Jet Modifications - Experimental Overview

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Abstract. This proceeding summarizes a selection of experimental results on jet modifications in the quark-gluon plasma from the XXXth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions, Quark Matter 2023.

1. Introduction Jets are fundamental objects in Quantum Chromodynamics (QCD) composed of sprays of particles that form when high-virtuality partons are produced in high-energy particle collisions. These partons from the initial hard scattering quickly shower and hadronize into final-state hadrons that we measure as jets. Thus, jets connect the perturbative QCD (pQCD) scale of the scattered parton with the non-perturbative QCD (npQCD) scale of final-state hadrons, making them useful tools to study the various energy regimes of QCD.

When jets are produced in heavy-ion (HI) collisions, they traverse the quark-gluon plasma (QGP) and interact, leading to jet energy loss and modification of the jets' internal structure, a phenomenon known as jet quenching. Jets are produced early in the collision before the QGP is formed and traverse its entire evolution, making them useful for extracting the microscopic properties of the medium. The jet energy loss can depend on the path length and the initial partons' flavor. Additionally, we expect different jet-medium interactions at different scales due to the complex and multi-scale nature of the jet and the QGP. First, the jet can experience momentum broadening, which widens the jet, causing energy loss outside the jet cone. The jet can also undergo wide-angle deflection due to point-like scattering. Additionally, the medium responds to the jet with a wake that can push soft particles back inside the jet.

When measuring jets in heavy ion collisions, we craft observables to separate different jet quenching effects and extract properties of the QGP. These proceedings provide an overview of new results of jet modification in the QGP at the XXXth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions, Quark Matter 2023.

2. Jets: complex experimental and theoretical QCD objects Jets are multi-scale dynamic objects whose complex structure contains QCD information. The complex nature of a jet makes measuring them challenging. For example, it is already challenging to find the jet signal underneath the large underlying event in HI collisions that can be on the order of the jet itself. Additionally, finding suitable observables sensitive to interesting physics that are calculable in theory so they can be compared to models is challenging but essential [1]. In the past few years, our jet measurements have made enormous strides to overcome these challenges, taking advantage of their dynamic multi-scale nature.

While these proceedings focus on new jet measurements in HI collisions, it is important to note that many new jet measurements in pp collisions were discussed. These provide a vacuum QCD measurement where no QGP is expected to be formed to study fundamental

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QCD. They also provide a baseline for measurements in HI collisions. We need to understand how well our models describe the pp baseline, which can vary for different observables, and provide input for improving and constraining our models [2]. Additionally, looking at the underlying distribution in pp collisions can affect our interpretation of HI measurements concerning different kinematic cuts and biases [3]. Finally, vacuum QCD measurements can provide new observables for future measurements in HI collisions.

3. Jet energy loss Jets lose energy in the QGP, resulting in an overall suppression of jet yield in HI relative to pp collisions that are quantified with the observable R_{AA}. We have many measurements of the R_{AA}, demonstrating the full phase space we can measure jets at our experimental facilities [4]. The ATLAS and CMS experiments at the LHC have high statistics to measure jets out to a TeV in jet p_{T}. The STAR and PHENIX (and future sPHENIX) experiments at RHIC measure very low p_{T} jets due to a lower $\sqrt{s_{\mathrm{NN}}}$. Finally, the ALICE experiment at the LHC measures jets at intermediate p_{T} due to precise tracking.

At this conference, a new result from ALICE used a novel background removal technique with mixed events to access even lower jet p_{T} than previous measurements at the LHC [5], reaching around 14 GeV and overlapping with jets at RHIC. In Fig. 1 (left), the ALICE result is compared to the R_{AA} from STAR [6]. A similar degree of suppression is observed. However, we must be careful when comparing measurements at LHC and RHIC because the underlying jet spectra differ due to the different center-of-mass energies [7].

3.1 Flavor dependence of energy loss Energy loss is expected to depend on the initial parton flavor, where the energy loss of gluons should be greater than quarks due to QCD color factors. Additionally, the energy loss of heavy quarks should be greater than light quarks due to the dead-cone effect. ATLAS presented two results on the flavor dependence of energy loss in Fig. 1 (right). First, a measurement of photon+tagged jets, where the tagged jet mainly consists of quark jets, is shown in orange [3, 8]. Additionally, ATLAS measured b-tagged jets in green, which corresponds to a beauty-quark jet enriched sample [9, 10]. These results are compared to inclusive jets in black, which contain significantly more gluon-initiated jets for jet $p_{\mathrm{T}} < 200$ GeV [8]. The photon and b-tagged jets are less suppressed than the inclusive jets, implying that the energy loss depends on the color charge and possibly the mass of the parton. Finally, STAR presented a measurement of $D0$-tagged jets in Fig. 1 (center), which selects jets from an initial charm quark [11]. The R_{CP} also shows a suppression of heavy flavor jets in more central collisions.

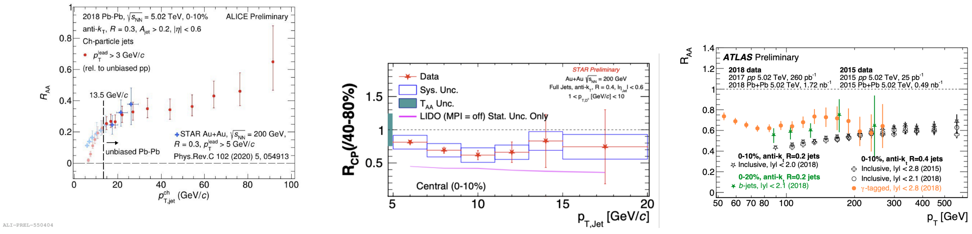

Figure 1. Left: The R_{AA} for charged-particle $R = 0.4$ jets measured by ALICE [5] compared to STAR [6]. Center: The R_{CP} for $D0$-tagged jets measured by STAR [11]. Right: A summary plot of recent ATLAS R_{AA} measurements for photon-tagged jets, b-tagged jets, and inclusive jets [3, 8–10].

3.2 Path length dependence of energy loss Energy loss is predicted to depend on the path length traveled in the QGP. At this conference, recent results aimed to quantify this experimentally in two ways: with dijet pairs or event geometry.

Dijet momentum imbalance: The two jets in a dijet pair must travel different paths in the QGP, resulting in a momentum imbalance x_J that is sensitive to the different paths and fluctuations in energy loss. ATLAS has made significant progress measuring the dijet asymmetry over the past decade, observing a clear asymmetry in HI compared to pp collisions [12]. At this conference, the observable was extended to include the jet resolution parameter R dependence [9, 13]. In Fig. 2 (left), when selecting very asymmetric jets that were significantly quenched in the QGP ($x_J \approx 0.5$), the dijet pairs are less suppressed at large R. This trend is consistent with the more quenched jets recovering energy with a larger radius.

Event geometry: We can use the event's geometry to select jets in or out of plane. The longer path traveled out-of-plane can result in a reduced out-of-plane yield. Specifically, we focus on the jet v_2, which should be positive due to differences in the in-plane and out-of-plane yield. The jet v_2 from ATLAS and ALICE, in Fig. 2 (right), is positive over a large p_T range from 30 to 300 GeV [5, 14]. STAR measured a positive jet v_2 in new collision systems starting at p_T of 10 GeV (center) - isobar (Ru+Ru and Zr+Zr) collisions in red and O+O collisions in blue [15]. Therefore, we observe a persistent jet v_2 across a wide kinematic range consistent with path length dependence of energy loss.

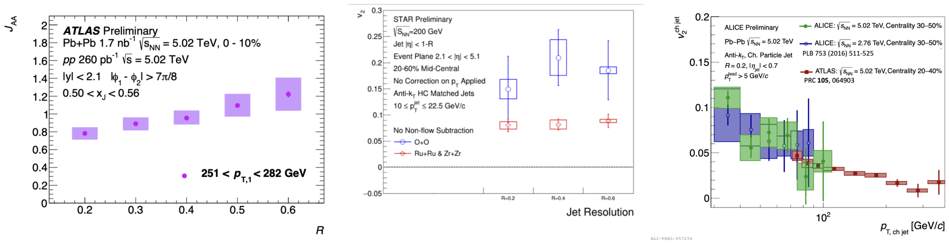

Figure 2. Left: The ATLAS J_{AA}, or per dijet pair R_{AA}, for asymmetric pairs as a function of jet R [9, 13]. Center: The STAR jet v_2 in isobar and O+O collisions as a function of jet R [15]. Right: The jet v_2 as a function of jet p_T for ALICE and ATLAS [5, 14] ·

4. Jet substructure modification Moving beyond energy loss, we can understand how the structure of a jet is modified in the medium with jet substructure observables. First, we can analyze hadron-level distributions sensitive to the medium response or momentum broadening. Additionally, we can examine subjets from hard parton splittings, which remove some softer components to become sensitive to the modification of the hard core of the jet. For example, subjets can probe coherence effects to determine whether the medium resolves or fails to resolve the structure within a jet to extract the resolution length of the medium.

4.1 Hadron-level jet substructure observables One example of a hadron-level observable is the Generalized angularities, a class of IRC-safe observables to summarize all substructure. They include exponential contributions of the angular and momentum scales that vary the aspects of QCD. ALICE measured the jet girth Fig. 3 (left), where the ratios of Pb-Pb to pp collisions reveal that the core of the jet is more modified than the large angle distributions [16]. STAR presented the first measurement of generalized angularities at RHIC in Fig 3 (right), where no significant modification was observed [17]. This measurement applies a new multidimensional unfolding method, Multifold, to HI collisions for the first time, obtaining a 7D correlation between observables that provides additional information.

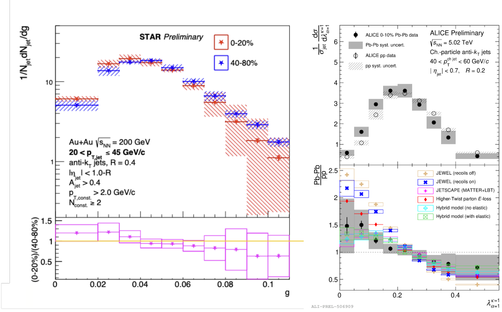

Figure 3. Left: The jet girth from STAR compared between central and peripheral collisions [17]. Right: The jet girth from ALICE compared between central Pb-Pb and pp collisions [16].

4.2 Jet splittings We can access hard parton splitting using grooming procedures like Soft Drop that find subjets inside jets. The angular distance between the subjets, R_g, is sensitive to the resolution length of the medium or the extent to which individual color charges in a jet have been resolved. ATLAS presented a measurement of R_g, shown in Fig. 4, where wider jets (large R_g) are more suppressed, or jets are narrowed in the QGP [18, 19].

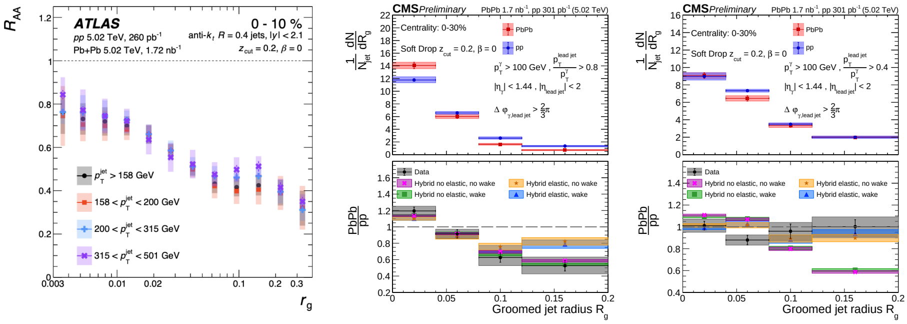

Figure 4. Left: The ATLAS R_{AA} as a function of R_g in different jet p_T intervals [18, 19]. Right: The CMS photon-tagged R_g compared between Pb-Pb and pp collisions [20, 21] for symmetric (center) and asymmetric pairs (right).

The narrowing effect is persistent in many jet substructure measurements, i.e., Ref. [18, 22]. This trend is consistent with color decoherence, where the medium resolves individual partons inside the jet further apart than a specific angular scale, but also with differences in quenching between quark and gluon jets. Regardless, our measurements have a selection bias where we measure less quenched, narrower jets that have survived the QGP [23, 24].

4.3 Photon+jet substructure Photon-tagged jets are proposed to address the selection bias. These jets are mainly quark jets and provide the initial momentum of the initial parton since photons don't lose energy in the QGP. This creates a more uniform initial jet sample of narrower quark jets and enables comparisons between jets in pp and HI collisions based on the unmodified photon p_T. Previous measurements of the photon-tagged jet asymmetry ($x_{J,\gamma}$) demonstrate a significant asymmetry in HI collisions, implying significant jet energy loss in the QGP [25, 26]. At this conference, CMS presented a measurement of photon+jet tagged substructure. Specifically, they measured the R_g of jets opposite a photon for different $x_{J,\gamma}$ values [20, 21]. The middle panel of Fig. 4 shows more balanced configurations where the jet opposite the photon is less quenched, and the narrowing behavior is still observed. The right panel displays unbalanced configurations, where the jet opposite the photon has undergone more quenching in the QGP, reducing the bias towards less quenched jets. The ratio shows no change in HI compared to pp collisions, so there is no longer a narrowing effect.

5. Jet deflection Measurements at this conference investigated the quasi-particle structure of the QGP by probing hard Moilere scattering off quasi-particles in the medium using two approaches. The first looks for an angular deflection between a hadron trigger and a jet, known as acoplanarity. In Figure 5, ALICE measured the acoplanarity in HI compared to pp collisions. The results show an enhancement at large angles for the largest R and smallest jet p_{T}, consistent with Moilere scattering [27, 28] (also seen at STAR [29]). The groomed hardest $k_{\mathrm{T}}^{\mathrm{g}}$ is also expected to be sensitive to Moilere scattering as a hard k_{T} kick. However, the right panel of Fig. 5 demonstrates a suppression of the large k_{T} subjets, consistent with the previously mentioned narrowing effect [16].

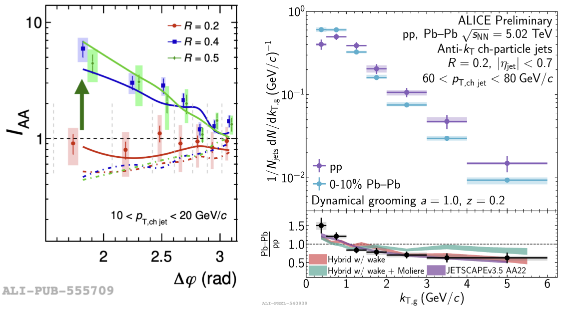

Figure 5. Left: The ALICE I_{AA} for semi-inclusive hadron+jets in Pb-Pb compared to pp collisions for different jet radii [27, 28]. Right: The hardest $k_{\mathrm{T}}^{\mathrm{g}}$ in Pb-Pb compared to pp collisions from ALICE [16].

A theoretical prediction from the Hybrid model addressed these measurements and proposed a way forward to find Moilere scattering [30]. In general, no clear evidence is found, but the hybrid model is sensitive to both Moilere and medium response effects from the wake. The accoplanarity appears more sensitive to wake effects than Moilere, but the hardest k_{T} seems more sensitive to Moilere (although not significantly enhanced).

6. Extracting QGP Properties Finally, a preliminary result from the JETSCAPE collaboration performed a global Bayesian analysis of jet and (for the first time) jet substructure data from the LHC and RHIC. The extracted QGP transport coefficient $\hat{q}$ [31] is shown in Fig. 6. This is an important stride towards combining our data to extract QGP medium properties.

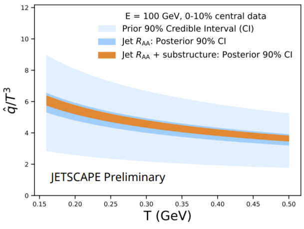

Figure 6. The extracted $\hat{q}$ from a global bayesian analysis of experimental jet data from JETSCAPE [31].

7. Conclusion and Future This conference brought many new results of jet modifications in the QGP. We saw observables sensitive to the path length dependence of energy loss, decoherence effects, and Moilere scattering. We often see a convolution of different jet-quenching effects, making more differential measurements and continued global Bayesian analyses important as we look forward to new data. New observables proposed by the theoretical community will be interesting to study in the future.

We had many talks at this conference discussing future measurements and experiments at the LHC and RHIC. After significant upgrades, LHC Run 3 is underway. This will be a precision era with a substantial increase in statistics, opening the possibility for rarer probes like heavy flavor jets in the charm and beauty sector and photon+tagged jets. Additionally, an Oxygen-Oxygen run is planned where a smaller system can probe the path length dependence of energy loss. At RHIC, STAR will continue taking data and benefit from a far-forward upgrade. Finally, the new sPHENIX detector turned on this year and has planned pp, p-Au, and Au+Au runs [32]. Jets are a pillar of the physics program for the sPHENIX detector.

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