Deciphering the nature of X(3872) in heavy ion collisions

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Exploring the nature of potential exotic candidates such as the X(3872) plays a pivotal role in understanding the Quantum Chromodynamics (QCD). Despite significant efforts, consensus on their very existence and internal structures is lacking. As a prime example, it remains a pressing open question to decipher the X(3872) state between two popular rivals: a loose hadronic molecule or a compact tetraquark. We demonstrate a novel approach to help address this problem by studying the X(3872) production in heavy ion collisions, where a hot fireball with ample light as well as charm (anti-)quarks is available for producing the exotics. Adopting a multi-phase transport model (AMPT) for describing such collisions and implementing appropriate production mechanism of either molecule or tetraquark picture, we compute and compare a series of observables for X(3872) in Pb-Pb collisions at the Large Hadron Collider. We find the fireball volume plays a crucial role, leading to a two-order-of-magnitude difference in the X(3872) yield and a markedly different centrality dependence between hadronic molecules and compact tetraquarks, thus offering unique opportunity for distinguishing the two scenarios. We also make the first prediction of X(3872) elliptic flow coefficient to be tested by future experimental measurements.

\textbf{Introduction.} — The strong interaction is one of the four basic forces in our universe, and its underlying theory is known as Quantum Chromodynamics (QCD). While QCD is based on fundamental particles called quarks and gluons, we can only directly observe hadrons in which quarks/gluons are confined by nonperturbative QCD interactions. To understand the making of all possible hadrons is a core question that has been a persistent challenge to our understanding of QCD \cite{1,2}.

The quark model, as a starting point of such inquiry, was known to allow multiquark configurations since the very beginning \cite{3}. However, it had been misinterpreted to only contain the quark-antiquark mesons and the three-quark baryons for quite a long time, due to the absent experimental evidence of the hadrons beyond those two configurations. The recent observations of the X(3872) \cite{4}, as the first exotic candidate, and other exotic candidates afterwards have driven the whole community to rethink about various possibilities of “exotic hadrons” in QCD. Comprehensive efforts \cite{5,19} have been made from both theoretical and experimental sides to predict/measure their existence and properties. However, the nature of these exotic candidates remains a significant open question with little consensus from the community perhaps on any of them. Taking the most-studied X(3872) as a prime example, the studies of its various production processes and decay modes \cite{20,24} would indicate different scenarios of its possible structure, dominated either by a loose hadronic molecule or by a compact tetraquark.

While conventionally leptonic or hadronic collisions are used to produce and study exotic hadrons, there has been increasing interest recently to study such states in heavy ion collisions. Indeed, given the abundant number of quarks and antiquarks for both light and heavy flavors, these collisions appear to provide the ideal environment for exotic hadron production. The first study was performed in the coalescence model in comparison with the statistical model \cite{24,25}. Later on, detailed analysis of the wave function for tetraquark state \cite{20} and the hadronic effects \cite{27} were considered in heavy ion collisions. Possible effect from a hot pion bath at late time on the properties of the X(3872) was further discussed \cite{28}. The possible influence of tetraquarks on chiral phase transitions and related QCD phase diagram was also explored \cite{29}. More discussions related to exotic states in heavy ion collisions can be found in a review article \cite{30} and references therein. Most recently, the CMS collaboration reported the first experimental evidence of X(3872) in Pb-Pb collisions at the Large Hadron Collider (LHC) \cite{31}, making an important first step toward quantitative investigation of exotic hadrons like the X(3872) in heavy ion collision experiments.

In this letter, we explore such emerging opportunity to study X(3872) production in heavy ion collisions and report two essential results. Firstly, we perform a first quantitative computation of X(3872) production within realistic bulk evolution model for a series of standard heavy ion observables (centrality-dependent yield, rapidity and \( p_T \) spectra) and the first prediction of X(3872) elliptic flow, which are critically needed for ongoing experimental program. This is done by adopting a multi-phase transport model (AMPT) \cite{32} for describing such collisions and implementing appropriate production mechanism of either molecule or tetraquark picture (as illustrated in Fig. 1). Secondly, our computations suggest...
a significantly larger yield of the $X(3872)$ as well as a markedly stronger centrality dependence when assuming its nature to be a hadronic molecule as compared with a compact tetraquark. This novel finding points at a unique opportunity for deciphering the nature of $X(3872)$ and help addressing a long-standing hadron physics challenge with heavy ion measurements, with the predicted difference between the two rival scenarios well beyond current experimental limitation. All these new results are readily testable and shall strongly motivate experimental efforts in the near future.

![Illustration of $X(3872)$ production](image)

**FIG. 1.** Illustration of $X(3872)$ production as hadronic molecule (left) or tetraquark (right) in heavy ion collisions.

**Framework.**—— In this study, we use the default version of AMPT to estimate the yield of the $X(3872)$ in Pb-Pb collisions at LHC energies. AMPT is a widely used event generator to describe the bulk evolution of heavy ion collisions. It incorporates four main components: the fluctuating initial conditions, partonic scatterings modeled by parton cascade, hadronization by using a quark coalescence model, and the subsequent hadronic rescattering. AMPT has been successfully applied to describe a variety of observables for collision energies ranging from CERN SPS to LHC. In particular, the yield and transverse momentum spectra of identified particles, anisotropic flows and particle correlations at RHIC and LHC can be well described, see for example Refs. [33–35].

The new element we introduce into the AMPT simulations is the mechanism to produce $X(3872)$ for its two possible configurations, i.e. the loosely bound hadronic molecular configurations and the compact tetraquark configurations. First of all, as the $X(3872)$ contains constituent charm quarks/anti-quarks, we need to get reasonable generation of individual $c$ and $\bar{c}$ quarks in the partonic phase. This can be calibrated by comparison with experimental data on D-meson production in Pb-Pb collisions from ALICE collaboration [36, 37]. It is known that in the default version of AMPT, some of the channels related to initial heavy quark production are missed and efforts to remediate such issue were recently made [38]. We adopt a similar strategy to enhance the initial $c$ and $\bar{c}$ spectra by a constant K-factor which leads to a reasonable agreement for the total production of $D^+(D^0) + D^{++}(D^{*0})$ meson between our AMPT results and ALICE measurements for $0 - 10\%$ and $30 - 50\%$ centralities. This procedure shall suffice for a meaningful first estimate of $X(3872)$ production and does not affect the comparison between the two configurations.

We next implement the production mechanism for the two possible $X(3872)$ configurations, i.e. hadronic molecule and tetraquark, of the $X(3872)$. Both scenarios stem from reasonable (albeit drastically different) underlying dynamics [14, 22, 23, 39–41] with supporting evidences and are hard to differentiate at the moment. Such hadronic physics challenge could present an opportunity in heavy ion collisions. Given their rather different structures, one may reasonably expect that their production in heavy ion collisions could also be very different, as we illustrate in Fig. 1. We consider both possibilities and evaluate $X(3872)$ production in each case accordingly. For the hadron molecule scenario, the $X(3872)$ is formed by the color neutral force between either $D$ and $\bar{D}$, or $D$ and $D^*$ with average size $5 \sim 7$ fm. In this case the “molecule”-X(3872) is formed in our simulations by coalescence of two proper charmed mesons with quantitative constraints: $5$ fm relative distance $< 7$ fm and $2M_D < \text{Pair Mass} < 2M_{D^*}$. For the tetraquark scenario, the $X(3872)$ is formed by colored force between diquark $[cq]_S$ and antidiquark $[\bar{c}\bar{q}]_{\bar{S}}$ with normal hadron size $\leq 1$ fm [38]. In this case the “tetra”-X(3872) is formed in our simulations by first creating diquarks and anti-diquarks via partonic coalescence and then performing coalescence of a diquark and an anti-diquark with quantitative constraints: relative distance $< 1$ fm and $M_{(00)_{\bar{S}}} < \text{Pair Mass} < M_{(11)_{S}}$ with $|SS\rangle_J$ as subindex, where $S$, $\bar{S}$ and $J$ are spins of diquark, antidiquark and total of them.

There is some subtlety in forming charmed mesons or (anti-)diquarks with the same flavor contents but different spin composition. In principle one needs to include the spin degrees of freedom to distinguish these configurations. Currently this is not possible in AMPT simulation which does not contain spin information and produces them all together, while we need to separate these channels. In our simulation, we estimate the ratio of yields between two such channels, e.g. $A$ and $B$ with mass $M_A$ and $M_B$, (either color neutral or colored ones) via thermal model relation:

$$R \equiv \frac{\text{Yield}(A)}{\text{Yield}(B)} = \exp \left( \frac{M_B - M_A}{T} \right),$$

with freeze out temperature $T = 160$ MeV [45]. For hadronic molecule picture, $A$ and $B$ are the $D^*$ and the $D$ mesons, respectively. For tetraquark picture, they are for the spin triplet $[cq]_S$ diquarks and the spin singlet

\footnote{For (anti-)diquark states, the label $|SS\rangle_J$ represents diquark spin $S$, anti-diquark spin $\bar{S}$ and total angular momentum $J$ [42, 43].}
\[ |c\rangle_0 \] diquarks, respectively. This estimate indicates a composition of (30\%, 70\%) for \( (D^+, D) \) and a composition of (35\%, 65\%) for spin (triplet, singlet) diquarks, which will be used in our simulations. To estimate the involved uncertainty, we will also obtain results by varying this composition up and down by 10\%.

Results.—With the aforementioned framework, we have generated a total of one million minimum bias events for Pb-Pb collisions at \( \sqrt{s} = 2.76 \) TeV from AMPT simulations. The inclusive yield of \( X(3872) \) is computed to be 220479 assuming it as hadronic molecule while to be 881 assuming it as compact tetraquark. A pronounced finding is a significantly more production of hadronic molecule state than that of tetraquark state by a factor of 250 — a two-order-of-magnitude difference. This result may be understood as follows: c and \( \bar{c} \) quarks are carried by bulk flow, randomly diffuse around the whole fireball volume, and in general would be somewhat separated in space by the time of freeze-out; in the molecular picture, the constituents \( D^* (\bar{D}^*) \) and \( \bar{D} (D) \) (containing either a c or \( \bar{c} \) quark) prefer to form \( X(3872) \) when they are well separated; in the tetraquark picture, the constituents diquark and anti-diquark (each also containing a c/\( \bar{c} \) quark) needs to stay very close in space; as such, there is a much higher probability for the formation of hadron molecules than tetraquark states.

\[ \begin{align*}
\text{Pb-Pb @ 2.76 TeV} \\
\text{X3872} \\
\text{Molecular} \\
\text{Tetraquark}
\end{align*} \]

FIG. 2. The centrality dependence of of the \( X(3872) \) in Pb-Pb collisions at \( \sqrt{s} = 2.76 \) TeV for hadronic molecular configuration (red solid boxes) and tetraquark configuration (blue shaded boxes), computed from our framework. The bands reflect uncertainty due to constituent composition as discussed around Eq. (1) and are obtained via varying the composition by \( \pm 10\% \) from thermal model estimate. Roughly it brings about 10\% relative uncertainty for hadronic molecule results while about 30\% for tetraquark results.

This interpretation appears to be further confirmed by the centrality dependence of the \( X(3872) \) yield shown in Fig. 2. Going from central to peripheral collisions, one observes a strongly decreasing trend for the molecular scenario while a rather mild change for the tetraquark scenario. Note as a baseline of expectation, the available number of c and \( \bar{c} \) quarks would gradually decrease with increasing centrality class, with the fireball spatial volume and evolution time also decreasing. The sharp decrease of molecular state production toward very peripheral collision is due to the shrinking volume available for accommodating the large size hadronic molecule. The relatively flat dependence of the tetraquark case is due to two compensating factors: decreasing numbers of c/\( \bar{c} \) quarks while increasing chances of small spatial separation between (anti-)diquarks due to shrinking fireball volume. Such observation suggests that it would be a good idea to probe the system-size dependence of \( X(3872) \) production, e.g. by measuring them across colliding systems like Pb-Pb, Au-Au, Xe-Xe, Cu-Cu, O-O, d-A/p-A, etc.

Differential measurements often prove valuable in heavy ion collisions. Thus we present the rapidity distribution of the \( X(3872) \) production in Fig. 3 as well as the transverse momentum spectra in Fig. 4 in minimum bias Pb-Pb collisions. The rapidity dependence of both scenarios is similar to various normal hadrons produced in Pb-Pb collisions at LHC energies, being rather flat within \( |y| < 4 \) while gradually decreasing toward even more forward/backward rapidity region. The \( p_T \) spectra of the \( X(3872) \) again show similar patterns between the two scenarios which are also similar to those for normal hadrons. The shape is indicative of production from thermal source with radial flow.

FIG. 3. Rapidity distribution of the \( X(3872) \) yield in Pb-Pb collisions at \( \sqrt{s} = 2.76 \) TeV for hadronic molecular configuration (red solid boxes) and tetraquark configuration (blue shaded boxes), computed from our framework. The bands are similarly determined as described in Fig. 2.

One interesting and natural question is: are the produced \( X(3872) \) hadrons part of the collective bulk fluid? To this end the anisotropic flows, especially the elliptic...
flow, would be the key observables. The first such calculation for \(X(3872)\) is performed in this study, with the resulting \(v_2(p_T)\) shown in Fig. 4 and compared with experimental data for \(v_2\) of \(J/\Psi\) and D-mesons at the same collision energy. The limited statistics due to low \(X(3872)\) yield would only allow a meaningful evaluation for the hadron molecule case. Our results predict a considerable elliptic flow for the produced \(X(3872)\) with a characteristic \(p_T\) dependence qualitatively similar to other hadrons. It may be useful to compare the results with measured \(v_2\) of \(J/\Psi\) which also contains \(c/\bar{c}\) and has a mass value not far from \(X(3872)\). We find the \(v_2\) of \(X(3872)\) is close to that of \(J/\Psi\), albeit only within the very large error bars. We also find that the \(X(3872)\) though has its \(v_2\) smaller than that of D-mesons. This is consistent with a relatively large spatial size of the hadronic molecule. If \(X(3872)\) were to be made via coalescence of two D-mesons in close proximity, then one would expect a sort of constituent scaling \(v_2^{X(3872)}(p_T) \sim 2 \times v_2^D(p_T/2)\). Instead, the actual \(X(3872)\) is typically made of two D-mesons far apart in space with rather different local flow velocity, thus leading to a smaller \(v_2\) for the produced \(X(3872)\). While we were not able to compute the \(v_2\) for tetraquark case at this time, one natural expectation (that could be tested with enough statistics) would be a certain quark-number scaling if \(X(3872)\) would be made out of four compact quarks. It appears to us that measuring the elliptic flow of \(X(3872)\) in heavy ion collisions is of great interest.

Summary.— In this work, we have demonstrated the novel opportunity to explore the nature of the \(X(3872)\) in high energy heavy ion collisions. Through implementing production mechanism for \(X(3872)\) either as hadronic molecule or as compact tetraquark on top of the widely used AMPT for bulk medium evolution, we have made quantitative predictions in both scenarios for a series of standard heavy ion observables (centrality-dependent yield, rapidity and \(p_T\) spectra and elliptic flow) which will provide valuable guidance for ongoing experimental programs. We particularly propose to measure the elliptic flow of the \(X(3872)\), which is computed for the first time and found to be sizable. A major highlight of our results is that the fireball volume is a key factor in the production of \(X(3872)\), leading to about two orders of magnitude higher yield as well as a significantly stronger centrality dependence when assuming its structure to be a hadronic molecule than that for a compact tetraquark. Such tantalizing finding could potentially open a new path for deciphering the nature of \(X(3872)\) via heavy ion measurements.

All these results together provide a multitude of predictions characterizing the \(X(3872)\) production in heavy ion collisions, which shall strongly motivate enthusiastic experimental activities in the near future. On the theoretical side, the present exploratory study shall also lead to many further investigations. To just mention a few natural ideas: calculating production of other exotic candidates (e.g. pentaquarks) in heavy ion collisions; improving the formation mechanism in heavy ion environment e.g. by more careful treatment of spin degrees of freedom; evaluations of these states within hydrodynamic evolution model; etc. It is tempting to envision an exciting time of vibrant and coherent theory/experiment efforts for exploring heavy ion collisions as a massive production factory of exotic hadrons to its fullest extent.

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FIG. 4. Transverse momentum spectra of the \(X(3872)\) yield in Pb-Pb collisions at \(\sqrt{s} = 2.76\) TeV for hadronic molecular configuration (red solid boxes) and tetraquark configuration (blue shaded boxes), computed from our framework. The bands are similarly determined as described in Fig. 2.

FIG. 5. The elliptic flow coefficient \(v_2\) versus transverse momentum \(p_T\) for produced \(X(3872)\) in minimum bias Pb-Pb collisions at \(\sqrt{s} = 2.76\) TeV, predicted from our computation for hadronic molecule picture. The bands are similarly determined as described in Fig. 2. These results are compared with experimental data for D-mesons and \(J/\Psi\) elliptic flow at the same collision energy.
