Production and nuclear modification of B_c mesons in relativistic heavy−ion collisions

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Outline of my talk

- ☐ **Introduction to quarkonia**
- ☐ **Initial production of B_c**
- ☐ **Linear Boltzmann Transport Model**
- ☐ **Medium modification of B_c**
- ☐ **Summary and outlook**

Introduction to quarkonia

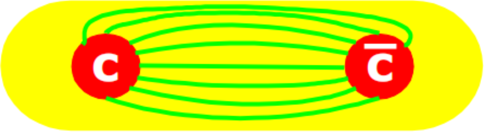
Photo from the Nobel Foundation archive.
Samuel Chao Chung Ting
Prize share: 1/2

Photo from the Nobel Foundation archive.
Burton Richter
Prize share: 1/2

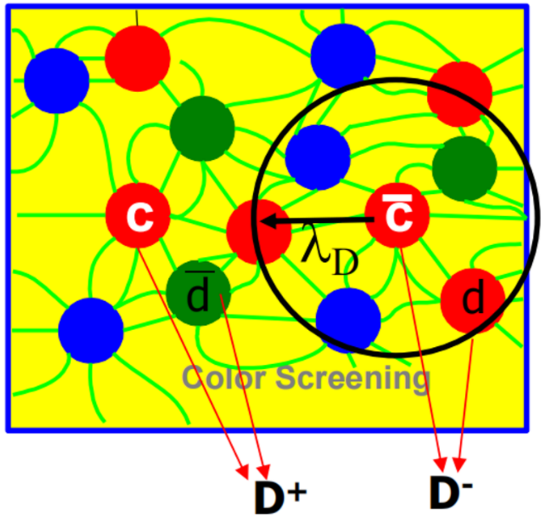
- 1974: Discovery of J/ψ,
  proof of charm quark.
- 1976: Nobel Prize in Physics.

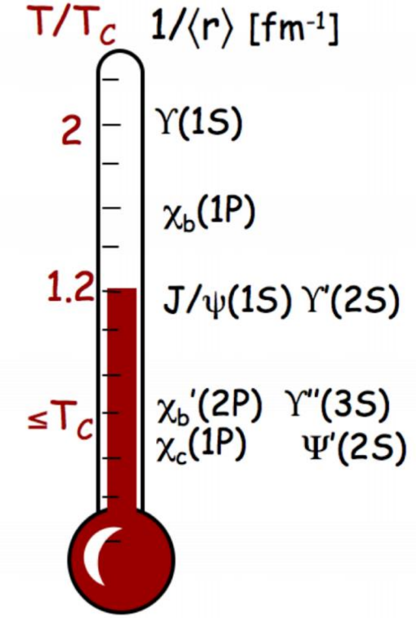
- Suppression of J/ψ yields is a key sign of QGP formation in heavy-ion collisions.

Vacuum



QGP





[Mocsy, EPJC 61 (2009) 705]

- Sequential melting of heavy quarkonia serves as a QGP thermometer.

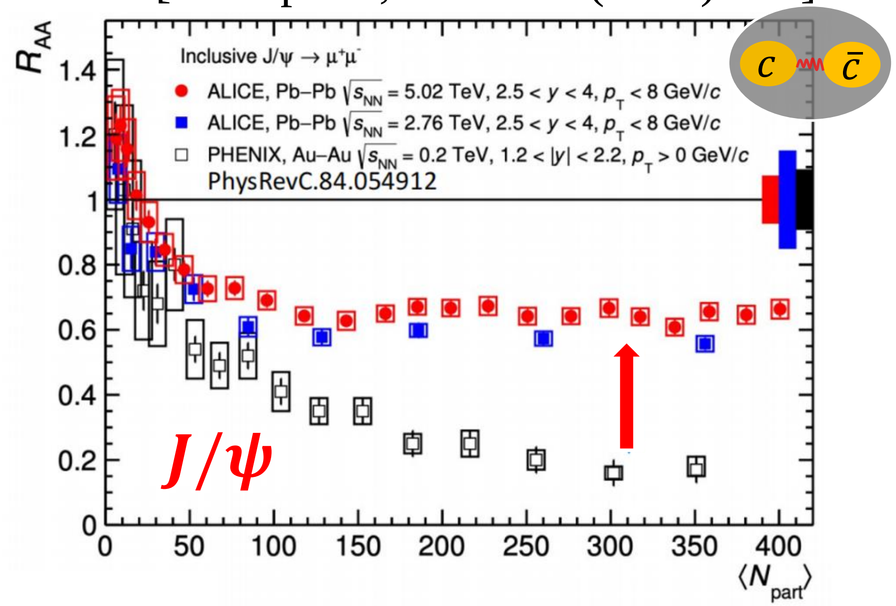
Introduction to quarkonia

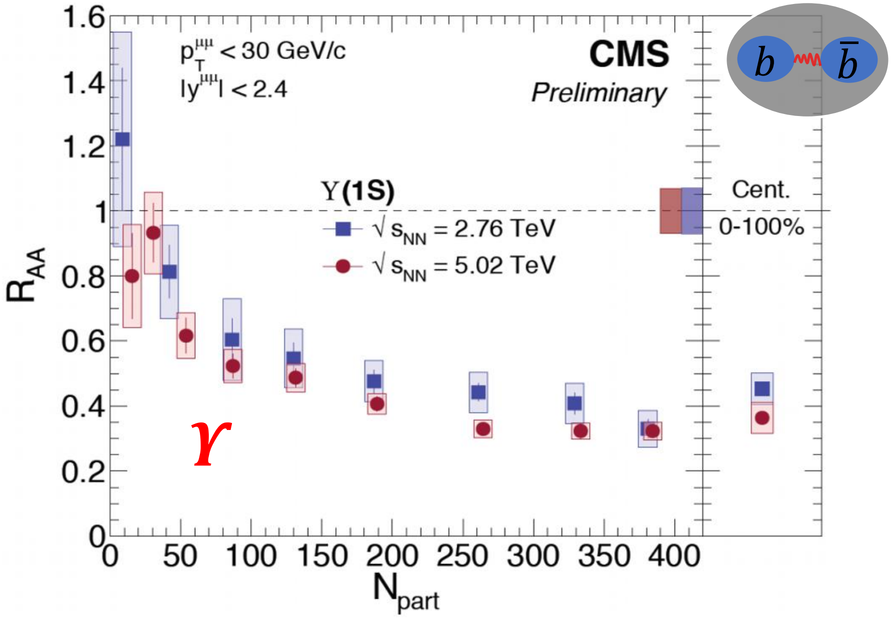
Nuclear modification factor:

$$R_{AA}(p_T) \equiv \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T \times \langle N_{coll} \rangle}$$

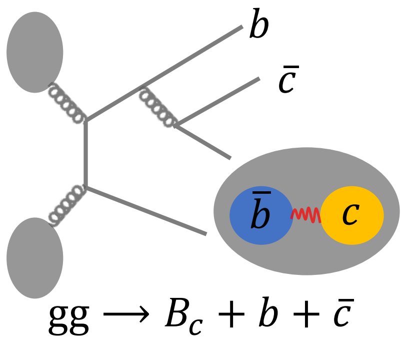
- PHENIX: strong J/ψ suppression, consistent with color screening.
- ALICE: weak J/ψ suppression, **Regeneration** of heavy quarkonia is important at high heavy quark density.
- CMS: Υ mesons do not exhibit recombination effects.

[Scomparin, NPA 967 (2017) 208]





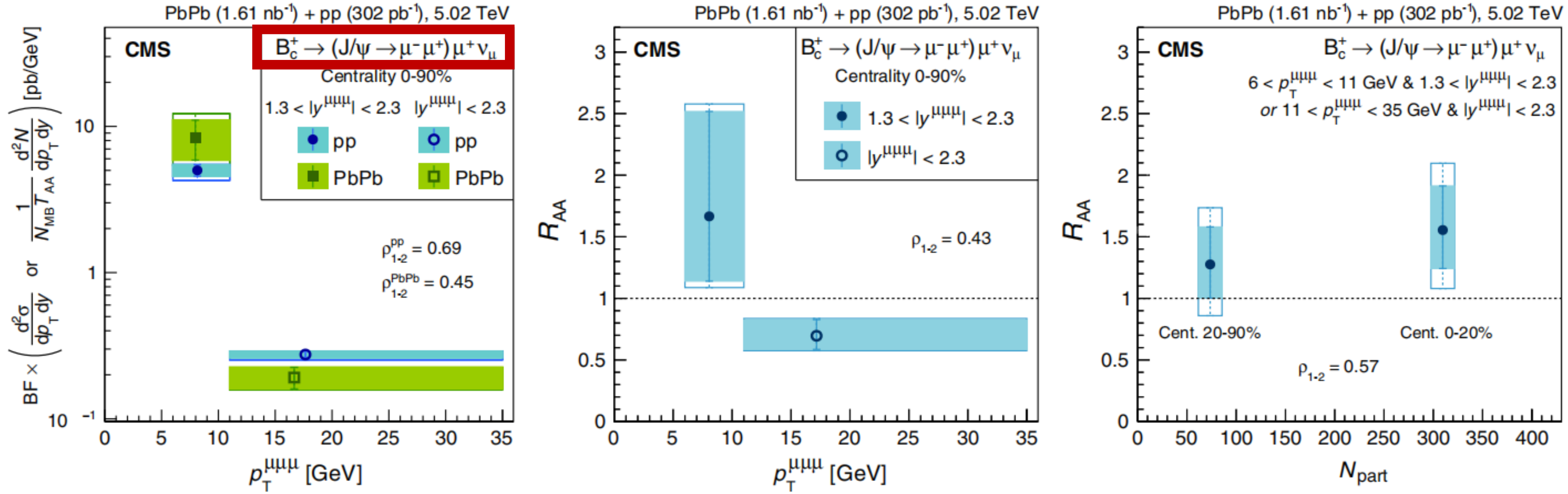
Introduction to B_c mesons



- $B_c^+(c\bar{b})$: study the energy loss of open heavy quarks and the formation mechanisms of heavy quark bound states.

□ pp: small yield □ AA: dissociation, fragmentation and recombination

[CMS, PRL 128 (2022) 252301]



- The R_{AA} of B_c mesons is greater than one in the low p_T and shows no obvious dependence on centrality.

Initial production of B_c

- Initial charm and bottom quarks: FONLL.
- D^0 and B^+ mesons in pp :

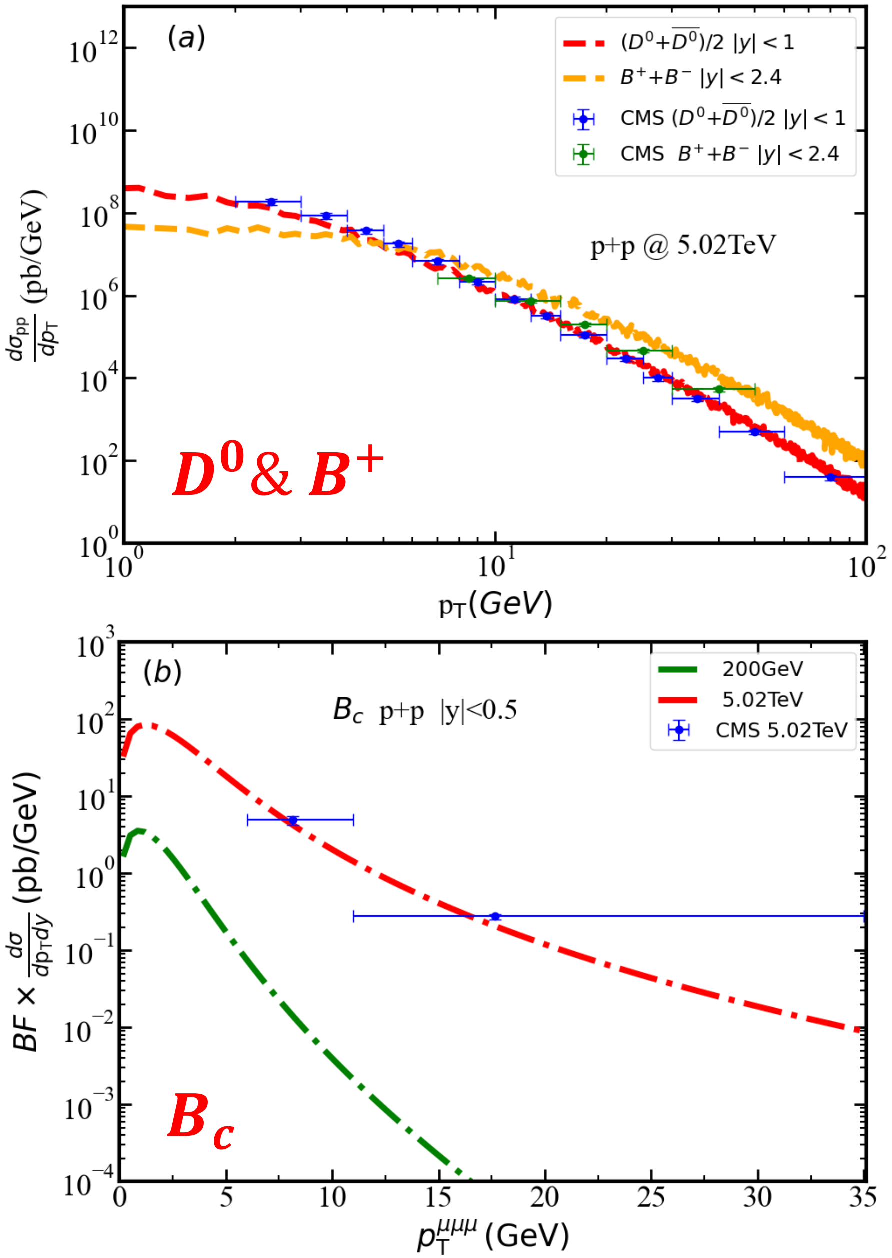
  c/b quark + Pythia fragmentation.
- B_c in pp:

  b quark + fitted fragmentation function.

  [Braaten, Cheung, Yuan, Phys. Rev. D 48 (1993) R5049]

$$D_{b\to B_c^-}(z) = N\frac{rz(1-z)^2}{[1-(1-r)z]^6} \times\Big[6-18(1-2r)z+(21-74r+68r^2)z^2 -2(1-r)(6-19r+18r^2)z^3 +3(1-r)^2(1-2r+2r^2)z^4\Big]$$

- About 0.3% of b quarks fragment into B_c mesons.
- NLO contribution not included in this calculation yet.



LBT model: heavy quark-QGP interaction

- **Boltzmann equation:** $p_a \cdot \partial f_a(x,p) = E_a[C_{el}(f_a) + C_{inel}(f_a)]$

- **Elastic scattering:**

$$\Gamma_{el}^{a}(\vec{p}_a, T) = \sum_{b,(cd)} \frac{\gamma_b}{2E_a} \int \prod_{i=b,c,d} \frac{d^3 p_i}{E_i (2\pi)^3} f_b(E_b, T)(2\pi)^4 \delta^{(4)}(p_a + p_b - p_c - p_d) \underline{|M_{ab\to cd}|^2}$$

potential scattering calculation

- **Inelastic scattering:** $\Gamma_{inel}^{a} = \int dx dl_\perp^2 \underline{\frac{dN_g^a}{dx dl_\perp^2 dt}}$ Higher-twist formalism

[X.F. Guo et.al., PRL 85 (2000) 3591; B.-W. Zhang et.al., PRL 93 (2004) 072301]

- **Elastic+Inelastic:** $P_{tot}^{a} = 1 - e^{-(\Gamma_{el}^{a} + \Gamma_{inel}^{a})\Delta t}$

Perturbative and non-perturbative interactions

- Heavy quark-QGP interaction potential: [Xing, Qin, Cao, PLB 838 (2023) 137733]

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

Yukawa(perturbative) **string(non-perturbative)**

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 string interaction strength.

- By Fourier transformation,

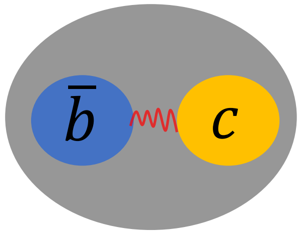
$$V(\vec{q},T) = -\frac{4\pi\alpha_s C_F}{m_d^2 + |\vec{q}|^2} - \frac{8\pi\sigma}{(m_s^2 + |\vec{q}|^2)^2}$$

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

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

Dissociation of B_c mesons

- **Quasi-free dissociation picture:** [Wu, Tang, He, Rapp, Phys. Rev. C 109 (2024) 014906]



$$v_{\bar{b}} = v_c \qquad m_{\bar{b}} \neq m_c$$

$$p_{\bar{b}} \neq p_c$$

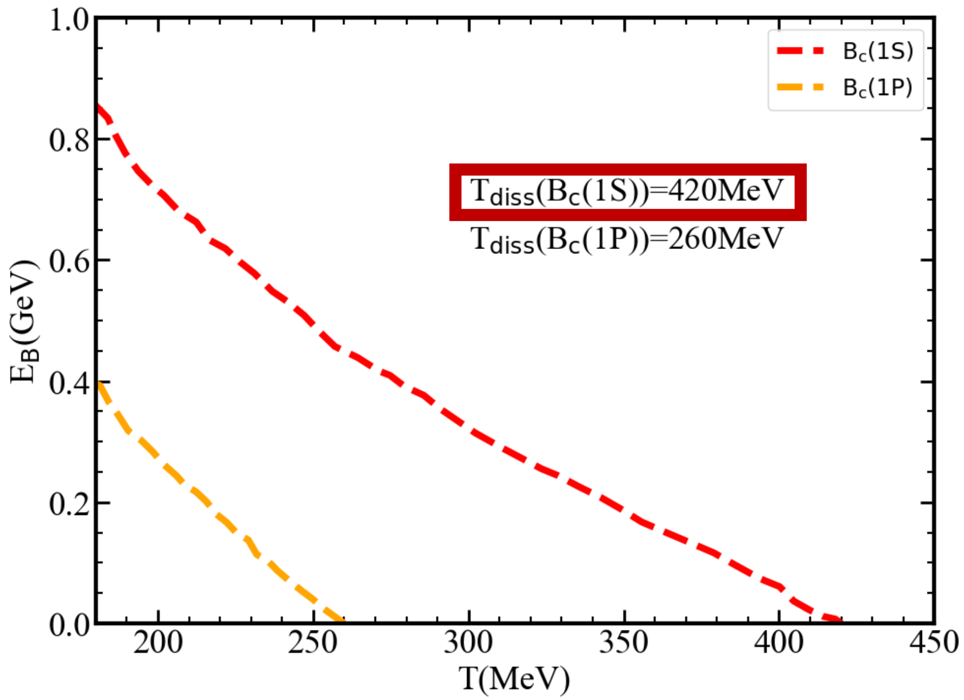
$$\gamma m_c v + \gamma m_{\bar{b}} v = p_{B_c}$$

$$\Gamma_{B_c}(\vec{p}, T) = \Gamma_c\left(\frac{m_c}{m_c + m_{\bar{b}}}\vec{p}, T\right) + \Gamma_{\bar{b}}\left(\frac{m_{\bar{b}}}{m_c + m_{\bar{b}}}\vec{p}, T\right)$$

$\Gamma_{c/\bar{b}}$: Rate of scattering (LBT model) with $k^2 > E_B^2$

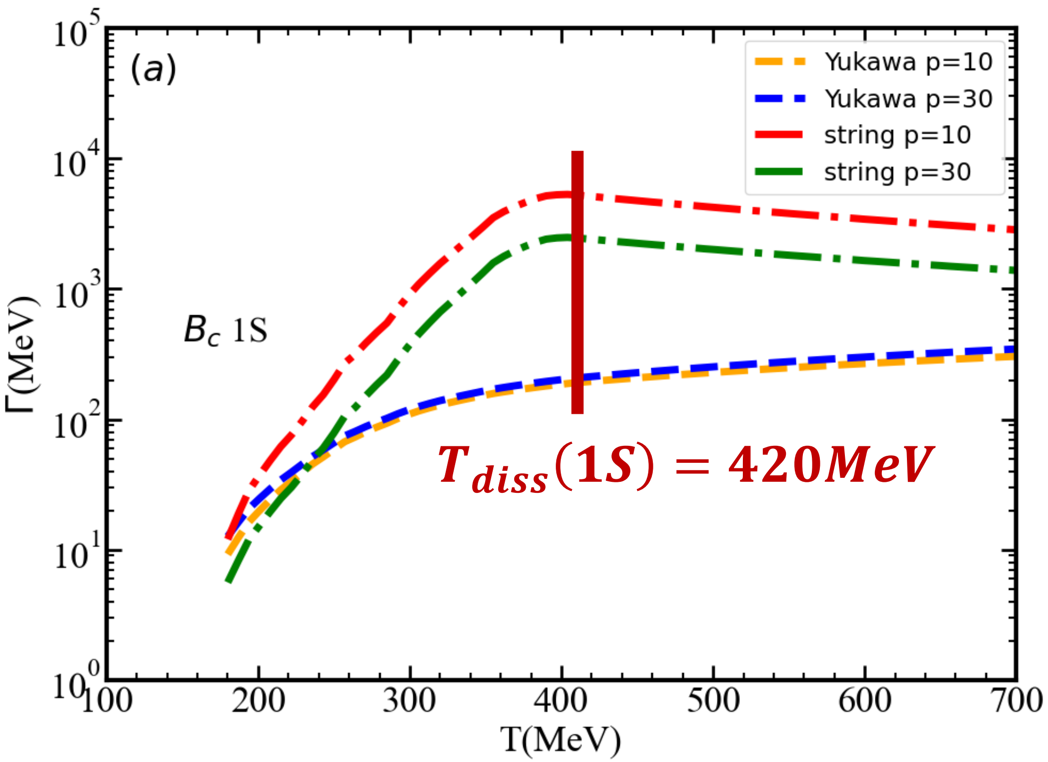
k: 4-momentum exchange

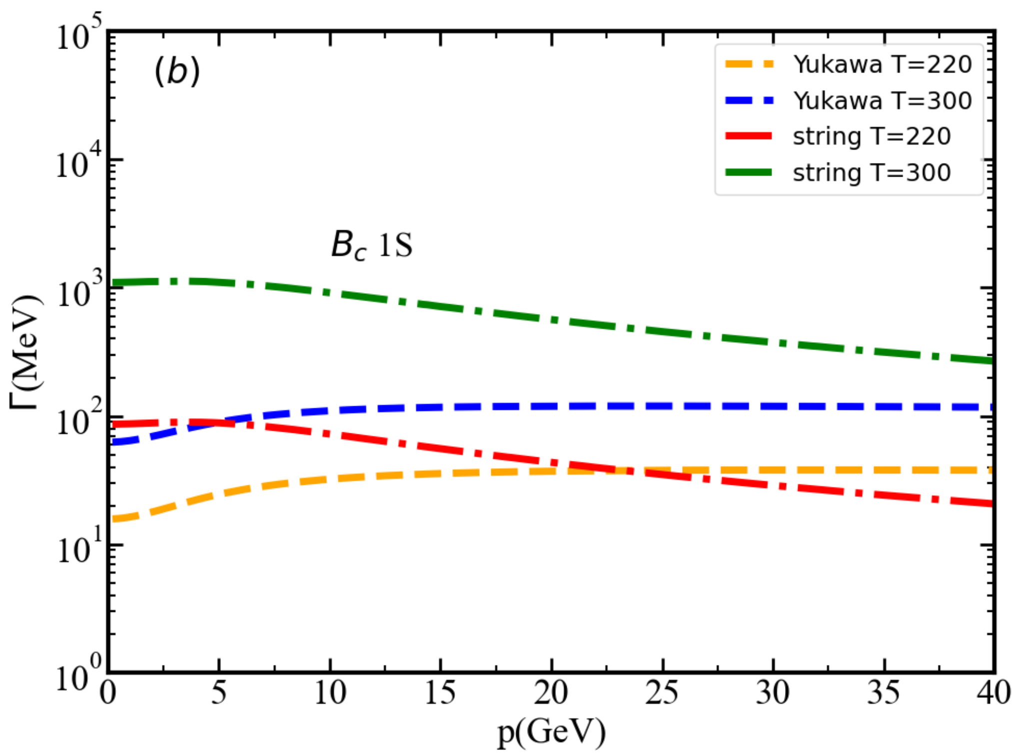
E_B: binding energy of B_c



T_{diss}: melting temperature of $B_c(E_B=0)$

Dissociation of B_c mesons





- Small momentum exchange dominates in non-perturbative interactions, making the $\mathbf{k^2 > E_B^2}$ cut more pronounced than in perturbative interactions.
- Generally, the string interactions result in much larger dissociation rates of B_c mesons than the Yukawa interactions.

B_c production after medium modification

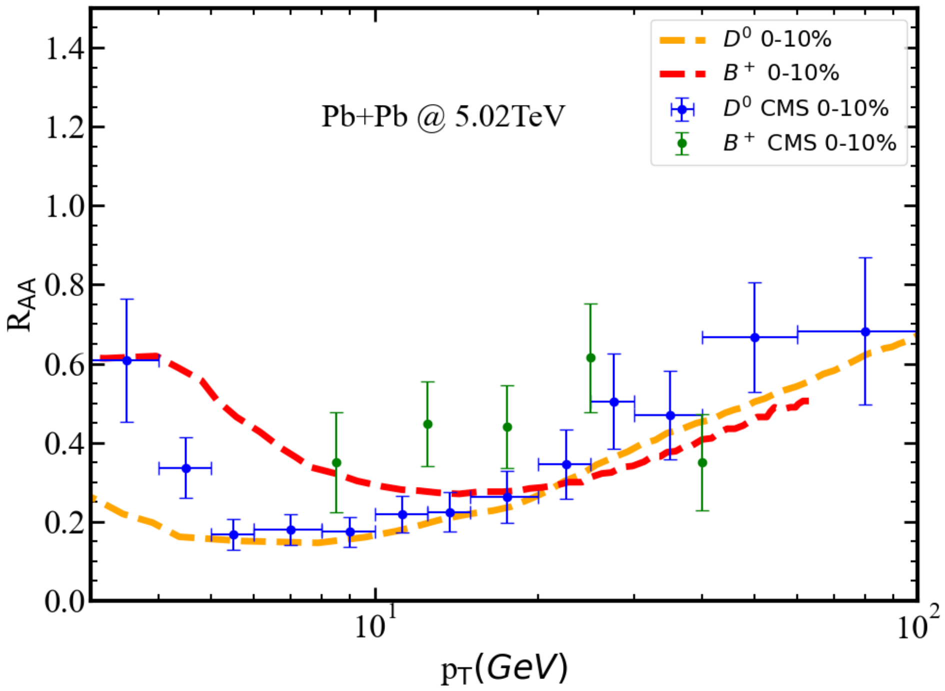
☐ Recombination to B_c mesons

Instantaneous Coalescence model(ICM)

$$\frac{d^3N_{B_c}(\vec{p})}{d^3\vec{p}} = C_r g_{B_c} \int d^3\vec{p}_c\, d^3\vec{p}_{\bar{b}} \frac{d^3N_c}{d^3\vec{p}_c} \frac{d^3N_{\bar{b}}}{d^3\vec{p}_{\bar{b}}} \delta^{(3)}(\vec{p} - \vec{p}_c - \vec{p}_{\bar{b}}) W(\vec{k})$$

- C_r: fit from N_{part} dependence of R_{AA}.
- g_{B_c}: spin-color statistical factor.
- The medium-modified spectra of c and $\bar{b}$ quarks: LBT model.
- D^0 and B^+ in PbPb: c/b quark + hybrid fragmentation coalescence model.

[Cao, Sun et.al., PLB 807 (2020) 135561]



B_c production after medium modification

☐ Recombination to B_c mesons

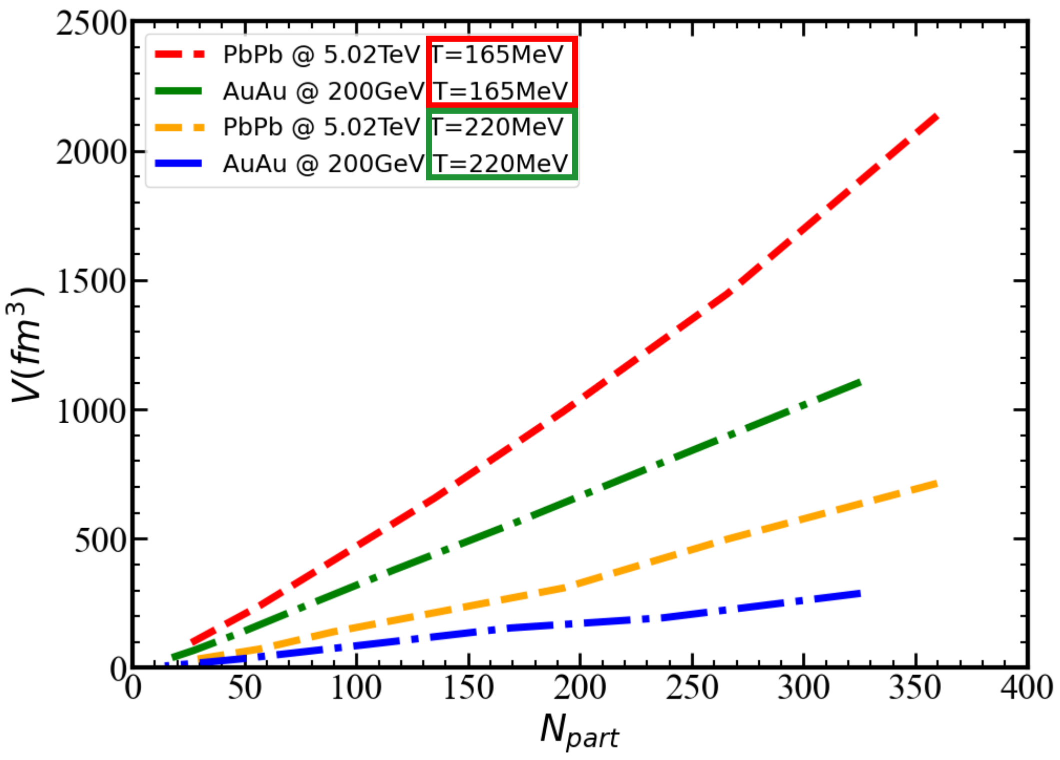
Instantaneous Coalescence model (ICM)

- **Wigner function:**

$$W_s(k) = \frac{(2\sqrt{\pi}\sigma_s)^3}{\boldsymbol{V}} e^{-\sigma_s^2 k^2}$$

$$W_P(k) = \frac{(2\sqrt{\pi}\sigma_p)^3}{\boldsymbol{V}} \frac{2}{3} \sigma_p^2 k^2 e^{-\sigma_p^2 k^2}$$

   - $\sigma_{s/p}$ from $B_c(1S/P)$ radii
   - V: average volume of the QGP at a fixed temperature (hydrodynamic calculations)



- $B_c(1S)$ regenerated at T = 220 MeV, $B_c(1P)$ at T = 165 MeV.

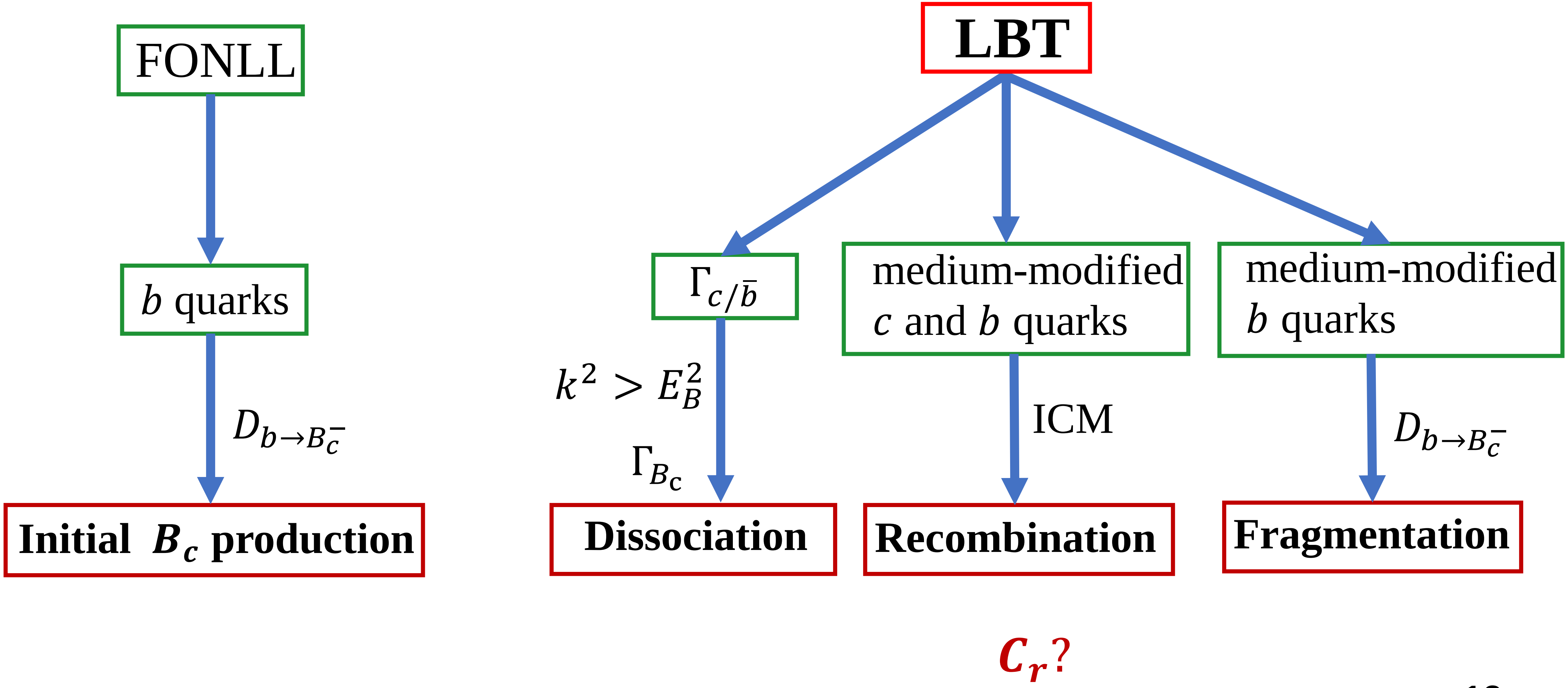
☐ Fragmentation to B_c mesons

Medium modified b quarks (at T = 165 MeV) + vacuum fragmentation function.

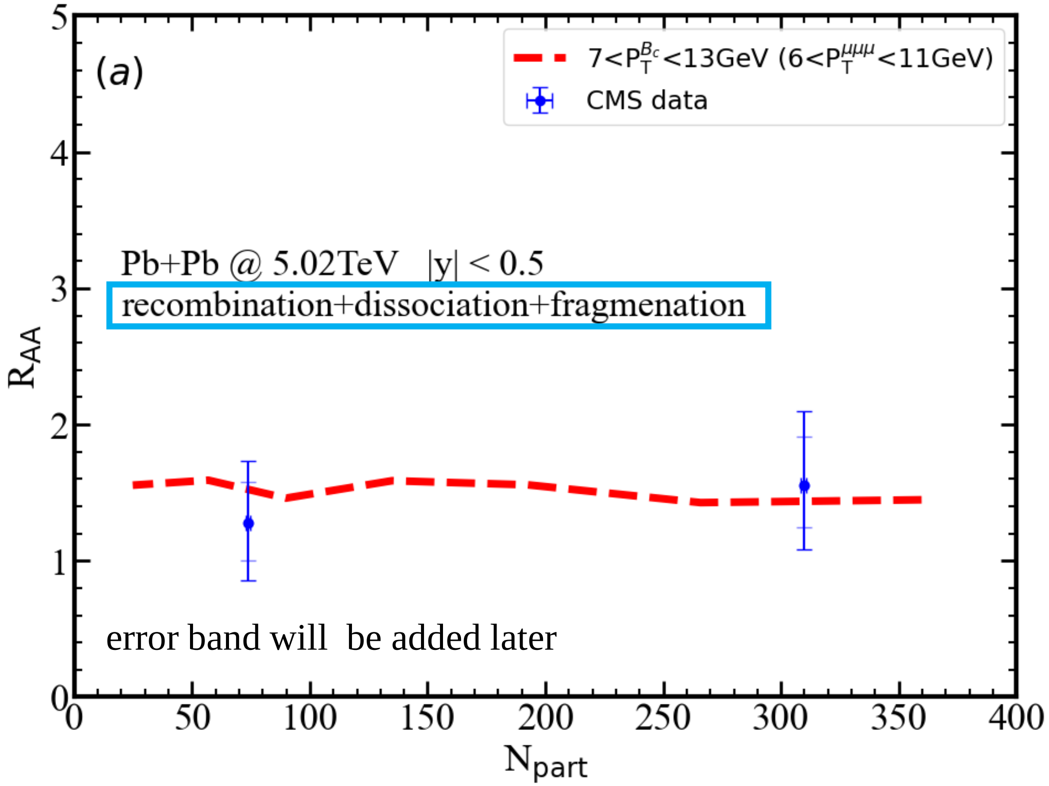
Summary of Methods

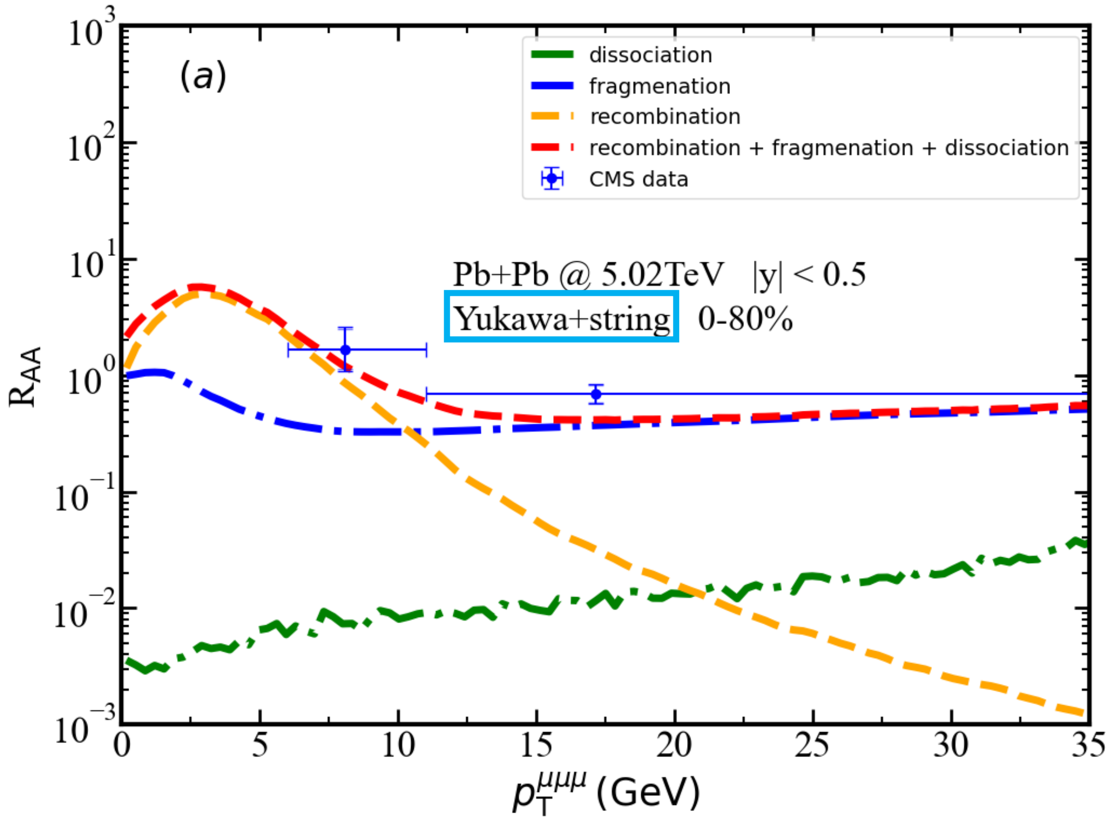
B_c production in pp

Medium modification of B_c in AA



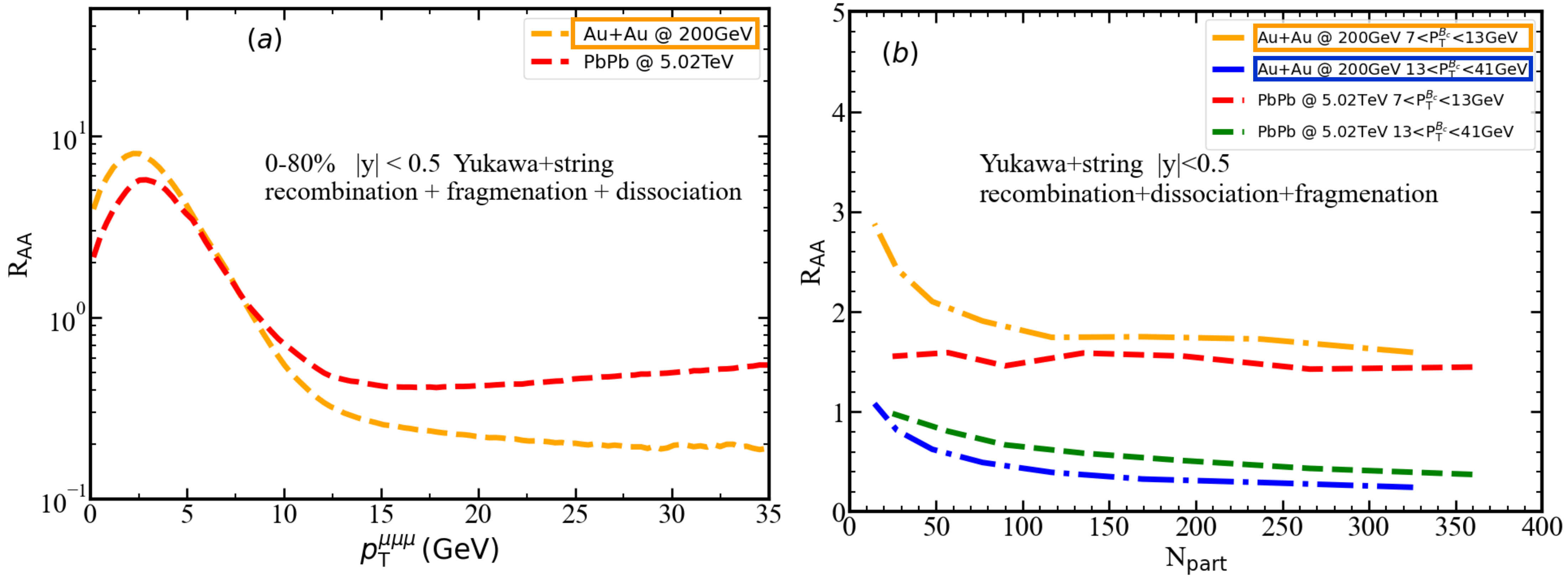
Nuclear modification factor of B_c





- Coalescence probability increases with heavy quark density, decreases with the QGP volume ⟶ weak dependence on N_{part}(used to fix C_r in coalescence).
- Reasonable description of the p_T dependence of R_{AA}.
- Little contribution from initially produced B_c, dominated by coalescence at low p_T, dominated by medium-modified b-quark fragmentation at high p_T.

Predictions on R_{AA} of B_c at RHIC vs. LHC



- RHIC > LHC at low p_T : dominated by coalescence (lower pp baseline and smaller V_{QGP} at RHIC).
- RHIC < LHC at high p_T : dominated by b-quark energy loss and fragmentation (softer b-quark spectrum at RHIC).
- Semi-analytical calculation at $V(N_{part}) \longrightarrow 0$ may not be reliable, will be improved by full MC.

Summary and outlook

- We studied the impact of perturbative and non-perturbative interactions between heavy quarks and QGP on B_c production.
- Most B_c mesons produced in the initial collisions are dissociated.
- Recombination dominates at low p_T and is highly dependent on the QGP volume, while fragmentation dominates at high p_T .
- In the future, we plan to use a full Monte Carlo method to simulate the dissociation, fragmentation, and recombination of B_c mesons, allowing for dynamic production and dissociation of B_c.

Thank You!

backup

$$\boldsymbol{V} = \boldsymbol{S} \cdot \boldsymbol{\tau} \cdot \Delta\boldsymbol{\eta}$$