Global $\chi^2$ RHIC and LHC Data Constraints on Soft-Hard Transport Properties of semi-Quark-Gluon-Monopole Plasmas with the CUJET3.1 Framework

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Abstract

We report results of a comprehensive new global $\chi^2$ analysis of nuclear collision data from RHIC (0.2 ATeV), LHC1 (2.76 ATeV), and recent LHC2 (5.02 ATeV) energies. We use the updated CUJET3.1 framework to evaluate jet energy loss distributions in various models of the color structure of the QCD fluids produced in such reactions. The framework combines consistently viscous hydrodynamic fields predicted by VISHNU2+1 (validated with soft $p_T < 2$ GeV bulk observables) and the DGLV theory of jet elastic and inelastic energy loss generalized to sQGMP fluids with color structure including effective semi-QGP color electric $q(T)+g(T)$ densities as well as an effective color magnetic monopole density $m(T)$ peaking near $T_c$. As in our previous CUJET3.0 analysis, the local $q,g,m$ color density composition of the sQGMP is constrained by non-perturbative lattice QCD data on the QCD entropy density $s(T)$, Polyakov loop $L(T)$, light quark susceptibility $\chi_{u}^2(T)$, and lattice data on the color electric and magnetic screening masses $\mu_E(T), \mu_M(T)$. We vary the two control parameters of the model: the maximum value of the running QCD coupling, $\alpha_c$, and the ratio, $c_m = \mu_M/\mu_E$, and predict the $p_T > 10$ GeV, the centrality, as well as the $\sqrt{s} = 0.2-5.0$ ATeV dependence of the nuclear modified jet fragment observables $R_{AA}$ and $v_2$. The global $\chi^2$ is found to be minimized to near unity for $\alpha_c \approx 0.9 \pm 0.1$, and $c_m \approx 0.25 \pm 0.03$. Thus, CUJET3.1 provides a non-perturbative solution to the long standing hard ($R_{AA}$ and $v_2$) versus soft “perfect fluidity” puzzle. An important theoretical advantage of the CUJET3.1 framework, is that it is not only $\chi^2$ consistent with soft and hard observables data at RHIC and LHC, but also with non-perturbative lattice QCD data. Most remarkably, estimates from this framework lead to a shear viscosity to entropy ratio ($\eta/s \sim T^3/\hat{q} \sim 0.1$) required for internal consistency of the sQGMP jet transport coefficient, $\hat{q}/T^3$, with the perfect fluidity property of QCD fluids near $T_c$. Predictions for future tests at LHC with 5.44 ATeV Xe+Xe and 5.02 ATeV Pb+Pb are also presented.

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I. INTRODUCTION

High energy quark and gluon jets, produced initially in rare perturbative QCD processes lose energy and diffuse transversely along their paths due to interactions with the microscopic constituents in the hot quark-gluon plasma created in heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). Such hard ($p_T > 10$ GeV) processes provide us an independent probe of the evolution history of the soft ($p_T < 2$ GeV) QCD matter produced in such collisions. Recent high precision data from LHC Pb+Pb collisions on jet quenching and azimuthal asymmetry observables over wide kinematics and centrality ranges provide an opportunity to quantitatively constrain and differentiate competing models of jet-medium interactions as well as varied assumptions of the chromo electric and magnetic field structure of the bulk QCD “perfect fluids” produced in ultra relativistic nuclear collisions.

Given (i) a detailed microscopy theory of jet medium interactions (e.g. DGLV [1-9], HT [10-13], AMY [14-16], or AdS [17, 18]), (ii) a detailed model of bulk initial conditions (e.g. Glauber [19], TRENTO [20], or CGC [21]), and (iii) a long wavelength collective transport theory of the bulk QCD matter, such as relativistic viscous hydrodynamics (e.g. VISHNU [22], vUSPHydro [23-25], or MUSIC [26, 27]), the observed attenuation pattern of hard jet observables and their correlations with soft bulk collective flow observables can help differentiate competing dynamical models of high energy A+A collisions. In Refs. [28, 29] we developed the CUJET3.0 framework that combines the DGLV theory of jet energy loss coupled with nearly “perfect QCD fluids” described by the viscous hydrodynamics theory (and simulated via VISHNU [30]) to constrain the color degrees of freedom.

The simplest class of hard observables in a specific centrality class, $C$, is the $p_T$ and relative azimuthal angle dependence of the nuclear modification factor $R_{AA}^f$ for final state hadrons (with flavor species denoted by $f$), which is Fourier decomposed into harmonics as:

$$R_{AA}^f (p_T; \phi; C; \sqrt{s}) = \frac{dN_{AA}^f(C)}{dp_T dp_T d\phi} \frac{d \sigma_{pp}}{dp_T dp_T d\phi} = R_{AA}^f (p_T; C; \sqrt{s}) \left[ 1 + 2 \sum_n \langle v_n^f (p_T; C; \sqrt{s}); \cos(n(\phi - \Psi_n)) \rangle_C \right]$$

(1)

where $T_{AA}(C)$ is the average number of binary nucleon-nucleon scattering per unit area in centrality class $C$. Typically $C$ is expressed as a percentage interval of the inelastic cross
FIG. 1: (color online) The nuclear modification factor $R_{AA}$ as well as the second and third harmonic coefficients $v_2$ & $v_3$ of the final hadron azimuthal distribution as functions of $p_T$ for 20-30% Pb+Pb collisions at 5.02 ATeV. The solid curves are from event-by-event calculations while the dashed from averaged smooth geometry. The CIBJET results in both soft and hard regions, with either Monte-Carlo Glauber (red) or Trento (blue) initial conditions, are in excellent agreement with experimental data from ALICE, ATLAS and CMS [31–35]. Similar CIBJET results for 30-40% centrality, with excellent agreement with experimental data, were shown in [36].

section, e.g. 10 - 20% of the charged multiplicity per unit rapidity distribution. The $p_T$ and $\phi$ are transverse momentum and azimuthal angle of observed leading hadrons, relative to the bulk collective flow azimuthal harmonics. It may be noted that the experimental measurements of hard particle harmonics $v_n^f$ are made with respect to the event-wise soft harmonics, and event-by-event fluctuations of the bulk initial condition may play an important role [37]. Within the CUJET3 framework, the influence of event-by-event fluctuations has been investigated with a generalized CIBJET(=ebeIC+VISHNU+DGLV) framework, with the results reported in Ref. [36]. The CIBJET results of $R_{AA}$, $v_2$ and $v_3$ observables across a very wide range of $p_T$ for 30-40% centrality Pb+Pb collisions at 5.02 ATeV were shown in [36], with excellent agreement with experimental data. Here in Fig. 1 we further present the CIBJET results of $R_{AA}$, $v_2$ and $v_3$ for a different centrality of 20-30%, which again show excellent agreement with experimental data and demonstrate the correct central-
ity dependence of the CIBJET results. One conclusion found with CIBJET is that the $p_T$ and centrality dependence of the elliptic $v_2(p_T, \mathcal{C})$ azimuthal harmonics shows quantitative consistency at $\sim 10\%$ level between calculations with averaged smooth bulk geometry and that with fluctuating initial conditions. This conclusion is true for varied centrality class and is in agreement with a similar consistency-check from the ebeIC+LBT+HT hard+soft framework in Ref. [33, 38], while different from the ebeIC+vUSPhydro+BBMG framework in Ref. [37] which found much larger factor $\sim 2$ sensitivity of the hard elliptic harmonic to event-by-event fluctuations. The finding from CIBJET justifies the use of averaged smooth geometry in the CUJET3 framework, as we shall adopt in the present paper.

The prime motivation of this work is to conduct a comprehensive new global $\chi^2$ analysis of nuclear collision data from RHIC(0.2ATeV), LHC1(2.76ATeV), and recent LHC2(5.02ATeV) energies for high $p_T$ light and heavy flavor hadrons. This analysis is performed with the updated CUJET3.1 framework to evaluate jet energy loss distributions in various models of the color structure of the QCD fluids produced in heavy ion collisions. The CUJET3.1 is based on our previous CUJET3.0 framework [28, 29] and successfully addressed a few issues in CUJET3.0. We include a brief introduction about CUJET3.0 as well as a detailed discussion on the improvement in CUJET3.1 in the two appendices. We will show that the CUJET3.1 provides a non-perturbative solution to the long standing hard ($R_{AA}$ and $v_2$) versus soft “perfect fluidity” puzzle. We further examine the crucial issue of consistency between soft and hard transport properties of the QCD fluid in this framework. Predictions for future tests at LHC with 5.44 ATeV Xe+Xe and 5.02 ATeV Pb+Pb will also be presented.

The organization of this paper is as follows. We perform the model parameter optimization in Sec. II based on the quantitative $\chi^2$ analysis with a comprehensive set of experimental data for light hadrons. In Sec. III we show the successful CUJET3.1 description of available experimental data for light hadrons as well as the successful independent test with heavy flavor hadrons. The temperature dependence of jet transport coefficient and the corresponding shear viscosity for the quark-gluon plasma, extracted from CUJET3.1, are presented in Sec. V. The CUJET3.1 predictions for on going experimental analysis are shown in Sec. IV. Finally we summarize the paper in Sec. VI. A brief introduction of the CUJET3 framework as well as the improvements made in CUJET3.1 are also included in the two appendices.
II. GLOBAL $\chi^2$ ANALYSIS WITH CUJET3

With the details discussed in Appendix A, the CUJET3 framework is a quantification model solving jet energy loss in a hydrodynamics background, implementing DGLV jet energy loss from both inelastic and elastic scattering, and interacts with both chromo electric and magnetic charges of the medium. There are two key parameters in the model. One parameter is $\alpha_c$ in Eq. (A4), which is the value of QCD running coupling at the non-perturbative scale $Q^2 = T^2_c$ and sensitively controls the overall opaqueness of the hot medium. The other is $c_m$ in Eq. (A7), which is the coefficient for magnetic screening mass in the medium and influences the contribution of the magnetic component to the jet energy loss.

To systematically constrain these two key parameters, a first step we take is to perform a quantitative $\chi^2$ analysis and utilize central and semi-central high transverse momentum light hadron’s $R_{AA}$ and $v_2$ for all available data. We compare the relative variance between theoretical expectation and experimental data, which is defined as the ratio of squared difference between experimental data point and corresponding CUJET3 expectation, to the quadratic sum of experimental statistic and systematic uncertainties for that data point:

$$\frac{\chi^2}{\text{d.o.f.}} = \frac{\sum_i (y_{\text{exp},i} - y_{\text{theo},i})^2}{\sum_s (\sigma_s)_{\text{i}}^2} \sum_i 1,$$

where $\sum_i$ runs over all experimental data point in the momentum range $8 \leq p_T \leq 50 \text{ GeV/c}$, and $\sum_s$ denotes summing over all sources of uncertainties, e.g. systematic and statistic uncertainties. We compute $\chi^2/\text{d.o.f.}$ for each of the following 12 data sets:

- 200 GeV Au-Au Collisions, 0-10% Centrality Bin, $R_{AA}(\pi^0)$: PHENIX [39, 40];
- 200 GeV Au-Au Collisions, 0-10% Centrality Bin, $v_2(\pi^0)$: PHENIX [40];
- 200 GeV Au-Au Collisions, 20-30% Centrality Bin, $R_{AA}(\pi^0)$: PHENIX [39, 40];
- 200 GeV Au-Au Collisions, 20-30% Centrality Bin, $v_2(\pi^0)$: PHENIX [40];
- 2.76 TeV Pb-Pb Collisions, 0-10% Centrality Bin, $R_{AA}(h^{\pm})$: ALICE [41];
- 2.76 TeV Pb-Pb Collisions, 0-10% Centrality Bin, $v_2(h^{\pm})$: ATLAS [42], CMS [43];
- 2.76 TeV Pb-Pb Collisions, 20-30% Centrality Bin, $R_{AA}(h^{\pm})$: ALICE [41];
- 2.76 TeV Pb-Pb Collisions, 20-30% Centrality Bin, $v_2(h^{\pm})$: ALICE [44], ATLAS [42], CMS [43];
- 5.02 TeV Pb-Pb Collisions, 0-5% Centrality Bin, $R_{AA}(h^{\pm})$: ATLAS-preliminary [32], CMS [33];
• 5.02 TeV Pb-Pb Collisions, 0-5% Centrality Bin, $v_2(h^\pm)$: CMS [34];
• 5.02 TeV Pb-Pb Collisions, 10-30% Centrality Bin, $R_{AA}(h^\pm)$: CMS [33];
• 5.02 TeV Pb-Pb Collisions, 20-30% Centrality Bin, $v_2(h^\pm)$: CMS [34];

and finally obtain the overall $\chi^2$/d.o.f. as the average over these data sets.

First of all, we perform the analysis in “slow” quark-libration scheme ($\chi^L_T$-scheme) for a wide range of parameter space: $0.5 \leq \alpha_c \leq 1.3$, $0.18 \leq c_m \leq 0.32$. As shown in Fig. 2, $\chi^2$/d.o.f. with only $R_{AA}$ data (left panel) or only $v_2$ data (middle panel) gives different tension and favors different regions of parameter space. Taking all data together (right panel), we identify a data-selected optimal parameter set as $(\alpha_c = 0.9, c_m = 0.25)$, with $\chi^2$/d.o.f. close to 1, while the “uncertainty region” spanned by $(\alpha_c = 0.8, c_m = 0.22)$ and $(\alpha_c = 1.0, c_m = 0.28)$ with $\chi^2$/d.o.f. about two times of the minimal value.

In order to test the necessity of chromo-magnetic-monopole degree of freedom as well as to explore potential influence of the theoretical uncertainties of different quark liberation schemes, we perform the same $\chi^2$ analysis with two other schemes: (a) the “fast” quark-libration scheme ($\chi^T_T$-scheme); (b) the weakly coupling QGP (wQGP) scheme, being equivalent to CUJET2.0 mode, assuming no chromo-magnetic-monopole, i.e. taking $f_E = 1$, $f_M = 0$, and cec fraction $\chi_T = 1$, while the running coupling takes the Zakharov formula as in Eq. (A5).

By using these 3 schemes with their corresponding most optimal parameter set:
• (i) sQGMP $\chi^L_T$-scheme: $\alpha_c = 0.9$, $c_m = 0.25$,
FIG. 3: (color online) CUJET expectation of light hadron $R_{AA}$ and $v_2$ by using 3 different schemes: sQGMP $\chi_T^2$-scheme (black solid), sQGMP $\chi_T^4$-scheme (red dashed), wQGP/CUJET2 scheme (blue dashed dotted). Corresponding $\chi^2$/d.o.f. are shown, with respect to following experimental data: PHENIX 2008 (orange solid circle) [39], PHENIX 2012 (magenta solid square) [40]; ALICE (magenta open diamond) [41, 43], ATLAS (green open circle) [32, 42], CMS (orange open square) [33, 34, 43].

- (ii) sQGMP $\chi_T^4$-scheme: $\alpha_c = 0.9$, $c_m = 0.34$,
- (iii) wQGP/CUJET2 scheme: $\alpha_{\text{max}} = 0.4$, (optimized by $R_{AA}$)

we show in Fig. 3 their comparison with above experimental data sets, including quantitative value of $\chi^2$/d.o.f. for each data set. While both sQGMP schemes ($\chi_T^2$ and $\chi_T^4$) give similar jet quenching variables, the QGP scheme gives similar $R_{AA}$ but less azimuthal anisotropy. Especially, one can see clearly from the quantitative value of their $\chi^2$/d.o.f. that the theoretical expectations of both sQGMP schemes are in good consistency with data, and that
of the QGP scheme, without cmm degree of freedom, differs significantly from the highly precise LHC $v_2$ measurements. The $\chi^2$ analysis strongly supports the necessity of chromo-magnetic-monopole degree of freedom, but remains robust on the specific quark liberation scheme.

While we will maintain the unification of CUJET3 model by using the same (global optimized) parameter set, it’s worth mentioning that quantitative $\chi^2$ analysis for different data set, e.g. different observable or different beam energy, flavors different parameter regime, as shown in Tab. I. When comparing to the $R_{AA}$ results, the azimuthal anisotropy measurement with more shrink uncertainties, yields higher $\chi^2$/d.o.f and hence On the other hand, in CUJET3 models, the RHIC results flavor stronger coupling (larger $\alpha_c$ or $c_m$) than the LHC results; while the latter are more precise and give better distinction on different models. Especially with 5.02 TeV data, one can see explicitly that the sQGMP schemes are more phenomenologically flavored than the wQGP scheme.

|        | sQGMP $\chi^2_{T}$ | sQGMP $\chi^2_{u}$ | wQGP                 |
|--------|---------------------|---------------------|----------------------|
|        | $\alpha_c$ | $c_m$ | $\chi^2$/d.o.f | $c_m$ | $\chi^2$/d.o.f | $\alpha_{\text{max}}$ | $\chi^2$/d.o.f |
| $R_{AA}$ | 0.9      | 0.24 | 0.57           | 0.31 | 0.60          | 0.4     | 0.67          |
| $v_2$   | 0.9      | 0.25 | 1.34           | 0.34 | 1.28          | 1.0     | 2.34          |
| 200 GeV | 1.2      | 0.28 | 0.40           | 0.40 | 0.42          | 0.6     | 0.61          |
| 2.76 TeV| 0.9      | 0.24 | 1.15           | 0.34 | 1.01          | 1.0     | 2.07          |
| 5.02 TeV| 0.7      | 0.28 | 0.76           | 0.34 | 1.43          | 1.0     | 8.61          |
| All     | 0.9      | 0.25 | 0.97           | 0.34 | 1.02          | 0.7     | 3.47          |

TABLE I: Optimal parameter and corresponding $\chi^2$/d.o.f. for different data sets in different schemes. Note that the sQGMP $\chi^2_{u}$ scheme is optimized with taking $\alpha_c \equiv 0.9$.

With the high statistics of 5.02 TeV Pb-Pb data, we further expect that highly precise jet quenching observables for heavy flavored hadrons, e.g. $D$ meson, could serve as an independent probe to discriminate sQGMP versus wQGP models. As shown in Fig. 4, we find sQGMP and wQGP models predicts similar $R_{AA}$, while their significant different predictions of $v_2$ would need future experimental data with higher accuracy and for higher $p_T$ to provide a decisive distinction.
FIG. 4: (color online) CUJET expectation of $D$ meson $R_{AA}$ and $v_2$ by using: sQGM $\chi^L_T$-scheme (black solid), and wQGP/CUJET2 scheme (blue dashed dotted). Comparison with preliminary-CMS data (orange solid square) [45, 46] are also shown. Corresponding $R_{AA}$ and $v_2$ data for light hadrons [32, 34] are also shown with gray symbols.

III. COMPARISON WITH EXPERIMENTAL DATA

With the systematic $\chi^2$ analysis, we obtained the optimal region of CUJET3 parameters constrained by only light hadron $R_{AA}$ and $v_2$, for central and semi-central collisions. To provide a critical independent test of the model, we compute CUJET3 results for both light and heavy flavor hadrons, with all centrality ranges up to semi-peripheral collisions, and perform apple-to-apple comparisons with all available experimental data.

Starting from this section, in CUJET3 simulations we employed the $\chi^L_T$-scheme assuming slow quark-libration, with keeping the theoretical uncertainties by taking the parameter region spanned by $(\alpha_c = 0.8, c_m = 0.22)$ and $(\alpha_c = 1.0, c_m = 0.28)$, which correspond to upper/lower bounds of $R_{AA}$ and lower/upper bounds of $v_2$, respectively.

A. Light Hadrons

First of all, in Figures 5-10, we compare CUJET3.1 results for light hadrons’ $R_{AA}$ and $v_2$, with all available data: PHENIX [39, 40] & STAR [47] measurements for 200 GeV Au-Au collisions; ALICE [41, 44], ATLAS [42, 48] & CMS [43, 49] results for 2.76 TeV Pb-Pb collisions; and ATLAS [32] and CMS [33, 34] data for 5.02 TeV Pb-Pb collisions. One can clearly see the excellent agreement for all centrality range at all these collision energies. In particular, it is worth to emphasize again that after the aforementioned correction, the
current CUJET3.1 simulation framework is able to correctly reproduce the $p_T$ and centrality dependence of both $R_{AA}$ and $v_2$.

|               | 200 GeV | 2.76 TeV | 5.02 TeV |
|---------------|---------|----------|----------|
| $T_{\text{ini,center}}$ (MeV) | 358 294 | 465 366 | 506 397 |
| $\epsilon_{2,\text{ini}}$ | 0.07 0.44 | 0.07 0.46 | 0.07 0.45 |
| $\tau_{\text{hydro}}$ (fm/c) | 9.4 5.2 | 11.4 6.3 | 11.8 6.7 |

TABLE II: Comparison of the initial central temperature $T_{\text{ini,center}}$, initial ellipticity $\epsilon_{2,\text{ini}}$, and life time $\tau_{\text{hydro}}$ in different collision conditions. The initial ellipticity is defined with respect to entropy density $s$ at hydro starting time $\tau = 0.6$ fm, $\epsilon_{2,\text{ini}} \equiv -\left[ \int s \rho^2 \cos(2\phi) \, dxdy \right] / \left[ \int s \, dxdy \right]$.

We note that such comprehensive data set covers a rich diversity of geometrical and thermal profiles of the QCD Plasma. In different centrality bins at various colliding energies, the bulk backgrounds are significantly distinctive in lifetime, size, ellipticity as well as temperature, and consequently, the path length of the jets, either direction averaging or depending, varies in a wide range. In Tab. II we show the quantitative comparison of the initial central temperature $T_{\text{ini,center}}$, initial ellipticity $\epsilon_{2,\text{ini}}$, and life time $\tau_{\text{hydro}}$. The temperature as well as the life time for such systems vary by a factor of $\sim 2$ while the geometries change from nearly symmetric to those with ellipticity $\sim 0.4$. The success in explaining $R_{AA}$ and $v_2$ from central to semi-peripheral data, at beam energies from 0.2 to 5.02 TeV, indicates the success of temperature and path dependence of the CUJET3 energy loss model.
FIG. 5: (color online) Light hadron $R_{AA}$ for 200 GeV Au-Au collisions in comparison with PHENIX [39, 40] and STAR [47] results. Magenta (blue) circles labeled PHENIX2004 (PHENIX2007) correspond to data published in Ref. [39] (Ref. [40]) analyzing RHIC 2004 (2007) data set.

FIG. 6: (color online) Light hadron $v_2$ for 200 GeV Au-Au collisions in comparison with PHENIX data [40].
FIG. 7: (color online) Light hadron $R_{AA}$ for 2.76 TeV Pb-Pb collisions in comparison with ALICE [41], ATLAS [48] and CMS [49] results.

FIG. 8: (color online) Light hadron $v_2$ for 2.76 TeV Pb-Pb collisions in comparison with ALICE [44], ATLAS [42] and CMS [43] results.
FIG. 9: (color online) Light hadron $R_{AA}$ for 5.02 TeV Pb-Pb collisions in comparison with ATLAS [32] and CMS [33] results.

FIG. 10: (color online) Light hadron $R_{AA}$ for 5.02 TeV Pb-Pb collisions in comparison with CMS data [34].
B. Heavy Flavor Measurements

With successfully describing high-$p_T$ $R_{AA}$ and $v_2$ data for light hadrons, we now perform further independent test of the energy loss mechanism by using heavy flavor data $^{50}$. In Figures 11-18 we compare CUJET3 results for the energy loss observables of prompt $D$ & $B$ mesons as well as electrons or muons from heavy flavor decay, with all available data: PHENIX $^{51}$, STAR $^{52}$ measurements for 200 GeV Au-Au collisions; ALICE $^{53}$-$^{57}$, CMS $^{58}$ data for 200 GeV Pb-Pb collisions; and finally CMS results $^{45, 46, 59}$ for 5.02 TeV Pb-Pb collisions. Again, one can find very good agreement between model and data, validating a successful unified description of CUJET3 for both light and heavy flavor jet energy loss observables.

FIG. 11: (color online) Heavy flavor decayed electron $R_{AA}$ for 200 GeV Au-Au collisions in comparison with PHENIX $^{51}$ and STAR $^{52}$ results.
2.76 TeV D meson $R_{AA}$ for 2.76 TeV Pb-Pb collisions in comparison with ALICE [53] and preliminary CMS [58] results.

$D_{0}$ ALICE CMS

FIG. 12: (color online) Prompt $D$ meson $R_{AA}$ for 2.76 TeV Pb-Pb collisions in comparison with ALICE [53] and preliminary CMS [58] results.

2.76 TeV $D^{0}$

0.0 0.5 1.0 1.5

FIG. 13: (color online) $D$ meson $v_2$ for 2.76 TeV Pb-Pb collisions in comparison with ALICE data [54].

$D_{0}$ ALICE

FIG. 14: (color online) Heavy flavor decayed electron $R_{AA}$ for 2.76 TeV Pb-Pb collisions in comparison with ALICE data [55].
FIG. 15: (color online) Heavy flavor decayed electron $v_2$ for 2.76 TeV Pb-Pb collisions in comparison with ALICE data [56].

FIG. 16: (color online) Heavy flavor decayed muon $R_{AA}$ for 2.76 TeV Pb-Pb collisions in comparison with ALICE data [57].

FIG. 17: (color online) Prompt $D$ meson $R_{AA}$ for 5.02 TeV Pb-Pb collisions in comparison with preliminary CMS data [46].
FIG. 18: (color online) Prompt $D$ meson $v_2$ for 5.02 TeV Pb-Pb collisions in comparison with preliminary CMS data \cite{45}.

FIG. 19: (color online) Prompt $B$ meson $R_{AA}$ for 5.02 TeV Pb-Pb collisions in comparison with CMS data \cite{59}.
IV. CUJET3 PREDICTIONS FOR OTHER EXPERIMENTAL OBSERVABLES

In above section we perform a successful test of the CUJET3 framework, which provides a united description for comprehensive sets of experimental data, from average suppression to azimuthal anisotropy, from light flavor to heavy flavor observables, with beam energy from 200 GeV to 5.02 TeV, and from central to semi-peripheral collisions. With new colliding system or new experimental observables, we expect more stringent test to help further constrain the CUJET3 energy loss model. In this section, we show the CUJET3 prediction for on-going experimental analysis, including jet quenching observables in $^{120}\text{Xe}-^{129}\text{Xe}$ collisions at 5.44 TeV and more heavy flavor signals in 5.02 TeV Pb-Pb collisions.

A. Light Hadron $R_{AA}$ in 5.44 TeV $^{129}\text{Xe}$-$^{129}\text{Xe}$ Collisions

![Graph showing $R_{AA}$ and $v_2$ for 5.44 TeV Xe-Xe collisions and 5.02 TeV Pb-Pb collisions](image)

FIG. 20: (color online) Light hadron $R_{AA}$ and $v_2$ for 5.44 TeV Xe-Xe collisions (blue bands) and 5.02 TeV Pb-Pb collisions (red dashed curves). The preliminary experimental data are also shown.

Recently the LHC ran collisions with a new species of nuclei, colliding xenon with 129 nucleons ($^{129}\text{Xe}$), with beam energy $\sqrt{s_{NN}} = 5.44$ TeV. In Xe-Xe collisions, the hot medium created is expected to be a bit cooler and shorter lived when comparing with the one created in 5.02 TeV Pb-Pb collisions. Given the similar beam energy, it’s expected that the difference
between observables from these two colliding system should provide valuable information on
the nature of the QGP, especially on how the hot medium interacts with high energy jets.

In Fig. 20 we show the light hadron $R_{AA}$ and $v_2$ for both systems. One can clearly see
that it produces higher $R_{AA}$ and lower $v_2$ in 5.44 TeV Xe-Xe collisions (blue bands),
when comparing with those in 5.02 TeV Pb-Pb collisions (red dashed curves). It indicates
the high-$p_T$ light hadrons produced in the former system are less suppressed than those
produced in latter. This shows the sensitivity of the jet-quenching observables to the system
size and density: when comparing to those created in Pb-Pb collisions, jets created in Xe-Xe
collisions travel with shorter path in the hot medium and interact with less dense matter,
hence they lose less energy. With this new colliding system, we are able to further test
the path length dependence of the CUJET3 jet energy loss model. It may be noted that
such predictions were made before the experimental measurements reported at the Quark
Matter 2018 conference. Our predictions are in good agreement with the recently released
preliminary data for charged hadron $R_{AA}$ from the ALICE [60], ATLAS [61], and CMS [62]
collaborations (as shown in Fig. 20). See also Ref. [62] for a detailed data-model comparison.

**B. $B$-decayed $D$ meson $R_{AA}$ in 5.02 TeV Pb-Pb collisions**

![Graph showing $R_{AA}$ for $D$ meson from $B$-decay (left), prompt $D$ meson (middle), and $B$
meson (right) in minimal-bias 5.02 TeV Pb-Pb collisions.]

FIG. 21: (color online) $R_{AA}$ for $D$ meson from $B$-decay (left), prompt $D$ meson (middle), and $B$
meson (right) in minimal-bias 5.02 TeV Pb-Pb collisions.

Another new experimental measurement is the $B$-decayed $D$ meson $R_{AA}$ in 5.02 TeV
Pb-Pb collisions. As shown in Fig. 21 the $R_{AA}$ of $B$-decay $D$ meson (left panel) has similar
$p_T$-dependence as that of $B$ mesons (right panel), and both of them are less suppressed
than the prompt $D$ meson (middle panel), especially for the region with lower momentum
(p_T < 20 GeV). We expect that future precise measurement of B-decay D meson R_{AA} should provide observation of the “dead cone” effect which suppresses the radiational energy loss of bottom jets.

C. High-p_T D mesons in 200 GeV Au-Au collisions

Recently the STAR Collaboration at RHIC installed the Heavy Flavor Tracker, which allows high precision measures of open heavy flavor hadrons. Early results of azimuthal anisotropy for lower p_T D mesons has shown interesting property of the low energy charm quarks [63]. With the CUJET3 predictions for D meson’s R_{AA} and v_2 shown in Fig. 22 we expect that precise measurements of high p_T D mesons’ jet quenching observable could allows us the direct comparison with heavy flavor data, and further test the consistency of HF sector of CUJET3 energy loss, for different beam energies.

FIG. 22: D meson’s R_{AA} and v_2 in 200 GeV Au-Au collisions. STAR data [63] [65] for lower p_T range are also shown. Red (magenta) symbols labeled STAR2010 (STAR2014) correspond to data published in Ref. [64] (Ref. [65]) analyzing RHIC 2010/11 (2014) data set.
D. Heavy Flavor Decayed Leptons in 5.02 TeV Pb-Pb collisions

Finally we show the CUJET3 predictions for heavy flavor decayed muons and electrons in Fig. 23 & 24. Being the decay product of both $D$ and $B$ mesons, the $R_{AA}$ in lower $p_T$ regime is sensitive to relative ratios between $D$ and $B$ absolute cross sections. We expect more stringent future test from the heavy flavor sector to help further constrain CUJET3.

FIG. 23: $R_{AA}$ for heavy flavor decayed muon in 5.02 TeV Pb-Pb collisions.

FIG. 24: $R_{AA}$ (left) and $v_2$ (right) for heavy flavor decayed muon in 5.02 TeV Pb-Pb collisions.
V. JET TRANSPORT COEFFICIENT AND SHEAR VISCOSITY

As discussed above, the jet quenching observables of light hadrons provide stringent constraints on values of the jet energy loss parameters. In the meanwhile, the comparison between three different schemes, (i) sQGMP-\(\chi_L^\perp\), (ii) sQGMP-\(\chi_T^\perp\), and (iii) wQGP, shows the necessity of chromo-magnetic-monopole degree of freedom, while robustness on quark liberation rate. It is of great interests to further compare how the jet and bulk transport properties differ in these schemes. This will pave the way for clarifying the temperature dependence of jet quenching and shear viscous transport properties based on available high \(p_T\) data in high-energy A+A collisions.

The jet transport coefficient \(\hat{q}\) characterizes the averaged transverse momentum transfer squared per mean free path \([66]\). For a quark jet (in the fundamental representation \(F\)) with initial energy \(E\), we calculate its \(\hat{q}\) in the same way as the previous CUJET3.0 computation in [28, 29], via

\[
\hat{q}_F(E, T) = \int_0^{\rho(T)} dq_\perp^2 \frac{2\pi}{(q_\perp^2 + f_E^2\mu^2(z))(q_\perp^2 + f_M^2\mu^2(z))} \cdot \left\{ [C_{qq}f_q + C_{qg}f_g] \cdot [\alpha_s^2(q_\perp^2)] \cdot [f_E^2q_\perp^2 + f_E^2f_M^2\mu^2(z)] + [C_{qm}(1 - f_q - f_g)] \cdot [1] \cdot [f_M^2q_\perp^2 + f_E^2f_M^2\mu^2(z)] \right\},
\]

and similarly for a gluon/cmm jet:

\[
\hat{q}_g(E, T) = \int_0^{\rho(T)} dq_\perp^2 \frac{2\pi}{(q_\perp^2 + f_E^2\mu^2(z))(q_\perp^2 + f_M^2\mu^2(z))} \cdot \left\{ [C_{gg}f_q + C_{gq}f_g] \cdot [\alpha_s^2(q_\perp^2)] \cdot [f_E^2q_\perp^2 + f_E^2f_M^2\mu^2(z)] + [C_{gm}(1 - f_q - f_g)] \cdot [1] \cdot [f_M^2q_\perp^2 + f_E^2f_M^2\mu^2(z)] \right\},
\]

\[
\hat{q}_m(E, T) = \int_0^{\rho(T)} dq_\perp^2 \frac{2\pi}{(q_\perp^2 + f_E^2\mu^2(z))(q_\perp^2 + f_M^2\mu^2(z))} \cdot \left\{ [C_{mg}f_q + C_{gm}f_g] \cdot [1] \cdot [f_E^2q_\perp^2 + f_E^2f_M^2\mu^2(z)] + [C_{mm}(1 - f_q - f_g)] \cdot [\alpha_s^2(q_\perp^2)] \cdot [f_M^2q_\perp^2 + f_E^2f_M^2\mu^2(z)] \right\}.
\]

The quasi-parton density fractions of quark (q) or gluon (g), denoted as \(f_{q,g}\), are defined as \(f_{q,g}\), are defined as

\[
f_q = c_qL(T), \quad f_g = c_gL(T)^2, \quad \text{if} \ \chi_L^\perp
\]

\[
f_q = c_q\chi_T^\perp, \quad f_g = c_gL(T)^2, \quad \text{if} \ \chi_T^\perp
\]
respectively for sQGMP $\chi_T^L$ and $\chi_T^u$ scheme. The magnetically charged quasi-particle density fraction is hence $f_m = 1 - \chi_T = 1 - f_q - f_g$. The color factors are given by
\[
C_{qq} = \frac{4}{9}, \quad C_{gg} = C_{mm} = C_{gm} = C_{mq} = \frac{9}{4},
\]
\[
C_{qq} = C_{gg} = C_{qm} = C_{mg} = 1.
\]

One can find that while switching to the wQGP scheme, by taking $f_q = c_q$, $f_g = c_g$, $f_E = 1$, $f_M = 0$, turning off the cmm channel, and employing the running coupling $\alpha_s(Q^2)$ defined in Eq. (A5), the jet transport coefficient $\hat{q}$ for a quark/gluon jet defined in Eq. (3.4) returns to that of the CUJET2.0 framework \[67\].

![Figure 25](image-url)

**FIG. 25**: (Color online) (Left) The temperature dependence of the dimensionless jet transport coefficient $\hat{q}_F/T^3$ for a light quark jet with initial energy $E = (a) 30$ GeV, (b) 3 GeV in the CUJET framework with the three schemes: (i) sQGMP-$\chi_T^L$ scheme (red solid), (ii) sQGMP-$\chi_T^u$ scheme (red dashed), and (iii) wQGP/CUJET2.0 scheme (green dotdashed). The $\mathcal{N} = 4$ leading order/next to leading order Super Yang-Mills $\hat{q}_{SYM-LO}/T^3 = \frac{\pi^{3/2}T(\frac{3}{4})}{T(\frac{5}{4})}\sqrt{\lambda}$ and $\hat{q}_{SYM-NLO}/T^3 = \frac{\pi^{3/2}T(\frac{5}{4})}{T(\frac{7}{4})}\sqrt{\lambda}(1 - \frac{1.957}{\sqrt{\lambda}})$ respectively \[17\] with coupling $\lambda = 4\pi \cdot 3 \cdot 0.31$, are plotted for comparisons. The green blobs in inset (b) shows the JET collaboration \[66\] model average of $\hat{q}_F/T^3$ while the boxes represent the uncertainties. (Right) The shear viscosity to entropy density ratio $\eta/s$ estimated with scheme (i) (red solid), (ii) (red dashed), and (iii) (green dotdashed). The inset shows quasi-particle number density fraction of q, g, m in the liberation scheme $\chi_T^L$ (solid) and $\chi_T^u$ (dashed).

Once the jet transport coefficient $\hat{q}$ has been computed, one can extrapolate $\hat{q}(T, E)$ down to thermal energy scales $E \sim 3T/2$ and estimate the shear viscosity to entropy density ratio
$\eta/s$, based on kinetic theory in a weakly-coupled quasi-particle picture [68–70]. An estimate of $\eta/s$ can be derived as

$$\eta/s = \frac{1}{s} \frac{4}{15} \sum_a \rho_a(p) a \lambda_a^\perp$$

$$= \frac{4T}{5s} \sum_a \rho_a \left( \sum_b \rho_b \int_0^{(s_{ab})/2} dq_\perp^2 \frac{4q_\perp^2}{(s_{ab})} \frac{d\sigma_{ab}}{dq_\perp^2} \right)^{-1}$$

$$= \frac{18T^3}{5s} \sum_a \rho_a/\hat{q}_a(T, E = 3T/2). \quad (8)$$

The $\rho_a(T) \equiv f_a \rho(T)$ is the quasi-parton density of type $a = q, g, m$. The mean thermal Mandelstam variable $\langle S_{ab} \rangle \sim 18T^2$. Clearly the $\eta/s$ of the system is dominated by the ingredient which has the largest $\rho_a/\hat{q}_a$.

In the left panel of Fig. 25, we show the temperature dependence of the dimensionless jet transport coefficient $\hat{q}_F/T^3$ for a light quark jet with initial energy $E = 30\text{GeV} / 3\text{GeV}$ with all three schemes. Corresponding results from JET collaboration [66] model average and AdS/CFT limit [17] are also plotted for comparisons. As discussed in previous CUJET3.0 papers [28, 29], the near-$T_c$ enhancement of dimensionless jet transport coefficient can be observed with robust dependence on quark liberation schemes.

In the right panel of Fig. 25, we show the shear viscosity to entropy density ratio $\eta/s$ estimated in the kinetic theory using the $\hat{q}$ extrapolation Eq. (8) with scheme (i) (red solid) (ii) (red dashed) (iii) (green dotdashed). The inset shows quasi-particle number density fraction of $q, g, m$ in the liberation scheme $\chi^T_L$ (solid) and $\chi^T_U$ (dashed). Note that in the near $T_c$ regime, in the $\chi^T_U$ scheme, the total $\eta/s$ is dominated by $q$, while in the $\chi^T_L$ “slow” quark liberation scheme the total $\eta/s$ is dominated by $m$. For each sQGMP scheme, there is a clear $\eta/s$ minimum at $T \sim 210$ MeV, which is comparable with the SYM limit $(\eta/s)_{\text{min}} = 1/4\pi$.

VI. SUMMARY

In this paper we presented the CUJET3.1 framework and performed a global quantitative $\chi^2$ analysis by comparing with a large set of light hadron jet quenching observables for central and semi-central heavy-ion collisions for beam energy $\sqrt{s_{NN}} = 200 \text{GeV}\text{(Au-Au)}, 2.76 \text{TeV}\text{(Pb-Pb)}$ and $5.02 \text{TeV}\text{(Pb-Pb)}$. This analysis allows the optimization of the two
key parameters in the CUJET3.1 framework, and the global $\chi^2$ is found to be minimized to near unity for $\alpha_c \approx 0.9 \pm 0.1$, and $c_m \approx 0.25 \pm 0.03$. With such parameters, the CUJET3 framework gives a unified, systematic and successful description of a comprehensive set of available data, from average suppression to azimuthal anisotropy, from light to heavy flavors, from central to semi-peripheral collisions, for all three colliding systems. Thus, CUJET3.1 provides a non-perturbative solution to the long standing hard ($R_{AA}$ and $v_2$) versus soft “perfect fluidity” puzzle. Such a quantitative analysis strongly supports the necessity of including interaction between jet and chromo-magnetic-monopoles to provide a consistent description of both $R_{AA}$ and $v_2$ across centrality and beam energy.

In this work, we also present CUJET3 predictions for a number of observables for additional test. We expect that the comparison between the light hadrons’ $R_{AA}$ in 5.44 TeV Xe-Xe collisions and those observed in 5.02 TeV Pb-Pb collisions, could further test the path length dependence of the CUJET3 jet energy loss model. The mass dependence of jet energy loss in CUJET3 can also be further tested by its predictions for $B$-decayed $D$ mesons’ $R_{AA}$ in 5.02 TeV Pb-Pb collisions to be compared with future precise measurement of this observable.

We end by emphasizing the important theoretical advantage of the CUJET3.1 framework. It is not only $\chi^2$ consistent with soft and hard observables data at RHIC and LHC, but also with nonperturbative lattice QCD data. Remarkably, estimates from this framework lead to a shear viscosity to entropy density ratio $\frac{\eta}{s} \sim 0.1$, which are not only consistent with extracted values from experimental soft+hard A+A phenomenology but also theoretically internally consistent with sQGMP kinetic theory link, $\frac{\eta}{s} \sim \frac{T^3}{4\pi(3)}$, between long distance collective fluid properties and short distance jet quenching physics especially near $T_c$.

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Appendix A: CUJET3 Framework

The CUJET3 model is a jet energy loss simulation framework built upon a non-perturbative microscopic model for the hot medium as a semi-quark-gluon-monopole plasma (sQGMP) which integrates two essential elements of confinement, i.e. the suppression of quarks/gluons and emergent magnetic monopoles. Detailed description of its framework can be found in previous CUJET papers \[9, 28, 29, 66, 67\]. The CUJET3 model employs TG elastic energy loss formula \[71–73\] for collisional processes, with energy loss given by

\[
\frac{dE(z)}{d\tau} = -C_R \pi \left[ \alpha_s(\mu(z))\alpha_s(6E(z)\Gamma(z)T(z)) \right] T(z)^2 \left( 1 + \frac{N_f}{6} \right) \times \log \left[ \frac{6T(z)\sqrt{E(z)^2\Gamma(z)^2 - M^2}}{(E(z)\Gamma(z) - \sqrt{E(z)^2\Gamma(z)^2 - M^2 + 6T(z)})\mu(z)} \right],
\]

(A1)

and the average number of collisions

\[
\bar{N}_c = \int_0^{\tau_{\text{max}}} d\tau \left[ \frac{\alpha(\mu(z))\alpha(6E(z)\Gamma(z)T(z))}{\mu(z)^2} \right] \left[ \Gamma(z) \frac{18\zeta(3)}{\pi} (4 + N_f)T(z)^3 \right],
\]

(A2)

where the \(E(z)\) integral equation is solved recursively. For radiational processes, the CUJET3 model employs the dynamical DGLV opacity expansion theory \[1, 3, 6, 74\] with Liao-Shuryak chromo-magnetic-monopole scenario \[75–79\]. The inclusive single gluon emission spectrum in the \(n = 1\) opacity series reads:

\[
x_E \frac{dN_g^{n=1}}{dx_E} = \frac{18C_R}{\pi^2} \frac{4 + N_f}{16 + 9N_f} \int d\tau \rho(z) \Gamma(z) \int d^2k_\perp \alpha_s \left( \frac{k_\perp^2}{x_+(1 - x_+)} \right)
\times \int d^2q \frac{\alpha_s^2(q_\perp^2) \left( f_E^2 + \frac{f_E f_M \mu^2(z)}{q_\perp^2} \right) \chi_T + \left( f_M^2 + \frac{f_E f_M \mu^2(z)}{q_\perp^2} \right) (1 - \chi_T)}{(q_\perp^2 + f_E^2 \mu^2(z))(q_\perp^2 + f_M^2 \mu^2(z))}
\times \frac{-2(k_\perp - q_\perp)}{(k_\perp - q_\perp)^2 + \chi^2(z)} \left[ \frac{k_\perp^2 + \chi^2(z)}{(k_\perp - q_\perp)^2 + \chi^2(z)} - \frac{1 - \cos \left( \frac{(k_\perp - q_\perp)^2 + \chi^2(z)}{2x_+ E} \frac{dx_+}{dx_E} \right)}{1 - \cos \left( \frac{(k_\perp - q_\perp)^2 + \chi^2(z)}{2x_+ E} \frac{dx_+}{dx_E} \right)} \right].
\]

(A3)

\(C_R = 4/3\) or 3 is the quadratic Casimir of the quark or gluon; the transverse coordinate of the hard parton is denoted by \(z = (x_0 + \tau \cos \phi, y_0 + \tau \sin \phi; \tau)\); \(E\) is the energy of the
hard parton in the lab frame; $\mathbf{k}_\perp$ ($|\mathbf{k}_\perp| \leq x_E E \cdot \Gamma(z)$) and $\mathbf{q}_\perp$ ($|\mathbf{q}_\perp| \leq 6T(z)E \cdot \Gamma(z)$) are the local transverse momentum of the radiated gluon and the local transverse momentum transfer respectively. The gluon fractional energy $x_E$ and fractional plus-momentum $x_+$ are connected by $x_+(x_E) = x_E[1 + \sqrt{1 - (k_\perp/x_E E)^2}]/2$. We note that in the temperature range $T \sim T_c$, the coupling $\alpha_s$ becomes non-perturbative [75, 77, 80, 81]. Analysis of lattice data [77] suggests the following thermal running coupling form:

$$\alpha_s(Q^2) = \frac{\alpha_c}{1 + \frac{9\alpha_c}{4\pi} \log\left(\frac{Q^2}{T_c^2}\right)}, \quad (A4)$$

with $T_c = 160$ MeV. Note that at large $Q^2$, Eq. (A4) converges to vacuum running $\alpha_s(Q^2) = \frac{4\pi}{9\log(Q^2/\Lambda^2)}$; while at $Q = T_c$, $\alpha_s(T_c^2) = \alpha_c$.

The particle number density $\rho(z)$ is determined by the medium temperature $T(z)$ via $\rho(T) = \xi_s s(T)$, where $\xi_s = 0.253$ for a $N_c = 3$, $N_f = 2.5$ Stefan-Boltzmann gas, and $s(T)$ is the bulk entropy density. In the presence of hydrodynamical 4-velocity fields $u_\mu^f(z)$, boosting back to the lab frame, one should take into account a relativistic correction $\Gamma(z) = u_\mu^f n_\mu$ [18, 82], where the flow 4-velocity $u_\mu^f = \gamma_f(\mathbf{1}, \mathbf{\beta}_f)$ and null hard parton 4-velocity $n^\mu = (1, \mathbf{\beta}_j)$. The bulk evolution profiles $(T(z), \rho(z), u_\mu^f(z))$ are generated from the VISH2+1 code [22, 83, 84] with MC-Glauber initial condition, $\tau_0 = 0.6$ fm/c, s95p-PCE Equation of State (EOS), $\eta/s = 0.08$, and Cooper-Frye freeze-out temperature 120 MeV [30, 85–89]. Event-averaged smooth profiles are embedded, and the path integrals $\int d\tau$ for jets initially produced at transverse coordinates $(x_0, \phi)$ are cutoff at dynamical $T(z(x_0, \phi, \tau)|_{\tau_{max}} \equiv T_{cut} = 160$ MeV hypersurfaces [67].

It might be worth noting that in the CUJET2 framework, assuming weakly-coupling QGP, the running coupling takes the form (with $\Lambda_{QCD} = 200$ MeV)

$$\alpha_s(Q^2) = \begin{cases} \alpha_{\max} & \text{if } Q \leq Q_{\min}, \\ \frac{4\pi}{9\log(Q^2/\Lambda_{QCD}^2)} & \text{if } Q > Q_{\min}. \end{cases} \quad (A5)$$

The Debye screening mass $\mu(z)$ is determined from solving the self-consistent equation

$$\mu^2(z) = \sqrt{4\pi\alpha_s(\mu^2(z))T(z)}\sqrt{1 + N_f/6} \quad (A6)$$

as in [90]; $\chi^2(z) = M^2 x_+^2 + m_g^2(z)(1 - x_+)$ regulates the soft collinear divergences in the color antennae and controls the Landau-Pomeranchuk-Migdal (LPM) phase, the gluon plasmon mass $m_g(z) = f_E\mu(z)/\sqrt{2}$. 

28
Since the sQGMP contains both chromo electrically charged quasi-particles (cec) and chromo magnetically charged quasi-particles (cmc), when jets propagate through the medium near \( T_c \), the total quasi-particle number density \( \rho \) is divided into EQPs with fraction \( \chi_T = \rho_E / \rho \) and MQPs with fraction \( 1 - \chi_T = \rho_M / \rho \). The parameter \( f_E \) and \( f_M \) is defined via \( f_E \equiv \mu_E / \mu \) and \( f_M \equiv \mu_M / \mu \), with \( \mu_E \) and \( \mu_M \) being the electric and magnetic screening mass respectively, following

\[
f_E(T(z)) = \sqrt{\chi_T(T(z))}, \quad f_M(T(z)) = c_m g(T(z)), \tag{A7}
\]

with the local electric “coupling” \( g(T(z)) = \sqrt{4\pi\alpha_s(\mu^2(T(z)))} \).

In current sQGMP modeling, the cec component fraction \( \chi_T \) remains a theoretical uncertainty related to the question of how fast the color degrees of freedom get liberated. To estimate \( \chi_T \), one notices that: (1) when temperature is high, \( \chi_T \) should reach unity, i.e. \( \chi_T(T \gg T_c) \rightarrow 1 \); (2) in the vicinity of the regime \( T \sim (1 - 3)T_c \), the renormalized expectation value of the Polyakov loop \( L \) (let us redefine \( L \equiv \ell = (\text{tr}\mathcal{P} \exp\{ig \int_0^{1/T_c} d\tau A_0\})/N_c \)) deviates significantly from unity, implying the suppression \( \sim L \) for quarks and \( \sim L^2 \) for gluons in the semi-QGP model [91–94]. Consequently, in the liberation scheme \( (\chi_T^L\text{-scheme}) \), we define the cec component fraction as

\[
\chi_T(T) \equiv \chi_T^L(T) = c_q L(T) + c_g L^2(T) \tag{A8}
\]

for the respective fraction of quarks and gluons, where we take the Stefan-Boltzmann (SB) fraction coefficients, \( c_q = (10.5N_f)/(10.5N_f + 16) \) and \( c_g = 16/(10.5N_f + 16) \), and the temperature dependent Polyakov loop \( L(T) \) parameterized as \( (T \text{ in GeV}) \)

\[
L(T) = \left[ \frac{1}{2} + \frac{1}{2} \text{Tanh}[7.69(T - 0.0726)] \right]^{10}, \tag{A9}
\]

adequately fitting both the HotQCD [95] and Wuppertal-Budapest [96] lattice results.

On the other hand, another useful measure of the non-perturbative suppression of the color electric DOF is provided by the quark number susceptibilities [97–100]. The diagonal susceptibility is proposed as part of the order parameter for chiral symmetry breaking/restoration in [97], and plays a similar role as properly renormalized \( L \) for quark DOFs. In this scheme, we parametrize the lattice diagonal susceptibility of \( u \) quark number density, renormalized the susceptibility by its value at \( T \rightarrow \infty \), as \( (T \text{ in GeV}) \)

\[
\tilde{\chi}_2^u(T) \equiv \frac{\chi_2^u(T)}{0.91} = \left[ \frac{1}{2} \{1 + \text{Tanh}[15.65(T - 0.0607)]\} \right]^{10}, \tag{A10}
\]
and define the cec component fraction in deconfinement scheme ($\chi^u_T$-scheme) as:

$$\chi_r(T) \equiv \chi^u_T(T) = c_q \tilde{\chi}^u_2(T) + c_g L^2(T).$$  \hspace{1cm} (A11)

These two different schemes, for the rate of “quark liberation”, with $\chi^u_L$ the “slow” and $\chi^u_T$ the “fast”, provide useful estimates of theoretical systematic uncertainties associated with the quark component of the sQGMP model.

Finally, in the CUJET3 framework, the $p$-$p$ spectra of light quarks and gluons are generated by LO pQCD \cite{101} calculations with CTEQ5 Parton Distribution Functions; while those of charm and bottom quarks are generated from FONLL calculation \cite{102} with CTEQ6M Parton Distribution Functions. In the meanwhile, the spectra of light hadrons are computed with KKP Fragmentation Functions \cite{103}; and those of open heavy flavor mesons computed Peterson Fragmentation Functions \cite{104} (taking $\epsilon = 0.06$ for D meson, and $\epsilon = 0.006$ for B meson). The decay of heavy flavor mesons into leptons, including $D \to \ell$, $B \to \ell$, and $B \to D \to \ell$ channels, follows the same parameterization as in \cite{102}.

**Appendix B: Improvements in CUJET3.1**

In this Appendix, we discuss the improvements of CUJET3.1 framework with respect to the earlier CUJET3.0 framework. One important motivation for the CUJET3.1 upgrade work reported in the present paper was to uncover causes and correct the discrepancy of CUJET3.0 predictions for LHC 5.02 ATeV Pb+Pb collusions, reported by CMS in Ref. \cite{33} with the nuclear modification factor $R_{AA}$ (see Fig. 26), as well as in Ref. \cite{34} with their observed $p_T$ and especially centrality dependence of the hard elliptic asymmetry $v_2$ (see Fig. 27).

After a systematic examination, we found and corrected two issues that existed in previous CUJET3.0 simulations for 5.02 ATeV Pb+Pb collisions. (i) Firstly, the initial parton spectra were not consistently read in: the flavor factor of 3, was missed for light quark spectra. As the result, a higher fraction of the final hadrons were fragmented from gluon jets, which are more quenched relative to quark jets and caused the over-quenched $R_{AA}$. (ii) Secondly, the probability distribution of initial jet production was incorrectly oriented (with $x$- and $y$-axis switched), hence wrong centrality dependence of $v_2$ was predicted. With correcting these two issues, the CUJET3.1 simulation correctly reproduces the $p_T$ and centrality dependence
FIG. 26: (color online) Reproduced from Fig. 5 of CMS Ref. [33] (with permission): The $R_{AA}$ results as a function of $p_T$ in (0 - 5)% centrality class. The vertical bars (shaded boxes) represent the statistical (systematic) uncertainties. The blue curve represent calculation made with the CUJET3.0 [29] model.

FIG. 27: (color online) Reproduced from Fig. 1 of CMS Ref. [34] (with permission): The $v_2$ and $v_3$ results from the SP method as a function of $p_T$, in seven collision centrality ranges from (0 - 5)% to (50 - 60)%. The vertical bars (shaded boxes) represent the statistical (systematic) uncertainties. The curves represent calculations made with the CUJET 3.0 [29] and the SHEE [37] models.
of both $R_{AA}$ and $v_2$. Details of the comparison are shown in Figs. 9 & 10 in Sec. IIIA.

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