Jet fragmentation in heavy ion collisions

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* Work in progress, in collaboration with Sony Martins

Outline

- Motivation
- Baseline: hadron production in pp collisions
- Production of neutral and charged hadrons in heavy ion collisions - most central collisions
- Present some approaches for jet energy loss
- Fragmentation functions modified by the medium (quenching weights approach)
- Estimates of the nuclear modification factor R_{AA}
  - π^0 @ RHIC
  - $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$: $h^{\pm}$ @ LHC
- Conclusions

Introduction & Main goal

- Suppression of high p_T jets is one of the signals of the formation of the Quark-Gluon Plasma (QGP) in heavy ion collisions
- Medium induced gluon radiation is claimed to be the dominant mechanism underlying the jet quenching phenomenon observed in heavy ion collisions
- In this contribution, we study the production of neutral and charged hadrons in ultrarelativistic heavy ion collisions - a scenary to test the properties of the hot and dense medium
- Consider some approaches to jet quenching and jet fragmentation
- Present estimates for the nuclear rates R_{AA} at RHIC and LHC.
- Infer some properties of the created quark gluon plasma - opacity, transport coefficient $\hat{q}$, etc
- Comment on how to include the hidrodynamic expansion of the QGP

Hadron production in pp collisions

- (LO) contributions: all $2 \to 2$ QCD processes: $ab \to cd, \quad c \to h$

$$\frac{d\sigma^{pp\to h+X}}{dp_T^2 dy} = J\left(m_T, y\right) \sum_{abcd} \int \frac{dz}{z^2} dy_2 x_a f_{a/p}\left(x_a, Q^2\right) x_b f_{b/p}\left(x_b, Q^2\right) \frac{d\hat{\sigma}}{d\hat{t}}^{ab\to cd} D_{h/c}\left(z, \mu_f^2\right)$$

- $f_{a,b/p}$: CTEQ6L parton distributions
- $x_{a,b} = \frac{q_T}{\sqrt{s}}\left(e^{\pm y_f} + e^{\pm y_2}\right)$, where y_f and y_2 are the rapidity of the produced partons.
- $\frac{d\hat{\sigma}}{d\hat{t}}$: LO partonic cross sections (all $2 \to 2$ QCD processes)
- $D_{h/c}(z, \mu_f^2)$: KKP fragmentation functions

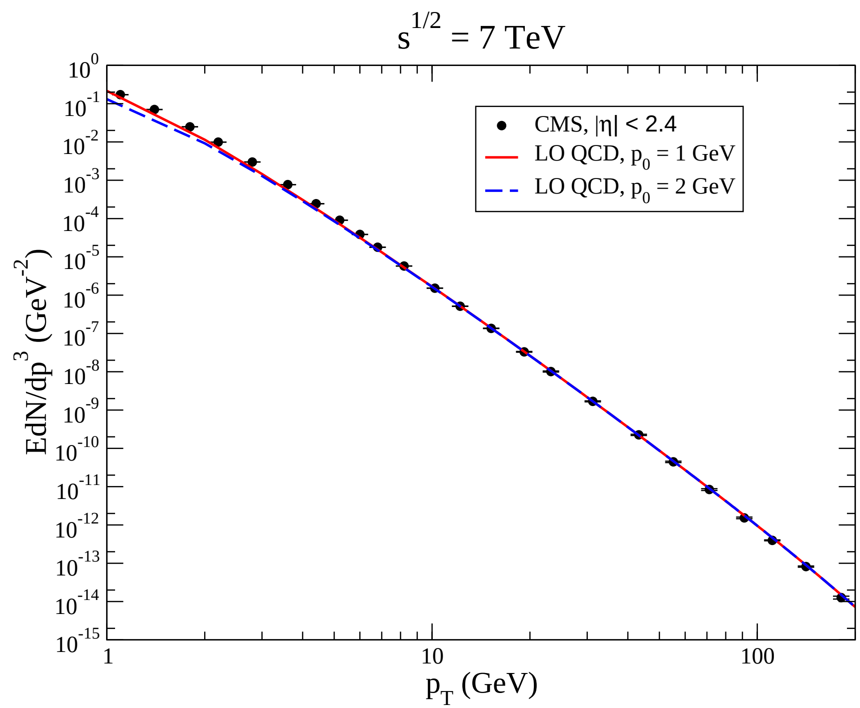
z: energy fraction of the parton carried by the hadron $\quad p_T = z\, q_T$

produced hadron h $\quad$ fragmenting parton c

$$J\left(m_T, y\right) = \left(1 - \frac{m^2}{m_T^2 cosh^2 y}\right)^{1/2}, \; y = \sinh^{-1}\left(\frac{p_T}{m_T}\sinh y_f\right)$$

Production of charged particles @ LHC

- $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ produced in pp collisions at $\sqrt{s} = 7\,TeV$



- Invariant differential yield well described with LO calculation, CTEQ6L parton distributions and KKP fragmentation functions
- pp baseline calculation, to be compared with AA colisions

Hadron production in heavy ion collisions

- First estimates: obtain σ_{AA} from σ_{pp} and some minimal modifications:

$$\frac{d\sigma^{AA\to h+X}}{dp_T dy} = J(m_T, y) \sum_{abcd} \int \frac{dz}{z^2} dy_2 x_a f_{a/A}\left(x_a, Q^2\right) x_b f_{b/A}\left(x_b, Q^2\right) \frac{d\hat{\sigma}}{d\hat{t}}^{ab\to cd} D_{h/c}\left(z^*, \mu_f^2\right)$$

- $f_{a,b/A}$: parton distributions in the nuclei (EPS09, nDS, nCTEQ)
- $D_{h/c}(z^*, \mu_f^2)$: fragmentation functions
  jet (leading parton) produced in central region looses energy, ΔE, in the medium $\to$ shift in the z variable.
  $q_T \quad \to \quad (q_T - \Delta E) \quad \to \quad p_T$
  $$z^* = \frac{z}{1 - \frac{\Delta E}{q_T}}$$
- There are several models to consider the non-abelian energy loss of the jet propagating in the medium (quark gluon plasma)
  $\longrightarrow$ Here we consider a simplified form of some models

Parton energy loss in the medium (QGP)

Non-Abelian energy loss in hot matter: Induced gluon radiation in the QGP

- BDMPS (**B**aier, **D**okshitzer, **M**ueller, **P**eigné, **S**chiff)
  In **thick** plasmas, for a great number of jet scatterings, $L/\lambda \gg 1$

$$\Delta E_{BDMPS} = \frac{C_R \alpha_s}{4} \frac{L^2 \mu^2}{\lambda_g} \tilde{\nu}$$

$\lambda_g = (C_A/C_R)\lambda$: radiated gluon mean free path

- Non-Abelian Energy Loss at Finite Opacity (**G**yulassy, **L**evai, **V**itev): reaction operator approach to opacity expansion

In **thin** plasmas, the mean number of jet scatterings, $\bar{n} = L/\lambda$, is small $\rightarrow$ opacity expansion

$\bar{n}$: measure of the opacity or geometrical thickness of the medium

Energy loss in first order in opacity:

$$\Delta E^{(1)}_{GLV} = \frac{2 C_R \alpha_s}{\pi} \frac{L}{\lambda_g} E \int_0^1 dx \int_0^{k^2_{max}} \frac{dk^2_\perp}{k^2_\perp} \int_0^{q^2_{max}} d^2 q_\perp \frac{\mu^2_{eff}}{\pi (q^2_\perp + \mu^2)^2} \frac{2 k_\perp \cdot q_\perp (k-q)^2_\perp L^2}{16 x^2 E^2 + (k-q)^4_\perp L^2}$$

$$\Delta E^{(1)}_{GLV} \approx \frac{C_R \alpha_s}{4} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu}$$

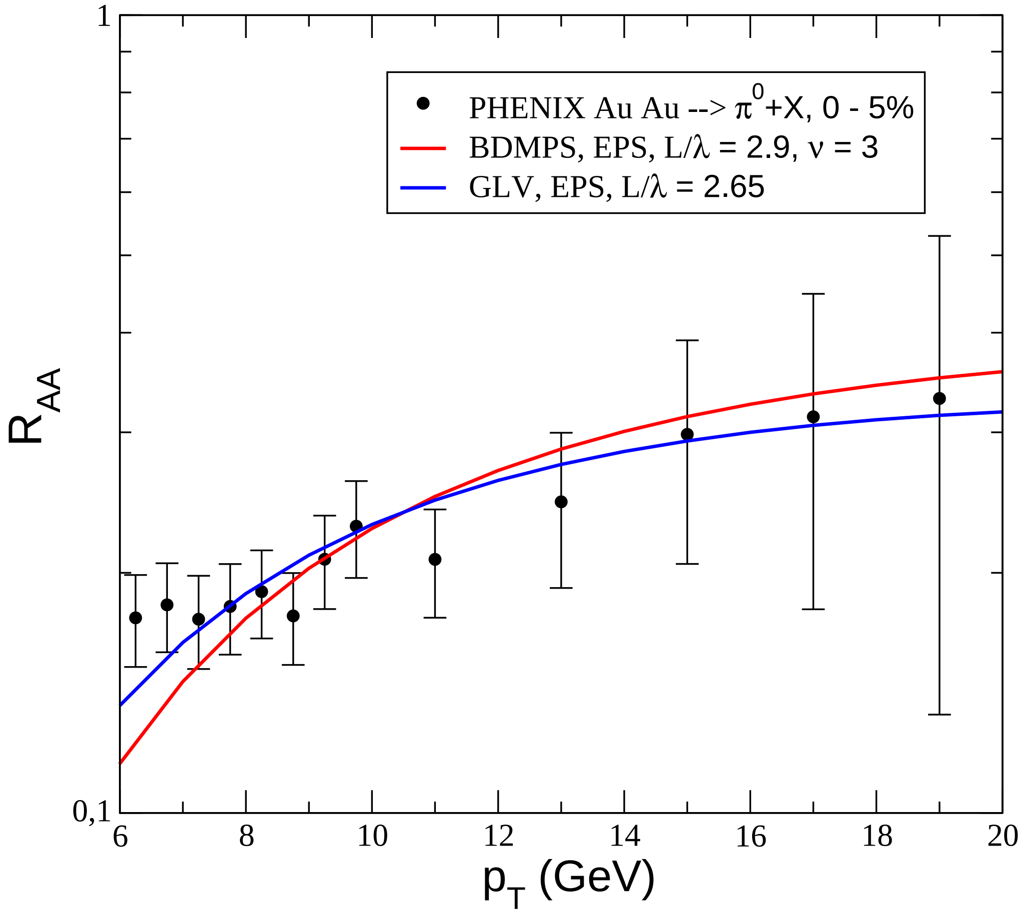
μ: screening scale from color Yukawa potential

QGP: $\lambda_g = 1\, fm$, $\mu = 0.5\, GeV$, $\alpha_s = 0.3$

Neutral π production @ RHIC

$$R_{AA} = \left.\frac{d^2\sigma(AA)}{d\eta dp_T}\right|_{|\eta|\leq 0.35} \Big/ A^2 \left.\frac{d^2\sigma(pp)}{d\eta dp_T}\right|_{|\eta|\leq 0.35}$$

AA collisions, $\sqrt{s} = 200\,GeV$

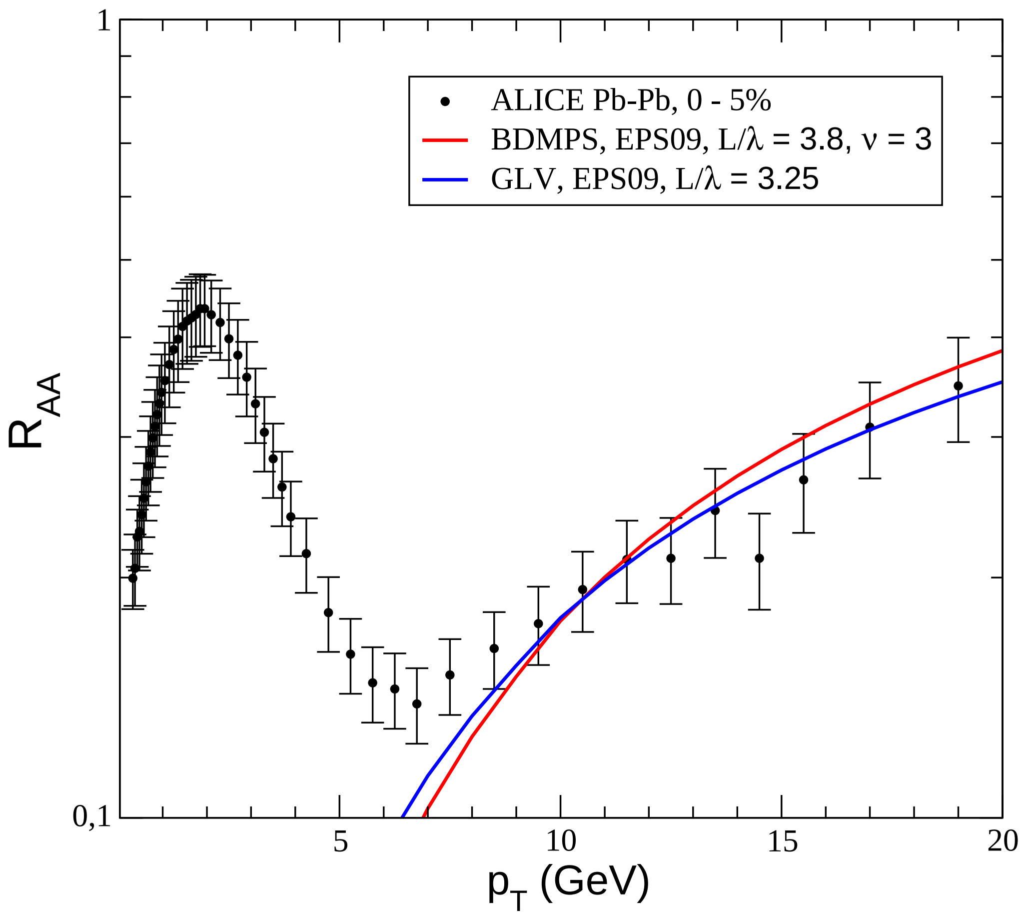


- Energy loss models: fair description of RHIC π^0 data
- estimates of the QGP oppacity at RHIC:
  - BDMPS: $L/\lambda = 2.9$
  - GLV: $L/\lambda = 2.65$
- Somewhat larger oppacities have been previously reported, in different implementation of the same effects (*Levai, NPA 862 (2011) 146*)

Charged hadron production @ LHC

$$R_{AA} = \frac{d^2\sigma(AA)}{d\eta dp_T}\Big|_{|\eta|\leq 0.8} \Big/ A^2 \frac{d^2\sigma(pp)}{d\eta dp_T}\Big|_{|\eta|\leq 0.8}$$

AA collisions, $\sqrt{s} = 2.76\, TeV$



- $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$
- Energy loss models: fair description of higher-p_T LHC data
- Not expected to describe low p_T data
- Estimates of the QGP oppacity at LHC:
  - BDMPS: $L/\lambda = 3.8$
  - GLV: $L/\lambda = 3.25$

  $\Rightarrow$ **larger than in RHIC**
- *Somewhat larger oppacities have been previously reported, in different implementation of the same effects (Levai, NPA 862 (2011) 146)*

Jet Energy Loss - Quenching Weights formalism

(**S***algado,* **W***iedemann*)

- Medium induced gluon radiation
- Produced parton looses with probability $P(\epsilon)$ an additional fraction of its energy, $\epsilon = \frac{\Delta E}{E_q}$
- $\Rightarrow$ Medium modified fragmentation function

$$D_{h/q}^{(med)}(z, Q^2) = \int_0^1 d\epsilon \frac{P(\epsilon)}{1-\epsilon} D_{h/q}\left(\frac{z}{1-\epsilon}, Q^2\right)$$

Quenching weights (energy loss probabilities):

$$P(\Delta E) = p_0 \sum_{k=0}^{\infty} \frac{1}{k!} \int \left[\prod_{i=1}^{k} d\omega_i \int_0^{\omega_i} dk_\perp \frac{dI^{med}(\omega_i)}{d\omega dk_\perp}\right] \delta\left(\sum_{j=1}^{k} \omega_j - \Delta E\right) = p_0\delta(\Delta E) + p(\Delta E)$$

p_0: probability of no energy loss ($\neq 0$ for finite medium)
$\frac{dI^{med}}{d\omega dk_\perp}$: spectrum of medium-induced gluons (path integral approach to opacity expansion)

- $P(\Delta E)$ available in two approximations:
    - Multi soft scattering approximation
    - Single hard scattering approximation ($\approx$ GLV)

Quenching Weights - limiting cases

- Multi soft scattering approximation:
  - partonic projetile performs a Brownian motion in transverse momentum (due to multi soft scatterings)
  - $\hat{q}$: transport coefficient, measures the scattering power of the medium (momentum broadening per unit length)
  - dimensioless parameter $R = \omega_c L \leftarrow$ kinematic constraint restricting p_T of radiated gluons (BDMPS: $R \to \infty$)
  - ω_c: characteristic gluon frequency: set scale of energy-loss probability distribution

- Single hard scattering approximation:
  - Incoherent superposition of very few $n_0 L$ single hard scattering processes in path length L
  - Single scatterer: Yukawa potential with Debye screening mass μ
  - kinematic constraint $\bar{R} = \bar{\omega}_c L$

Quenching Weights & model parameters

- L: medium length
- $P(\Delta E)$ in two limiting cases:
  - Multi soft scattering approximation: $R = \hat{q}L^3/2$, $\omega_c = \hat{q}L^2/2$, $xx = \omega/\omega_c = \epsilon E_q L/R$
  - Single hard scattering approximation: $\bar{R} = \mu^2 L^2/2$, $\bar{\omega}_c = \mu^2 L/2$, $xx = \omega/\bar{\omega}_c = \epsilon E_q L/\bar{R}$
- μ^2: Debye screening mass
- transport coefficient $\hat{q}$ for "static" medium: $\hat{q} = \frac{\langle q_\perp^2 \rangle_{med}}{\lambda}$
- ratio $R/\bar{R} = \frac{\hat{q}L^3}{2}\frac{2}{\mu^2 L^2} = \frac{\langle q_\perp^2 \rangle_{med}}{\lambda}\frac{L}{\mu^2} \approx \frac{L}{\lambda}$ $\leftarrow$ a measure of the medium opacity

Quenching weigths for an expanding medium

- Expansion in the multi soft scattering approximation: $R = \hat{q}L^3/2$, $\omega_c = \hat{q}L^2/2$
- Transport coefficient $\hat{q}$
  - for "static" medium: $\hat{q} = \frac{\langle q_\perp^2 \rangle_{med}}{\lambda}$
  - for an expanding medium: assuming a scaling with the local energy density ε
    $\hat{q} = 2K\varepsilon^{3/4}(\tau) \quad \Rightarrow \quad \hat{q} = \hat{q}_0 \left(\frac{\tau_0}{\tau}\right)^\alpha$, $\alpha \leq 3$,
    ($\alpha = 1$: longitudinal expansion, $1 < \alpha \leq 3$: addit. transverse expansion)
- Using a dynamical scaling law, $\langle \hat{q} \rangle$ and $\bar{\omega}_c$ can be mapped onto an equivalent static scenario:

$$\langle \hat{q} \rangle = \frac{2}{L^2} \int_{\tau_0}^{L+\tau_0} d\tau(\tau - \tau_0)\hat{q} \qquad \bar{\omega}_c = \frac{\langle \hat{q} \rangle L^2}{2}$$

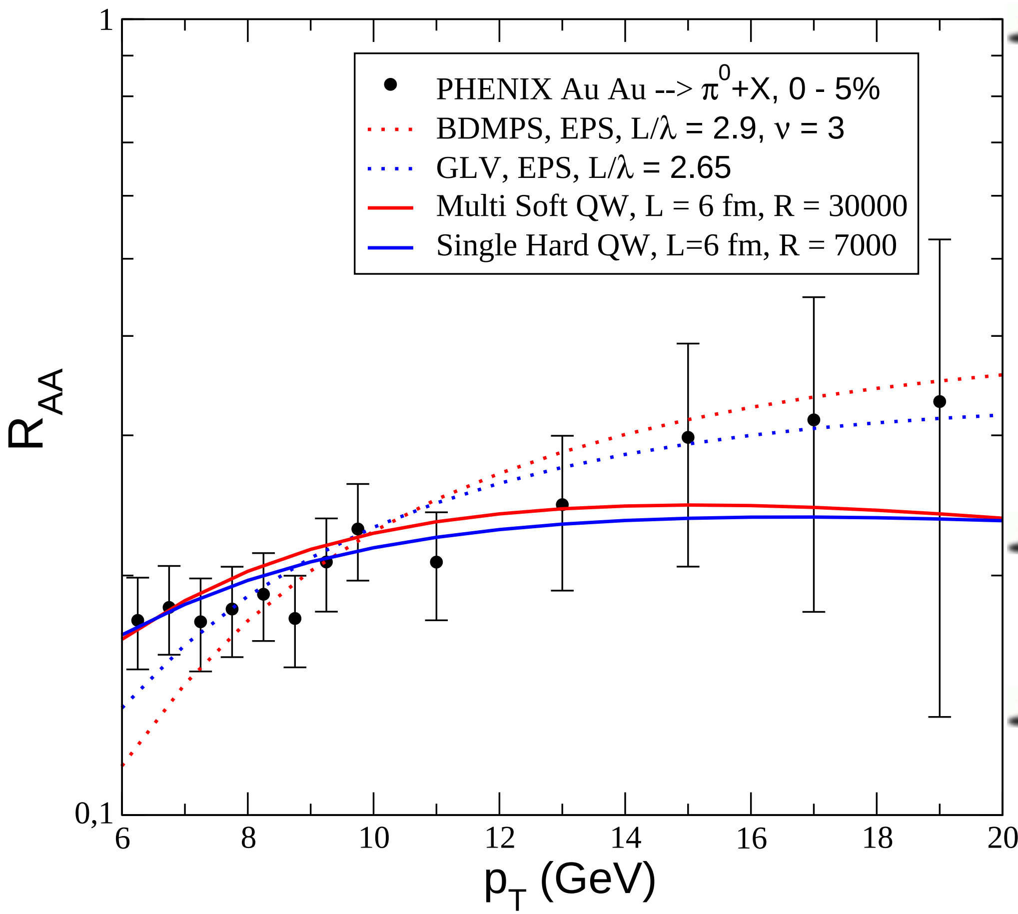
$\Rightarrow$ Using the rescaled kinematic constraint $\langle R \rangle = \frac{1}{2}\langle \hat{q} \rangle L^3$, the dynamical QW agree with the static medium case

	RHIC	LHC
L	6 fm	7 fm
τ_0	0.6 fm	0.5 fm
$\hat{q}_0$	$18.5\, GeV^2/fm$	?

- There is an analogous dynamic scaling in the single hard scattering approximation

Neutral π production @ RHIC

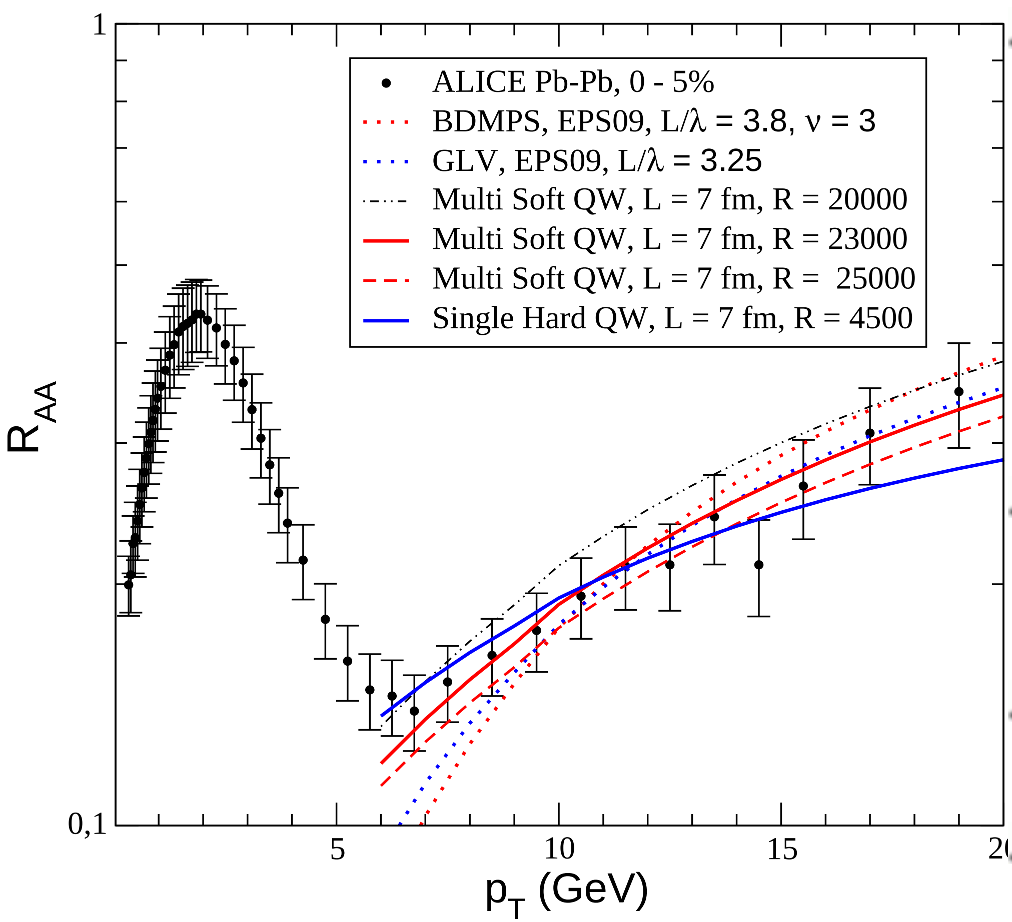
Preliminary results



- Quenching weigths: reasonable description of RHIC π^0 data for $\neq$ values of kinematic constraint R
  - multi soft scattering approx: $R = 30000$
  - single hard scattering approx: $R = 7000$
- different trend compared with previous energy loss approaches
- estimation of QGP opacity via ratio $L/\lambda \approx R/\bar{R} = 4.3$

Charged hadron production @ LHC

Preliminary results



- Quenching weigths: reasonable description of higher p_T LHC data for $\neq$ values of kinematic constraint R
  - multi soft scattering approx: $R = 23000$
  - single hard scattering approx: $R = 4500$
- Not expected to describe low p_T data. Hydro, Cronin effect, non-perturbative effects...?
- estimation of QGP opacity at LHC $L/\lambda \approx R/\bar{R} = 5.1 \leftarrow$ **larger than in RHIC**
- somewhat odd values for "best" R: smaller than in RHIC !!?
- $\rightarrow$ still not reasonable to obtain the correct transport coefficient $\hat{q}$ ($\hat{q}_0$)

Conclusions and discussion

- Assuming a certain model for energy loss, one may estimate some properties of the QGP, which reasonably describe RHIC and LHC heavy ion data on neutral and charged hadron production.
- Model dependence of QGP properties not desirable...
- Quenching weights; unified and easy-to-implement modification in the fragmentation functions...
- Consider other nPDF's (DS, HKN, nCTEQ) and FF's
- Generalize this study to several centrality classes, from central to more peripheral collisions (use the correct geometry)
- Other approaches: medium modified splitting functions alter the evolution of fragmentation functions...
- Considere more realistic hydrodynamical quantities: transversal expansion, T and ε dependency of transport coefficients, etc
- Pin down the cold matter effects in pA collisions, where the QGP is not criated
- Complement these studies with Monte Carlo implementations like QPythia and others...
- Necessary to study other observables: dihadron correlations, two jet asymmetries, etc