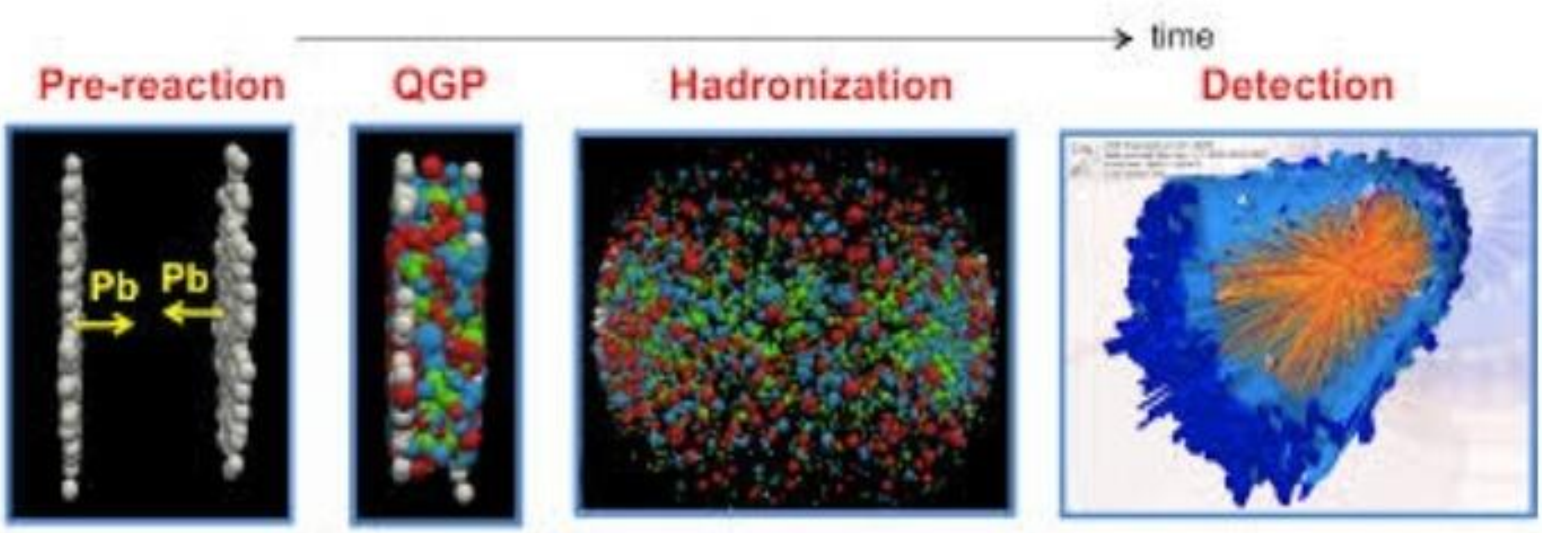
Open heavy flavors: Theory



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Indian Institute of Technology Goa
Goa, India

OUTLINE

- **R_{AA} vs v_2: Heavy quark diffusion**

  D_s, Heavy quark thermalization

- **Recent developments**

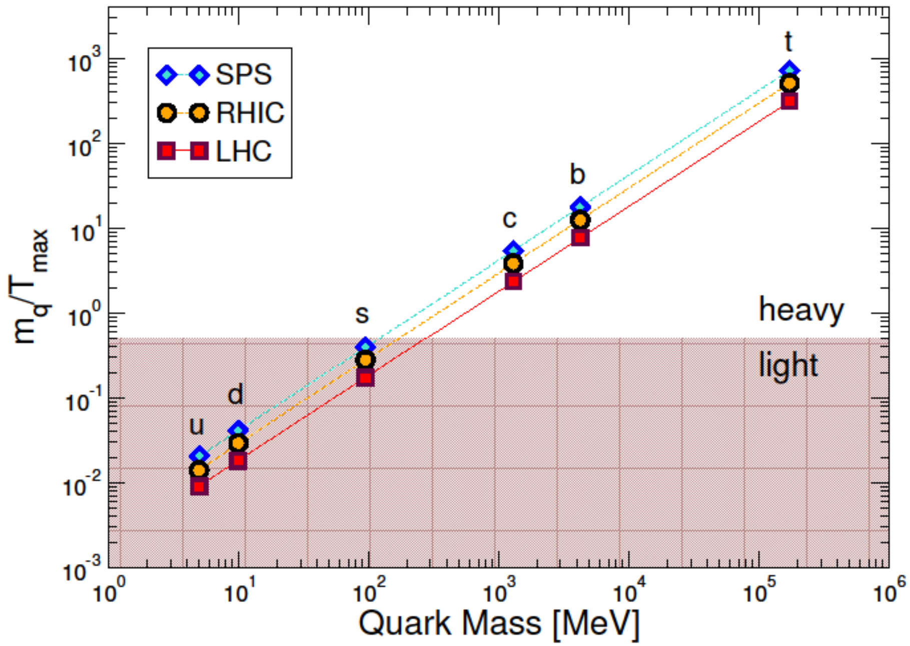
  New observables, Radiation, Hadronization

  Non-equilibrium effect, Small system

- **Heavy quark as a probe of Initial stage**

  EM fields, Glasma, Verticity

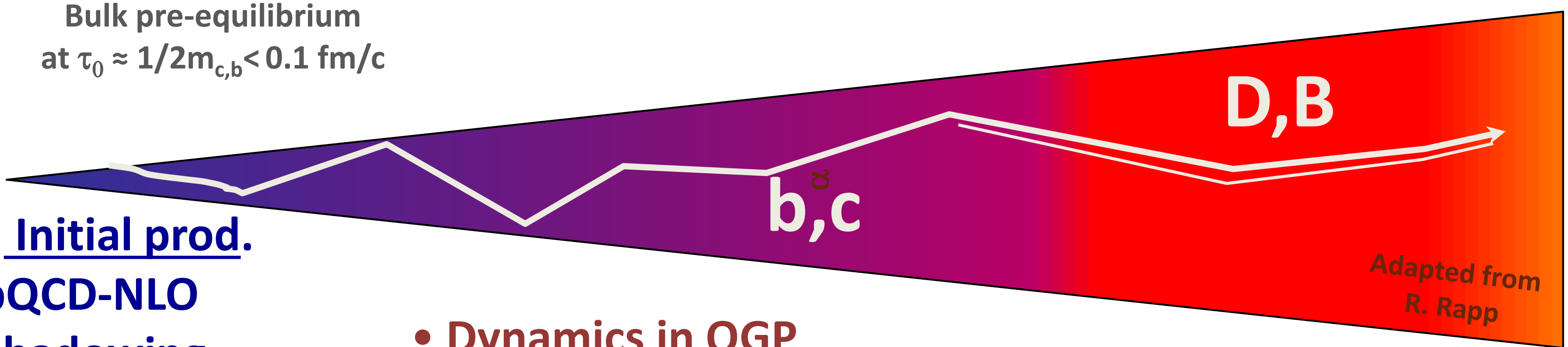
Heavy Quark in Quark-Gluon Plasma



- $m_{c,b} >> \Lambda_{QCD}$ pQCD initial production
- $m_{c,b} >> T_{RHIC,LHC}$ negligible thermal production (not @FCC)
- $\tau_0 < 0.08$ fm/c $<< \tau_{QGP}$ witness of all the QGP evolution
- $\tau_{th} \approx \tau_{QGP} >> \tau_{q,g}$ carry more information of their evolution
- $m_{c,b} >> gT_{RHIC,LHC}$ soft scatterings → Brownian motion (low p charm)

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

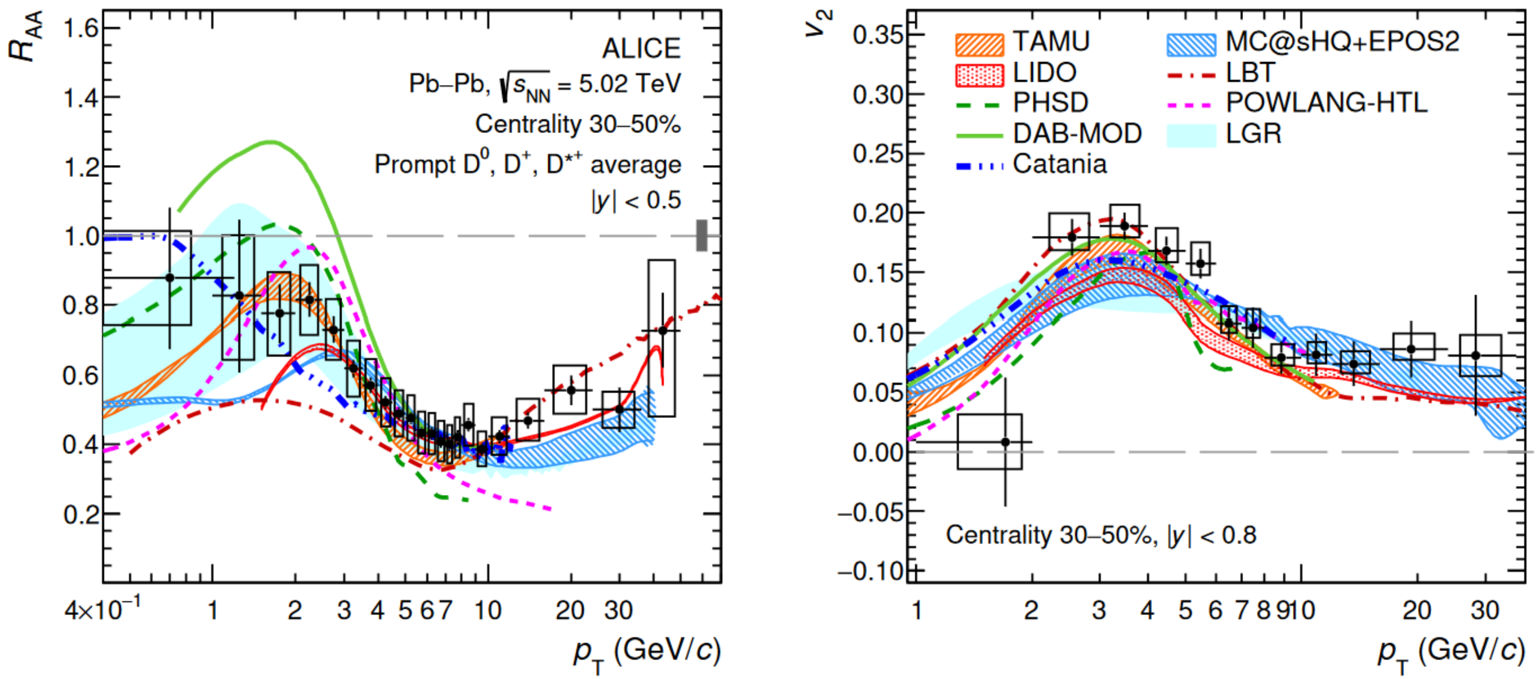
Heavy quark momentum evol.

(Langevin/Boltzmann/E. loss model)

- **Hadronization:**

coalescence and/or
fragmentation.
Hadronic rescattering

R_{AA} and v_2
Comparison with models

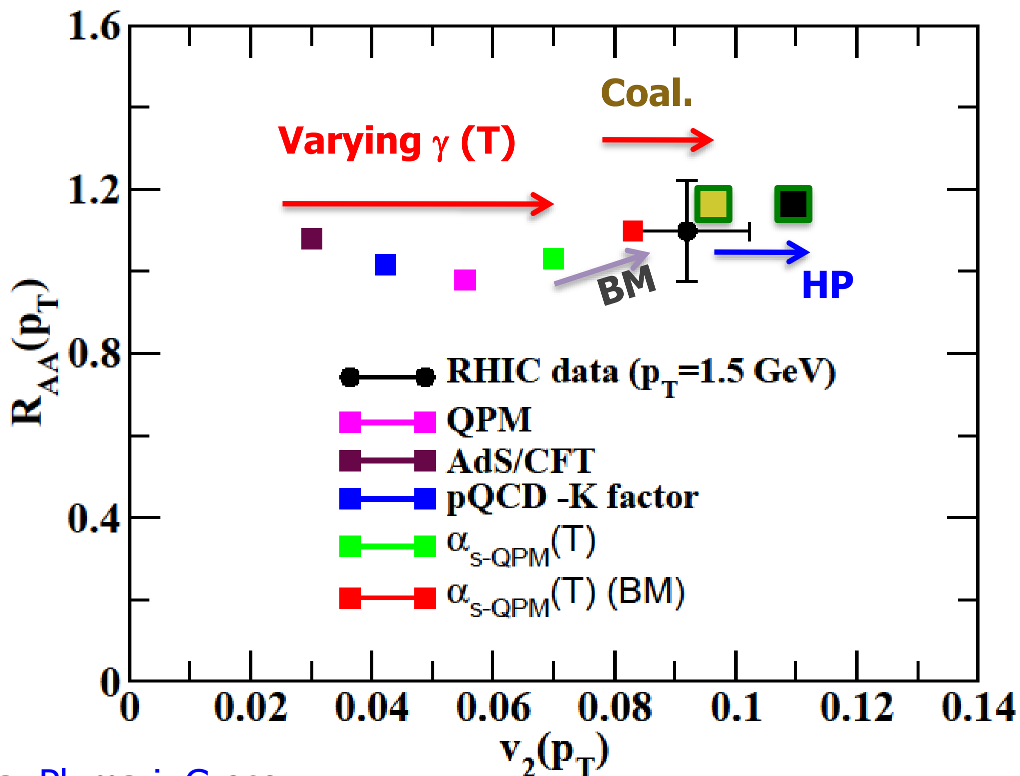


ALICE, JHEP 01 (2022) 174

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, colliding energy, system size.

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

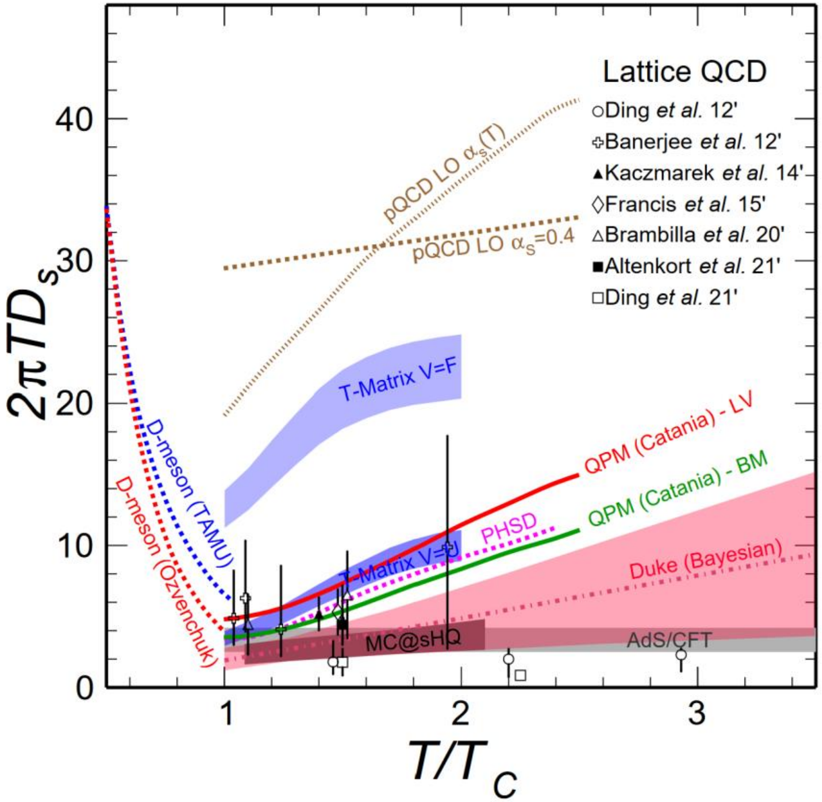


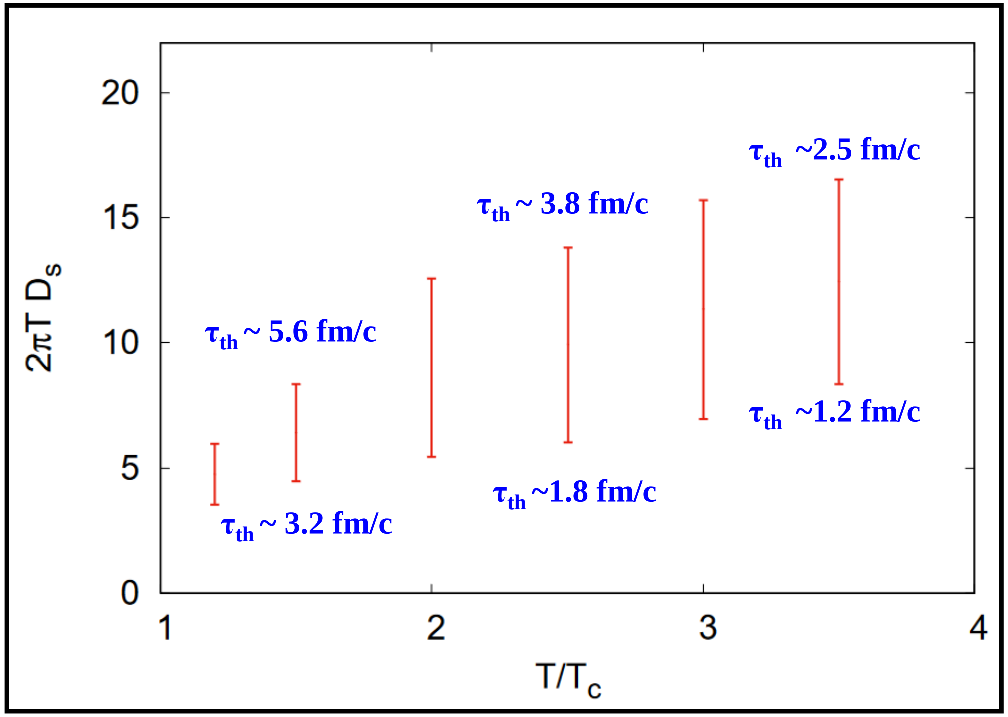
TAMU, Nantes, Catania, BAMPS, PHSD, Duke, POWLANG-HTL, UrQMD, Duke, LBL-CCNU, CUJET, DREENA,……

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





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

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

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

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

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

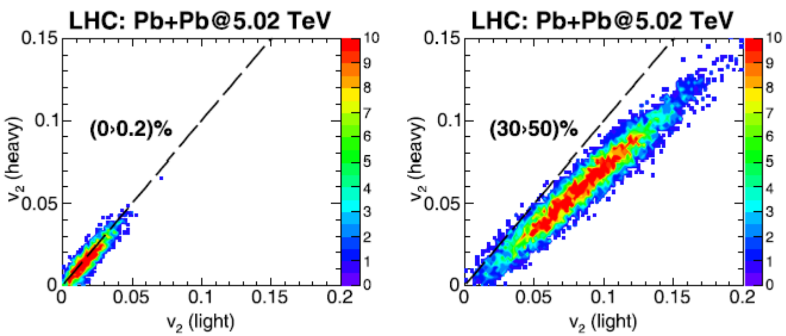
$2\pi T D_s \propto T^2$,corresponds to a constant thermalization time.

Memory effect can impact the HQ thermalization

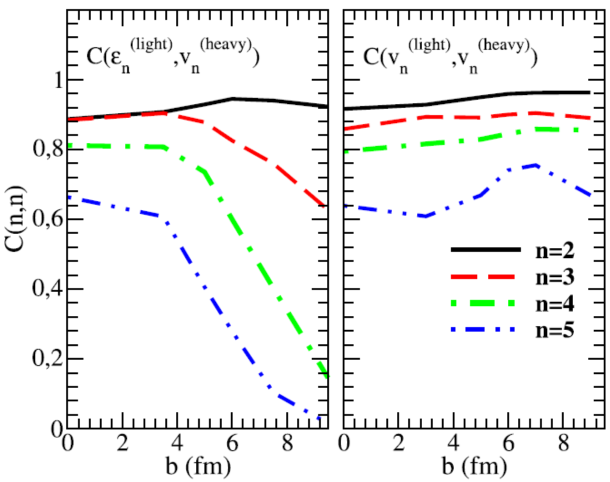
Ruggieri, Pooja, Jai Prakash, Das, PRD, 106 (2022)

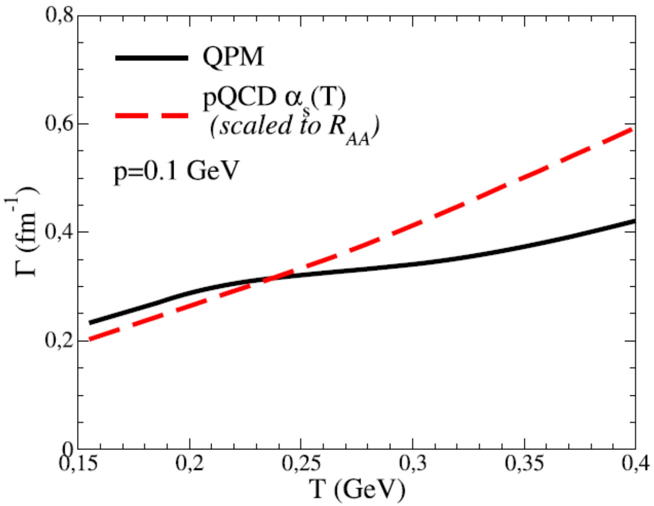
Recent Developments

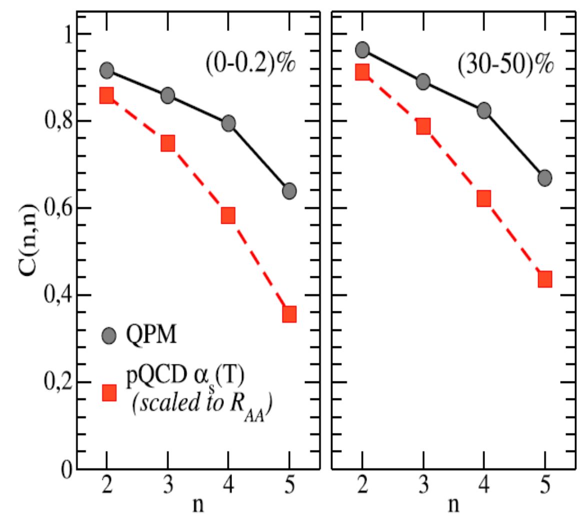
Heavy-light event-by-event correlation



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







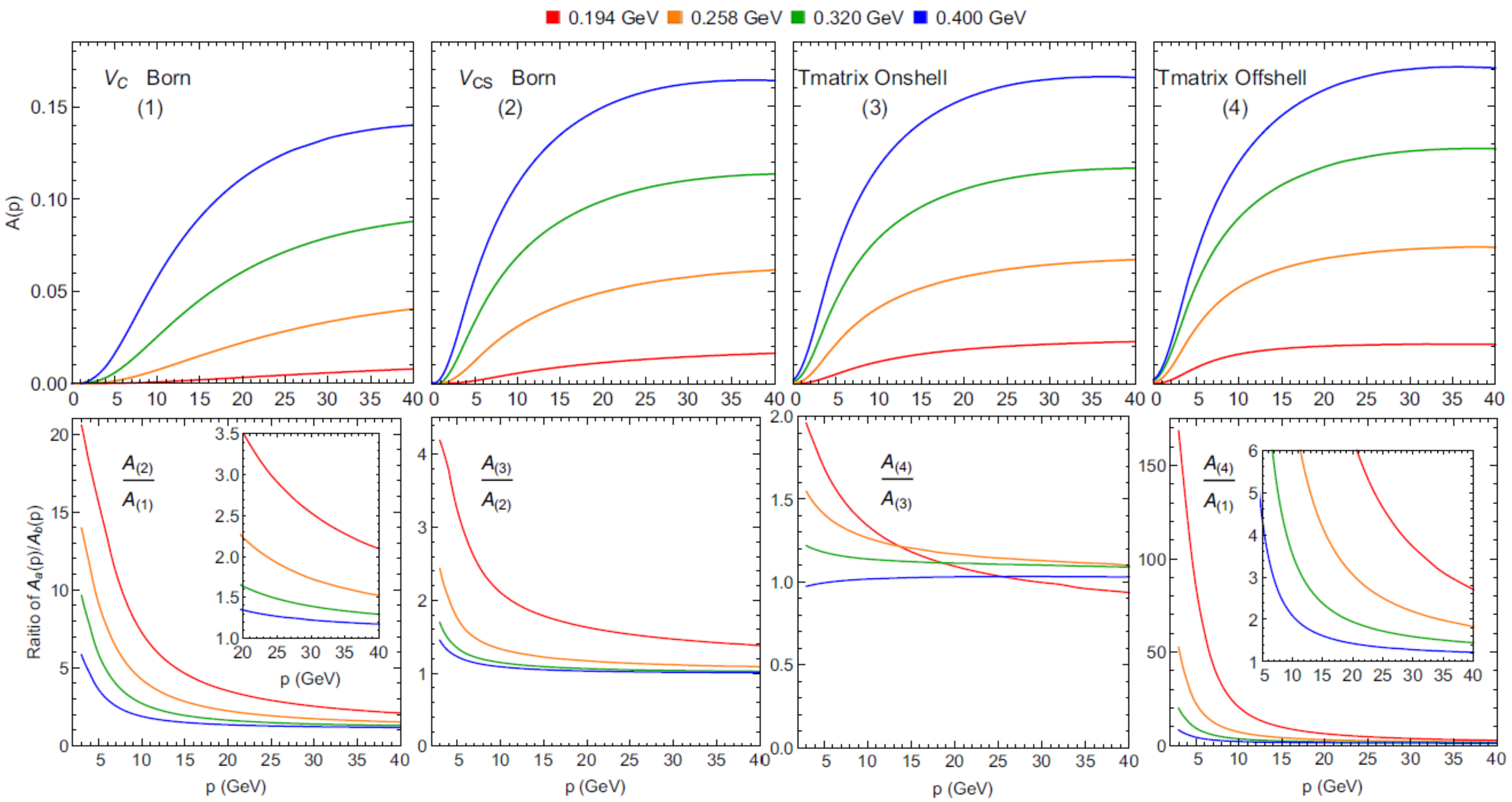
V_n(D) more correlated to $v_n(N_{ch})$ than ε_n

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

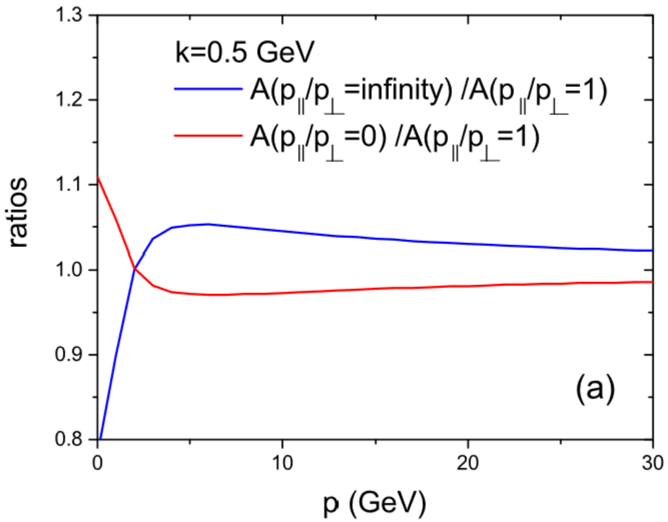
Heavy quark radiation in T-matrix approach

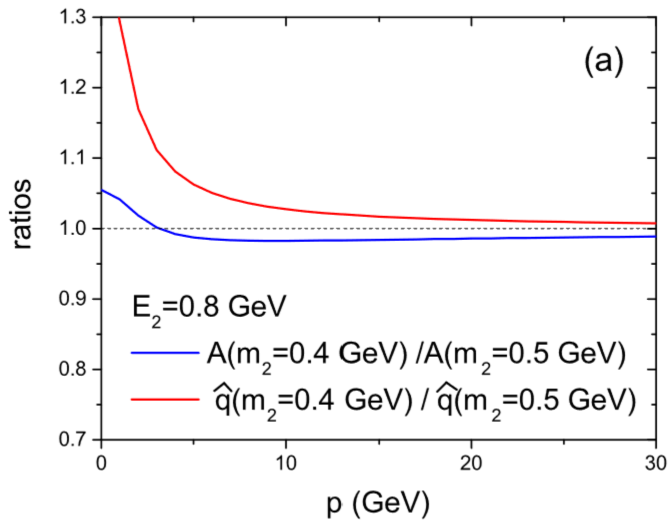


Liu, Rapp, JHEP 08 (2020) 168

- **Perturbative processes experience a strong suppression due to thermal mass**
- **Nonperturvative effect enhance the radiative contribution at low p and T.**
- **But its magnitude is small compared to the elastic contribution.**

Heavy quark transport coefficients: Non-equilibrium effect





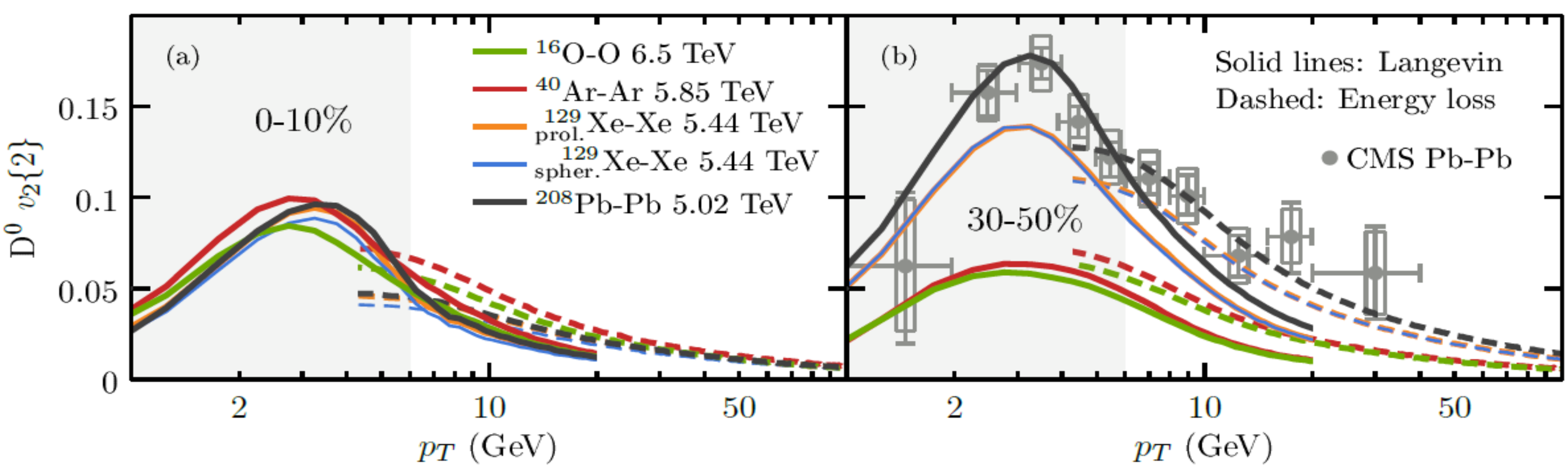
Anisotropic bulk distribution

Shift in poll mass

Each non-equilibrium scenario affects *A* of charm quarks in a different way.

Song, Moreau, Aichelin, Bratkovskaya, PRC, 101 (2020)

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

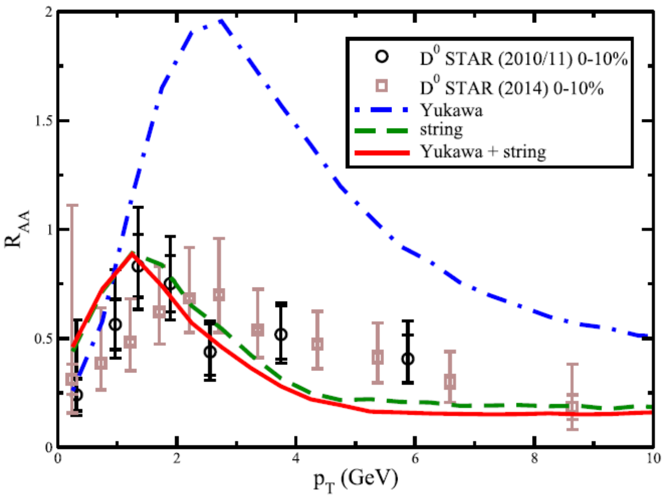


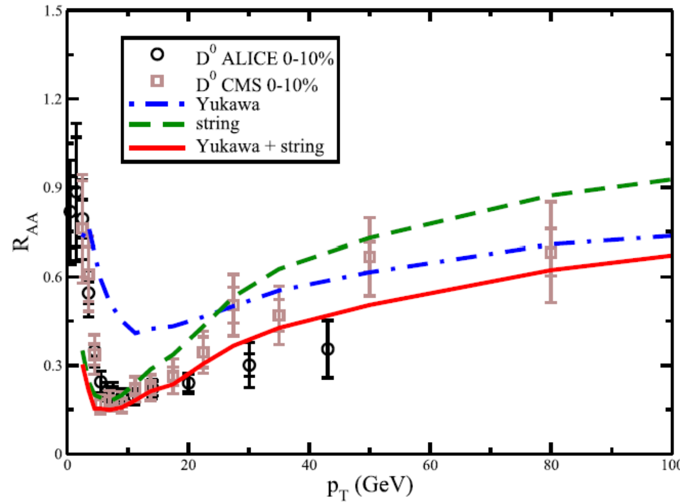
In central collisions the v2 is independent of system size.

System size vs Eccentricity

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

In-medium heavy quark potential from the open heavy flavor observables



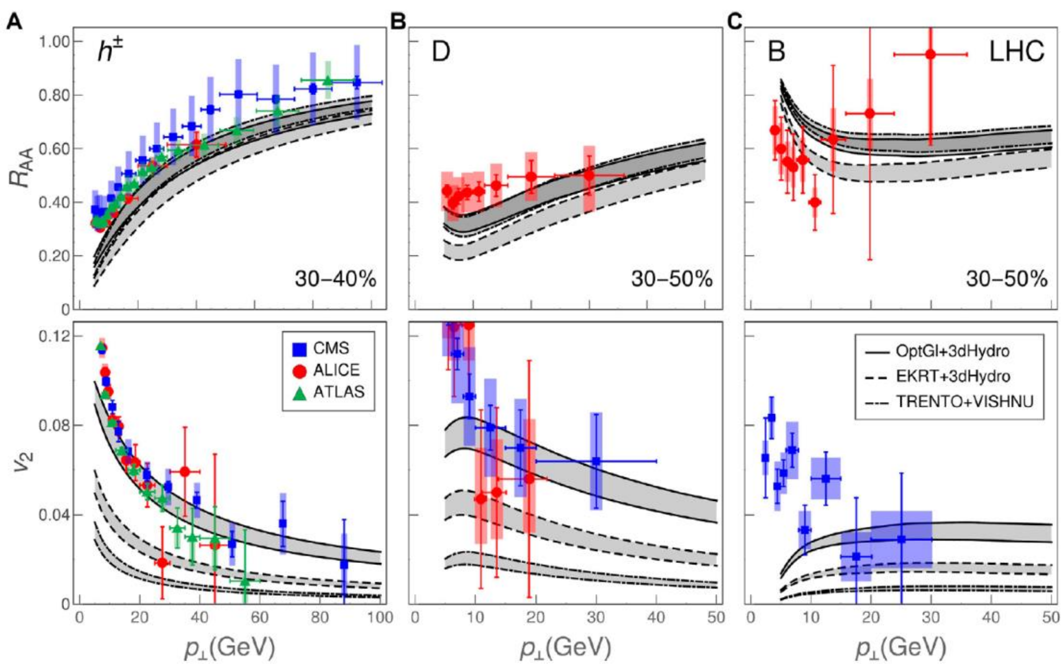


Xing, Qin, Cao
PLB 838 (2023) 137733

❖ **Xing's Talk (Wed)**

High pT are dominated by the short-range Yukawa potential.
Low pT are dominated by the long-range string potential

Dynamical Radiative and Elastic Energy loss Approach-A



Exploit differences in temperature profiles

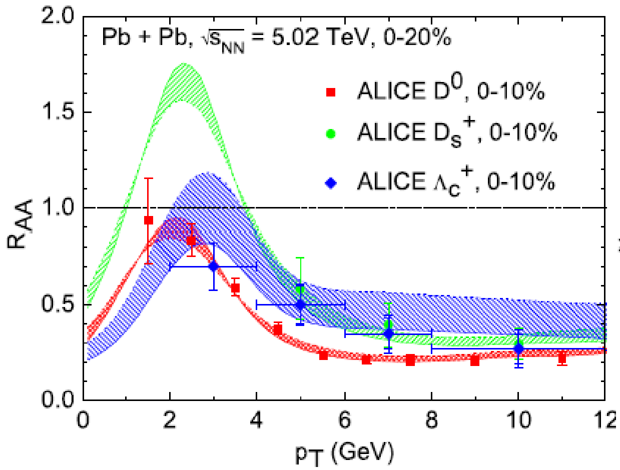
Can describe the data at high p_T

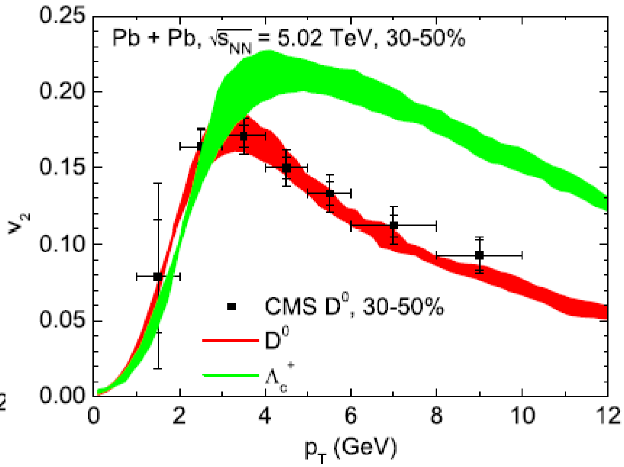
❖**Djordjevic's Talk (Tus)**

Zigic, Salom, Auvinen, Huovinen, Djordjevic
FIP 10(2022) 957019

Heavy quark hadronization

❖ Beraudo's Talk (Wed)

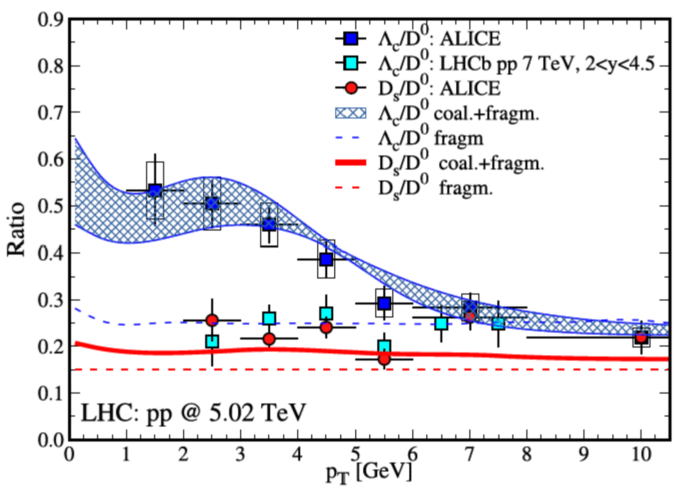


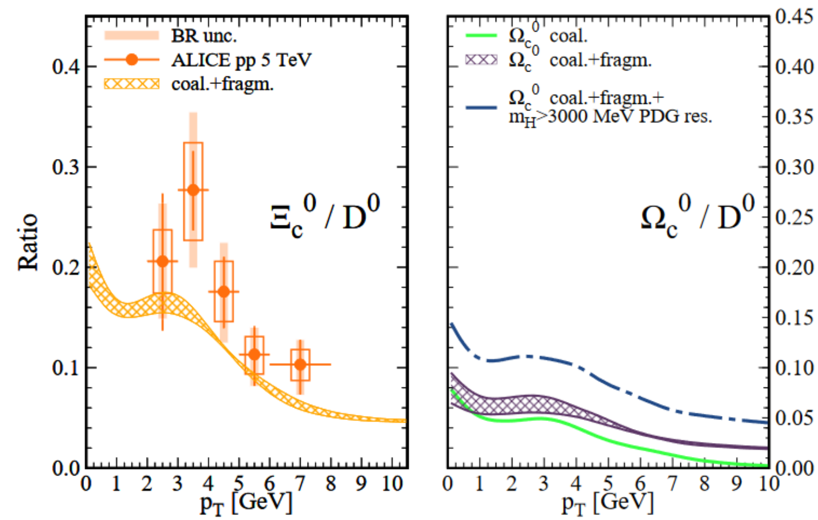


- 4-momentum conserving three-body recombination
- Equilibrium limit
- Improved HF hadrochemistry

He, Rapp, PRL 124 (2020) 042301

Charm hadrons coalescence plus fragmentation in pp

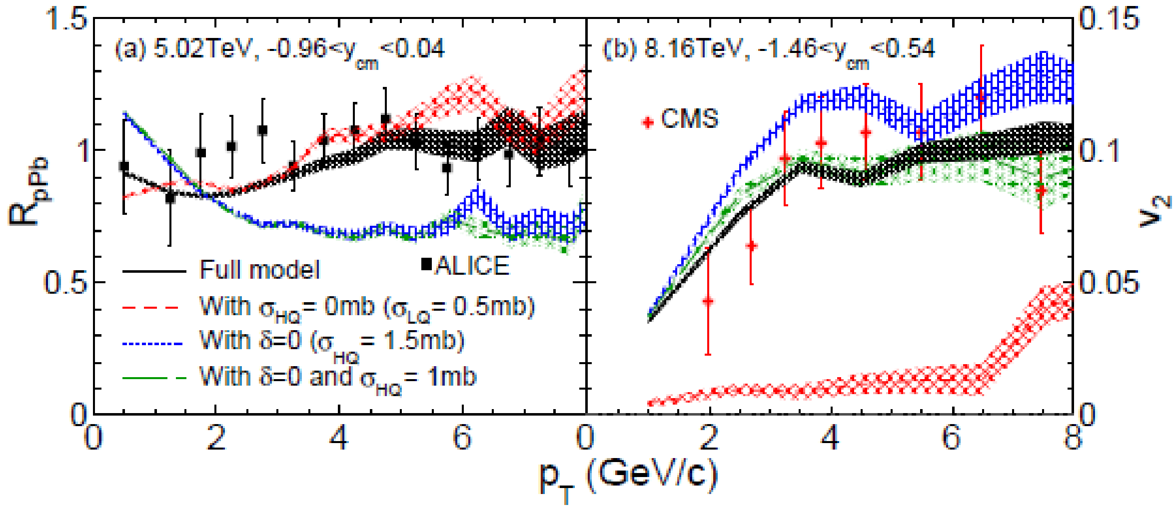




$$P_{fragm} = 1 - P_{coal}. \qquad \lim_{p\to 0} P^{tot}_{coal} = 1.$$

Minissale, Plumari, Greco, PLB 821(2021) 136622

R_{pA} and v_2 puzzle of D mesons in p-Pb collisions



v2: charm quark interaction
RpPb: Cronin effect

No radiation
No T and p-dependence interaction

Cronin effect enhances the charm quark yield at relatively high pT and cancels out the effect from jet quenching.

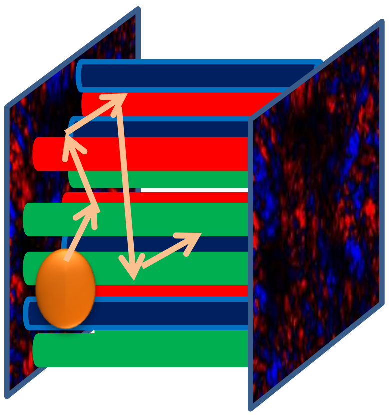
- **Lin's Talk (Wed)**

Zhang, Zheng, Shi, Lin, arXiv: 2210.07767[nucl-th]

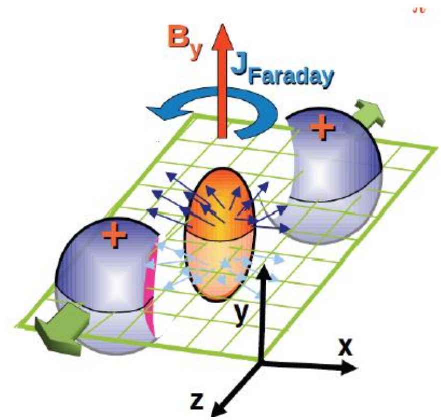
Heavy quark as a probe of Initial stage

Heavy quark as a probe of Initial stage

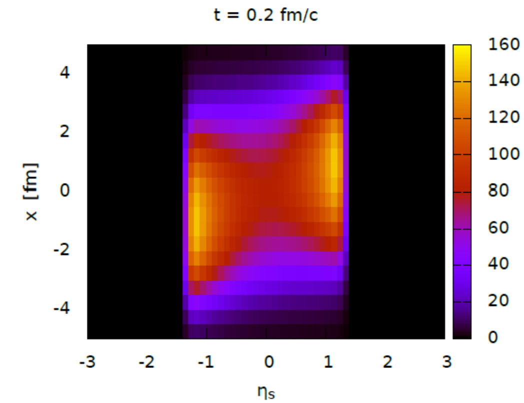
(Adapted from M. Ruggieri)



Impact of Glasma phase



Electromagnetic field



Vorticity

Initial Glasma in Pre-equilibrium phase can induce strong diffusion

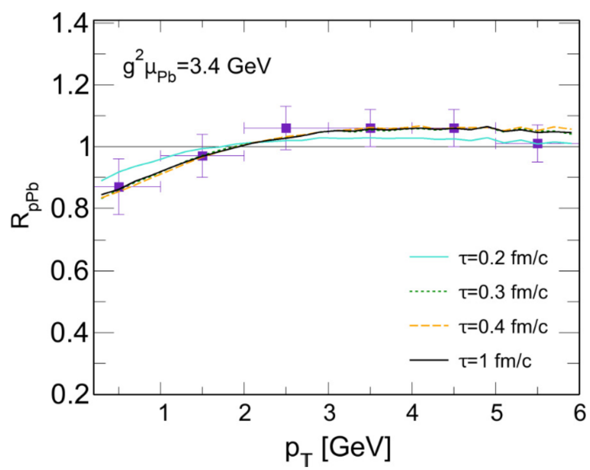
Mrowczynski, EPJA 54 (2018)
Ruggieri and Das, PRD98 (2018)

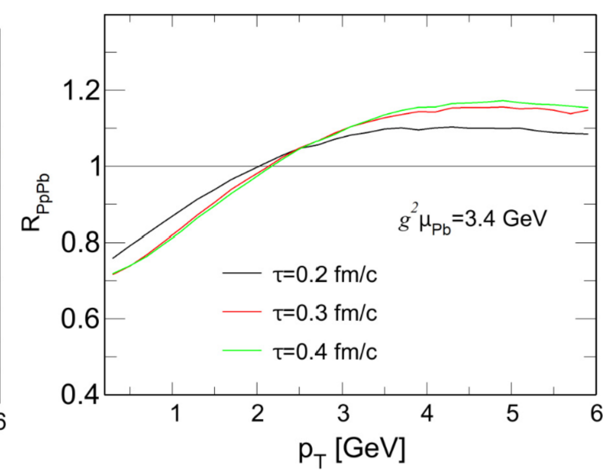
$$\frac{dx_i}{dt} = \frac{p_i}{E},$$

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

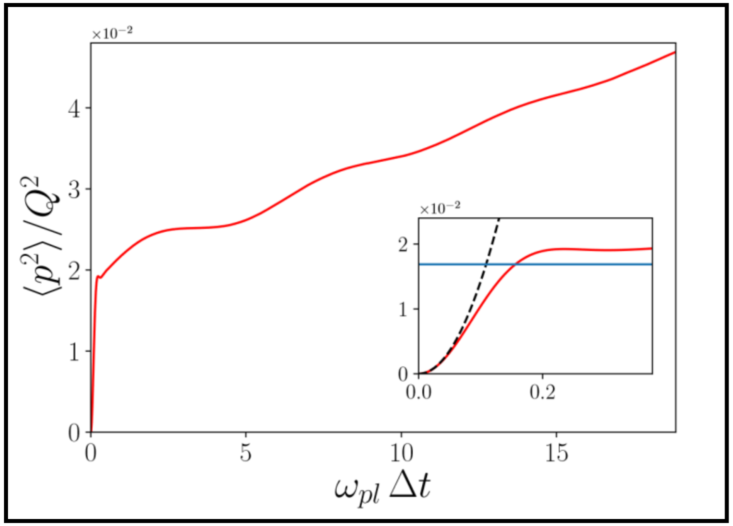
$$E\frac{dQ_a}{dt} = -gQ_c \varepsilon^{cba} \boldsymbol{A}_b \cdot \boldsymbol{p};$$

Wong (1979)





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



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

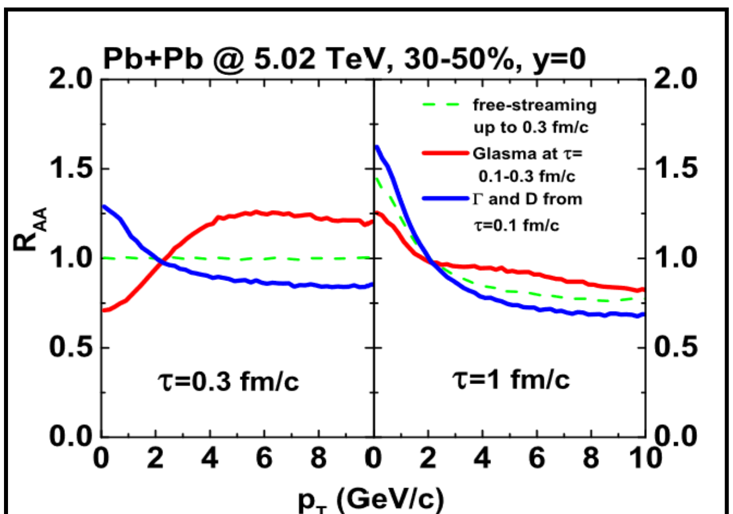
Correlator method

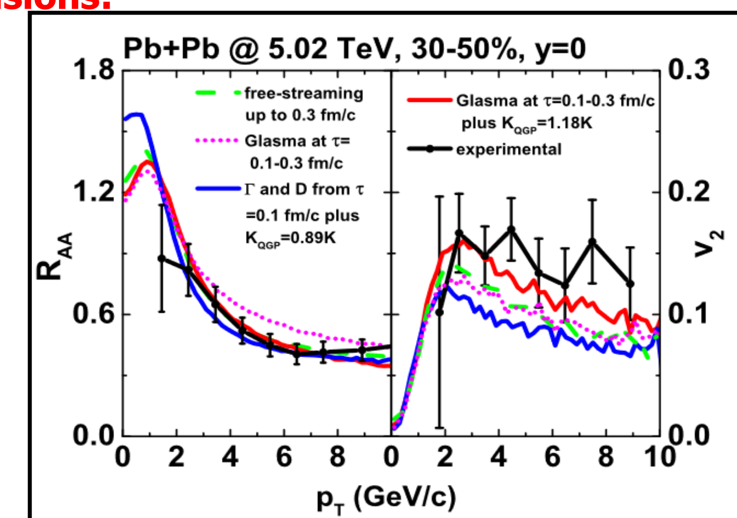
$$\langle \dot{p}_i(t)\dot{p}_i(t')\rangle = \frac{g^2}{2N_c}\langle E_i^a(t)E_i^a(t')\rangle$$

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}**

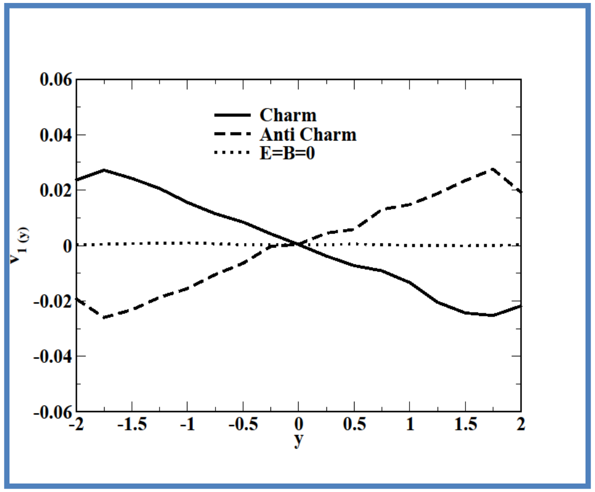
Impact of Glasma phase on nucleus-nucleus collisions:

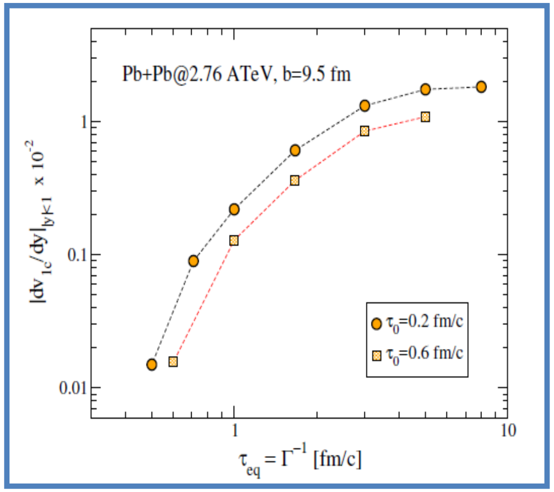




Sun, Coci, Das, Plumari, Ruggieri, Greco
PLB, 798 (2019) 134933

Heavy quark directed flow in EM fields



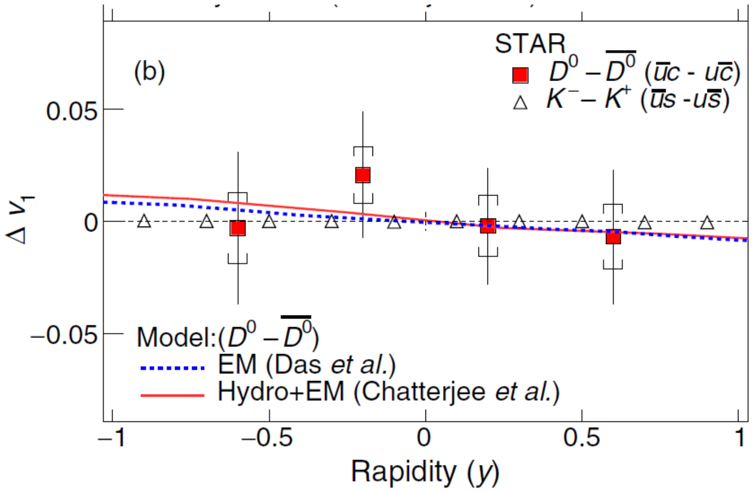


Das, Plumari, Chartarjee, Scardina, Greco, Alam
Phys. Lett. B, 768 (2017) 260

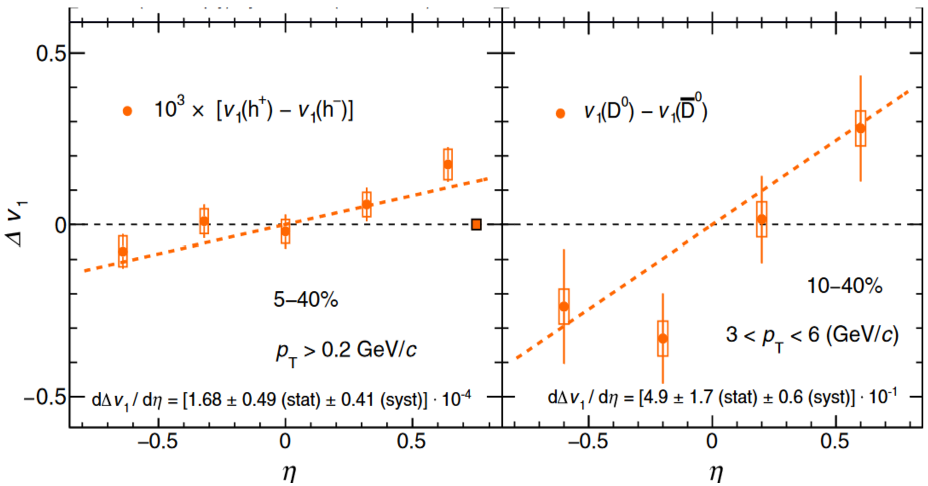
- ❖ **Order of magnitude larger than light hardon v_1**
- ❖ **Opposite v_1 for charm and anti-charm**

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

Heavy meson directed flow at RHIC & LHC:

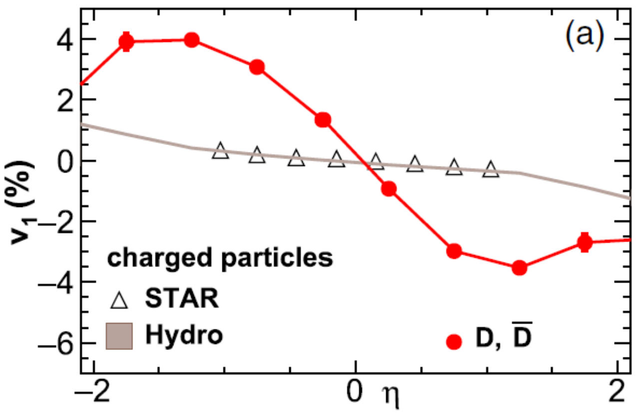


STAR Collaboration PRL 123, 162301 (2019)

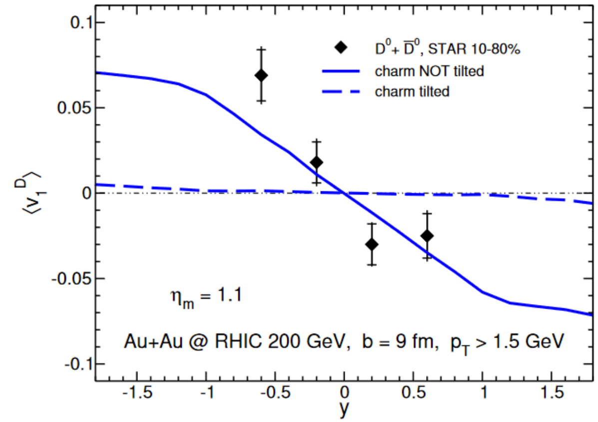


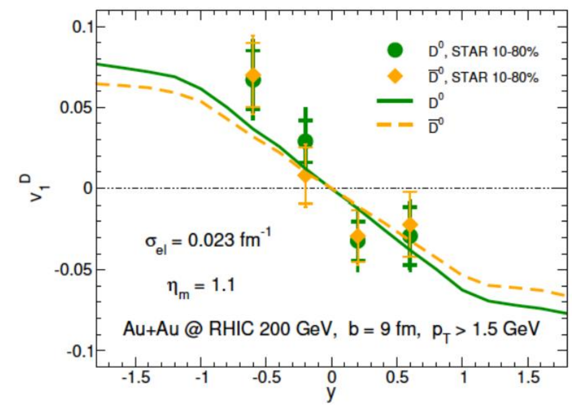
ALICE Collaboration PRL 125, 022301 (2020)

Heavy quark as a probe of initial stage: vorticity

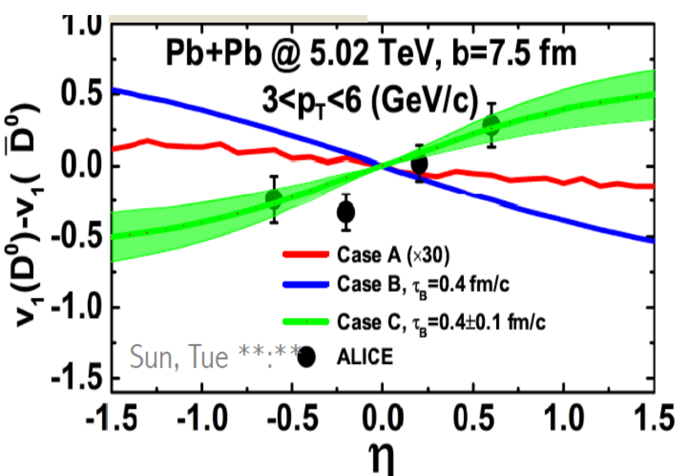


Chatterjee and Bozer, PRL, 120 (2018)





Oliva, Plumari, Greco, JHEP (2021)



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

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

τ <1 fm/c

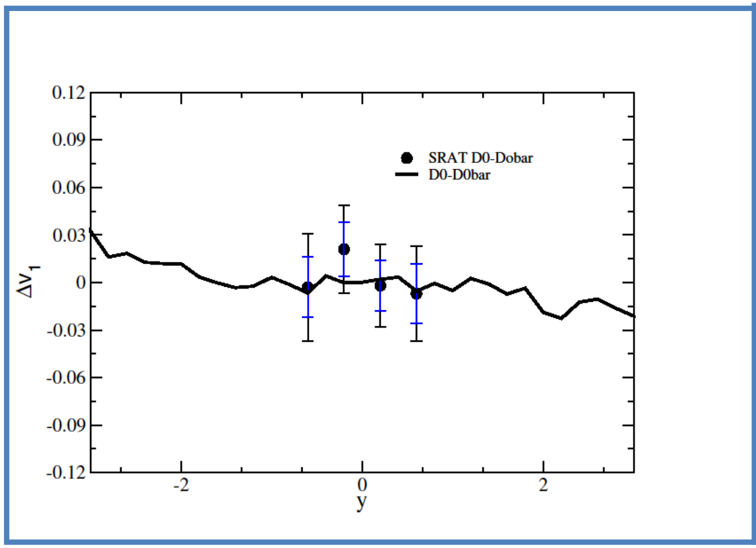
$B(\tau) \approx B(\tau)$

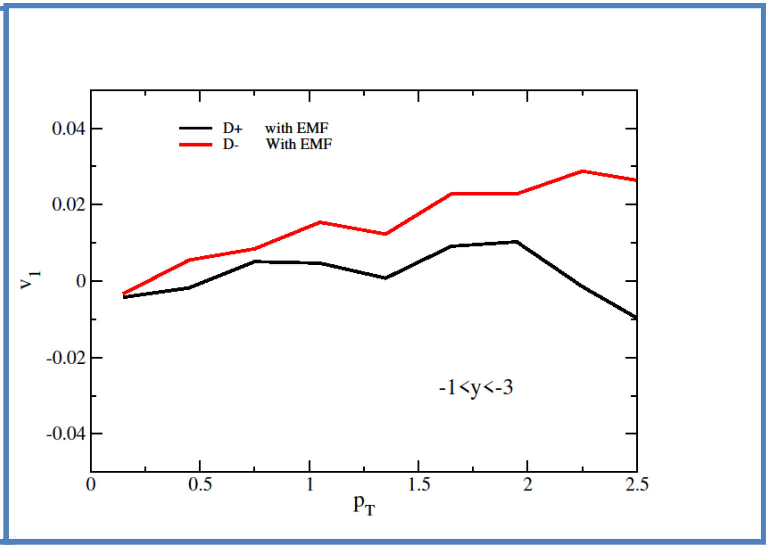
$E_x(\tau) > E_x(\tau)$

- ❖ **Large directed flow of heavy meson than the light hadron**
- ❖ **Charm quarks distribution are not tilted**
- ❖ **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)

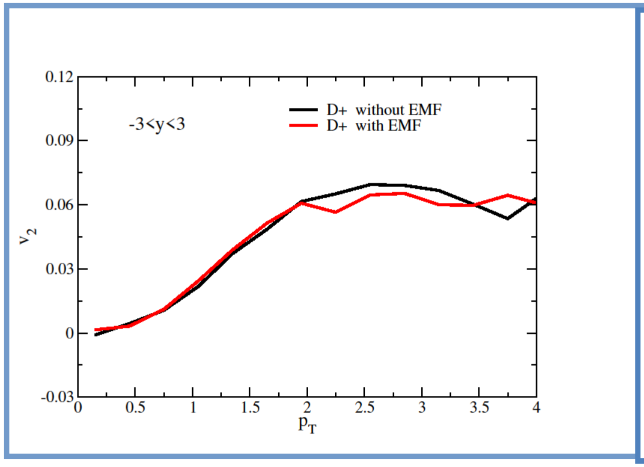
Heavy quark directed flow within PHSD @ RHIC

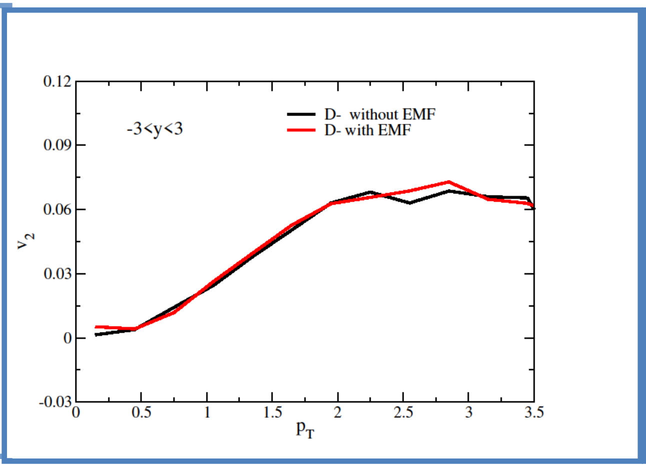


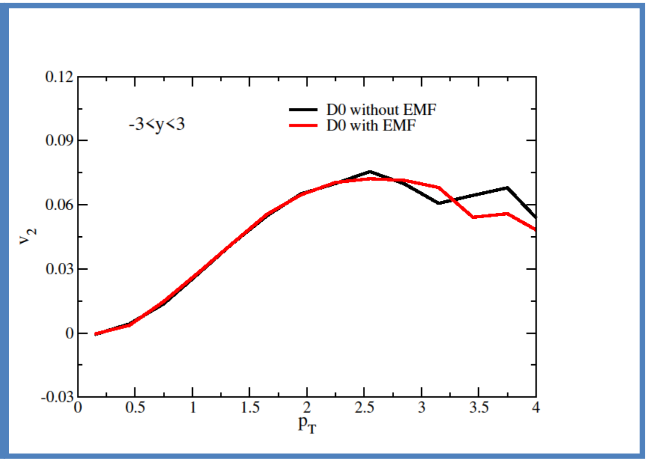


The splitting is larger as a function of momentum

Das, Soloveva, Song, Bratkovskaya
Under preparation







Impact of electromagnetic field on heavy quark elliptic flow is negligible

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, Λ_c, p->0,...

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

- **Heavy quark can act as an excellent probe of the early stage dynamics**

  Pre-equilibrium phase, EM fields, Vorticity

- **Time to focus heavy quark dynamics in small system, Bean energy scan….**

  So far major focus: Highest RHIC energy and LHC energies

  Recent STAR data on HF decay electron@ 54.4 GeV and 27 GeV…


Thank You

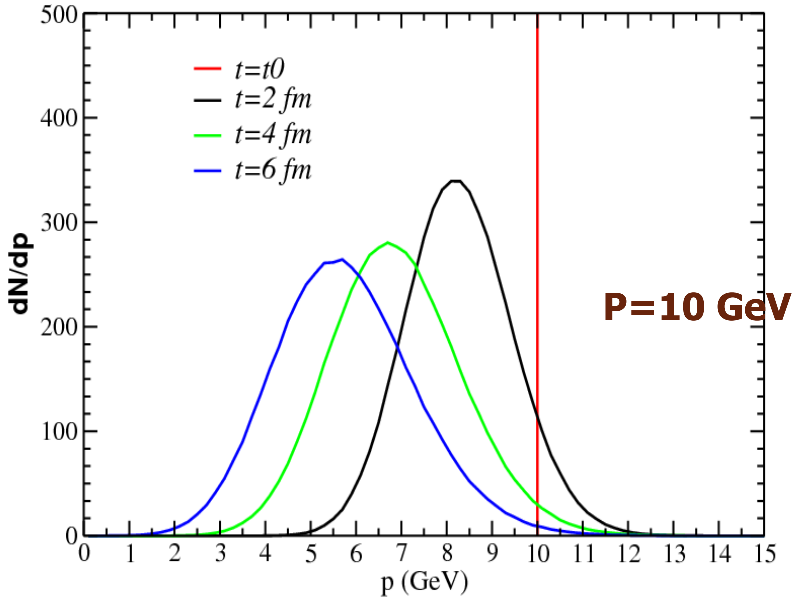
4th Heavy Flavour Meet

IIT Goa, 2-4 Nov 2023

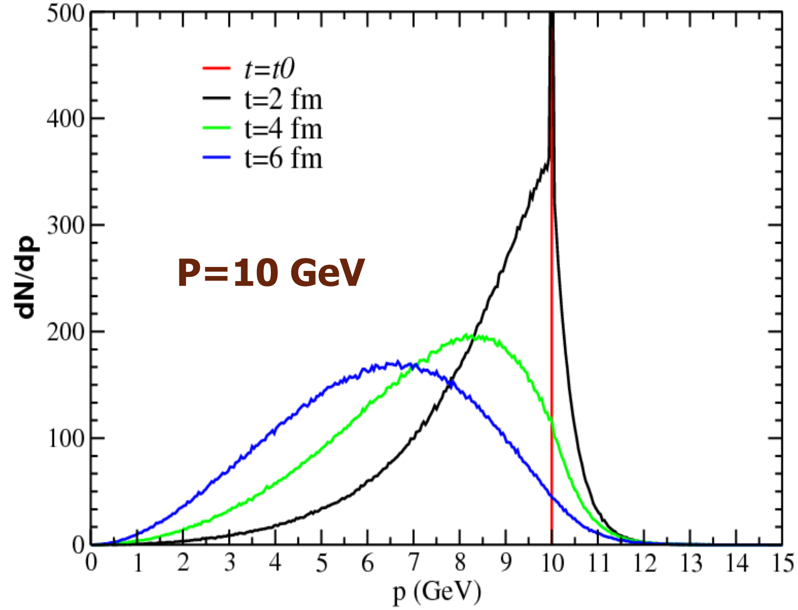
Momentum evolution starting from a δ (Bottom)

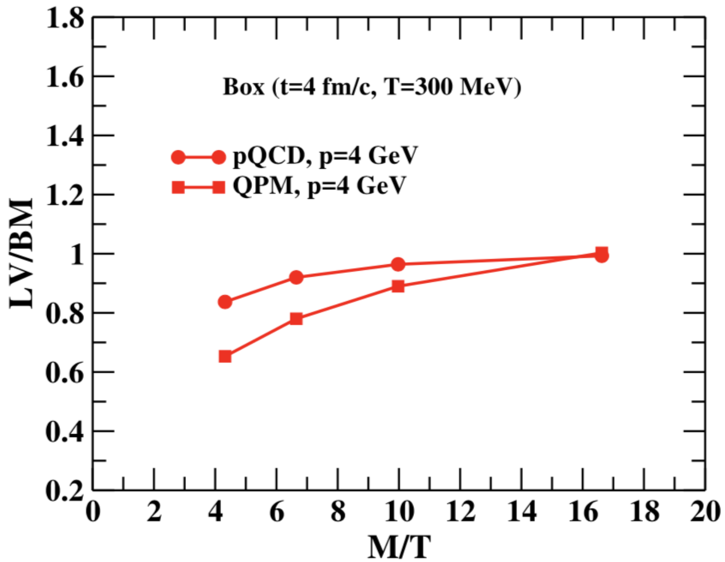
In a Box

Langevin



Boltzmann



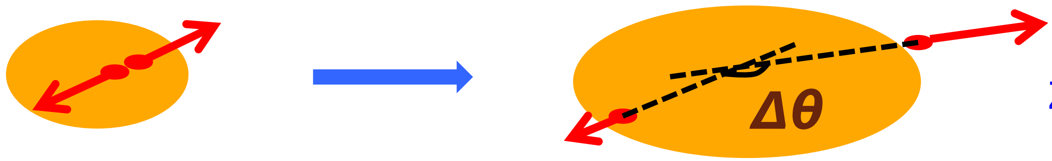


Das, Scardina, Plumari and Greco
PRC,90,044901(2014)

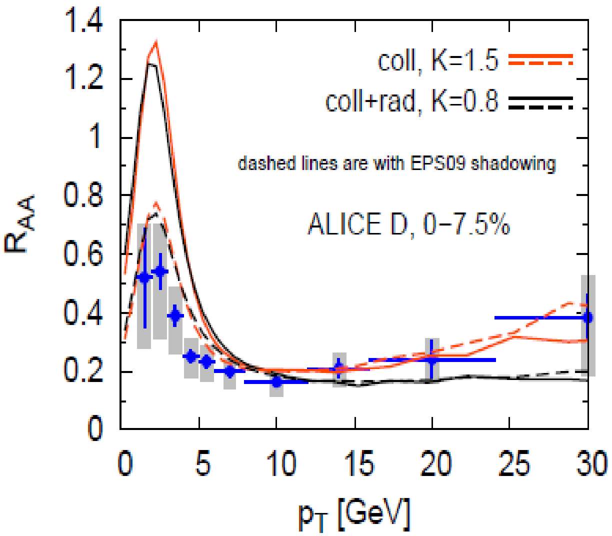
Langevin dynamics overestimate the interaction
Boltzmann generate more v2 for the same RAA.

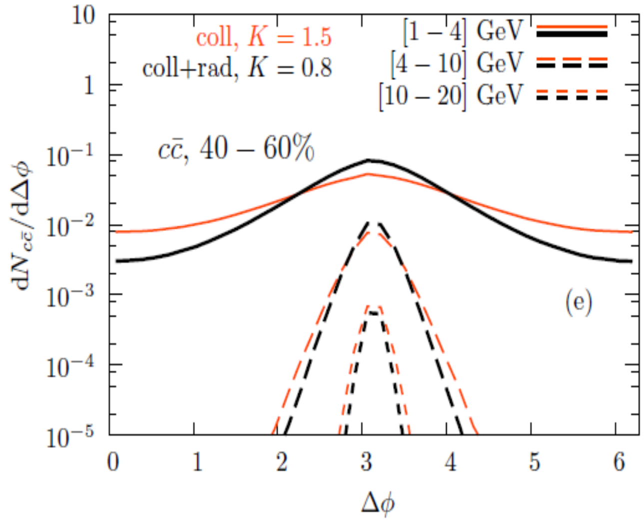
Rapp et. al. EMMI-RRTF, NPA 979 (2018)

Angular De-correlation of *c*cbar:



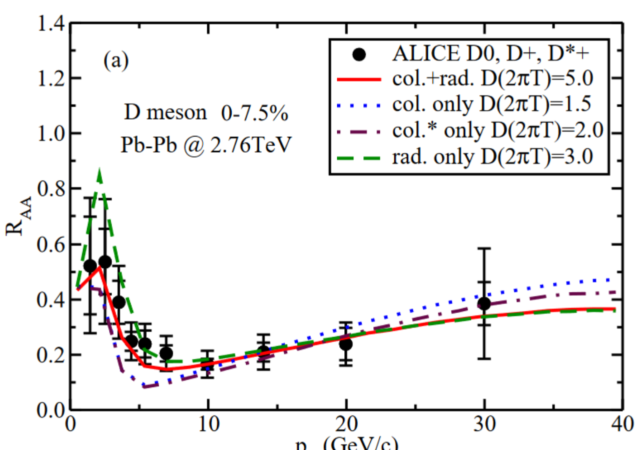
Zhu ,Xu, Zhuang, PRL100, 152301 (2008)

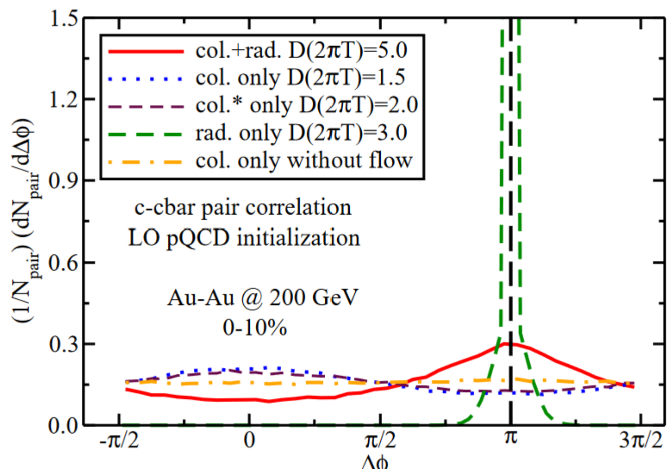




DDbar correlation is sensitive to energy loss mechanism

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

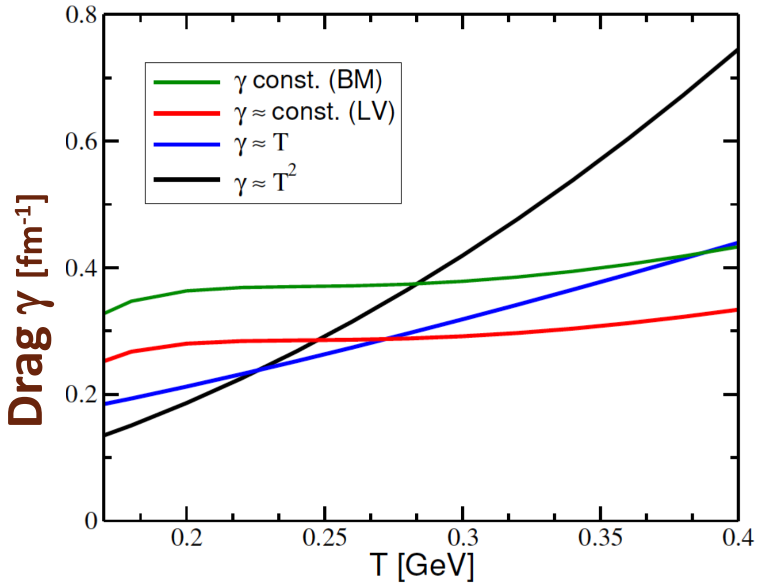




DDbar correlation can disentangle different Energy loss mechanism

Cao, Qin, Bass
PRC, 95 (2015)

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

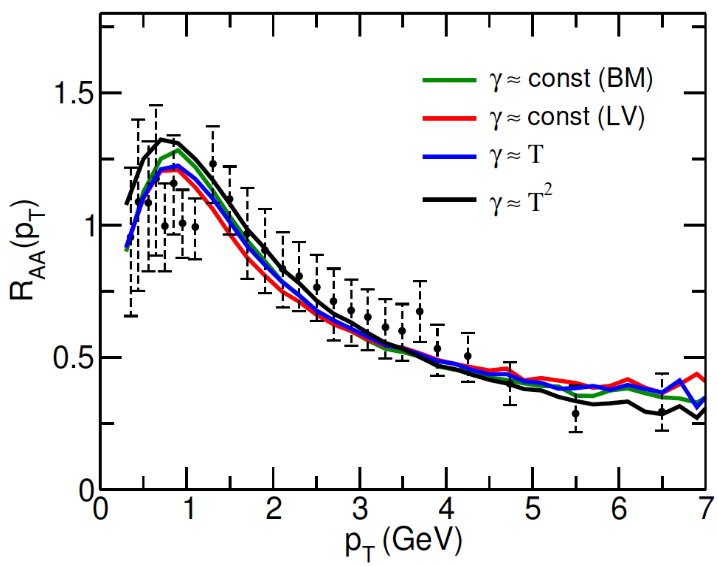


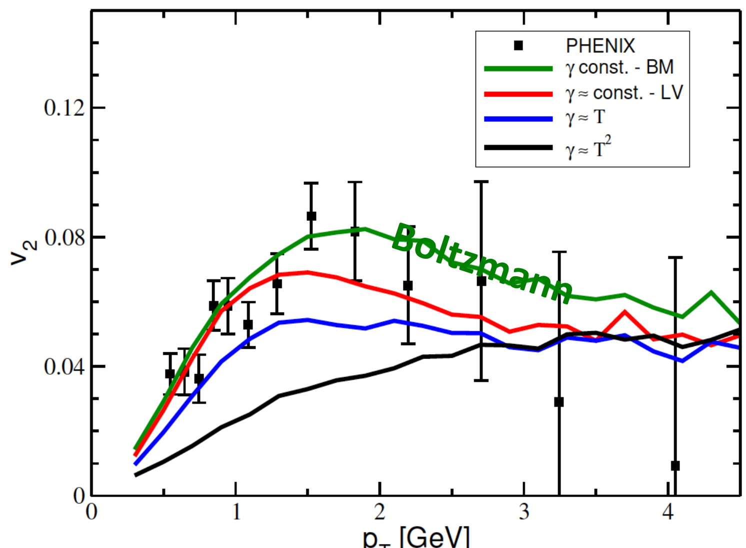
Looking at it beyond the specific modelings

- $\gamma \approx T^2$ [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