Non-Perturbative Jet Quenching
from Geometric Data

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**Outline**

- Brief Introduction: Jet Quenching & Geometric Tomography
- Strong Enhancement of Jet Quenching Near Transition
- Geometric Data and Modeling from RHIC to LHC
- Summary
Strong Jet Quenching

Significant energy loss $\Rightarrow$ color-opaque medium
(high Pt yield (Raa), di-hadron correlation,......)

\[ R_{A-A}(p_t) = \frac{d^2 N^{A-A}/dp_t d\eta}{T_{A-A} d^2 \sigma^{N-N}/dp_t d\eta} \]

Strong jet quenching at LHC too: see recent talks at QM2011 and this conference
**Geometric Tomography**

Geometry of nuclei and geometry of collisions play essential roles in jet quenching.

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

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Same dynamics, different geometry $\rightarrow$ predictable change in exp. outcome with geometry!
**Geometric Data: V2(hard)**

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

In-Plane

Out-of-Plane

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

Positive $v_2$ for high $P_t$ particles:

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

More sensitivity, better discriminating power
**From Geometry to Dynamics**

- **Jet energy loss** along its path through the fireball

\[ \Delta E = \int_{\text{path}} F[J \mid M \mid J + M] \, dx \]
\[ F[J \mid M \mid J + M] = \frac{dE}{dx} = E^\delta \kappa[s] s \, x^n \]
\[ E_f = E_i \exp \left[ - \int_{\text{path}} \kappa[s] s \, x^n \, dx \right] \]

The “quenching integral” is essential:
- Initial jet spot (binary coll. profile)
- Jet orientation (random)
- Medium density (part. profile) & evolution
- Quenching strength
- Path length dependence (LPM, AdS, ...)

Using geometric data to test the dynamical features of jet quenching!
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 $Pt \sim 4\text{GeV}$
- Shuryak (01): completely opaque bulk, surface emission,
  hard sphere geometry $\rightarrow$ still considerably smaller $\rightarrow$ VERY puzzling
- More data out, till $Pt \sim 6\text{GeV}$, 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 $v_2$
- PHENIX Run4 data, Run7 preliminary: extending to $Pt \sim 15\text{GeV}$
  $\rightarrow$ rather flat above $6\text{GeV}$, 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:

*all previous models failed to describe the (already high quality) geometric data by producing too small anisotropy ($v_2$) 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 → measure geometry to pin physics

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:
\[ \kappa[s] \Rightarrow \text{constant} \]

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

With such strong enhancement
→ Enhance quenching at late time
→ Pick up more the “egg white” geometry
Near-Tc Matter: Thermodynamics

Near Tc is NOT a single point or narrow interval. It is a wide window in terms of entropy density!
Near T_{c} Matter (between HRG and QGP) occupies large space time volume (~1/3) during the fireball evolution.

Teaney & Shuryak

Heinz & Song
Near-Tc Enhancement Explains Geometric Data

Two components: near Tc & QGP.
Assume certain relative quenching strength $\xi$.
Overall quenching strength fixed by Raa.

Data favors $\xi \sim 0.2$: VERY strong enhancement of jet quenching in near Tc matter!
A Lately Story: $L^3$ Scenario

Naïve: $n=0$, linear, $L$
LPM: $n=1$, quadratic, $L^2$
(some) AdS: $n=2$, cubic, $L^3$

Larger $n \Rightarrow$ stronger path-length dependence
  $\Rightarrow$ amplify the in-/out-of-plane difference
  $\Rightarrow$ effectively delay jet quenching to later time

At RHIC, the bulk evolution is such that:
  near $T_c$ scenario & $L^3$ scenario $\Rightarrow$ similar phenomenological consequence.

CAN WE FURTHER DISTINGUISH THEM, e.g. at LHC???
**Geometric Data & Modeling @ RHIC**

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

$L^2$ model does NOT describe $v_2$ 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:** $L^2 + \text{Near Tc}$  
**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!
**Summary**

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

<table>
<thead>
<tr>
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<th>Raa @RHIC</th>
<th>V2(hard) @RHIC</th>
<th>Raa @LHC</th>
<th>V2(hard) @LHC</th>
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<tbody>
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<td>(L^2) model</td>
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<td>(L^2 + ) near-Tc</td>
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◆ Precision RHIC data & preliminary LHC data together are much in favor of the model with

*strongly enhanced jet quenching in near-Tc matter!*
Post-Summary: Physics of Near-Tc.

**sQGP as an E-M SEE-SAW QGP**

Vacuum: confined

\[ T_c \]

sQGP

wQGP

\[ T \]

**Magnetic:**

\[ g \sim 1 \]

**Electric:**

\[ e \sim 1 \]

RHIC

\[(semi-QGP)\]

Strongly coupled plasma with E & M charges

(magnetic scenario)

**Electric:**

\[ e \ll 1, \text{ light, dense} \]

**Magnetic:**

\[ g \gg 1, \text{ heavy, dilute} \]

JL & Shuryak, PRC(07), PRL(08)
BACKUP SLIDES
Raa characterizes the **overall medium opacity**.
Directly related to average of quenching integral.

![Graphs showing Raa as a function of pT](image)

Various models fit Raa well;
Four pQCD-based models require
very different, but all large values of q-hat.
**The State-of-Art RHIC Data**

**PHENIX Run4 & Run7**


Jet quenching in the near Tc matter yields the largest geometric anisotropy!

Scan the fireball geometry layer by layer

\[ \kappa[s] = \kappa_c * \Theta[s - s_a] * \Theta[s_b - s] \]
**Related Supportive Hints**

Eta/s & \( \hat{q} \)-hat (Majumder, Muller, Wang, '07):

\[
\frac{\eta}{s} \times \frac{\hat{q}}{T^3} \sim \text{constant}
\]

GW/GLV jet quenching model (Gyulassy, et al)

\[
\frac{\hat{q}}{n_g} \sim \alpha \times \log \left[ \frac{Q_{UV}}{M_D} \right]
\]
Related Supportive Hints

Lattice Q-bar-Q potential: significant separation energy peaked around Tc

Heavy quark phenomenology favors “valley” of diffusion constant around Tc

(R Rapp & collaborators)
**Recent 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)
- physical 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
  - Marquet & Renk; Jia & Wei; Renk-Heinz et al.
**Near-Tc v.s. $L^3$**

*Can we distinguish the two different scenarios?*

**AuAu to CuCu:**
- $L^3$ more sensitive to system size

**Gamma-hadron correlation:**
- Pt fraction $z$ tells path length;
- Look at $I_{aa}$ and $I_{aa}(\phi)$
E-M SEE-SAW

Vacuum: confined

Tc

sQGP

wQGP

T

Magnetic: g ~ 1

Electric: e ~ 1

RHIC

Magnetic: g << 1, light, condensed!

Electric: e >> 1, heavy, confined!

Electric: e << 1, light, dense

Magnetic: g >> 1, heavy, dilute

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

Dual Faraday’s Law

$\frac{d\phi_E}{dt} |_{\Sigma} = \int_{\Sigma} \vec{B} \cdot \vec{a}$
The See-saw in Density & Coupling

See-saw at work!
Expect rapid change at higher $T$

JL & Shuryak, 06,07,08; Claudia & Shuryak, 08;
(Lattice) Delia, et al, 07; (semi-QGP) Pisarski, et al, 08.