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

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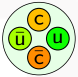
Outline

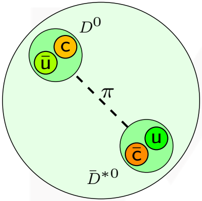
- X(3872) in Vacuum and Heavy-Ion Collisions
- Transport Analysis
  - Rate Equation & Transport Parameters
  - Time evolution & observables (centrality & p_{T} spectra)
- Conclusion

X(3872) in Vacuum

- Mass [PDG'18, Choi *et al.*(Belle) '03]
  - Mass X(3872) $\approx \bar{D}^{*0}(2007) + D^{0}(1865)$
- Total width
  - $\Gamma(X(3872)) < 1.2\,\mathrm{MeV}$
- Possible structures



Tetraquark
(Compact diquark anti-diquark)

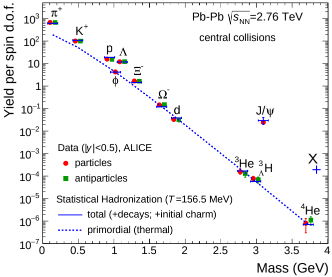


Molecular
(Loosely-bound)

- Can ultra-relativistic heavy-ion collisions (URHICs) provide new structure information of X(3872)?

Current Approaches to X(3872) in URHICs

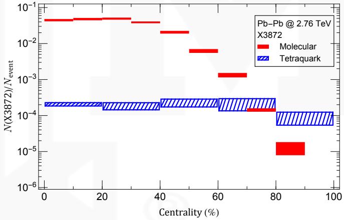
- Statistical hadronization model
  - Yields only depend on masses
  - No internal structure information



[Andronic *et al.*'19]

- Coalescence model
  - Constituent-quark distribution functions & produced-particle Wigner functions
  - Production ratio $\frac{N_{\text{mol}}}{N_{\text{tet}}}$ up to 250

[Cho *et al.*'11, Fontoura *et al.*'19; Cho *et al.* '13, Abreu *et al.* '16; ...]



[Zhang *et al.*'20]

Transport Approach

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

- Rate equation used in calculating charmonia in URHICs

$$\frac{dN_X}{d\tau} = -\Gamma(T)\left[N_X - N_X^{\rm eq}(T,\gamma_{\rm c})\right]$$

- Equilibrium limit from statistical model

$$N_X^{\rm eq}(T,\gamma_{\rm c}) = \gamma_c^2 \int \frac{d^3P}{(2\pi)^3} e^{-\sqrt{m_X^2+P^2}/T}$$

- Fugacity $\gamma_{\rm c}\,(T)$: charm number conservation

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

Open-charm hadron density: $n_{\rm op} = \sum_\alpha n_\alpha\,(T; m_\alpha)$

$N_{c\bar{c}}$: direct $c\bar{c}$ related to the charm cross section

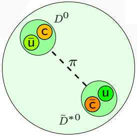
Molecular vs. Tetraquark Scenario

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

    $\Gamma \simeq 65\,\mathrm{MeV}$ at $T \simeq 160\,\mathrm{MeV}$ in pion gas, [Cleven *et al.*'19]
    Scale up by total hadron density at $T_0 = 180\,\mathrm{MeV}$:
    $\Gamma_0 \sim 300\text{-}500\,\mathrm{MeV}$
  - Tetraquark: Compact diquark anti-diquark bound state

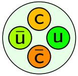
    Not well known, $\Gamma_0 \sim 30\text{-}50\,\mathrm{MeV}$
  - Little sensitivity to the power $n \sim 0\text{-}5$
- Initial condition at chemical freeze-out
  - Molecular: 0

    Loosely-bound molecular state only forms later

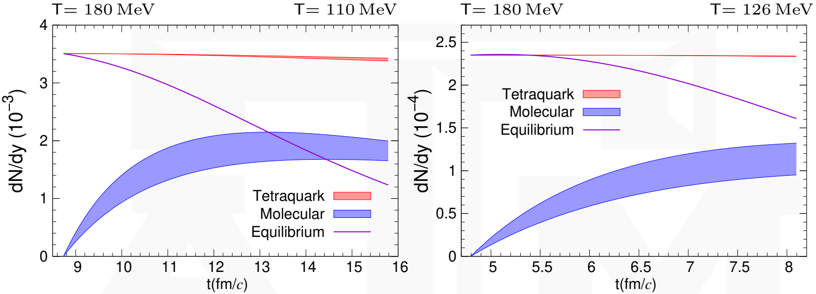


  - Tetraquark: N_{eq}

    Compact diquark anti-diquark bound state,
    likely to form in the QGP phase



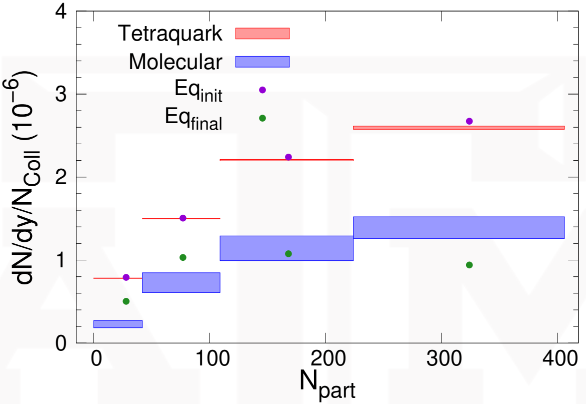
X(3872) Evolution in 5 TeV Pb-Pb Collisions



Central collisions　　　Semi-central collisions

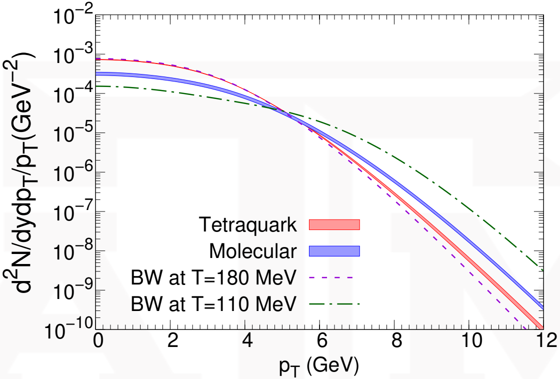
- Tetraquark state: small reaction rate $\Rightarrow$ mainly from the initial yield at chemical freeze-out
- Molecular state: large reaction rate $\Rightarrow$ affected greatly by the equilibrium limit
- Ratio of yields at thermal freeze-out $N_{\rm Tet}/N_{\rm Mol} \sim 2$

Centrality Dependence in 5 TeV Pb-Pb Collisions



- Molecular (tetraquark) state yield is close to the equilibrium limit at thermal (chemical) freeze-out for all centralities
- Ratio at thermal freeze-out $N_{\rm Tet}/N_{\rm Mol} \sim 2$ for all centralities

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



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

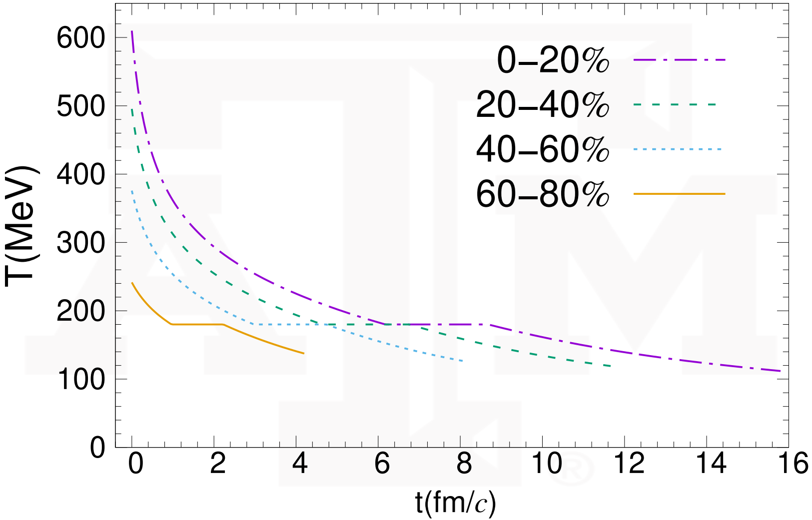
Conclusion

- We calculate the evolution of X(3872) in hadronic phase in 5 TeV Pb-Pb collisions using the kinetic rate equation
- The rate equation has been previously used in the calculation of charmonia in heavy-ion collisions
- The X(3872) structure information is encoded in the reaction rate and the initial condition
- The molecular bound state is produced later than the tetraquark and is suppressed by a factor about 2 due to drop of the equilibrium limit as a function of temperature
- $N_{\mathrm{Tet}}/N_{\mathrm{Mol}}$ is of order 2 which is quantitatively and qualitatively different from the coalescence model predictions
- Molecular state has harder p_{T} spectra

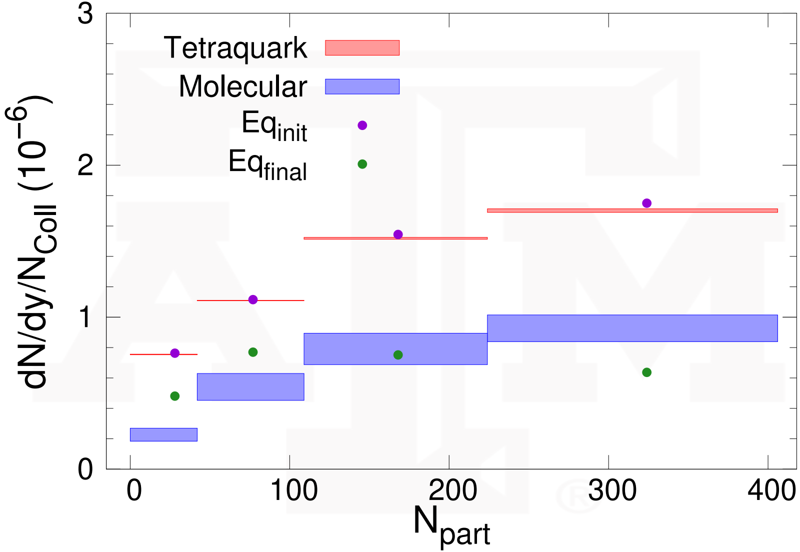
Thanks for your attention!

Backup

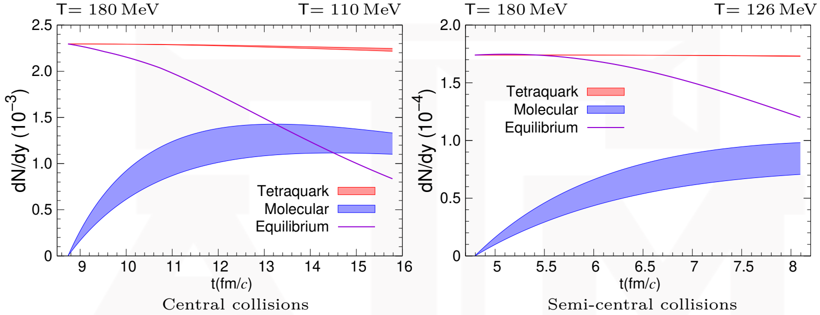
Temperature of the Fireball



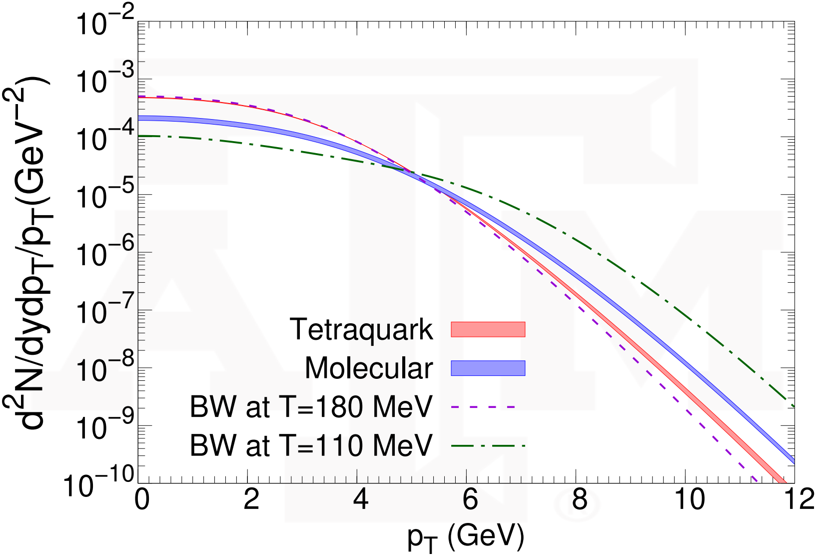
Centrality Dependence with Shadowing Effect



X(3872) Evolution with Shadowing Effect



X(3872) p_T Spectra with Shadowing Effect



X(3872) Evolution without Shadowing Effect