Production of X(3872) in Ultra-Relativistic Heavy-Ion Collisions

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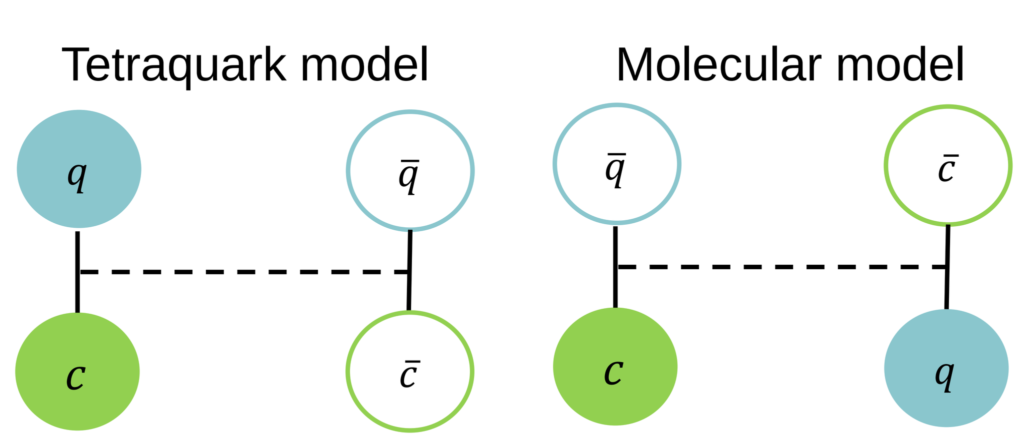
Introduction

Ultra-relativistic heavy-ion collisions (URHICs) allow us to study hot and dense QCD matter. These collisions are characterized by an expanding quark-gluon plasma which hadronizes at chemical freezeout temperatures (around 160-170 MeV), after which a hadronic medium persists until kinetic freezeout occurs at T≈100 MeV. By studying the hadronic phase of URHICs we can get a better understanding of the hadronization mechanisms present. In this project we focus on the X(3872) particle which is of particular interest due to its nontrivial structure.

X(3872)

X(3872) is of particular interest because its structure is still controversial. First discovered in 2003 by the Belle Collaboration, by observing a state with a mass of 3871.8 MeV decaying into $\pi^+\pi^- J/\psi$ [1]. The LHCb collaboration later confirmed the quantum numbers J^{PC} of X(3872) to be 1^{++} in 2012 [2]. The production width has also been determined to be $\Gamma \leq 1.2\ MeV$ in a vacuum [3]. What has not been determined yet is its structure. It is believed that its quark makeup is $q\bar{q}c\bar{c}$ however there are two competing models as to how they are bound. The first is the tetraquark model which has the anti-/diquarks bound together, the pairs are then tightly bound through color interactions leading to a smaller decay width. The second model is called the "mesonic molecule". In this case it is a D meson and an anti D-meson forming a bound $D\bar{D}$ pair leading to a larger decay width.



Method

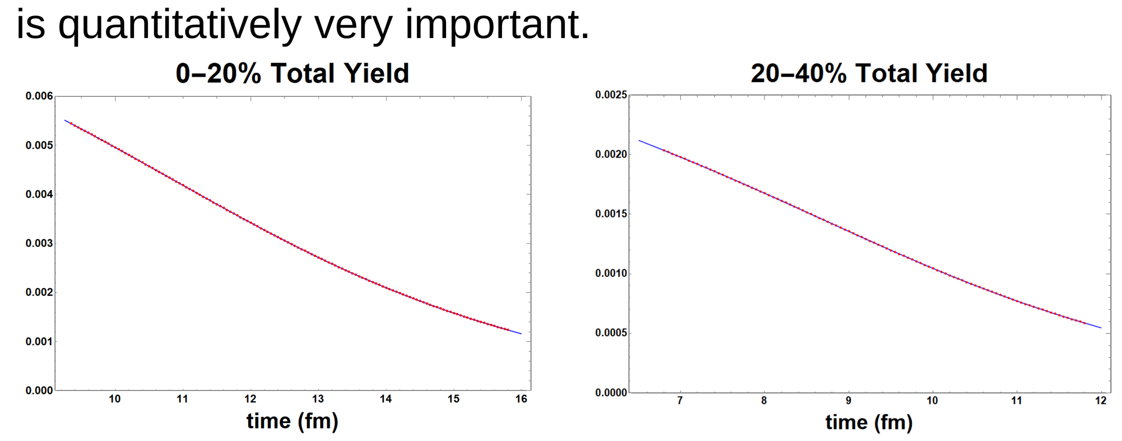
1. Simulate an URHIC using an expanding fireball model [4]
   - PbPb collisions at $\sqrt{s_{NN}} = 5\ TeV$
   - 0-20% and 20-40% centrality
   - This gives us temperature (T), charm quark fugacity (γ_c), radius (R), volume (V), surface velocity (β_S), time (t)
2. Calculate equilibrium yields
3. Generate transverse-momentum (P_T) spectra at freezeout temperatures
4. Use a kinetic rate equation to compute time evolution of yields and P_T spectra

Equilibrium Yields

We calculate total yields with respect to time by taking a particle density equation:

$$n_x = d_x \gamma_c^2 \int \frac{d^3P}{(2\pi)^3} e^{\sqrt{m_x^2+P^2}/T}$$

and converting it to absolute yields by multiplying it by a volume [5]. The fugacity, γ_c, is constructed from total charm-quark number conservation in the hadronic phase, it is quantitatively very important.



0-20%
- T=170 MeV, Yield of 0.00546
- T=111.8 MeV, Yield of 0.00122

20-40%
- T=170 MeV, Yield of 0.00189012
- T=118 MeV, Yield of 0.0005878

P_T Spectra

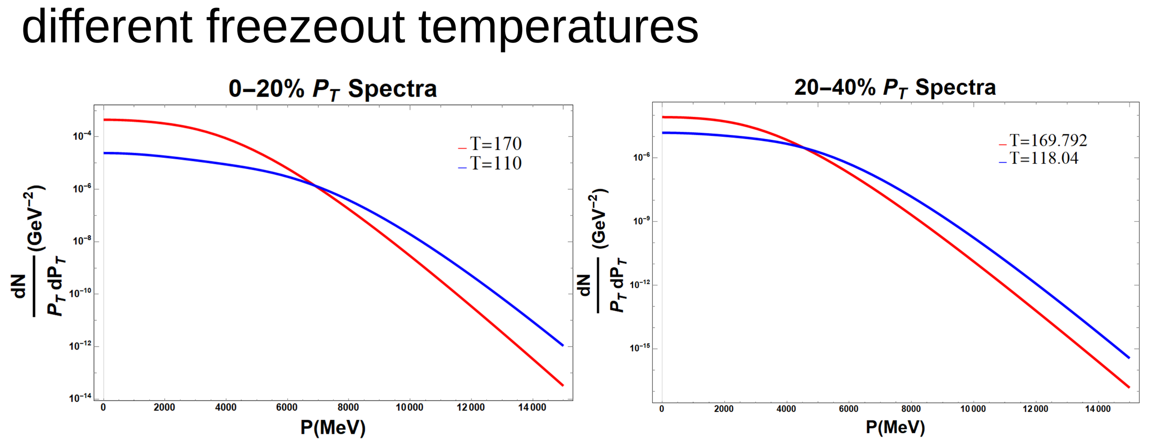
We generate transverse-momentum spectra using a thermal blastwave expression [5]:

$$\frac{dN_x}{P_T dP_T} = C\int_0^R r dr m_T I_0\left(\frac{P_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \sinh(\rho)}{T}\right)$$

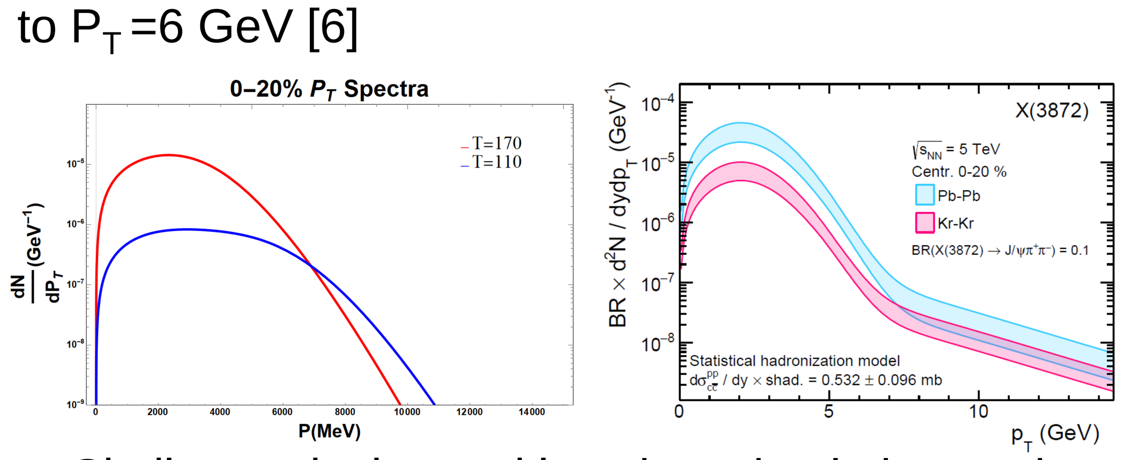
Where…

$$\rho = tanh^{-1}\left(\beta_s\left(\frac{r}{R}\right)^n\right)$$

Which gives the following results for 0-20% and 20-40% central PbPb collisions, respectively, at the different freezeout temperatures



We compare our P_T spectra to the results from Andronic et al. which also use a blastwave model up to P_T=6 GeV [6]



- Similar peak size and location, simulation works
- Differences are mostly due to different temperature chosen (they use T=156.5 MeV)

0-20% Production Rate

To calculate the time evolution of yields we utilize a kinetic rate equation:

$$\frac{dN}{dt} = -\Gamma(N - N^{eq})$$

Which solves to…

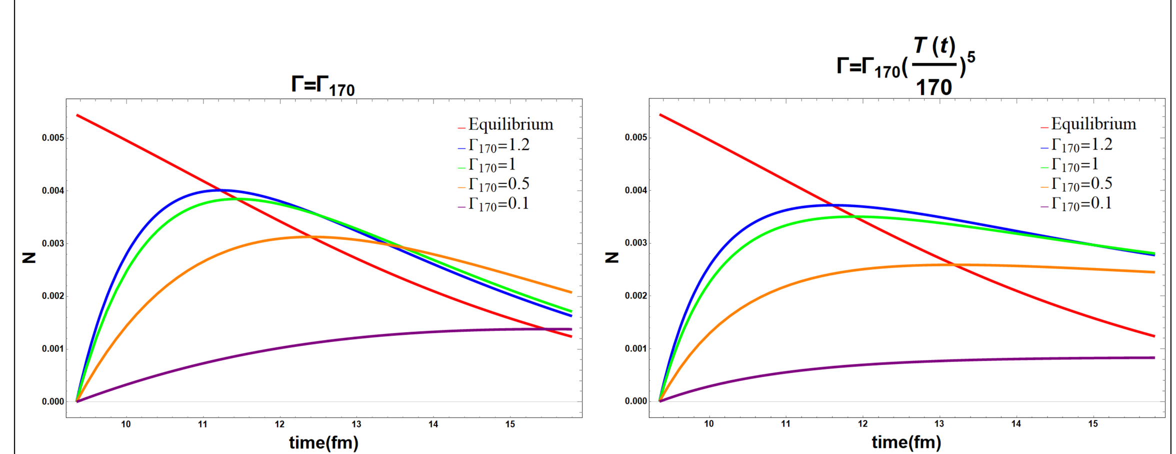
$$N(t) = \frac{\int_{t_0}^{t} e^{\int_{t_0}^{t'}\Gamma dt''}\Gamma N^{eq} dt' + C}{e^{\int_{t_0}^{t}\Gamma dt'}}$$

Where…

$$\Gamma = \Gamma_{170}\left(\frac{T(t)}{170}\right)^n,\ n=0,1,2,3,4,5$$

With initial condition $N(t_0)=0$, Γ is the in-medium reaction rate, and Γ_{170}=1.2,1,.5,.1 fm^{-1} is the production width at T=170 MeV [7].

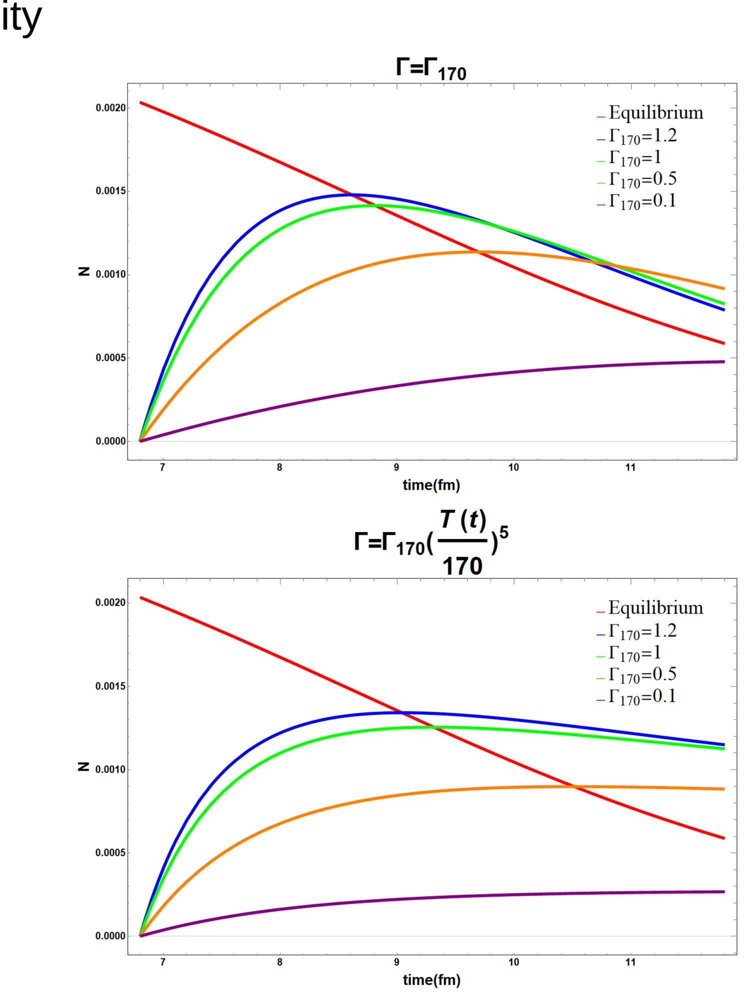
This produces the following results, compared to the equilibrium production:



- Production goes down with Γ
- Shape and production change slightly with n
- Cuts through equilibrium limit with a slope of 0, as expected (approaches equilibrium)

20-40% Production Rate

Same formulation as above however with a different centrality



Much shorter production time compared to 0-20%

Extracted P_T Spectra

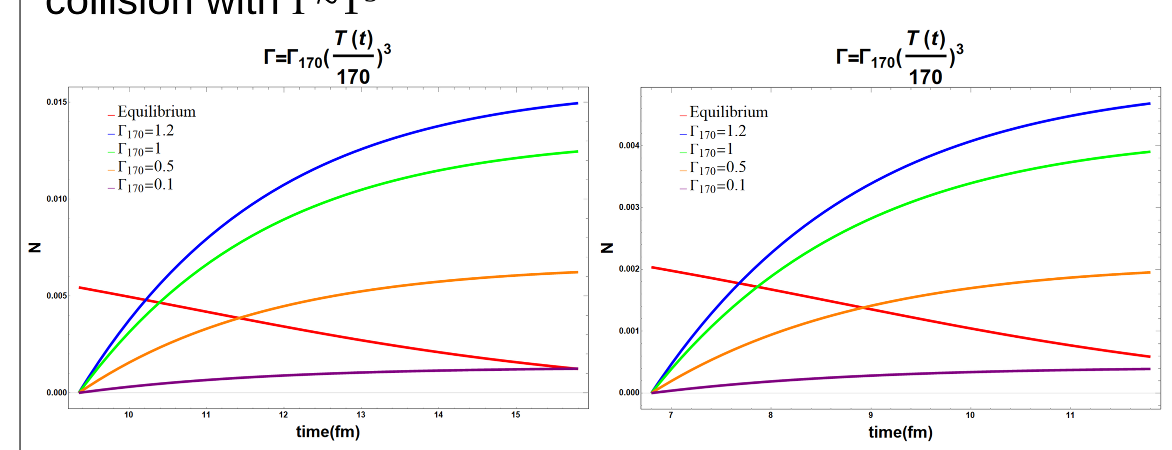
We extract P_T Spectra from the production rate by:

$$\sum \Delta N_{gain} \bar{F}$$

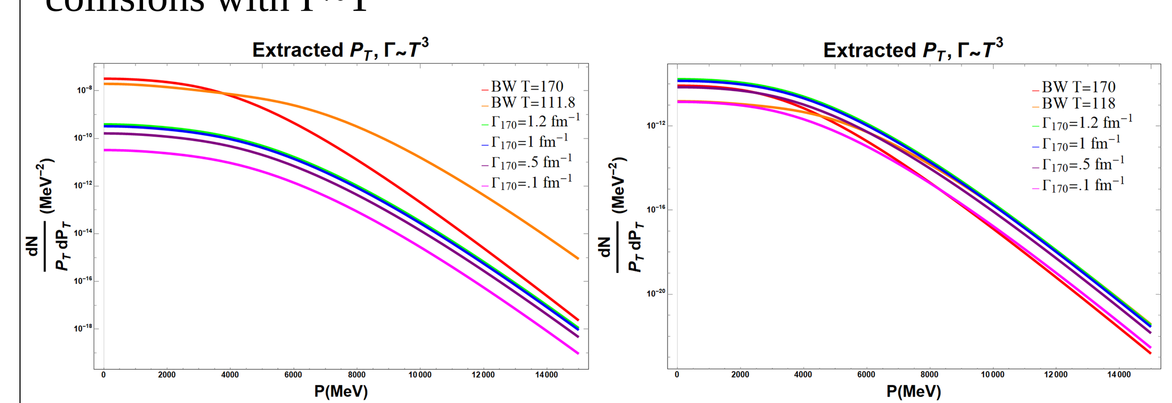
Where $\bar{F}$ is the normalized blastwave expression

And $N_{gain} = \int_{t_0}^{t} e^{\int_{t_0}^{t'}\Gamma dt''}\Gamma N^{eq} dt'$

Example N_{gain} Plots for 0-20% and 20-40% central PbPb collision with $\Gamma \sim T^3$



Extracted P_T Spectra for 0-20% and 20-40% central PbPb collisions with $\Gamma \sim T^3$



- For 0-20% central collisions, P_T spectra are lower than equilibrium P_T spectra at the freezeout temperatures
- For 20-40% central collisions, P_T spectra are comparable to equilibrium P_T spectra at the freezeout temperatures

Conclusions

- URHICs are an effective means of studying hadronization mechanisms
- Due to its nontrivial internal structure, X(3872) is a particularly interesting object to study in URHICs
- Modelled URHIC with expanding fireball model with charm-quark number conservation
- Computed equilibrium abundance and time evolution of X(3872) production
- Reaction rates affect production yields, however effects in P_T spectra are more subtle

Acknowledgements

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