Jet-induced Medium Response: Experimental Overview

Yeonju Go[1,*]

[1]Brookhaven National Laboratory

Abstract. In this Quark Matter 2023 conference proceedings, recent measurements at RHIC and the LHC and theoretical developments on the jet-induced medium response are summarized.

1 Introduction

The Quark-Gluon Plasma (QGP), a hot and dense state of matter well-established in Quantum Chromodynamics (QCD), has been actively investigated in the realm of heavy-ion collisions at RHIC and LHC over the past few decades. Jets, collimated sprays of particles emerging from the fragmentation of highly energetic partons, are expected to experience redistribution of the energy of the initial parton as they traverse the QGP, a phenomenon commonly referred to as jet quenching. Extensive measurements at RHIC and LHC have revealed modifications in the properties of jets, including changes in their rates and structures.

Jets in heavy ion collisions undergo modifications due to the surrounding medium, and concurrently, jets influence the properties of the medium. As jets serve as multi-scale probes experiencing a complex interplay of physical effects, including radiative energy loss, medium response, and Moliere scattering, it is crucial to untangle and distinguish the distinct contributions of these phenomena to reveal the mechanisms underlying QCD interactions. Additionally, the jet-induced medium response provides access to the bulk properties of the QGP and information about in-medium thermalization [1].

Many theoretical models implement the medium response via two primary approaches: the weakly coupled recoil model and the strongly coupled hydrodynamic model. In the former, a medium parton with energy surpassing the medium scale is scattered by a hard parton, subsequently propagating through the medium [2–4]. On the other hand, hydrodynamics comes into play when the energy of the medium parton is comparable to or smaller than the medium energy scale, implemented as a source term in the hydrodynamic equation [5]. Some models incorporate both approaches [6, 7]. Terms such as Mach cone, sonic boom, shock wave, diffusion wake, and others are all associated with medium response.

2 Experimental Results

2.1 Hadron-triggered Jet I_{AA}

Jet-hadron correlations have been proposed as one of the most sensitive observables of medium response. ALICE measured the per-trigger charged-particle jet yield ratio between

*e-mail: ygo@bnl.gov

Pb+Pb and pp collisions (I_{AA}) for the jets recoiling from a high-transverse momentum (p_T) hadron trigger of $20 < p_T < 50$ GeV [8, 9]. The enhancement at low-$p_T^{\text{ch jet}}$ and the broadening in azimuthal angular separation, $\Delta\phi$, between the hadron trigger and the recoil jet in Pb+Pb collisions are well described by the JEWEL and Hybrid models with medium response as shown in Figure 1. The medium response in theoretical calculations is critical to explain the trend at low p_T in the data.

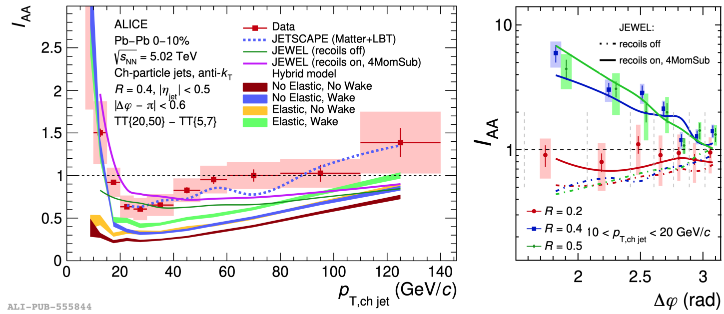


Figure 1: The I_{AA} for recoil jets triggered by hadrons as a function of $p_T^{\text{ch jet}}$ (left) and $\Delta\phi$ (right) by ALICE. Figures reproduced from Refs. [8, 9]

2.2 Z boson-tagged Hadron I_{AA}

One can conduct similar measurements using electroweak bosons as the trigger particle, providing access to information about the unmodified, initially hard-scattered parton as a colorless object does not strongly interact with the medium. Figure 2 shows the I_{AA} of charged particles tagged by Z bosons measured by CMS and ATLAS. In the opposite direction of the Z boson (towards the jet), there is an enhancement in charged particle yields at low p_T^{trk} ($\lesssim 2$ GeV) and a suppression at high p_T^{trk} ($\gtrsim 2$ GeV). Theoretical calculations predict a significant difference between scenarios with and without the wake effect, particularly at low p_T^{trk}, and effectively reproduce the data for the case with medium response.

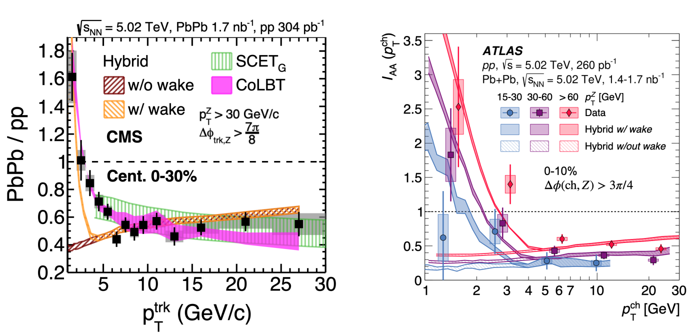


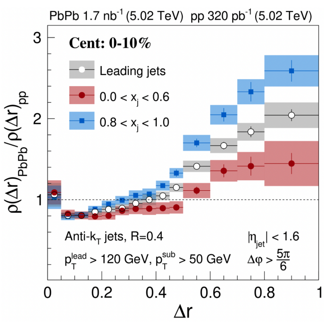
Figure 2: The I_{AA} for charged particles tagged by Z bosons as a function of p_T^{trk} measured by CMS (left) and ATLAS (right). Figures reproduced from Refs. [10, 11].

2.3 Jet Shape and Jet Mass

To study how the energy is redistributed inside jets, the jet shape function ρ is defined as

$$\rho(r) = \frac{1}{N_{\rm jet}} \sum_{\rm jet} \left[\frac{1}{p_{\rm T}^{\rm jet}} \frac{\sum_{\rm trk \in (r-\delta r/2, r+\delta r/2)} p_{\rm T}^{\rm trk}}{\delta r} \right] \tag{1}$$

where r is the radial distance from the jet axis. The coupled jet-fluid model suggests that the medium response effect significantly broadens the jet shape function, particularly in the large r region, in agreement with the CMS results at 2.76 TeV [5, 12]. The recent CMS measurement [13] extends this analysis to include the dependence on $x_{\rm j} = p_{\rm T}^{\rm subleading}/p_{\rm T}^{\rm leading}$ as shown in Figure 3 (left). The leading jets in balanced dijets ($0.8 < x_{\rm j} < 1.0$) are more modified at larger r compared to that of the unbalanced dijets ($0.0 < x_{\rm j} < 0.6$). One possible explanation is that the leading jets in unbalanced events are more likely to be selected in proximity to the surface of the plasma. This leads to shorter path lengths, resulting in less interaction with the medium.



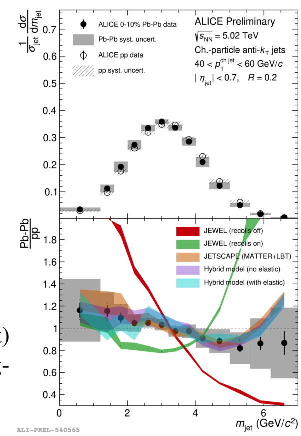


Figure 3: Jet shape function $\rho(r)$ measured by CMS (left) and jet mass distribution measured by ALICE (right). Figures reproduced from Refs. [13, 14]

The (ungroomed) jet mass distribution measured by ALICE [14] is shown in Figure 3 (right). The distribution in Pb+Pb collisions appears to be slightly shifted towards smaller mass. The data are compared to theoretical calculations. Neither the recoil nor the non-recoil scenarios in JEWEL adequately capture the trend in data.

In this context, a careful approach is necessary when employing JEWEL calculations. It is recommended to compare experimental data with JEWEL featuring recoil and subtraction, utilizing the latest method, namely "constituent subtraction", which aligns closely with the background subtraction used in experimental data [15]. The calculations with both recoil and subtraction are the only prescription that makes physical sense whereas the calculations without recoil or with just recoil (without background subtraction) are essentially unphysical extremes. Ensuring a more consistent application and providing a clear definition of the configuration will mitigate ambiguity for ease of discussion, and develop a better understanding across various results.

2.4 Jet-Hadron Correlation in γ-jet events

One major challenge when investigating medium response is the entanglement of modifications with other physics effects, e.g. in-medium parton showers from the propagating jet. Experimentally, distinguishing between "ordinary" in-cone radiation and the medium response that falls into the cone is extremely difficult. As a result, our interpretations heavily depend on comparisons with theoretical models. The CoLBT authors proposed an "unambiguous" signal of medium response by probing the diffusion wake, characterized by a depletion of soft hadrons in the opposite direction to the jet propagation [16]. The hadron yields at low-p_{T} ($0.5 < p_{\mathrm{T}} < 2.0$ GeV) as a function of the angular distance in pseudorapidity ($\Delta\eta$) between the jet and hadron when $|\Delta\phi(\text{jet,track})| > \pi/2$ have been measured by ATLAS [17]. The relative yield ratio between the signal events and mixed events is shown in Figure 4 (left), which gauges the modification of the medium, i.e. diffusion wake. For small $x_{\mathrm{J}\gamma} = p_{\mathrm{T}}^{\text{jet}}/p_{\mathrm{T}}^{\gamma}$ events where jets are expected to lose more energy in the medium, no significant diffusion wake signal is found at $\Delta\eta \sim 0$ within the current sensitivity. The result provides limits on the amplitude for the double ratio of small $x_{\mathrm{J}\gamma}$ to large $x_{\mathrm{J}\gamma}$ as shown in Figure 4 (right). The CoLBT prediction is not ruled out at the 68% confidence limit. The current probability distribution is constrained by statistical uncertainties, and therefore, future measurements with increased statistics will provide valuable insights.

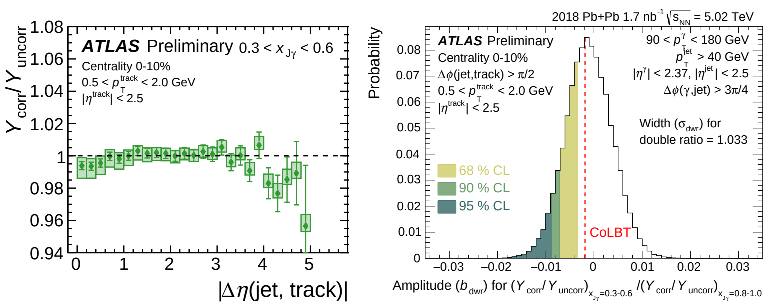


Figure 4: Relative hadron yield ratio between signal and mixed events as a function of $|\Delta\eta(\text{jet,track})|$ (left) and probability distribution of the amplitude ratio between $0.3 < x_{\mathrm{J}\gamma} < 0.6$ and $0.8 < x_{\mathrm{J}\gamma} < 1.0$ (right). Figures reproduced from Ref. [17].

2.5 Baryon-to-Meson Ratio

The baryon-to-meson ratio within jets is another proposed signal of medium response as the excited medium changes the chemical composition of particles around jets via parton coalescence. The coupled jet-fluid model predicts a significant enhancement of the proton-to-pion ratio (p/π) in heavy ion collisions compared to pp collisions [18]. The excess is particularly pronounced at large angles with respect to the jet axis (r) as shown in Figure 5 (left). Figure 5 (right) shows the STAR measurement of p/π for jets with a radius of R=0.3. The results suggest no significant modification in Au+Au collisions within the current uncertainties. Future studies with larger datasets and increased jet radius would be beneficial.

2.6 R Scan of Nuclear Modification Factor

The nuclear modification factor (R_{AA}) is one of the most common observables used in heavy ion physics and defined as

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}^2 N^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} \Bigg/ \langle N_{\mathrm{coll}} \rangle \frac{\mathrm{d}^2 N^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}, \tag{2}$$

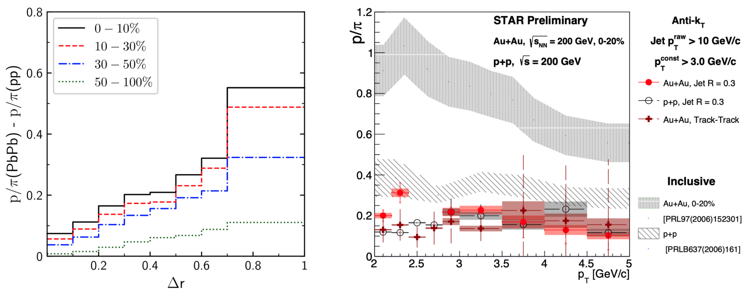


Figure 5: The difference in p/π between Pb+Pb and pp collisions as a function of r calculated by the coupled jet-fluid model (left) and p/π as a function of $p_{\rm T}$ for pp and Au+Au measured by STAR (right). Figures reproduced from Refs. [18, 19].

where $N^{\rm AA}$ (N^{pp}) is the jet yields per nucleus-nucleus collisions (pp collisions) and $\langle N_{\rm coll}\rangle$ is the average number of binary nucleon-nucleon (NN) collisions. Many theoretical models have seen that there is a significant contribution of medium response in their $R_{\rm AA}$ predictions for jets with various resolution parameter R [15, 20–22].

The ratio in $R_{\rm AA}$ of jets with larger R to those with smaller R = 0.2, $R_{\rm AA}(R)/R_{\rm AA}(0.2)$, was measured by CMS at high $p_{\rm T}^{\rm jet}$ ($p_{\rm T}^{\rm jet} > 200$ GeV) for R=0.3-1.0 [23]. The data indicated a mild dependence on R in $R_{\rm AA}$. The ALICE [24] and ATLAS [25] collaborations also measured the double ratio at low $p_{\rm T}^{\rm jet}$ ($40 < p_{\rm T}^{\rm jet} < 200$ GeV). The double ratio from ALICE is smaller than unity, whereas the result from ATLAS is larger than unity as shown in Figure 6. While some tensions exist between the ALICE [24] and ATLAS [25] results, notable differences between them include:

1. ALICE measures charged-particle jets, whereas ATLAS measures full jets.
2. Different $\eta^{\rm jet}$ ranges are utilized: $|\eta^{\rm jet}| < 0.9$ - R for ALICE, while ATLAS $|\eta^{\rm jet}| < 2.1$ for all R.
3. Distinct background subtraction methods are applied: ALICE employs a machine learning technique, while ATLAS utilizes the iterative underlying event (UE) subtraction method and a fake-jet rejection method via fragmentation requirement.
4. ALICE measures $R_{\rm AA}$, whereas ATLAS measures $R_{\rm CP}$.

Interpreting the results of the difference in $R_{\rm AA}$ between smaller and larger radii is complicated, as the observable is sensitive to various underlying physics effects. The double ratio being greater than unity could be attributed to factors such as scattered energy recovery at larger radii. Conversely, the double ratio might be smaller than unity if soft particles at larger angles, on average, lose more energy through interactions with the medium. Additionally, one must consider differences in the quark-/gluon-initiated jet fraction between different radii in pp collisions [26]. Similarly, difference in the steepness of the $p_{\rm T}^{\rm jet}$ spectra in pp collisions between different radii [27] also leads to different $R_{\rm AA}$ values, even when assuming no difference in energy loss between them. In future studies, it would be beneficial to decompose various effects and minimize contributing factors in measurements. For instance, R-dependent $R_{\rm AA}$ for γ-tagged jets can reduce color-charge dependence, and utilizing observables such as fractional energy loss, $S_{\rm loss}(p_{\rm T})$, can mitigate $p_{\rm T}$ slope dependence in pp collisions [28].

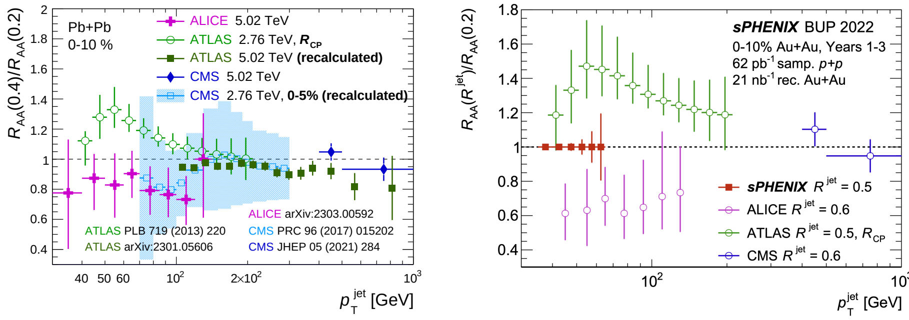


Figure 6: The double ratio, $R_{AA}(R)/R_{AA}(0.2)$, for $R = 0.4$ (left) and $R = 0.6$ or 0.5 (right) for the results of CMS 5.02 TeV [23], CMS 2.76 TeV [29], ATLAS 5.02 TeV [30], ATLAS 2.76 TeV [25], and ALICE 5.02 TeV [24]. The vertical lines and shaded boxes associated with the points represent the combined statistical and systematic uncertainties. The uncertainties of the data points labeled as ‘recalculated’ are calculated by treating the R_{AA} of $R = 0.2$ and R_{AA} of R=0.4 as uncorrelated. The vertical lines associated with the sPHENIX data points represent the projected statistical uncertainties. The figure on the right is reproduced from Ref. [31].

All double ratio results are compared with numerous theoretical models [23–25]. At low-p_T^{jet}, some models align more with ATLAS results, while others favor ALICE results. At high-p_T^{jet}, many of these models show tensions with the CMS results, particularly for jets with larger R. The projection of sPHENIX [31], as shown in Figure 6 (right), will extend into the low-p_T^{jet} region, benefiting from a smaller UE background contribution compared to the LHC. Future measurements from sPHENIX are expected to offer additional insights when combined with existing LHC results.

3 Summary

This proceeding provides an overview of experimental efforts to understand jet-induced medium response in heavy-ion collisions. Over the last few decades, the exploration of jet quenching in high-energy nuclear physics has significantly contributed to our understanding of the modifications of jet properties in a dense medium. Building upon this foundation, the question addressed in more recent years is whether the medium, in turn, undergoes modifications induced by the passage of jets.

In this effort, various experimental results for medium response, measured from RHIC and the LHC, have been discussed. Key observations include the enhancement of soft particles at larger angles, broadening of jet shape, and acoplanarity. Unique observables such as 2-dimensional jet-hadron angular correlations in γ-jet events and the baryon-to-meson ratio are suggested, though current measurements are constrained by statistical limitations. The nuclear modification factor of jets with a larger resolution parameter (R) has been extensively measured at the LHC, raising questions in interpretation and tensions between results, as well as between data and theoretical calculations.

Looking ahead, further precise experimental measurements across various observables will be crucial for both constraining and enhancing our understanding of medium response and the underlying interaction mechanisms of parton-to-QCD medium.

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