TAMU Transport Approach to Quarkonia in Heavy-Ion Collisions

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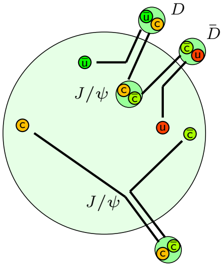
Transport Approach

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



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

$$\frac{dN_{\mathcal{Q}}}{d\tau} = -\overset{\text{Reaction rate}}{\Gamma_{\mathcal{Q}}(T)}\left[\underset{\text{Primordial}}{N_{\mathcal{Q}}} - \underset{\text{Regeneration}}{N^{\text{eq}}_{\mathcal{Q}}(T,\gamma_{\text{c}})}\right]$$

- Equilibrium limit from statistical model

$$N^{\text{eq}}_{\mathcal{Q}}(E_B, T) = \mathrm{d}\,V_{\text{FB}}\gamma_{Q_1}\gamma_{Q_2}\int\frac{d^3p}{(2\pi)^3}\,e^{-\sqrt{m_{\mathcal{Q}}^2+p^2}/T}$$

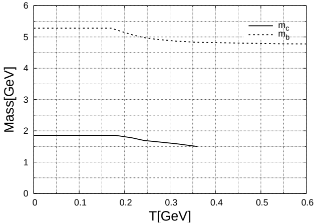
E_B: from in-medium Cornell potential ⇒ vacuum spectroscopy as $T \Rightarrow 0$

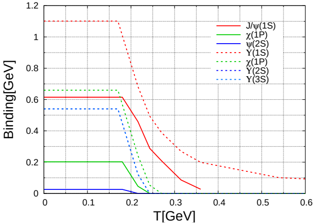
- Fugacity $\gamma_{\text{Q}}(T)$: Heavy Quark (HQ) number conservation

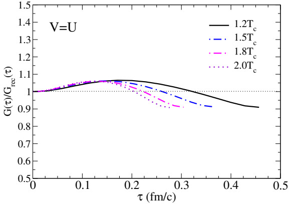
$$N_{Q\bar{Q}} = \frac{1}{2}\gamma_Q(T)\,n_{\text{op}}\,V_{\text{FB}}\frac{I_1(\gamma_Q(T)n_{\text{op}}\,V_{\text{FB}})}{I_0(\gamma_Q(T)n_{\text{op}}\,V_{\text{FB}})} + \gamma_Q^2(T)\,n_{\text{hid}}\,V_{\text{FB}}, \qquad N_{Q\bar{Q}} = \frac{N_{\text{coll}}\sigma^{\text{pp}}_{Q\bar{Q}}}{\sigma^{\text{pp}}_{\text{inel}}}$$

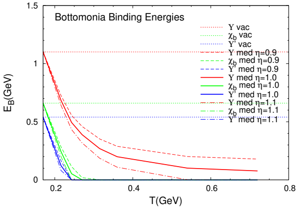
In-Medium Charm- and Bottom-quark Masses and Binding Energies

- In-medium potential U [Riek *et al.*'10, Zhao *et al.*'10, Du *et al.*'17]
- Constraint from lattice: Euclidean correlators $G_\alpha(\tau, T) = \int \frac{dE}{2\pi} \rho_\alpha(E, T) \frac{\cosh[E(\tau - 1/2T)]}{\sinh[E/2T]}$









- Increase (decrease) the binding:

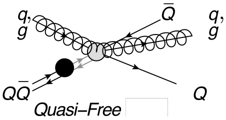
$$E_B^\eta(T) \equiv E_B^{\mathrm{vac}} - \eta \Delta E_B(T)$$

$$\eta = 0.9\ (1.1)$$

$$\Delta E_B(T) = E_B^{\mathrm{vac}} - E_B^\eta(T)$$

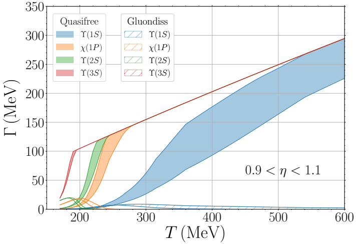
Reaction Rates $\Gamma_{\mathcal{Q}}(T)$

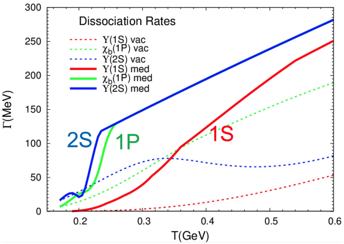
[Grandchamp *et al.*'01+'04, Zhao *et al.*'11, Du *et al.*'15+'17, Lin *et al.*'00]

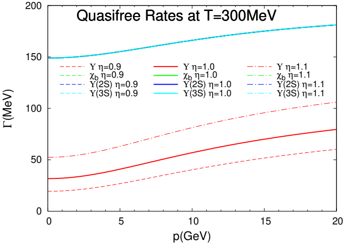


- Quasi-free (massive quasi-particles): $\mathcal{Q}+q,g \leftrightarrows Q+\bar{Q}+q,g$
- Sensitive to the in-medium binding energies
- Hadronic rates: effective SU(4) interaction⇒hadron resonance gas
- Interference effects in the quasi-free rate: decrease for deeply bonded mesons:

$$\Gamma_{\Upsilon}^{\rm qf}(p,T)=\sum_p \int \frac{\mathrm{d}^3 p_p}{(2\pi)^3}\, d_p f_p\left(\omega_p, T\right) v_{\rm rel}\sigma_{\Upsilon p\to b\bar{b}p}(s) \Rightarrow \left(1-e^{i\vec{q}\cdot\vec{r}}\right)$$





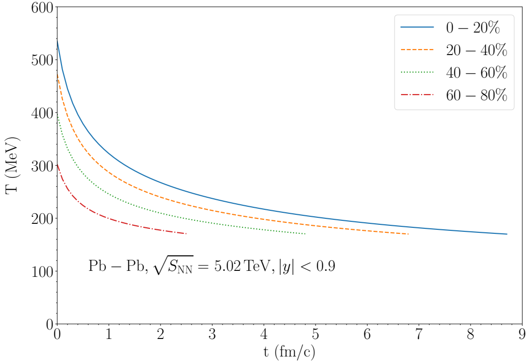


Medium evolution

[Grandchamp *et al.*'01+'04, Zhao *et al.*'10]

- Isentropically and cylindrically expanding isotropic fireball:

$$V_{\mathrm{FB}}(\tau) = \left(z_0 + v_z\tau + \tfrac{1}{2}a_z\tau^2\right)\pi\left(R_0 + \frac{\sqrt{1+(a_\perp\tau)^2}-1}{a_\perp}\right)^2$$

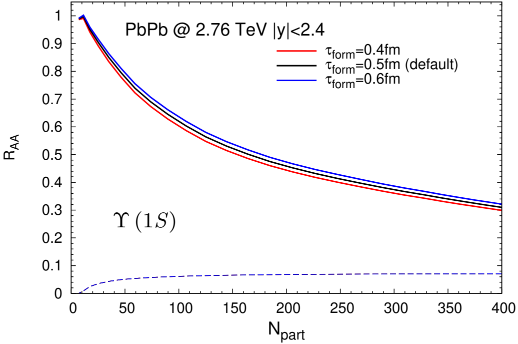


- Blast-wave type, taken from fits to experimental data for π, p and K hadrons
- Total entropy fit to experimentally measured charged-hadron multiplicities
- Conservation of entropy and EoS with massive quasi-particles$\Rightarrow T(t)$

Quarkonium Formation times

[Du *et al.*'17]

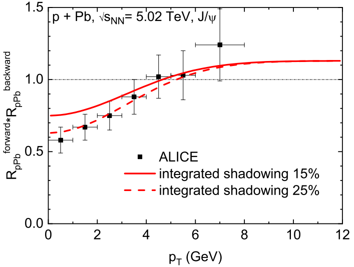
- Pair production time $\tau_{Q\bar{Q}} \leq 0.1\,\mathrm{fm}/c$
- Bound-states formation time $\tau_{\text{form}} \sim 1/E_B \sim 0.2\text{-}2\,\mathrm{fm}/c$
- Build-up of wave function reduces dissociation rate $\alpha_Y(\vec{p}, T(\tau)) \equiv \Gamma_Y(\vec{p}, T(\tau)) \frac{\tau}{\tau_{\text{form}}} \frac{m_Y}{\sqrt{p^2+m_Y^2}}$

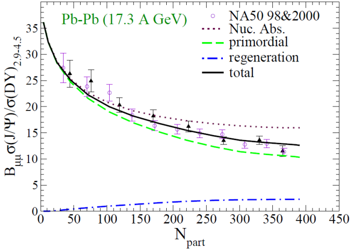


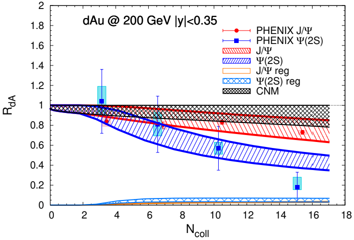
- Higher excited Υ and ψ states have larger formation time
- Relatively small effect in heavy-ion collisions
- Microscopically: quantum evolution of wave package

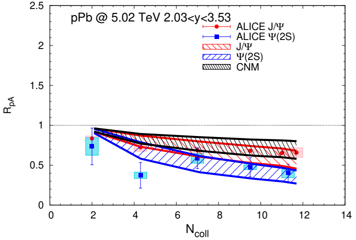
Cold-Nuclear Matter Effects [Grandchamp *et al.*'01+'03, Zhao *et al.*'07, He *et al.*'22]

- Nuclear shadowing: modification of the initial production
- Cronin effect + Nuclear absorption (low$\sqrt{s}$: SPS+RHIC)
- Non-perturbative (K factor): constraint on $\psi(2S)$ rates







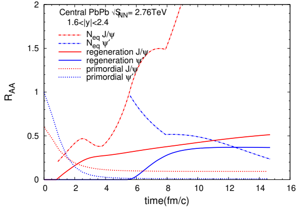


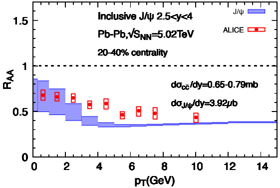
Transverse momentum spectra

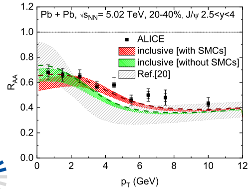
[Zhao *et al.*'07+'11, Du *et al.*'17, He *et al.*'20]

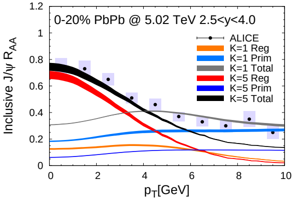
- p_T dependence from blast-wave at average freezeout time τ

$$\frac{\mathrm{d}N_{\Psi}^{\mathrm{reg}}}{p_t\ \mathrm{d}p_t} = N_0\,(b)\, m_t \int_0^R r dr K_1\left(\frac{m_t \cosh y_t}{T(\tau)}\right) I_0\left(\frac{p_t \sinh y_t}{T(\tau)}\right),\ m_t = \sqrt{m_{\Psi}^2 + p_t^2}$$









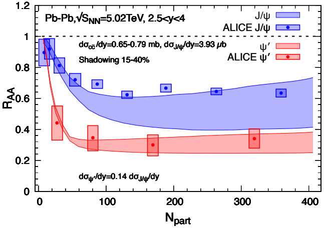
- p_T suppression ⇒ Boltzmann equation
- Average regeneration temperatures $T\,(\tau)$ (taken from the average production time): different for ground and excited states
- Resonance recombination model (RRM) ⇒ space-momentum correlations (SMCs) of heavy quarks with partons in expanding fireball.
- Transported charm-quarks essential for large regeneration (softening)

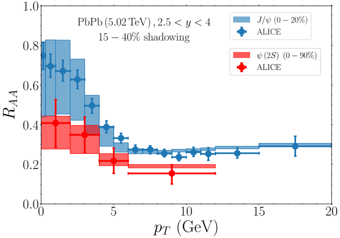
Results for Quarkonia in 5 TeV Pb-Pb Collisions

[ALICE, ’20]

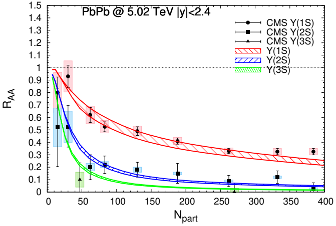
J/ψ

ψ'





[CMS, ’19] [Du *et al.*, ’17]



Υ

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

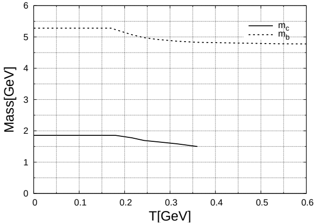
- Charmonia with most recent open-charm cross section + shadowing
    - ψ' results predictions
- Bottomonia, B_c and X(3872) are treated in the same approach

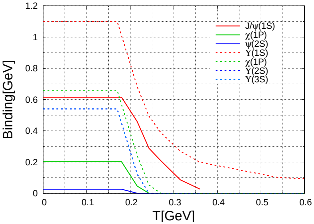
Thank you!

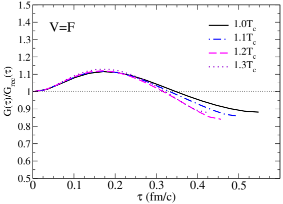
Backup

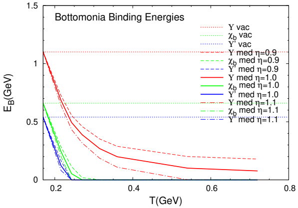
In-Medium Charm- and Bottom-quark Masses and Binding Energies

- Free Energy F [Riek *et al.*'13, Zhao *et al.*'10, Du *et al.*'17]
- Constraint from lattic: Euclidean correlators $G_\alpha(\tau, T) = \int \frac{dE}{2\pi} \rho_\alpha(E, T) \frac{\cosh[E(\tau-1/2T)]}{\sinh[E/2T]}$









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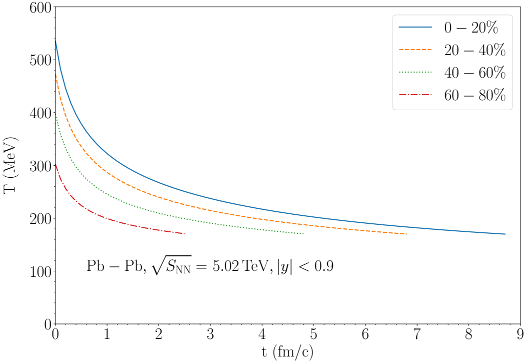
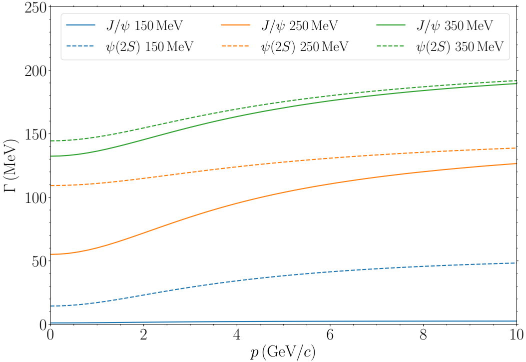
$$E_B^\eta(T) \equiv E_B^{\rm vac} - \eta \Delta E_B(T)$$

$$\eta = 0.9\ (1.1)$$

$$\Delta E_B(T) = E_B^{\rm vac} - E_B^\eta(T)$$

The space time evolution

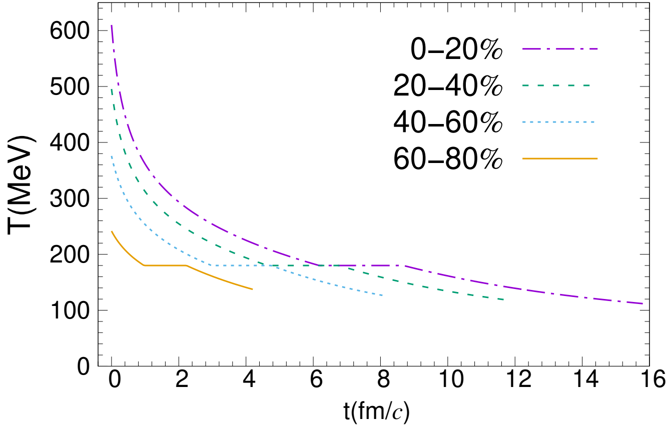




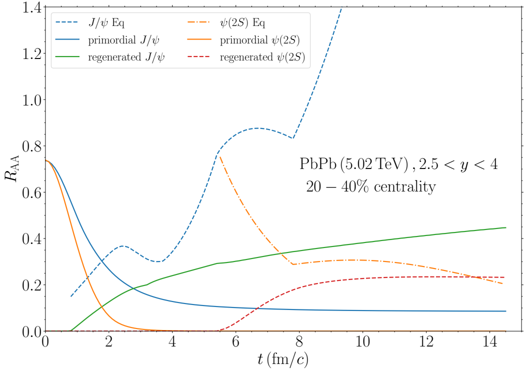
- Expanding fireball
- Conservation of entropy and EoS $\Rightarrow T(t)$

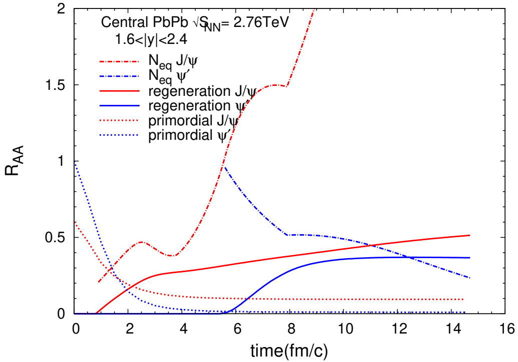
- Quasi-free reaction rate

Temperature of the Fireball

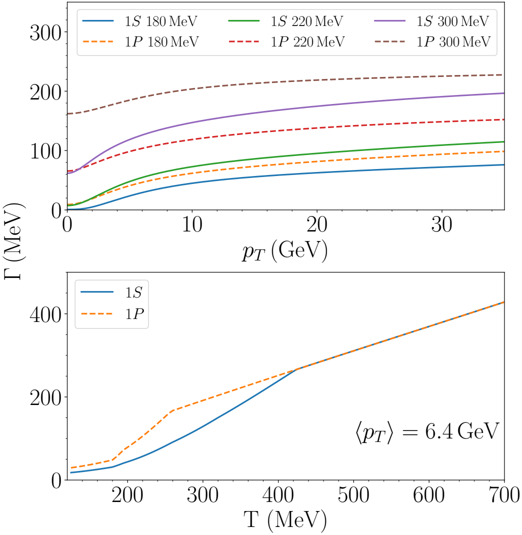


Time evolution of Charmonia



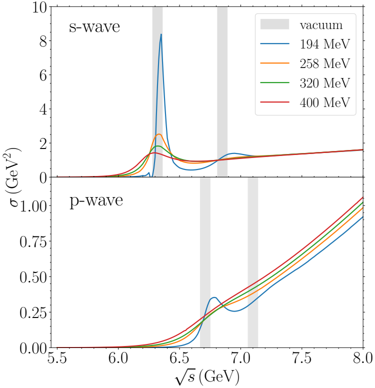


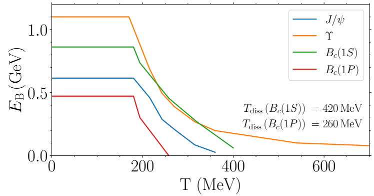
B_c Quasi-free rates

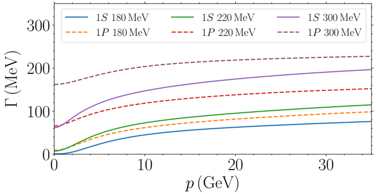


B_c In-medium Binding Energy and Reaction Rates

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

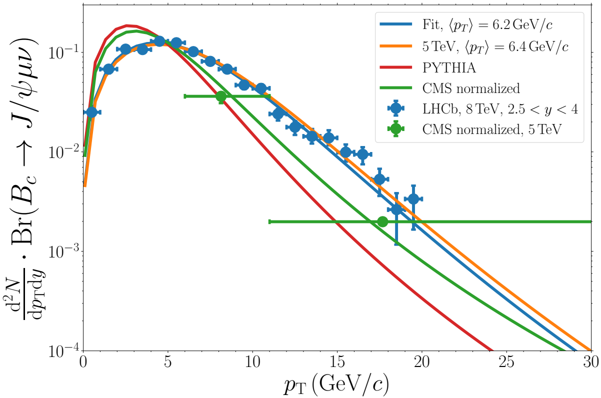






- Vacuum mass: $B_c(1S) = 6324\,$MeV
  $B_c(2S) = 6850\,$MeV
- B_c spectral functions:
  In-medium T-matrix calculation
- PDG: $B_c(1S) = 6274.47 \pm 0.27 \pm 0.17$ MeV
  $B_c(2S) = 6871.2 \pm 1.0\,$MeV
- $T_{\rm diss}\,(1S) = 420\,$MeV
  $T_{\rm diss}\,(1P) = 260\,$MeV

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

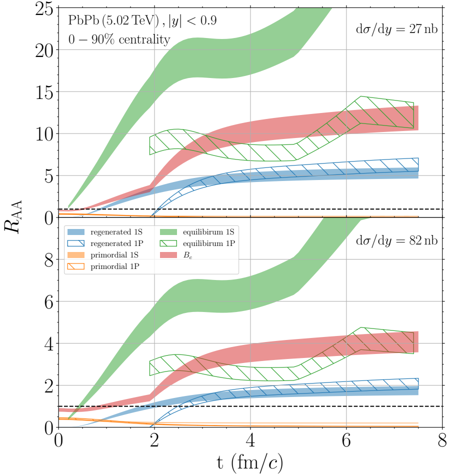
- Theoretical calculations:

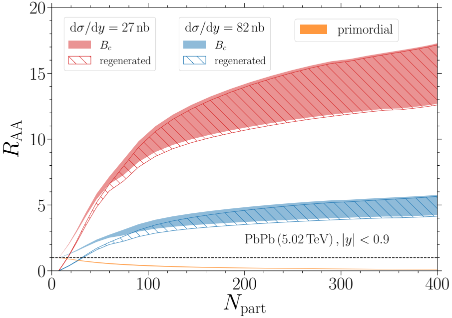
  $\mathrm{BR}\,(B_c \to J/\psi\mu\bar{\nu}) \sim 1.4\% - 7.5\%$

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

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

B_c Time Evolution in 5.02 TeV Pb-Pb Collisions

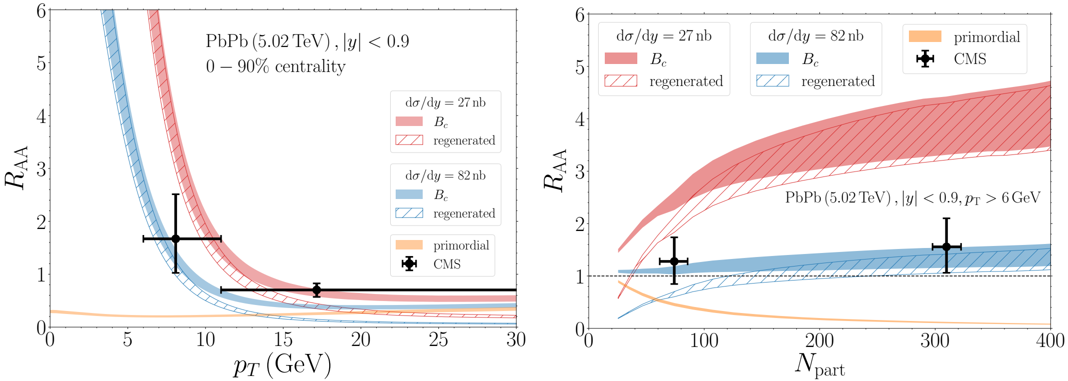




- Onset of regeneration at $T_{\rm diss}$

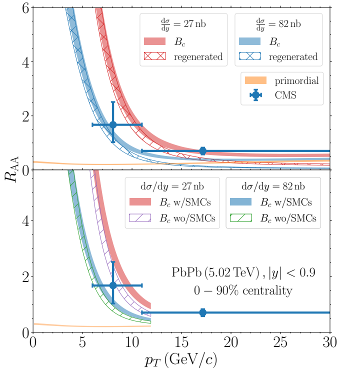
- $R_{\rm AA} = \dfrac{N_{\rm Coll} N^{\rm pp}_{B_c} S_{B_c} + N^{\rm reg}_{B_c}}{N_{\rm Coll} N^{\rm pp}_{B_c}}$
- $N^{\rm tot}\,(1S) = N^{\rm dir}\,(1S) + {\rm BR}\,(1P \to 1S)\;\; N^{\rm dir}\,(1P)$
- ${\rm BR}\,(1P \to 1S) = 100\%$
- regeneration predicted without new parameters

B_c in 5 TeV Pb-Pb Collisions

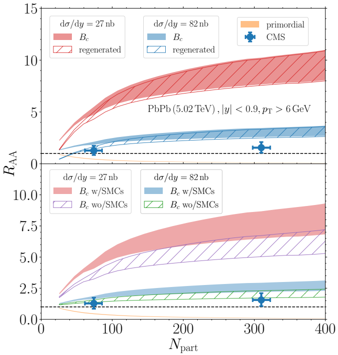


- $B_c\,(p_T)$: coalescence: $\bar{b} + c \to B_c^+$
- Dominated by regeneration, better agreement for smaller $\sigma_{B_c}^{pp}$

Results with/without Momentum Space Correlations (SMCs)

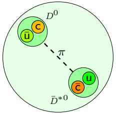


[He *et al.*, PRL 128, 162301]

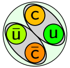


- B_c p_T is harder than the spectra without SMCs.
- B_c R_{AA} is enhanced by the implement of SMCs.

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

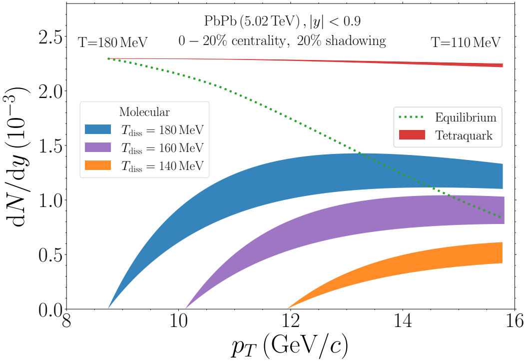
    $\Gamma_0 \sim 30\text{-}50\,\mathrm{MeV}$
  - Depends weakly on n

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

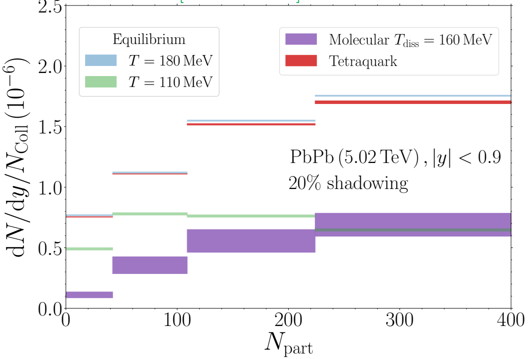
    Small binding energy, destroyed in QGP
  - Tetraquark: $N(T = T_C) = N^{eq}(T_C)$

    Likely to form in the QGP phase

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

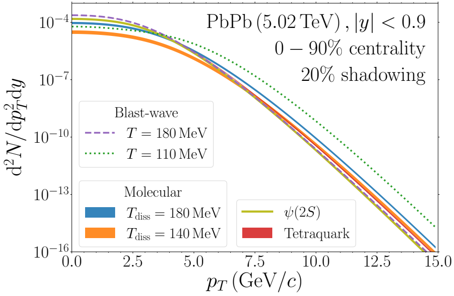


[Wu *et al.* '21]



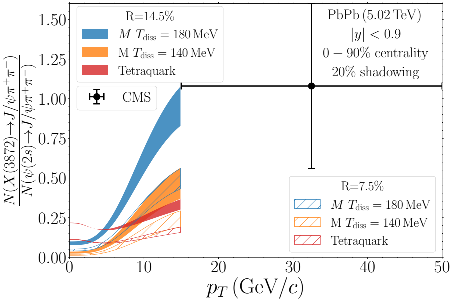
- Tetraquark: small reaction rate ⇒ mainly from the initial yield at hadronization
- Molecular: large reaction rate ⇒ approaches the equilibrium at $T = 110$ MeV
- Molecular: close to the thermal freeze-out equilibrium limit
- Tetraquark: close to the equilibrium limit at hadronization
- Final ratio $N_{\rm Tet}/N_{\rm Mol} \sim 3$ for most centralities

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



[Wu *et al.* '21]

[CMS, '22]



- 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

[PDG, '22]

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

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

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