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Dijet Acoplanarity in CUJET3 as a Probe of the Nonperturbative Color Structure of QCD Perfect Fluids

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Abstract

Using the CUJET3=DGLV+VISHNU jet-medium interaction framework, we show that dijet azimuthal acoplanarity in high energy $A + A$ collisions is sensitive to possible non-perturbative enhancement of the jet transport coefficient, $\hat{q}(T, E)$, in the QCD crossover temperature $T \sim 150 - 300$ MeV range. With jet-medium couplings constrained by global RHIC& LHC χ^2 fits to nuclear modification data on $R_{AA}(p_T > 20)$ GeV, we compare predictions of the medium induced dijet transverse momentum squared, $Q_s^2 \sim \langle \hat{q} L \rangle \sim \Delta\phi^2 E^2$, in two models of the temperature, T, and jet energy E dependence of the jet medium transport coefficient, $\hat{q}(T, E)$. In one model, wQGP, the chromo degrees of freedom (dof) are approximated by a perturbative dielectric gas of quark and gluons dof. In the second model, sQGMP, we consider a nonperturbative partially confined semi-Quark-Gluon-Monopole-Plasma with emergent color magnetic dof constrained by lattice QCD data. Unlike the slow variation of the scaled jet transport coefficient, $\hat{q}_{wQGP}/T^3$, the sQGMP model $\hat{q}_{sQGMP}/T^3$ features a sharp maximum in the QCD confinement crossover T range. We show that the dijet path averaged medium induced azimuthal acoplanarity, $\Delta\phi^2$, in sQGMP is robustly ~ 2 times larger than in perturbative wQGP. even though the radiative energy loss in both models is very similar as needed to fit the same R_{AA} data. Future A+A dijet acoplanarity measurements *constrained* together with single jet R_{AA} *and* v_n measurements therefore appears to be a promising strategy to search for possible signatures of critical opalescence like phenomena in the QCD confinement temperature range.

Keywords: Quark Gluon Plasmas, Heavy Ion Collision, Jet Quenching, Dijet Acoplanarity

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1. Introduction and Conclusions

Dijet relative azimuthal angle acoplanarity, $\Delta\phi^2 = (\pi - \phi_1 + \phi_2)^2 = (Q^2_{vac} + Q^2_s)/E^2$, as a probe of Quark Gluon Plasmas (QGP) produced in high energy nuclear collisions, has a long history, see e.g. [1, 2, 4, 3, 5, 6, 7]. In both $p + p$ and $A + A$ collisions this observable is always dominated by $Q^2_{vac}/E^2 \sim \alpha_s^2 \sim 0.1$ due to (Sudakov) multiple gluon emission into the vacuum associated with all hard QCD processes[8].

The BDMS[2] medium dependent "saturation" scale, $Q_s^2 = \langle \hat{q} L \rangle = \langle \int dt \; \hat{q}(T(t)) \rangle$, is a jet path averaged measure of jet straggling transverse to its initial direction $\hat{\mathbf{n}}(\phi_0)$. It is the average transverse momentum squared accumulated over a path length L. For a jet with color,flavor a, the jet transport coefficient $\hat{q}_a$ in a QCD fluid of temperature $T = T(\mathbf{x}, t)$, $\hat{q}_a(T) = \langle q^2/\lambda \rangle_a = \int dq^2 \; q^2 \Gamma_a(q^2, T)$. It depends on the composition densities , $\{\rho_b(T); b = q, g, m, \cdots\}$, of effective color electric and magnetic degrees of freedom (dof) as well as on the microscopic differential scattering rates, $\Gamma_a(q^2, T) \equiv \sum_b \rho_b(T) d\sigma_{ab}(T)/dq^2$.

In fact, $Q_s^2(\hat{\mathbf{n}}, E_{fin}) = \langle \int dt \;\; \hat{q}(T(\mathbf{z}(t), t), E_{ini}) \rangle_{\{E_{ini}, \mathbf{z}(0)\}}$, is only one of a large set of jet path line integral functionals depending on jet paths, $\mathbf{z}(t) = \mathbf{x}_0 + t \;\; \hat{\mathbf{n}}(\phi_0)$ that control the medium modification of jets in $A + A$. In particular, the correct geometric averaging of $\langle Q_s^2(E_{fin}) \rangle$ for given observed jet energy and direction requires simultaneous calculation of radiative and elastic energy loss functionals as well: $\Delta E_{rad} \sim \int dt \;\; t \;\; \hat{q}(t) \;\; \mathcal{F}_{rad}(t, E)$ and $\Delta E_{el} \sim \int dt \;\; \hat{q}(t)/T(t)$. This is because jet quenching strongly biases the spatial distribution of jet initial production points, $\mathbf{x}_0$, to a sub region of the medium transverse geometry from which jets in a given direction $\hat{n}(\phi_0)$ emerge with given final energy E_{fin}. Note that in the asymptotic $E \to \infty$ BDMS limit $\Delta E_{rad}^{BDMS} \sim \int dt \;\; t\hat{q} \approx \langle \hat{q} L^2 \rangle/2$ because $\mathcal{F}_{BDMS}(t, \infty) \equiv 1$. However, for non-asymptotic $E < 100$ GeV jet energies of interest here, the DGLV[15] formalism predicts that $\Delta E_{rad}^{DGLV} = \int dt \int d^2\mathbf{q} \; \Gamma_a(\mathbf{q}, T(t)) \; \left\{ \int dx d^2\mathbf{k} \; A(\mathbf{q}, \mathbf{k}, M^2(x, T)) \left((1 - \cos[t((\mathbf{k} - \mathbf{q})^2 + M^2(x, T))/(2xE)] \right) \right\}$. We found numerically that only in the high energy ($E > 100$ GeV) limit can we approximate $\mathcal{F}_{rad}(t, E > 100) \approx 1$. In the CUJET framework the DGLV energy loss integrals $\int dt d^2\mathbf{q} dx \mathbf{k} \cdots$ needed to compute $\Delta E_{rad}^{DGLV} \neq \int dt \;\; t\hat{q}_{DGLV}$ and hence ΔE_{rad}^{DGLV} does not simply scale for moderate energy jets with $\hat{q}$ as does $Q_s^2[elas]$ by definition.

As emphasized in [1] long ago, dijet acoplanarity , as a stand alone observable cannot uniquely discriminate between different models of the color dof $\rho_b(T)$ and the microscopic $d\sigma_{ab}$ cross sections. This ambiguity is further amplified by the strong dependence of all jet path functionals on the non static, inhomogeneous, anisotropic temperature field , $T(\mathbf{z}, t)$ produced in finite $A + A$ collisions. The unavoidable geometric bias caused by jet quenching implies that the triple set of hard jet observables $\{R_{AA}, \; v_n, \; \Delta\phi\}$ must be strongly correlated. Hence, measuring the correlation between these three observables should enhance the discriminating power of hard jet and dijet observables to probe the color structure of QCD fluids, as we emphasized in [6, 9].

Current interest in $A + A$ dijet acoplanarity observables is motivated by the first preliminary data from RHIC[25, 26] and LHC[27] that suggest [10, 11] that future higher statics measurements of the acoplanarity distribution in the "sweet spot" $20 < E_{fin} < 80$ GeV jet energy range will be able to resolve medium induced corrections, $\Delta\phi_{med}^2 = Q_s^2/E^2$ from the dominant Sudakov source of dijet acoplanarity[8] that can be directly measured in $p + p$.

Another important motivation for our focus on dijet acoplanarity here is that there exist currently several independent frameworks[12, 13, 14] with rather different combinations of quenching dynamics and viscous hydrodynamics modeling that have tested equally well at the $\chi^2/dof < 2$ level against currently available soft *and* hard R_{AA} and v_n data in $A + A$ at RHIC and LHC. This work is thus also motivated by the question: "Can dijet acoplanarity help experimentally to break the current degeneracy between soft+hard modeling of $A + A$?"

The CUJET3 framework used here utilized the temperature and flow velocity fields predicted by VISHNU2+1 [13] code with Glauber Initial Conditions. The DGLV jet quenching theory[15] is then applied to evaluate both ΔE and Q_s^2 jet path functionals in the VISHNU2+1 viscous hydrodynamic fluid fields. See Refs.[16, 17, 18, 19, 20, 21] for details. Our global $\chi^2/dof < 2$ fit[16] to available soft+hard data constrained the two free parameters of CUJET3: the maximum of the running coupling $\alpha_c = 0.9 \pm 0.1$ and the ratio of magnetic to electric screening scales, $c_m = \mu_M(T)/(g(T)\mu_D(T)) \approx 0.25 \pm 0.03$. We use the same values of the two parameters to compute $Q_s^2(E)$ here.

The CUJET3 jet path functionals are evaluated in two models, wQGP and sQGMP, of the color composition of the QCD fluid . The wQGP composition model assumes the color structure of the QCD fluid can be approximated by perturbative two component color di-electric model with one loop dynamically screened quark and gluon dof. However, for consistency with lattice QCD equation of state, the Stefan-Boltzmann partial pressures, $P_b^{SB}(T) = T\rho_b^{SB}(T)$, are scaled down by the ratio of the nonperturbative lattice

QCD pressure, $P_{lat}(T)$, to the ideal gas pressure $T(\rho_q^{SB} + \rho_g^{SB})$.

The sQGMP composition model includes emergent color magnetic monopole (cmm) degrees of freedom, as proposed in [22, 23, 24] to solve the $R_{AA} \times v_2$ puzzle. In CUJET3, the sQGMP model further generalizes wQGP by not only adding the monopole dof but also by further reducing the q and g dof partial pressures by powers of the nonperturbative lattice Polyakov loop, $L(T)$, and/or the light quark susceptibility, $\chi_s^u(T)$, data as proposed by [28]. See [16, 17, 18, 19, 20, 21] for further details.

In Fig.1 (Left panel) we plot the the global $R_{AA}\,\chi^2$ data constrained quark jet transport fields, $\hat{q}_{sQGMP}(T, E)$ and $\hat{q}_{wQGP}(T, E)$. Note that $\hat{q}_{sQGMP}(T, E)$ is strongly enhanced relative to $\hat{q}_{wQGP}(T, E)$ in the QCD crossover temperature range $160 < T < 320$ MeV. This is due to enhanced jet-monopole interactions with $d\sigma_{qm} \propto \alpha_E\alpha_M = 1 \gg d\sigma_{qg} \propto \alpha_E^2$. The question addressed here is whether R_{AA} constrained acoplanarity could serve to search for such "critical opalescence" like phenomena near the confinement temperature range. Our answer is positive, as we show below.

In the Middle panel of Fig.1, the spacetime isochrone evolution of the VISHNU temperature field in central 0-10% $Pb + Pb$ 5 ATeV is shown. In the Right panel of Fig.1 the isochronous evolution of $\hat{q}_{wQGP}$ and $\hat{q}_{sQGMP}$ are compared as a function of the reaction plane x coordinate with at $y = 0$. The emergent monopole degrees in the crossover temperature range near the freeze-out surface $T = 160$ MeV and at late times are seen to enhance $\hat{q}_{sQGMP}$ by a factor ~ 4. The enhancement of $\hat{q}$ near the crossover surface regions plays the decisive role , as proposed in [22, 23, 24], in enhancing the CUJET3 predicted elliptic azimuthal asymmetry, v_2, in agreement with data. .

Our main new result shown in Fig.2 is that with charged hadron R_{AA} constrained $\hat{q}(x, t)$ transport fields, the medium induced single jet acopanarity broadenning $\Delta\phi^2$ is robustly a factor of ~ 2 larger in a QGP fluid with magnetic monopole degrees of freedom than in a purely di-electric (pQCD/HTL type) "wQGP" fluid. .

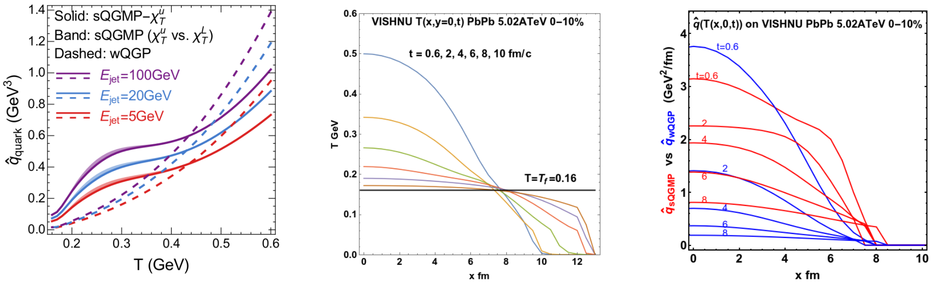

Fig. 1. (color online) (Left) The CUJET3.1 R_{AA} constrained [16, 17, 18, 19] jet transport field, $\hat{q}_F(T, E)$ for quark jets with $E_{ini} = 5, 20, 100$ GeV are compare to wQGP and sQGMP models of the chromo electric and magnetic dof in the QCD fluid. Dashed curves for wQGP assume only color di-electric dof while solid curves for sQGMP assume that the color electric quark and gluon dof are suppressed by lattice Polyakov loop and quark susceptibility factors, χ_T^u, due to only partial confinement in $160 < T < 320$ MeV QCD transition range. In sQGMP the remaining dof are assumed to be color magnetic monopole quasi-parton dof. (Center) The isochronous evolution of temperature field, $T(x, 0, t)$,from VISHNU2+1 viscous hydrodynamics[13] for 0-10% $Pb+Pb$ 5.02ATeV is shown. (Right) The isochronous evolution of the jet transport coefficients, $\hat{q}_{wQGP}$ (Blue) and $\hat{q}_{sQGMP}$ (Red), for $E = 20$ GeV are compared at given $x, y = 0$ at times $t = 0.6, \cdots, 10$ fm/c . Note that $\hat{q}_{sQGMP}$ is strongly enhanced compared to $\hat{q}_{wQGP}$ in the surface regions and in interior at late times.

Our previous study[6] of dijet acoplanarity concentrated on the tails of the $dN/\Delta\phi$ distributions in the $2.4 < \Delta\phi < 3$ range and showed that future experiments must reach sub-percent levels of precision to discriminate between medium dependent BDMS Gaussian and DGLV, power law like Rutherford tails convoluted on top of the dominant Sudakov vacuum radiation tails. The present study[9], summarized in Fig.2, utilized the CUJET3=DGLV+VISHNU framework [16, 17, 18, 19] to compute, at leading partonic level, the elastic $Q_s^2[E_{fin}] = \langle \int dt\hat{q}(T(t), E_{fin} + \Delta E(\mathbf{x}_0, \phi_0)\rangle$, taking into account the unavoidable geometric "sunny side up" bias due to jet energy loss via $\Delta E(\mathbf{x}_0, \phi_0) = \Delta E_{rad} + \Delta E_{elas}$, that we constrained by global fits to data on nuclear modification os high p_T hadron fragments, $R_{AA}^{ch}(p_T)$. We compared different models of the temperature dependence of the color dof composition of the QCD fluid constrained not only by R_{AA}^{ch} data but also by numerical lattice QCD equation of state data.

Our main new result, shown in Fig.2a, is that elastic scattering Q_s^2 is predicted to be robustly ~ 2 times larger in sQGMP than in wQGP models of the color structure[7]. Future work must next resolve the current

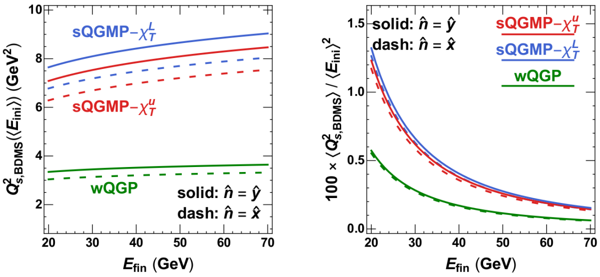

Fig. 2. (Left) Comparison of R^{ch}_{AA} constrained CUJET3.1 predictions for single parton jet level Q_s^2 in 20-30% centrality Pb+Pb 5.02 ATeV. The final quenched energy , E_{fin}, dependence of the average BDMS transverse momentum squared scale is compared for the three models of the color structure of QCD fluids as in Fig.1a but using the evolving VISHNU fluid $T(x,t)$ filed 20-30% centrality class. Green curves show predictions in wQGP fluids, blue curves show sQGMP with semi quark and and semi gluon degrees of freedom suppressed by powers, $L(T)^1$ and $L(T)^2$ resp., of lattice Polyakov loop data. The red curves show results assuming an sQGMP fluid with semi quarks suppressed by lattice light quark susceptibility data on $\chi_2^u(T)$, while semi-gluons are suppressed by $L(T)^2$ (see [16] for details). (Right) CUJET3.1 predictions for medium induced azimuthal angle broadening width squared $\Delta\phi^2 = Q_s^2/\langle E_{\mathrm{ini}}\rangle^2$ at the single parton level averaged over both q and g jets. The abscissa is scaled up by a factor 100 for clarity.

debate on the sign and magnitude of radiative corrections, $\Delta Q_s^2[rad]$ to elastic $Q_s^2[elas]$ [29, 30, 31]. Our preliminary estimates, to be reported elsewhere [31], agree with Ref. [30] that $\Delta Q_s^2[rad]$ reduces moderately the magnitude of elastic scattering induced acoplanarity.

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References

[1] D. A. Appel, Phys. Rev. D **33**, 717 (1986); J. P. Blaizot and L. D. McLerran, Phys. Rev. D **34**, 2739 (1986).
[2] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne and D. Schiff, Nucl. Phys. B **484**, 265 (1997).
[3] A. Majumder et al., Phys. Rev. C **80**, 031902 (2009); 125020 (2009).
[4] F. D'Eramo et al.JHEP **1901**, 172 (2019); JHEP **1305**, 031 (2013).
[5] T. Luo, S. Cao, Y. He and X. N. Wang, Phys. Lett. B **782**, 707 (2018).
[6] M. Gyulassy, P. Levai, J.Liao, S. Shi, F. Yuan and X. N. Wang, Nucl. Phys. A **982**, 627 (2019)
[7] S. Shi, J.Liao, M.Gyulassy, P.M. Jacobs, X.-N. Wang, in prep.
[8] S. D. Ellis and W. J. Stirling, Phys. Rev. D **23**, 214 (1981).
[9] M. Gyulassy, Quark Matter 2019, https://indico.cern.ch/event/792436/contributions/3535718/attachments/1939248/3215717/MGyulassy_110619_QM19_vff.pdf
[10] A. H. Mueller, B. Wu, B. W. Xiao and F. Yuan, Phys. Lett. B **763**, 208 (2016); Phys. Rev. D **95**, 034007 (2017).
[11] L. Chen, G. Y. Qin, S. Y. Wei, B. W. Xiao and H. Z. Zhang, Phys. Lett. B **773**, 672 (2017) [arXiv:1607.01932 [hep-ph]].
[12] J. Noronha-Hostler, B. Betz, J. Noronha and M. Gyulassy, Phys. Rev. Lett. **116**, no. 25, 252301 (2016)
[13] C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass and U. Heinz, Comput. Phys. Commun. **199**, 61 (2016)
[14] H. Niemi, K. J. Eskola and R. Paatelainen, Phys. Rev. C **93**, no. 2, 024907 (2016)
[15] M. Gyulassy, P. Levai and I. Vitev, Phys. Rev. D**66**, 014005(2002); M. Djordjevic et al., Nucl. Phys. A**733**, 265(2004)
[16] S. Shi, J. Liao and M. Gyulassy, Chin. Phys. C **43**, no. 4, 044101 (2019) [arXiv:1808.05461 [hep-ph]].
[17] S. Shi, J. Liao and M. Gyulassy, Chin. Phys. **C42** (2018) 104104, arXiv:1804.01915 [hep-ph];
[18] S. Shi, J. Xu, J. Liao and M. Gyulassy, Nucl. Phys. A **967**, 648 (2017) [arXiv:1704.04577 [hep-ph]].
[19] J. Xu, J. Liao and M. Gyulassy, JHEP **1602**, 169 (2016) [arXiv:1508.00552 [hep-ph]].
[20] J. Xu, J. Liao and M. Gyulassy, Chin. Phys. Lett. **32**, no. 9, 092501 (2015) [arXiv:1411.3673 [hep-ph]];
[21] J. Xu, A. Buzzatti and M. Gyulassy, JHEP **1408**, 063 (2014) [arXiv:1402.2956 [hep-ph]].
[22] J. Liao and E. Shuryak, Phys. Rev. C **75**, 054907 (2007) [hep-ph/0611131].
[23] J. Liao and E. Shuryak, Phys. Rev. Lett. **101**, 162302 (2008) [arXiv:0804.0255 [hep-ph]].
[24] J. Liao and E. Shuryak, Phys. Rev. Lett. **102**, 202302 (2009) [arXiv:0810.4116 [nucl-th]].
[25] PHENIX, A. Adare et al. , PRC77, 011901 (2008);STAR L. Adamczyk *et al.*, Phys. Lett. B **760**, 689 (2016).
[26] L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. C **96**, no. 2, 024905 (2017)
[27] J. Adam *et al.* [ALICE Collaboration], JHEP **1509**, 170 (2015)
[28] Y. Hidaka and R. D. Pisarski, Phys. Rev. D **78**, 071501 (2008)
[29] J. P. Blaizot and F. Dominguez, Phys. Rev. D **99**, no. 5, 054005 (2019)
[30] B. G. Zakharov, Zh. Eksp. Teor. Fiz. **156**, 615 (2019) [J. Exp. Theor. Phys. **129**, no. 4, 521 (2019)]
[31] S.Shi, J.Liao, and M.Gyulassy, in preparation.