − p* ratio of m_g distributions for monoenergetic quark and gluon jets at E_{init} = 140 GeV (left), and for inclusive and photon-triggered jets with p_T^{jet} = 140–160 GeV (right).

Acknowledgments

This work was supported in part by the National Science Foundation (NSF) within the framework of the JETSCAPE collaboration, under grant number OAC-2004571 (CSSI:X-SCAPE), and in part by the US Department of Energy, Office of Science, Office of Nuclear Physics under grant numbers DE-SC0013460 and DE-FG02-05ER41367.

References

[1] D. Krohn, J. Thaler, L.T. Wang, Jet Trimming, JHEP **02**, 084 (2010), `0912.1342`. 10.1007/JHEP02(2010)084

[2] A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft Drop, JHEP **05**, 146 (2014), `1402.2657`. 10.1007/JHEP05(2014)146

[3] A.J. Larkoski, S. Marzani, J. Thaler, Sudakov Safety in Perturbative QCD, Phys. Rev. D **91**, 111501 (2015), `1502.01719`. 10.1103/PhysRevD.91.111501

[4] J.H. Putschke et al., The JETSCAPE framework (2019), `1903.07706`.

[5] Y. Tachibana et al. (JETSCAPE), Hard jet substructure in a multistage approach, Phys. Rev. C **110**, 044907 (2024), `2301.02485`. 10.1103/PhysRevC.110.044907

[6] Y. Tachibana et al. (JETSCAPE), Enhanced signal of momentum broadening in hard splittings for γ-tagged jets in a multistage approach (2025), `2503.23693`.

[7] C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass, U. Heinz, The iEBE-VISHNU code package for relativistic heavy-ion collisions, Comput. Phys. Commun. **199**, 61 (2016), `1409.8164`. 10.1016/j.cpc.2015.08.039

[8] J.S. Moreland, J.E. Bernhard, S.A. Bass, Alternative ansatz to wounded nucleon and binary collision scaling in high-energy nuclear collisions, Phys. Rev. C **92**, 011901 (2015), `1412.4708`. 10.1103/PhysRevC.92.011901

[9] A. Majumder, Incorporating Space-Time Within Medium-Modified Jet Event Generators, Phys. Rev. C **88**, 014909 (2013), `1301.5323`. 10.1103/PhysRevC.88.014909

[10] S. Cao, A. Majumder, Nuclear modification of leading hadrons and jets within a virtuality ordered parton shower, Phys. Rev. C **101**, 024903 (2020), `1712.10055`. 10.1103/PhysRevC.101.024903

[11] A. Kumar et al. (JETSCAPE), JETSCAPE framework: $p+p$ results, Phys. Rev. C **102**, 054906 (2020), `1910.05481`. 10.1103/PhysRevC.102.054906

[12] X.N. Wang, Y. Zhu, Medium Modification of γ-jets in High-energy Heavy-ion Collisions, Phys. Rev. Lett. **111**, 062301 (2013), `1302.5874`. 10.1103/PhysRevLett.111.062301

[13] S. Cao, T. Luo, G.Y. Qin, X.N. Wang, Linearized Boltzmann transport model for jet propagation in the quark-gluon plasma: Heavy quark evolution, Phys. Rev. C **94**, 014909 (2016), `1605.06447`. 10.1103/PhysRevC.94.014909

[14] A. Kumar et al. (JETSCAPE), Inclusive jet and hadron suppression in a multistage approach, Phys. Rev. C **107**, 034911 (2023), `2204.01163`. 10.1103/PhysRevC.107.034911

[15] Y. Tachibana (JETSCAPE), Extraction of jet-medium interaction details through jet substructure for inclusive and gamma-tagged jets, in *12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions: Hard Probes 2024* (2025), `2506.15990`