Jet Quenching in a semi-Quark-Gluon Monopole Plasma: Light & Heavy Flavors Raa & V2 at RHIC & LHC

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Research Supported by NSF & DOE
The Making of CUJET3
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CUJET3: a simulation framework based on a microscopic picture of Semi-quark-gluon monopole plasma
The Making of CUJET3

Heavy Flavor Puzzle (CUJET1)

CUJET1: Buzzatti & Gyulassy 1106.3061
Including E & M screening; elastic+inelastic; ...

...
The Making of CUJET3

Surprising transparency: Horowitz-Gyulassy; Betz-Gyulassy; Zhang-Liao; ...

CUJET2: Xu, Buzzatti, Gyulassy, 1402.2956
Including strong running coupling from RHIC to LHC; realistic bulk viscous hydro; ...
High Pt V2 was a long standing challenge for nearly all models (including CUJET1 and CUJET2)
Till ~ 2008, there was clear discrepancy between accurate data and model predictions.
Where Are Jets Quenched (More Strongly)?

- Taken for granted in all previous models: “waterfall” scenario.
- We realized the puzzle may concern more radical questions:
  - Where are jets quenched (more strongly)?

Geometry is a sensitive feature:
- “Egg yolk” has one geometry, “Egg white” has another.
Near-Tc Enhancement of Jet-Medium Coupling

Three major findings:

(1) With fixed Raa, the jet v2 is VERY sensitive to the T-dependence of jet-medium coupling;
(2) Energy loss around Tc region enhances the jet v2;
(3) RHIC data suggests a very strong enhancement near Tc.

In the paper PRL(2009) we concluded:

“In relativistic heavy ion collisions the jets are quenched about 2--5 times stronger in the near-Tc region than the higher-T QGP phase.”

— Confirmed by many studies later!
Looking Under the Hood of sQGP

Some of us started a while ago to ask: What makes the sQGP nearly prefect liquid? In particular, what are the relevant degrees of freedom?
sQGP: A Plasma of Chromo E & M Charges

Liberation of Thermal DoF

Degree of color liberation

Shuryak, Liao, ...: this is a chromo-magnetic monopole plasma!

Pisarski, Hidaka, ...: this is a semi-QGP!

The two pictures are in complement, from Electric or Magnetic language respectively, and reconciled into one coherent picture.
The sQGP is a new emergent phase of QCD matter, with suppressed quarks/gluons and a significant monopole component: It naturally bridges the confined phase and wQGP!
The Making of CUJET3

CUJET3: a simulation framework based on a microscopic picture of Semi-quark-gluon monopole plasma
CUJET3: Semi-Quark-Gluon Monopole Plasma

Consistency of Perfect Fluidity and Jet Quenching in Semi-Quark-Gluon Monopole Plasmas

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(Received 31 July 2015)

We utilize a new framework, CUJET3.0, to deduce the energy and temperature dependence of the jet transport parameter, $\hat{q}(E > 10\text{ GeV}, T)$, from a combined analysis of available data on nuclear modification factor and azimuthal asymmetries from high energy nuclear collisions at RHIC/BNL and LHC/CERN. Extending a previous perturbative-QCD based jet energy loss model (known as CUJET2.0) with (2+1)D viscous hydrodynamic bulk evolution, this new framework includes three novel features of non-perturbative physics origin: (i) the Polyakov loop suppression of color-electric scattering (aka 'semi-QGP' of Pisarski et al.), (ii) the enhancement of jet quenching due to emergent magnetic monopoles near $T_c$ (aka 'magnetic scenario' of Liao and Shuryak), and (iii) thermodynamic properties constrained by lattice QCD data. CUJET3.0 reduces to $\hat{q}=2.0$ at high temperatures $T > 400\text{ MeV}$, while greatly enhances $\hat{q}$ near the QCD deconfinement transition temperature range. This enhancement accounts well for the observed elliptic harmonics of jets with $p_T > 10\text{ GeV}$. Extrapolating our data-constrained $\hat{q}$ down to thermal energy scales, $E=2\text{ GeV}$, we find for the first time a remarkable consistency between high energy jet quenching and bulk perfect fluidity with $\eta/s=\frac{1}{2} q=0.1$ near $T_c$.

PACS: 25.75.-q, 12.38.Mh, 24.85.+p, 13.87.-a

DOI: 10.1088/0264-9381/32/9/092501

Bridging soft-hard transport properties of quark-gluon plasmas with CUJET3.0

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A Sophisticated Simulation Framework

DGLV-CUJET framework for describing multi-parton scattering:

\[
\frac{dN_{qg}^{n=1}}{dx_E} = \frac{18C_R}{\pi^2} \frac{4 + N_f}{16 + 9N_f} \int d\tau \, n(z) \Gamma(z) \int d^2k \\
\times \alpha_s \left( \frac{k^2}{x_+(1-x_+)} \right) \int d^2q \frac{\alpha_s^2(q^2)}{\mu^2(z)} \frac{f_E^2 \mu^2(z)}{q^2(q^2 + f_E^2 \mu^2(z))} \\
\times \frac{-2(k-q)}{(k-q)^2 + \chi^2(z)} \left[ \frac{k}{k^2 + \chi^2(z)} - \frac{(k-q)}{(k-q)^2 + \chi^2(z)} \right] \\
\times \left[ 1 - \cos \left( \frac{(k-q)^2 + \chi^2(z)}{2x+E} \right) \right] \left( \frac{x_E}{x_+} \right) \left| \frac{dx_+}{dx_E} \right| .
\]

Original DGLV formalism has only quark/gluon scattering centers

We now include both color-electric and color-magnetic scattering centers.

\[
x \frac{dN}{dx} \propto \ldots \int q^2 \left[ \frac{n \alpha_s^2(q^2) f_E^2}{q^2(q^2 + f_E^2 \mu^2)} \right] \ldots \\
\left[ \frac{n_e (\alpha_s(q^2) \alpha_s(q^2)) f_E^2}{q^2(q^2 + f_E^2 \mu^2)} + \frac{n_m (\alpha^e(q^2) \alpha^m(q^2)) f_M^2}{q^2(q^2 + f_M^2 \mu^2)} \right]
\]

Our goal is to implement the nonperturbative NEAR-Tc Physics

\[\longrightarrow \text{CUJET3.0}\]

Xu, JL, Gyulassy, arXiv:1411.3673
The Making of sQGP in CUJET3.0

The model implementations of electric and magnetic components are carefully **constrained by available lattice data.**

* Electric density: L-loop suppression

\[ \chi_T = c_q L + c_g L^2 \]

* Magnetic density: constrained by total pressure

\[ (1 - \chi_T) \]

* Running coupling:

\[ \alpha_s(Q^2) = \alpha_c \left[ 1 + \frac{9\alpha_c}{4\pi} \log \left( \frac{Q^2}{T_c^2} \right) \right] \]

* Screening:

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

[Xu, JL, Gyulassy, arXiv:1411.3673(CPL); 1508.00552(JHEP)]
Systematic Calibration of CUJET3

Using light hadron Raa and v2 at RHIC200GeV, LHC2.76TeV, LHC5.02TeV with central and semi-central collisions.

We constrain the two key parameters of sQGMP by a chi-square analysis.

[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]
Systematic Calibration of CUJET3

Chi-square map on the parameter plane

Different set of data show different sensitivity in constraining parameters.

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Systematic Calibration of CUJET3

*Chi-square map on the parameter plane*

Optimized choice of parameters:

\[ \alpha_c = 0.9 \quad c_m = 0.26 \]

Model uncertainty band

\[ \alpha_c = 0.75 \quad c_m = 0.22 \]
\[ \alpha_c = 1.05 \quad c_m = 0.30 \]

[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]
Systematic Calibration of CUJET3

Optimized parameters: Comparison with RHIC200GeV [PHENIX data]

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Optimized parameters: Comparison with LHC2.76TeV
[ALICE Raa; ATLAS V2]

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[CMS data]

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Systematic Calibration of CUJET3

Optimized parameters: Comparison with LHC5.02TeV [CMS data]

[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]
Independent Test with Heavy Flavor

*The HF serves as an independent test: These data are NOT part of model parameter calibration.*

*D0 Raa and v2 compared with CMS at LHC5.02TeV*

[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]
Independent Test with Heavy Flavor

The HF serves as an independent test:
These data are NOT part of model parameter calibration.

D0 Raa and v2 compared with ALICE at LHC2.76TeV

[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]
Independent Test with Heavy Flavor

The HF serves as an independent test:
These data are NOT part of model parameter calibration.

D0 Raa and v2 compared with STAR at RHIC200GeV

[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]
The Challenge to Every Model

CUJET3 has passed this challenge. Look forward to every model taking up this challenge.
Event-by-Event Jet Quenching

Harmonic Jet Tomography

Event-by-event azimuthal anisotropy of jet quenching in relativistic heavy ion collisions

Xilin Zhang¹,³* and Jinfeng Liao¹,²†

\[ R_{AA}(\phi) = R_{AA} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n^J)] \right) \]

[X. Zhang, J. Liao, 1202.1047; 1208.6361; 1210.1245; 1311.5463]
Event-By-Event Jet Quenching

A first try of e-by-e CUJET3 exercise (for 10 events — computationally expensive!)

[Hydro background from Jaki Noronha-Holster]
Event-By-Event Jet Quenching

Correlated soft & hard responses to initial geometry
Event-By-Event Jet Quenching

Correlated soft & hard responses to initial geometry
Event-By-Event Jet Quenching

High-Pt V2 gets enhanced in e-by-e simulations.


A wealth of physics to be explored in e-by-e CUJET3!
**Summary**

*CUJET3*: a simulation framework based on a microscopic picture of Semi-quark-gluon monopole plasma

* The **CUJET3** successfully describes an large set of available single-hadron data: $R_{aa}$ & $v2$ @ varied centrality & beam energies for light & heavy flavors.

* Preliminary event-by-event jet quenching in **CUJET3** suggests enhanced $v2$. 

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Discussions

Connecting the soft and hard physics in sQGMP