11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

Constraining the in-medium heavy quark potential and diffusion coefficient within a unified perturbative and non-perturbative transport approach

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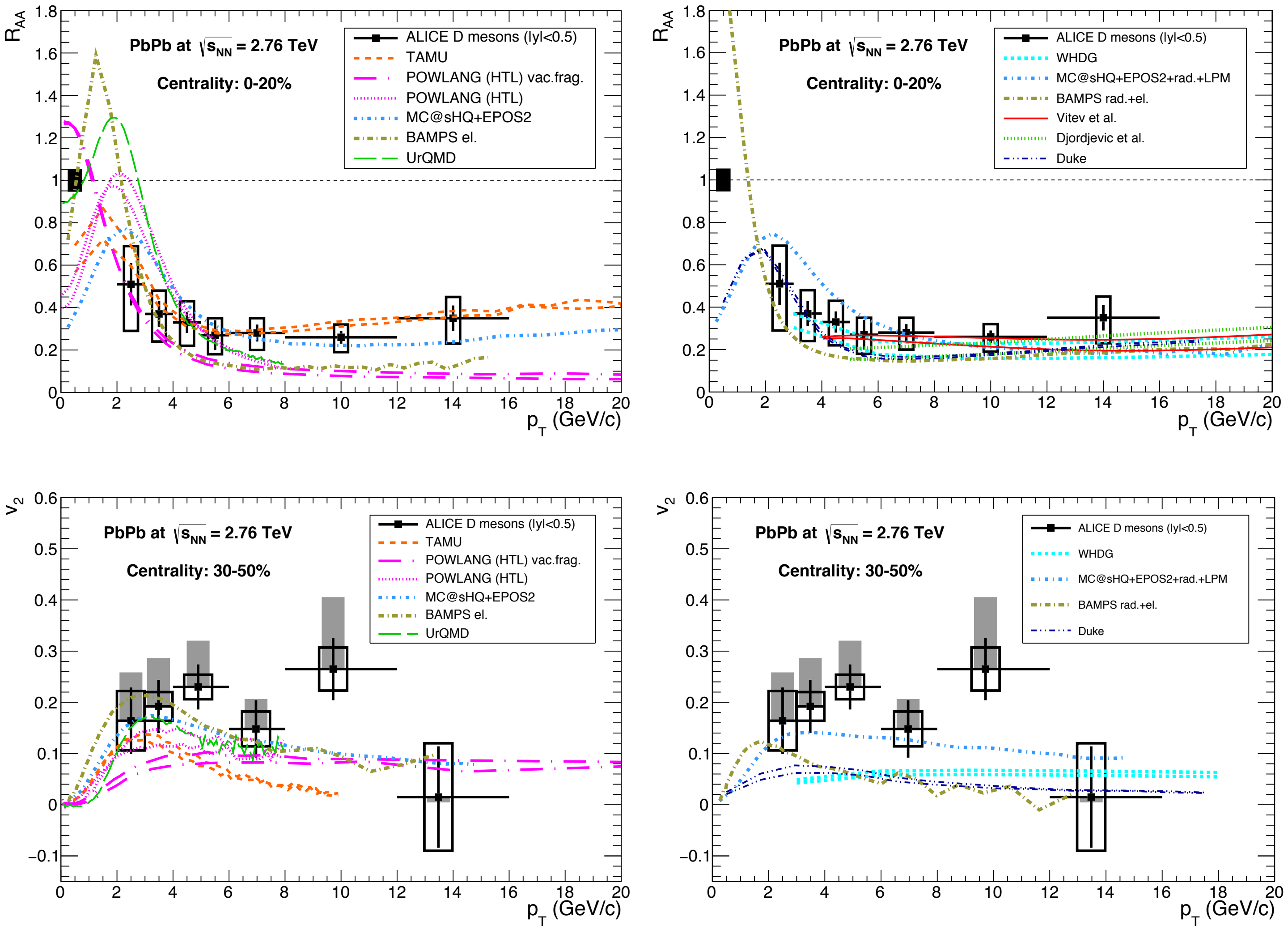
Outline of my talk

Wen-Jing Xing, Qin, Cao, Phys. Lett. B 838 (2023) 137733

- ☐ Introduction
- ☐ Perturbative and non-perturbative interactions between heavy quarks and QGP
- ☐ R_{AA} and v_2 of heavy mesons and heavy flavor leptons
- ☐ Heavy quark potential and transport coefficients
- ☐ Summary

Heavy flavor R_{AA} and v_2

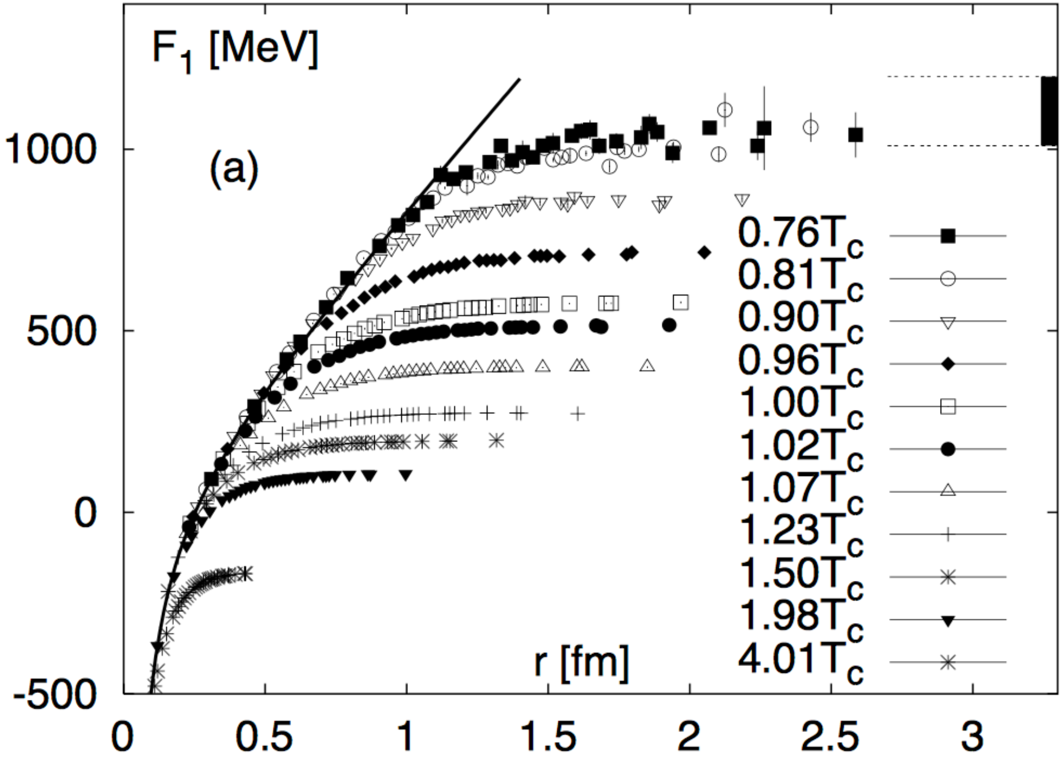


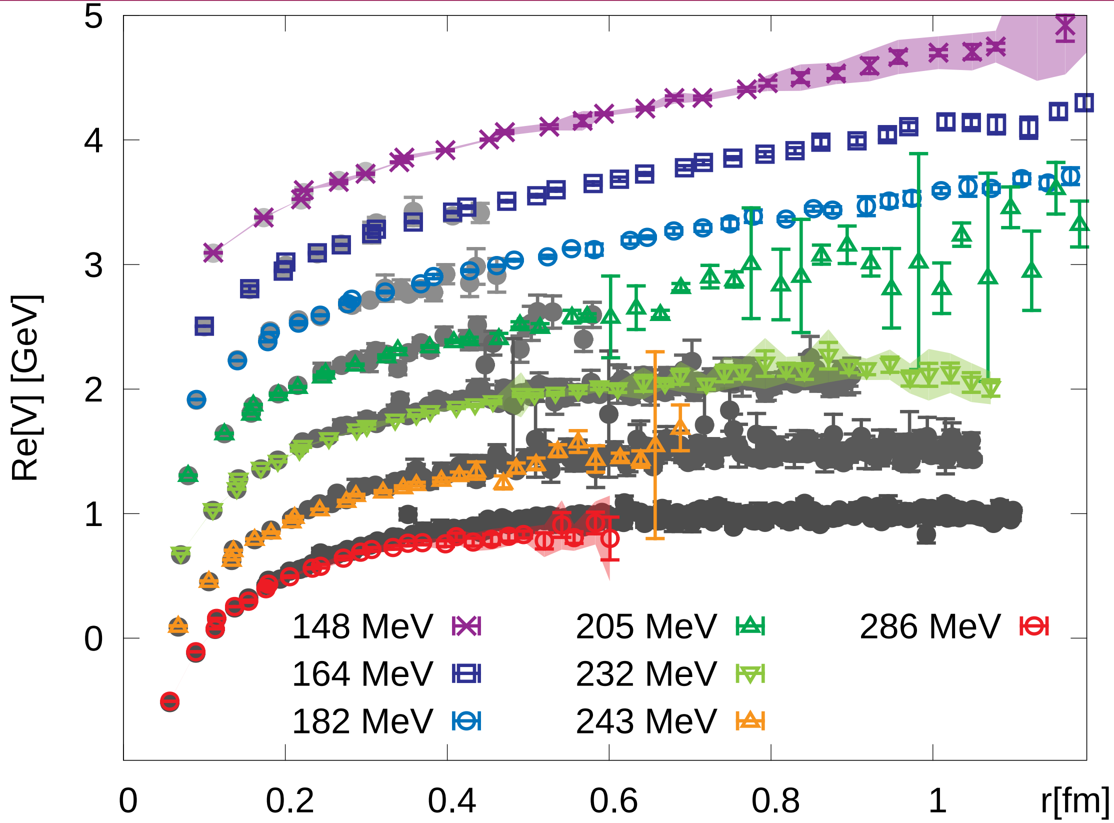
[A. Andronic, et. al, EPJC (2016)]

- Different transport models vary in a few aspects: radiative & collisional energy loss, fragmentation & recombination, partonic & hadronic interactions, shadowing, ……

- At low and intermediate p_T, simultaneous description of *D* mesons R_{AA} and v_2 challenges models.

Non-perturbative effects





[Y. Burnier, et. al, PRL 114, 082001 (2015)].

- In vaccum, $V_{Q\bar{Q}} = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$.

- **At $T < 2T_c$, the residual of confining interaction exists.**

Perturbative and non-perturbative interaction between HQ and QGP

- **The functional form of in-medium heavy quark potential is:** [Shuai Y.F. Liu, et al PRC 97, (2018) 3, 034918]

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

Yukawa — confining (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 interaction strength.

- **By Fourier transformation,**

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

- **For $Qq \longrightarrow Qq$ process, we express the scattering amplitude with effective potential propagator,** [F. Riek and R. Rapp, PRC (2010)]

$$iM = iM_Y + iM_S = \bar{u}\gamma^\mu u V_Y \bar{u}\gamma^\nu u + \bar{u}u V_S \bar{u}u$$

Perturbative and non-perturbative $|M|^2$

- **For $Qq \longrightarrow Qq$ process:**

$$|M_{Qq}|^2 = \frac{64\pi^2\alpha_s^2}{9}\frac{(s+m_Q^2)^2+(m_Q^2-u)^2+2m_Q^2u}{(t-m_d^2)^2} + \frac{(8\pi\sigma)^2}{N_c^2-1}\frac{t(t-4m_Q^2)}{(t-m_s^2)^4}$$

Perturbative Yukawa term $|M_Y|^2$

Non-perturbative string term $|M_S|^2$

- **For $Qg \longrightarrow Qg$ process:**

$$|M_{Qg}|^2 = \frac{64\pi^2\alpha_s^2}{9}\frac{(s-m_Q^2)^2+(m_Q^2+u)^2+2m_Q^2(s+2m_Q^2)}{(s-m_Q^2)^2} + \frac{64\pi^2\alpha_s^2}{9}\frac{(s-m_Q^2)^2+(m_Q^2-u)^2+2m_Q^2(u+2m_Q^2)}{(u-m_Q^2)^2}$$

$$+8\pi^2\alpha_s^2\frac{5m_Q^4+3m_Q^2t-10m_Q^2u+4t^2+5tu+5u^2+(m_Q^2-s)(m_Q^2-u)}{(t-m_d^2)^2}$$

$$+\frac{16\pi^2\alpha_s^2}{9}\frac{m_Q^2(4m_Q^2-t)}{(s-m_Q^2)(m_Q^2-u)} + 16\pi^2\alpha_s^2\frac{3m_Q^4-3m_Q^2s-m_Q^2u+s^2}{(s-m_Q^2)(t-m_d^2)} + 16\pi^2\alpha_s^2\frac{3m_Q^4-m_Q^2s-3m_Q^2u+u^2}{(u-m_Q^2)(t-m_d^2)}$$

$$+\frac{C_A}{C_F}\frac{(8\pi\sigma)^2}{N_c^2-1}\frac{t(t-4m_Q^2)}{(t-m_s^2)^4}$$

- **The improved $|M|^2$ include both perturbative and non-perturbative interaction between heavy quarks and QGP.**

LBT model

[S. Cao, et. al, PLB(2018); S. Cao, et. al, PRC (2016); Y. He, et. al, PRC (2015)]

- **Boltzmann equation:** $p_a \cdot \partial f_a(x,p) = E_a\ \mathcal{C}[f_a]$

- **Elastic scattering:**

$$\Gamma^a_{\rm el} = \sum_{b,c,d} \frac{\gamma_b}{2E} \int \frac{d^3p_b}{(2\pi)^3 2E_b} \int \frac{d^3p_c}{(2\pi)^3 2E_c} \int \frac{d^3p_d}{(2\pi)^3 2E_d} \times f_b(\vec{p}_b)\,[1 \pm f_c(\vec{p}_c)]\,[1 \pm f_d(\vec{p}_d)] \times (2\pi)^4 \delta^{(4)}(p + p_b - p_c - p_d) |\mathcal{M}_{ab\to cd}|^2$$

$$P^a_{\rm el} = 1 - e^{-\Gamma^a_{\rm el}\Delta t}$$

The improved $|M|^2$:

$$|M|^2 = |M_Y|^2 + |M_S|^2$$

- **Inelastic scattering:**

$$\langle N^a_g \rangle = \Gamma^a_{\rm inel}\ \Delta t = \Delta t \int dx dk^2_\perp \frac{dN^a_g}{dx dk^2_\perp dt}$$

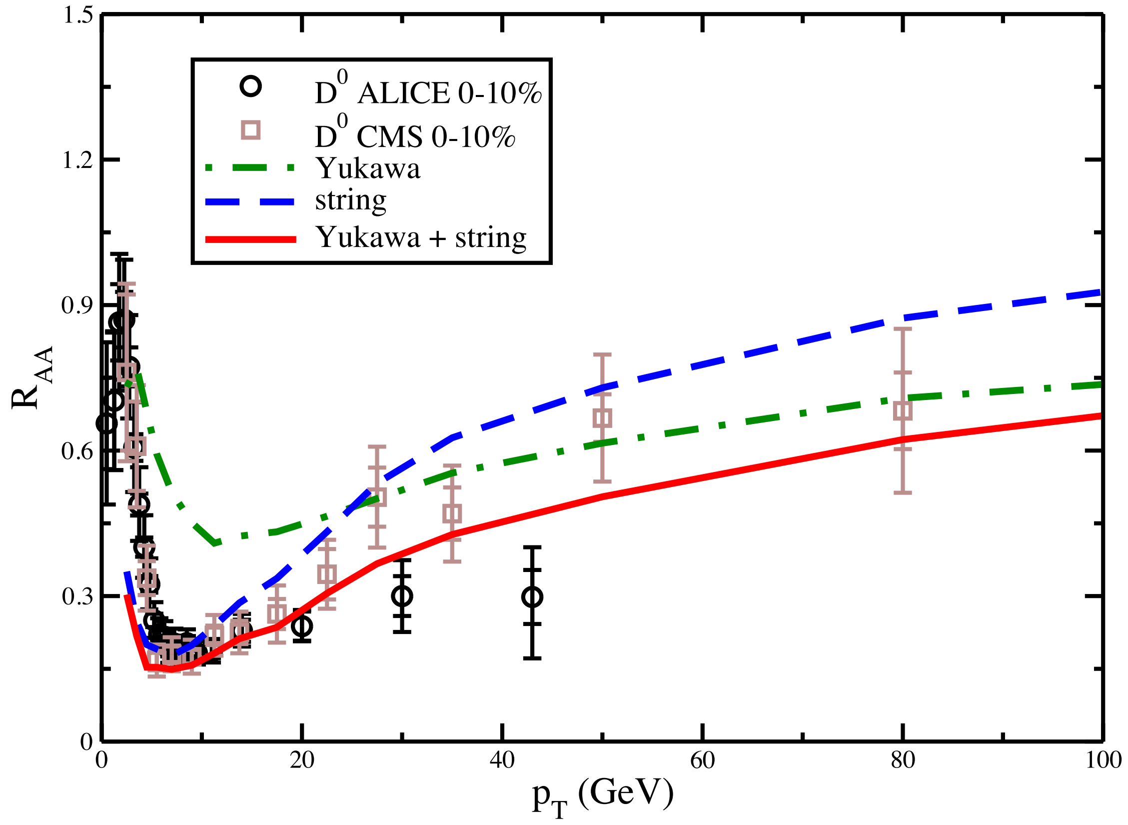
$$P^a_{\rm inel} = 1 - e^{-\langle N^a_g \rangle}$$

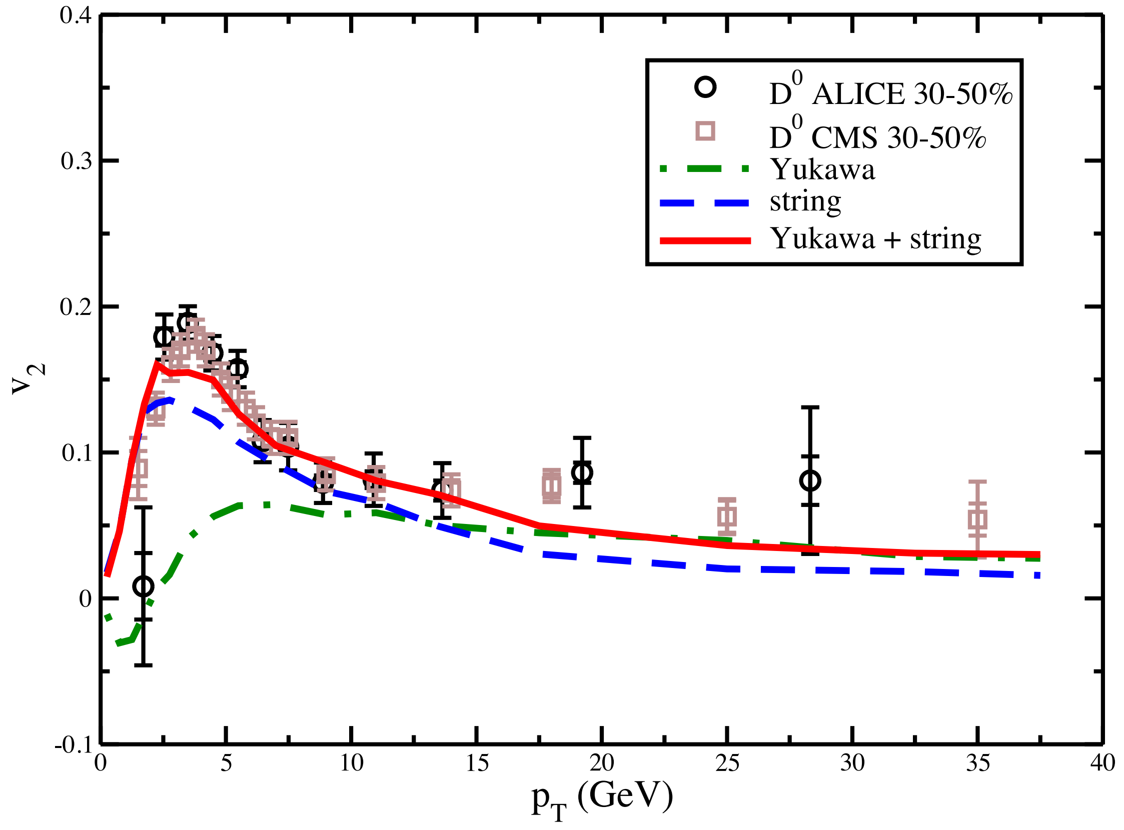
- **Elastic + Inelastic:** $P^a_{\rm el} = 1 - e^{-(\Gamma^a_{\rm el} + \Gamma^a_{\rm inel})\Delta t}$

- **The values of in-medium heavy quark potential parameters:**

$\alpha_s = 0.27, m_d = 0.2 + 2 * T, m_s = \sqrt{0.1 * T}, \sigma = 0.45$ GeV²

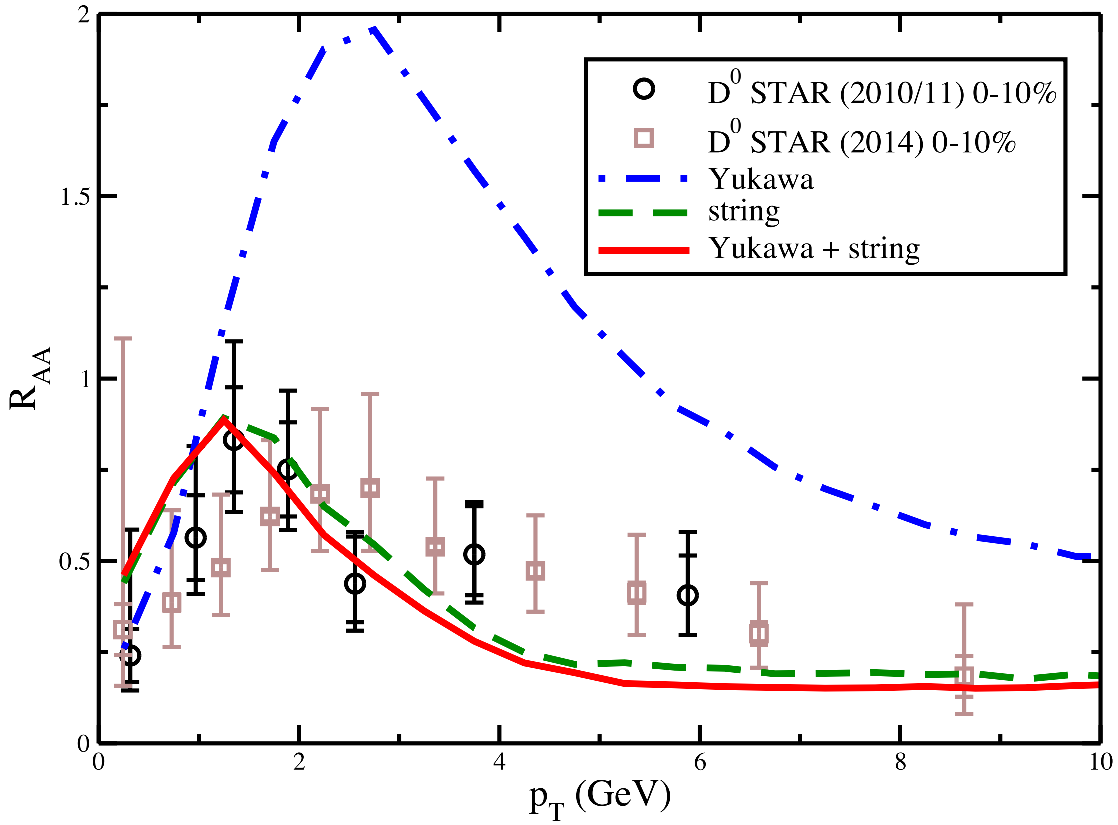
D meson' R_{AA} & v_2 in Pb-Pb@5.02TeV

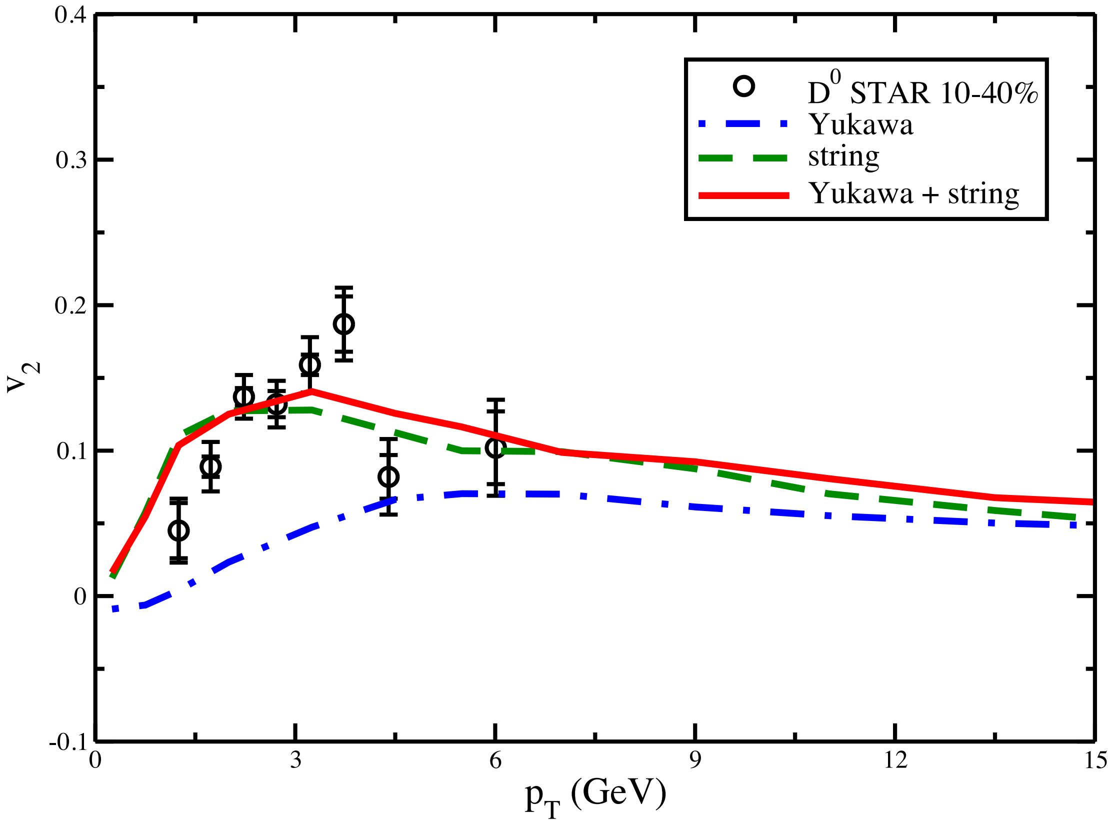




- Perturbative interactions dominate D meson R_{AA} and v_2 at high p_T, non-perturbative interactions dominate at low and intermediate p_T.

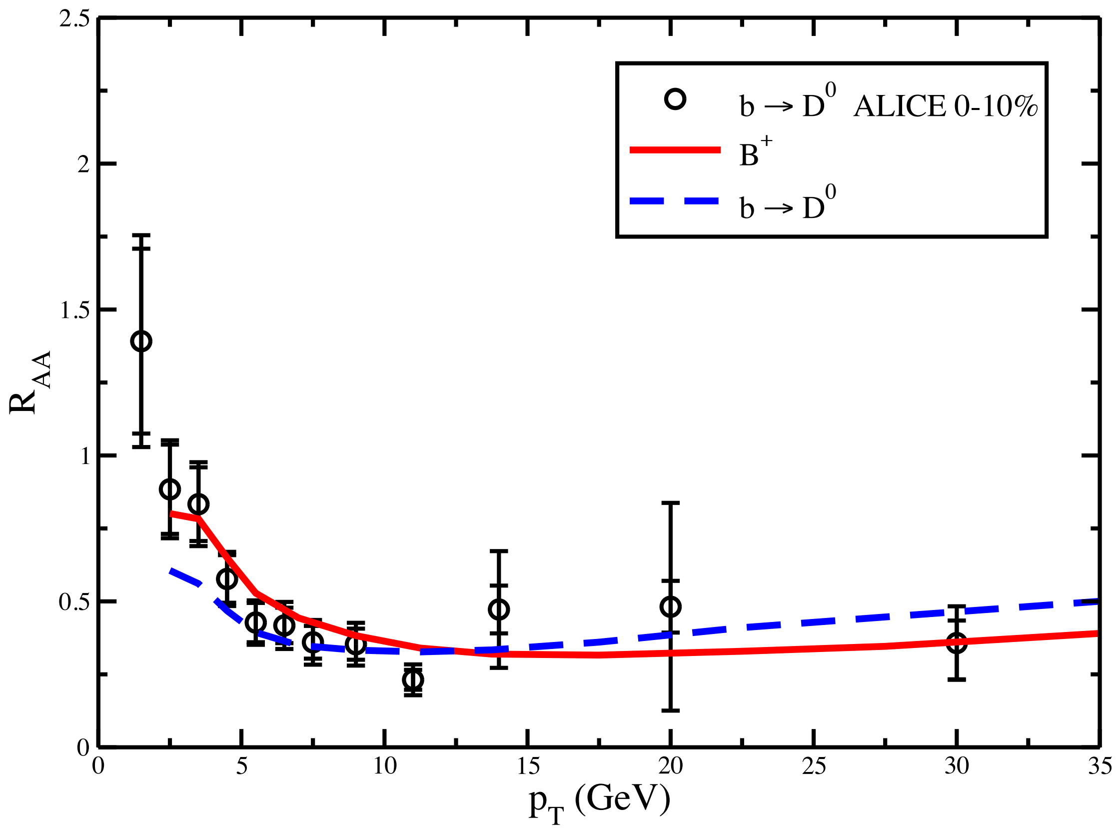
D meson' R_{AA} & v_2 in Au-Au@200GeV

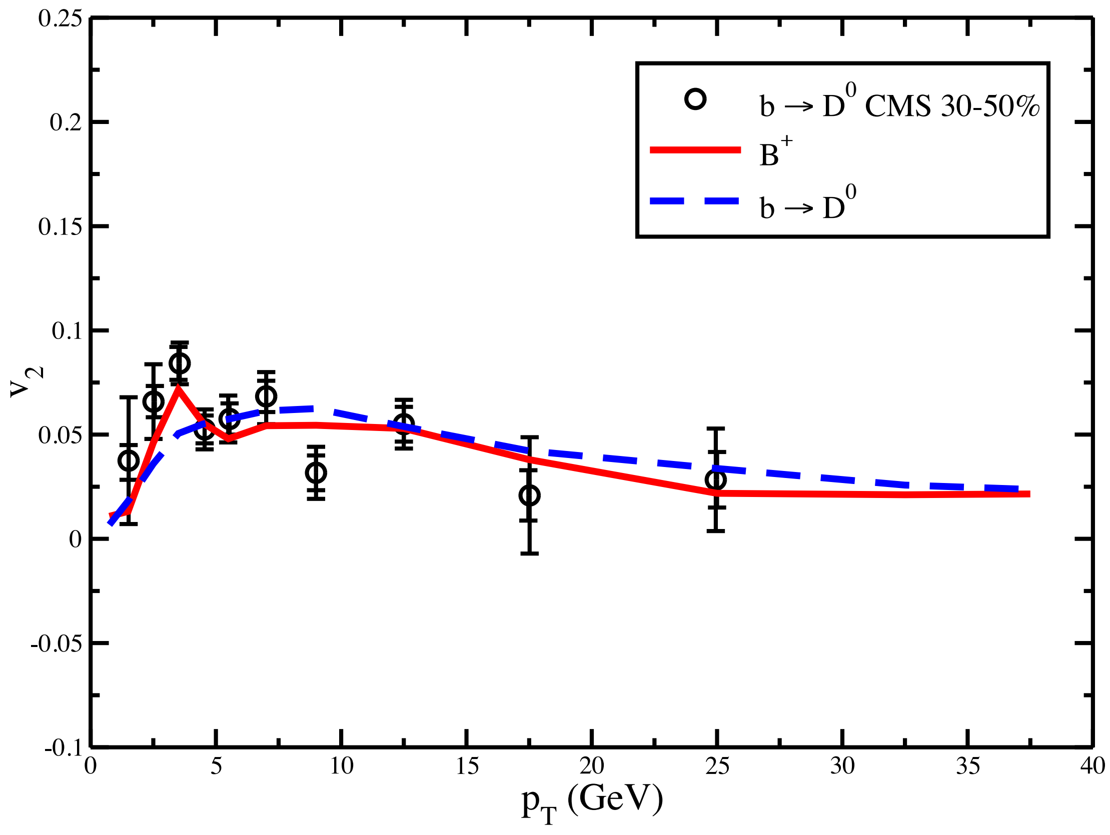




- Non-perturbative interactions alone can describe D meson R_{AA} and v_2 at RHIC.

B and $b \to D^0$ R_{AA} & v_2 in Pb-Pb@5.02TeV

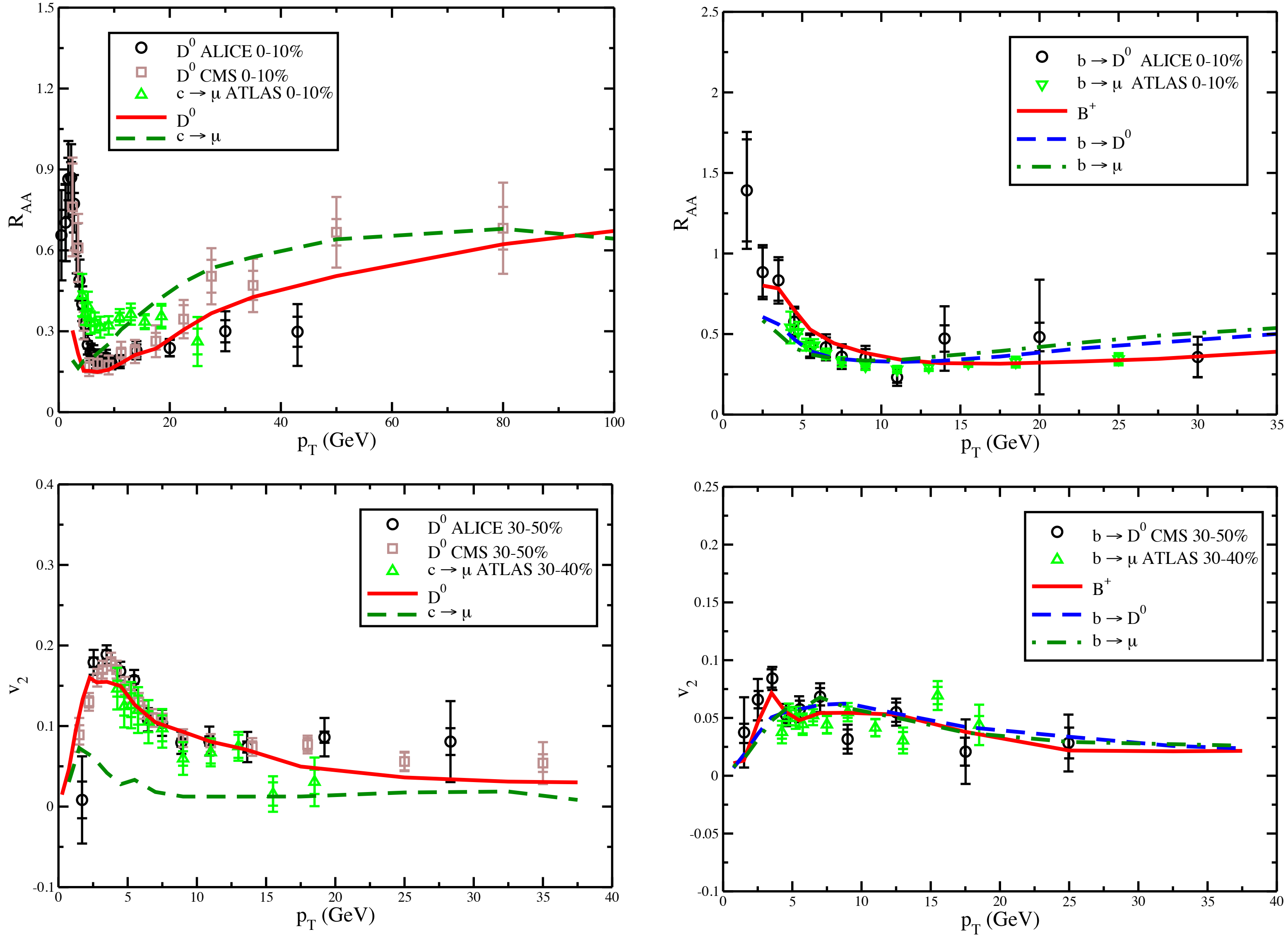




- B mesons are decayed to D^0 through PYTHIA.

➢ Our model can give a reasonable description of $b \to D^0$ R_{AA} and v_2 at LHC.

$c \to \mu$ and $b \to \mu$ R_{AA} & v_2 in Pb-Pb@5.02TeV

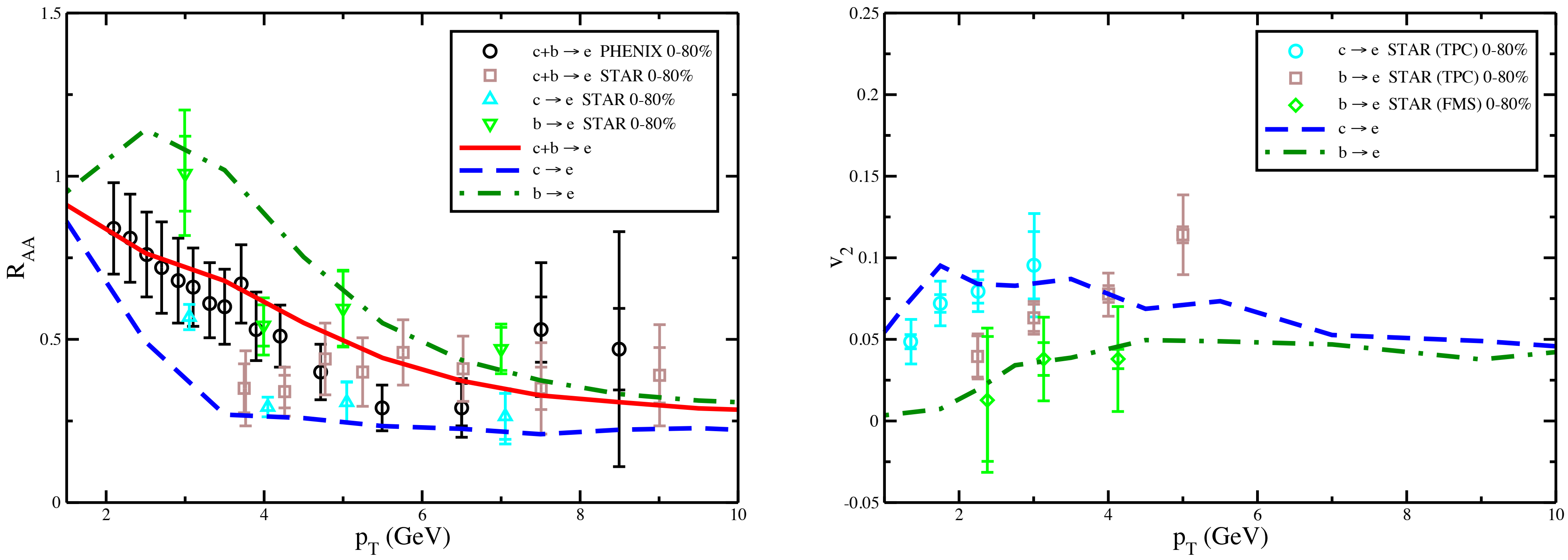


- c hadrons and b hadrons are decayed to μ through PYTHIA.

➢ Our model underestimates v_2 data of $c \to \mu$ at the LHC.

➢ Next, we will investigate the decay functions of heavy flavor hadrons.

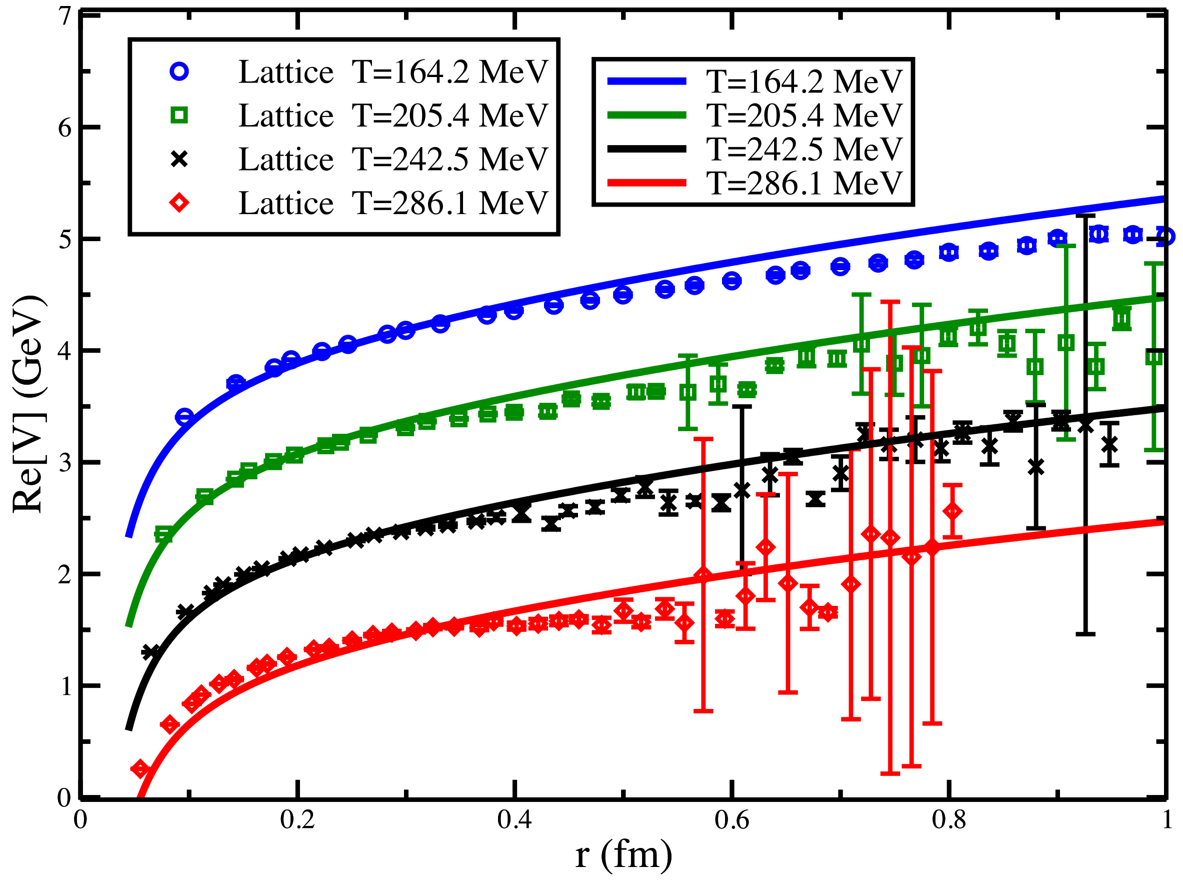
$c \rightarrow e$ and $b \rightarrow e$ R_{AA} & v_2 in AuAu@200GeV



- c hadrons and b hadrons are decayed to e through PYTHIA.

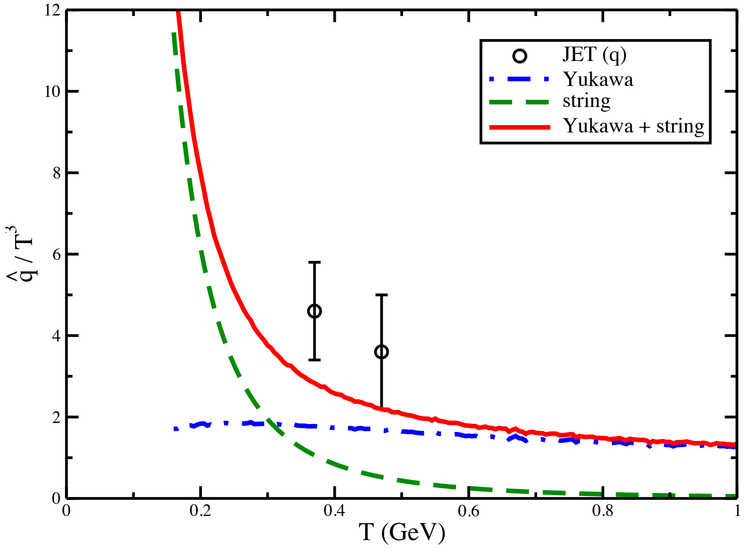
➢ Our model can give a reasonable description of $c \rightarrow e$ and $b \rightarrow e$ R_{AA} and v_2 at RHIC.

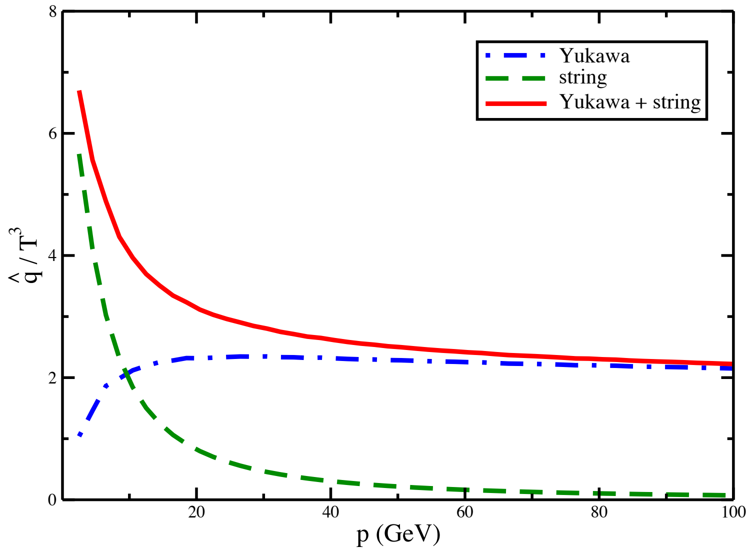
Heavy quark potential from D meson R_{AA} & v_2



- Through model-to-data comparison, the in-medium heavy quark potential is obtained from open heavy flavor observables for the first time.
- The extracted potential is in reasonable agreement with the lattice QCD calculation.
  [Y. Burnier, et. al, PRL 114, 082001 (2015)].

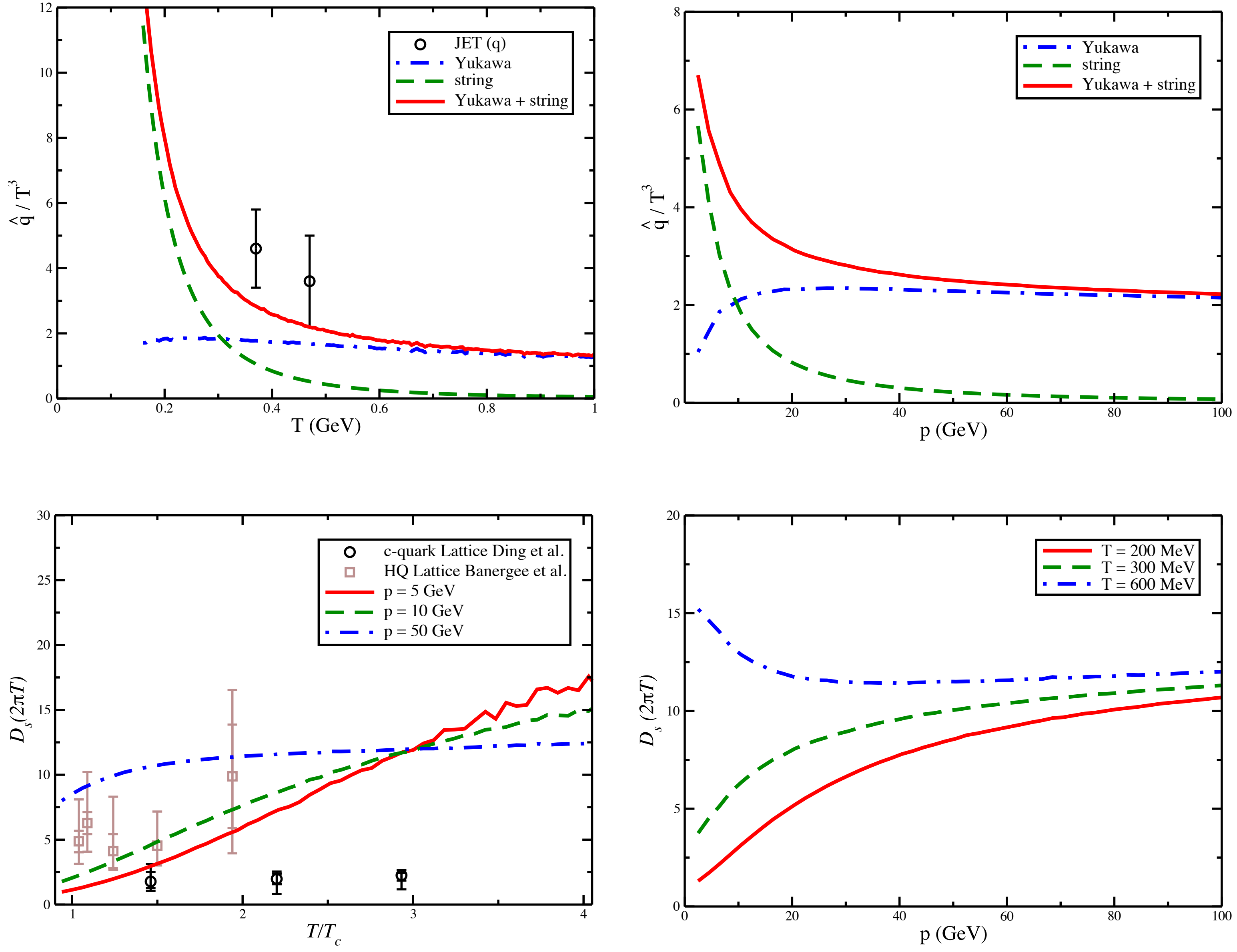
Transport coefficients





- ➢ **Yukawa interactions dominate $\hat{q}/T^3$ at high T and large p, string interactions dominate at low T and small p.**

Transport coefficients



- **Yukawa interactions dominate $\hat{q}/T^3$ at high T and large p, string interactions dominate at low T and small p.**
- **For low-p_T heavy quarks, $D_s(2\pi T)$ strongly depend on T.**
- **For different T, $D_s(2\pi T)$ shows different p dependence.**

Summary

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- We improve the LBT model for simulating both perturbative (Yukawa) interaction and non-perturbative (string) interactions between heavy quarks and QGP medium.

- We find that perturbative interactions dominate heavy flavor observables at high p_T, non-perturbative interactions dominate at low and intermediate p_T.

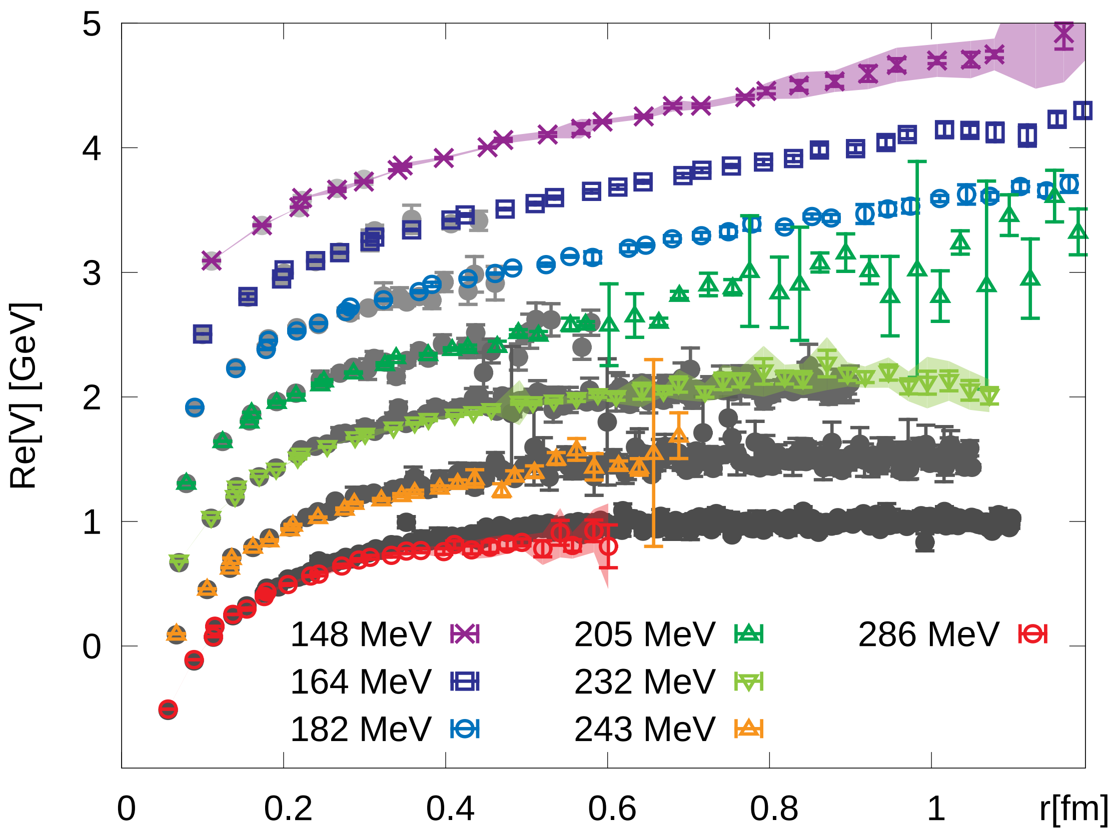
- Through model-to-data comparison, we have obtained the in-medium heavy quark potential from open heavy flavor observables for the first time.

Thank You !

Back-up

The following are Back-up pages

In-medium heavy quark potential from Lattice



- In the limit $m \to \infty$, the leading part of the potential $V(t, r)$ can be obtained as,

$$V(r) = \sum_{t\to\infty} \frac{i\partial_t W(t,r)}{W(t,r)},$$

where $W(t, r)$ is the real-time thermal Wilson loop.

- Through a Fourier transformation,

$$W(t,r) = \int_{-\infty}^{+\infty} d\omega \rho(\omega, r) e^{-i\omega t},$$

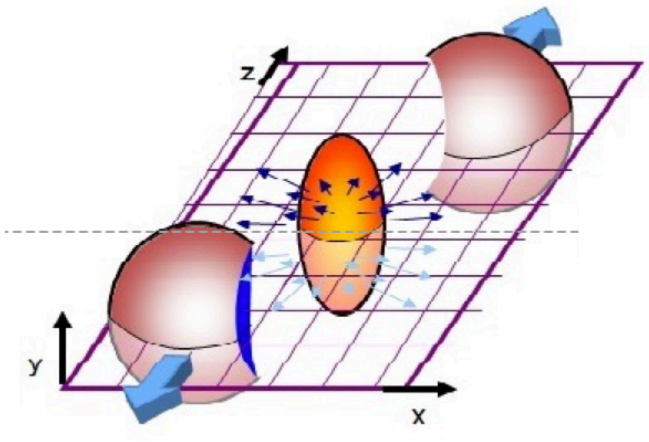
where $\rho(\omega, r)$ is the spectral function of the real-time Wilson loop.

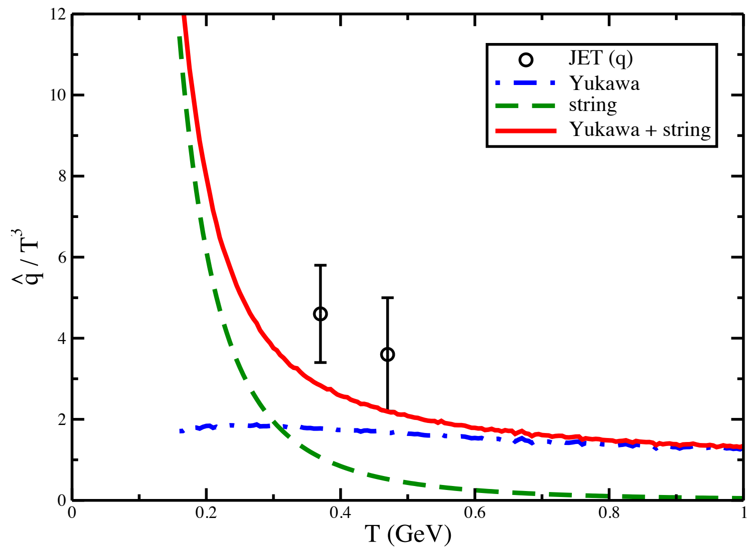
- The above equation can be analytically continued to the Euclidean time, giving

$$W(\tau,r) = \int_{-\infty}^{+\infty} d\omega \rho(\omega, r) e^{-\omega\tau}.$$

$W(\tau, r)$ is the usual Euclidean-time Wilson loop which can be obtained from lattice QCD calculations.

D meson v_2 in Pb-Pb@5.02TeV





- At low-p_T, heavy quark's elliptic flow (v_2) originates from the coupling to asymmetrically expanding medium.
- Asymmetric medium flow gets stronger at the later stage ($T \rightarrow T_c$).
- The strong string interactions at low T help low-p_T heavy quarks obtain larger v_2 from the later stage of QGP.