Hot Jets: Advancing the Understanding of High Temperature QCD with Jets

Wednesday 8 January 2025 - Friday 10 January 2025

Loomis Lab (UIUC)

Book of Abstracts

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Relativistic (a)causality in hydrodynamics and its effect on Bayesian analyses

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Relativistic fluid dynamics remains the backbone of modern simulations, which affects both bulk properties and rare probes such as jets. However, there have long been questions about whether it is being used outside its regime of validity in modern simulations. An important new tool for answering this question is a causality analysis – if the evolution equations do not respect relativistic causality, they are not a faithful representation of the underlying theory (i.e., QCD). Using this non-linear criterion, it has been shown that hydrodynamics is indeed being used outside its regime of validity, at least sometimes.

In this talk I will explore some phenomenological implications of this, and in particular the quantitative effects of demanding limits on acausality in a modern Bayesian parameter estimation. I will also make a few comments about the relationship to jets traversing the medium – just like at early times when the system finds itself far from equilibrium and must thermalize sufficiently for hydrodynamics to be valid, energy deposited by jets can locally bring the system out of equilibrium, and a similar hydrodynamization process could apply.

Reference: arXiv:2409.17127

Morning Session / **4**

High-p_T physics in the inaugural sPHENIX physics Run-24

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The new sPHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) has recently finished in its inaugural physics run with proton-proton and gold-gold collisions in 2024. sPHENIX is a large acceptance and high rate experiment, equipped with hermetic electromagnetic and hadronic calorimeter systems, the latter of which is unique at RHIC. The calorimeters, along with an efficient trigger system and high-efficiency and resolution tracking systems, enable qualitatively new measurements of jet, isolated photon, and jet (sub-)structure at RHIC. This talk provides an overview of the performance of the calorimeter system, the reconstruction and calibration of high-pT objects, and the progress towards first measurements of jet and photon physics with the sPHENIX detector. Lastly, we present highlights of the envisioned physics program enabled by this dataset at sPHENIX and outline a path for future measurements leading to the completion of the RHIC science mission.

Morning Session / **5**

Jet measurements at STAR

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TBD

Morning Session / **6**

Quantifying jet quenching and medium response with two particle correlations with PHENIX

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As energetic patrons produced in heavy-ion collisions traverse the quark-gluon plasma, they lose energy before fragmenting into a jet of particles such that the observed jet is modified compared to jets produced in p+p collisions. In heavy-ion collisions, the number of jets observed is suppressed and the distribution of particles or energy within the jet is modified compared to expectations from p+p collisions. In addition, the parent partons of jets can influence the QGP as they traverse it, eliciting medium responses also measurable in jet observables.

By measuring all the hadrons associated with a high momentum photon or jet constituent, we can access both the jet particles and the correlated medium effects. Free from any biases introduced by a jet finding algorithm, PHENIX studies dijet and direct photon-jet pairs via two-particle correlations. In 2014 PHENIX collected its largest data set for 200 GeV Au+Au collisions. Neutral pion-hadron correlations have been published from this data set and the yield of pion-hadron pairs as a function of the azimuthal difference ($\delta\phi$) in Au+Au collisions relative to p+p collisions are compared to the Hybrid model with and without medium response. The data are well described by the model when medium effects (the "wake") are included. This study will be extended to direct photon hadron correlations which can directly access evidence of an additional emergent phenomenon known as the diffusion wake.

Afternoon Session / **7**

Multipoint Energy Correlators in Heavy Ion Collisions at RHIC Energies from Simulation

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Energy-energy correlators and their three point counterpart have recently been of great interest to the heavy ion jet community as they directly provide the virtuality scale and are relatively simple to calculate. Recent measurements of the two point correlator in PbPb collisions compared to pp collisions by CMS show interesting trends, even when accounting for the energy loss causing a shift in virtuality. This talk will present results from a Monte Carlo study using PYTHIA and JEWEL at

RHIC energies to investigate the potential of measuring ENCs at sPHENIX and STAR given the relatively large heavy-ion background compared to the jet energy. Additionally, the potential physics that can be learned from such measurements will be discussed.

Afternoon Session / **8**

Medium modification calculations of collinear drop observables

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Collinear drop observables suppress energetic, collinear contributions and enhance the sensitivities to soft radiation where medium modifications are most significant. While the Lund plane contains comprehensive information about radiation, collinear drop observables can be concretely designed to probe specific regions of phase space which qualitative features of medium modifications may reside. In this talk I will discuss the strategy of constructing collinear drop observables, using soft-collinear effective theory with glauber interactions (SCET_G) as a jet modification model example.

Morning Session / **9**

ML biases in background subtraction to measure jet quenching

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Jet quenching measurements in central ultra-relativistic heavy ions collisions are a principle experimental probe of the quark-gluon plasma (QGP). The measurement resolution is limited, particularly at lower values of transverse momentum, by the high density of background particles. Many recent studies have demonstrated that neural networks (NNs) trained on jet substructure are capable of significantly increasing the resolution of jet background corrections relative to the standard area-based method. However, the modification of substructure in quenched jets biases these NN corrections. It is essential to understand and quantify these biases to qualify using NNs in jet quenching measurements. To this end, we use the JETSCAPE framework with MUSIC to simulate realistic hydrodynamically modelled QGP in central Au+Au collisions at RHIC energies with associated jet quenching. This quenching is compared to the quenching in computationally simpler fixed-length bricks of QGP. We train NNs for background subtraction using unquenched jets embedded into realistic backgrounds from JETSCAPE+MUSIC and present the biases of the NNs'background corrections for quenched jets. To demonstrate the propagation of these biases in measurement, we present an R_{AA} calculated using NNs for background correction and compare it to the generator-level R_{AA} of a JETSCAPE MC spectrum of quenched jets.

Afternoon Session / **10**

An EEC Way to See the Interplay Between Elastic Scatterings and Jet Wakes

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Quark gluon plasma (QGP), when viewed at length scales of order the inverse of its temperature, behaves as a strongly coupled liquid. However, when it is probed at shorter length scales or with sufficiently high momentum transfer, asymptotic freedom mandates the presence of quark-like and gluon-like quasi-particles. High energy partons within jets can trigger these high-momentum exchanges, making jets valuable probes for revealing the presence of such quasi-particles. In this talk, we describe an implementation of such elastic scatterings within the hybrid strong/weak coupling model. High-energy partons in jets undergo elastic Molière scatterings with quasi-particles in the medium. A jet parton that scatters is deflected, kicking a medium parton, which recoils. Subsequently, as both of these partons propagate further through the medium they each lose energy and momentum to the medium, producing hydrodynamic wakes in the droplet of QGP. That is, elastic scattering results in modifications to both the parton shower and to the wake that the shower excites in the droplet of QGP.

Energy-energy-correlators (EECs) characterize the substructure of the energy flow within jets. Using two-point and three-point EEC observables we are able to reveal the relevant angular regions at which (modified) parton showers and wakes in the QGP each dominate, offering a new way with which to visualize and constrain the corresponding dynamics. We compare our calculations to recent CMS measurements of two-point EECs of charged-particle tracks in anti-k_t $R = 0.4$ jets. We show that our calculations agree with the CMS measurements only when elastic scattering is included and when the elastically scattered recoil-partons produce their own wakes.

Afternoon Session / **11**

Investigating jet modification in absence of QGP-medium

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We explore modification of jet properties in high-multiplicity proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV, utilizing the PYTHIA 8 Monash 2013 Monte Carlo simulation. While the formation of a quark-gluon plasma (QGP) is typically associated with jet quenching, our investigation focuses on jet modifications arising purely from non-QGP mechanisms, including color reconnection (CR) and multiparton interactions (MPI).

We analyze intra-jet properties, specifically the jet shape observable $\rho(r)$ and fragmentation distribution z^{ch}. Our results demonstrate that the interplay between MPI, CR, and gluonic contributions to jets in high-multiplicity events leads to significant broadening and softening of jets compared to minimum bias events, particularly at low-p_{T} regime. A direct correlation is observed between the average number of multiparton interactions, the gluonic contribution, and the extent of modification in $\rho(r)$, indicating that higher number of MPIs and/or gluonic contributions correspond to greater modifications in jet properties. These findings underscore the rich interplay of dynamics in high-multiplicity environments, providing valuable insights into the mechanisms at play, independent of QGP formation.

Morning Session / **12**

Flow Effects on Charged Hadron R_{AA} and v_n in Heavy Ion Collisions

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We discuss the flow-induced anisotropic contribution to jet-broadening, "jet drift", showing that this effect results in a deflection of hard partons, and thus jets, in the direction of the medium flow. Next, we study this effect in both toy models and a full-fledged hybrid transport simulation of $\sqrt{s}$ = 5.02 TeV PbPb collisions at the LHC, tracking trajectories of hard partons with perturbative energy loss and drift. We show that sub-eikonal anisotropic effects, including flow-mediated jet drift, are sensitive to properties of the medium that traditional eikonal isotropic effects are insensitive to, demonstrating that including these effects leads to modifications to jet and hard particle observables that survive averaging over events. We show that jet drift leads to an enhancement of the anisotropic flow (v_n) of charged hadrons and modification of the acoplanarity of dihadrons. Finally, we discuss the implications for jet substructure and medium response effects.

Morning Session / **13**

Recent multiplicity-based measurements in jet physics

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Observables based on multiplicity play a crucial role in jet measurements. An influential contribution to the analysis of event multiplicity distributions is the Koba-Nielsen-Olesen (KNO) scaling hypothesis, which states that the multiplicity distributions can all be collapsed onto a universal scaling curve. Phenomenological studies based on proton–proton collisions have found a similar scaling behavior within jets and concluded that the KNO scaling may be violated by processes outside the jet development, such as single and double-parton scatterings or softer multiple-parton interactions. In this contribution, recent results are presented that can help validate different fragmentation models.

Measurements from the LHC show an enhancement of both charm and beauty baryon-to-meson production ratios in the low-transverse-momentum region when compared to model predictions based on e+e- collisions. We explored this enhancement in terms of event activity using the color-reconnection model beyond leading color approximation to determine whether the enhancement is a result of processes connected to the jet development or the underlying event. We propose sensitive probes relying on event shape that can help differentiate between multiple proposed charm- and beauty-production scenarios using new LHC Run-3 data.

Morning Session / **14**

Response of Jets to Collective Flow in Heavy-Ion Collisions

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The highly-successful program of jet quenching in heavy-ion collisions relies upon a separation of energy scales between the jet p_T and the medium. At leading power in this high-p_T "eikonal" expansion, scattering in the medium leads to isotropic transverse momentum broadening and radiative energy loss, but the medium is approximately static in this limit. When extended to incorporate the first sub-eikonal order, however, scattering in the medium is sensitive to other degrees of freedom, including in particular the velocity field of the medium. In response to a flowing medium, jets experience both a net deflection in the direction of the flow and a velocity-dependent bias in their emitted radiation. In this talk, I will discuss the origin of these effects and their potential impact in heavy-ion phenomenology.

Morning Session / **15**

Jet Drift in Heavy Ion Collisions: Acoplanarity and v_2

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We introduce a sub-eikonal anisotropic contribution to jet-broadening, "jet drift," that couples to the flow of the nuclear medium, showing that this effect results in a deflection of hard partons, and thus jets, in the direction of the medium flow. We study Two-jet observables i.e. v_2 and acoplanarity for $\sqrt{s}$ = 5.02 TeV PbPb collisions at the LHC. We show that jet drift leads to an enhancement of the elliptic flow (v_2) of charged hadrons and modification of the acoplanarity of dihadrons and discuss the implications for jet substructure and medium response effects. We also demonstrate that we can obtain independent information about the event geometry encoded in the drift modification to acoplanarity vs v_2 enhancement, whereas the temperature dependence of these observables is qualitatively different. By entangling this temperature vs geometry dependence of these observables, we can add discriminatory power to our analysis.
Next, we study acoplanarity & v_2 across different system sizes and collisional energies i.e. 200 GeV AuAu collision at RHIC using our in-house simulation package (APE). Our analysis will be critical for understanding and generalizing dynamical jet-QGP interactions for different collisional systems and energies. We further plan on investigating the "jet drift"effect on these observables for deformed nuclear systems (XeXe, UU, etc.) from ultra central collisions which will aid event engineering (designing selection cuts to maximize jet drift signal) applications in the future.

Morning Session / **16**

Probing jet hadrochemistry with measurements of π, K, and p in jets and the underlying event in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with ALICE

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Measurements of jet substructure observables in heavy-ion collisions can constrain how energetic partons interact with the medium. Though there has been remarkable progress in particle-species-inclusive jet substructure measurements, a complete understanding of the identified particle composition of the jet and its modification in heavy-ion collisions remains elusive. Jet quenching models

predict that the jet hadrochemical composition may be modified in heavy-ion collisions due to jet-medium interactions and modified particle composition in the jet wake. Measurements of identified particles in jets can help discriminate between parton-QGP interaction mechanisms.

In this talk, we present the first measurements of π, K, and p ratios within jets and the underlying event as a function of particle transverse momentum in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. Enabled by the excellent PID capabilities of ALICE, this study aims to understand soft particle production mechanisms and distinguish modified jet fragmentation from bulk effects.

Afternoon Session / **18**

Investigation of medium effects on energy-energy correlation (EEC) in jets within the CoLBT-hydro model.

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Energy-energy correlators(EECs) has recently emerged as an excellent jet substructure to study space-time information of parton shower. We explore the EECs within γ-jets using our LBT and CoLBT-hydro frameworks. We investigate the effects of jet quenching, medium-induced gluon radiation, and medium response on EECs in AA collisions compared to pp collisions. Additionally, we find that the angular distribution is sensitive to the Debye screening mass μ_D, which determines the angular scales of each jet-medium scattering and characterizes the structure of the QGP medium in our model simulations. Furthermore, we analyze the medium modification of single inclusive jet EECs in AA collisions relative to pp collisions. Through this analysis, we aim to provide insights into the hadronization process in high-energy heavy-ion collisions.

Afternoon Session / **19**

Exploring QCD dynamics with charm-tagged jet substructure studies with ALICE

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Jet substructure provides precise tests of Quantum Chromodynamics (QCD) and offers a distinct way to study hadronization mechanisms, compared to measurements of hadrons alone. QCD predicts that jet radiation patterns depend on the mass and color charge of the initiating parton. Parton showers, in particular, are sensitive to the Casimir factors of quarks and gluons, as well as the parton mass, leading to the dead-cone effect.

This talk presents the recent substructure results of charm-tagged jets, tagged by the presence of a fully reconstructed D0-mesons, obtained by ALICE at the LHC. These results include the first direct measurement of the dead-cone effect, measured by exploiting iterative declustering techniques, the radial distribution of D0-mesons with respect to the jet axis, and the first measurement of the charm-tagged jet angularity, an observable that can be tuned to be sensitive to mass and Casimir effects. Additionally, I will present the first measurement of charm-tagged jet energy-energy correlators (EECs), defined as the energy-weighted cross section of particle pairs within jets. Comparisons to inclusive jets (gluon-dominated) and various MC event generators reveal sensitivity to both flavor-dependent effects in the parton shower and hadronization mechanisms. Moreover, comparisons

with next-to-leading order calculations emphasize the need for improved theoretical modeling of heavy-quark jets and provide critical insights into the parton-to-hadron transition in QCD.

Afternoon Session / **20**

Jets in ATLAS

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Jets in pp in ALICE

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Afternoon Session / **22**

TBD

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Calibrated (3+1)D hydrodynamic medium for ultrarelativistic collision physics

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Afternoon Session / **24**

TBD

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Searching for Jet Quenching in High-Multiplicity Proton-Lead Collisions at LHC

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Factorized approach for jet production and substructure observables in HICs

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High pT jets in a charged, viscous medium

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Including a source term in hydrodynamic simulations

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Asymmetric jet shape due to jet-flow interaction

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Jet Substructure at LHCb

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The Large Hadron Collider beauty (LHCb) experiment allows for the exploration of jet substructure in novel ways. It is a fully instrumented spectrometer in the forward region, permitting increased sensitivity for heavy flavor hadron production as well as jets initiated by a light quark produced in association with a Z0 boson. This allows for an analysis of the mass and flavor dependence of jet

fragmentation and substructure
properties, as well as a comprehensive comparison with gluon-dominated inclusive jet samples from other LHC experiments. Jet substructure measurements in pp collisions provide insight on heavy quark fragmentation and hadronization in vacuum, which can be used as a baseline to understand modification in the presence of quark-gluon plasma (QGP) produced in heavy-ion collisions. Heavy flavor production requires a hard process with energy above the heavy quark mass threshold and is therefore suppressed at later stages in high-energy collisions. This offers an ideal probe of medium evolution that is produced in the initial stages of heavy-ion collisions and perturbed throughout the lifetime of the plasma, accessible through the substructure of jets containing heavy flavor hadrons. In addition, the fantastic particle identification (PID) capabilities of LHCb allow for flavor-dependent correlations amongst jet constituents to be observed. Therefore, jets measured at LHCb provide a unique laboratory for studying in detail the process by which color charged partons become color neutral hadrons, how this process depends on the parton mass, and how it is affected in the high temperatures and energy densities of QGP produced in heavy-ion collisions. We present recent measurements of fragmentation properties for jets containing heavy quarkonia, as well as jets produced in association with a Z0 boson. In addition, ongoing measurements of jet substructure for jets containing open heavy flavor hadrons in pp collisions will be discussed, as well as plans for future measurements in both pp and heavy-ion collisions.

Afternoon Session / **33**

Discussion & Wrap-up

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First D0-tagged jet axes difference measurement in pp collisions at 5.02 TeV with ALICE

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Substructure measurements of jets containing heavy-flavor hadrons play an important role in testing pQCD calculations in proton-proton (pp) collisions and are critical tools for studying the quark-gluon plasma (QGP) created in heavy-ion collisions. We study three different D0-tagged jet axis definitions with varying degrees of sensitivity to wide-angle radiation: Standard, Soft Drop groomed (SD), and Winner-Takes-All (WTA). By considering the angular difference between different axes at relatively low jet momentum, we can study the radiation pattern inside the reconstructed jets and provide insight into the associated charm-quark fragmentation and hadronization processes. We present the first D0-tagged jet axes difference studies carried out in pp collisions at 5.02 TeV with the ALICE experiment at the LHC, for jets of transverse momentum ⊠T,jet > 5 GeV/⊠ and D0 mesons with ⊠T,D0 > 2 GeV/⊠. The measurements of the radial distributions of D0 mesons with respect to the jet axis, Δ⊠(D,jet), is reported. We also study the opening angle, Δ⊠axis, between various definitions for the axis of a D0-tagged jet. These measurements will serve as important groundwork for an in-depth understanding of charm-quark diffusion in the QGP.

Afternoon Session / **35**

Discussion

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Machine Learning Application in Jet Quenching Analysis

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