Jets in heavy ion collisions

Christine Nattrass

Assistant Professor, Physics Department, University of Tennessee, Knoxville, TN, USA-37996

E-mail: `christine.nattrass@utk.edu`

Abstract. High energy collisions of heavy nuclei permit the study of nuclear matter at temperatures and energy densities so high that the fundamental theory for strong interactions, QCD, predicts a phase transition to a plasma of quarks and gluons. This matter, called a Quark Gluon Plasma (QGP), has been studied experimentally for the last decade and has been observed to be a strongly interacting liquid with a low viscosity. High energy partons created early in the collision interact with the QGP and provide unique probes of its properties. Hard partons fragment into collimated sprays of particles called jets and have been studied through measurements of single particles, correlations between particles, and measurements of fully reconstructed jets. These measurements demonstrate partonic energy loss in the QGP and constrain the QGP's properties. Measurements of the jet structure give insight into the mechanism of this energy loss. The information we have learned from studies of jets and challenges for the field will be reviewed.

1. Introduction

Jets are formed when a parton in a nucleon or nucleus scatters off of a parton in another nucleon or nucleus. After the scattering, the parton forms a parton shower which then hadronizes, leading to a collimated spray of hadrons. Jet production from collisions with a sufficiently high momentum transfer can be calculated perturbatively. The majority of hard scatterings are 2→2, meaning that a jet has a partner jet approximately 180° away in azimuth. Partons interacting with the Quark Gluon Plasma (QGP) formed in high energy nucleus-nucleus collisions may lose energy before the formation of the final hadrons, a process called jet quenching. Jet quenching is generally understood to occur dominantly through medium-induced gluon bremsstrahlung, with some contribution from collisional energy loss, leading to a broadening and softening of the distribution of particles in the jet. Quenching can be studied by measuring jets and the hadrons they comprise and this can be used to determine the properties of the QGP.

Jet quenching can be measured in heavy ion collisions using single high momentum hadrons, correlations between high momentum hadrons, fully reconstructed jets, and correlations between fully reconstructed jets and either other jets or hadrons. These measurements indicate that jets in heavy ion collisions are broadened and their fragmentation softened. However, a greater understanding of the bias in the jet population imposed by our measurement techniques and of cold nuclear matter effects is required to fully understand partonic energy loss in the QGP.

2. Single particle nuclear modification factor R_{AA}

Jet suppression can be quantified using measurements of the nuclear modification factor, R_{AA}

$$R_{AA} = \frac{dN^{AA}/dp_T}{T_{AA}d\sigma^{p+p}/dp_T} \tag{1}$$

where dN^{A+A}/dp_T is the spectrum of particles in $A+A$, $d\sigma^{pp}/dp_T$ is the cross section in $p+p$ collisions, respectively, and $T_{AA} = N_{coll}/\sigma_{inel}^{pp}$ is nuclear overlap integral, the number of binary nucleon-nucleon collisions in an $A+A$ collision divided by the inelastic cross section in $p+p$ collisions. An $R_{AA} < 1$ indicates suppression and an $R_{AA} > 1$ indicates enhancement. Colored probes are expected to lose energy in the medium, but the QGP should be transparent to electromagnetic probes. At RHIC the direct photon R_{AA} is consistent with 1, indicating no energy loss in the medium [1]. All hadrons (unidentified hadrons [2–4], π^0 [5], η [6], ϕ [7], protons [8], J/ψ [9], ω [10], and $K^{\pm}$ [8]) and electrons from heavy flavor decays [11] have an $R_{AA} < 1$ for $p_T > 4$ GeV/c and approach a common value of $R_{AA} \approx 0.2$ at high momenta, consistent with substantial jet suppression. At the LHC single hadrons are also observed to be suppressed [12–14] while electromagnetic probes including direct photons [15], the W [16], and the Z [17] have an R_{AA} consistent with one.

Energy loss of a parton in the medium is defined theoretically by $\hat{q} = Q^2/L$ where Q is the momentum transfer from the parton to the medium and L is the path length traversed by the parton [18]. The single hadron R_{AA} was used by the JET collaboration to constrain the value of $\hat{q}$ to 1.2 ± 0.3 GeV^2/fm in Au+Au at $\sqrt{s_{NN}} = 200$ GeV and 1.9 ± 0.7 GeV^2/fm in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for a 10 GeV/c quark at $\tau_0 = 0.6$ fm/c [19].

3. Measurements of reconstructed jets

All experiments primarily use the anti-k_T algorithm [20] to identify jet candidates, but there are several approaches to address the large combinatorial background from unrelated processes, called the underlying event, in heavy ion collisions. Without any background suppression and subtraction techniques, jet candidates may either be distorted by the inclusion of particles from the underlying event or be comprised entirely of particles from the underlying event. For R_{AA} measurements ALICE suppresses the background by requiring a hadron with $p_T > 5$ GeV/c to be included in the jet, measuring the average background by drawing random cones in the event, and subtracting the average background from the reconstructed jet energy [21]. ATLAS [21] and CMS [22] both have iterative procedures, first finding jet candidates, then calculating the estimated background by omitting high energy jet candidates from the background subtraction. For R_{AA} measurements ATLAS additionally requires calorimeter jets to be matched to a track jet comprised of tracks above 4 GeV/c. When the R_{AA} from each of these measurements is compared, the ALICE and CMS measurements are comparable and all measurements are in agreement at 100 GeV/c, but the ATLAS R_{AA} is roughly twice as high as the other measurements at 60 GeV/c. This is likely due to the different biases imposed by the methods.

The di-jet asymmetry is defined as the difference between the momenta of the leading and subleading jets divided by the sum of the momenta:

$$A_j = \frac{p_T^{leading} - p_T^{subleading}}{p_T^{leading} + p_T^{subleading}}. \tag{2}$$

An alternate definition uses the energies of the jets instead of the momenta. Even in $p+p$ collisions, dijets' energies will not be perfectly balanced all of the time and there will be some spread of the distribution of A_J about zero. A_J in $A+A$ collisions is therefore compared to that in $p+p$ collisions. In $A+A$ collisions, the leading and subleading jets' energies are even more

imbalanced, with the distribution of A_J no longer even centered about zero, demonstrating that jets are quenched in the QGP [23, 24]. When lower momentum particles are included in the reconstructed jets, the energy balance is restored [25]. This is one of the indications that the fragmentation function is softened in heavy ion collisions.

Fragmentation functions are the distribution of particles in a jet, usually measured as a function of $z = p_T^{hadron}/E_{jet}$ or $\xi = ln(1/z)$, and can be measured directly usiung fully reconstructed jets. These measurements also indicate that the fragmentation function is softened [26–28].

4. Di-hadron correlations

Jets can also be studied by looking at the correlations between two sufficiently high mometum hadrons. A high momentum trigger particle is used to define the coordinate system and the distribution of particles relative to that trigger particle is measured. There is a near-side peak arising from the same jet as that which created the trigger particle and an away-side peak centered around 180° away arising from the partner jet. These measurements allow studies of lower momentum jets but have a fairly low signal to background. Early studies were useful for demonstrating jet suppression at RHIC [29–33,33,34], before full jet reconstruction was possible. These measurements have a large combinatorial background which is correlated with the signal, quantified by the Fourier coefficients of the decomposition of the distribution of particles relative to the reaction plane, v_n. At low momenta, the non-zero v_n are understood to arise largely due to hydrodynamical flow of the medium [35–37]. A large fraction of published studies did not take odd v_n into account for the background subtraction, which does not qualitatively change the interpretation at high momenta (where the signal to background ratio is high) but substantially modifies the interpretation at lower momenta. Lower momenta data [38, 39] have been reanalyzed using a different background subtraction technique [40]. The reanalyzed data demonstrate that the away-side peak is strongly suppressed in Au+Au collisions and somewhat broader than that in d+Au collisions [41]. This is in contrast to the complete suppression seen at intermediate momenta [30] and the "Mach cone" structure seen at lower momenta [33,33,38,42,43], but consistent with other measurements demonstrating a softening and broadening of the fragmentation function.

5. Issues with the definition and bias

In order to compare to theory, even in elementary collisions, it is necessary for both theory and experiment to use the same jet finding algorithm [44]. The parton shower and the process of hadronization can move particles in or out of the jet cone. Even in p+p collisions, hadronization must be taken into account in perturbative calculations of jet cross sections in order to describe the data [45]. A measurement of a jet therefore should not be thought of as a direct measurement of the parton.

In addition, the measurement techniques introduced to suppress and subtract background in heavy ion collisions, introducing a bias in the surviving population of jets. This bias should be considered part of the definition of the measurement. Most measurements focus on narrow cone radii ($R < 0.3$) and either explicitly or implicitly require hard fragments. Since the background scales with the area of the jet, jets with narrow cone radii have less background and fewer fluctuations in the background. Selection of harder particles also reduces the background. However, these approaches bias the jet population towards quark jets rather than gluon jets. Measurements of jets in e^+e^- collisions indicate that gluon jets are broader and fragment into more, softer particles than quark jets [46, 47]. Even though there are more gluon jets produced, the bias towards quark jets may be significant in some kinematic regions. The selection of jets which fragment harder and into narrow cones also imposes a survivor bias, where jets that are retained in the population are less likely to have interacted significantly with the medium. By

looking only at jets which do not look like the background, we are likely missing the most severely modified jets. These biases and their impact on the jet population needs to be understood better.

6. Cold nuclear matter effects

The goal of measurements of jets in heavy ion collisions is to look for the impact of hot nuclear matter on the parton, so any possible modifications of jet production in cold nuclear matter need to be understood for proper interpretation of measurements in $A+A$ collisions. However, there are a number of indications of cold nuclear matter effects, including indications of collective effects [48–50], suppression of the J/ψ [51] at midrapidity, and suppression of particles from the decays of hadrons containing heavy quarks at forward rapidities [52, 53]. The minimum bias nuclear modification factors in p+Pb and d+Au collisions, R_{pPb} and R_{dAu}, are consistent with one at midrapidity for single charged hadrons [54–57] and fully reconstructed jets [58–60], indicating no cold nuclear matter effects at midrapidity. ATLAS studies at forward rapidities indicate a centrality dependence that cannot be fully explained by a bias in the centrality selection [58, 59]. This indicates that cold nuclear matter effects are not fully understood and measurements need to be interpreted with care, particularly at forward rapidities.

7. Conclusions

Jet quenching is observed through measurements of the single particle R_{AA}, measurements of di-hadron correlations, and measurements of fully reconstructed jets. These measurements indicate that jets are broadened and their fragments are softened in heavy ion collisions relative to jets in p+p collisions, as expected if partons lose energy through gluon bremsstrahlung or collisional energy loss. Our understanding of partonic energy loss has improved dramatically with the wealth of measurements and theoretical calculations, particularly through the quantitative constraint of $\hat{q}$ by the JET collaboration.

However, the biases in jet definitions imposed by the measurement techniques make it difficult to directly compare results for different experiments and to interpret the results. Nearly all measurement techniques bias the jet population towards jets which have had fewer interactions with the medium and towards quark jets. These effects need to be understood better quantitatively. This requires a significant effort from both theorists and experimentalists to understand the impact of the measurement technique. Furthermore, the observation of cold nuclear matter effects warrants further study in order to properly interpret results from hot nuclear matter.

References

 [1] Afanasiev S *et al.* (PHENIX) 2012 *Phys. Rev. Lett.* **109** 152302 (*Preprint* 1205.5759)
 [2] Adams J *et al.* (STAR) 2003 *Phys.Rev.Lett.* **91** 172302 (*Preprint* nucl-ex/0305015)
 [3] Adler S *et al.* (PHENIX) 2003 *Phys.Rev.Lett.* **91** 072301 (*Preprint* nucl-ex/0304022)
 [4] Back B *et al.* (PHOBOS) 2004 *Phys.Rev.* **C70** 061901 (*Preprint* nucl-ex/0406017)
 [5] Adare A *et al.* (PHENIX) 2008 *Phys. Rev. Lett.* **101** 232301 (*Preprint* 0801.4020)
 [6] Adare A *et al.* (PHENIX) 2010 *Phys. Rev.* **C82** 011902 (*Preprint* 1005.4916)
 [7] Adare A *et al.* (PHENIX) 2016 *Phys. Rev.* **C93** 024904 (*Preprint* 1509.06337)
 [8] Adare A *et al.* (PHENIX) 2013 *Phys. Rev.* **C88** 024906 (*Preprint* 1304.3410)
 [9] Adare A *et al.* (PHENIX) 2007 *Phys. Rev. Lett.* **98** 232301 (*Preprint* nucl-ex/0611020)
[10] Adare A *et al.* (PHENIX) 2011 *Phys. Rev.* **C84** 044902 (*Preprint* 1105.3467)

[11] Adare A *et al.* (PHENIX Collaboration) 2011 *Phys.Rev.* **C84** 044905 (*Preprint* 1005.1627)

[12] Aamodt K *et al.* (ALICE) 2011 *Phys.Lett.* **B696** 30–39 (*Preprint* 1012.1004)

[13] Chatrchyan S *et al.* (CMS) 2012 *Eur.Phys.J.* **C72** 1945 (*Preprint* 1202.2554)

[14] 2016 Measurement of the charged particle nuclear modification factor in PbPb collisions at sqrt(sNN) = 5.02 TeV Tech. Rep. CMS-PAS-HIN-15-015 CERN Geneva URL cds.cern.ch/record/2155301

[15] Chatrchyan S *et al.* (CMS) 2012 *Phys. Lett.* **B710** 256–277 (*Preprint* 1201.3093)

[16] Chatrchyan S *et al.* (CMS) 2012 *Phys. Lett.* **B715** 66–87 (*Preprint* 1205.6334)

[17] Chatrchyan S *et al.* (CMS) 2011 *Phys. Rev. Lett.* **106** 212301 (*Preprint* 1102.5435)

[18] Salgado C A and Wiedemann U A 2003 *Nucl. Phys.* **A715** 783–786 (*Preprint* hep-ph/0209025)

[19] Burke K M *et al.* (JET) 2014 *Phys.Rev.* **C90** 014909 (*Preprint* 1312.5003)

[20] Cacciari M, Salam G P and Soyez G 2008 *JHEP* **04** 063 (*Preprint* 0802.1189)

[21] Adam J *et al.* (ALICE) 2015 *Phys.Lett.* **B746** 1–14 (*Preprint* 1502.01689)

[22] Khachatryan V *et al.* (CMS) 2016 (*Preprint* 1609.05383)

[23] Aad G *et al.* (ATLAS) 2010 *Phys.Rev.Lett.* **105** 252303 (*Preprint* 1011.6182)

[24] Chatrchyan S *et al.* (CMS) 2011 *Phys. Rev.* **C84** 024906 (*Preprint* 1102.1957)

[25] Adamczyk L *et al.* (STAR) 2016 (*Preprint* 1609.03878)

[26] Aad G *et al.* (ATLAS) 2014 *Phys.Lett.* **B739** 320–342 (*Preprint* 1406.2979)

[27] Chatrchyan S *et al.* (CMS) 2014 *Phys.Rev.* **C90** 024908 (*Preprint* 1406.0932)

[28] Chatrchyan S *et al.* (CMS) 2012 *JHEP* **1210** 087 (*Preprint* 1205.5872)

[29] Adler C *et al.* (STAR) 2003 *Phys.Rev.Lett.* **90** 082302 (*Preprint* nucl-ex/0210033)

[30] Adams J *et al.* (STAR) 2003 *Phys. Rev. Lett.* **91** 072304 (*Preprint* nucl-ex/0306024)

[31] Adams J *et al.* (STAR) 2004 *Phys.Rev.Lett.* **93** 252301 (*Preprint* nucl-ex/0407007)

[32] Adams J *et al.* (STAR) 2006 *Phys.Rev.Lett.* **97** 162301 (*Preprint* nucl-ex/0604018)

[33] Adare A *et al.* (PHENIX) 2007 *Phys.Rev.Lett.* **98** 232302 (*Preprint* nucl-ex/0611019)

[34] Adler S *et al.* (PHENIX) 2006 *Phys.Rev.* **D74** 072002 (*Preprint* hep-ex/0605039)

[35] Abelev B *et al.* (STAR) 2009 *Phys. Rev.* **C80** 064912

[36] Agakishiev G *et al.* (STAR) 2012 *Phys. Rev.* **C85** 014903

[37] Abelev B *et al.* (STAR) 2010 *Phys. Lett.* **B683** 123–128

[38] Agakishiev H *et al.* (STAR) 2010 (*Preprint* 1010.0690)

[39] Agakishiev H *et al.* (STAR) 2014 *Phys. Rev.* **C89** 041901

[40] Sharma N, Mazer J, Stuart M and Nattrass C 2016 *Phys. Rev.* **C93** 044915 (*Preprint* 1509.04732)

[41] Nattrass C, Sharma N, Mazer J, Stuart M and Bejnood A 2016 *Phys. Rev.* **C94** 011901 (*Preprint* 1606.00677)

[42] Adare A *et al.* (PHENIX) 2008 *Phys.Rev.* **C77** 011901 (*Preprint* 0705.3238)

[43] Abelev B *et al.* (STAR) 2010 *Phys.Rev.Lett.* **105** 022301 (*Preprint* 0912.3977)

[44] Huth J E *et al.* 1990 *1990 DPF Summer Study on High-energy Physics: Research Directions for the Decade (Snowmass 90) Snowmass, Colorado, June 25-July 13, 1990* pp 0134–136 URL http://lss.fnal.gov/cgi-bin/find_paper.pl?conf-90-249

[45] Abelev B *et al.* (ALICE) 2013 *Phys.Lett.* **B722** 262–272 (*Preprint* 1301.3475)

[46] Akers R *et al.* (OPAL) 1995 *Z. Phys.* **C68** 179–202

[47] Abreu P *et al.* (DELPHI) 1996 *Z. Phys.* **C70** 179–196

[48] Adam J *et al.* (ALICE) 2016 *Phys. Lett.* **B753** 126–139 (*Preprint* 1506.08032)

[49] Khachatryan V *et al.* (CMS) 2015 *Phys. Rev. Lett.* **115** 012301 (*Preprint* 1502.05382)

[50] Aad G *et al.* (ATLAS) 2014 *Phys. Rev.* **C90** 044906 (*Preprint* 1409.1792)

[51] Adare A *et al.* (PHENIX) 2013 *Phys. Rev. Lett.* **111** 202301 (*Preprint* 1305.5516)

[52] Adare A *et al.* (PHENIX) 2012 *Phys. Rev. Lett.* **109** 242301 (*Preprint* 1208.1293)

[53] Adare A *et al.* (PHENIX) 2014 *Phys.Rev.* **C89** 034915 (*Preprint* 1311.1427)

[54] Adler S S *et al.* (PHENIX) 2007 *Phys. Rev. Lett.* **98** 172302 (*Preprint* nucl-ex/0610036)

[55] Abelev B I *et al.* (STAR) 2010 *Phys. Rev.* **C81** 064904 (*Preprint* 0912.3838)

[56] Abelev B *et al.* (ALICE) 2013 *Phys. Rev. Lett.* **110** 082302 (*Preprint* 1210.4520)

[57] Aad G *et al.* (ATLAS) 2016 (*Preprint* 1605.06436)

[58] Adare A *et al.* (PHENIX) 2016 *Phys. Rev. Lett.* **116** 122301 (*Preprint* 1509.04657)

[59] Aad G *et al.* (ATLAS) 2014 (*Preprint* 1412.4092)

[60] Adam J *et al.* (ALICE) 2016 *Eur. Phys. J.* **C76** 271 (*Preprint* 1603.03402)