Measurements of jets in heavy ion collisions

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Abstract. The Quark Gluon Plasma (QGP) is created in high energy heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). This medium is transparent to electromagnetic probes but nearly opaque to colored probes. Hard partons produced early in the collision fragment and hadronize into a collimated spray of particles called a jet. The partons lose energy as they traverse the medium, a process called jet quenching. Most of the lost energy is still correlated with the parent parton, contributing to particle production at larger angles and lower momenta relative to the parent parton than in proton-proton collisions. This partonic energy loss can be measured through several observables, each of which give different insights into the degree and mechanism of energy loss. The measurements to date are summarized and the path forward is discussed.

1 Introduction

A hot, dense liquid of quarks and gluons called the Quark Gluon Plasma (QGP) is formed when heavy ions collide at relativistic speeds. High energy partons scattered early in the collision can be used as probes of the medium. In high energy collisions where a QGP is not formed, such as $p+p$ collisions, these hard scattered partons will fragment into a collimated spray of particles called a jet. Partons traversing a QGP can lose energy either radiatively or through collisions with medium partons. These interactions lead to jets which are broader on average than those in $p+p$ collisions, with fewer particles carrying a large fraction of the jet's energy, $z = p_T/E_{jet}$, and more particles at lower z.

This picture of partonic energy loss, concurrent with broadening of the jet and softening of the fragmentation function, has been qualitatively confirmed by several measurements [1]. Recently a number of novel observables, mostly used in particle physics for distinguishing between quark and gluon jets, have been investigated as a means for measuring the modifications of the struture of jets through medium interactions in greater detail.

While there are extensive measurements, the constraints of the properties of the QGP from measurements of jets are largely informed by only a handful of measurements of the modifications of single particle spectra [2]. As the field works to measure jet observables to higher precision, it is worth remembering some of the lessons from particle physics about the complications of measurements of jets. The background in heavy ion collisions is very large and the experimental techniques may lead to a number of biases in the results.

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2 Measurements of jets

In $p+p$ collisions, hard partons scattered early in the collision fragment into collimated sprays of particles called jets. As high energy partons traverse the medium, they lose energy though emission of gluons and collisions with medium partons. This lost energy retains most of its spatial correlations with the parent parton, so jet quenching will result in a suppression of final state hadrons carrying a large fraction of the parton's momentum and an enhancement in particles carrying a small fraction of the parton's momentum. On average the final state hadrons will be somewhat less correlated with the parent parton's momentum than before medium interactions, resulting in a broadening of the distribution of jet constituents.

2.1 Energy loss

The most straightforward way to measure partonic energy loss is through the measurement of the nuclear modification factor

$$R_{AA} = \frac{\sigma^{NN}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta} \tag{1}$$

where σ^{NN} is the integrated nucleon-nucleon cross section, $\langle N_{coll} \rangle$ is the average number of binary nucleon-nucleon collisions for a given range of impact parameter, N_{AA} is the number of particles, p_T is the transverse momentum, η is the pseudorapidity, and σ_{pp} is the inelastic cross section in $p+p$ collisions. If nucleus-nucleus collisions were simply a superposition of nucleon-nucleon collisions, R_{AA} would be approximately one because the high p_T particle cross section would scale with the number of binary collisions.

The R_{AA} has been measured for several different final state hadrons, ranging in mass from pions [3, 4] to B mesons [5], and the production rate of all of these colored probes are suppressed at high momenta in central heavy ion collisions. In contrast, the medium is nearly transparent to electroweak probes. The R_{AA} of reconstructed jets is also substantially suppressed [6–8]. Even heavy quarks are suppressed at comparable levels to light hadrons, as shown by measurements of single final state particles [5, 9, 10] and reconstructed jets [11–13]. This energy loss has also been seen using dihadron correlations [14–16], hadron-jet correlations [17, 18], the azimuthal anisotropies of jets [19, 20], and di-jet energy asymmetries [21–23].

2.2 Fragmentation

The most direct observations of the broadening of the distribution of jet constituents and the softening of those constituents is through measurements of the fragmentation function. At leading order, isolated direct photons are produced in inverse Compton scattering, q+g → q+γ. The energy of the outgoing quark jet will equal the energy of the photon. Fragmentation functions can be measured through this process and demonstrate both a suppression of high $z = p_T/E_{jet}$ hadrons and an enhancement of low z processes [24]. Measurements of fragmentation functions using reconstructed jets also show this suppression [25–27]. As for energy loss, modified fragmentation in heavy ion collisions has been observed through high momentum di-hadron correlations [28], jet-hadron correlations [29, 30], and measurements of di-jet energy asymmetries [23].

Partonic energy loss is expected to be path length dependent. The path length can be varied using measurements of jets relative to the reaction plane. Studies of jet-hadron correlations with the angle of the jet relative to the reaction plane varied found no path length dependence within uncertainties [31]. This can be explained by theoretical models which include jet-by-jet fluctuations in the amount of energy lost [32], meaning that while on average jets traveling out-of-plane will lose more energy and

be more modified by interactions with the medium than those traveling in-plane because they see more medium, a particular jet going out-of-plane may lose less energy than a particular jet going in-plane. This indicates that fluctuations such as these can have a large impact on observables and may be more important than the path length dependence of energy loss in some cases.

2.3 Jet structure and new observables

Recent studies have begun investigating new observables to see if they may be more sensitive to medium modifications of jets in the medium than traditional observables. Many of these observables are used in particle physics for separating quark and gluon jets. The jet girth, g, is given by

$$g = \sum_i \frac{p_T^i}{p_T^{jet}} |r_i|, \tag{2}$$

where r_i is the angular distance between the jet axis and particle i. The dispersion is given by

$$p_T^D = \sqrt{\Sigma_i p_{T,i}^2 / \Sigma_i p_{T,i}} \tag{3}$$

where $p_{T,i}$ is the momentum of a constituent and the sum is over the constituents. The girth and the dispersion both are measures of the width of the jet. Measurements by ALICE indicate that, if anything, surviving jets in $Pb + Pb$ collisions are narrower than in $p+p$ collisions [33]. This apparent contradiction with the observations of modified fragmenation can be explained by a bias in the surviving jets reconstructed by a jet finder. Jets which are reconstructed at high momenta may be more likely to be unmodified or to have been quark jets, which are narrower. It is important to note that nearly every observable is biased towards a particular selection of jets, so it is necessary to look at multiple observables to get a complete picture of partonic energy loss.

LeS ub, the difference between the momenta of the leading and subleading jet constituents, has also been measured in $Pb + Pb$ collisions and is consistent with expectations for both unmodified jets and jets which have interacted with the medium [33]. This observable is robust to a high background but may not be sensitive. Jet grooming, a technique to measure the substructure of jets, is also under investigation [34, 35], as are measurements of the jet mass [36, 37].

3 The path forward

Several important steps were proposed in [1] in order to determine the properties of the medium with higher precision from measurements of jets. The main improvements required are to understand the biases in measurements, make more quantitative measurements, make more quantitative comparisons to theory, and to come to an agreement on the treatment of background in heavy ion collisions. Each of these points is summarized below.

3.1 Understand bias

The techniques used for the suppression and subtraction of background impose biases in the results. Even the use of a jet finder may bias the sample towards less modified jets. This is unavoidable because of the large backgrounds in central heavy ion collisions, but the discussions of these techniques should not be relegated to the method section. Attempts to correct for these biases often use jets from PYTHIA embedded in a heavy ion collision. Jets in heavy ion collisions fragment differently so such corrections may skew the results. Rather than trying to correct for such biases, the bias should be considered part of the definition of the measurement. Theoretical calculations should apply the same techniques in order to be comparable to the data.

3.2 An agreement on the treatment of background

The history of the definition of jets in particle physics provides some useful lessons for measurements in heavy ion collisions. After years of different definitions of jets in theory and experiment, the Snowmass Accord postulated that a good jet finding algorithm must be both infrared and colinear safe, meaning that the same jet would be found in the presence of either soft radiation (which cannot be calculated to high precision perturbatively) and if a leading parton had a colinear splitting [38]. Seeded cone algorithms were replaced by sequential algorithms [39]. The definition of the jet is a combination of the jet finding algorithm and the resolution parameter, which limits the size of the jet.

There are several experimental approaches to the treatment of background. For example, ALICE explicitly requires a jet to have a constituent of at least 5 GeV/c [6] and ATLAS requires jets to be matched to a track jet consisting of high momentum tracks [7]. In the limit of high energy jets, these algorithms appear to give consistent results, but at lower energies they may not. An example of this is the tension between ALICE, ATLAS, and CMS measurements of jet R_{AA} [1]. Since these background subtraction and suppression algorithms impose a bias, a similar approach to that in particle physics is probably necessary, that the background suppression and subtraction techniques be considered part of the definition of a jet.

Experimentally, the operational distinction between the jet signal and the background is based on whether or not final state hadrons retain some short range correlations with the parent parton, typically $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \le 1$. Theoretically, it is less clear what should be considered a background particle. We therefore called for a meeting in [1] to discuss the definition of the background and come to an agreement between theorists and experimentalists on the definition and treatment of the background.

3.3 Make more quantitative comparisons to theory

The best constraint of the properties of the medium to date comes from the JET collaboration [2]. In this study, the partonic energy loss of a hard parton traveling through a static brick of QGP was calculated using several different theoretical models for partonic energy loss. These calculations were systematically compared to measurements of single hadron R_{AA} in order to constrain $\hat{q}$, the partonic energy loss in the medium squared divided by the path length. While this is a monumental achievement, theoretical developments allowing more accurate calculations of partonic energy loss and comparisons to other observables would likely constrain the properties of the medium better.

The JETSCAPE collaboration is working on developing realistic event generators combining realistic hydrodynamical simulations with realistic partonic energy loss models. The final stage of the JETSCAPE project will be to use these models to do a Bayesian analysis in order to constrain the properties of the QGP. Such analyses have been done incorporating measurements of single hadron spectra and azimuthal anisotropies [40, 41]. These Bayesian analyses require detailed accounting of systematic uncertainties and their correlations with each other and possibly with other experiments. This detailed accounting of systematic uncertainties is not currently the norm in the field, but without it we cannot optimize our constraints of QGP properties.

3.4 Make more differential measurements

Since the field to date has not had a full simulation of jets in a hydrodynamical fluid, it has not yet been possible to apply experimental methods to a model to see which observables are least sensitive to the background and most sensitive to the properties of the QGP. In the era of JETSCAPE such studies will be possible. It may turn out that some of the new observables to measure jet structure are the most sensitive, however, it is still unclear. It is important that the field do these detailed studies to

find the best observables and to stop focusing on observables which turn out to be insensitive to the properties of the QGP. Measurements of jets by the sPHENIX experiment will also be important for constraining the properties of the medium at RHIC energies.

4 Conclusions

Jets are used to measure partonic energy loss, a process which can lead to constraints on the properties of the QGP. An impressive array of measurements have demonstrated that the theoretical picture of partonic energy loss in the medium is correct, however, very few of these measurements have yet informed quantitative constraints on the properties of the QGP. Forthcoming theoretical developments will allow the incorporation of jet observables into Bayesian analyses so that they can be used to constrain QGP properties. However, to do this successfully requires an agreement between theorists and experimentalists on the appropriate treatment of the background. It furthermore requires an understanding of measurement biases and the sensitivities of various observables to medium properties. It will also require careful reporting of systematic uncertainties and their correlations. We will only be able to make precision constraints of the properties of the medium by doing these things.

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