Interaction Dynamics & Hadronization mechanism in HQ production in AA

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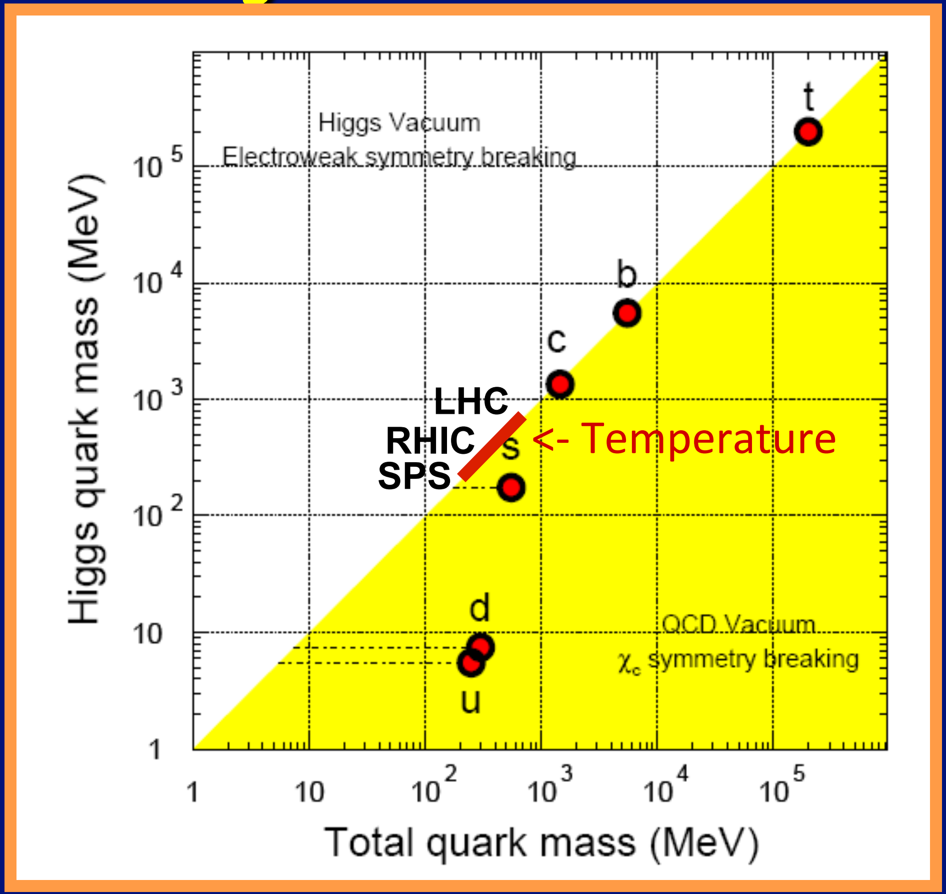
Outline

Heavy Quark in the Hot QGP

- Problematic relation between R_{AA} and v_2:
  - T - dependence of the interaction (Drag)
  - Boltzmann vs Langevin (Fokker-Planck)
  - Hadronization: Coalescence vs Fragmentation

- Boltzmann vs Fokker-Planck -> $c\bar{c}$ angular correlation

Heavy Quark & QGP



Adapted from Zhu et al. (2006)

Heavy because:

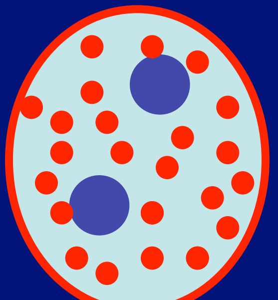
- ✧ **M >> Λ_{QCD} (particle physics)**
- ✧ **M>> T (plasma physics)**
- ✧ **but there is another scale…**

<u>BEFORE RHIC</u>:

$m_Q >> m_q$ HQ not dragged by the expanding medium:

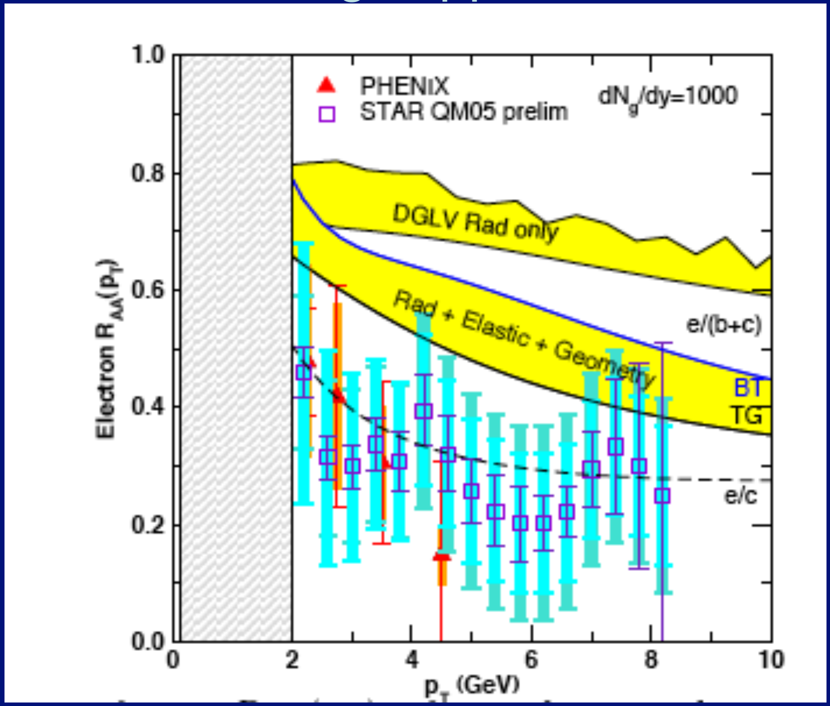
- spectra close to the pp one-> large R_{AA}

- small elliptic flow v_2



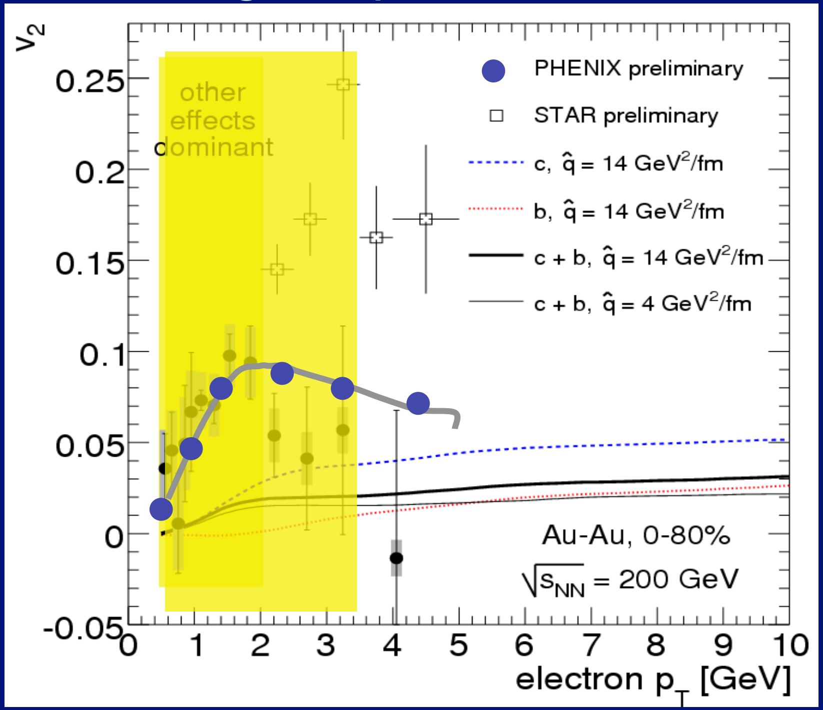
Problems with idea 1

Strong suppression



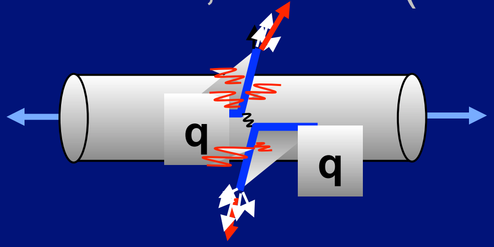
S. Wicks et al. (QM06)

Large elliptic Flow



N. Armesto et al., PLB637(2006)362

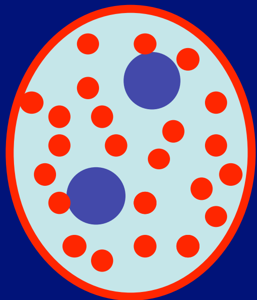
- Radiative energy loss not sufficient
- Charm seems to flow like light quarks



Heavy Quark strongly dragged by interaction with light quarks

pQCD does not work may be the real cross section is a K factor larger?

Charm dynamics with upscaled pQCD cross section

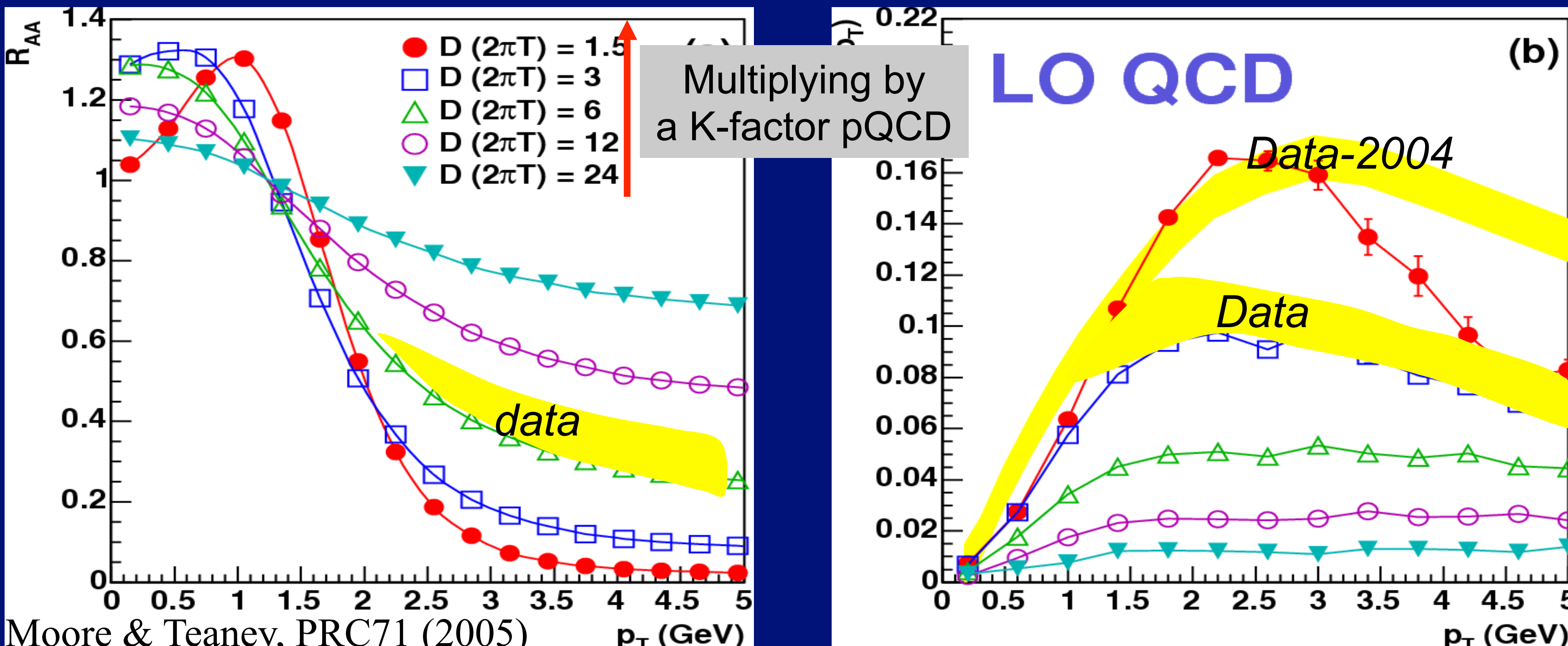


Fokker-Plank for charm interaction in a hydro bulk

Diffusion coefficient

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

scattering matrix



Moore & Teaney, PRC71 (2005)

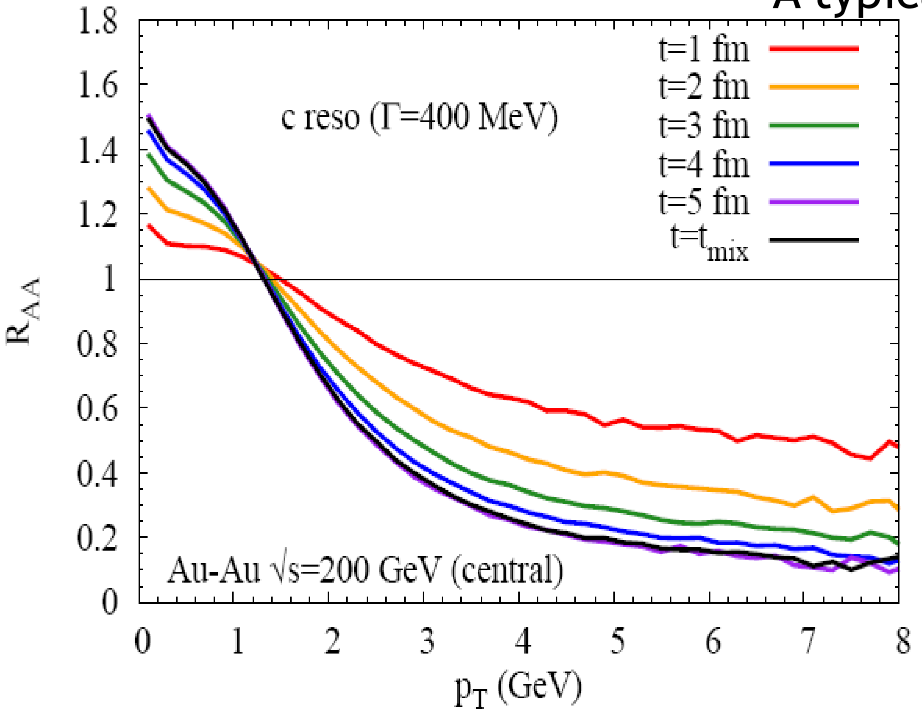
It's not just a matter of pumping up pQCD elastic cross section: too low R_{AA} or too low v_2

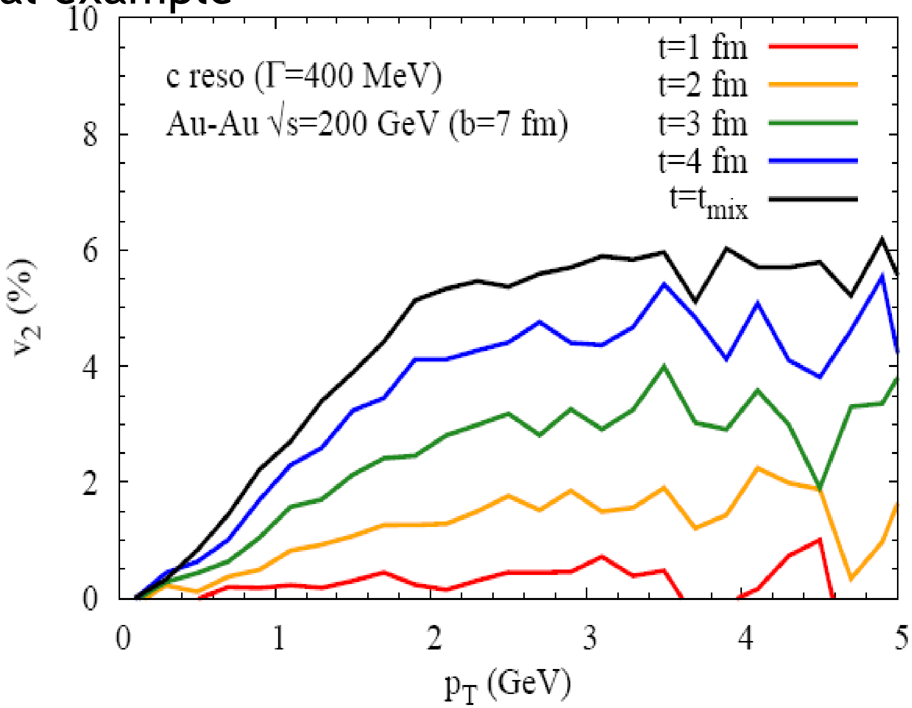
R_{AA} and v_2 correlation

No interaction means R_{AA}=1 and v_2=0. More interaction decrease R_{AA} and increase v_2

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

A typical example



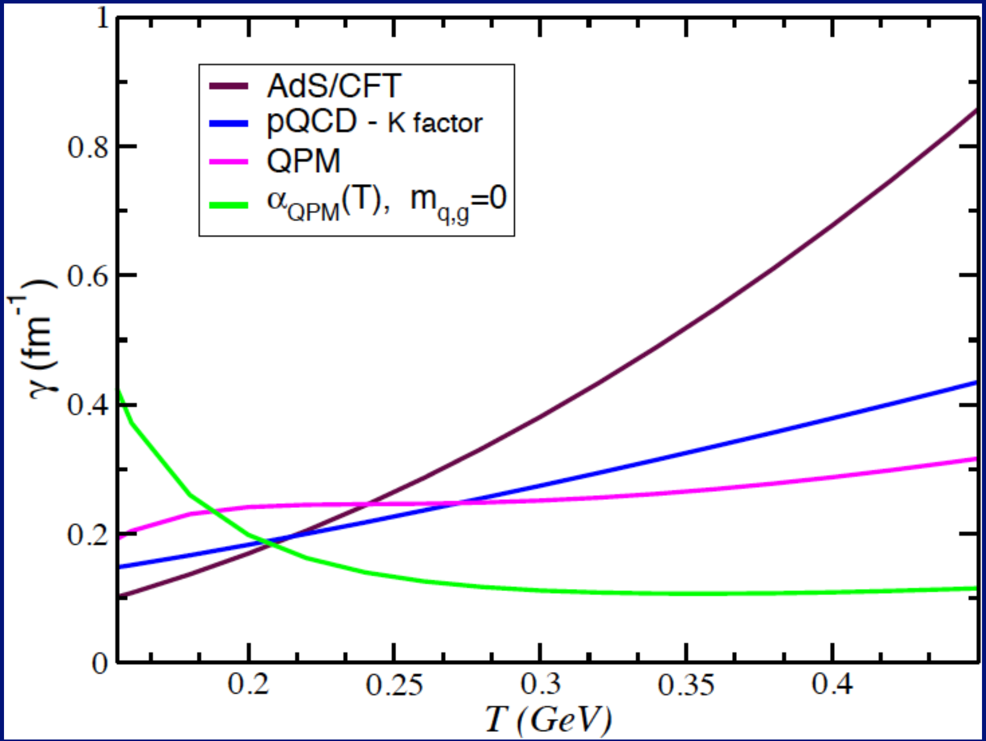


The relation between R_{AA} and time is not trivial and depend on how one interacts and loose energy with time.

This is general, seen also for light quarks, Scardina, Di Toro, Greco, PRC82(2010)

T- dependence of the Drag Coefficient

Drag Coefficient



pQCD *(Combridge cross-section)*

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

AdS/CFT

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

Akamatsu-Hatsuda-Hirnao, PRC79 (09) 054907

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

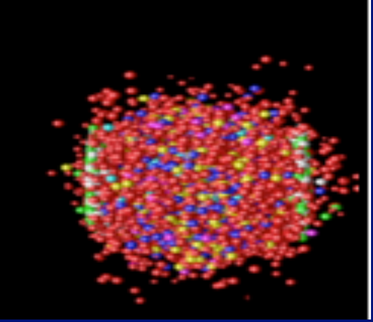
$$g_{QP}^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2}$$

λ=2.6
T_s=0.57 T

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

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

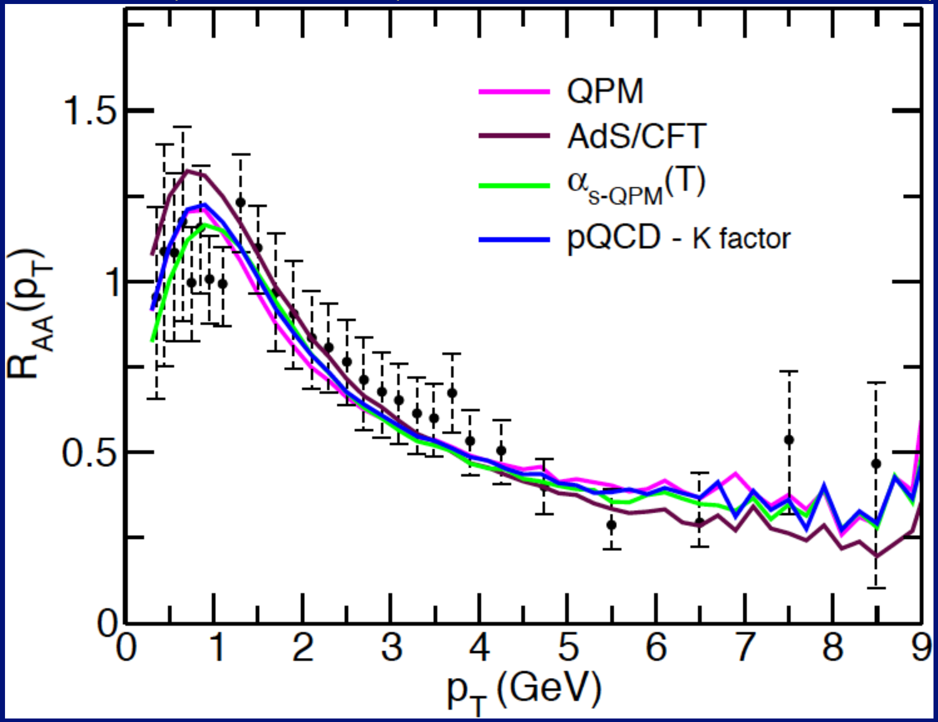
we mean simply the coupling of the QPM,
but with a bulk of massless q and g

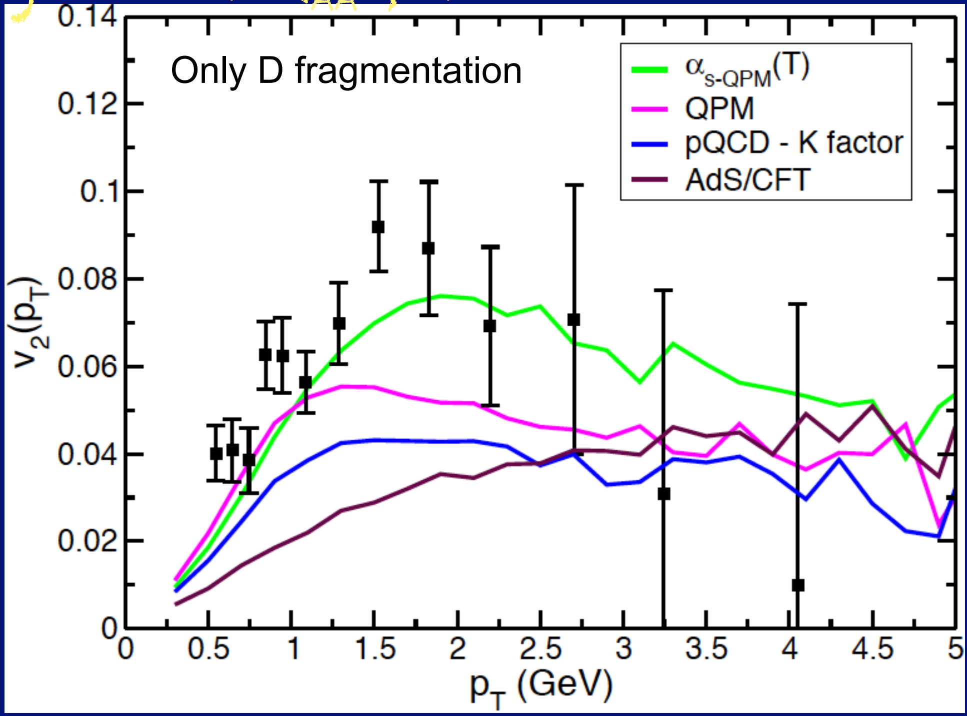


Impact of T-dependence of the Drag

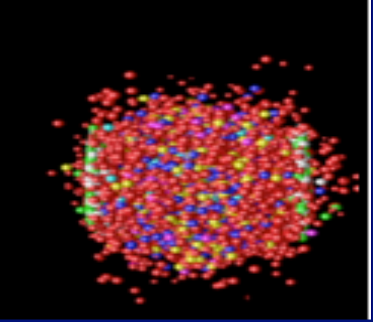
Au+Au@200AGeV, b=8 fm

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



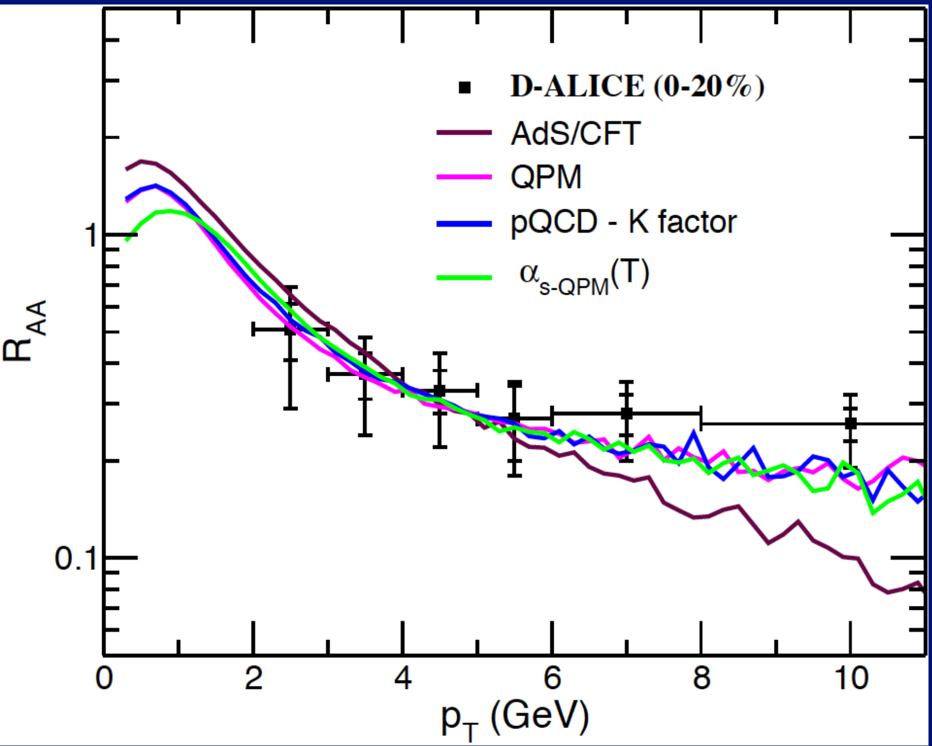


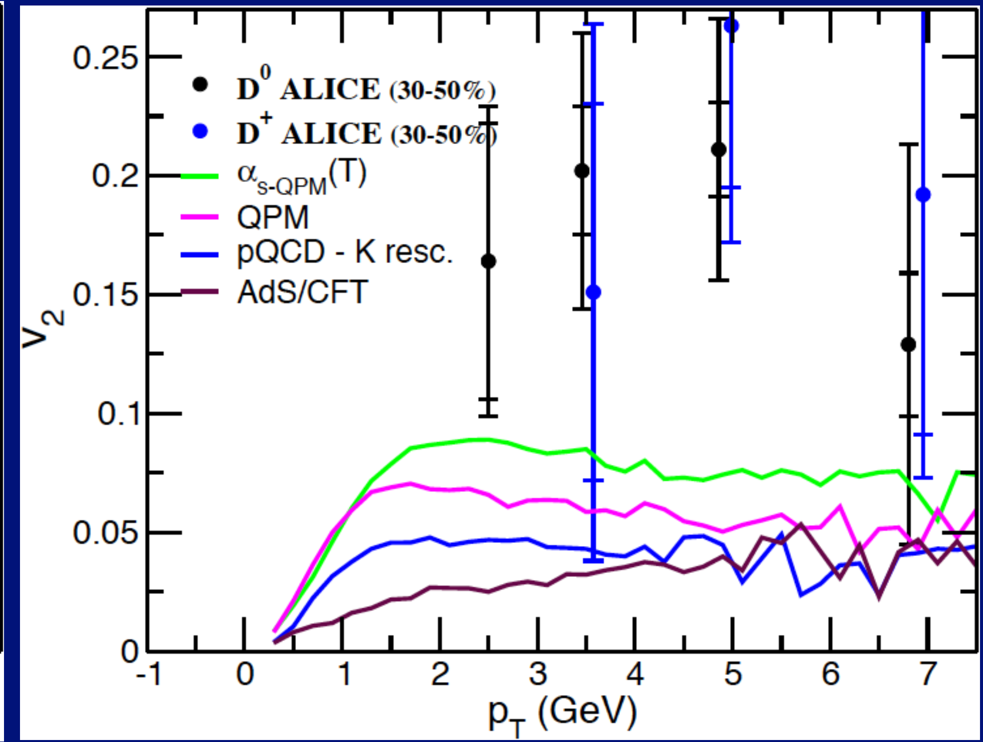
- $R_{AA}(p_T)$ well reproduced whatever is the T-dependence
- $\gamma \approx T^2$ AdS/CFT like, correct $R_{AA}(p_T)$ but does not lead to significant v_2
- At fixed $R_{AA}(p_T)$ -> $v_2(p_T)$ quite larger if T -> T_c



Impact of T-dependence of the Drag

LHC – Pb+Pb@2.76ATeV

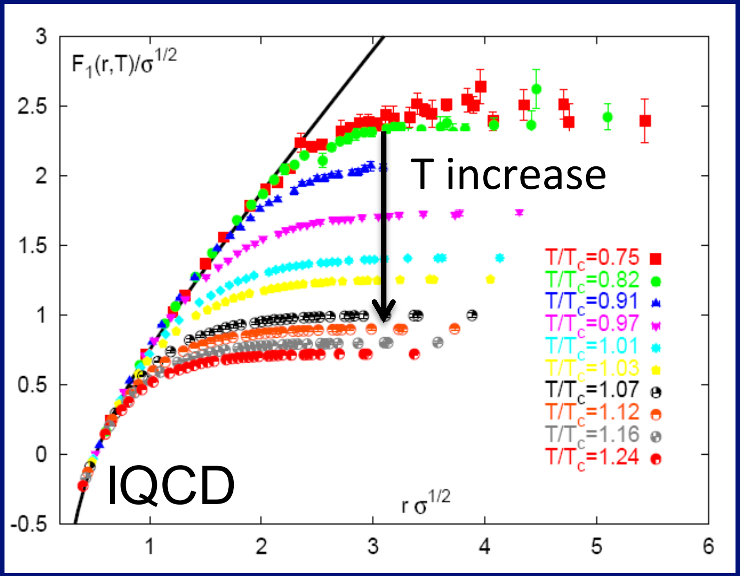


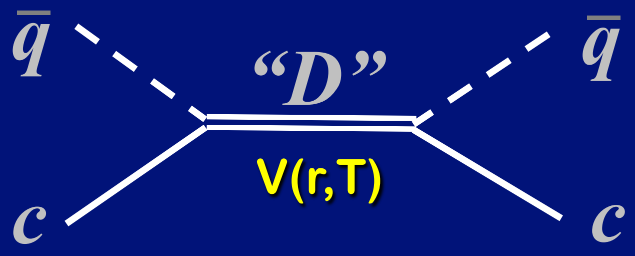


- ❖ Similar trends as for RHIC case
- ❖ $\gamma \approx T^2$ and p-indepedent like in AdS/CFT fails also the p_T dependence at LHC

What can be the physics of larger interaction as $T \to T_c$?

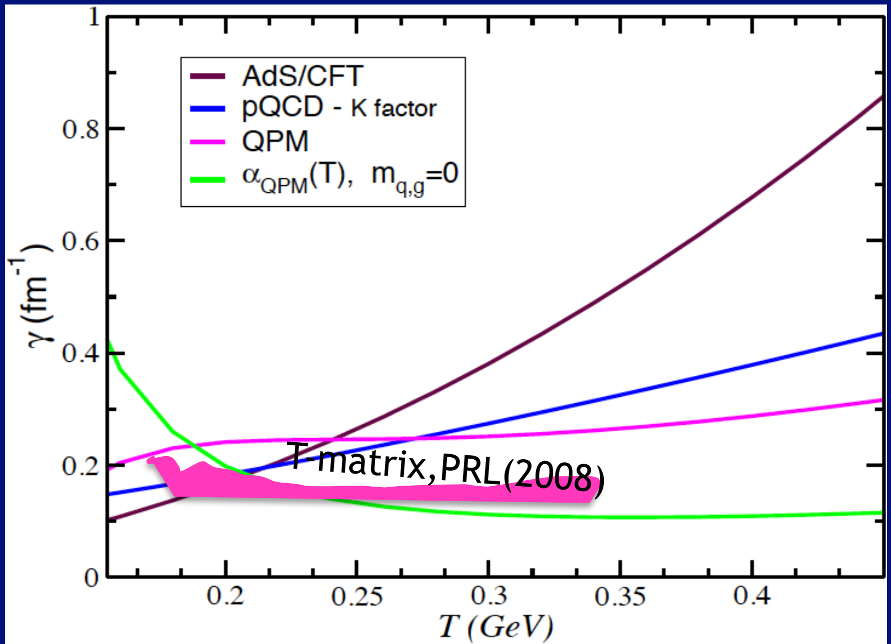
T-matrix approach: scattering under V(r,T)

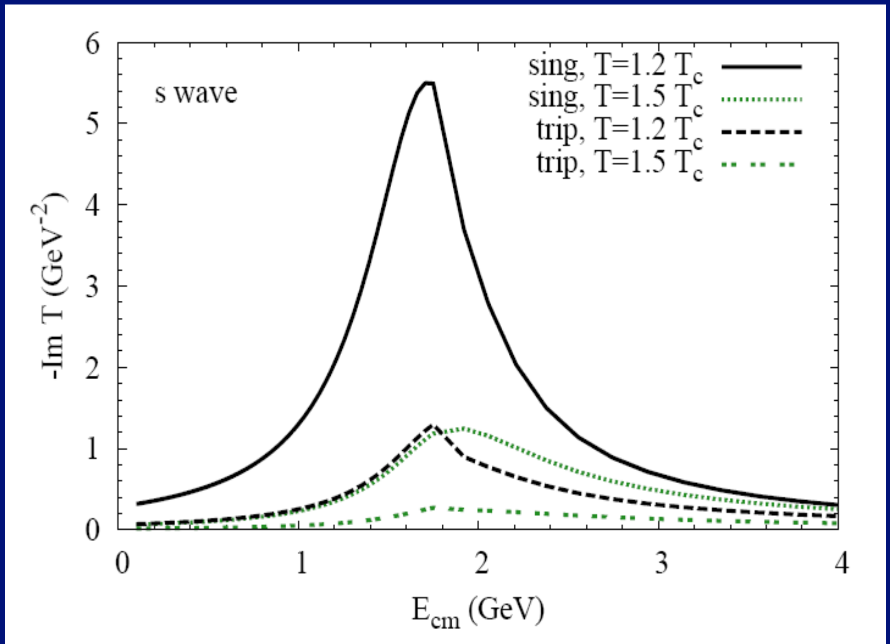




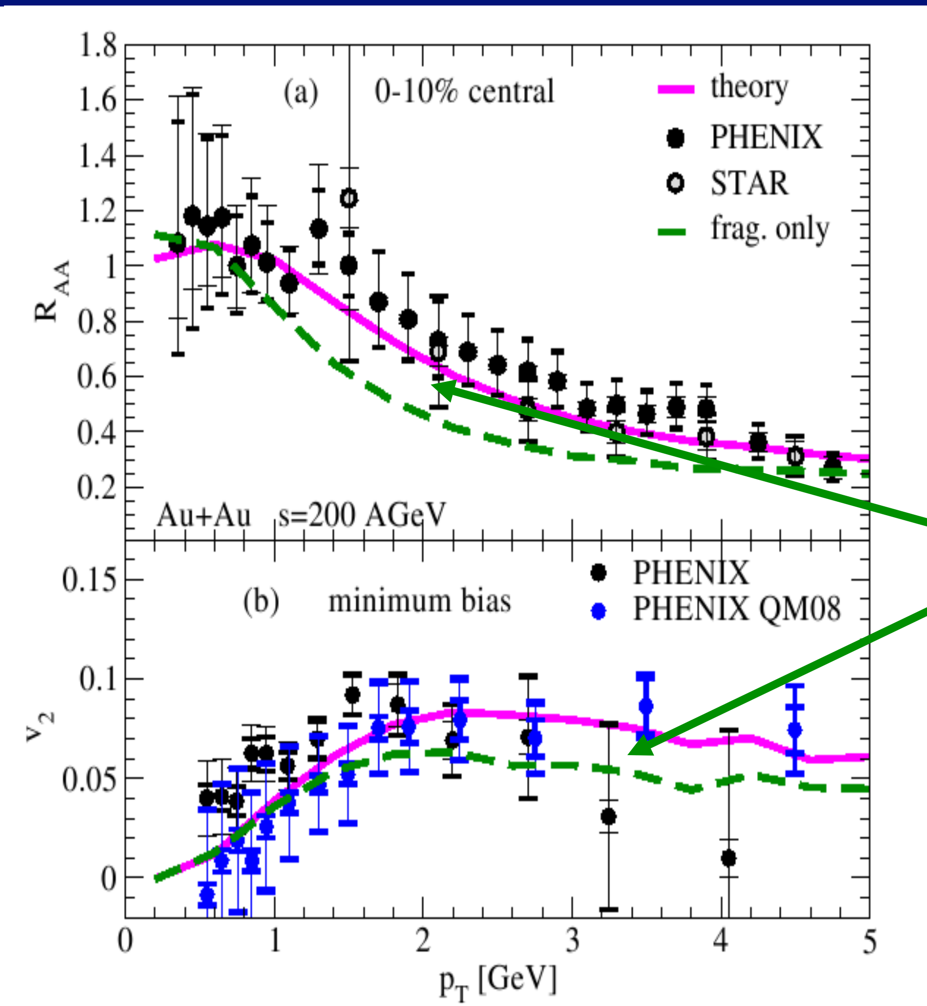
Resonant Scattering
Rapp's talk

"Im T" dominated by meson and diquark channel





Impact of hadronization mechanism



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

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

add quark momenta

Uncertainties:

- ✓ extraction of V(r) - (U vs F)
- ✓ V_2 of the bulk and hypersurface

Impact of hadronization

Coalescence increase

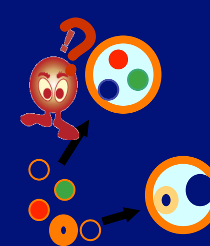
both R_{AA} and v_2

reverse the correlation

toward agreement with data

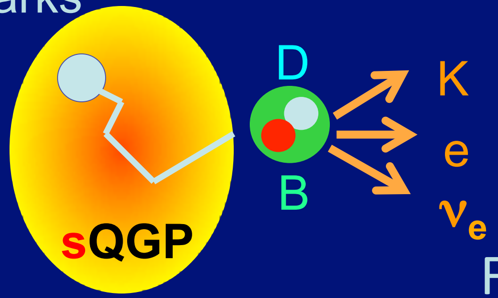
f_q from π, K

Greco,Ko,Levai - PRL90



Is the charm really Heavy and its scattering soft ?

Standard Description of HQ propagation in the QGP



Brownian Motion?

From scattering matrix $|\mathcal{M}|^2$

HQ scattering in QGP

$$\frac{\partial f_{c,b}}{\partial t} = \gamma \frac{\partial (p f_{c,b})}{\partial p} + D \frac{\partial^2 f_{c,b}}{\partial p^2}$$

T<<m_Q

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

- Elastic pQCD
- T-matrix V(r)-lQCD
- Soft gluon radiation
- QPM
- …

Now what we are doing :

- study the validity of the Brownian motion assumption, is it really small momentum transfer dynamics?
  - ✧ R_{AA} is as small as for light mesons
  - ✧ If resonant scattering is important can it be that the momentum transfer per collisions is not small

Relativistic Boltzmann Equation

$$\left\{p^{\mu}\partial_{\mu} + m^{*}\partial^{\mu}m^{*}\partial_{\mu}^{p}\right\} f_{HQ}(x,p) = C_{2\leftrightarrow 2}$$

Free streaming   Field Interaction   Collisions

Molnar'05, Ko'06, Greiner '08, Gossiaux '09, Bass '12 ...

$f_Q(x,p)$ is a one-body distribution function for HQ in our case

$f_{q,g}$ is integrated out as bulk dynamics in the Coll. integral

The relativistic collision integral can be re-written in terms of transferred momentum k=p-p'

$$\mathcal{C}[f_{HQ}](x,p) = \int d^3k \quad [\omega(p+k,k) f_{HQ}(x,p+k) - \omega(p,k) f_{HQ}(x,p)] \qquad (2)$$

Gain

Loss

Defining the probability ***w*** for HQ to be scattered from p -> p+k

$$\omega(p,k) = \int \frac{d^3q}{(2\pi)^3} f_g(x,p) v_{rel} \frac{d\sigma_{g+Q\to g+Q}}{d\Omega}$$

Expansion for small Momentum transfer

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

Relativistic Boltzmann Equation

$$\left\{ p^{\mu}\partial_{\mu} + m^{*}\partial^{\mu} m^{*}\partial^{p}_{\mu} \right\} f_{HQ}(x,p) = C_{2\leftrightarrow 2}$$

Free streaming Field Interaction Collisions

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Expansion for small Momentum transfer

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

Defining the probability ***w*** for HQ to be scattered from p -> p+k

$$C_{22} \cong \int d^3k \left[k_i \frac{\partial}{\partial p_i}(\omega f) + \frac{1}{2} k_i k_j \frac{\partial^2}{\partial p_i \partial p_j} \right] \omega(p,k) f(p)$$

Fokker – Planck equation

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

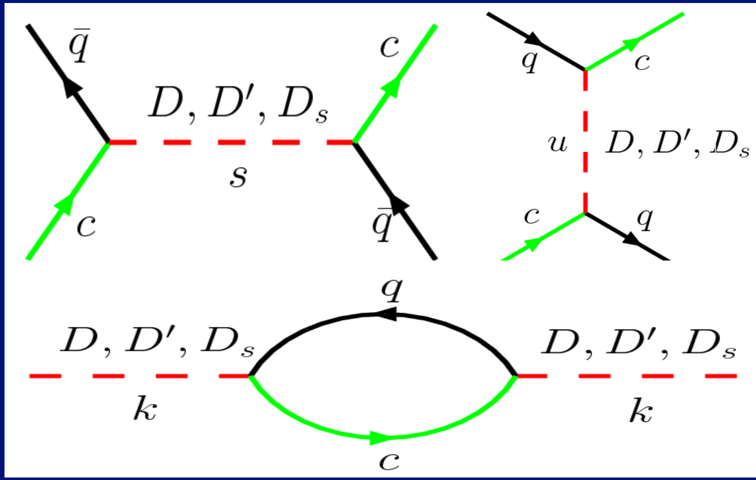
$$\mathbf{A_i} = \int \mathbf{d^3k}\,\omega(\mathbf{p},\mathbf{k})\mathbf{k_i} \rightarrow \text{Drag}$$

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

Drag: $\langle p \rangle$ Diffusion: $\langle \Delta p^2 \rangle$

Common Origin -> two approaches: LV and BM

$\mathcal{M}$ scattering matrix of the collision process



Langevin approach

$\mathcal{M}$ -> A_i, B_{ij}

Boltzmann approach

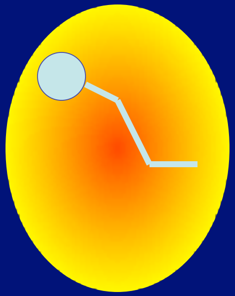
$\mathcal{M}$ -> $d\sigma/d\Omega$

Drag Coefficient -> <p>

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

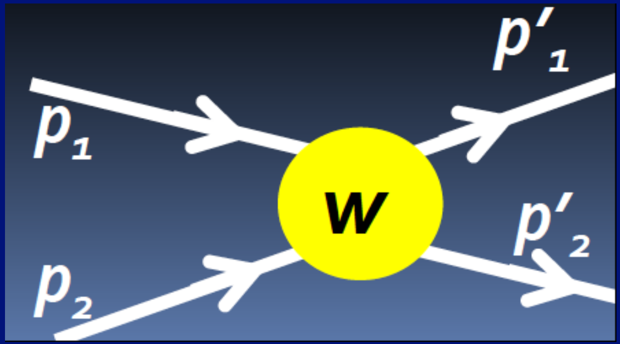
Diffusion coefficient -> <Δp²>

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



Total and differential cross section

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

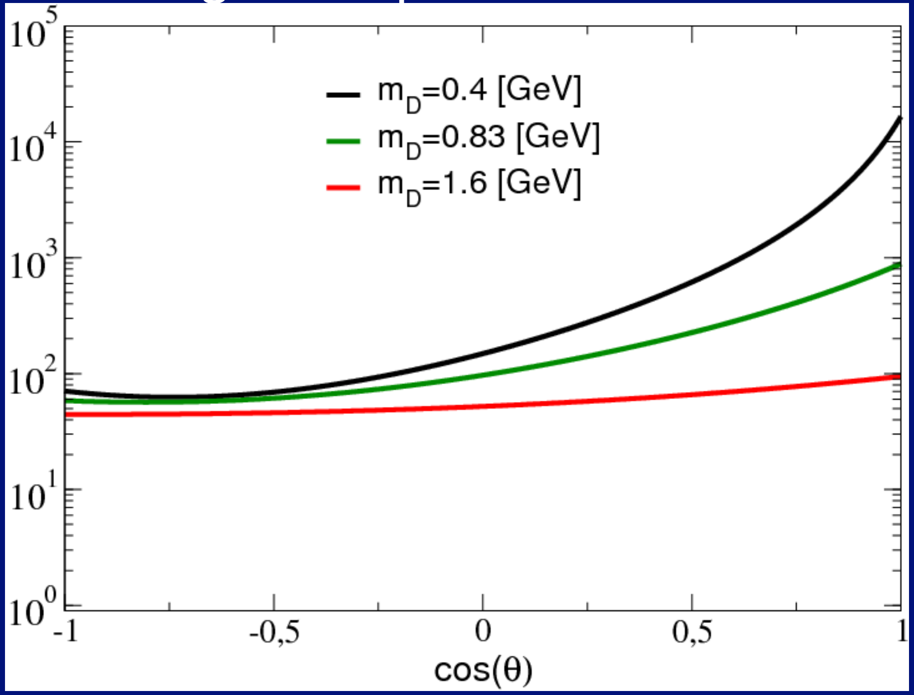


Differential Cross section and momentum transfer: Charm

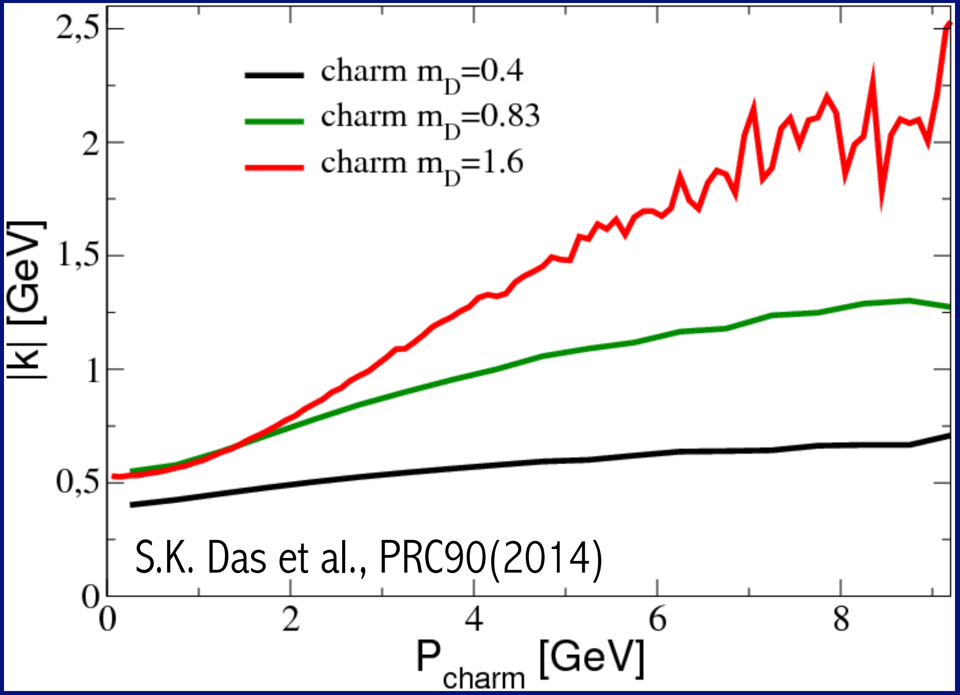
- Changing m_D simulates different angular dependencies of scatterings
- m_D=gT =0.83 GeV for α_s=0.35 (Combridge cross section)

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{\left(q^2(\theta)+m_D^2\right)^2}$$

Angular dependence of σ



Momentum transfer

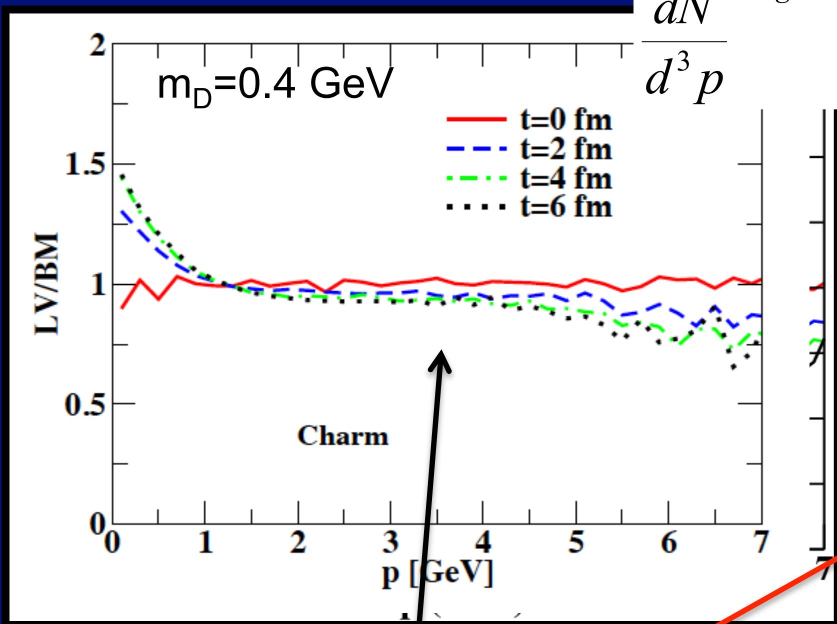


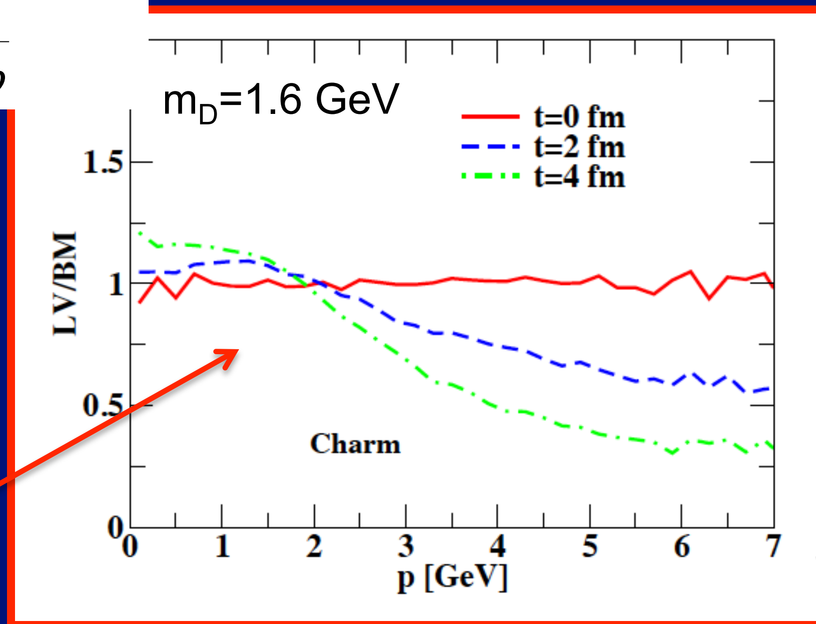
- σ more isotropic -> Larger average momentum transfer
- For Charm isotropic cross section can lead K> M_c

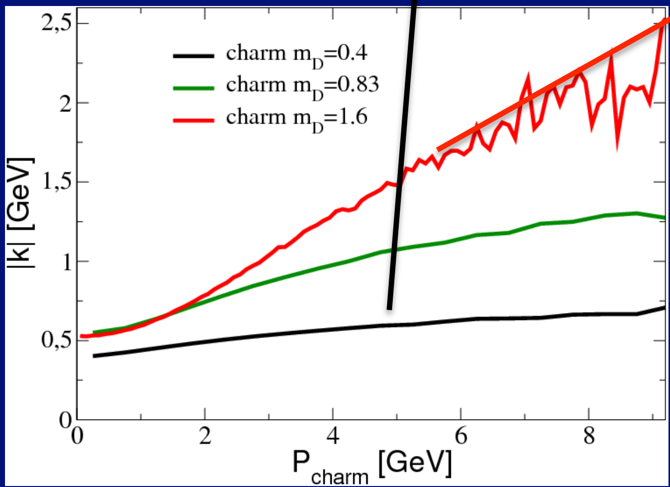
Boltzmann vs Langevin (Charm)

Time evolution of the p-spectra

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





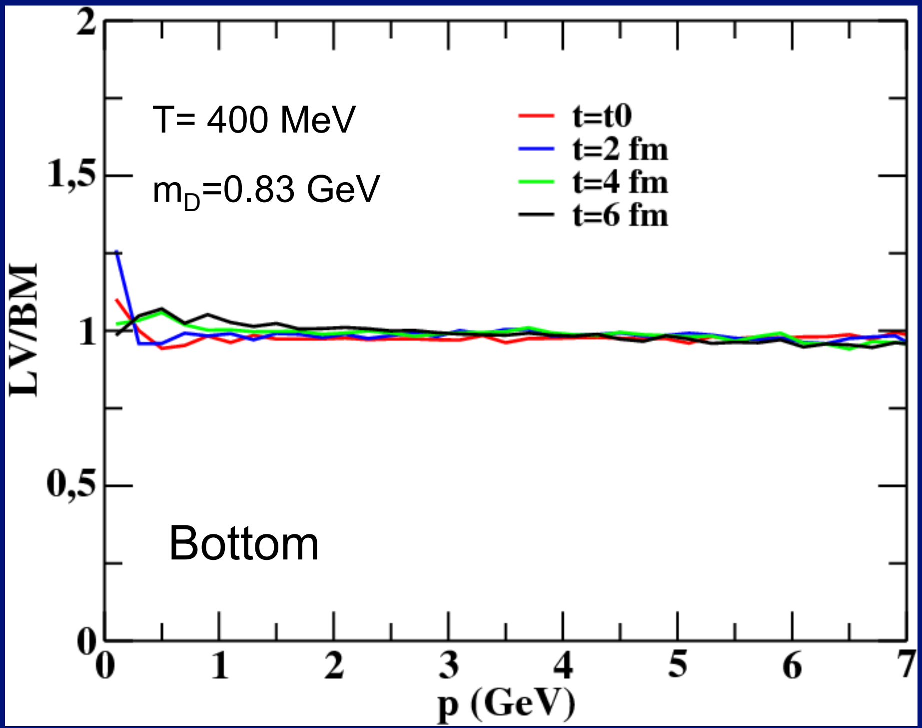


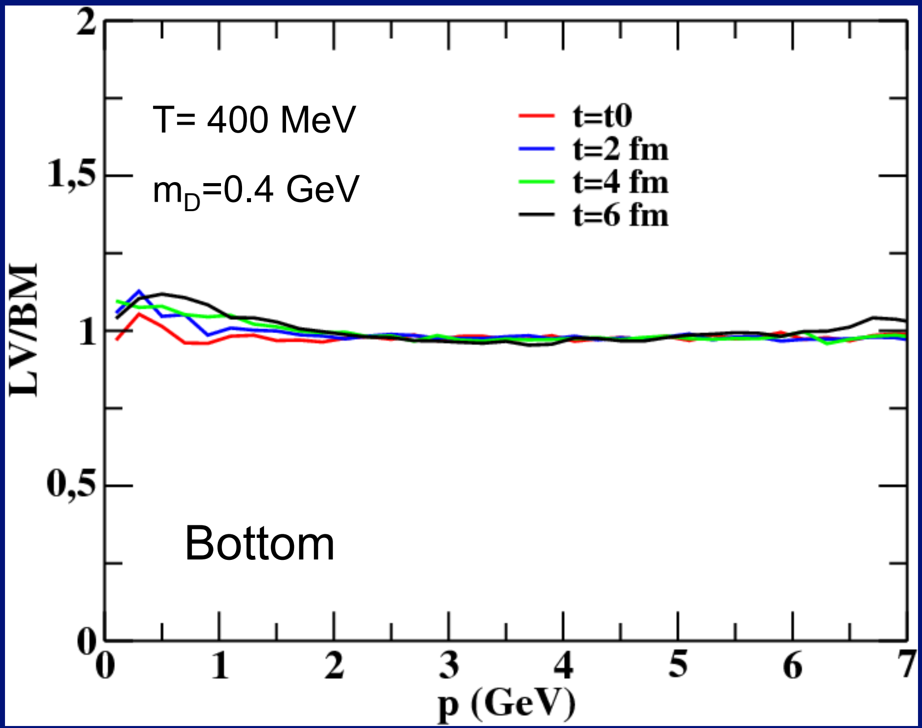
- The smaller <k> the better Langevin approximation works
- At t ≈ 4-6 fm/c difference can be quite large for $m_D \geq 0.8$ GeV ($K \approx M_c \approx 3T$)

S.K. Das et al.,arXiv:1312.6857 – PRC90 (2014)

Bottom R_{AA}: Boltzmann = Langevin

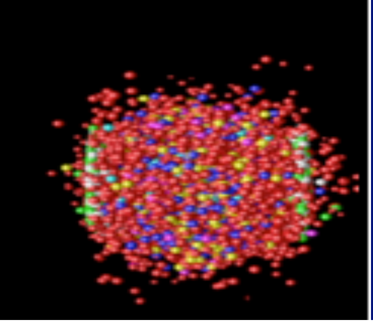
Calculation in a Box





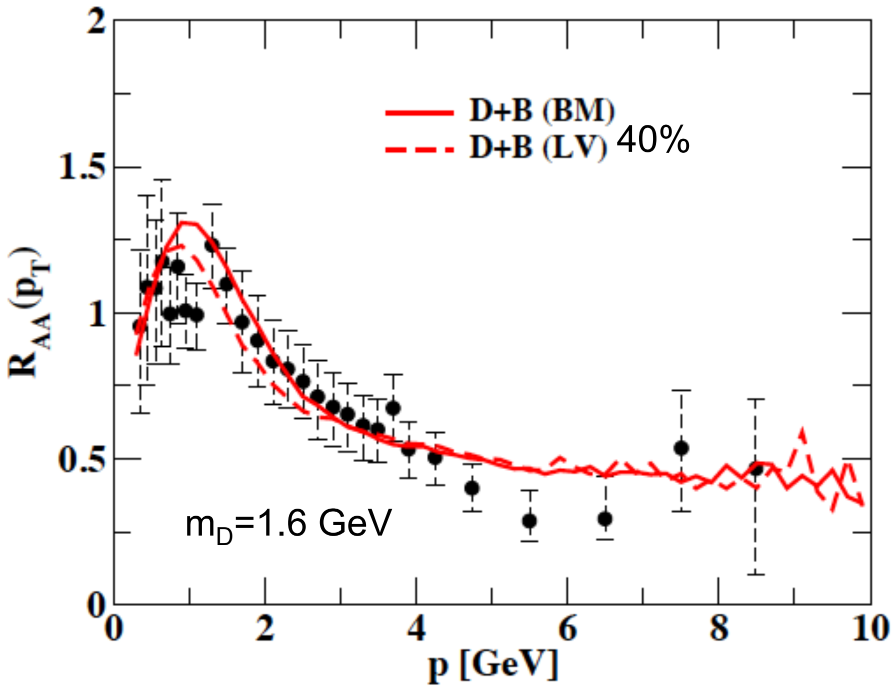
In bottom case Langevin approximation ≈ Boltzmann

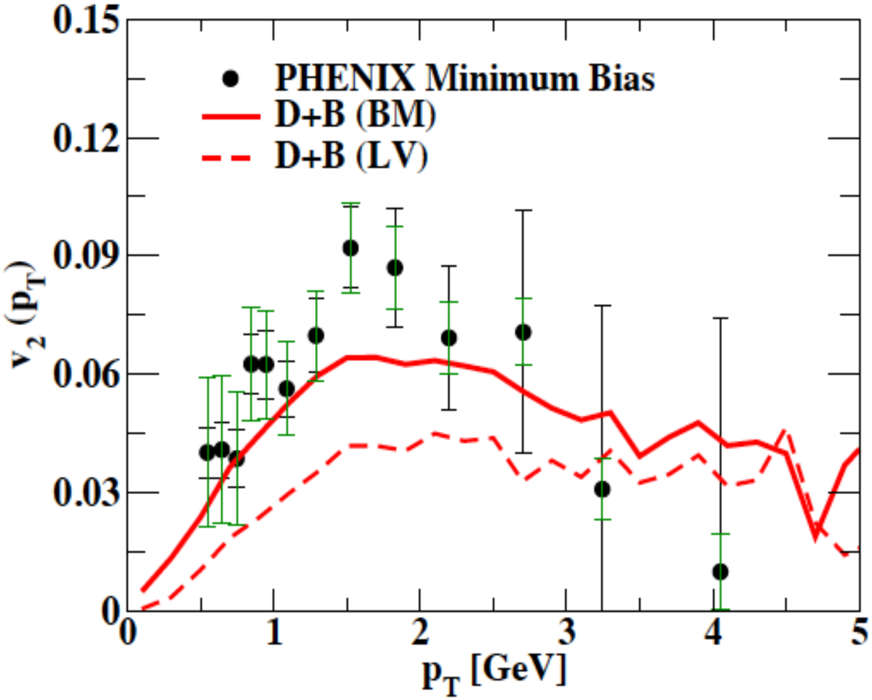
But Larger M_b/T (≈ 10) the better Langevin approximation works



R_{AA} & v_2 Boltzmann vs Langevin

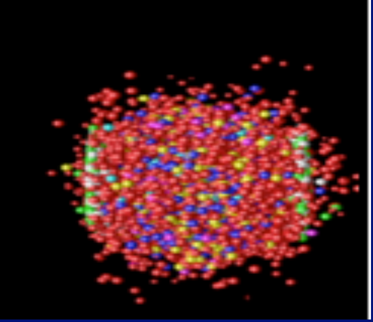
Au+Au@200AGeV, b=8 fm





✓ Fixed same $R_{AA}(p_T)$ [reduce γ by 40%] → $v_2(p_T)$ 35% higher (m_D=1.6 GeV)
- dependence on the specfic scattering matrix (isotropic case -> larger effect)

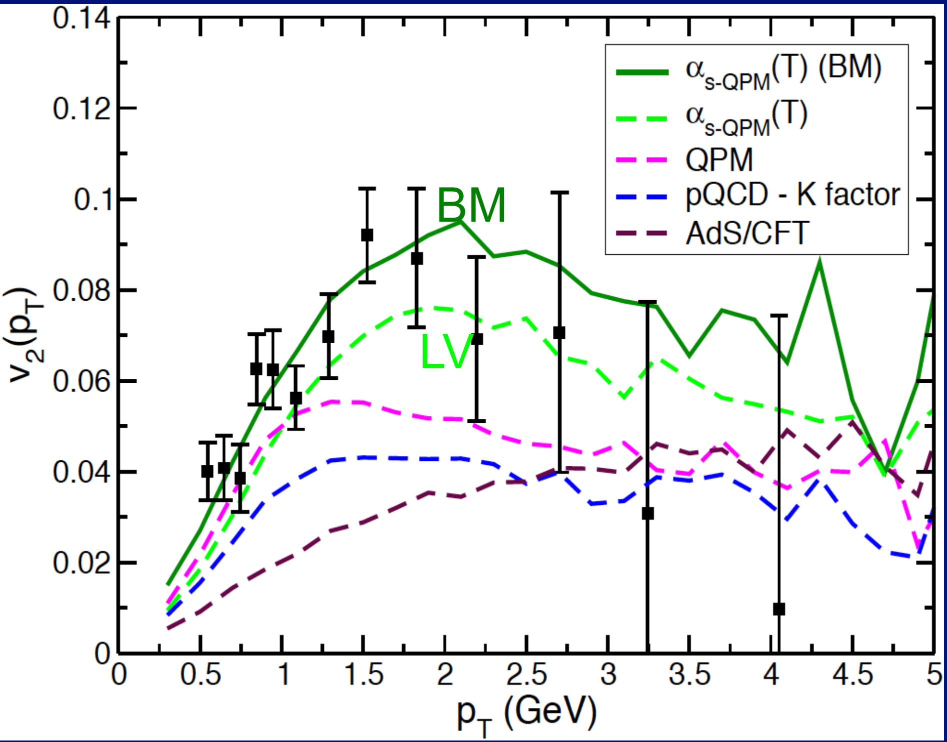
Hadronization by coalescence not included



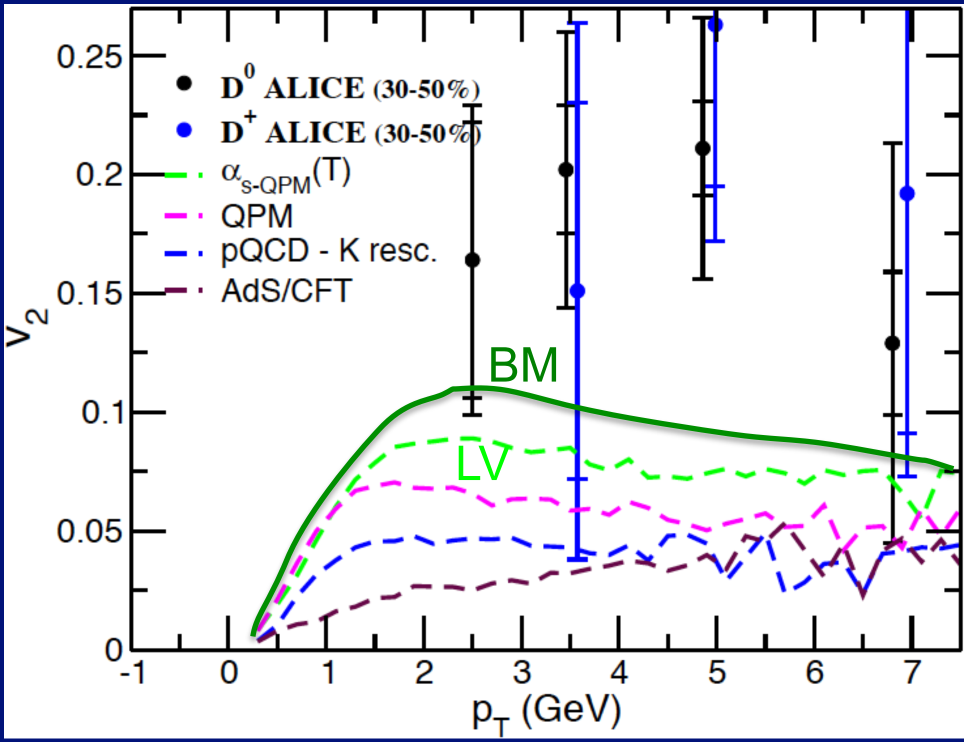
R_{AA} & v_2 Boltzmann vs Langevin

Impact of the Boltzmann dynamics for $\alpha_{QPM}(T)$ case

Au+Au@200AGeV, b=8 fm

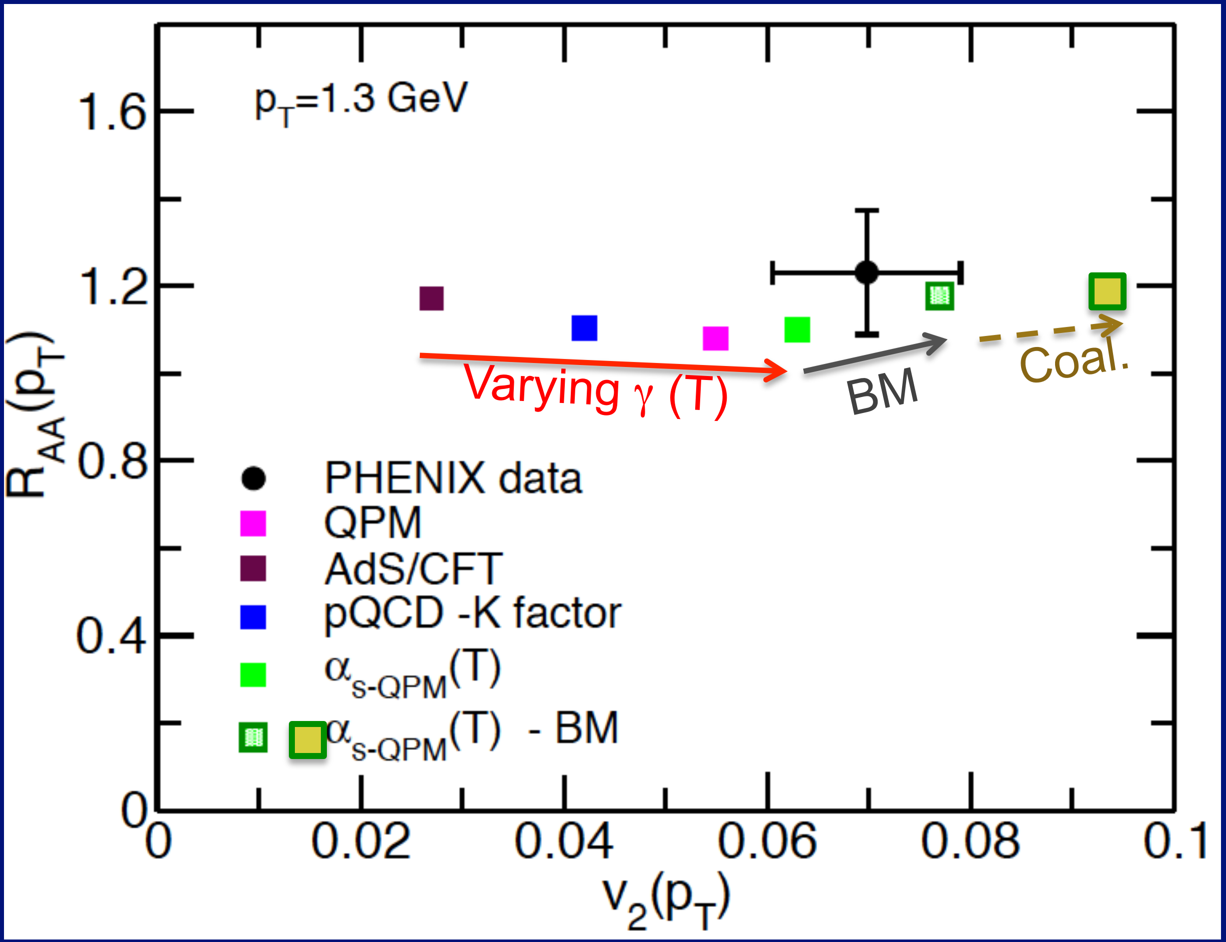


LHC – Pb+Pb@2.76ATeV



No coalescence included, only fragmentation

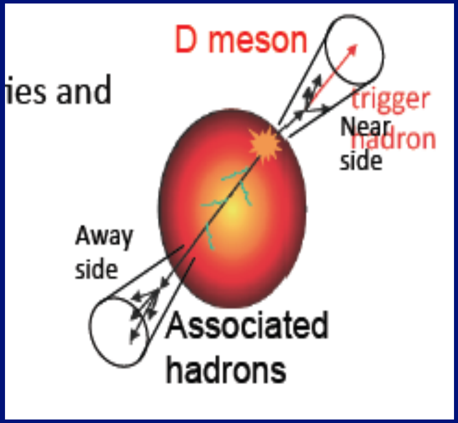
Summary on the build-up of v_2 at fixed R_{AA}



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

One step further into the details of the dynamics (selection in p_{1t}, p_{2t} and $\Delta\phi=\phi_1-\phi_2$):

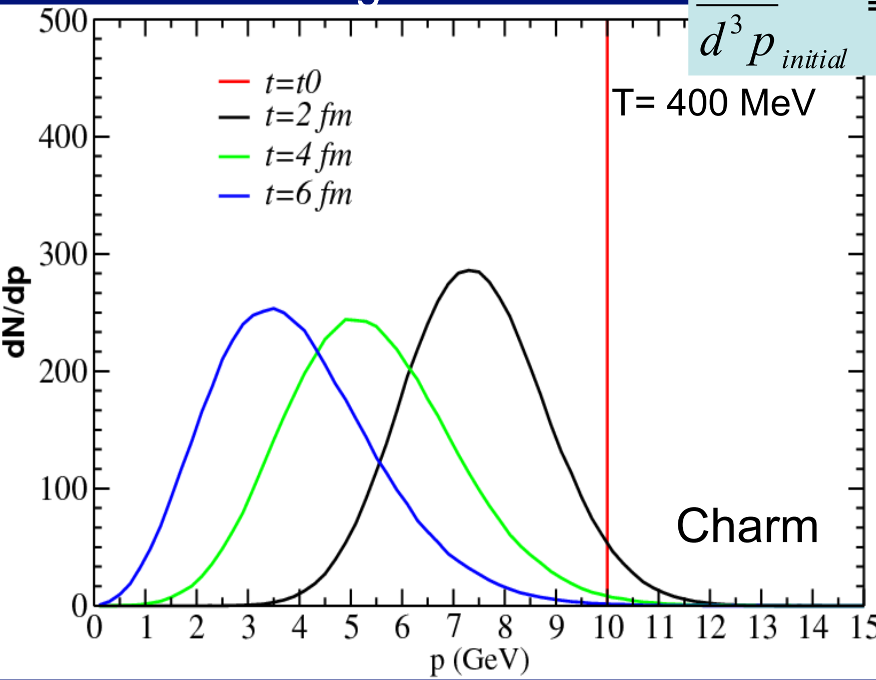
- Energy loss of a single HQ
- Angular correlation between c and c-bar



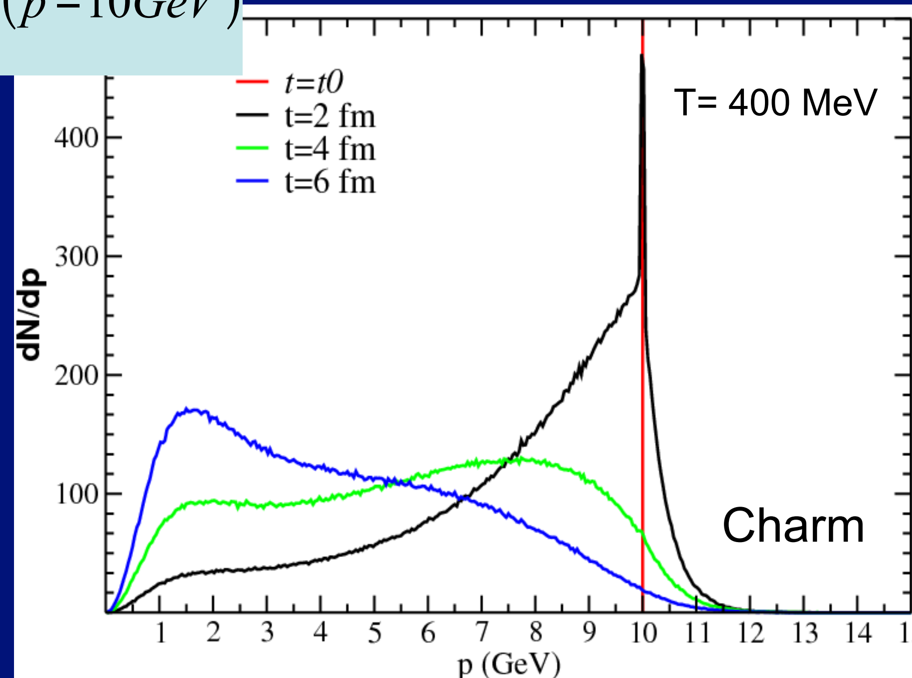
Momentum evolution of a single Charm

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

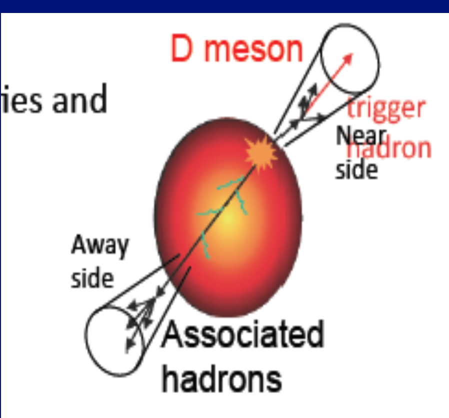
Langevin



Boltzmann



S.K. Das et al., PRC90 (14) 044901



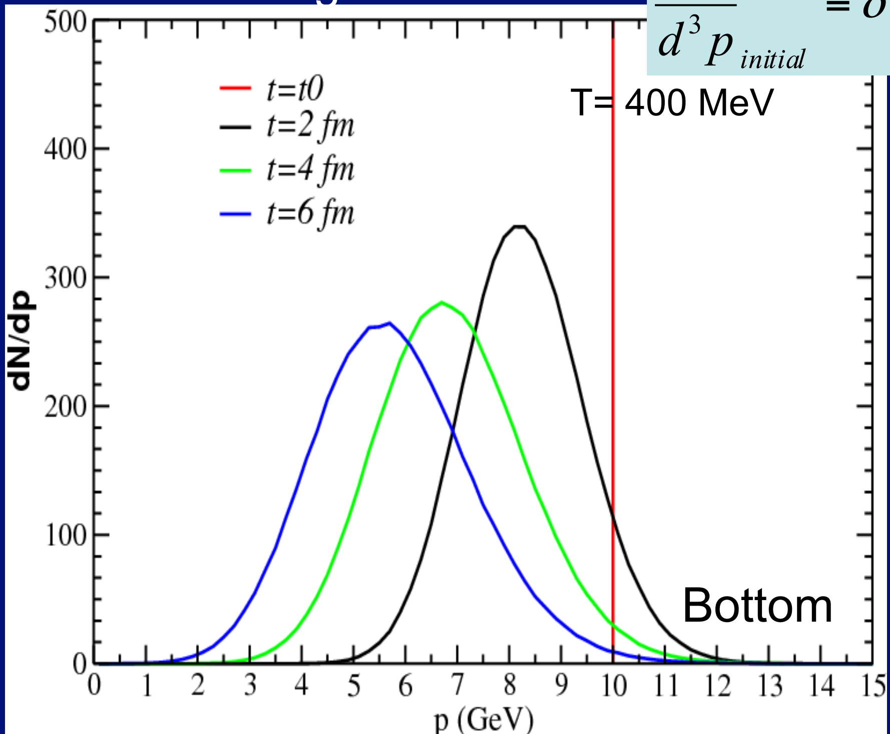
- Kinematics of collisions (Boltzmann) can throw particles at very low p soon.
- The motion of single HQ does not appear to be of Brownian type, on the other hand $M_c/T=3$ -> $M_c/\langle p_{bulk}\rangle = 1$

Larger momentum spread -> large spread in the angular distributions -> back to back Charm-antiCharm angular correlation

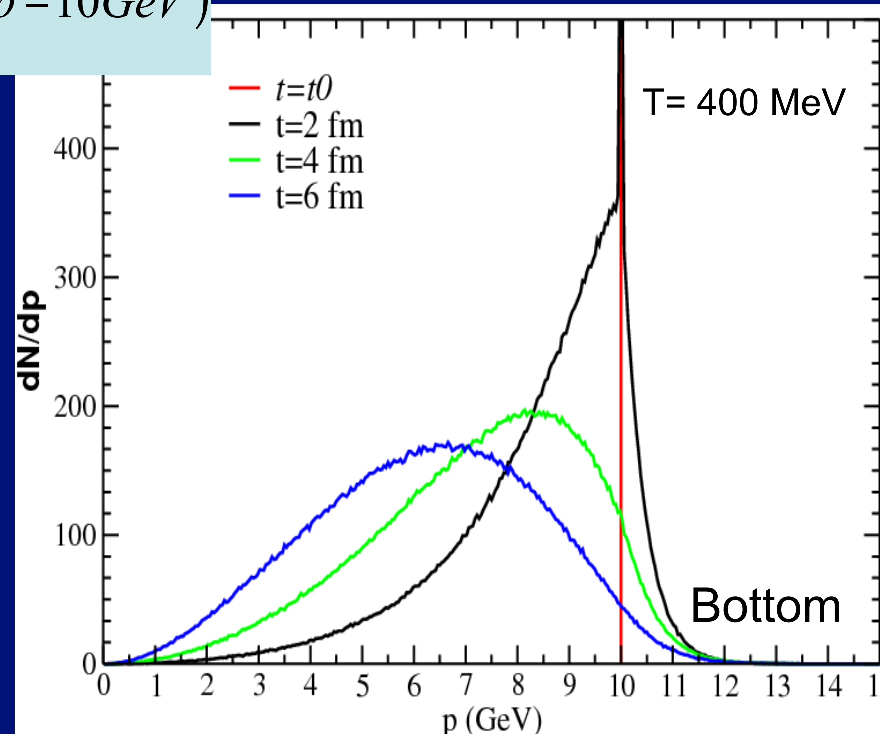
Momentum evolution of a single Bottom

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

Langevin



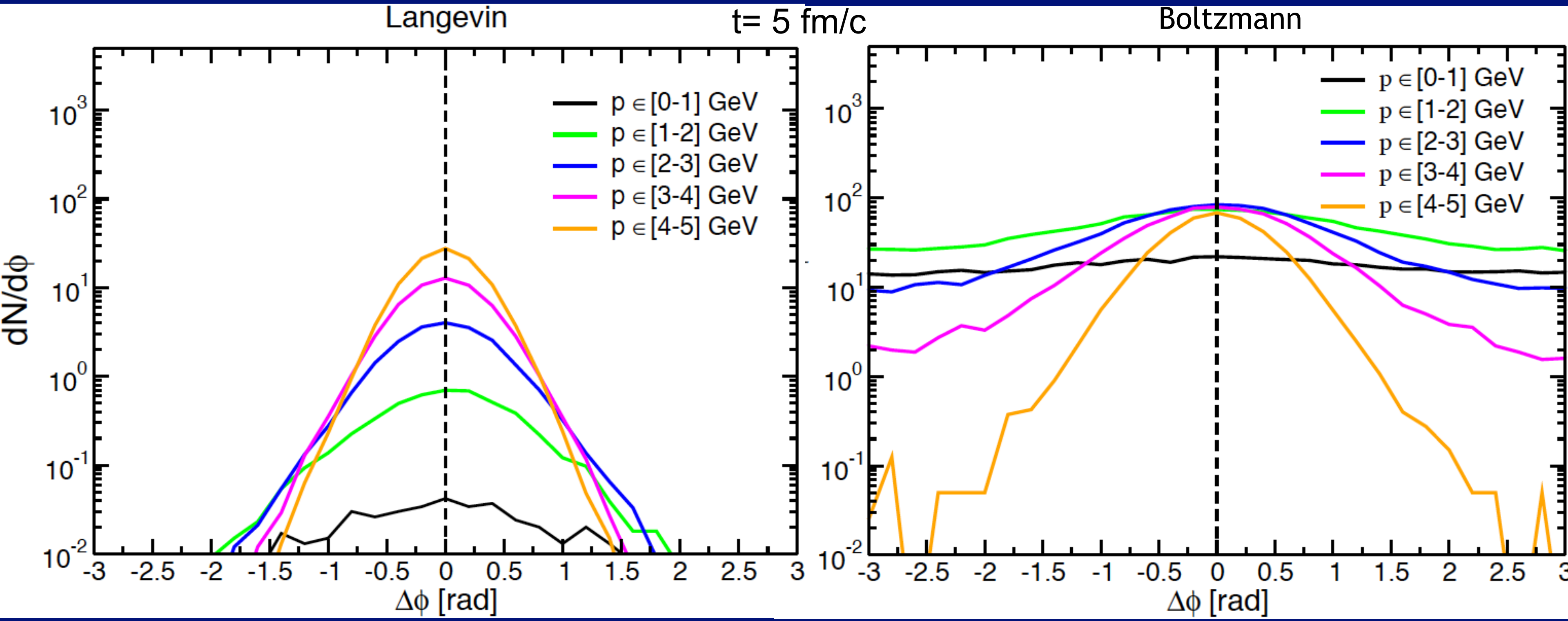
Boltzmann

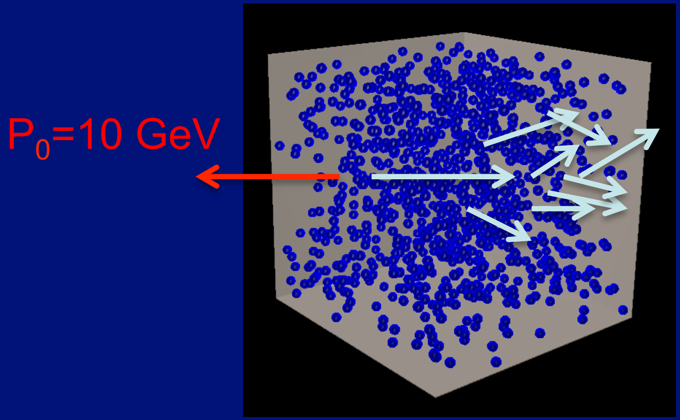


- For Bottom one start to see a peak moving with a width even if it is more reminiscent of Poisson distribution

More close to Brownian motion, on the other hand $M_b/T=10$

Langevin vs Boltzmann p-evolution





Striking difference also at $\Delta\phi = 0$:

- The evolution of the yield from 2 to 5 GeV is about 10^2 times different
- Boltzmann much more efficient toward full thermalization

Summary

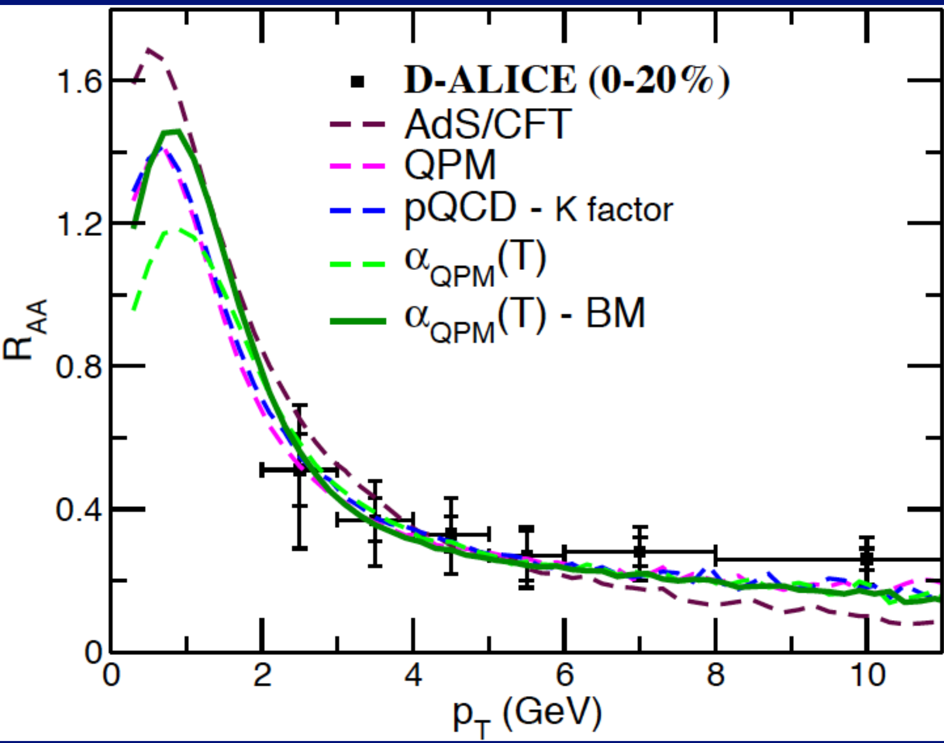
❖ R_{AA}- v_2 of charm seems to indicate:

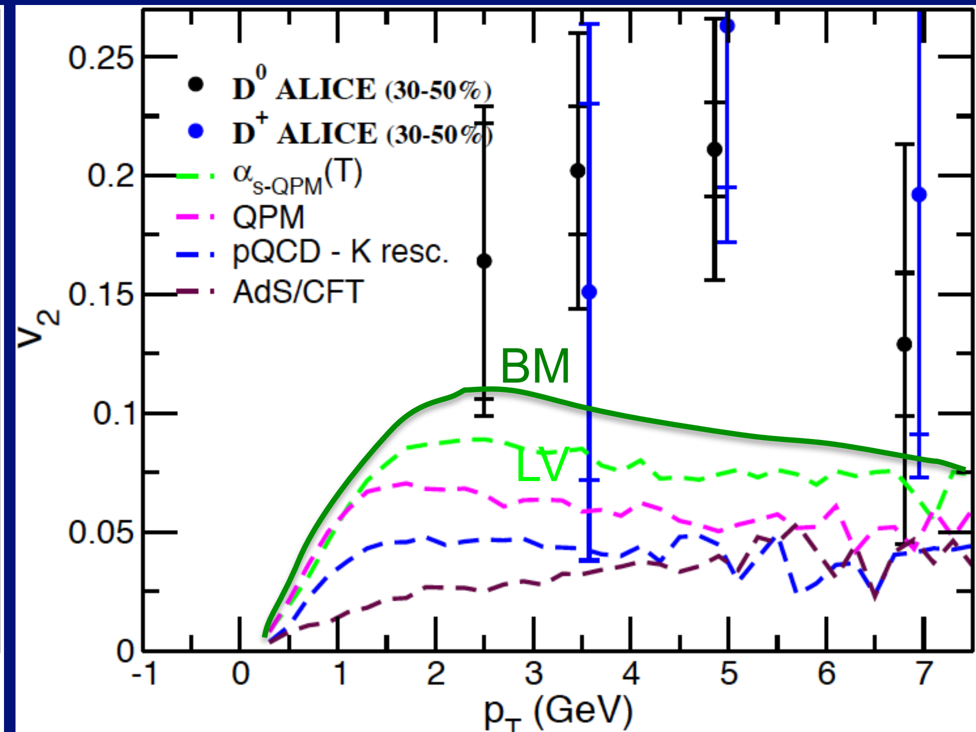
- Drag about constant in T → ≈ v_2 exper. (effect of confinement)
- Boltzmann dynamics more efficient for v_2 even at fixed R_{AA}
- Hadronization of coalescence of heavy quarks: modify R_{AA}-v_2 corr.

❖ Boltzmann vs Langevin:

- If interested to simultaneous R_{AA}, v_2, $dN_{cc}/d\Delta\phi$ we can realize that <u>charm</u> in hot QGP is not that heavy and the motion not really Brownian.
- Very similar dynamics for <u>Bottom</u> at least for R_{AA} and V_2

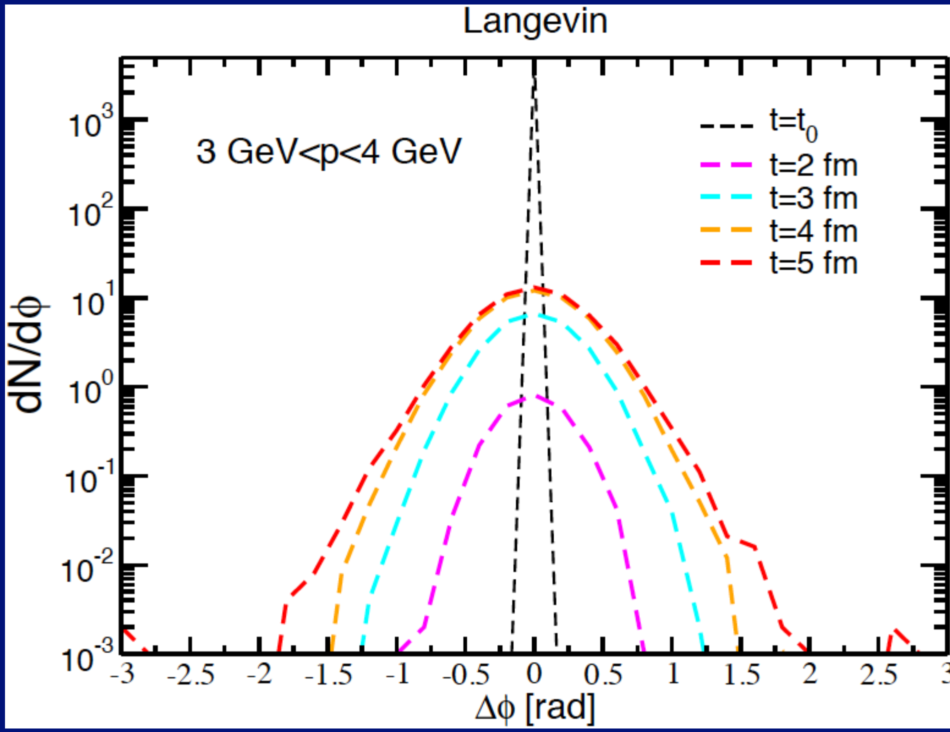
LHC – Pb+Pb@2.76ATeV



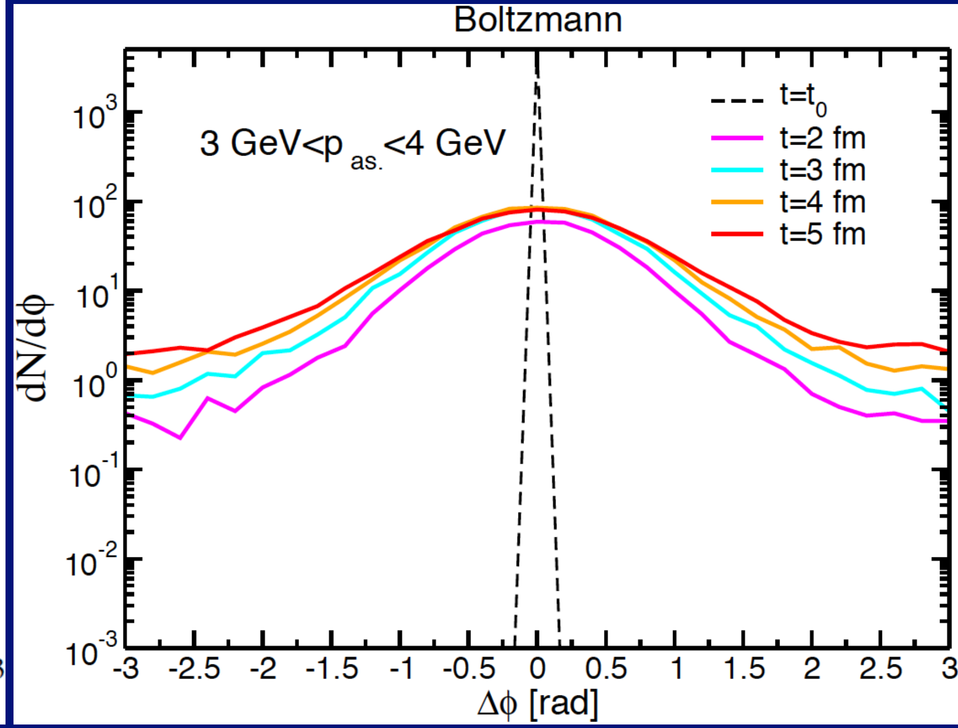


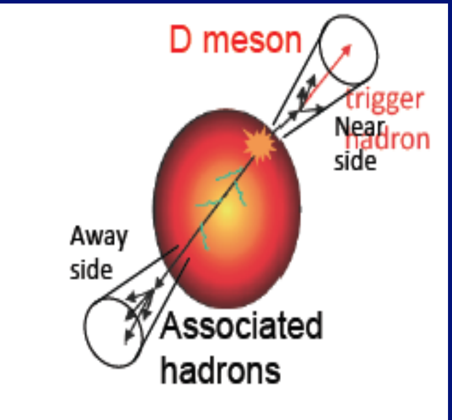
C-barC angular correlation

Langevin

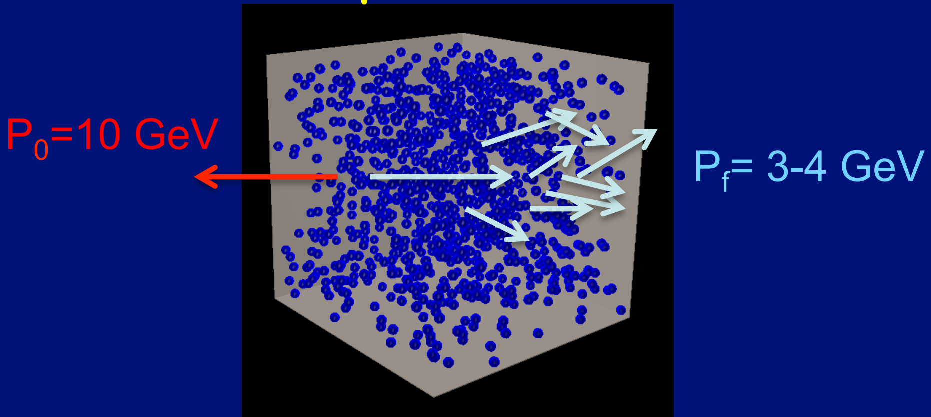


Boltzmann





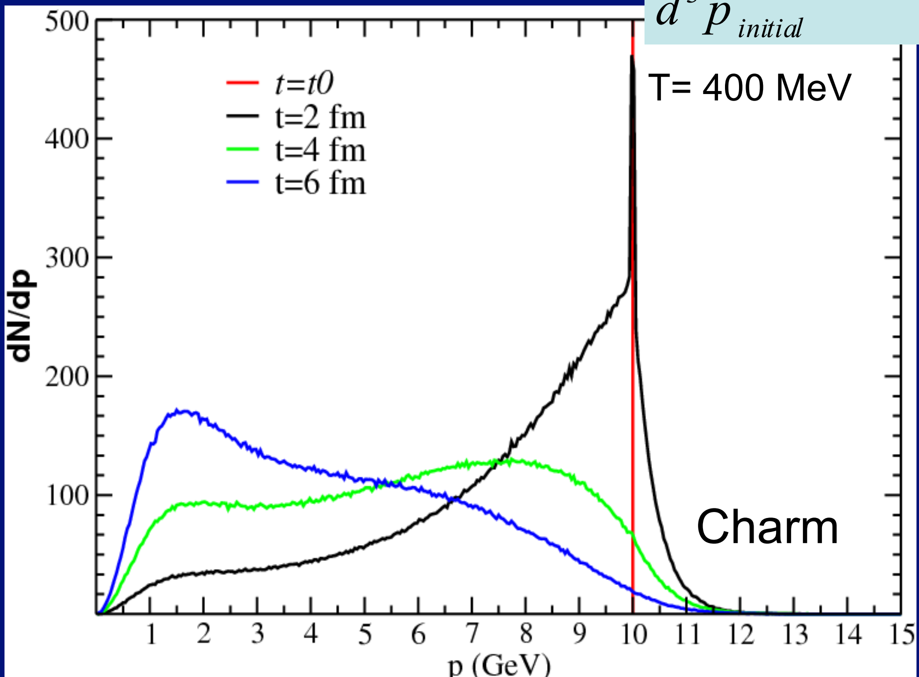
c-c pair in a box



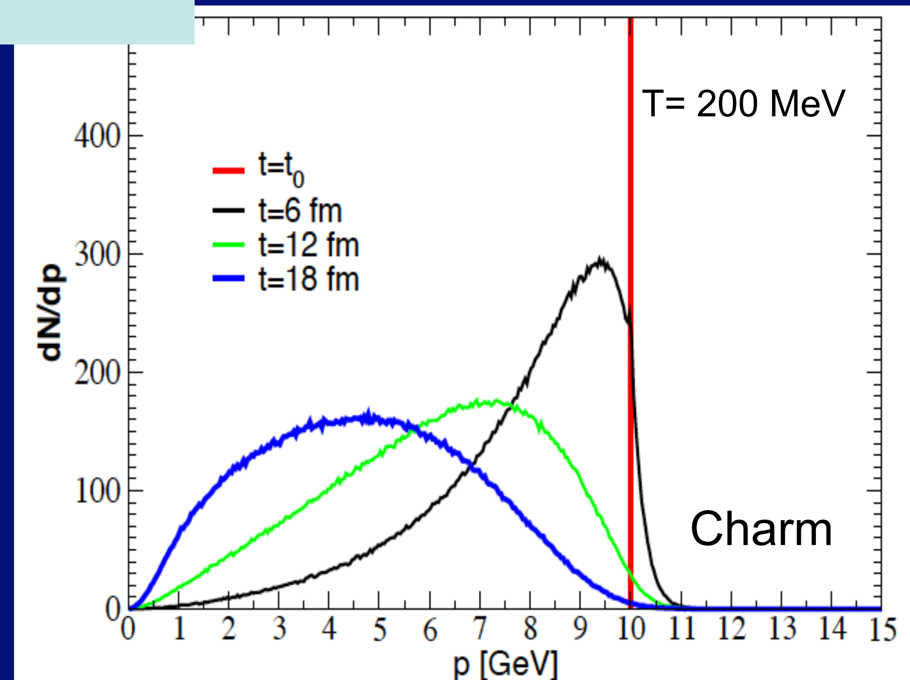
Momentum evolution for charm vs temperature

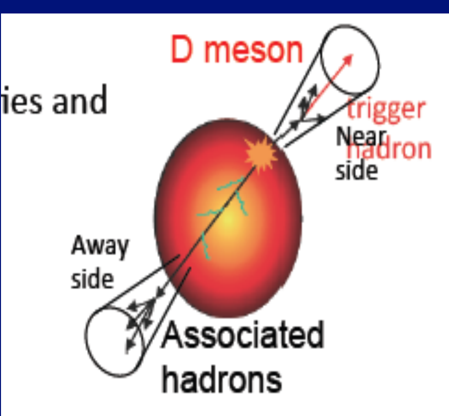
$$\left.\frac{dN}{d^3p}\right|_{initial} = \delta\left(p - 10GeV\right)$$

Boltzman



Boltzmann



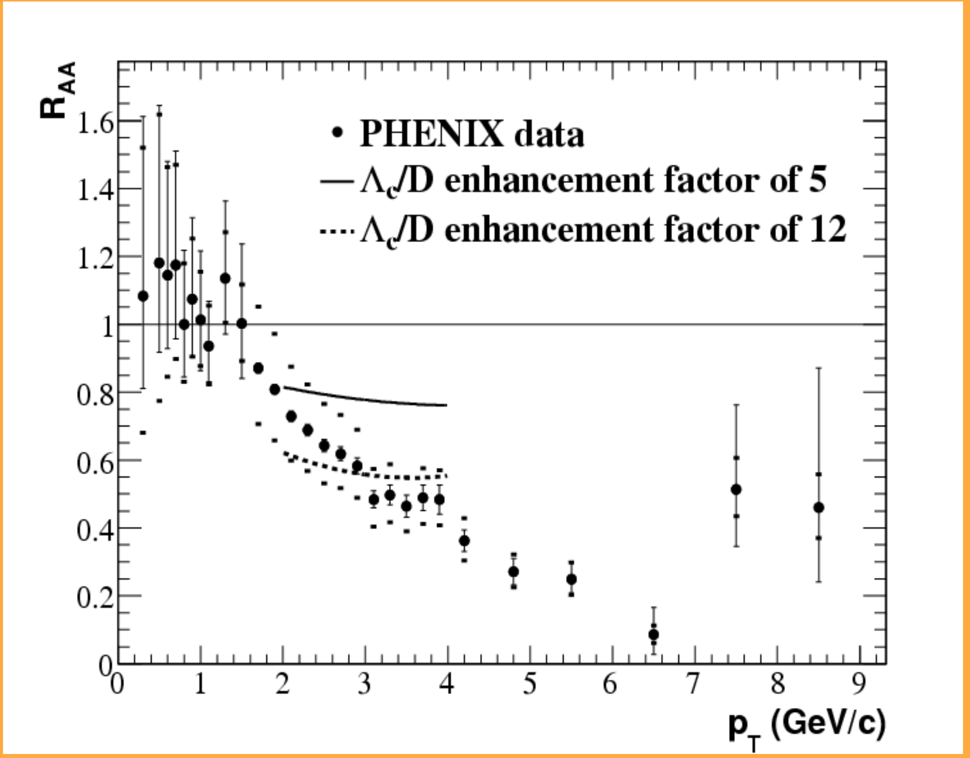


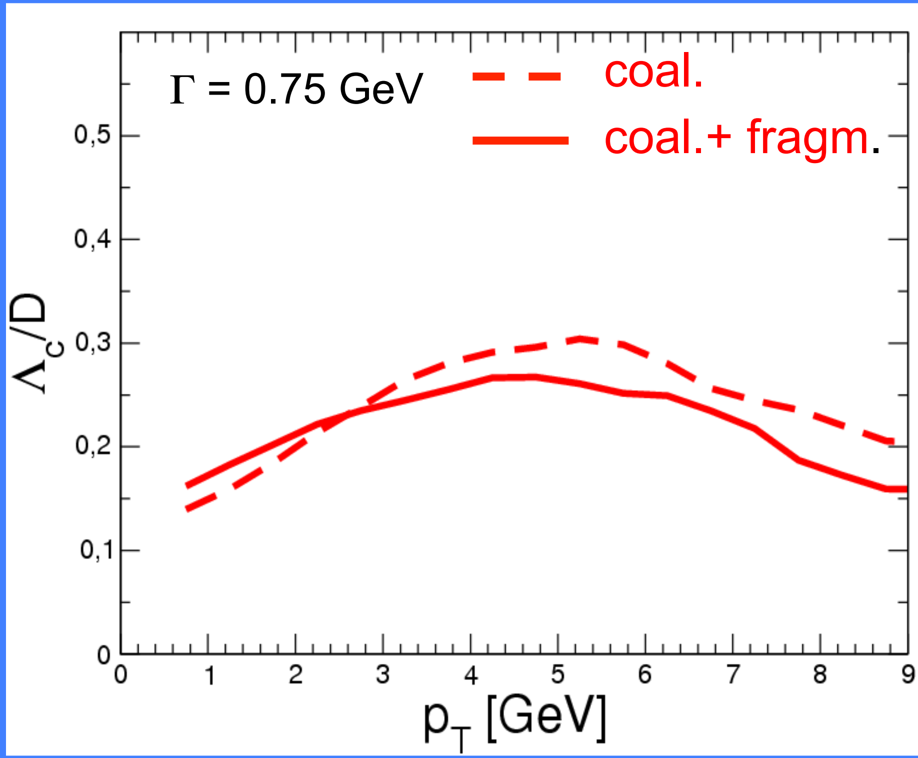
- At 200 MeV Mc/T= 6.5-> start to see a peak with a width

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

Baryon contamination due to coalescence … !?

P. Soresen, nucl-ex/0701048, PRC (07)
G. Martinez-Garcia et al., hep-ph/0702035 PLB(08)



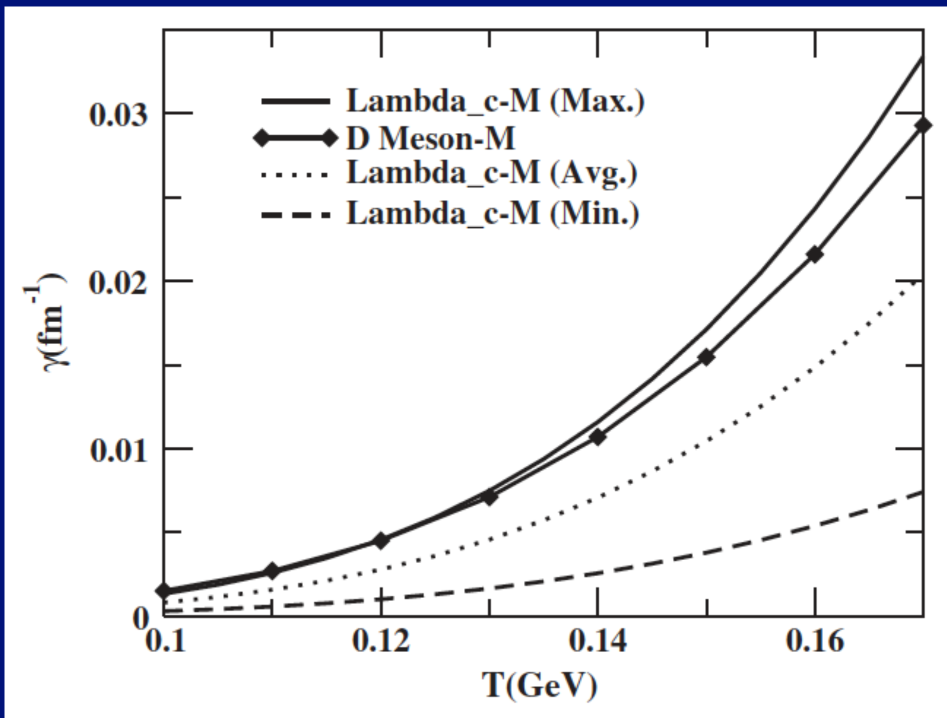


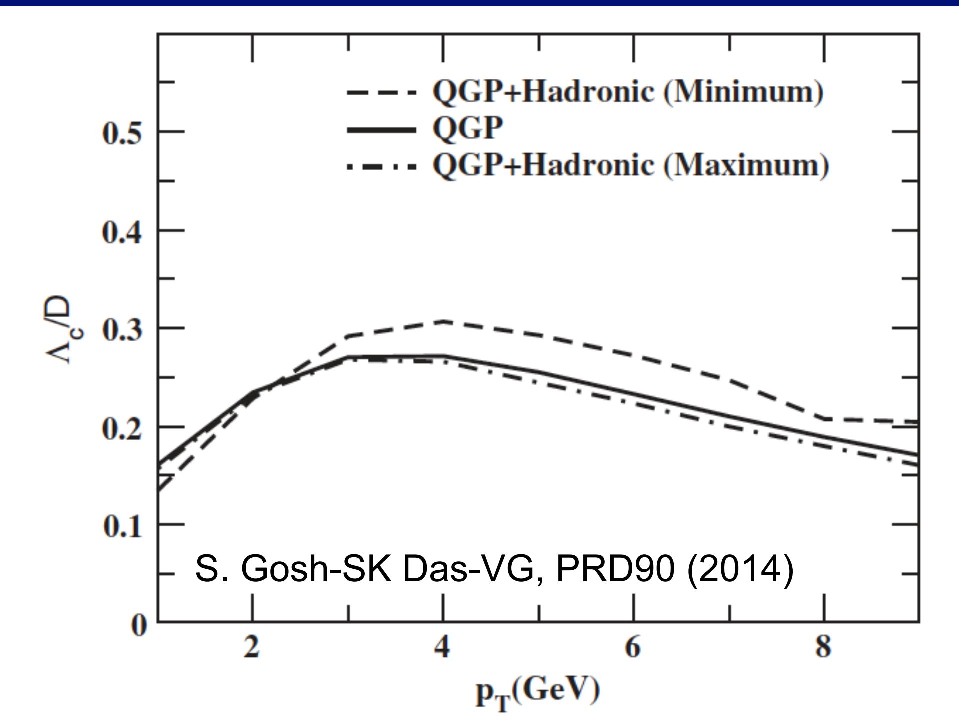
Apparent reduction if Λ_c/D ~1
due to different branching ratio
- Effect at pt~2-4 GeV region were it is more apparent the coalescence effect)

- Explanation for large v_{2e} : $v_{2\Lambda c}$ > v_{2D}

Some coalescence model predict
a much larger enhancement…
possibility to reveal diquark correlations?

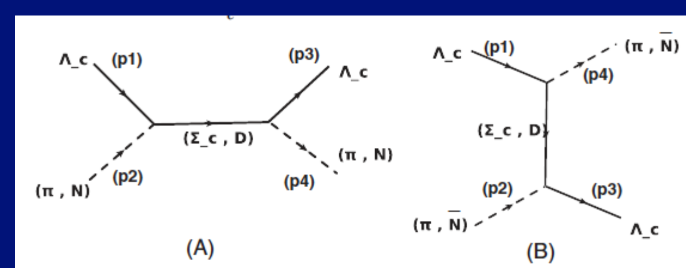
Impact of hadronic rescattering on Λ_c/D ratio



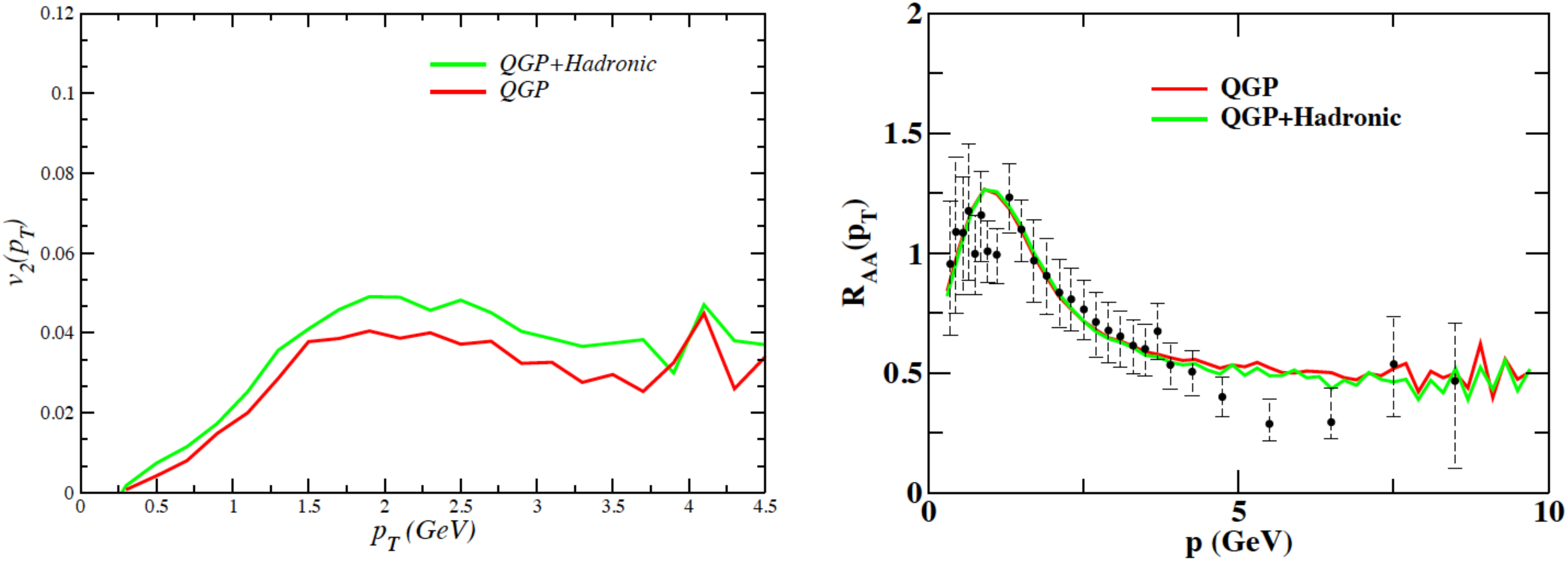


$$\mathcal{L}_{\Lambda_c\Sigma_c\pi} = \frac{g}{m_\pi}\overline{\Lambda_c}\gamma^5\gamma^\mu \mathrm{Tr}(\vec{\tau}\cdot\vec{\Sigma}_c\vec{\tau}\cdot\vec{\pi}) + \mathrm{H.c.},$$

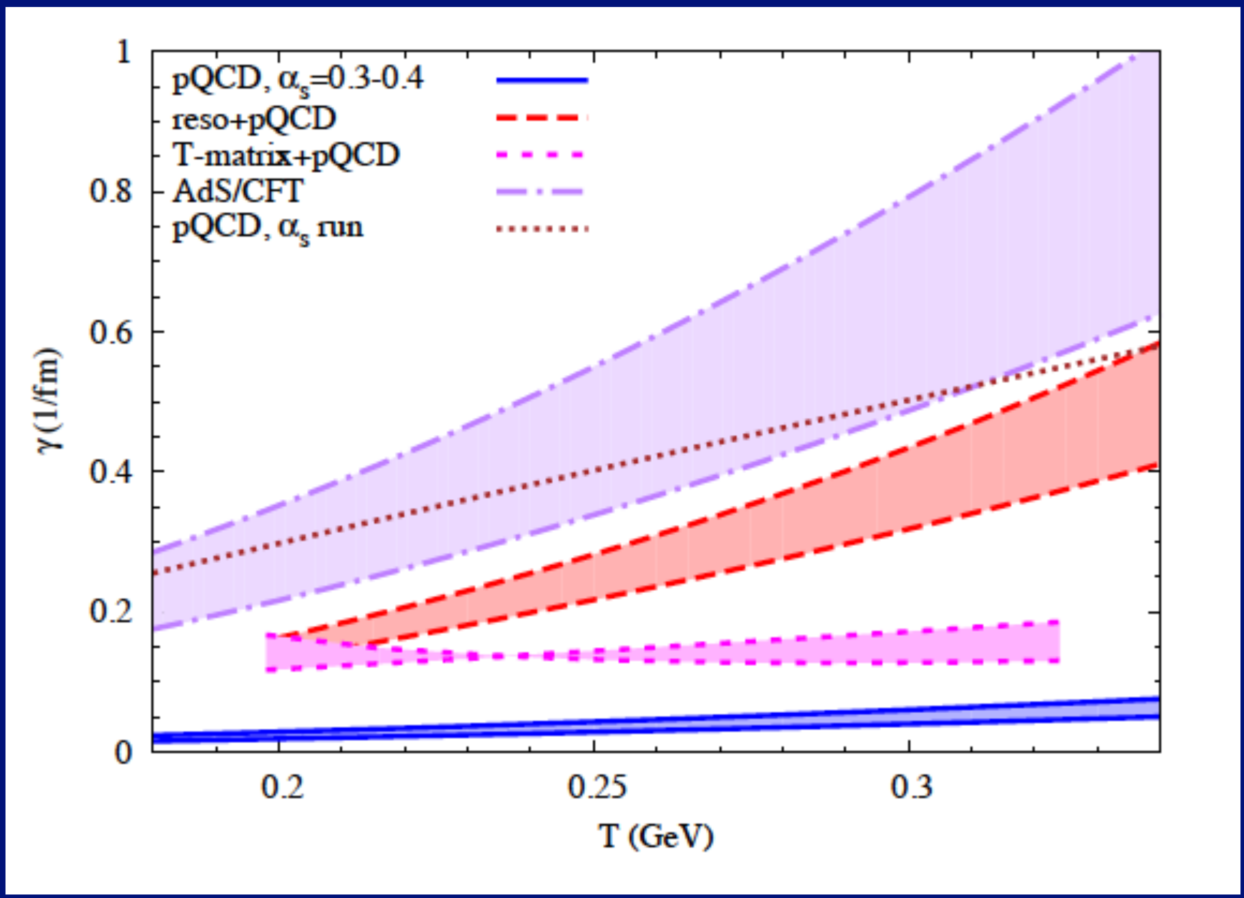
$$\mathcal{L}_{\Lambda_c ND} = \frac{f}{m_D}\bar{N}\gamma^5\gamma^\mu\Lambda_c\partial_\mu D + \partial_\mu\bar{D}\,\overline{\Lambda_c}\,\gamma^5\gamma^\mu N,$$



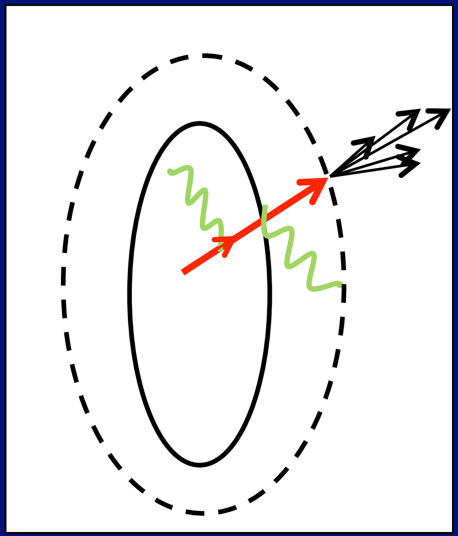
Impact of Hadronic Reinteraction for D meson



T_{QGP}=165 MeV


pQCD, α_s=0.3-0.4
reso+pQCD
T-matrix+pQCD
AdS/CFT
pQCD, α_s run
γ(1/fm)
T (GeV)
0
0.2
0.4
0.6
0.8
1
0.2
0.25
0.3

Jet quenching for light q and g



GLV radiation formula

$$\frac{\Delta E}{\Delta \tau} = \frac{9\pi C_R \alpha_s^3}{4} \tau \rho(\tau, r, \phi_0) \log\left(\frac{2 P_{T0}}{\tau \mu(\tau)^2}\right)$$

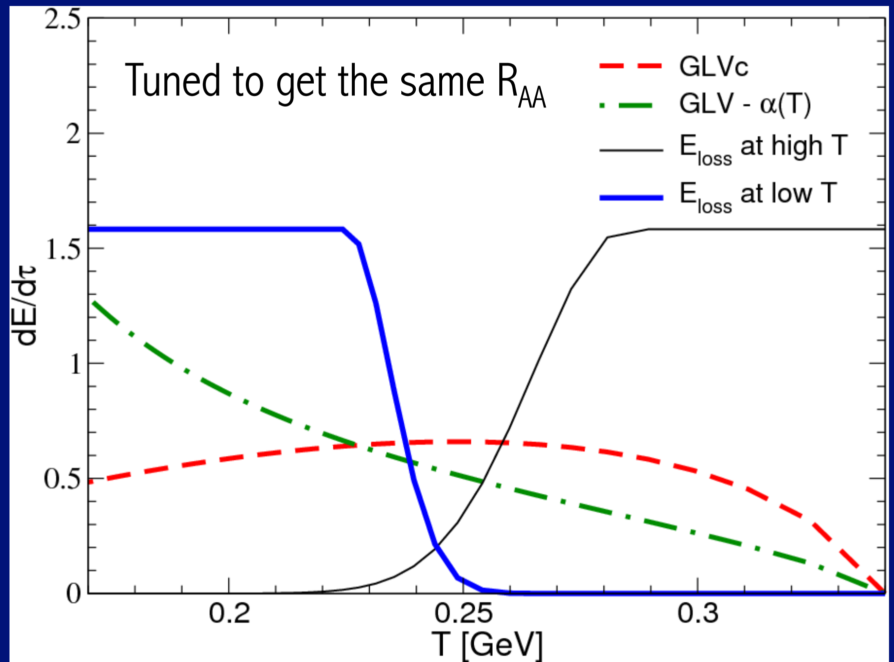
Simple modeling: jets going straight and radiate energy

Elliptic flow only from path length

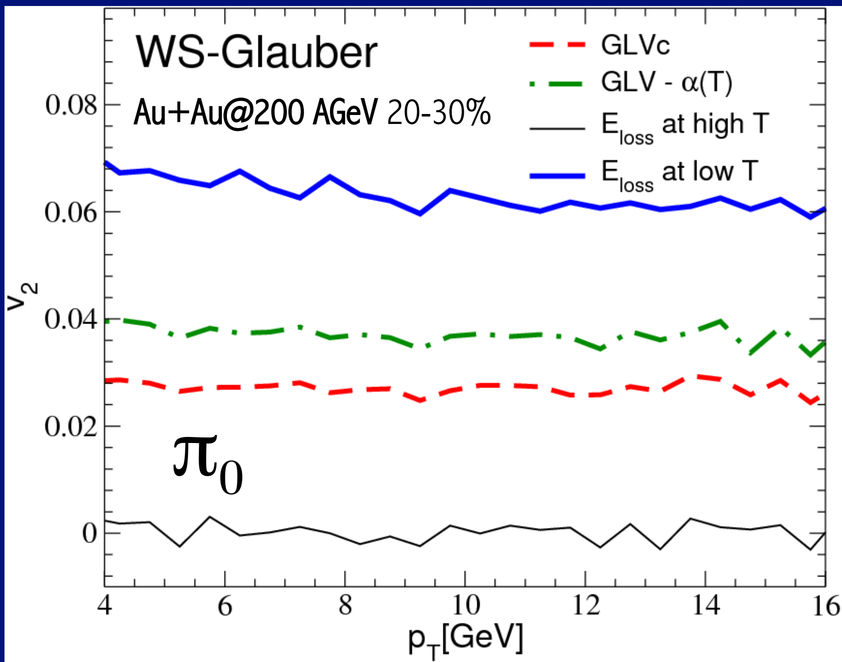
Scardina, Di Toro, Greco, PRC82(2010)

Liao, Shuryak PRL 102 (2009)

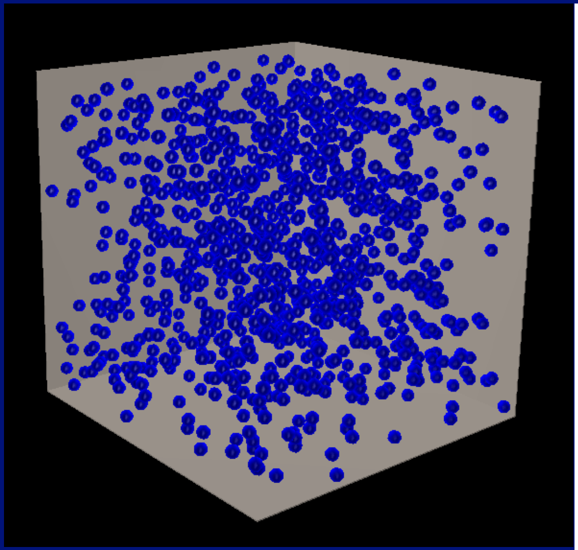
Time dependence of E_{loss}

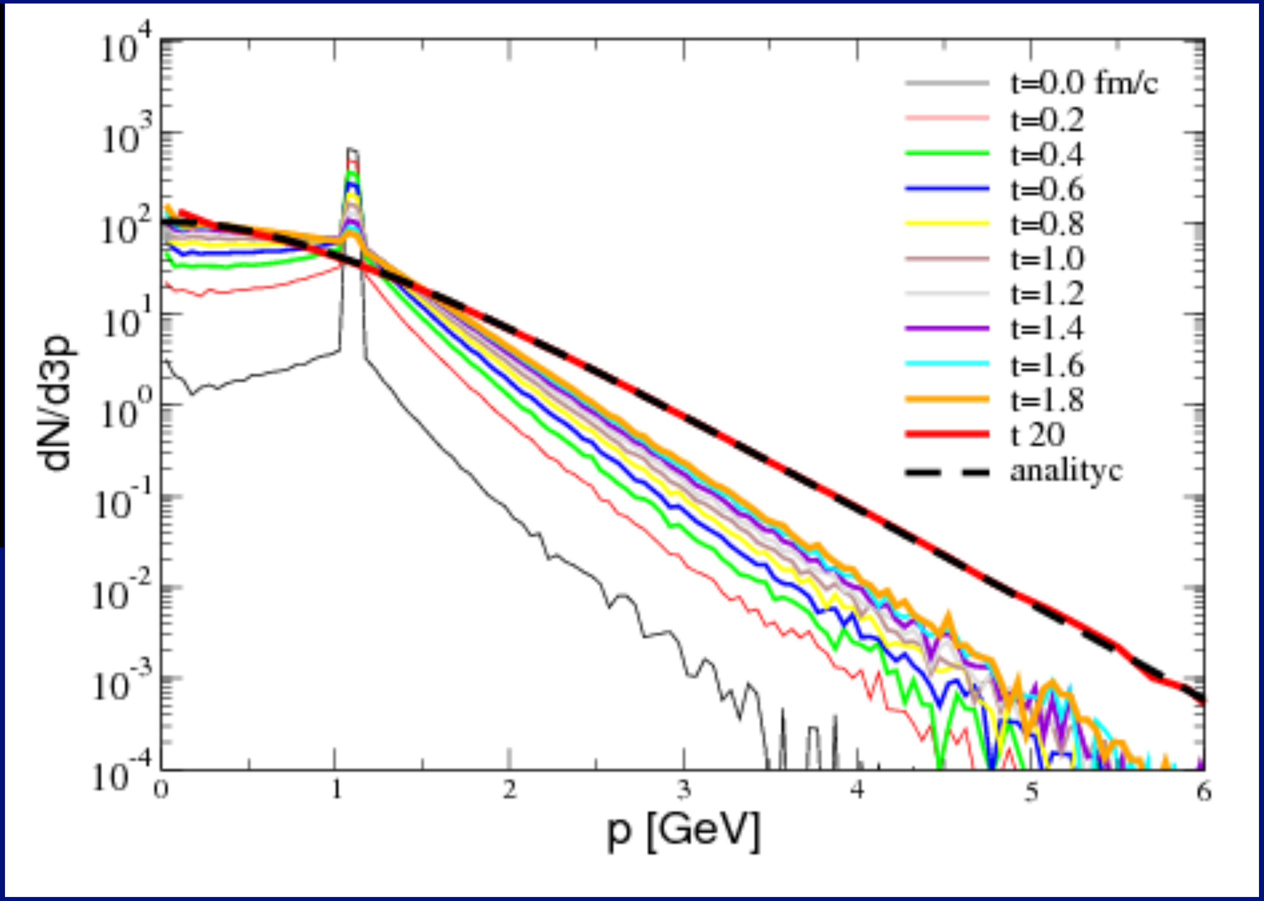


Elliptic Flow

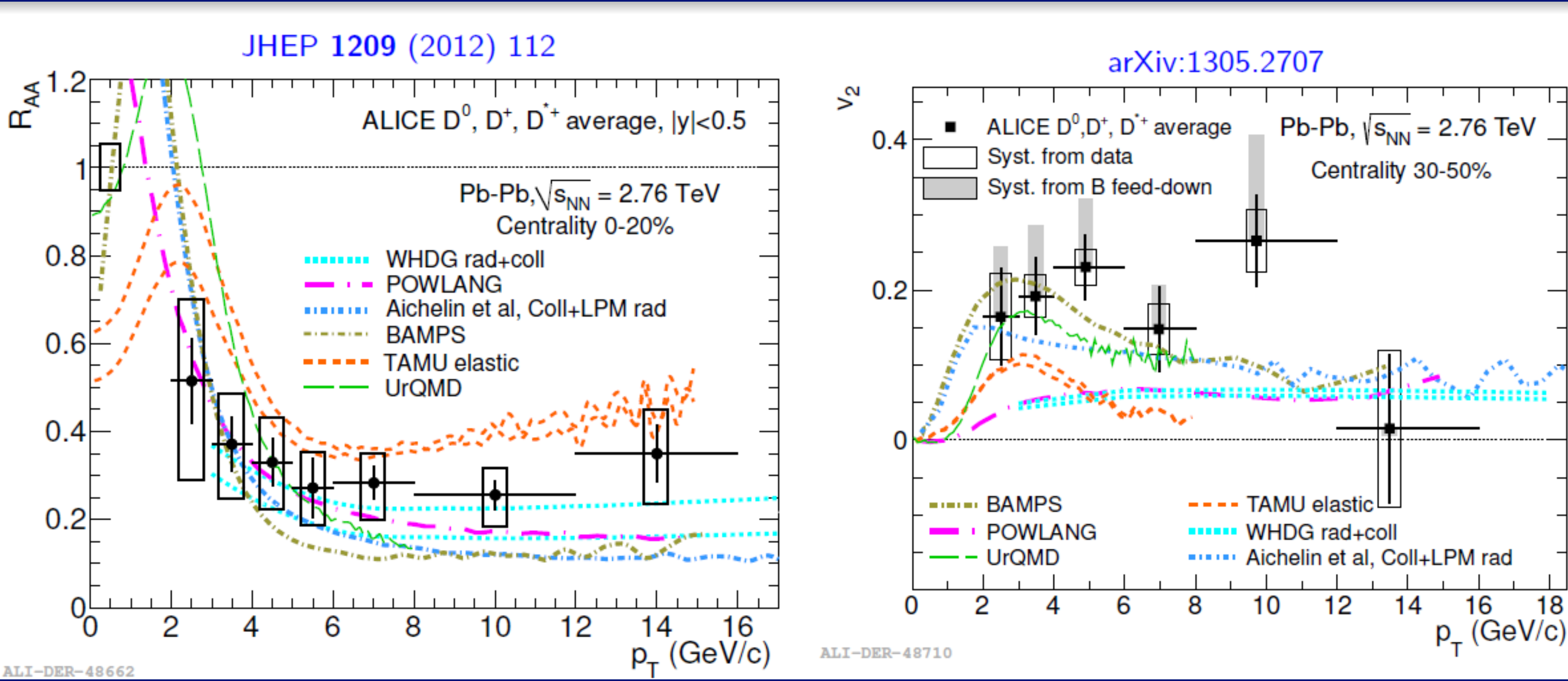


We consider as initial distribution in p-space a δ(p-1.1GeV) for both C and B with px=(1/3)p



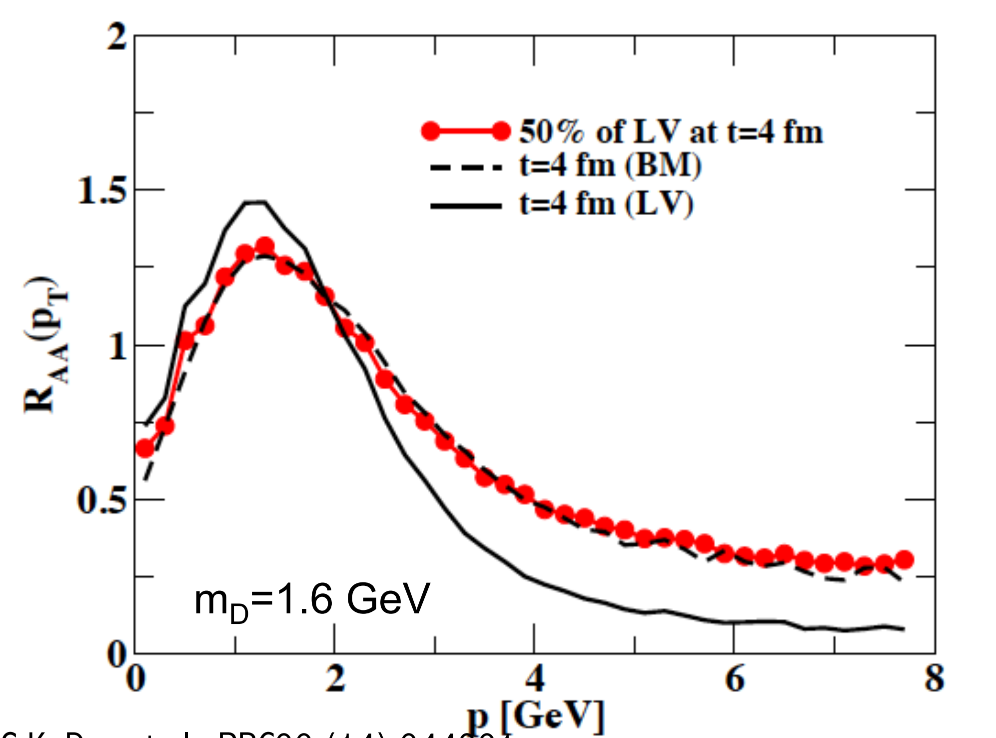


Various Models at Work for LHC



- ✓ Models fails to get both, some hope for TAMU elastic (if radiative added)
- ✓ Pure radiative jet quenching gets the lower v_2 (LPM helps…)
- ✓ Apart from BAMPS & Aichelin Fokker-Planck is used for HQ dynamics.
- ✓ Those getting close have heavy-quark coalescence V. Greco et al., PLB595(04)202

Implication for observable, R_{AA}?



S.K. Das et al., PRC90 (14) 044901

Once R_{AA} is fixed the main point is if **v_2** and angular correlation are the same?

→ Realistic simulation of A+A

However one can mock the differences of the microscopic evolution and reproduce the same R_{AA} of Boltzmann equation just changing the diffusion coefficient by about a 15-30-50 %