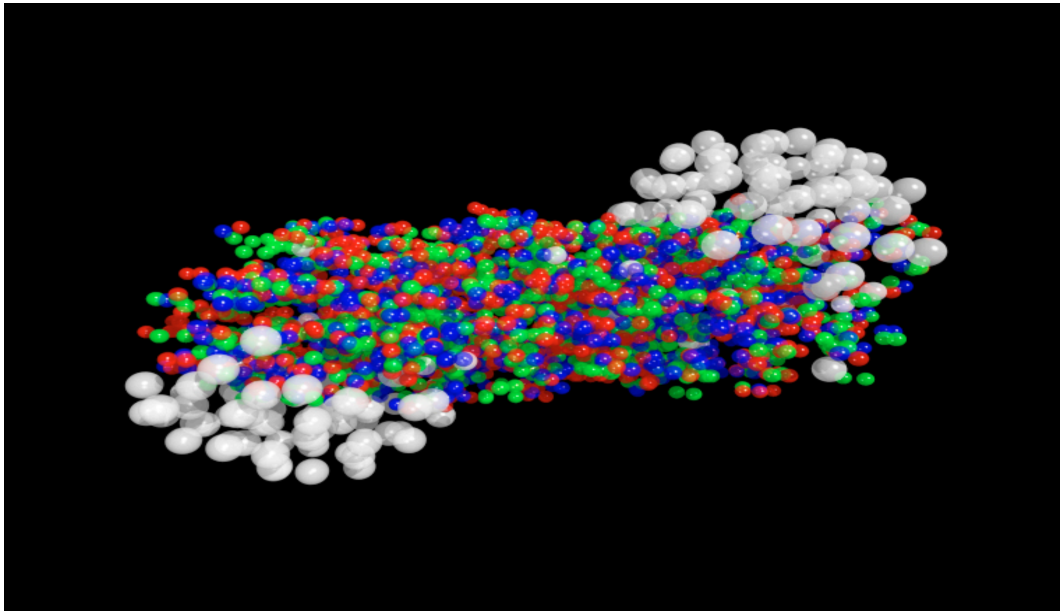
University of Catania
INFN-LNS

Toward a understanding to RAA and v2 puzzle for heavy quarks



Santosh Kumar Das

In collaboration with: Vincenzo Greco
Francesco Scadina
Salvatore Plumari

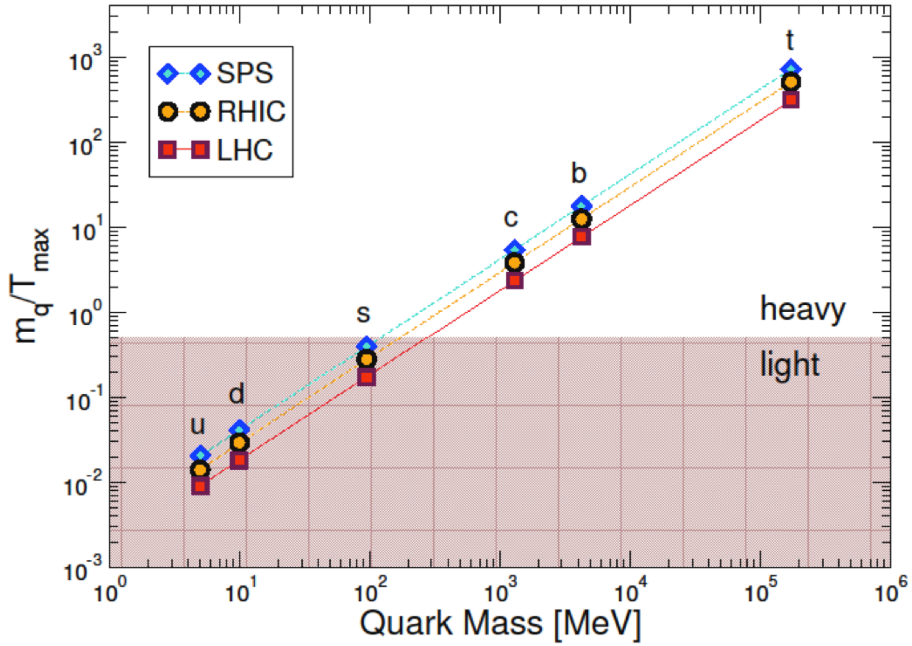
SQM DUBNA 2015

Outline of my talk…………..

- **Introduction**
- **Impact of T dependence drag on heavy quarks observables**
  - **I) Nuclear suppression factor**
  - **II) Elliptic flow**
- **RAA vs v2**
  - **1) Evolution: Langevin vs Boltzmann**
  - **2) Hadronization: Coalescence vs Fragmentation**
  - **3) Hadronic medium**
- **Impact of pre-equilibrium phase?**
- **Summary and outlook**

Heavy Quark & QGP

At very high density and temperature hadrons melt to a new phase of matter called Quark Gluon Plasma (QGP).



SPS to LHC

$\sqrt{s} = 17.3 GeV\ to\ 2.76 TeV$ **~100 times**

$T_i = 200\ MeV\ to\ 600\ MeV$ **~3 times**

$M_{c,b} >> \Lambda_{QCD}$ **Produced by pQCD process (out of Equil.)**

$\tau_{c,b} >> \tau_{QGP}$ **They go through all the QGP life time**

$M_{c,b} >> T_0$ **No thermal production**

Boltzmann Kinetic equation

$$\left(\frac{\partial}{\partial t}+\frac{P}{E}\frac{\partial}{\partial x}+\mathrm{F}.\frac{\partial}{\partial p}\right)f(x,p,t)=\left(\frac{\partial f}{\partial t}\right)_{col}$$

- The plasma is uniform ,i.e., the distribution function is independent of x.
- In the absence of any external force, F=0

$$R(p,t)=\left(\frac{\partial f}{\partial t}\right)_{col}=\int d^3k\left[\omega(p+k,k)f(p+k)-\omega(p,k)f(p)\right]$$

$$\omega(p,k)=g\int\frac{d^3q}{(2\pi)^3}f'(q)v_{q,p}\sigma_{p,q\to p-k,q+k}$$ → is rate of collisions which change the momentum of the charmed quark from p to p-k

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

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

B. Svetitsky PRD 37(1987)2484

where we have defined the kernels ,

$$\mathbf{A_i}=\int \mathbf{d^3k}\,\omega(\mathbf{p},\mathbf{k})\mathbf{k_i}$$ → **Drag Coefficient**

$$\mathbf{B_{ij}}=\int \mathbf{d^3k}\,\omega(\mathbf{p},\mathbf{k})\mathbf{k_i}\mathbf{k_j}$$ → **Diffusion Coefficient**

Langevin Equation

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

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

where Γ **is the deterministic friction (drag) force**

C_{ij} **is stochastic force in terms of independent**

Gaussian-normal distributed random variable

$$\rho = (\rho_x, \rho_y, \rho_z) \quad , \quad P(\rho) = \left(\frac{1}{2\pi}\right)^3 \exp\left(-\frac{\rho^2}{2}\right)$$

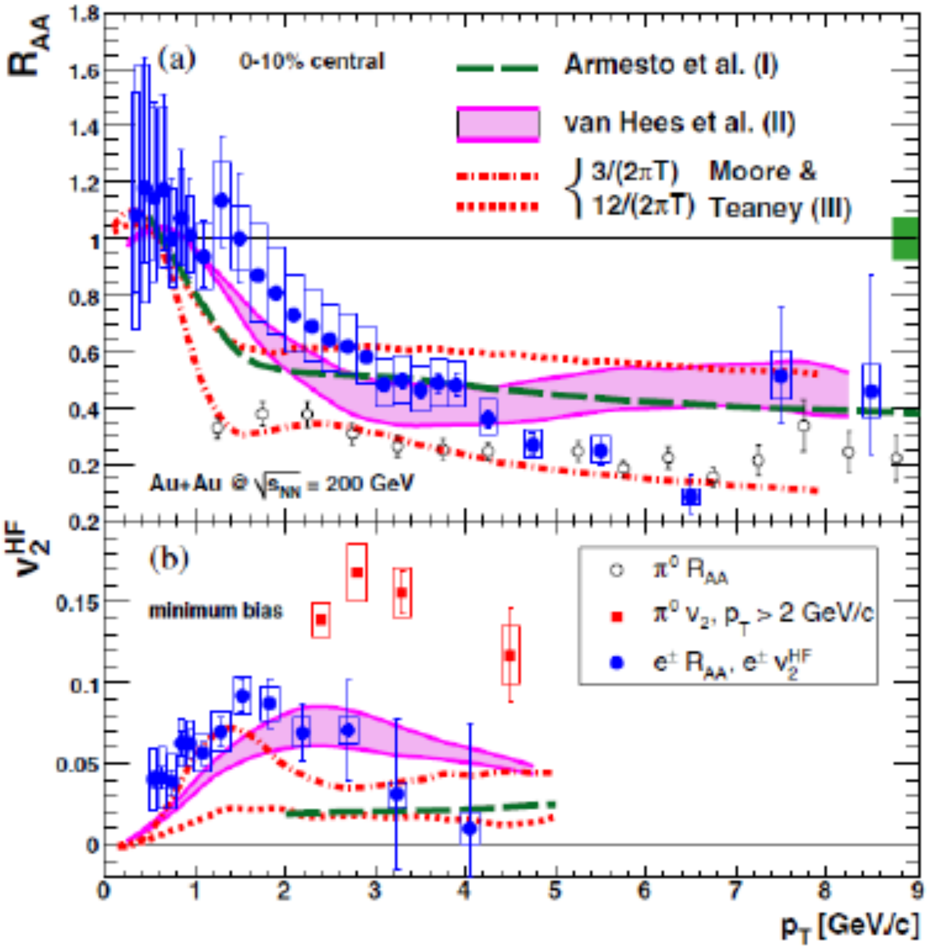
With $< \rho_i(t)\rho_k(t') >= \delta(t - t')\delta_{jk}$

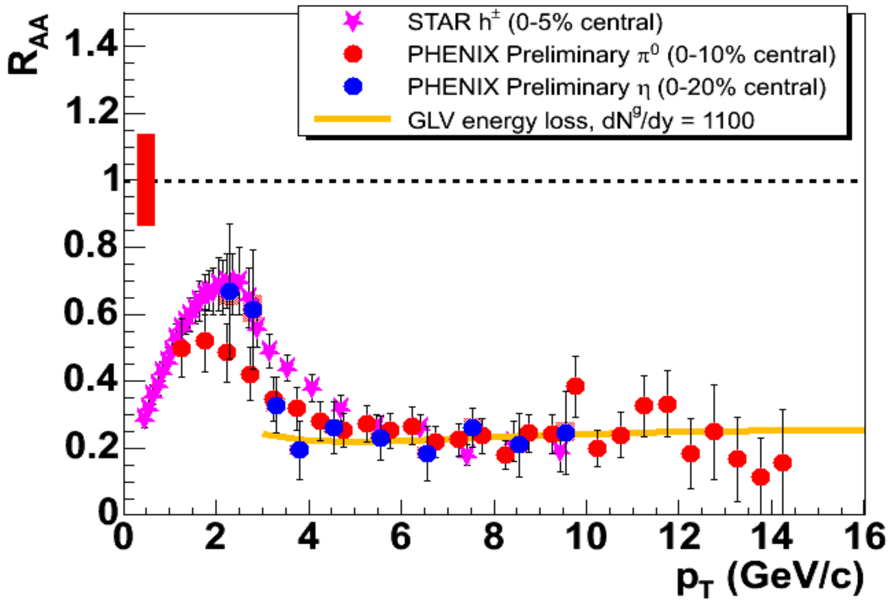
H. v. Hees and R. Rapp
arXiv:0903.1096

$\xi = 0$ **the pre-point Ito**

interpretation of the momentum argument of the covariance matrix.

Heavy flavor at RHIC



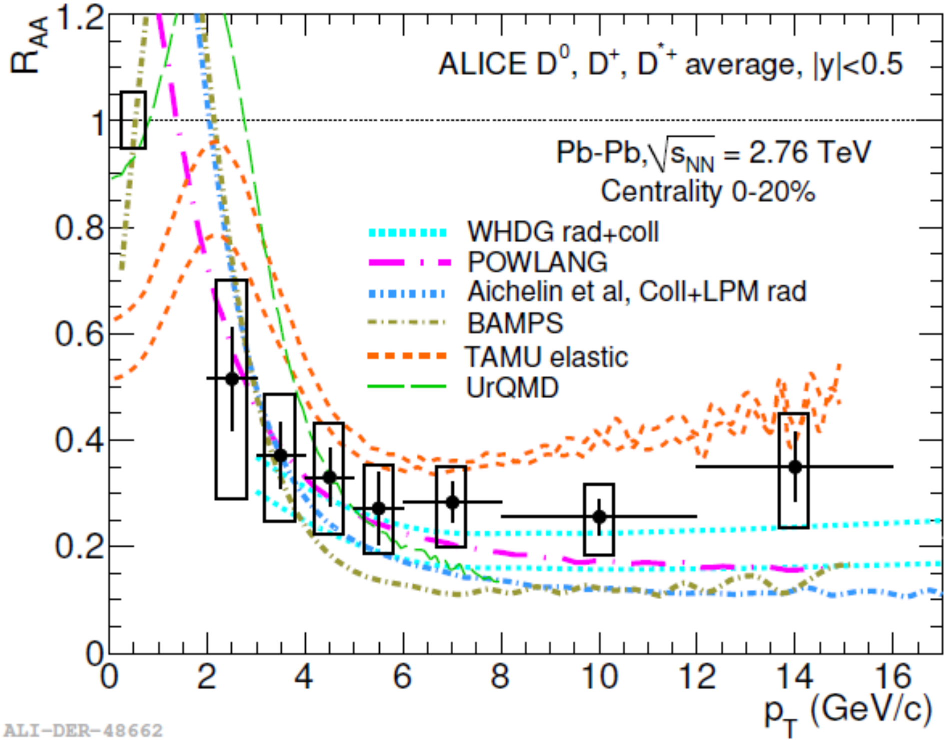


At RHIC energy heavy flavor suppression is similar to light flavor

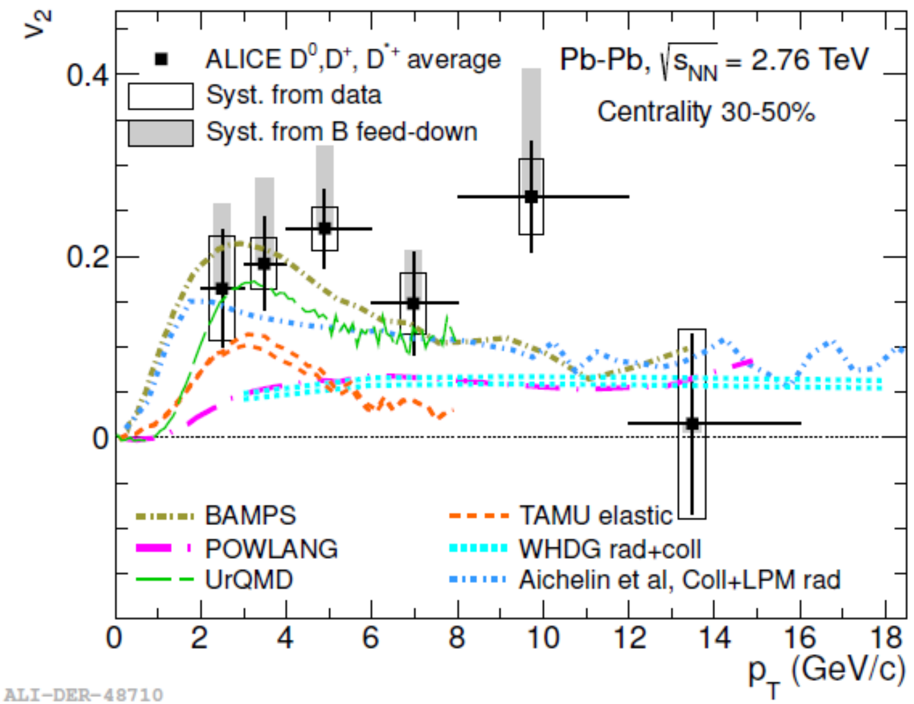
Simultaneous description of RAA and v2 is a tough challenge for all the models.

Heavy Flavors at LHC

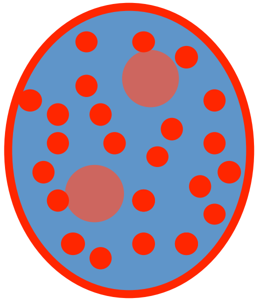
JHEP **1209** (2012) 112



arXiv:1305.2707

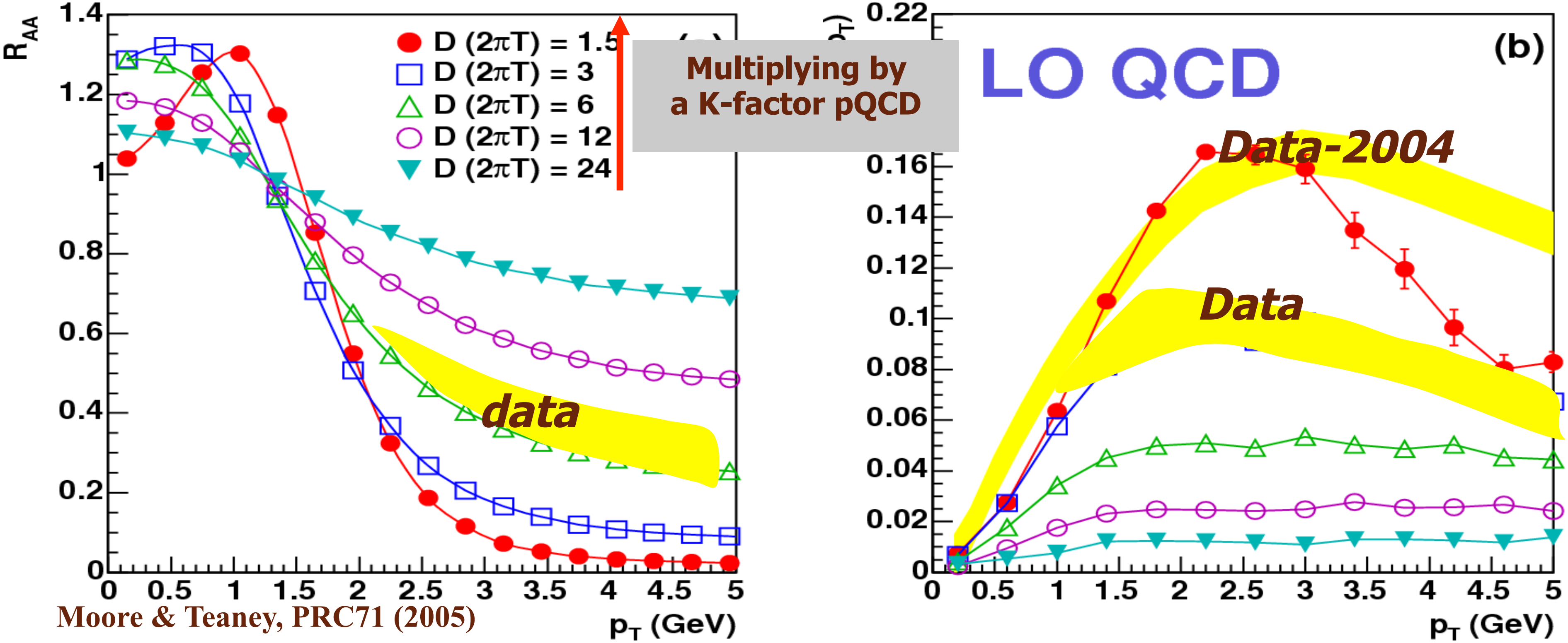


Charm dynamics with upscaled pQCD cross section



Fokker-Plank for charm interaction in a hydro bulk

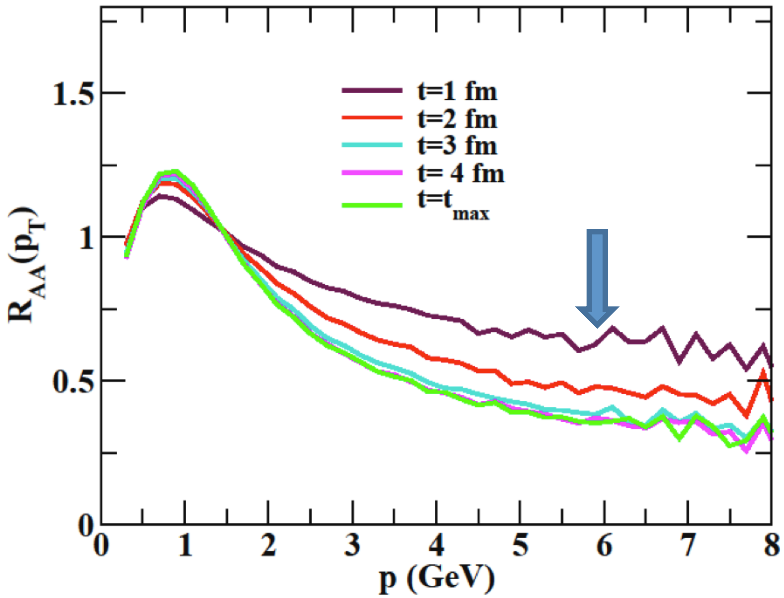
$$D \propto \int d^3k \left| M_{g(q)c \to g(q)c}(k,p) \right|^2 k^2$$

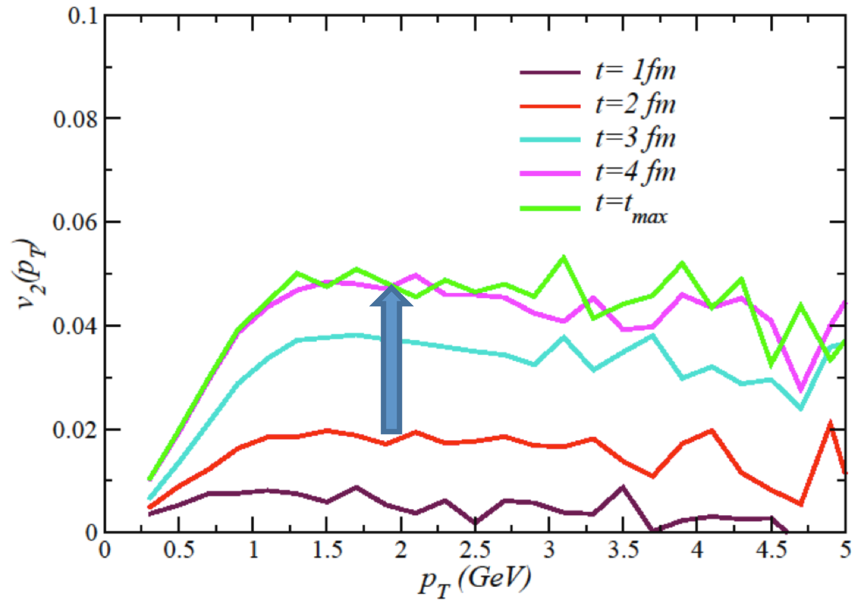


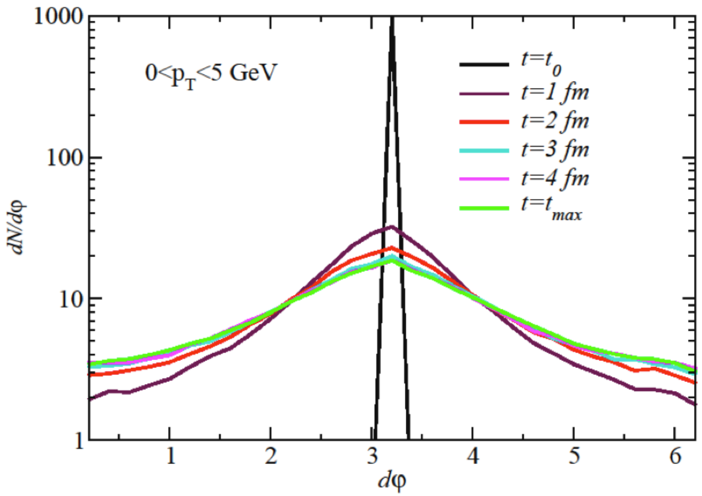
Moore & Teaney, PRC71 (2005)

It's not just a matter of pumping up pQCD elastic cross section: too low R_{AA} or too low v_2

Time evolution of Heavy quarks observables







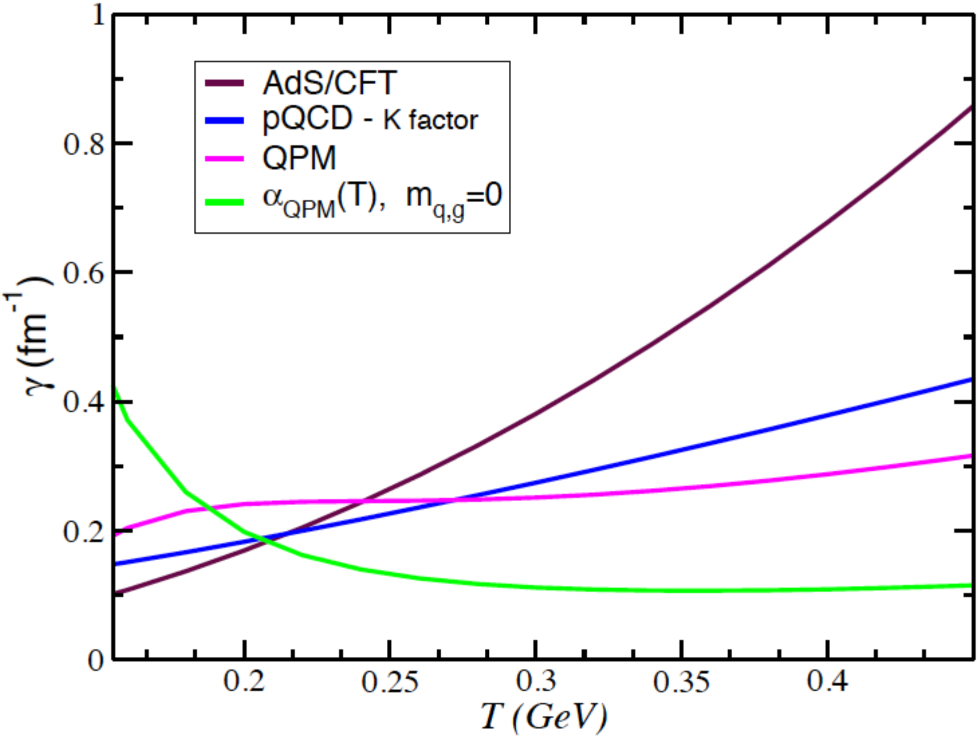
RAA and dN/dphi_ccbar developed during the early stage of the evolution → T_i

V2 developed duringing the later stage of the evolution → T_c

T dependence of the interaction i.e the transport Coefficients are the essential ingradiant for the symultanious description of HQ observabbles

T- dependence of the Drag Coefficient

Drag Coefficient



Das, Scardina, Plumari, Greco
PLB 747 (2015)260-264

Plumari at. al. PRD, 84, 094004 (2011)

Berrehrah et. al, PRC, 89, 054901 (2014)

pQCD *(Combridge)*

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

AdS/CFT

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

Gubser
PRD,74,126005 (2006)
Akamatsu, Hatsuda, Hirano
PRC, 79, 054907 (2009)
Das and Davody
PRC, 89,054912 (2014)

Quasi-Particle-Model *(fit to lQCD ε,P)*

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

λ=2.6
T_s=0.57

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

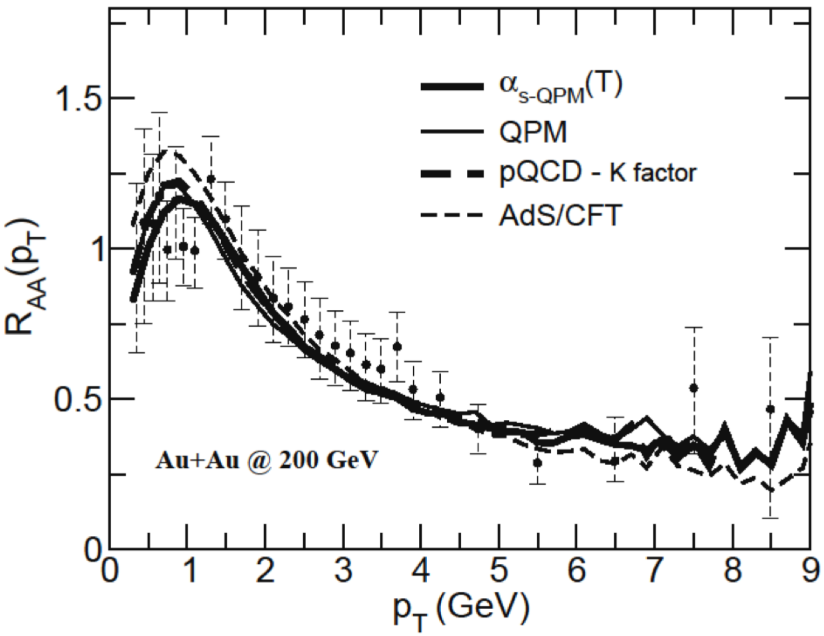
$$m_q^2 = \frac{N_c^2 - 1}{8N_c}g^2T^2$$

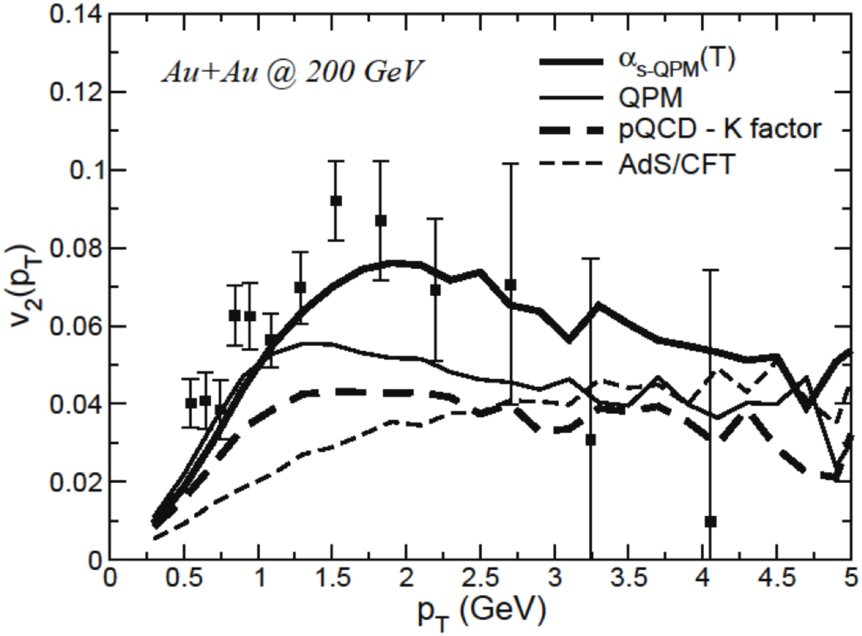
α_{QPM}(T) , $m_{q,g}$=0

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

RAA and v2 @ RHIC

(Au+Au@200AGeV, b=8 fm)





Das, Scardina, Plumari, Greco
PLB 747 (2016)260-264

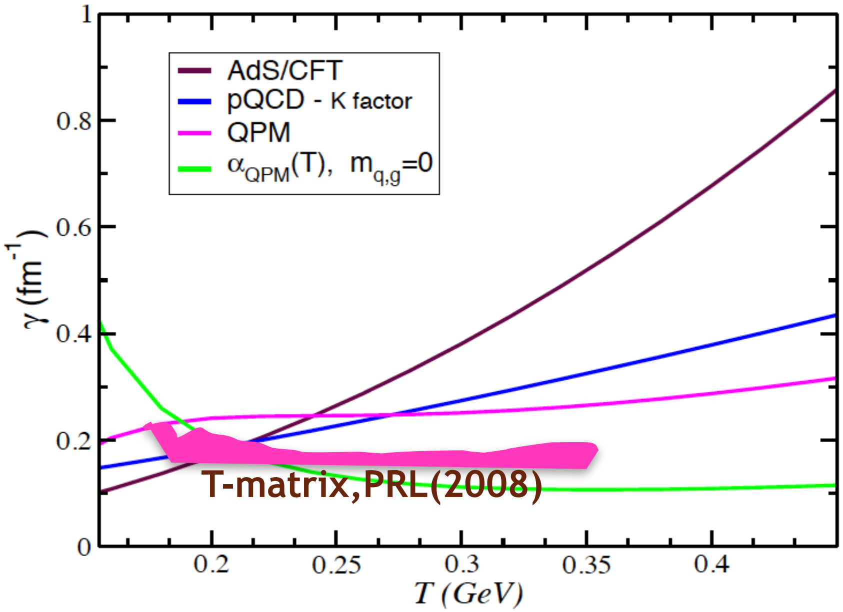
Light flavor sector:

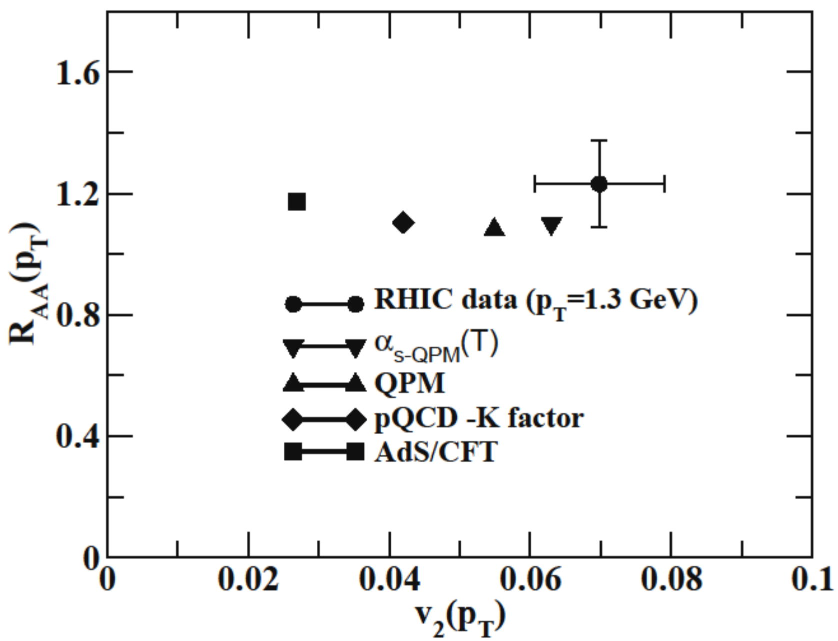
Liao, Shuryak, PRL102 (2009) 202302

Scardina, Toro, Greco, PRC,82 (2010) 054901

Xu, Liao, Gyulass y, arXiv:1411.3637

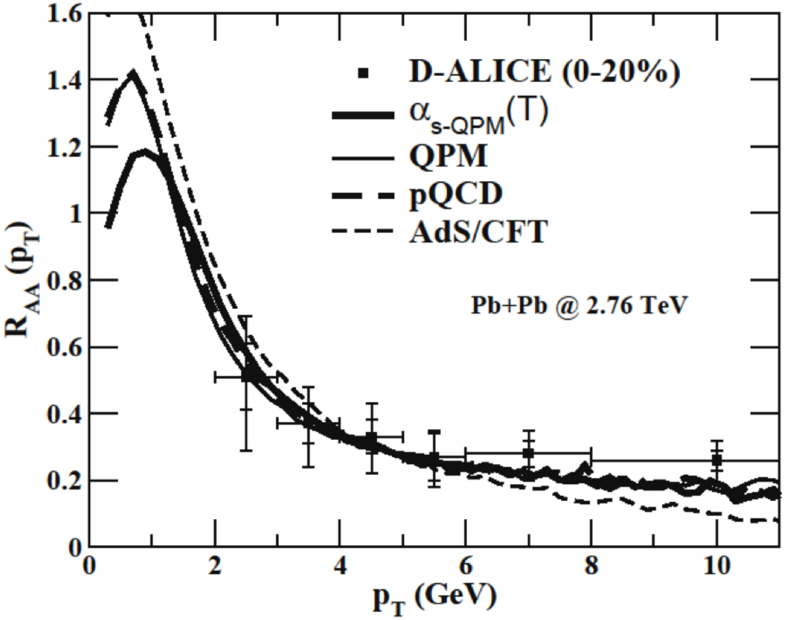
RAA vs v2 @ RHIC (Au+Au 200 GeV)

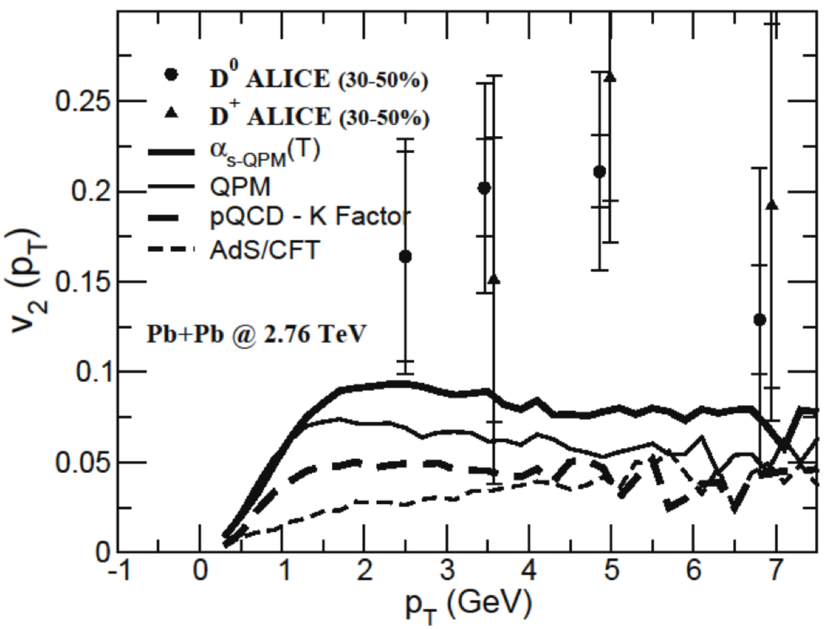




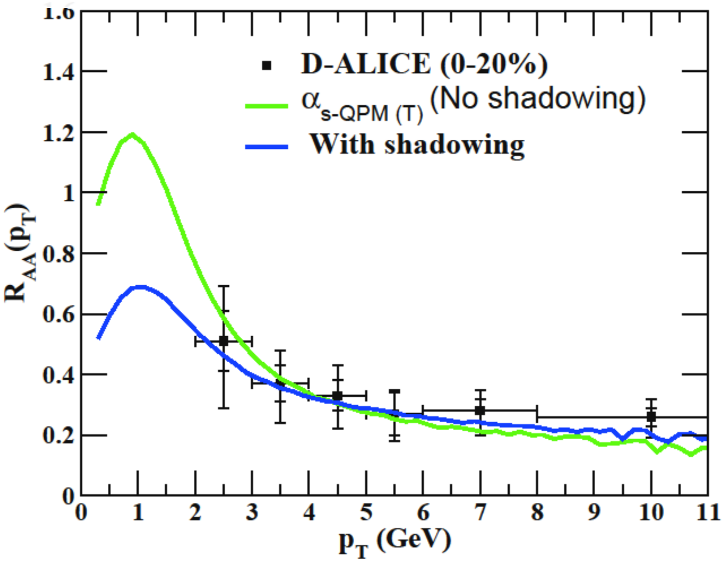
Das, Scardina, Plumari, Greco
PLB 747 (2016)260-264

RAA and v2 @ ALICE





Das, Scardina, Plumari, Greco
PLB 747 (2015) 260-264



Eskola, Paukkunen, Salgado
JHEP,0807, 102 (2008)

❖ **RAA vs v2**

1) **Evolution: Langevin vs Boltzmann**

2) **Hadronization: Coalescence vs Fragmentation**

3) **Hadronic medium**

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

Boltzmann Equation **Fokker Planck**

It will be interesting to study both the equation in a identical environment to ensure the validity of this assumption at different momentum transfer and their subsequent effects on RAA and v2.

Langevin dynamics:

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

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

H. v. Hees and R. Rapp
arXiv:0903.1096

Γ **is the deterministic friction (drag) force**

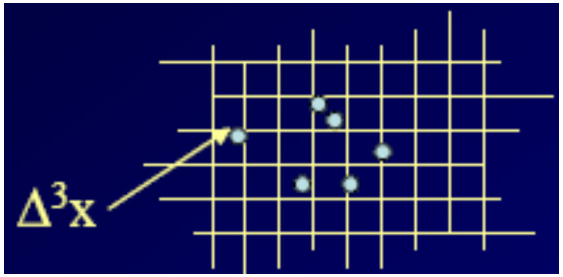
C_{ij} **is stochastic force in terms of independent Gaussian-normal distributed random variable.**

Transport theory

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

We consider two body collisions

$$C_{22} = \frac{1}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int\frac{d^3p_1'}{(2\pi)^3 2E_1'}\frac{d^3p_2'}{(2\pi)^3 2E_2'}f_1'f_2'|\mathcal{M}_{1'2'\to 12}|^2(2\pi)^4\delta^{(4)}(p_1'+p_2'-p_1-p_2)$$
$$-\frac{1}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int\frac{d^3p_1'}{(2\pi)^3 2E_1'}\frac{d^3p_2'}{(2\pi)^3 2E_2'}f_1f_2|\mathcal{M}_{12\to 1'2'}|^2(2\pi)^4\delta^{(4)}(p_1+p_2-p_1'-p_2')$$



$$\Delta t \to 0$$

$$\Delta^3 x \to 0$$

Exact solution

Collision integral is solved with a local stochastic sampling

[Z. Xhu, et al. PRC71(04)]
Greco et al PLB670, 325 (08)]

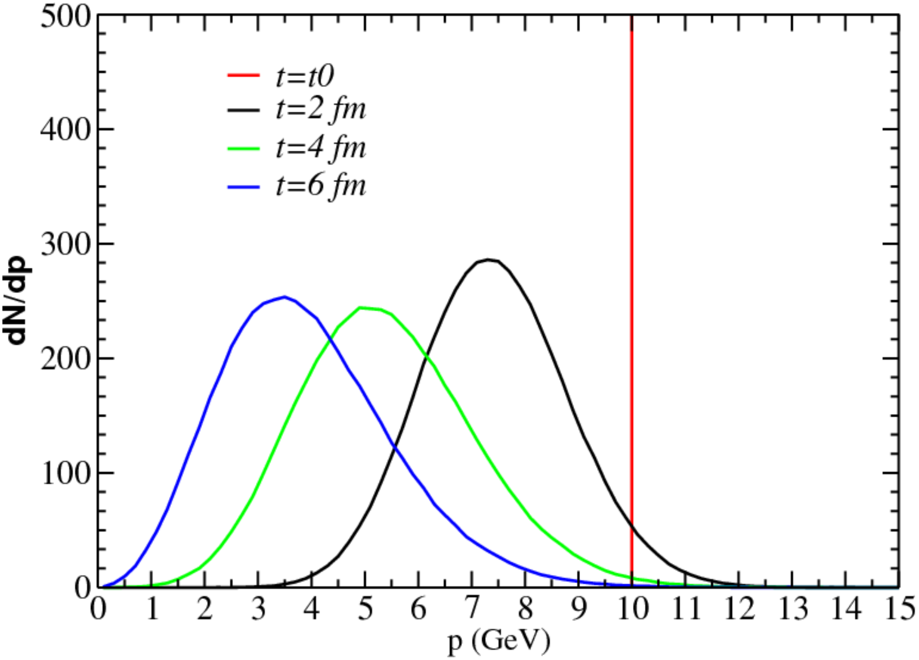
$$P_{22} = \frac{\Delta N_{coll}^{2\to 2}}{\Delta N_1 \Delta N_2} = v_{rel}\sigma_{22}\frac{\Delta t}{\Delta^3 x}$$

Evolution: Boltzmann vs Langevin (Charm)

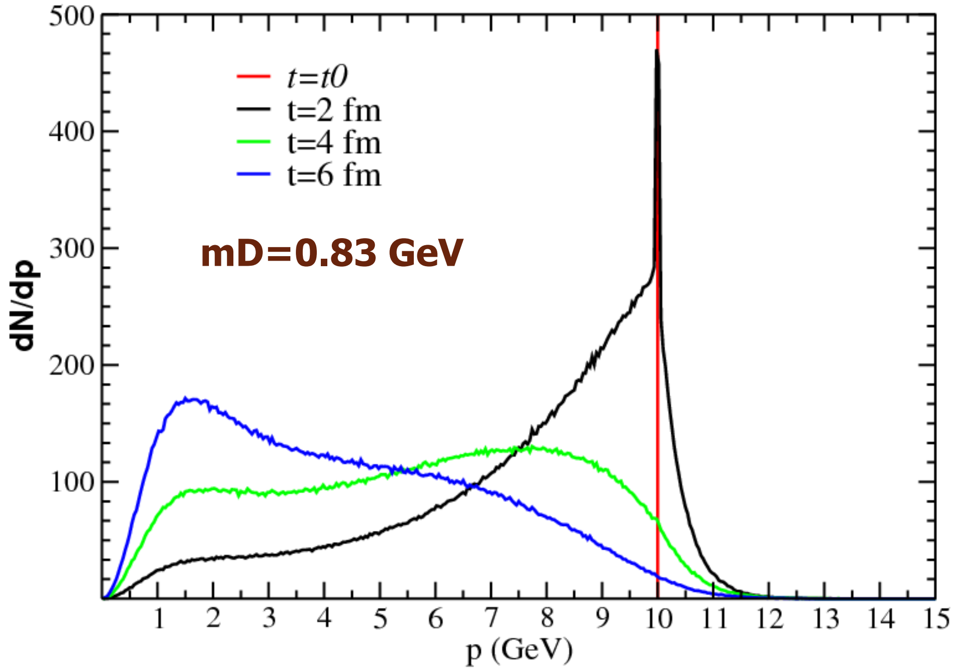
Momentum evolution starting from a δ (Charm) in a Box

$$\left.\frac{dN}{d^3p}\right|_{initial} = \delta(p - 10GeV)$$

Langevin



Boltzmann



In case of Langevin the distributions are Gaussian as expected by construction

In case of Boltzmann the charm quarks does not follow the Brownian motion

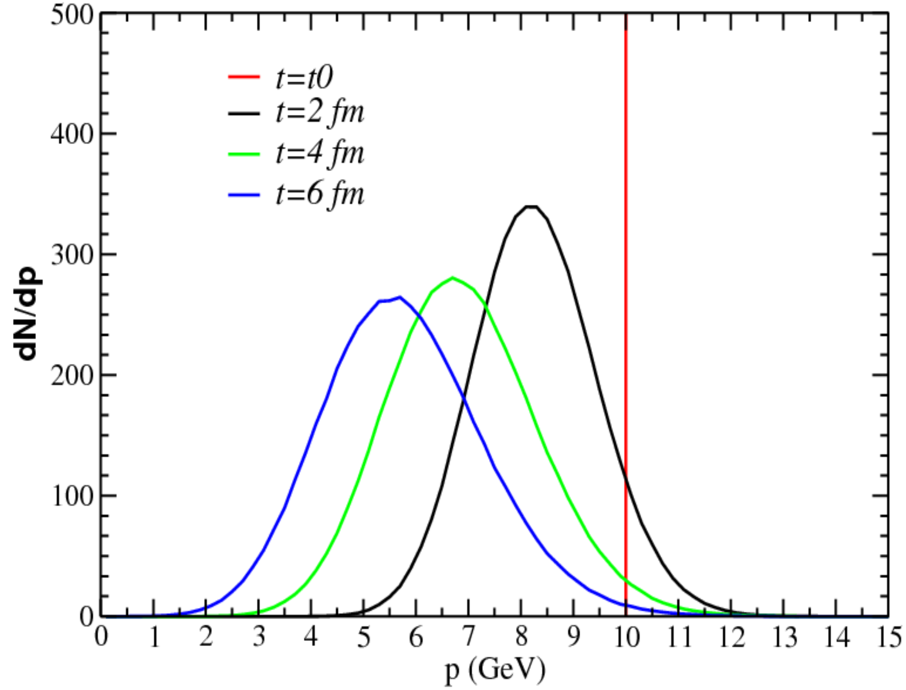
Das, Scardina, Plumari and Greco
PRC,90,044901(2014)

Momentum evolution starting from a δ (Bottom)

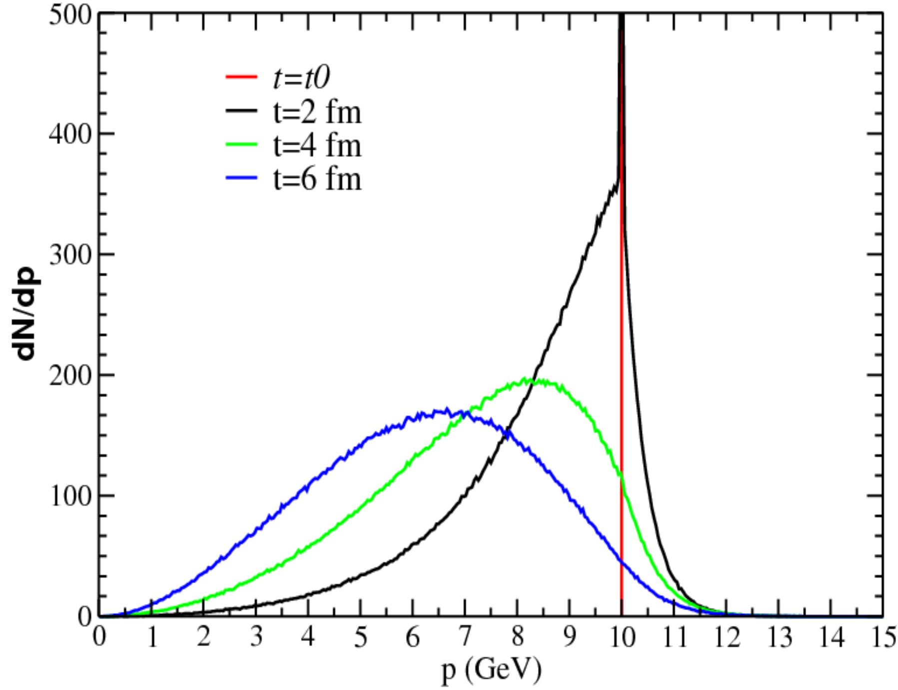
In a Box

$$\left.\frac{dN}{d^3p}\right|_{initial} = \delta\left(p - 10GeV\right)$$

Langevin



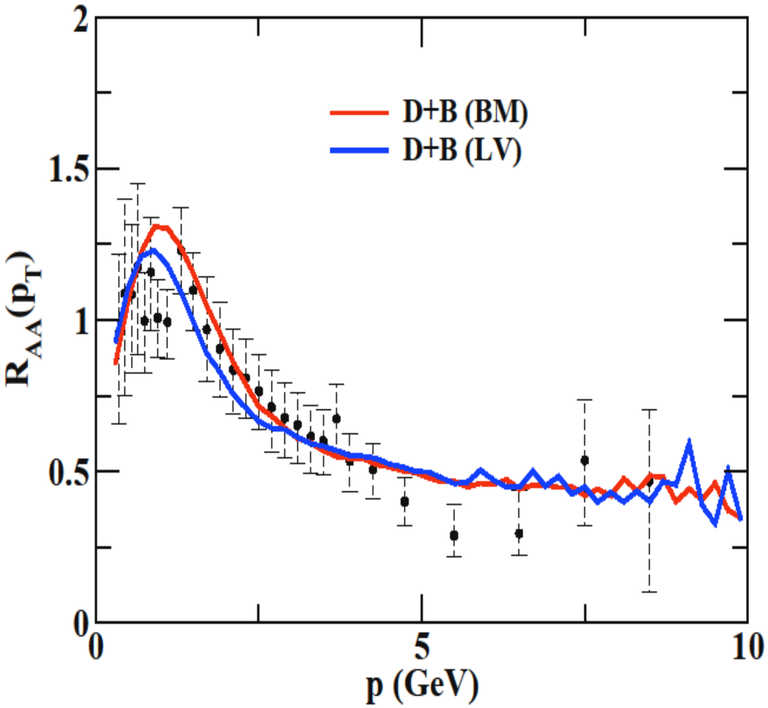
Boltzmann

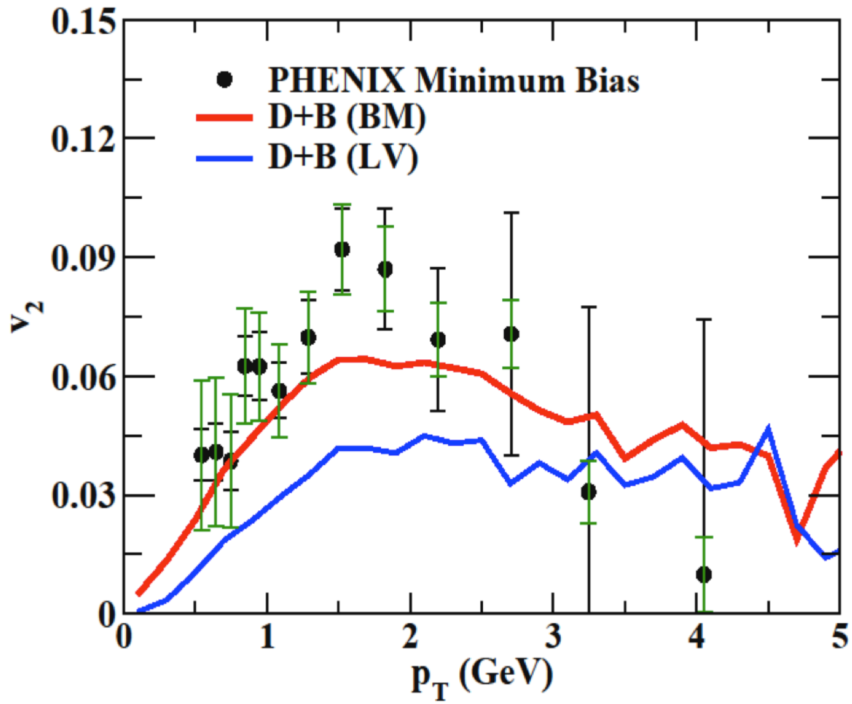


T=400 MeV Mc/T≈3 Mb/T≈10

R_{AA} and v2 at RHIC

(With near isotropic cross-section)



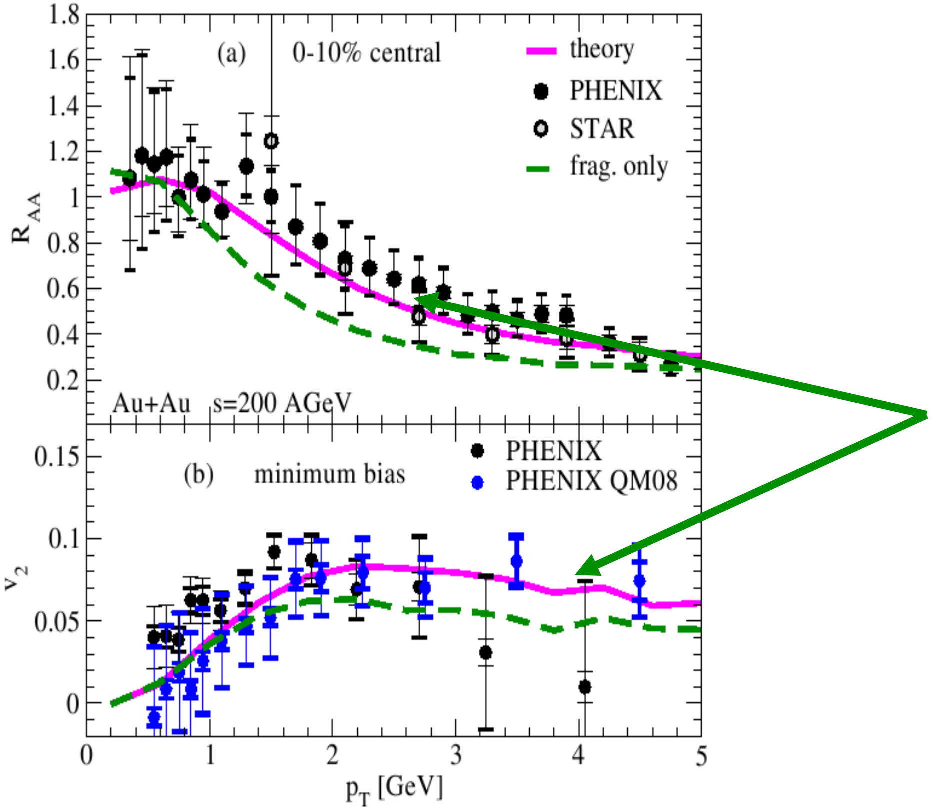


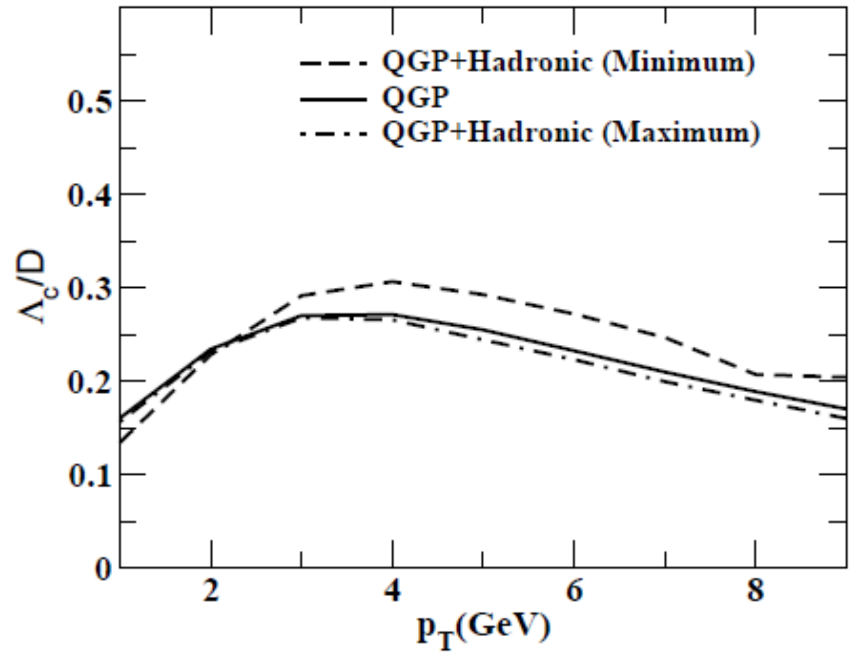
Das, Scardina, Plumari and Greco
PRC,90,044901(2014)

At fixed RAA Boltzmann approach generate larger v2 .
(depending on mD and M/T)

With isotropic cross section one can describe both RAA and V2 simultaneously within the Boltzmann approach !

Impact of hadronization mechanism



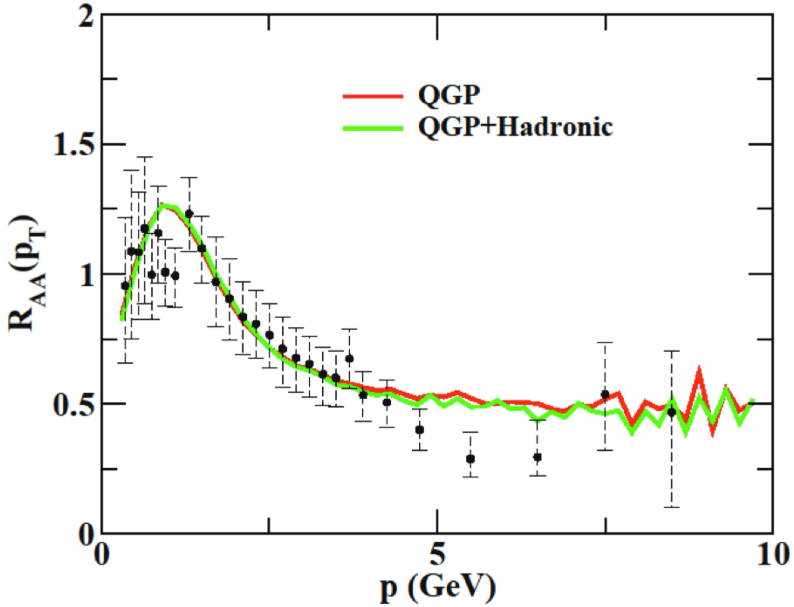


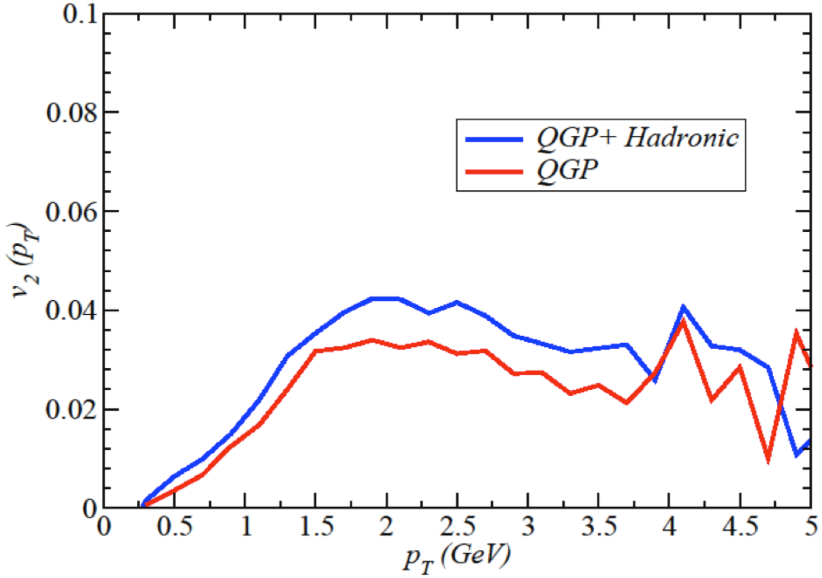
Ghosh, Das, Greco, Sarkar and Alam
PRD,90, 054018 (2014)

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

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

Hadronic Phase





He, Fries, Rapp, PRL 110 , 112301 (2013)

Das, Ghosh, Sarkar, Alam, PRD,88,017501 (2013)

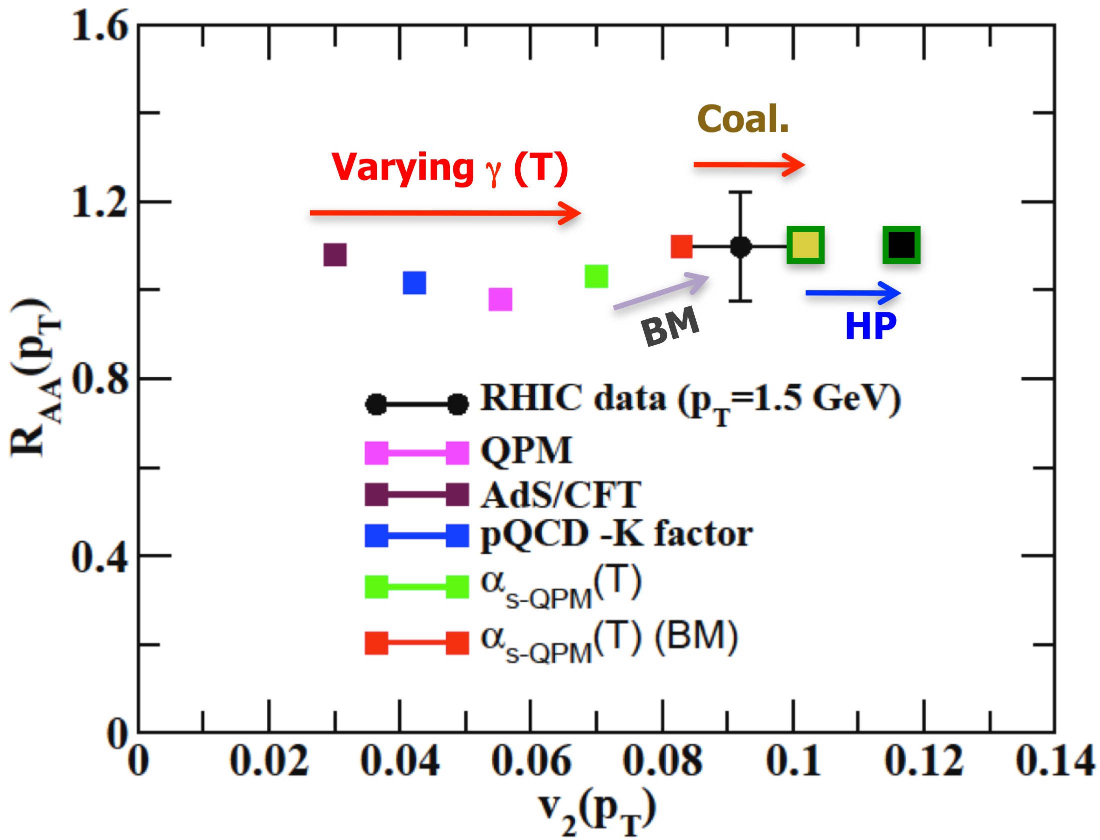
He, Fries , Rapp , PLB, 735 (2014) 445-450

Ozvenchuk, Torres-Rincon, Gossiaux, Aichelin, Tolos, PRC, 90 (2014)5, 054909

Cao, Qin, Bass, NPA931 (2014) 569-574

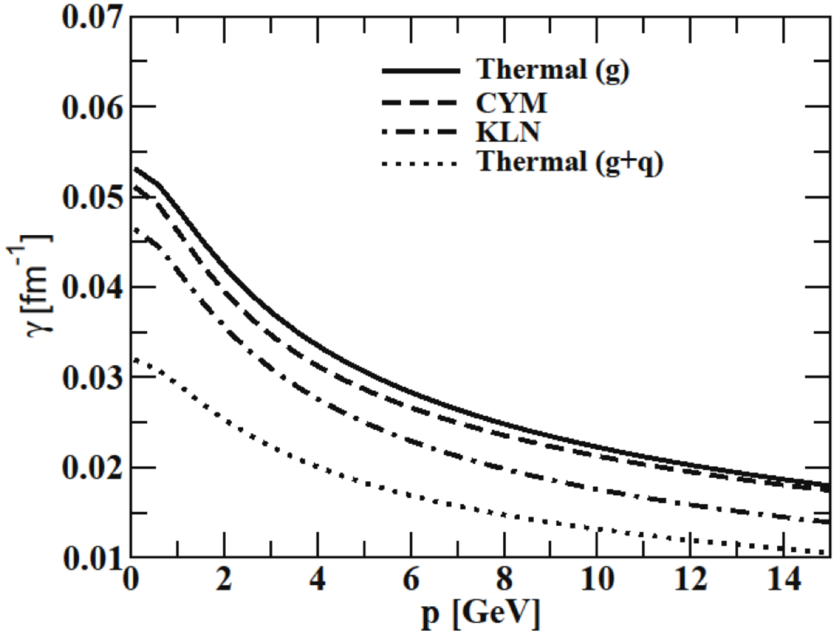
T. Song et. al, arXiv:1503.03039

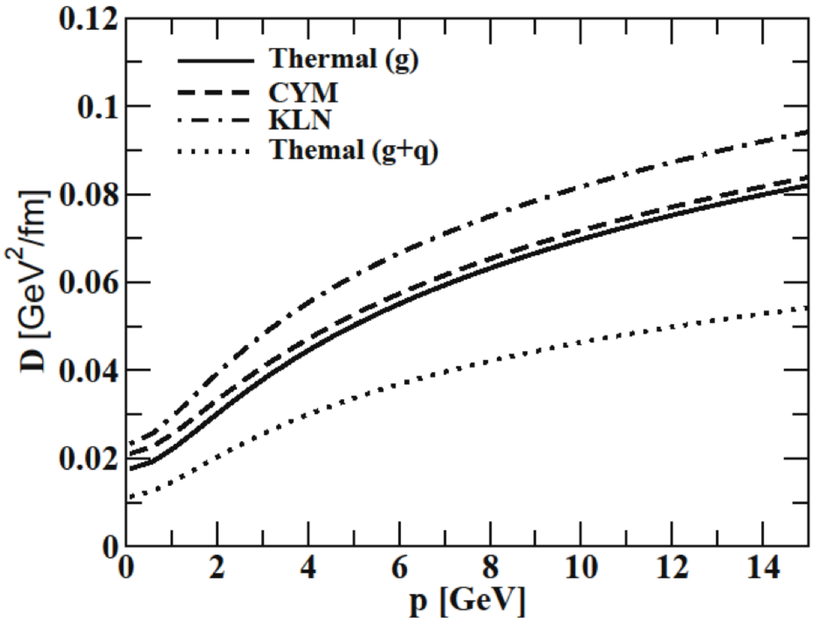
Summary on the build-up of v_2 at fixed R_{AA}



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 2-3
γ(T) + Boltzmann dynamics+ hadronization+ hadronic phase

Impact of Pre-equilibrium Phase ?





Das, Ruggieri, Mazumder, Greco, Alam
arXiv:1501.07521

It will be interesting to study the role of Pre-equilibrium on R_{AA} and v_2.

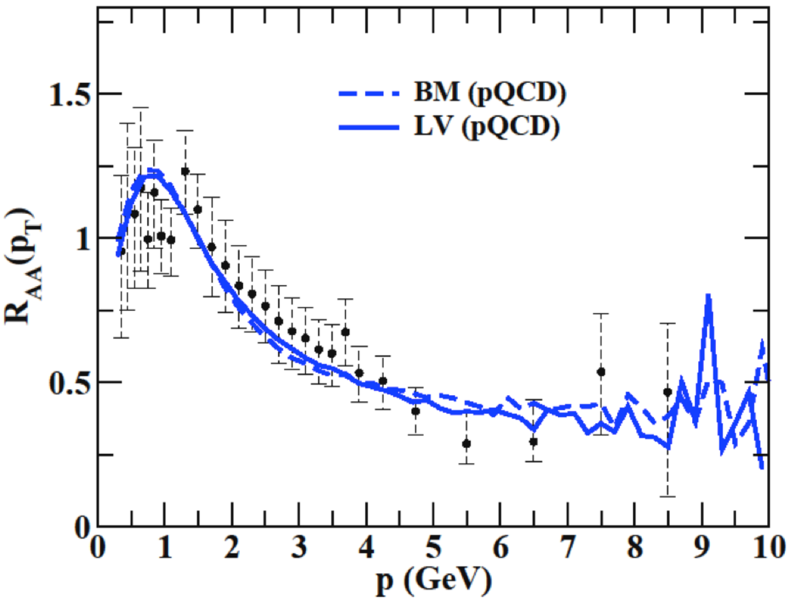
Summary & Outlook ……

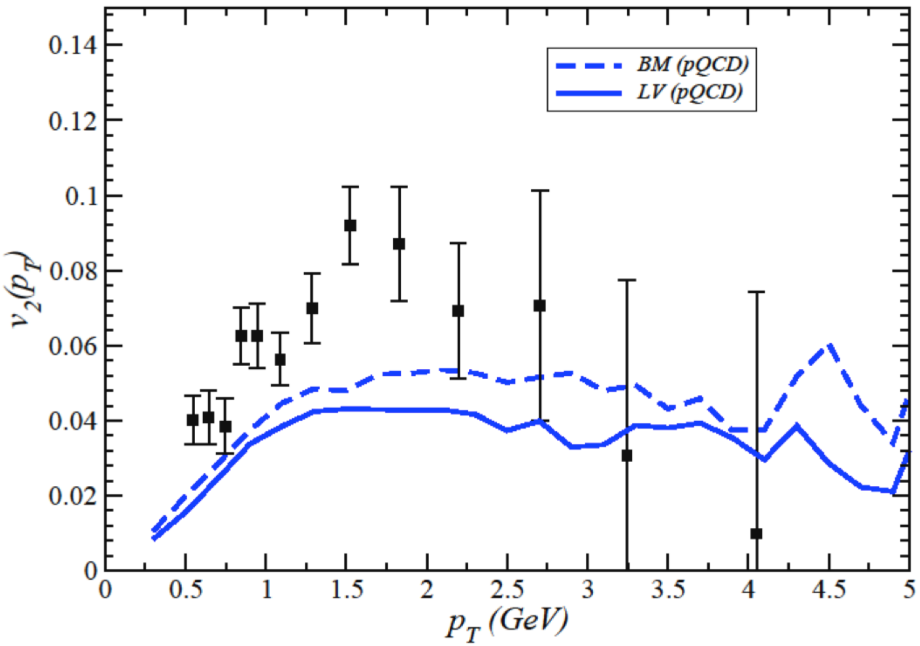
- R_{AA}- v_2 of charm quarks seems to indicate:
  - Drag about constant in T or weak T dependence to describe both RAA and v2 simultaneously.
  - Boltzmann dynamics more efficient for v_2 even at fixed R_{AA}.
  - Hadronization by coalescence of heavy quarks as well as the role of hadronic medium modify R_{AA} vs v_2 relation toward a better agreement with the data.

- Implementation of all these effects including radiation within a single framework (within Boltzmann equation) is going on.


Thank You . . . .

R_{AA} and v2 at RHIC at mD=gT

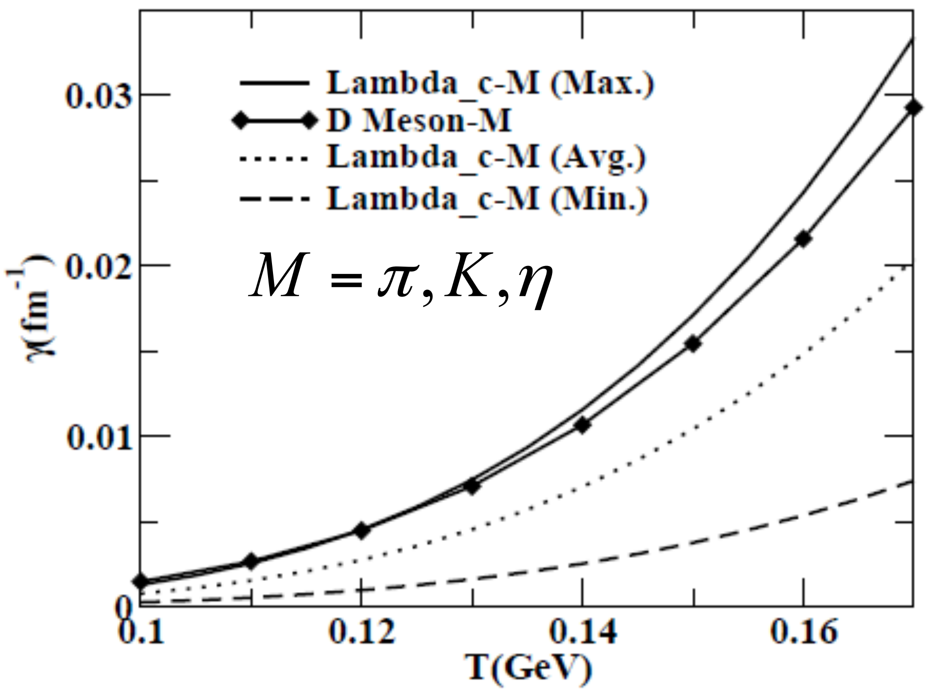


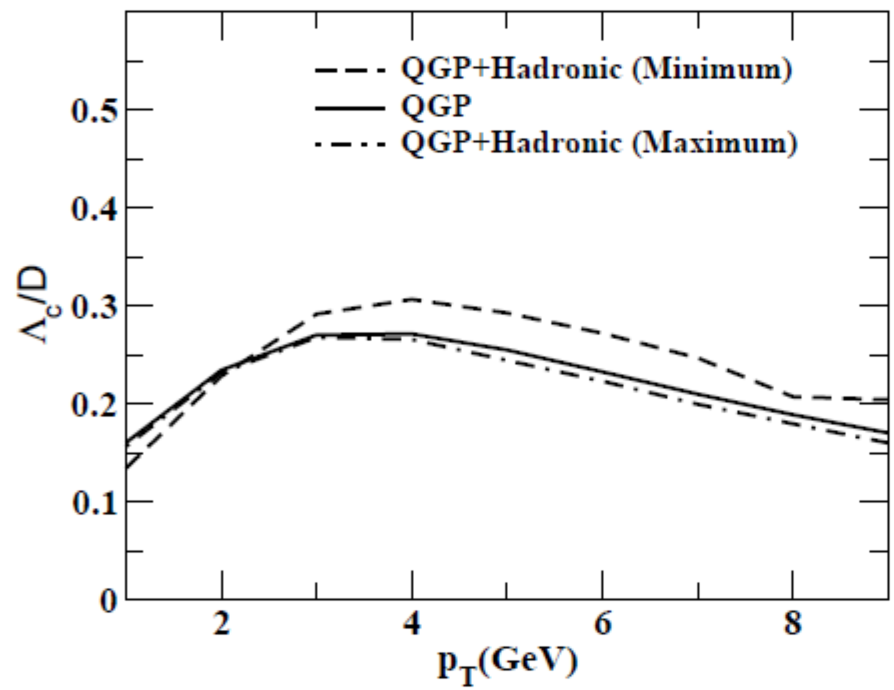


Das, Scardina, Plumari and Greco
PRC,90,044901(2014)

At fixed RAA Boltzmann approach generate larger v2 .
(depending on mD and M/T)

Heavy Baryon to Meson Ratio

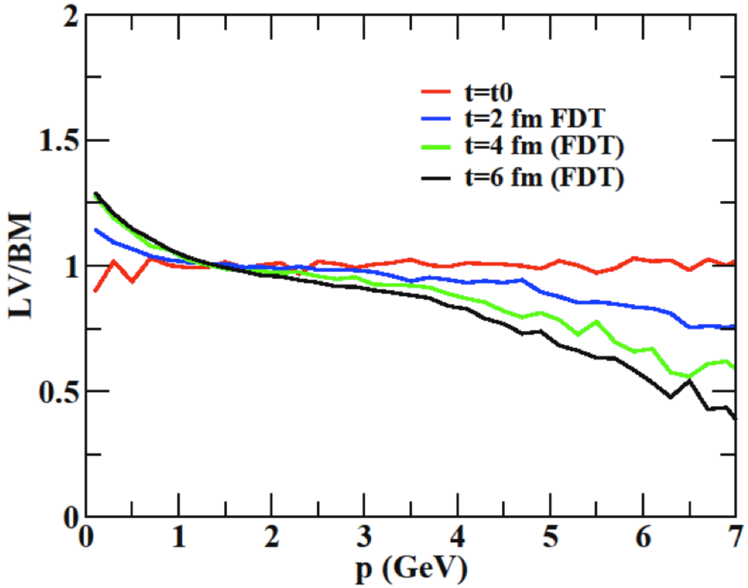




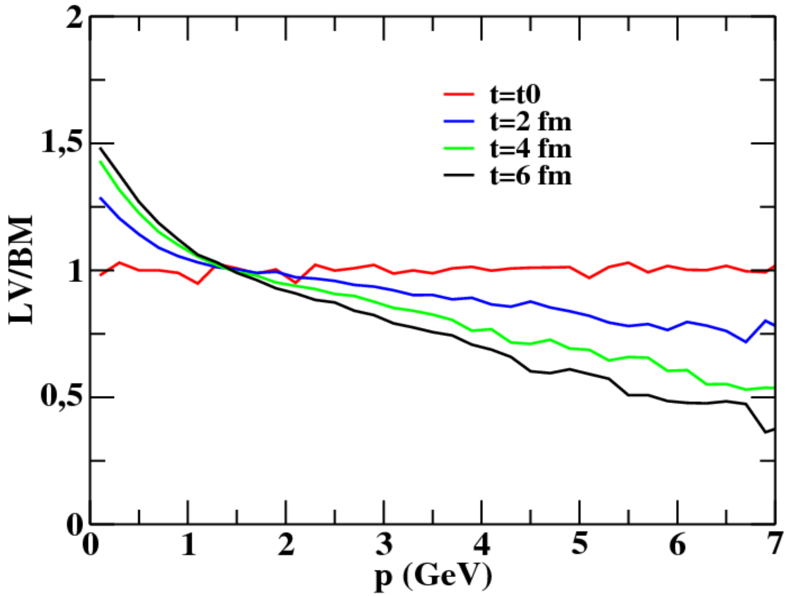
Ghosh, Das, Greco, Sarkar and Alam
PRD,90, 054018 (2014)

Z. Liu, S. Zhu, PRD 86, 034009 (2012);
NPA 914,494 (2013

Lee, Ohnishi, Yasui, Yoo, Ko
PRL,222310,100(2008)



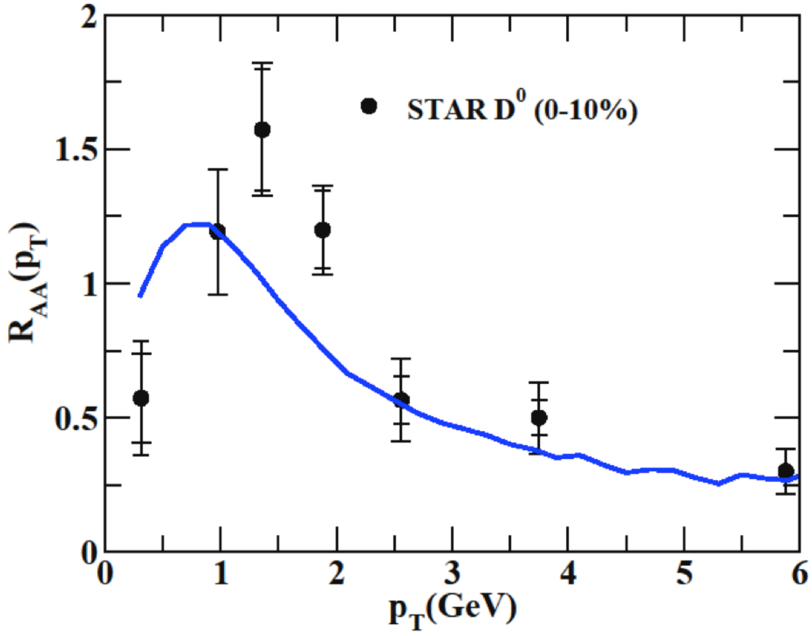
With FDT

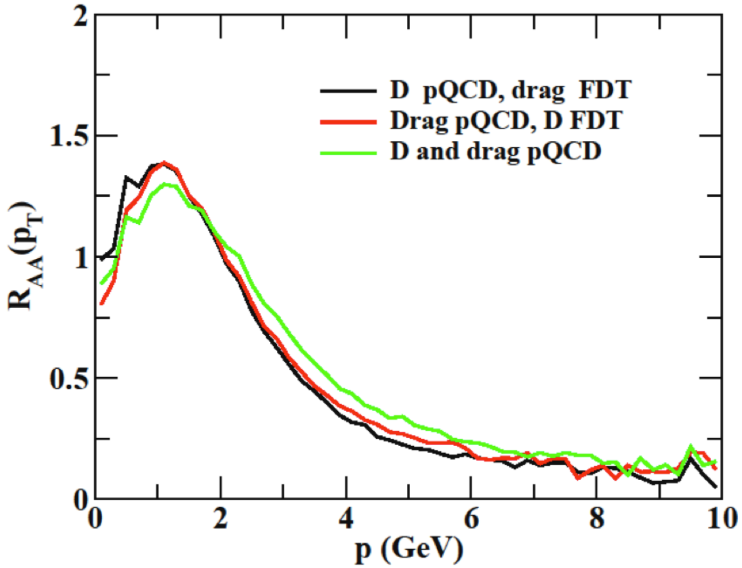


With pQCD

RHIC D-meson RAA

Au+Au@200GeV, b=3.25 fm)





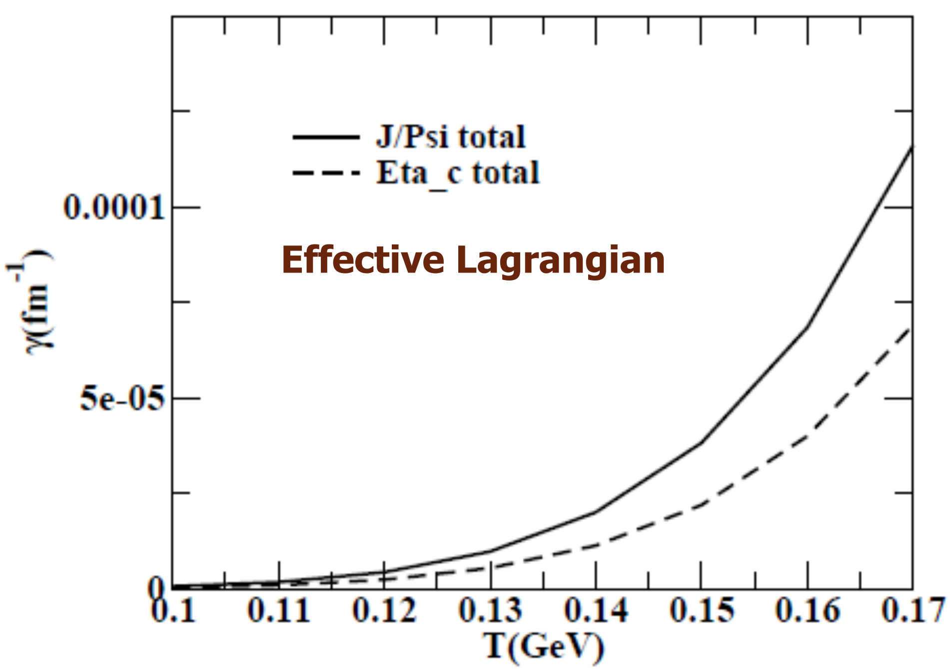
J/Psi in Hadronic Phase

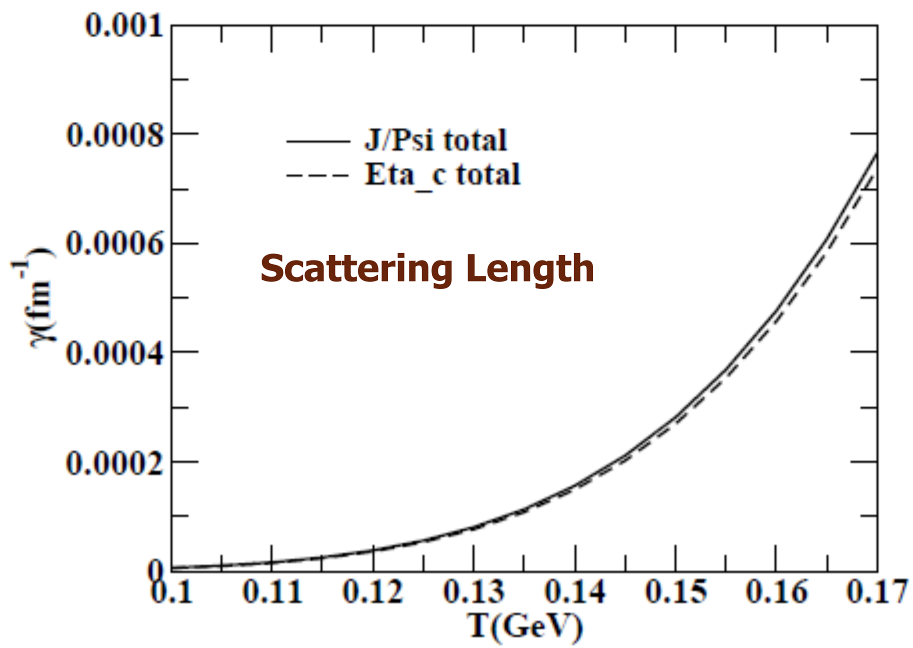
$$J + V \to \eta_c \to J/\Psi + V$$
$$\eta_c + V \to J/\psi \to \eta_c + V$$
$$V = \rho, \omega, \phi$$

Haglin ,Gale, PRC 63, 065201(2001).

$$J/\psi\pi \to J/\psi\pi \qquad \eta_c\pi \to \eta_c\pi$$
$$J/\psi\rho \to J/\psi\rho \qquad \eta_c\rho \to \eta_c\rho$$
$$J/\psi N \to J/\psi N \qquad \eta_c N \to \eta_c N$$

Yokokawa, Sasaki, Hatsuda and Hayashigaki PRD 74, 034504 (2006)

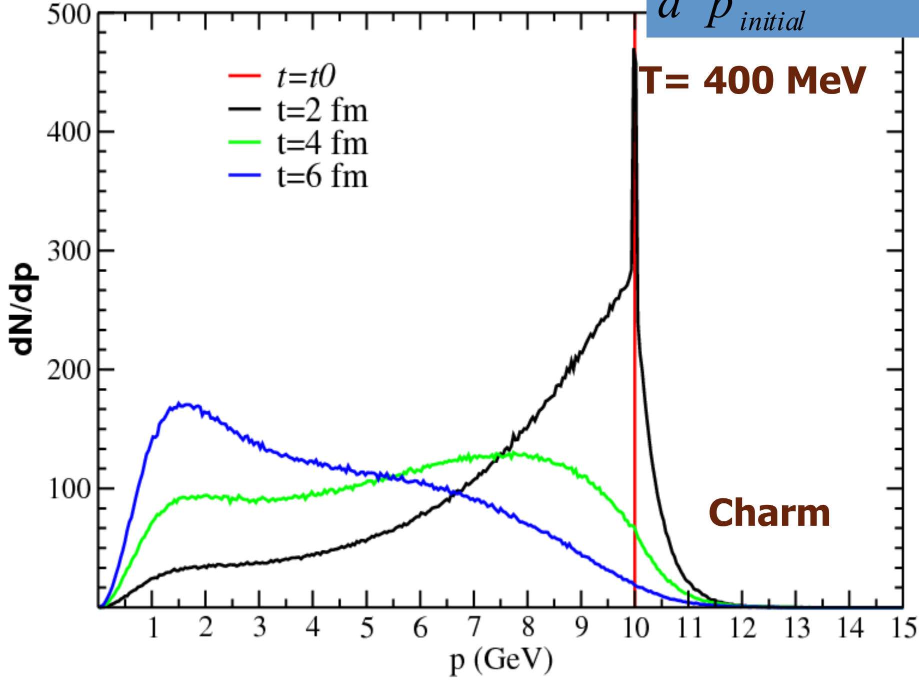


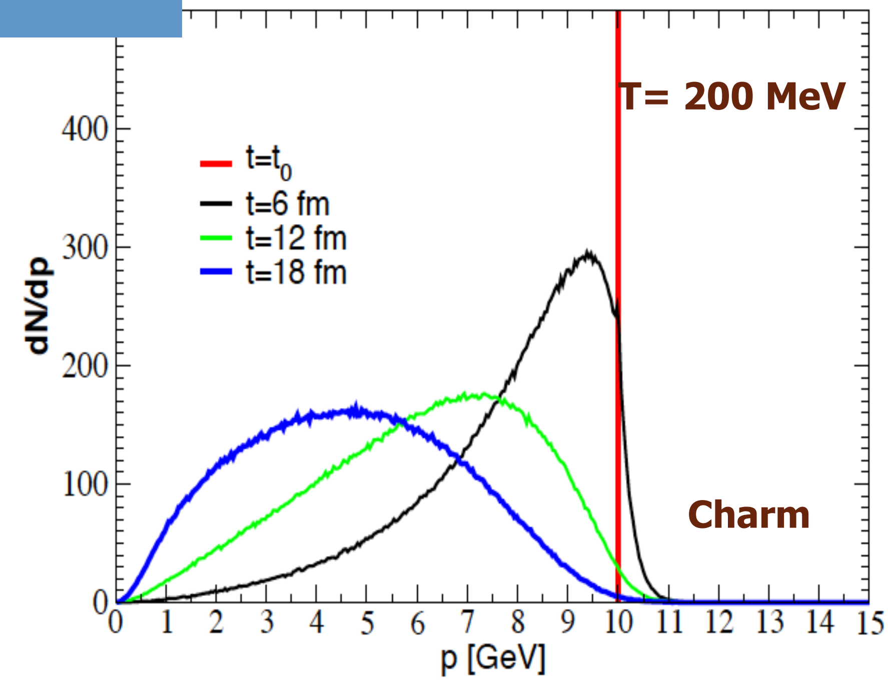


Mitra, Ghosh, Das, Sarkar and Alam arXiv:1409.4652

Momentum evolution for charm vs temperature

$$\left.\frac{dN}{d^3p}\right|_{initial} = \delta\left(p - 10GeV\right)$$





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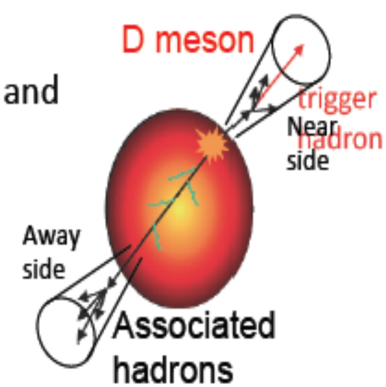


- **At 200 MeV Mc/T= 6 -> start to see a peak with a width**

Such large spread of momentum implicates a large spread in the angular distributions that could be experimentally observed studying the back to back Charm-antiCharm angular correlation

Boltzmann Kinetic equation

$$\left(\frac{\partial}{\partial t} + \frac{P}{E}\frac{\partial}{\partial x} + \mathrm{F}.\frac{\partial}{\partial p}\right) f(x, p, t) = \left(\frac{\partial f}{\partial t}\right)_{col}$$

- The plasma is uniform ,i.e., the distribution function is independent of x.
- In the absence of any external force, F=0

$$R(p,t) = \left(\frac{\partial f}{\Gamma \partial t}\right)_{col} = \int d^3k\left[\omega(p+k,k) f(p+k) - \omega(p,k) f(p)\right]$$

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

→ is rate of collisions which change the momentum of the charmed quark from p to p-k

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

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

Fokker-Planck equation

B. Svetitsky PRD 37(1987)2484

where we have defined the kernels ,

$$\mathbf{A_i} = \int \mathbf{d^3k}\,\omega(\mathbf{p},\mathbf{k})\mathbf{k_i} \rightarrow \textbf{Drag Coefficient}$$

$$\mathbf{B_{ij}} = \int \mathbf{d^3k}\,\omega(\mathbf{p},\mathbf{k})\mathbf{k_i}\mathbf{k_j} \rightarrow \textbf{Diffusion Coefficient}$$

H. v. Hees and R. Rapp arXiv:0903.1096

Fokker planck equation can be solved Stocastically by Langevin eqation

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

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

Γ **is the drag force and** C_{ij} **is the stochastic force.**

I) LPM effect : Suppression of bremsstrahlung and pair production.

Formation length ($l_f = \frac{\hbar}{q_\perp}$) : The distance over which interaction is spread out

1) It is the distance required for the final state particles to separate enough that they act as separate particles.

2) It is also the distance over which the amplitude from several interactions can add coherently to the total cross section.

As $q_\perp$ increase → l_f reduce → Radiation drops proportional

S. Klein, Rev. Mod. Phys **71** (1999)1501

(II) Dead cone Effect : Suppression of radiation due to mass

$$\frac{1}{\sigma}\frac{d^2\sigma}{dz d\theta^2} \sim C_F \frac{\alpha_s}{\pi}\frac{1}{z}\frac{\theta^2}{\left(\theta^2 + 4\gamma\right)^2}$$

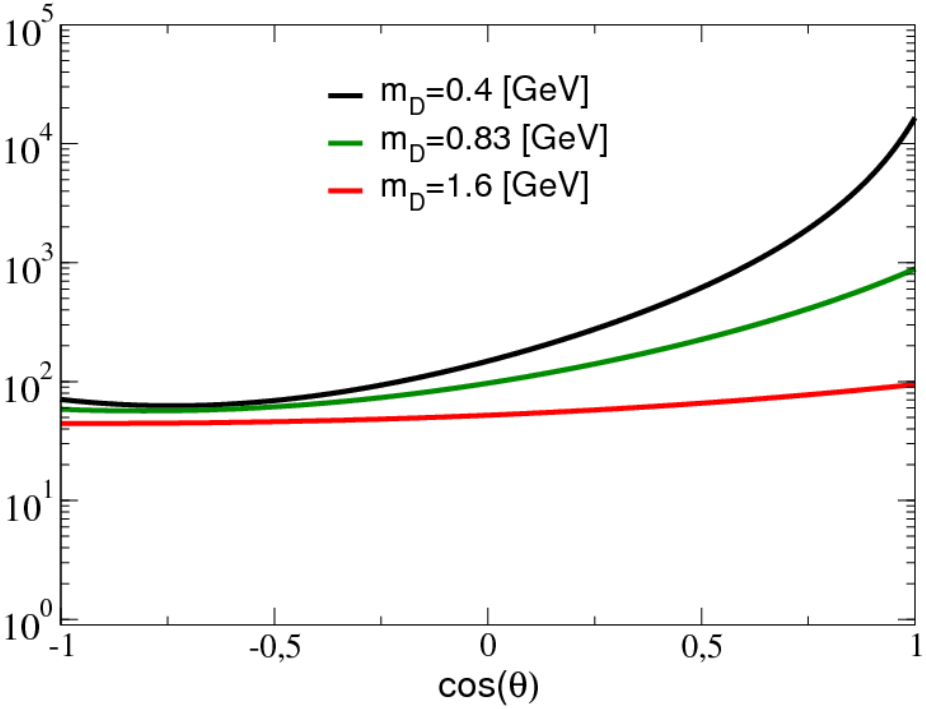
where $z = 2 - x_1 - x_2$ *and* $\gamma = \frac{m^2}{s}$

Where $x_1 = 2E_q/\sqrt{s}$ and $x_2 = 2E_{\bar{q}}/\sqrt{s}$ ⟶ the energy fraction of the final state quark and anti-quark.

Radiation from heavy quarks suppress in the cone from $\theta = 0$ (minima) to $\theta = 2\sqrt{\gamma}$ (maxima)

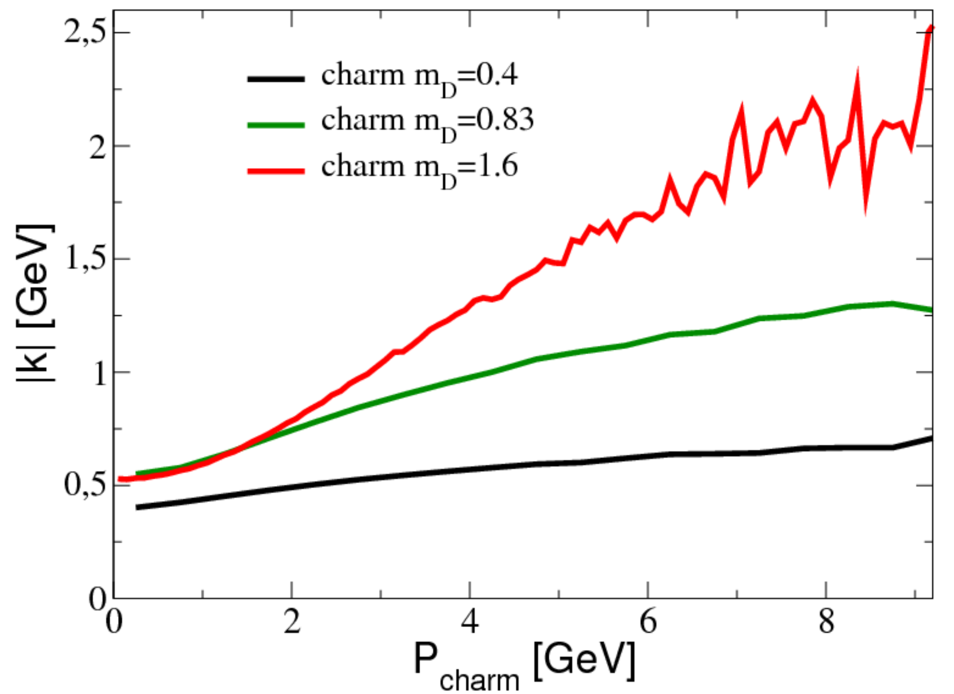
Boltzmann vs Langevin (Charm)

Angular dependence of σ



Decreasing m_D makes the σ more anisotropic

Mometum transfer vs P

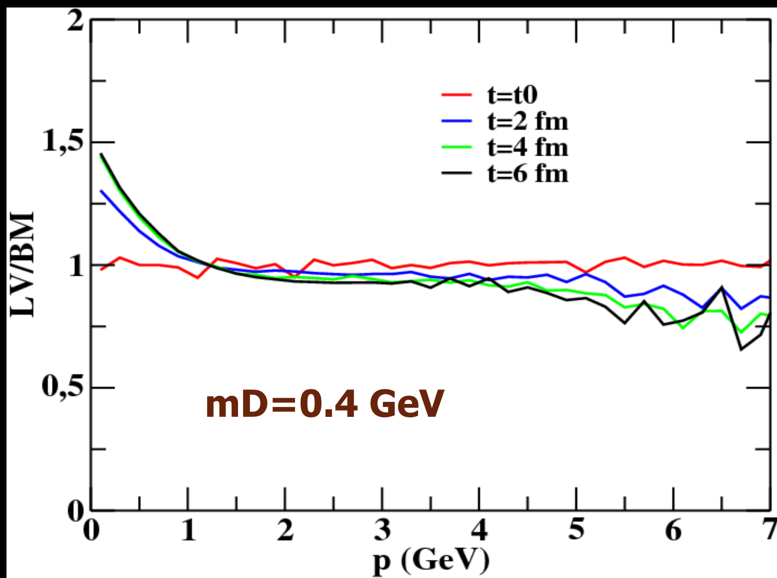


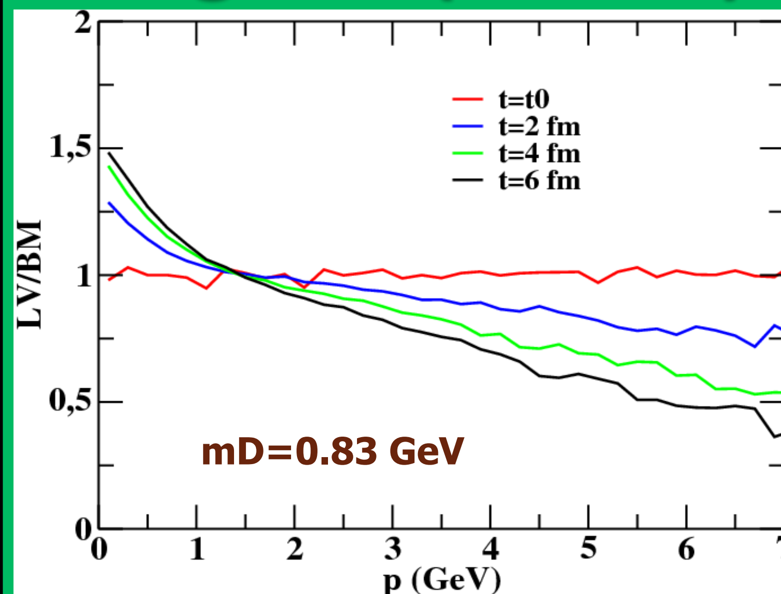
➡ **Smaller average momentum transfer**

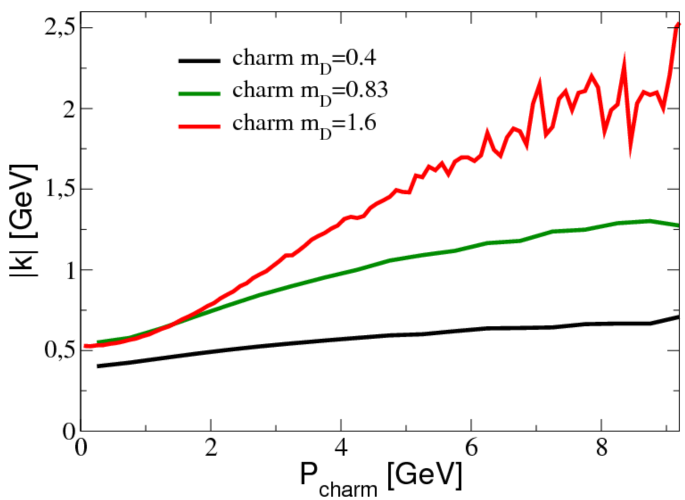
Hees, Mannarelli,Greco,Rapp, PRL100(2008)
Hees,Greco,Rapp. PRC73 (2006) 034913

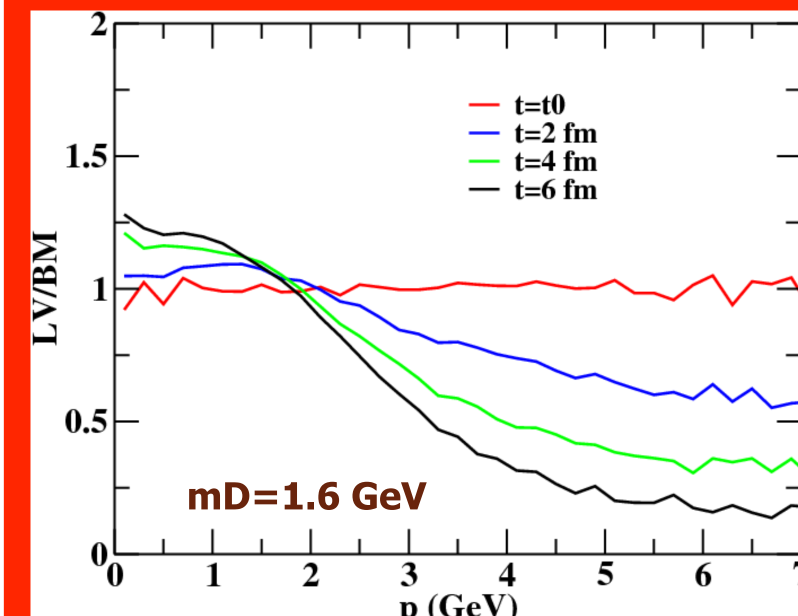
Das, Scardina, Plumari and Greco
arXiv:1312.6857

Boltzmann vs Langevin (Charm)



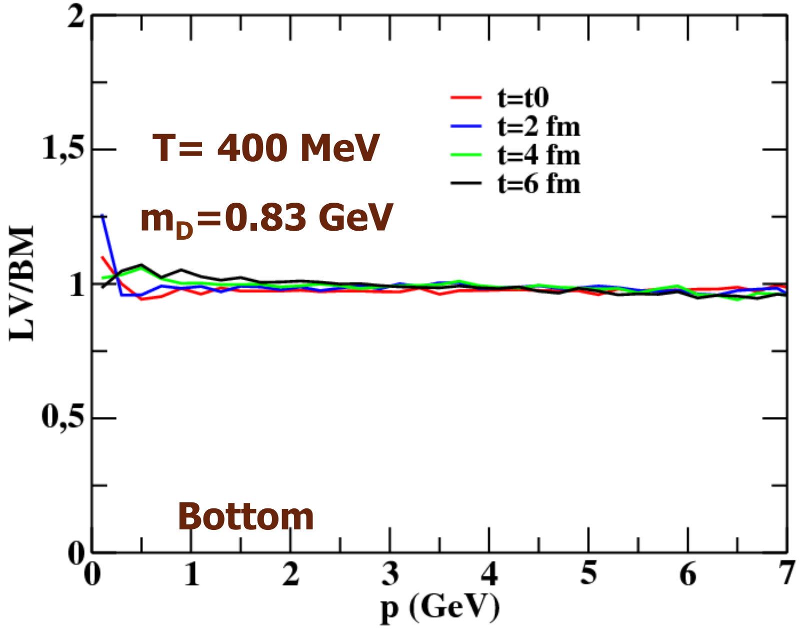


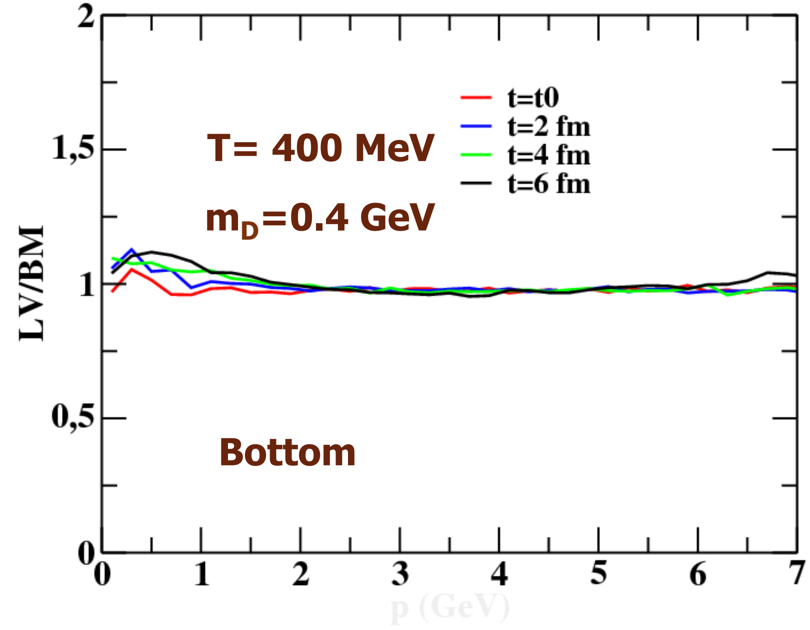


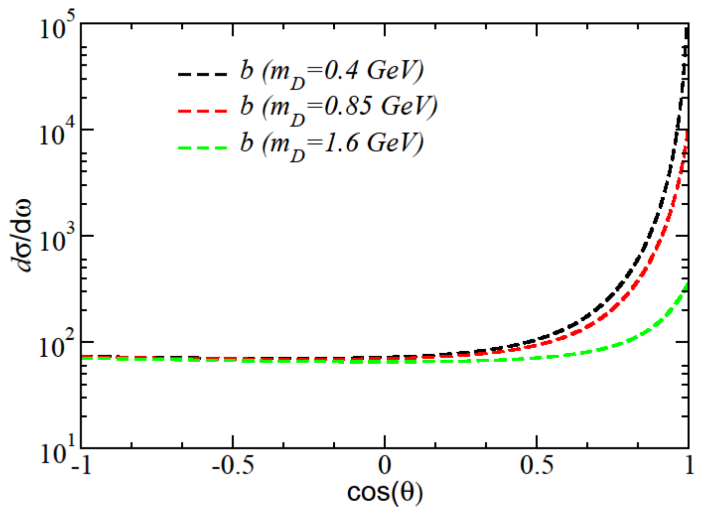


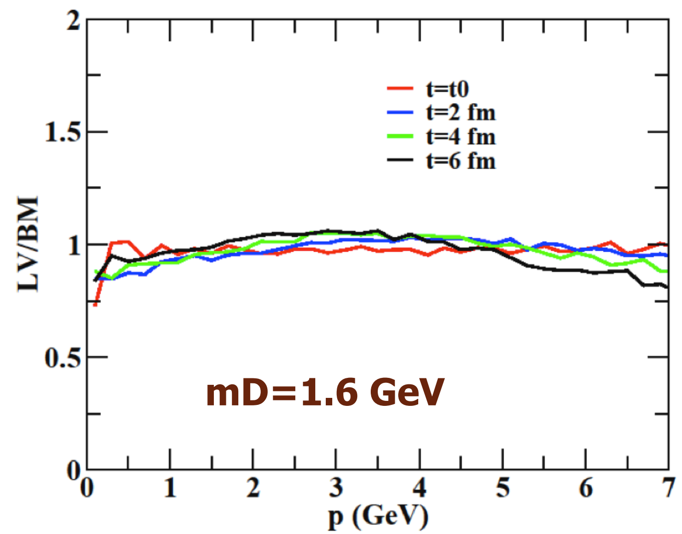
Das, Scardina,Plumari and Greco
arXiv:1312.6857 (PRC, In press)

Bottom: Boltzmann = Langevin









But Larger M_b/T (≈ 10) the better Langevin approximation works