Quantifying a Possibly Reduced Jet-Medium Coupling of the sQGP at the LHC

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Quark Matter Conference 2012
Washington, D.C., August 14, 2012

PRC 84, 024913 (2011); PRC 86, 024903 (2012)
Transparency of the QGP

- Remarkable similarity of jet quenching at RHIC and LHC
- $p_T$-rise in data readily understood from generic perturbative physics

→ Puzzle: RHIC constrained models tend to overquench $R_{AA}$ at LHC

→ Is the jet-medium coupling at LHC weaker? By how much?
Energy-Loss Mechanisms

Generic model of jet-energy loss:

\[ \frac{dP}{d\tau}(x_0, \phi, \tau) = -\kappa P^a(\tau) \tau^z T^{c=2-a+z} \left[ x_{\perp}(\tau), \tau, b \right] \]

generalized from Jia’s survival model
J. Jia et al., PRC 82 (2010), 024902

considering Bjorken expansion for \( \tau_0 = 1 \) fm, including fragmentation, and examining an “averaged scenario” for Glauber and CGC-like in. cond.

B. Betz et al., PRC 84, 024913 (2011)

CGC-like, deformed Glauber in. cond. (dcgc1.2):

\[ x \rightarrow s_x x, \quad y \rightarrow s_y y \]

\[ s_x = \sqrt{\frac{\langle x^2 \rangle_{CGC}}{\langle x^2 \rangle_{G1}}}, \quad s_y = \sqrt{\frac{\langle y^2 \rangle_{CGC}}{\langle y^2 \rangle_{G1}}} \]

with the assumption

\[ \epsilon_{CGC} = f \cdot \epsilon_{G1} \quad f = 1.2 \pm 0.1 \]

Jet-energy and path-length dependencies (4 main scenarios):

| a | z | c | in. cond. |
|---|---|---|-----------|
| 0 | 1 | 3 | Glauber   |
| 1/3 | 1 | 8/3 | Glauber dcgc1.2 |
| 1 | 2 | 3 | ”Jia” dcgc1.2 |

see A. Ficnar QM’12 Poster
A. Ficnar, arXiv: 1201.1780

pure binary collisions for \( a = 1 \)
J. Jia et al., PRC 82 (2010), 024902
RHIC vs. LHC
Extrapolation from RHIC to LHC energies leads to an overquenching of the $R_{AA}$ at LHC energies.

W. Horowitz et al, Nucl. Phys. A 872 (2011) 265
What is the physical meaning of a reduced coupling?

**pQCD:** \( \kappa \propto \alpha^3 \)

\[
\alpha_{\text{LHC}} = \left( \frac{\kappa_{\text{LHC}}}{\kappa_{\text{RHIC}}} \right)^{1/3} \alpha_{\text{RHIC}} \quad \alpha_{\text{RHIC}} \sim 0.3
\]

fit to LHC most central data: \( \alpha_{\text{LHC}} \sim 0.24 - 0.28 \)

(independent of initial time)

\[\text{B. Betz et al., PRC 86, 024903 (2012)}\]

\[\text{→ Reasonable moderate reduction of the running coupling}\]

**AdS/CFT:** \( \kappa \propto \sqrt{\lambda} \) \( \text{← t’Hooft coupling} \)

\[
\lambda_{\text{LHC}} = \left( \frac{\kappa_{\text{LHC}}}{\kappa_{\text{RHIC}}} \right)^2 \lambda_{\text{RHIC}} \quad \lambda_{\text{RHIC}} \sim 20 \text{(heavy quarks)}
\]

with the values used: \( \lambda_{\text{LHC}} \sim 5 - 10 \)

\[\text{→ Rather strong conformal symmetry breaking over a narrow temperature interval (1-2)T_c is required}\]
\nNon-conformal gravity dual generalizations are under construction (Mia, Ficnar, Noronha, ...
$R_{AA}(p_T)$ at the LHC

→ Linear $p_T$-dependent ($a=1$) model describes RHIC $p_T<10$ GeV data well but is falsified at LHC

→ Rapid rise of $R_{AA}(p_T)$ rules out any model with $dE/dx \sim E^{a>1/3}$
$R_{AA}(p_T)$ at RHIC

- $a=0$ and $a=1/3$ energy exponents are consistent with data within error bars

- Higher statistics measurements at RHIC with $5 < p_T < 30$ GeV are needed

sPHENIX Upgrade Concept, arXiv:1207.6378
$R_{AA}$ and $v_2$ at RHIC

- “Jia” dcgc1.2 model is excluded by the $p_T$-dependence of the $R_{AA}$ at LHC
- $a=0, 1/3$ scenarios fail to describe the $v_2$(Centr.)

$$\rightarrow$$ Disagreement with $v_2$ data at RHIC FOR THIS intermediate $p_T$-regime

$$\rightarrow$$ SMALL difference between path-length dependence $z=1$ and $z=2$
Intermediate $v_2(p_T)$ range ($2 < p_T < 10$ GeV)

While hadronization via $1\text{parton} \rightarrow 1\pi$ or independent fragmentation approximately preserves elliptic flow at high $2 < p_\perp < 6$ GeV [3], parton coalescence enhances $v_2$ two times for mesons and three times for baryons. Hence, the same hadron elliptic flow can be reached from $2 - 3$ times smaller parton $v_2$, i.e., with smaller parton densities and/or cross sections.

> parts of the $v_2$(intermediate $p_T$) could originate from bulk tails
see Eqs. (16) – (18) in M. Gyulassy et al., Phys. Rev. Lett. 86, 2537 (2001)

> pure jet fragmentation and absorption models should NOT be expected to fully describe the intermediate $p_T$-range

D. Molnar, J. Phys. G 30, S235 (2004)
Unlike the intermediate $p_T$, the deep ultraviolet $p_T>10$ GeV is much better explained by standard jet tomography at LHC.

For $1 < p_T < 5$ GeV, it is difficult to separate the jet contribution to $v_2$ from the high-$p_T$ tails of the bulk QGP elliptic flow.

Very high $p_T>10$ GeV $v_2$ is rather insensitive to 20% variations in the eccentricity between Glauber and CGC.
Fixed vs. Temperature-Dependent Coupling
**Temperature-dependent Coupling**

\[ \kappa_2 = 3 \kappa_1 \]

\[ T_f = 113 \text{MeV} \quad T_c = 173 \text{MeV} \]

Assumes the same \( k(T) \) at RHIC and LHC!

\[ \zeta = \frac{\kappa_1}{\kappa_2} \]

\( \zeta \) Eff \( \kappa_{LHC} \) < \( \zeta \) Eff \( \kappa_{RHIC} \) because \( T_{max}^{LHC} \sim 1.3 T_{max}^{RHIC} \)
Temperature-dependent and reduced couplings lead to similar $R_{AA}(p_T)$

Running coupling CUJET and SL $a=0 \, \zeta=1/3,1$ all similar for $p_T > 10$ GeV
Summary & Open Problems

- Puzzle of overquenching $R_{AA}$ at LHC can be solved:
  - reduced jet-medium coupling at LHC, $\alpha \sim 0.27 - 0.28$
  - running coupling
  - temperature-dependent jet-medium coupling
  - or a combination

- $dE/dx \sim E^{a=1}$ best describing RHIC data but is falsified at LHC
- Rapid rise of $R_{AA}(p_T)$ rules out any model with $dE/dx \sim E^{a>1/3}$
- An energy loss with $dE/dx \sim E^{a=0}$ is slightly favoured over $dE/dx \sim E^{a=1/3}$
- Disentangling of initial conditions with high-$p_T$ $v_2$ difficult once the coupling is fixed to a single $R_{AA}$ reference point
- Unlike the intermediate $p_T$, the deep ultraviolet $v_2(p_T>10$ GeV) is much better explained by standard jet tomography at LHC

→ Cross checking RHIC vs. LHC at all combinations of available data is essential to test consistency of all models
Backup
$R_{AA}$ and $v_2$ at RHIC

Similar results for event-by-event and averaged scenarios

B.Betz et al., PRC 84, 024913 (2011)
We set $\tau_0 = 1\text{ fm}$

H. Song et al., PRL 106, 192391 (2011)

Jia’s model has $\tau_0 = 0\text{ fm}$

A. Adare et al., PRL 105, 142301 (2010)

→ A smaller $\tau_0$ reduces the $v_2$(Centr.) and increases the difference between the pQCD and AdS/CFT results
Initial time

\[ \tau_0 = 1\text{fm} \quad \rightarrow \quad \textbf{Assumption: NO energy loss within 1fm} \]

- pQCD does not give excuse for this ansatz,
  \[ \tau_0 = 0\text{fm} \text{ most natural assumption} \]
- describes formation time of hydrodynamics
  \[ \rightarrow \text{no pressure at early times, everything is free flow} \]

\[ \tau_0 = 1\text{fm} \quad \rightarrow \quad \text{essentially equivalent to AdS/CFT} \]
  energy loss suppression of early times

\[ \rightarrow v_2(\text{high- } p_T) \text{ not sensitive to long distance } \frac{dE}{dx} \sim l^1 \]
  vs. \[ \frac{dE}{dx} \sim l^2, \text{ but to short distance properties } < 1\text{fm}! \]

\[ \rightarrow \text{We cannot access the center of the collision!} \]

Adare et al, Phys. Rev. Lett. \textbf{105}, 142301 (2010)
Remarkably insensitive to the initial conditions

⇒ It’s NOT sufficient to just study ONE variable!

B.Betz et al., PRC 86, 024903 (2012)
Reduced Jet-Medium Coupling

Effective Coupling $\kappa$ assuming $\tau_0 = 1.0$ fm/c

| $\sqrt{s}$ | Glauber $a=1/3$ $z=1$ | dcgc1.2 $a=1/3$ $z=1$ | Glauber $a=1/3$ $z=2$ | Glauber $a=0$ $z=1$ | "Jia" $a=1$ $z=2$ |
|---|---|---|---|---|---|
| 0.20 | 0.93 | 1.09 | 0.55 | 3.30 | 0.057 |
| 2.76 | 0.66 | 0.66 | 0.33 | 2.72 | 0.017 |

LHC/RHIC | 0.71 | 0.61 | 0.60 | 0.82 | 0.33 |

Effective Coupling $\kappa$ assuming $\tau_0 = 0.01$ fm/c

| $\sqrt{s}$ | Glauber $z=1$ | dcgc1.2 $z=1$ | Glauber $z=2$ |
|---|---|---|---|
| 0.20 | 0.60 | 0.58 | 0.44 |
| 2.76 | 0.45 | 0.43 | 0.26 |

LHC/RHIC | 0.75 | 0.74 | 0.59 |
Temperature-dependent Coupling

\[ \kappa_2 = 3 \kappa_1 \]

J.Liao et al., PRL 102 (2009) 202302

\[ \zeta = \frac{\kappa_1}{\kappa_2} \]

\[ dE/dx \propto E^0 \tau^1 T^3 \quad \tau_0 = 1 \text{fm} \]

RHIC

(a) \( p_T = 7.5 \text{ GeV} \)

(b)

(c) \( p_T = 10 \text{ GeV} \)

LHC

ATLAS prelim

ALICE prelim

CMS prelim

(b)

Glauber, SL, \( \zeta = 1/3 \)

Glauber, SL, \( \zeta = 0 \)

dcg1.2, SL, \( \zeta = 1/3 \)

dcg1.2, SL, \( \zeta = 1 \)
\( R_{AA}(p_T) \) at RHIC, LS model

\( \zeta = 1/3 \) scenario consistent with RHIC data on \( R_{AA}(p_T) \)

\[
dE/dx = -\kappa(T)E^0T^3
\]
$v_2(p_T, \text{Centrality})$ at LHC, LS model

Small difference between $\zeta=1/3$ and $\zeta=1$
### Effective Coupling in the LS Model

| $\zeta = \kappa_1 / \kappa_2$ | in. cond. | $\sqrt{s}$          | $\kappa_1$ | $\kappa_2$ |
|-------------------------------|-----------|---------------------|------------|------------|
| 1/3                           | Glauber   | RHIC&LHC            | 1.82       | 5.47       |
| 1/3                           | dgc1.2    | RHIC&LHC            | 1.75       | 5.45       |
| 0                             | Glauber   | RHIC&LHC            | 0.0        | 7.65       |
| 1                             | dgc1.2    | RHIC                | 3.80       | $\kappa_2 = \kappa_1$ |
| 1                             | dgc1.2    | LHC (red.)          | 2.66       | $\kappa_2 = \kappa_1$ |

$\tau_0 = 1.0 \text{ fm/c}$

B.Betz et al., in preparation
The “Geometric Optics” Limit

For the generic energy-loss model

\[ \frac{dP}{d\tau}(\vec{x}_0, \phi, \tau) = -\kappa P^a(\tau) \tau^z T^{c=2-a+z}[\vec{x}_\perp(\tau), \tau, b] \]

the initial parton momentum depends on the final parton momentum

\[ P_0(P_f) = \left[ P_f^{1-a} + K \int_{\tau_0}^{\tau_f} \tau^z T^c[\vec{x}_\perp(\tau), \tau] d\tau \right]^{\frac{1}{1-a}}, \quad K = (1 - a)\kappa C_2 \]

For \( a=1 \), this leads to a pure exponential dependence of the initial parton momentum

\[ P_0(P_f) = P_f e^{\chi_{z,c}} \]

with the jet-energy independent effective opacity

\[ \chi_{z,c}(\phi) = \kappa C_2 \int_{\tau_0}^{\tau_f} d\tau \tau^z T^c(\tau, \phi) \]

This corresponds to a generalized “geometric optics” limit.
The reason is the following. If, from the solid blue curve in Figure 1, we can roughly conclude that the energy loss is linear in time, $dE/dt \sim t$, and we know that $(\Delta x)_{max} \sim E^{1/3}$, it can be shown that this is actually the typical qualitative behavior of energy loss of light quarks in pQCD in the strong LPM regime [18]. This suggests a tempting idea that the phenomenon of light quark jet quenching may have a roughly universal qualitative character, regardless of whether we are dealing with a strongly or a weakly coupled medium.

Furthermore, a known generic feature of pQCD energy loss in the strong LPM regime is the rise of $R_{AA}$ at high transverse momenta $p_T$, a qualitative behavior exhibited by the LHC data for light quarks [18]. And if we can roughly conclude that here we have the same qualitative behavior of energy loss as in pQCD, there is hope that an $R_{AA}$ computed from a falling string energy loss would yield the same characteristic rise at high $p_T$. However, if there was a pronounced late-time Bragg peak in the energy loss (the dashed red curve in Figure 1), then the energy loss would scale more like $dE/dt \sim t^2$ and would not yield the same behavior as in pQCD, and therefore might not result in an $R_{AA}$ rising at high $p_T$ [18].