Toward a solution of the R_{AA} and v_2 puzzle for heavy quarks

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Outline

- The puzzling Relation between R_{AA} and v_2 for Heavy Flavors
  - T-dependence of the interaction
  - Boltzmann vs Fokker-Planck approach
- Boltzmann vs Fokker-Planck: $c\bar{c}$ and $b\bar{b}$ angular correlation

Introduction Heavy Quarks

$M_{HQ} >> gT \approx K$ ($M_{Charm} \approx 1.3$ GeV; $M_{Bottom} \approx 4.2$GeV)

HQ propagation in the QGP is described by the **Fokker-Planck eq.**

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

The interaction is encoded in the **drag** and **diffusion coefficents**

$$A = \int d^3k \left|M(k,p)\right|^2 p$$

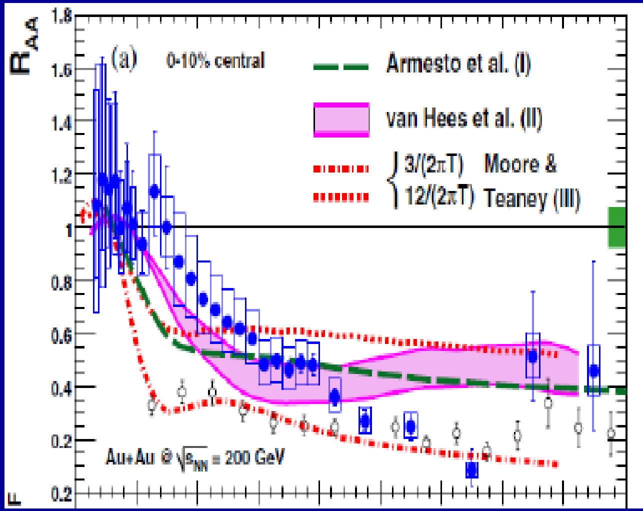
$$B = \frac{1}{2}\int d^3k \left|M(k,p)\right|^2 p^2$$

Evaluated from scattering matrix $|M|^2$

From experiments and theoretical simulations we know that

drag from pqcd -> R_{AA} larger than exp. data

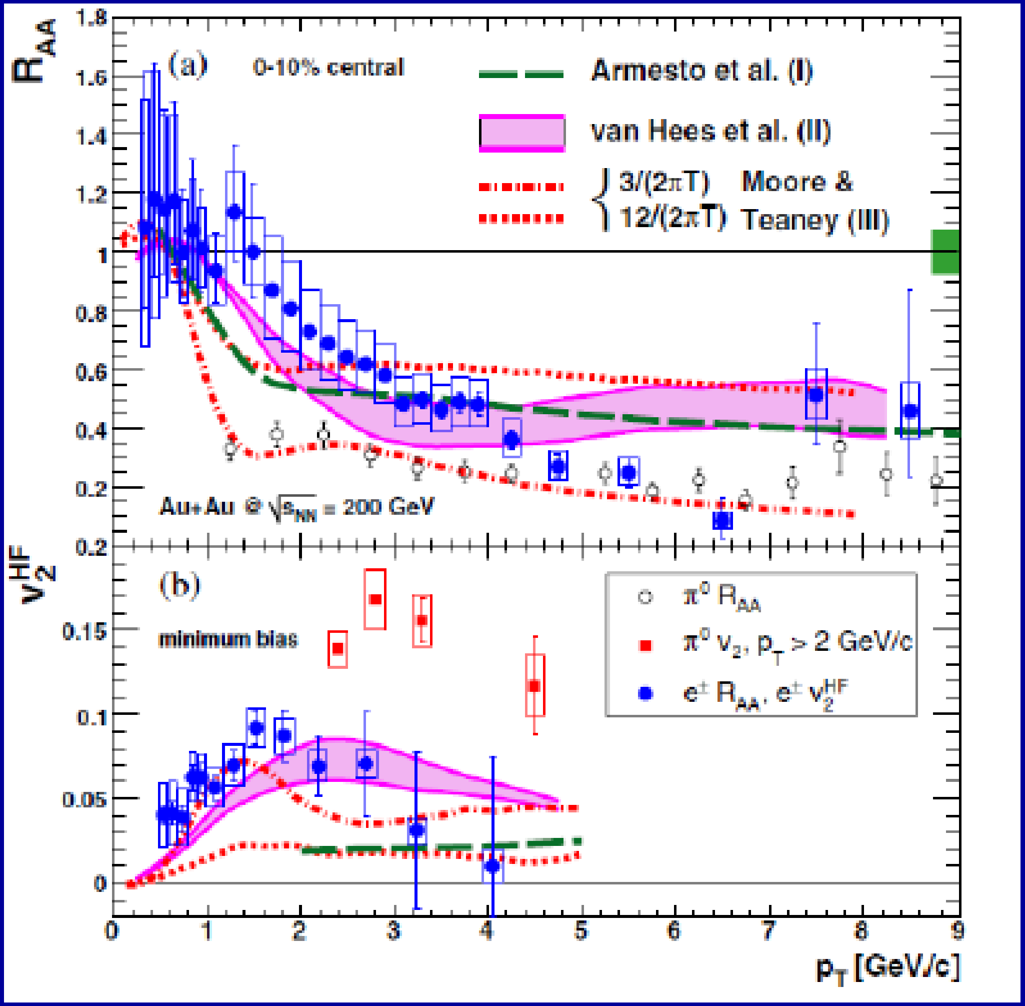
R_{AA} gives information on the average strenght of the interactions beween HQ and the bulk



The relation between R_{AA} and v_2 can give further informations on the interaction

Various model at work for RHICs

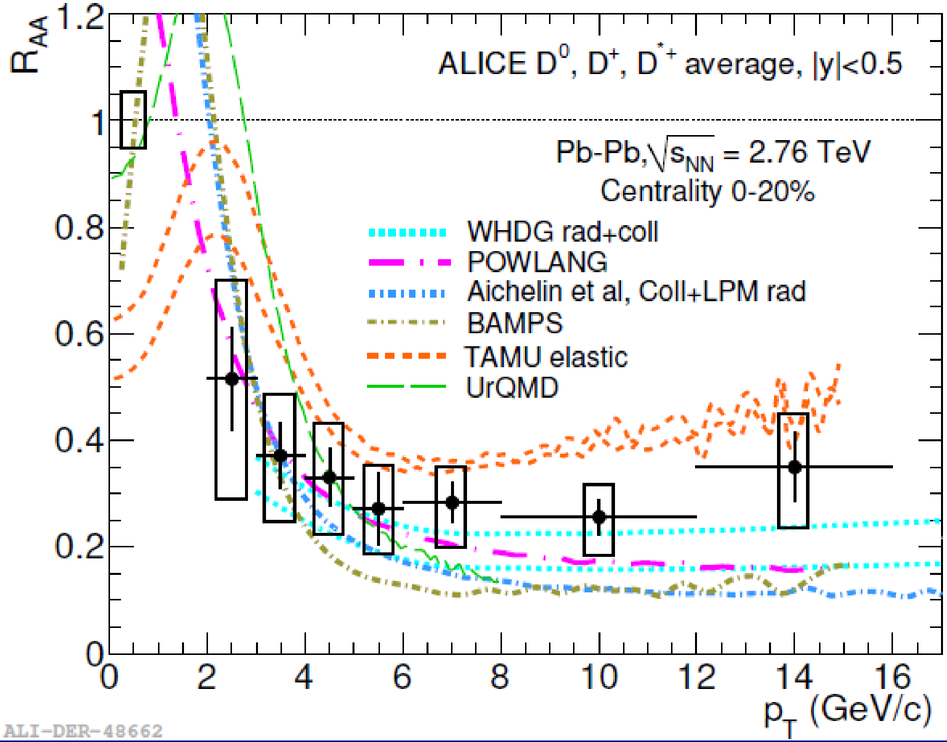
Single electron measurements



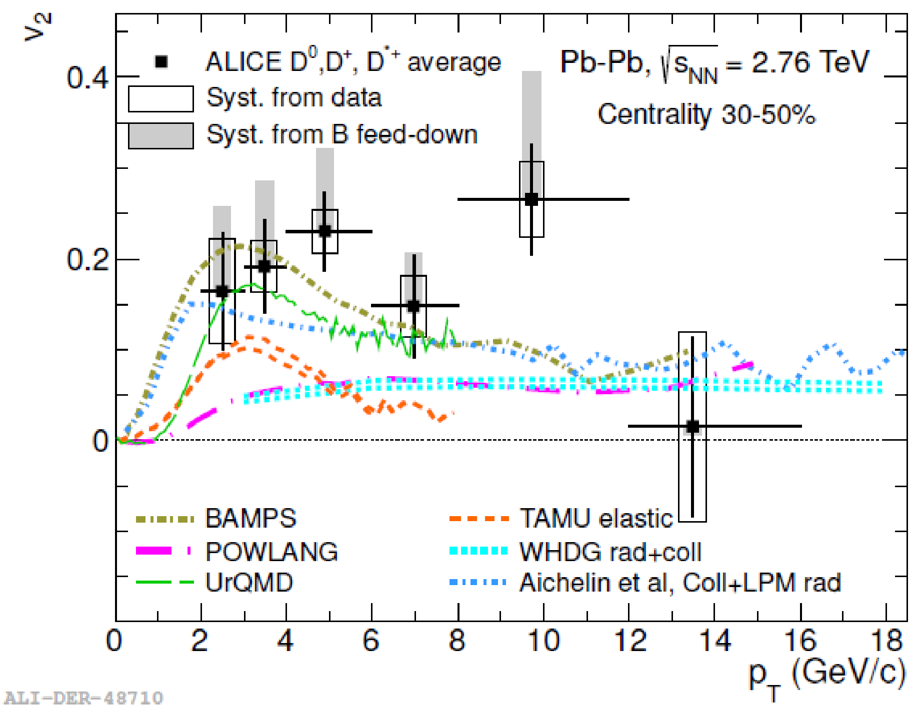
Simultaneous description of R_{AA} and v_2 is a tough challenge for all models

Various model at work for LHC

JHEP **1209** (2012) 112



arXiv:1305.2707

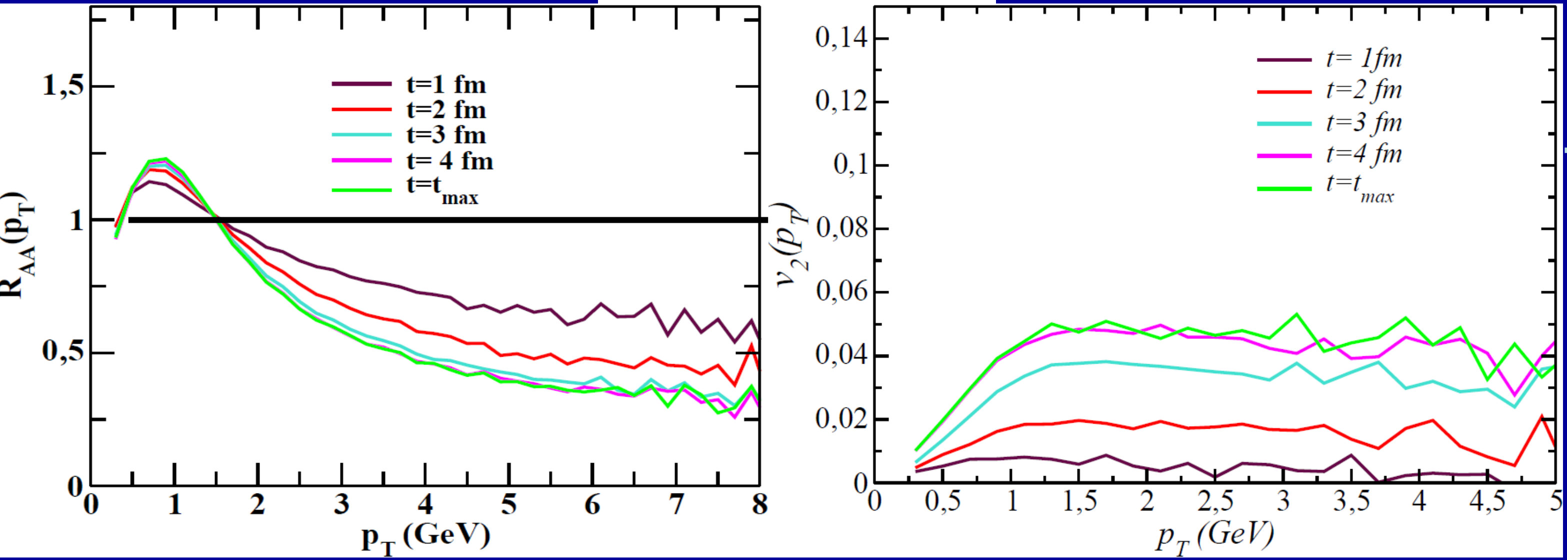


Simultaneous description of R_{AA} and v_2 is a tough challenge for all models

R_{AA} and v_2 correlation

Larger interaction -> smaller R_{AA} -> larger the v_2

A typical example



R_{AA} can be "generated" faster than v_2

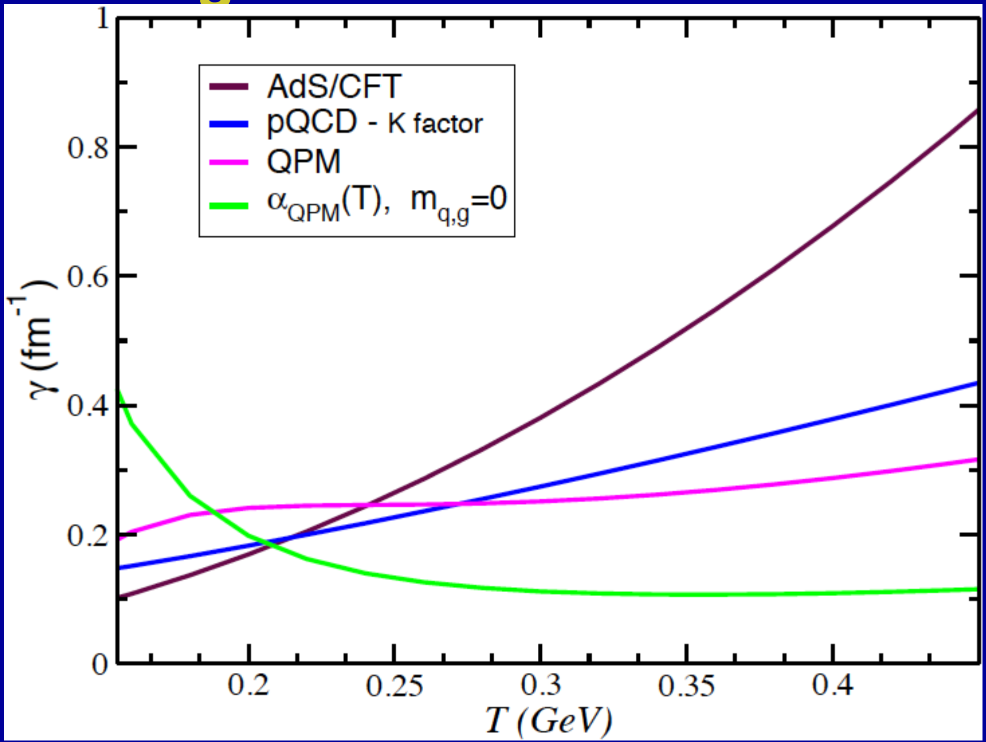
The correlation between R_{AA} and v_2 is related with the time-dependence of the interaction (for an expanding medium) <-> Temperature-dependence

This is general, seen also for light quarks

[Scardina, Di Toro, Greco, PRC82(2010)] [J.Liao and E. Shuryak PRL 102 (2009)]

T- dependence of the Drag Coefficient

Drag Coefficient



[Scardina et al PLB747 (2015) 260-264]

✓ **pQCD** *(Combridge cross-section)*

$$\alpha_{pQCD} = \frac{4\pi}{11\ln\left(2\pi T\Lambda^{-1}\right)}$$

✓ **AdS/CFT**

$$g_{AdS/CFT} = k\frac{T^2}{M}$$

[Akamatsu et al. PRC79 (09) 054907]
[S. K. Das PRC89 (2014) 054912]

✓ **Quasi-Particle-Model** *(fit lQCD e,P)*

$$m_g^2 = \frac{1}{6}\left(N_c + \frac{1}{2}N_f\right)g^2T^2 \qquad m_q^2 = \frac{N_c^2-1}{8N_c}g^2T^2$$

$$g_{QP}^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2}$$

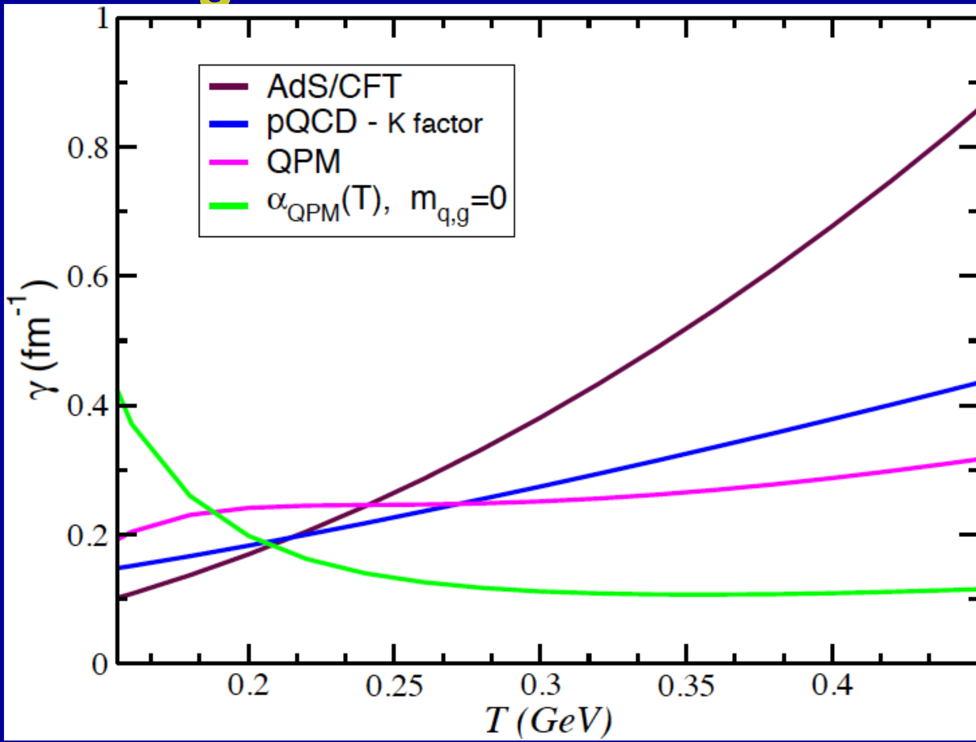
[S.Plumari et al PRD 84 094004 (2011)]

✓ **a_{QPM}(T) , $m_{q,g}$=0**

we mean simply the coupling of the QPM, but with a bulk of massless q and g

T- dependence of the Drag Coefficient

Drag Coefficient



Model independent discussion within a Fokker-Planck dynamics

It is only a way to have different Temperature Dependence of the drag coefficent

- ✓ **pQCD** *(Combridge cross-section)*

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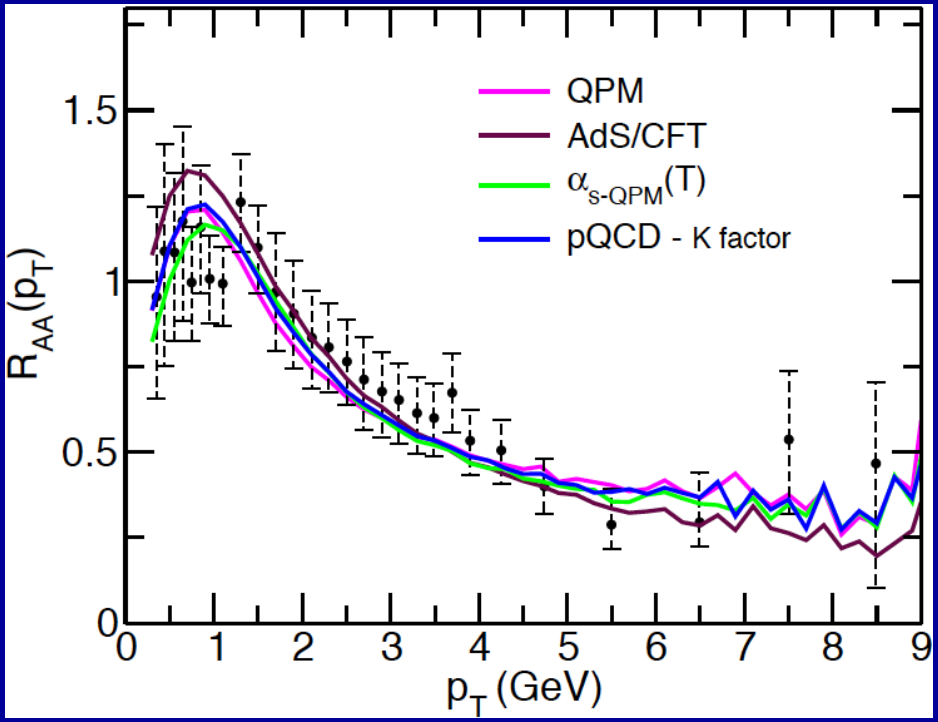
- ✓ **$\alpha_{QPM}(T)$, $m_{q,g}=0$**

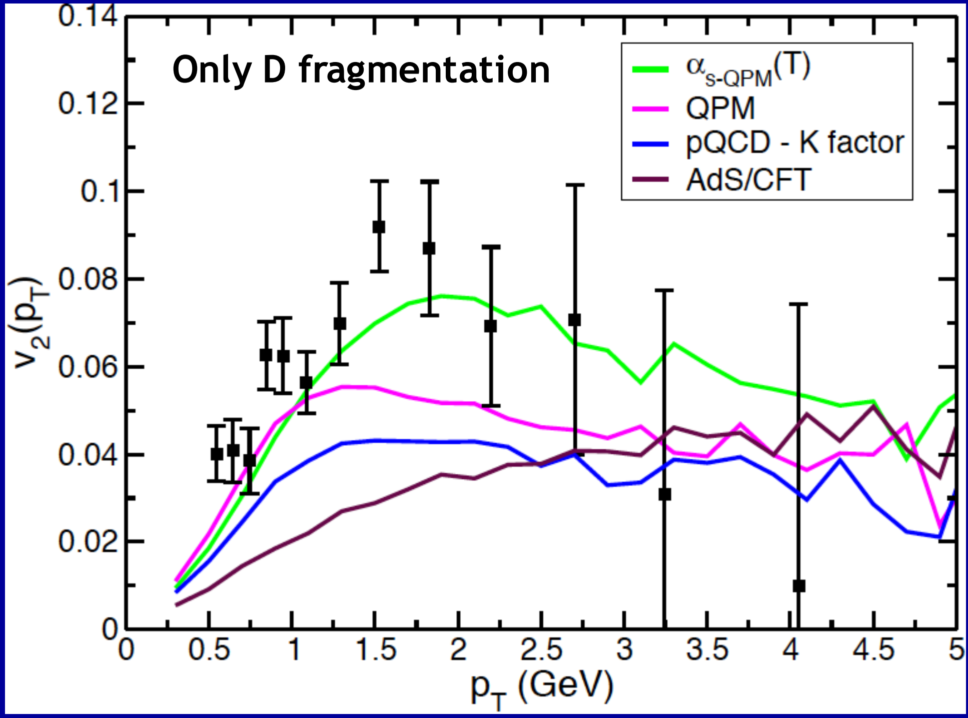
we mean simply the coupling of the QPM, but with a bulk of massless q and g

Impact of T-dependence of the Drag

Au+Au@200AGeV, b=8 fm

Interaction rescaled to have very similar R_{AA} for all the cases



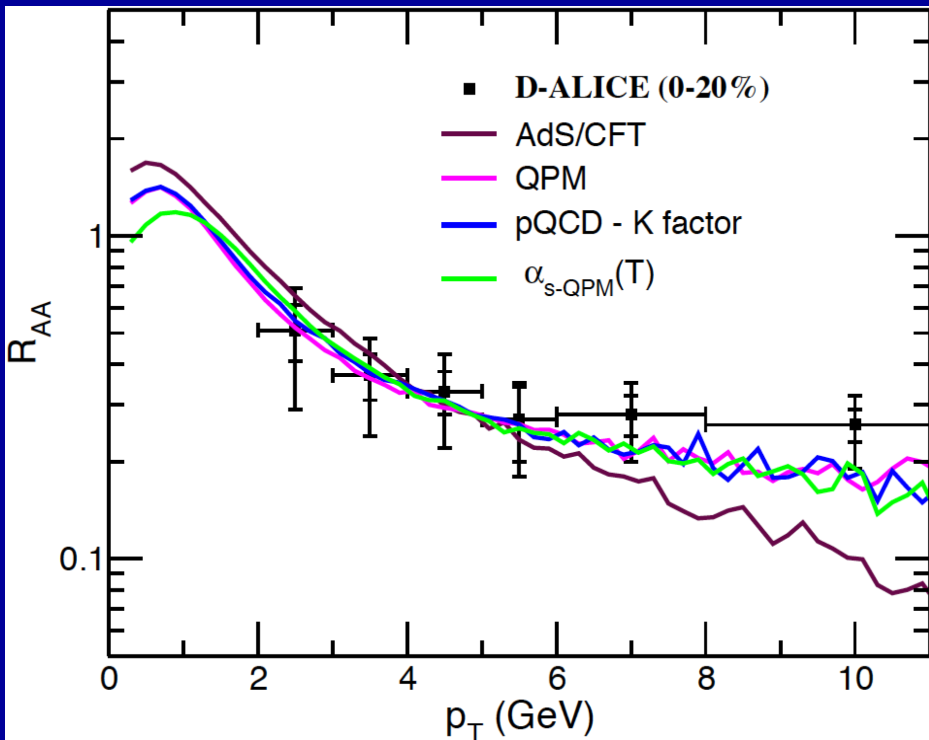


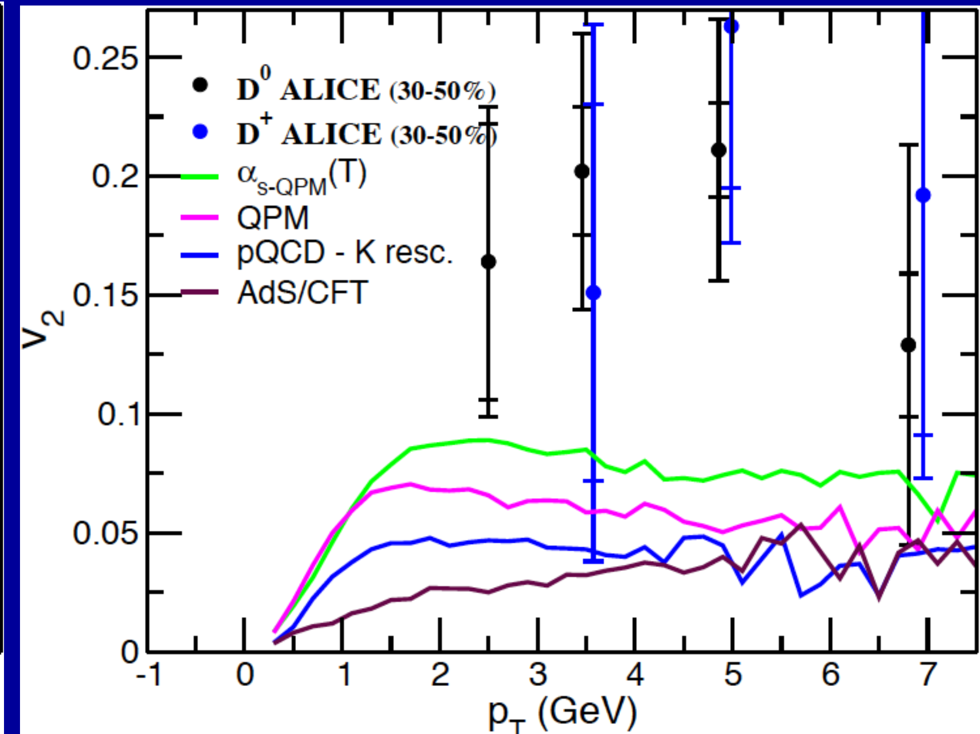
- $R_{AA}(p_T)$ well reproduced whatever is the T-dependence
- At fixed $R_{AA}(p_T)$ -> $v_2(p_T)$ is larger if γ is larger at low T

[Scardina et al PLB747 (2015) 260-264]

Impact of T-dependence of the Drag

LHC - Pb+Pb@2.76ATeV





- Similar trends as for RHIC case

[Scardina et al PLB747 (2015) 260-264]

Boltzmann approach

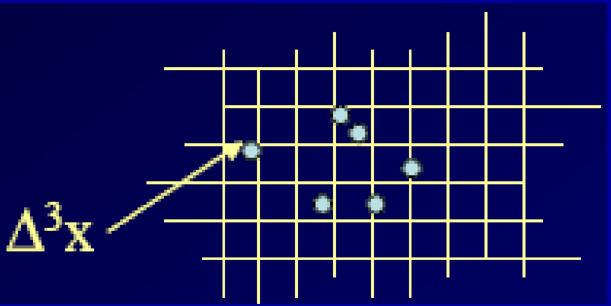
$$\underbrace{p^{\mu}\partial_{\mu} f(x,p)}_{\text{Free-streaming}} + \underbrace{M(X)\partial_{\mu} M(X)\partial_{p}^{\mu} f(X,p)}_{\text{Mean Field}} = \underbrace{C_{22}}_{\text{Collisions}}$$

$$\frac{\partial f}{\partial t} + \vec{v}\cdot\nabla_{r} f + \vec{F}\cdot\nabla_{p} f = C_{22}$$

Classic Boltzmann equation

Describes the evolution of the one body distribution function f(x,p)

It is valid to study the evolution of both bulk and Heavy quarks



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)

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

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

The Collision integral is solved by means of a stochastic algorithm

Boltzmann vs Fokker Planck approach

The Fokker Planck eq can be derived from the B-E making an expansion of the collision integral in terms of the trasfered momentum k

B-E

$$\left(\frac{\partial}{\partial t}+\frac{P}{E}\frac{\partial}{\partial x}\right)f\left(x,p,t\right)=C_{22}$$

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

If |k|<< |P|

$$\omega(p+k,k)f(p+k)\approx\omega(p,k)f(p)+k.\frac{\partial}{\partial p}(\omega f)+\frac{1}{2}k_ik_j\frac{\partial^2}{\partial p_i\partial p_j}(\omega f)$$

F-P

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

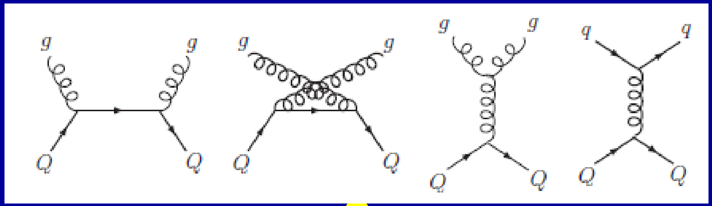
The Fokker-Planck equation is equivalent to an ordinary stochastic differential equation

$$dx_j=\frac{p_j}{E}dt$$

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

Evaluation of Drag and diffussion

Common approach between LV and BM



The infrared singularity is regularized introducing a Debye-screaning-mass m_D

$$\frac{1}{t} \rightarrow \frac{1}{t-m_D}$$

Langevin approach

For Collision Process the A_i and B_{ij} can be calculated as following :

M -> A_i, B_{ij}

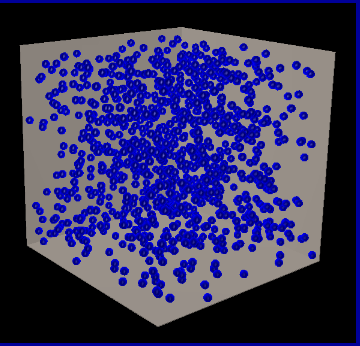
$$A_i = \frac{1}{2E_p}\int\frac{d^3q}{(2\pi)^3 2E_q}\int\frac{d^3q'}{(2\pi)^3 2E_{q'}}\int\frac{d^3p'}{(2\pi)^3 2E_{p'}}\frac{1}{\gamma_c}\sum|M|^2$$
$$(2\pi)^4\delta^4(p+q-p'-q')f(q)[(p-p')_i] = \langle\langle(p-p')_i\rangle\rangle$$

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

Boltzmann approach

M -> σ

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

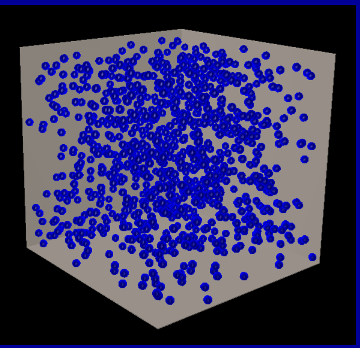


Boltzmann vs Langevin

static medium

T=400 MeV

We have considered different average momentum transferred <-> different m_D



Boltzmann vs Langevin

static medium

T=400 MeV

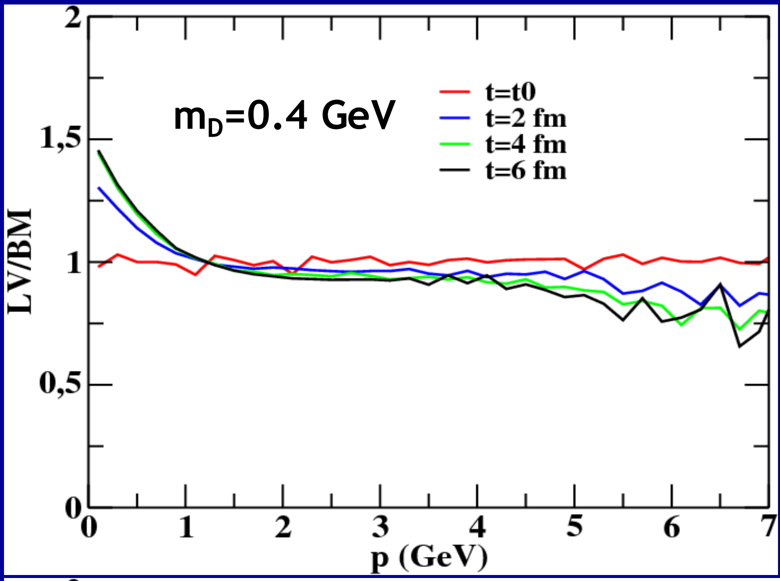
We have considered different average momentum transferred <-> different m_D

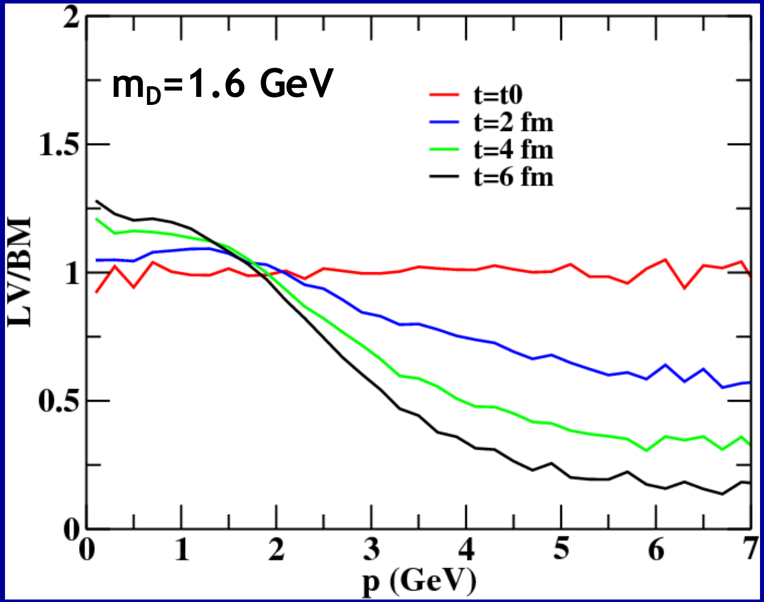
We have plotted the results as a ratio between:

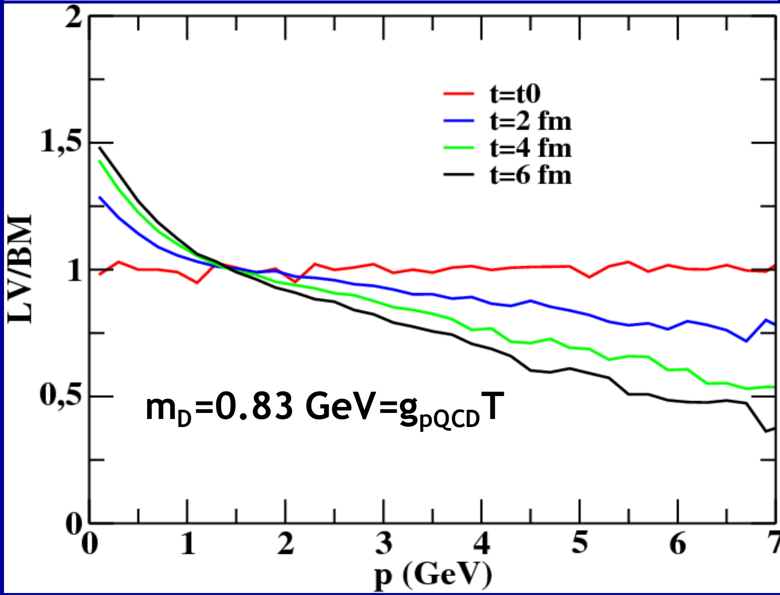
$$\frac{dN}{d^3p}^{Langevin} \Big/ \frac{dN}{d^3p}^{Boltzmann}$$

at different time

to quantify how much the ratio differs from 1

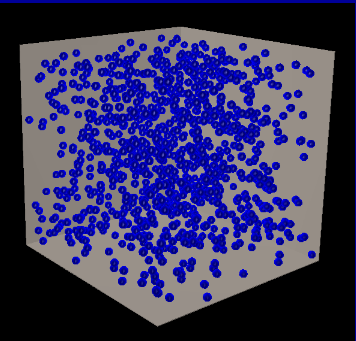






[S. K. Das , F. Scardina, V. Greco PRC90 044901 (2014)]

Boltzmann vs Langevin

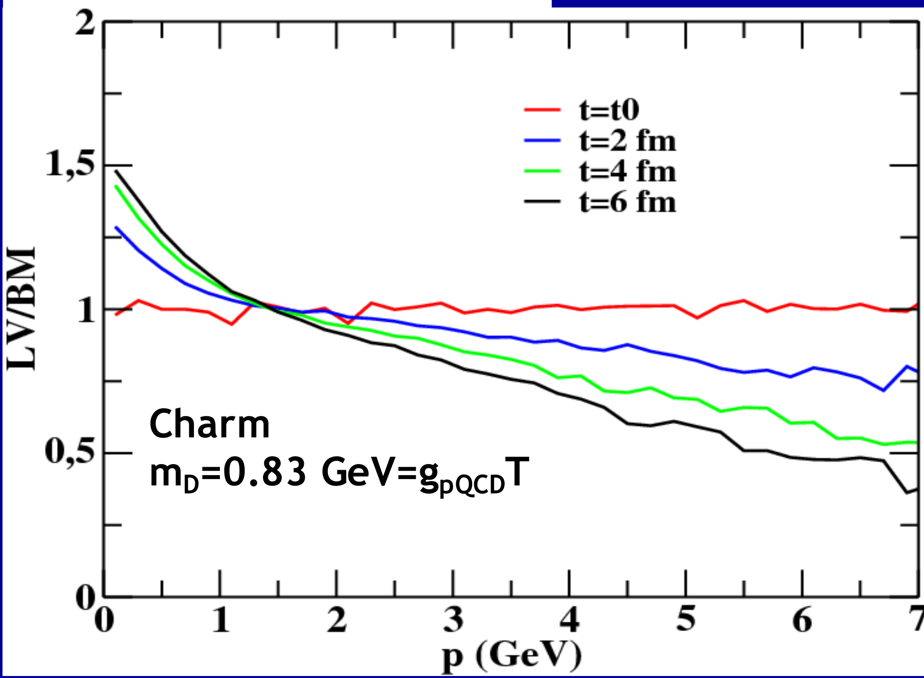


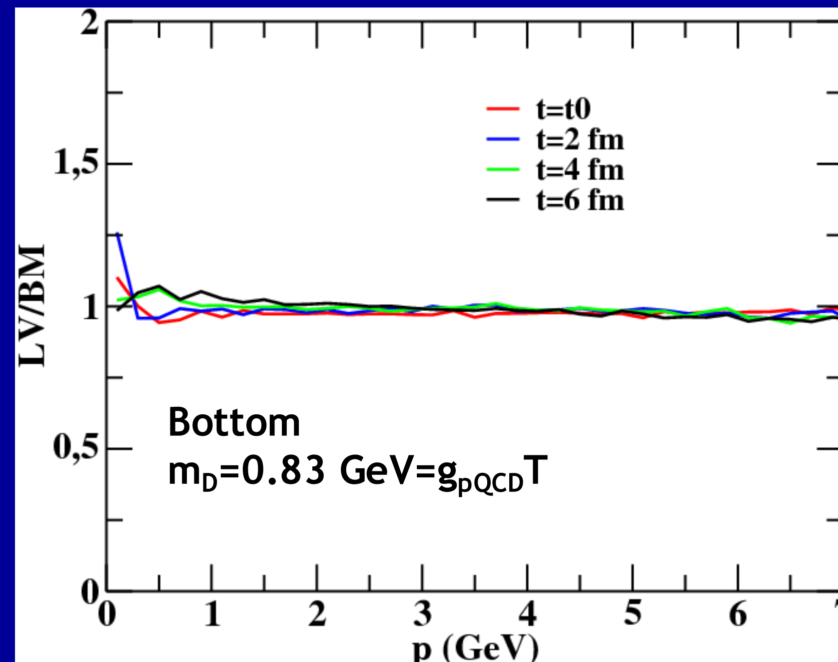
static medium

T=400 MeV

We have plotted the results as a ratio between LV and BM at different time to quantify how much the ratio differs from 1

$$\left.\frac{dN}{d^3p}^{Langevin}\right/\frac{dN}{d^3p}^{Boltzmann}$$





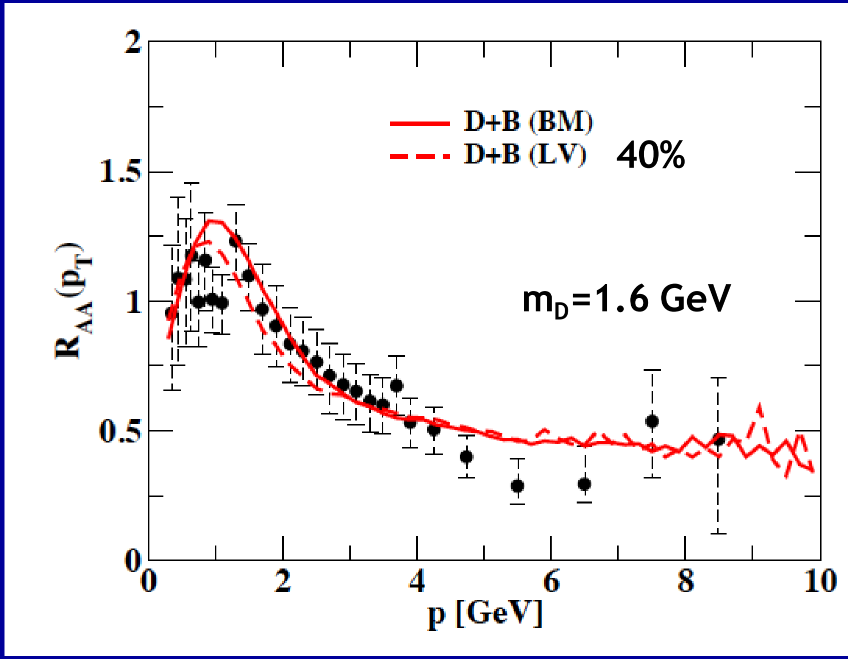
The differences between BM and LV depends on:

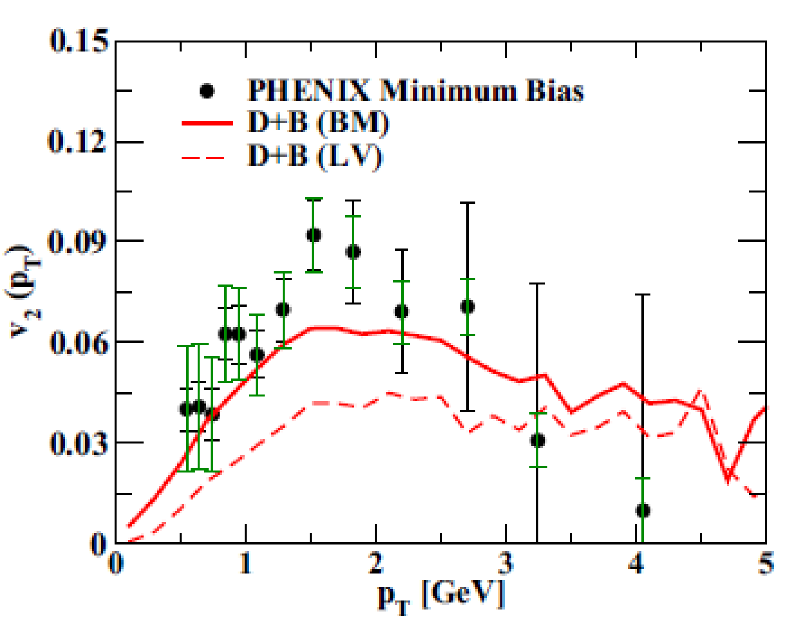
- Average momentum transferred
- Mass

[S. K. Das , F. Scardina, V. Greco PRC90 044901 (2014)]

R_{AA} and v_2 Boltzmann vs Langevin

Au+Au@200AGeV, b=8 fm





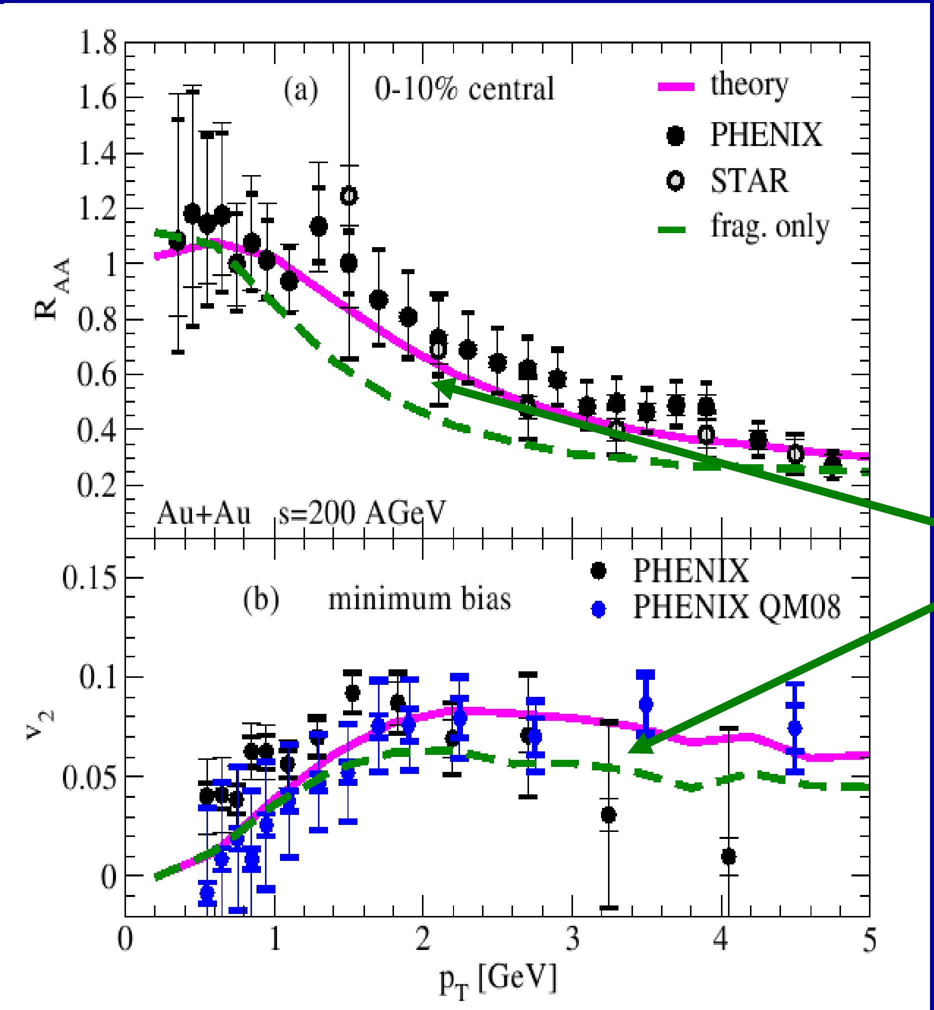
- ✓ Fixed same $R_{AA}(p_T)$ [reduce the drag by 40%]

Same R_{AA} but different v_2

The differences between F-P and BM are larger for a more differential observable like the v_2

[S. K. Das , F. Scardina, V. Greco PRC90 044901 (2014)]

Impact of hadronization mechanism



Impact of hadronization

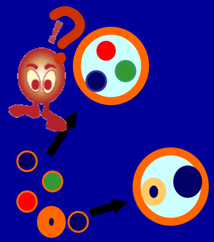
Coalescence increase both R_{AA} and v_2 reverse the correlation toward agreement with data

Hees-Mannarelli-Greco-Rapp, PRL100 (2008)

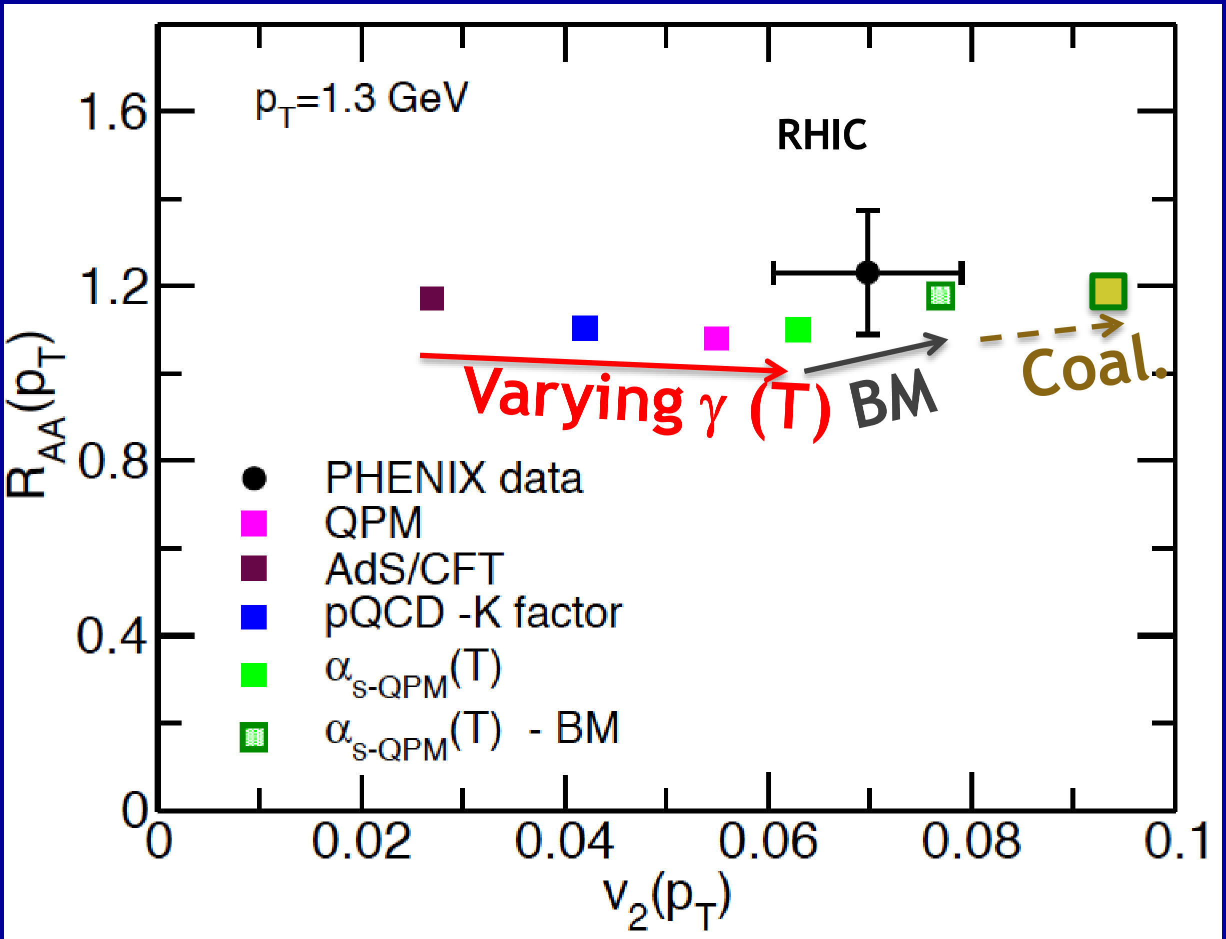
$$\frac{d^3N_{D,B}}{d^3P} = C_{D,B}\int_{\Sigma} f_{c,b} \otimes f_{\bar{q}} \otimes \Phi_M + \int_{\Sigma} f_{c,b} \otimes D_{c,b\to D,B}$$

f_q from π, K

Greco,Ko,Levai - PRL90

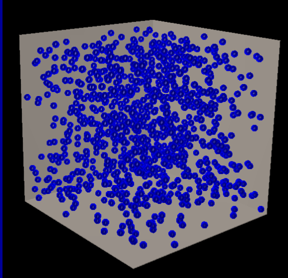


Summary on the build-up of v_2 at fixed R_{AA}



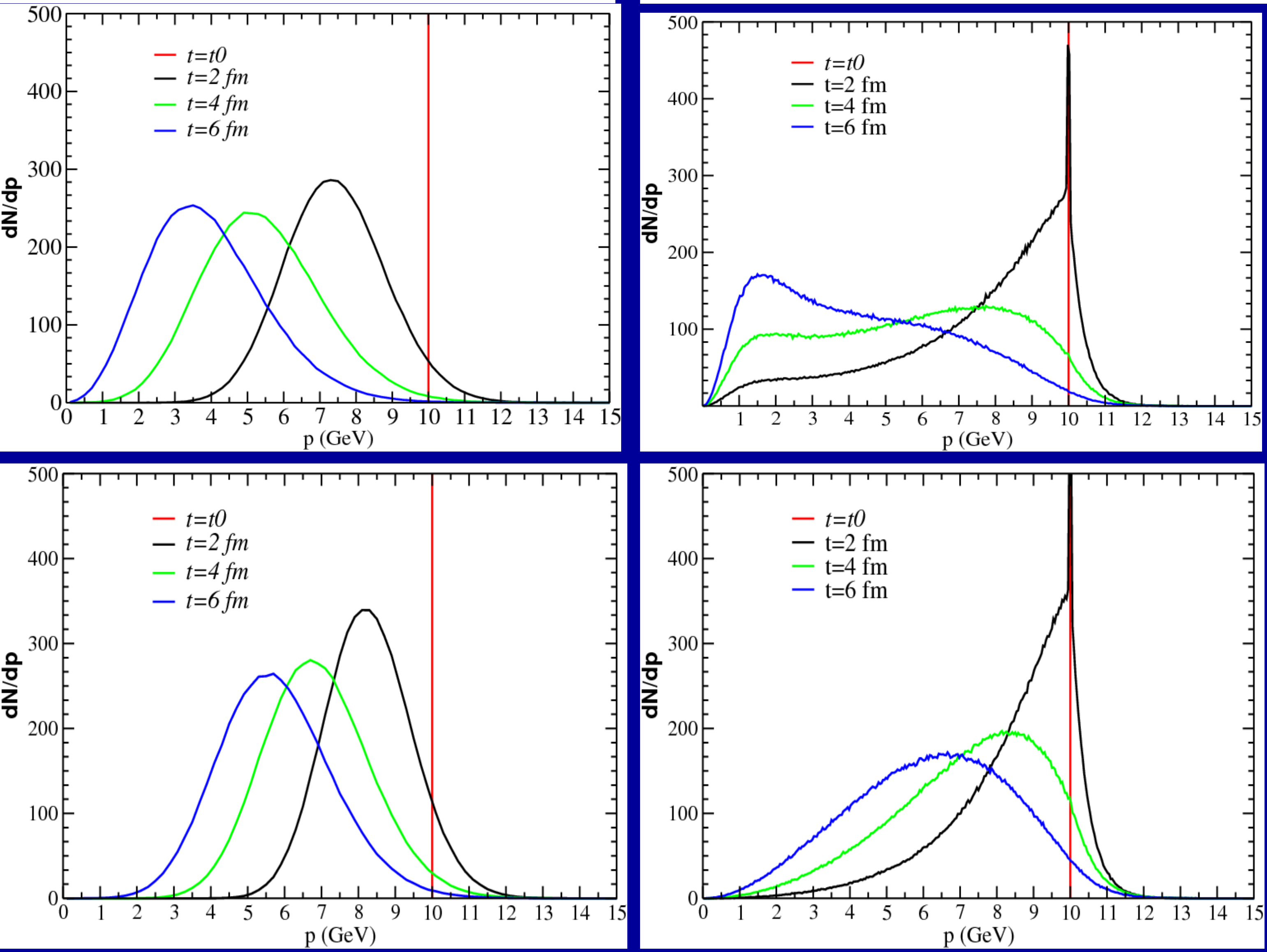
R_{AA} and V_2 are correlated but still one can have
R_{AA} about the same while V_2 can change up to a factor 3:
$\gamma(T)$ + Boltzmann dynamics+ hadronization

LV vs BM approach: Energy loss of a single HQ



Static medium
T=400 MeV

Langevin	Boltzmann



Charm

$M_c/T \approx 3$

Bottom

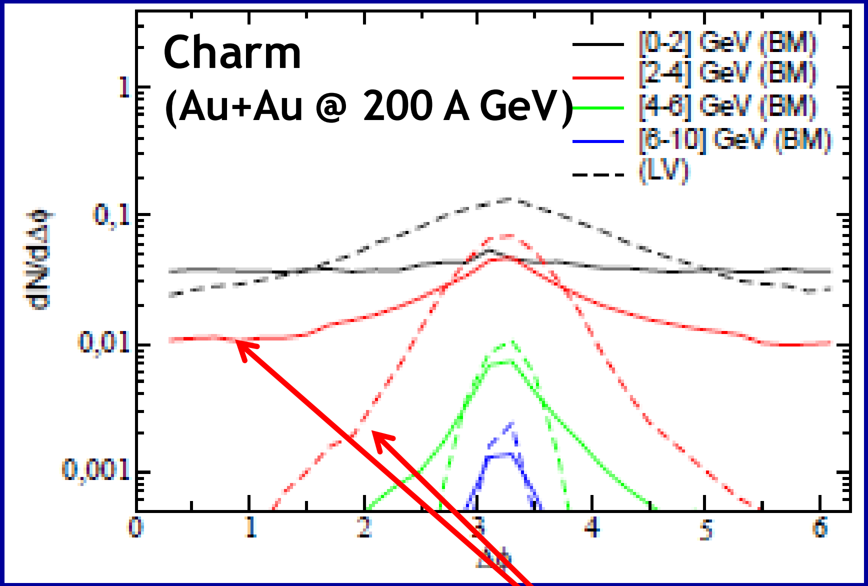
$M_b/T \approx 10$

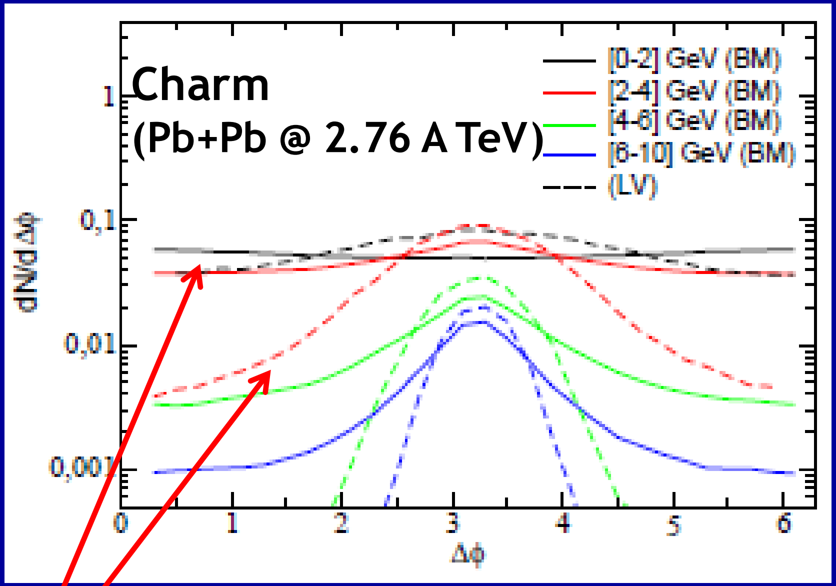
T=400 MeV Mc/T≈3 Mb/T≈10 [F. ScardinaJ.Phys.Conf.Ser. 535 (2014) 012019]

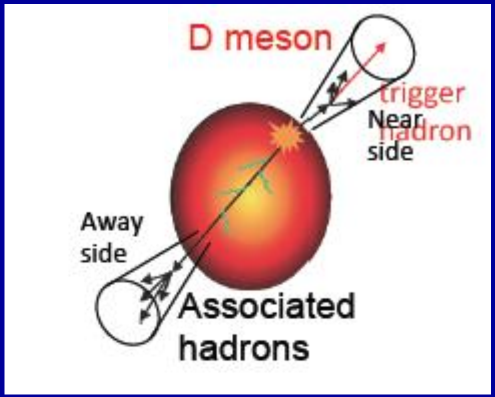
Langevin vs Boltzmann angular correlation

Initially the $c\text{-}\bar{c}$ and $b\text{-}\bar{b}$ are distributed back to back (LO)

We have fixed the RAA on exp. data for both the two approaches



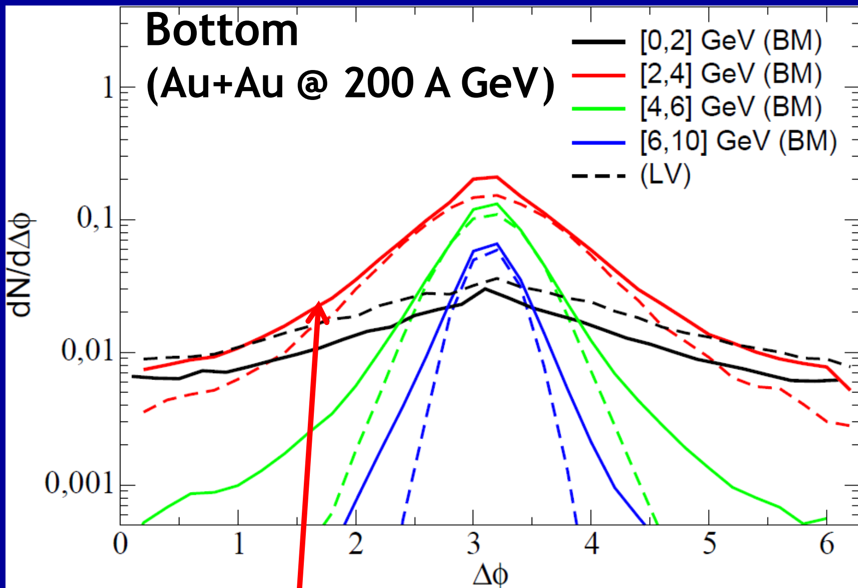


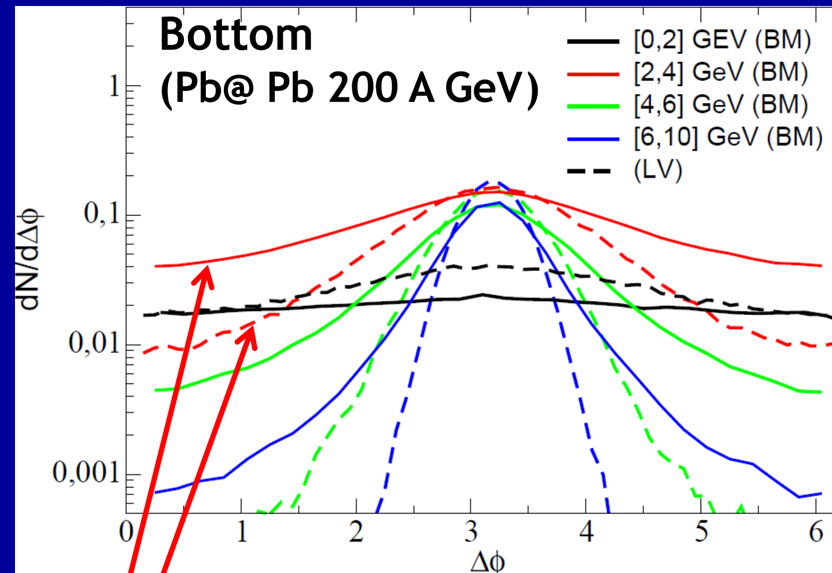


A difference of an order of magnitude

Langevin vs Boltzmann angular correlation

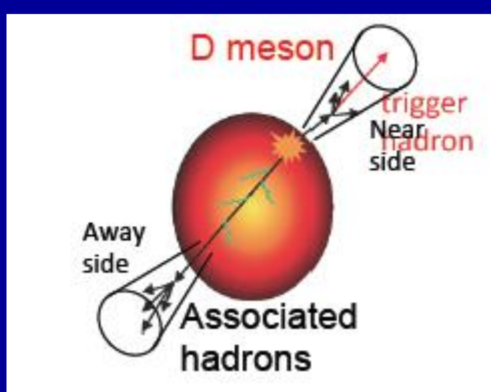
Initially the c-$\bar{c}$ and b-$\bar{b}$ are distributed back to back (LO)





There are not differences at RHIC

Significant differences at LHC



Summary

- ✓ The exp. data for R_{AA} and v_2 seem to indicate an interaction about constant in T

- ✓ The more one looks at differential observables R_{AA}->V_2-> $dN_{cc}/d\Delta\phi$ the more the differences between the BM and F-P approach increases

- ✓ We can realize that charm in hot QGP is not that heavy and the motion not really Brownian

- ✓ Very similar dynamics between F-P and BM for Bottom at least for R_{AA} and V_2 , not negligible differences instead for azimuthal correlations especially at LHC