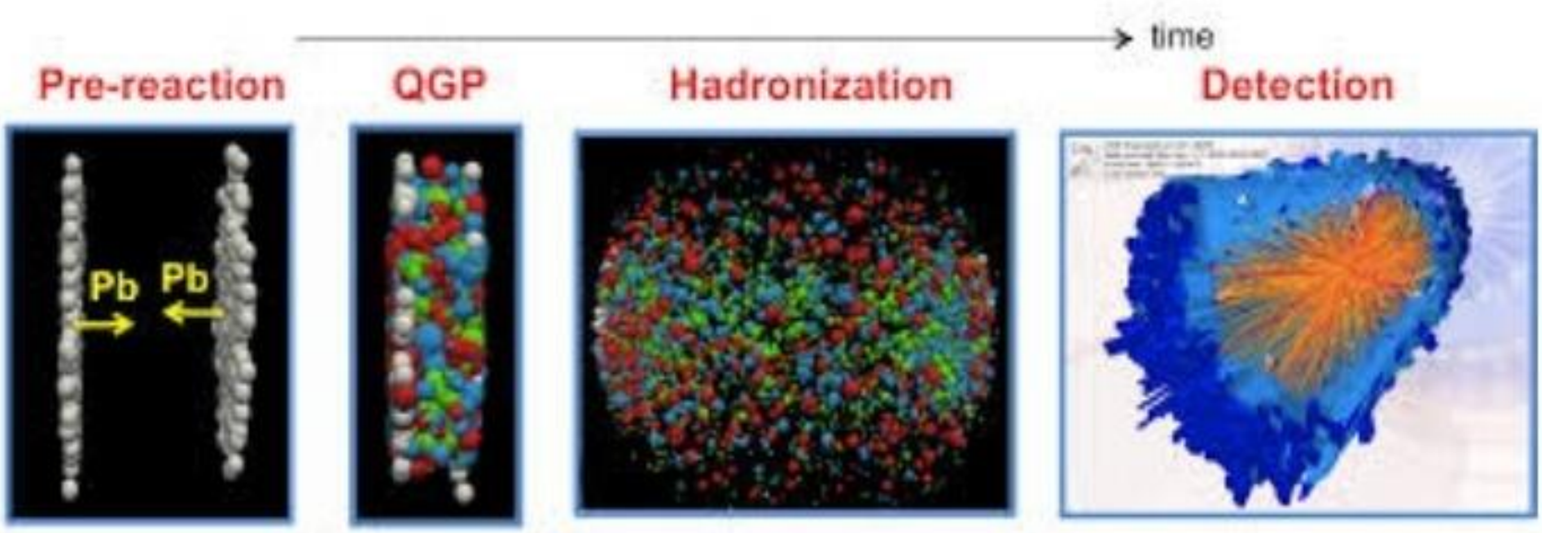
Dynamics of Heavy quark in Heavy-ion Collisions



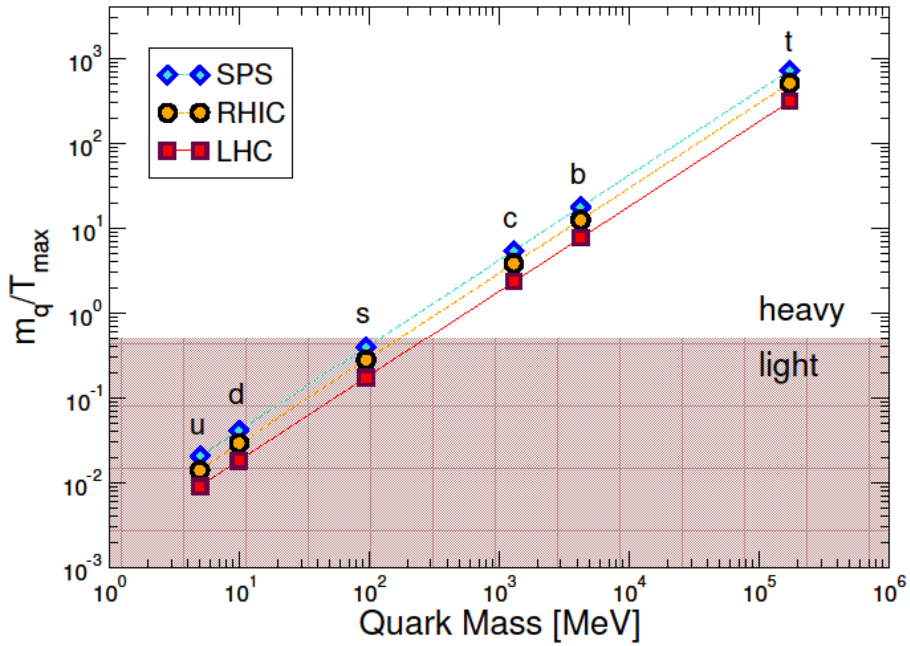
Santosh Kumar Das

School of Physical Science
Indian Institute of Technology Goa
Goa, India

OUTLINE

- R_{AA} vs v_2: Heavy quark diffusion
- New observables
- Heavy quark hadronization
- Heavy quark as a probe of Initial stage

Heavy Quark & 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 (before equilibrium) (Early production)

$$\tau_{c,b} >> \tau_{QGP}$$

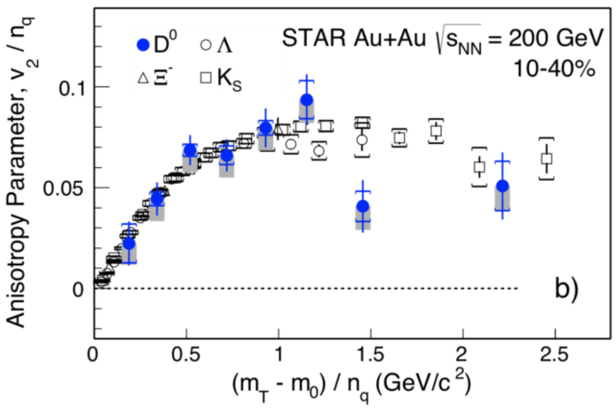
They go through all the QGP life time

$$M_{c,b} >> T_0$$

No thermal production

Heavy quark physics at different scales

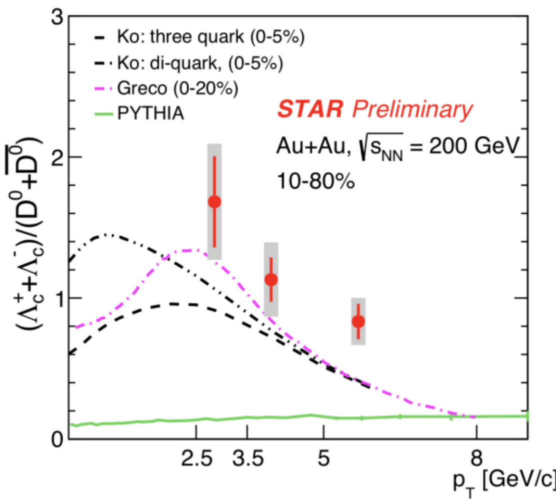
low p_T



Study thermalization process of HQ

Constrain diffusion coefficient D_s

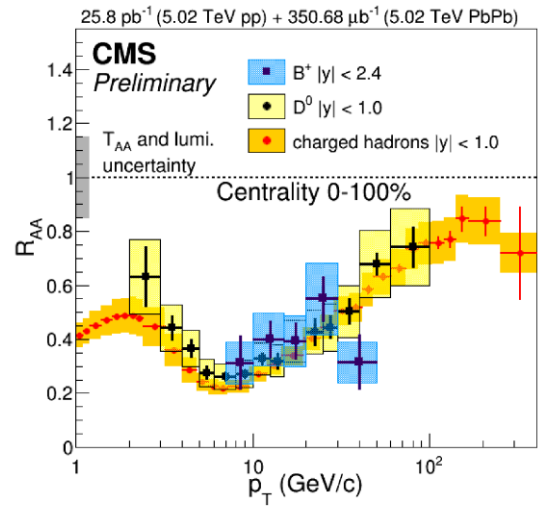
medium p_T



Study hadronization process of HQ

Constrain hadron wave-function

high p_T



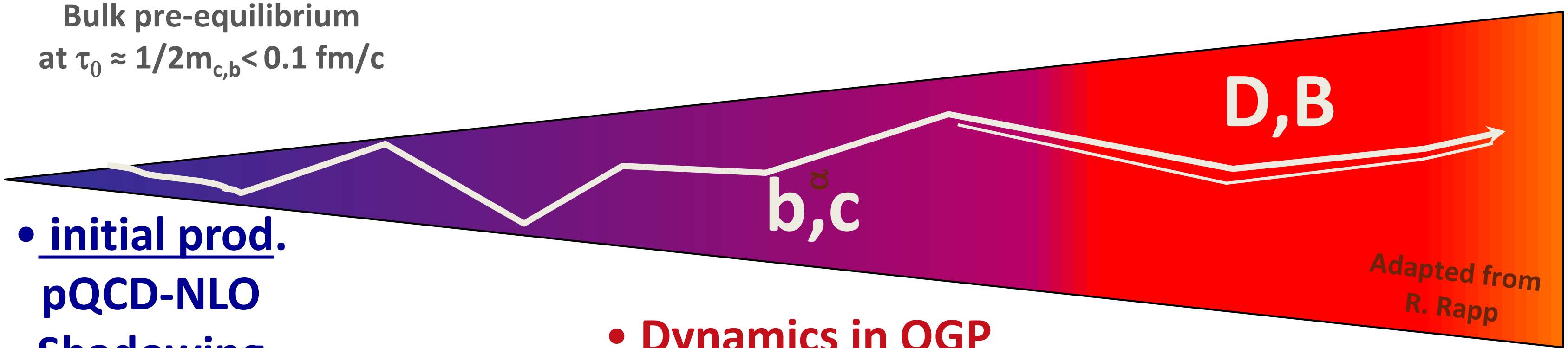
Study parton energy loss and mass effect

Constrain jet transport parameter $\hat{q}$

S. Cao (HP 2018)

Studying the HF dynamics in HIC

Bulk pre-equilibrium
at $\tau_0 \approx 1/2m_{c,b} < 0.1$ fm/c

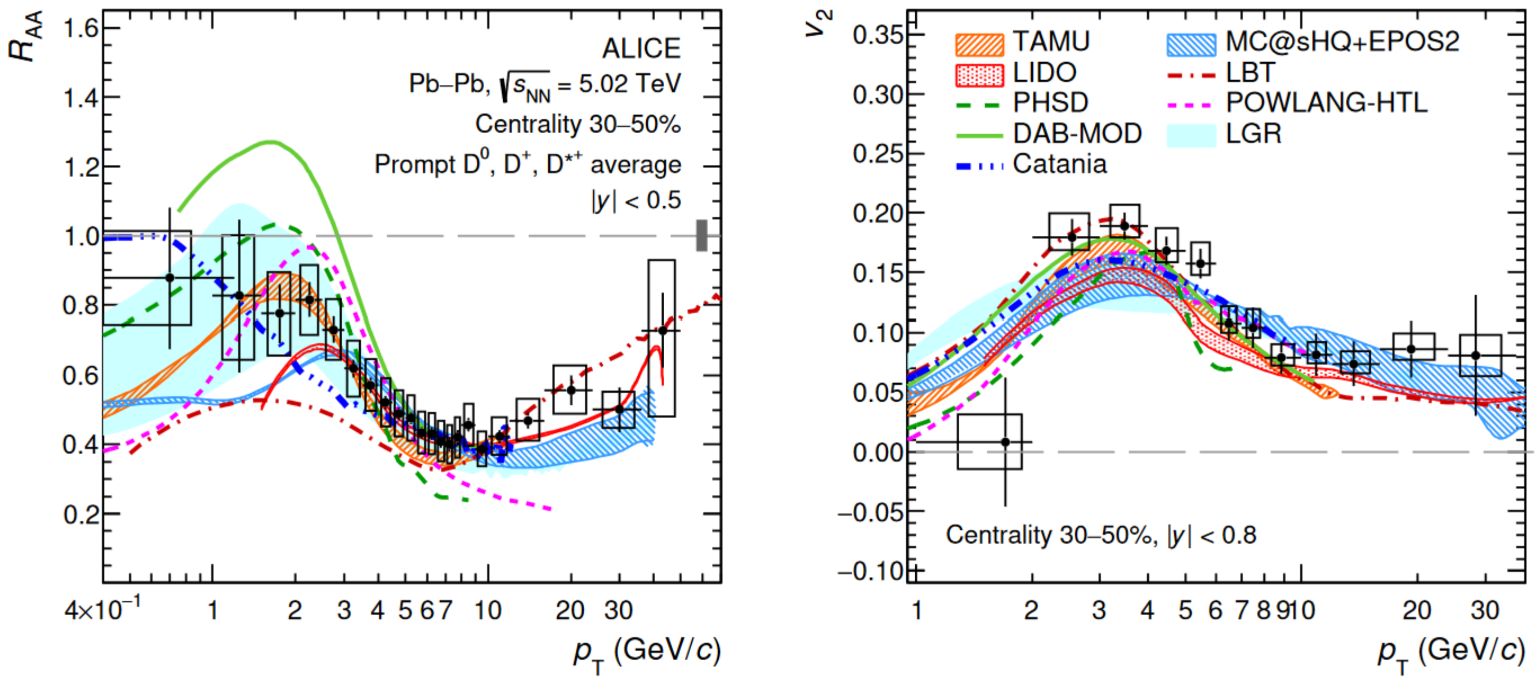


- **initial prod.**
  pQCD-NLO
  Shadowing
  Pre-equilibrium
  Effect/Glasma
  Electromagnetic
  Filed/Vorticity

- **Dynamics in QGP**
  Heavy quark QGP interaction
  Transp. coeff. of QCD matter
  -> thermalization ?!
  Mass & color in Jet quenching
  Heavy quark momentum evol.
  (Langevin/Boltzmann/E. loss model)

- **hadronization:**
  coalescence and/or
  fragmentation.
  Hadronic rescattering

R_{AA} and v_2
Comparison with models

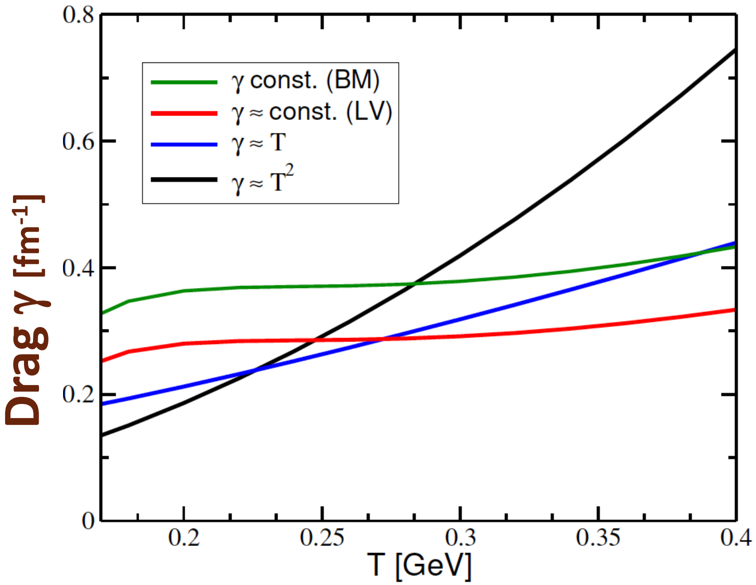


ALICE, JHEP 01 (2022) 174

Most of the models able to describe both R_{AA} and v_2 in certain p_T domain

Simultaneous description of R_{AA} and v_2 is still a challenge in the whole measured p_T and centrality ranges

Impact of T dep. interaction on $R_{AA} - v_2$

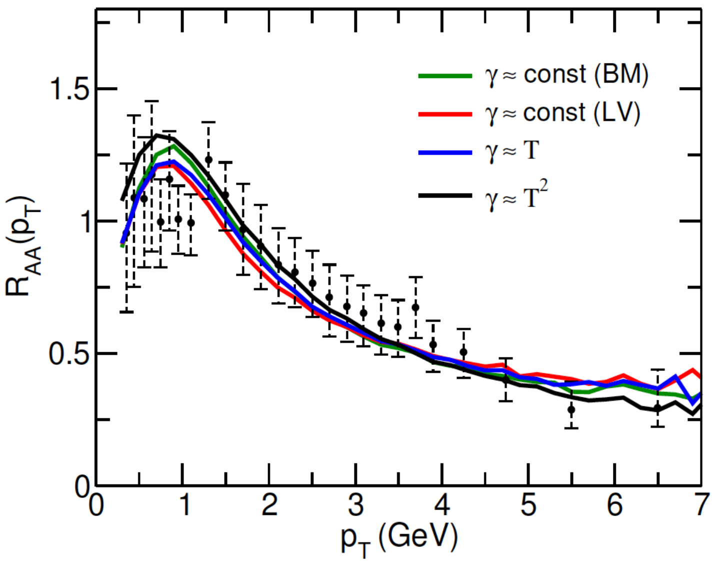


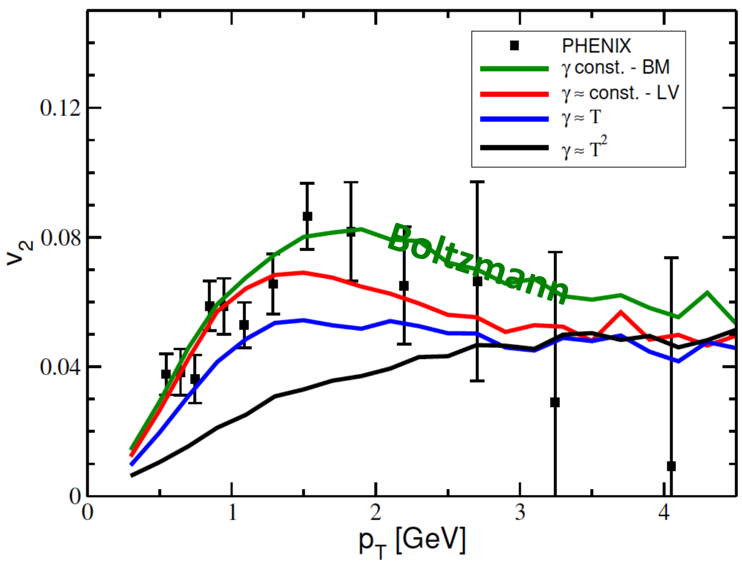
Looking at it beyond the specific modelings

- $\gamma \approx T^2$ [Ads/CFT, pQCD α_s=const]
- $\gamma \approx T$ [pQCD strong α_s running]
- $\gamma \approx$ const. [QPM, PHSD, T-matrix]

γ rescaled to fit $R_{AA}(p_T)$, D from FDT

$$\frac{d\mathbf{p}}{dt} = -\gamma \mathbf{p} + \eta(t)$$

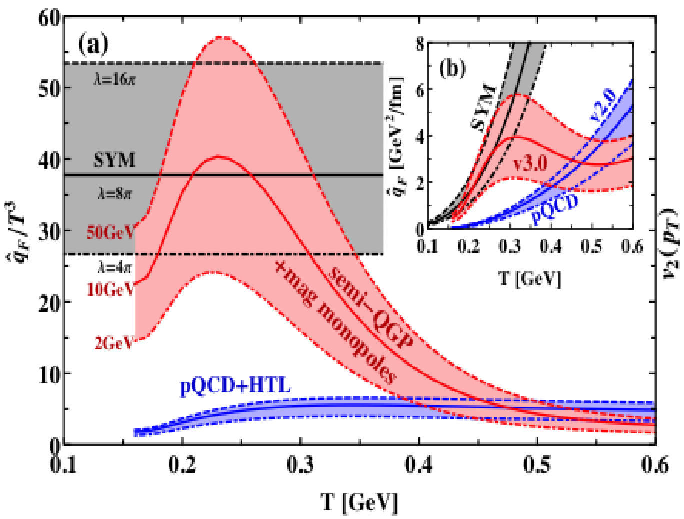


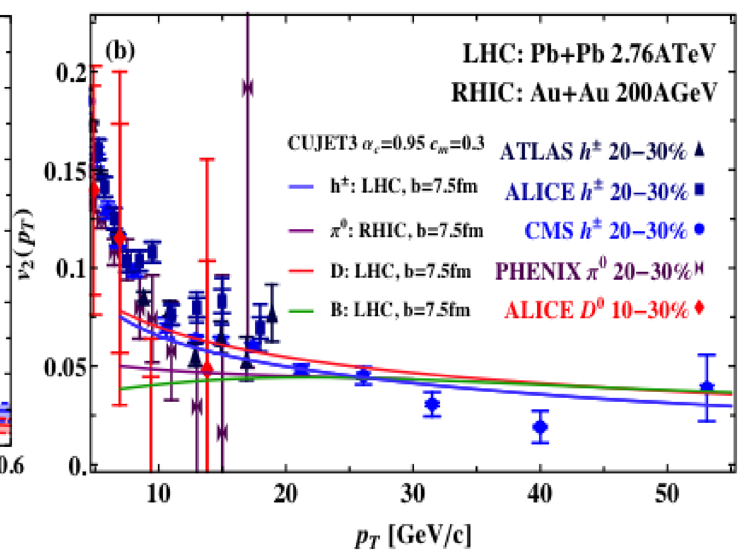


Das, Scardina, Plumari, Greco
Phys. Lett. B 747 (2015)260-264

R_{AA} vs. v_2 : T-dependence of transport coefficients

Different temperature dependence of the interaction may lead to different v_2 for the same R_{AA}.

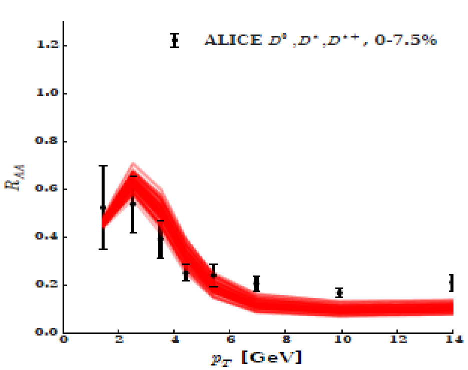


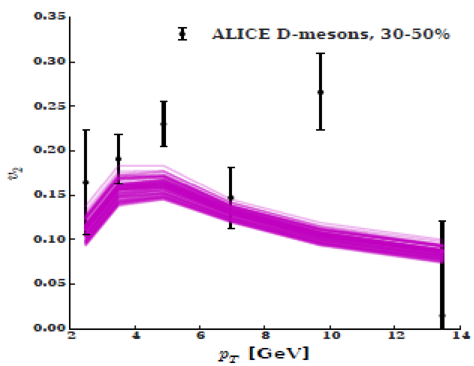


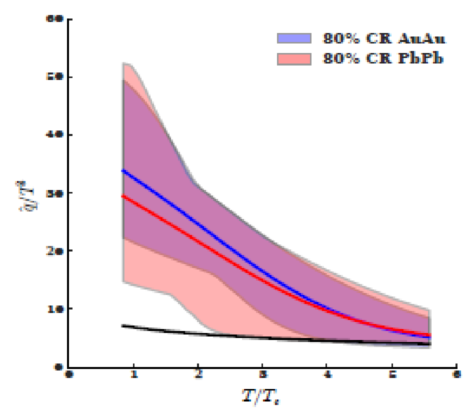
Semi-quark-gluon monopole plasma model increases $\hat{q}$ around T_c and enhances hard probes' v_2.

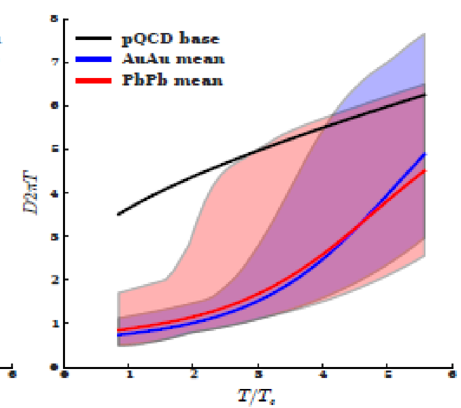
Xu, Liao and Guylassi
CPL. 32, 092501 (2015)

Bayesian model to data analysis [Xu et al., PRC (2018)]:





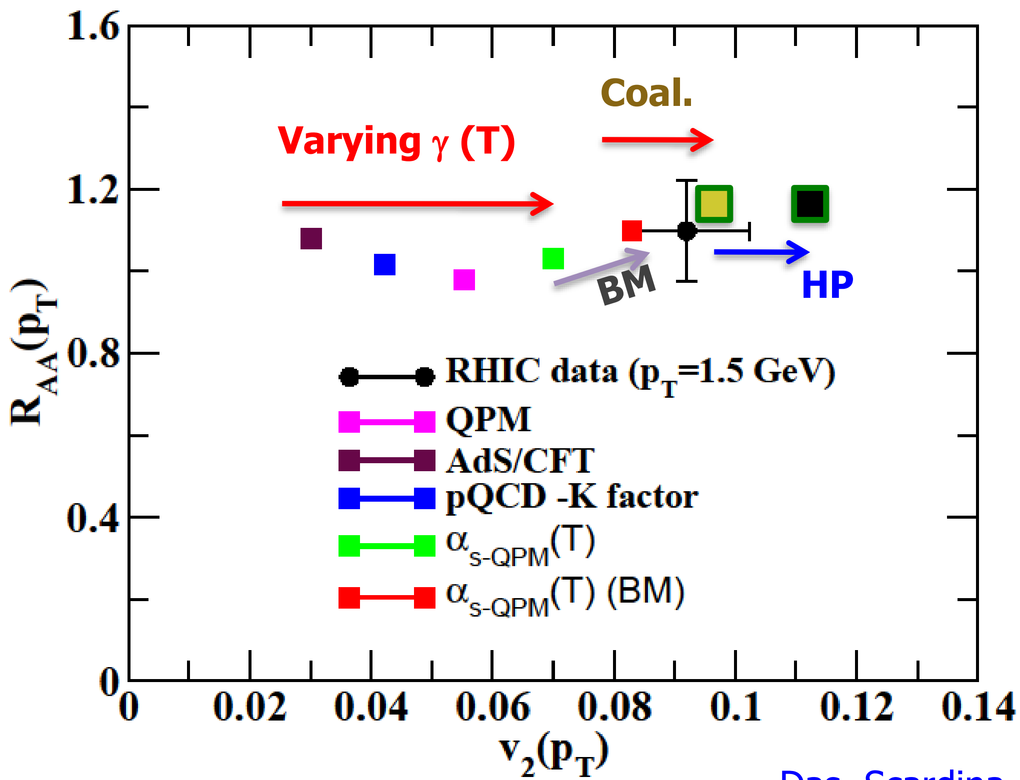




T,p-dependence: $\hat{q} = \hat{q}_{pQCD} * preK * (1 + K_p e^{-\frac{|p|^2}{2\sigma_p^2}}) * (1 + K_T e^{-\frac{(T-T_c)^2}{2\sigma_T^2}})$

$D_s = T^2/\hat{q}$

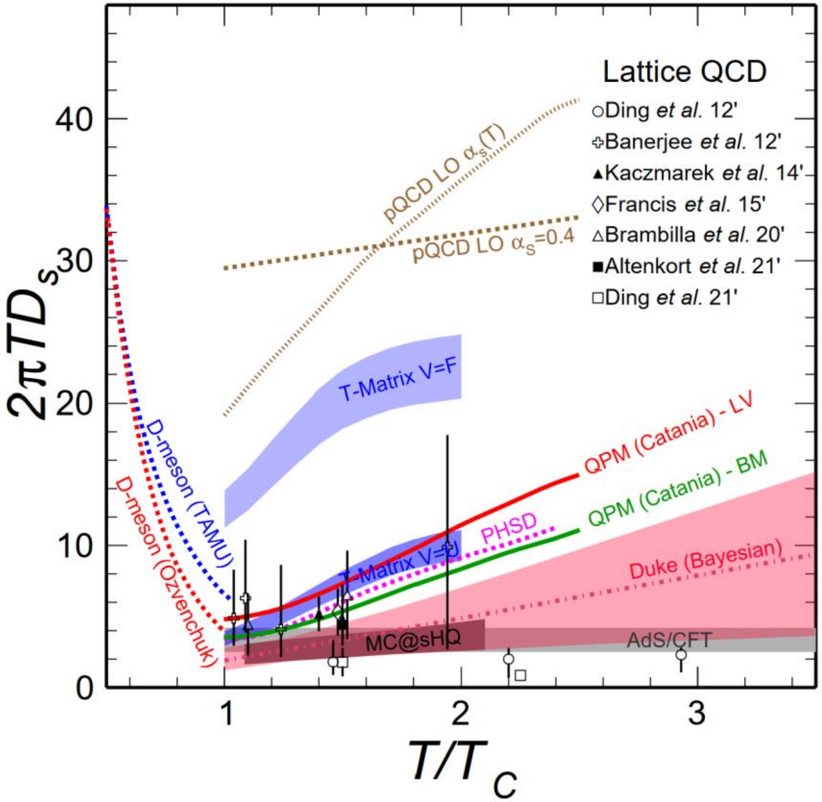
Summary on the build-up of v_2 at fixed R_{AA}

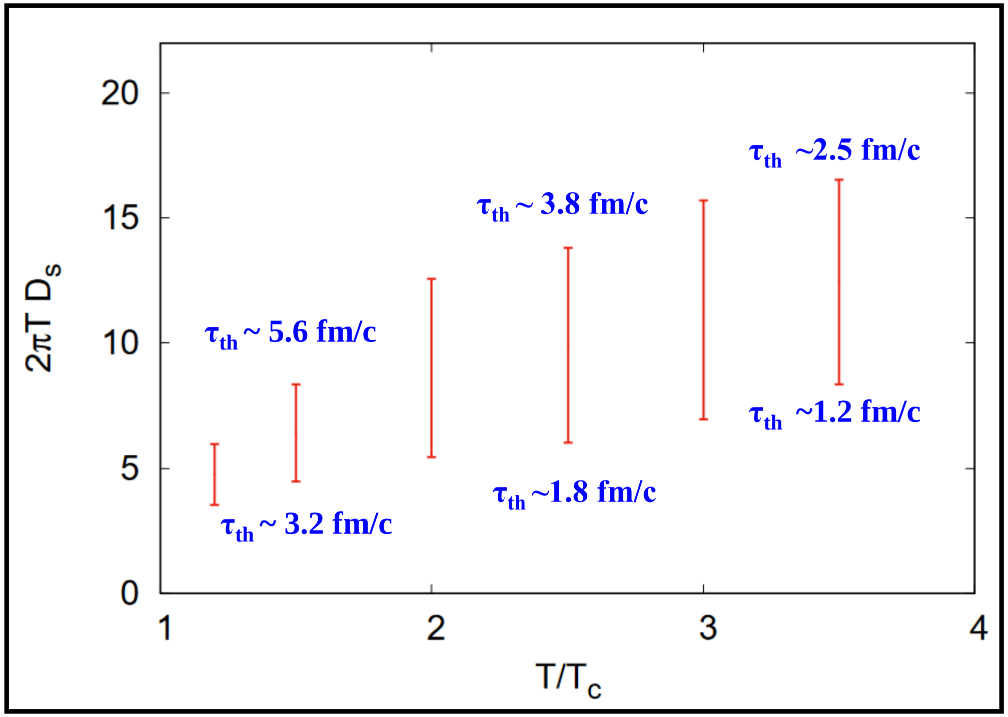


Das, Scardina, Plumari, Greco
Phys. Lett. B 747 (2016)260-264

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

Heavy quark diffusion





$$D_s = T/M * \gamma(p \to 0)$$

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

Banerjee, Datta, Gavai, Majumdar
arxiv: 2206.15471 [hep-ph]

$$\tau_{\text{th}} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8 \frac{2\pi T D_s}{(T/T_c)^2} \text{ fm/c}$$

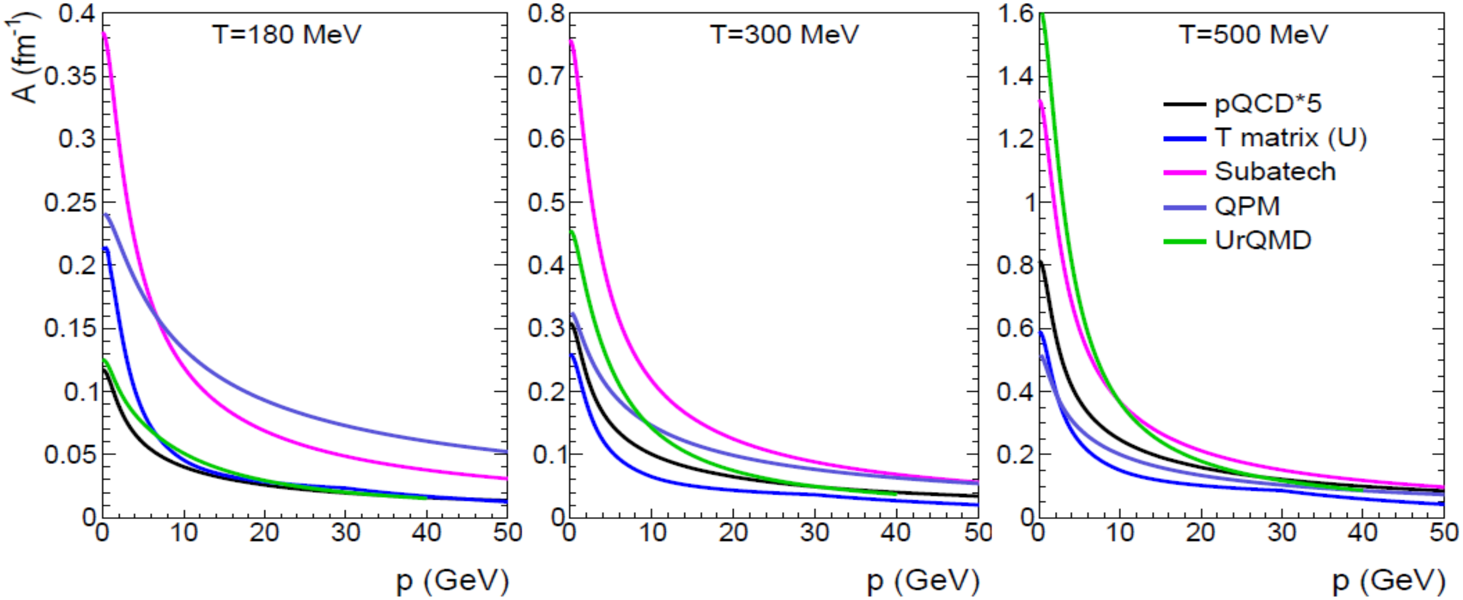
Scardina, Das, Minissale, Plumari, Greco
PRC,96, 044905 (2017)

$2\pi T D_s \propto T^2$,corresponds to a constant thermalization time.

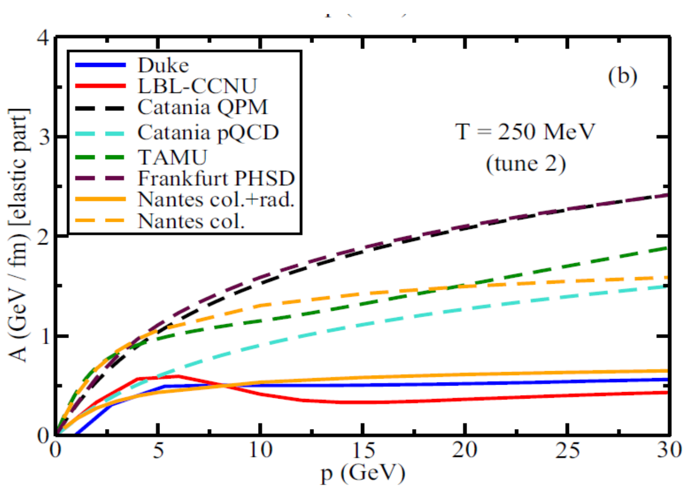
Memory effect can impact the HQ thermalization

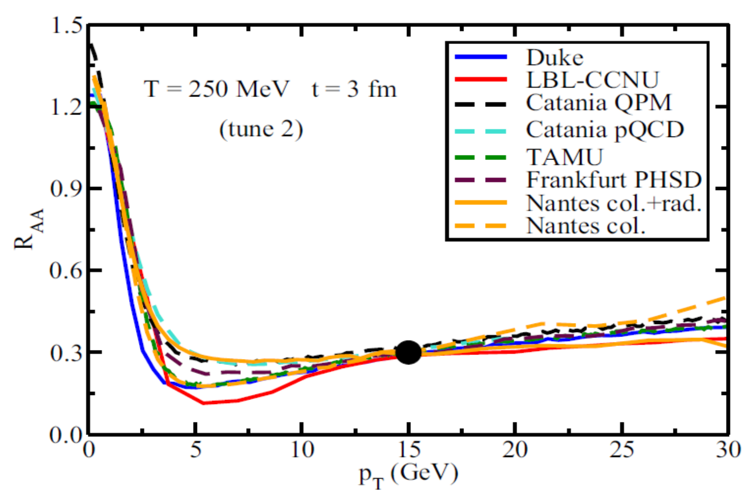
Ruggieri, Pooja, Jai Prakash, Das, PRD, 106 (2022)

A systematic attempts are going on within the EMMI-RRTF and "JET-HQ" working groups to find a common agreement between different groups:



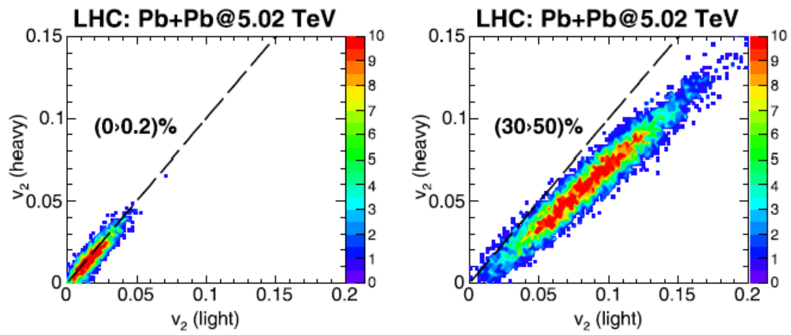
R. Rapp et.al NPA 979 (2018)   (EMMI-RRTF)





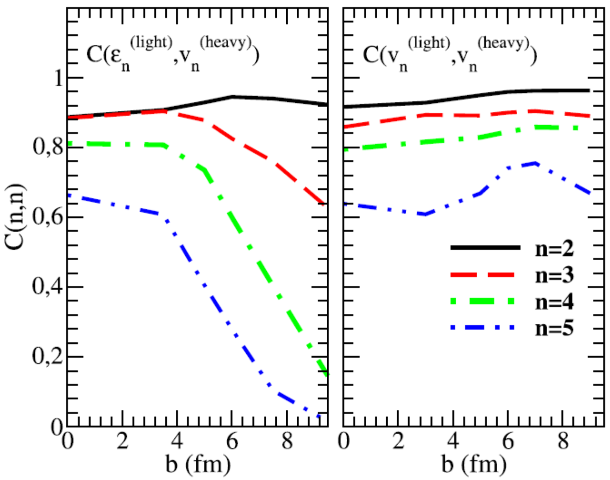
S. Cao et. al PRC 99, 054907 (2019) (JET-HQ)

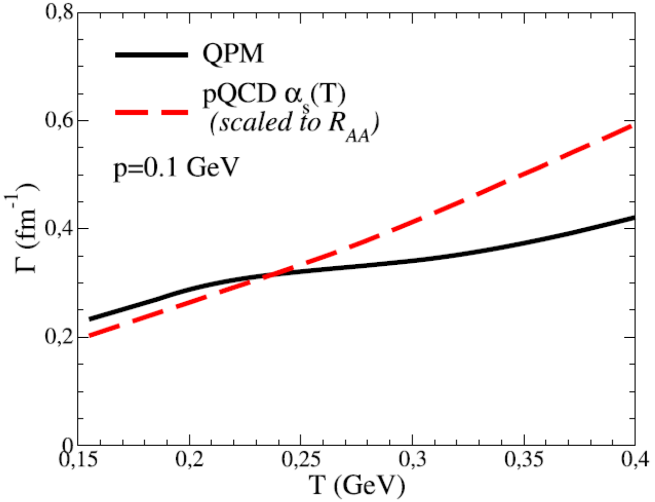
New observables:

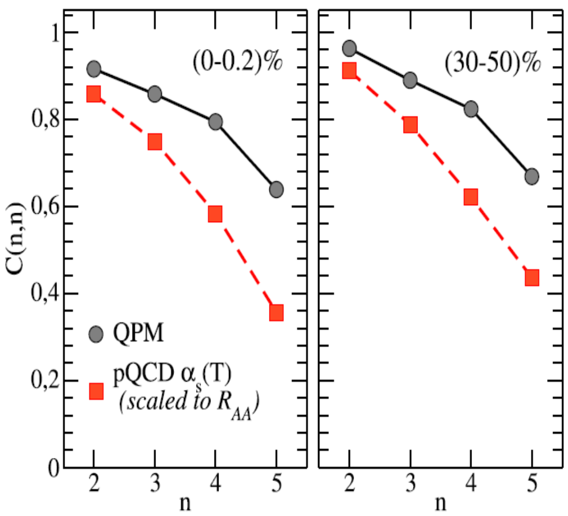


Heavy-light event-by-event correlation

$$C(n,m) = \frac{\sum_i (v_n^{L,i} - \langle v_n^L \rangle)(v_m^{H,i} - \langle v_m^H \rangle)}{\sqrt{\sum_i (v_n^{L,i} - \langle v_n^L \rangle)^2 \sum_i (v_m^{H,i} - \langle v_m^H \rangle)^2}}$$







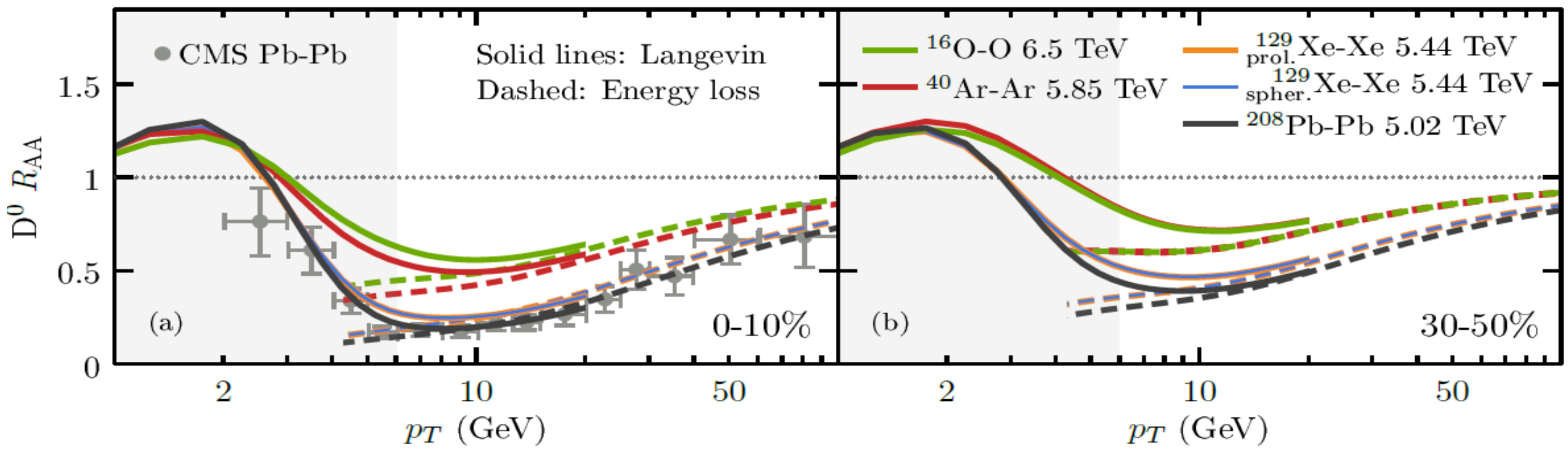
$V_n(D)$ more correlated to $v_n(N_{ch})$ than ε_n

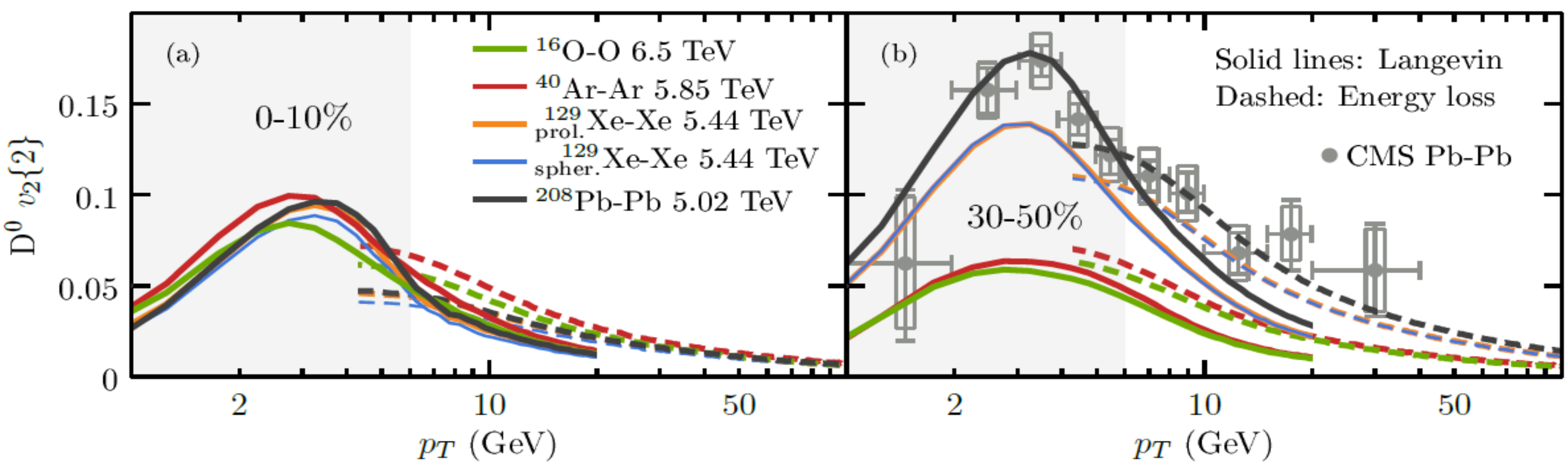
Very large sensitivity to T dep. of Ds

This can put further constrain on heavy quark transport coefficients

Plumari, Coci, Minissale, Das, Sun, Greco
PLB 805 (2020) 135460

System size scan of D meson R_{AA} and v_2

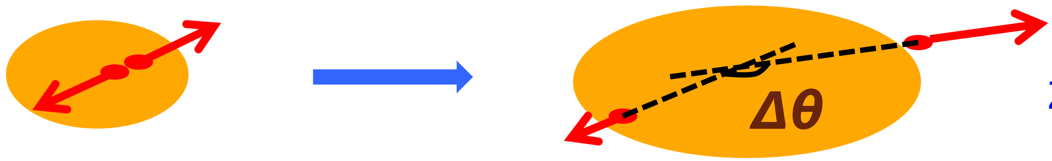




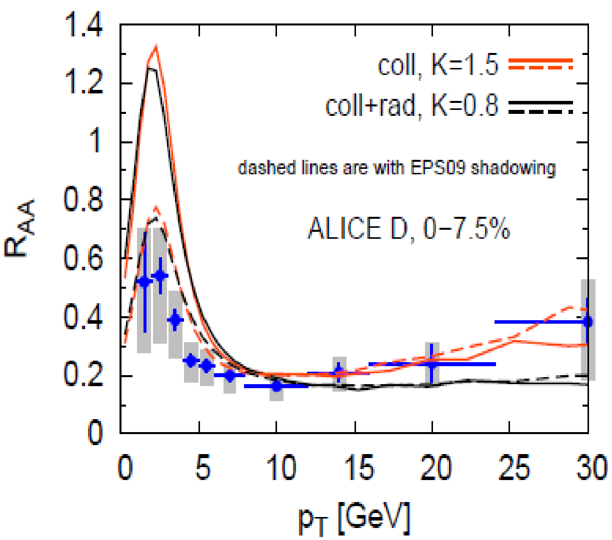
In central collisions the v_2 is independent of system size.
System size vs Eccentricity

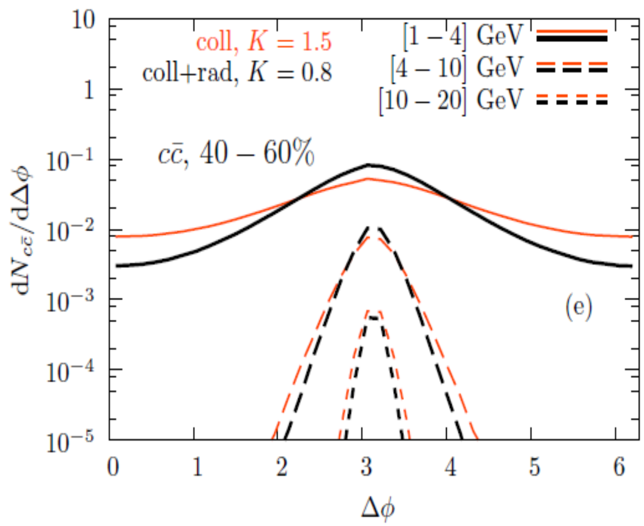
R. Katz et. al, PRC,102 (2021)

Angular De-correlation of *c*cbar:



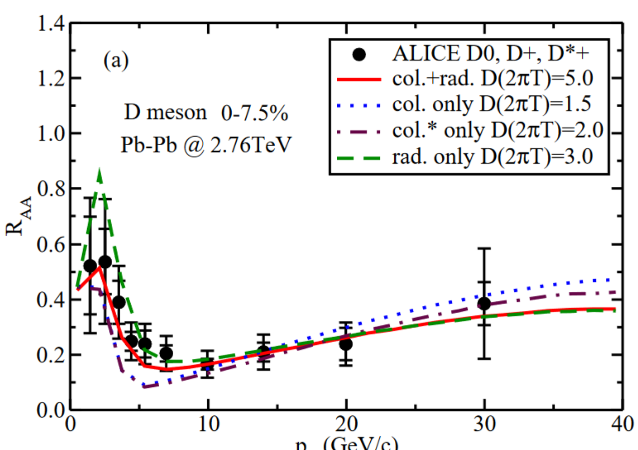
Zhu ,Xu, Zhuang, PRL100, 152301 (2008)

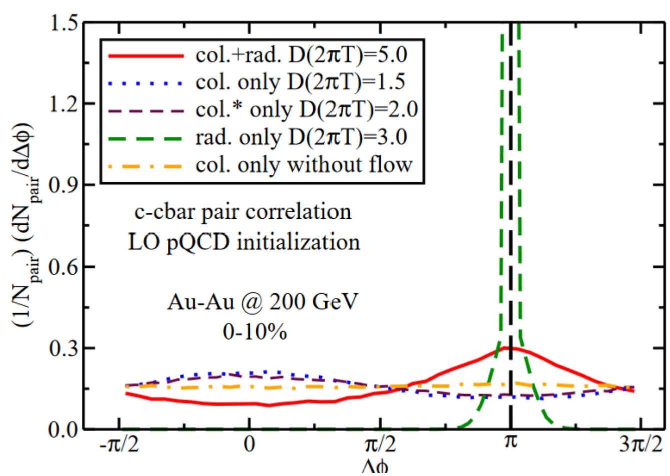




DDbar correlation is sensitive to energy loss mechanism

Nahrgang, Aichelin, Gossiaux, Werner
PRC,90, 024907 (2014)





DDbar correlation can disentangle different Energy loss mechanism

Cao, Qin, Bass
PRC, 95 (2015)

Hadronization: Coalescence plus Fragmentation

Fragmentation function gives the probability to get a hadron from a parton:

$$f_H(p_T) = \sum_p f_p(p_T / z) \otimes D_{p\to H}(z)$$

<z>~0.9 for charm quark and <z>~0.5 for light quark

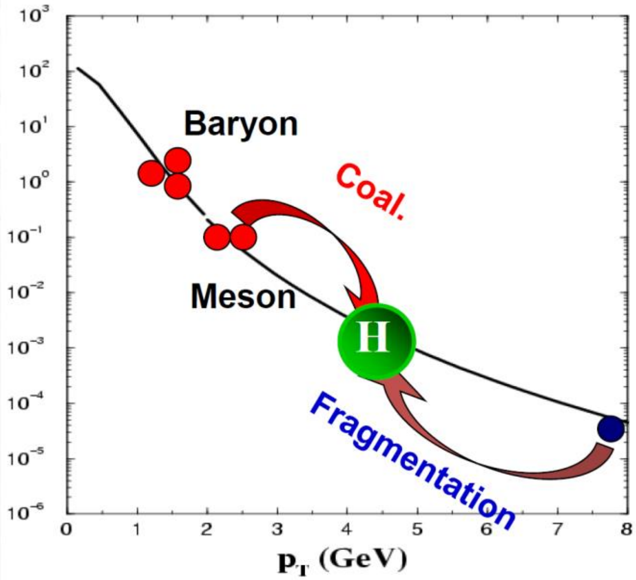
Coalescence is the convolution of two /three parton distribution folded by a wave function:

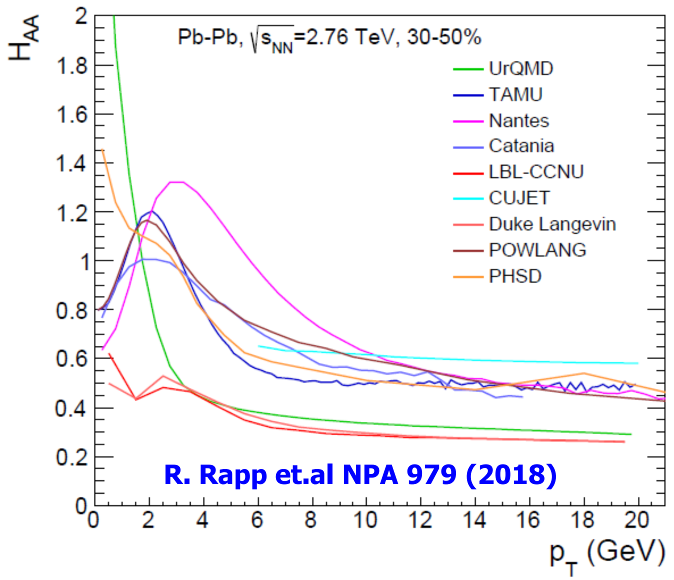
$$\frac{dN_{Meson}}{d^2 p_T} = g_M \sum_{i,j} P_q(i) P_q(j) \delta^{(2)}(p_T - p_{iT} - p_{jT}) f_M(x_i, x_j; p_i, p_j)$$

V. Greco, C.M. Ko, and P. L´evai PRL 90 , 202302 (2003)

Hadron wave function

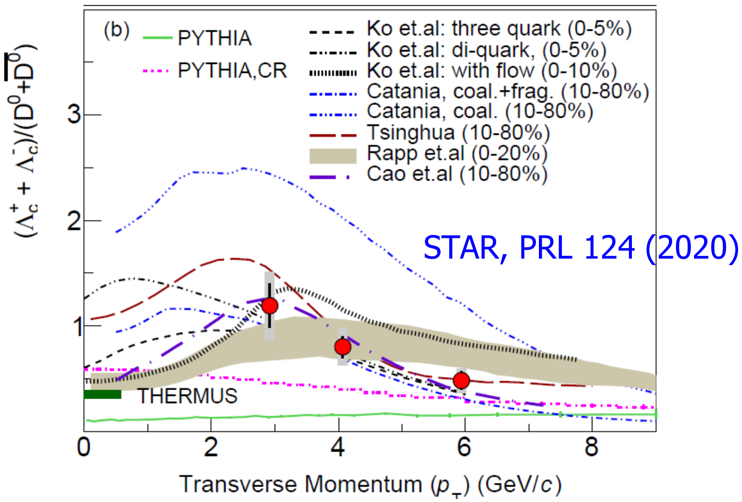
$$\frac{dN_{Baryon}}{d^2 p_T} = g_B \sum_{i,j,k} P_q(i) P_q(j) P_q(k) \delta^{(2)}(p_T - p_{iT} - p_{jT} - p_{kT}) f_B(x_i, x_j, x_k; p_i, p_j, p_k)$$

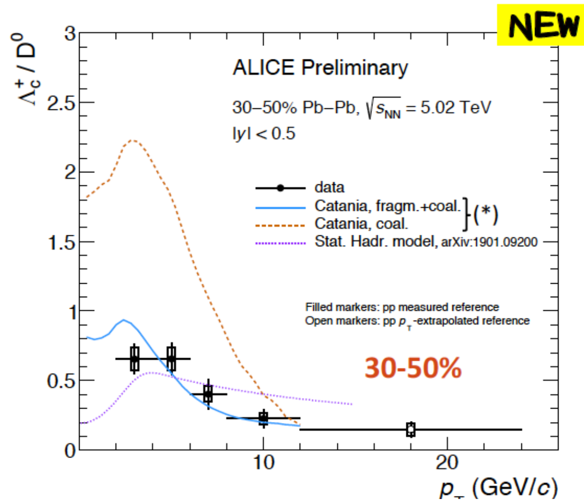


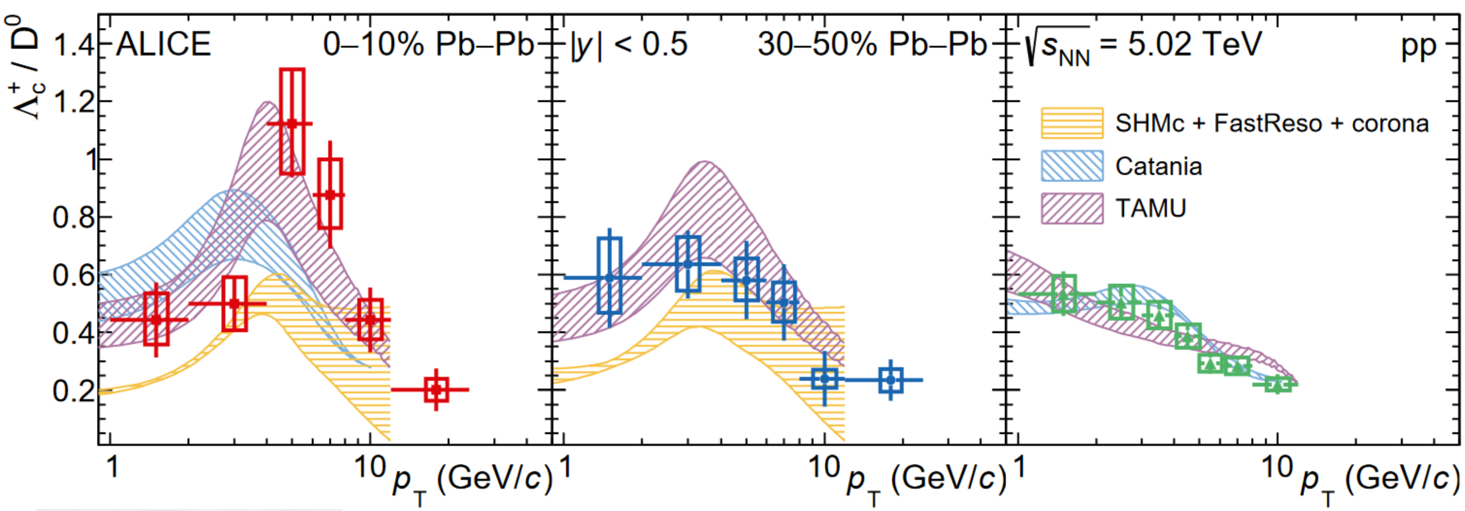


Heavy Baryon to meson ratio

(Serve as a tool to disentangle different hadronization mechanisms)







ALICE:2112.08156

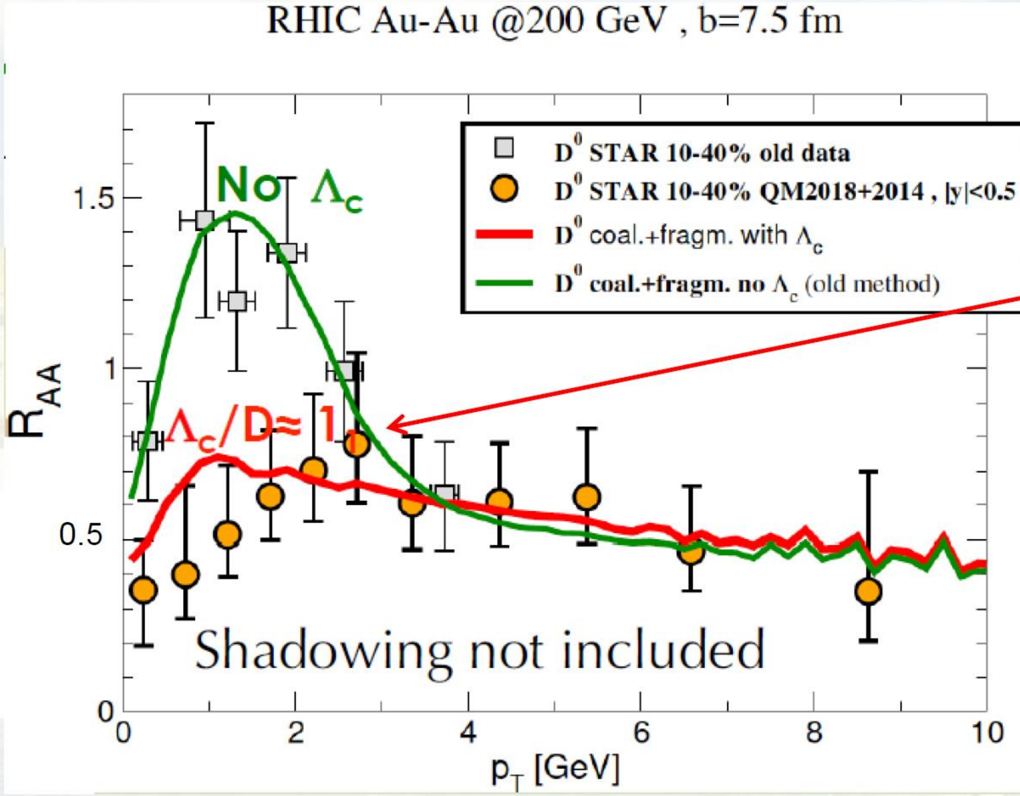
$P_{coal}=1$ to all hadron at p→0

Baryon in resonance recombination model

Plumari, Minissale, Das, Cosi, Greco
EPJC 78 (2018) 4, 348

He, Rapp, PRL **124 (2020) 042301**

Impact of heavy baryon to meson ratio on heavy quark suppressions



New STAR data in QM2018

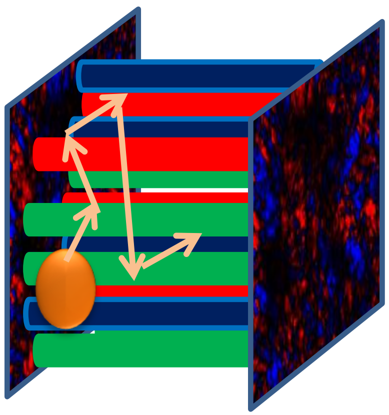
- Big effect at RHIC where coalescence dominates
- Smaller but still significant also at LHC

R_{AA} of D^0 decreases because part of charm quark makes coalescence in charmed Lambdas, while in pp charm quarks fragment mainly in D mesons

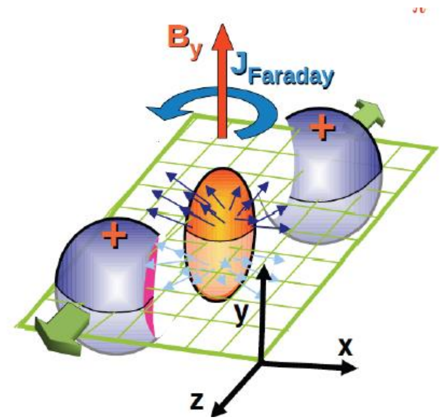
Minissale at.al (SQM-2019)

Heavy quark as a probe of Initial stage

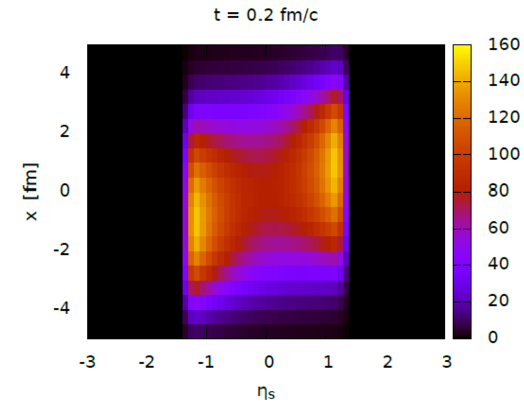
(Adapted from M. Ruggieri)



Impact of Glasma phase



Electromagnetic field



Vorticity

Initial Glasma in Pre-equilibrium phase can induce strong diffusion

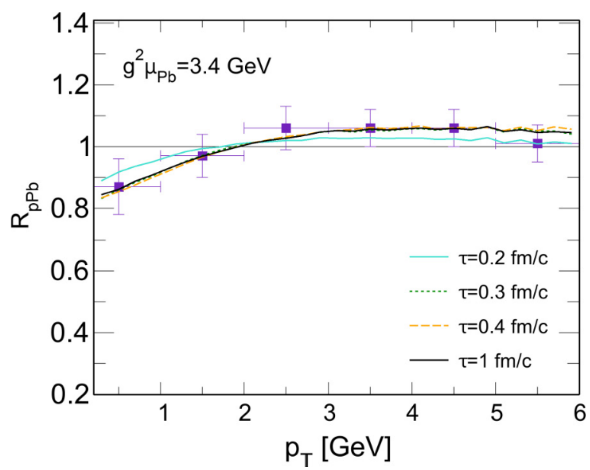
Mrowczynski, EPJA 54 (2018)
Ruggieri and Das, PRD98 (2018)
Pooja et al. EPJP 137 (2022)

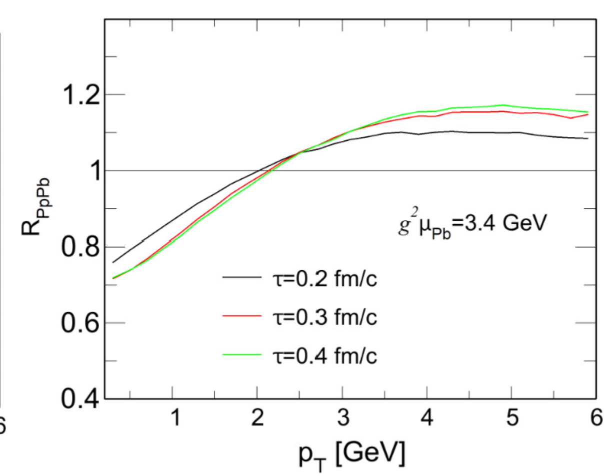
$$\frac{dx_i}{dt} = \frac{p_i}{E},$$

$$E\frac{dp_i}{dt} = gQ_a F^a_{i\nu} p^\nu,$$

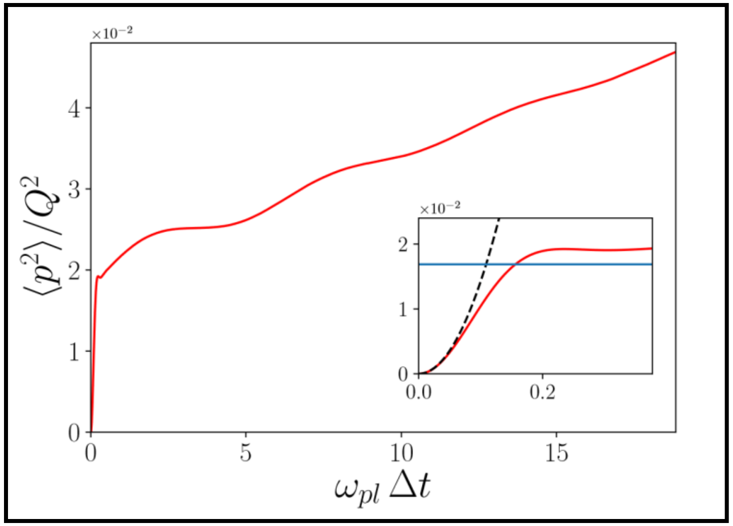
$$E\frac{dQ_a}{dt} = -gQ_c \varepsilon^{cba} \boldsymbol{A}_b \cdot \boldsymbol{p};$$

Wong (1979)





Liu, Plumari, Das, Greco, Ruggieri, PRC, 102 (2020)



Boguslavski, Kurkela, Lappi and J. Peuron, JHEP (2020)

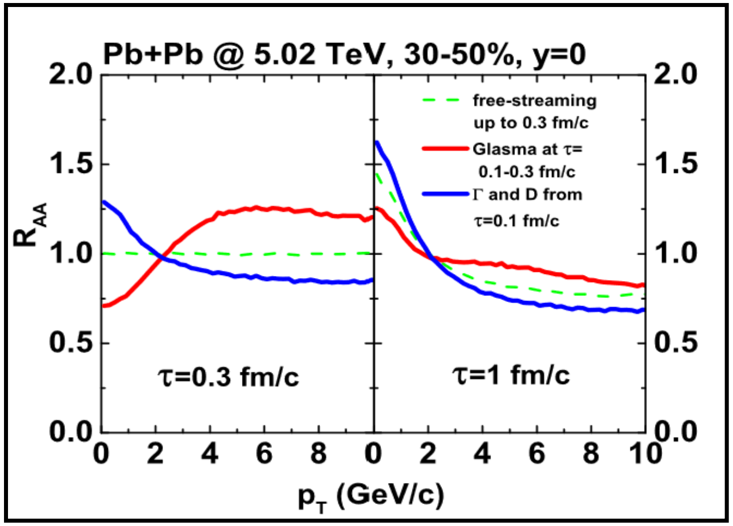
Correlator method

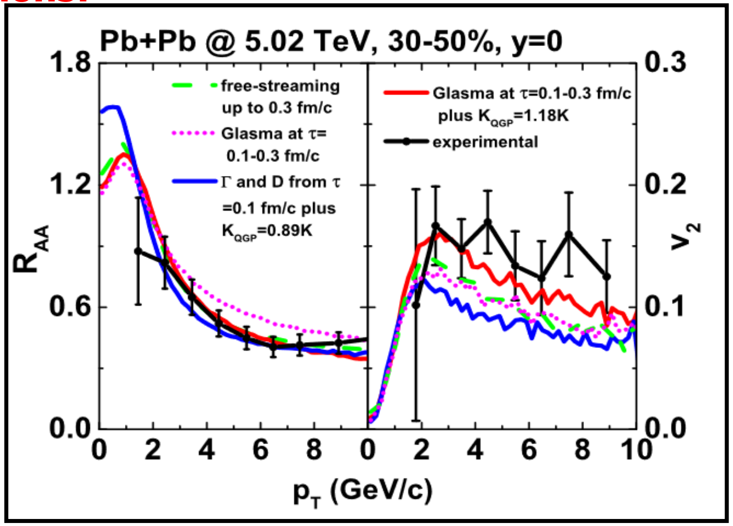
$$\langle \dot{p}_i(t)\dot{p}_i(t')\rangle = \frac{g^2}{2N_c}\langle E_i^a(t)E_i^a(t')\rangle$$

Strong heavy quark diffusion in Glasma:

- **Can affect the D-Dbar correlation**
- **Strong diffusion enhance the R_{AA} in AA**
- **Leads to large v_2 to have the same R_{AA}**

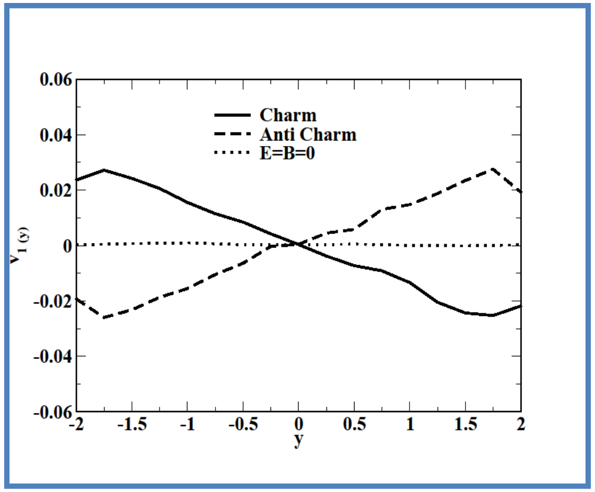
Impact of Glasma phase on nucleus-nucleus collisions:

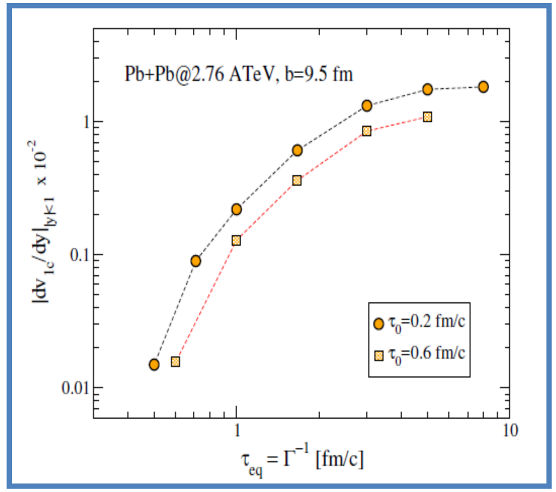




Sun, Coci, Das, Plumari, Ruggieri, Greco
PLB, 798 (2019) 134933

Heavy quark directed flow in EM fields



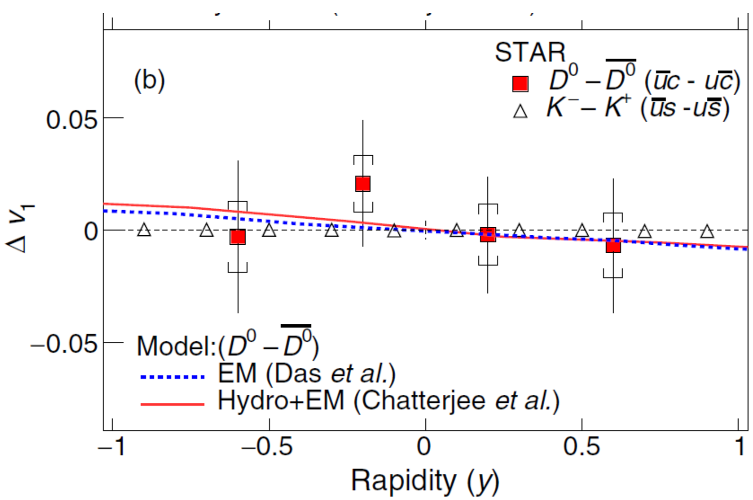


Das, Plumari, Chartarjee, Scardina, Greco, Alam
Phys. Lett. B, 768 (2017) 260

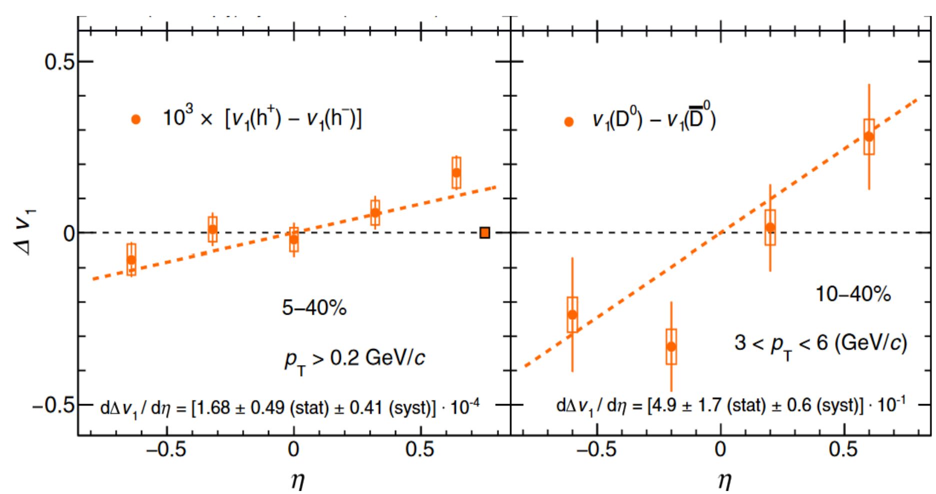
- ❖ **Order of magnitude larger than light hardon v_1**
- ❖ **Opposite v_1 for charm and anti-charm**

$$\Delta v_1(\mathrm{D}) = \mathrm{v}_1(\mathrm{D}^0) - \mathrm{v}_1(\overline{\mathrm{D}}^0)$$

Heavy meson directed flow at RHIC & LHC:

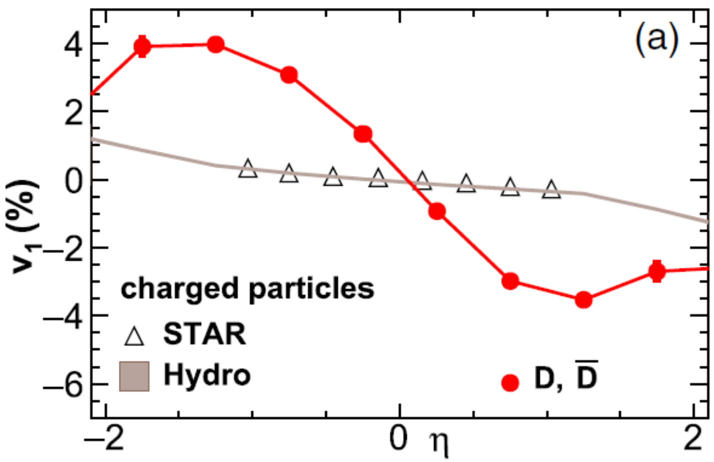


STAR Collaboration PRL 123, 162301 (2019)



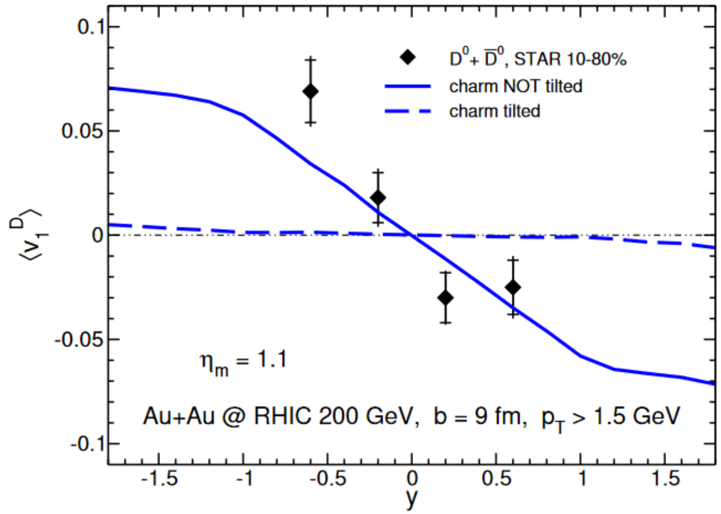
ALICE Collaboration PRL 125, 022301 (2020)

Heavy quark as a probe of initial stage: vorticity



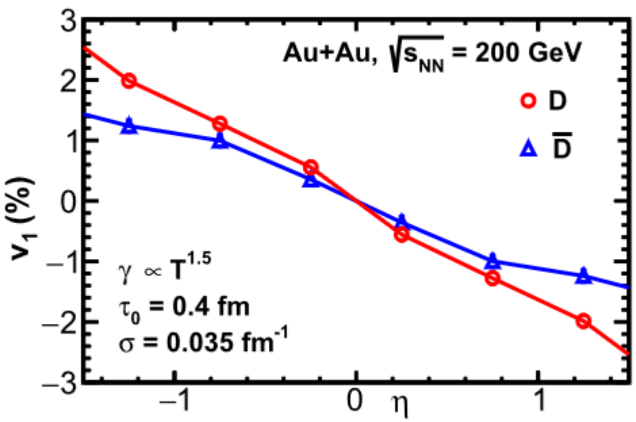
Large directed flow of heavy meson than the light hadron.

Chatterjee and Bozer, PRL, 120 (2018)

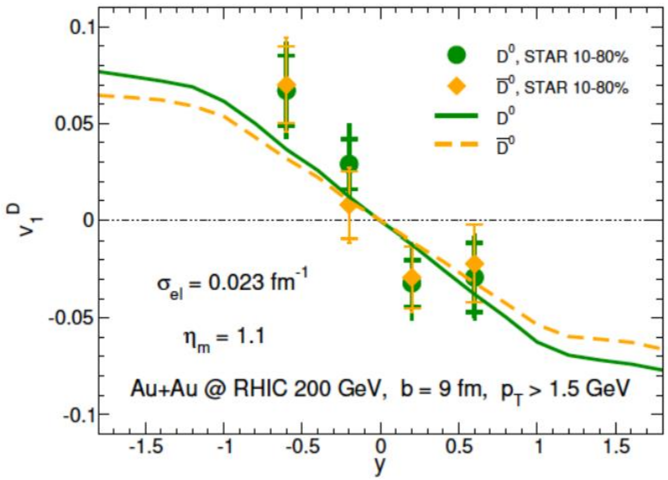


Charm quark distribution is not tilted

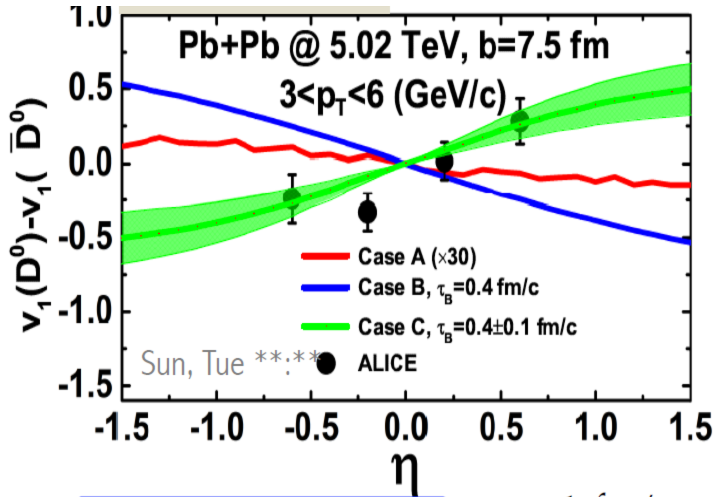
Oliva, Plumari, Greco, JHEP (2021)



Chatterjee and Bozer, PLB, 798 (2019)



Oliva, Plumari, Greco, JHEP (2021)



$$B(\tau) = eB_0/(1+\tau^2/\tau_B^2)$$

$$B(\tau) = eB_0/(1+\tau/\tau_B)$$

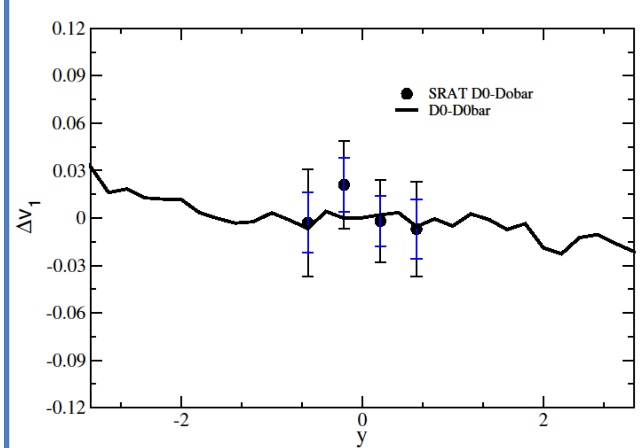
$\tau < 1$ fm/c

$B(\tau) \approx B(\tau)$

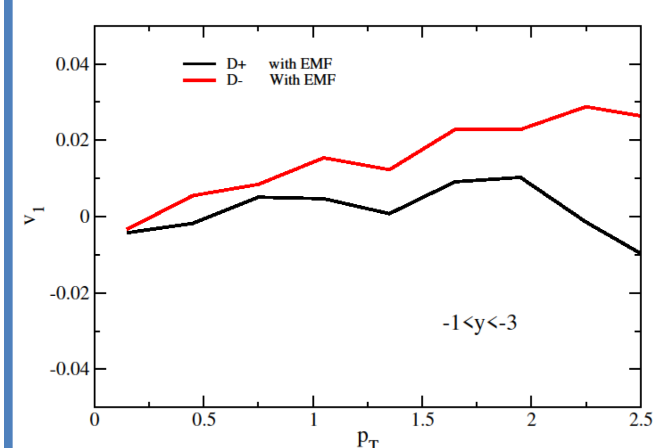
$E_x(\tau) > E_x(\tau)$

- ❖ **Yet to understand the Δv_1 sign change from RHIC to LHC**
- ❖ **Computation of early stage EM field is very essential**

Sun, Plumari, Greco, PLB, 861 (2021)



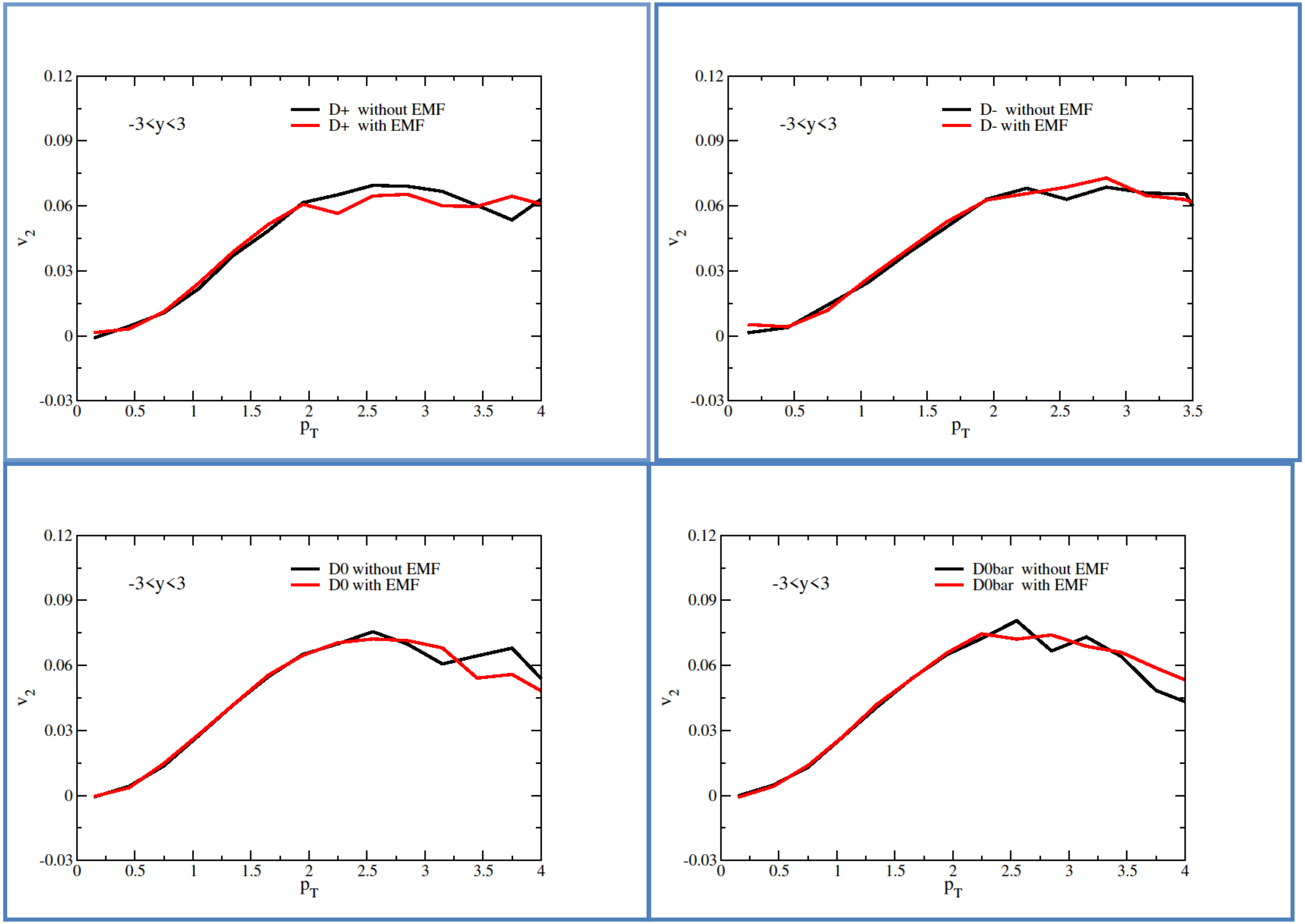
RHIC



The splitting is larger as a function of momentum

Das, Soloveva, Song, Bratkovskaya
Under preparation

D meson elliptic flow in presence of electromagnetic flow at RHIC



Das, Soloveva, Song, Bratkovskaya
Under preparation

Conclusions and Perspectives:

- **Present calculations indicate τ_{th} ~ 2-6 fm/c for low p_T charm quark.**

- **More precision data and additional observables can further constrain the D_s**

  Heavy-light event-by-event correlation, System size scan, D-Dbar correlation, B meson …….

- **Experimental data support coalescence plus fragmentation as hadronization**

- **Time evolution of EM field in HIC -> opposite sign of HF v1 from RHIC to LHC**

- **Heavy quark diffusion in pre-equilibrium phase is crucial.**

4th Heavy Flavour Meet

IIT Goa, 2-4 Nov 2023

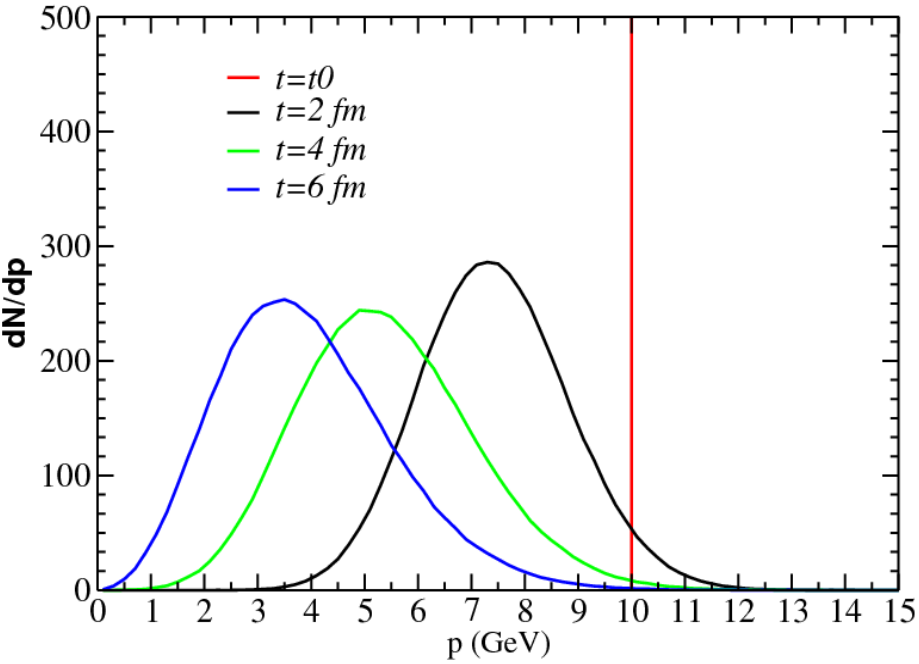

Thank You . . . .

Evolution: Boltzmann vs Langevin (Charm)

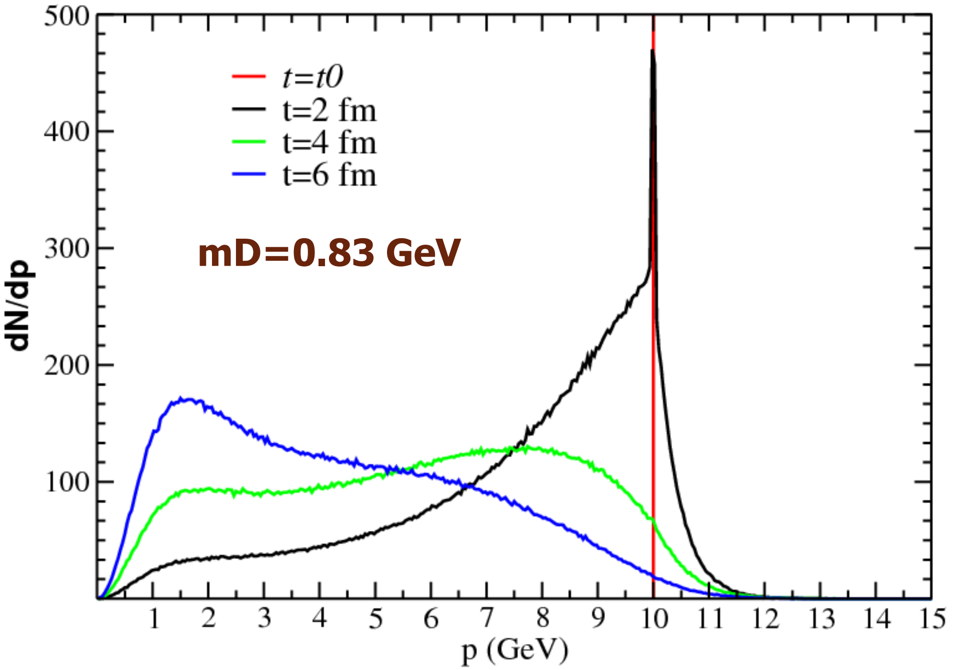
Momentum evolution starting from a δ (Charm) in a Box

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

Langevin



Boltzmann



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

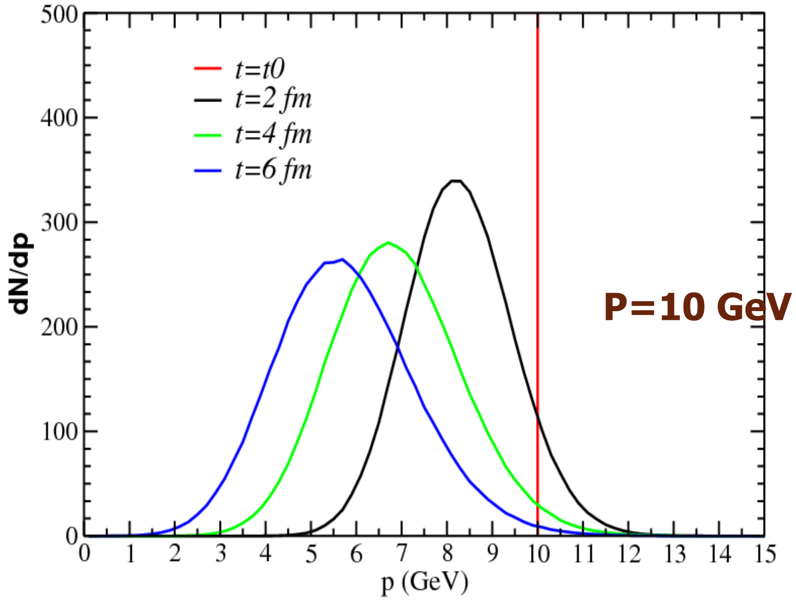
In case of Boltzmann the charm quarks does not follow the Brownian motion

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

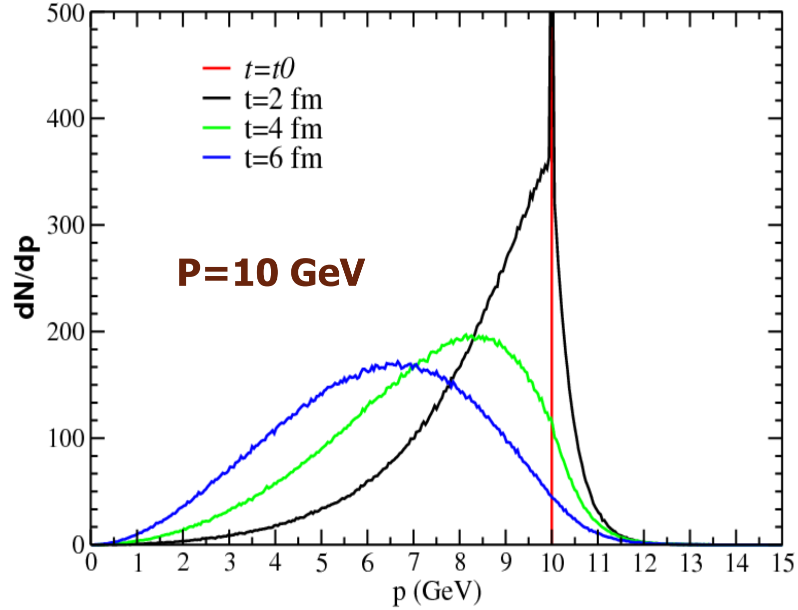
Momentum evolution starting from a δ (Bottom)

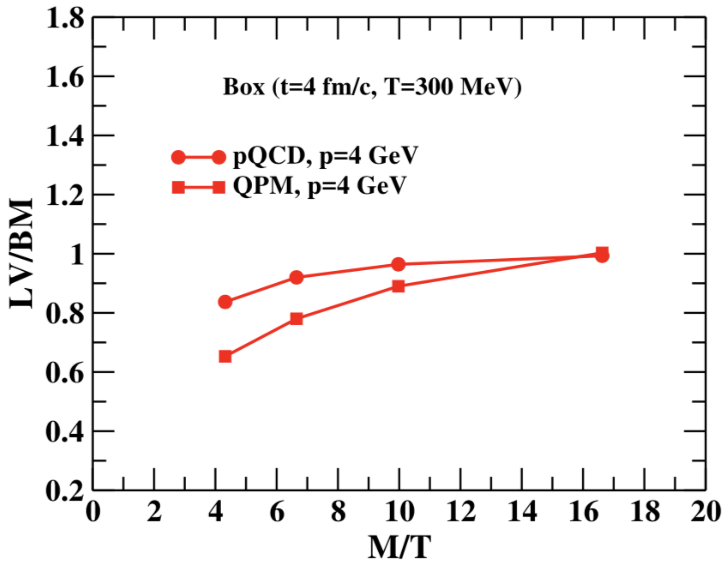
In a Box

Langevin



Boltzmann



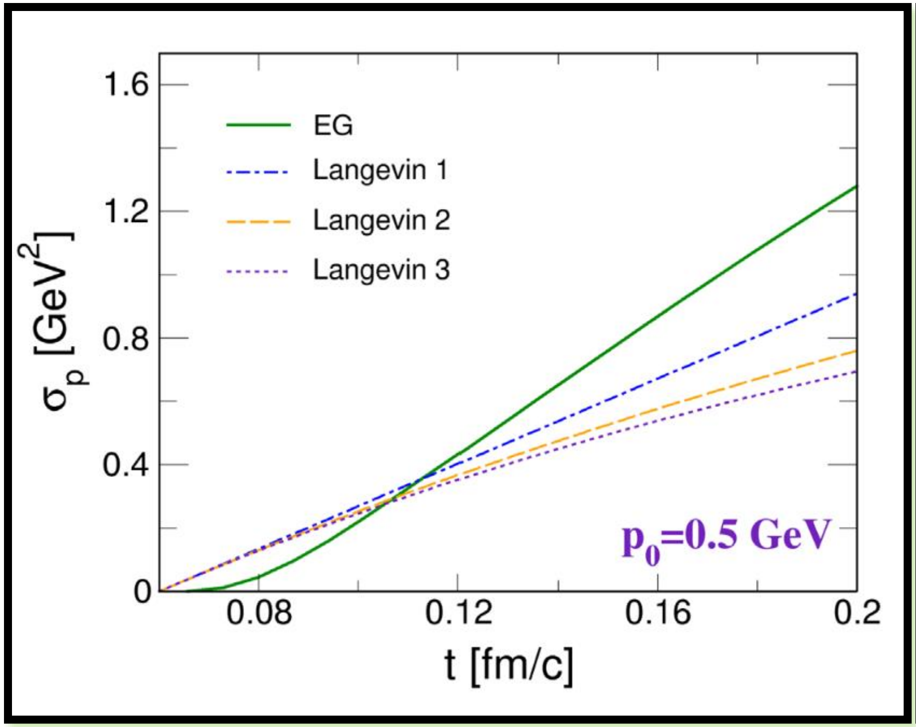


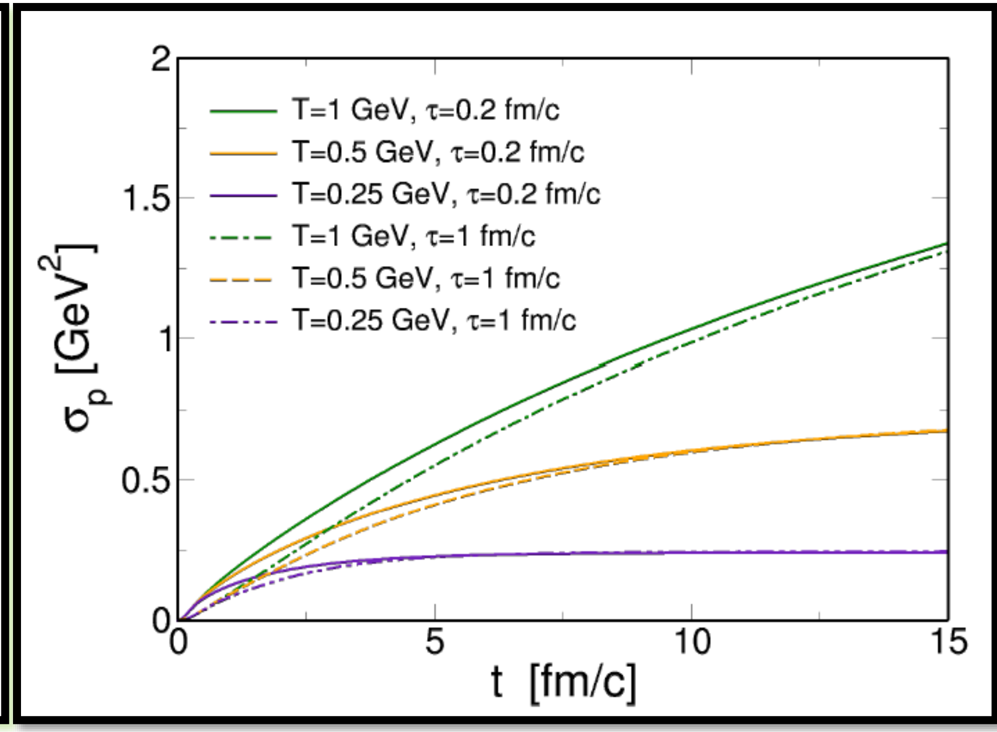
Das, Scardina, Plumari and Greco
PRC,90,044901(2014)

Langevin dynamics overestimate the interaction
Boltzmann generate more v2 for the same RAA.

Rapp et. al. EMMI-RRTF, NPA 979 (2018)

Impact of memory on heavy quark thermalization





$$\sigma_p = \frac{1}{2}\langle (p_x(t) - p_{0x})^2 + (p_y(t) - p_{0y})^2 \rangle$$

$$\sigma_p = \langle (p_T - \langle p_T \rangle)^2 \rangle$$

Memory delay the thermalization time

Liu, Das, Greco, Ruggieri, PRD 103, 034029 (2021)

Ruggieri, Pooja, Jai Prakash, Das, arxiv: 2203.06712 [hep-ph]