Mass hierarchy of heavy quark energy loss within a perturbative-non-perturbative transport model

arXiv:2307.14808

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2024. 5. 16

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- **The Linear Boltzmann Transport (LBT) model**
- **Different mass hierarchy of heavy flavor R_{AA} between low and high p_T**
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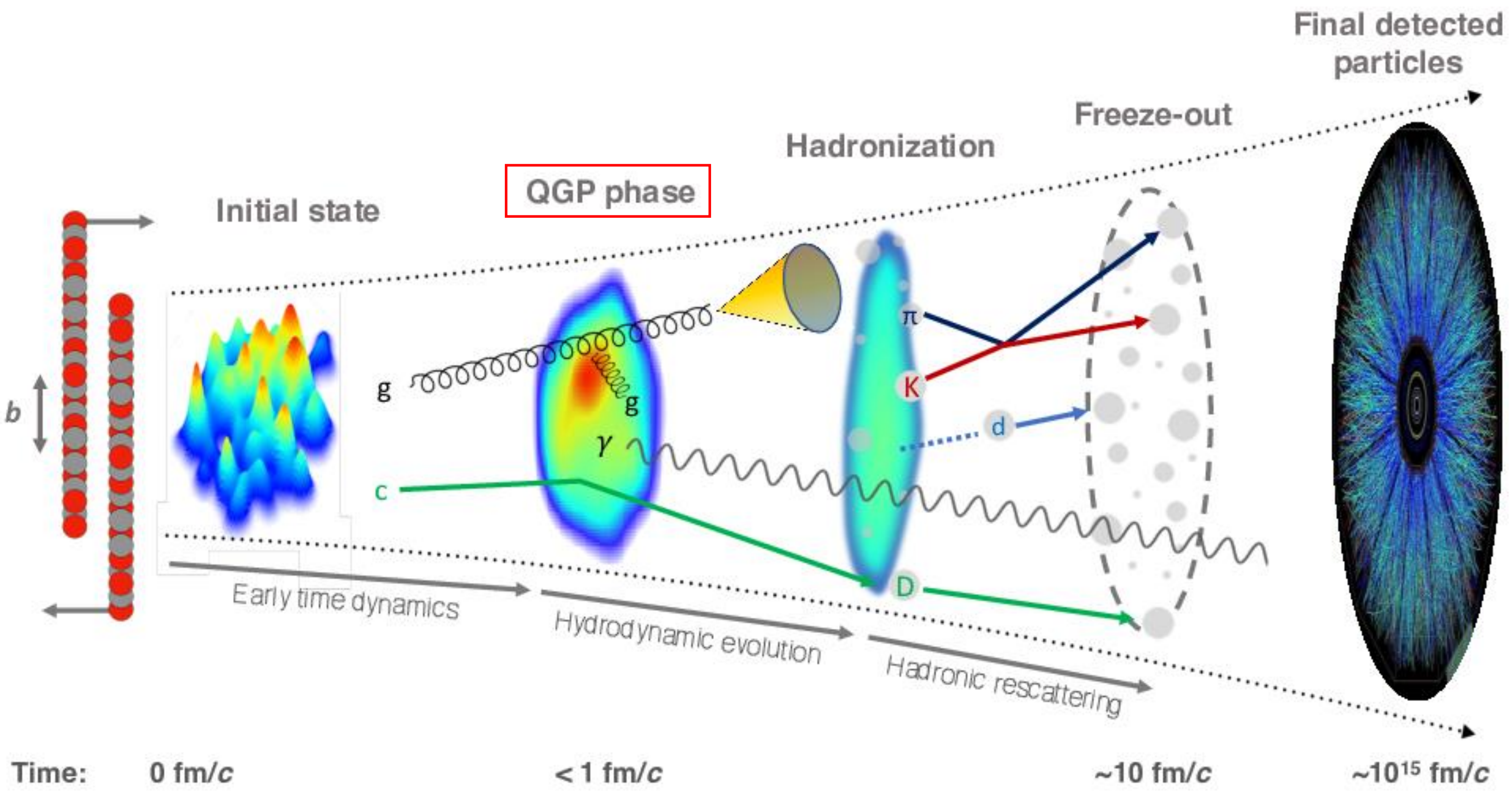
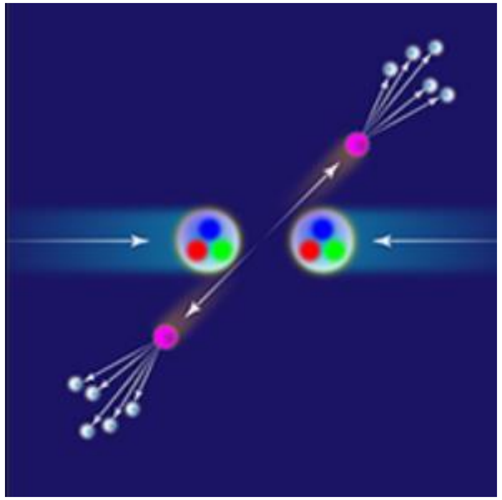
Introduction

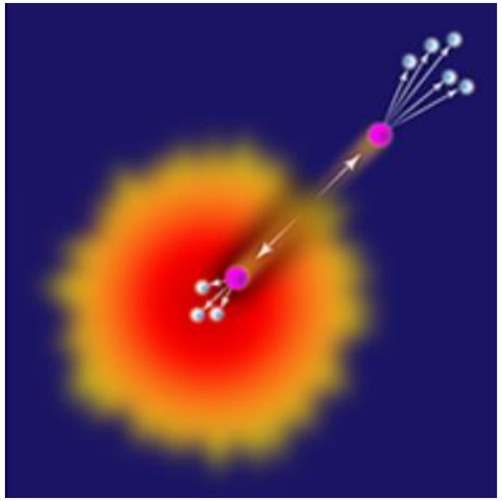


- Quark gluon plasma (QGP): ideal fluid, composed of deconfined quarks.
- Heavy flavor quark: produced early and calculable with pQCD, traverse QGP with flavor conserved.
- Both perturbative and non-perturbative calculation are needed in quark scattering.

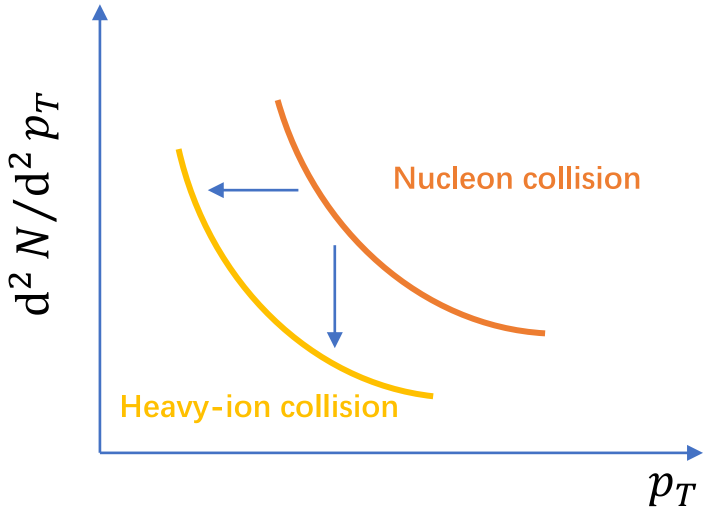
Nuclear modification factor



Nucleon collision

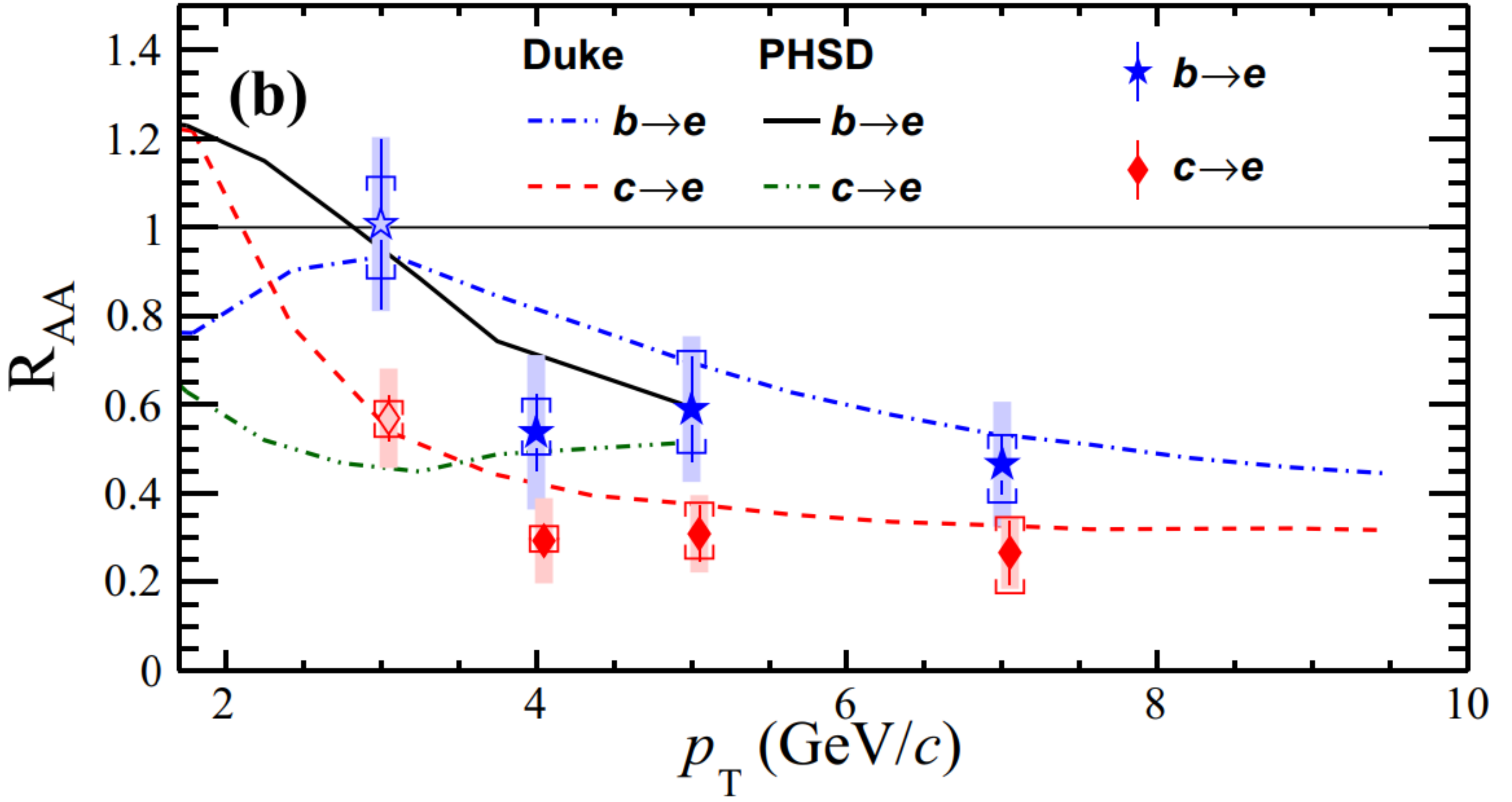


Heavy-ion collision



- **To extract the QGP properties using heavy quarks, people compare heavy flavor observables in pp collision and heavy-ion collision.**

$$R_{AA} \equiv \frac{d^2N^{AA}/dydp_\perp}{d^2N^{pp}/dydp_\perp \times \langle N_{coll}^{AA} \rangle}$$



- R_{AA} of charm hadron decayed lepton is smaller than that of bottom, which indicates the smaller energy loss of bottom than that of charm.

[Abdallah *et al. Eur. Phys. J. C* 82, 1150 (2022).]

Linear Boltzmann Transport model

- The Boltzmann Transport equation:

$$\frac{\mathrm{d}}{\mathrm{d}t} f(\vec{x}, \vec{p}, t) = \mathrm{C}[f] = \text{gain - loss}$$

For channel $\boldsymbol{a} + \boldsymbol{b} \to \boldsymbol{c} + \boldsymbol{d}$, the collision term is:

$$\mathrm{C} = \int d^3p_b d^3p_c d^3p_d \,[f_c f_d \omega(p_a p_b | p_c p_d) - f_a f_b \omega(p_c p_d | p_a p_b)]$$

- Considering one single particle to traverse QGP, only the loss term is needed, and simultaneously, the integral of $\boldsymbol{f_b} * \omega$ can be regarded as scattering rate Γ, which is related to the amplitude M:

$$\Gamma = -\int d^3k \, w\left(\vec{p}, \vec{k}\right) f_b \sim |M_{a+b\to c+d}|^2$$

Perturbative-non-perturbative transport model

- In the elastic scattering amplitude term $\mathcal{M}$, the Cornell-type potential is used to include both Yukawa term (perturbative term) and string term(non-perturbative term):

$$V(r) = V_{\mathrm{Y}}(r) + V_{\mathrm{S}}(r) = -\frac{4}{3}\alpha_{\mathrm{s}}\frac{e^{-m_d r}}{r} - \frac{\sigma e^{-m_s r}}{m_{\mathrm{s}}}$$

where m_d and m_s are the parameterized Debye screening mass:

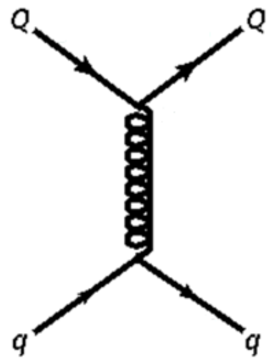
$$m_d = a + bT \qquad m_s = \sqrt{a_s + b_s T}$$

Parameters $\alpha_s, a, b, \sigma, a_s, b_s$ are extracted from model to data comparison.

Perturbative-non-perturbative transport model

- Take $Qq \longrightarrow Qq$ elastic scattering process as an example, the scattering amplitude with effective potential propagator can be written as:

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



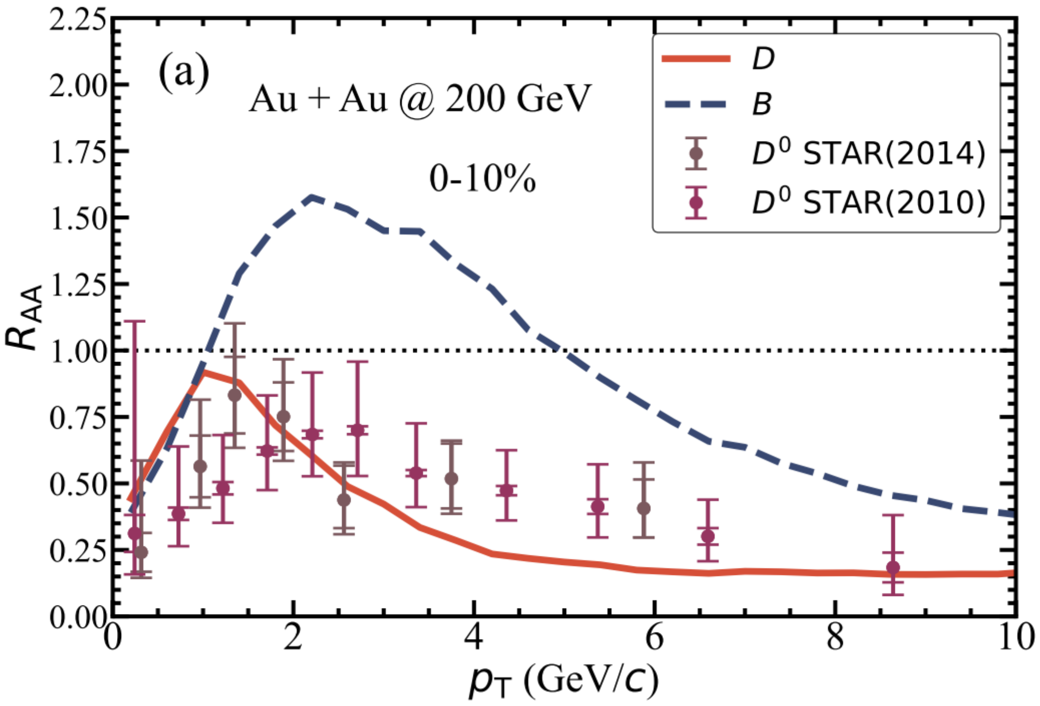
- If the mass of heavy quark is $\boldsymbol{m_Q}$, and light quark is massless, the corresponding squared amplitude reads:

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

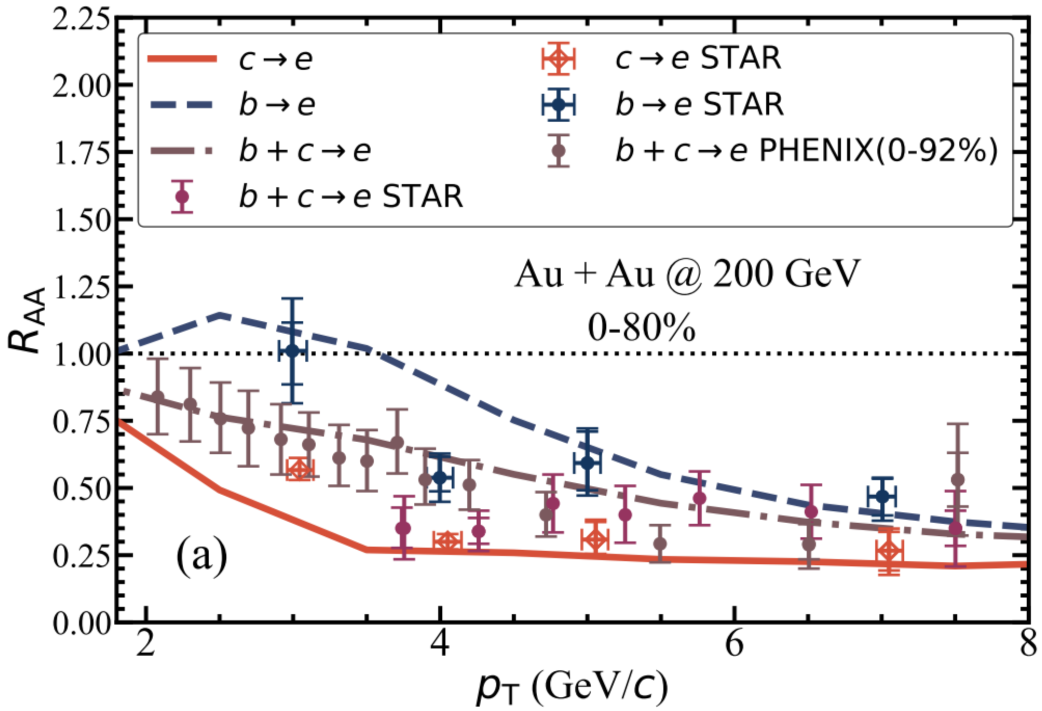
→ The lighter the heavy quark is, the smaller the string term is!
The higher the temperature is, the smaller the string term is!

R_{AA} of hadrons and leptons at low p_T

- R_{AA} of meson



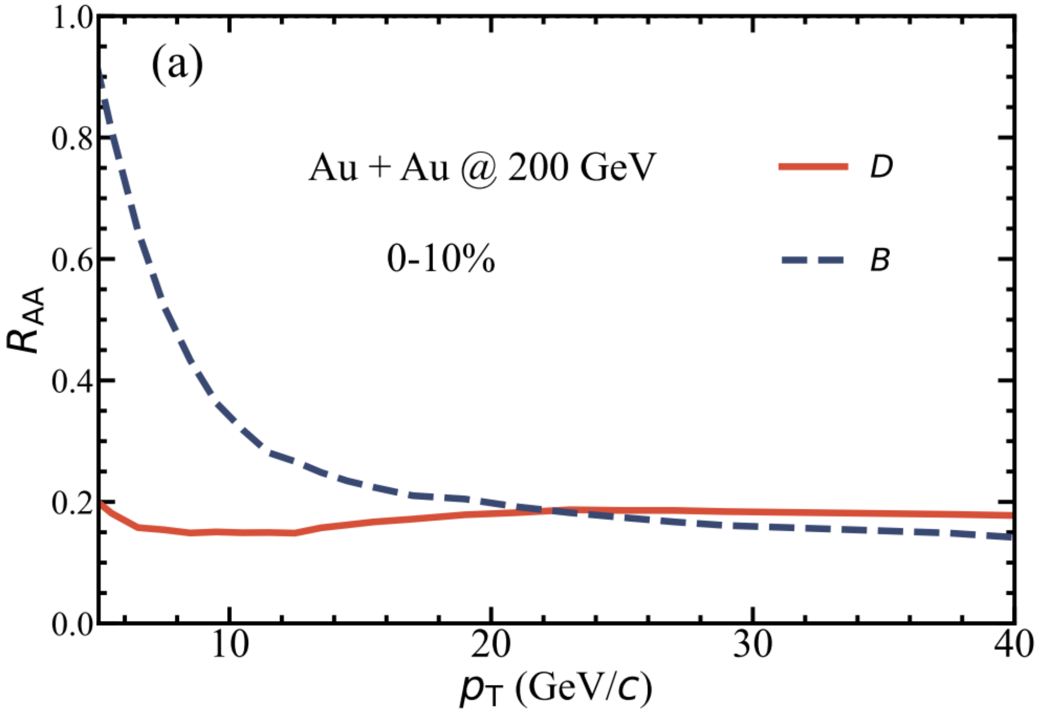
- R_{AA} of electron



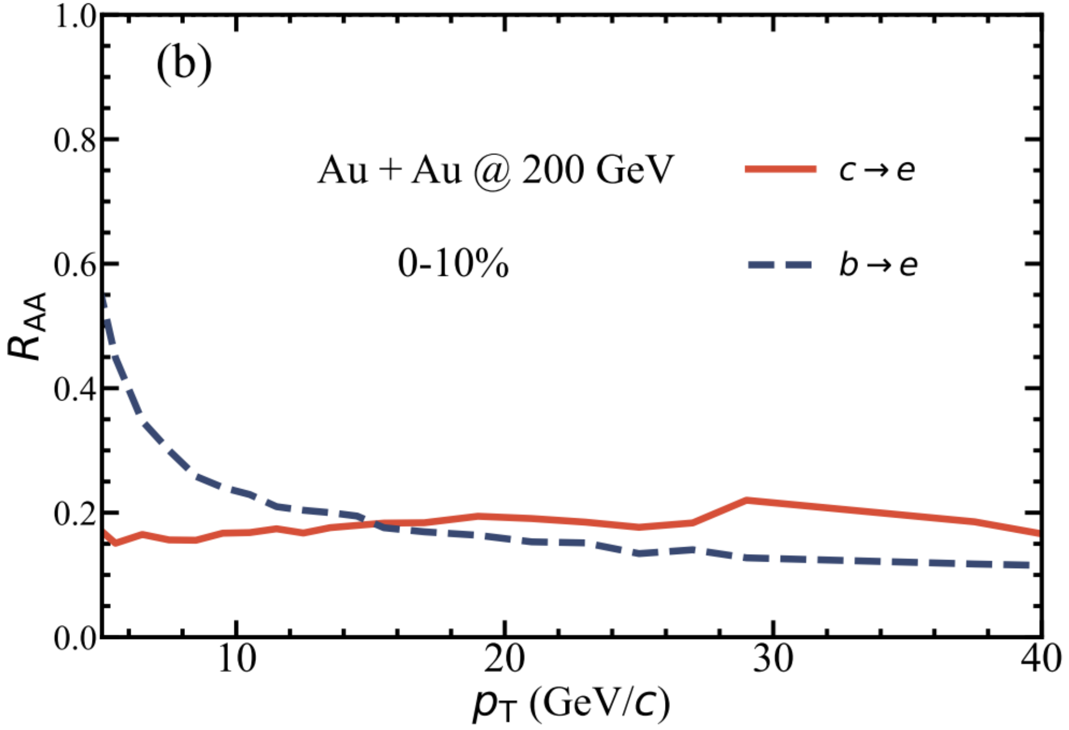
➢ **Based on our model, we plot R_{AA} vs. transverse momentum p_T for both heavy mesons and meson-decayed electrons, which can describe the experimental data.**

R_{AA} of hadrons and leptons at high p_T

- R_{AA} of mesons at high p_T



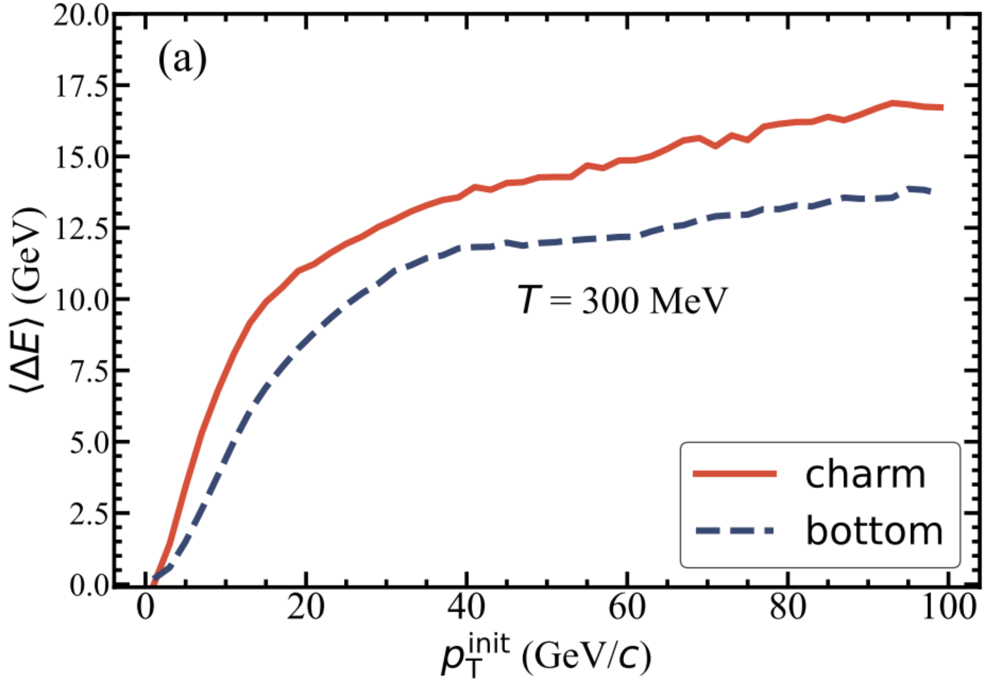
- R_{AA} of electrons at high p_T



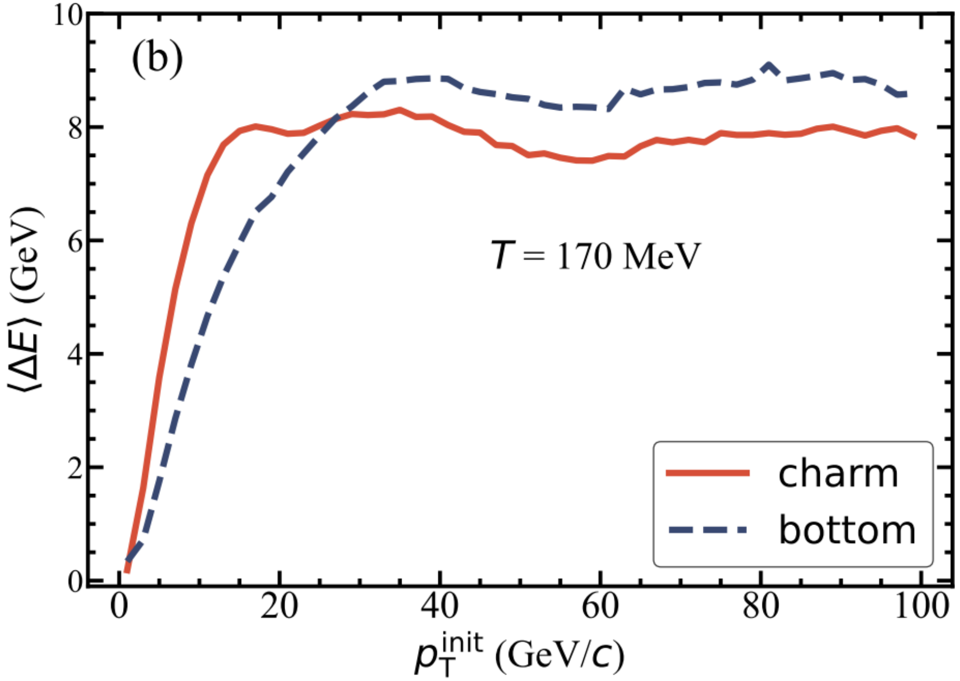
➢ **The crossover appears in both meson's and lepton's R_{AA} at high p_T.**
➢ **We can find similar observation at the LHC energy.**

The energy loss of heavy quarks in different temperature

- **Energy loss in static medium with temperature of 300 MeV**



- **Energy loss in static medium with temperature of 170 MeV**

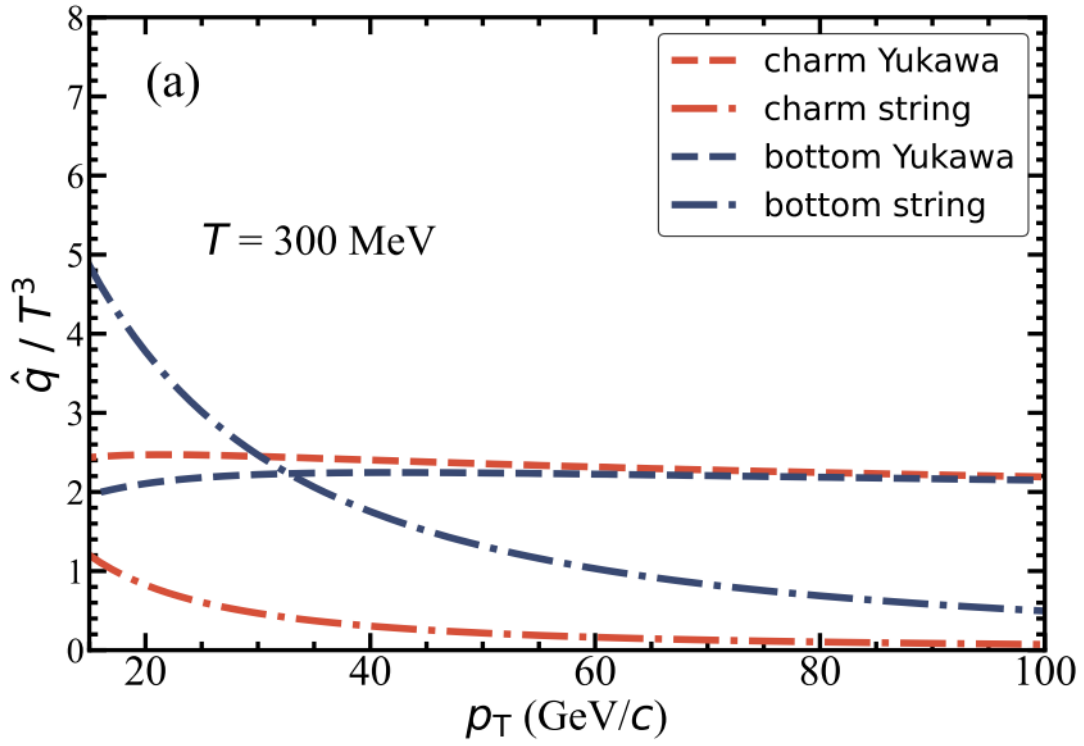


➢ **The crossover disappears at higher temperature.**

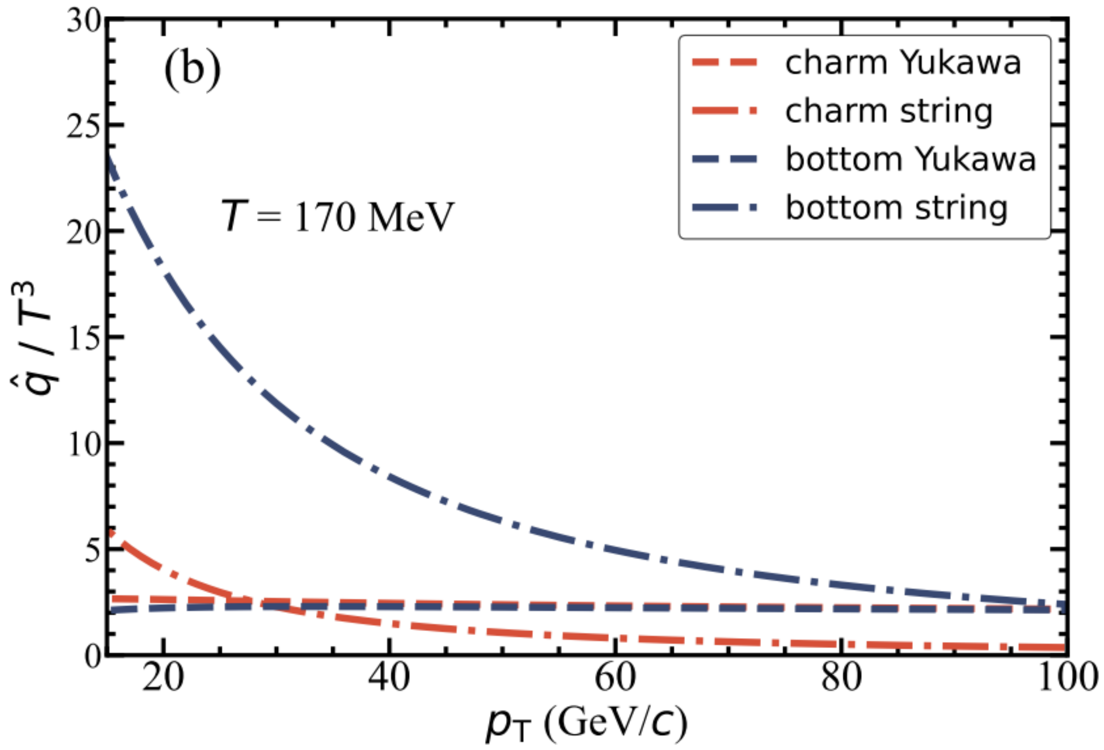
➢ **Remember the string term** , $\frac{(8\pi\sigma)^2}{N_c^2-1}\frac{t^2-4m_Q^2 t}{(t-m_s^2)^4}$, **is larger when temperature is lower.**

Contribution from Yukawa term and string term

- $\hat{q}$ in medium with temperature 300 MeV



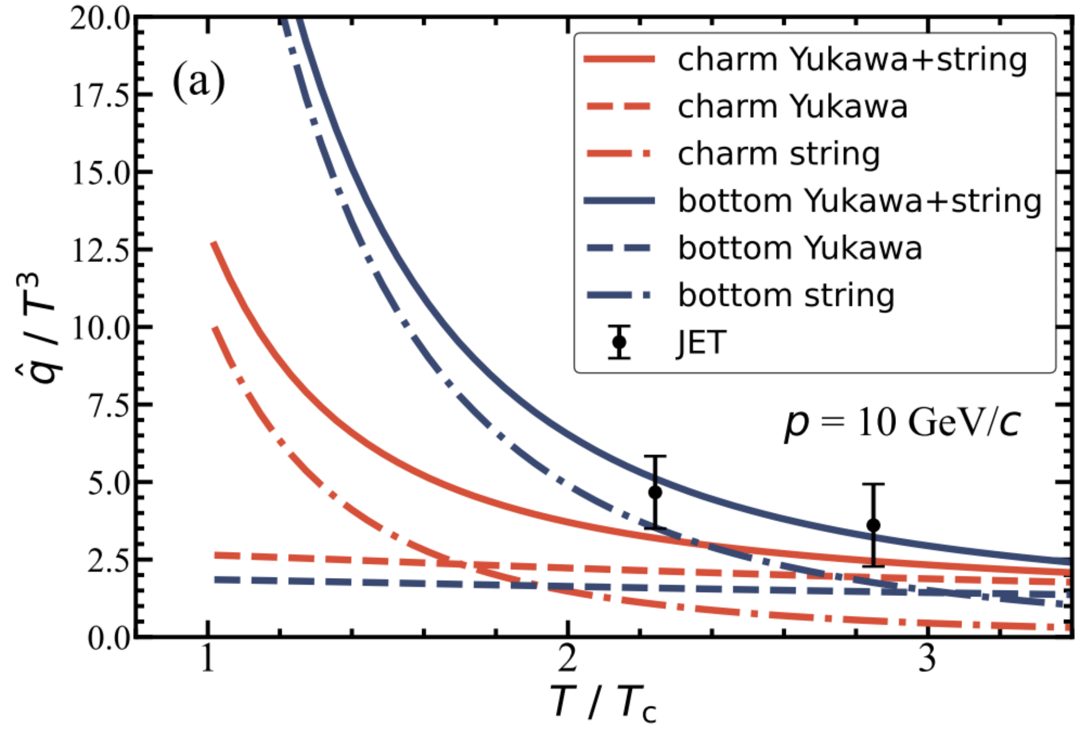
- $\hat{q}$ in medium with temperature 170 MeV



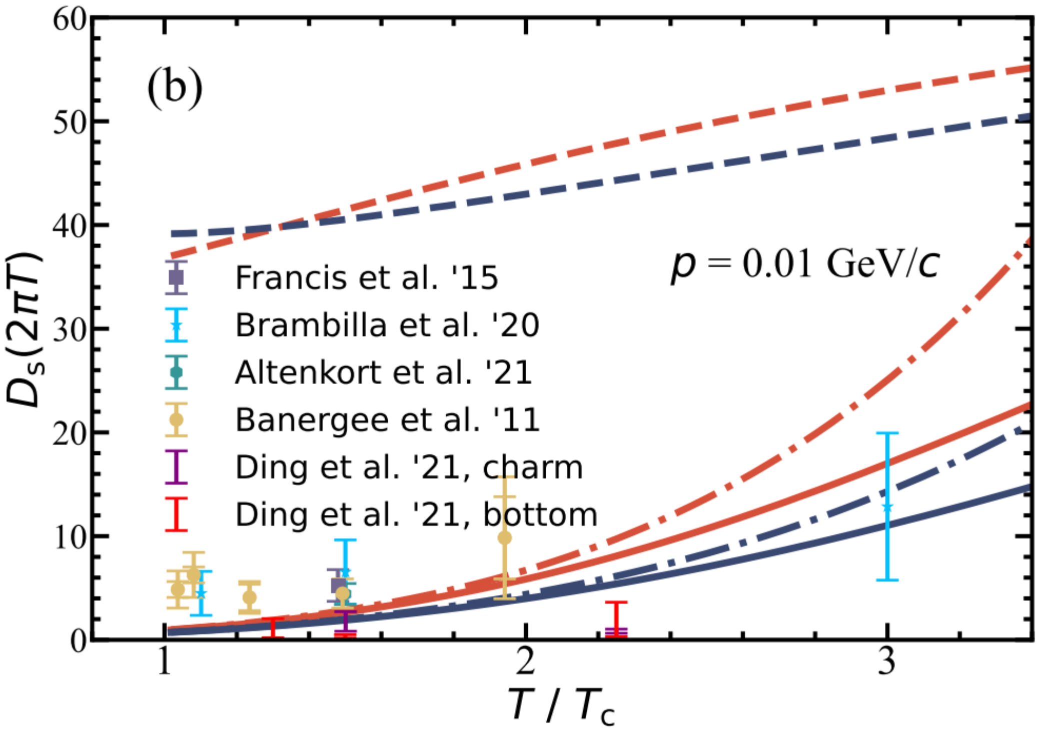
- ➢ **String term causes the more energy loss of bottom.**
- ➢ **At higher temperature, the Yukawa term dominates at high p_T, while at lower temperature, the string term of bottom dominates at high p_T.**

$\hat{q}$ and diffusion coefficient D_s

- $\hat{q}$ vs. T



- D_s vs. T



➢ **The string term decreases with the increase of temperature, while Yukawa term is almost the same.**

➢ **We calculated the diffusion coefficient D_s, which agree with the results from lattice QCD.**

Factors affecting energy loss

- **In elastic scattering (*Δ* E_c < *Δ* E_b):** the string term lead to the more energy loss of bottom.

	Low temperature	High temperature
Low momentum	string term	string term
High momentum	string term	Yukawa term

- **In inelastic scattering (*Δ* E_c > *Δ* E_b):**

Dead cone effect: the energy loss decreases with the increase of *m*/*E*, which lead to the less bottom quarks' energy loss than that of charm quarks at low p_T.

➢ The unexpected mass hierarchy of energy loss comes from the **competition** between **the effect of string interaction** on elastic scatterings and **the dead cone effect** on inelastic scatterings.

	Low temperature	High temperature
Low momentum	Dead cone effect	Dead cone effect
High momentum	String interaction effect	Dead cone effect & Yukawa interaction effect

Summary

- We studied the R_{AA} of heavy mesons and heavy flavor leptons from low to high p_T.
- We found the counterintuitive mass hierarchy of heavy quark energy loss, which can be explained by the competition between string term contribution and the dead cone effect, and we forecasted the R_{AA} of heavy quarks behavior at high p_T.
- Conclusion is model dependent, and difference between charm and bottom RAA is small.

Thank you!

Back up