Consistency and Uniqueness of combined models of hard jet quenching and soft perfect fluid observables at RHIC and LHC and Non-perturbative Lattice QCD data

Part 1: Perturbative and Nonperturbative Aspects of Jet Tomography In Ideal Event Averaged A+A Spacetime Geometries

Part 2: Jet Quenching Coupled to Event by Event Fluctuating Viscous Hydrodynamic “Perfect Fluids”

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Perturbative vs NonPerturbative Jet Tomography in 2+1D viscous hydrodynamic backgrounds

1) Data on (RAA and v2) at (RHIC&LHC) on high pT (pi, D,B) can be simultaneously “fit” with many different dEdx models combined with different viscous hydrodynamic background models.

2) CUJET3 with sQGMonopole plasma parameters constrained by lattice QCD provides a chromo-elec+mag quasi-parton model of qhat(E,T) consistent with RHIC+LHC1+LHC2 data as well as perfect fluidity $\eta/s \sim 1/qhat(E \sim 3T, T) \sim 1/4\pi$ at least in smooth VISHNU fields.


3) There exists a pQCD/HTL dEdx model coupled to event by event viscous hydro consistent with hard&soft data but with qhat(E~3T, T) incompatible with perfect fluidity.

Event-by-event hydrodynamics + jet energy loss: A solution to the $R_{AA} \otimes v_2$ puzzle
Jacquelyn Noronha-Hostler (Houston U.), Barbara Betz (Frankfurt U.), Jorge Noronha (Sao Paulo U.), Miklos Gyulassy
PRL116 (2016), PRC95 (2017)

4) See other soft+hard model combinations this week workshop.

The Existence of multiple incompatible microscopic descriptions that can account for hard and soft data (at similar $\chi^2/NDF < 4$ level of confidence) remains an obstacle in drawing objective conclusions about the physics of the the new form(s) of matter produced in AA, pA, pp at RHIC and LHC. This talk outlines our strategy to proceed forward.
Can we utilize Soft-Hard Event Engineering (SHEE) to constrain quantitatively the model parameter-space iso-chi^2 hypersurfaces(s)?

Goal is to put experimental constraint bands on top of Lattice QCD cyber-data!

Does there exist an internally consistent band of description(s) that can account with reasonable chi^2<4 or better for all RHIC & LHC data simultaneously on soft-soft, soft-hard, and hard-hard observed correlations AND that can predict falsifiable future observables?

In this talk I review two such models in that band.
Can we eventually put exp. Chi^2 constraint bands on these Thermal Lattice QCD data And bridge heavy ion phenomenology with the fundamental physics of confinement ??

Lattice Constraints: Polyakov Loop, EOS, E & M Screening Masses

Semi-QGP

The color elec Q + G d.o.f. are Suppressed due to semi confinement

Pisarski etal

Magnetic screen suggests emergent Chromo-Mag Monopole d.o.f. near Tc which could condense T<Tc to explain confinement
P. Petreczky proposed light quark susceptibility data $\Rightarrow$ semi-Quark color elec dof may be liberated more quickly than suggested by Polyakov loop suppressed semi-Quarks

As a measure of the sensitivity CUJET3 fits to the assumed color structure of the sQGMP we compare results with Slow quark liberation to Fast quark liberation

$$\chi_T^L = c_q L + c_g L^2$$
$$\chi_T^u = c_q \chi_2^L(T)/\chi_2^u(\infty) + c_g L^2$$

Our “greedy” goal with CUJET3 and future CUJET4= ebe CUJET3 and SHEE approaches is to try to put experimental (via RAA,v2,v3) Chi^2 constraint bands on the chromo composition/structure of sQGMP quark and gluon color electric quasi-monopoles dof and color magnetic quasi-monopoles dof consistent with

1) lattice EOS $P(T)$
2) screening masses,
3) minimal $\eta/s\sim T^3/qhat$ soft-hard phenom.
The Challenge to Every Model

Raa & V2
@ varied centrality

PASS!

Heavy & Light

200GeV
& 2.76TeV
& 5.02TeV
Consistency between Soft Perfect Fluidity and Hard Jet Quenching

\[ \frac{\eta(T)}{s(T)} \sim \lim_{E \to 3T} \left( \frac{T^3}{\hat{q}(E, T)} \right) \]
The Challenge to Every Model

Consistency with Lattice QCD data
On EOS, Screening Polyakov, ...

Consistency between Soft Perfect Fluidity and Hard Jet Quenching
\[
\frac{\eta(T)}{s(T)} \sim \lim_{E \to 3T} \left( \frac{T^3}{\hat{q}(E, T)} \right)
\]

Raa & V2
@ varied centrality

Heavy & Light

200GeV & 2.76TeV & 5.02TeV

Pass
My extension 3 of Jinfeng Liao's Quark Matter 2017 slide 29

The Challenge to Every Model

Consistency with Lattice QCD data
On EOS, Screening Polyakov, ...

Consistency with NLO, NNLO...
Jet and subJet observables

Consistency between Soft Perfect Fluidity and Hard Jet Quenching

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\frac{\eta(T)}{s(T)} \sim \lim_{E \to 3T} \left( \frac{T^3}{\hat{q}(E,T)} \right)
\]

3+1D SHEE
Soft-Hard Event Subclass Engineering

Consistency with NLO, NNLO...
Jet and subJet observables

The Challenge to Every Model

Raa & V2 @ varied centrality

Heavy & Light

200GeV & 2.76TeV & 5.02TeV

Pass
A+B inhomogeneous fluctuating “perfect fluids” &/or “gglasmas”:
( L. McLerran, R. Venugopalan 1994. ...B. Schenke et al 2017 )

Longitudinal “Glasma” fields generalize ~1fm Lund strings in HIJING
To both electric and magnetic flux tubes of sub nucleon transverse scales 1/Qsat ~ 0.2 fm
Example of evolution of typical lumpy event with **disconnected isotherm surfaces**


PRC88 (2013)

Energy density profile event 5467

Temperature profile event 5467

“Hard” jets probe Path Integrals of dEdx through such Dynamic “Soft” pT < 2 GeV Matter/Fields
A+A (eta, phi) problem similar to Multi Component problem of 3+1D Supernova Core Collapse
(General rel. + nuclear chem + neutrino transport + 3D instabilities)


Fig. 7. Snapshots displaying isosurfaces where the mass fraction of $^{56}$Ni plus n-rich tracer $X$ equals 3% for model W15-2-cw (top row), L15-1-cw (second row), N20-4-cw (third row), and B15-1-pw (bottom row). The isosurfaces, which roughly coincide with the outermost edge of the neutrino-heated ejecta, are shown at four different epochs starting from shortly before the SN shock crosses the C+O/He composition interface in the progenitor star until the shock breakout time. The colors give the radial velocity (in units of km s$^{-1}$) on the isosurface, with the color coding indicated in the bottom left corner of each panel.
The Challenge to Every Model

Consistency with Lattice QCD data
On EOS, Screening Polyakov, ...

Consistency between Soft Perfect Fluidity and Hard Jet Quenching
\[ \frac{\eta(T)}{s(T)} \sim \lim_{E \to 3T} \left( \frac{T^3}{\hat{q}(E, T)} \right) \]

Review of current progress toward this level with CUJET3.1
Idea with CUJET3 is to deform DGLV HTL kernel with non-perturbative Lattice QCD data, fit (RAA,v2) data with min chi2 to fix max alpha and the ratio of magnetic/electric screen masses, and check if qhat(E->3T,T) extrapolates near 4 pi T^3 with

\[ \eta(T) \sim \lim_{E \to 3T} \left( \frac{T^3}{\hat{q}(E,T)} \right) \]
$\alpha_{\text{max}} = 0.42$

$\chi^2$/d.o.f for

VISH2+1 $\otimes$ CUJET2.1

Shuzhe Shi 2017

Alessandro Buzzatti, J.Xu, MG, JHEP (2014)

Looked Good by Eye Ball
However $\chi^2 > 15$ Falsified Model !!
CUJET3.0 status at QM15 (J.Xu, J Liao, mg, NPA956 (2016) ) improved

Fig. 2. (Color online) CUJET3.0 results of (a) light hadron (LH, neutral pion $\pi^0$ and charge particle $h^\pm$)’s $R_{AA}$, (b) open heavy flavor (HF, $B$ meson and prompt $D$ meson)’s $R_{AA}$, (c) LH’s $v_2$, and (d) HF’s $v_2$, at high $p_T > 8\text{GeV}$ in semi-peripheral A+A collisions, compared with data from RHIC and LHC [2]. The variations of predicted jet quenching observables from different schemes within CUJET3.0 suggest that data on high $p_T$ leading hadron $R_{AA}$ and $v_2$ in heavy-ion collisions can rigorously constrain the nonperturbative chromo-electric and chromo-magnetic structure of the QCD matter near $T_c$, and provide critical information about color confinement.
CUJET3.0 qhat at QM15 was consistent with Perfect fluidity near Tc (J.Xu, J Liao, MG (2016) )

Fig. 3. (Color online) (a) The temperature dependence of the scaled jet transport parameter \( \hat{q}/T^3 \) for a quark jet (in the fundamental representation \( F \) of SU\( (N_c=3) \)) with initial energy \( E_0 = 10 \) GeV in various schemes within the CUJET3.0 framework, compared with the CUJET2.0 counterpart, as well as \( \mathcal{N} = 4 \) Supersymmetric Yang-Mills (SYM) \( \hat{q}_{\text{SYM}} \) results from leading order (LO) AdS/CFT calculations (\( \hat{q}_{\text{SYM}} = \left[ \pi^{3/2} \Gamma(3/4)/\Gamma(5/4) \right] \sqrt{L T^3_{\text{SYM}}} \)). Note that \( 3T^3_{\text{SYM}} \approx T^3 \) because of different number of degrees of freedom in \( N_c = 3 \) SYM and three-flavor QCD [16]. The gray band with dashed black edges corresponds to using ’t Hooft coupling \( \lambda = 12\pi\alpha_s(Q^2) \). (b) The shear viscosity to entropy density ratio \( \eta/s \) estimated in the kinetic theory extrapolation \( \eta/s \sim T^3/\hat{q} \) from jet quenching parameters in panel (a). Note that \( T_c = 160 \) MeV. In CUJET3.0, a \( (\hat{q}/T^3)_{\text{max}} \) and \( (\eta/s)_{\text{min}} \) appear at \( T \sim 1.4T_c \) where the scaled number density of emergent chromo-magnetic monopoles near \( T_c \) peaks. The \( (\eta/s)_{\text{min}} \) is influenced by the EM fractions. Its value in both \( \chi_T^{L,i} \) schemes converge to approximately the KSS quantum bound \( \eta/s = 1/4\pi \) [4]. At high \( T \), the \( \eta/s \) from sQGMP and weakly-coupled QGP (wQGP) coincide because of similar color screening structures.
Note LHC2 data are much Higher Precision! V2 CMS challenge now to 1% accuracy?!

\[ (\alpha_c, c_m) = (0.9, 0.25) \]
Shuzhe Shi found 3 bugs in CUJET3.0 and corrected now in CUJET3.1:

1) Initial parton spectra for 5.02 ATeV were erroneously read from a Pythia file rather than from pQCD Wang code used previously

2) VISHNU hydro fluid grid was misread into CUJET3.0 path integrals

3) Initial parton spectra cut off set at 200 instead of 400 GeV

At IS16 and QM17 CMS discrepancies of CUJET3.0 reported for 5A TeV RAA and $v_2$

Bugs led at 5TeV to:

1) overquench RAA

2) predict wrong Centrality dep of $v_2$
pQGP/CUJET2.1 vs sQGMP/CUJET3.1 vs RHIC&LHC vs ebe/vUSP+BBMG (J. Noronha-Hostler PRC95 (2017))
Recent HigherTwist $xG(x,Q^2(L))$ model should also be compared via $\text{Chi}^2/dof$

E. Bianchi, J. Elledge, A. Kumar, A. Majumder, G. Y. Qin and C. Shen,
``The $x$ and $Q^2$ dependence of $\hat{q}$, quasi-particles and the JET puzzle'' arXiv:1702.00481 [nucl-th]

Appears to over quench LHC $\text{RAA}(p_T<40)$ in central
And over predict $v2(p_T<20)$ in semi-central
Needs functional variation $xG(x,Q)$ to minimize $\text{Chi}^2(LHC)$?
Combined RHIC+LHC1+LHC2 data RAA+v2 fit Chi^2(\alpha_c, c_m)

Assuming slow Polyakov color electric semi-q+g liberation

\[ \chi^L_T = c_q L + c_g L^2 \]

Fig. 1. (color online) The $\chi^2/d.o.f$ distribution on $(\alpha_c, c_m)$ parameter plane, from comparing CUJET3 results for pion high $p_T$ observables with central and semi-central data from RHIC 200GeV, LHC 2.76TeV as well as 5.05TeV collisions: (left) including both $R_{AA}$ and $v_2$ data; (middle) including only $R_{AA}$; (right) including only $v_2$.

The main next open question next is how will inclusion of event-by-event fluctuations Modify CUJET4.0 = ebe CUJET3.1 predictions?
central and semi-central $R_{AA}$ and $v_2$ of high $p_T$ pions

\[ VISH2+1 \otimes CUJET3.1 \]
Event-By-Event Jet Quenching

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

2760 AGeV, 20–30%

\[ \int_\phi \cos(2\phi - 2\psi_2^{\text{hard}}(p_T)) \]

[Hydro background from Jaki Noronha-Holster]
Good fit to RAA+v2+v3! With simple perturbative QCD $dE/dx = k L^1 T^3$ linear path depend

- Initial Conditions+Hydrodynamics that fit soft $v_n$’s $\rightarrow$ match high $p_T$ flow!
- But pQCD $qhat(3Tc,Tc)$ does not extrapolate to $4\pi Tc^3$

Other groups currently checking: EKRT+Quenching Weights and $v$-USPhydro+CUJET3.0
Predictions confirmed with CMS data for LHC Run 2

Over full range of centralities at 5ATeV

\[ \frac{v_2\{4\}(p_T)}{v_2\{SP\}(p_T)} \] encodes soft vs. hard fluctuations

References

- CMS \( v_n m(p_T) \) arXiv:1702.00630
- \( v-\text{USPhydro+BBMG} \) JNH, Betz, Gyulassy, Luzum, Noronha, Portillo, Ratti arXiv:1609.05171
What are $R_{AA}$ and $v_n$’s sensitive to?

Test weak HTL pQCD like $dE/dx \sim L^1 T^3$ versus infinitely coupled AdS like $dE/dx \sim L^2 T^4$.

Centrality Dependence could be a key discriminator.

Decoupling temperature affects only $v_3$. 

SHEE : Soft-Hard Event Engineering

In addition to centrality bins based only on soft Multiplicity or ET binning, more information could be extracted from subclasses of event based on soft v2, v3 .. bins. In which hard jet response is tested subclasses of fluctuating geometries.

**Centrality subclass (Mult 0-20%, less eccentric v2soft 0.01-0.02)**

**Centrality subclass (Mult 40-60%, more eccentric v2soft 0.12-0.15)**
Status as of today:

There exists (at least) two combinations of Soft vn +Hard RAA+ Hard vn dynamical models

That are compatible at $\chi^2 < 4$ level with RHIC+LHC1+LHC2 data sets at 0-10% and 20-30%


1) is compatible with aexp data including v3, but the weak $L^1$ jet dynamics qhat(E,T) does not extrapolate to the Perfect Fluidity limit near Tc as E-$\rightarrow$3Tc. The jet-medium interaction $L^1$ does not know about Lattice QCD physics near Tc.

The strong coupling AdS/CFT $L^2$ version is compatible to Perfect Fluidity but LHC2 CMS hints that maybe they can rule this out! Centrality dependence appears as key observable

2) sQGMP via corrected CUJET3.1 version is also compatible with present data And builds in all lattice QCD thermal data and does extrapolate near Tc to Perfect fluidity. However, 3.1 still has not taken into account ebe fluctuations and hence fails on odd vn. Shuzhe Shi is developing CUJET4 = ebe-vUSPH/VISHNU + CUJET3.1 (numerically challenging)

(Stay tuned )
Averaged: one hydro run on event average IC in 40-50% centrality
Smooth: 20 hydro runs in centrality bin on 20 different bins of soft v2(pT<2)
Fluctuating: Smooth times event fluctuation estimate

**IE** linear response holds

\[
\frac{v_2(p_T)}{v_{2\text{hard}}(p_T)} \approx 1 + \frac{1}{2} \left\langle \left( \frac{\delta v_{2\text{soft}}}{v_{2\text{soft}}} \right)^2 \right\rangle - 2 \left\langle \left( \delta v_2(p_T) \right)^2 \right\rangle
\]

(J.Noronga-Hostler et al PRL 2016)

Assuming linear hard-soft response:

\[
v_{2\text{hard}}(p_T) = \chi_{hs}(p_T) v_{2\text{soft}} = \chi_{hs}(p_T) \varepsilon^2
\]

Ebe Fluctuations of soft v2 do not explain hard v2 data in 10-30 GeV range in this model

Model reproduces RAA well
But still misses Hard jet v2

Shanshan Cao et al
PRELIMINARY for HP16

(all with CCNU-LBL hydro)
CUJET2.0 = rc DGLV + VISH2+1 at RHIC and LHC and where VISH is bulk flow pT<2 GeV constrained viscous 2+1 D hydro UHeinz etal

\[
\frac{dN_{Q \to Q+g}(x, \phi)}{dx} = \int d\tau \rho_{QGP}(x + \hat{n}(\phi)\tau, \tau) \int \frac{d^2q}{\pi} \frac{\alpha_s(q^2)}{(q^2 + f_E^2 \mu^2(\tau))(q^2 + f_M^2 \mu^2(\tau))} \int \frac{d^2k}{\pi^2} \frac{\alpha_s(k_T^2)/(x(1-x))}{2x+1}
\]

VISH2+1

\[
\times \frac{12(k+q)}{(k+q)^2 + \chi(\tau)} \left( \frac{(k+q)}{(k+q)^2 + \chi(\tau)} - \frac{k}{k^2 + \chi(\tau)} \right) \left( 1 - \cos \left( \frac{(k+q)^2 + \chi(\tau)}{2x+1} \right) \right).
\]

where \( \mu^2(\tau) = 4\pi \alpha_s(4T^2) \) is the local HTL color electric Debye screening mass squared in a pure gluonic plasma with local temperature \( T(\tau) \propto \rho_{QGP}(x, \tau) \) along the jet path \( x(\tau) \) through the plasma. Here \( \chi(\tau) = M^2x_+^2 + f_E^2\mu^2(T(\tau))(1-x_+)/\sqrt{2} \) controls the “dead cone” and LPM destructive interference effects due to both the finite quark current mass \( M \), and a thermal gluon mass \( m_g = f_E\mu(T)/\sqrt{2} \).

Includes effects due to bulk Radial and Elliptic transverse flow of sQGP as well as boost invariant Bjorken longitudinal flow

These suppress jet v2 by factor of 2 (as in D. Molnar and D. Sun, NPA932 (2014))

J.Xu, A.Buzzatti, MG, JHEP 1408 (2014)