

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

Introduction

- Study of suppression of high- p_T particles in **PbPb** collisions at the LHC and **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 **EKRT event-by-event** description of the medium.
- Study done for **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.

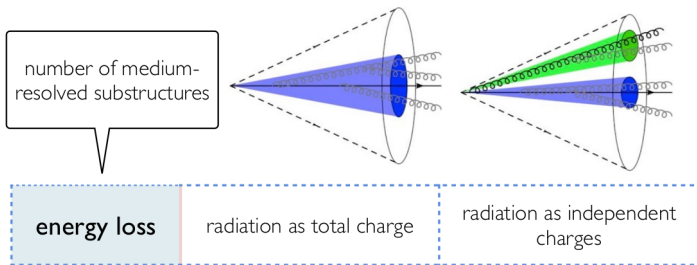
Quenching Weights

- 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



KT HP2016

- **Totally coherent case:**
 - Vacuum-like fragmentations.
 - Jets losing 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 $\tau_{form} = \sqrt{\omega/\hat{q}} \ll L$.
- 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: $\sigma(\mathbf{r})n(\xi)$.
- In the multiple soft scattering approximation we use

$$\sigma(\mathbf{r})n(\xi) \simeq \frac{1}{2}\hat{q}(\xi)\mathbf{r}^2$$

- **Perturbative tails neglected.**
- We specify the relation between $\hat{q}(\xi)$ and the medium properties given by our hydrodynamic model as

$$\hat{q}(\xi) = K\hat{q}_{QGP}(\xi) \simeq K \cdot 2\epsilon^{3/4}(\xi)$$

- 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 ρ_{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 $\xi < \tau_0$.

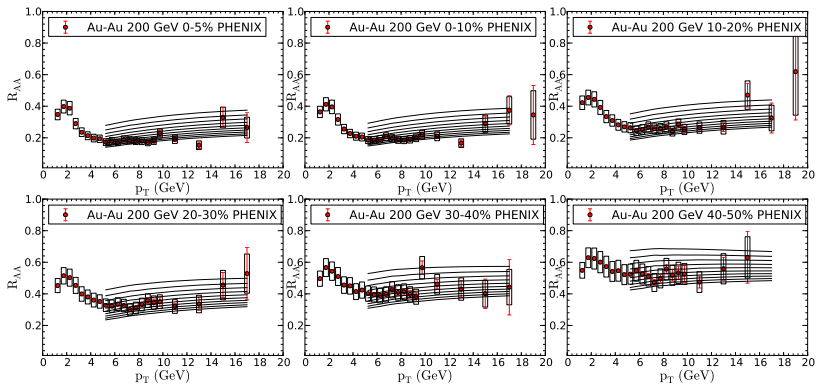
Nuclear modification factor

- We use R_{AA} experimental data:

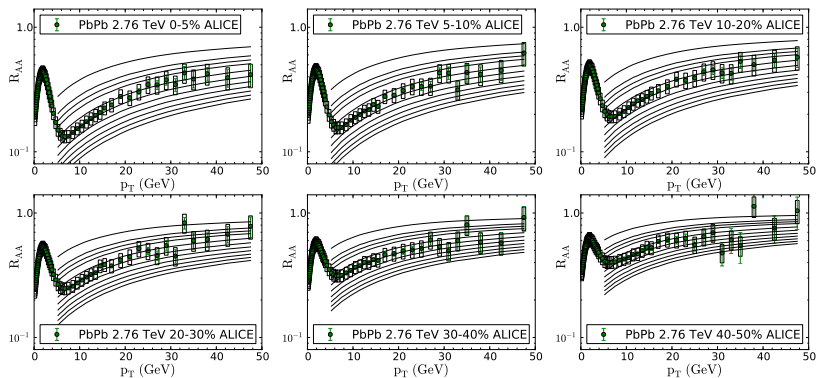
$$R_{AA} = \frac{dN_{AA}/d^2p_T dy}{\langle N_{coll} \rangle dN_{pp}/dp_T^2 dy}$$

- 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 π_0 R_{AA} $p_T > 5$ GeV, arXiv:0801.4020 [nucl-ex].

R_{AA} at $\sqrt{s_{NN}} = 200$ GeV for different centralities

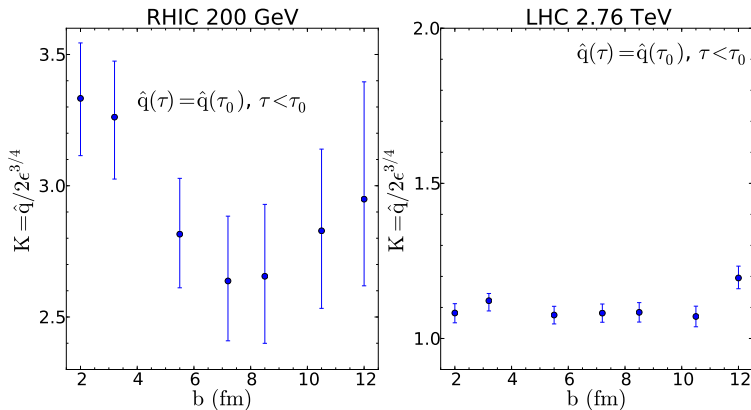


R_{AA} at $\sqrt{s_{NN}} = 2.76$ TeV for different centralities



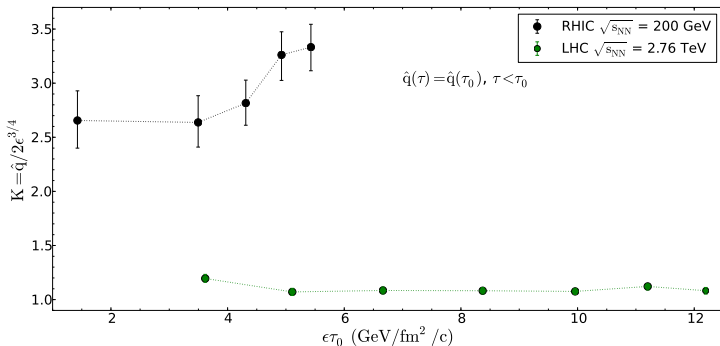
χ^2 to the best value of K . $\Delta\chi^2 = 1$.

K-factor vs. impact parameter



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

K-factor vs. $\epsilon\tau_0$



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??

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

Multiple soft scattering approximation for a static medium

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

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

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

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

- $n(\xi)$, density of scattering centers.
- $\sigma(\mathbf{r})$, strength of a single elastic scattering.

- The production weight is given by

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

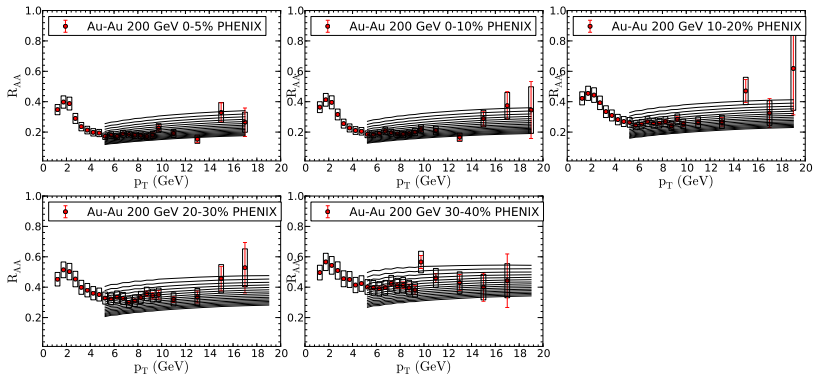
- The average values of an observable and in particular of our fragmentation functions is computed as

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

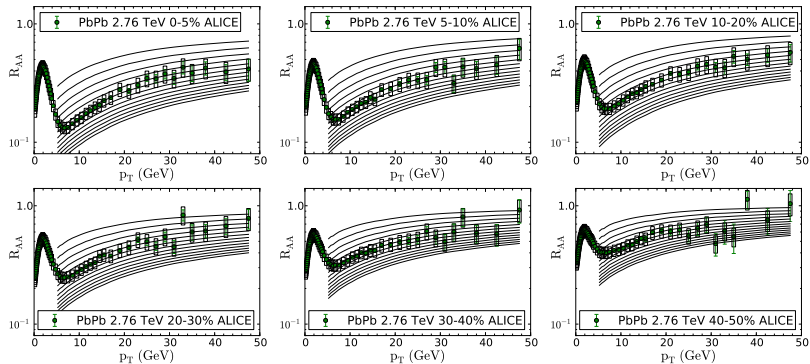
$$\begin{aligned} \langle D_{k \rightarrow h}^{(med)}(z, \mu_F^2) \rangle &= \frac{1}{N} \int d\phi dx_0 dy_0 \omega(x_0, y_0) \\ &\times \int d\zeta P(x_0, y_0, \phi, \zeta) \frac{1}{1-\zeta} D_{k \rightarrow h}^{(vac)}\left(\frac{z}{1-\zeta}, \mu_F^2\right) \end{aligned}$$

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

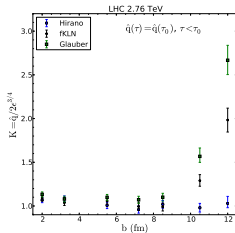
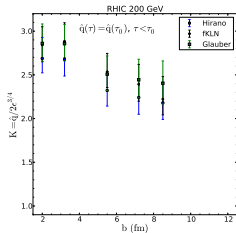


R_{AA} at $\sqrt{s_{NN}} = 2.76$ TeV for different centralities

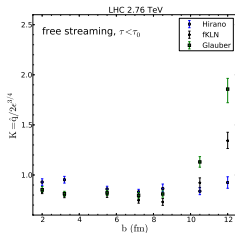
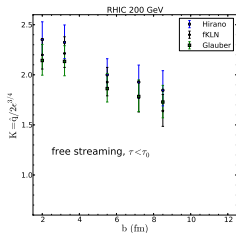


χ^2 to the best value of K . $\Delta\chi^2 = 1$.

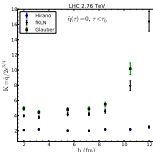
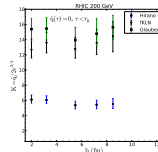
K-factor vs. impact parameter



Energy density constant before thermalization.



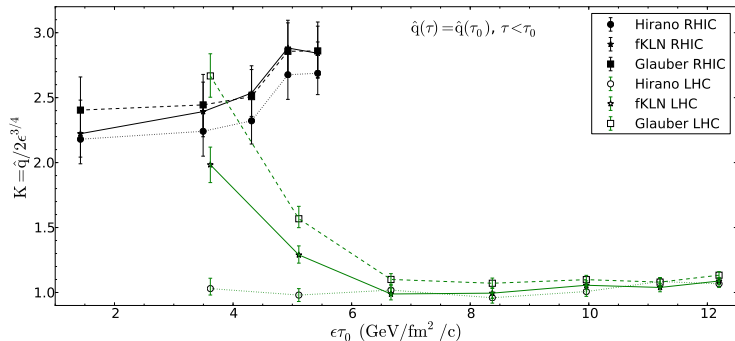
Free-streaming case.



$\hat{q}(\xi) = 0$ before thermalization.

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

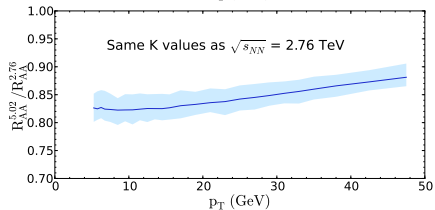
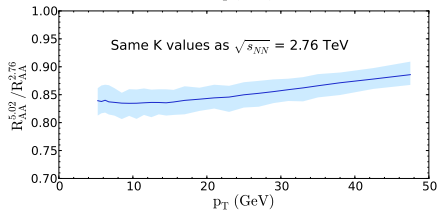
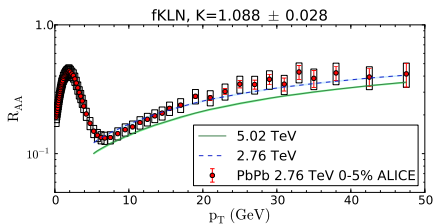
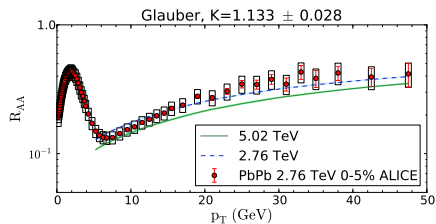


Estimates taken from: arXiv:1509.06727 [nucl.ex] PHENIX Collaboration and arXiv:1603.04775 [nucl.ex] ALICE collaboration.

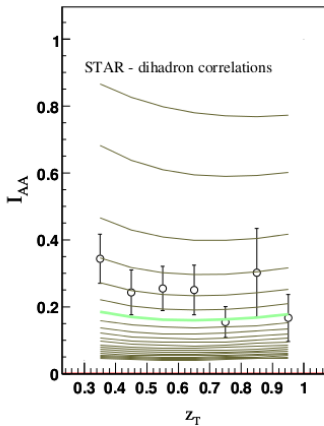
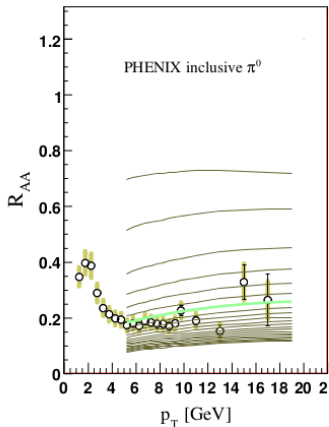
Difficult to reconcile the energy and centrality dependence!! A new puzzle??

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

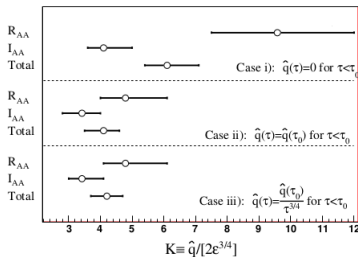
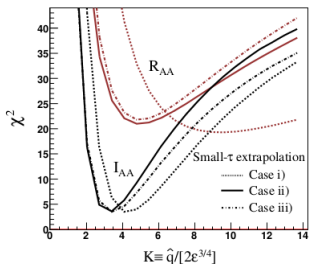
Using $K_{5.02} = K_{2.76}$
If $R_{AA}^{2.76} = R_{AA}^{5.02} \Rightarrow K_{5.02} \sim 0.85 K_{2.76}$



RHIC results



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 $K' = 0.5, 1, 2, 3, \dots, 20$. The green line in the curve corresponding to the minimum of the common fit to R_{AA} / 16



Left: χ^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 π_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 χ^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 ρ_{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

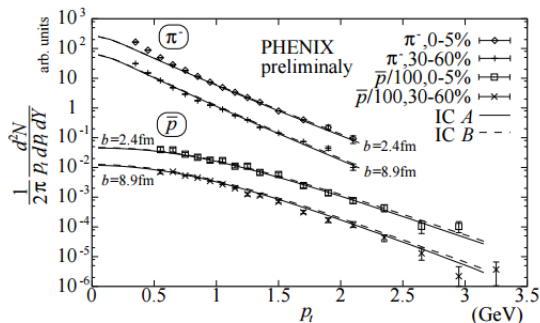


FIG. 3. Scaled transverse momentum distribution of negative pions and anti-protons in Au+Au 130 A GeV central and semi-central collisions. Solid lines and dashed lines correspond to initial conditions A and B, respectively. Experimental data are observed by the PHENIX Collaboration.

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

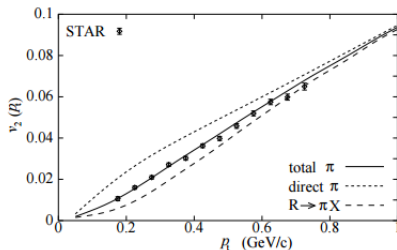


FIG. 12: $v_2(p_t)$ for charged pions. The solid, dotted, and dashed lines correspond to total pions, pions directly emitted from freeze-out hypersurface, and pions from resonance decays. Data from Ref. [56].

Multiplicity at RHIC

Matthew Luzum and Paul Romatschke, arXiv:0804.4015 [nucl-th]

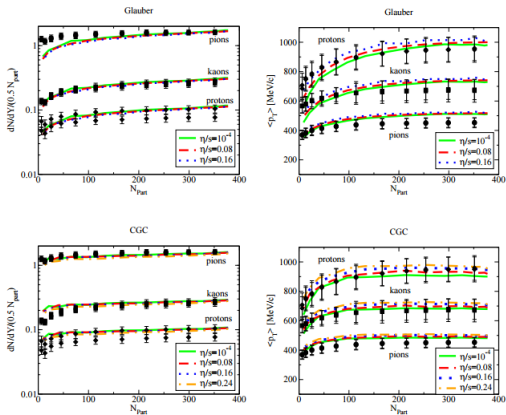
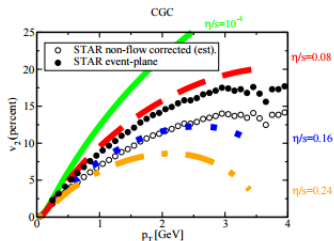
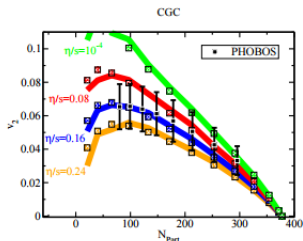
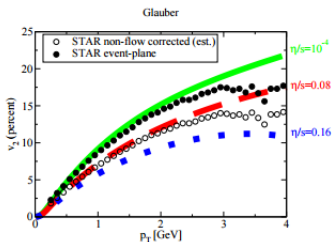
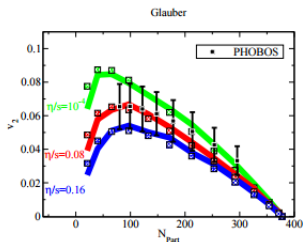


FIG. 7: (Color online) Centrality dependence of total multiplicity dN/dY and $\langle p_T \rangle$ for π^+ , π^- , K^+ , K^- , p and \bar{p} from PHENIX [84] for Au+Au collisions at $\sqrt{s} = 200$ GeV, compared to the viscous hydrodynamic model and various η/s , for Glauber initial conditions and CGC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

Matthew Luzum and Paul Romatschke, arXiv:0804.4015 [nucl-th]



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

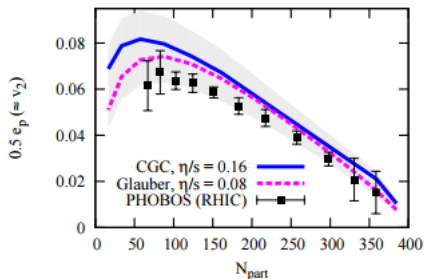


FIG. 2: (Color online) Anisotropy (3) prediction for $\sqrt{s} = 5.5$ TeV Pb+Pb collisions (LHC), as a function of centrality. Prediction is based on values of η/s for the Glauber/CGC model that matched $\sqrt{s} = 200$ GeV Au+Au collision data from PHOBOS at RHIC ([31], shown for comparison). The shaded 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]

Initial temperatures for Hirano's hydro

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 | 00-05%: 373.2 MeV |
| 05-10%: 476.6 MeV | 00-10%: 369.6 MeV |
| 10-20%: 463.6 MeV | 10-20%: 356.8 MeV |
| 20-30%: 444.6 MeV | 20-30%: 341.1 MeV |
| 30-40%: 421.5 MeV | 30-40%: 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 η/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.

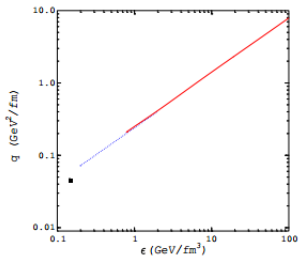
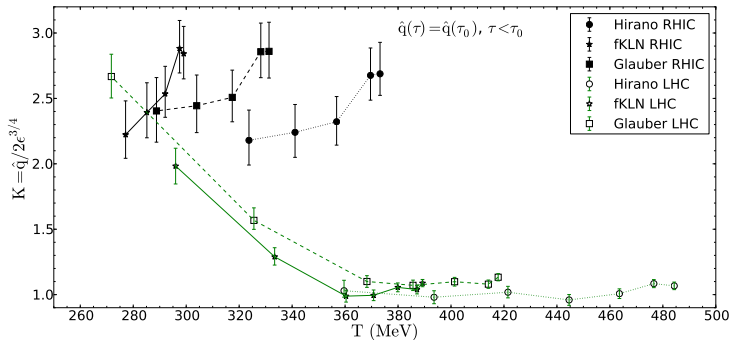


Figure 3. Transport coefficient as a function of energy density for different media: cold, massless hot pion gas (dotted) and (ideal) QGP (solid curve)

K versus initial temperature



K versus initial energy

