Simulating Charm Quarks in IP-Glasma Initial Stage and Quark-Gluon Plasma: A Hybrid Approach for charm quark phenomenology

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Relativistic heavy-ion collisions (HICs) & Heavy Quarks (HQs)

Heavy quarks as effective probes to characterize the hot QCD medium created at HICs

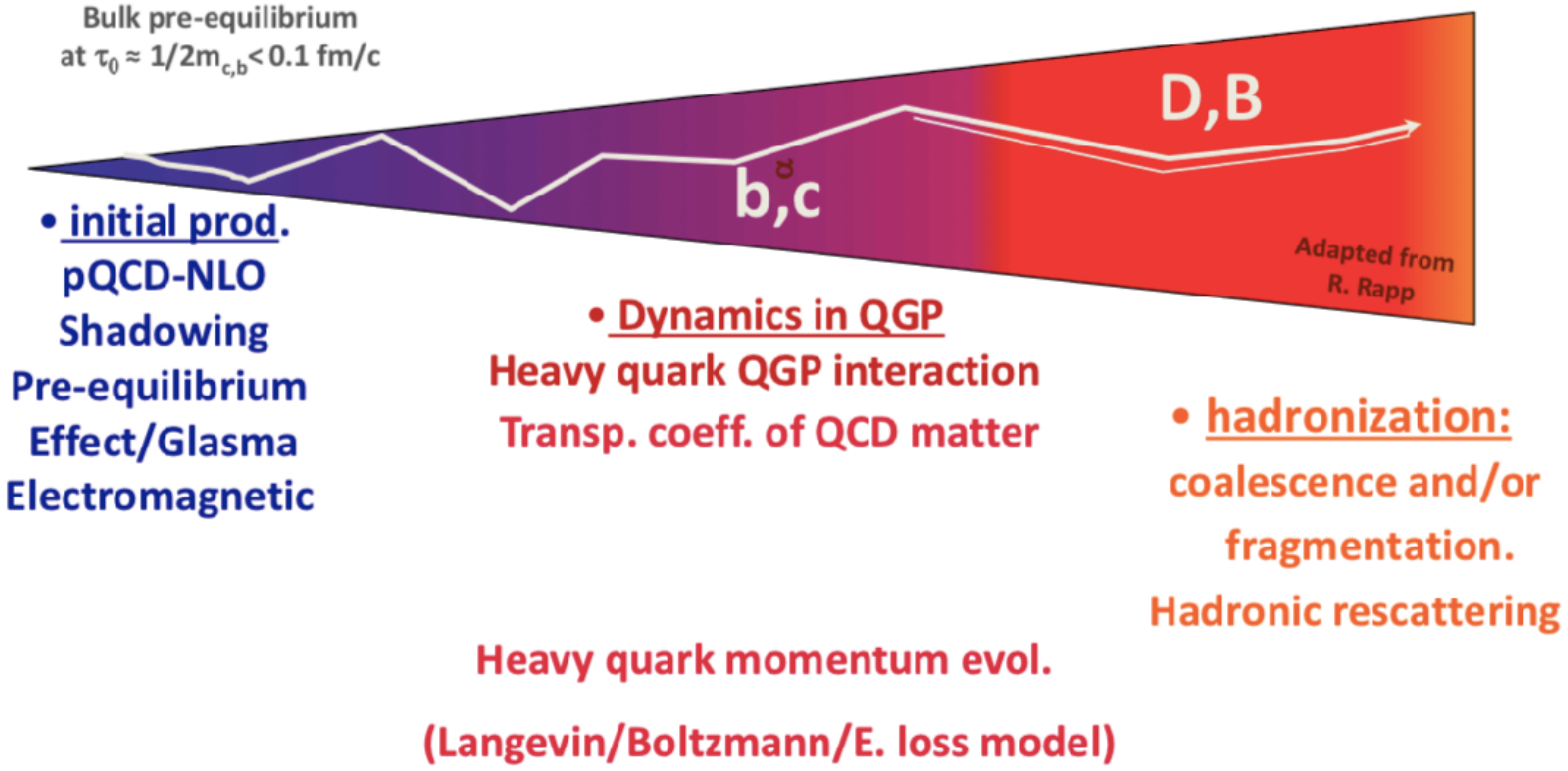
- Mostly produced at the very early stage of the collision in partonic scattering processes. Small rate of thermal production in the QGP

- Transverse through the medium while interacting with the medium constituents and witness the QGP evolution.

- Their dynamics can be studied within the scope of Brownian motion *H. van Hees, et.al., PRL 125, 192301 (2008); [PHENIX Collaboration], PRL 98, 172301 (2007); S. Cao et al., PRC 99, 054907 (2019),G.D. Moore and D. Teaney, PRC 71 (2005) 064904…..*

Stages of collision

HQ evolution



HQ key observables

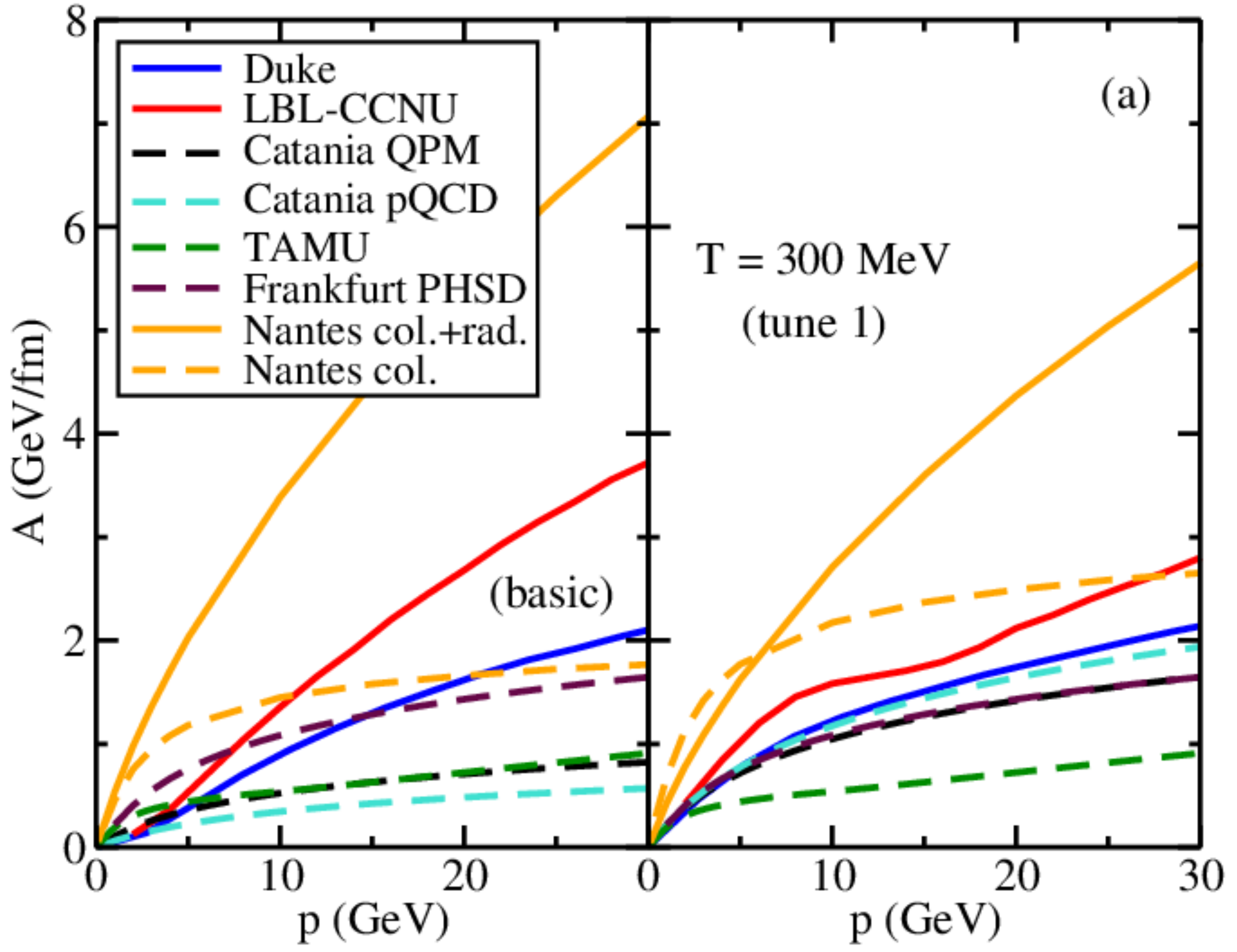
- Nuclear Suppression factor, Elliptic flow of heavy mesons: HQ interaction as the input parameter

- "Essentially all the models show some difficulties to describe simultaneously both R_{AA} and v_2 and such a trait is not only present at RHIC energy but also in the results from collisions at LHC energy……" [*S.K. Das et.al. PLB 768, 260-264 (2017)*]

- Experimental measurements start to provide constraints to the models for the characterisation of the HQ interaction with the medium

- Updates on HQ puzzle
  - Radiative process, Non-perturbative effects (T matrix model, Quasiparticle description, ..)
  - Hardronization process (fragmentation and coalescence processes)
  - Medium evolution, …….

- **Observation**: Charm quarks are sensitive to the history of the QGP evolution and retain information on the entire time evolution from initial condition up to the late stage of the reaction (*Y. Xu et.al, PRC 99 (2019), 014902*)



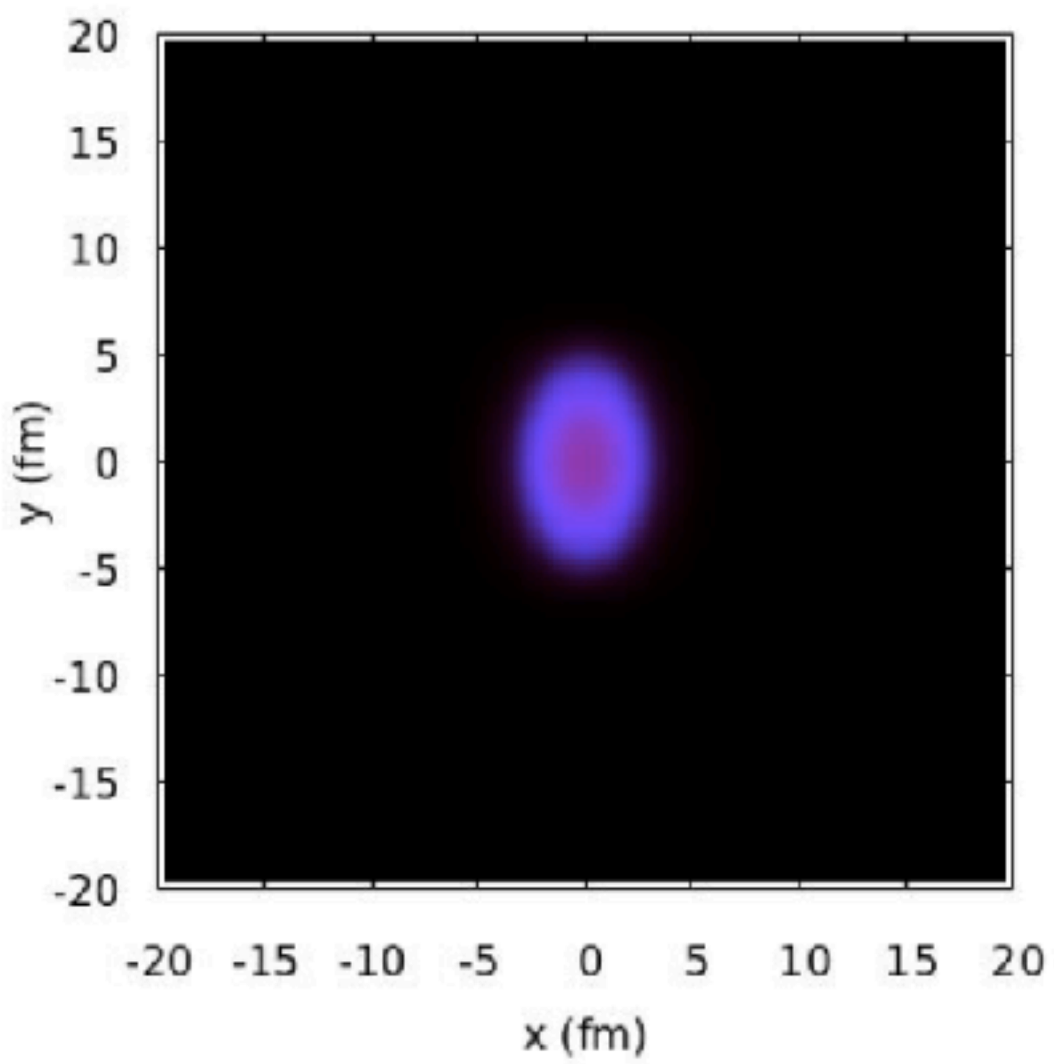
S.Cao et.al. PRC 99 (2019), 054907

Motivation

- Owing to the fact that heavy quark is mostly created in the very early stage of the collision event, they retain imprints of the initially produced matter in nucleus-nucleus collisions.

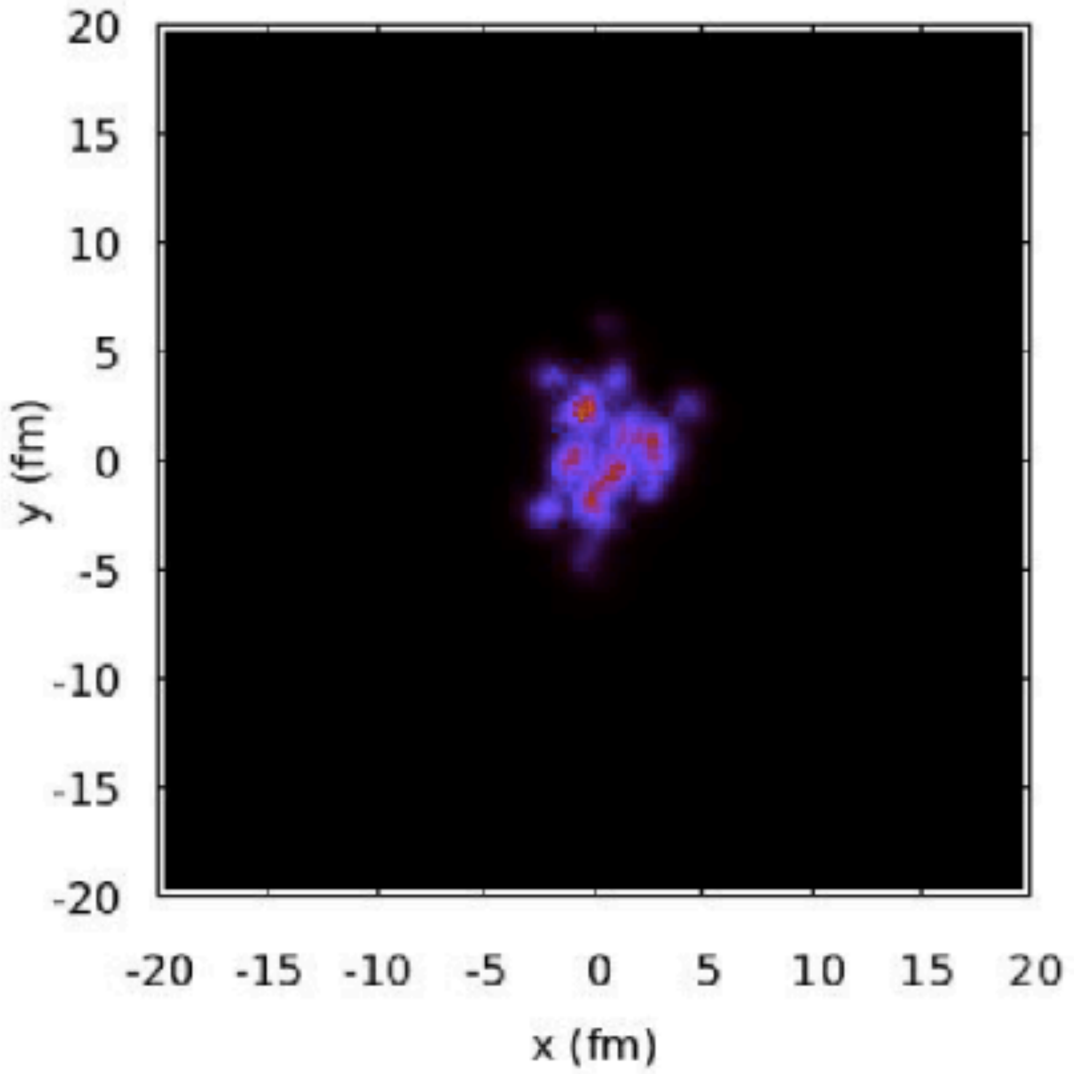
- The initial stage of collision, which sets the initial conditions for the hydrodynamical evolution of the QGP, is a substantial source of uncertainty of the relativistic heavy-ion collisions.

- Various models provide different initial energy density profiles with anisotropies in the transverse plane.



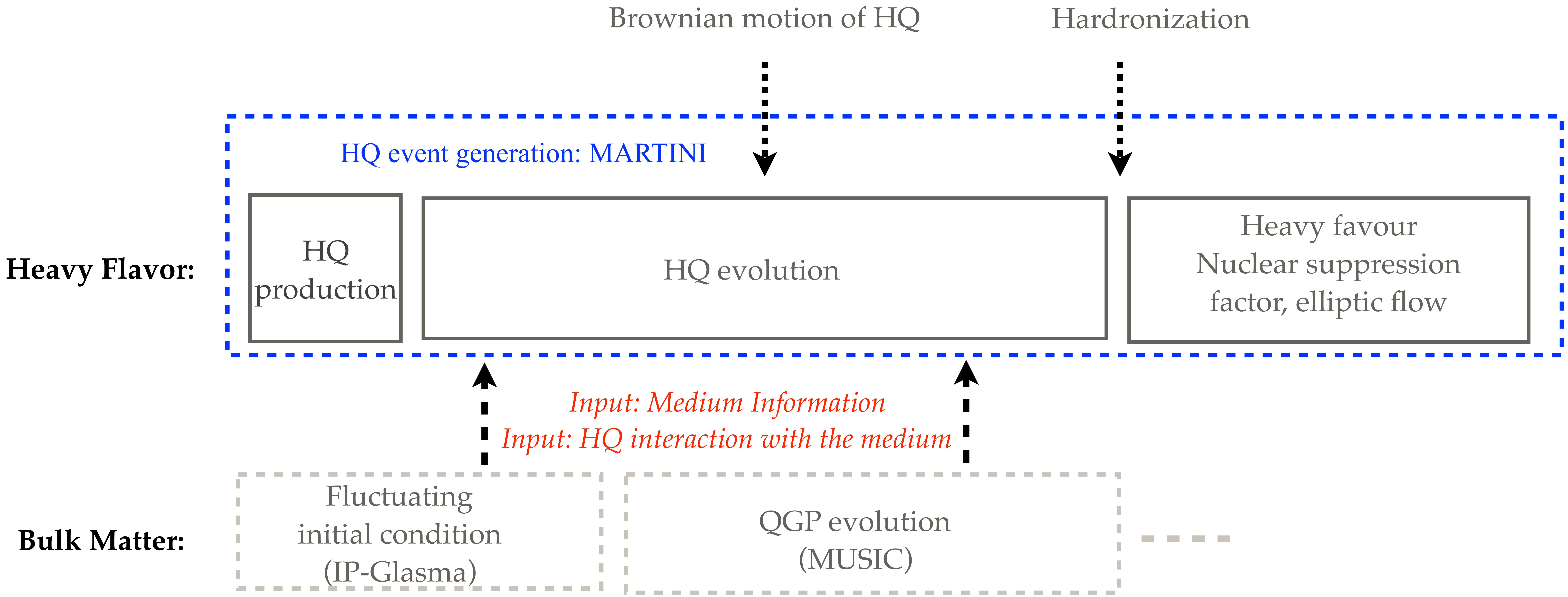
• Smooth initial condition

• Fluctuating initial condition



- One possible way to study the evolution of charm quark in non-Abelian background is to consider them as classical colored particles with Wong's equations as the governing equation of classical particles in the Glasma [See, *Pooja (Poster), M. Ruggieri (Poster)*]

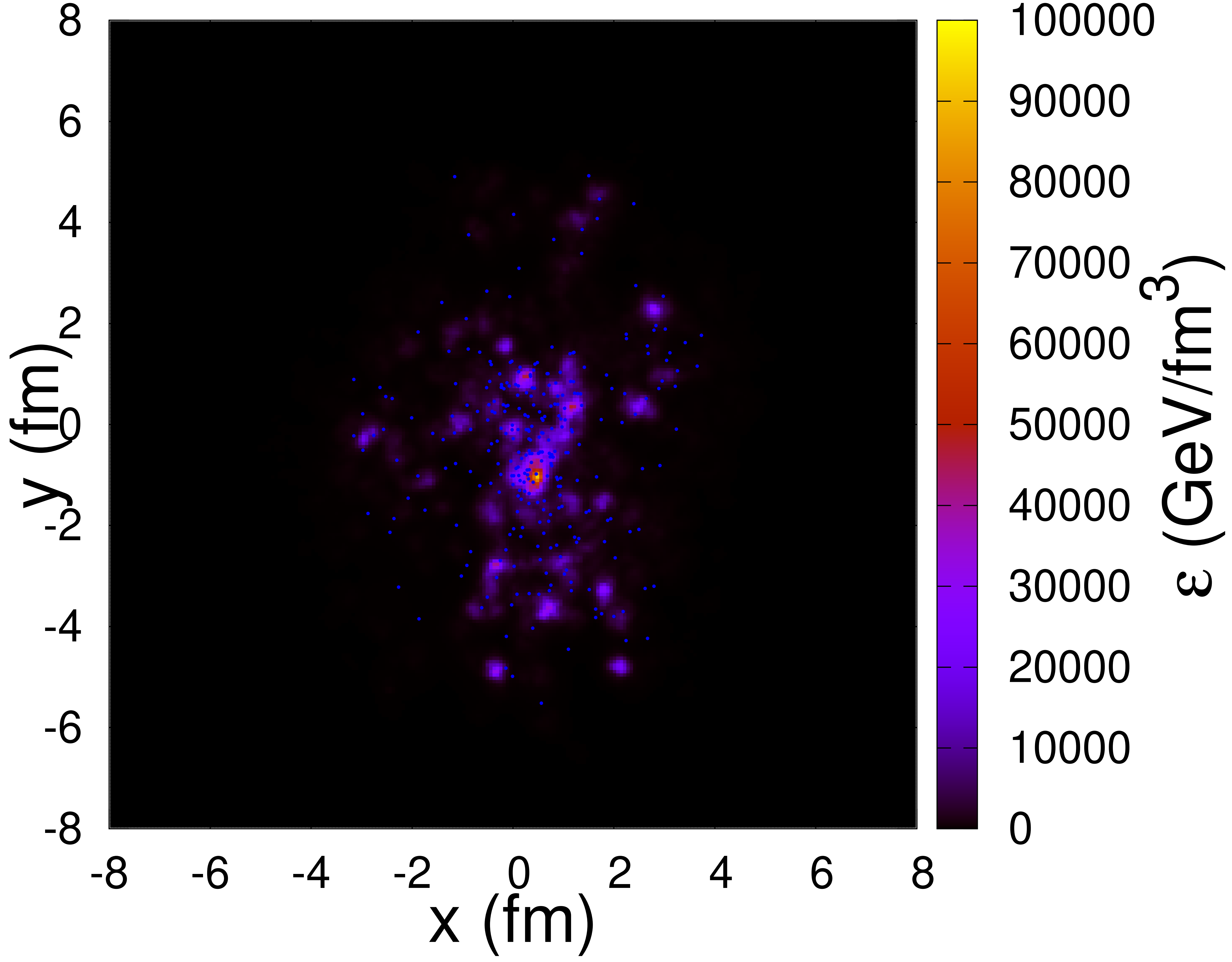
Our framework



B. Schenke, P. Tribedy, and R. Venugopalan, PRL 108, 252301 (2012)

B. Schenke, S. Jeon, C. Gale, PRC 82, 014903 (2010)

HQ evolution in Initial phase



- In realistic scenario with event-by-event initial condition, charm quarks may witness hot spots as they evolve in the Initial phase.

- The precise evolution of charm quark in the expanding space-time geometry that captures the gluon fields in the fluctuating initial state is non-trivial

- As a first step, we considered the evolution of HQ in the initial state as the Brownian motion of HQ in a bath of thermalized, massless gluons with energy density

HQ transport coefficients: FP approach

B. Svetitsky, PRD 1988
M.G.Mustafa, D.Pal, D.K.Srivastava, PRC 1998

- Transport coefficients: Drag and momentum Diffusion
- Simplified Boltzmann Equation
- Soft momentum transfer

$$\frac{\partial f_{HQ}}{\partial t} = \frac{\partial}{\partial p_i}\left[A_i(\mathbf{p})\, f_{HQ} + \frac{\partial}{\partial p_j}\left[B_{ij}(\mathbf{p})\, f_{HQ}\right]\right]$$

For the process $HQ(P) + g/q(Q) \rightarrow HQ(P') + g/q(Q')$

$$A_i = \frac{1}{\gamma_c}\frac{1}{2P^0}\int\frac{d^3\mathbf{q}}{(2\pi)^3 2Q^0}\int\frac{d^3\mathbf{p}'}{(2\pi)^3 2P'^0}\int\frac{d^3\mathbf{q}'}{(2\pi)^3 2Q'^0}(2\pi)^4\delta^4(P+Q-P'-Q')\sum|\mathcal{M}_{HQ,g/q}|^2 f_{g/q}(Q)\left(1\pm f_{g/q}(Q')\right)\left(\mathbf{p}-\mathbf{p}'\right)_i$$

$$\equiv \langle\langle (\mathbf{p}-\mathbf{p}')_i \rangle\rangle$$

HQ drag ⟶ thermal average of the momentum transfer

$$A_i = p_i A(p^2, T)$$

$$B_{ij} = \langle\langle (\mathbf{p}-\mathbf{p}')_i (\mathbf{p}-\mathbf{p}')_j \rangle\rangle$$

Momentum diffusion ⟶ square of the momentum transfer

$$B_{ij} = \left(\delta_{ij} - \frac{p_i p_j}{p^2}\right)B_0(p^2,T) + \frac{p_i p_j}{p^2}B_1(p^2,T)$$

HQ interaction strength: recent updates

- Static limit $$D_s = \frac{T}{m_c A(p \to 0, T)}$$

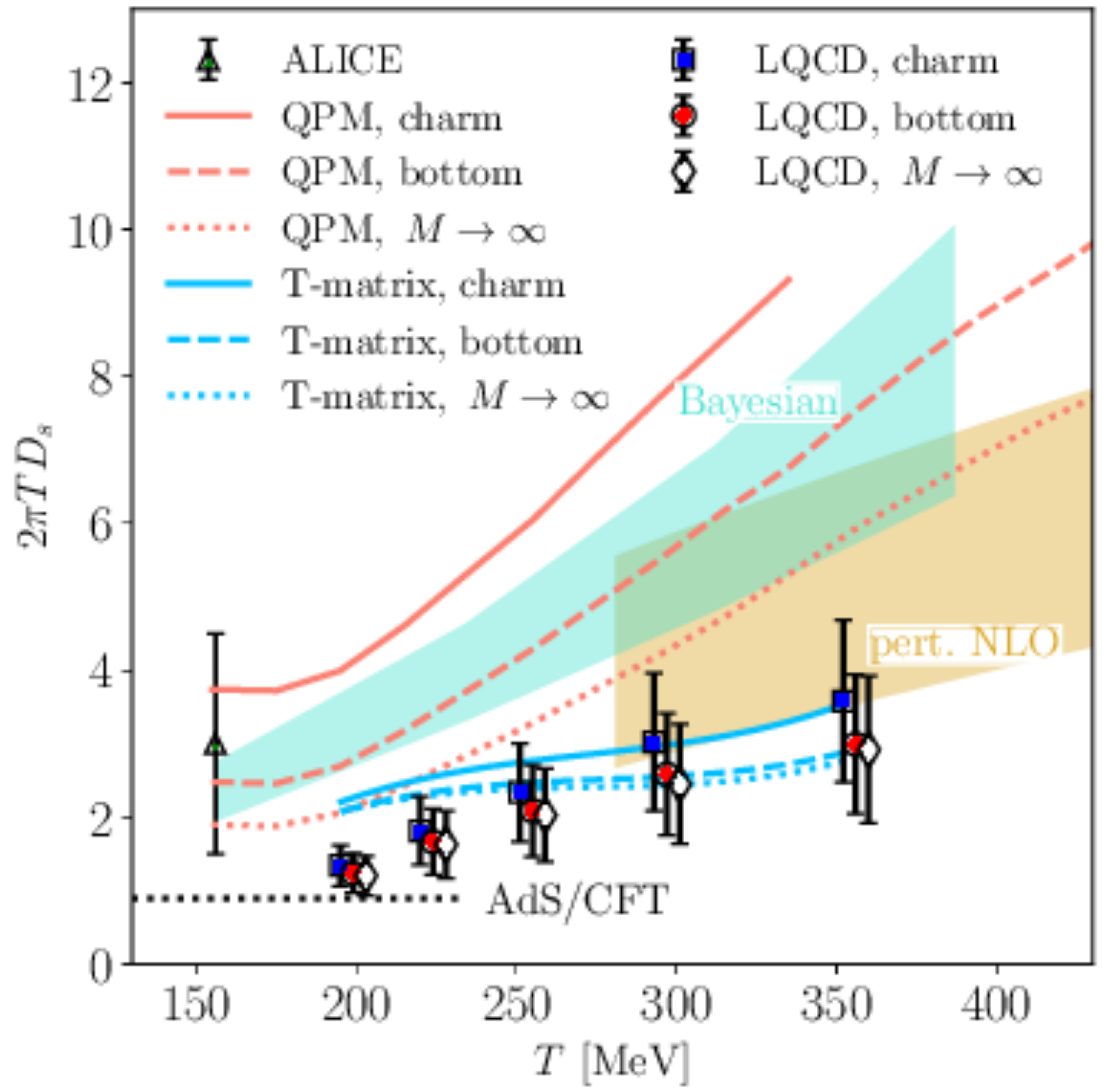
- pQCD estimations lies in the range ~30-40.

- Viscous effects are negligible, especially at high T
  Charm quark dynamics in quark-gluon plasma with 3 + 1D viscous hydrodynamics, M. Kurian, et. al., PRC 2020

- Non- perturbative effects: Quasiparticle model (*F. Scardina, et.al., PRC, 2017*), T-Matrix estimation (*Z. Tang, et,al. EPJA 60, 92 (2024)*)

- Model-to-data comparison: *Y. Xu et.al., PRC 97, 014907 (2018)*

- Lattice results: (*D. Banerjee, et.al., PRD, 2012*)
  First lattice data (2+1 flavor):
  [HotQCD Collaboration] PRL 130, 231902 (2023)



[HotQCD Collaboration] PRL 132, 051902 (2024)

Consequences on HQ observables

Estimation of HQ observables within Langevin dynamics

$$dx_i = \frac{p_i}{E} dt,$$
$$dp_i = -A_i\, dt + \xi_i(\mathbf{p}) dt,$$

Drag force Stochastic force

Choice of heavy quark transport coefficients

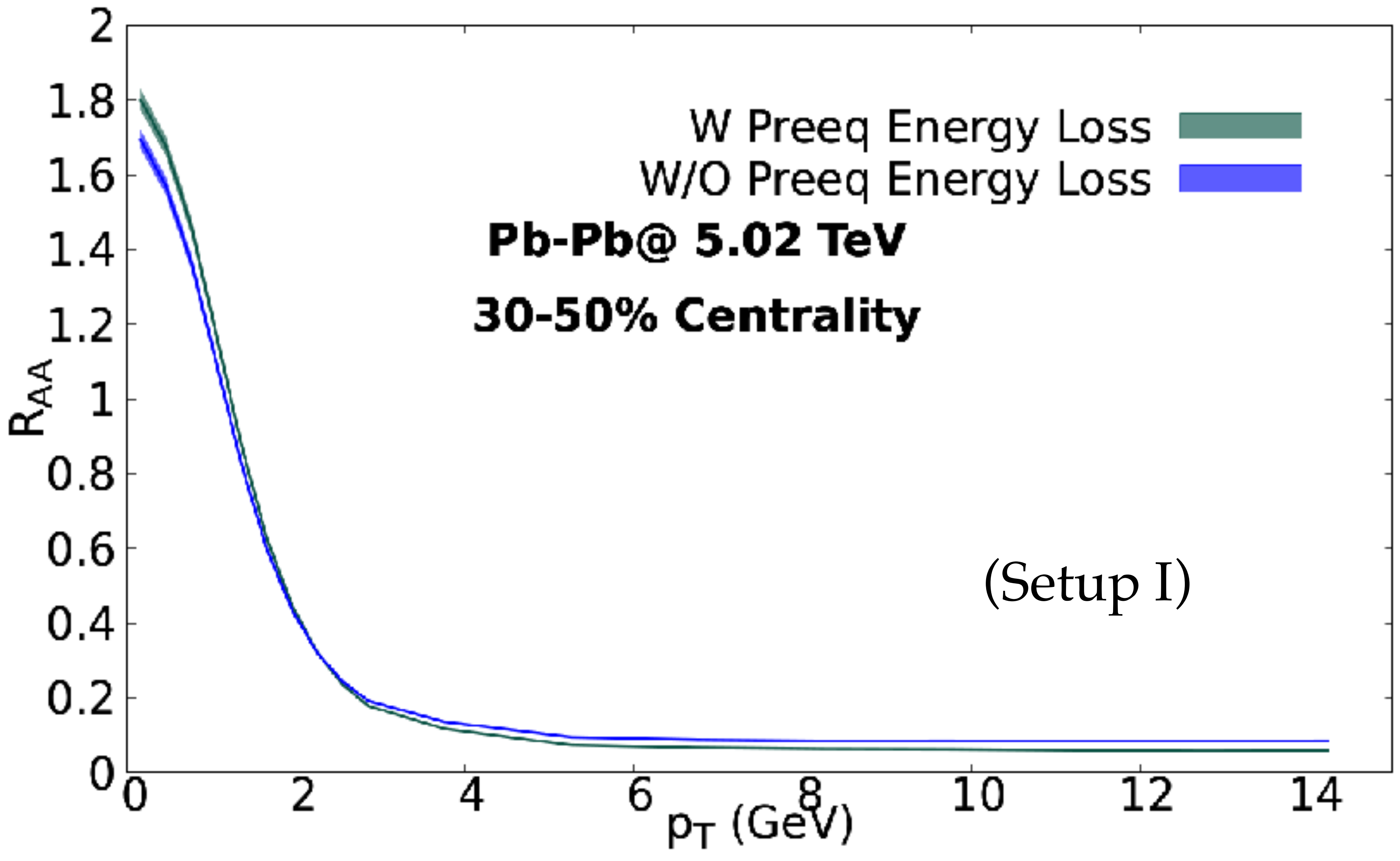
Setup I: Temperature-dependent $2\pi D_s T$ (2+1 lattice result)

Setup II: Temperature and momentum dependent heavy quark transport coefficients $A(p,T), B_0(p,T), B_1(p,T)$

$B_1(p,T)$ has a sharp rise with an increase in heavy quark momentum (within Fokker-Planck approach), which indicates large random kicks to the heavy quark

→ Fluctuation-dissipation relation *G.D. Moore and D. Teaney, PRC 71 (2005) 064904*

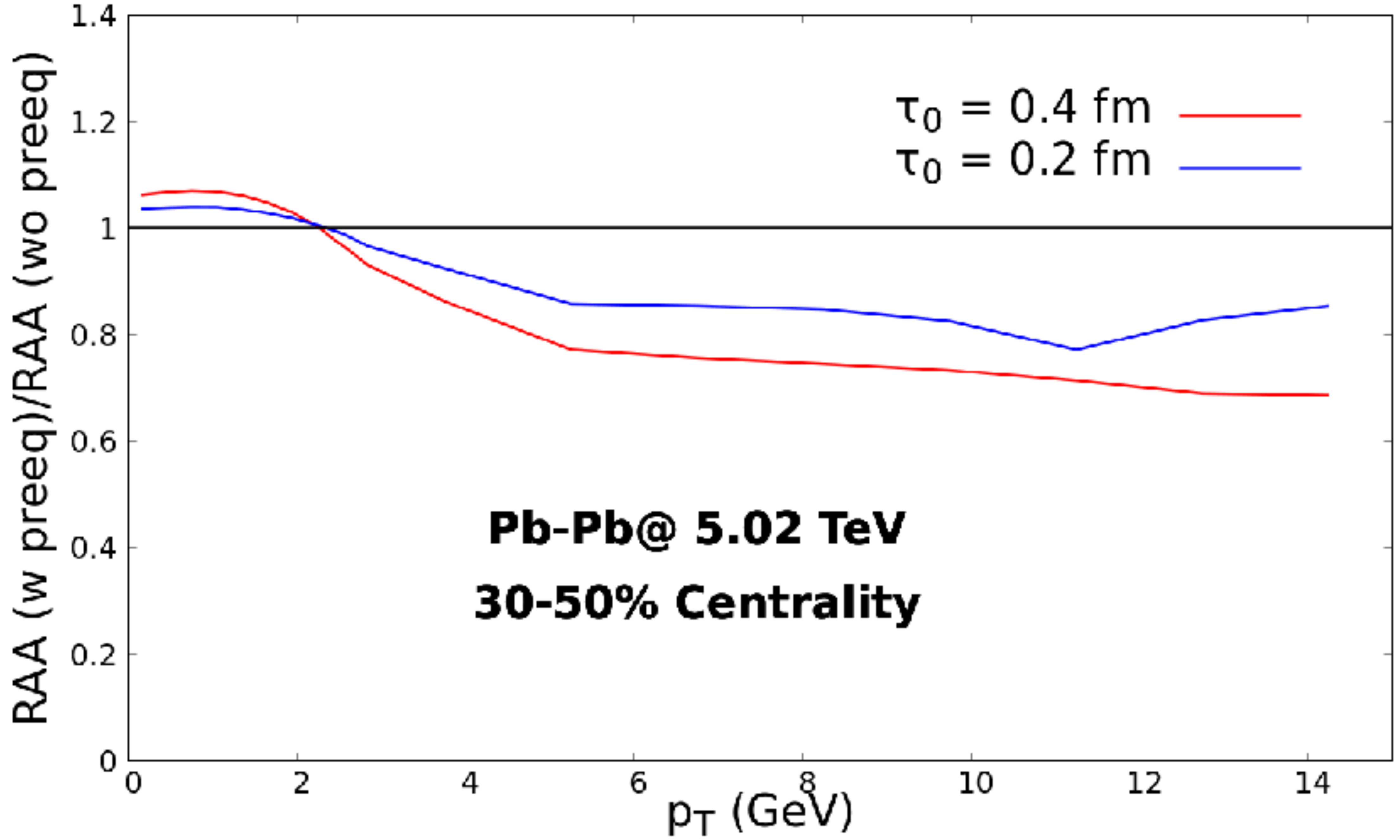
D-meson results: Preliminary



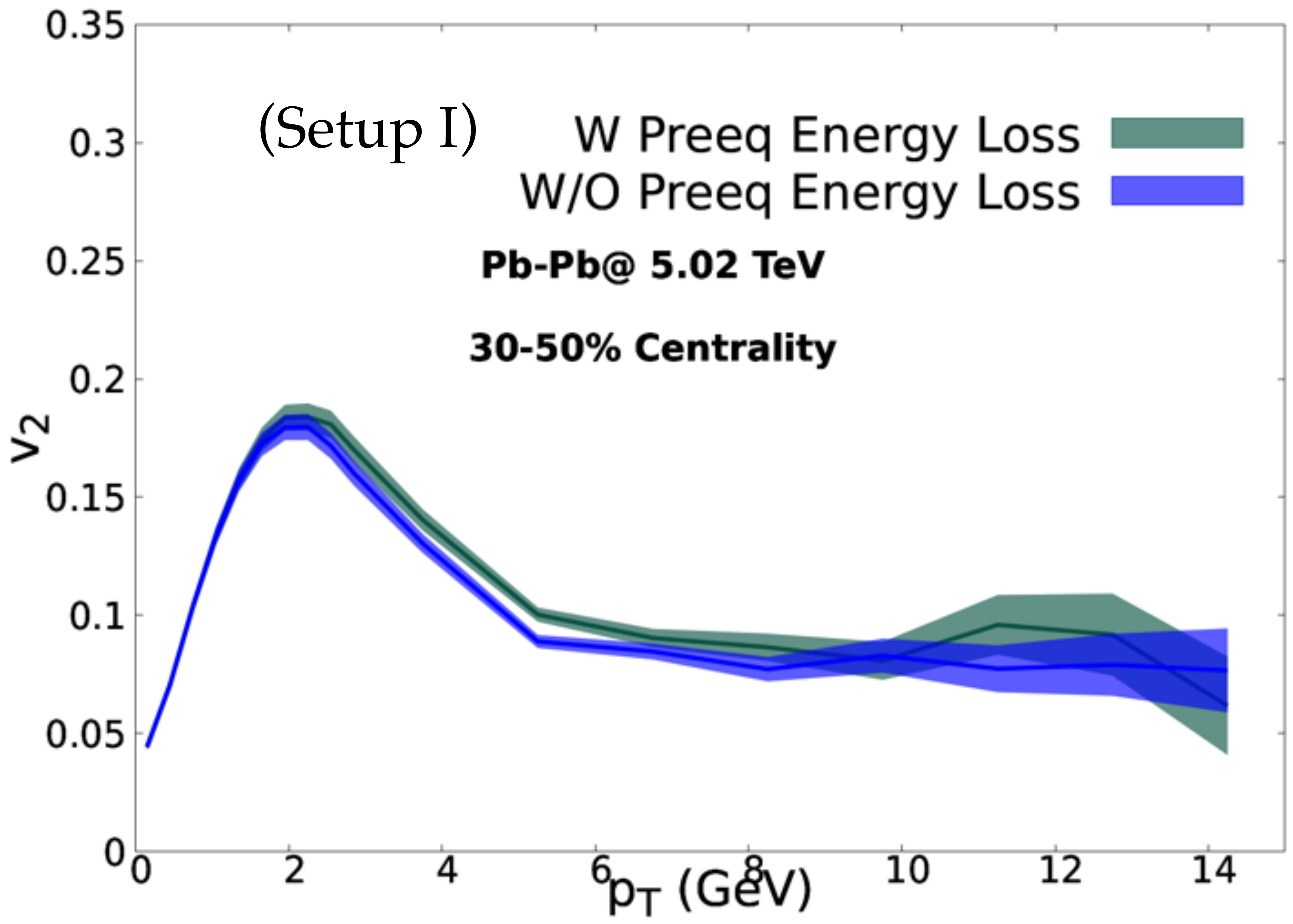
- One parameter that quantifies the impact of pre-equilibrium energy loss is the switching time from Initial state to plasma state.

- Hadronization by fragmentation process

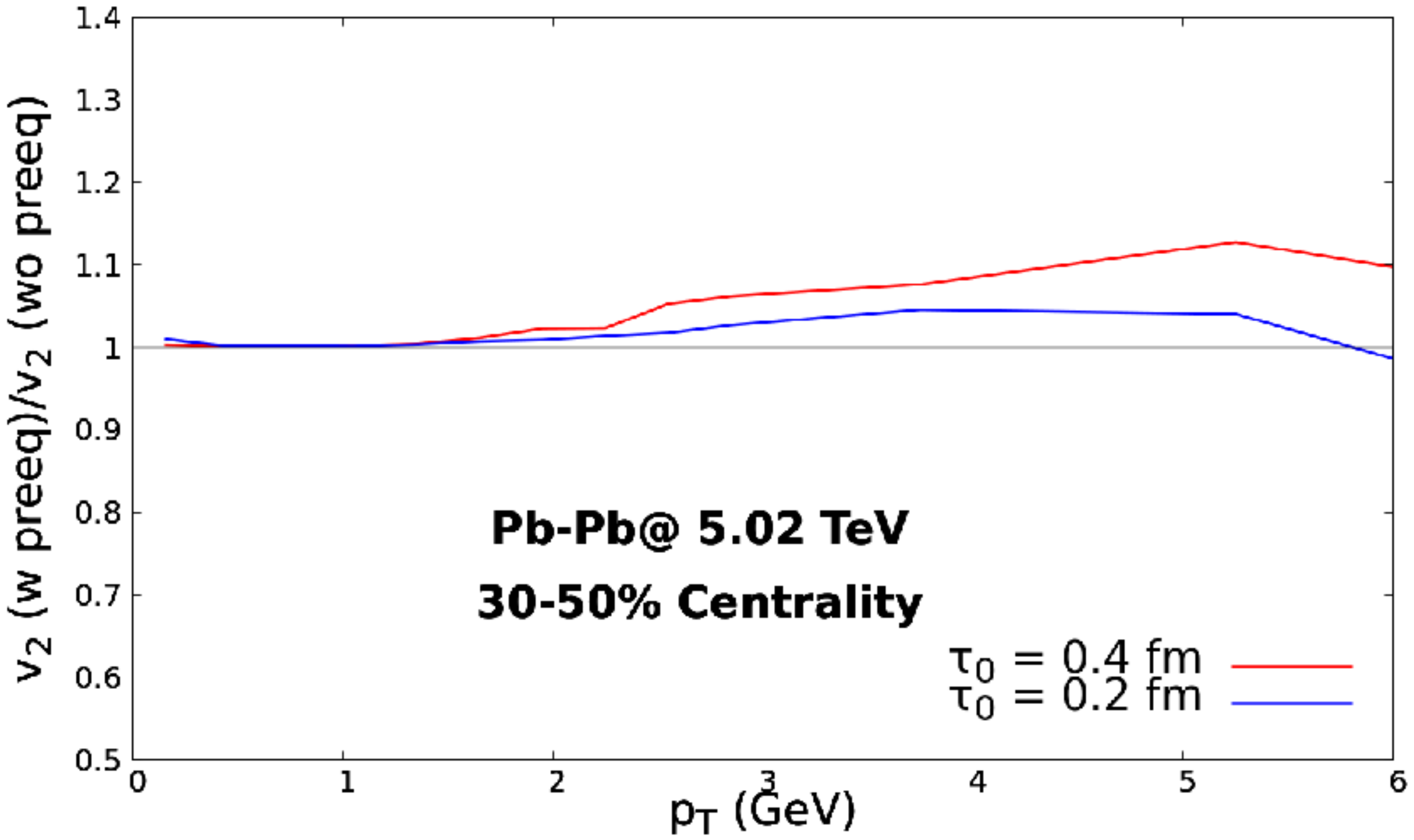
- The impact of HQ energy loss in the initial stage is non-negligible, especially at higher momentum



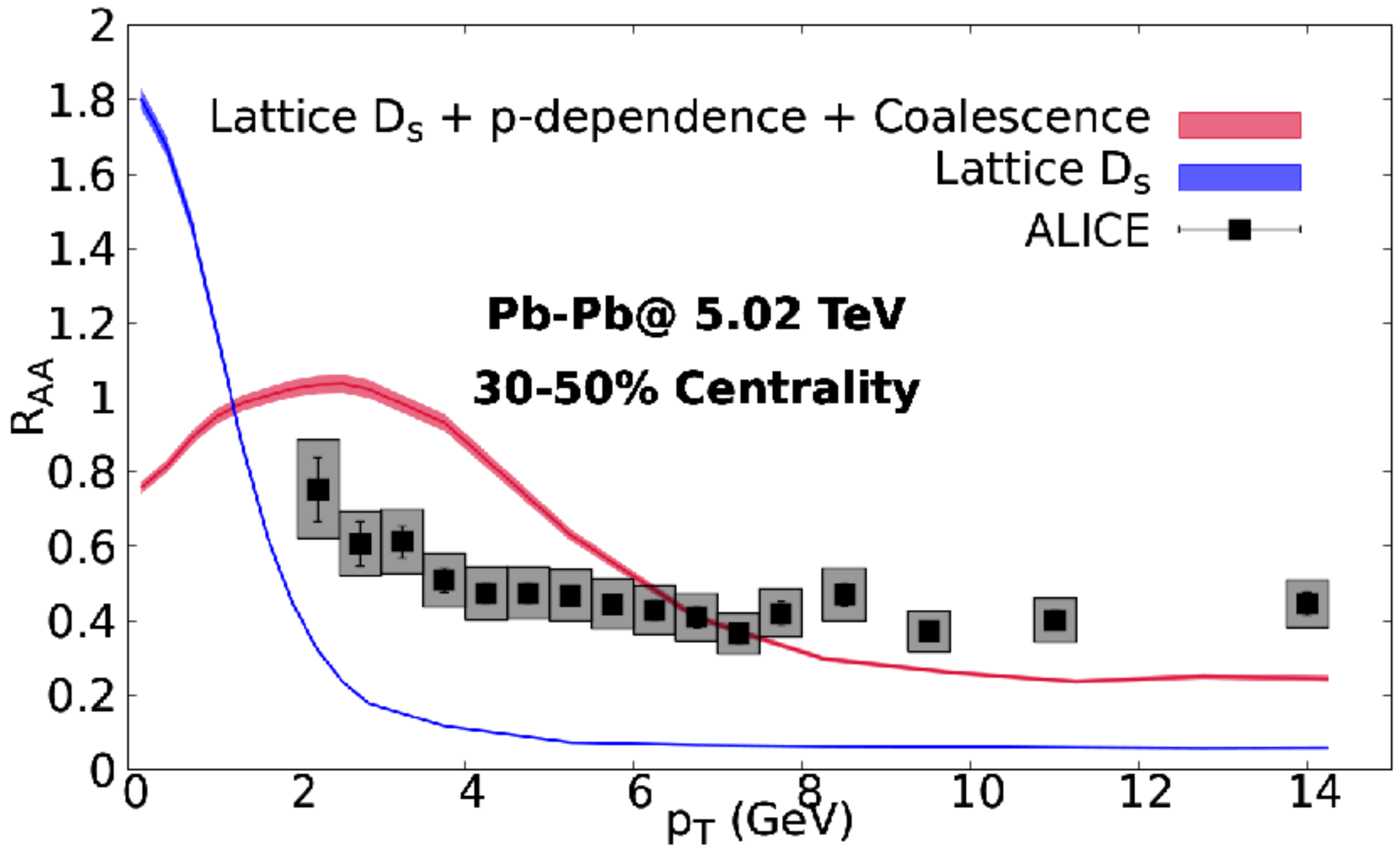
D-meson results: Preliminary

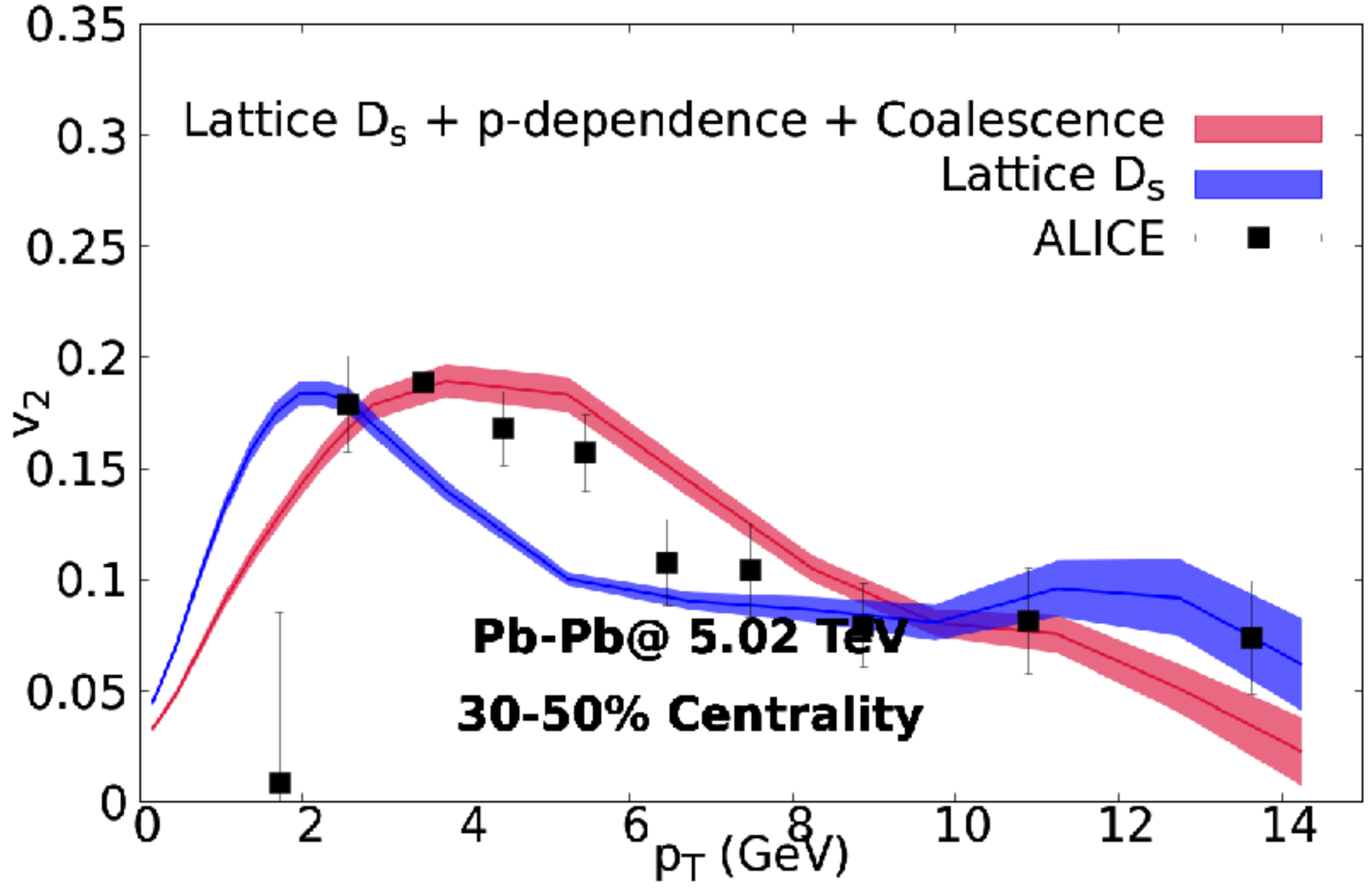


- More flow with the pre-equilibrium energy loss
- Effects are visible at higher momentum regime



D-meson results: Preliminary





- Red curves (Setup II) are with Fragmentation + Coalescence hadronization model
- The momentum dependence of the heavy quark diffusion coefficient also seems to have an important role

Summary

- Heavy quark is mostly created in the very early stage of the collision event, and they carry imprints of the initial state in nucleus-nucleus collisions.

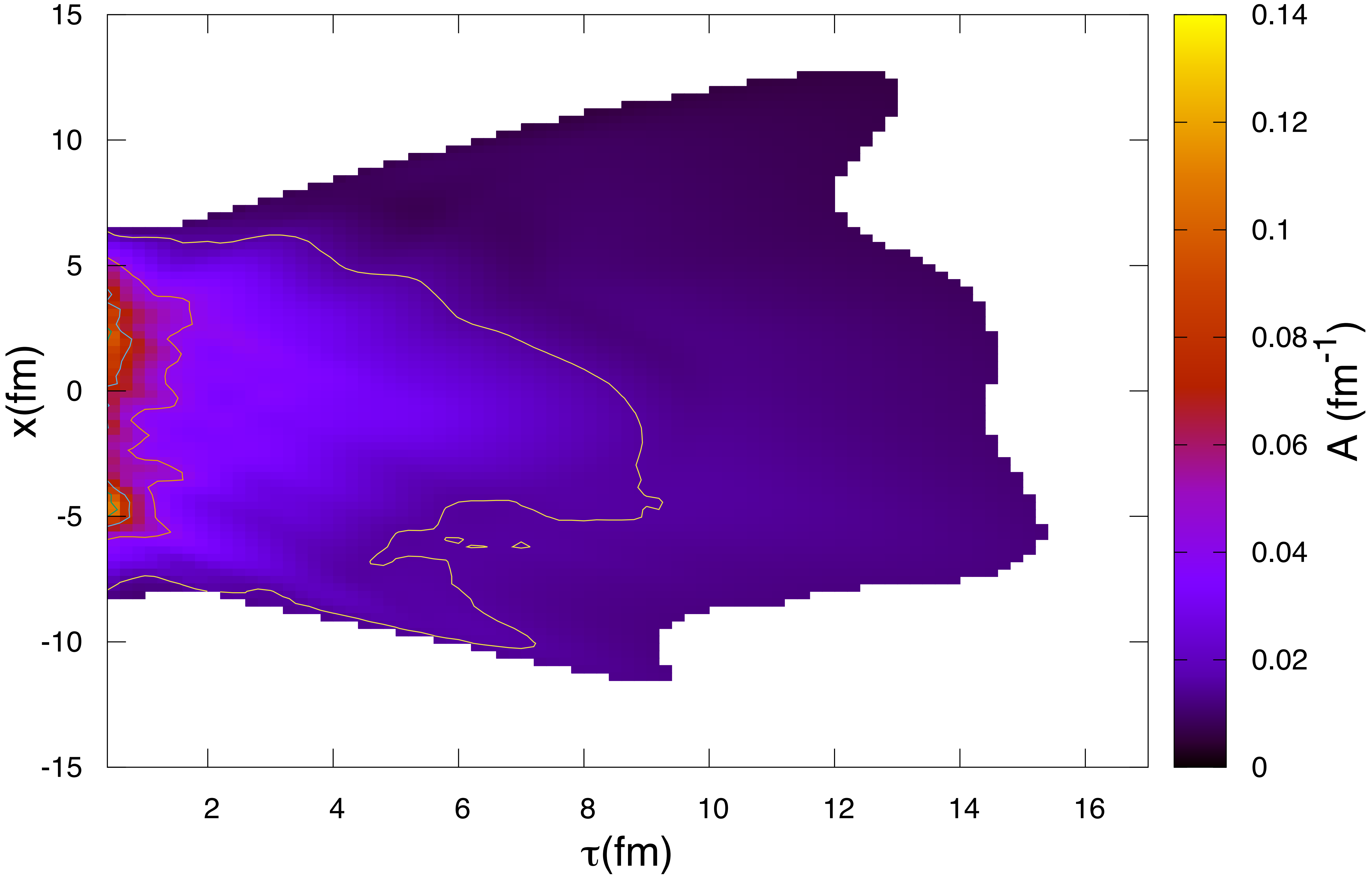
- We modelled relativistic heavy-ion collisions at LHC energy with a hybrid dynamical approach consisting of a fluctuating IP-Glasma initial state followed by viscous hydrodynamics (MUSIC).

- We observe that nuclear modification factor and flow coefficient of D-mesons in Pb+Pb collisions at 5.02 TeV are sensitive to the energy loss of charm quarks during the early stages of the collision

Thanks!

Back-up

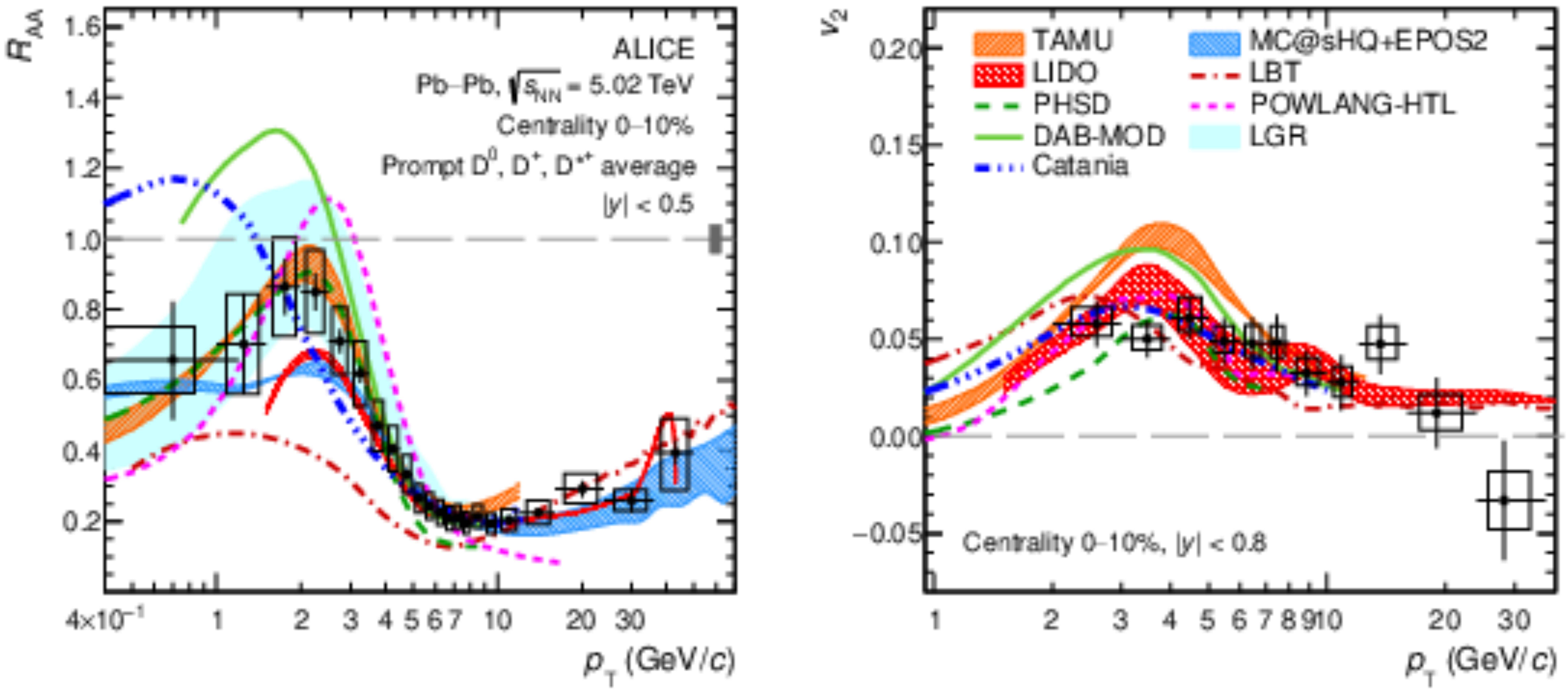
Charm quark drag in an expanding QGP



Drag coefficient of a charm quark with momentum p = 5 GeV at different space-time points. Curved lines indicate constant drag coefficient contours.

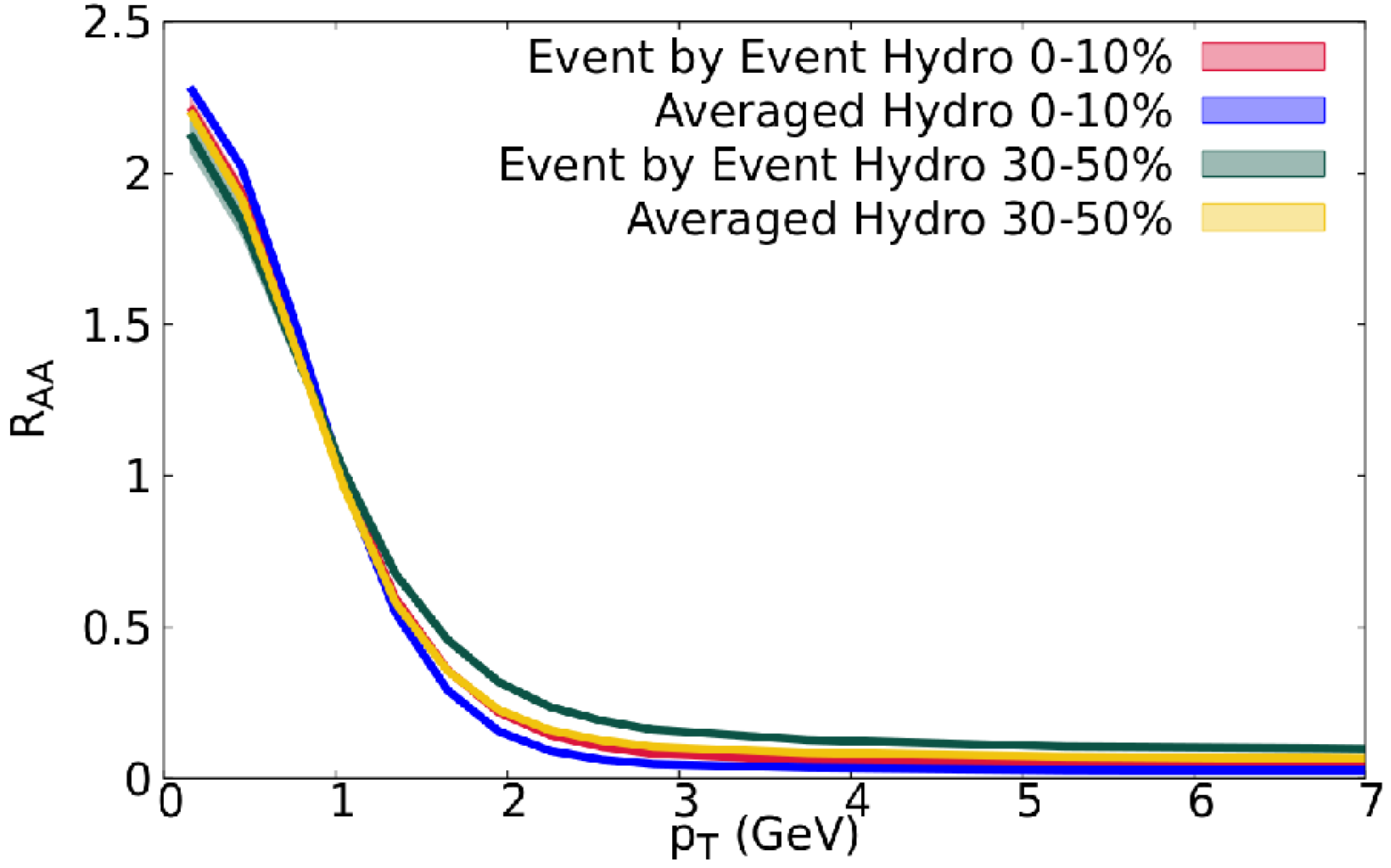
- Pb+Pb collision at 2.76 TeV
- Charm quark interaction is depends on the medium evolution (pQCD estimation of drag coefficient is shown as an example)
- However, pQCD calculation significantly under predicts the HQ energy loss in medium!!

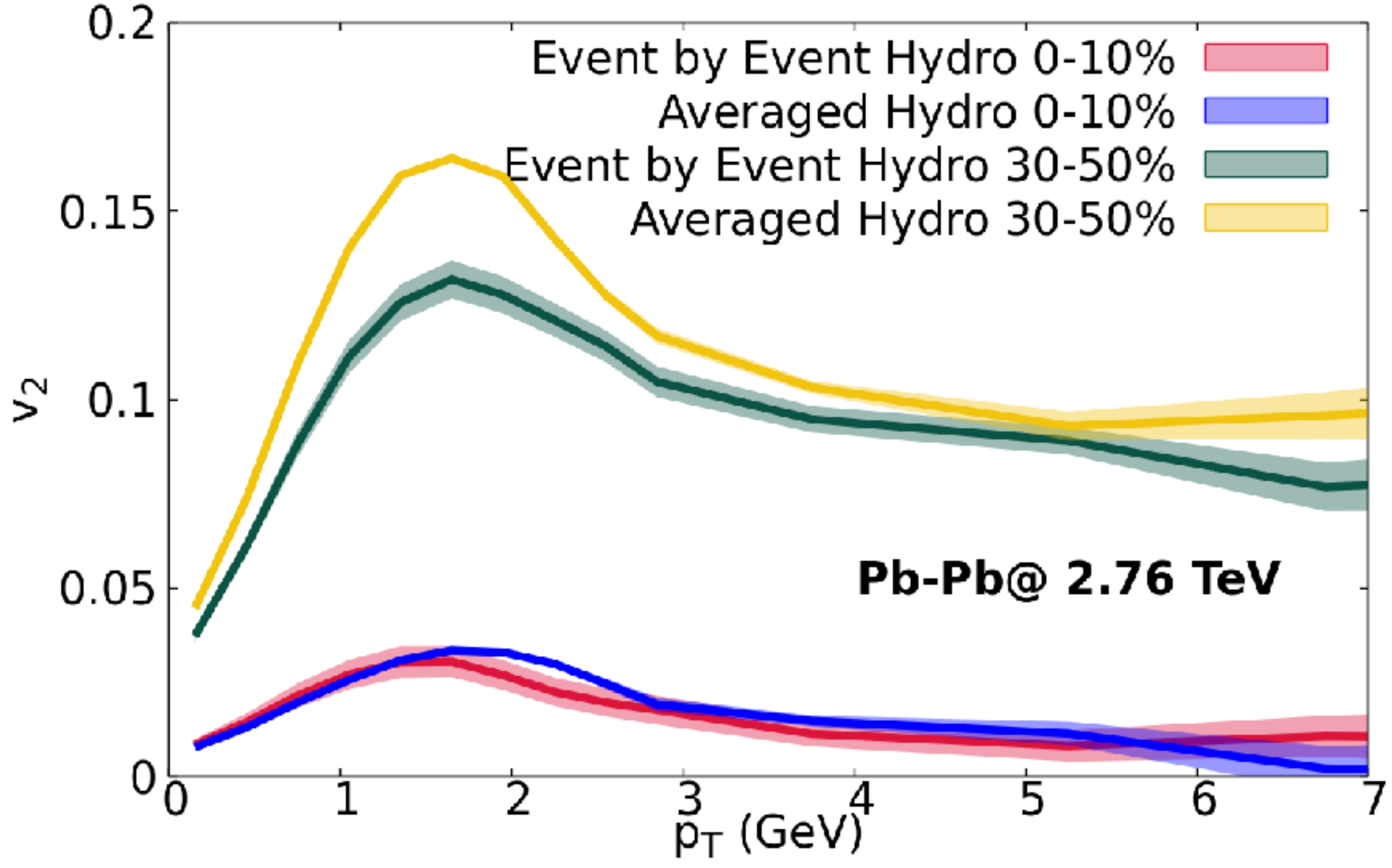
HQ observables



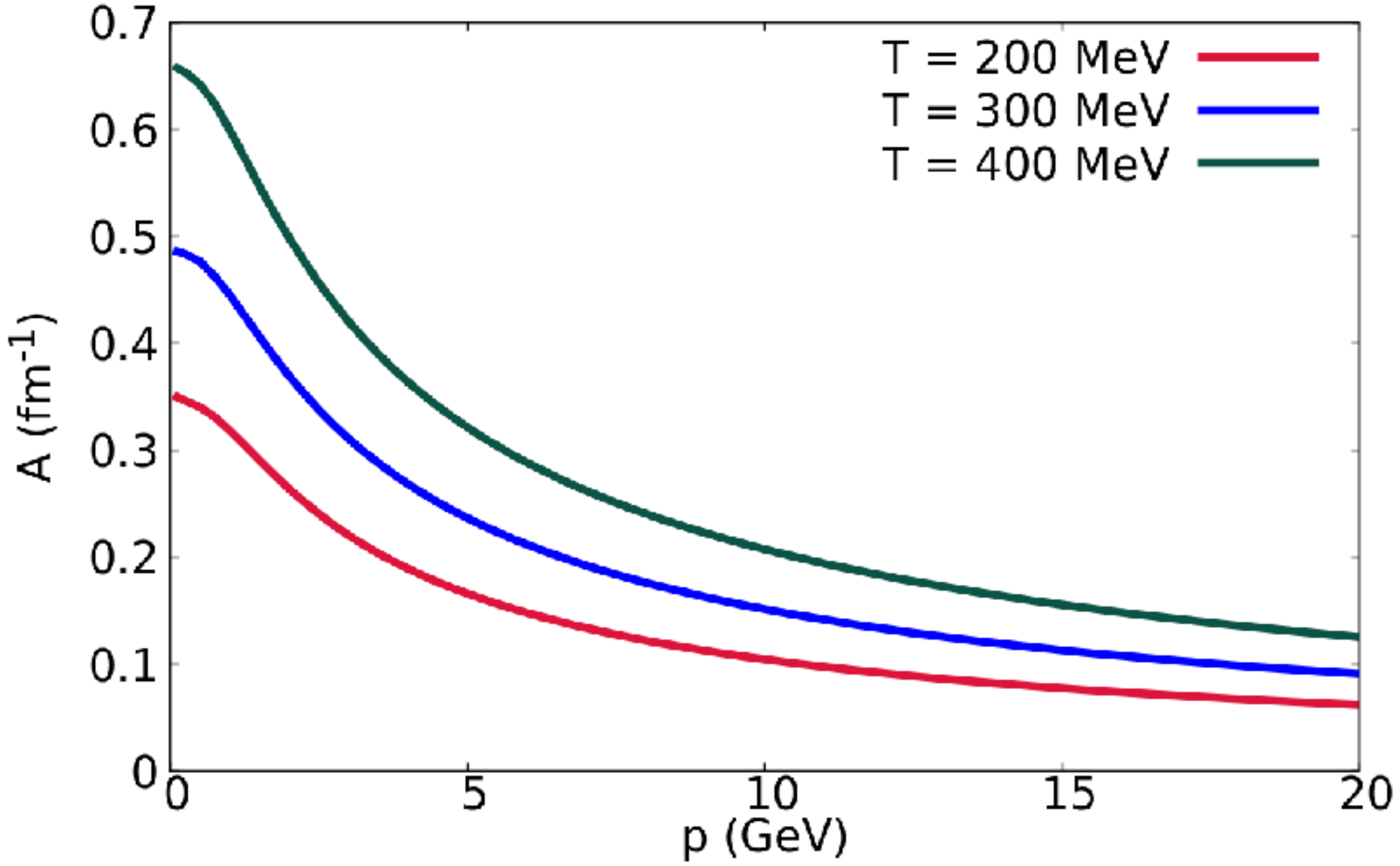
D-meson results

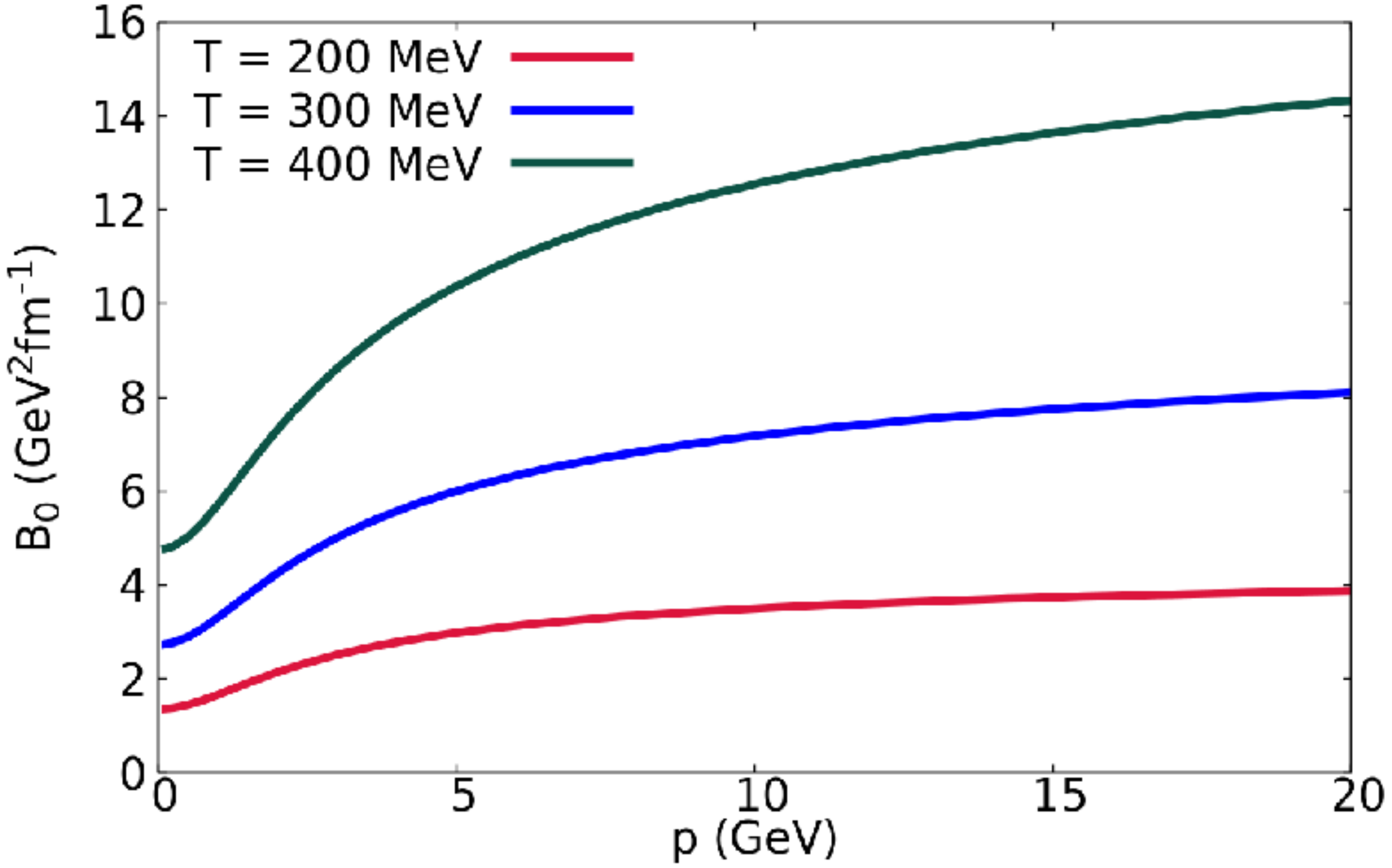
Pb+Pb 2.76 TeV 30-50%





Momentum dependence of HQ coefficients





M. Singh, M. Kurian, S. Jeon, C. Gale, PRC 108, 054901108 (2023)