Extracting $\hat{q}$ from single inclusive data at RHIC and at the LHC for different centralities: a new puzzle?

Carlota Andrés

Universidade de Santiago de Compostela

4th Heavy-Ion Jet Workshop, École Polytechnique, Paris

N. Armesto, Carlos A. Salgado, Matthew Luzum and Pia Zurita
arXiv:1606.04837 [hep-ph]

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

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Outline

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 **different hydrodynamical** descriptions of the medium.
- Study done for **different centrality clases**.
- **First study** of centrality and energy dependence of R_{AA}.

Single inclusive cross section

- The production of a hadron h at transverse momentum p_T and rapidity y can be described by

$$\frac{d\sigma^{AA\to h+X}}{dp_T dy} = \int \frac{dx_2}{x_2}\frac{dz}{z}\sum_{i,j} x_1 f_{i/A}(x_1, Q^2) x_2 f_{j/A}(x_2, Q^2) \times \frac{d\hat{\sigma}^{ij\to k}}{d\hat{t}} D_{k\to h}(z, \mu_F^2)$$

- We use CTEQ6M (NLO) free proton parton densities.
- We take the factorization scale as $Q^2 = (p_T/z)^2$ and the fragmentation scale as $\mu_F = p_T$.
- We absorb **energy loss** in a redefinition of the fragmentation functions:

$$D^{(med)}_{k\to h}(z, \mu_F^2) = \int_0^1 d\epsilon P_E(\epsilon) \frac{1}{1-\epsilon} D^{(vac)}_{k\to h}\left(\frac{z}{1-\epsilon}, \mu_F^2\right)$$

where $P_E(\epsilon)$ is the **Quenching Weight** and the vacuum fragmentation function, $D^{(vac)}_{k \to h}(z, \mu_F^2)$, is taken from *Florian, Sassot and Stratmann*.

- FF are **not** modified by medium-induced gluon radiation through QW **coherently**.
- Jet loses energy as a whole.
- nPDF are taken from the EPS09 (NLO) analysis.

Quenching Weights

- The probabilility distribution of a fractional energy loss, $\epsilon = \Delta E/E$, quenching weight, of the parton in the medium is 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 has been assumed.
- QW are Poisson distributions.
- Support in recent works:
  - Coherence: arXiv:1209.4585 [hep-ph] J.P. Blaizot, F. Dominguez, E. Iancu and Y. Mehtar-Tani.
  - Ressumation: arXiv:1209.4585 [hep-ph], arXiv:1311.5823 [hep-ph], J.P. Blaizot, F. Dominguez, E. Iancu and Y. Mehtar-Tani.

Multiple soft scattering approximation for a static medium

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

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

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

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

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

- In the multiple soft scattering approximation we use

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

with $\hat{q} = \frac{\langle q_\perp^2 \rangle_{med}}{\lambda}$ for a static medium. **Perturbative tails neglected.**
- This is the definition of $\hat{q}$.
- All the information about the medium is contained in two quantities: $\hat{q}$ and L or ω_c and R.
- For a static medium: $\omega_c = \frac{1}{2}\hat{q}L^2$ and $R = \omega_c L$.
- In a dynamic medium we use a scaling law which relates the energy distribution in a collision of arbitrary dynamical expansion to an equivalent static scenario.
- We make use of the following scaling relations:

$$\omega_c^{eff}(x_0, y_0, \tau_{prod}, \phi) = \int d\xi \xi \hat{q}(\xi),$$

$$R^{eff}(x_0, y_0, \tau_{prod}, \phi) = \frac{3}{2}\int d\xi \xi^2 \hat{q}(\xi),$$

- 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**

- 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

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

$$\langle D^{(med)}_{k\to h}(z, \mu_F^2) \rangle = \frac{1}{N} \int d\phi dx_0 dy_0 \omega(x_0, y_0) \times \int d\zeta P(x_0, y_0, \phi, \zeta) \frac{1}{1-\zeta} D^{(vac)}_{k\to h}\left(\frac{z}{1-\zeta}, \mu_F^2\right)$$

where $N = 2\pi \int dx_0 dy_0 \omega(x_0, y_0)$.

Hydrodinamic medium modelling

- Energy density obtained by solving the relativistic hydrodynamic equations.
- We use several hydrodynamic simulations:
  - "Hirano": no viscous, optical Glauber model, $\tau_0 = 0.6$ fm.
  - "Glauber": viscous η/s=0.08, energy density proportinal to ρ_{bin} as initial condition, $\tau_0 = 1$ fm.
  - "fKLN": viscous η/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.

Energy loss for times prior to hydrodynamic behavior

- Ambiguity on the value of the transport coefficient for values smaller than the thermalization time τ_0.
- We use three 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 $\xi < \tau_0$

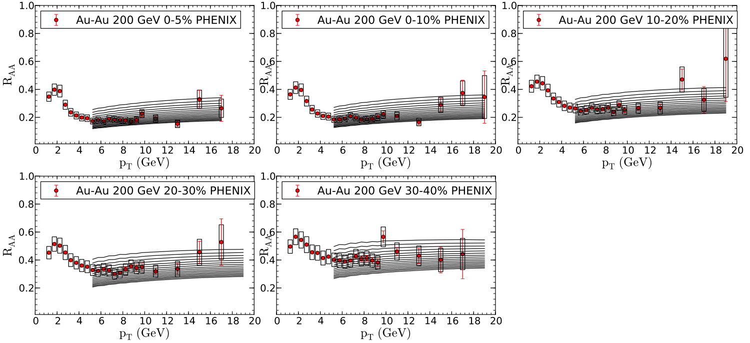
Nuclear modification factor

- The experimental data used in our analysis are given in terms of the nuclear modification factor for single measurements

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

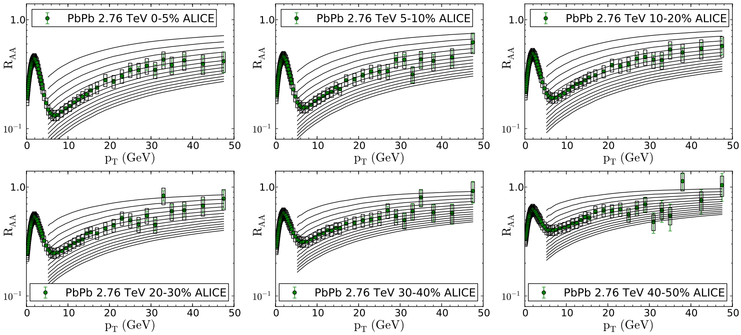
- Experimental data is: Pb-Pb collisions at LHC energy $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and Au-Au at RHIC energy $\sqrt{s_{\mathrm{NN}}} = 200$ GeV.
- ALICE data on R_{AA} for charged particles with $p_T > 5$ GeV in different centrality classes and for $|\eta| < 0.8$, arXiv:1208.2711 [hep-ex].
- PHENIX data on π_0 R_{AA} $p_T > 5$ GeV, arXiv:0801.4020 [nucl-ex].
- Results for different values of $K = K'/1.46$, where $K = \hat{q}/2\epsilon^{3/4}$.

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



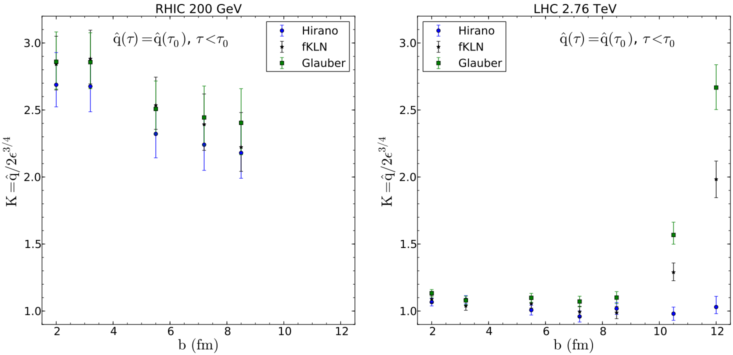
Suppression of inclusive π^0 in AuAu collisions at $\sqrt{s_{\rm NN}} = 200$ GeV for different values of K compared with PHENIX data at different centralities. Curves from top to bottom correspond to $K = K'/1.46$, with $K' = 2, 2.25, 2.5, \ldots, 6$, using the "Hirano" model and $\hat{q}$ constant before thermalization.

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



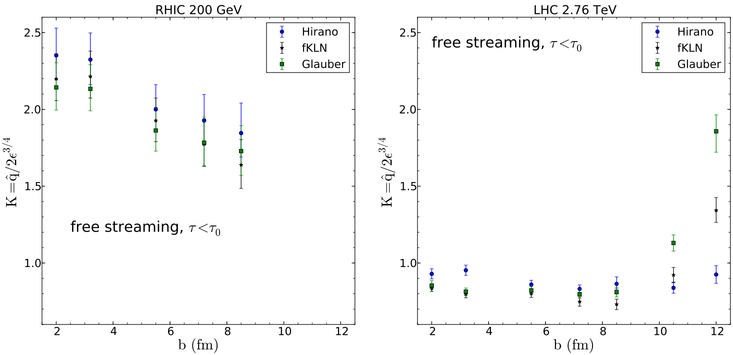
R_{AA} in PbPb collisions at $\sqrt{s_{NN}}$ =2.76 TeV for different values of K compared to ALICE data at different centralities. Curves from top to bottom correspond to $K = K'/1.46$, with $K' = 0.5, 0.7, 0.9, \ldots, 3.1$, using the "Hirano" model and $\hat{q}$ constant before thermalization.

K-factor vs. b for $\hat{q}$ constant before thermalization



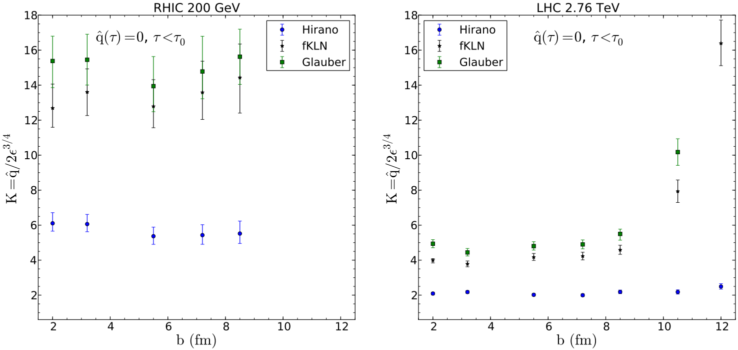
K-factors obtained from fits to PHENIX $R_{\rm AA}$ data *(left panel)* and to ALICE $R_{\rm AA}$ data*(right panel)* using different hydrodynamic profiles versus the average impact parameter for each centrality class and the energy density constant before thermalization.

K-factor vs. b for the free-streaming extrapolation



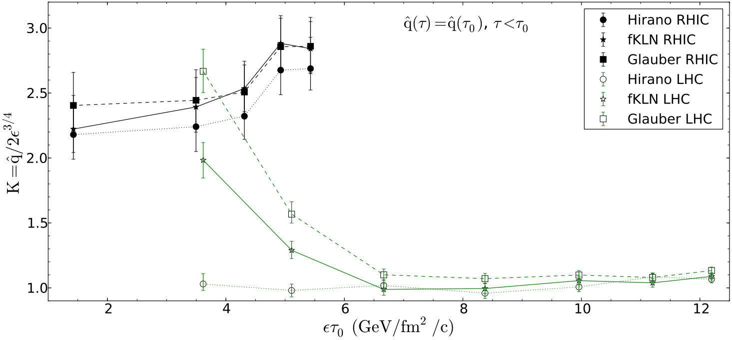
K-factors obtained from fits to PHENIX R_{AA} data *(left panel)* and to ALICE R_{AA} data *(right panel)* using different hydrodynamic profiles as a function of the average impact parameter for each centrality class and for the free-streaming case.

K-factor vs. b for $\hat{q}(\xi) = 0$ before thermalization



K-factors obtained from fits to PHENIX $R_{\rm AA}$ data *(left panel)* and to ALICE $R_{\rm AA}$ data *(right panel)* using different hydrodynamical profiles versus the average impact parameter for each centrality class and for $\hat{q}(\xi) = 0$ before thermalization.

K-factor vs. $\epsilon\tau_0$ for $\hat{q}$ constant before thermalization



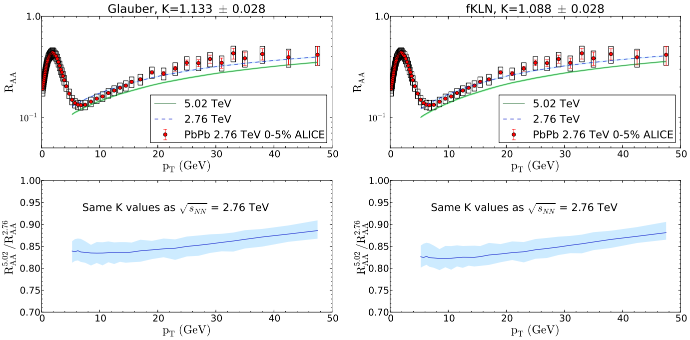
K-factor obtained from fits to R_{AA} data at RHIC and LHC energies for different centrality classes plotted as a function of an estimate of the energy density times formation time τ_0 of the QCD medium formed in each case.

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

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

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

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



Top: Curves for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ (dashed blue) and 5.02 (solid green) TeV and the 0-5% centrality class using "Glauber" and "fKLN" hydrodynamic evolution and $\hat{q}$ constant before thermalization. Bottom: Ratios of the corresponding curves for 5.02 TeV w.r.t. 2.76 TeV.

Limitations

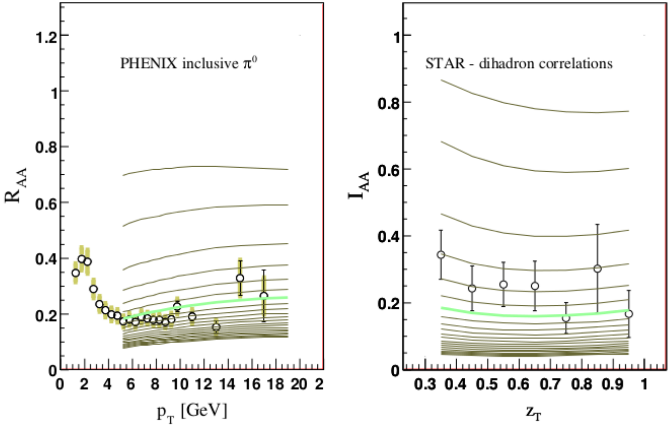
- The definition of $\hat{q}$ neglects the **perturbative tails** of the distributions.
- The QW find support in the **coherence** analysis of the medium: if coherence is broken they could fail.
- Scaling relations have been only proved for $\hat{q}(\tau) \propto 1/\tau^{\alpha}$.
- Finite lenght corrections.
- Finite energy corrections.
- $\hat{q}$ energy or length independent.
- *Collisional energy loss* is neglected.

Conclusions

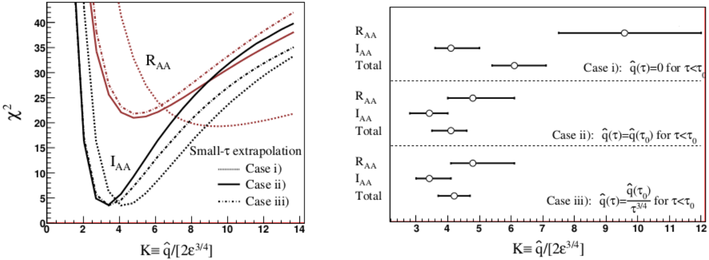
- We fit the single-inclusive experimental data at RHIC and LHC for different centralities.
- The fitted value at RHIC confirms large corrections to the ideal case.
- For the case of the **LHC**, the extracted value of K is close to **unity**.
- K-factor is $\sim 2-3$ times larger for RHIC than at the 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

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



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 $\Delta\chi^2 = 1$.

Tetsufumi Hirano, arXiv: nucl-th/0108004

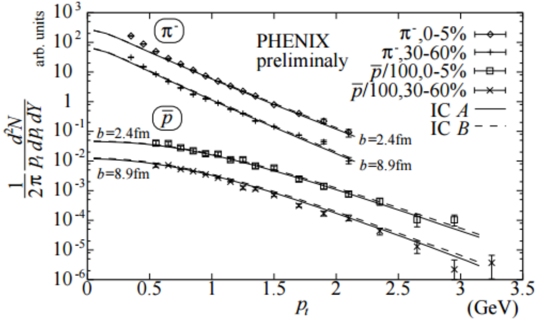


FIG. 3. Scaled transverse momentum distribution of negative pions and anti-protons in Au+Au 130 A GeV central and semi-central collisions. Solid lines and dashed lines correspond to initial conditions A and B, respectively. Experimental data are observed by the PHENIX Collaboration.

v_2 for charged pions

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

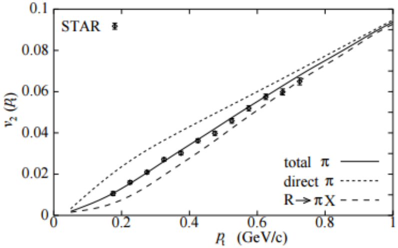


FIG. 12: $v_2(p_t)$ for charged pions. The solid, dotted, and dashed lines correspond to total pions, pions directly emitted from freeze-out hypersurface, and pions from resonance decays. Data from Ref. [56].

Multiplicity at RHIC

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

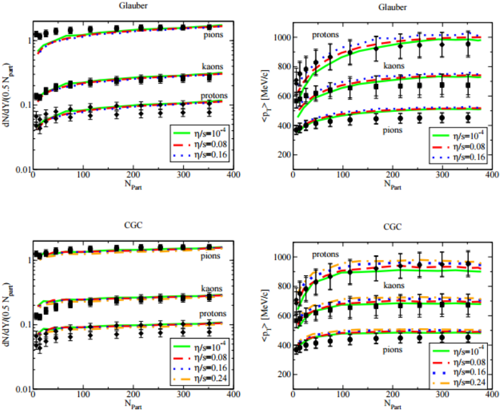
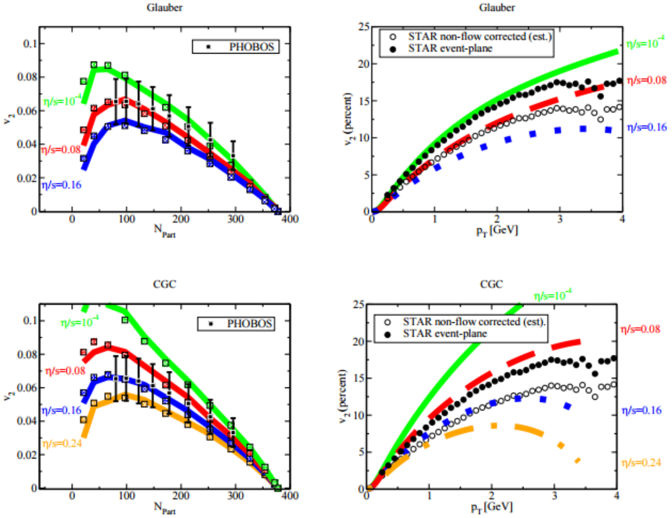


FIG. 7: (Color online) Centrality dependence of total multiplicity dN/dY and $< p_T >$ for $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ from PHENIX [84] for Au+Au collisions at $\sqrt{s} = 200$ GeV, compared to the viscous hydrodynamic model and various η/s, for Glauber initial conditions and CGC initial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

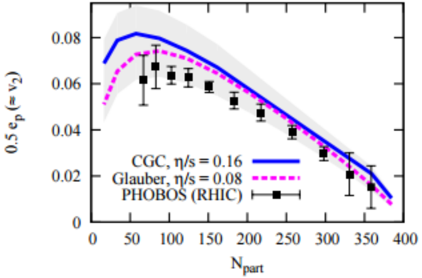


FIG. 2: (Color online) Anisotropy (3) prediction for $\sqrt{s} = 5.5$ TeV Pb+Pb collisions (LHC), as a function of centrality. Prediction is based on values of η/s for the Glauber/CGC model that matched $\sqrt{s} = 200$ GeV Au+Au collision data from PHOBOS at RHIC ([31], shown for comparison). The shaded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

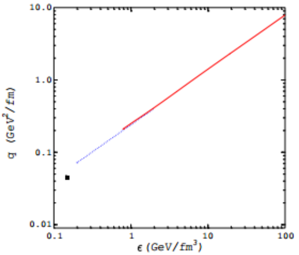
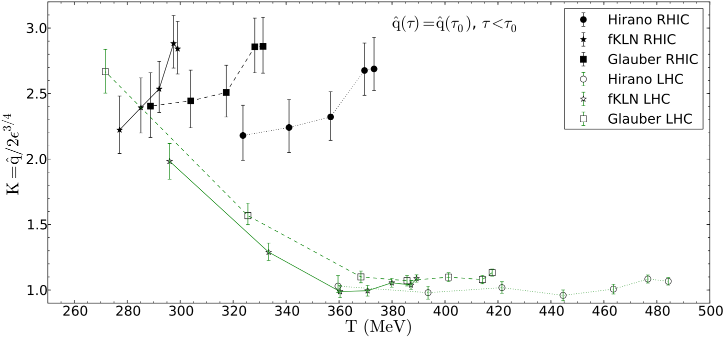


Figure 3. Transport coefficient as a function of energy density for different media: cold, massless hot pion gas (dotted) and (ideal) QGP (solid curve)

K versus intial temperature



K versus intial energy