Hard Probe of Geometry and Fluctuations from RHIC to LHC

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We study the event-by-event hard probe of geometry and fluctuations in the initial condition of heavy ion collisions from RHIC to LHC energies. Results for the dominant harmonic, \( v_2 \) at high \( p_t \) from jet quenching models with varied path-length and matter-density dependences are compared with precise data sets at both RHIC and LHC. We find that too strong a path-length dependence (e.g. cubic) is ruled out by data at LHC, while the model with strong near-\( T_c \) enhancement of jet-medium interaction fully describes data. Quantification of azimuthal harmonics \( v_n \) (n=1,2,3,4,5,6) of high \( p_t \) hadrons are presented for LHC 2.76 TeV as well as 5.5 TeV collisions. We also point out that the near-\( T_c \) enhancement model naturally expects a less color-opaque medium at LHC.

\textit{Introduction.}—Searching for new forms of matter is a fundamental quest. In the strong interaction sector of the Standard Model described by the Quantum Chromodynamics (QCD), various forms of QCD matter may exist in the Nature, e.g. inside the compact stars and in the early Universe a few microseconds after the “Big Bang”. Studying the “condensed matter physics of QCD” has been essential for advancing our understanding of matter and of the QCD dynamics as well. A highly nontrivial prediction based on the salient feature of QCD, the asymptotic freedom \[1\], is that we shall expect a new, deconfined, and weakly coupled phase of QCD matter at asymptotically high temperature\[2,3\]. A deconfinement transition at certain temperature \( T_c \) and a quark-gluon plasma (QGP) phase above that temperature \[4\] are expected and have been extensively studied using lattice QCD simulations. Experimentally such hot QCD matter has been created in heavy ion collisions (“Little Bang”), with its many properties measured in the past decade at the Relativistic Heavy Ion Collider (RHIC) \[5\] and now also at the Large Hadron Collider (LHC) \[6\].

The era of RHIC plus LHC provides unique opportunities for uncovering the underlying structure of hot deconfined QCD matter and deepening our understanding of how QCD operates in a strongly interacting many-body setting. The various major findings at RHIC (with AuAu collisions up to \( \sqrt{s} = 200\text{GeV} \)) coherently hint at a strongly coupled QGP (sQGP) \[7\] above but close to \( T_c \), which is drastically different from the naively expected “asymptotically free matter” (AFM). While a full microscopic picture of the sQGP is yet to come, there have been important progresses suggesting that the QCD plasma near \( T_c \) is an emergent matter dominated by dense and light (chromo-)magnetic monopoles \[8\]. These thermal monopoles are peculiar to the region above but close to \( T_c \), and their condensation at \( T_c \) marks the onset of confinement. With LHC colliding PbPb at \( \sqrt{s} = 2.76\text{ TeV} \) now (and \( \sqrt{s} = 5.5\text{ TeV} \) in the future), thus creating an even hotter QGP of much higher density, it is tempting to ask: if the sQGP at RHIC bears peculiar near-\( T_c \) nature, is that quickly turning off with noticeable changes in the QGP properties at LHC which shifts to higher \( T \) further away from \( T_c \), and how much is the QGP at LHC getting closer to the AFM? This paper attempts to extract insights into these questions by studying the hard probe of geometry and fluctuations at both collision energies.

\textit{Jet quenching and geometric tomography.}—Just like the X-ray imaging of normal materials, the highly energetic partons produced in the initial binary hard collisions provide natural imaging tools to study the created hot matter in heavy ion collisions. Such a partonic jet carries an energy much higher than the medium energy scale and when it travels through the dense medium it experiences multiple collisions with medium constituents and loses its energy significantly (i.e. jet quenching) \[9\]. As a result the hadrons eventually produced from the jet will differ from the case without medium effects e.g. in a proton-proton collision at the same energy. Measuring such differences is a most useful way of learning about the properties of medium and the jet-medium interactions. A conventional observable to quantify the jet quenching is the nuclear modification factor \( R_{AA} \) defined as:

\[
R_{AA}(p_t, \phi, \eta) \equiv \frac{d^2N_{AA}}{dp_t d\phi d\eta} \frac{T_{AA} d^2\sigma_{NN}}{d^2N/d\phi d\eta} , \tag{1}
\]

where in the denominator the the nuclear overlap function \( T_{AA} \) scales up single Nucleon-Nucleon (NN) cross section to Nucleus-Nucleus (AA) according to the expected number of binary NN collisions assuming no modification. Thus a value of \( R_{AA} \) smaller (larger) than unity means suppression (enhancement) due to medium effect. For physics related to jet quenching, we focus on \( R_{AA} \) measured for detected hadrons with large enough transverse momentum (e.g. \( p_t > 6\text{GeV} \) for RHIC and \( p_t > 8\text{GeV} \) for LHC) and for \( \eta \) at mid-rapidity (as per most detectors). The \( \phi \) is the azimuthal angle of the measured hadron’s transverse momentum, and one may examine the \( R_{AA} \) either integrated or differential in \( \phi \).

Significant suppression of hadron production at large transverse momentum \( p_t \), was first observed at RHIC, with \( R_{AA} \) reaching about 0.18 in the most central collisions. Measurements of charged particle, identified
hadron, heavy flavor production, photon production, triggered di-hadron correlations have coherently pointed to a created medium that is extremely opaque to “colored” hard probe. For reviews see e.g. [10]. New and extensive LHC data on various hard probe observables have shown similar strong jet quenching [11], and the apt question is to quantitatively analyze whether the hotter medium becomes less opaque or not (in the context that medium density roughly doubles).

A very powerful idea in jet quenching study is the so-called geometric tomography [12–13]. The hot medium created in a heavy ion collision event is generally anisotropic in the transverse plane (perpendicular to the collision beam axis), therefore high energy partons traversing the medium along different azimuthal directions will “see” different medium thickness and thus lose different amount of energy. That will lead to a measurable anisotropy in the $R_{AA}(\phi)$. It is well-known that the dominant geometric anisotropy is the elliptic component $\sim \cos 2(\phi - \Psi_2)$ (with $\Psi_2$ related to matter anisotropy axis) and the coefficient is the $v_2$ for high $p_t$ hadrons.

Notably, a lot of studies [14–21] have shown that such geometric observable of jet quenching is very sensitive to the underlying dynamics of jet energy loss e.g. its dependence on the in-medium path length. More recently the idea has been extended to systematically quantify the jet response to various harmonic components of the anisotropy arising from the strong event-by-event fluctuations in the initial condition of heavy ion collisions [22, 23].

Near-$T_c$ enhancement of jet quenching. —Substantial studies of jet quenching azimuthal anisotropy specified by $v_2$ at high $p_t$ at RHIC, however, led to a clear discrepancy between various model results and the already quite accurate PHENIX data extending to $\sim 20\text{GeV}$ [11, 22] till around 2008. All previous jet quenching models, with either linear or the LPM-induced quadratic [25] path-length dependence, underproduced the $v_2$ at high $p_t$ significantly (often by a factor of 2) after properly constrained in the overall opaqueness by $\phi$-integrated $R_{AA}$. Efforts toward reconciling $R_{AA}$ and $v_2$ at high $p_t$ fostered a more radical proposal in [15] that is in contrary to the assumption (taken for granted in all previous considerations) that the energy loss is simply proportional to plasma constituent density (e.g., as per entropy density $s$). Instead, the key insight of [15] is that the jet-medium interaction has non-trivial dependence on matter density and particularly is strongly enhanced in the near-$T_c$ region. Such near-$T_c$ enhancement of jet quenching, in analogy with the well-known “critical opalescence”, is well motivated by the aforementioned emergence of magnetic monopoles in the same regime [8]. Phenomenologically this model for the first time achieved a simultaneous description of $R_{AA}$ and $v_2$ at high $p_t$. It shall be emphasized that the effect of near-$T_c$ enhancement on jet quenching anisotropy is robust and generic: similar successes were reported by incorporating the near-$T_c$ enhancement in a variety of different approaches for jet quenching [26].

For a more formal discussion on the path-length dependence and matter-density dependence of jet quenching, let us adopt here the geometric models that have been widely used and successful in describing the gross features of jet quenching [14–19]. In such a model one assumes that the total energy $E_t$ of a jet with initial energy $E_i$ after traveling an in-medium path $P$ (specified by the jet initial spot and momentum direction) can be parameterized as $E_t = E_i \times f_P$ with the $f_P$ given by

$$f_P = \exp \left\{ - \int_P \kappa(s(l)) s(l) t'^{\delta} dl \right\} . \quad (2)$$

Here $s(l)$ is the local entropy density along the jet path, while the $\kappa(s)$ represents the local jet-medium interaction strength which as a property of underlying matter depends on the local density $s(l)$. We choose to explicitly separate out the density $s(l)$ itself, and the combination $\kappa(s)s$ approximately corresponds to $\hat{q}$ in many jet quenching models. Different choices of $m$ and $\kappa(s)$ mean different path-length and matter-density dependences, and here we consider three classes of models. The near-$T_c$ enhancement (NTcE) model as in [15] [19] is implemented by assuming $m = 1$ (i.e. quadratic) and introducing a strong jet quenching component in the vicinity of $T_c$ (with density $s_c$ and span of $s_w$) via

$$\kappa(s) = \kappa_0[1 + \xi \exp(-(s - s_c)^2/s_w^2)] , \quad (3)$$

with $\xi = 6$, $s_c = 7/fm^3$, and $s_w = 2/fm^3$. (see [15, 19] for the details.) For contrast, we also consider two other classes of models that both assume $\kappa(s) = \kappa_0$ being a constant independent of density, while have $m = 1$ and $m = 2$ respectively, referred to as L$^2$ and L$^3$ models hereafter. The parameter $\kappa_0$ controls the overall opaqueness in each of the three models and will be fixed by $R_{AA} \approx 0.18$ in the $0-5\%$ collisions at RHIC $\sqrt{s} = 200\text{GeV}$. The L$^2$ model represents the generic feature of most radiative energy loss models with LPM effect, while the L$^3$ model is motivated by certain energy loss calculations for strongly coupled Yang-Mills plasma based on the AdS/CFT correspondence [10, 27]. It is worth mentioning, though, that at RHIC it turns out the L$^3$ model is also able to describe $v_2$ at high $p_t$ [11, 28]. The reason may be that the L$^3$ dependence effectively enhances the later time quenching which mimics the similar effect from near-$T_c$ enhancement. Therefore further discrimination between the two models is called for and LHC test is crucial.

Hard probe of geometry and fluctuations from RHIC to LHC. —In this study we report the first event-by-event quantification of the azimuthal anisotropy in jet quenching due to both geometry and fluctuations at both RHIC and LHC energies. In particular we will show results for $v_2$ at high $p_t$ from all three geometric models, the NTcE, L$^2$ and L$^3$ models, and compare with experimental data.

In general for a given event, there are strong initial fluctuations in both the participant density (which...
The overall quenching $R_{AA}$ as well as the azimuthal harmonics $v_n$ and the corresponding n-axis $\psi_n^\phi$ can then be determined from the above in each event, followed by average over events ($\sim 10^4$ for each impact parameter in this study). The second harmonic $v_2$ is the most robust and reflects the hard probe of anisotropy both from geometry and fluctuation, while all the other harmonics are jet responses to fluctuations and provide further insights into the initial conditions in addition to what have been learned from the bulk collective expansion dynamics [31].

To perform the event-by-event simulation, we have used the standard Monte-Carlo Glauber model to generate fluctuating initial conditions [32] and followed most hydrodynamics literature for setting the relevant implementation procedures and parameters [33–34]. The NN cross section $\sigma_{inel}$ is set as $\sigma_{inel} = 42.62$, and $66 \text{mb}$ for $\sqrt{s} = 0.2, 2.76$, and $5.5 \text{TeV}$. With calculated participant density $\rho_p(r^+)_{\phi}$ and binary collision density $\rho_c(r^+)_{\phi}$ in the transverse plane, the initial entropy density at equilibrium time $\tau_0 \equiv 0.6 \text{fm/c}$ (assumed the same for different energies) is scaled with $\rho_p(r^+)_{\phi}$ at RHIC, and $(1 - \delta)/2 \times \rho_p(r^+)_{\phi} + \delta \times \rho_c(r^+)_{\phi}$ at LHC ($\delta = 0.118$ for both 2.76 and 5.5 TeV cases) with the proportionality constants determined from multiplicities at different energies [33]. Energy loss in the pre-equilibrium stage is quite possible but quantitatively uncertain, and may be improved in the future with developing understanding of the thermalization process [35]. We’ve adopted the strategy in [16] to “turn on” the pre-equilibrium density for $\tau < \tau_0$ with a linear increase and then for $\tau \geq \tau_0$ to decreases the entropy density as $1/\tau$ thus taking into account the boost-invariant longitudinal expansion.

Let us now first show in Fig. 1 the results for $v_2$ at high $p_t$ from all three models and compare them with data from both RHIC [28] and LHC [36–38]. It shall be emphasized again that all models have their parameters fixed only with RHIC 0–5% data once and for all. For the RHIC comparison, the simple $L^2$ model clearly fails to describe data while the NTcE and $L^3$ models are indeed both compatible with data. Moving to the LHC comparison, however, one immediately sees that too strong a path-length dependence (i.e. the $L^3$ model) is ruled out, while both the NTcE and $L^2$ models are now consistent with data. With RHIC plus LHC, therefore, only the model with LPM-type quadratic path-length dependence and strong near-$T_c$ enhancement of jet-medium interaction fully describes data at both collision energies.

We further come to fully quantify other azimuthal harmonics $v_n (n=1,2,3,4,5,6)$ of high $p_t$ hadrons based on our event-by-event computation in NTcE model. The results for LHC 2.76 TeV collisions are shown in Fig. 2 together with available data for $v_3, 4, 5, 6$ [36–37]. One shall however be cautious with the comparison of higher harmonics with data. Different from $v_2$ for which both the final bulk matter event plane and the final hard response (quenching) plane are tightly correlated with the initial
LHC 5 predictions for the comparison between computations and event-distributions (n=1,2,3,4,5,6) of high p_t hadrons at LHC 2.76 TeV collisions. With precise data sets for high fluctuations in the initial condition of heavy ion collisions.

FIG. 2: (color online) The v_n (n=1,2,3,4,5,6) of high p_t hadrons at LHC 2.76 TeV collisions computed from NTcE model. Available data for v_3,4,5 are shown as asterisks (ALICE 10−20 GeV), open and filled diamonds (ATLAS 8−12 and 12−16 GeV).

FIG. 3: (color online) Predictions from NTcE model for v_n (n=1,2,3,4,5,6) of high p_t hadrons at LHC 5.5 TeV collisions.

participant plane, for those higher harmonics from fluctuations the responses of both the soft and hard sectors are much less correlated with the initial ε_n plane and therefore the comparison between computations and event-plane-based measurements for higher harmonics could be rather tricky. Finally in Fig. 3 we show the first predictions for v_n (n=1,2,3,4,5,6) of high p_t hadrons at LHC 5.5 TeV collisions, which will be tested in few years.

Summary and Discussions.—In summary we’ve studied the event-by-event hard probe of the geometry and fluctuations in the initial condition of heavy ion collisions. With precise data sets for high p_t azimuthal anisotropy at RHIC plus LHC, jet quenching models with varied path-length dependence and matter-density dependence can be discriminated. We’ve found that too strong a path-length dependence (e.g., cubic) is ruled out by data at LHC, while the model with strong near-T_c enhancement of jet-medium interaction fully describes data at both collision energies. Finally full quantification of the azimuthal harmonics v_n (n=1,2,3,4,5,6) of high p_t hadrons are presented for LHC 2.76 TeV as well as 5.5 TeV collisions. Admittedly the modeling in this study is not the most sophisticated, but we expect the gross conclusion from studying generic geometric features to be robust. Further improvements (e.g., including energy dependence, integration with realistic hydrodynamic modeling, possibility of incorporating the NTcE component with other widely used jet quenching schemes, etc) are underway and will be reported in the future.

The near-T_c enhancement model implies a strong decrease of jet-medium interaction with hotter temperature and naturally expects a less color-opaque medium at LHC despite only modest increase of temperature from RHIC. Consistent messages have been reported recently from a variety of independent jet quenching studies. The underlying picture of emergent plasma near T_c may imply a more rapid running than what would be expected from perturbative picture and it might be possible that in LHC top energy heavy ion runs the created quark-gluon plasma could be considerably closer toward the long expected asymptotically free matter.

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