

Jet quenching: an iconic result revisited

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Early measurements at the Relativistic Heavy Ion Collider (RHIC) demonstrated jet quenching through the suppression of pairs of high momentum hadrons. These dihadron correlations have a large correlated background. As our understanding improved, we realized that a significant term was omitted from the background and several dihadron correlation results were quantitatively and qualitatively incorrect. The original measurements demonstrating jet quenching have not been revisited. These measurements are repeated in this paper in a kinematic range similar to the original measurement using publicly available data, applying our current knowledge about the background. The new results are qualitatively consistent with the previous results, demonstrating complete suppression of the away-side within uncertainties.

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I. INTRODUCTION

The Quark Gluon Plasma (QGP), a hot, dense liquid of quarks and gluons, is formed in high energy heavy ion collisions [1–4]. One of the main signatures of the QGP is jet quenching, partonic energy loss in the medium through collisions with medium partons and gluon bremsstrahlung. This leads to a suppression of jet fragments carrying a large fraction of the parent parton's momentum (high $z = p_T^{hadron}/E_{jet}$) and an enhancement of jet fragments carrying a small fraction of the parent parton's momentum (low z). There is extensive experimental evidence for jet quenching, including the suppression of high momentum hadrons relative to expectations from proton-proton collisions [5–10], the suppression of hadrons 180° away in azimuth from a high momentum hadron [11–13], and the direct observation of an asymmetry in the energy of di-jet pairs [14, 15].

The role of high momentum dihadron correlations in providing experimental evidence for jet quenching is difficult to overstate. Over forty measurements to date of correlations of hadrons, photons, and leptons with high momentum hadrons in nucleus-nucleus collisions have been published by experiments at RHIC and the LHC. The paper reporting the suppression of particles 180° away from a high momentum paper has over 750 citations [12]. This paper continues to be cited as evidence for jet quenching and its iconic plot is shown, both among those studying the QGP and outside the field. This is despite widespread knowledge within the community that the background subtraction omitted a key term, the third order coefficient of the Fourier distribution of azimuthal anisotropy, v_3 [16, 17]. While there is substantial experimental evidence establishing jet quenching [18], there has been no reanalysis in a similar kinematic regime to the initial paper to determine if evidence for jet suppression is robust at the momenta in the original study.

Data in a similar kinematic regime are used in this paper in order to update the measurement in [12] with our current knowledge about the background in dihadron cor-

relations. The form of the background is briefly reviewed and publicly available data [19, 20] are used to produce updated dihadron correlations in a similar kinematic regime to [12]. This updated plot is qualitatively consistent with the original. There are some limitations in the analysis possible with publicly available data because the first order coefficient of the azimuthal anisotropy, v_1 , is poorly constrained. Two approaches to the background subtraction are used, one which includes v_1 in a fit to the background-dominated region but is susceptible to unstable fits and one approach which uses independent measurements of the v_n and fixes $v_1 = 0$.

II. SEPARATING SIGNAL AND BACKGROUND IN DIHADRON CORRELATIONS

In high momentum dihadron correlations, a high momentum trigger particle is selected and the distribution of particles relative to that trigger particle in azimuth, $\Delta\phi = \phi^{trigger} - \phi^{associated}$, is measured. The correlation function is dominated by $2 \rightarrow 2$ processes. The signal from jet-like correlations is typically described as a near-side peak ($\Delta\phi < \pi/2$) from particles produced by fragmentation of the same jet as a the trigger particle and an away-side peak ($|\Delta\phi - \pi| < \pi/2$) from its partner jet.

The correlation function will have contributions from all physical correlations in the event. Hanbury-Brown-Twiss (HBT) correlations, quantum correlations between particles from the same source, are suppressed by a difference between the momentum of the trigger and associated particles [21, 22]. Correlations between decay daughters and electron-positron pairs from conversions are suppressed by focusing on high momentum. Any remaining contributions from HBT and decays are effectively considered part of the signal. In heavy ion collisions, both the jet signal and the flow-modulated combinatorial background are correlated with the reaction

plane, the former due to the path length dependence of partonic energy loss and the latter due to hydrodynamical flow. Spatial asymmetries in the initial overlap region between two nuclei are converted to momentum anisotropies in the final state [23]. Since both the signal and the background are correlated with the reaction plane, they will be correlated with each other. Furthermore, the minimal threshold on the momentum of the trigger particle increases the probability that it was produced in a jet but does not guarantee it. There is therefore a correlated background which can be described by its Fourier decomposition [24]

$$B(\Delta\phi) = B_0 \left(1 + 2 \sum_{n=1}^{\infty} v_n^a v_n^t \cos(n\Delta\phi) \right). \quad (1)$$

In the case that the correlated background is dominated by flow, the v_n in these correlations are the same as independent measurements of the v_n due to flow. Initially, the odd n terms were assumed to be zero because the average distribution of nucleons in nucleus is symmetric. It was later proposed that fluctuations in the positions of the nucleons could lead to odd n v_n [16, 17], which were later observed [25, 26].

The omission of v_3 in particular led to two artifacts, the “ridge” on the near-side [20, 27], a structure which was correlated in $\Delta\phi$ but roughly independent of $\Delta\eta$, and the “Shoulder” or “Mach cone” on the away-side [19, 20, 28–30], a dip at $\Delta\phi \approx \pi$ with two peaks additional peaks offset from $\Delta\phi \approx \pi$. These effects were considerable for trigger momenta $4 < p_T^t < 6$ GeV/c and associated momenta $2 < p_T^a < 4$ GeV/c, the region used for the original dihadron correlation demonstrating jet quenching [12], motivating a reconsideration of the signal in this range.

Background subtraction has generally been done using the assumption that the yield is zero near $\Delta\phi \approx 1$ combined with v_n from independent measurements, called the Zero-Yield-At-Minimum (ZYAM) method [31]. There have since been method developments to avoid these assumptions [32, 33].

The correlation function in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in [12] is for $4 < p_T^t < 6$ GeV/c and $2 < p_T^a < 4$ GeV/c and pseudorapidities $|\eta| < 0.7$. The precise centrality range is not given, however, other STAR papers using the same data set use 0–5% central collisions [5] and the thesis including these measurements includes correlations from both 0–5% and 0–10% central collisions [34]. The data from [12] are not publicly available before background subtraction.

The publicly available data set with a kinematic range similar to the original paper was chosen as the focal point of this analysis. Correlation functions in 0–12% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for $4 < p_T^t < 6$ GeV/c, $2 < p_T^a < 4$ GeV/c, and $|\eta| < 1.0$ from [20] were measured as a function of both azimuth and pseudorapidity. A correction for the pair acceptance in $\Delta\eta$ was applied in [20] which was not applied in [12]. It would in principle be possible to undo this correction assuming a

form of $a(\Delta\eta) = |2.0 - \Delta\eta/2.0|$. Undoing this correction would increase the away-side by nearly a factor of two, since it is nearly independent of $\Delta\eta$, and lead to a slight increase in the near-side. Since the away-side is observed to be consistent with zero, the correction is not undone in order to minimize manipulations of the data.

A rapidity-even v_1 due to flow has been observed to be comparable to v_2 and v_3 [35, 36]. The value of v_1 is difficult to determine because there is no clear technique which can be used to separate contributions from flow and jets. In [35, 36] dihadron correlations are used where the trigger and associated particles are separated in $\Delta\eta$ and assuming that the coefficient of $\cos(\Delta\phi)$ is $v_1^a v_1^t$. The near-side is suppressed by the large $\Delta\eta$ gap between the trigger and associated particles, but there is a residual contribution from the away-side. Any residual contribution from jets on the away-side will lead to an artificially high v_1 , particularly for the values in [35] which use particles as close as $\Delta\eta = 0.7$. The data in [35] are from 20–60% central Au+Au collisions and measurements in [36] have a somewhat larger $\Delta\eta$ gap, but are at a different collision energy. There therefore are no measurements which can be used to fix v_1 for central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

The Near-Side Fit (NSF) method fits the background-dominated correlation function on the near-side at large $\Delta\eta$ to determine the B and v_n simultaneously [33] and v_1 can be included. The NSF method is applied to the data from Au+Au collisions from [20] to determine the background, allowing a non-zero v_1 . The NSF method can be sensitive to the fit region. The ZYAM method is therefore also applied to the data in [20] as a cross check using the v_2 from [20]. The v_3 from 0–10% central Au+Au collisions were estimated based on [25], increasing the uncertainty slightly to take the different momentum and centrality regions into account. The v_1 are assumed to be zero for the ZYAM method.

The v_n from the fit and the ZYAM method are shown in table I. The value of v_1 can be estimated from [35], leading to approximately $v_1^a v_1^t = 0.008 \pm 0.004$. This is substantially lower than that derived from the NSF method, although that may be due to the difference in centrality. The uncertainties are estimated conservatively due to the residual contamination from the away-side. The standard deviation between values of $v_1^a v_1^t$ from the fit and from independent measurements are also shown in table I. The v_1 is somewhat lower than the values from [35] while the v_2 and v_3 are somewhat higher.

Unfortunately the d +Au data from [20] are not available. Instead correlation functions from minimum bias d +Au collisions at $\sqrt{s_{NN}} = 200$ GeV and 20–60% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for tracks with $\eta < 1$ in two regions in $\Delta\eta$ ($|\Delta\eta| < 0.7$ and $0.7 < |\Delta\eta| < 2.0$) from [19] are used. Data from Au+Au collisions are in bins of the angle between the trigger particle and the reconstructed reaction plane, $\phi_s = \phi^t - \psi$ and were reanalyzed in [37] using the Reaction Plane Fit method [33]. The data Au+Au collisions from all bins relative to the reaction

Method	$v_1^a v_1^t$	v_2^a from [20]	v_2^t from [20]	$v_2^a v_2^t$	v_3^a from [25]	v_3^t from [25]	$v_3^a v_3^t$
NSF	0.00225 ± 0.00034	—	—	0.00845 ± 0.00033	—	—	0.00573 ± 0.00033
σ	-1.4	—	—	+1.2	—	—	$+0.69$ $+0.61$
ZYAM	0	0.082 ± 0.002	0.077 ± 0.019	0.0063 ± 0.0017	0.067 ± 0.010	0.072 ± 0.010	$0.0048^{+0.0015}_{-0.0013}$

TABLE I: v_n from the NSF method, number of standard deviations away from expectations, and v_n used in the ZYAM method.

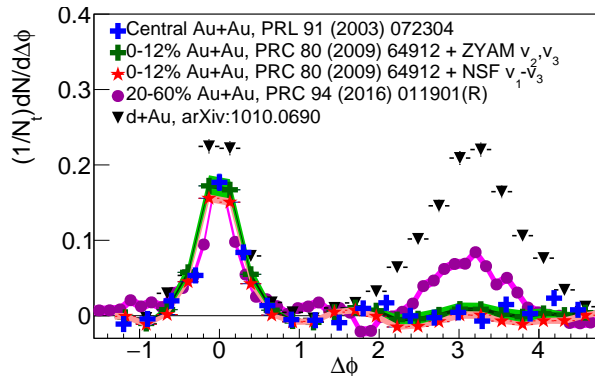


FIG. 1: Dihadron correlations with $4 < p_T^t < 6$ GeV/ c and $2 < p_T^a < 4$ GeV/ c from minimum bias d +Au collisions at $\sqrt{s_{NN}} = 200$ GeV from [19], 20–60% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from [19] reanalyzed in [37], central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from [12], and 0–12% collisions from [20] reanalyzed using both the NSF method described in [37] and the ZYAM method using v_2 from [20] and v_3 from [25].

plane and $2 < p_T^a < 3$ GeV/ c and $3 < p_T^t < 4$ GeV/ c are combined to get the same momentum region as [12]. A constant background is assumed for data from d +Au collisions. Both the d +Au and the 20–60% Au+Au collisions from [20] are from $|\Delta\eta| < 0.7$. The slightly different acceptance range could decrease the near-side yield, though such effects are likely negligible. The correction for acceptance in $\Delta\eta$ was not applied to these data.

III. RESULTS

Figure 1 shows the background subtracted correlations comparable to the analysis in [12] but incorporating our current knowledge about the background. The slightly different acceptances in $\Delta\eta$ described in section II could overestimate the away-side in 0–12% central Au+Au collisions by up to a factor of two relative to 20–60% Au+Au collisions and d +Au collisions, however, it is consistent with zero and the previous results for both the ZYAM and NSF methods. The slight differences in the near-side between minimum bias d +Au, 20–60% central Au+Au, and 0–12% central Au+Au collisions may be due to the differences in $\Delta\eta$ and η acceptance described in section II, or may be due to slight modifications of the near-side. The largest difference is seen for the 20–60% central Au+Au collisions, where there are no apparent

shape modifications. For central Au+Au collisions, despite qualitatively different observations on the away-side when taking v_3 into account for slightly lower momentum particles, results on the away-side in this particular kinematic regime happen to be qualitatively consistent with those reported in [12].

Some caution is warranted due to uncertainty in the appropriate value of v_1 . For both the NSF and ZYAM method shown above, the results are consistent. The values of v_1 in [35] would lead to a non-zero away-side, but these values are probably overestimates due to contamination of the v_1 measurements by the jet signal and the difference in centrality.

There is not currently a motivation for emphasizing this kinematic regime. The initial studies were limited in statistics, which motivated studying lower momentum trigger particles, where the probability that the trigger is from a jet is somewhat lower. Contemporary data sets allow much higher momentum trigger particles. Nonetheless, studies of low momenta associated particles still require precision subtraction of the large combinatorial background. Ultimately this requires a better understanding of the contribution of v_1 . The reaction plane fit method [33] may be one way to overcome this, with more stability in the fit.

Figure 2 compares the original data from p + p and d +Au collisions from [12] to the 0–12% central Au+Au data [20] from analyzed using the NSF method [37]. The NSF method is chosen because this approach takes v_1 into account. The slight difference in pseudorapidity acceptance between the data in [12] ($|\eta| < 0.7$) and in [19] ($|\eta| < 1.0$) does not lead to a noticeable difference on the near-side but leads to an away-side which is roughly 30% lower in d +Au. The data in [20] are both in a different pseudorapidity range ($|\eta| < 1.0$) from [12] and have an acceptance correction applied in $\Delta\eta$, leading to small differences on the near-side. Since the away-side is nearly completely suppressed, this does not impact the comparison of the 0–12% data from [20] to the d +Au data from [12]. The message of figure 2 is in agreement with the message in [12].

IV. CONCLUSIONS

There is comprehensive experimental evidence for jet quenching, but an early, iconic result has not been reassessed previously, long after it was widely recognized in the field that the background subtraction was incomplete. Using data in a similar kinematic regime, this measurement was repeated using our current understand-

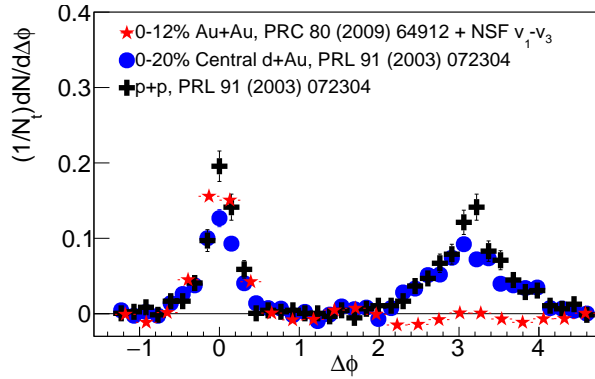


FIG. 2: Dihadron correlations with $4 < p_T^t < 6$ GeV/ c and $2 < p_T^a < 4$ GeV/ c from 0–20% central d +Au collisions at $\sqrt{s_{NN}} = 200$ GeV from [12], p + p collisions at $\sqrt{s_{NN}} = 200$ GeV from [12], and 0–12% collisions from [20] reanalyzed using the NSF method described in [37].

ing of the data. These results could be improved further by using a background subtraction technique which can constrain v_1 better. Fortunately for the community, the same qualitative conclusion can be drawn – that the away-side is nearly completely suppressed.

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- [1] K. Adcox et al. (PHENIX), Nucl. Phys. **A757**, 184 (2005).
 - [2] J. Adams et al. (STAR), Nucl. Phys. **A757**, 102 (2005).
 - [3] B. B. Back et al., Nucl. Phys. **A757**, 28 (2005).
 - [4] I. Arsene et al. (BRAHMS), Nucl. Phys. **A757**, 1 (2005).
 - [5] J. Adams et al. (STAR), Phys. Rev. Lett. **91**, 172302 (2003), nucl-ex/0305015.
 - [6] S. Adler et al. (PHENIX), Phys.Rev.Lett. **91**, 072301 (2003).
 - [7] B. Back et al. (PHOBOS), Phys.Rev. **C70**, 061901 (2004).
 - [8] K. Aamodt et al. (ALICE), Phys.Lett. **B696**, 30 (2011).
 - [9] S. Chatrchyan et al. (CMS), Eur.Phys.J. **C72**, 1945 (2012).
 - [10] V. Khachatryan et al. (CMS), JHEP **04**, 039 (2017), 1611.01664.
 - [11] C. Adler et al. (STAR), Phys.Rev.Lett. **90**, 082302 (2003).
 - [12] J. Adams et al. (STAR), Phys. Rev. Lett. **91**, 072304 (2003).
 - [13] J. Adams et al. (STAR), Phys.Rev.Lett. **93**, 252301 (2004).
 - [14] G. Aad et al. (ATLAS), Phys.Rev.Lett. **105**, 252303 (2010).
 - [15] S. Chatrchyan et al. (CMS), Phys. Rev. **C84**, 024906 (2011).
 - [16] P. Sorensen, J. Phys. G **37**, 094011 (2010).
 - [17] B. Alver and G. Roland, Phys. Rev. **C81**, 054905 (2010), [Erratum: Phys. Rev.C82,039903(2010)], 1003.0194.
 - [18] M. Connors, C. Nattrass, R. Reed, and S. Salur (2017), 1705.01974.
 - [19] H. Agakishiev et al. (STAR) (2010), 1010.0690.
 - [20] B. Abelev et al. (STAR), Phys.Rev. **C80**, 064912 (2009).
 - [21] M. A. Lisa, S. Pratt, R. Soltz, and U. Wiedemann, Ann. Rev. Nucl. Part. Sci. **55**, 357 (2005).
 - [22] M. A. Lisa and S. Pratt (2008).
 - [23] S. A. Voloshin, A. M. Poskanzer, and R. Snellings (2008), 0809.2949.
 - [24] J. Bielcikova, S. Esumi, K. Filimonov, S. Voloshin, and J. Wurm, Phys.Rev. **C69**, 021901 (2004).
 - [25] A. Adare et al. (PHENIX), Phys. Rev. Lett. **107**, 252301 (2011).
 - [26] K. Aamodt et al. (ALICE), Phys. Rev. Lett. **107**, 032301 (2011), 1105.3865.
 - [27] B. Alver et al. (PHOBOS), Phys.Rev.Lett. **104**, 062301 (2010).
 - [28] A. Adare et al. (PHENIX), Phys.Rev. **C77**, 011901 (2008).
 - [29] A. Adare et al. (PHENIX), Phys.Rev. **C78**, 014901 (2008).
 - [30] S. Afanasiev et al. (PHENIX), Phys.Rev.Lett. **101**, 082301 (2008).
 - [31] J. Adams et al. (STAR), Phys.Rev.Lett. **95**, 152301 (2005).
 - [32] A. Sickles, M. P. McCumber, and A. Adare, Phys.Rev. **C81**, 014908 (2010).
 - [33] N. Sharma, J. Mazer, M. Stuart, and C. Nattrass, Phys. Rev. **C93**, 044915 (2016).
 - [34] M. Miller, Ph.D. thesis, Yale University (2004).
 - [35] M. Luzum and J.-Y. Ollitrault, Phys. Rev. Lett. **106**, 102301 (2011), 1011.6361.
 - [36] G. Aad et al. (ATLAS), Phys. Rev. **C86**, 014907 (2012), 1203.3087.
 - [37] C. Nattrass, N. Sharma, J. Mazer, M. Stuart, and A. Bejnood, Phys. Rev. **C94**, 011901 (2016).