Jet Tomography of Fluctuating Initial Conditions and the “Hard Ridge”

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OUTLINE

• Jet quenching & geometric tomography:
  a specific idea: near-Tc enhancement

• Hard Probe of Geometric Fluctuations

• Di-hadron correlations: what’s in the hard ridge?

• Summary

X. Zhang, JL, in preparation
JL, arXiv:1109.0271 [nucl-th]
Hot QCD Matter from RHIC to LHC

RHIC Event

LHC Event

Beautiful “little bang” delivered!
Great lever arms!
Hot QCD Matter from RHIC to LHC

Unique opportunity to better understand BOTH!

• A more “perfect” fluid or less?
• A more opaque medium or less?

• Theoretically: what’s the structure of the QCD matter at RHIC energy and how should that change at LHC energy?
• What to expect at the LHC top energy HIC?
Emergent QCD Matter

\[ T << \text{Lambda}_\text{QCD} \quad \quad T \sim \text{Lambda}_\text{QCD} \quad \quad T >> \text{Lambda}_\text{QCD} \]

Vacuum: confined

\[ Tc \]

sQGP

wQGP: screening

Electric Flux Tube:
Magnetic Condensate

Dual superconductor
\'t Hooft; Mandelstam late 70’s
Manifested in Seiberg-Witten

Plasma of E-charges
E-screening: \( gT \)
M-screening: \( g^2 T \)
SQGP as an E-M SEE-SAW QGP

Vacuum: confined

Tc

sQGP

wQGP

Electric: $e \sim 1$

Magnetic: $g \sim 1$

RHIC

Strongly coupled plasma with E & M charges
(magnetic scenario)

JL & Shuryak, PRC(07), PRL(08)

Electric: $e \gg 1$, heavy, confined!

Magnetic: $g \ll 1$, light, condensed!

Electric: $e \ll 1$, light, dense

Magnetic: $g \gg 1$, heavy, dilute

$\frac{d\Phi_E}{dt} \bigg|_{\Sigma} = \int_{\Sigma} \mathbf{B} \cdot d\mathbf{a}$

Dual Faraday's Law
Magnetic Scenario for sQGP

- Generic E-M Duality: at strong gauge coupling, chromo-magnetic monopoles become the dominant degrees of freedom.

- Plasma close to $T_c$ is special: a strong magnetic component, dominant around $T_c$.

- **Rapid turn-off when getting away from $T_c$**
  
  (-----the quickest message to take away)

JL & Shuryak:

Near Tc: a wide window in terms of entropy density!

What is the nature of confinement transition? 
Can H.I.C. help us understand the matter just about to confine?

The world is much richer than just a HRG and a Stefan-Boltzmann QGP!
**Near-Tc Matter: Hydrodynamics**

Near Tc Matter (between HRG and QGP) occupies **large space time volume** (~1/3) during the fireball evolution.

*Teaney & Shuryak*

*Heinz & Song*
Geometry of Jet Quenching
Geometry of nuclei and geometry of collisions play essential roles in jet quenching.

Gyulassy, Vitev, Wang; ......

Same dynamics, different geometry → predictable change in exp. outcome with geometry!
Geometric Data: $V_2$(hard)

Non-central collision $\rightarrow$ matter spatial anisotropy $\rightarrow$ quenching anisotropy

Out-of-Plane

$R_{aa} (\phi)$

$I_{in} < I_{out} \Rightarrow (R_{aa})_{in} > (R_{aa})_{out}$

Positive $v_2$ for high $P_t$ particles:

$$v_2 \ (\text{high } P_t) = \frac{(R_{aa})_{in} - (R_{aa})_{out}}{2 \ [(R_{aa})_{in} + (R_{aa})_{out}]}$$

More sensitivity, better discriminating power

In the last 2-3 years: fluctuations bring even more interesting geometry!!
Correlated Geometric Observables


And many more multi-observable correlations to constraint models:

Raa, V2, Iaa, V2_Iaa, ...

NOW EVEN MORING INTERESTING:

V1, V3, V4, V5, V6, ...

Need to be studied!
A Bit of History

- Gyulassy-Vitev-Wang (01); Wang (01): pQCD based model predictions
- STAR preliminary data showed much larger $v_2$ for semi-hard $Pt \sim 4$GeV
- Shuryak (01): completely opaque bulk, surface emission,
  hard sphere geometry $\rightarrow$ still considerably smaller $\rightarrow$ VERY puzzling
- More data out, till $Pt \sim 6$GeV, the puzzle persisted
- Drees-Feng-Jia (05): more realistic geometric modeling, Glauber geometry,
  various path dependence, $Raa$ as constraint $\rightarrow$ even worse
- pQCD based models continued to significantly underpredict $v2$
- PHENIX Run4 data, Run7 preliminary: extending to $Pt \sim 15$GeV
  $\rightarrow$ rather flat above 6GeV, still large compared with various models
- ??? “an area that is kind of stuck with models not quite working and lack of ideas how to proceed”

Till about ~ 2008:
previous models failed to describe the (already high quality) geometric data:
producing too small anisotropy ($V2$) with fixed opacity ($Raa$).
Pinning the Right Geometry

The puzzle may concern more radical questions:

Where are jets quenched ???

"Egg yolk" has one geometry, "Egg white" has another:
overall opacity can not tell \( \rightarrow \)
measure geometry to pin physics

\[ R_{aa}(\phi) \]

*JL & Shuryak, PRL102:202302,2009*
The “Egg Yolk v.s. White”

\[ I = \int_{\text{path}} \kappa(s) s x^n \, dx \]

Taken for granted in ALL previous models: \( \kappa(s) \to \text{constant} \)

Instead, we think it shall have \textit{non-monotonic dependence}, particularly enhanced near the phase boundary due to \textit{Nonperturbative dynamics related to confinement}!

With such strong enhancement
\( \rightarrow \) Enhance quenching at late time
\( \rightarrow \) Pick up more the “egg white” geometry
Near-Tc Enhancement Explains Geometric Data

Data favors $\xi \sim 0.2$: VERY strong enhancement of jet quenching in near Tc matter!
Near-Tc Enhancement Explains Geometric Data

PHYSICAL REVIEW C 80, 054907 (2009)

High-\(p_T\) \(\pi^0\) production with respect to the reaction plane in Au + Au collisions at \(\sqrt{s_{NN}} = 200\) GeV


One potential resolution of the problem with energy-loss calculations not reproducing the measured azimuthal dependence of yields is a recent calculation that allowed the high-\(p_T\) parton to resonantly scatter with the medium [33], increasing the energy lost by a parton at plasma densities that correspond to temperatures near the critical temperature. This produces a sharper dependence of the energy loss on the spatial variation of the medium’s energy density and hence the model is able to simultaneously reproduce both \(R_{AA}(p_T)\) and \(R_{AA}(\Delta \phi)\). A critical check will be to examine whether the same parameters work for the full range of collision centralities.
**Later Developments**

- confirmation of near Tc scenario in e.g. GLV, ASW type of jet quenching models
  - Renk-Holopainen-Heinz-Shen (arXiv:1010.1635)
  - Francesco-Di Toro-Greco (arXiv:1009.1261)
  - Fries & students (to appear)
- some near-Tc mechanism (pre-hadron loss in resonance matter; radiation of Cherenkov meson)
    - [Panuev, formation time ~3fm]
- alternative late-stage jet quenching via $L^3$ path-length dependence (holography)
  - Marquet & Renk; Jia & Wei; et al.
From RHIC to LHC

◆ over-quenching if one simply uses the same average “opaqueness” from RHIC
◆ at LHC, weighing more in much higher density
  --- expect decrease of average jet-medium coupling
  ---- to be short, q-hat is NOT simply scaling up with density/multiplicity
**Geometric Data & Modeling @ RHIC**

RED: $L^2$ model  BLUE: $L^2 + \text{Near-Tc}$  BLACK: $L^3$ model

$L^2$ model does NOT describe $v2$ data across all centrality.

$L^2$ with near-Tc enhancement AND $L^3$ model both are OK --- they both effective enhance later-stage quenching!
**Geometric Data & Modeling @ LHC**

**RED: L^2 model**  
**BLUE: L^2 + Near Tc**  
**BLACK: L^3**

**L^2 model**: over quenching (due to strong density scaling-up); describing v2 OK.

**L^2 model**: too much anisotropy (due to strong path-length power); describing Raa OK.

**L^2 with near-Tc enhancement**: describe both Raa and V2 very well!
**Tomo- v.s. Mono- v.s. Holo- Graphy**

- Jet quenching: geometric data provides essential test for the dynamics of jet-medium interaction.

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Raa @RHIC</th>
<th>V2(hard) @RHIC</th>
<th>Raa @LHC</th>
<th>V2(hard) @LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L^2$ model</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>$L^2$ + near-$T_c$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$L^3$ model</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
</tr>
</tbody>
</table>

- Precision RHIC data & preliminary LHC data together are in favor of the model with **strongly enhanced jet quenching in near-$T_c$ matter!**
Medium More Transparent @ LHC?!

Horowitz & Gyulassy, arXiv:1104.4958

GLV/WHDG: “surprising transparency of sQGP at LHC”?! (using the same coupling at RHIC and scaling up with density)

ALICE & CMS results at QM11
Medium more Transparent @ LHC?!


Applying the same scaling analysis for DATA at RHIC & LHC

These values are fireball-average and they FAIL to scale with density/multiplicity!!
Reduced Jet-Medium Coupling @ LHC

Betz & Gyulassy, arXiv:1201.0281

- over-quenching if one simply uses the same “opaqueness” from RHIC
- reducing jet-medium coupling by factor 2 for describing LHC data

$$\kappa_{LHC} \approx (0.6 \pm 0.1) \kappa_{RHIC}$$
Glimpse into QCD Non-Purt. Running?!  

\[ T_{(LHC)} \approx 1.3 \times T_{(RHIC)} \]

Betz & Gyulassy, arXiv:1201.0281:

\[ \alpha_{(LHC)} \approx (80 \sim 90) \% \times \alpha_{(RHIC)} \]

Zakharov, arXiv:1105.2028

\[ \alpha_{(LHC)} \approx (70 \sim 80) \% \times \alpha_{(RHIC)} \]

This is very exciting!!

An urgent call for all jet quenching practioners: test it in your own scheme!

JL & Shuryak, PRL(2008)
Quenching & Viscosity Linked-up: from Near Tc to Higher T

Inverse relation between viscosity and opacity
Majumder-Muller-Wang 2007; Dusling-Moore-Teaney 2009

First hints of “less-perfect” fluid at LHC 2.76TeV?!
(Frankfurt group; Ohio group)

LHC: 2.76 → top energy, exciting possibility!

Will we see a systematic deviation from RHIC to LHC?
Rapid change in a narrow regime 1-3Tc.
Geometric Fluctuations in the Initial Condition

Strong fluctuations in the initial condition $\rightarrow$ bulk matter harmonic flows

Can we use the jet to probe such geometric fluctuations?
Harmonic Fluctuations

Characterize the strong fluctuations with n-th harmonics
Each harmonic deformation: magnitude \( \epsilon_n \) and axis orientation
→ bulk matter expansion in response to the harmonic fluctuations
→ Penetrating jet in response to the SAME harmonic fluctuations

Correlation between the SOFT and HARD responses
due to their COMMON correlations to the geometric fluctuations!
Jet Response to Harmonic Fluc.


- Approximately linear response
- Strong response in 1, 2, 3
- Fluctuations in part. & coll. are both very important
Jet Response Spectrum


Compared with bulk collective flow response:
- Similar strength for $n=2,3$
- Much stronger response for $n=1$
\[ C[\Delta \phi] = \sum_{n=1,2,3,...} 2 < v^h_n v^s_n > \cos(n\Delta \phi) \]


SOFT Response ← GEOMETRY → HARD response
The away-side “dip”: room for other effects

After subtracting v2,v4 --- remnant of jet correlation on the away-side?
More of a bunch of hot spots, or a smooth matter with vague geometric profile, or maybe both? --- The answer may rely upon: What observables you look at, and what energy/centrality you look at.
Event by event: not only initial n-Part-Plane but also n-Quench-Plane
**Summary**

- **Geometric tomography** provides essential information on the mechanism of jet quenching.
- A new way of **probing the initial condition fluctuations** and an important contribution to the **hard-soft di-hadron correlations (the hard ridge and the double-hump)**
- Geometric modeling and comparison with data from RHIC to LHC supports a new picture on the question of **“where are jets quenched (more strongly)?”**: strong jet quenching component at late stage, corresponding to the matter near phase boundary.
- Will be even more **exciting to see LHC data at 5.5TeV**