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Experimental measurement of medium response and hard-soft correlation

Christopher McGinn[1,*]

[1]Massachusetts Institute of Technology, USA

Abstract. The observation of jet energy loss, or 'quenching', as a result of jet-medium interactions has long been held as a fundamental signature of the hot-and-dense state of matter known as the quark-gluon plasma (QGP). Jet-medium interactions responsible for quenching should also induce perturbations in the QGP, termed medium response, and result in correlations between the hard and soft scales. In these proceedings, recent results sensitive to medium response, such as jet nuclear modification factors for a variety of radius parameters R, jet hadrochemistry measurements, and energy-energy correlator measurements, will be reviewed. In addition, the search for direct evidence of medium response in boson-jet-track correlations will be discussed.

1 Introduction

Collisions of ultrarelativistic heavy ions at the LHC and RHIC are of sufficient energy density and temperature that a new state of matter is formed. This hot QCD matter is characterized by partons deconfined from their traditional colorless hadron configurations, and is commonly called the quark-gluon plasma (QGP). Because the QGP is opaque to color-charge carriers, hard-scattered partons produced in the initial collision should interact with the resulting medium and lose energy in a phenomena known as 'jet quenching'. First proposed by J.D. Bjorken in an unpublished technical report [1], jet quenching has since been seen at RHIC with the suppression of high-p_T hadrons [2, 3], and subsequently at the LHC with centrality-dependent modifications to dijet asymmetry [4]. These measurements established hard-scattered partons as probes of the QGP's fundamental properties.

One QGP phenomena of interest is medium response, or changes in the medium's evolution as a result of energy lost by the hard-scattered parton, potentially manifesting as a wake [5]. After the observation of jet quenching at the LHC, hard-soft correlation studies showed an excess of soft particles distributed at large angles relative to the jet axis, suggesting such a response [6]. Many subsequent studies, such as hadron correlations with high-p_T Z bosons [7], have shown models better agree with the data when they incorporate medium response. However, this cannot be taken as unambiguous evidence of medium response, as the softening fragmentation patterns of quenched jets might mimic this signature. Disentangling modified fragmentation from medium response effects is an experimental challenge, and most statements regarding evidence for medium response remain model dependent.

In these proceedings, recent experimental measurements of medium response and hard-soft correlations are reviewed. Specifically, results on medium modifications to jet spectra

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[*]e-mail: christopher.mc.ginn@cern.ch

as a function of radius parameter R, to jet hadrochemistry, and to energy-energy correlators are discussed, along with the implications for medium response in modeling. Finally, two recent searches for an unambiguous, model-independent signature of medium response via the depletion wake in Z/γ boson+jet+hadron correlations are compared, with suggestions for future searches.

2 Radial scans of jet spectra

Measurements of jet spectra produced in heavy-ion collisions are sensitive to parton-medium interactions. The nuclear modification factor, or R_{AA}, is defined as the ratio of spectra produced in AA with the spectra produced in reference pp collisions, with the denominator scaled for the number of binary nucleon-nucleon collisions. The dependence of the jet R_{AA} on the jet radius parameter R has been shown to be sensitive to the implementation of medium response effects in a number of energy-loss models [8–10]. Therefore, precise measurement of jet R_{AA} as a function of R can constrain medium response on a model-dependent basis.

Fig. 1 shows the R_{AA} radial dependence from CMS, from $R = 0.2$ to $R = 1.0$. Since fluctuations in the underlying event (UE) scale with increasing jet R, reconstruction at the largest R values is challenging. Thus, to scale away UE contributions, large R is restricted to high-p_{T} jets, from 500–1000 GeV. The data shows no dependence on R at this p_{T}, while models do show dependencies depending on the details of medium response effects.

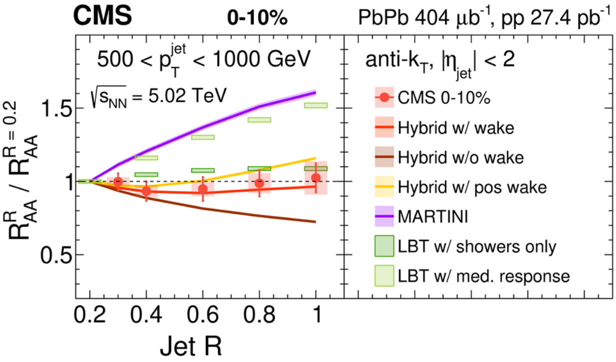

Figure 1. Radial scan of R_{AA} from $R = 0.2$ to $R = 1.0$ in jet p_{T} from 500–1000 GeV as measured by CMS. Data is plotted as red filled circles, with vertical red bars representing statistical uncertainties and shaded boxes representing systematic uncertainties. Models with and without medium response effects are plotted for comparison, per legend. Adapted from Ref. [11].

Recently, radial scans have pushed to lower jet p_{T}. In Fig. 2, results from the ALICE and ATLAS collaborations of R_{AA} ratios for $R = 0.6/R = 0.2$ are plotted as a function of jet p_{T}. The ALICE results employ a novel machine-learning background subtraction enabling reconstruction down to low jet p_{T} [12]. There is an enhanced suppression of $R = 0.6$ jets compared to $R = 0.2$ jets, with the R_{AA} ratio increasinging from ~0.6-0.7 with jet p_{T}. This result is consistent within one standard deviation of most models comparisons, emphasizing the need to improve on current uncertainties to distinguish between different physics mechanisms [1].

By contrast, in the right panel of Fig. 2 the R_{AA} ratio of $R = 0.6$ to $R = 0.2$ for leading and subleading jets from dijet pairs is measured by ATLAS. While the data covers a

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[1] A new radial scan of R_{AA} from ALICE is available, consistent with this result. See poster by Nadine Gruenwald.

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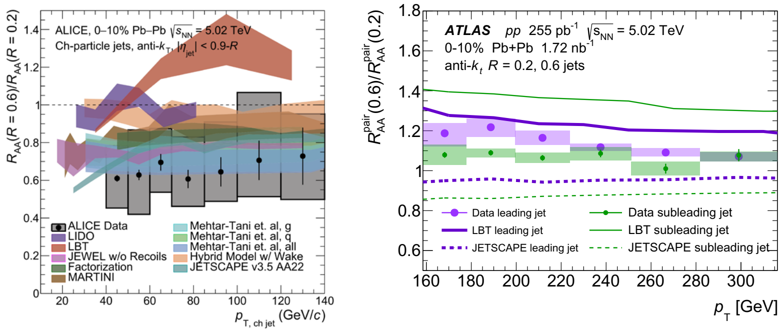

Figure 2. Left: Ratio of $R = 0.6$ to $R = 0.2$ R_{AA} as a function of jet p_T as measured by ALICE. Data is plotted as black filled circles, with vertical bars representing statistical uncertainties and filled grey boxes representing systematic uncertainties. Comparisons with models are plotted, per legend. Adapted from Ref. [12]. Right: Leading (purple filled circles) and subleading (green filled circles) jet R_{AA} ratios of $R = 0.6$ to $R = 0.2$ as a function of jet p_T as measured by ATLAS. Vertical bars represent statistical uncertainties and shaded boxes represent systematic uncertainties. Adapted from Ref. [13].

slightly higher kinematic range in p_T than the ALICE measurement, it is notable that a reduced suppression is shown in $R = 0.6$ compared to $R = 0.2$ jets. This is the opposite of the radial dependence seen in the ALICE data. There are a number of caveats in making this comparison: ALICE measures charged-particle jets compared to charged+neutral particles in ATLAS, the ALICE selection is inclusive compared to a dijet selection in ATLAS, and the pseudorapdiity η differs. Nevertheless, this discrepancy of roughly two standard deviations should be understood for future extraction of medium response properties.

3 Jet hadrochemistry

Another signature of medium response is modified jet hadrochemistry, as proposed in Ref. [14]. Specifically, medium response should enhance the ratio of protons to pions in AA compared to pp collisions. The enhancement will increase with distance from the jet axis and is explained by the coalescence of medium excitations. Notably, medium response is not the only mechanism for hadrochemistry modification. Enhanced parton splittings without response can also produce this signature [15].

Jet hadrochemistry results from STAR and ALICE offer new insights into medium effects at RHIC and LHC energies [2]. STAR results are for jet R of 0.2, 0.3, and 0.4, and study constituents as a function of p_T and distance from jet axis Δr. In-jet proton-to-pion ratios in AuAu show no significant disagreement with pp data. This result, however, is restricted to Δr less than 0.3. Ref. [14] predicts strongest enhancements beyond the jet cone.

ALICE proton-to-pion ratio results are for $R = 0.4$ jets with p_T ranging from 60–140 GeV, as a function of constituent p_T only. In these results, an enhancement in PbPb ratio is seen relative to the pp reference data, of roughly two standard deviations. Whether the difference with respect to STAR is a result of differences in QGP properties as produced at RHIC versus LHC energies, or a consequence of something else is as yet unknown. In this regard, subsequent analysis of ALICE data as a function of constituent Δr with respect to the jet axis to test if the enhancement increases as expected could be invaluable.

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[2] For STAR results, see talk from Gabriel Dale-Gau. For ALICE results, see talk from Sierra Cantway.

4 Energy-energy correlators

Recent theoretical developments have resulted in a renewed interest in a class of observables referred to as energy-energy correlators (EECs) [16]. With studies performed in CMS open data demonstrating the feasability of measurement [17], EECs are now studied in hadronic environments with modern detectors of high spatial resolution. CMS has recently produced a measurement [3] of EECs in PbPb and pp reference collisions [18]. Specifically, the p_T-weighted two-particle correlator is measured as a function of Δr between constitutents, and the nuclear modification is extracted by taking a ratio of PbPb and pp distributions.

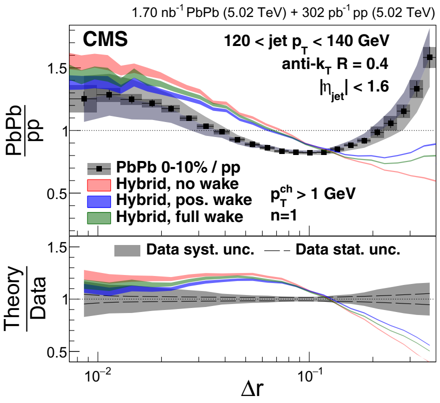

Figure 3. Measurement of nuclear modification of EECs in PbPb relative to pp reference by CMS. The data is plotted as black filled boxes, with vertical bars representing statistical uncertainties and shaded boxes representing systematic uncertainties. Comparisons with the Hybrid model with and without medium response effects are plotted [19]. Adapted from Ref. [18].

Fig. 3 shows the resulting nuclear modification with comparison to the Hybrid model with no medium response effects, positive wake only, and full wake with positive and negative contributions. Notably the large Δr behavior observed in data is not captured in any modeling scenario, although better agreement qualitatively is observed as wake effects are incorporated.

5 Search for the depletion wake

Thus far, all signatures of medium response discussed are of the category “sensitive but not unambiguous”; in other words, medium response could explain the data, but not exclusively. The search for the depletion wake by ATLAS and CMS, however, is uniquely unambiguous. While medium-induced gluon radiation and enhanced partonic splitting can create excesses in energy or particle multiplicities in the final state, neither cannot create a depletion, as proposed in Ref. [20]. The left panel in Fig. 4 is an ATLAS study using γ+jet+hadron events, searching for such a depletion of charged hadrons in the γ direction. By taking ratios of hadron production in the γ-going direction as a function of photon-jet balance $x_{J\gamma}$, with which the magnitude of medium response scales, a depletion should emerge. However, the search was not statistically sensitive, and instead a limit was set on the magnitude of medium response in central PbPb [21].

For comparison, the right panel in Fig. 4 shows the results of a similar search in the Z+hadron channel from CMS [22]. Eliding the jet selection and $x_{J\gamma}$ binning, this analysis

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[3] ALICE preliminary EEC results are qualitatively consistent with the CMS result. See talk by Ananya Rai.

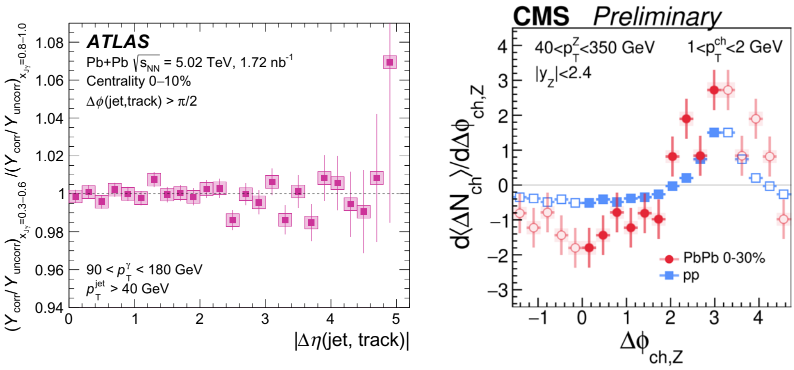

Figure 4. Left: γ+jet+hadron correlations ratio of γ-jet balance $x_{J\gamma}$ bin 0.3–0.6 to 0.8–1.0, as a function of $|\Delta\eta(\text{jet, track})|$. The data is plotted as pink filled circles, with vertical bars representing statistical uncertainties and shaded boxes representing systematic uncertainties. Adapted from Ref. [21]. Right: Z+hadron correlations in 0–30% PbPb and pp reference collisions. PbPb data is plotted as red circles while pp data is plotted as blue boxes. Vertical bars represent statistical uncertainties while shaded boxes around points represent systematic uncertainties. Adapted from Ref. [22].

instead compared the shapes of self-normalized Z boson correlations with hadrons in PbPb and pp, and found a significant shape distortion in the Z boson direction in azimuthal angle and rapidity. This modification cannot be reproduced with models in the absence of medium response effects and is attributed to the depletion wake. In contrast with the ATLAS search in γ+jet+hadron correlations, the absence of an explicit jet p_T selection allows for the inclusion of events with maximally quenched jets, enhancing potential signal. Follow-up study is needed in both channels to fully understand the depletion wake.

6 Conclusion

Studies of hard-soft correlations at RHIC and the LHC have produced a wealth of data informing our current understanding of QGP-induced jet energy loss and possible medium response effects. Radial scans of jet spectra, study of jet hadrochemsitry, energy-energy correlator nuclear modification, and searches for the depletion wake represent just a few of the recent measurements. Future measurements, with a particular focus on isolating and precisely characterizing the depletion wake, are a key part of both constraining jet energy loss models and improving our understanding of the complex interplay of processes that manifest as ‘jet quenching’.

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