Modeling jet quenching with Quenching Weights

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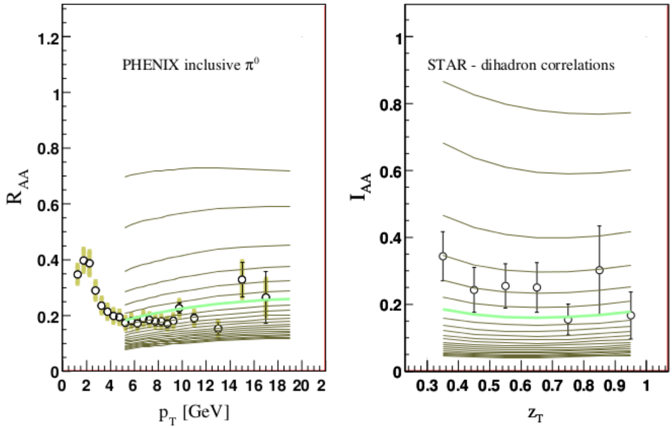
Outline

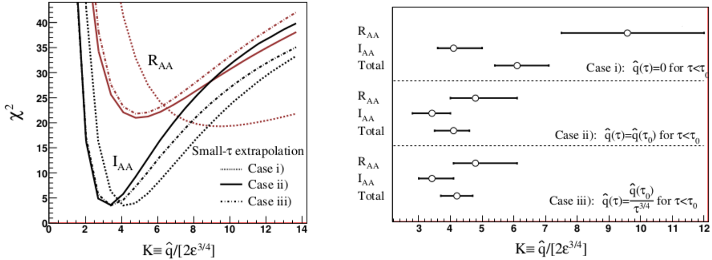
Introduction

- Study of suppression of high-p_T particles in central PbPb collisions at LHC.
- Analysis based on the quenching weights (QW) for medium-induced gluon radiation.
- QW computed in multiple soft scattering approximation.
- Embedded in a hydrodynamical description of the medium.
- This analysis has already been done for RHIC: arXiv:0907.0067[hep-ph] (N. Armesto, M. Cacciari, T. Hirano, James L. Nagle and Carlos A. Salgado.
- We will try to compare the information obtained for RHIC and for LHC.

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 $K' = 0.5, 1, 2, 3, ..., 20$. The green line in the curve corresponding to the minimum of the common fit to R_{AA} and I_{AA} data: **K =4.1**.



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 $\Delta\chi^2 = 1$.

Hydrodynamical medium modeling

- In relativistic heavy-ion collisions, the medium evolves dynamically.
- 3D ideal hydrodynamics is used to describe this evolution.
- Using the results of *Tetsufumi Hirano et al.* for

$$\partial_\mu T^{\mu\nu} = 0$$

  in (τ, x, y, η_s) with $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$ and with thermal equilibrium time $\tau_0 = 0.6\text{fm/c}$. Initial conditions are: $u_x(\tau_0) = u_y(\tau_0) = u_{\eta_s}(\tau_0) = 0$.
- For the Quark-Gluón-Plasma (QGP) phase we use the EOS

$$p = \frac{1}{3}(\epsilon - 4B)$$

  with $B^{\frac{1}{4}} = 247$ MeV.
- These hydrodynamical solutions will be used to constraint the transport coefficient $\hat{q}$.

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 CTEQ6L (LO) free proton parton densities.
- We take the factorization scale as $Q^2 = (p_T/z)^2$ and the fragmentation scale as $\mu_F = p_T$.
- **Medium modified fragmentation functions** are modeled as

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

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 modified by medium-induced gluon radiation through QW.
- Fragmentation takes place in vacuum.
- nPDF are taken from the EKS98 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.
- QW is the normalized sum of the emission probabilities for an arbitrary number of n gluons which carry away the total energy ΔE.
- $\frac{dI^{(med)}}{d\omega}$ is calculated as $\frac{dI^{(med)}}{d\omega} = \frac{dI^{(tot)}}{d\omega} - \frac{dI^{(vac)}}{d\omega}$ in the **multiple soft scattering approximation**.

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
- All the information about the medium is contained in $\hat{q}$ and L.
- But partons propagate under a rapidly expanding medium, so $\hat{q}$ depends on time

$$\hat{q}(\xi) = \hat{q}_0 \left(\frac{\xi_0}{\xi}\right)^\alpha$$

  where alpha is the expansion parameter.
- In a dynamical medium we use a scaling law which relates the energy distribution in a collision of arbitrary dynamical expansion to an equivalent static scenario.

Energy loss implementation

- We use QW in the multiple soft scattering approximation.
- They depend on two quatities, ω_c and R, which for a static medium are given by $\omega_c = \frac{1}{2}\hat{q}L^2$ e $R = \omega_c L$.
- In a dynamical medium we make use of the following scaling relations:

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

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

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

- We choose to use ω_c^{eff} and R^{eff}.

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

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

- 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 $\hat{q}$ and and the medium-modified fragmentations functions are computed as

$$\langle \hat{q} \rangle = \frac{1}{N} \int d\phi dx_0 dy_0 \omega(x_0, y_0) \frac{\left[[\hat{q}L]^{eff}(x_0, y_0, \phi)\right]^2}{2\omega_c^{eff}(x_0, y_0, \phi)}$$

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

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

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 $\xi < \tau_0$

Single-inclusive results

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

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

- Experimental data are all for Pb-Pb collisios at LHC energy $\sqrt{s_{NN}} = 2.76$ TeV.
- ALICE data on R_{AA} for charged particles with $p_T > 5$ GeV in the centrality class 0-5 % and for $|\eta| < 0.8$.
- CMS data on R_{AA} for charged particles with $p_T > 5$ GeV in the centrality class 0-5 % and for $|\eta| < 1$.
- Results for different values of $2K = K'/0.73$, with $K' = 0.5, 1, 2, 3, ..., 20$.

Double-inclusive results

$$I_{AA} = \frac{D_{AA}(z_T, p_T^{trig})}{D_{pp}(z_T, p_T^{trig})}$$

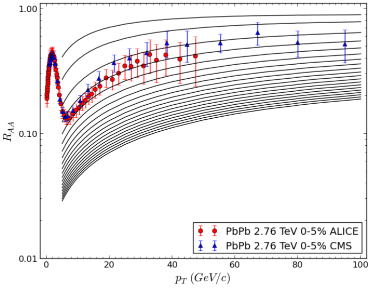
where

$$D_{AA}(z_T, p_T^{trig}) \equiv p_T^{trig} \frac{d\sigma_{AA}^{h_1 h_2}/dy^{trig}\, dp_T^{trig}\, dy^{assoc}\, dp_T^{assoc}}{d\sigma_{AA}^{h_1}/dy^{trig}\, dp_T^{trig}}$$

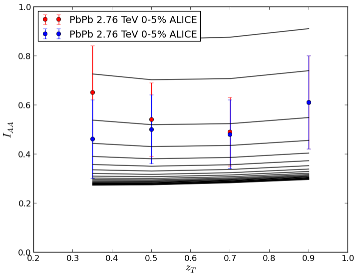
and $z_T = p_T^{assoc}/p_T^{trig}$ and the factorization scale is taken as the p_T of the hadrons

- ALICE data on I_{AA} on the away side for central (0-5 %) PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.
- Results for different values of $2K = K'/0.73$, with $K' = 0.5, 1, 2, 3, ..., 20$.

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



Curves that best fit experimental data are the corresponding to $K = 1.37$ and $K = 2.05$.



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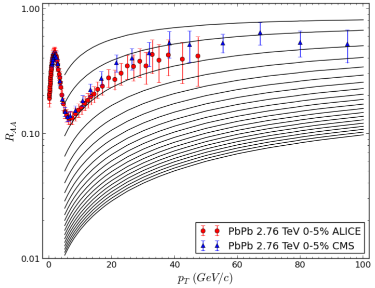
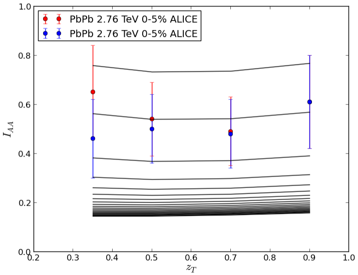
Case ii) $\hat{q}(\xi) = \hat{q}(\tau_0)$ for $\xi < \tau_0$





Curves that best fit experimental data are the corresponding to $K = 0.68$ and $K = 1.37$.

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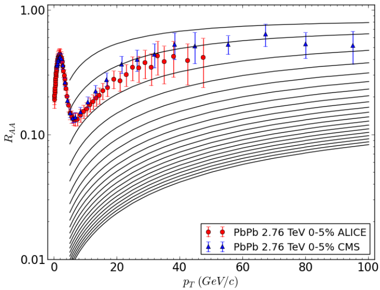
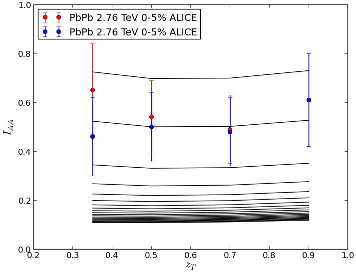
Case iii) $\hat{q}(\xi) = \hat{q}(\tau_0)/\xi^{3/4}$ for $\xi < \tau_0$





The value of K obtained in this case is $K = 0.68$.

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Conclusions

- Good agreement with experimental data.
- Results for single-inclusive measurements compatible with double-inclusive measurements.
- Results influenced by the early time treatment chosen. The case $\hat{q}(\xi)=0$ *before thermalization* is very different from the rest.
- In our model, medium more transparent at LHC than at RHIC.
- Extension to the the case of massive quarks: in progress.

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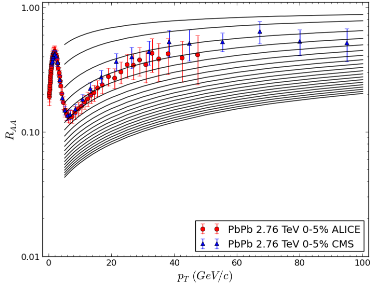
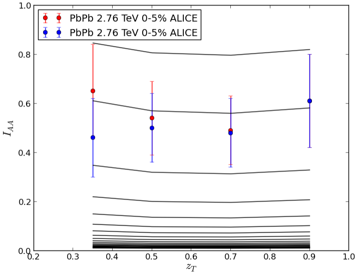
Backup

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

Results choosing $[\hat{q}L]^{eff}$ and ω_c^{eff}





The curves that best fit experimental data are the corresponding to $K = 2.05$ and $K = 2.73$.

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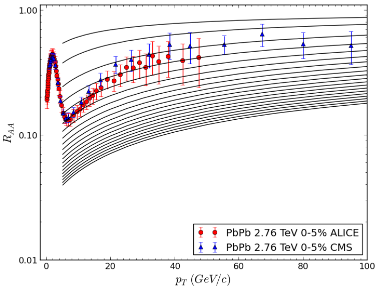

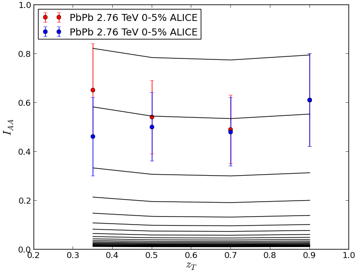

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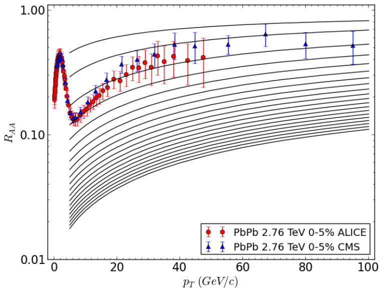

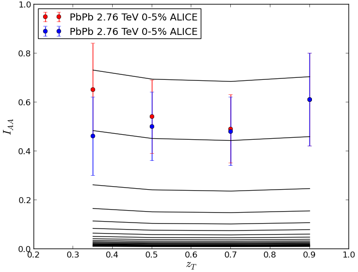

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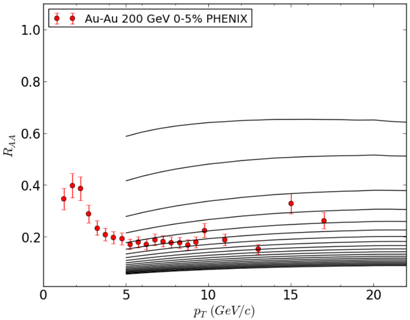
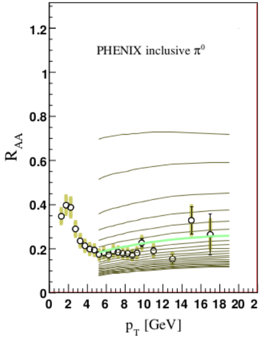
RHIC results with $\hat{q}(\xi) = \hat{q}(\tau_0)$ for $\xi < \tau_0$





Choosing ω_c^{eff} and R^{eff}

Choosing $[\hat{q}L]^{eff}$ and ω_c^{eff}