Extracting $\hat{q}$ in event-by-event hydrodynamics and the centrality/energy puzzle

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1. Introduction

2. Energy loss implementation

3. Hydrodynamic modelling of the medium

4. Results

5. Limitations and conclusions
Study of suppression of high-$p_T$ particles in $\text{PbPb}$ collisions at the LHC and $\text{AuAu}$ collisions at RHIC.

Analysis based on the quenching weights ($QW$) for medium-induced gluon radiation.

$QW$ computed in multiple soft scattering approximation.

Embedded in $\text{EKRT}$ event-by-event description of the medium.

Study done for different centrality classes.
The single inclusive cross section is described by

\[
\frac{d\sigma_{AA\rightarrow h+X}}{dp_T\,dy} = \int \frac{dx_2}{x_2} \frac{dz}{z} \sum_{i,j} x_1 f_i/A(x_1, Q^2) x_2 f_j/A(x_2, Q^2) \times \frac{d\hat{\sigma}_{ij\rightarrow k}}{d\hat{t}} D_{k\rightarrow h}(z, \mu_F^2)
\]

Factorization scale \(Q^2 = (p_T/z)^2\). Fragmentation scale as \(\mu_F = p_T\).

- CTEQ6M + EPS09 (NLO).
- We absorb energy loss in a redefinition of the fragmentation functions:

\[
D_{k\rightarrow h}^{(med)}(z, \mu_F^2) = \int_0^1 d\epsilon P_E(\epsilon) \frac{1}{1 - \epsilon} D_{k\rightarrow h}^{(vac)} \left( \frac{z}{1 - \epsilon}, \mu_F^2 \right)
\]

- \(P_E(\epsilon)\) is the Quenching Weight and \(D_{k\rightarrow h}^{(vac)}(z, \mu_F^2)\), DSS fragmentation functions.
The **ASW Quenching Weights** are given by

\[
P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[ \prod_{i=1}^{n} \int d\omega_i \frac{dl^{(med)}(\omega_i)}{d\omega} \right] \times \delta \left( \Delta E - \sum_{i=1}^{n} \omega_i \right) \exp \left[ - \int_{0}^{\infty} d\omega \frac{dl^{(med)}}{d\omega} \right]
\]

- **Independent** gluon emission assumed.
- QW are Poisson distributions.
- Support in recent works of **coherence** and **resummation** by J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk...
Coherence

- Totally coherent case:
  - Vacuum-like fragmentations.
  - Jets loosing energy as a single parton.
- This picture is in agreement with LHC data.

Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk, PLB 725 (2013) 357.
Independent gluon emission

- **Interference** effects may break independent gluon emission.

- They are **absent** for $\tau_{form} = \sqrt{\omega/\hat{q}} << L$.

- Independent gluon emission is a **good approximation** for soft radiation.


- For soft radiation and no finite energy effects **QW and rate equations** are **equivalent**.

In \( \frac{dI^{(med)}}{d\omega} \) the medium properties appear in: \( \sigma(r)n(\xi) \).

In the multiple soft scattering approximation we use

\[
\sigma(r)n(\xi) \approx \frac{1}{2} \hat{q}(\xi) r^2
\]

Perturbative tails neglected.

We specify the relation between \( \hat{q}(\xi) \) and the medium properties given by our hydrodynamic model as

\[
\hat{q}(\xi) = K \hat{q}_{QGP}(\xi) \approx K \cdot 2\epsilon^{3/4}(\xi)
\]

\( K \) is our fitting parameter.

Energy density obtained by solving the relativistic hydrodynamic equations.
Hydrodynamic medium modelling

**Before...**  
- We used several ’event-averaged’ hydro simulations:  
  - “Hirano”: no viscous, optical Glauber model, $\tau_0 = 0.6$ fm.  
  - “Glauber”: viscous $\eta/s = 0.08$, energy density proportional to $\rho_{bin}$ as initial condition, $\tau_0 = 1$ fm.  
  - “fKLN”: viscous $\eta/s = 0.16$, factorised Kharzeev-Levin-Nardi model, $\tau_0 = 1$ fm.

**Now...**  
- We use **EKRT event-by-event** hydro: arXiv:1505.02677 [hep-ph].  
  - Initial conditions given: minijet + saturation model.  
  - $\tau_0 = 0.197$ fm.  
  - $\eta/s = 0.2$.

- Ambiguity before thermalization:  
  - $\hat{q}(\xi) = \hat{q}(\tau_0)$ for $\xi < \tau_0$. 
Nuclear modification factor

- We use $R_{AA}$ experimental data:

$$R_{AA} = \frac{dN_{AA}/d^2p_Tdy}{\langle N_{coll}\rangle dN_{pp}/dp_T^2dy}$$

- From Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and Au-Au at $\sqrt{s_{NN}} = 200$ GeV.

- ALICE data on $R_{AA}$ for charged particles with $p_T > 5$ GeV in different centrality classes and for $|\eta| < 0.8$, arXiv:1208.2711 [hep-ex].

- PHENIX data on $\pi_0$ $R_{AA}$ $p_T > 5$ GeV, arXiv:0801.4020 [nucl-ex].
$R_{AA}$ at $\sqrt{s_{NN}} = 200$ GeV for different centralities

![Graphs showing $R_{AA}$ for different centralities and Au-Au collisions at 200 GeV](image)
$R_{AA}$ at $\sqrt{s_{NN}} = 2.76$ TeV for different centralities

$\chi^2$ to the best value of $K$. $\Delta \chi^2 = 1$. 
$K$-factor vs. impact parameter

$K = \hat{q}/2\hat{e}^{3/4}$

$\hat{q}(\tau) = \hat{q}(\tau_0), \tau < \tau_0$

$K$ depends mainly on the energy and it is almost independent of the centrality of the collision!!
$K$-factor vs. $\epsilon \tau_0$

\begin{align*}
\hat{q}(\tau) &= \hat{q}(\tau_0), \quad \tau < \tau_0 \\
K &= \frac{\hat{q}}{2\epsilon^{3/4}} \\
\hat{q} &= \hat{q}_0
\end{align*}


Difficult to reconcile the energy and centrality dependence!! A new puzzle??

Possible explanations already being studied: Amir Kumar Session 5.4 We 8:50.
Limitations

- The definition of $\hat{q}$ neglects the **perturbative tails** of the distributions.

- The QW find support in the **coherence** analysis of the medium: if coherence is broken they could fail.

- Finite energy corrections.

- $\hat{q}$ energy or length independent.

- *Collisional energy loss* is neglected.
Conclusions

- We fit the single-inclusive experimental data at RHIC and LHC for different centralities.
- The fitted value at RHIC confirms large corrections to the ideal case.
- For the case of the LHC, the extracted value of $K$ is close to unity.
- $K$-factor is $\sim 2 - 3$ times larger for RHIC than at the LHC.
- Centrality dependences at RHIC and the LHC are rather flat.
- The change in the value of $K$ does not look to be simply due to the different local medium parameters.
- Unexpected result!!
The inclusive energy distribution of gluon radiation off an in-medium produced parton is given by

$$\omega \frac{dI^{(med)}}{d\omega} = \frac{\alpha_s C_R}{(2\pi)^2 \omega^2} 2 \text{Re} \int_{\xi_0}^{\infty} dy_l \int_{y_l}^{\infty} d\bar{y}_l \int_0^\infty du \int d\mathbf{k}_\perp$$

$$\times e^{-i\mathbf{k}_\perp \cdot \mathbf{u}} e^{-\frac{1}{2} \int_0^{\infty} d\xi n(\xi) \sigma(\mathbf{u})} \frac{\partial}{\partial \mathbf{y}} \cdot \frac{\partial}{\partial \mathbf{u}} \int_{y=0}^{\mathbf{u}=\mathbf{r}(\bar{y}_l)} D\mathbf{r}$$

$$\times \exp \left[ i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2} \left( \dot{\mathbf{r}}^2 - \frac{n(\xi) \sigma(\mathbf{r})}{i\omega} \right) \right]$$

- $n(\xi)$, density of scattering centers.
- $\sigma(\mathbf{r})$, strength of a single elastic scattering.
The production weight is given by

$$\omega(x_0, y_0) = T_{Pb}(x_0, y_0) T_{Pb}(\vec{b} - (x_0, y_0))$$

The average values of an observable and in particular of our fragmentations functions is computed as

$$\langle O \rangle = \frac{1}{N} \int d\phi dx_0 dy_0 \omega(x_0, y_0) O(x_0, y_0, \phi)$$

$$\langle D^{(med)}_{k \to h}(z, \mu^2_F) \rangle = \frac{1}{N} \int d\phi dx_0 dy_0 \omega(x_0, y_0)$$

$$\times \int d\zeta P(x_0, y_0, \phi, \zeta) \frac{1}{1 - \zeta} D^{(vac)}_{k \to h} \left( \frac{z}{1 - \zeta}, \mu^2_F \right)$$

where $N = 2\pi \int dx_0 dy_0 \omega(x_0, y_0)$. 
$R_{AA}$ at $\sqrt{s_{NN}} = 200$ GeV for different centralities
$R_{AA}$ at $\sqrt{s_{NN}} = 2.76$ TeV for different centralities

$\chi^2$ to the best value of $K$. $\Delta \chi^2 = 1.$
**K-factor vs. impact parameter**

Energy density constant before thermalization.

Free-streaming case.

\[ \hat{q}(\xi) = 0 \text{ before thermalization.} \]

\[ K \text{ depends mainly on the energy and it is almost independent of the centrality of the collision!!} \]
$K$-factor vs. $\epsilon\tau_0$ for $\hat{q}$ constant before thermalization

Difficult to reconcile the energy and centrality dependence!! A new puzzle??

$R_{AA}$ predictions for $\sqrt{s_{NN}} = 5.02$ TeV

Using $K_{5.02} = K_{2.76}$

If $R_{AA}^{2.76} = R_{AA}^{5.02} \Rightarrow K_{5.02} \sim 0.85K_{2.76}$

Glauber, $K=1.133 \pm 0.028$

fKLN, $K=1.088 \pm 0.028$

Same K values as $\sqrt{s_{NN}} = 2.76$ TeV
Nuclear modification factors $R_{AA}$ for single-inclusive and $I_{AA}$ for hadron-triggered fragmentation functions for different values of $2K = K'/0.73$, with $K' = 0.5, 1, 2, 3, \ldots, 20$. The green line in the curve corresponding to the minimum of the common fit to $R_{AA}$ and $I_{AA}$ is $K = 4.1$.6
Left: $\chi^2$-values for different values of K for light hadrons and for the three different extrapolations for $\xi < \tau_0$. Red lines correspond to single-inclusive $\pi_0$ data from PHENIX ($R_{AA}$) and black ones to the double-inclusive measurements by STAR ($I_{AA}$).

Right: the corresponding central values (minima of the $\chi^2$) and the uncertainties computed by considering $\Delta \chi^2 = 1$. 

Case i): $\hat{q}(\tau) = 0$ for $\tau < \tau_0$

Case ii): $\hat{q}(\tau) = \hat{q}(\tau_0)$ for $\tau < \tau_0$

Case iii): $\hat{q}(\tau) = \frac{\hat{q}(\tau_0)}{\tau^{3/4}}$ for $\tau < \tau_0$
Hydrodynamic medium modelling

- We use several hydrodynamic simulations:
  - “Hirano”: no viscous, optical Glauber model, $\tau_0 = 0.6$ fm.
  - “Glauber”: viscous $\eta/s=0.08$, energy density proportional to $\rho_{bin}$ as initial condition, $\tau_0 = 1$ fm.
  - “fKLN”: viscous $\eta/s=0.16$, factorised Kharzeev-Levin-Nardi model, $\tau_0 = 1$ fm.

- Uncertainty coming from the hydrodynamic background is negligible with respect to our conclusions.

- Ambiguity before thermalization. 3 extrapolations:
  - Case i): $\hat{q}(\xi) = 0$ for $\xi < \tau_0$.
  - Case ii): $\hat{q}(\xi) = \hat{q}(\tau_0)$ for $\xi < \tau_0$.
  - Case iii): $\hat{q}(\xi) = \hat{q}(\tau_0)/\xi^{3/4}$ for $\xi < \tau_0$. 
Scaled transverse momentum distributions

Tetsufumi Hirano, arXiv: nucl-th/0108004

FIG. 3. Scaled transverse momentum distribution of negative pions and anti-protons in Au+Au 130 A GeV central and semi-central collisions. Solid lines and dashed lines correspond to initial conditions A and B, respectively. Experimental data are observed by the PHENIX Collaboration.
$v_2$ for charged pions

Tetsufumi Hirano and Keiichi Tsuda, arXiv:nucl-th/0205043

FIG. 12: $v_2(p_t)$ for charged pions. The solid, dotted, and dashed lines correspond to total pions, pions directly emitted from freeze-out hypersurface, and pions from resonance decays. Data from Ref. [56].
Multiplicty at RHIC


FIG. 7: (Color online) Centrality dependence of total multiplicity $dN/dY$ and $<p_T>$ for $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ from PHENIX [84] for Au+Au collisions at $\sqrt{s} = 200$ GeV, compared to the viscous hydrodynamic model and various $\eta/s$, for Glauber initial conditions and CGC initial conditions. The model parameters used here are $\tau_0 = 1$ fm/$c$, $\tau_H = 6\eta/s$, $\lambda_1 = 0$, $T_f = 140$ MeV and adjusted $T_i$ (see Table I).
$\nu_2$ at RHIC

\( v_2 \) at LHC


FIG. 2: (Color online) Anisotropy (3) prediction for \( \sqrt{s} = 5.5 \) TeV Pb+Pb collisions (LHC), as a function of centrality. Prediction is based on values of \( \eta/s \) for the Glauber/CGC model that matched \( \sqrt{s} = 200 \) GeV Au+Au collision data from PHOBOS at RHIC ([31], shown for comparison). The shaded band corresponds to the estimated uncertainty in our prediction from additional systematic effects: using \( e_p/2 \) rather than \( v_2 \) (5%) [1]; using a lattice EoS from [29] rather than [27] (5%); not including hadronic cascade afterburner (5%) [38].
In the case of 'Hirano’s ideal hydro', the values of the temperature at \( \tau=0.6 \) fm and \( x=y=\eta=0 \) for RHIC and LHC are:

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>RHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>00-05%</td>
<td>484.3 MeV</td>
<td>373.2 MeV</td>
</tr>
<tr>
<td>05-10%</td>
<td>476.6 MeV</td>
<td>369.6 MeV</td>
</tr>
<tr>
<td>10-20%</td>
<td>463.6 MeV</td>
<td>356.8 MeV</td>
</tr>
<tr>
<td>20-30%</td>
<td>444.6 MeV</td>
<td>341.1 MeV</td>
</tr>
<tr>
<td>30-40%</td>
<td>421.5 MeV</td>
<td>323.7 MeV</td>
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<tr>
<td>40-50%</td>
<td>393.6 MeV</td>
<td></td>
</tr>
<tr>
<td>50-60%</td>
<td>359.6 MeV</td>
<td></td>
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</tbody>
</table>
'Matt’s viscous hydro for two different initial conditions and \( \eta/s \). Initial temperatures at \( x=y=0, \tau=1 \) fm:

**Glauber:**
- \( b=2 \) fm LHC: 418 MeV
- \( b=12 \) fm LHC: 272 MeV
- \( b=2 \) fm RHIC: 331 MeV

**fKLN:**
- \( b=2 \) fm LHC: 389 MeV
- \( b=12 \) fm LHC: 296 MeV
- \( b=2 \) fm RHIC: 299 MeV
\( \hat{q} \sim T^3 \sim \epsilon^{3/4} \) both for hadronic and partonic phase


Figure 3. Transport coefficient as a function of energy density for different media: cold, massless hot pion gas (dotted) and (ideal) QGP (solid curve)
$K$ versus initial temperature

\[ K = \frac{\hat{q}}{2\epsilon^{3/4}} \]

\[ \hat{q}(\tau) = \hat{q}(\tau_0), \; \tau < \tau_0 \]

- Hirano RHIC
- fKLN RHIC
- Glauber RHIC
- Hirano LHC
- fKLN LHC
- Glauber LHC
$K$ versus initial energy

\[ K = \frac{\hat{q}}{2\epsilon^{3/4}} \]

\[ \hat{q}(\tau) = \hat{q}(\tau_0), \quad \tau < \tau_0 \]

Hirano RHIC
fKLN RHIC
Glauber RHIC
Hirano LHC
fKLN LHC
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