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

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Introduction

- Study of suppression of high-$p_T$ particles in \textbf{PbPb} collisions at the LHC and \textbf{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 \textbf{EKRT event-by-event} description of the medium.

- Study done for \textbf{different centrality classes}. 
Single inclusive cross section

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

\[ P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[ \prod_{i=1}^{n} \int d\omega_i \frac{dI^{(med)}(\omega_i)}{d\omega} \right] \times \delta \left( \Delta E - \sum_{i=1}^{n} \omega_i \right) \exp \left[ - \int_0^{\infty} d\omega \frac{dI^{(med)}}{d\omega} \right] \]

- **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 $\tau_{\text{form}} = \sqrt{\omega / \hat{q}} \ll L$.

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

  J. P. Blaizot, F. Dominguez, E. Iancu and Y. Mehtar-Tani, JHEP 1301 (2013) 143.

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

  S. Turbide, C. Gale, S. Jeon and G. D. Moore, Phys. Rev. C 72 (2005) 014906.
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…

Eur. Phys. J. C (2016) 76, 475

- 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 $\xi < \tau_0$. 

\[ \hat{q}(\xi) = \hat{q}(\tau_0) \text{ for } \xi < \tau_0. \]
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 of Au-Au collisions at 200 GeV.](image-url)
$R_{AA}$ 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

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

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

RHIC 200 GeV

LHC 2.76 TeV

$K$ depends mainly on the energy and it is almost independent of the centrality of the collision!!
**Introduction**

Energy loss implementation

**Hydrodynamic modelling of the medium**

**Results**

**Limitations and conclusions**

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**$K$-factor vs. $\epsilon\tau_0$**

![Graph showing $K = \frac{\hat{q}}{2\epsilon^{3/4}}$ vs. $\epsilon\tau_0$](image)

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

Estimates taken from: arXiv:1509.06727 [nucl.ex] PHENIX Collaboration and arXiv:1603.04775 [nucl.ex] ALICE collaboration.

**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!!
Backup
The inclusive energy distribution of gluon radiation off an in-medium produced parton is given by

\[ \omega \frac{dI^{(med)}}{d\omega} = \frac{\alpha_s C_R}{(2\pi)^2 \omega^2} 2 \text{Re} \int_0^\infty dy_l \int_0^\infty d\bar{y}_l \int d\mathbf{u} \int d\mathbf{k}_\perp \chi \omega \times e^{-i \mathbf{k}_\perp \cdot \mathbf{u}} e^{-\frac{1}{2} \int_0^\infty d\xi n(\xi) \sigma(\mathbf{u})} \frac{\partial}{\partial y_l} \cdot \frac{\partial}{\partial u} \int_{y=0}^{\bar{y}_l} D\mathbf{r} \times \exp \left[ i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2} \left( \dot{\mathbf{r}}^2 - \frac{n(\xi) \sigma(\mathbf{r})}{i\omega} \right) \right] \]

- \( n(\xi) \), 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

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

\[ \langle D_{k \rightarrow h}^{(med)}(z, \mu_F^2) \rangle = \frac{1}{N} \int d\phi dx_0 dy_0 \omega(x_0, y_0) \]

\[ \times \int d\zeta P(x_0, y_0, \phi, \zeta) \frac{1}{1 - \zeta} D_{k \rightarrow h}^{(vac)} \left( \frac{z}{1 - \zeta}, \mu_F^2 \right) \]

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.

$K$ 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

Estimates taken from: arXiv:1509.06727 [nucl.ex] PHENIX Collaboration and arXiv:1603.04775 [nucl.ex] ALICE collaboration.

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 $R_{AA}^{2.76} = R_{AA}^{5.02} \Rightarrow K_{5.02} \sim 0.85K_{2.76}$
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 $K' = 0.5, 1, 2, 3, ..., 20$. The green line in the curve corresponding to the minimum of the common fit to $R_{AA}$ and $I_{AA}$ data:

$K' = 4.1$. 

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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 $\Delta \chi^2 = 1$. 
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 $\xi < \tau_0$. 
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].
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).
\( v_2 \) at RHIC

Matthew Luzum and Paul Romatschke, arXiv:0804.4015 [nucl-th]
$v_2$ at LHC

Matthew Luzum and Paul Romatschke, arXiv:0901.4588 [nucl-th]

**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:

|    | LHC            | RHIC           |
|----|----------------|----------------|
| 00-05%: | 484.3 MeV      | 373.2 MeV      |
| 05-10%: | 476.6 MeV      | 369.6 MeV      |
| 10-20%: | 463.6 MeV      | 356.8 MeV      |
| 20-30%: | 444.6 MeV      | 341.1 MeV      |
| 30-40%: | 421.5 MeV      | 323.7 MeV      |
| 40-50%: | 393.6 MeV      |                |
| 50-60%: | 359.6 MeV      |                |
Initial temperatures for Matt’s hydros

'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

arXiv:hep-ph/0209038, R. Baier.

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

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

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

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

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

Hirano RHIC
fKLN RHIC
Glauber RHIC
Hirano LHC
fKLN LHC
Glauber LHC

$\epsilon_0$ (GeV/fm$^3$)