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The production of doubly charmed exotic hadrons in heavy ion collisions

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Hadron spectroscopy provides direct physical measurements that shed light on the non-perturbative behavior of quantum chromodynamics (QCD). In particular, various exotic hadrons such as the newly observed T_{cc}^+ by the LHCb collaboration, offer unique insights on the QCD dynamics in hadron structures. In this letter, we demonstrate how heavy ion collisions can serve as a powerful venue for hadron spectroscopy study of doubly charmed exotic hadrons by virtue of the extremely charm-rich environment created in such collisions. The yields of T_{cc}^+ as well as its potential isospin partners are computed within the molecular picture for Pb-Pb collisions at center-of-mass energy 2.76 TeV. We find about three-order-of-magnitude enhancement in the production of T_{cc}^+ in Pb-Pb collisions as compared with the yield in proton-proton collisions, with a moderately smaller enhancement in the yields of the isospin partners T_{cc}^0 and T_{cc}^{++}. The T_{cc}^+ yield is comparable to that of the $X(3872)$ in the most central collisions while shows a considerably stronger decrease toward peripheral collisions, due to a "threshold" effect of the required double charm quarks for T_{cc}^+. Final results for their rapidity and transverse momentum p_T dependence as well as the elliptic flow coefficient are reported and can be tested by future experimental measurements.

Introduction Because of the color confinement property of Quantum chromodynamics (QCD), the theory of strong interaction, experiments can only directly detect color singlet hadrons, instead of fundamental quarks and gluons. As a result, the properties of hadrons, such as the origin of proton mass and spin, structure functions, hadron spectroscopy, and hadron productions/decays in various processes, are very important for understanding the mystery of non-perturbative dynamics in QCD. The study of hadron spectroscopy historically played crucial roles in the development of the conventional quark model, with the classical example of the Ω baryon discovery that helped establish the model. Today, extensive efforts on hadron spectroscopy have been actively carried out by experimental collaborations worldwide such as LHCb, BESIII, BelleII, JLab, CMS, ATLAS, with particular interest in the search of possible exotic hadrons.

Recently, the study of hadrons with two (or more) heavy quarks (or antiquarks) has attracted significant attention. Such states, while expected to exist in both conventional quark model and in the exotic sector, are difficult to create and detect experimentally, due to the apparent absence of any heavy-flavor valence quarks in the beam particles and thus highly suppressed production rate. Nevertheless the available beam energy at the Large Hadron Collider (LHC) and the highly capable detectors have started to offer such opportunity, as shown in the observation of the Ξ_{cc}^{++} by LHCb [1]. Just earlier this month, the LHCb collaboration also reported a $J^P = 1^+$ T_{cc}^+ state with significance over 10 σ in the prompt $D^0D^0\pi^+$ invariant mass distribution in the proton-proton (pp) collisions [2, 3], which is the first observation of a doubly charmed tetraquark with quark content $cc\bar{u}\bar{d}$. Its mass is very close to the D^0D^{*+} and D^+D^{*0} thresholds with width about 410 keV. There are many theoretical studies of the open double heavy tetraquark system in the literature, focusing on key issues such as the formation mechanism (i.e. whether the double heavy tetraquark system is bound or not in either molecular picture or compact tetraquark picture) [4–19], the double heavy exotic spectrum [20–28] and the decay modes/production mechanism [29–32] and their magnetic dipole moments [33]. Detailed measurements on the p_T, rapidity, multiplicity and centrality dependence could help unravel the production mechanism and the internal structures of these hadrons [34–37]. The observation of the exotics with two or more heavy quarks also provides a way to shed light on the potential symmetry (such as diquark-antiquark symmetry [38–40]). For reviews of the study of these exotic states, we refer to Refs. [41–50].

The crucial "bottleneck" for the creation of doubly charmed hadrons is the need of at least two charm quarks (which require production of two charm-anti-charm pairs in the initial hard scatterings). In this regard, high energy heavy ion collisions can serve as a powerful venue for the production of doubly charmed exotic hadrons by virtue of the extremely charm-rich environment in such collisions. Indeed, a central heavy ion collision at LHC energies could have many dozens of charm and anti-charm quarks available in a single event [51, 52]. This unique advantage has been shown for the case of $X(3872)$ production in heavy ion collisions [36, 53–62]. It was proposed that the centrality dependence of $X(3872)$ yield could help distinguish a large size hadronic molecular scenario from a compact tetraquark scenario [53]. Given that the T_{cc}^+ production requires at least two $c\bar{c}$ pairs while the $X(3872)$ requires at least one pair, the heavy ion collision should be even more advantageous for producing the T_{cc}^+. In this letter, we demonstrate this by computing the yields of T_{cc}^+ as well as its potential isospin partners T_{cc}^{++} and T_{cc}^0 in Pb-Pb collisions at center-of-mass energy $\sqrt{s} = 2.76\,\text{TeV}$. The closeness of the T_{cc}^+ to the D^0D^{*+} and D^+D^{*0} thresholds not only implies its potential molecular picture, but also indicates large isospin breaking effects in its decay [29], which is similar to the case of the $X(3872)$ [63–65] with the nearby $D^0\bar{D}^{*0} + c.c.$ and $D^+D^{*-} + c.c.$ thresholds. Given the above, our calculation is performed within the molecular picture and we use the $X(3872)$ yield to set a benchmark for the T_{cc}^+. As we shall show below, the yield of the T_{cc} [1] is enhanced by roughly three-order-of-magnitude as compared with the yield in pp collisions and is comparable to that of the $X(3872)$ in the most central collisions while shows a considerably stronger decrease toward peripheral collisions. Furthermore, we will also present results for the rapidity and transverse momentum p_T dependence as well as the elliptic flow coefficient that can be tested by future measurements.

Framework For this study, we adopt the framework developed in Ref. [53] to generate a total of one million minimum bias events from the default version of AMPT transport model for Pb-Pb collisions at $\sqrt{s} = 2.76\,\text{TeV}$ for simulating the production of both $X(3872)$ and the T_{cc} in these collisions. The charmed mesons D and D^* ($\bar{D}^*$) are collected after the hadronization process and coalesced to the T_{cc} states with the following conditions based on the molecular picture: the relative distance within the region $[5\text{fm}, 7\text{fm}]$ and the invariant mass within the region $[2M_D, 2M_{D^*}]$. In the DD^* molecular picture, there are four possible states:

$$T_{cc}^0: \quad D^0D^{*0} \quad I=1, \quad I_3=-1, \tag{1}$$
$$T_{cc}^{++}: \quad D^+D^{*+} \quad I=1, \quad I_3=1, \tag{2}$$
$$T_{cc}^{(\prime)+}: \quad D^{0/+}D^{*+/0} \quad I=1,0 \quad I_3=0. \tag{3}$$

The first two correspond to the iso-triplet states T_{cc}^0 and T_{cc}^{++} [10, 66, 67] that may potentially be produced. The last two T_{cc}^+ and $T_{cc}^{\prime+}$ could be mixtures of isospin triplet and singlet. As the possible interference between the D^0D^{*+} and D^+D^{*0} components is not implemented in the simulation framework, we do not distinguish these $T_{cc}^{(\prime)+}$ components here. In what follows, we use T_{cc}^+ to denote these two states. As the charmed mesons are formed in the AMPT model based on quark flavor content while lacking spin information, the relative yield ratios between e.g. D^{*+} versus D^+ or that between D^{*0} and D^0 need to be estimated from the thermal model relation

$$R(\frac{A}{B}) \equiv \frac{\text{Yield}(A)}{\text{Yield}(B)} = e^{-(m_A - m_B)/T_{\text{freezeout}}}, \tag{4}$$

with m_A and m_B the masses of hadrons A and B, respectively. Here $T_{\text{freezeout}} \simeq 160$ MeV is the freeze-out temperature. With the physical masses of $D^{(*)+}$ and $D^{(*)0}$, we find that the relevant fractions to be 29.3% versus 70.7% for D^{*+} versus D^+ and 29.2% versus 70.8% for D^{*0} versus D^0, respectively. To calibrate potential influence associated with this procedure, we estimate the uncertainty of our results by varying the fractions in the regions $[20\%, 40\%]$ and $[80\%, 60\%]$ for D^+ and D^{*+}, respectively. As a sanity check, we also verified that our model simulation results for the total $D+D^*$ yields agree with experimental measurements [68].

Results and Discussions In this work we focus on estimating the T_{cc}^+ yield from the coalescence of D^0D^{*+} and D^+D^{*0} pairs within the aforementioned framework. As a benchmark for comparison, we also estimate the $X(3872)$ production within the same framework as the average yield from coalescence of the $D^0\bar{D}^{0*}$, $D^{0*}\bar{D}^0$, D^+D^{-*}, $D^{+*}D^-$ pairs [53]. Additionally the yields of T_{cc}^0 and T_{cc}^{++} states are computed from coalescence of the D^0D^{*0} and D^+D^{*+} pairs, respectively. With a total of one million minimum bias events from our simulations for Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV, the inclusive yields of the $X(3872)$, T_{cc}^0, T_{cc}^{++} and T_{cc}^+ are found to be around 49000, 44000, 44000 and 50000, respectively, for $\text{R}(\frac{D}{D+D^*}) = 70\%$. The fact that these four are almost of the same order may appear counter-intuitive at first sight. Given that the c and $\bar{c}$ quarks must be pair produced and thus have the same abundance in each event, a naive counting may suggest that there would be more $c\bar{c}$ pairs than cc pairs and thus more likelihood to form $X(3872)$ than T_{cc}. Indeed, assuming on average there are N charm and N anti-charm quarks generated in a given event, there would be a total of N^2 $c\bar{c}$ pairs and $N*(N-1)/2$ cc pairs. For $N >> 1$, roughly it is a factor of 2 difference which is also confirmed from our simulations. However, the formation of either $X(3872)$ or T_{cc}^+ in the molecular picture requires a D with a D^* instead of the charm quarks/anti-quarks. This changes the counting: assuming a ratio R for $\frac{D}{D+D^*}$ (and similarly for $\frac{\bar{D}}{\bar{D}+\bar{D}^*}$), there would be roughly NR of D and $N(1-R)$ of D^* as well as NR of $\bar{D}$ and $N(1-R)$ of $\bar{D}^*$. So in the end one gets a similar count of $N^2R(1-R)$ for both DD^* pairs and $D\bar{D}^*$ pairs [2]. This helps explain why the inclusive yields of them are fairly close at large N, i.e. the central centrality region discussed below.

[1] When the charged property of T_{cc} is not specified, it includes all the states, i.e. T_{cc}^{++}, T_{cc}^0 and T_{cc}^+.

[2] Notice that the yields of the $X(3872)$ (49000 discussed above) is equal to that of the T_{cc}^+ (50000 discussed above) within their statistic uncertainties.

To see the fireball volume effect on the T_{cc} production, we plot the centrality dependence of their yields in Fig. 1, where a significant decrease from central to peripheral collisions is found. This trend may be expected for a hadron molecule with relatively large size. In heavy ion collisions the charm quarks and anti-quarks are carried by bulk flow and the produced charm mesons spread out over the whole fireball [53]. In peripheral collisions the fireball volume becomes small and results in a relatively small spatial separation between the relevant charm mesons, which disfavors the formation of molecular states. Our results for centrality dependence clearly demonstrate the unparalleled advantage of heavy ion collisions for producing the doubly charmed exotic hadrons, especially in the central and semi-central collisions.

Furthermore, a comparison between the T_{cc} yields and $X(3872)$ yield as shown by the ratio of the two in Fig. 1 (lower panel) reveals an even stronger suppression of the former in the peripheral collisions. This behavior points to an interesting "threshold" effect of the required double charm quarks for T_{cc} formations. Again, let us assume an average of N charm and N anti-charm quarks in a given event with a ratio R for $\frac{D}{D+D^*}$ (and similarly for $\frac{\bar{D}}{\bar{D}+\bar{D}^*}$). The production of $X(3872)$ requires at least one pair of $D+\bar{D}^*$ or $\bar{D}+D^*$, for which the probability is $P_X = 1 - R^{2N} - (1-R)^{2N}$. The production of T_{cc}, on the other hand, requires at least one pair of $D+D^*$, for which the probability is $P_T = 1 - R^N - (1-R)^N$. Note that $R < 1$ and $(1-R) < 1$, so the chance becomes considerably smaller for T_{cc} production than $X(3872)$ especially when the number N becomes smaller. To given an extreme example: when $N \to 1$ (i.e. in the limit of only one $c\bar{c}$ pair per event), $P_T = 0$ while $P_X > 0$. The essence of such a suppression on the T_{cc} production is essentially a "threshold" effect occurring in the limit of ultra-low charm abundance. In heavy ion collisions, the number N of $c\bar{c}$ pairs per event scales with the number of initial hard scatterings which in turn scales with the so-called binary collision number N_{coll} [69]. The N_{coll} drops very rapidly from central toward peripheral region, thus providing an explanation of the observed pattern for T_{cc} centrality dependence.

To gain further insight, we perform an extrapolation of the centrality dependence with a third-order polynomial function for the relative yield ratio between T_{cc} and $X(3872)$ toward the ultra-peripheral regime, as indicated by the color bands in Fig. 1 (lower panel). One can see that the yield of the T_{cc}^+ is at least three orders smaller than that of the $X(3872)$ in the ultra-peripheral collisions, which are expected to approach the limit of elementary *pp* collisions. We note that the extrapolated result in that limit shows consistency with the corresponding ratio between T_{cc}^+ and $X(3872)$ in *pp* collisions from LHCb measurements [2, 3, 35, 70–74]. Finally, the extrapolation suggests the yield of the iso-triplet states is at least two orders of magnitude smaller than that of the T_{cc}^+, which may provide a plausible reason for the absence of the iso-triplet T_{cc}^{++} so far in LHCb data [3].

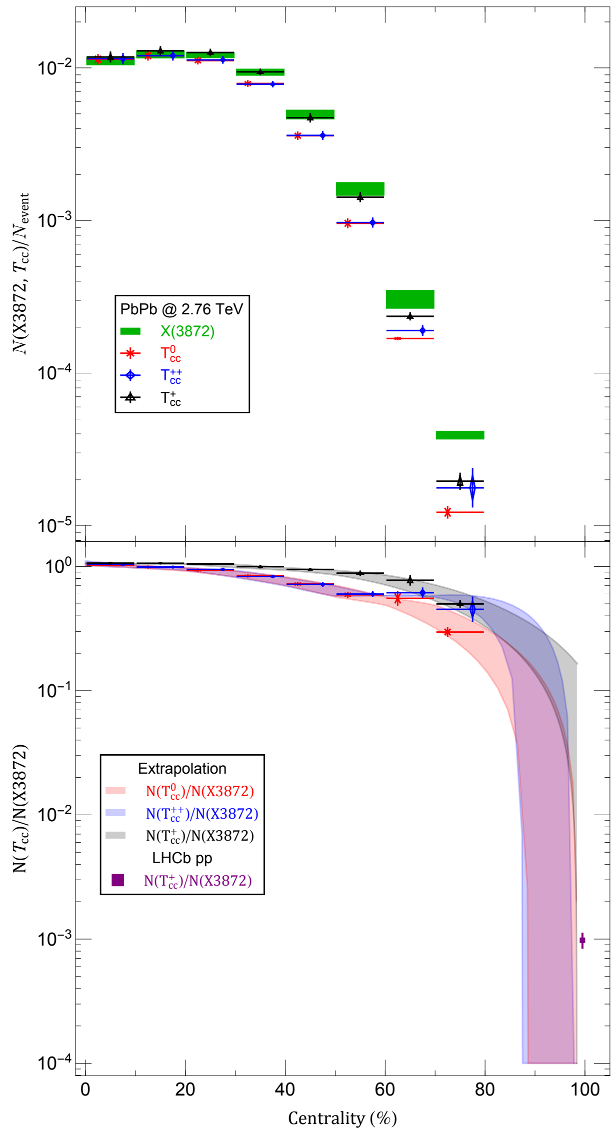

FIG. 1. The centrality dependence of the $X(3872)$ (green solid boxes), T_{cc}^0 (red stars), T_{cc}^{++} (blue diamonds) and T_{cc}^+ (black triangles) in the $D\bar{D}^* + c.c.$, D^0D^{*0}, D^+D^{*+} and D^0D^{*+}/D^+D^{*0} hadronic molecular picture, respectively. The bands reflect the uncertainty due to constituent composition as discussed in Eq. (4) that are obtained from varying the composition fraction by $\pm 10\%$. The ratios of the yields for the three T_{cc}s relative to that for the $X(3872)$ are also presented in the lower panel, where an extrapolation with a third-order polynomial function of the T_{cc}^0 (gray shaded band) and T_{cc}^{++} (pink shaded band) yield ratios toward ultra-peripheral region are also presented. The purple square is the ratio extracted from the experimental data [2, 3, 35, 70–74].

In Fig. 2 we present the rapidity and the transverse momentum distributions of these states, which are found to be similar to those of the usual hadrons [75, 76]. The

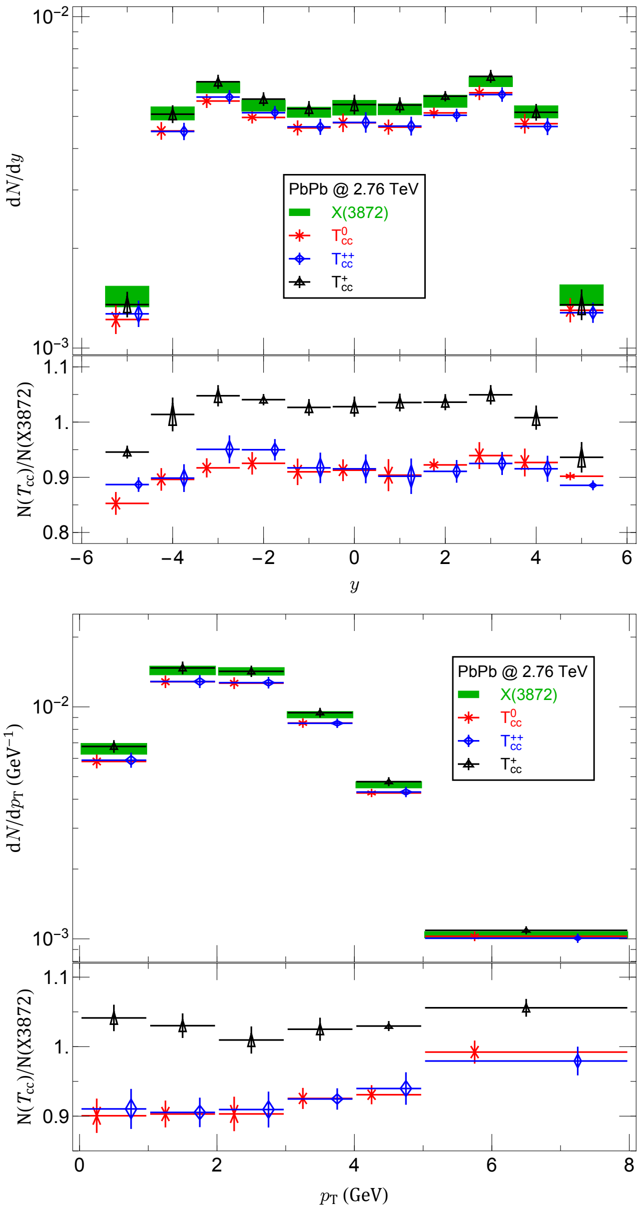

FIG. 2. The rapidity and transverse momentum distributions for the $X(3872)$ (green solid boxes), T_{cc}^0 (red stars), T_{cc}^{++} (blue diamonds) and T_{cc}^+ (black triangles) in the $D\bar{D}^* + c.c.$, D^0D^{*0}, D^+D^{*+} and D^0D^{*+}/D^+D^{*0} hadronic molecular picture, respectively. The uncertainties are obtained in the same way as that in Fig. 1. The ratios of the yields for the three T_{cc}s relative to that for the $X(3872)$ are also presented in the lower panels.

rapidity dependence is flat in the middle and decreasing at the forward/backward region. The p_T spectra decreases very strongly with increasing p_T, which may be expected from production from the thermal source with radial flow [53]. Finally we also show the results for the elliptic flow coefficient v_2 of these states in Fig. 3, which suggest a very similar elliptic flow pattern among these states. The elliptic flow of a particle like $X(3872)$ or T_{cc} would be sensitive to the charm mesons that coalesce into them, especially the spatial distributions of these mesons in the fireball. The similarity in v_2 among them is due to a similar spatial distributions of various D, D^*, $\bar{D}$ and $\bar{D}^*$ mesons, as we verified from our simulations.

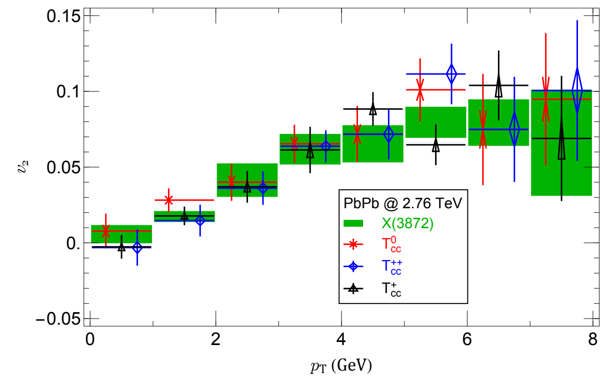

FIG. 3. The elliptic flow coefficient v_2 versus transverse momentum p_T for the $X(3872)$ (green solid boxes), T_{cc}^0 (red stars), T_{cc}^{++} (blue diamonds) and T_{cc}^+ (black triangles) in the $D\bar{D}^* + c.c.$, D^0D^{*0}, D^+D^{*+} and D^0D^{*+}/D^+D^{*0} hadronic molecular picture, respectively. The uncertainties are obtained in the same way as that in Fig. 1.

Summary and Outlook In this work, we estimate the yields of the recently observed T_{cc}^+ as well as its potential isospin partners T_{cc}^0 and T_{cc}^{++} within the DD^* hadronic molecular picture in Pb-Pb collisions at center-of-mass energy 2.76 TeV. Our main finding is a strong enhancement, about three orders of magnitude, for the T_{cc} yield in the central collisions as compared with the very peripheral collisions which would approach the pp baseline. In comparison with the $X(3872)$ yield computed in the same framework, we find their inclusive yields are close to each other in the central region but the T_{cc} production shows a much stronger suppression into the peripheral region, which can be understood from an interesting "threshold" effect of the required double charm quarks for T_{cc} formation. Final results are obtained for the rapidity and transverse momentum p_T dependence of T_{cc} production as well as for the elliptic flow coefficient. Overall, we have demonstrated how heavy ion collisions can serve as a powerful venue for hadron spectroscopy study of doubly charmed exotic hadrons by virtue of the extremely charm-rich environment created in such collisions. It would be exciting to anticipate future experimental efforts that will look for T_{cc} states in heavy ion collisions and test the findings from the present work. Given the advantage of heavy ion collisions in producing an abundance of these doubly charmed exotics, it is conceivable that measurements from heavy ion experiments would offer great opportunities to nail down their structures and properties.

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