Jet Measurements in Heavy Ion Collisions with an Upgraded PHENIX Detector

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Abstract. The PHENIX Collaboration is pursuing an upgrade to the PHENIX detector to enable investigations of specific, outstanding questions that will advance our understanding of the strongly coupled quark-gluon plasma (sQGP). The greatly upgraded detector, called sPHENIX, consists of a superconducting solenoid and electromagnetic and hadronic calorimeters with a fiducial acceptance of $\Delta \phi = 2\pi$ and $|\eta| < 1$ around an existing silicon tracking detector, the VTX. It will have excellent capabilities for measuring an important set of jet observables. These measurements, in conjunction with similar measurements at the LHC, will provide information about energy loss, transport coefficients, and the fundamental constituents of the sQGP in the domain of strongest coupling, near $T_c$.

1. Introduction
Experimental data from RHIC and from the LHC have established that hadronic matter, subjected to extremes of temperature and density, transitions to a new state of matter—a plasma of quarks and gluons [1–4]. Investigation of the properties of this state of matter indicate that it behaves as a strongly coupled fluid with an extremely low ratio of shear viscosity to entropy density—perhaps within a factor of two of a conjectured quantum lower bound [5, 6]. Because of this strong coupling, it has become common to describe the plasma state as the strongly-coupled quark-gluon plasma (sQGP).

Several key questions to answer regarding the properties of the sQGP include the following. How does the strongly coupled quark-gluon plasma emerge from an asymptotically free theory of quarks and gluons? How rapidly does the quark gluon-plasma transition from the most strongly coupled system near $T_c$ to a weakly coupled system of partons? What are the dynamical and other underlying changes to the medium as one crosses this temperature expanse?

The PHENIX Collaboration is pursuing an upgrade to the PHENIX detector to enable investigations of these, and other, outstanding questions that will advance our understanding of the sQGP.

2. Temperature dependence of strong coupling
The sQGP created at RHIC energies ($\sqrt{s_{NN}} \sim 200$ GeV) is believed to achieve initial temperatures one to two times $T_c$ [7]. The higher energy collisions of heavy-ions at the LHC ($\sqrt{s_{NN}} = 2760$–$5500$ GeV) achieve temperatures significantly higher than those at RHIC [8]. It is important to investigate the temperature dependence of the dynamical properties of the sQGP, using this large energy and temperature range as a lever arm. One of the key parameters describing the...
dynamics of the system is the transport coefficient, \( \eta/s \), which is shown in the left panel of Figure 1 as a function of \( T \) for a variety of calculations embodying different assumptions. At very low \( T \), below the transition to the sQGP, the system exists as a high viscosity hadron gas [9]. At asymptotically high temperatures, for which \( \alpha_s \ll 1 \), perturbative QCD calculations can rigorously establish the temperature dependence of \( \eta/s \) [10]. At temperatures right in the vicinity of \( T_c \), where the coupling is maximal, the viscosity to entropy density ratio is near a minimum—perhaps within a factor of two of the conjectured quantum lower bound. What is not known reliably is the dependence of \( \eta/s \) on \( T \) as one raises the temperature from those attained at RHIC to those attained at the LHC and beyond.

Conventional QED fluids, such as water, show strong changes in \( \eta/s \) in the vicinity of \( T_c \). The ADS/CFT duality has been used to calculate \( \eta/s \) in strong coupling, but it describes a system with no quasiparticles and it does not result in a temperature dependence for the viscosity. Therefore measuring the temperature dependence crucially advances our understanding of the nature of the sQGP.

Figure 1: A variety of curves showing the possible evolution of \( \eta/s \) (left panel) and \( \hat{q} \) versus \( T \). The curves include the bound from string theory [5], weakly coupled pQCDArnold:2003zc, hydrodynamics with IR QCD [11], hadron gas [9], gluodynamics [12], semi-QGP [13], and QPM [14]. At both very low and very high values of \( T \), the dependence of \( \eta/s \) on \( T \) is well founded. Similarly, at very weak coupling, the relationship of \( \eta/s \) and \( \hat{q} \) can be reliably established. In the right panel, in addition to curves representing the asymptotic behavior expected in weakly coupled calculations, there is a curve from the paper by Liao and Shuryak [15] showing a greatly enhanced value of \( \hat{q} \) in the vicinity of \( T_c \). This difference in expected behavior of the transport coefficient presents a challenge to theory and an opportunity for experiment.

Hydrodynamic calculations do not directly determine the temperature dependence of \( \eta/s \), but if given an assumed dependence as input, they can be used to determine the value of final state observables such as the elliptic flow. The solid black curves in the left panel of Figure 1 represent somewhat arbitrary scenarios for how \( \eta/s \) might evolve with \( T \), but they have not been drawn without some foundation. The curves labeled I and II correspond closely to \( \eta/s \) curves used as input in recent hydrodynamic calculations [16; 17]. The curve labeled III has been engineered to pass through the \( \eta/s \) point taken from a gluodynamics lattice calculation [12]. The range of possibilities for the evolution of the shear viscosity from near \( T_c \) to much higher temperatures shows that little is known in a reliable way about this fundamental characteristic of the sQGP.
The shear viscosity is an important transport coefficient, but there are others, such as $\hat{q}$, which measures the transverse momentum accumulated by a parton traversing the medium, and $\hat{\epsilon}$, which measures the energy loss of a parton. These coefficients are amenable to measurement by jet observables. One can, in particular circumstances, relate different transport coefficients to one another. For instance, in a weakly coupled turbulent plasma, a relationship between $\eta/s$ and $\hat{q}$ can be determined [18]:

$$\eta/s = 1.25T^3/\hat{q}$$

(1)

By deducing $\eta/s$ and $\hat{q}$ separately and then comparing them by way of such a relation, one can establish the degree to which the system deviates from a weakly coupled system.

The right panel of Figure 1 is the straightforward translation of the curves from the left panel using Equation 1. In the figure there is also a curve showing a greatly enhanced $\hat{q}$ near $T_c$ that has been obtained by a fit to current RHIC data [15].

By measuring both sides of Equation 1, one can directly investigate the degree to which a weak coupling description works. Or, conversely, one can look for the explicit breakdown of a result obtained in a weak coupled description.

3. Constituents of the sQGP
Another key characteristic of any medium concerns its relevant degrees of freedom. In particular, one might look for the role of well-defined quasiparticles in the medium. The answer to this question is clearly scale dependent. At relatively large distances, the description of a QED superconductor is appropriately given in terms of Cooper pairs of correlated electrons; at sufficiently small distances the individual electrons themselves are the appropriate degrees of freedom.

Identifying the appropriate degrees of freedom for the sQGP (in a scale dependent way) is an important element of understanding the medium. Figure 2 illustrates the range of scales over which one could explore the medium. At the smallest distance scales, the medium must be describable in terms of partons, but at longer distance scales it is not known whether well-defined quasiparticles play a role in the sQGP.

4. Jet observables
Discussions with the DOE Topical Collaboration on Jets in Heavy-ion Collisions [19] have helped identify specific observables that one could measure to address the questions outlined in Section 1. One example can be found in Figure 3, based on the calculations by Coleman-Smith of a simple parton cascade. Two different measures of the effect of the medium on jets can be obtained through the jet energy asymmetry, $A_J = (E_{jet1} - E_{jet2})/(E_{jet1} + E_{jet2})$, and the nuclear modification factor, $R_{AA}$, which is the jet yield in nuclear collision normalized to the appropriately scaled yield in $p+p$ collisions. The left panel of the figure shows good agreement between $A_J$ in the calculation and $A_J$ determined experimentally in $Pb+Pb$ collisions at the LHC. The right panel then shows the predicted $A_J$ distribution for RHIC energies. The different curves correspond to different values of $\alpha_s$ in the calculation. Here, $\alpha_s$ is a proxy for an effective coupling between the parton and the medium; values as high at $\alpha_s = 0.6$ have been used in other calculations to describe RHIC data [20].

5. Jets at RHIC
RHIC has made large improvements in its delivered heavy-ion luminosity, precociously achieving the goals of RHIC II [23], through the use of full three-dimensional stochastic cooling and other upgrades. With these developments in place, one can reliably project anticipated rates of jets and other hard probes in future RHIC runs. Figure 4 is based on an NLO calculation of rates in $p+p$ collisions, scaled to central $Au+Au$ by the number of binary nucleon-nucleon collisions [24].
**Figure 2:** (Left) A quark in the sQGP exchanges a virtual gluon with the medium. The nature of that object—whether it is a well-defined quasiparticle or not—its effective mass and other properties are all important characteristics of the medium. (Right) Changing the scale of the interaction with the medium by changing the $Q^2$ of the interaction of the parton with the medium, explores a range of possibilities for the effective constituents of the medium.

**Figure 3:** (Left) Calculation in VNI parton cascade of dijet $A_J$ with $T = 0.35$ GeV and $\alpha_s = 0.3$ compared to the CMS data [21]. (Right) Calculation for RHIC jet energies, $E_T > 20$ GeV, for a circular geometry of radius 5 fm of $A_J$ for different values of $\alpha_s$ increasing to $\alpha_s = 0.6$ (red line) [22].

The advantage of jets over high-$p_T$ $\pi^0$s is quite clear. Jets have a much larger production cross section (since there is no penalty due to fragmentation, as is the case for single hadrons), and therefore they provide a much larger reach in $p_T$ for a given integrated luminosity.
Figure 4: Jet, photon and $\pi^0$ rates with $|\eta| < 1.0$ from NLO pQCD [24] calculations scaled to Au+Au central collisions. The scale uncertainties on the pQCD calculations are shown as additional lines. Ten billion Au+Au central collisions correspond to one count at $10^{-10}$ at the bottom of the y-axis range.

Table 1 shows the rates of jets and direct photons one could expect to accumulate in a nominal 20 week RHIC run. The numbers of such probes are comparable for Au+Au, d+Au and p+p. In addition, the flexibility of RHIC enables the collision of large, deformed nuclei (e.g., U+U) and of asymmetric systems (e.g., Cu+Au), both of which have successfully been demonstrated recently.

Table 1: Table of jet rates for different systems. Each column shows the number of jets or direct photons that would be measured within $|\eta| < 1$ in one 20 week running period.

| System          | $> 20 \text{ GeV}$ | $> 30 \text{ GeV}$ | $> 40 \text{ GeV}$ | $> 50 \text{ GeV}$ |
|-----------------|---------------------|---------------------|---------------------|---------------------|
| Au+Au (central 20%) | $10^7$ jets | $10^6$ jets | $10^5$ jets | $10^4$ jets |
|                 | $10^4$ photons | $10^3$ photons | $10^2$ photons | $10^3$ photons |
| p+p             | $10^6$ jets | $10^5$ jets | $10^4$ jets | $10^3$ jets |
| d+Au            | $10^7$ jets | $10^6$ jets | $10^5$ jets | $10^4$ jets |

A concept for a suitable detector to measure these jet observables at RHIC has been studied. The basic design requirements are azimuthally complete coverage, uniform response, hadron calorimetry near mid-rapidity, and sufficient acceptance to capture a large fraction of jet, di-jet
and $\gamma$+jet events. An engineering rendering of the sPHENIX concept is shown in Figure 5. The basic components are the existing PHENIX VTX as an inner tracker, a superconducting solenoid with a field strength of 2 T, an electromagnetic calorimeter and a hadronic calorimeter.

![Figure 5: An engineering rendering of the sPHENIX upgrade showing the inner silicon tracker (the current PHENIX VTX), the 2 T superconducting solenoid, and the electromagnetic and hadronic calorimeters.](image)

RHIC will produce jets with appreciable rates, and the sPHENIX design concept will capture those jets (and their partner di-jet or $\gamma$), but one still has to demonstrate that it is possible to extract a clean signal above the fluctuating event by event background found in a heavy-ion collision. To do that, we have published the results of an extensive study based on a simulation of approximately one billion HIJING events [25]. Figure 6 shows an illustration of the results from that study. The basic technique involved instrumenting HIJING so that every time the internal routine to process a hard scattering was called, it passed the daughter particles through the anti-$k_T$ jet reconstruction algorithm from FASTJET and recorded the outcome for later analysis. Any jet later found among the final state particles that could not be matched with one of these proto-jets was considered to be a “fake” jet. For jets with a reconstructed energy above 20 GeV, the background coming from fake jets is well-controlled.

Having established that we can find jets in heavy-ion collisions, it is important to determine the energy resolution with which those jets are reconstructed in a realistic sPHENIX detector. Figure 7 shows the results of a study in which jets are first reconstructed from their truth particles. Those particles are then propagated through a full GEANT4 description of the sPHENIX detector and the energy they deposit in the calorimeter is collected into towers (i.e., cells in $\eta$–$\phi$ space). The same anti-$k_T$ algorithm with the same jet radius parameter is used to reconstruct jets using the simulated calorimeter information. The two results are compared to determine a jet energy resolution of $\sigma_E/E \approx 90\%$.

Another important issue concerns the degree to which jet observables are distorted due to detector resolution and underlying event fluctuations. The technique of unfolding is a well
Figure 6: The results of a study [25] showing that one can reconstruct a clean jet signal at RHIC energies. Using the anti-kt algorithm with $R = 0.2$, the signal to background exceeds one for reconstructed jet energies above $20 \text{ GeV}$. The panels on the right show the distribution in true jet energy, $E_{\text{true}}$, for two slices in reconstructed jet energy. In the plot at top one can still see some intrusion into the distribution coming from fake jets. The bottom plot shows that this contamination is essentially gone for reconstructed jets at sufficiently high energy.

Figure 7: Jet energy resolution in sPHENIX. The single particle energy resolution in the calorimeters is better than $75\%/\sqrt{E}$, but the energy resolution for jets is typically 1.2 times worse than the single particle resolution [26]. Current simulations of sPHENIX jet reconstruction performance are compatible with this experience.
established method for removing the average contribution of these effects [27]. Figure 8 shows the effectiveness of unfolding when applied to the distribution of inclusive jets as would be measured by sPHENIX. As one can see, the unfolded distribution reproduces the input distribution very closely. Because the truth distribution of jets falls nearly exponentially with increasing jet energy, and because the main effect of instrumental resolution is a Gaussian blurring, the dominant difference between the measured and truth distributions is a shift upward in jet energy. The unfolding procedure removes this shift very effectively. The right panel of Figure 8 shows the ability of sPHENIX to use the unfolded distribution in Au+Au and in p+p to determining $R_{AA}$ for jets out to 60 GeV.

Figure 8: The left panel shows the effectiveness of an unfolding procedure for recovering the truth distribution of inclusive jets. The input distribution is shown as a black histogram. This distribution is subjected to a smearing coming from detector resolution effects and also to fluctuations coming from the underlying event. This is the blue dashed histogram. The raw measured distribution is then subjected to a 1D unfolding procedure and the resulting histogram (in red) largely reproduces the input distribution. The panel on the right shows how well, with unfolding, one could measure the $R_{AA}$ for jets in central Au+Au collisions.

Di-jet and $\gamma$+jet observables require, in principle, the application of a multi-dimensional unfolding procedure in order to recover the relevant truth distribution. Fortunately, much of the effect of a full 2D unfolding is already apparent in a simpler 1D unfolding of the trigger jet in the correlation observables. Since the dominant effect of the unfolding is a straightforward shift in the energy of the jet, one can approximate the full 2D unfolding by merely shifting the energy of the trigger jet downward in energy. How well this procedure works can be seen Figure 9, which compares the raw distribution of $A_J$ for PYTHIA (the vacuum case) and PYQUEN (a quenched model of Au+Au data) in the left panel with the unfolded distributions (compared to the input truth distributions) in the right panel. The approximate unfolding, even of just the trigger jet, largely recovers the truth information.

The case of unfolding applied to $\gamma$+jet is shown in Figure 10. Here a 1D iterative Bayes unfolding procedure has been used to largely recover the truth distribution of $x \equiv E_{jet}/E_{\gamma}$ from the measured values.

The sPHENIX detector will provide the ability to make the first high-rate fully calorimetric jet measurements at RHIC. Studies indicate that with an approach derived from the technique
Figure 9: The results of a study demonstrating the degree to which the “truth” $A_J$ distribution can be measured by sPHENIX. The left panel shows the $A_J$ distribution given by Pythia and by Pyquen as it would appear in a first-pass sPHENIX analysis. The distribution shows the smearing effects of the underlying event and the calorimeter energy resolution. The right panel shows how effectively a simple 1D unfolding procedure can be used to recover the input “truth” distribution.

Figure 10: A result similar to that shown in Figure 9, showing how well a 1D unfolding procedure can recover the input “truth” distribution of $E_{jet}/E_{\gamma}$ for $\gamma$+jet events. In this case, the unfolding is particularly effective because the energy of the photon is quite precisely measured by $\sim 15%/\sqrt{E}$ energy resolution of the electromagnetic calorimeter.

used by the ATLAS experiment at the LHC, one can extract a clean inclusive jet signal for $R = 0.2$ for jet $E_T > 20$ GeV [28]. And with a clean trigger jet, it is possible to study di-jet and $\gamma$+jet observables with good dynamic range. Other interesting possibilities such a jet $v_n$ and jet-hadron correlations present themselves. With this excellent set of jet observables, one can investigate with good sensitivity outstanding questions about the properties of the sQGP, such as its relevant degrees of freedom, the interaction of the jet with the hot, dense medium, and the detailed mechanisms of energy loss. Properly answering these issues will clearly require the integration of results from RHIC energies, where the medium is near $T_c$, and from the LHC, where the medium is closer to a weakly coupled system for which pQCD techniques may be applicable. It will also require further theoretical development to establish more firmly the connection between experimentally accessible observables and the underlying properties of the
deconfined matter. Experimental, theoretical and technical issues are discussed at length in the sPHENIX proposal [29].

The sPHENIX detector concept is technically achievable and could be ready for data taking later this decade. The key elements of sPHENIX are not based on beyond-state-of-the-art technology. These components are used in innovative ways in order to facilitate industrial production techniques, an approach which keeps costs low while still providing the physics capabilities needed to carry out the sPHENIX program.

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