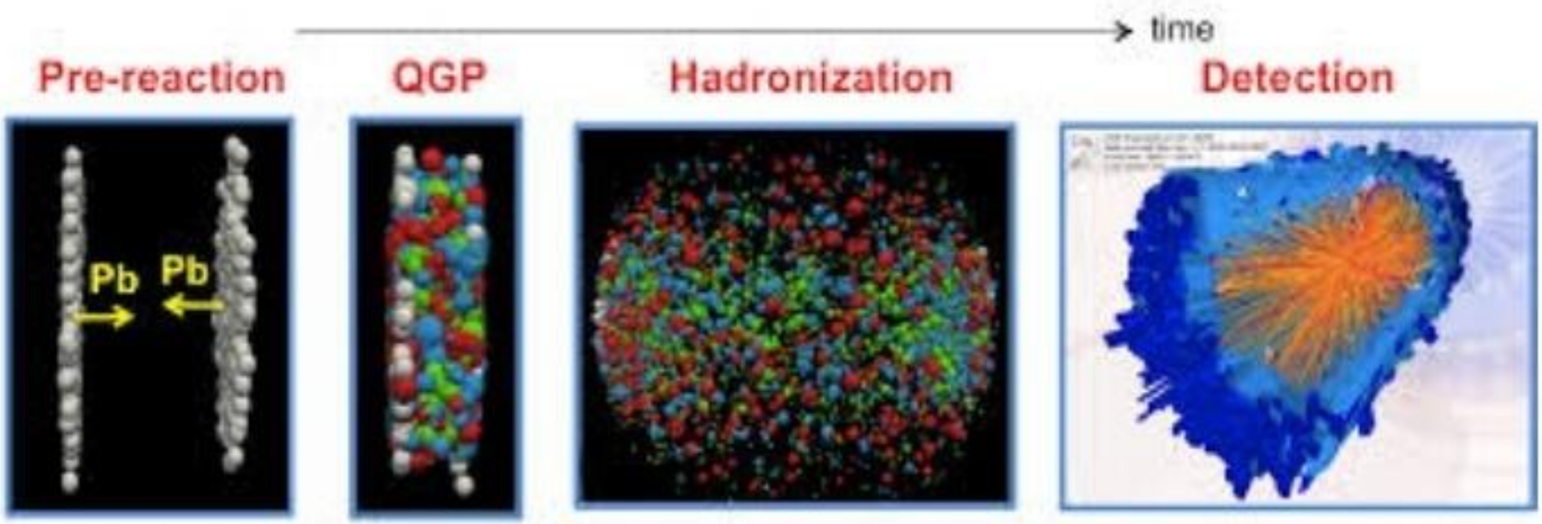
Heavy quark diffusion in the hot QCD matter



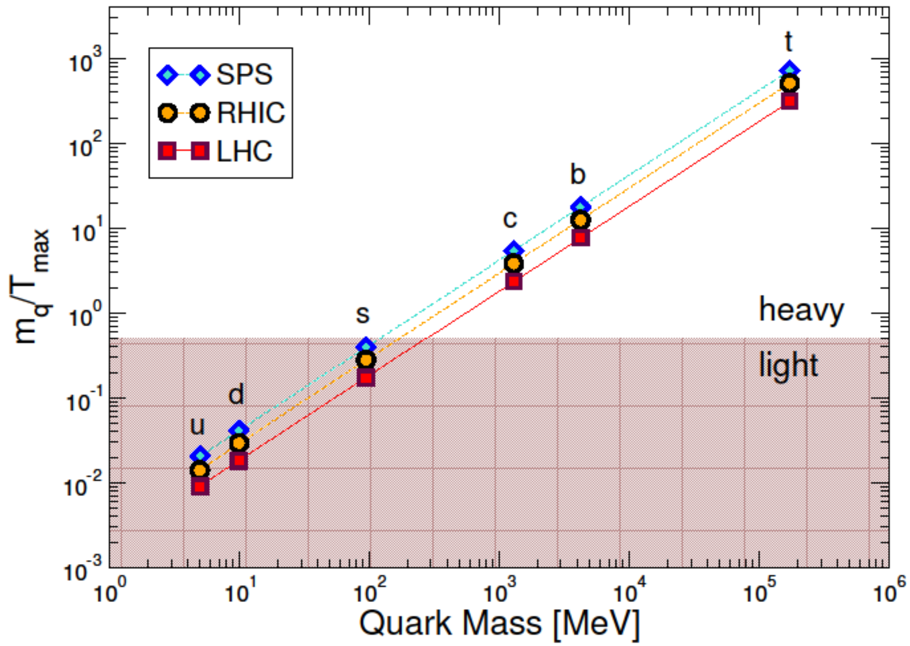
Santosh Kumar Das

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

OUTLINE ....

- Introduction
- Heavy transport coefficients in QGP
- Heavy quark thermalization
- Impact of electromagnetic field
- Impact of pre-equilibrium phase
- Summary and outlook

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)

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

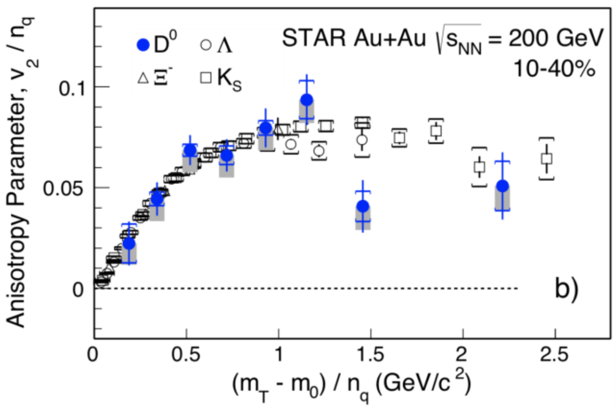
They go through all the QGP life time

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

No thermal production

Heavy quark physics at different scales

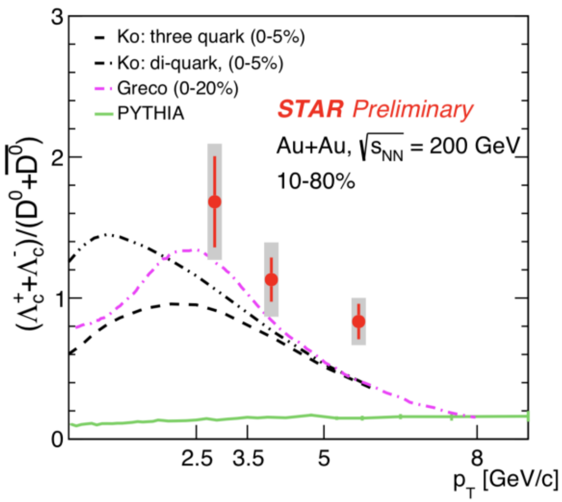
low p_T



Study thermalization process of HQ

Constrain diffusion coefficient D_s

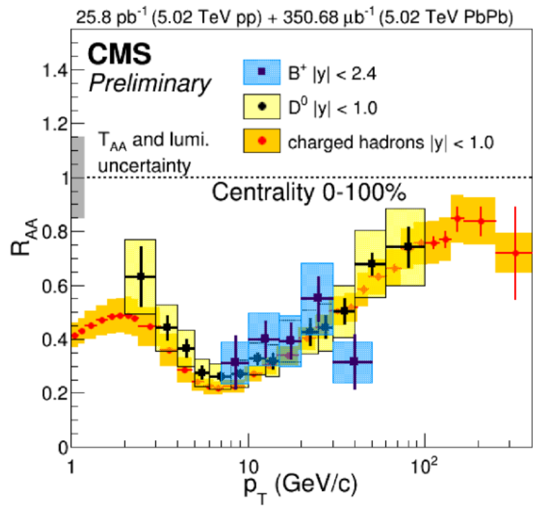
medium p_T



Study hadronization process of HQ

Constrain hadron wave-function

high p_T

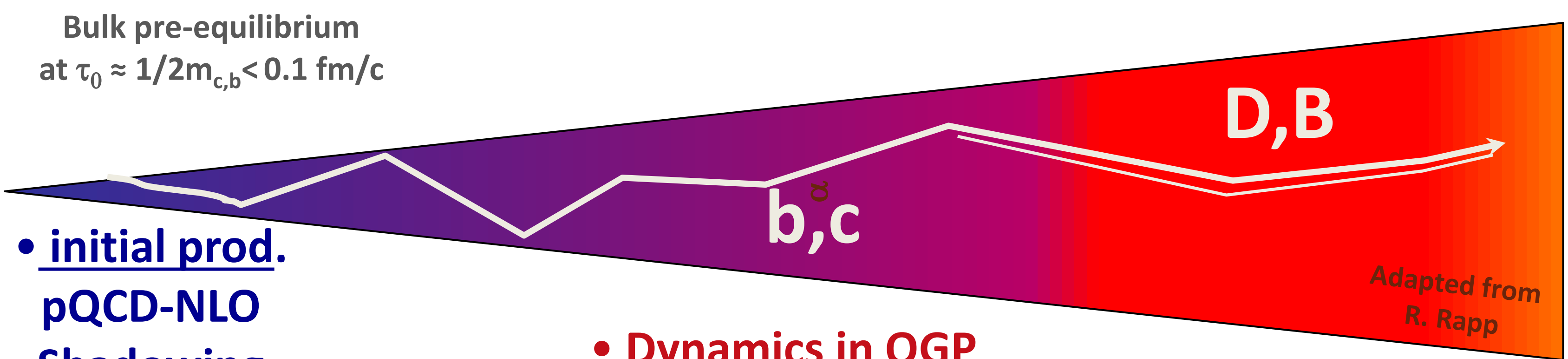


Study parton energy loss and mass effect

Constrain jet transport parameter $\hat{q}$

S. Cao (HP 2018)

Studying the HF dynamics in HIC



- **initial prod.**

pQCD-NLO
Shadowing
Pre-equilibrium Effect/Glasma
Electromagnetic filed

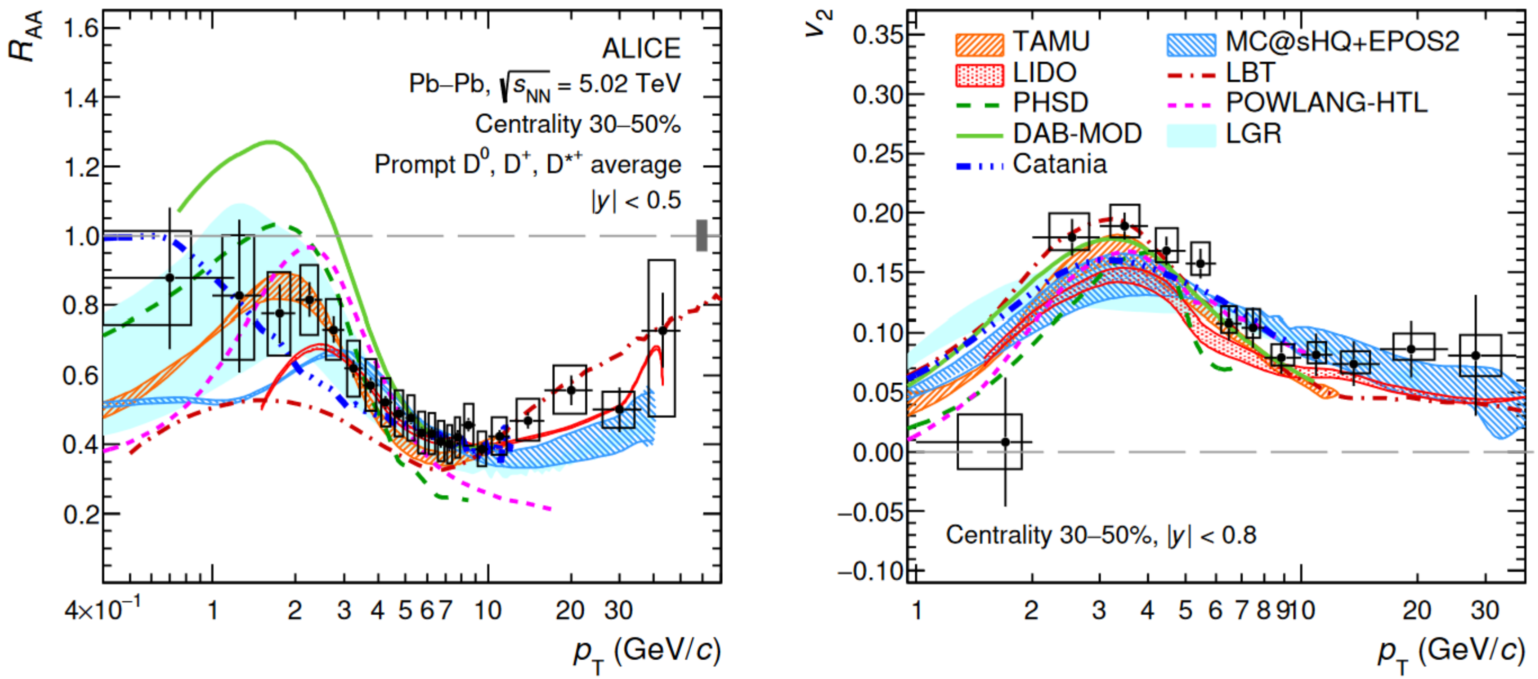
- **Dynamics in QGP**

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

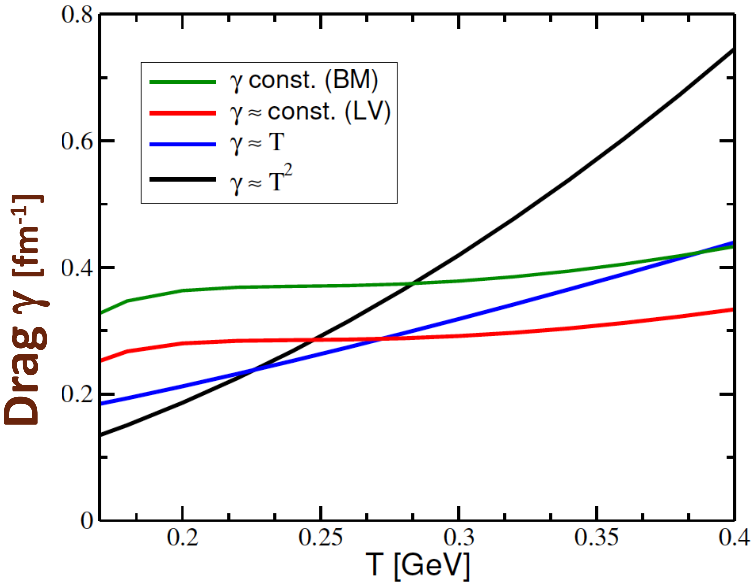


ALICE, JHEP 01 (2022) 174

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 $R_{AA} - v_2$

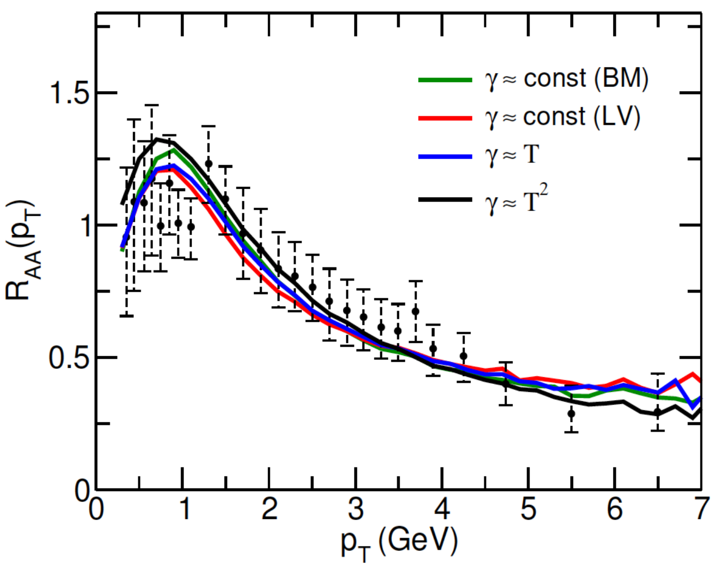


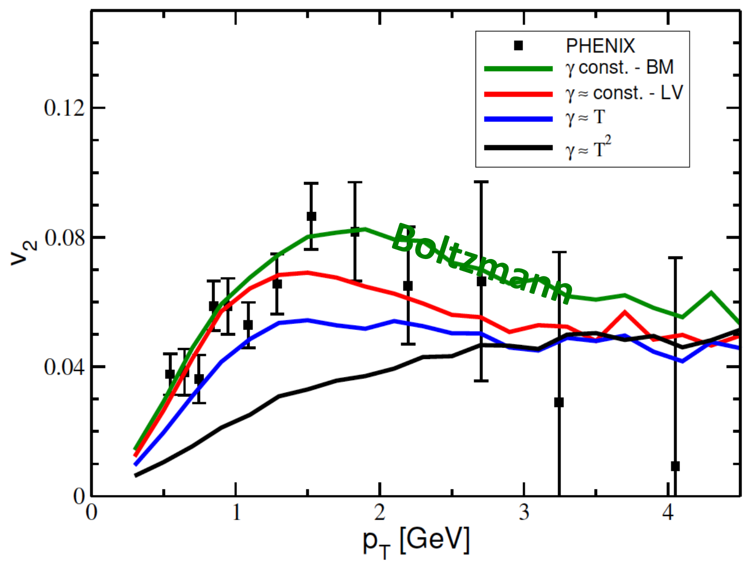
Looking at it beyond the specific modelings

- $\gamma \approx T^2$ [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

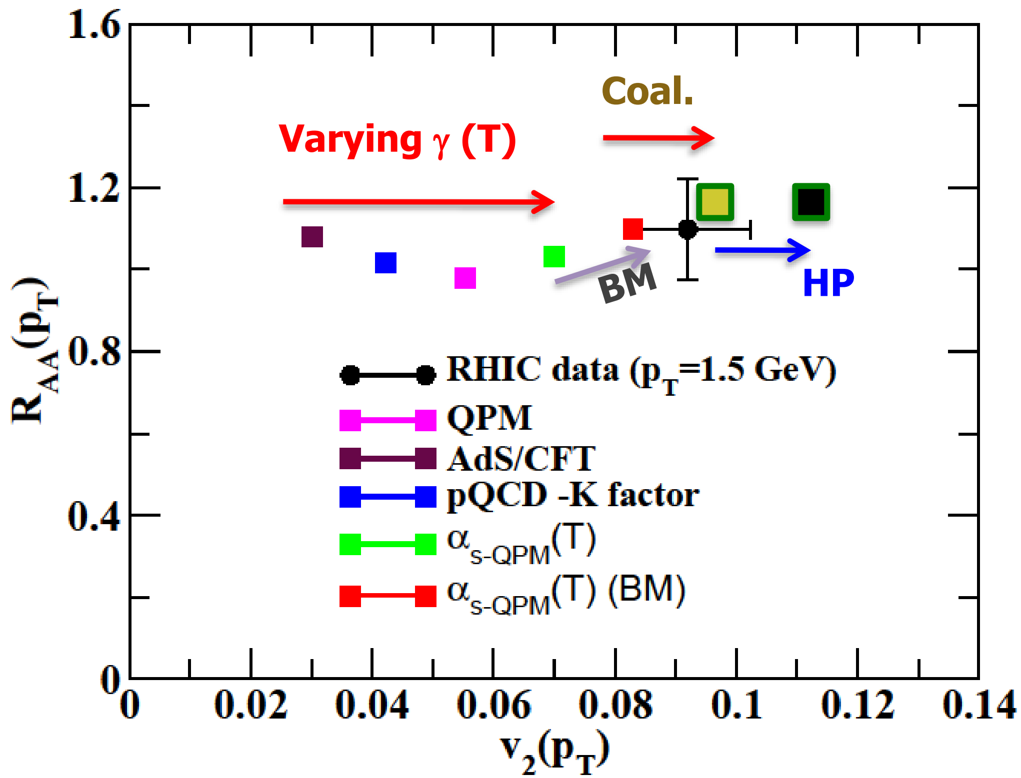
$$\frac{d\mathbf{p}}{dt} = -\gamma \mathbf{p} + \eta(t)$$





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

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

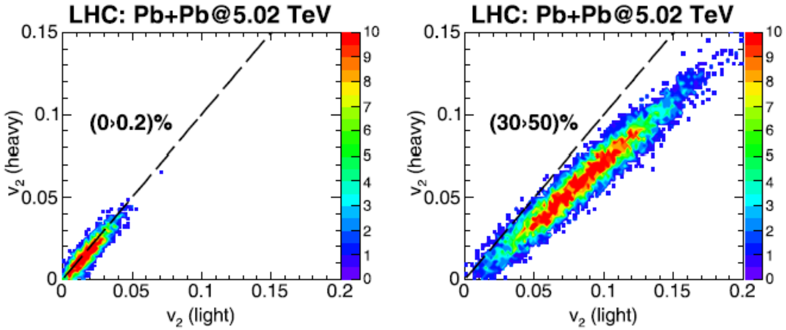


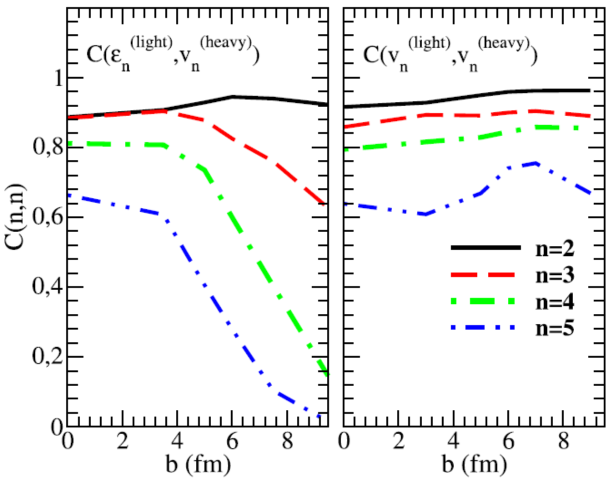
R_{AA} and V_2 are correlated but still one can have
R_{AA} about the same while V_2 can change up to a factor 2-3
γ(T) + Boltzmann dynamics+ hadronization+ hadronic phase

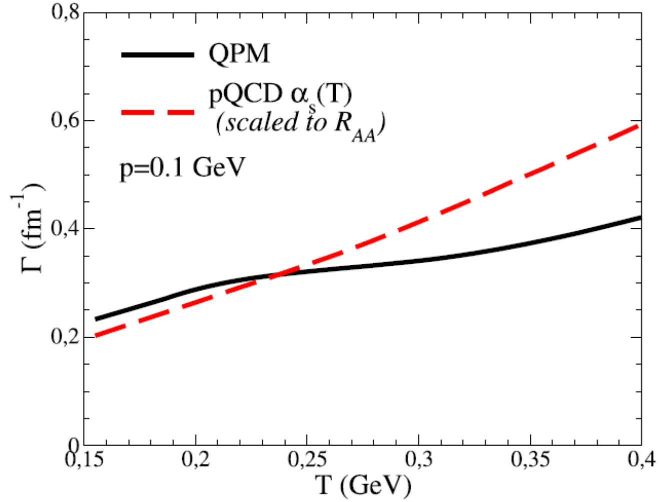
New observables:

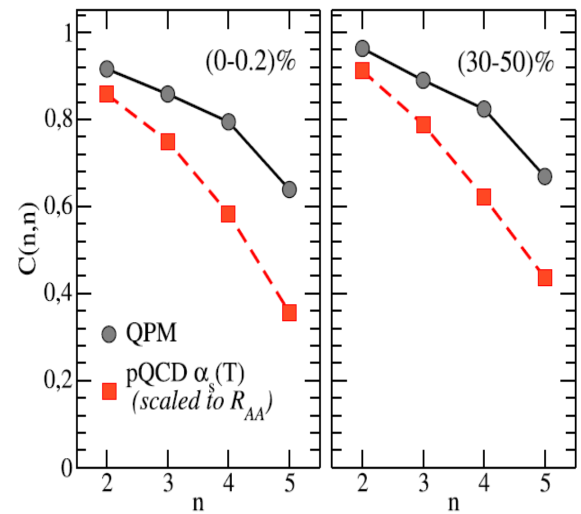
Heavy-light event-by-event correlation

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









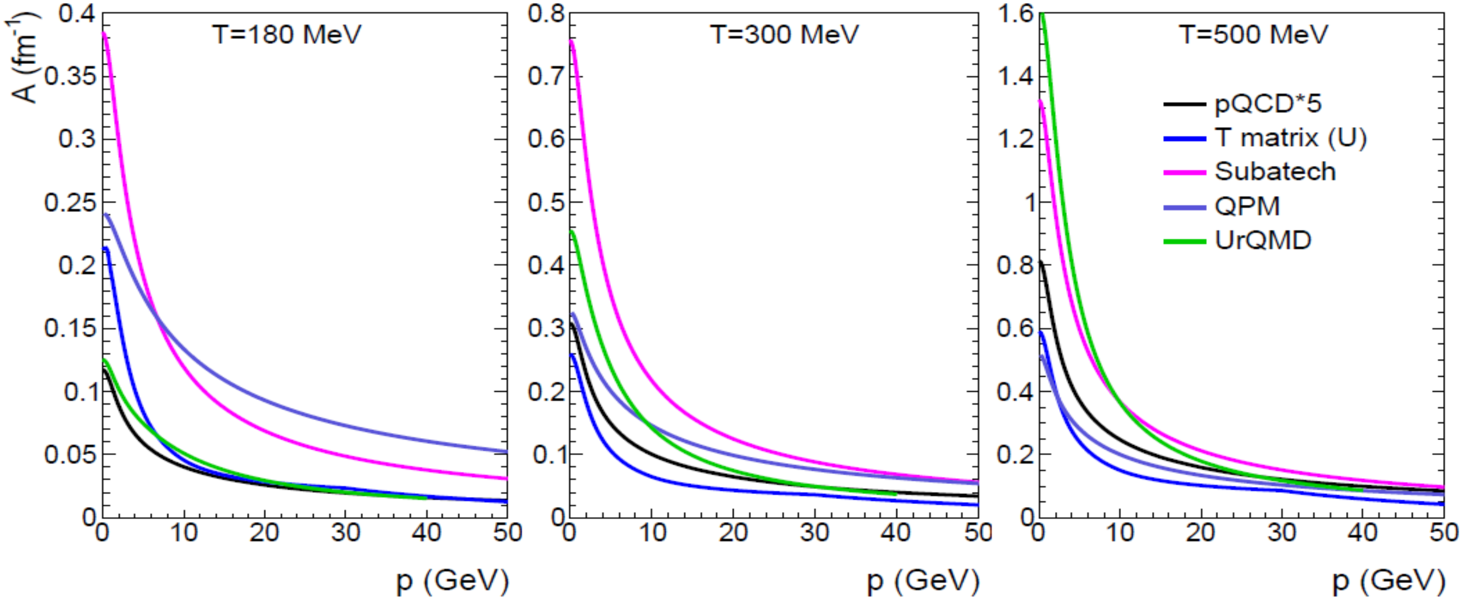
$V_n(D)$ more correlated to $v_n(N_{ch})$ than ε_n

Very large sensitivity to T dep. of Ds

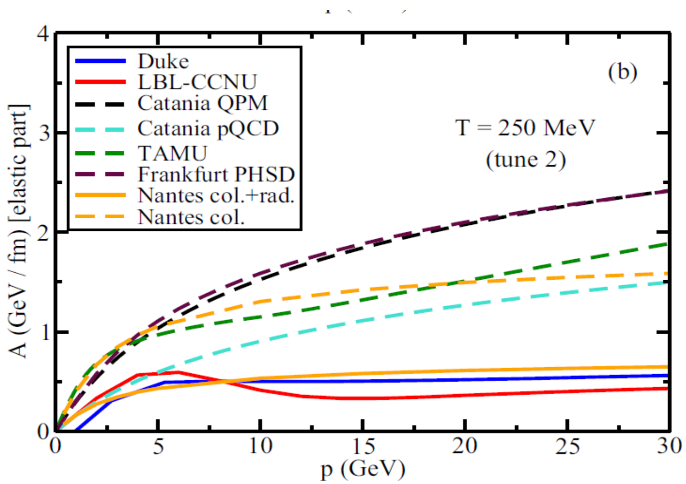
This can put further constrain on heavy quark transport coefficients

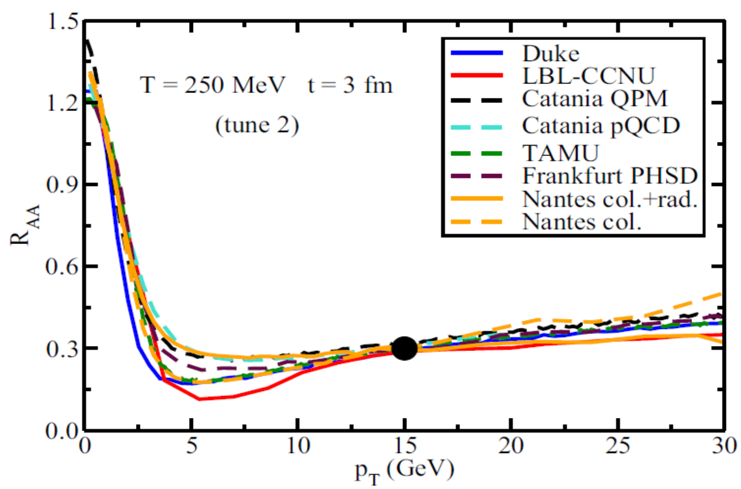
Plumari, Coci, Minissale, Das, Sun, Greco
PLB 805 (2020) 135460

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



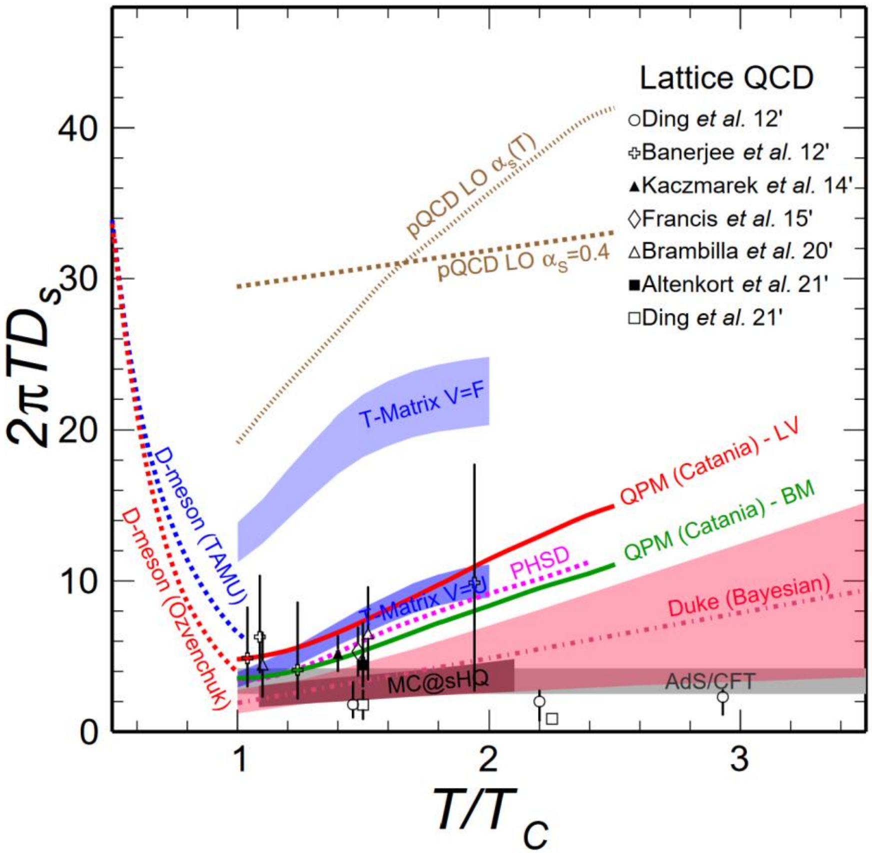
R. Rapp et.al NPA 979 (2018) (EMMI-RRTF)

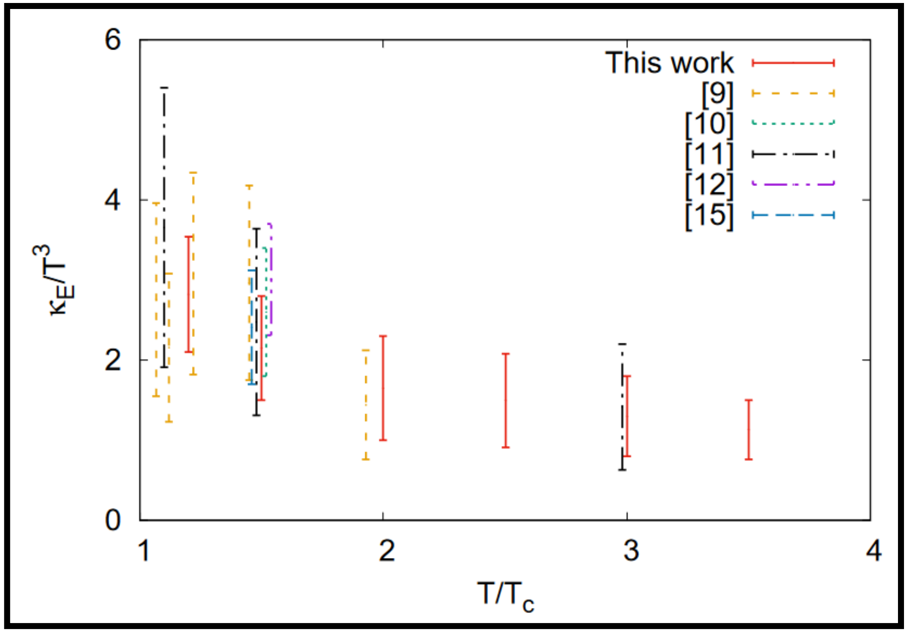




S. Cao et. al PRC 99, 054907 (2019) (JET-HQ)

Heavy quark thermalization





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

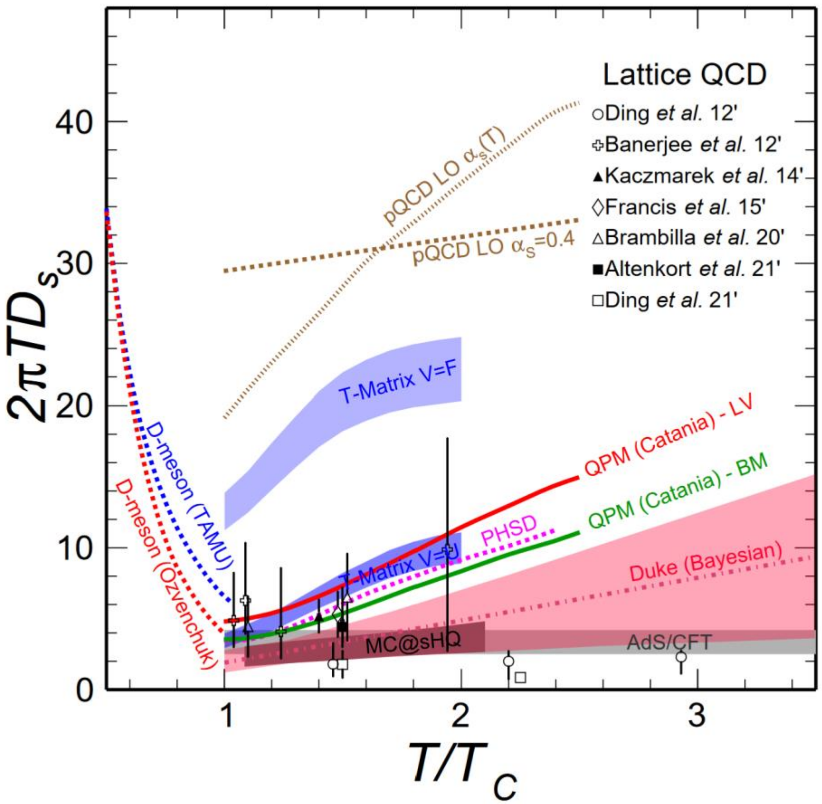
Apolinário et. al., arxiv:2203.16352 [hep-ph]

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

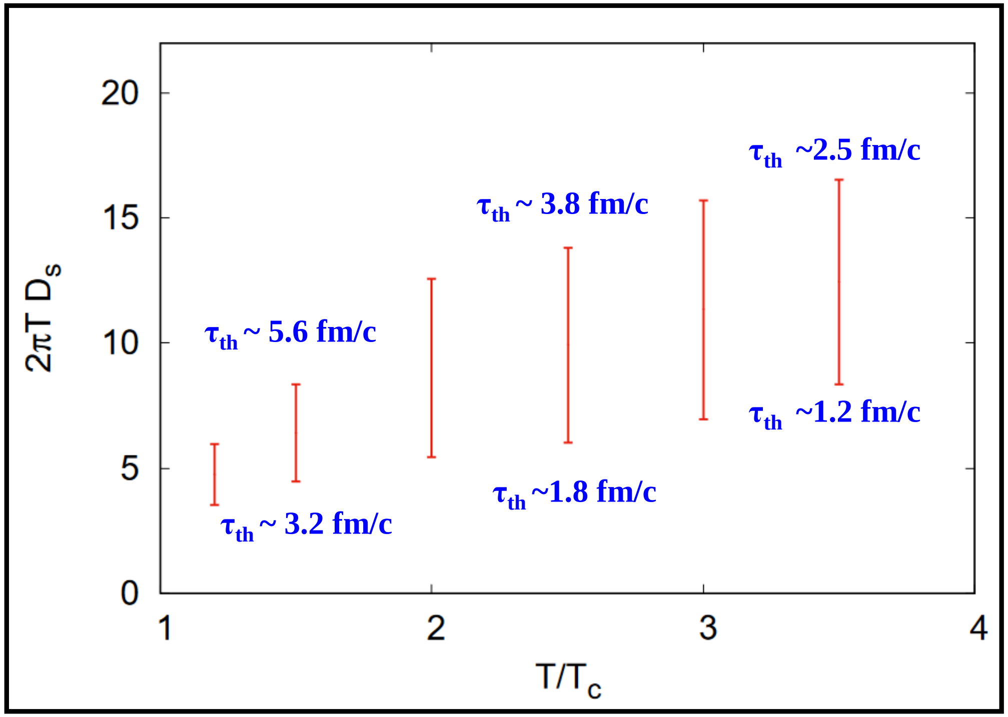
$$D_s = T/M * \gamma(p \to 0)$$

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

Heavy quark thermalization



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



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

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

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

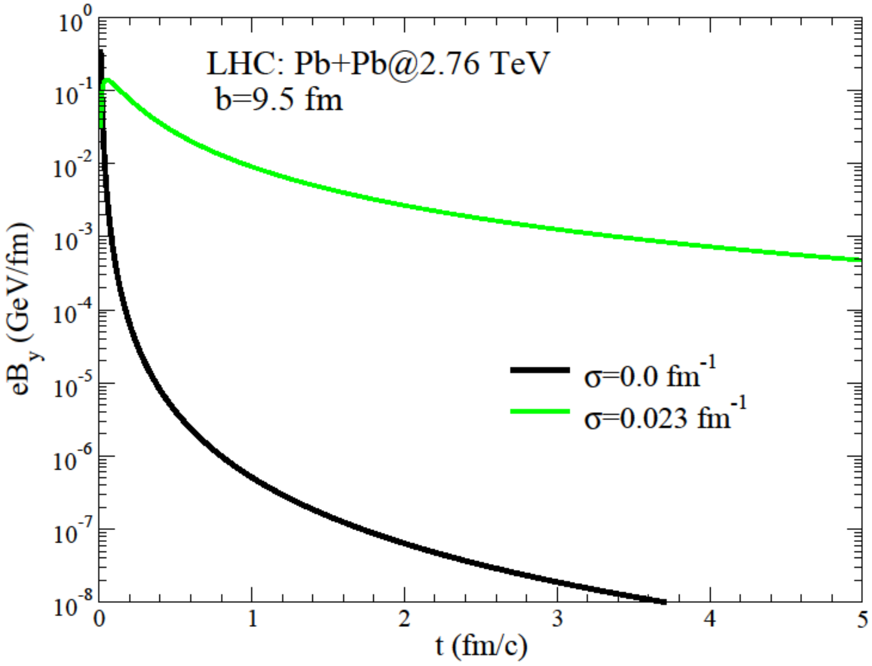
Scardina, Das, Minissale, Plumari, Greco
PRC,96, 044905 (2017)

Impact of EM field on heavy quark dynamics at LHC

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

$$F_{ext} = q(E^{'} + v \times B^{'})$$

$$E' = \gamma\left(E + v \times B\right) - \left(\gamma - 1\right)\left(E \cdot \hat{v}\right)\hat{v}$$
$$B' = \gamma\left(B - v \times E\right) - \left(\gamma - 1\right)\left(B \cdot \hat{v}\right)\hat{v}$$



[Gursoy et al., PRC89 (2014)]

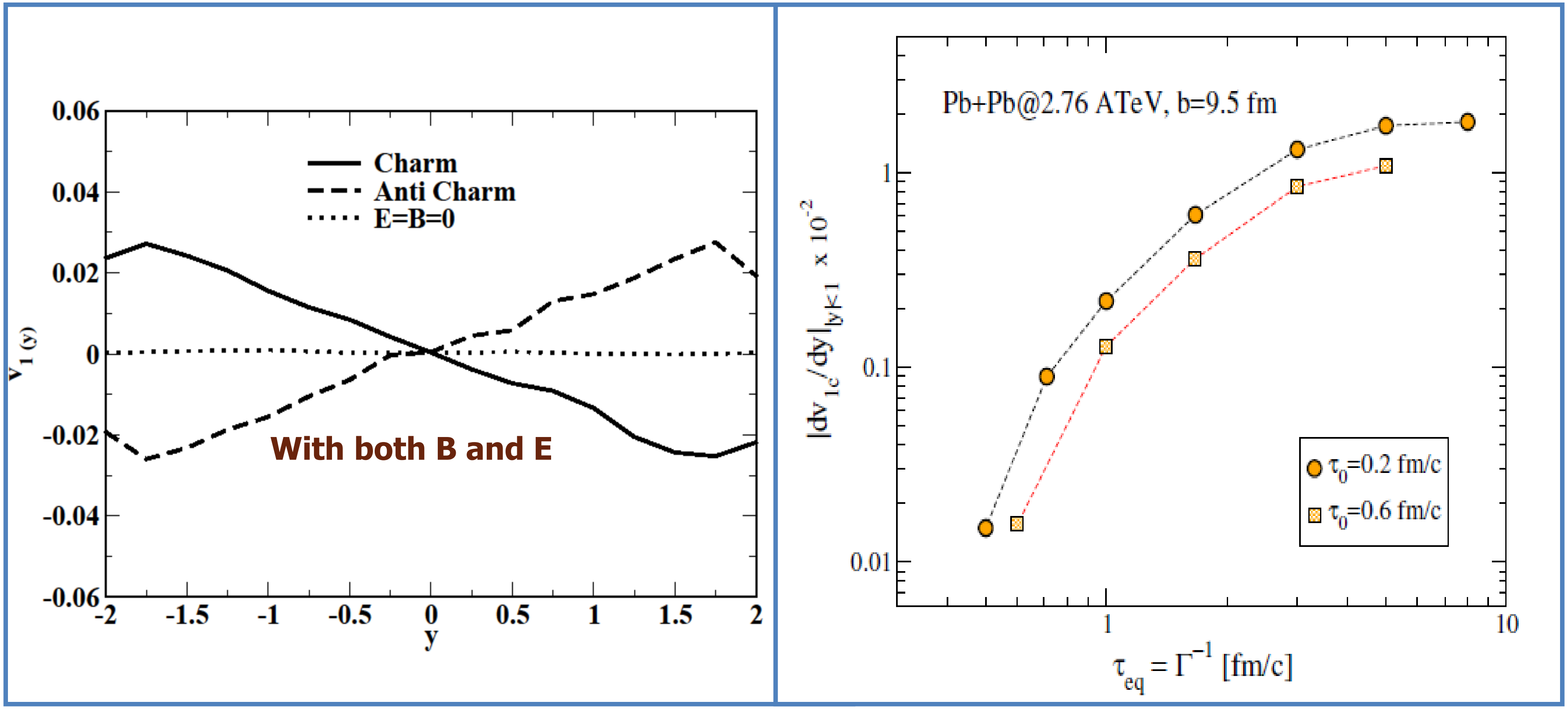
Electromagnetic field has been included in the Langevin equation as a external force.

We consider both E and B.

$$v_1 = < \frac{p_x}{p_T} >$$

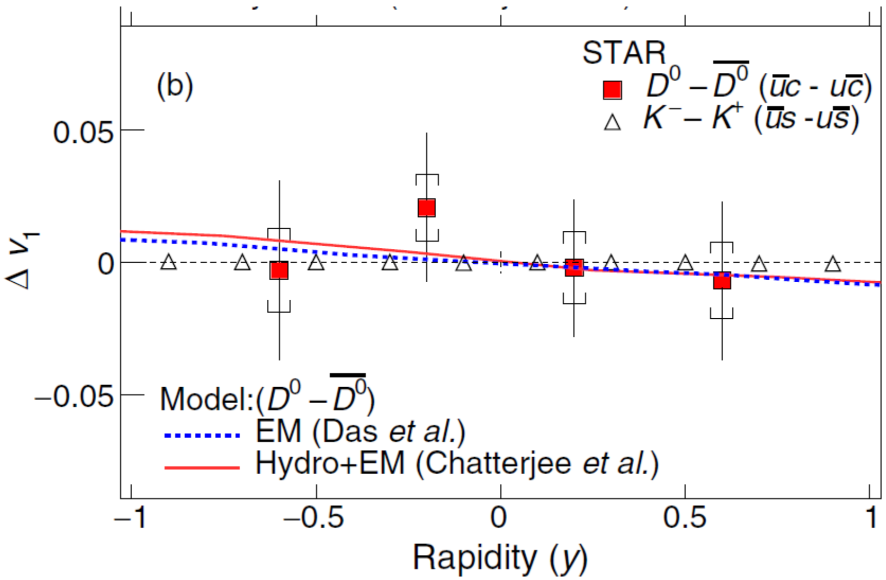
Das, Plumari, Chartarjee, Scardina, Greco, Alam Phys. Lett. B, 768 (2017) 260

Heavy quark v1@LHC

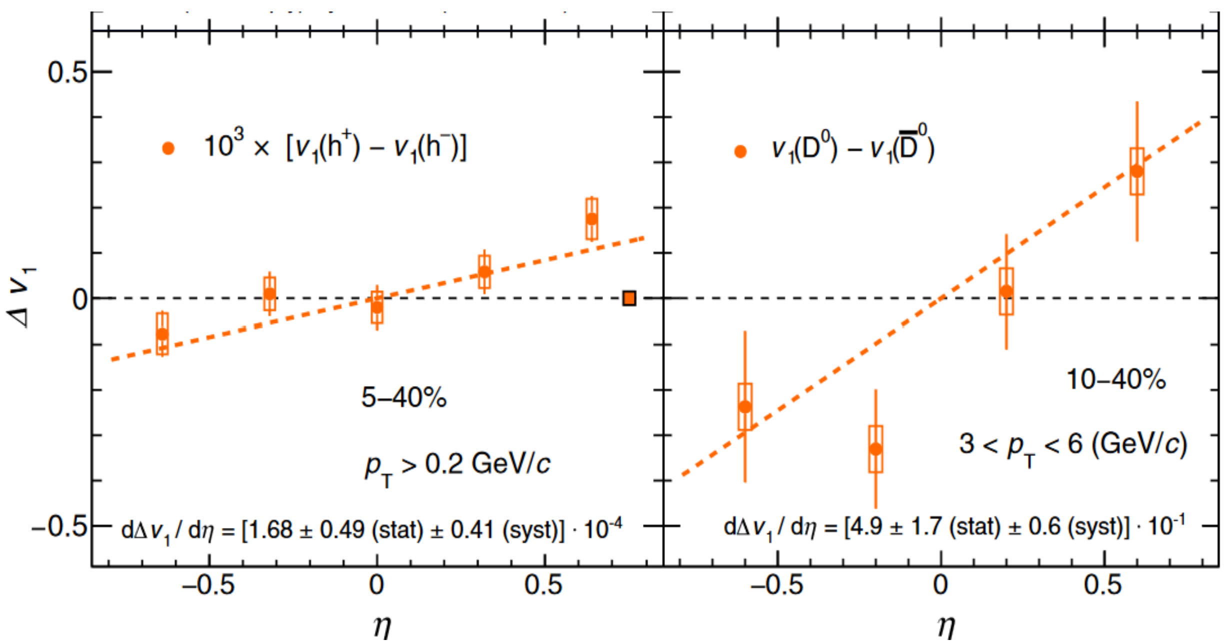


Das, Plumari, Chartarjee, Scardina, Greco, Alam
Phys. Lett. B, 768 (2017) 260

Heavy quark v1@RHIC and LHC



STAR Collaboration
PRL 123, 162301 (2019)

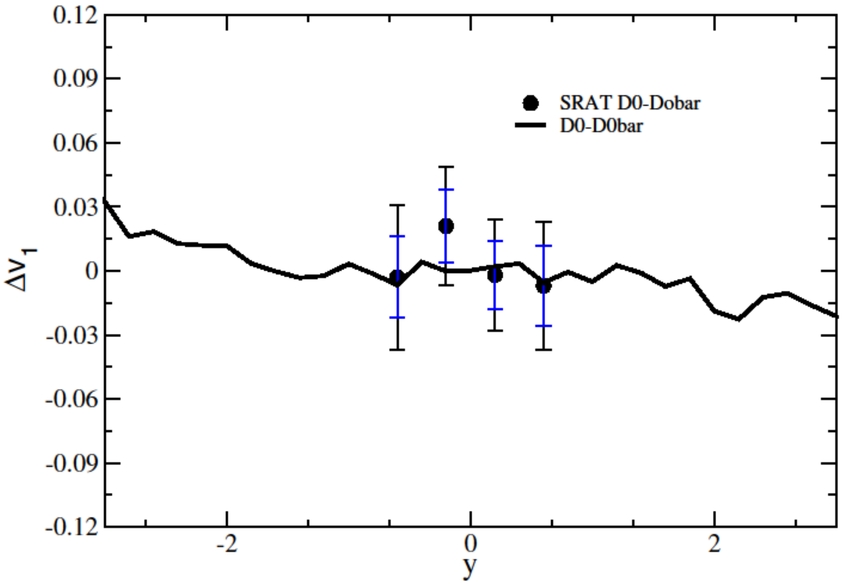


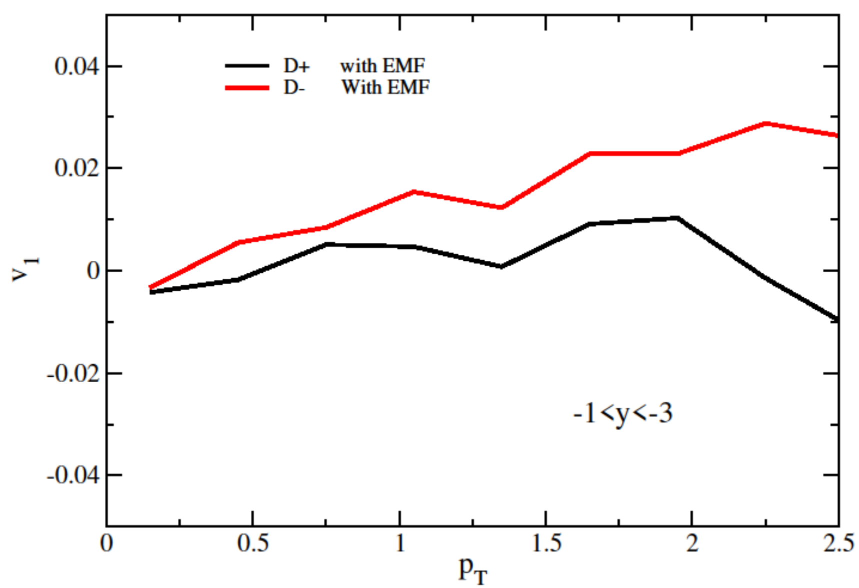
ALICE Collaboration
PRL 125, 022301 (2020)

Heavy quark dynamics in presence of EM field at RHIC within PHSD

$$p^{\mu}\left(\frac{\partial}{\partial x^{\mu}} - F_{\mu\nu}\frac{\partial}{\partial p^{\nu}}\right) f = C[f]$$

Voronyuk, Toneev, Cassing, Bratkovskaya
Konchakovski, Voloshin, PRC, 83, 054911, 2022

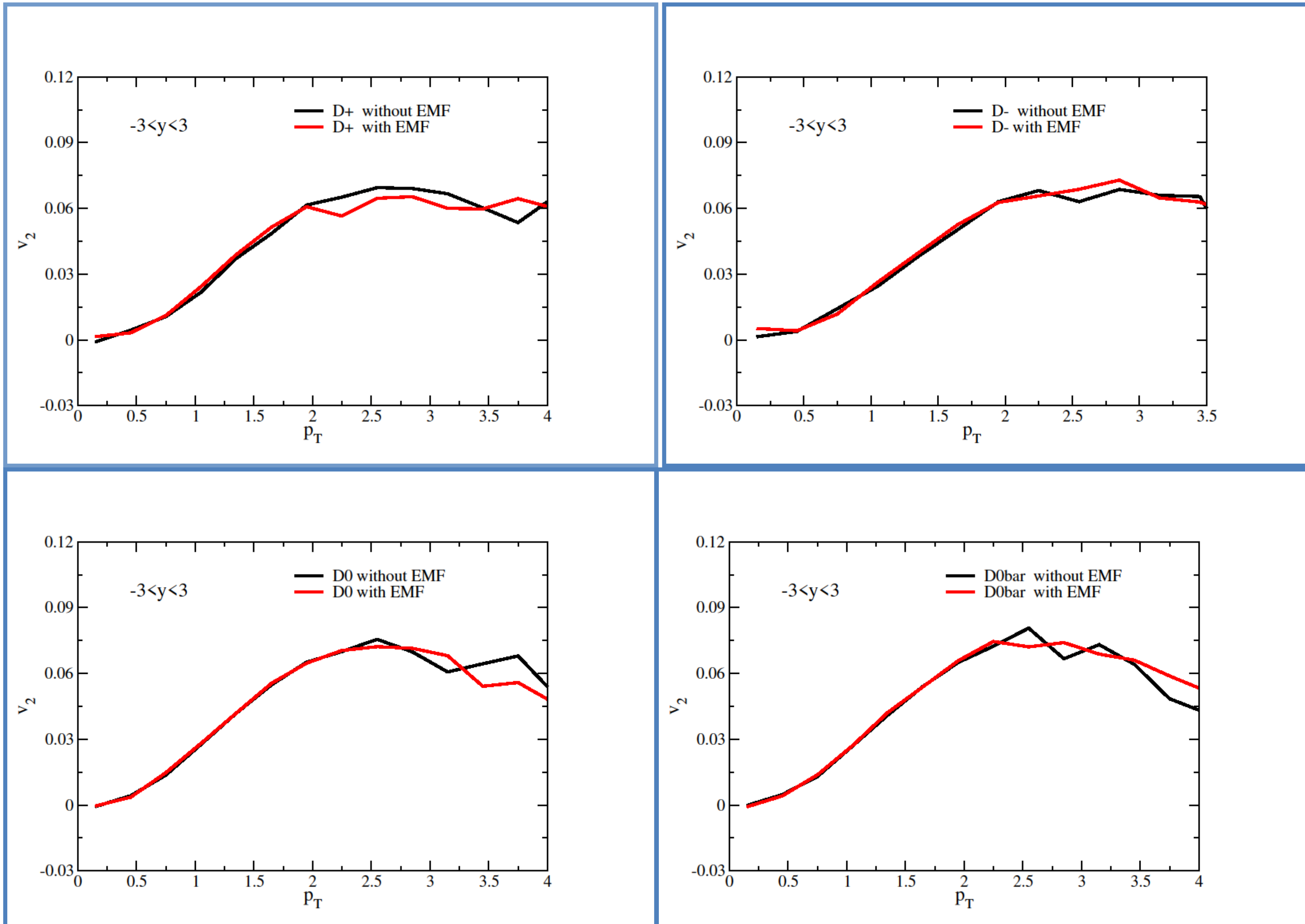




The splitting is larger as a function of momentum

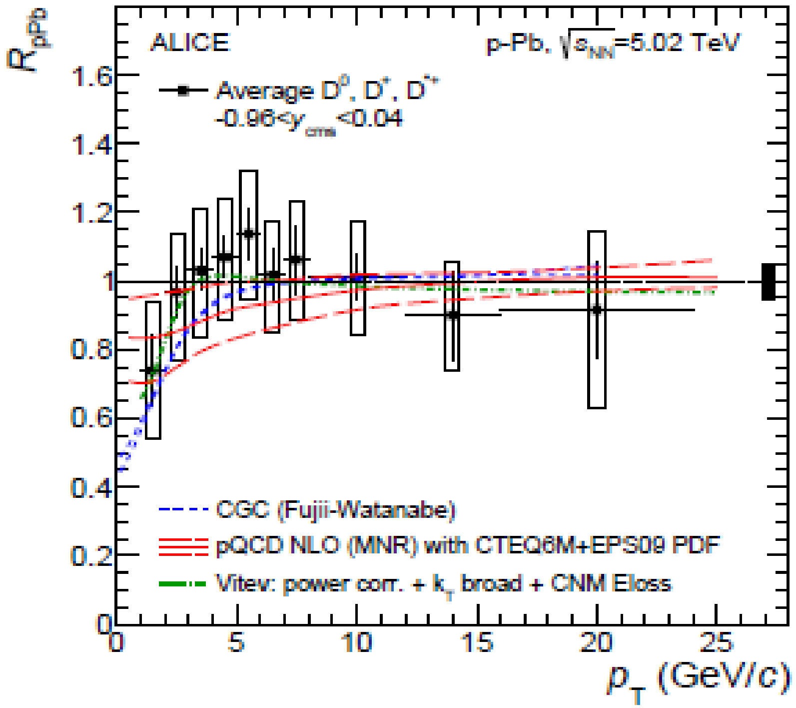
Das, Soloveva, Song, Bratkovskaya
Under preparation

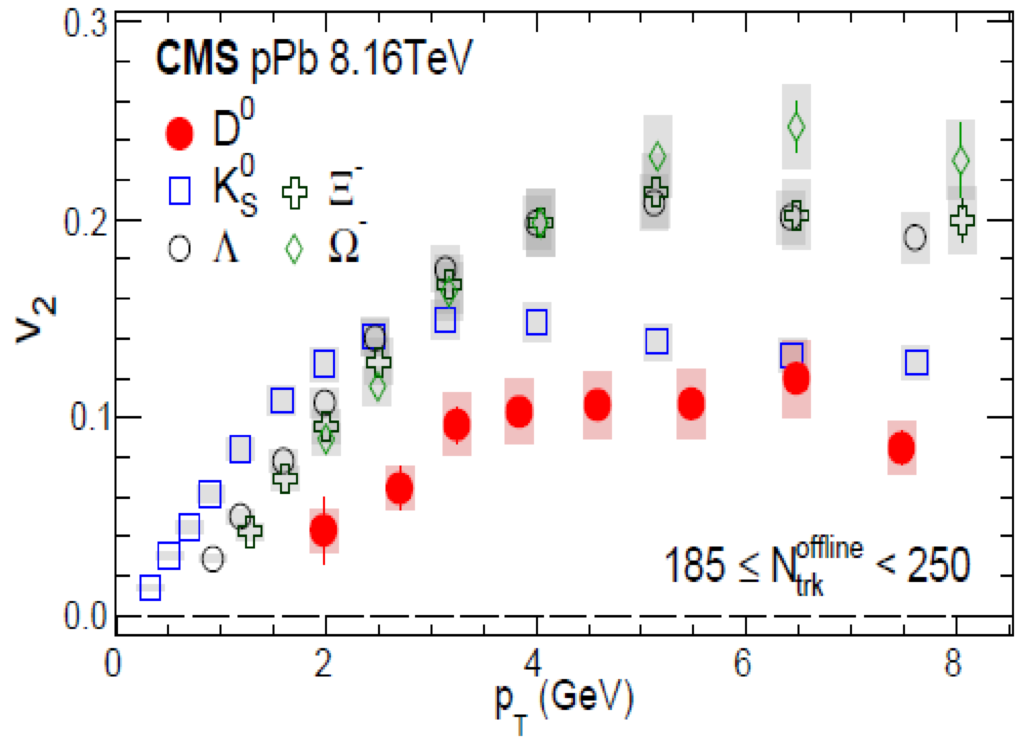
D meson elliptic flow in presence of electromagnetic flow at RHIC



Das, Soloveva, Song, Bratkovskaya
Under preparation

Heavy quark in small system (p-nucleus)



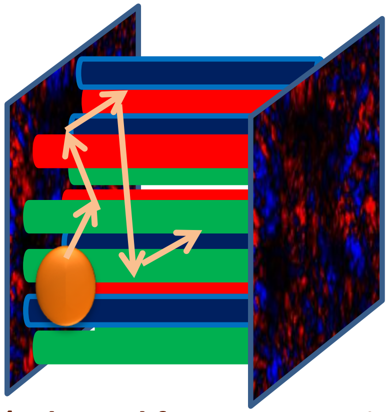


ALICE Collaboration
Phys. Rev. Lett. 113 (2014) 232301

CMS Collaboration
arXiv:1804.09767v2

What mechanism could build up v_2 without energy loss?

Heavy quarks as probes of the evolving Glasma



(Adapted from M. Ruggieri)

$$t_{\text{formation}} \approx \frac{1}{2m_c} \approx 0.06\ \text{fm/c}$$

HQs can probe the very early evolution of the Glasma fields

Hamilton equations of motion of *c*-quarks:

$$\frac{dx_i}{dt} = \frac{p_i}{E} \qquad E = \sqrt{\boldsymbol{p}^2 + m^2}$$

$$\boldsymbol{v} \equiv \frac{\boldsymbol{p}}{E}$$ ***(Relativistic) Velocity***

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

$$\frac{d\boldsymbol{p}}{dt} = q\boldsymbol{E} + q\left(\boldsymbol{v} \times \boldsymbol{B}\right)$$ ***Lorentz force***

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

Wong (1979)

$$D_\mu J^\mu_a = 0$$

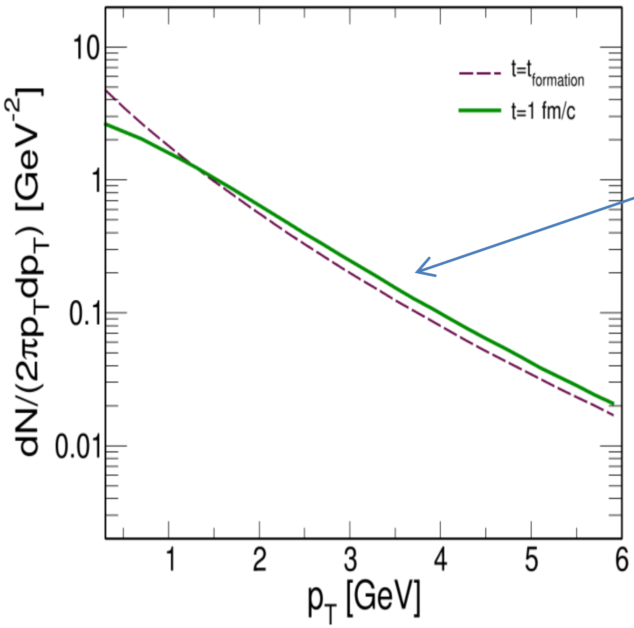
Gauge-invariant conservation of the color Current carried by charm quaks + gluons

$$J^\mu_a = \bar{c}\gamma^\mu T_a c$$

Equations of motion of heavy quarks are solved in the background given by the evolving Glasma fields

p-Pb @ 5.02 TeV

Nuclear modification factor (R_{pPb}) for p-Pb collisions

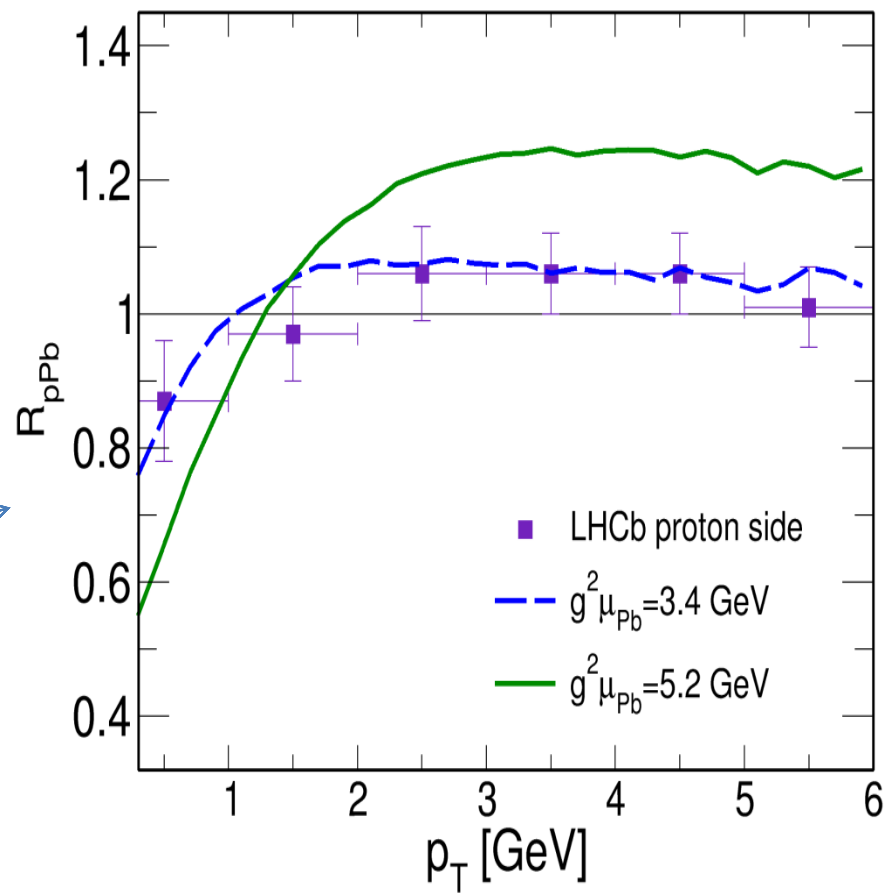


Initial distribution: from perturbative QCD
Evolution: interaction with the Glasma

$$R_{\mathrm{pPb}} = \frac{(dN/d^2p_T)_{\mathrm{final}}}{(dN/d^2p_T)_{\mathrm{pQCD}}}$$

D-mesons R_{pPb}

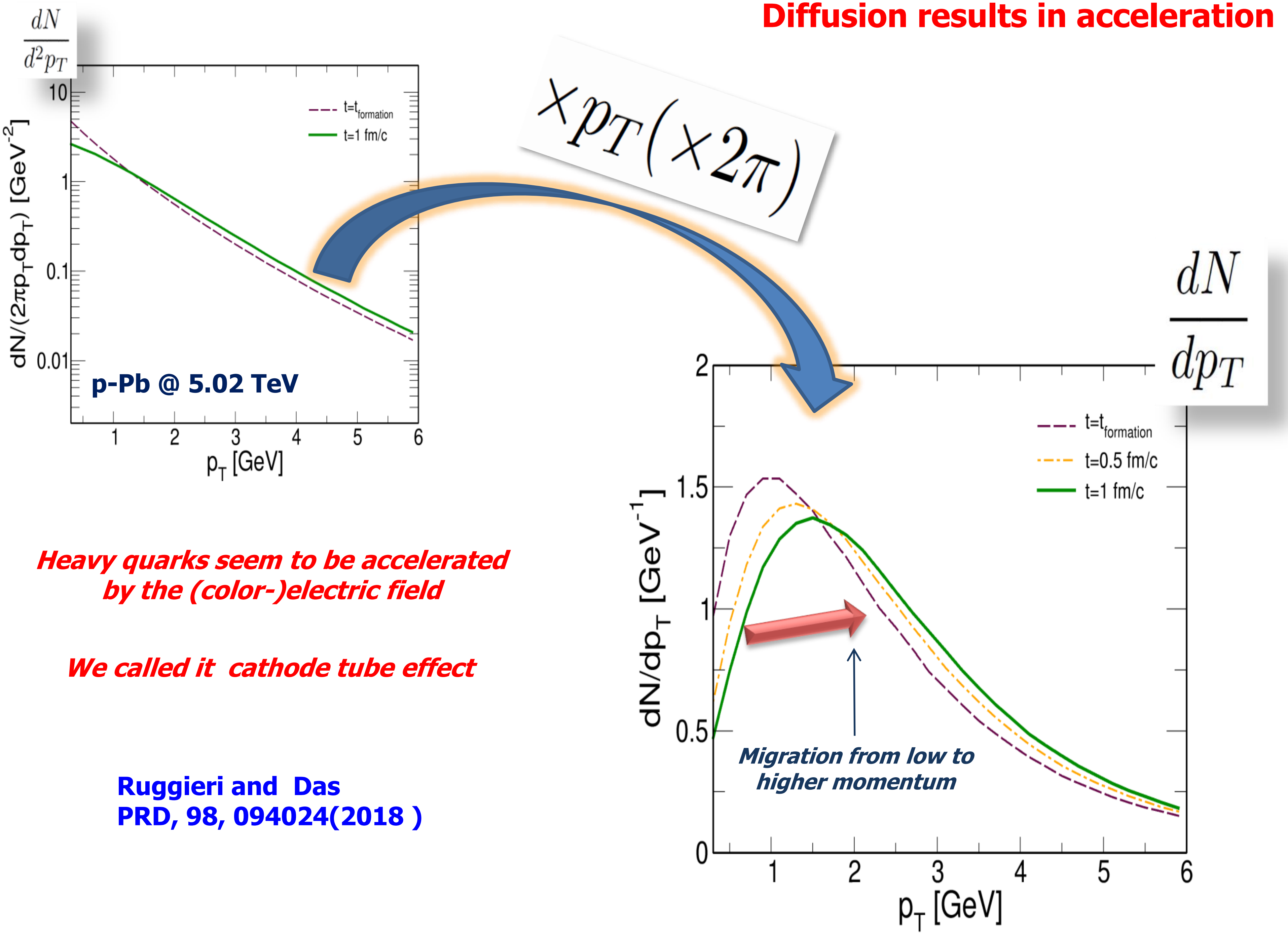
Standard fragmentation **[Peterson *et al.*(1983)]**



$R_{pPb} \neq 1$
Interaction with the fields created by the collision

Ruggieri and Das
PRD, 98, 094024(2018)

Diffusion results in acceleration



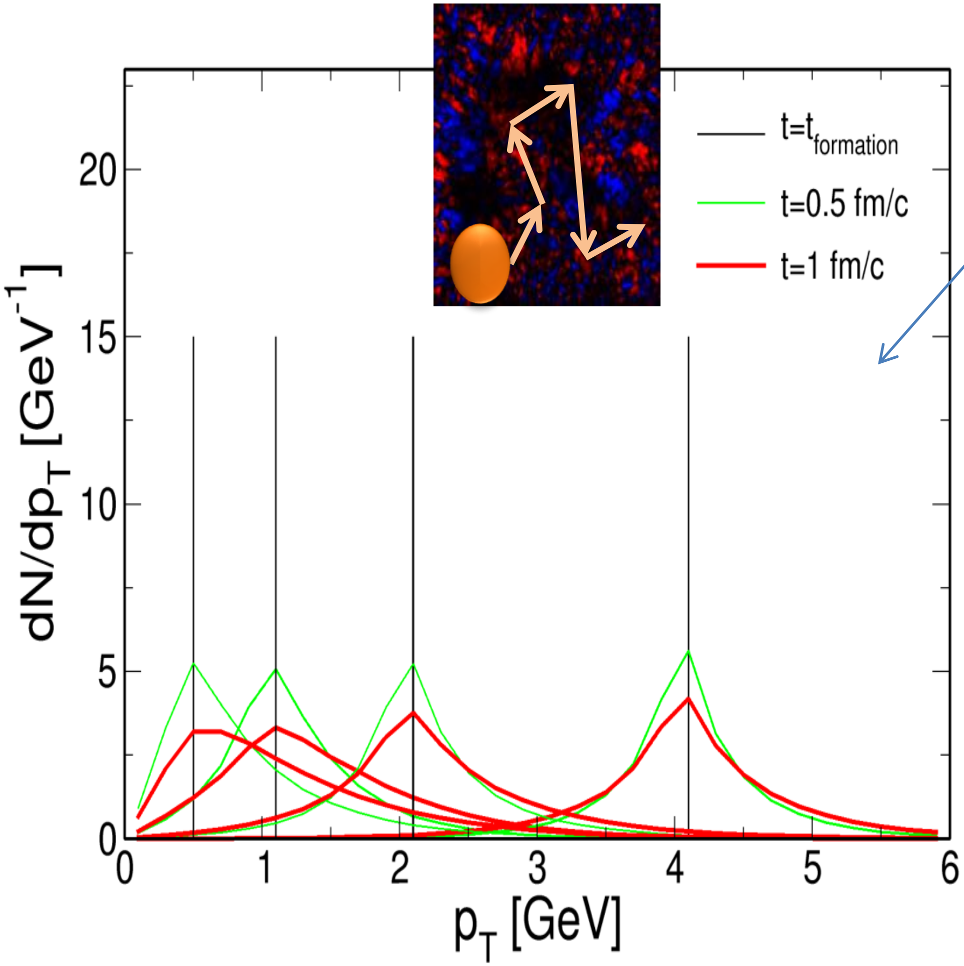
Heavy quarks seem to be accelerated by the (color-)electric field

We called it cathode tube effect

Ruggieri and Das
PRD, 98, 094024(2018)

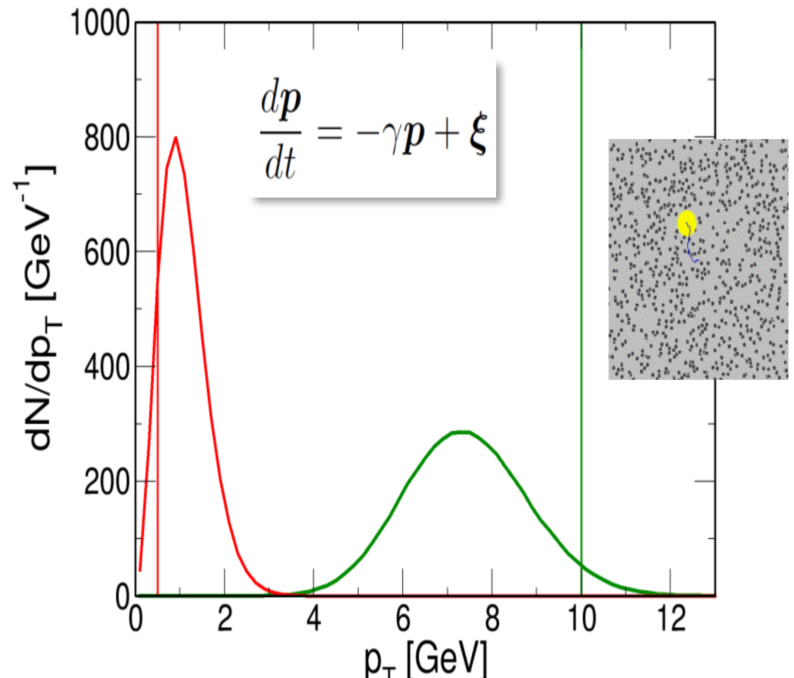
Heavy quarks diffusion: Plasma vs Glasma

HQs in Glasma



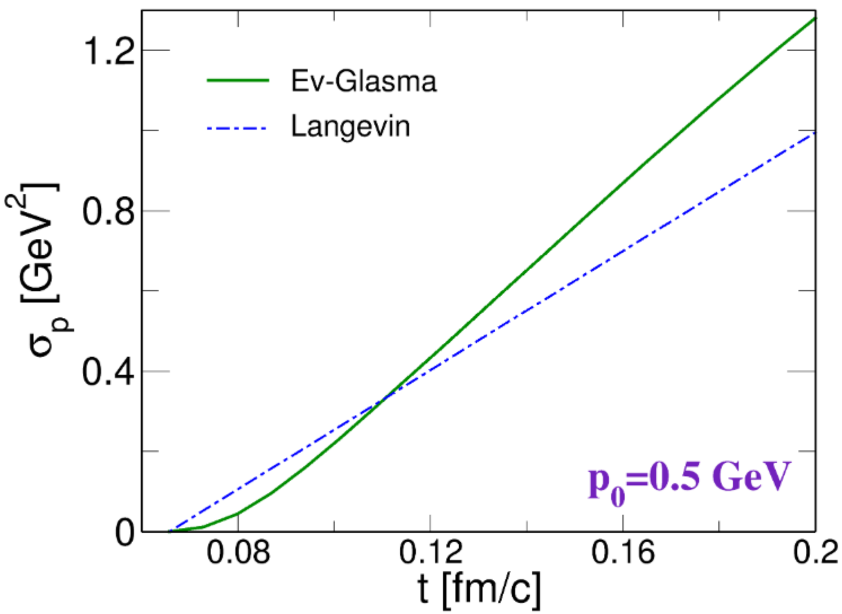
Diffusion in momentum space

T=500 MeV ***HQs in hot plasma***



Ruggieri and Das
PRD, 98, 094024(2018)

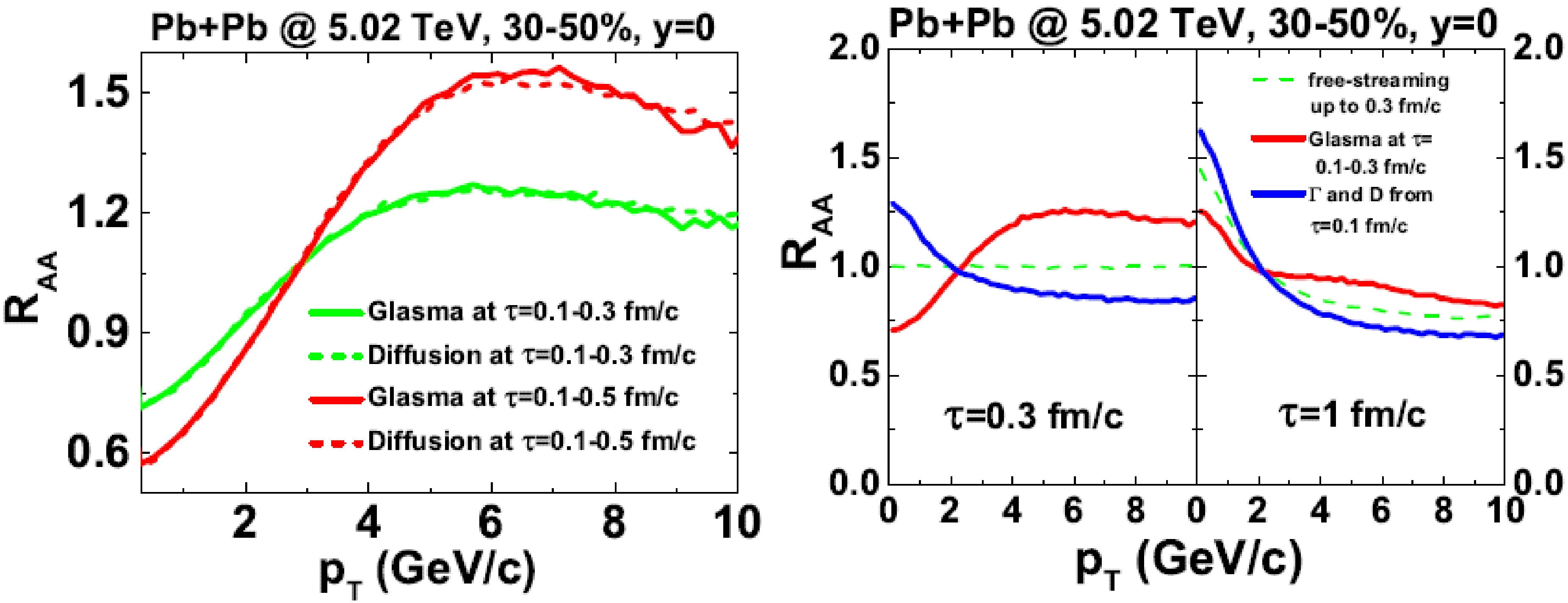
Impact of memory on heavy quark thermalization



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

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

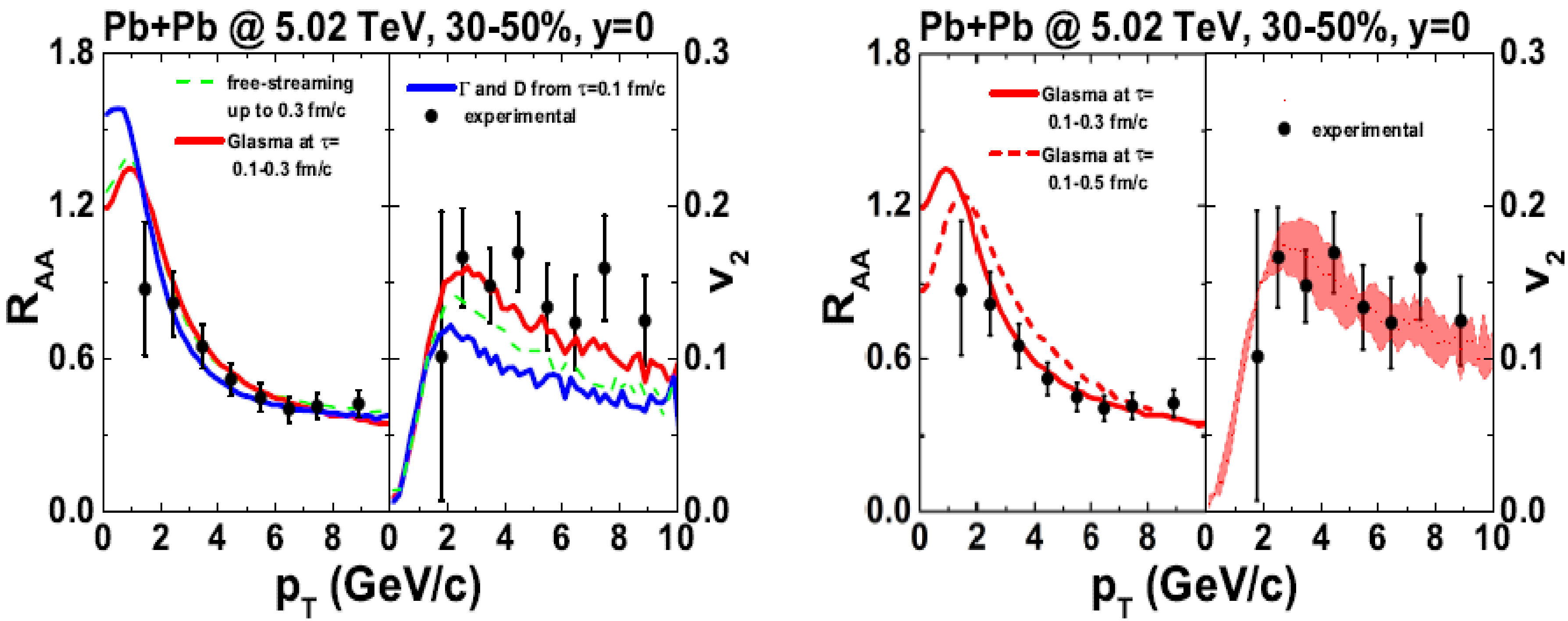
Impact of Glasma on a heavy quark observables at LHC
(Glasma vs Plasma)



Glasma induce a diffusion of charm quarks in momentum space resulting in a tilt of their spectrum without a significant drag.

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

Impact of Glasma on a heavy quark observables at LHC
(Heavy quark dynamics in Glasma plus Plasma)



This indicates an initial pre-thermal stage is unlikely to be described in terms of a standard drag and diffusion dynamics, because even if one tune such coefficients to reproduce the same $R_{AA}(p_T)$ this would imply a significantly smaller v_2.

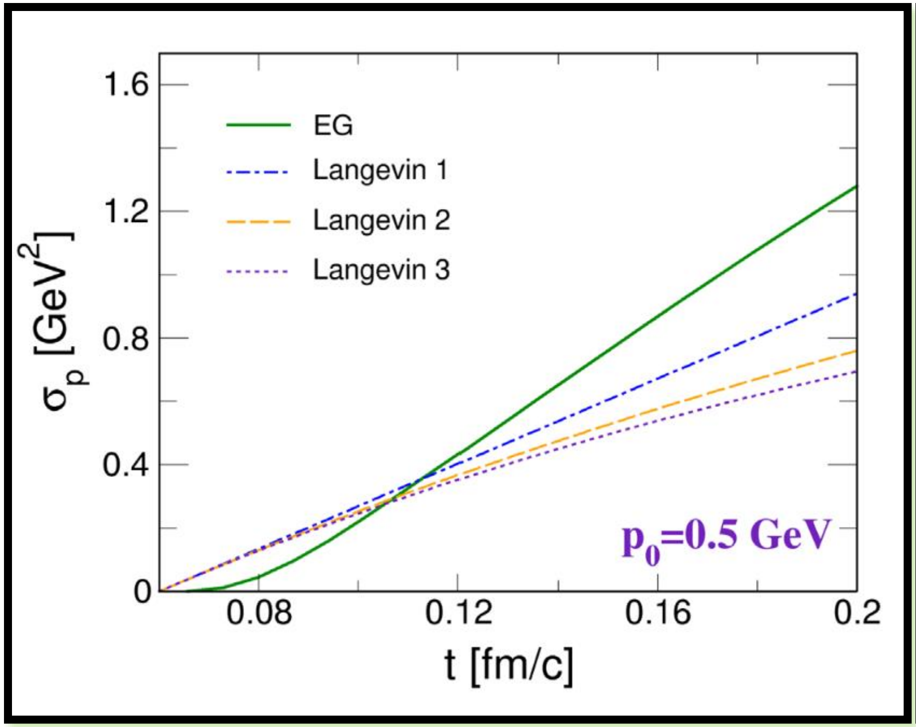
Sun, Coci, Das, Plumari, Ruggieri, Greco
PLB, 798 (2019) 134933

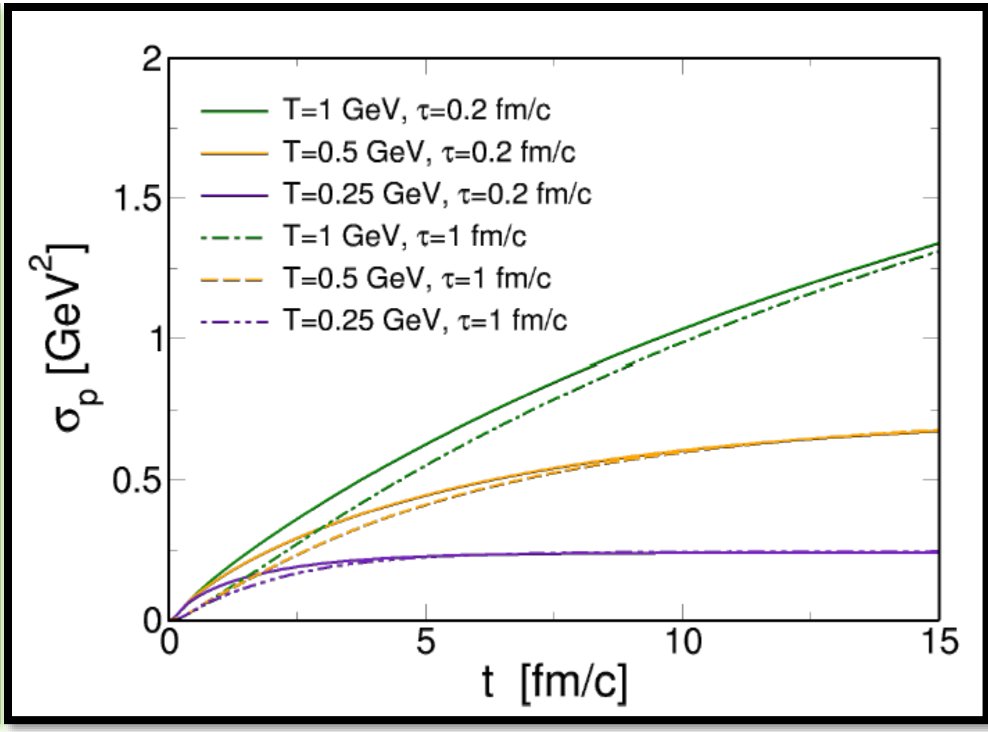
Conclusions and Perspectives:

- Present calculations indicate $\tau_{th} \sim$ 2-6 fm/c for low p_T charm quark.
- Heavy-light event-by-event correlation can further constrain the heavy quark transport coefficients
- Heavy quark directed flow as a function of pT is sensitive to EMF
- Impact of EMF on heavy quark elliptic flow is negligible
- Heavy quark diffusion in pre-equilibrium phase is crucial.


Thank You . . . . .

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]