Jet Flavor Tomography of Quark Gluon Plasmas at RHIC and LHC

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A new Monte Carlo model, CUJET1.0, of jet quenching in nuclear collisions is applied to predict the jet flavor tomography spectrum in central $C = 0 - 5\%$, Au+Au $\sqrt{s} = 0.2$ ATeV at RHIC and Pb+Pb 2.76 ATeV at LHC for fragments $f = \pi, D, B, e^-$. The nuclear modification factors, $R_{AA\rightarrow f}(p_T; s, C)$, are predicted to exhibit a novel level crossing pattern over a wide transverse momentum range $5 < p_T < 100$ GeV that could provide stringent tests of jet-medium dynamics in quark gluon plasmas.

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Introduction: Jet quenching observables provide tomographic information about the density evolution and jet medium dynamics in quark gluon plasmas (QGP) produced in high energy nuclear collisions. Extensive studies of hard probes at the Relativistic Heavy ion Collider (RHIC) at energies (per nucleon pair) $0.02 < \sqrt{s} < 0.2$ ATeV have recently been extended to much higher cm energies $\sqrt{s} = 2.76 - 5.5$ ATeV at the Large Hadron Collider (LHC). Upgraded detectors at RHIC and the built in heavy quark capabilities of the ALICE, ATLAS, and CMS detectors at LHC will soon open a new chapter in jet tomography by allowing for the first time the measurement of the full jet parton flavor $a = g, u, c, b$. The nuclear modification factors, $R_{AA\rightarrow f}(p_T; s, C)$, for a wide variety of final fragments, e.g., $f = \pi, D, B, e^-$, over much wider kinematic ranges and centrality (impact parameter) classes $C$. We propose in this Letter that the quenched jet flavor “spectrum” could provide stringent new constraints on both perturbative QCD (pQCD) and string theory inspired (conformal and nonconformal) gravity dual holographic models of jet-medium dynamics in strongly interacting quark gluon plasmas.

We report results of a new Monte Carlo pQCD tomographic model, CUJET1.0, that predicts a strikingly novel level crossing pattern of flavor dependent nuclear modification factors at RHIC and LHC. This model extends the development of the GLV, DGLV, and WHDG opacity series approaches by including several dynamical features that require extra computational power most easily accessible via Monte Carlo techniques. CUJET1.0 was developed as part of the ongoing DOE JET Topical Collaboration effort with the objective to develop numerical codes to reduce previous large theoretical and numerical systematic uncertainties that obstruct quantitative jet tomography and to predict new observables that could better discriminate between dynamical models. In this letter, we focus on the jet flavor dependence of nuclear modification factors.

The current CUJET1.0 code features:

1. Dynamical jet interaction potentials that can interpolate between the pure HTL dynamically screened magnetic and static electric screening limits,
2. the ability to calculate high order opacity corrections up to $N = 10$ to interpolate numerically between $N = 1$ and $N = \infty$ analytic approximations,
3. full jet path proper time integration over longitudinal and transverse diffuse QGP geometries,
4. the ability to evaluate systematic theoretical uncertainties such as sensitivity to formation and decoupling phases of the QGP evolution, local running coupling and screening scale variations, and other effects out of reach with analytic approximations,
5. in addition to radiative fluctuating energy loss distributions as well as fluctuating jet path length geometries for all flavors,
6. convolution over $\sqrt{s}$ and flavor dependent pQCD invariant jet spectral density (without local in $p_T$ spectral index approximations),
7. convolution over final fragmentation, $D_{f/a}(x, Q)$, as well as semileptonic decay distributions.

Motivation for the development of the Monte Carlo based CUJET model includes also addressing key open A+ Au phenomenology problems: (1) the heavy quark jet quenching puzzle discovered at RHIC $\sqrt{s} = 2.76, 5.5$ ATeV, (2) the surprising increase of jet transparency of the QGP at LHC as compared to the expected linear in $dN_{ch}/dy(2.76, 0 - 5\%) = 1600$ scaling of the jet opacity, as suggested by preliminary ALICE charged hadron quenching data on $R_{PbPb\rightarrow h}(p_T; \sqrt{s} = 2.76, C = 0 - 5\%)$, and (3) the need to find hard probe observables that can better discriminate between tomographic and holographic paradigms of jet medium interactions. As we show below the flavor dependence of LHC nuclear modification factor level crossing pattern out to $p_T < 100$ GeV at LHC could provide rather stringent test of jet-medium dynamical models. In addition, we predict that future RHIC jet flavor tomography out to $p_T < 50$ GeV could provide important consistency checks of the pQCD paradigm due to the large $\sqrt{s}$ variation of the unquenched jet distributions between RHIC and LHC.

The CUJET Model: The CUJET1.0 code uses Monte Carlo techniques to compute finite order, $N$, in opacity contributions to the jet medium induced gluon radia-
tive spectrum replacing the static (Debye screened) effective potential [1, 4, 3] (GLV eq. (113), DGLV eq. (17)) in the multiple collision gluon radiation kernel with a normalized but path dependent effective dynamical (magnetic enhanced) transverse momentum, $q$, exchange distribution from the pure HTL dynamically magnetically screened model [3] to the form [3]

$$\tilde{v}^2(z, q, r_m) = \frac{\mathcal{N}(\mu_c(z), r_m)}{(q^2 + \mu^2_c(z))(q^2 + r_m^2 + \mu^2_c(z))},$$

where $0 \leq r_m = \mu_c(z)/\mu_c \leq 1$ is the ratio of a possible nonperturbative static color magnetic screening mass, $\mu_c \sim O(g^2 T)$, to the standard static HTL color electric Debye mass, $m_e = gT$ (see also [10]). Preliminary results up to third order in opacity with different $r_m$ were reported in ref. [BG] [3].

To illustrate of the proposed jet flavor tomography test of jet-medium dynamical models, we show here results only for the simplest non-trivial case with $N = 1$ order in the pure $r_m = 0$ HTL limit [3]. At first order, the inhomogeneous, non-static plasma generalization of the dynamical MD ($r_m = 0$) model of the induced radiated gluon number per (collinear) light cone momentum fraction, $x_a$, from massive quark jets of flavor $a$ produced at position $x$ with (transverse) energy $E$ and propagating through a QGP density field, $\rho_{QGP}(x, \tau)$, in azimuthal direction $\phi$ is given by

$$x_+ \frac{dN_{g/a}}{dx_+}(x, \phi) = \kappa_a \int d\tau \rho_{QGP}(x + \tilde{n}(\phi)\tau, \tau) \times \frac{1}{\pi} \frac{d^2 k}{q^2 + \mu^2(\tau)} \int \frac{d^2 \mathbf{q}}{\pi} \frac{2(k+q)}{(k+q)^2 + \chi_a(\tau)} \times \left( 1 - \cos \left[ \frac{(k+q)^2 + \chi_a(\tau)}{2x_+E} \right] \right),$$

where $\kappa_a = 9C_2(a)x_+_a^3/2$ with $C_2(g) = 3, C_2(q) = 4/3$, and $x_+$ is the fraction of plus momentum carried away by the radiated gluon. Also $\mu(\tau) = gT(x(\tau, \phi), \tau)$ is the local path dependent Debye screening mass with $x(0, \phi) = x$ as the jet production point. Here $\chi_a(\tau) = M_3^2 x_+^2 + \mu^2(\tau)(1-x_+)/\sqrt{2}$ controls the “dead cone” effect due to the finite jet current quark mass for $a = g, u, c, b$ as well as the local HTL asymptotic gluon thermal mass $\mu(x + v_T\tau, \tau)/\sqrt{2}$. We include fluctuations of the radiative energy loss due to gluon number fluctuations computing $P_a(\epsilon)$, the probability distribution of radiating a fraction of energy $\epsilon$, as in WHDG via a Poisson convolution of the spectrum $dN_g/dx_g \equiv (dx_g/dx_E)dN_g/dx_E$, with $x_E$ the energy fraction carried away by the radiated gluon. We also convolute the TG model for elastic energy loss assuming Gaussian fluctuations as in WHDG.

However, in contrast to WHDG, where longitudinal expansion was only approximately taken into account via a mean proper time $\tau = L/2$ approximation, the CUJET Monte Carlo integration code computes numerically the full proper time integral and allows us to study systematic uncertainties associated with both short time transient nonequilibrium QGP formation effect on a proper time interval as well as study uncertainties associated with varying the decoupling times. We have tested the sensitivity of the nuclear modification factors to three extreme scenarios of the initial opacity evolution by replacing the standard Bjorken $\tau_0/\tau$ longitudinal expansion factor by a temporal envelope $f(\tau/\tau_0)$ that reduces to the Bjorken $\tau_0/\tau$ factor only after $\tau > \tau_0$. For the present Letter we utilize the default form

$$\rho_{QGP}(x, \tau) = \frac{3dN_{ch}/dy}{2N_{part}} \rho_{part}(x) \frac{1}{(\tau + \tau_0)},$$

where $\rho_{part}(x)/N_{part}$ is the normalized Glauber transverse participant nucleon density profile that depends on $A, s$, and impact parameter $b$, and $dN_{ch}/dy$ is the bulk charged hadron rapidity density. The level crossing pattern turns out to be surprisingly sensitive to the value of $\tau_0$ as will be shown elsewhere. For illustration here, we set $\tau_0 = 0.5$ fm/c.

We assume a thermal freeze-out hypersurface $T(x + v(\phi)\tau_f, \tau_f) = T_f$ with $\mu_f = g(T_f)T_f = 200$ MeV to terminate jet path integrations. The average over initial transverse jet production production points is according to the standard binary collision Glauber $T_{AA}(x, b = 2$ fm) density profile and the jet $\phi$ angles are averaged uniformly.

For each flavor jet and initial $x, \phi$ CUJET computes the fractional energy loss $\epsilon$, probability distribution $P_a(\epsilon; p_i, x, \phi)$ for a specified range of initial $p_i$ and includes delta function contributions at $\epsilon = 0$ and 1. CUJET then numerically averages the results over the initial jet production profile and initial jet $\phi$ in order to obtain the final quenched partonic invariant cross section:

$$\frac{d\sigma_a(p_f)}{dydp_f} \equiv R_{AA}(p_f) \frac{d\sigma_a^0(p_f)}{dydp_f} = \left( \int de P_a(\epsilon; p_i, x, \phi) \frac{d^2 p_i}{dydp_i} \frac{d\sigma_a^0(p_i)}{dydp_i} \right)_{x, \phi},$$

where $p_i = p_f/(1-\epsilon)$. Note that CUJET avoids the local spectral index approximation $R_{AA}^0 \approx ((1-\epsilon)a_{(p)}e^{-2})^{-1}$ to eliminate that possible source of numerical uncertainty.

The pQCD initial jet flavor invariant $pp$ cross sections, $d\sigma^b_1/\sqrt{s}$ for $\sqrt{s} = 0.2, 2.76$, and $y = 0$ for light gluon and quark ($a=g,u$) jet flavors were computed from the LO pQCD CTEQ5 code of X.N. Wang [13] as in WHDG11 [14]. NLO charm and bottom quark invariant cross sections for both RHIC and LHC were provided by R. Vogt [20].

**RHIC and LHC Results:**

Our central physical tomographic assumption leading to our main result, Figure 1, is that aside from the
unavoidable $\sqrt{s}$ dependence of the initial pQCD partonic invariant cross sections, the sole $\sqrt{s}$ dependent nuclear input in CUJET is the variation of the bulk final pion rapidity density, $dN_{AA}/dy$ with $\sqrt{s}$. Therefore, as in WHDG11\cite{14}, we assume that the charged particle pseudo-rapidity density $dN^{LHC}_{ch}/d\eta = 1600$ reported by ALICE\cite{17} for $c = 0 - 5\%$ central $Pb + Pb$ at 2.76 ATeV translates directly into a factor 2.2 increase of $\rho_{QGP}$ at LHC relative to RHIC (for the same centrality). Furthermore, we fix the RHIC partonic level, $dN/dy = 1000$ with $\alpha_s = 0.3$, in Eq.(3) to constrain one reference $p_T = 10$ GeV point of pion $R^{\pi}_{AA} = 0.2$ at RHIC. The RHIC constrained extrapolation to LHC is then parameter free (assuming $\alpha_s$, $T_f$ and $T_T$ do not vary with $\sqrt{s}$). Systematic uncertainties associated with variations of the effective jet medium coupling\cite{4,13} as well as initial and final temperature field profiles will be reported elsewhere. Because of CUJET includes dynamical MD magnetic enhanced potential\cite{8}, our assumed moderately small coupling is sufficient to account for the RHIC data with $dN (RHIC)/dy = 1000$ as we check below (see fig. 2).

In Fig.1 on left side, the splitting between pion and electron $R_{AA}$ is found to remain large below 10 GeV in spite of the use $r_m$ dynamically enhanced potential. Also shown are the separate contribution of D and B mesons that future detector upgrades at RHIC could test. The importance of experimentally isolating and observing charged heavy mesons cannot be overstated since the mass splitting between c and b jets is a particularly robust prediction of pQCD in a deconfined QGP medium. The heavy quark quenching puzzle therefore remains unsolved in the CUJET calculations shown. Holographic gravity dual models predict a qualitatively different heavy quark quenching pattern\cite{18}. The novel inversion of the $\pi < D < e < B$ $R_{AA}$ hierarchy ordering at high $p_T$ to near the steeper initial invariant jet distributions of c and b jets at RHIC\cite{20} as also noted in\cite{21}.

Future LHC data will provide an opportunity to test details of the jet flavor dynamics at densities at least a factor of two greater than at RHIC. On the right side of Figure 1, the RHIC constrained LHC extrapolated jet flavor tomographic pattern is shown. With the much wider kinematic window accessible at LHC, the predicted flavor dependent $p_T$ spectrum of nuclear modifications is seen to involve multiple level crossings that are qualitatively different than at RHIC energies because of the complicated interplay between flavor dependent spectral shapes and opacity enhanced jet energy loss. While the details of the level crossings depend sensitively on specific dynamical details such as the effective coupling, initial formation time, and freeze-out, that the differential in $p_T$, $\sqrt{s}$, $C$, and $A$ variations of the jet flavor quenching pattern appear particularly promising to discriminate between jet medium dynamical models already at this single inclu-
sive level. Of course flavor tagged dihadron and hadron-lepton correlations will enable much more detailed quantitative information to be extracted eventually.

In Fig.2 we compare our CUJET constrained predictions for pion $R_{AA}^{p}(p_T)$ to central 0-5% PHENIX/RHIC data and preliminary ALICE/LHC data. We also compare to previous LHC predictions that used the static Debye screened potential (IV02) and recently updated WHDG11 models. CUJET is seen to interpolate between the later two curves, and the curves have a tendency to fall below the preliminary LHC data (as do several other recent predictions not shown). This suggests the intriguing possibility that the jet-medium coupling at LHC is possibly weaker than at RHIC. See 14, however, for a detailed discussion of many open caveats in this connection. It also remains an important open question if bulk elliptic QGP flow at LHC shows any signs of weaker coupling.

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