B_c Meson and X(3872) Transport in High-Energy Heavy-ion Collisions

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Outline

- Transport Approach
  - Rate Equation & Transport Parameters
- B_c Meson in Heavy-Ion Collisions
- X(3872) in Vacuum and Heavy-Ion Collisions
- Conclusion

Transport Approach

[Grandchamp *et al.*'04, Zhao *et al.*'11, Du *et al.*'17]

- Rate equation used in calculating quarkonia ($\mathcal{Q}$) in URHICs

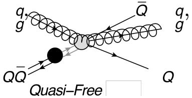
Reaction rate

$$\frac{dN_{\mathcal{Q}}}{d\tau} = -\Gamma(T)\left[N_{\mathcal{Q}} - N_{\mathcal{Q}}^{\rm eq}(T,\gamma_{\rm c})\right]$$

Primordial   Regeneration

- Quasi-free approximation

$$\mathcal{Q} + q, g \leftrightarrows Q + \bar{Q} + q, g$$



- Equilibrium limit from statistical model

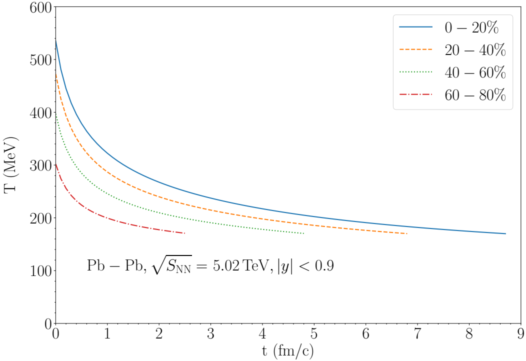
$$N_X^{\rm eq} = {\rm d}\, V_{\rm FB}\gamma_c^2 \int \frac{d^3p}{(2\pi)^3}\, e^{-\sqrt{m_X^2+p^2}/T},\ N_{B_c}^{\rm eq} = {\rm d}\, V_{\rm FB}\gamma_c\gamma_b \int \frac{d^3p}{(2\pi)^3}\, e^{-\sqrt{m_{B_c}^2+p^2}/T}$$

- Fugacity $\gamma_{\rm Q}\,(T)$: Heavy Quark (HQ) number conservation

$$N_{Q\bar{Q}} = \frac{1}{2}\gamma_Q\,(T)\, n_{\rm op}\, V_{\rm FB} \frac{I_1(\gamma_Q(T) n_{\rm op} V_{\rm FB})}{I_0(\gamma_Q(T) n_{\rm op} V_{\rm FB})} + \gamma_Q^2\,(T)\, n_{\rm hid}\, V_{\rm FB}$$

$$N_{Q\bar{Q}} = \frac{N_{\rm coll}\,\sigma_{Q\bar{Q}}^{\rm pp}}{\sigma_{\rm inel}^{\rm pp}}$$

The space time evolution



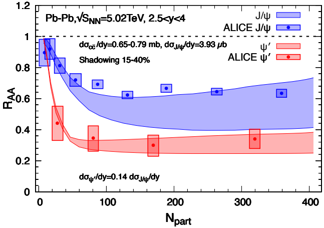
- Expanding fireball
- Conservation of entropy and EoS $\Rightarrow T(t)$

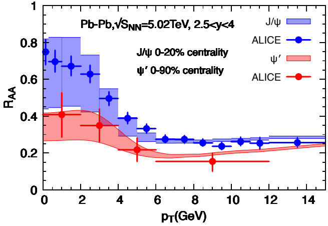
Results of Quarkonia in 5 TeV Pb-Pb Collisions

[ALICE, '20]

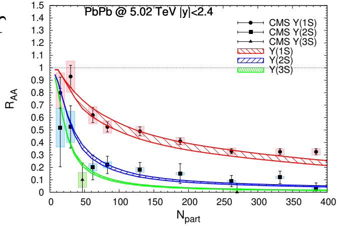
J/ψ

ψ'





Υ

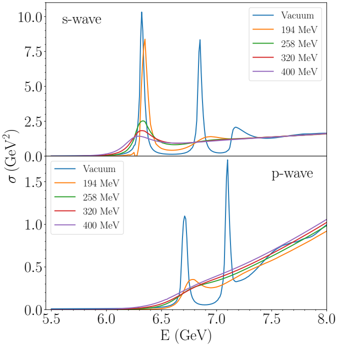


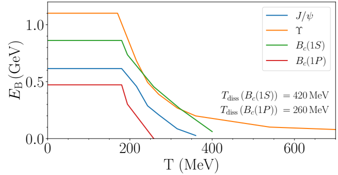
- $R_{\mathrm{AA}} = \dfrac{N^{\mathrm{PbPb}}}{N_{\mathrm{coll}} N^{\mathrm{pp}}}$
- Charmonia with most recent open-charm cross section + shadowing
  - ψ' results predictions
  - bottomonia within same approach

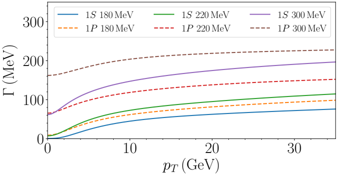
[CMS, '19]
[Du *et al.*, '17]

B_c In-medium Binding Energy and Reaction Rates

[Z. Tang *et al.* '21]

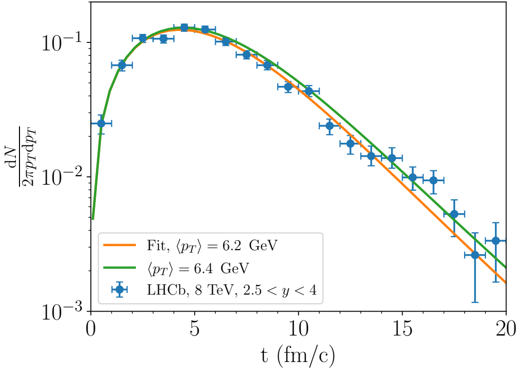






- B_c spectral functions: In-medium T-matrix calculation.
- Vacuum mass: $B_c(1S) = 6.324$ GeV, $B_c(2S) = 6.850$ GeV
- PDG: $B_c(1S) = 6.274$ GeV, $B_c(2S) = 6.871$ GeV
- $T_{\rm diss}\,(1S) = 420$ MeV and $T_{\rm diss}\,(1P) = 260$ MeV

B_c p_T spectra and cross section in 5 TeV pp Collisions



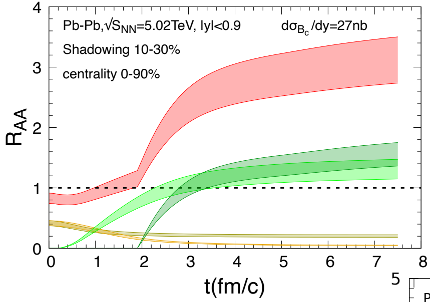
[LHCb, '15]

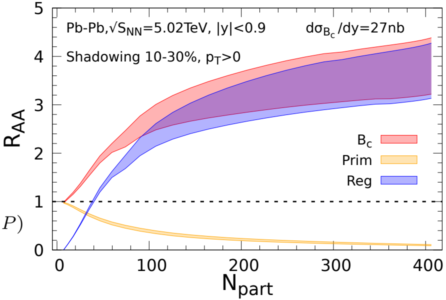
- $\frac{\mathrm{d}N_{pp}^{B_c}}{2\pi p_T \mathrm{d}p_T} = \frac{N}{(1+\frac{p_T}{A\langle p_T \rangle})^n}$, fitted to 8 TeV, forward-rapidity

[S. Acharya *et al.*, '19,'17]

- $\langle p_T \rangle \Rightarrow$ 5.02 TeV and mid-rapidity
- Theoretical calculations: $\mathrm{BR}\,(B_c \to J/\psi \mu \bar{\nu}) \sim 1.4\% - 7.5\%$
- $\mathrm{BR} \sim 4 \pm 2\%$, $\frac{\mathrm{d}\sigma_{B_c}^{pp}}{\mathrm{d}y} = 27 - 82\,\mathrm{nb}$

B_c Time Evolution in 5.02 TeV Pb-Pb Collisions

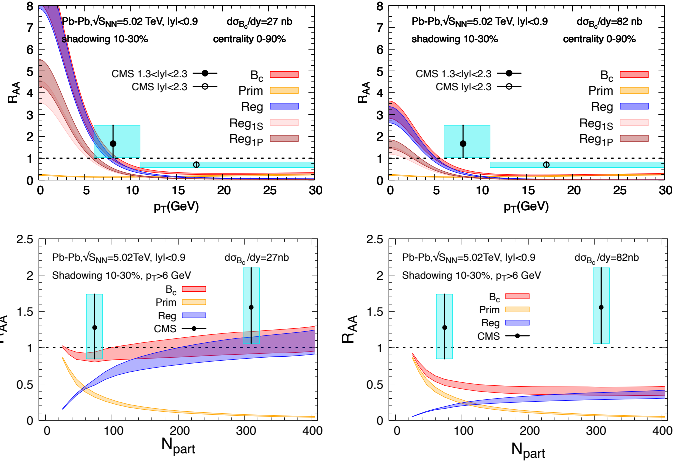




- $R_{AA} = \frac{N_{\rm Coll} N^{\rm pp}_{B_c} {\rm S}_{B_c} + N^{\rm reg}_{B_c}}{N_{\rm Coll} N^{\rm pp}_{B_c}}$
- Regeneration forms at $T_{\rm diss}$
- $N^{\rm tot}(1S) =$
  $N^{\rm dir}(1S) + {\rm BR}(1P \to 1S)\ N^{\rm dir}(1P)$
- ${\rm BR}(1P \to 1S) = 100\%$
- regeneration predicted without new parameters

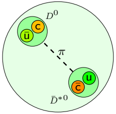
B_c in 5 TeV Pb-Pb Collisions

$$\frac{\mathrm{d}\sigma^{pp}_{B_c}}{\mathrm{d}y} = 27\,\mathrm{nb} \qquad \frac{\mathrm{d}\sigma^{pp}_{B_c}}{\mathrm{d}y} = 82\,\mathrm{nb}$$



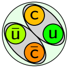
- $B_c\,(p_T)$: coalescence: $\bar{b} + c \to B_c^+$
- Dominated by regeneration, better agreement for smaller $\sigma^{pp}_{B_c}$

X(3872): Molecular vs. Tetraquark Scenario



- Vacuum mass of X(3872) $\approx \bar{D}^{*0}(2007) + D^0(1865)$ ~

- Vacuum width: $\Gamma(X(3872)) < 1.2\,\mathrm{MeV}$ ~



- Reaction rate in fireball: $\Gamma \sim \Gamma_0 \left(\frac{T}{T_0}\right)^n$
  - Molecular: Loosely-bound molecular state

    $\Gamma_0 \sim 300\text{-}500\,\mathrm{MeV}$ [Cleven *et al.*'19]
  - Tetraquark: Compact diquark anti-diquark bound state

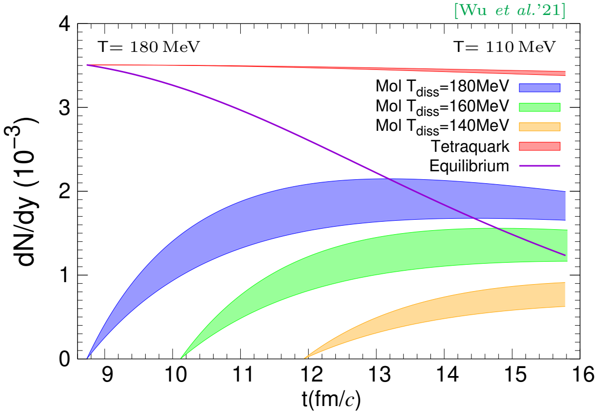
    $\Gamma_0 \sim 30\text{-}50\,\mathrm{MeV}$
  - Weak dependence on n

- Initial condition at hadronization
  - Molecular: $N(T = T_C) = 0$

    Small binding energy, destroyed in QGP
  - Tetraquark: $N(T = T_C) = N^{eq}(T_C)$

    Likely to form in the QGP phase

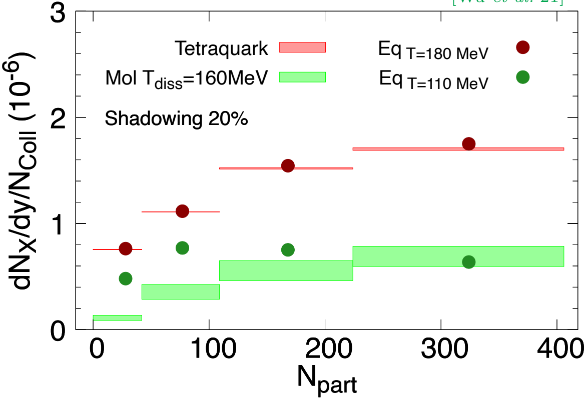
X(3872) Time Evolution in 5 TeV Pb-Pb Collisions



- Tetraquark: small reaction rate ⇒ mainly from the initial yield at hadronization
- Molecular: large reaction rate ⇒ approaches to equilibrium at $T = 110\,\text{MeV}$

X(3872) Centrality Dependence

[Wu *et al.*'21]



- Molecular is close to the thermal freeze-out equilibrium limit
- Tetraquark is close to the equilibrium limit at hadronization
- Final ratio $N_{\mathrm{Tet}}/N_{\mathrm{Mol}} \sim 3$ for all centralities

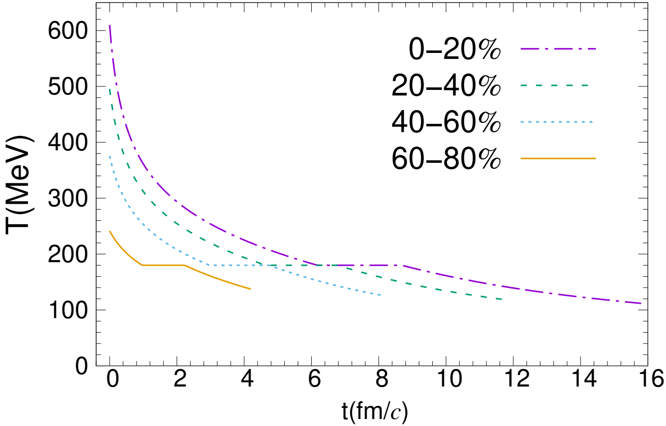
Conclusion

- Calculated B_c and X(3872) in URHICs using the rate equation
- R_{AA} of B_c meson dominated by the regeneration
- Senstive to the cross section $\sigma_{B_c}^{\mathrm{pp}}$
- X(3872) structure information: reaction rate and initial condition
- Molecule produced later than tetraquark $\Rightarrow$ suppressed by a factor about 3 (equilibrium limit drops with T)
- $N_{\mathrm{Tet}} > N_{\mathrm{Mol}} \Rightarrow$ qualitatively different from coalescence model predictions

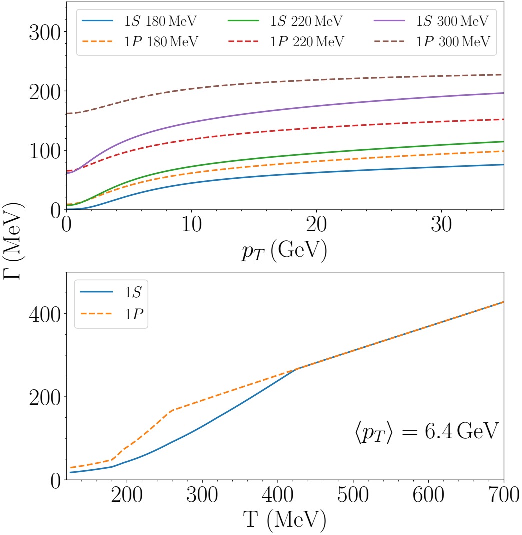
Thank you!

Backup

Temperature of the Fireball

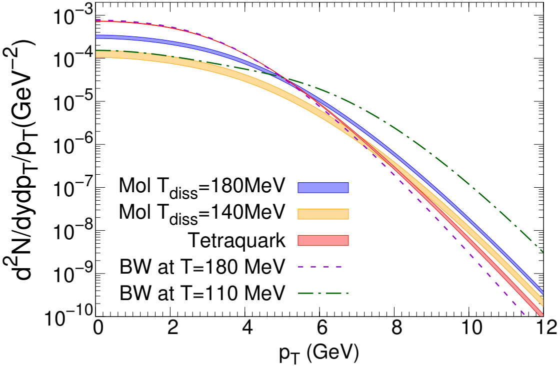


Temperature of the Fireball



X(3872) p_T Spectra in 5 TeV Pb-Pb Central Collisions

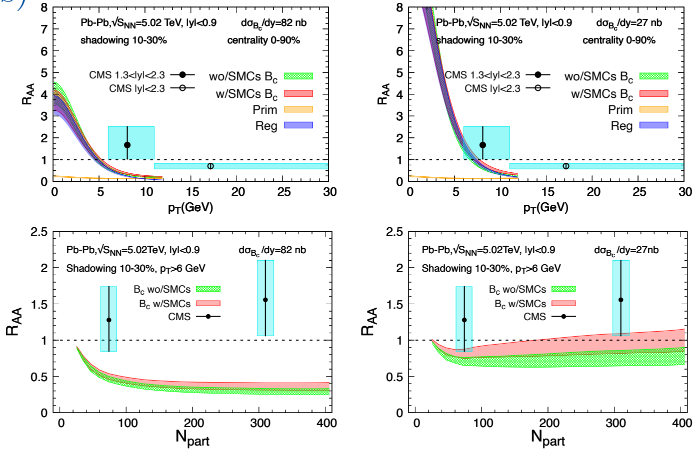
[Wu *et al.*'21]



- Both scenarios in between of the blast wave p_T spectra at hadronization and thermal freeze-out
- Tetraquark: close to the blast wave p_T at hadronization
- Molecular: produced later ⇒ has harder p_T spectra

Results with/without Momentum Space Correlations (SMCs)

[He *et al.*, PRL 128, 162301]



- B_c p_T is harder than the spectra without SMCs.
- B_c R_{AA} is enhanced by the implement of SMCs.