Probing QGP properties with heavy quark transport

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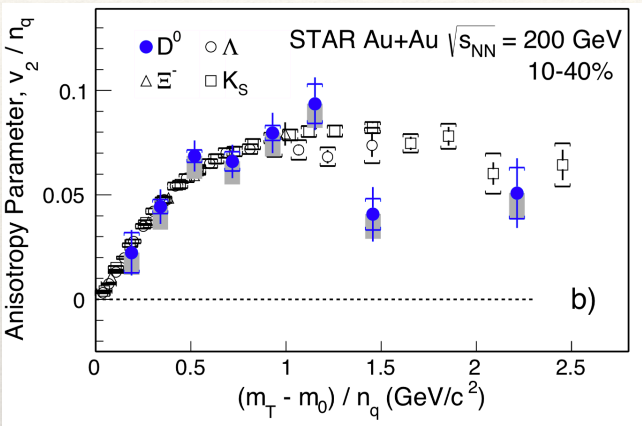
Outline

- **Heavy quark theories/models at different momentum scales**
  - Heavy quark energy loss at high p_T
  - Color potential interaction at low p_T

- **Probing properties of nuclear matter in heavy-ion collisions**
  - System size dependence of QGP properties
  - Medium geometry and evolution profile of the strong electromagnetic field

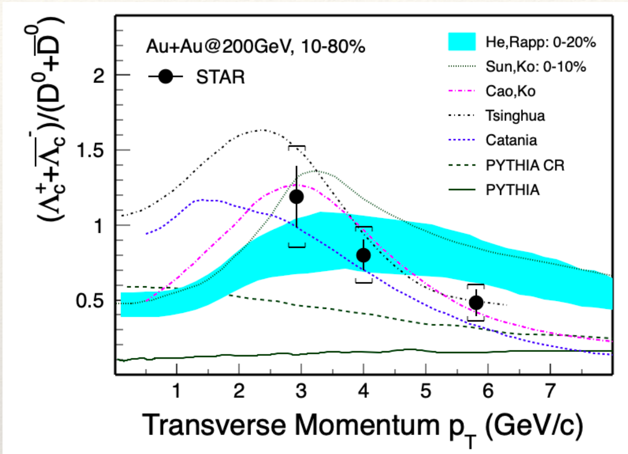
Heavy quark physics at different scales

low p_T



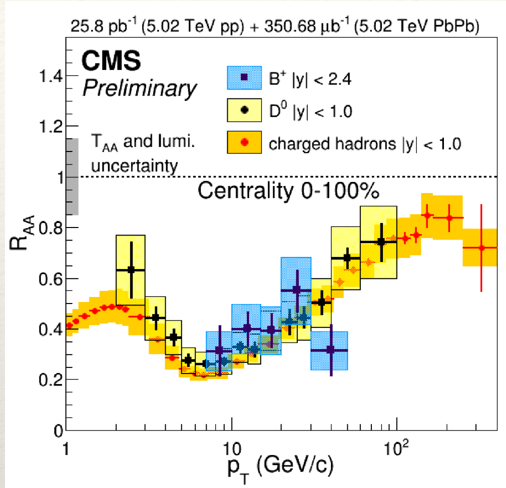
- Study the thermalization process of heavy quarks
- Constrain the color potential of HQ-medium interaction

medium p_T



- Study the hadronization process of heavy quarks
- Constrain the in-medium hadron wave-function

high p_T



- Study the energy loss process of heavy quarks
- Constrain the flavor hierarchy of parton energy loss

High p_T parton-medium interaction

Linear Boltzmann Transport (LBT)

$$p_a \cdot \partial f_a(x_a, p_a) = E_a(\mathscr{C}_a^{\mathrm{el}} + \mathscr{C}_a^{\mathrm{inel}})$$

Elastic energy loss ($ab \rightarrow cd$)

$$\mathscr{C}_a^{\mathrm{el}} = \sum_{b,c,d} \int \prod_{i=b,c,d} \frac{d[p_i]}{2E_a} (\gamma_d f_c f_d - \gamma_b f_a f_b) \cdot (2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) \left| \mathscr{M}_{ab\rightarrow cd} \right|^2$$

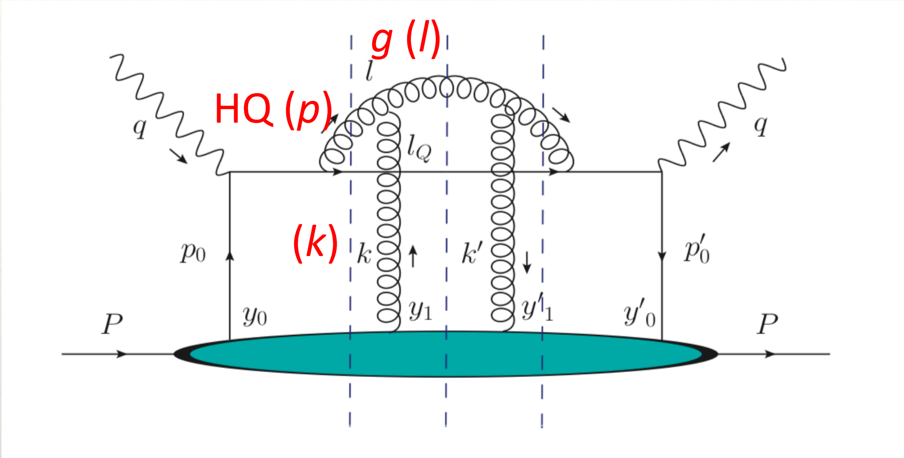
$2 \rightarrow 2$ scattering matrices

loss term: **scattering rate**
(for Monte-Carlo simulation)

$$\Gamma_a^{\mathrm{el}}(\mathbf{p}_a, T) = \sum_{b,c,d} \frac{\gamma_b}{2E_a} \int \prod_{i=b,c,d} d[p_i] f_b \cdot (2\pi)^4 \delta^{(4)}(p_a + p_b - p_c - p_d) \left| \mathscr{M}_{ab\rightarrow cd} \right|^2$$

Inelastic energy loss

- **Inelastic scattering with a general medium**



[Majumder PRD 85 (2012); Zhang, Wang and Wang, PRL 93 (2004)]

- **Higher-twist**: collinear expansion ($\langle k_\perp^2 \rangle \ll l_\perp^2 \ll Q^2$)

$$\frac{d\Gamma_a^{\text{inel}}}{dz dl_\perp^2} = \frac{dN_g}{dz dl_\perp^2 dt} = \frac{6\alpha_s P(z) l_\perp^4 \hat{q}}{\pi (l_\perp^2 + z^2 M^2)^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

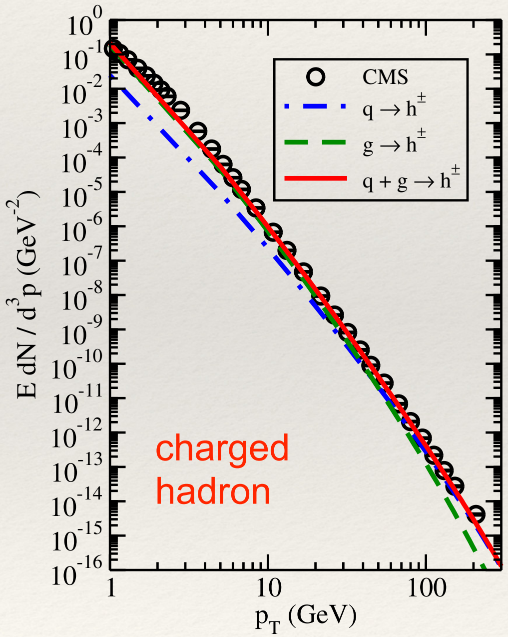
- Medium information absorbed in $\hat{q} \equiv d\langle p_\perp^2 \rangle / dt$

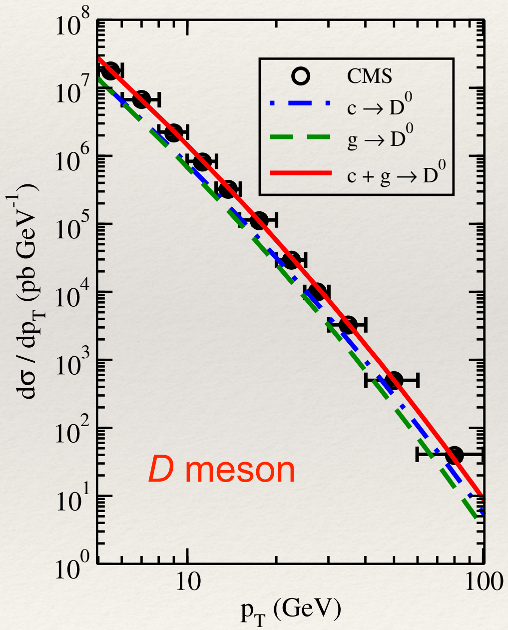
Flavor hierarchy of jet quenching

Clean perturbative framework is sufficient for describing the flavor hierarchy at high p_T (> 8 GeV)

[Xing, Cao, Qin and Xing, Phys. Lett. B 805 (2020) 135424]

- NLO (gluon spitting) contribution to heavy vs. light hadron production





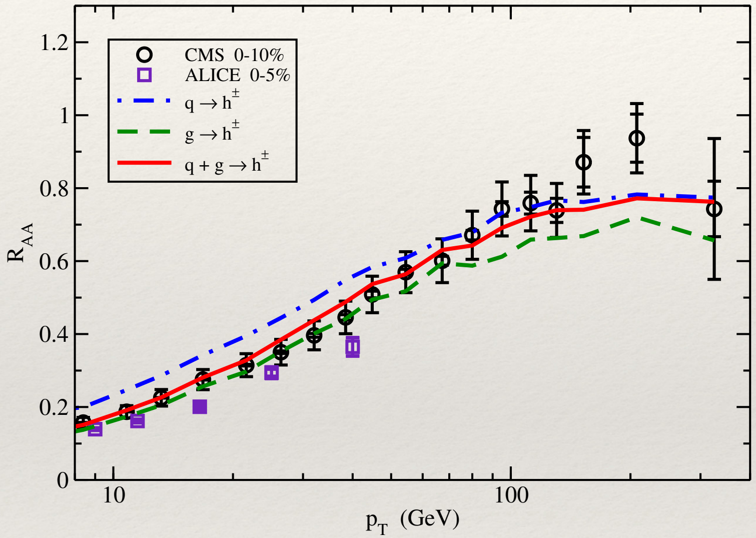
Gluon fragmentation

- dominates $h^{\pm}$ production up to 50 GeV
- contributes to over 40% *D* up to 100 GeV

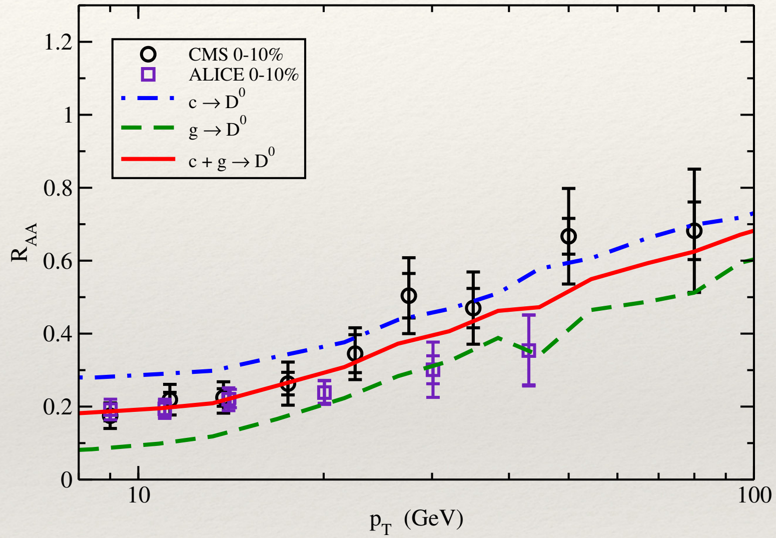
Flavor hierarchy of jet quenching

NLO initial production and fragmentation + Boltzmann transport (elastic and inelastic energy loss) + hydrodynamic medium for QGP

charged hadron



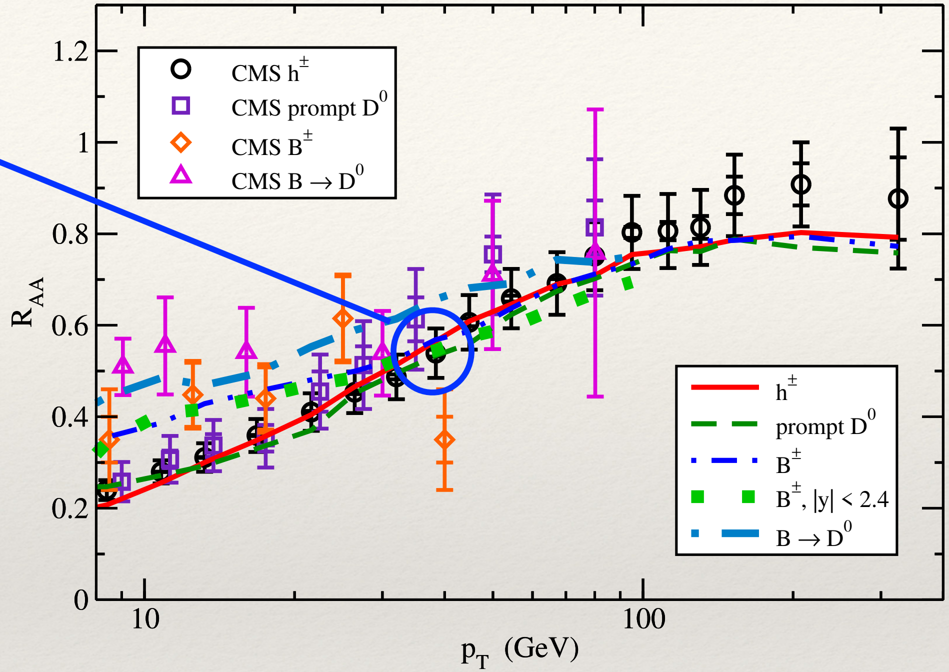
D meson



- *g*-initiated *h* & *D* R_{AA} < *q*-initiated *h* & *D* R_{AA} => $\boldsymbol{\Delta E_g > \Delta E_q > \Delta E_c}$ **holds**
- Although R_{AA} (*c->D*) > R_{AA} (*q->h*), R_{AA} (*g->D*) < R_{AA} (*g->h*) due to different fragmentation functions => $\boldsymbol{R_{AA}(h) \approx R_{AA}(D)}$

Flavor hierarchy of jet quenching

Merging of *D* and *B* R_{AA} at p_T ~ 40 GeV



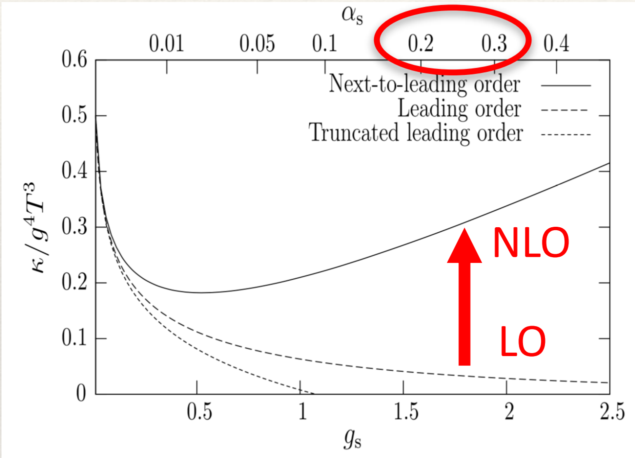
[Xing, Cao, Qin and Xing, Phys. Lett. B 805 (2020) 135424]

- A simultaneous description of charged hadron, *D* meson, *B* meson, *B*-decay *D* meson R_{AA}'s starting from p_T ~ 8 GeV
- Predict R_{AA} separation between *B* and *h* / *D* below 40 GeV, but similar values above – **wait for confirmation from future precision measurement**

Low p_T HQ's — color potential interaction

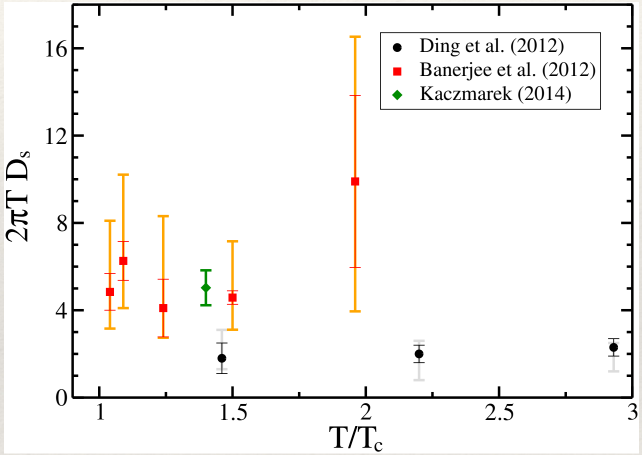
- Suppression of radiative energy loss due to the "dead cone effect"
- Heavy quark diffusion, **diffusion coefficient** κ or D_s as important input into transport models

Perturbation calculation fails at low p_T



- LO: Svetitsky, PRD 37 (1988)
  Moore and Teaney, PRC 71 (2005)
- NLO: Caron-Huot and Moore, JHEP 02 (2008)
- A factor of over 5 increase at NLO

Inputs from lattice calculations

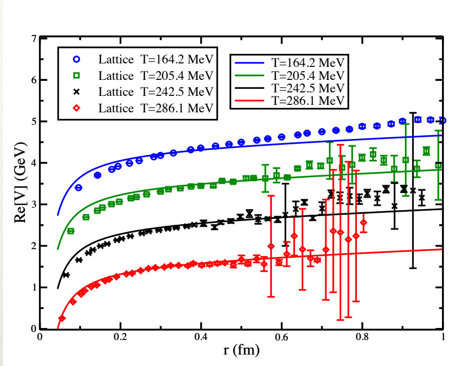


- Uncertainty is still large
- No results for finite momentum HQ yet

Perturbative calculation with effective propagator approach

- **Parametrization of the heavy-quark-QGP interaction potential:**

Parameters can describe the lattice potential



Burnier, Kaczmarek and Rothkopf , Phys. Rev. Lett. 114 (2015) 082001

$$V(r,T) = -\frac{4}{3}\alpha_s \frac{e^{-m_d r}}{r} - \frac{\sigma}{m_s} e^{-m_s r}$$

Yukawa (color coulomb) String

in which $m_d = a + b * T$ and $m_s = \sqrt{a_s + b_s * T}$ are the respective screening masses, α_s and σ are the respective Yukawa and confining interaction strength.

- **By Fourier transformation,**

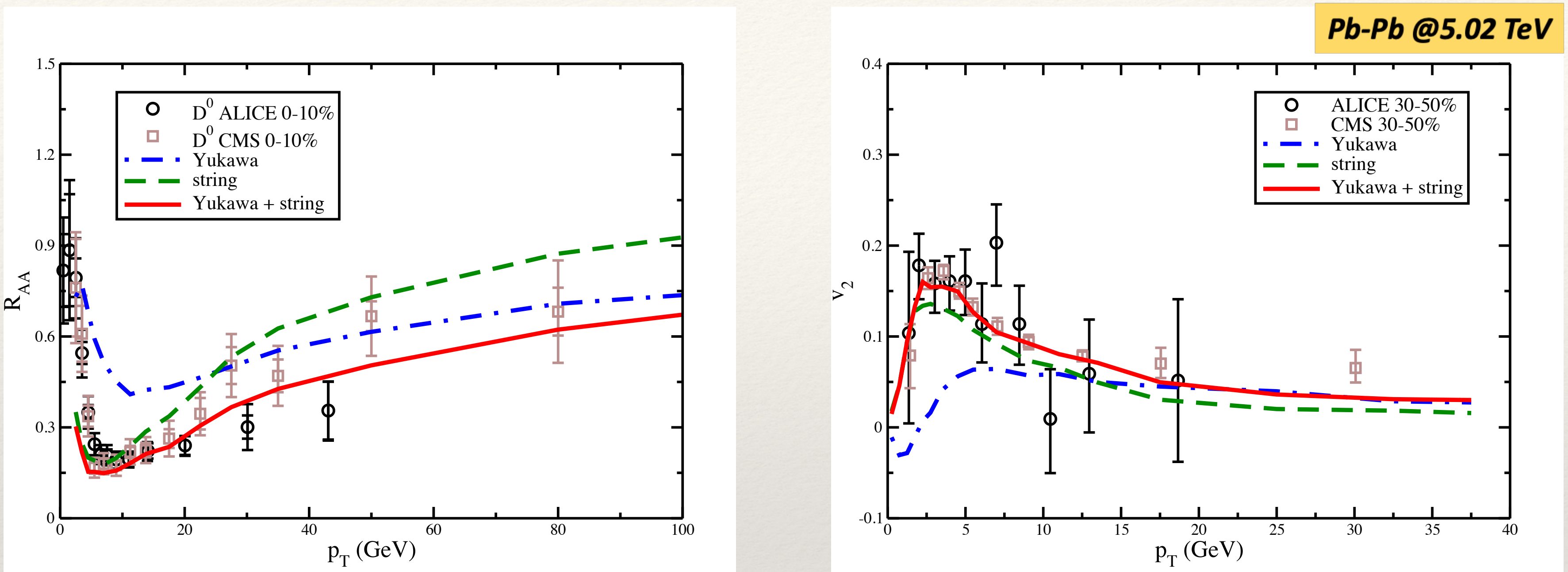
$$V(\vec{q},T) = -\frac{4\pi\alpha_s C_F}{m_d^2 + |\vec{q}|^2} - \frac{8\pi\sigma}{\left(m_s^2 + |\vec{q}|^2\right)^2}$$

- **For $Qq \longrightarrow Qq$ process, we express the scattering amplitude with effective potential propagator,**

Riek and Rapp, Phys. Rev. C 82 (2010) 035201

$$iM = iM_C + iM_S = \bar{u}\gamma^\mu u V_c \bar{u}\gamma^\nu u + \bar{u}u V_s \bar{u}u$$

R_{AA} and v_2 of D mesons at LHC

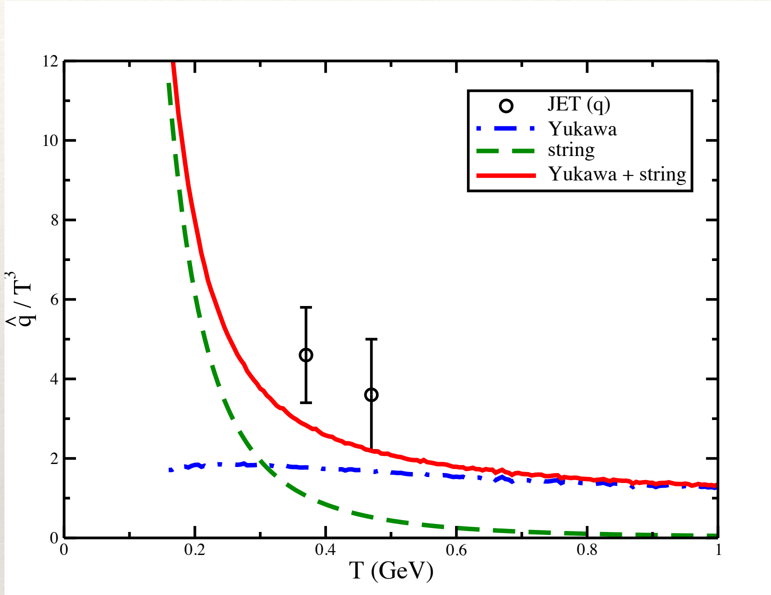


Xing, Qin, Cao, arXiv:2112.15062

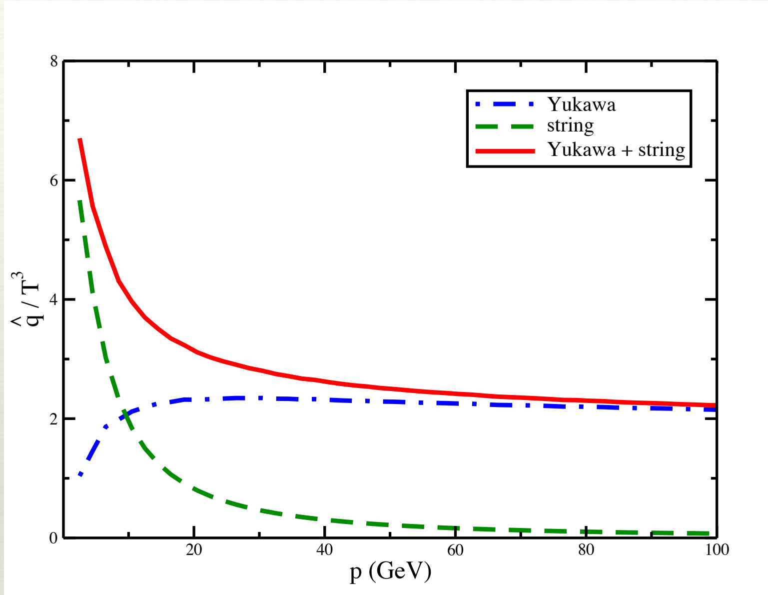
- At high p_T, the Yukawa interaction dominates heavy-quark-medium interaction
- At low to intermediate p_T, the string interaction dominates, stronger contribution at later evolution stage (near T_c)

Transport coefficients — $\hat{q}$

Temperature dependence



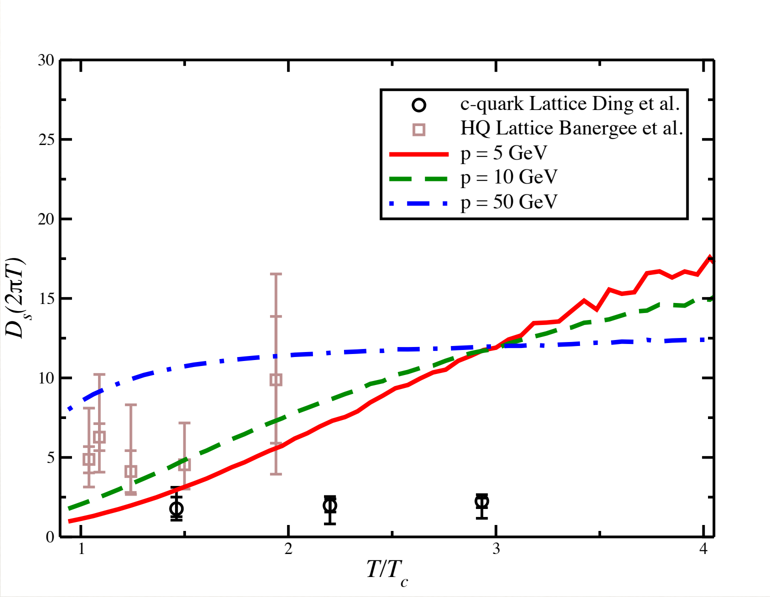
Momentum dependence



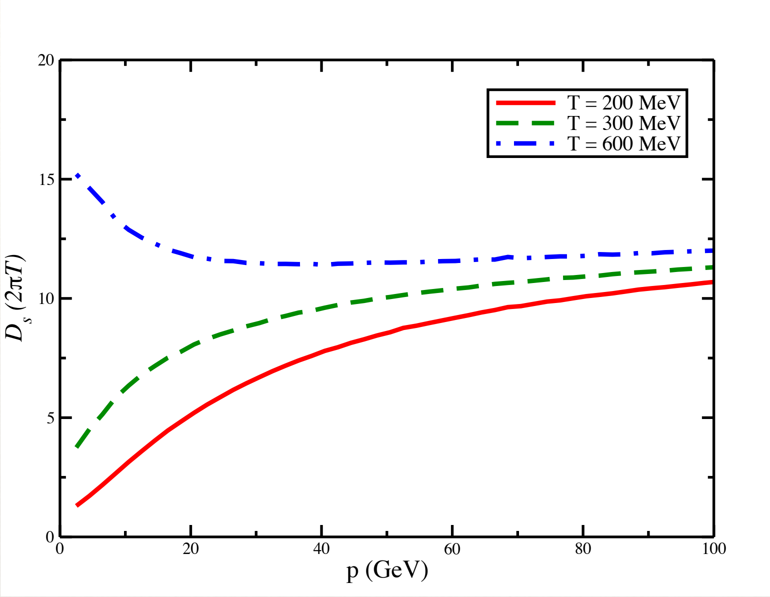
- Yukawa interaction dominates at high temperature and high momentum
- String interactions dominates at low temperature and low momentum

Transport coefficients — D_s

Temperature dependence



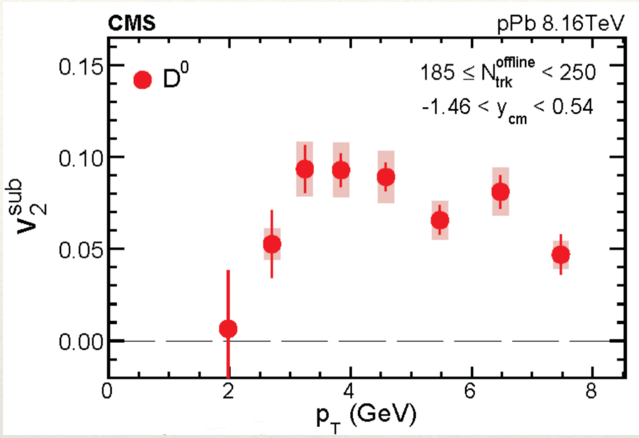
Momentum dependence



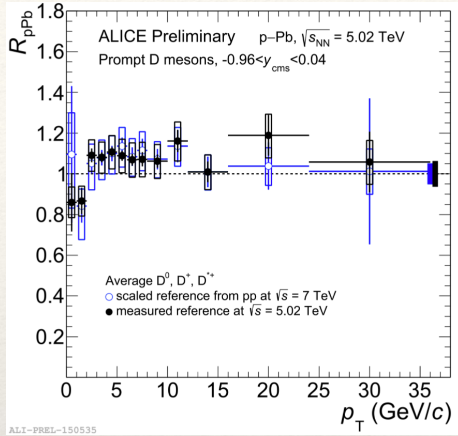
- Stronger temperature dependence at lower momentum
- Different momentum dependence at different temperature

Probing system size dependence of energy loss

Small system (p-Pb) puzzle



Large *D* meson v_2 up to 8 GeV



Almost no suppression

- Not consistent with the QGP effect
- Proposal of the initial state effect [Zhang, Marquet, Qin, Wei and Xiao, PRL 122 (2019)]
- Separation of initial state and QGP effect — a system size scan of nuclear modification to bridge large and small systems

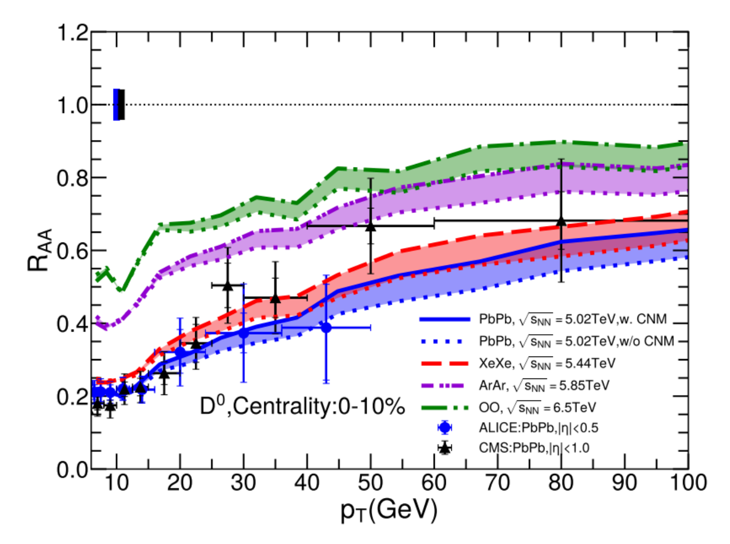
D meson R_{AA} in different systems

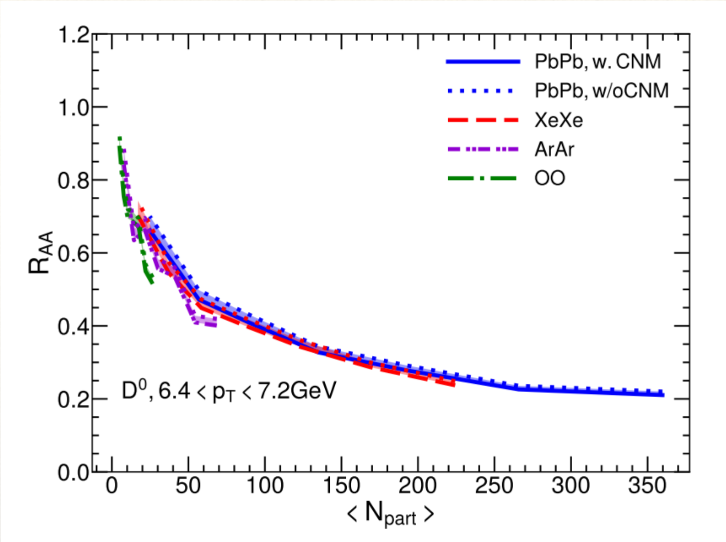
O-O

Ar-Ar

Xe-Xe

Pb-Pb

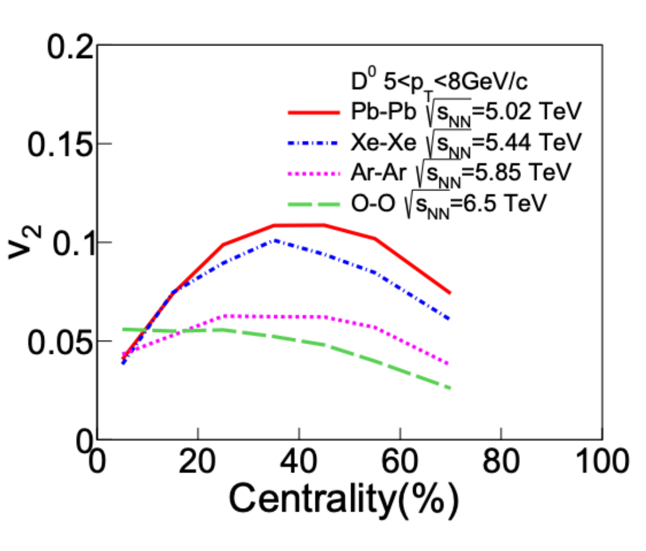


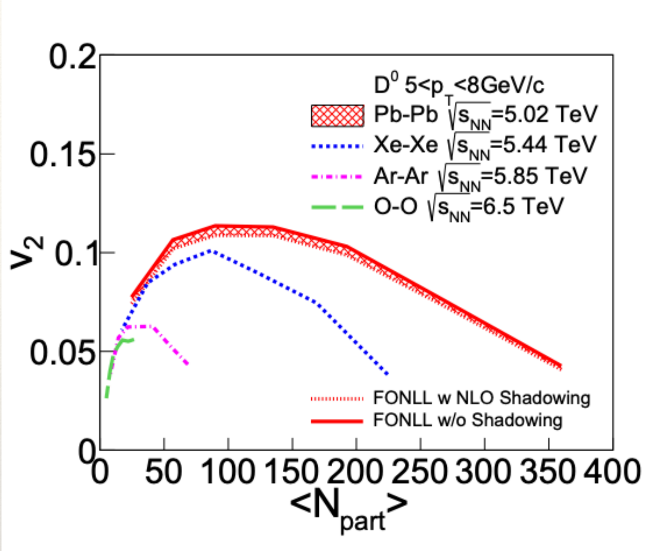


Liu, Xing, Wu, Qin, Cao, Xing, PRC 105 (2022) 4, 044904

- Clear hierarchy of R_{AA} with respect to the system size
- Significant R_{AA} in the small O-O system, existence of QGP
- Scaling of R_{AA} with the system size (quantified by N_{part}) across different collision systems

D meson v_2 in different systems

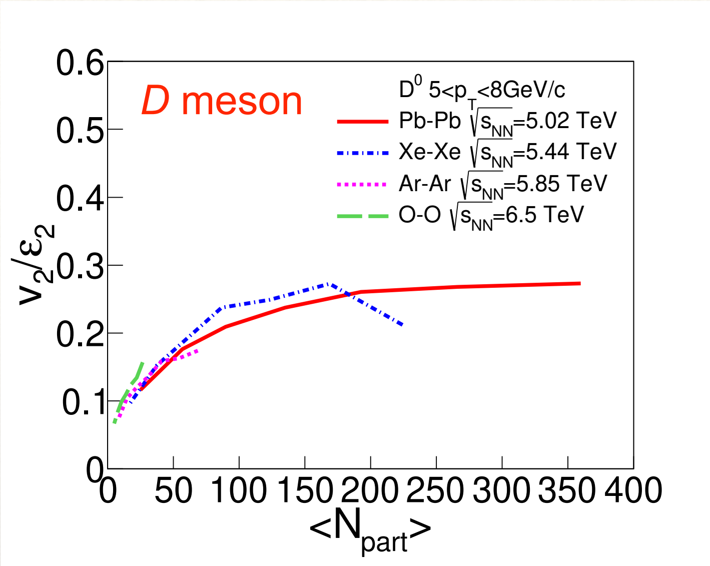


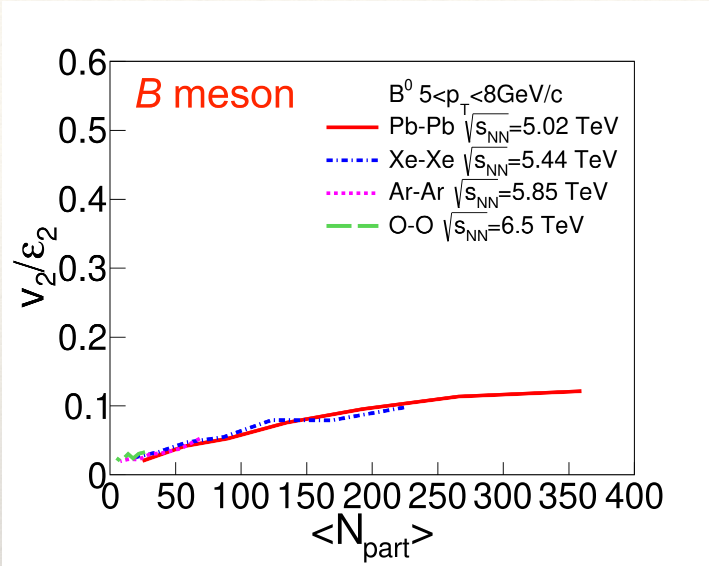


Li, Xing, Wu, Cao, Qin, EPJC 81 (2021) 11, 1035

- Energy loss effect: for a given centrality, v_2 increases with the system size
- Geometry effect: for a given N_{part}, v_2 increases from O-O, Ar-Ar, Xe-Xe to Pb-Pb

Scaling of v_2/ε_2 with respect to N_{part}



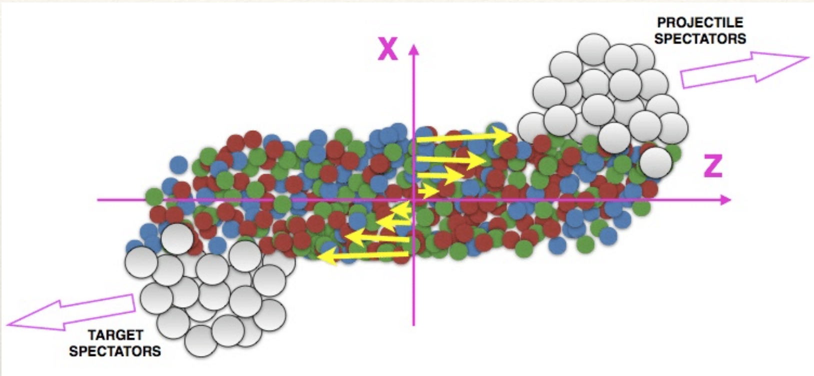


Li, Xing, Wu, Cao, Qin, EPJC 81 (2021) 11, 1035

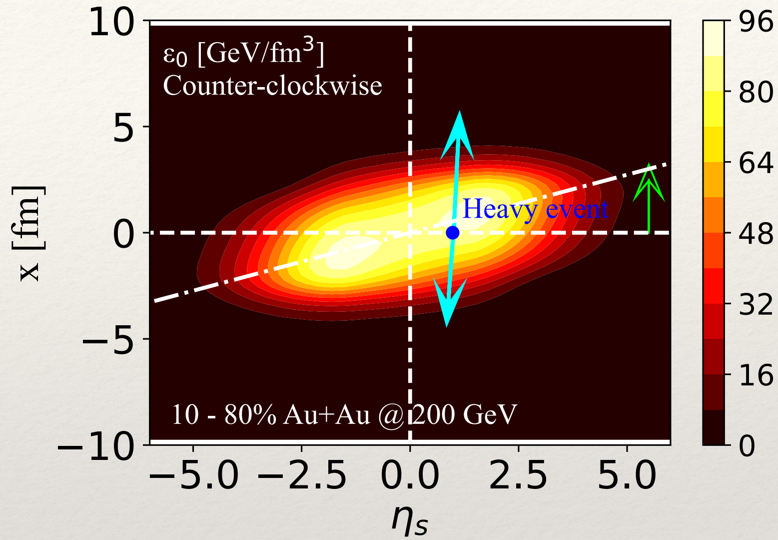
- Separate energy loss and geometry effects by rescaling heavy quark v_2 with bulk ε_2
- v_2/ε_2 scales with the system size across different collision systems
- Search for the breaking of the scaling with future experiments — initial state effect overwhelms QGP effect

Probing medium geometry and E & M field

Non-central heavy-ion collisions



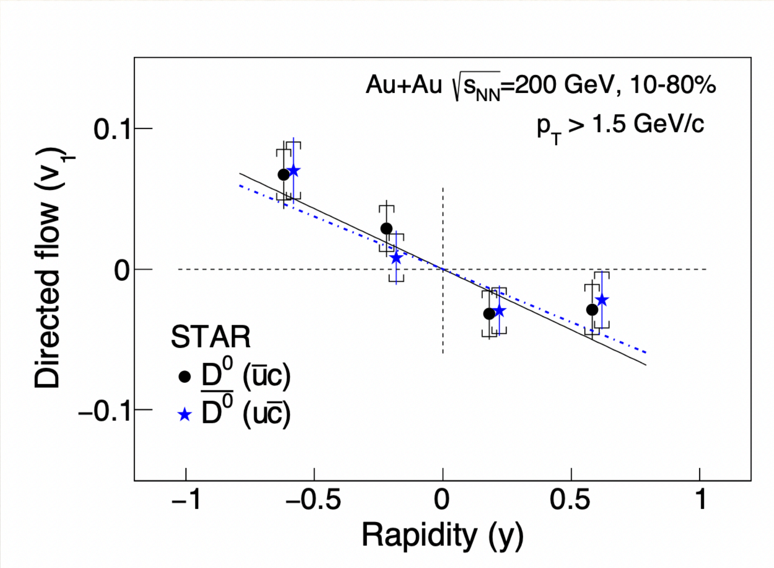
Counter clockwise tilt of the medium



- At $\eta_s > 0$, longer path length (more energy loss) of heavy quark towards $+\hat{x}$ than $-\hat{x}$
- Directed flow: $v_1 = \langle p_x / p_T \rangle < 0$ of heavy quarks at $\eta_s > 0$
- E & M field deflects c and $\bar{c}$ towards different directions → v_1 separation (Δv_1) between D^0 and $\overline{D}^0$

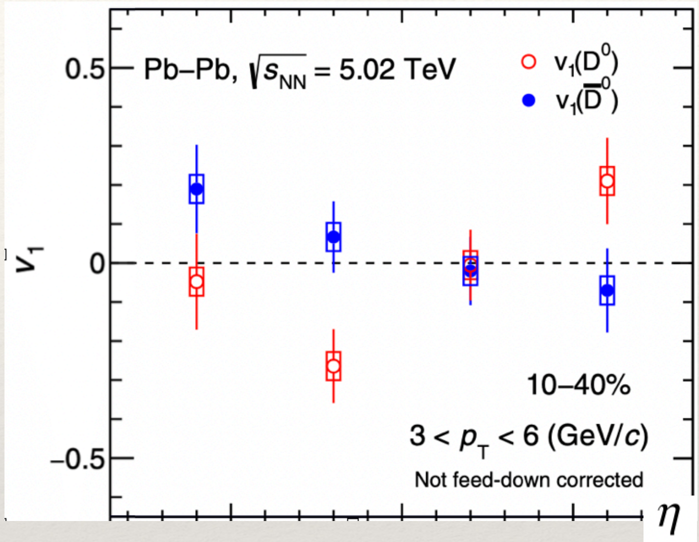
Different observations at RHIC and LHC

RHIC/STAR [PRL 123 (2019)]



- Negative slope for both D^0 and $\overline{D}^0$

LHC/ALICE [PRL 125 2020]



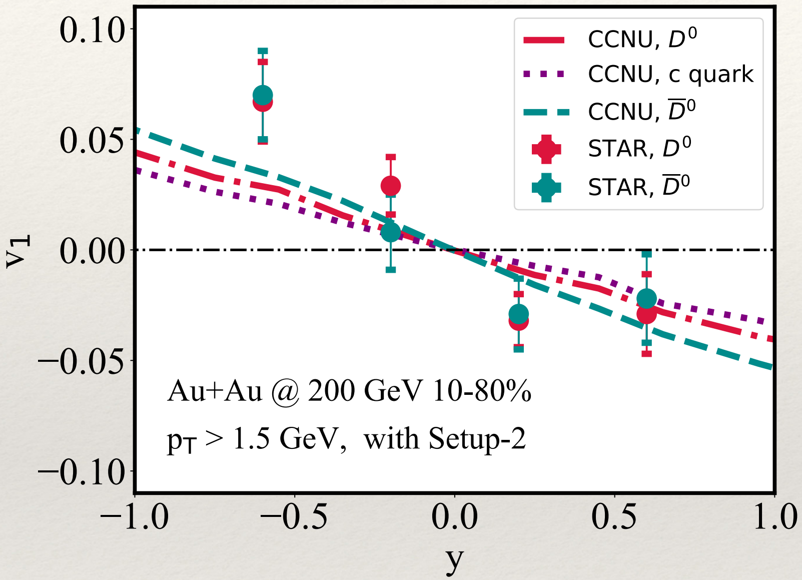
- Negative slope for $\overline{D}^0$, positive for D^0

Different dominant mechanisms for directed flow of *D* between RHIC and LHC

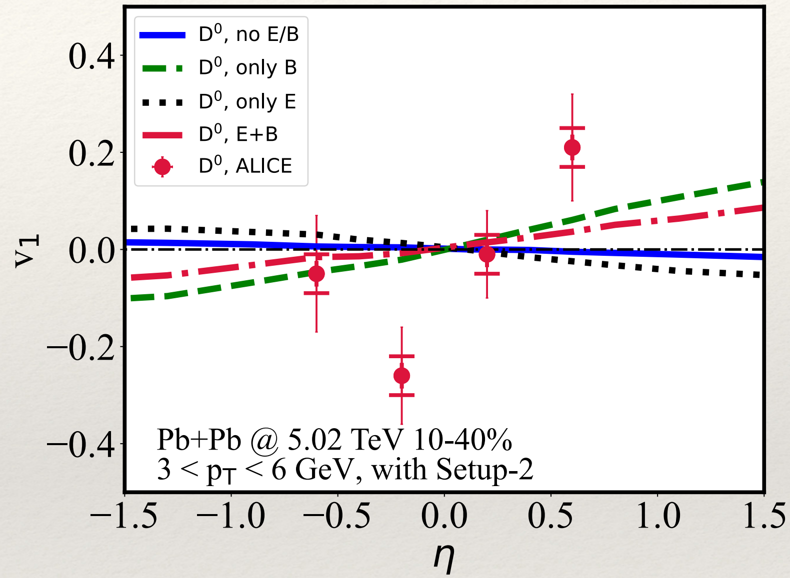
Understand the difference between RHIC and LHC

Jiang, Cao, Xing, Wu, Yang, Zhang, PRC 105 (2022) 3, 034901

RHIC



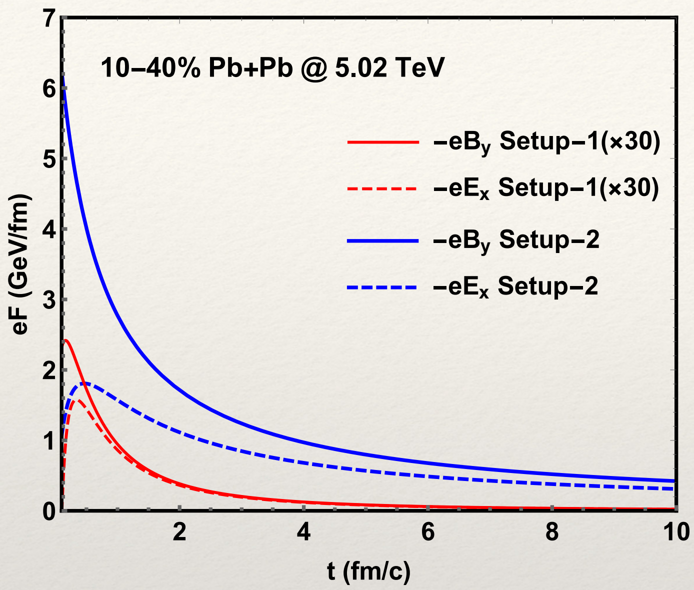
LHC

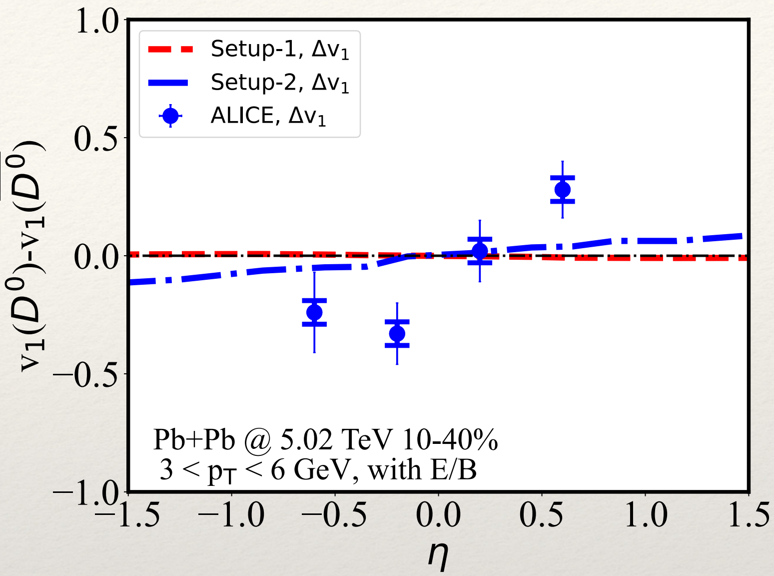


- Less energetic collision
- Stronger tilted initial geometry (dominant effect)
- Weaker E & M field

- More energetic collision
- Weaker tilted initial geometry
- Stronger E & M field (dominant effect)

Probing evolution profiles of the E & M field





- Compare two model calculations of E & M field
  - Setup 1: Direct solution of Maxwell equation with constant electric conductivity $\sigma = 0.023\ \text{fm}^{-1}$
  - Setup 2: Model $B_y(\tau) \sim B_y^{\text{vac}}(0)/(1+\tau/\tau_B)$, then solve E_x from B_y with Maxwell equation
- Δv_1 data favor larger magnitude of B_y than E_x $\rightarrow$ guide improvement for E & M calculation

Summary

Heavy-quark-QGP interaction at different p_T and in different collision systems

- pQCD is sufficient to describe flavor hierarchy of jet quenching above 8 GeV
- Color potential interaction significantly improves model calculation at low p_T
- Scaling behaviors of heavy quark R_{AA} and v_2 across different collision systems may help distinguish initial state and QGP effects at different system size
- Heavy quark v_1 probes medium deformation at RHIC, while E & M field at LHC