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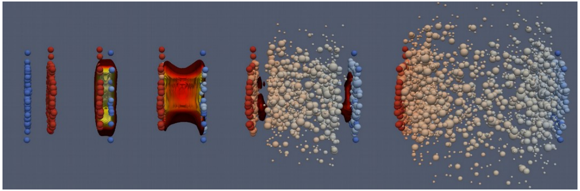
Probing the pre-equilibrium stage of heavy-ion collisions with charm quarks

Mayank Singh[1], **Manu Kurian**[2], **Björn Schenke**[3], **Sangyong Jeon**[4], **Charles Gale**[4]

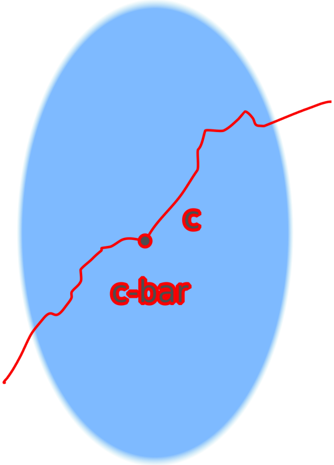
[1] Vanderbilt University
[2] RIKEN BNL Research Center, Brookhaven National Laboratory
[3] Brookhaven National Laboratory
[4] McGill University

Heavy flavor in heavy-ion collisions

- Heavy-flavor quarks are mostly produced at the very early stage of the collision
- They traverse the medium while interacting with it
- They explore every stage of the medium evolution

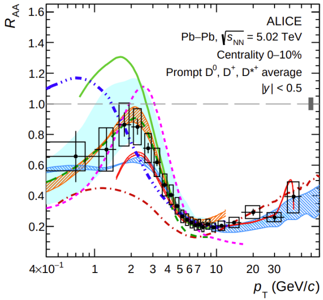


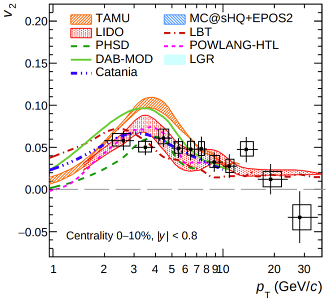
MADAI Collaboration, H Petersen, J Bernhard



R_{AA} and v_2

- Two principal observables are the nuclear modification factor R_{AA} and the elliptic flow coefficient v_2
- Usually an increase in HQ interaction strength leads to a lowering of R_{AA} and an enhancement in v_2 making it difficult to simultaneously describe both





ALICE Collaboration, JHEP (2022)

The random walk of charm

- The propagation of charm quarks can be considered a random walk
- In the hydrodynamic phase, it can be described in a Fokker Planck or Langevin approach

$$dp_i = -Ap_i dt + \xi_i(\mathbf{p})dt$$

- The physical parameters are the drag and diffusion coefficients
- The diffusion coefficient is related to fluctuation by the fluctuation-dissipation theorem,

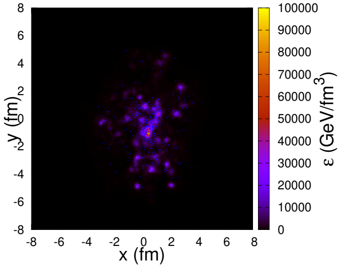
$$\langle \xi_i(t)\xi_j(t') \rangle = B\delta_{ij}\delta(t - t')$$

The pre-equilibrium phase

- The pre-equilibrium is the least understood phase, both in terms of the charm interactions and the background medium
- A dynamical description is provided by the IP-Glasma model B. Schenke, P. Tribedy, R. Venugopalan, PRL (2012)
- Color field fluctuations are sampled using the saturation scale obtained from the IP-Sat model H. Kowalski, D. Teaney, PRD (2003)
- The color fields are evolved using the classical Yang-Mills equations

$$[D_\mu, F^{\mu\nu}] = J^\nu$$

- The charm could be in a hotspot in pre-equilibrium phase



Does pre-equilibrium energy loss matter?

- Heavy-quark interactions in the pre-equilibrium phase are often ignored
- The lifetime of the phase was considered too short to have any important phenomenological implications
- Also, it is challenging to model HQ energy loss in pre-equilibrium phase. One approach is to consider it as a classical colored particle in Glasma fields. Another is to evolve charm in the QCD kinetic theory

J.-H. Liu, S. K. Das, V. Greco, M. Ruggieri, PRD (2021); M. E. Carrington, A. Czajka, S. Mrowczynski, PRC (2022); X.Du, arxiv:2306.02530; K. Boguslavski, A. Kurkela, T. Lappi, F. Lindenbauer, J. Peuron, PRD (2024); L. Backfried, K. Boguslavski, P. Hotzy, arxiv:2408.12646 H. Pandey, S. Schlichting, S. Sharma PRL (2024); D. Avramescu, V. Greco, T. Lappi, H. Mantysaari, D. Muller, arxiv:2409.10564; ...

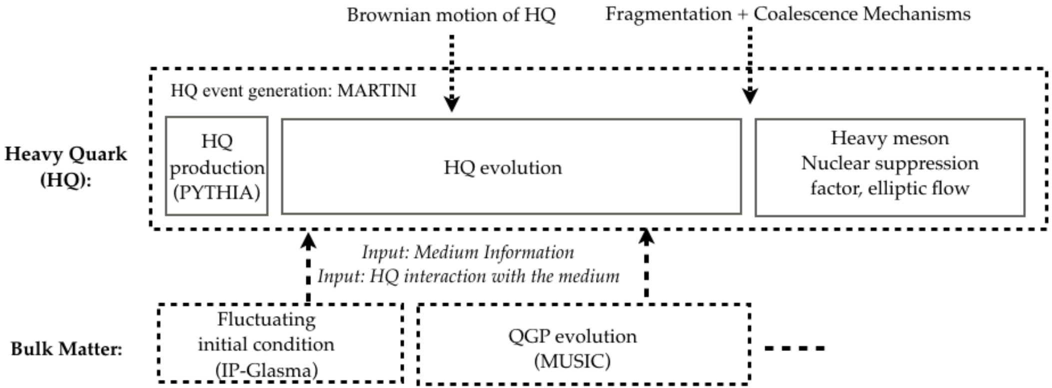
Our motivation

- The question we aim to answer is if pre-equilibrium energy loss coupled with realistic HQ evolution in hydrodynamic medium, affect the observables
- Can we get a rough estimate of the magnitude of this effect?

Some simplifications

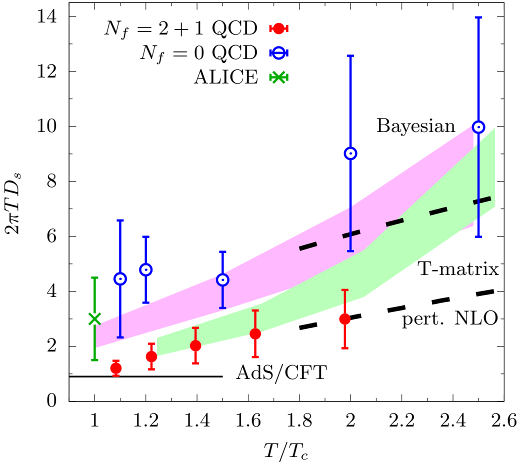
- We define a temperature from the local energy density in the glasma phase using an ideal-gas equation of state
- The HQ evolution in this “thermalized” glasma is described by the Langevin equation
- We used a boost-invariant background for the medium with a non-boost invariant HQ distribution

Our framework



Diffusion rates from lattice

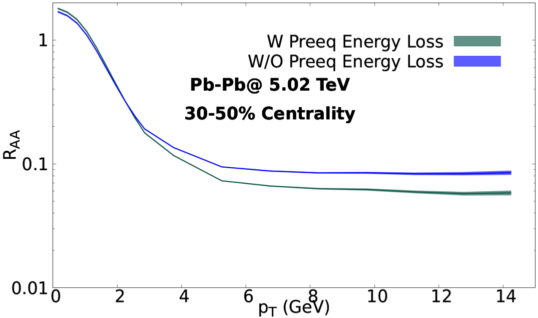
- Recent lattice results provide spatial diffusion coefficient in 2+1 flavor QCD
- We used the older 0 flavor results in the Glasma phase
- Interaction strength larger than previously thought

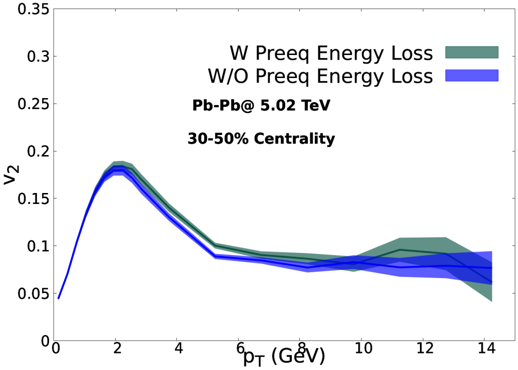


HotQCD, PRL (2023)

R_{AA} and v_2 from lattice rates

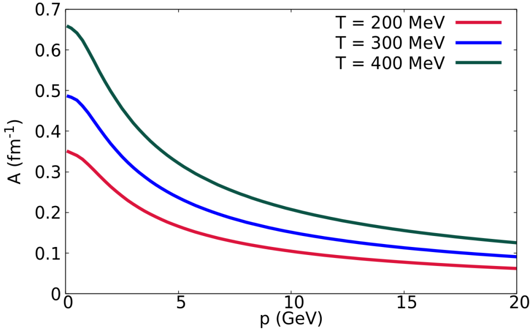
- D-mesons hadronized by fragmentation only
- Sizeable effect at larger momentum

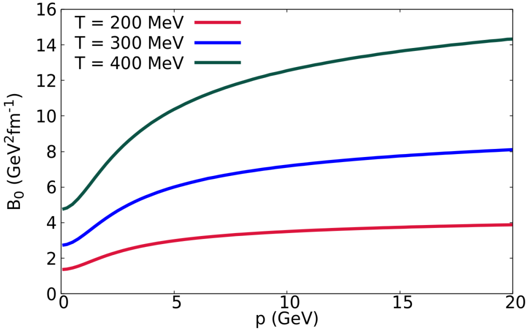




Momentum dependence

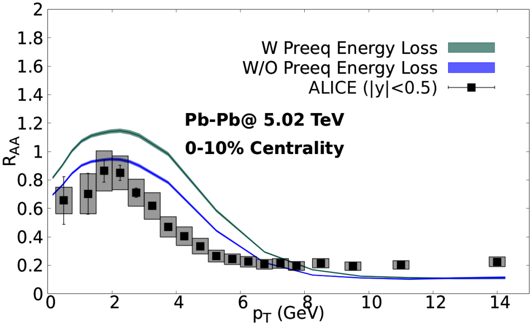
- Lattice does not provide p_T dependence of interaction strength
- Parameterized momentum dependence from pQCD calculations. Matched to lattice results at $p_T \to 0$

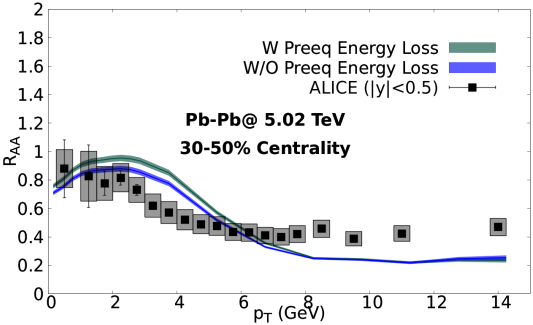




M. Singh, M. Kurian, S. Jeon, C. Gale, PRC (2023)

With p_T dependent interactions and coalescence

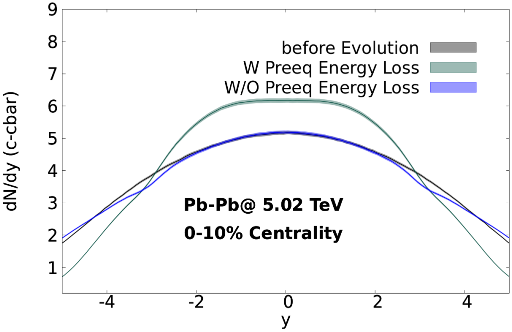


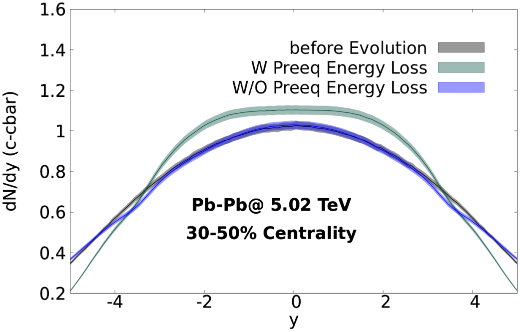


- The momentum dependence of dissipation coefficients can be tuned to obtain a better fit
- The pre-equilibrium energy loss seems to be causing enhancement! How is that possible?

Can pre-equilibrium energy loss cause enhancement?

- Large diffusion at very early times can rearrange the rapidity of charm quarks
- Large kicks change the direction of low-p_T quarks changing their rapidity





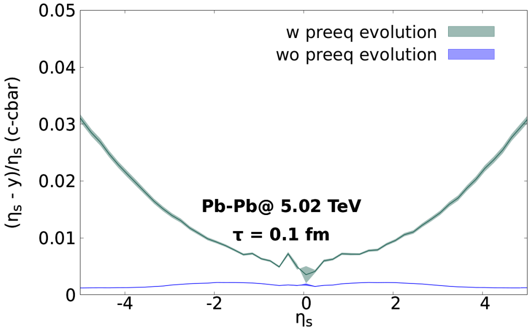
Rapidity dynamics

- Enhancement can be understood as an interplay between spacetime rapidity η_s and momentum rapidity y

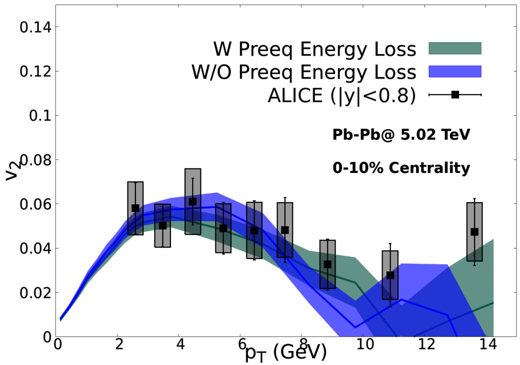
$$\eta_s = \tanh^{-1}(z/t)$$

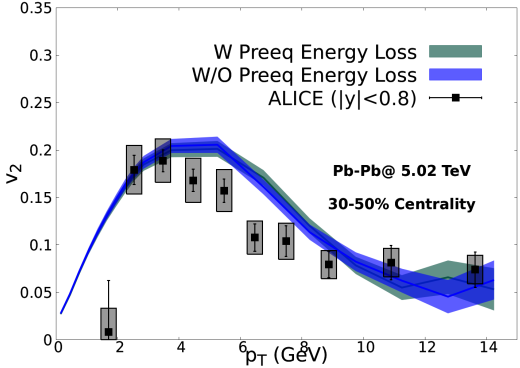
$$y = \tanh^{-1}(p_z/E)$$

- If there were no interactions, $\eta_s = y$



v_2





- The flow is not significantly affected

Summary and Outlook

- Pre-equilibrium energy loss can have significant and counter-intuitive effects on charm observables
- The rapidity dynamics is the most significant cause of surprising enhancement
- Will depend on details of momentum dependent rates, hadronization mechanism
- Can be leveraged to better tune the transport coefficient
- The calculation can be generalized to include a full 3D background
- Other methods can be used to model early time energy loss in this setup