In-medium Transport of Charmonia, X(3872) and B_c at the LHC

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Outline

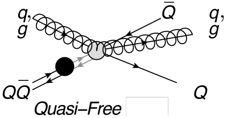
- Transport Approach
  - Rate Equation & Transport Parameters
- Charmonia in Heavy-Ion Collisions
- X(3872) in Vacuum and Heavy-Ion Collisions
- B_c Meson in Heavy-Ion Collisions
- Conclusion

Transport Approach

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

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

$$\frac{dN_{\mathcal{Q}}}{d\tau} = -\overset{\text{Reaction rate}}{\Gamma(T)}\left[\underset{\text{Primordial}}{N_{\mathcal{Q}}} - \underset{\text{Regeneration}}{N_{\mathcal{Q}}^{\mathrm{eq}}(T,\gamma_c)}\right]$$



- Quasi-free approximation: $\mathcal{Q}+q,g \leftrightarrows Q+\bar{Q}+q,g$

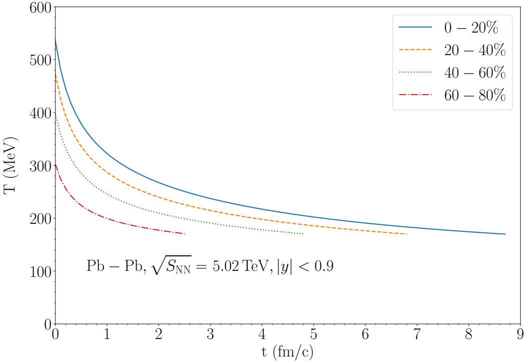
- Equilibrium limit from statistical model

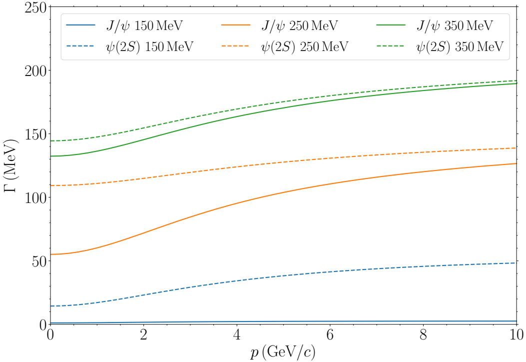
$$N_X^{\mathrm{eq}} = \mathrm{d}\,V_{\mathrm{FB}}\gamma_c^2 \int \frac{d^3p}{(2\pi)^3}\, e^{-\sqrt{m_X^2+p^2}/T}, \qquad N_{B_c}^{\mathrm{eq}} = \mathrm{d}\,V_{\mathrm{FB}}\gamma_c\gamma_b \int \frac{d^3p}{(2\pi)^3}\, e^{-\sqrt{m_{B_c}^2+p^2}/T}$$

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

$$N_{Q\bar{Q}} = \frac{1}{2}\gamma_Q\,(T)\, n_{\mathrm{op}}\, V_{\mathrm{FB}}\frac{I_1\left(\gamma_Q(T) n_{\mathrm{op}}\, V_{\mathrm{FB}}\right)}{I_0\left(\gamma_Q(T) n_{\mathrm{op}}\, V_{\mathrm{FB}}\right)} + \gamma_Q^2\,(T)\, n_{\mathrm{hid}}\, V_{\mathrm{FB}}, \qquad N_{Q\bar{Q}} = \frac{N_{\mathrm{coll}}\sigma_{Q\bar{Q}}^{\mathrm{pp}}}{\sigma_{\mathrm{inel}}^{\mathrm{pp}}}$$

The space time evolution





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

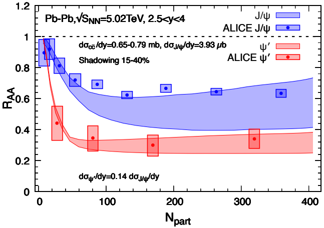
- Quasi-free reaction rate

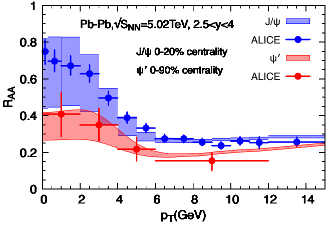
Results for Quarkonia in 5 TeV Pb-Pb Collisions

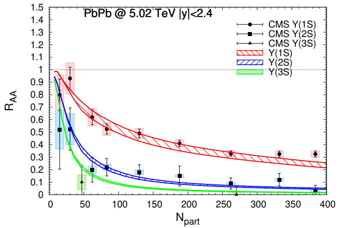
[ALICE, '20]

J/ψ

ψ'







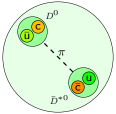
Υ

- $R_{\mathrm{AA}} = \dfrac{N^{\mathrm{PbPb}}}{N_{\mathrm{coll}} N^{\mathrm{pp}}}$

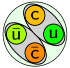
[CMS, '19] [Du *et al.*, '17]

- Charmonia with most recent open-charm cross section + shadowing
  - ψ' results predictions
  - bottomonia within same approach

X(3872): Molecular vs. Tetraquark Scenario



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



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

- 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

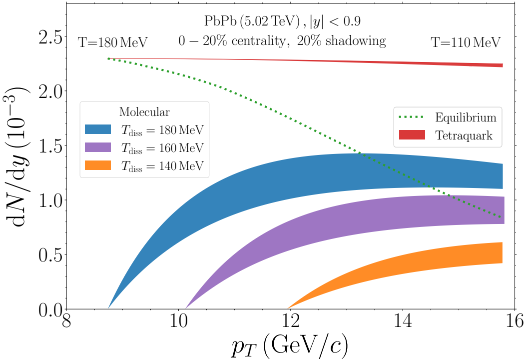
    $\Gamma_0 \sim 30\text{-}50\,\mathrm{MeV}$
  - Depends weakly on n

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

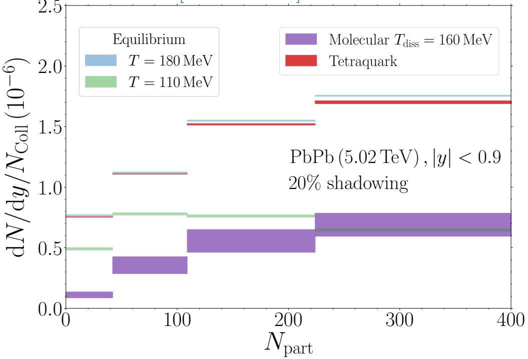
    Small binding energy, destroyed in QGP
  - Tetraquark: $N(T = T_C) = N^{eq}(T_C)$

    Likely to form in the QGP phase

X(3872) Time and Centrality Dependence in 5 TeV Pb-Pb Collisions



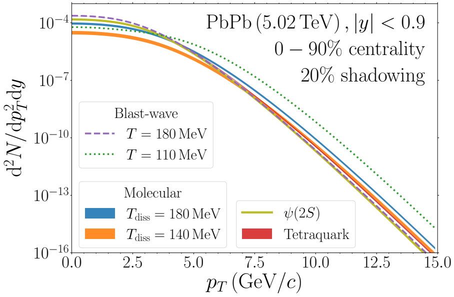
[Wu *et al.* '21]



- Tetraquark: small reaction rate ⇒ mainly from the initial yield at hadronization
- Molecular: large reaction rate ⇒ approaches the equilibrium at $T = 110$ MeV

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

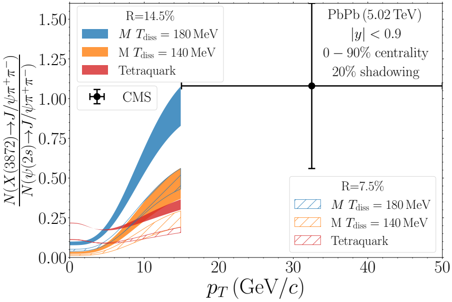
X(3872) p_{T} Spectra in 5 TeV Pb-Pb Central Collisions



[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

[CMS, '22]



[PDG, '22]

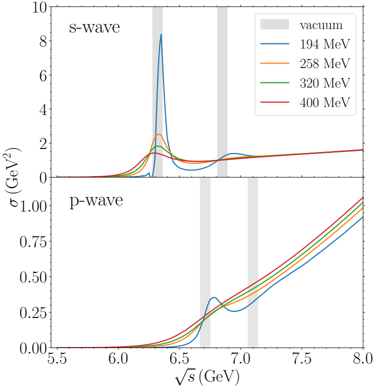
- $\mathrm{BR}\left(\psi(2S) \to J/\psi\pi^+\pi^-\right) = 34.68 \pm 0.30\%$

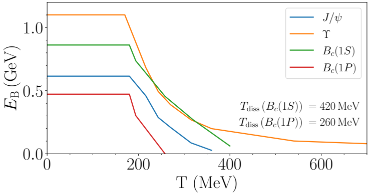
$$\mathrm{BR}\left(X(3872) \to J/\psi\pi^+\pi^-\right) = 3.8 \pm 1.2\%$$

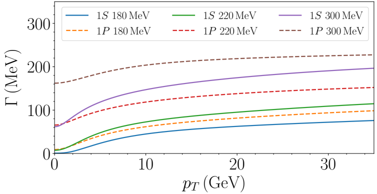
$$R = \frac{\mathrm{BR}\left(X(3872)\to J/\psi\pi^+\pi^-\right)}{\mathrm{BR}\left(\psi(2S)\to J/\psi\pi^+\pi^-\right)} = 11.0 \pm 3.5\%$$

B_c In-medium Binding Energy and Reaction Rates

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

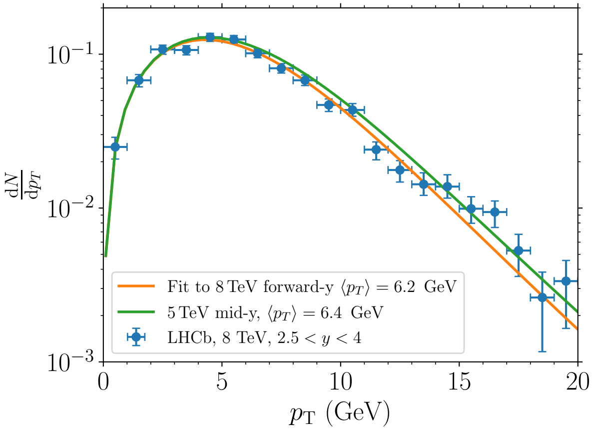






- Vacuum mass: $B_c(1S) = 6324$ MeV
  $B_c(2S) = 6850$ MeV
- B_c spectral functions:
  In-medium T-matrix calculation
- PDG: $B_c(1S) = 6274.47 \pm 0.27 \pm 0.17$ MeV
  $B_c(2S) = 6871.2 \pm 1.0$ MeV
- $T_{\rm diss}(1S) = 420$ MeV
  $T_{\rm diss}(1P) = 260$ MeV

B_c p_T spectra and cross section in 5 TeV pp Collisions



- $\frac{dN_{pp}^{B_c}}{2\pi p_T dp_T} = \frac{N}{(1+\frac{p_T}{A\langle p_T\rangle})^n}$

  fitted to 8 TeV, forward-rapidity

- $\langle p_T \rangle \Rightarrow$ 5.02 TeV and mid-rapidity

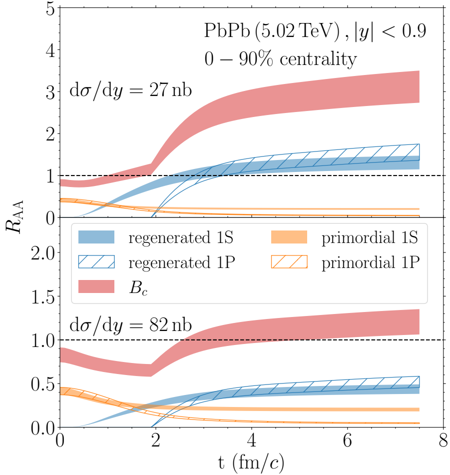
- Theoretical calculations:

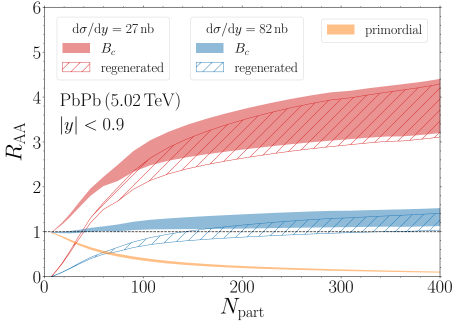
  $\mathrm{BR}\,(B_c \to J/\psi \mu \bar{\nu}) \sim 1.4\% - 7.5\%$

- $\mathrm{BR} \sim 4 \pm 2\%$, $\frac{d\sigma_{B_c}^{pp}}{dy} = 27 - 82$ nb

[LHCb, '15] [S. Acharya *et al.*, '19,'17]

B_c Time Evolution in 5.02 TeV Pb-Pb Collisions

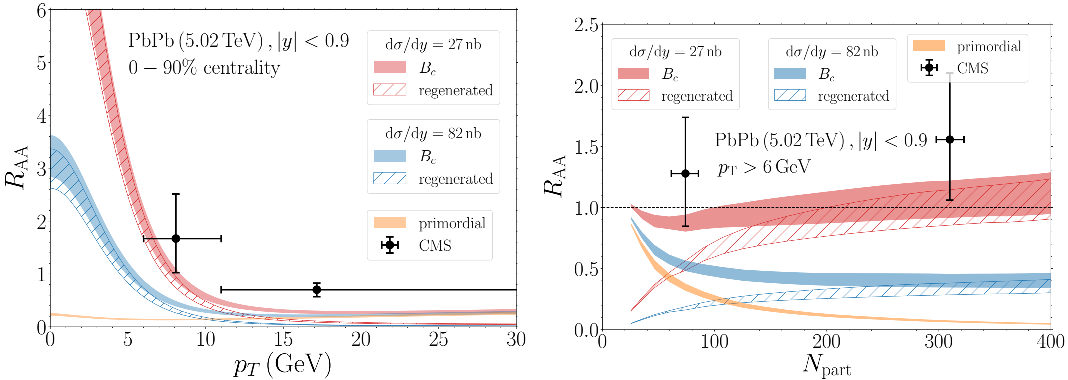




- Onset of regeneration at T_{diss}

- $R_{AA} = \dfrac{N_{\text{Coll}} N^{\text{pp}}_{B_c} S_{B_c} + N^{\text{reg}}_{B_c}}{N_{\text{Coll}} N^{\text{pp}}_{B_c}}$
- $N^{\text{tot}}(1S) = N^{\text{dir}}(1S) + \text{BR}(1P \to 1S)\ N^{\text{dir}}(1P)$
- $\text{BR}(1P \to 1S) = 100\%$
- regeneration predicted without new parameters

B_c in 5 TeV Pb-Pb Collisions



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

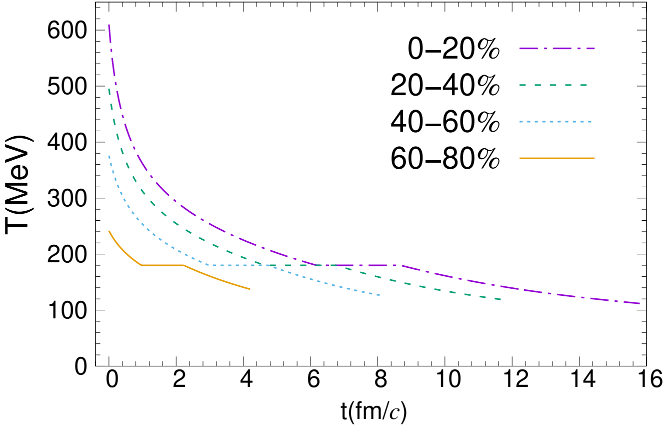
Conclusion

- Calculated quarkonia, X(3872) and B_c in URHICs using the rate equation
- 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
- R_{AA} of B_c meson dominated by the regeneration
- Sensitive to the cross section $\sigma_{B_c}^{\mathrm{pp}}$

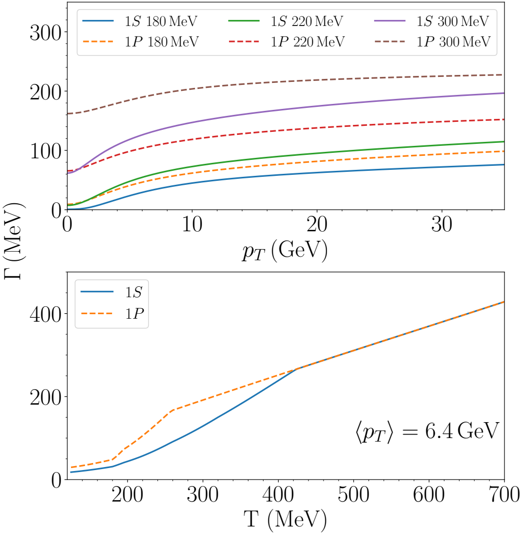
Thank you!

Backup

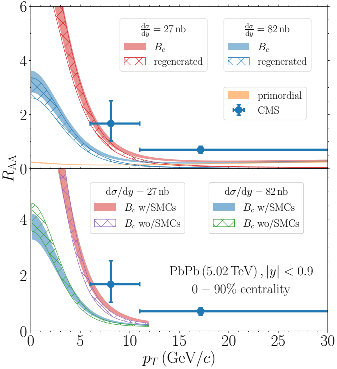
Temperature of the Fireball



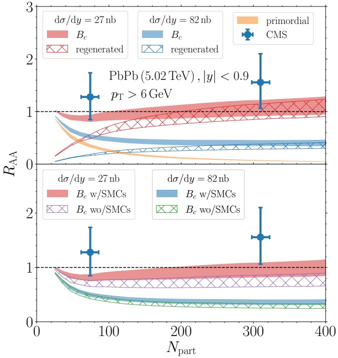
Temperature of the Fireball



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.