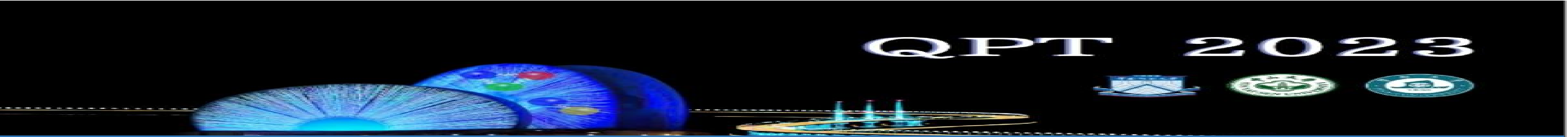

The 15th Workshop on QCD Phase Transition and Relativistic Heavy-Ion Physics (QPT 2023)

Scaling behaviors of heavy flavor meson suppression and flow in different nuclear collision systems at the LHC

Shu-Qing Li (Jining University)

with Wen-Jing Xing, Xiang-Yu Wu, Shanshan Cao，Guang-You Qin

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Dec 17th 2023 Zhuhai

濟寧學院 JINING UNIVERSITY

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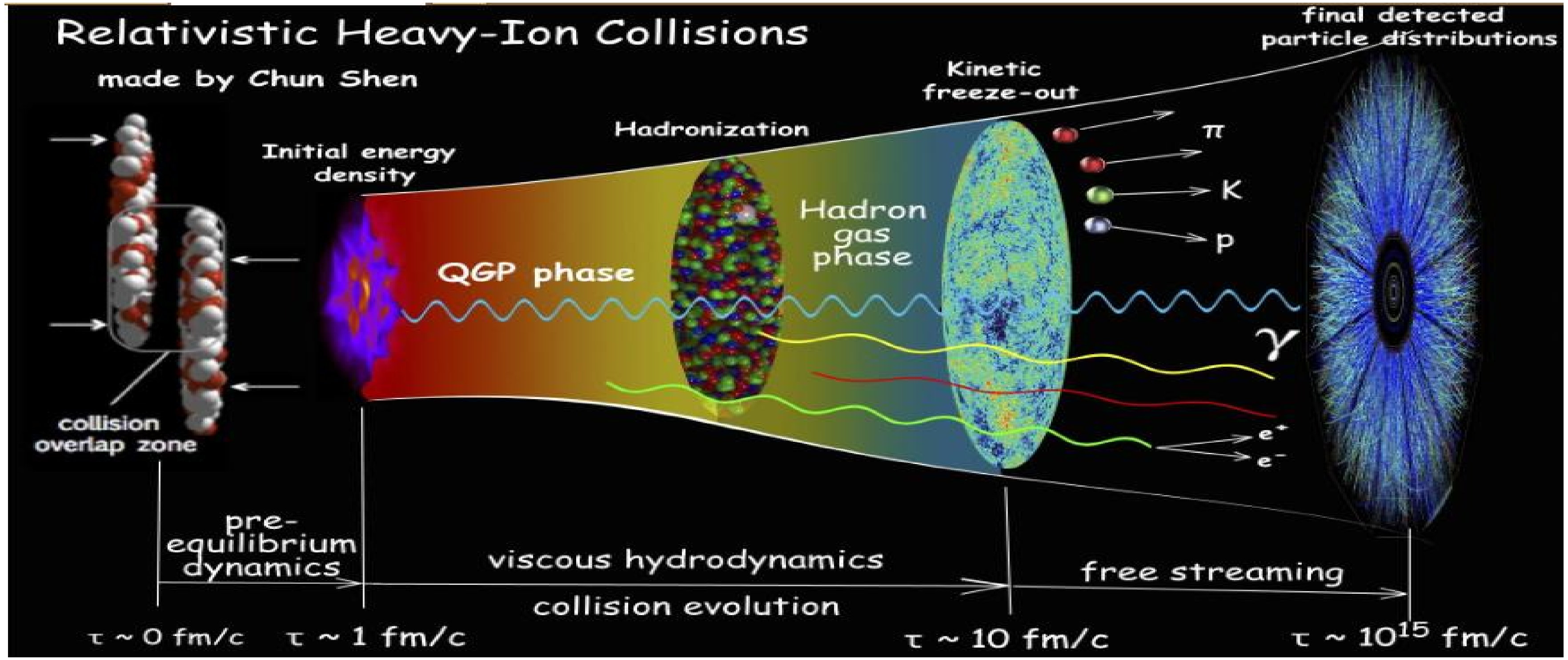
Outline

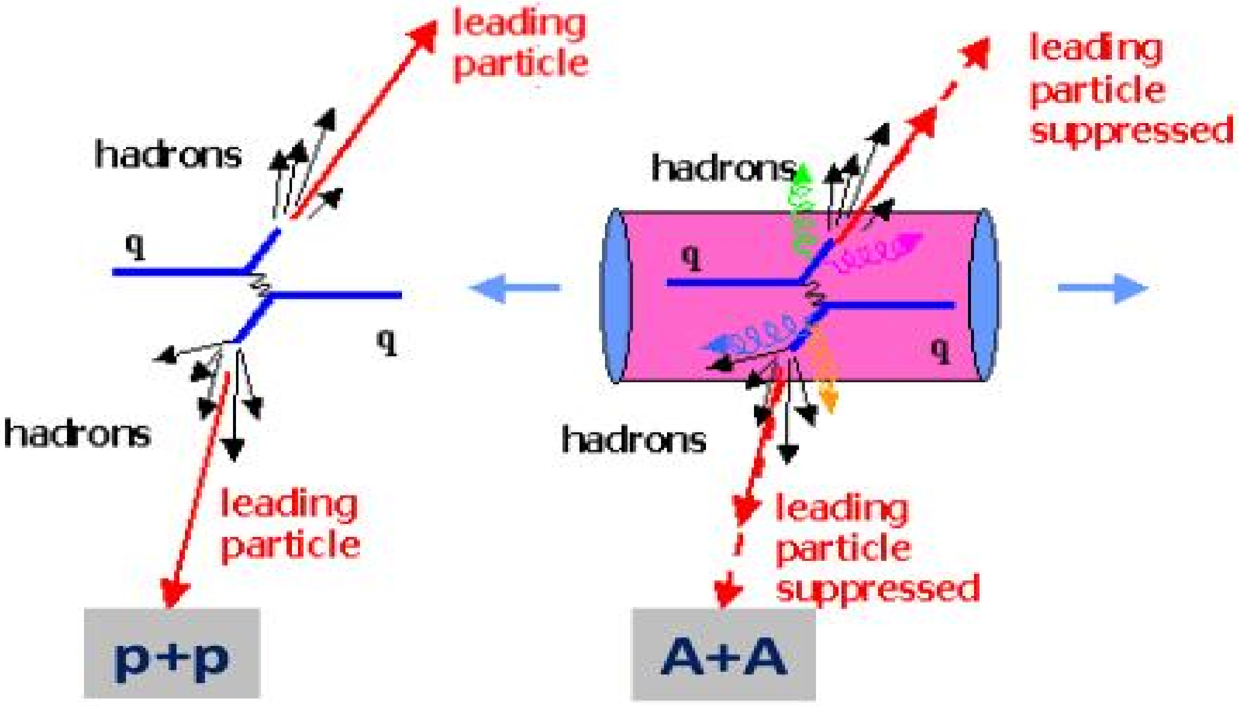
- **Introduction**
- **Langevin-hydrodynamics framework**
- **Numerical results**
- **Summary**

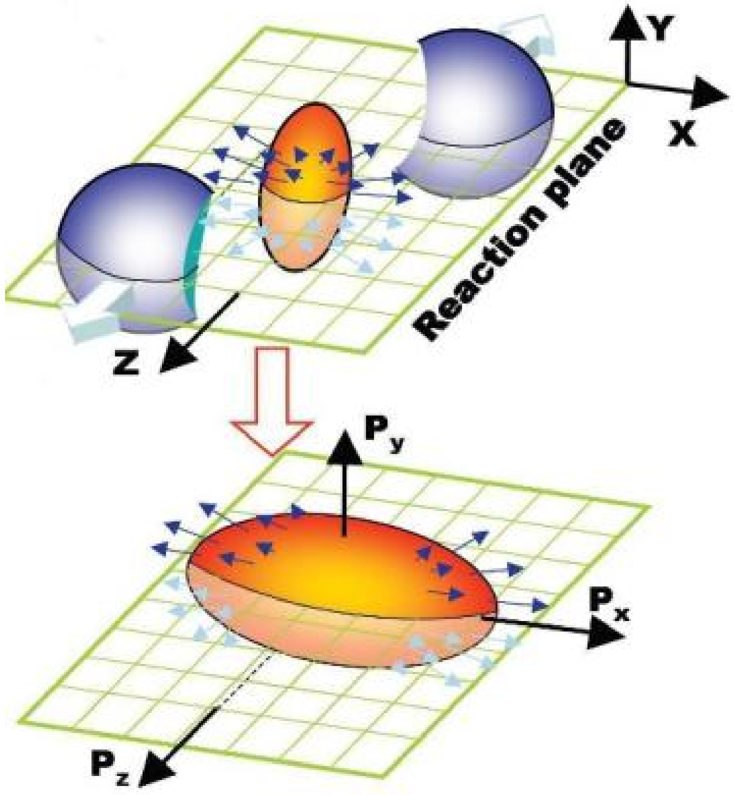
Introduction: Heavy flavor quenching in heavy ion collision



- Heavy Ion Collision
  - ☐ high temperature and density experimental conditions
- QGP
  - ☐ the strongly-coupled nature of this fluid-like QGP
- Heavy flavor Quenching and anisotropic flow
  - ☐ the two most important signatures

Introduction: Heavy flavor quenching and anisotropic flow





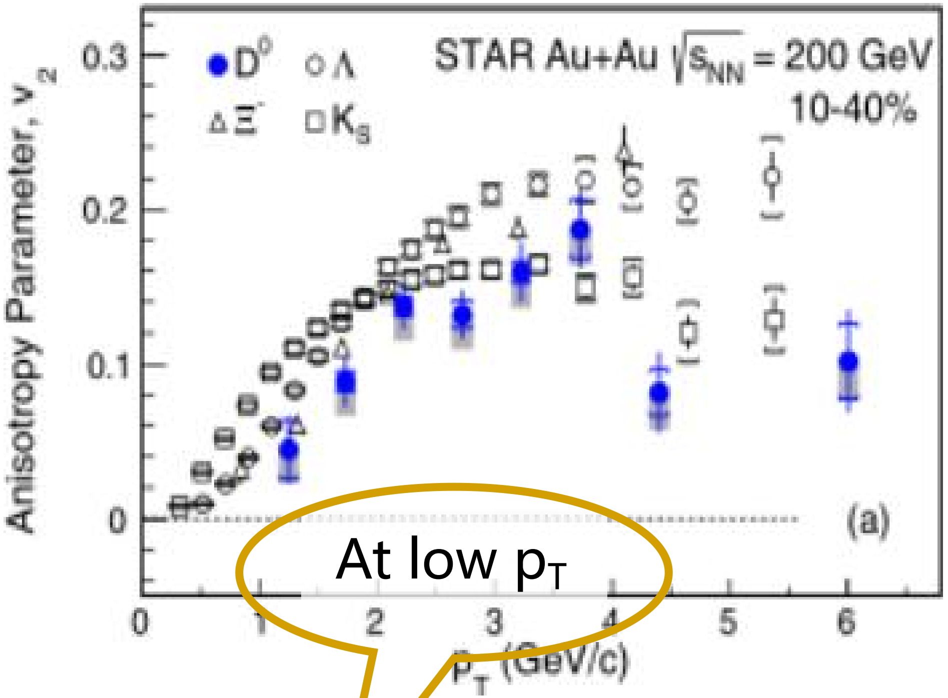
$$R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{dN^{AA}/dp_T}{dN^{PP}/dp_T}$$

$$v_2(p_T) = \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

Introduction: Experimental results at the RHIC and LHC

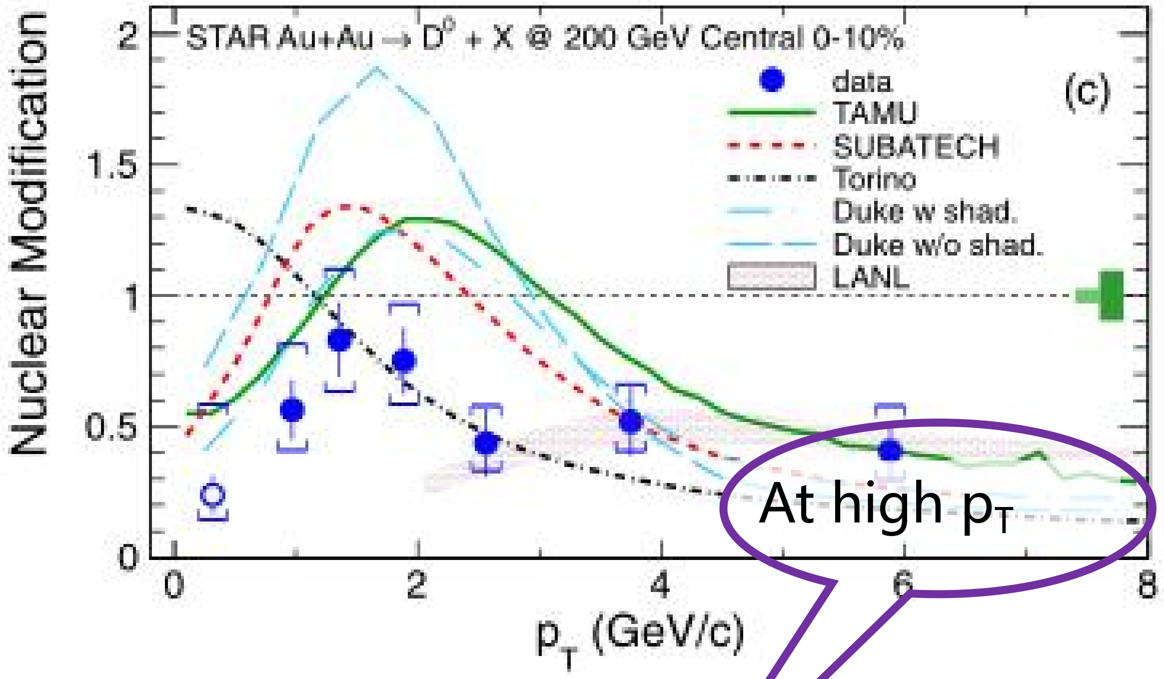
- **RHIC Au+Au**

Phys. Rev. Lett. 121,229901(E)(2018)



At low p_T

exhibit strong anisotropy



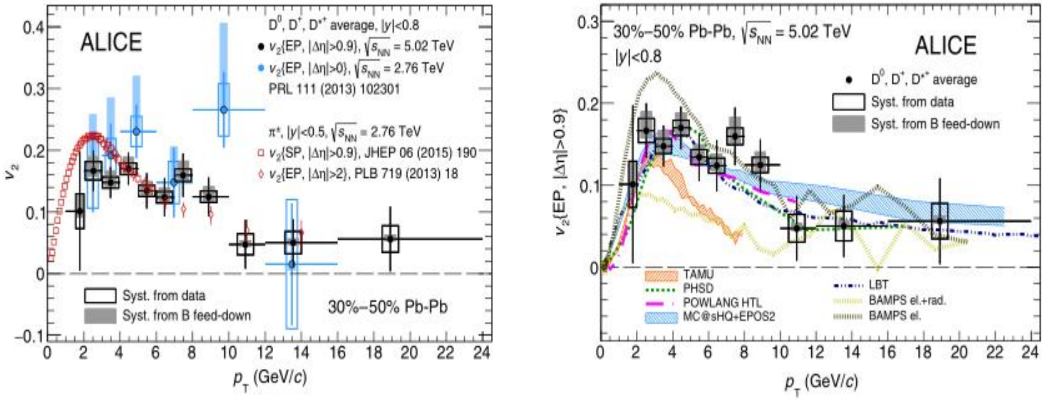
At high p_T

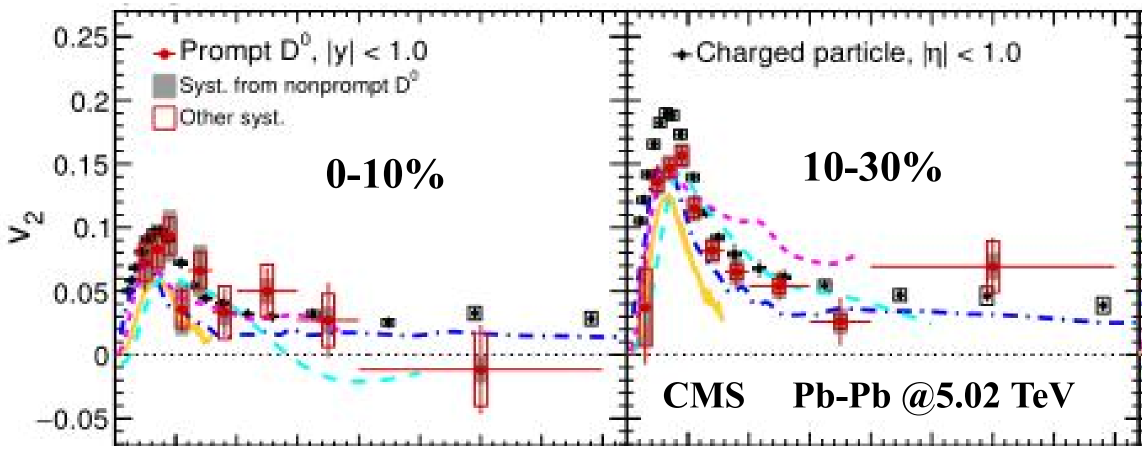
are significantly quenched

Introduction: Experimental results at the RHIC and LHC

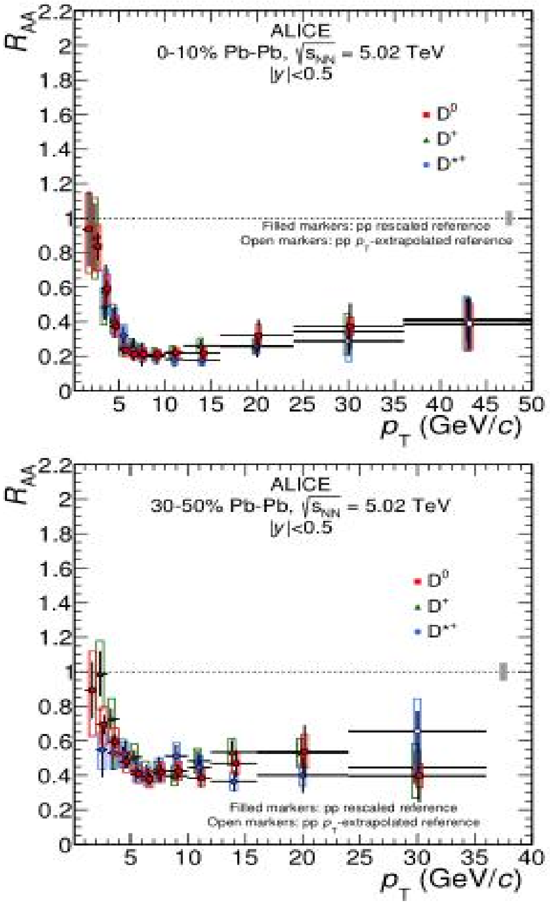
- **LHC Pb+Pb**

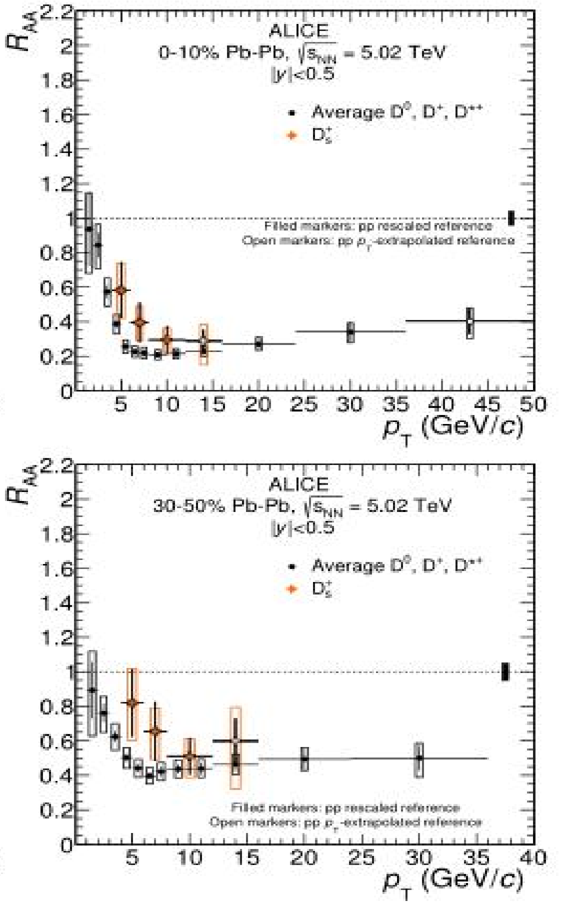
Phys. Rev. Lett. 120, 102301 (2018)





Phys. Rev. Lett. 118, 212301 (2017) **JHEP 10, 174 (2018)**





At low p_T : exhibit strong anisotropy

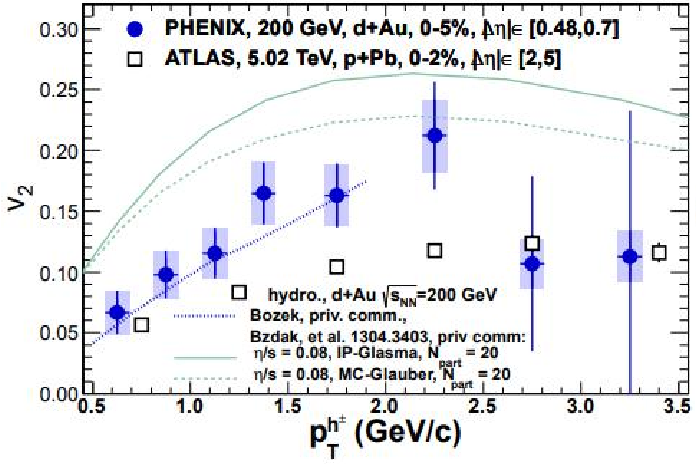
At high p_T : are significantly quenched

Introduction: Experimental results in small collision systems

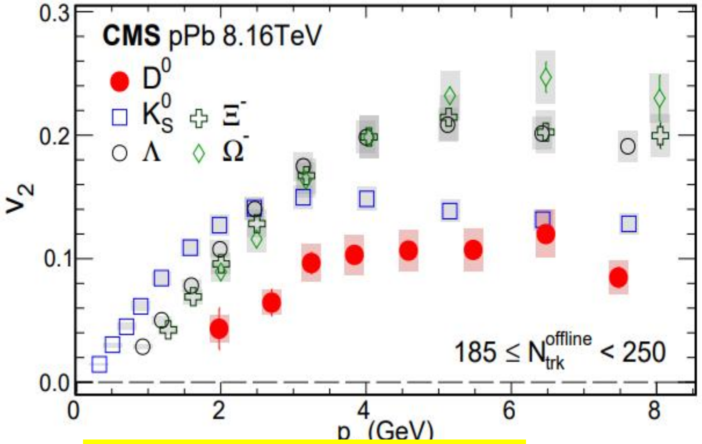
- **RHIC d-Au**

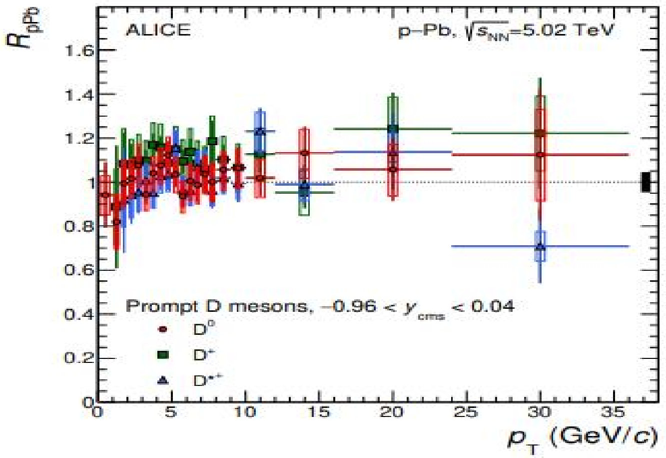
LHC p-Pb

PRL 111 (2013) 21, 212301

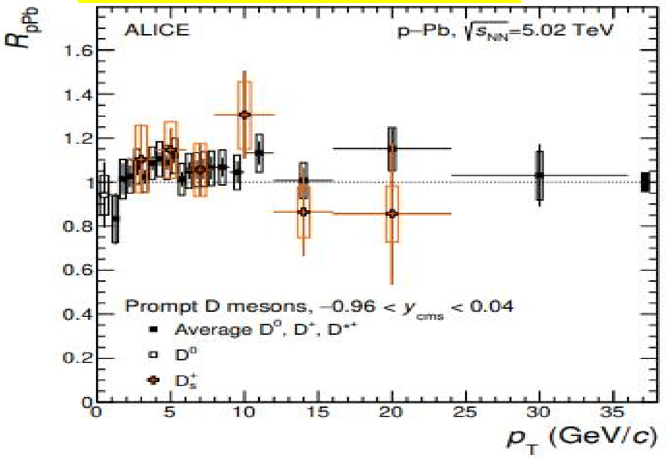


PRL 121 (2018) 8, 082301





JHEP 12 (2019) 092



- ☐ large anisotropic flows have been observed in small collision systems.
- ☐ implying the possible formation of mini-QGP in such small systems.
- ☐ R(pPb) of D mesons is consistent with unity in p-Pb collisions.

The collectivity observed in small systems originates from :

◆ final state QGP effects

◆ from initial state gluon saturation effects

Introduction: Theoretical current status

One possible way

- Disentangle the initial state and final state contributions to jet observables.
- Scan the jet quenching effect across various sizes of nuclear collision systems.
- This would bridge the gap between large and small systems.
- May hopefully help dentify the boundary across which QGP disappears.

Theoretical efforts

- Explore the nuclear modification effects on high p_T hadrons in systems smaller than Pb–Pb collisions at the LHC enegies.
- How parton energy loss depends on the size of collision systems.

Chin. Phys. C 43, 044101 (2019)
Phys. Rev. C 102, 041901 (2020)
Phys. Rev. C 101, 021901 (2020)
Phys. Rev. C 103, 054903 (2021)
Phys. Rev. Lett. 126, 192301 (2021)

Our work Using heavy quarks to probe QGP with different sizes.

Langevin-hydrodynamics framework

MC simulation General framework

(3 + 1)-dimensional CLVisc hydrodynamic model

Dynamical evolution of the QGP medium in AA collisions

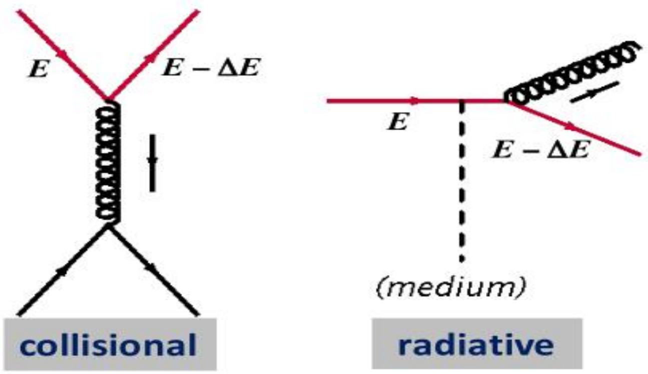
Heavy quarks are mainly produced via initial hard scatterings

Initial momentum distribution given by PQCD

Heavy quarks evolution inside QGP

Modified Langevin equation

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g$$



Heavy flavor mesons

Heavy flavor meson suppression(R_{AA}) and flow(v_2)

Hybrid coalescence-fragmentation model

Low p partons combine with thermal partons into hadrons

High p partons fragment into hadrons

Numerical results： Heavy Flavor Meson R_{AA} and v_2

Langevin-hydrodynamics framework

$D_s(2\pi T) = 4$

☐ Four collision systems

- ✓ Pb–Pb @5.02 TeV
- ✓ Xe–Xe @5.44 TeV
- ✓ Ar–Ar @5.85 TeV
- ✓ O–O @6.5 TeV

☐ Three collision centralities

- ✓ 0-10%
- ✓ 30-40%
- ✓ 60-80%

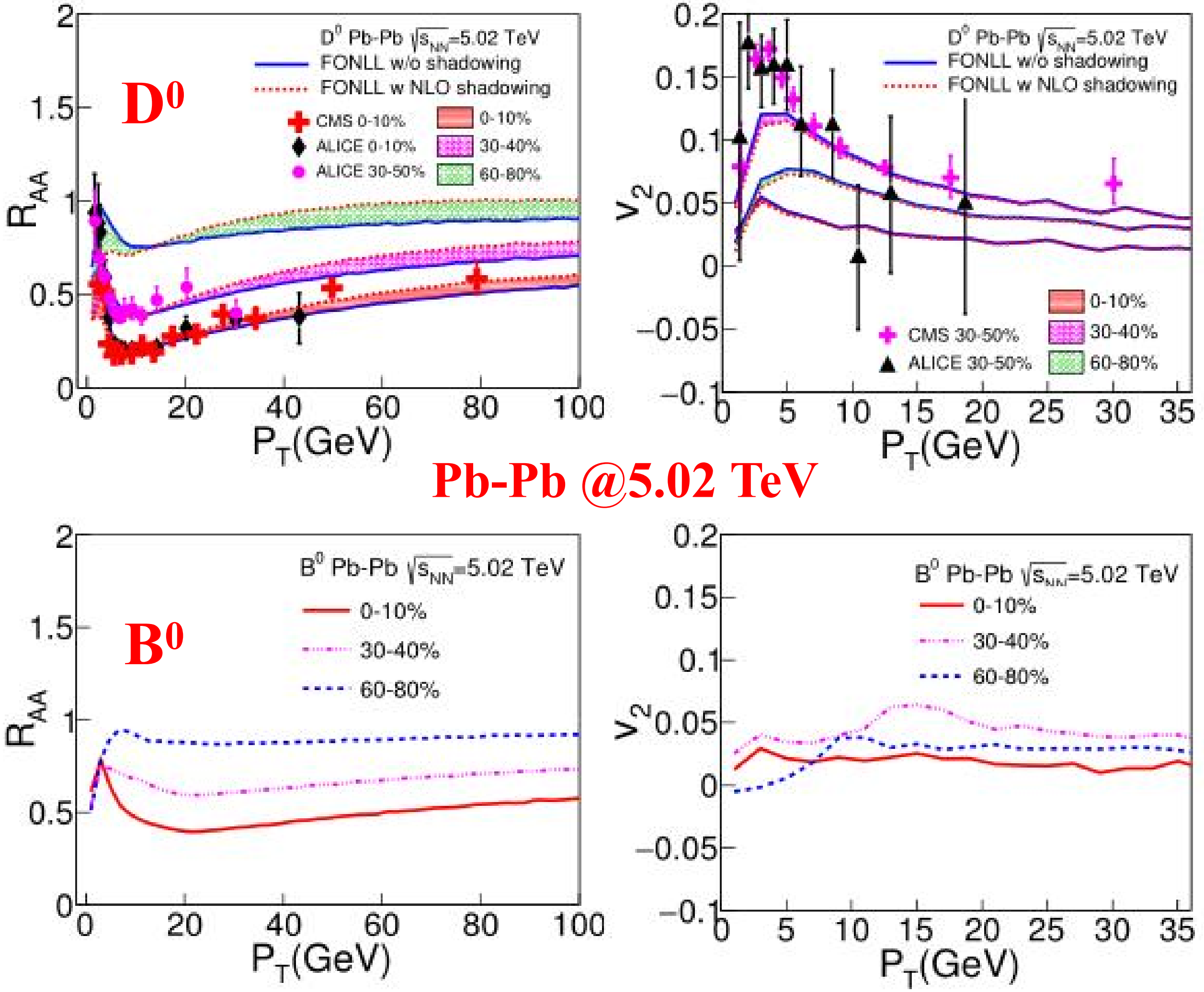
☐ Two heavy mesons

- ✓ D meson
- ✓ B meson

☐ Two physical observabiles

- ✓ R_{AA} vs. p_T , v_2 vs. p_T
- ✓ R_{AA} vs. $< N_{part} >$, v_2 vs. $< N_{part} >$
- ✓ R_{AA} vs. centrality, v_2 vs. centrality
- ✓ v_2 / ε_2 vs. $< N_{part} >$

Numerical results : Heavy Flavor Meson R_{AA} and v_2



Pb-Pb @5.02 TeV

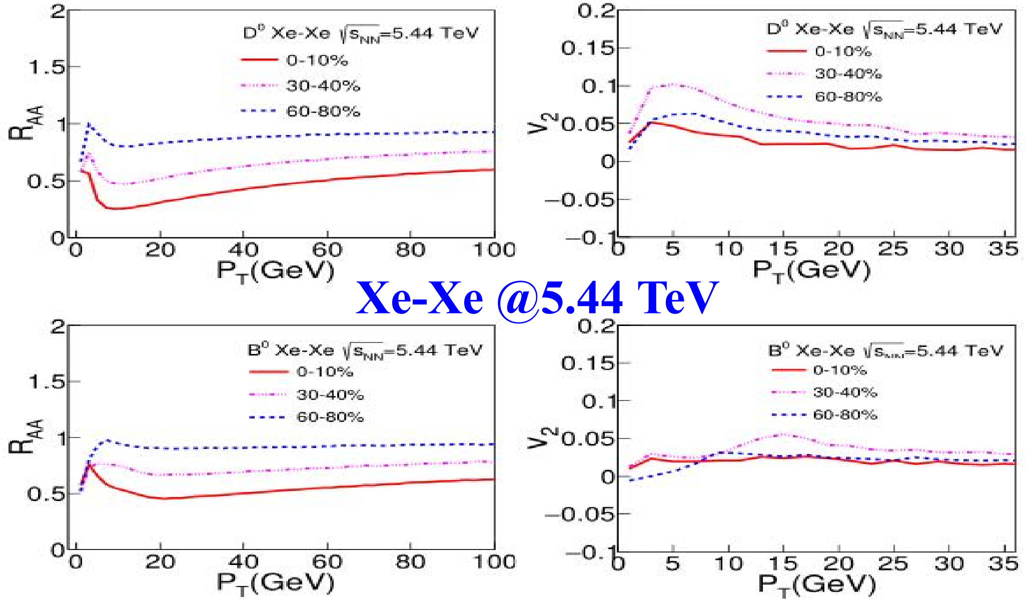
- A suppression of the D^0 R_{AA} at low p_T, while an enhancement (anti-shadowing) at high p_T. this shadowing effect has little impact on the D^0 v_2.

- The results are consistent with the exerimental data . This helps confirm the satisfactory path-length dependence of parton energy loss embedded in our transport model.

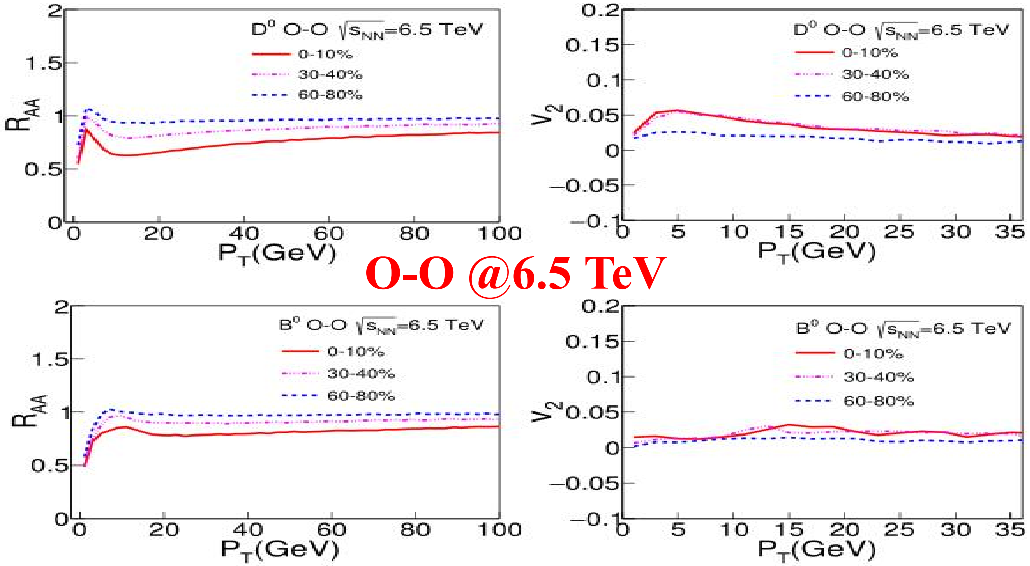
- A clear hierarchy in the heavy meson $R_{AA.}$ Larger heavy quark energy loss in more central collisions leads to a smaller nuclear modification factor. A maximum for elliptic flow v_2 in semi-central/peripheral collisions.

- D^0 have smaller R_{AA} and larger v_2 than B^0 because charm quarks have much smaller mass than bottom quarks.

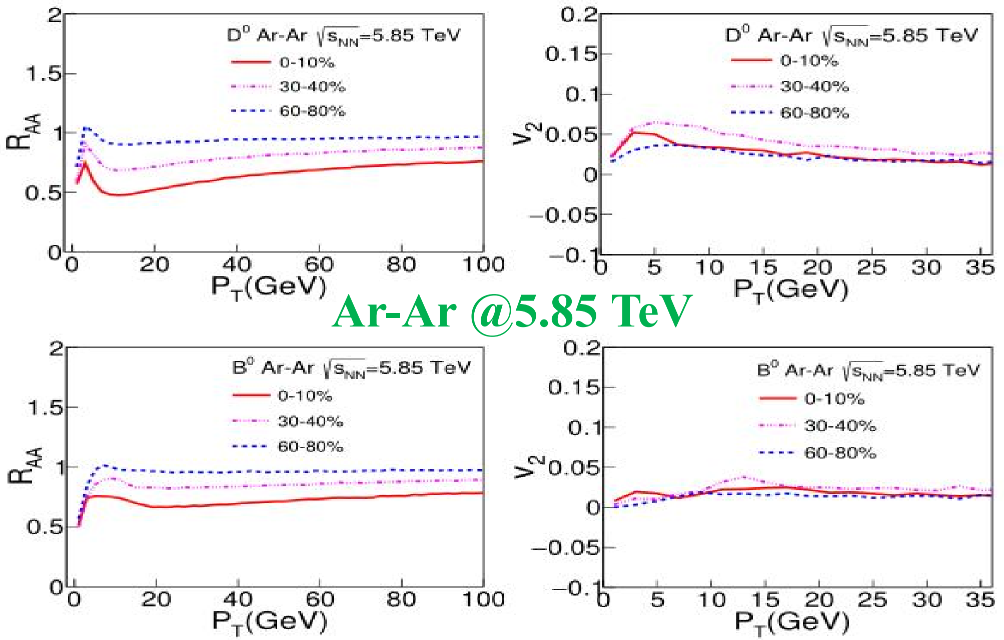
Numerical results： Heavy Flavor Meson R_{AA} and v_2



Xe-Xe @5.44 TeV



O-O @6.5 TeV



Ar-Ar @5.85 TeV

- Similar to previous results for Pb–Pb collisions.
- Parton energy loss becomes weaker inside a smaller collision system.
- The larger heavy flavor meson R_{AA} and smaller v_2 inside a smaller collision system within the same centrality.

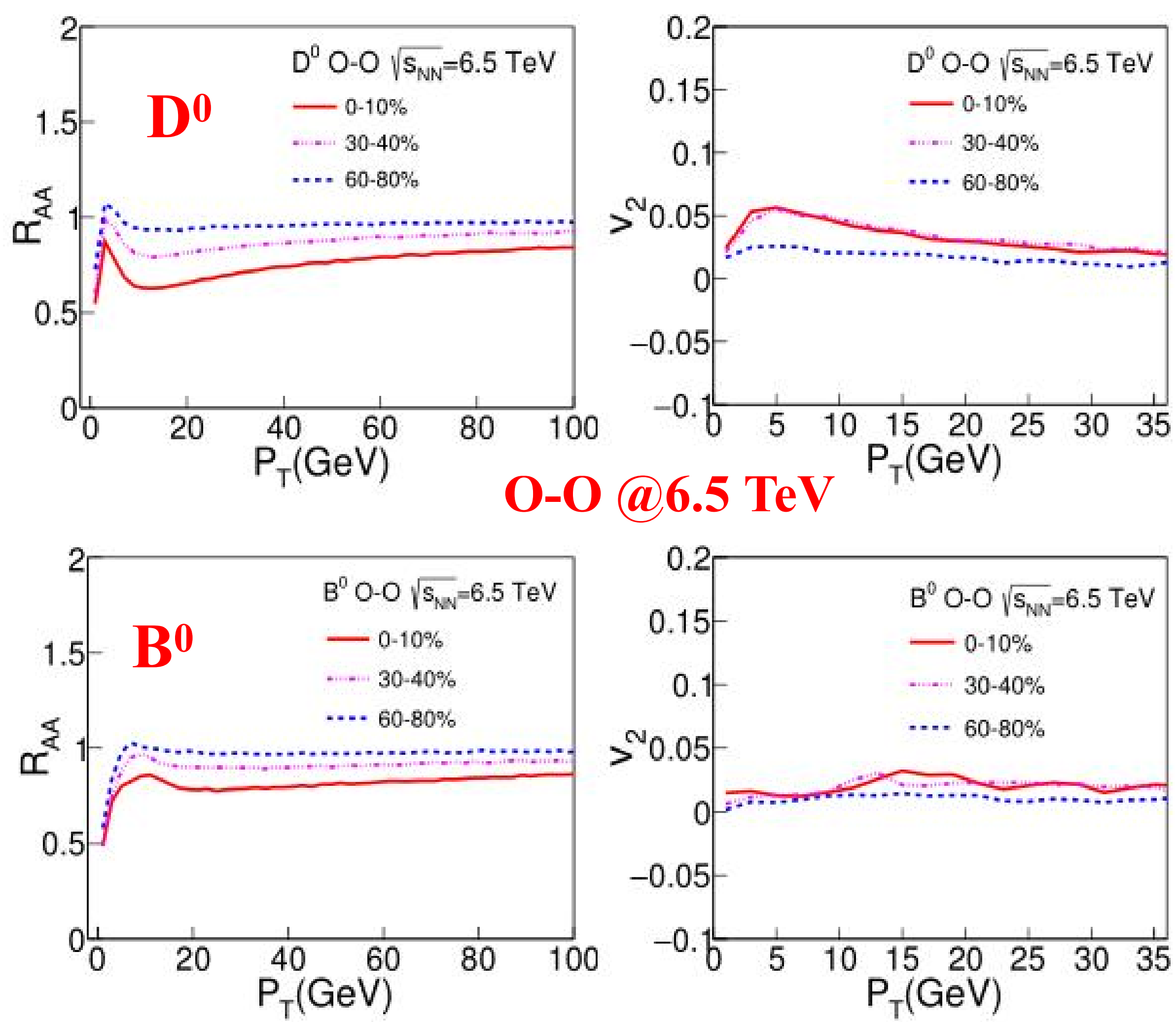
Numerical results： Heavy Flavor Meson R_{AA} and v_2

- Amount of energy loss effects are found for both charm and bottom quarks in the most central collisions with O–O collisions.

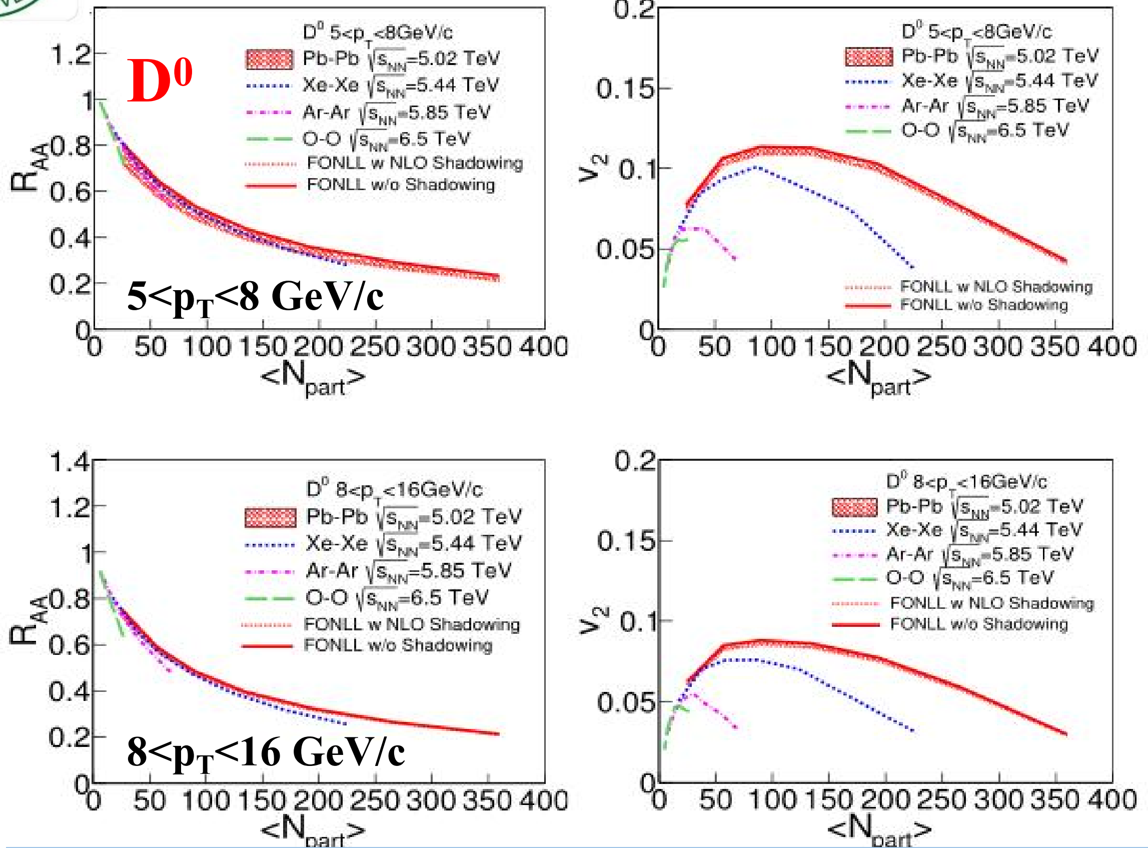
- From central to peripheral collisions, heavy flavor meson R_{AA} increases and approaches unity at high p_T in peripheral collisions.

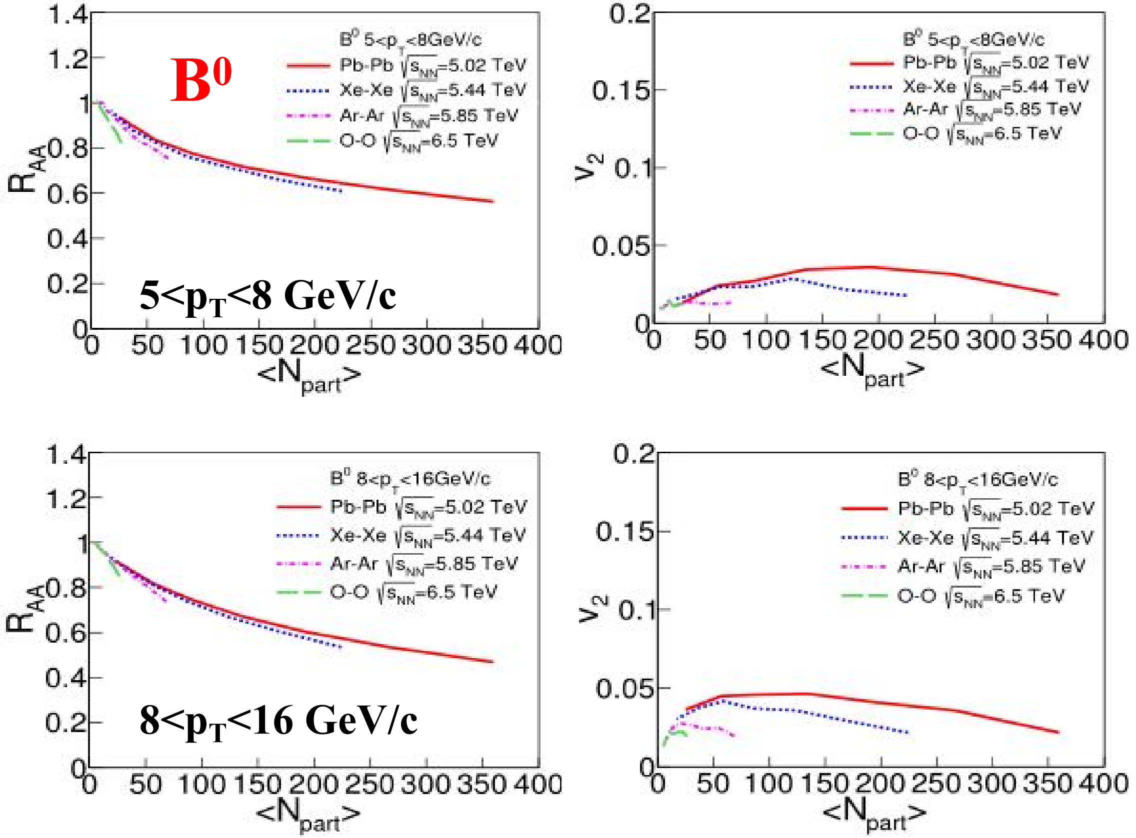
- The rise-and-fall structure of R_{AA} at low p_T region is due to the coalescence mechanism in heavy hadron formation in the presence of QGP medium.

- The heavy flavor meson v_2 first increases and then decreases as a function of centrality class due to the competing effects between parton energy loss and geometric anisotropy of the collision zone.



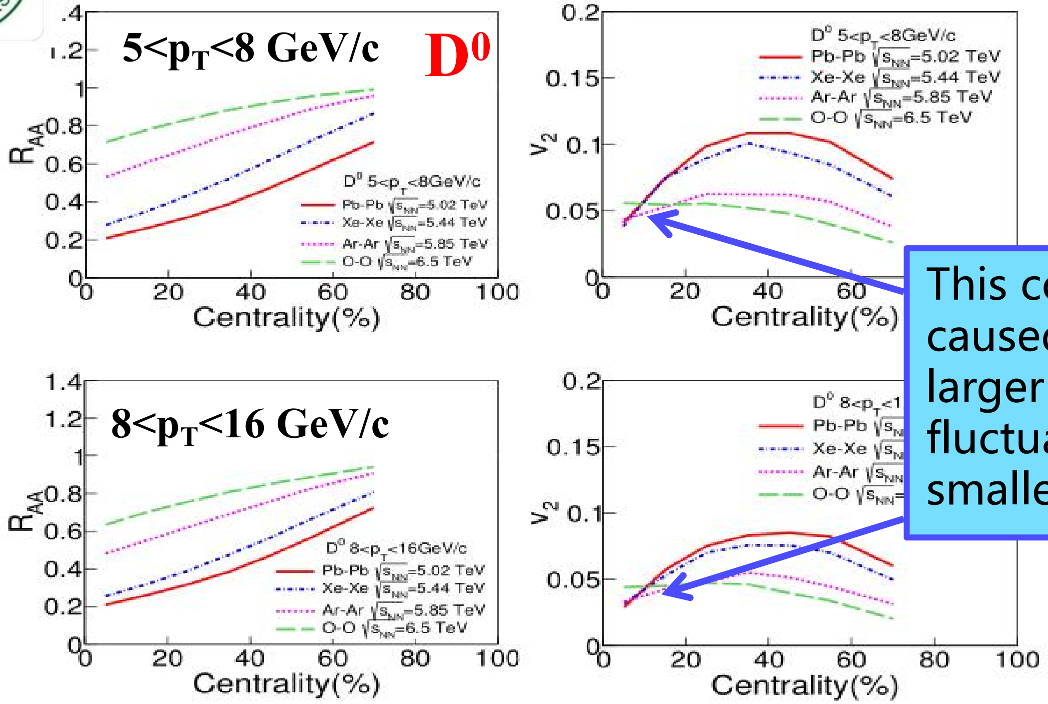
Numerical results： Heavy Flavor Meson R_{AA} and v_2



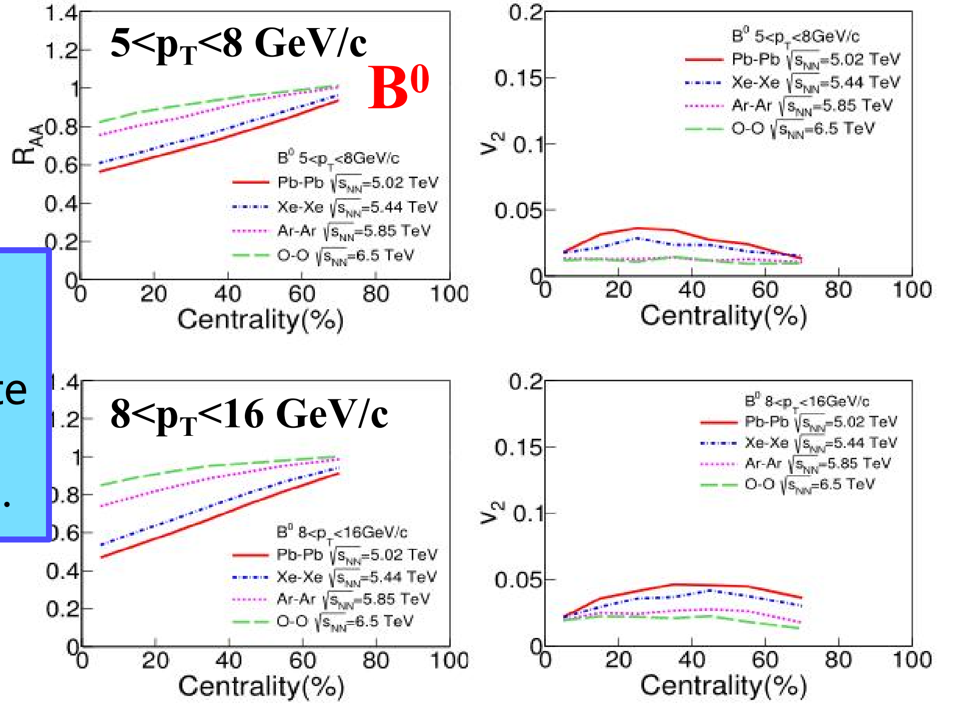


- A stronger nuclear modification of heavy mesons with a larger Npart.
- A clear nuclear modification of both D and B mesons even in the small-size O–O collisions as long as Npart is not small.
- Heavy flavor mesons produced from different collision systems share a similar R_{AA} as long as Npart is fixed.
- The hierarchy of Pb–Pb > Xe–Xe > Ar–Ar > O–O for the heavy meson v_2.

Numerical results： Heavy Flavor Meson R_{AA} and v_2



This could be caused by the larger initial state fluctuations in smaller O nuclei.



◆ The heavy flavor meson R_{AA} increases from central to peripheral collisions due to smaller heavy quark energy loss in more peripheral collisions.

◆ v_2 first increases and then decreases due to the competing effects between parton energy loss and medium geometry.

- A clearly observe the hierarchies of both R_{AA} and v_2 of heavy flavor mesons.
  R_{AA} : Pb–Pb < Xe–Xe < Ar–Ar < O–O
  v_2. : Pb–Pb > Xe–Xe >Ar–Ar > O–O

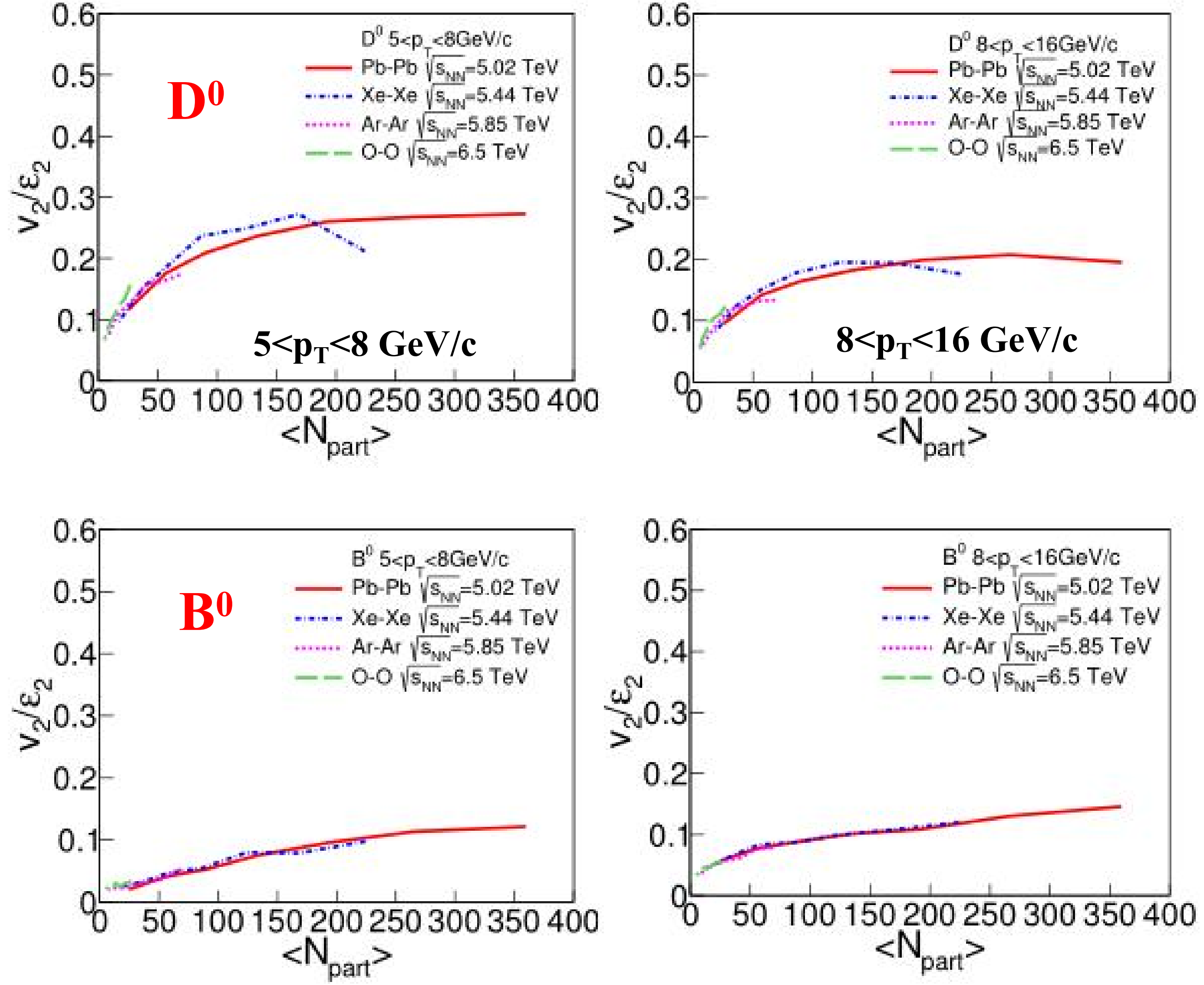
- D mesons have much smaller R_{AA} and much larger v_2 than B mesons due to the mass dependence of charm and bottom quark energy loss through the QGP.

Numerical results: Heavy Flavor Meson R_{AA} and v_2

- The rescaled v_2/ε_2 is mainly determined by the amount of parton energy loss, thus scales with the system size or Npart between different collision systems. This behavior is very similar to heavy meson R_{AA}.

- The main source of the heavy meson v_2/ε_2, the coupling of heavy quark motion to the QGP flow and the hadronization process can also affect the final state heavy meson v_2 .

- Such breaking is more prominent for low energy heavy quarks and when the bulk radial flow is strong.



Summary

- Within the Langevin-hydrodynamics framework, we have performed a systematic study on the system size dependence of heavy quark energy loss in heavy-ion collisions at the LHC energies.
- A clear system size dependence of heavy meson $R_{AA.}$,their v_2 simultaneously depends on the size and anisotropy of the QGP.
- A clear mass dependence of parton energy loss that yields smaller R_{AA} and larger v_2 of D mesons than B mesons for the same collision system and the same centrality class.
- The bulk-eccentricity-rescaled heavy meson elliptic flow (v_2/ε_2) is found to scale with Npart.
- This work provides a crucial bridge between large and small systems of relativistic nuclear collisions.
- Future system-size-scan experiments on jet quenching is expected to help resolve several open questions in high-energy nuclear physics, such as the precise path-length dependence, mass dependence of parton energy loss, and help dentify the boundary across which QGP disappears ……

Thanks for your attention!

(3 + 1)-dimensional CLVisc hydrodynamic model

Phys. Rev. C 97, 064918 (2018)
Phys. Rev. C 98, 024913 (2018)

- ☐ the equation of motion and the dissipative equation

$$\partial_\mu T^{\mu\nu} = 0$$

$$\pi^{\mu\nu} = \eta_v \sigma^{\mu\nu} - \tau_\pi [\Delta^{\mu\nu}_{\alpha\beta} u^\lambda \partial_\lambda \pi^{\alpha\beta} + \frac{4}{3}\pi^{\mu\nu}\theta] \qquad (1)$$

- ☐ The full initial entropy density distribution

$$\mathrm{S}(\tau_0, x, y, \eta_s) = Ks(x,y)H(\eta_s)\big|\tau_0 \qquad (2)$$

- ☐ The local entropy density s(x, y)

$$\mathrm{s}(x,y) = \left(\frac{T_A{}^p + T_B{}^p}{2}\right)^{\frac{1}{p}} \qquad (3)$$

- ☐ The envelope functions

$$\mathrm{H}(\eta_s) = \exp[-\frac{(|\eta_s| - \eta_0)^2}{2\sigma_{\eta_s}^2}\theta(|\eta_s| - \eta_0)] \qquad (4)$$

- ☐ the Woods–Saxon distribution

$$\rho(r,\theta) = \frac{\rho_0}{1 + \exp[\frac{r - R(\theta)}{d}]}[1 + \omega \frac{r^2}{R(\theta)^2}] \qquad (5)$$

Nucleus	R_θ【fm】	d[fm]	ω	β_2	β_4
^{208}Pb	6.62	0.546	0	0	0
^{129}Xe	5.40	0.590	0	0.180	0
^{40}Ar	3.53	0.542	0	0	0
^{16}O	2.608	0.513	-0.051	0	0

$\eta/s=0.16$, $T_c=137$MeV, $\tau_0=0.6$fm/c

The modified Langevin equation

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g$$

Phys. Rev. C 88, 044907 (2013)
Phys. Rev. C 92, 024907 (2015)

- **classical Langevin equation**

- **recoil due to gluon emission**
  $\vec{f}_g = -d\vec{p}_g / dt$

Elastic Process

- The fluctuation-dissipation relation
  $\eta_D(p) = \kappa/(2TE).$
- The momentum diffusion coefficient of HQ κ.
- The spatial diffusion coefficient
  $D_s \equiv T/[M\eta_D(0)] = 2T^2/\kappa$

→ **$D_s(2\pi T)$**

Inelastic Process

- **$\vec{p}_g$ is the momentum of the emitted gluon**

$$P_{rad}(t,\Delta t) = \langle N_g(t,\Delta t)\rangle = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

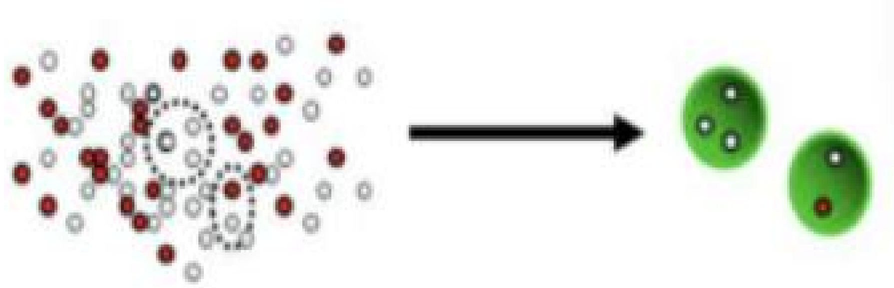
- **Radiated gluon spectrum (Higher-twist)**

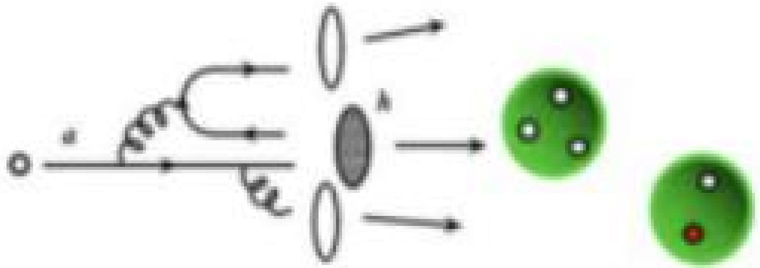
$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s P(x)\hat{q}}{\pi k_\perp^4} \sin^2\left(\frac{t-t_i}{2\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^4$$

Hybrid coalescence-fragmentation model

Physics Letters B 807 (2020) 135561

T_c=160MeV





Coalescence(recombination)
Low p partons combine with thermal partons into hadrons

Fragmentation
High p partons fragment into hadrons
[Low p parPeterson FONNL, Pythia, etc]

Instantaneous coalescence: coalescence probability~wavefunction overlap

Probability: Wigner function $f_M^W \equiv \left|\left\langle M \middle| q_1, q_2 \right\rangle\right|^2$

Encodes information of microscopic hadron structures

$$f_M^W(\vec{r},\vec{q}) = g_M \int d^3 r' e^{-i\vec{q}\cdot\vec{r}'} \phi_M(\vec{r}+\frac{\vec{r}'}{2}) \phi_M^*(\vec{r}-\frac{\vec{r}'}{2})$$