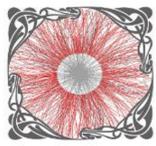


# The puzzling relation between the $R_{AA}$ and the $v_2$ for heavy mesons in a Boltzmann and in a Langevin approach



XXIV  
QUARK  
MATTER  
DARMSTADT  
2014

## Boltzmann and in a Langevin approach

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## Two different approaches for the Propagation of Heavy quark in the QGP

The heavy quarks (HQ), Charm and bottom, are ideal probes to study the Quark Gluon Plasma (QGP). HQ are considered heavy for a two-fold reason: first, typical of particles physics, is that the mass is much larger than  $\Lambda_{QCD}$  which make possible the evaluation of the cross section and momentum spectra within the next to lead order; the second more inherent to plasma physics is that their masses are much larger than the temperature and therefore they may expect to decouple from the medium and moreover their thermal production in the QGP is expected to be negligible. Therefore they are produced mainly in the initial hard parton scatterings of nucleon-nucleon interactions being witness of the entire-space time evolution of the system and can reveal important information about the properties of QGP. Both at RHIC and LHC energies it has been observed a puzzling correlation between the nuclear suppression factor  $R_{AA}$  and the elliptic flow  $v_2$  that has challenged all the existing models. The propagation of heavy quarks through the quark-gluon plasma (QGP) has been quite often treated within the framework of Langevin equation (LV), i.e. assuming the heavy flavor momentum transfer is small or the scatterings are sufficiently forward peaked. We address a direct comparison between the Langevin dynamics and the Boltzmann collisional integral (BM).

### Transport approach

Boltzmann equation (B-E)

$$p^\mu \partial_\mu f(x, p) = C_{22}$$

Describes the evolution of the one body distribution function  $f(x, p)$  of the bulk and also of Heavy Quarks

Collision Integral

$$C_{22} = \int d^3k [\omega(p+k, k) f_{HQ}(p+k) - \omega(p, k) f_{HQ}(p)]$$

Transition rate for collisions of Heavy quarks with heath bath changing the HQ momentum from  $p$  to  $p-k$

$$\omega(p, k) = g \int \frac{d^3q}{(2\pi)^3} f(q) v_{rel} \sigma_{p, q \rightarrow p-k, q+k}$$

To solve numerically the B-E we divide the space into a 3-D lattice and we use the standard test particle method to sample  $f(x, p)$ .

$C_{22}$  is solved using a stochastic algorithm consisting into the evaluation of the collision probability  $P_{22}$  for each couple of particle in the cells.

$$P_{22} = \frac{\Delta N_{coll}}{\Delta N_{HQ} \Delta N_g} = v_{rel} \sigma_{gHQ \rightarrow qHQ} \frac{\Delta t}{\Delta^3 x}$$

Fokker Planck equation

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial p_i} \left[ A_i(p) f + \frac{\partial}{\partial p_j} [B_{ij}(p) f] \right]$$

Drag and Diffusion Coefficients

$$A_i = \int d^3k \omega(p, k) k_i \quad B_{ij} = \int d^3k \omega(p, k) k_i k_j$$

The Fokker-Planck equation is equivalent to an ordinary stochastic differential equation :  
The Langevin equation (L-E)

$$dx_i = \frac{p_i}{E} dt$$

$$dp_j = -\Gamma p_j dt + \sqrt{D} C_{jk}(t, p + \xi dp) \rho_k$$

The Fokker Planck equation can be derived from the Boltzmann equation expanding the collision integral in terms of the transferred momentum  $k$  making the assumption that  $k$  is  $\ll$  than the momentum  $p$  of the HQ.

$\Gamma$  is the deterministic friction (drag) force  
 $C_{ij}$  is a stochastic force in terms of independent Gaussian-normal distributed random variable  $\rho = (\rho_x, \rho_y, \rho_z)$

The covariance matrix and  $\Gamma$  are related to the diffusion matrix and to the drag coefficient by

$$C_{jk} = \sqrt{2B_0} P_{jk}^\perp + \sqrt{2B_1} P_{jk}^\parallel$$

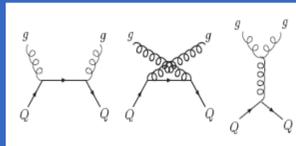
$$A_i = p_j \Gamma - \xi C_{jk} \frac{\partial C_{ij}}{\partial p_l}$$

[S. K. Das, F. Scardina, V. Greco arXiv:1312.6857], [J. Uphoff, O. Fochler, Z. Xu and C. Greiner PRC 84 024908; PLB 717] [B. Zhang, L. W. Chen and C. M. Ko, Phys. Rev. C 72 (2005) 024906] [P. B. Gossiaux, J. B. Aichelin PRC 78 014904] [D. Molnar, Eur. Phys. J. C 49(2007) 181]

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### pQCD evaluation of $\sigma$ , $A_i$ and $B_{ij}$

$$\sigma_{gHQ \rightarrow gHQ} = \frac{1}{16\pi(s-M_c^2)^2} \int_{(s-M_c^2)^2/s}^0 dt \sum |M|^2$$

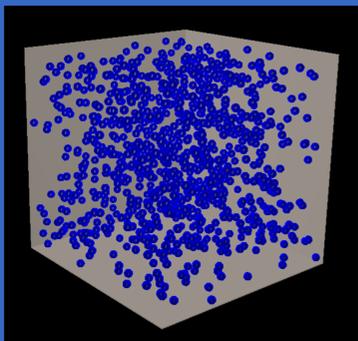


$$A_i = \frac{1}{2E_p} \int \frac{d^3q}{(2\pi)^3} 2E_q \int \frac{d^3q'}{(2\pi)^3} 2E_{q'} \int \frac{d^3p'}{(2\pi)^3} 2E_{p'} \frac{1}{\gamma_c} \sum |M|^2$$

$$(2\pi)^4 \delta^4(p+q-p'-q') f(q) [(p-p')_i] = \langle\langle (p-p')_i \rangle\rangle$$

$$B_{ij} = \frac{1}{2} \langle\langle (p-p')_i (p-p')_j \rangle\rangle$$

## Simulations in a static medium

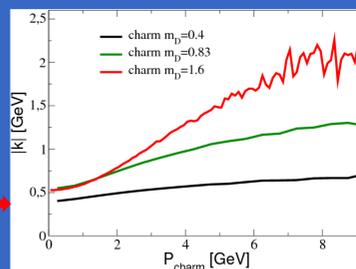


- ✓ Simulations in which a particle ensemble in a box evolves dynamically
- ✓ Bulk composed only by gluons in thermal equilibrium at  $T=400$  MeV
- ✓ Heavy Quarks are distributed uniformly in coordinate space

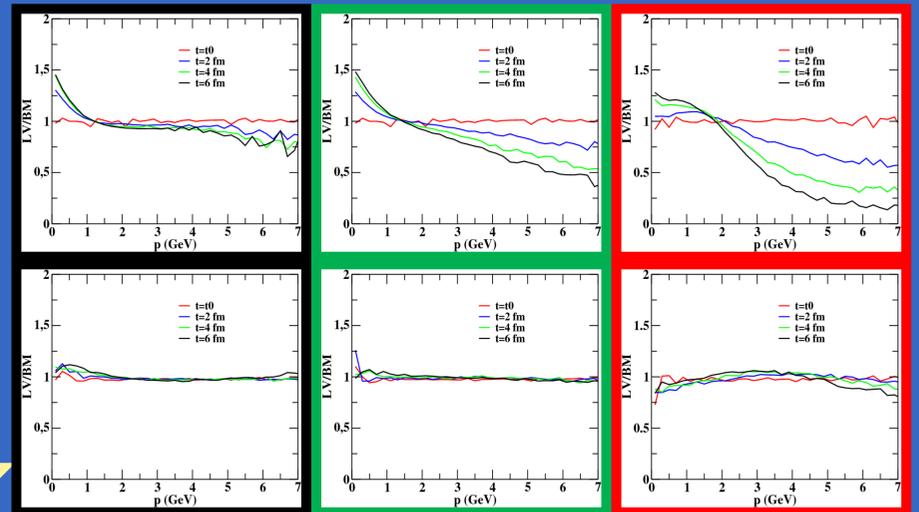
LV/BM

$$\frac{dN}{d^3p} \Big|_{\text{Langevin}} / \frac{dN}{d^3p} \Big|_{\text{Boltzmann}}$$

To analyze the comparison between the Fokker-Planck approach and the Boltzmann approach we have studied the ratio between the spectra coming from the simulations with LV and the spectra coming from the BM. In order to study the mass dependence of the approximation involved in the LV we have compared such a ratio for both charm ( $M_c=1.3$  GeV) and Bottom ( $M_b=4.2$  GeV). Moreover we have compared LV and BM simulating different values of the average momentum transferred  $k$  (different values of the Debye screening mass  $m_D$ .)



Mass dependence of the LV/BM



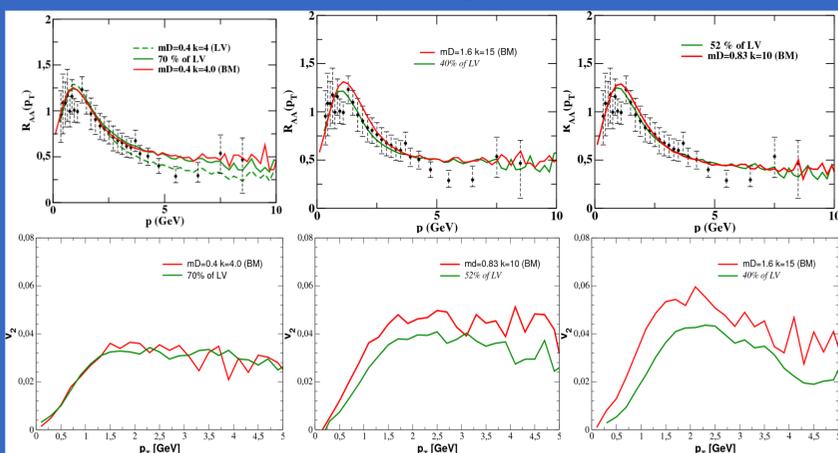
Average momentum transfer  $\langle k \rangle$  dependence of the LV/BM

[S. K. Das, F. Scardina, V. Greco arXiv:1312.6857]

### RHIC

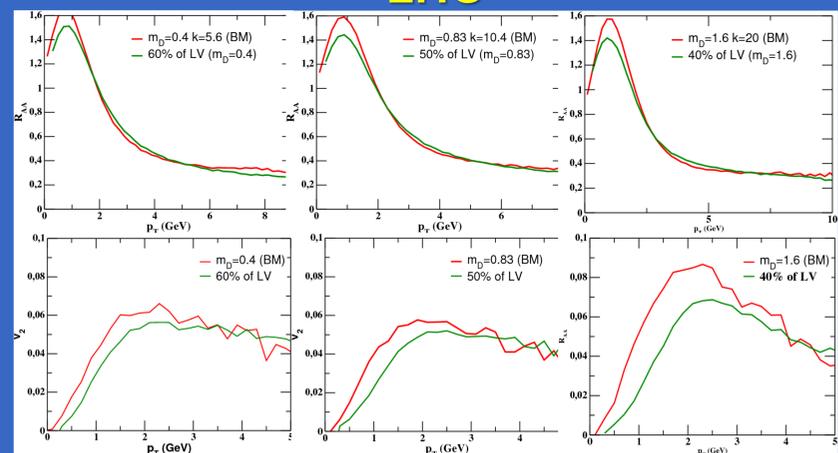
## Realistic simulation of HIC

### LHC



$R_{AA}(p_T)$

$v_2(p_T)$



- ✓ The Langevin dynamics overestimates the interaction for charms (large suppression) while in case of bottom quarks the approximation appears to be quite reasonable
- ✓ However one can get very similar  $R_{AA}$  for both the approaches just reducing the diffusion coefficient
- ✓ Boltzmann is more efficient in producing  $v_2$  for fixed  $R_{AA}$  especially for large average momentum transfer
- ✓ This together with a coalescence hadronization mechanism may quench the puzzling  $R_{AA}$  and  $v_2$  observations