Zeroing in on jet quenching: a PHENIX perspective

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Abstract

We review recent progresses on jet quenching measurements by PHENIX. With increased statistics, PHENIX has gone beyond the single hadron suppression $R_{AA}$, and made measurements on multiple jet quenching observables, such as $v_2$, $I_{AA}$ and $v_2^{AA}$. We argue that, by combining these observables together, one can achieve a better understanding of the energy loss mechanism. We present new $\gamma$-hadron correlation results with associated hadrons extended to low $p_T$; an enhancement has been observed, suggesting a contribution of genuine medium response that is relatively unbiased by the initial geometry fluctuations. The status of full jet reconstruction and future perspective of PHENIX jet quenching program are discussed.

Keywords: Quark gluon plasma, Jet quenching, single hadron suppression, di-hadron correlation, gamma-hadron correlation

1. Introduction

Jet quenching or suppression of high $p_T$ jets and di-jets is one of the most intensely studied probes of the strongly-interaction quark gluon plasma (sQGP) created in Au+Au collisions at RHIC. Since the suppression level is directly caused by the interaction of the jets with the medium, jet quenching measurements allow us to infer the properties of the sQGP. After nearly a decade long effort, jet quenching, as an experimental phenomena, has been firmly established at RHIC. However, the exact mechanism for jet quenching is still under intense debate. The often-used pertubative QCD (pQCD) framework, which works well in elementary $p+p$ collisions, fail to describe simultaneously the light and heavy quark suppression. In contrast, non-perturbative approaches, for example those based on AdS/CFT gauge gravity duality [1], seem to work well. Even within the pQCD framework, there are many models that are based on different and often uncontrolled approximations [2], which, when tuned to the same data, predict very different medium properties.

One way to improve the situation is to study multiple jet quenching observables at once, capitalizing on their different sensitivities to the energy loss mechanism. These observables include single hadron suppression $R_{AA}$ and its azimuthal anisotropy relative to the reaction plane (RP) $R_{AA}(\phi - \Psi_{RP})$ or $v_2$, di-hadron suppression $I_{AA}$ and its azimuthal anisotropy relative to the RP $I_{AA}(\phi - \Psi_{RP})$ or $v_2^{AA}$, as well as modifications of electron-hadron correlation, $\gamma$-hadron correlations and fully reconstructed jets. The idea is to fix the energy loss mechanism, while dramatically varying the path length that the probes transverse, for example by comparing $R_{AA}$, $v_2$, $I_{AA}$, and $v_2^{AA}$ for light hadrons; or fix the path length and vary the interaction between jet and medium, for example by comparing di-hadron and electron-hadron correlations. The goal of this proceedings is to summarize recent PHENIX results on all these observables, and discuss the physics insights obtained by combining these results. Reader should refer to [3] for a theoretical review on this subject.
2. Leading hadron suppression: does $R_{AA}$ rise with $p_T$?

Single hadron suppression $R_{AA}$ is the most studied observable for jet quenching. Due to the steeply falling spectrum, this observable suffers from energy loss bias (observed hadron tends to have small energy loss), which limits its ability in distinguishing various model scenarios. Nevertheless, as the $R_{AA}$ measurements become more precise, one can regain some discriminating power. For example, recent precision measurements of $\pi^0$ and $\eta$ mesons have started to pin down the shape of the $R_{AA}$ at high $p_T$. This is important for understanding the energy loss mechanism. A slow rise of the $R_{AA}$, for instance, is expected for radiative energy loss due to its logarithmic dependence on the initial jet energy.

Results for the 0-5% centrality bin are shown in Fig. 1 where RUN4 $\pi^0$ and RUN7 $\eta$ $R_{AA}$ are fitted with a linear function $R_{AA} = b + m p_T$ to extract the slope parameter $m$. The data do indicate a small positive slope, but the significance is less than 1$\sigma$ for RUN4 $\pi^0$ and slightly above 1$\sigma$ for $\eta$. The RUN7 $\pi^0$ $R_{AA}$ seem to suggest somewhat more significant increasing trend with $p_T$. The updated numbers should come out soon.

3. Azimuthal anisotropy of leading hadron suppression: what is the path length dependence of energy loss?

The overlap zone of the Au+Au collision is not symmetric; consequently, the emission rate of high $p_T$ particle may vary with its angle relative to the reaction plane (RP) $\phi - \Psi_{RP}$. This azimuthal anisotropy can be characterized by either $v_2$ parameter or $R_{AA}(\phi - \Psi_{RP})$, whose magnitudes directly reflect the path length dependence of the energy loss. Figure 2 shows the $p_T$ dependence of the $R_{AA}$ separately for in-plane ($R_{AA}^{in}$) and out-of-plane ($R_{AA}^{out}$). At low $p_T$, the $R_{AA}^{in}$ varies by almost a factor of 2 while that for out-of-plane direction is almost unchanged; this can be interpreted as a stronger radial flow influence in the in-plane direction. At high $p_T$, the $R_{AA}^{out}$ is more suppressed than $R_{AA}^{in}$, reflecting greater path length for out-of-plane going jets. Interestingly, $R_{AA}^{out}$ also shows a stronger $p_T$ dependence than the in-plane direction, suggesting that the $R_{AA}^{out}$ can better expose the true shape of the $R_{AA}$ at high $p_T$ from jet quenching.
Figure 3a shows the centrality dependence of $v_2$ at high $p_T$ [5]. The $v_2$ values are large and increase toward peripheral collisions. They are compared to various pQCD model calculations [6]. These models are calculated with different geometry and different implementation of energy loss processes. For example, the HT and ASW models include only coherent radiative energy loss, while the AMY and WHDG models also include collisional energy loss. The calculations are tuned to the $R_{AA}$ value in the 0-5% centrality bin (right panel), thus the centrality dependence of $v_2$ and $R_{AA}$ are predictions. All models describe the centrality dependence of $R_{AA}$ reasonably well, but significantly under-predict the $v_2$ data. Furthermore, the calculated $v_2$ values differ among themselves. Since $R_{AA}$ and $v_2$ are anti-correlated, $i.e.$ a small $R_{AA}$ implies a large $v_2$ and vice versa, it is unlikely that one can describe both $v_2$ and $R_{AA}$ by simply re-tuning the quenching parameters in these models.

How to resolve this apparent discrepancies between data and theories? A recent estimation [7] shows that the calculated $v_2$ could be increased by 30-40% by considering modifications of collision geometry due to event-by-event fluctuations and CGC effects (dashed line in Fig. 3a). However, the calculation still falls below the data. Unless there are other modifications of collision geometry that we are not aware of, this large discrepancy implies that our current picture of pQCD-based energy loss is not complete. For example, the quadratic $l$ dependence formula for radiative energy loss, $\Delta E \propto \int_{\tau_0}^{\tau_{\infty}} d\tau \int_{0}^{R_{AA}} \rho'(r+\Delta r) \rho' \left( r + \Delta r + \rho' \right) \rho' \left( r + \rho' \right) \sim l^2$ (where $\rho_{\text{part}}$ is participant density), may need to be changed to increase the anisotropy. There are three ideas along this line of reasoning. Liao and Shuryak [8] do this by requiring that most of the energy loss in sQGP be concentrated around $T_c$. One can increase the $v_2$ by increasing the formation time $\tau_0$ to 1.5 - 2.0 fm/c [9]. One can also increase the $v_2$ with a cubic $l$ dependence of energy loss: $\Delta E \propto \int_{\tau_0}^{\tau_{\infty}} d\tau \left( \frac{\Delta r}{\tau_0} \right)^2 \rho'(r+\Delta r) \rho'(r+\Delta r) \rho'(r+\Delta r) \sim l^3$; such dependence is expected in certain non-perturbative energy loss calculations based on AdS/CFT gravity-gauge dual theory [10]. Indeed, Fig. 3b shows that our data agree well with calculations [11] based on such $l$ dependence.

To further pinpoint the influence of the collision geometry and the path length dependence to high $p_T$ anisotropy, we studied the $l$ scaling behavior of the $R_{AA}$ for various centrality and $\phi - \Psi_{R_P}$ angle bins. The idea is that if two selections have different $N_{\text{part}}$ and $\phi - \Psi_{R_P}$, but similar average energy loss ($\Delta E$), their suppression levels should be similar. Thus if real energy loss scales as $\Delta E \propto \int_{\tau_0}^{\tau_{\infty}} d\tau \rho_{\text{part}}(r+\Delta r) \rho_{\text{part}}(r+\Delta r) \rho_{\text{part}}(r+\Delta r) \sim l^1$; such dependence is expected in certain non-perturbative energy loss calculations based on standard Glauber geometry, $I_{\text{q}}(\rho_{\text{part}}')$ corresponds to quadratic $l$ dependence in standard Glauber geometry, $I_{\text{q}}(\rho_{\text{CGC}}')$ corresponds to cubic $l$ dependence in CGC geometry with E-E fluctuations, and $I_{\text{q}}(\rho_{\text{CGC}}')$ corresponds to cubic $l$ dependence in CGC geometry with E-E fluctuations. Comparing the three panels, we see that the $R_{AA}$ does not scale with $I_{\text{q}}(\rho_{\text{part}}')$ and $I_{\text{q}}(\rho_{\text{CGC}}')$, although the latter is slightly better; but it scales very well with $I_{\text{q}}(\rho_{\text{CGC}}')$. Figure 3: The centrality dependence of $v_2$ (left panels) and $R_{AA}$ (right panels) in 6-9 GeV/c range. They are compared with various pQCD model calculations (top panels), and schematic calculations that explore the roles of geometry and cubic path length dependence (right panels).
Figure 5 shows the energy dependence of $v_2$ from $\sqrt{S_{NN}} = 39 - 200$ GeV. The $v_2$ at $\sqrt{S_{NN}} = 200$ GeV shows a gradual drop from 3 GeV/c to 7-10 GeV/c and remain positive at higher $p_T$. The $v_2$s at $\sqrt{S_{NN}} = 39$ and 62 GeV have limited $p_T$ reach, but their magnitudes are consistent with 200 GeV results, both at low $p_T < 2$ GeV/c where collective flow dominates and at $p_T > 4$ GeV/c where jet quenching should play a significant role. The former result suggests that, even at low energies, the medium already has to thermalize quickly and have small dissipation. The latter result is quite surprising, since we know that the $R_{AA}$s at low energies are less suppressed than at $\sqrt{S_{NN}} = 200$ GeV. It would be interesting to see how well the pQCD models, which describe the $R_{AA}$ at low $\sqrt{S_{NN}}$ [12], can reproduce the $v_2$.

![Figure 4](image-url)  
**Figure 4:** The $R_{AA}$ vs $I_s = \int_0^\infty d\tau e^{-\tau} \rho_{\text{per}}(r+nt)$ $(m = 1, 2)$ for 6 centrality and 6 angle bins, calculated for standard Glauber geometry (left), CGC geometry with E-by-E fluctuation (middle and right).

![Figure 5](image-url)  
**Figure 5:** The $x^0 v_2$ versus $p_T$ for $\sqrt{S_{NN}} = 200, 62$ and 39 GeV.

4. **Di-hadron suppression $I_{AA}$ and its azimuthal anisotropy $I_{AA}(\phi - \Psi_{RP})$: Further probing into the path length dependence of energy loss with away-side jet**

High $p_T$ hard-scattered jets, at leading order, are produced in pairs that are back-to-back in the azimuthal direction. One observable of interest is the suppression pattern of the away-side jet opposite to the trigger hadron above a certain $p_T$ threshold. This suppression is quantified by $I_{AA}$, the ratio of the per-trigger yield (away-side jet multiplicity normalized by number of triggers) in Au+Au collisions to that in p+p collisions. Pure geometrical consideration would suggest $I_{AA} < R_{AA}$ due to a longer path length traversed by the away-side jet. But a recent PHENIX measurement [13] shows that $I_{AA}$ is constant for associated hadron $p_T > 3$ GeV/c, and this constant level is above the $R_{AA}$ for the trigger hadrons, i.e. $I_{AA} > R_{AA}$ (see Fig. 5). Furthermore, the constant level of $I_{AA}$ becomes even less suppressed for higher trigger $p_T$. This result can be explained, at least partially, by the bias of the away-side jet energy by the trigger $p_T$: the initial away-side jet spectra are harder for higher trigger $p_T$, consequently, a larger fractional energy loss is required for the same $I_{AA}$ value. This result rules out the pure jet attenuation scenario where the jet survival probability depends only on the path length.

The data in Figure 5 are compared with several pQCD model calculations. The quenching parameters of these calculations have been tuned to reproduce the $R_{AA}$ data, so the calculations can be regarded as predictions. The ACHNS model (based on ASW framework) tends to predict $I_{AA} \lesssim R_{AA}$, thus disagreeing with the data, while ZOWW...
model (based on HT framework) can describe the data rather well. This is another example showing that one can discriminate models by combining multiple experimental observables.

PHENIX also measured the anisotropy of the away-side suppression, that is $I_{AA}$ as a function of angle relative to the RP (see Fig. 7) [14]. While the near-side $I_{AA}$ is essentially unmodified, the away-side $I_{AA}$ shows a strong variation with $\phi_s = \phi - \Psi_{RP}$, sometimes by more than factor of two from in-plane to out-of-plane. This variation corresponds to an anisotropy parameter of $v_{2}^{AA} = 0.29^{+0.15}_{-0.11}$ and is much bigger than that for inclusive $\pi^0$ in the same trigger $p_T$ range $v_2 = 0.13 \pm 0.01$. This measurement is statistics limited, however if the result holds, it would have severe consequence for energy loss models since they usually predict much smaller anisotropy (for example, ASW calculation predicts $v_2 < 0.05$).

Before closing this section, we want to point out that the four observables, $R_{AA}$, $v_2$, $I_{AA}$ and $v_{2}^{AA}$, are intrinsically correlated. A smaller $R_{AA}$ naturally implies a larger $v_2$, and a smaller $I_{AA}$ implies a larger $v_{2}^{AA}$. The relation between $R_{AA}$ and $I_{AA}$ also depends on the away-side spectra shape controlled by trigger $p_T$, but in general a smaller $R_{AA}$ implies a smaller $I_{AA}$. Thus it is rather surprising to see that $I_{AA}$ is less suppressed than $R_{AA}$ ($I_{AA} > R_{AA}$), yet has a larger anisotropy ($v_{2}^{AA} > v_2$).

5. Non-photonic electron-hadron correlation: probing the in-medium modifications of heavy quark jets

The observation of large suppression for non-photonic single electron (NPE), at a level similar to that for inclusive hadrons, remains a challenge for pQCD models [15]. Since most of these electrons come from semi-leptonic decay of charm and bottom mesons, the large suppression suggests that the charm and bottom quarks interact with the sQGP much more than expected from pQCD models. Non-photonic electron-hadron correlations provide valuable complementary information for heavy quark energy loss. This is because a large fraction of heavy quarks are produced in back-to-back pair at RHIC energy, and the fragmentation of the companion heavy quark is expected to contribute significantly to away-side hadrons associated with triggering electrons.
Results from a first measurement of the NPE-hadron correlation from PHENIX 16 (see Fig. 8) suggests that the away-side hadrons are strongly modified relative to p+p. The away-side hadron yield, when integrated in a ±30° window around $\Delta\phi = \pi$, indicates an enhancement below 1.5 GeV/c and a suppression above 1.5 GeV/c. Unfortunately, the large statistical uncertainties do not allow us to conclude whether the modification patterns are the same as that for di-hadron correlations 17. PHENIX has installed a silicon vertex detector (VTX) for the next run (RUN11). VTX has the ability to directly reconstruct and distinguish between charm and bottom mesons. This should allow us to directly correlate charm and bottom mesons with charged hadrons. We expect PHENIX to carry out the same as that for di-hadron correlations 17. PHENIX has installed a silicon vertex detector (VTX) for the next run (RUN11). VTX has the ability to directly reconstruct and distinguish between charm and bottom mesons. This should allow us to directly correlate charm and bottom mesons with charged hadrons. We expect PHENIX to carry out the first measurement of charm and bottom separated heavy flavor suppression and correlation measurements in RUN11.

6. Direct $\gamma$-hadron correlation: an unbiased probe for jet quenching and medium response

Our discussions of the jet quenching so far have been focused on the single hadron and di-hadron correlation observables. These observables are subject to energy loss bias and geometrical bias, and they represent a complicated convolution of jets with different initial energy and different energy loss. In contrast, direct $\gamma$ and fully reconstructed jet are much less affected by these biases. For example, one can gauge the away-side jet energy with a direct $\gamma$ trigger, and one can systematically control the surface bias by studying the jet $R_{AA}$ as a function of jet cone size. $\gamma$-hadron and jet-hadron correlations also give us direct access to jet modification and medium response.

To leading order in pQCD, the energy of a direct $\gamma$ is a good approximation of the away-side jet energy. Thus one can measure the in-medium jet fragmentation via $\gamma$-h correlation. Results for p+p and 0-20% Au+Au 18 are shown in Fig. 9, plotted as a function of fragmentation variable $\xi = -\ln\left(p_T^+/p_T^\gamma \cos \Delta \phi\right) \approx -\ln(z)$. Small $\xi$ corresponds to high $p_T$ and vice versa. The fragmentation function from TASSO (mostly quark jets) and in-medium modified jet fragmentation function from a MLLA calculation, both for 7 GeV jets, are shown as lines to compare with the p+p and Au+Au data, respectively. Note that the TASSO data and MLLA calculation are scaled down by factor of 10 to match the our data. This factor is needed since the PHENIX detector has limited $\eta$ acceptance, thus only catches a fraction of the fragments of the away-side jet.

The $I_{AA}$, or ratio of fragmentation functions of Au+Au to p+p, is shown as filled circles in the right panel of Fig. 9. The $\xi$ range is cut off at 2 due to limited $p_T$ of the p+p reference data. However, we can extend the $\xi$ range by calculating $I_{AA}$ using the scaled TASSO data as reference instead (open circles). The two $I_{AA}$S are consistent with each other. The data clearly show a suppression at small $\xi$ (large associated hadron $p_T$) due to jet quenching, but an enhancement at large $\xi$ (small associated hadron $p_T$) possibly due to medium response to the quenched jet.

The enhancement of the associated hadron yield at low $p_T$ was observed in di-hadron correlations 17, as a double hump structure centered around one radian from $\pi$. However, the interpretation of this enhancement in terms of jet in-medium response, e.g. Mach cone, is complicated by possible contributions of E-by-E collective flow fluctuations 19. It has been argued that such fluctuations lead to significant non-zero $v_1$ and $v_2$ components which can mimic such double hump structure 20. Since the direct $\gamma$ does not interact strongly with medium, it should have very small flow signal as indicated by PHENIX preliminary measurements on direct $\gamma v_2$ (Left panel of Fig. 10). Hence the $\gamma$-h correlation should be relatively unaffected by the $v_n$ contribution, and the associated hadron at low $p_T$ is a robust measure for the medium response 21. Current $\gamma$-h correlation indicates some broadening at the away-side (Right
The statistical and systematic uncertainties are still too large for a definite conclusion. With the VTX installed in the next run, PHENIX expects to have a factor of 20 increase in the effective pair acceptance for associated hadrons around $\Delta\phi = \pi/2$, a region that is most crucial for medium response studies.

7. Modification of fully reconstructed jets

PHENIX has carried out full jet reconstruction in $p+p$ and $Cu+Cu$ collisions using the Gaussian filter method [22]. This method is infra-red and collinear safe, and is suitable for limited acceptance detector. One of the primary challenges for full jet reconstruction in the heavy ion environment is how to handle the large underlying background fluctuations, especially at low $p_T$. PHENIX employed a fake rejection method [22], in which a certain criterion is defined to suppress fake jets from background fluctuations that tend to have high multiplicity and large width. This method can directly suppress fake jets with high purity, so the systematic error due to underlying event is smaller than that for the direct background subtraction method. However, the jet sample passing the rejection criteria are subject to some efficiency loss and bias, which need to be evaluated carefully.

Figure 11 summarizes the current status of the jet reconstruction in PHENIX [22]. The left panel shows the full jet spectrum in $p+p$ collisions, unfolded to particle level, up to 60 GeV. The result is consistent with an NLO calculation and PYTHIA. The middle panel shows the jet $R_{AA}$ in central $Cu+Cu$ collisions, unfolded to $p+p$ jet energy scale, for two different jet cone sizes. Comparison between different jet cone sizes was argued to directly probe the jet shape modifications [23]. We see that the $R_{AA}$ for larger cone size is less suppressed, but the uncertainty also is much larger presumably due to increased background fluctuation in a larger cone. The right panel shows the di-jet acoplanarity for several centrality classes. The widths extracted via Gaussian fits are consistent across all centrality bins, suggests a small $k_T$ broadening for surviving partons traversing the medium.
8. Future of jet quenching physics in PHENIX

The primary goal for jet quenching physics is to obtain a coherent picture of the interaction of the jets with sQGP. The challenge for the field is that we are not yet able to simultaneously understand multiple jet quenching observables, such as $R_{AA}$, $I_{AA}$, $v_2$, $v_2^{AA}$, and heavy flavor suppression. In order to meet this challenge, we need not only more precise measurements for existing experimental observables, but also the capability to measure new observables that can provide much more detailed picture about jet medium interactions. Examples of latter category include reconstructed jets and di-jets in a broad acceptance and kinematic range, direct $\gamma$-jet correlation, and heavy meson tagged jet, just to name a few. PHENIX has planned aggressive mid-term (2010-2015) and long-term (beyond 2015) detectors upgrades to fulfill these requirements.

In the mid-term, PHENIX will see the completion of VTX and FVTX detectors. These detectors should allow us to tag D and B meson directly, and provide extended acceptance for low $p_T$ charged hadrons for light/heavy hadron-hadron correlation measurements. The upgraded data acquisition (Super-DAQ) will take full advantage of the increased RHIC luminosity. In the long-term, PHENIX plans to replace the existing outer central detectors with a compact large acceptance EMCal and HCal, which together with VTX, FVTX, additional tracking layers and high DAQ rate, will allow us to measure jets, dijets, heavy flavor jets, and direct photon-jet correlations in a broad kinematic ranges. We refer more detailed discussion to [24].

9. Summary

PHENIX has made several new measurements on single hadron and di-hadron correlation observables. By combining information from multiple observables, we are now able to better constrain jet quenching mechanisms and discriminate different models. We show that the $R_{AA}$ measurement, with increased precision, suggests a gradual increase at high $p_T$. We find that the $v_2$ at high $p_T$ exceeds the pQCD predictions, suggesting a non-trivial path length dependence of the energy loss. We also find that the $I_{AA}$ is less suppressed than $R_{AA}$, $I_{AA} > R_{AA}$, yet its anisotropy is larger than single hadrons, $v_2^{AA} > v_2$. This result is rather non-trivial given the anti-correlation between $R_{AA}$ and $v_2$, and between $I_{AA}$ and $v_2^{AA}$.

PHENIX also made good progresses on $\gamma$-hadron correlations and full jet reconstruction. These measurements are challenging either due to their low rate ($\gamma$-hadron) or large underlying-event background fluctuation (full jet reconstruction). By extending the $\gamma$-hadron correlations to low associated $p_T$, we observed strong evidence of enhancement due to energy dissipation of quenched jets. We have measured jet spectra in p+p and Cu+Cu collisions, and explored the modification of jet shape and di-jet broadening. These measurements will benefit tremendously from future detector and luminosity upgrade of the PHENIX.

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