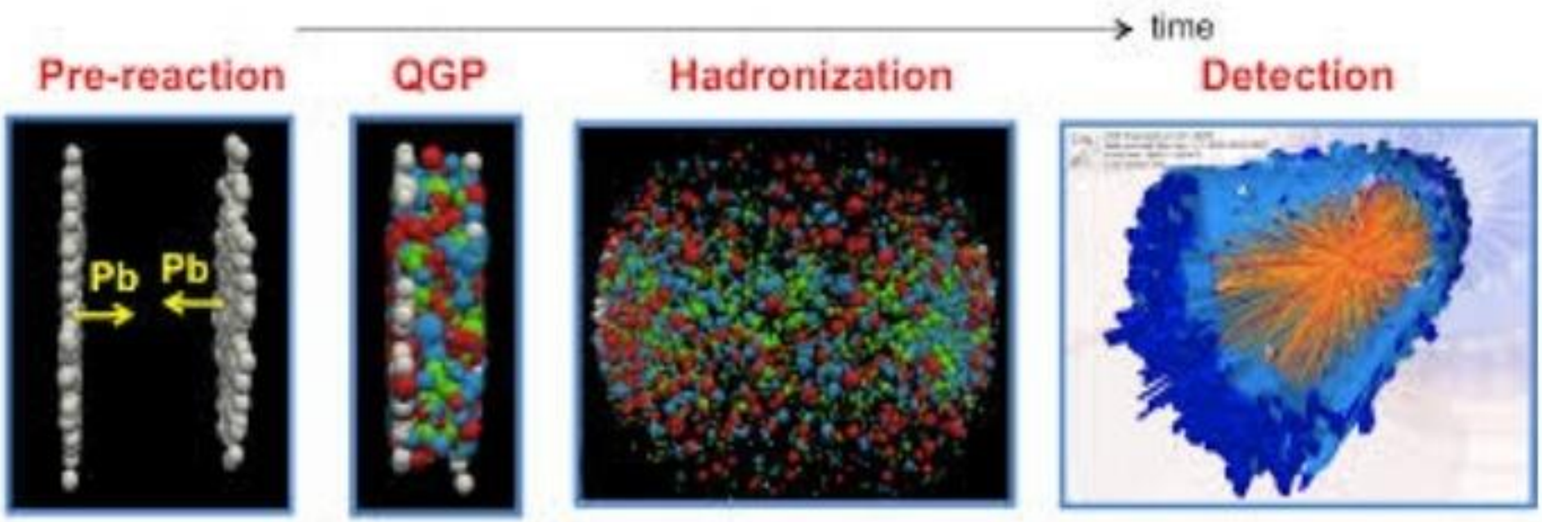
Impact of Memory on Heavy Quark Diffusion in Hot QCD Matter



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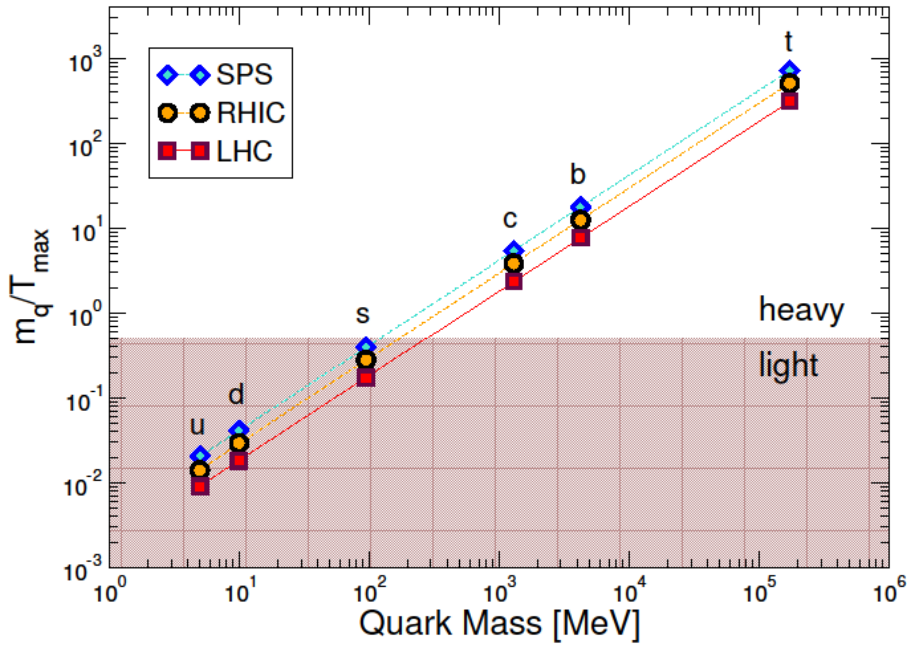
India-JINR workshop on elementary particle and nuclear physics, and condensed matter research

OUTLINE ....

- Introduction
- Heavy quark diffusion in QGP
- Exponential and Power-law Memory
- Thermalization & Diffusion with memory
- 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**

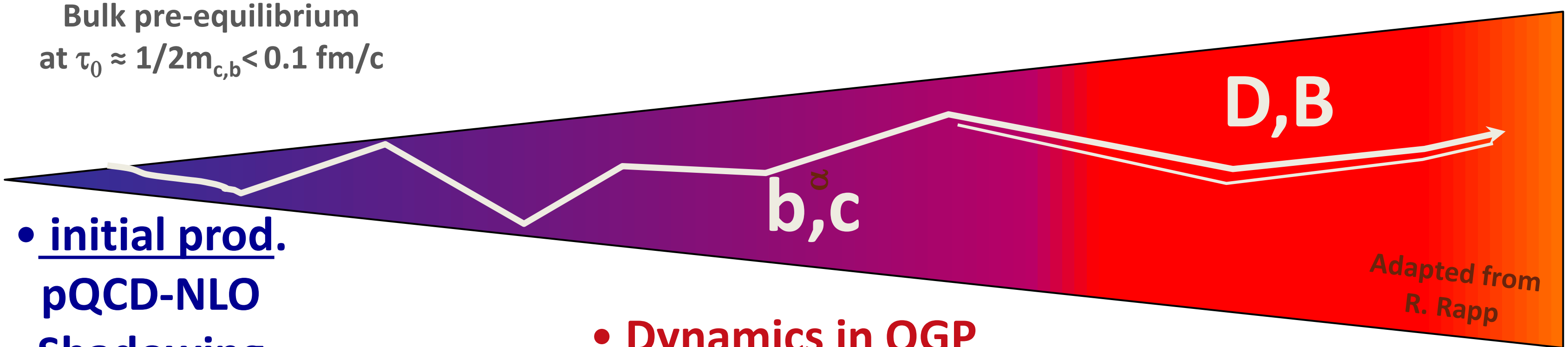
$M_{c,b} >> \Lambda_{QCD}$ **Produced by pQCD process (before equilibrium) (Early production)**

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

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

Studying the HF dynamics in HIC

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

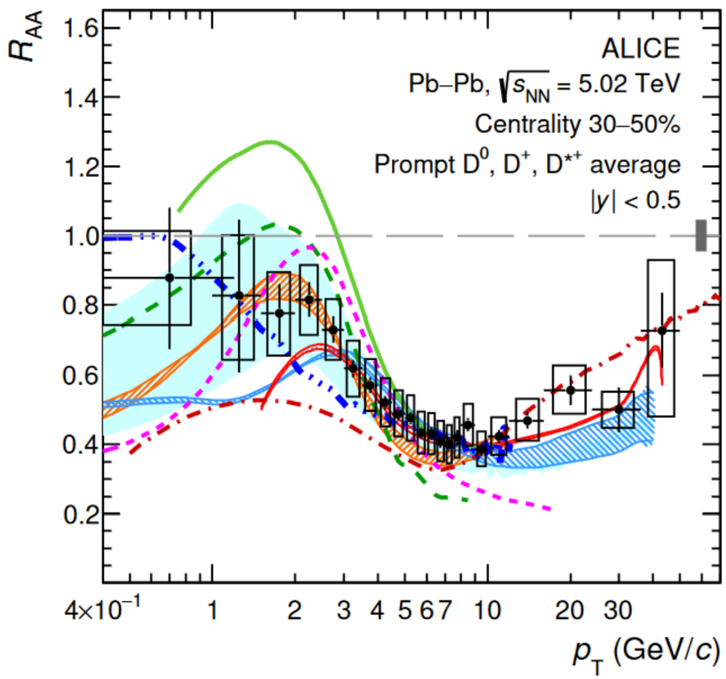


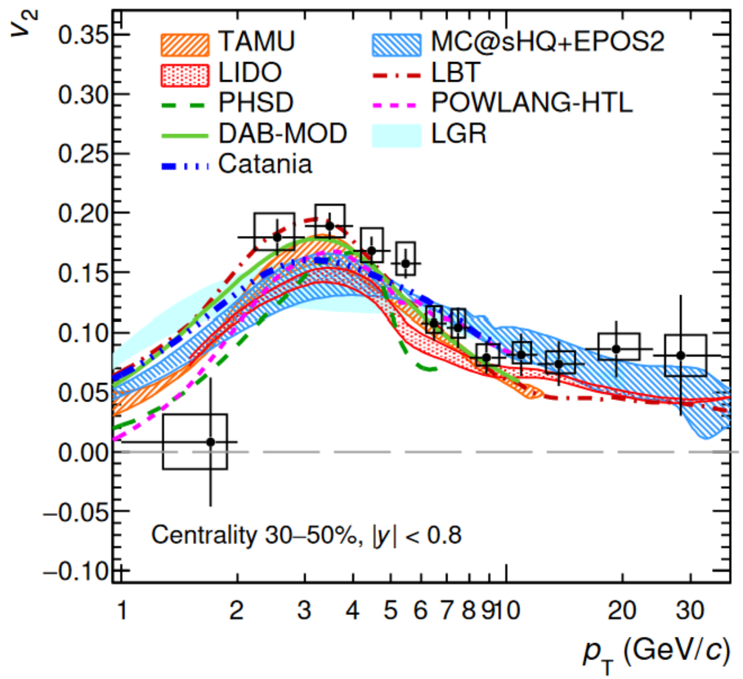
• **initial prod.**
pQCD-NLO
Shadowing
Pre-equilibrium
Effect/Glasma
Electromagnetic
filed

• **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



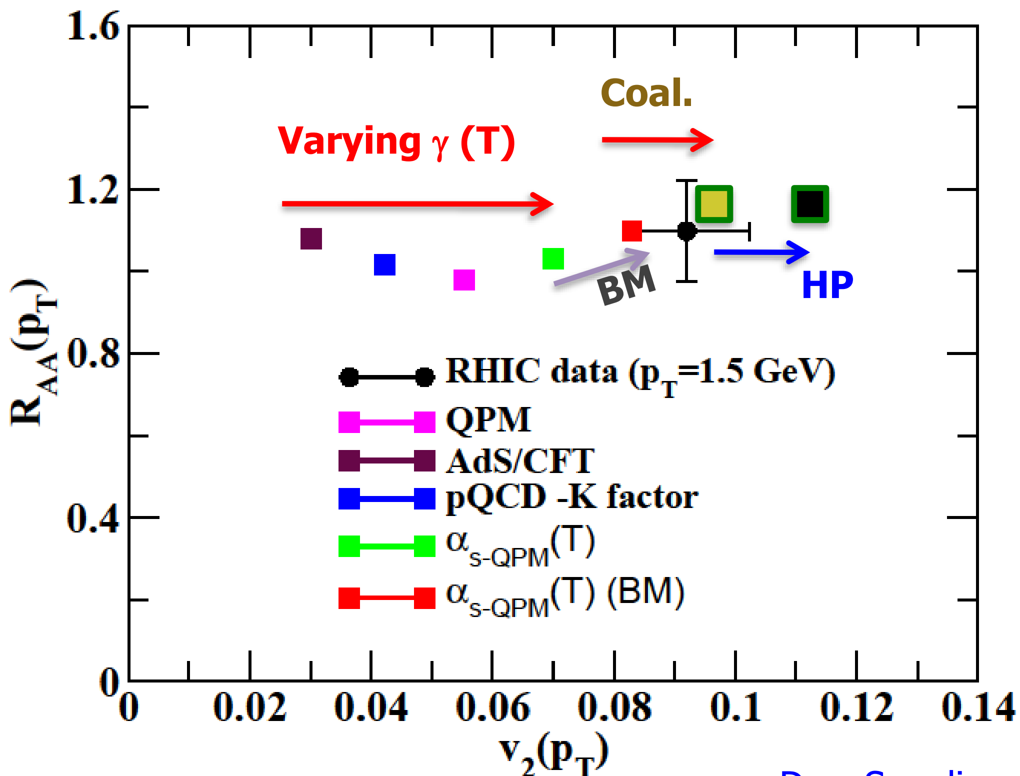


ALICE, JHEP 01 (2022) 174

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

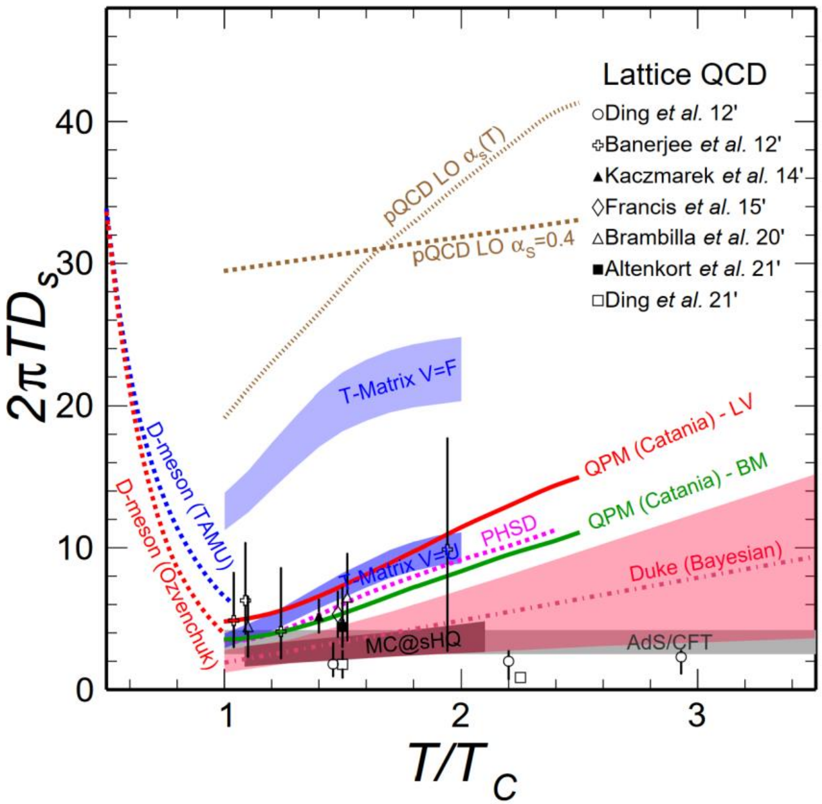
Summary on the build-up of v_2 at fixed R_{AA}

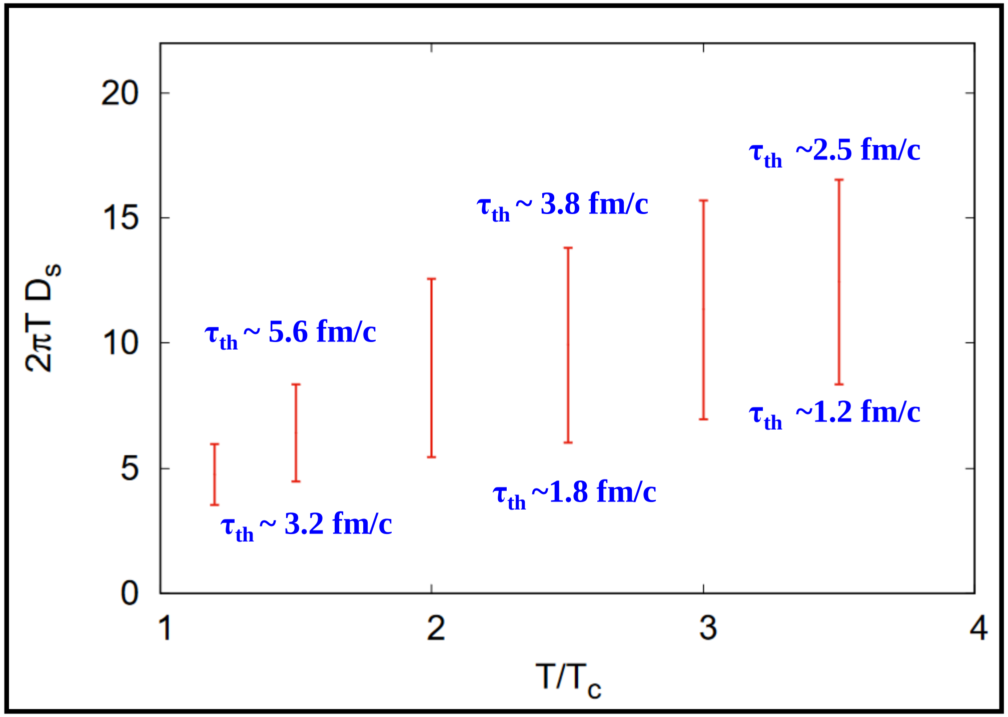


Das, Scardina, Plumari, Greco
Phys. Lett. B 747 (2016)260-264

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





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

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

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

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

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

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

Heavy quark dynamics with memory effect

- Langevin Equation

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

- $\langle \eta(t) \rangle = 0$
- $\langle \eta(t)\eta(t') \rangle = 2D\delta(t - t')$

- Generalized Langevin Equation

$$\frac{dp}{dt} = -\int_0^t \gamma(t, t')p(t')dt' + \eta(t)$$

Ruggieri, Pooja, Jai Prakash, Das
PRD, 106 (2022) 3, 034032

- The correlation of fluctuations

$$\langle \eta(t)\eta(t')\rangle = 2Df(|t-t'|)$$
$$\langle \eta(t)\rangle = 0$$

$$f(|t-t'|) = \frac{1}{2\tau}e^{-|t-t'|/\tau}$$

- Ancillary process

$$\eta(t) = \sqrt{\frac{2D}{\tau}}h(t)$$

$$\frac{dh}{dt} = -\alpha h + \alpha\rho$$

$$\alpha = \frac{1}{\tau}$$

$$\langle h(t)h(t')\rangle \approx \frac{e^{-\alpha|t-t'|}}{2}$$

The drag from FDT:

$$\gamma(t,t') = \frac{2D}{ET}\frac{e^{-|t-t'|/\tau}}{2\tau}$$

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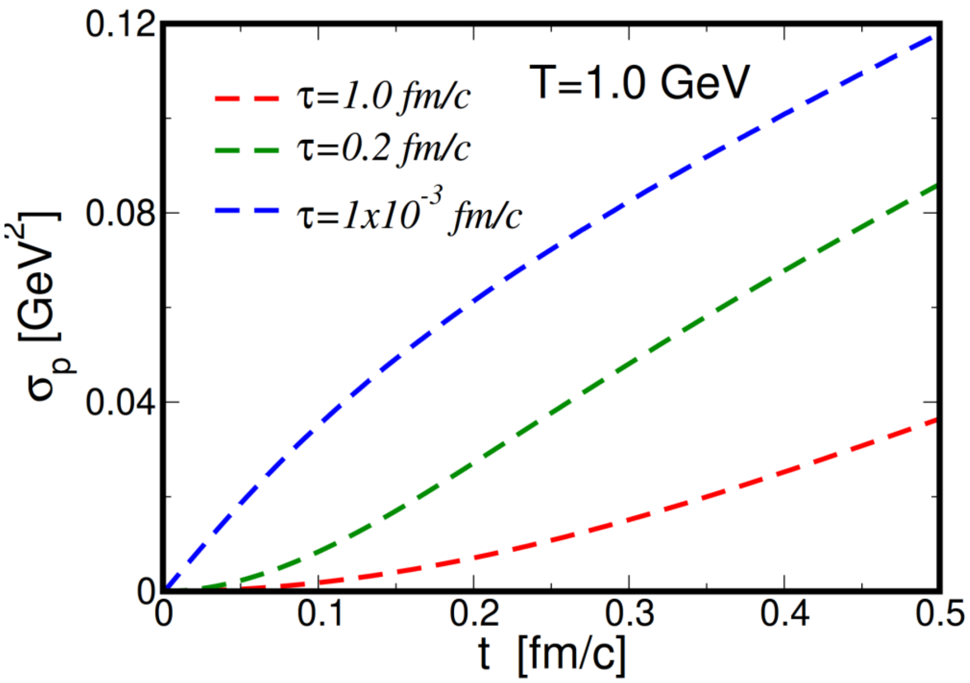
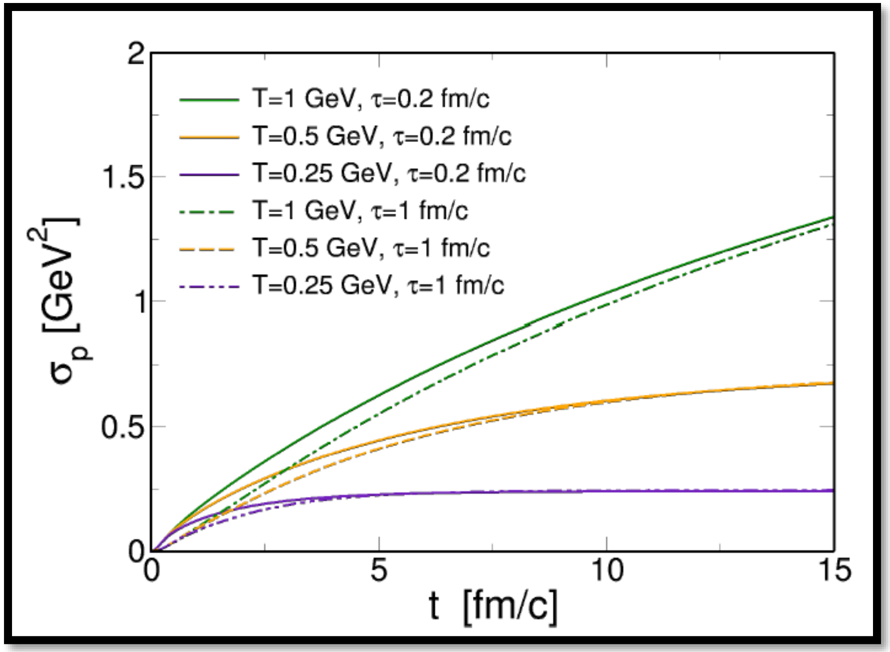
Impact of memory on heavy quark thermalization





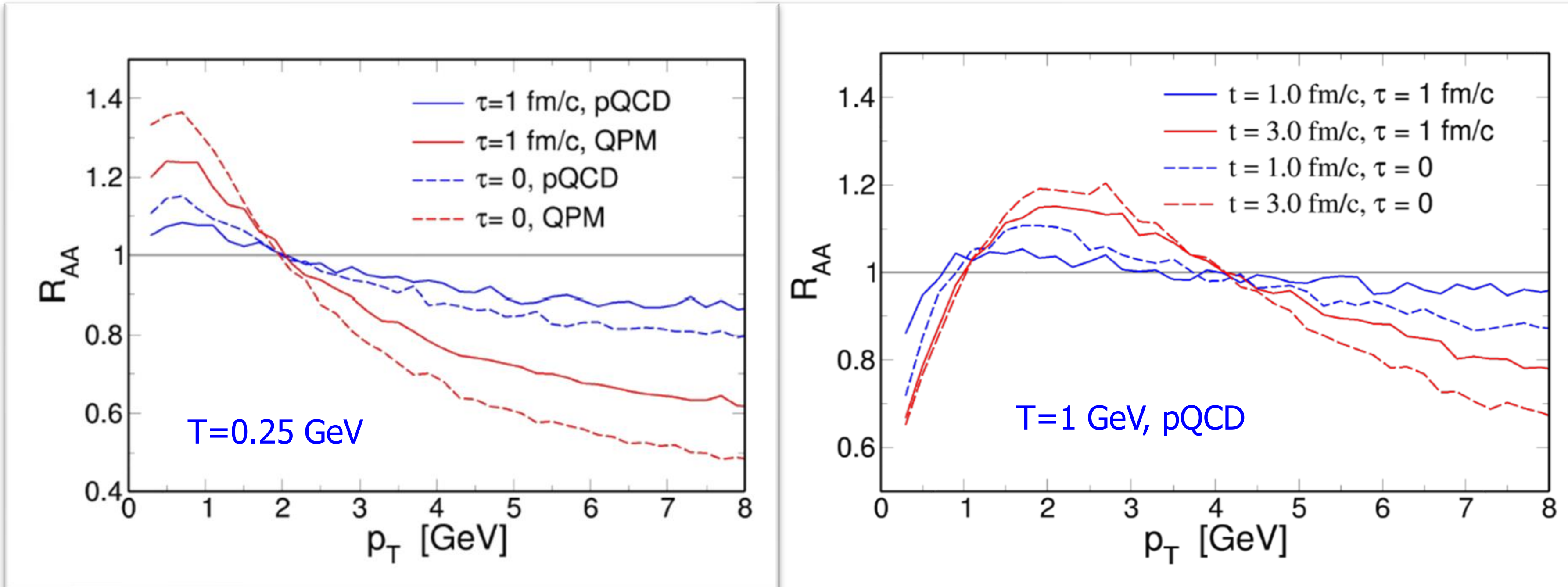
$$\sigma_p = \langle (p_T - \langle p_T \rangle)^2 \rangle$$

Memory delay the thermalization time

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

Ruggieri, Pooja, Jai Prakash, Das, PRD, 106 (2022) 3, 034032

Impact of memory on heavy quark suppression



Formation of R_{AA} are slowed down by memory

Ruggieri, Pooja, Jai Prakash, Das
PRD, 106 (2022) 3, 034032

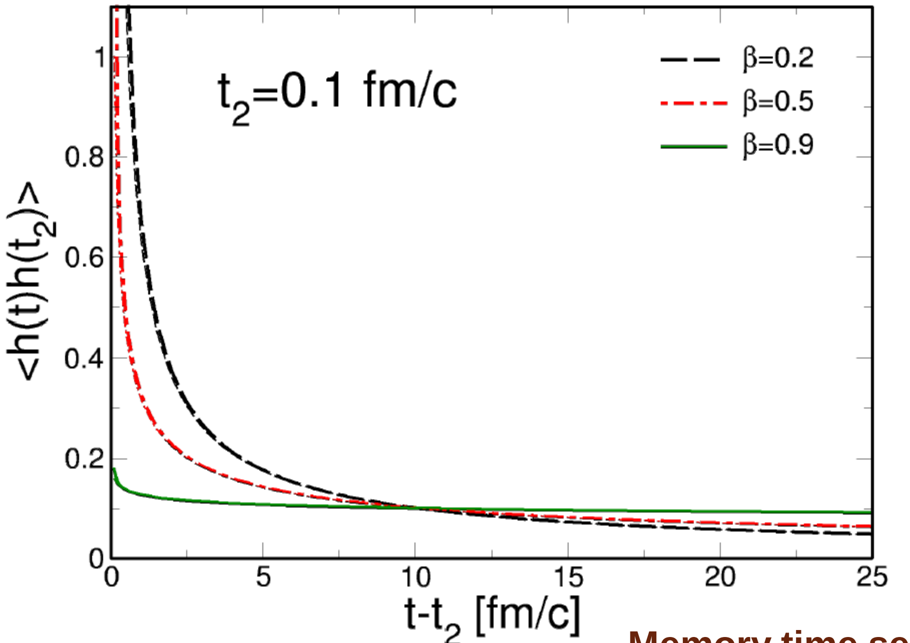
Longtail memory: time correlations decaying with a power law

$$h(t) = \sqrt{\kappa}\frac{\sqrt{\beta}}{\tau^\beta}\int_0^t (t-u)^{\beta-1}\xi(u)du, \qquad 0 < \beta < 1$$

β fixes the power law at which correlations decay.

ξ is a standard Gaussian noise

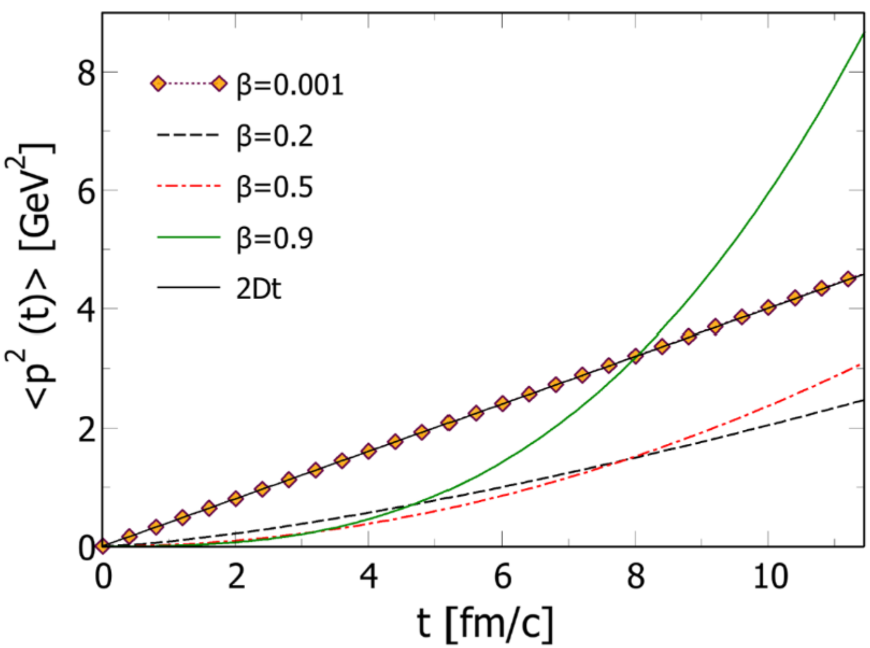
$$\langle h(t_1)h(t_2)\rangle = \kappa\tau^{-2\beta+1}\beta\int_0^{t_{\min}}(t_1-u)^{\beta-1}(t_2-u)^{\beta-1}du,$$

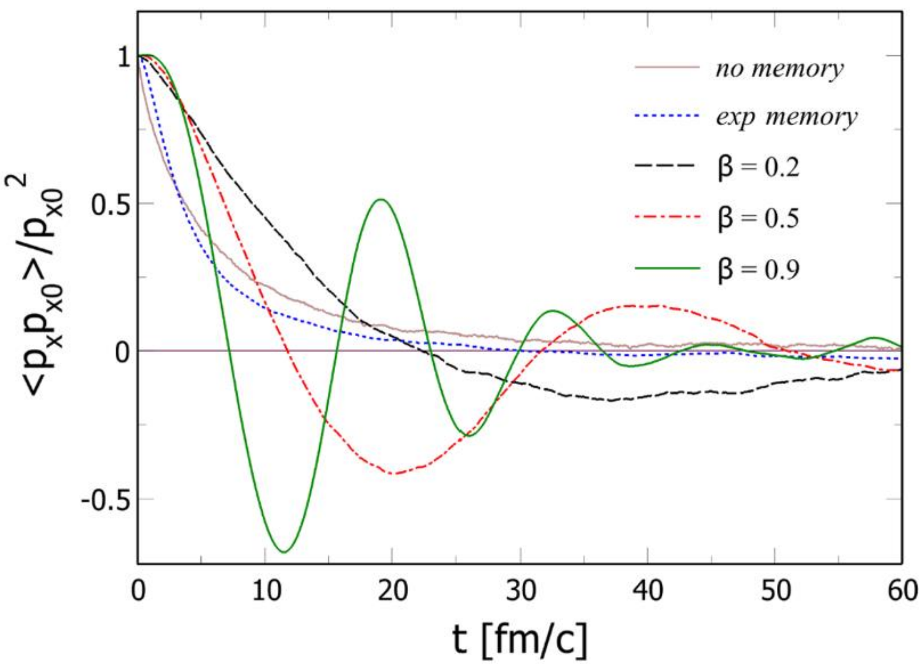


Pooja, Das, Greco, Ruggieri
PRD 108, 054026 (2023)

Memory time set the time scale at which correlations decay.

Longtail memory: Momentum broadening and randomization



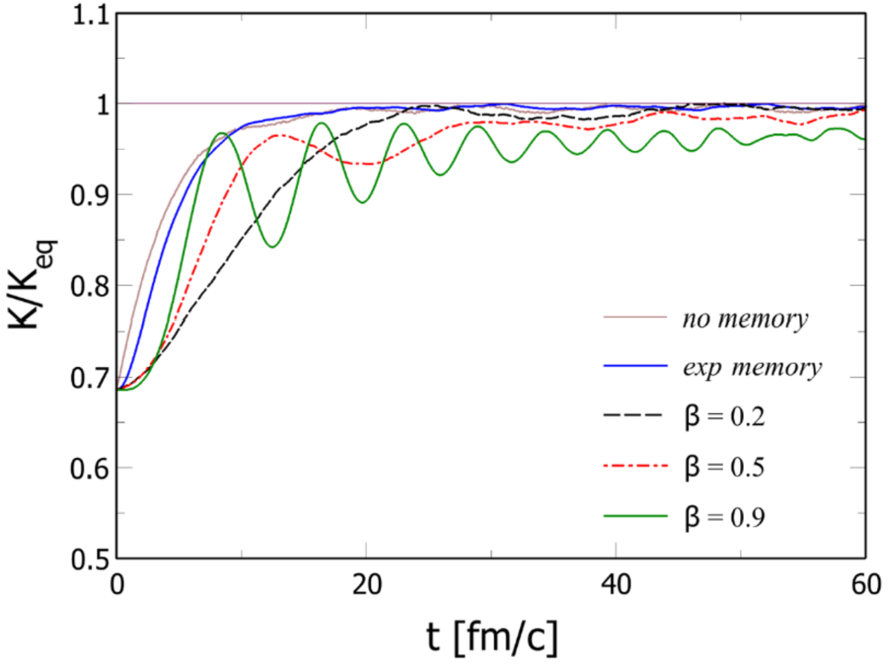


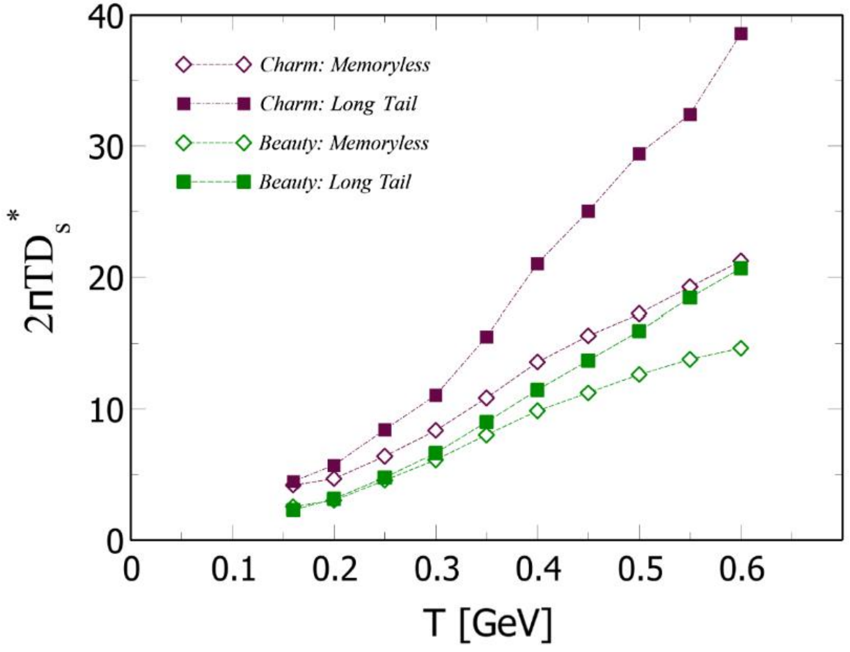
For larger β the ⟨$p^2(t)$⟩ increases with a power of time larger than one.

The drag kernel is proportional to the correlator of h, and in the early evolution, this gets suppressed if β → 1. Consequently, the effect of the damping given by the drag force is lowered by increasing β. The resulting motion is qualitatively similar to that of a damped oscillator.

Pooja, Das, Greco, Ruggieri
PRD 108, 054026 (2023)

Longtail memory: Thermalization and D_s





$$K_{\rm eq} \equiv \frac{\int \frac{d^3p}{(2\pi)^3}\left(\sqrt{p^2+m^2}-m\right)e^{-\beta\sqrt{p^2+m^2}}}{\int \frac{d^3p}{(2\pi)^3}e^{-\beta\sqrt{p^2+m^2}}}.$$

Need higher momentum diffusion coefficient D or, equivalently, a smaller Ds is in order to reproduce the experimental data.

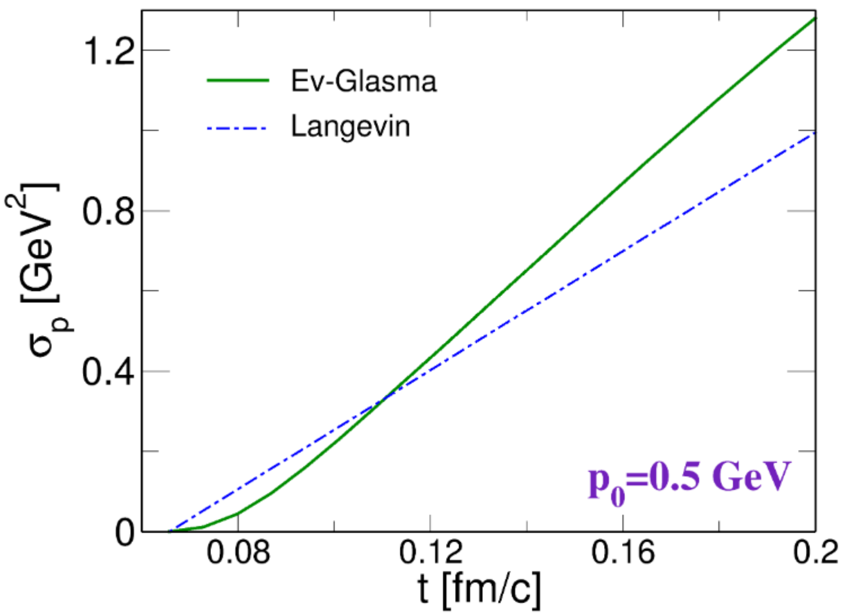
Pooja, Das, Greco, Ruggieri
PRD 108, 054026 (2023)

Conclusions and Perspectives:

- We have studied heavy quark diffusion with exponential and power-law memory.
- Memory slows down the momentum evolution of heavy quarks.
- Formation of R_{AA} and v_2 are slowed down by memory
- Thermalization time of the heavy quarks become larger.
- Requires smaller D_s To reproduce the data.


Thank You . . . .

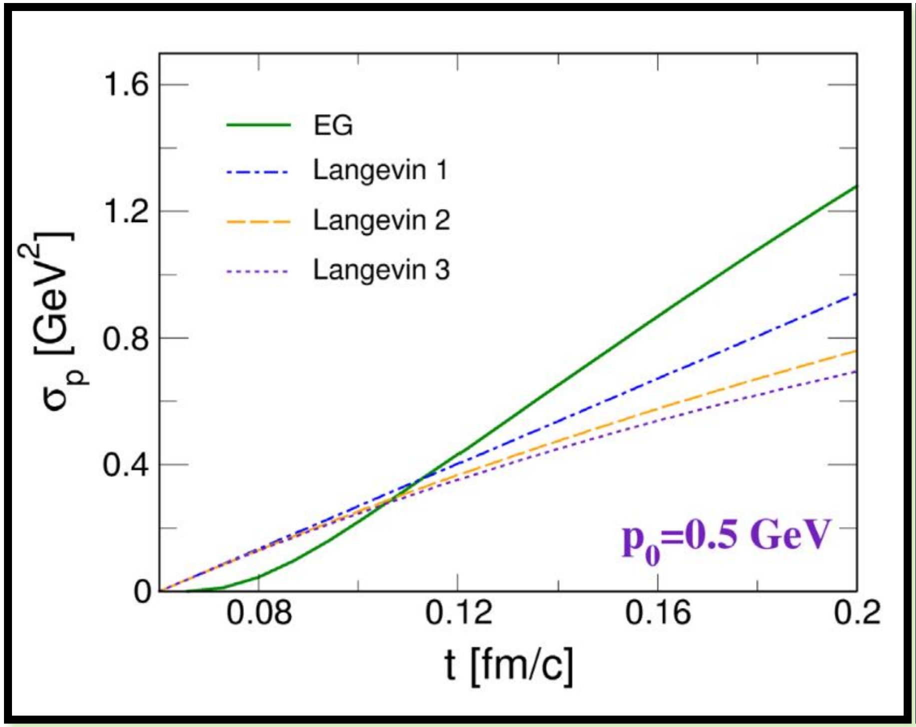
Impact of memory on heavy quark thermalization

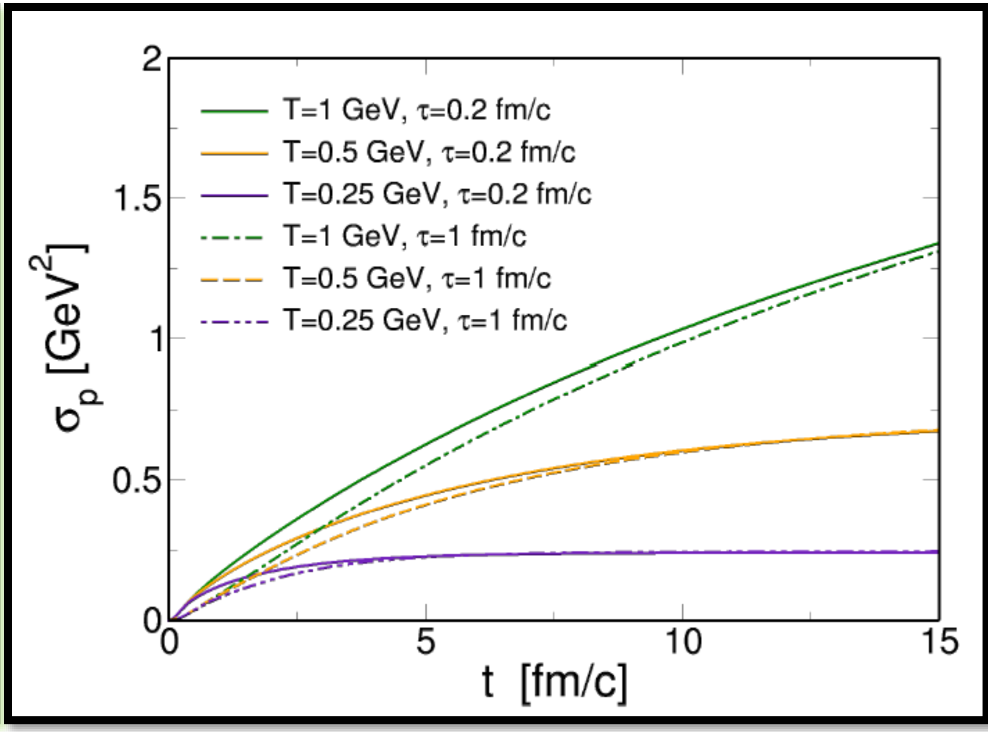


$$\sigma_p = \frac{1}{2}\langle (p_x(t) - p_{0x})^2 + (p_y(t) - p_{0y})^2 \rangle$$

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

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]