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

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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 $R_{AA}$ @LHC

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


Energy-Loss Mechanisms

Generic model of jet-energy loss:

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

generalized from Jia’s survival model

J. Jia et al., PRC 82 (2010), 024902

considering Bjorken expansion for \( \tau_0 = 1\, \text{fm} \), 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):

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

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

with the assumption

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

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

<table>
<thead>
<tr>
<th>a</th>
<th>z</th>
<th>c</th>
<th>in. cond.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>3</td>
<td>Glauber</td>
</tr>
<tr>
<td>1/3</td>
<td>1</td>
<td>8/3</td>
<td>Glauber</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>”Jia” dcgc1.2</td>
</tr>
</tbody>
</table>

Jet-energy and path-length dependencies for \( a=1 \)


see A. Ficnar QM’12 Poster

B. Betz et al., PRC 86, 024903 (2012)

pure binary collisions for \( a=1 \)

J. Jia et al., PRC 82 (2010), 024902

08/14/12

Quark Matter Conference 2012, Washington, D.C.
RHIC vs. LHC
Extrapolation from RHIC to LHC energies leads to an overquenching of the $R_{AA}$ at LHC energies

Reduced Jet-Medium Coupling

What is the physical meaning of a reduced coupling?

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

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

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

(independent of initial time)

\( \rightarrow \) Reasonable moderate reduction of the running coupling

AdS/CFT: \( \kappa \propto \sqrt{\lambda} \)

\[
\lambda_{\text{LHC}} = (\kappa_{\text{LHC}}/\kappa_{\text{RHIC}})^2 \lambda_{\text{RHIC}} \quad \lambda_{\text{RHIC}} \sim 20 \) (heavy quarks)

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

\( \rightarrow \) Rather strong conformal symmetry breaking over a narrow temperature interval \((1-2)T_C\) is required

Non-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 $dE/dx \sim E^{a>1/3}$
RHIC vs. LHC
$R_{AA}(p_T)$ 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" dgcgc1.2 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.

$\rightarrow$ parts of the $v_2$(intermediate $p_T$) could originate from bulk tails


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

\( v_2(p_T, \text{Centrality}) \) at LHC

- Unlike the intermediate \( p_T \), the deep ultraviolet \( p_T > 10 \text{ GeV} \) is much better explained by standard jet tomography at LHC.

- For \( 1 < p_T < 5 \text{ GeV} \), it is difficult to separate the jet contribution to \( v_2 \) from the high-\( p_T \) tails of the bulk QGP elliptic flow.

\( \rightarrow \) Very high \( p_T > 10 \text{ GeV} \) \( v_2 \) is rather insensitive to 20% variations in the eccentricity between Glauber and CGC.
Fixed vs. Temperature-Dependent Coupling
Temperature-dependent Coupling

\[ \kappa_2 = 3 \kappa_1 \]

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

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

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

\[ \text{eff } \kappa_{\text{LHC}} < \text{eff } \kappa_{\text{RHIC}} \]

because \( T_{\text{LHC}}^{\text{max}} \sim 1.3 T_{\text{RHIC}}^{\text{max}} \)

\[ \frac{dE}{dx} \propto E^0 \tau^1 T^3 \]

\( \tau_0 = 1 \text{ fm} \)

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

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

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

(\( d_{cgc1.2} \), SL, \( \zeta = 1/3 \))
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 $R_{AA}$@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 $v_2(p_T>10\text{ GeV})$ 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)
Initial time

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 $v_2(\text{Centr.})$ and increases the difference between the pQCD and AdS/CFT results
Initial time

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

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

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

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

$$\rightarrow \text{We cannot access the center of the collision!}$$
Remarkably insensitive to the initial conditions

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

\( R_{AA}(p_T, \text{Centrality}) \) at LHC

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

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

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>Glauber $a=1/3$ $z=1$</th>
<th>dgcg1.2 $a=1/3$ $z=1$</th>
<th>Glauber $a=1/3$ $z=2$</th>
<th>Glauber $a=0$ $z=1$</th>
<th>”Jia” $a=1$ $z=2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.93</td>
<td>1.09</td>
<td>0.55</td>
<td>3.30</td>
<td>0.057</td>
</tr>
<tr>
<td>2.76</td>
<td>0.66</td>
<td>0.66</td>
<td>0.33</td>
<td>2.72</td>
<td>0.017</td>
</tr>
</tbody>
</table>

**LHC/RHIC**

| Glauber $z=1$ | 0.71 | 0.61 | 0.60 | 0.82 | 0.33 |

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

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>Glauber $z=1$</th>
<th>dgcg1.2 $z=1$</th>
<th>Glauber $z=2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.60</td>
<td>0.58</td>
<td>0.44</td>
</tr>
<tr>
<td>2.76</td>
<td>0.45</td>
<td>0.43</td>
<td>0.26</td>
</tr>
</tbody>
</table>

**LHC/RHIC**

| 0.75 | 0.74 | 0.59 |
Temperature-dependent Coupling

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

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

B. Betz et al., in preparation

\[ \frac{dE}{dx} \propto E^0 T^3 \]

\[ \tau_0 = 1 \text{ fm} \]

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

(b) \( R_{AA}^\pi \)

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

(d) Centrality [%]

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

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

dgcg1.2, SL, \( \zeta = 1/3 \)

dgcg1.2, SL, \( \zeta = 1 \)

\( T_I = 113 \text{ MeV} \)

\( T_c = 173 \text{ MeV} \)
$R_{AA}(p_T)$ at RHIC, LS model

$\zeta=1/3$ scenario consistent with RHIC data on $R_{AA}(p_T)$
$v_2(p_T, \text{Centrality})$ at LHC, LS model

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

<table>
<thead>
<tr>
<th>$\zeta = \kappa_1 / \kappa_2$</th>
<th>in. cond.</th>
<th>$\sqrt{s}$</th>
<th>$\kappa_1$</th>
<th>$\kappa_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>Glauber</td>
<td>RHIC&amp;LHC</td>
<td>1.82</td>
<td>5.47</td>
</tr>
<tr>
<td>1/3</td>
<td>dcgc1.2</td>
<td>RHIC&amp;LHC</td>
<td>1.75</td>
<td>5.45</td>
</tr>
<tr>
<td>0</td>
<td>Glauber</td>
<td>RHIC&amp;LHC</td>
<td>0.0</td>
<td>7.65</td>
</tr>
<tr>
<td>1</td>
<td>dcgc1.2</td>
<td>RHIC</td>
<td>3.80</td>
<td>$\kappa_2 = \kappa_1$</td>
</tr>
<tr>
<td>1</td>
<td>dcgc1.2</td>
<td>LHC (red.)</td>
<td>2.66</td>
<td>$\kappa_2 = \kappa_1$</td>
</tr>
</tbody>
</table>

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, \( dE/dt \sim t^1 \), 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].