Particle suppression and jet fragmentation in heavy ion collisions

Cristiano Brenner Mariotto

cristianomariotto@furg.br

Universidade Federal do Rio Grande - FURG

Rio Grande, Brazil

* 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
- Initial attempts to describe R_{AA} with b-dependent nuclear PDF's + energy loss - centrality classes
- Conclusions

Introduction & Main goal

- Suppression of high p_T jets: one of the signals of the formation of the Quark-Gluon Plasma (QGP) in heavy ion collisions
- Medium induced gluon radiation: 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 (last published ALICE data: p_T up to 50 GeV)
- Infer some properties of the created quark gluon plasma - opacity, transport coefficient $\hat{q}$, etc
- b-dependent nuclear PDF's and R_{AA} in different centrality classes

Hadron production in pp collisions

- simplest approximation: all $2 \to 2$ QCD processes: $ab \to cd$, $\quad c \to h$

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

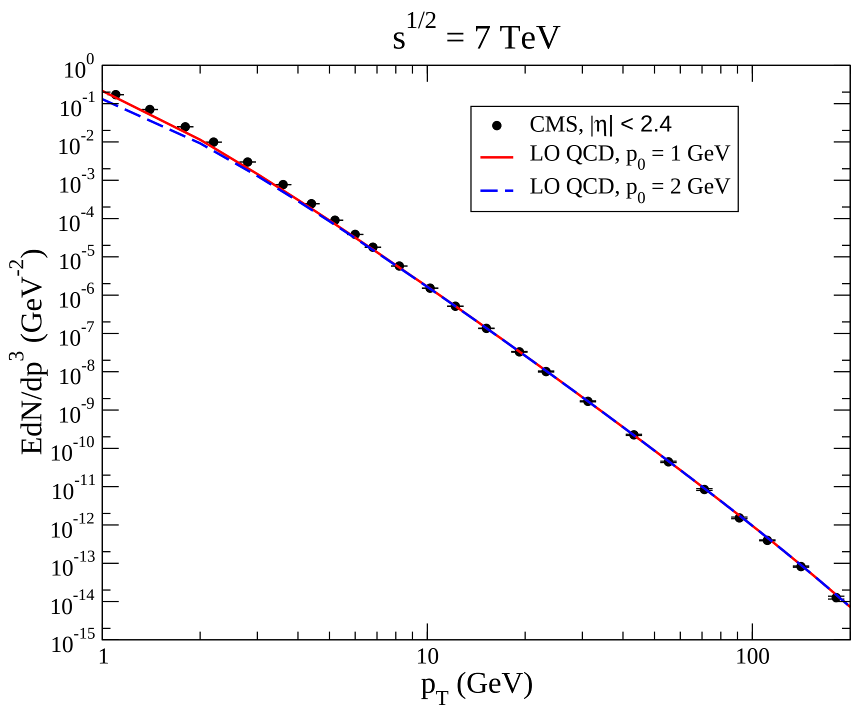
- $f_{a,b/p}$: CTEQ6L parton distributions
- $\frac{d\hat{\sigma}}{d\hat{t}}$: partonic cross sections
- $D_{h/c}(z, \mu_f^2)$: KKP fragmentation functions
- $z_c = \frac{x_T e^{-y}}{2x_b} + \frac{x_T e^{y}}{2x_a}$, $\quad x_{a,min} = \frac{x_T e^{y}}{2 - x_T e^{-y}}$, $\quad x_{b,min} = \frac{x_a x_T e^{-y}}{2x_a - x_T e^{y}}$, $\quad x_T = \frac{2m_T}{\sqrt{s}}$
  $x_{a,b} = \frac{q_T}{\sqrt{s}}\left(e^{\pm y_f} + e^{\pm y_2}\right)$, y_f and y_2 are the rapidities of the produced partons.

z_c: momentum fraction of the parton carried by the hadron $\qquad p_T = z_c\, q_T$

produced hadron h $\qquad$ fragmenting parton c

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:

$$E_h \frac{d\sigma^{AA}}{d^3p} = \int d^2b T_{AA}(b) \sum_{abcd} \int \frac{dx_a dx_b}{\pi z_c} f_a^A\left(x_a, Q^2\right) f_b^A\left(x_b, Q^2\right) \frac{d\hat{\sigma}}{d\hat{t}}^{ab\to cd} \frac{z_c^*}{z_c} D_{h/c}\left(z_c^*, \mu_f^2\right)$$

- $f_{a,b/A}$: parton distributions in the nuclei (EPS09, nDS, nCTEQ...)
- $T_{AA}(b) = \int d^2 s T_A(s) T_A(|\vec{b} - \vec{s}|)$: nuclear overlap function
- $D_{h/c}(z_c^*, \mu_f^2)$: fragmentation functions
  jet (leading parton) produced in central region looses energy, ΔE, in the medium $\rightarrow$ shift in the z_c variable.
  $q_T \quad \rightarrow \quad (q_T - \Delta E) \quad \rightarrow \quad p_T$
  $$z_c^* = \frac{z_c}{1 - \frac{\Delta E}{q_T}}$$
- 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 $\to$ opacity expansion
$\bar{n}$: measure of the opacity or geometrical thickness of the medium
Energy loss in first order in opacity:

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

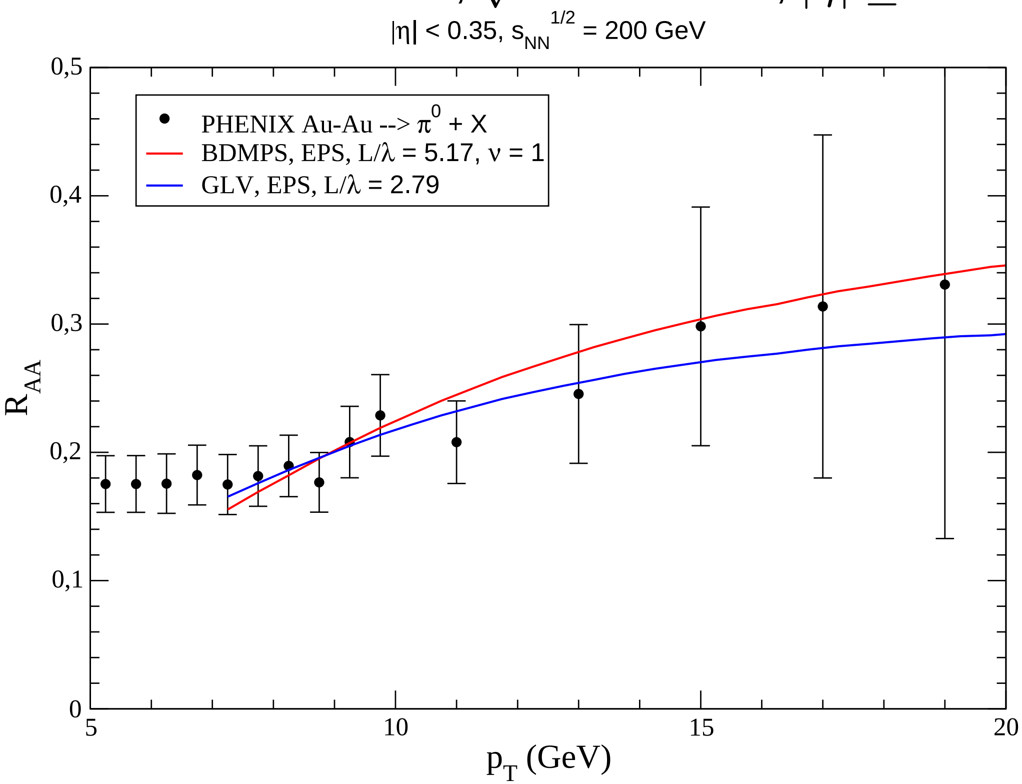
$$\Delta E^{(1)}_{GLV} \approx \frac{C_R \alpha_s}{4} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu}$$

μ: screening scale from color Yukawa potential
QGP: $\lambda_g = 1\, fm$, $\mu = 0.5\, GeV$, $\alpha_s = 0.3$

Neutral π production @ RHIC

$$R_{AA} = \frac{d^2N(AA)}{d\eta dp_T} \Big/ < N_{coll} > \frac{d^2N(pp)}{d\eta dp_T}$$

AA collisions, $\sqrt{s} = 200\,GeV$, $|\eta| \leq 0.35$

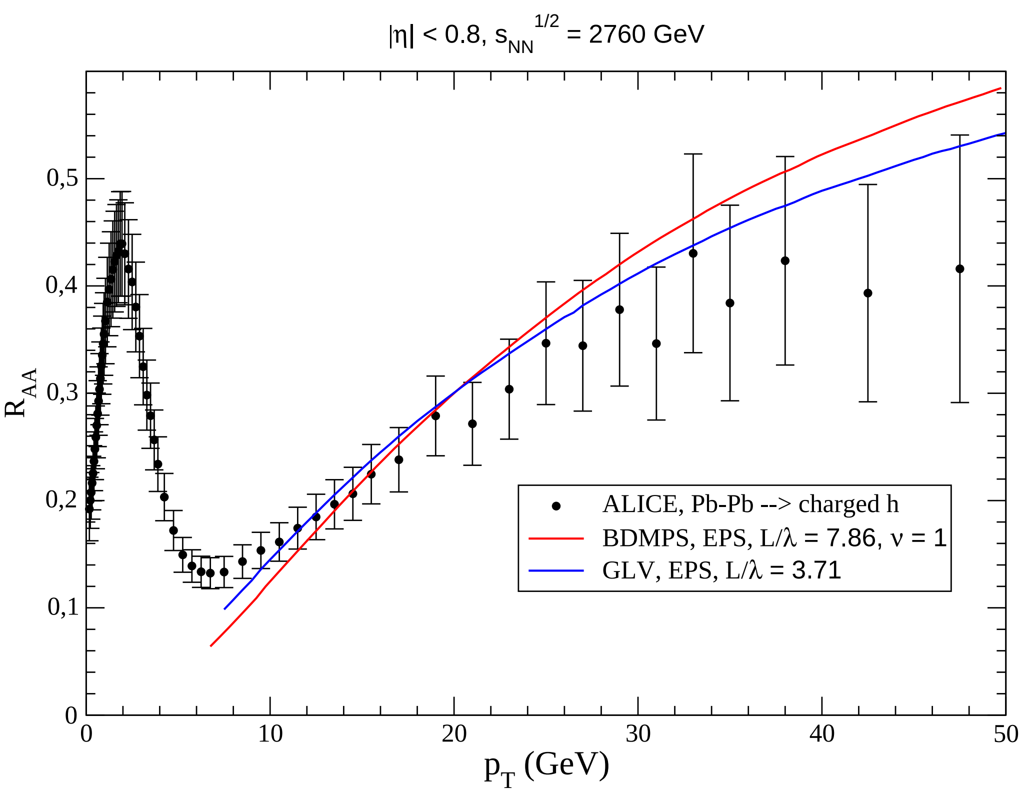


- Energy loss models: fair description of RHIC π^0 data
- estimates of the QGP oppacity at RHIC:
  - BDMPS: $L/\lambda = 5.17$
  - GLV: $L/\lambda = 2.79$
- Somewhat larger oppacities have been previously reported, in different implementation of the same effects (*Levai, NPA 862 (2011) 146*)

Charged hadron production @ LHC

$$R_{AA} = \frac{d^2N(AA)}{d\eta dp_T} \Big/ < N_{coll} > \frac{d^2N(pp)}{d\eta dp_T}$$

AA collisions, $\sqrt{s} = 2.76\,TeV$, $|\eta| \leq 0.8$



- $\pi^{\pm}$, $K^{\pm}$, 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: $L/\lambda = 7.86$
  - GLV: $L/\lambda = 3.71$

$\Rightarrow$ **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:

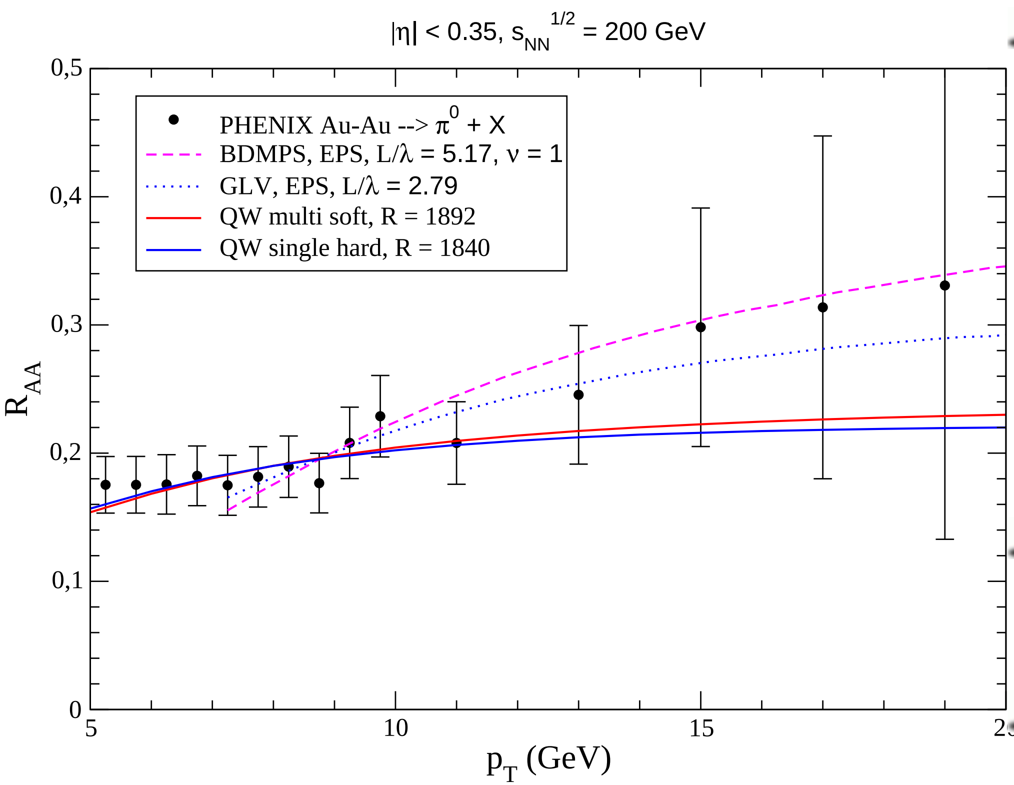
$$\langle \hat{q} \rangle = \frac{2}{L^2} \int_{\tau_0}^{L+\tau_0} d\tau (\tau - \tau_0) \hat{q} \qquad \bar{\omega}_c = \frac{\langle \hat{q} \rangle L^2}{2}$$

  $\Rightarrow$ 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
$\hat{q}_0$	?	?

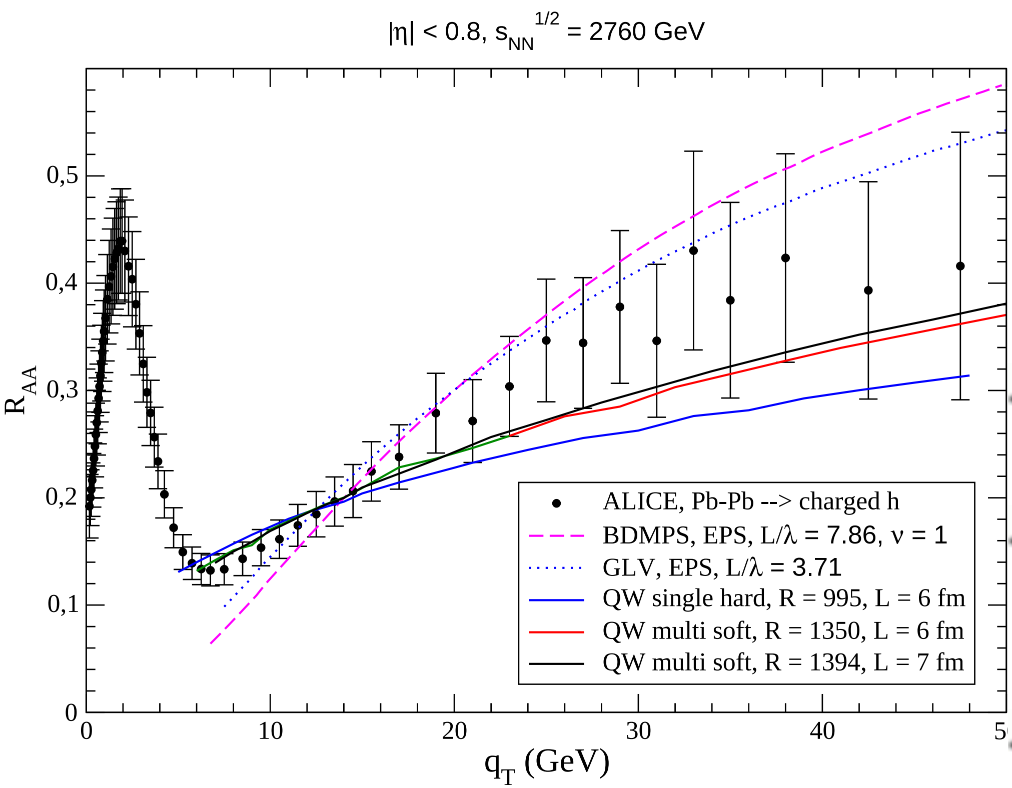
- There is an analogous dynamic scaling in the single hard scattering approximation

Neutral π production @ RHIC



- Quenching weigths: reasonable description of RHIC π^0 data for $\neq$ values of kinematic constraint R
  - multi soft scattering approx: $R = 1892$
  - single hard scattering approx: $\bar{R} = 1840$
- different trend compared with previous energy loss approaches
- estimation of QGP opacity via ratio $L/\lambda \approx R/\bar{R} = 1.02$

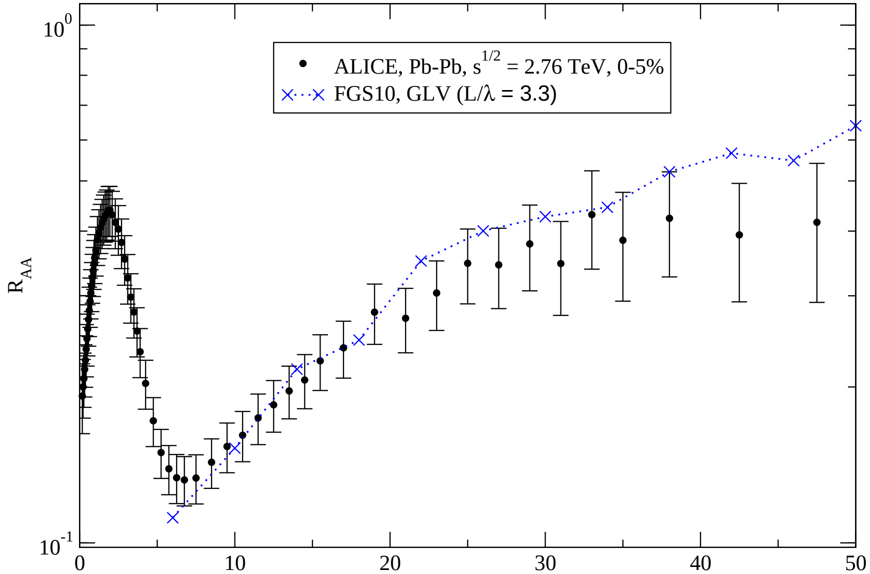
Charged hadron production @ LHC

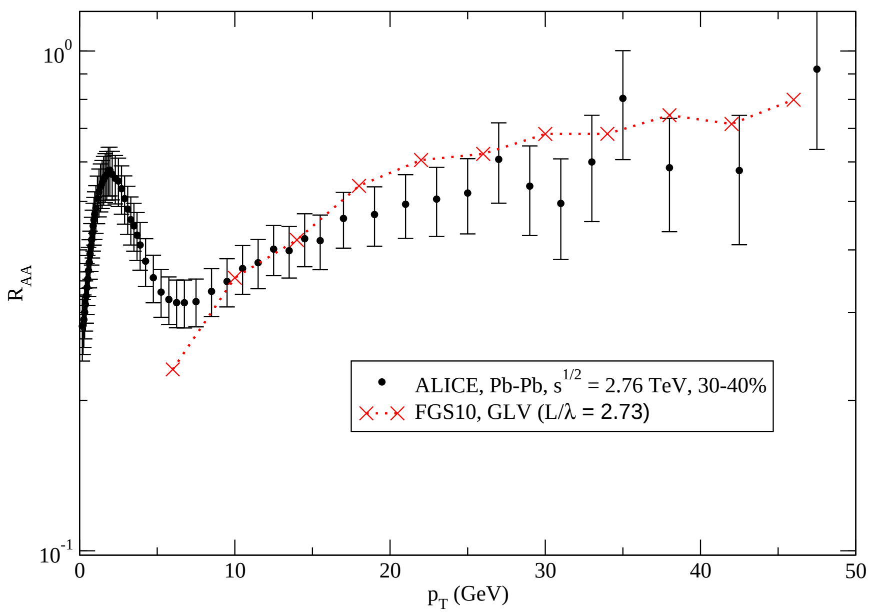


- Quenching weigths: fair description of higher p_T LHC data for $\neq$ values of kinematic constraint R
  - multi soft scattering approx: $R = 1350$
  - single hard scattering approx: $\bar{R} = 995$
- QW: R_{AA} seems to grow slower than data
- Not expected to describe low p_T data. Hydro, radial flow, non-pQCD effects...?
- estimation of QGP opacity at LHC $L/\lambda \approx R/\bar{R} = 1.36 \leftarrow$ **larger than in RHIC**
- somewhat odd values for "best" R: smaller than in RHIC !!?
- $\rightarrow$ from this one could obtain the transport coefficient $\hat{q}$ ($\hat{q}_0$)...

Centrality dependency of R_{AA} @ LHC

Preliminary results





- Leading twist nuclear shadowing (**F**rankfurt, **G**uzey, **S**trikman, *Phys.Rep. (2012)*) $\rightarrow$ b-dependent nuclear PDF's **FGS10**
- Energy loss models: GLV for simplicity
- Alice results on centrality dependence PLB 720 (2013)
- Very preliminary estimates for R_{AA} (more on the way)
- To include other centrality classes
- *Still not possible to describe different centrality classes with the same oppacity*
- *Reasonable for more peripherical collisions (less or no QGP?), but it should work for more central classes...*

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...
  - QW model pushed into p production (π + K + p), originally though only for meson production...
- 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). Only fast preliminary results up to now...
- 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
- Necessary to study other observables: dihadron correlations, two jet asymmetries, etc

MUCHAS GRACIAS!!!