

Comparative study of T_{cc} versus $X(3872)$ production in pp collisions at $\sqrt{s} = 7$ TeV

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The production of exotic hadrons T_{cc} and $X(3872)$ in pp collisions at $\sqrt{s} = 7$ TeV is compared using the parton and hadron cascade model together with the dynamically constrained phase-space coalescence model. In the simulation, the compact tetraquark state and the loose molecular state are formed in the partonic and hadronic levels, respectively. Our analysis of the transverse momentum spectra reveals a significant discrepancy between the compact state and the molecular states. Furthermore, the production asymmetry between T_{cc}^+ and T_{cc}^- is investigated. Finally, the coalescence parameters are extracted from the calculated spectra to further characterize the emission source properties. These distributions are proposed as valuable criteria for distinguishing between these states and investigating their internal structures in experimental measurements.

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I. INTRODUCTION

The quark model has been an important tool for understanding the low-energy region of QCD, and unveiling the internal structure of hadrons [1,2]. The majority of observed hadrons can be classified within this framework as baryons with three quarks or mesons composed of a quark-antiquark pair. However, the requirement of color neutrality alone does not preclude the existence of more complex configurations, such as tetraquarks and pentaquarks, etc. Indeed, the existence of exotic states was also suggested by Gell-Mann [1] and Zweig [2] at the early stage of the quark model. Such exotic hadrons, which lie beyond the conventional configurations, provide a unique window to decode the mystery of hadronization.

To date, dozens of so-called XYZ exotic states lying outside the conventional quark model are observed in experiments, and various theoretical investigations have been proposed for these new forms of matter, such as compact tetraquarks [3,4], hadronic molecules [5], hybrids [6], normal heavy quarkonium [7], and so on, with the potential

to disclose new information about the fundamental strong force. Despite the abundance of theoretical interpretations regarding the properties of exotic states, controversial interpretations are often seen in the literature. To deepen our understanding of exotic hadrons, physicists are putting tremendous effort into exploring novel research methods and topics.

The first candidate of the exotic state, $X(3872)$ with quark content of $c\bar{c}u\bar{u}$ or $c\bar{c}d\bar{d}$, was observed by Belle Collaboration in 2003 [8]. Recently, the LHCb Collaboration announced the observation of the first doubly charm tetraquark, $T_{cc}(3875)$ with quark content of $cc\bar{u}\bar{d}$ or $\bar{c}\bar{c}ud$, near the DD^* threshold [9,10]. The masses of $T_{cc}(3875)$ (open-charm state) and $X(3872)$ (hidden-charm state) are very close. Their striking characteristics have sparked extensive discussions about their nature. Experimental observations [11–13] and theoretical interpretations [14–22] of the T_{cc} and $X(3872)$ indicate that these states may be interpreted as compact tetraquarks, loosely bound hadronic molecular configuration, while hybrid (admixture) configurations have also been proposed in recent studies [16,20]. Based on these considerations, the compact tetraquark and hadronic molecular frameworks remain the two leading structural scenarios, as both can account for the observed masses but involve different underlying physics. Therefore, in this work, we comparatively investigate the production of the T_{cc} and $X(3872)$ within the compact tetraquark and hadronic molecular frameworks to provide further insight into their internal structures.

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In this paper, we explore the production of T_{cc} (including T_{cc}^+ and its antimatter counterpart T_{cc}^-) and $X(3872)$ in pp collisions at $\sqrt{s} = 7$ TeV employing the parton and hadron cascade (PACIAE) model [23] and the dynamically constrained phase-space coalescence (DCPC) model [24]. The compact tetraquark and hadronic molecular scenarios are both investigated and compared. First, the production asymmetry between T_{cc}^+ and T_{cc}^- is investigated. To investigate the physical nature of T_{cc} and $X(3872)$, we then compare their yields and kinematic distributions (i.e., transverse momentum p_T and coalescence parameters).

The remainder of this paper is organized as follows. The methodologies are detailed in Sec. II. Section III presents the numerical results and analysis. Finally, our findings and conclusions are discussed in Sec. IV.

II. METHOD

A. PACIAE model

The PACIAE model [23,25] is a phenomenological model based on the PYTHIA code [26], which can be used successfully to simulate relativistic elementary particle collisions and nucleus-nucleus collisions [23,25,27,28]. With the PACIAE model framework, a pp collision is divided into the initial parton stage, the parton rescattering stage, the hadronization stage, and the hadron rescattering stage.

In the first stage, the collision of the proton-proton pair is executed by PYTHIA [26] with hadronization temporarily turned-off. Consequently, an initial partonic state is established following the QCD hard scattering and the associated initial- and final-state radiations. Here a process of the gluons breaking-up and energetic quarks and antiquarks deexcitation is then executed [23]. In the subsequent stage, the lowest-order perturbative quantum chromodynamics (LO-pQCD) parton-parton interaction cross sections [29] are used. The results of partonic final state (PFS) comprising numerous quarks and antiquarks with four-coordinates and four momenta, are generated after partonic rescattering. During the hadronization stage, the Lund string fragmentation regime or the coalescence model is implemented to generate an intermediate hadronic state, and the latter is chosen in this work. The final stage is hadronic

rescattering, which produces the hadronic final state (HFS), which consists of abundant hadrons with four coordinates and four momenta.

B. DCPC model

The DCPC model was originally proposed to investigate the production of light nuclei and antinuclei in pp and nucleus-nucleus collisions [24,30] and has since been successfully extended to calculate the production of exotic hadrons including the $X(3872)$, $Z_c(3900)$, P_c , following simulations with the transport model PACIAE [31–35]. The DCPC model can be used to form the compact tetraquark state and the loose molecular state in the partonic and hadronic levels, respectively.

Grounded in the principles of quantum statistical mechanics [36,37], the yield of an N -particle cluster (formed by partons in PFS or hadrons in HFS) is defined as

$$Y_N = \int_{E_\alpha \leq E \leq E_\beta} \prod_{i=1}^N \frac{d\vec{q}_i d\vec{p}_i}{h^{3N}}, \quad (1)$$

where E_α and E_β denote the lower- and upper-energy thresholds of the cluster, respectively. h is the Planck constant ($h = 2\pi\hbar$). $\vec{q}_i$ and $\vec{p}_i$ represent the three-dimensional coordinate and momentum of the i th constituent particle. For a valid cluster to be formed naturally, the constituent particles should satisfy three constraints; the constituent-composition constraint, the coordinate-space constraint, and the momentum-space constraint. The latter two constitute the dynamical constraints in the DCPC model.

For the tetraquark state, it is coalesced (hadronized) in PFS using the DCPC model by four component quarks, specifically, charm quark ($c/\bar{c}$) and light quark $q(\bar{q})$ (with $q = u/d$, the same notation applies hereafter). The yield of the tetraquark state is calculated by

$$Y_{\text{Tetraquark}} = \int_{E_\alpha \leq E \leq E_\beta} \delta_{1234} \frac{\prod_{i=1}^4 d\vec{q}_i d\vec{p}_i}{h^{12}}, \quad (2)$$

where

$$\delta_{1234} = \begin{cases} 1 & \text{if } 1 \equiv c/\bar{c}, 2 \equiv c/\bar{c}, 3 \equiv u/\bar{u}/d/\bar{d}, 4 \equiv u/\bar{u}/d/\bar{d}, \\ & 2 m_D \leq m_{\text{inv}} \leq 2 m_{D^*}, \\ & |\vec{q}_{i0}| \leq R_0 \ (i = 1, 2, 3, 4), \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

In Eq. (3), R_0 and $|\vec{q}_{i0}|$ denote the radius of the tetraquark state and the relative distance between the i th constituent quark (or antiquark) and the cluster's center of mass, respectively. The m_{inv} is the invariant mass of the four-component system, calculated as

$$m_{\text{inv}} = \sqrt{\left(\sum_{i=1}^4 E_i\right)^2 - \left(\sum_{i=1}^4 \vec{p}_i\right)^2}, \quad (4)$$

where, E_i and $\vec{p}_i$ ($i = 1, 2, 3, 4$) are the energy and three-momentum of the i th constituent quark.

Similarly, the yield of the molecular state is defined as

$$Y_{\text{Molecular}} = \int_{E_a \leq E \leq E_b} \delta_{12} \frac{d\vec{q}_1 d\vec{p}_1 d\vec{q}_2 d\vec{p}_2}{h^6}. \quad (5)$$

In the above equation, δ_{12} is expressed as

$$\delta_{12} = \begin{cases} 1 \equiv D, 2 \equiv D^*, \\ 1 \text{ if } 2 m_D \leq m_{\text{inv}} \leq 2 m_{D^*}, \\ |\vec{q}_{i0}| \leq R_0 (i = 1, 2), \\ 0 \text{ otherwise,} \end{cases} \quad (6)$$

where $|\vec{q}_{i0}|$ is the relative distance between the i th component meson (D or D^* meson in this work) and the molecular cluster's center of mass. The R_0 is the radius of the molecular state. The invariant mass m_{inv} is calculated as $m_{\text{inv}} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$, where E_1, E_2 and $\vec{p}_1, \vec{p}_2$ are the energy and three-momentum of the component particle D mesons, respectively.

III. RESULTS AND DISCUSSION

A. Production and yield

In the paper, we utilize PACIAE 3.0 and the DCPC model to simulate the production of T_{cc}^+, T_{cc}^- and $X(3872)$ in pp collisions at $\sqrt{s} = 7$ TeV. In our framework, the production of exotics involves a two-step process; the generation of their constituents and the subsequent formation of the exotic state. The primary PACIAE model parameters of the allowed number of deexcitation generation and the threshold energy of deexcitation the energetic (anti)quark deexcitation process, i.e., $\text{adj1}(16) = 1$ and $\text{adj1}(17) = 1.8$ GeV, are fixed by fitting the ALICE data of D^0 and D^+ yield in pp collisions at $\sqrt{s} = 2.76$ TeV [38]. Subsequently, the tetraquark state and molecular state are formed in PFS and HFS by DCPC model, respectively.

In tetraquark picture, we first generated component quarks in PFS by PACIAE. The compact tetraquark state is then coalesced (hadronized) via four component

particles of $c(\bar{c})$ and q (anti)quarks ($q = u/d$) by DCPC model. The components of T_{cc}^+, T_{cc}^- and $X(3872)$ are $cc\bar{u}\bar{d}$, $\bar{c}\bar{c}ud$, and $c\bar{c}u\bar{u}$, respectively. Taking into account the phase space constraints in DCPC model, $R_0 < 1.0$ fm are set, treating the compact state as a pointlike particle [39,40], and set to $3729.68 < m_{\text{inv}} < 4020.52$ MeV for T_{cc}^+ and T_{cc}^- , $3729.68 < m_{\text{inv}} < 4013.70$ for $X(3872)$ [41].

Similarly, in the molecular picture, they are hadronized by the coalescence of two mesons in the FHS. In this paper, we simulate the production of the $D^0 D^{*+}$ and $D^+ D^{*0}$, $D^0 D^{*-}$ and $D^- D^{*0}$, $D^0 \bar{D}^{*0}$ and $D^{*0} \bar{D}^0$ for the formation of the T_{cc}^+, T_{cc}^- and $X(3872)$, respectively. The constraints for Eq. (6) are set as follows; $3729.68 < m_{\text{inv}} < 4020.52$ MeV for T_{cc}^+ , $3729.68 < m_{\text{inv}} < 4013.70$ for $X(3872)$ [41], and $1.0 \text{ fm} < R_0 < 10.0 \text{ fm}$ for the molecular state (R_0 should be larger than the sum of the radius of two component mesons and less than the interaction range of 20 fm).

In total, we simulate 600 million pp collision events to generate molecular states, and 18.6 million pp collision events for tetraquark states. The yield is predicted and summarized in Table I.

As shown in Table I, the molecular state is more likely to be produced than the tetraquark state. Meanwhile, the yield of the $X(3872)$ state is significantly higher than those of T_{cc}^+ and T_{cc}^- for both the molecular and tetraquark configurations. This disparity is attributed to the fact that the yield of $c\bar{c}$ pairs is statistically larger than that of cc or $\bar{c}\bar{c}$ pairs. Consequently, $X(3872)$ is naturally more abundant than double-charm states T_{cc} .

B. Transverse momentum distribution

To gain further insight, we calculate the transverse momentum spectra of these states under both the molecular and tetraquark states. The distributions are presented in Fig. 1. As illustrated in Fig. 1, the p_T spectra exhibit a steep decline with increasing p_T , which is consistent with theoretical expectations. Beyond the difference in total yields, the distributions for the molecular and tetraquark states show distinct characteristics. Consequently, the p_T spectra distribution of them in high-statistics measurements at experiments can be able to discriminate its structure in the future.

To further quantify this difference, we calculate the yield ratios between tetraquark state and molecular state of T_{cc}^+, T_{cc}^- and $X(3872)$, respectively, as a function of p_T . The

TABLE I. The PACIAE + DCPC model simulated yield of the molecular and tetraquark T_{cc}^+, T_{cc}^- and $X(3872)$ in pp collisions at $\sqrt{s} = 7$ TeV, without any kinematic constraint. The uncertainties are the statistic ones.

	T_{cc}^+	T_{cc}^-	$X(3872)$
Molecular	$(7.55 \pm 0.347) \times 10^{-7}$	$(7.55 \pm 0.358) \times 10^{-7}$	$(5.91 \pm 0.100) \times 10^{-6}$
Tetraquark	$(2.94 \pm 0.126) \times 10^{-5}$	$(2.90 \pm 0.125) \times 10^{-5}$	$(11.09 \pm 0.077) \times 10^{-4}$
Ratio (T/M)	38.88 ± 2.470	38.44 ± 2.460	187.55 ± 3.432

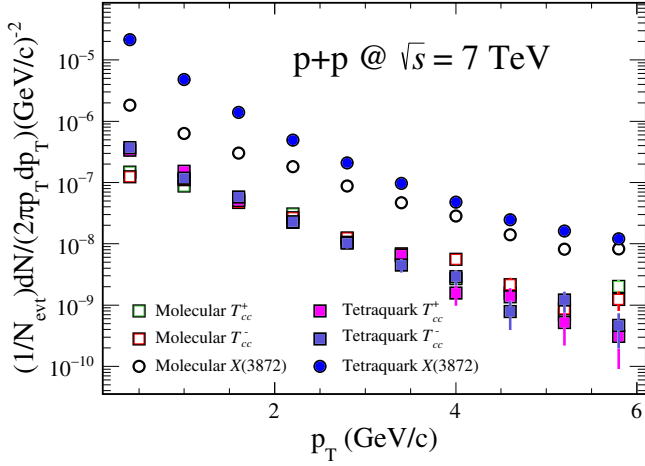


FIG. 1. The transverse momentum spectra distribution of T_{cc} and $X(3872)$ within the molecular and tetraquark framework in pp collisions at $\sqrt{s} = 7$ TeV. The vertical bars are for statistic uncertainties.

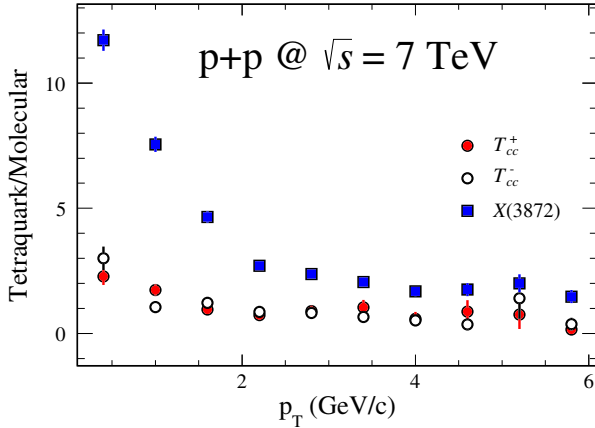


FIG. 2. The ratio of yield between the tetraquark and molecular state of T_{cc} and $X(3872)$ in pp collisions at $\sqrt{s} = 7$ TeV as functions of p_T .

distributions of the ratio are shown in Fig. 2. The ratio is observed to decrease as p_T increases, characterized by a rapid drop in low p_T , accompanied by a more gradual decline in higher p_T . Additionally, the ratio for $X(3872)$ decreases more significantly than that of the T_{cc} states. For T_{cc}^+ and T_{cc}^- , the distributions are consistent with each other within error bars. Then, we analyze their asymmetry.

C. Asymmetry

Ref. [17] concluded that the compact tetraquark exhibits a significant production asymmetry between T_{cc}^+ and T_{cc}^- , enabling the unambiguous determination of the internal structure of the tetraquark. To discriminate the tetraquark and molecular state of T_{cc} , we introduce the asymmetry of the production of T_{cc}^+ and T_{cc}^- , which is defined as

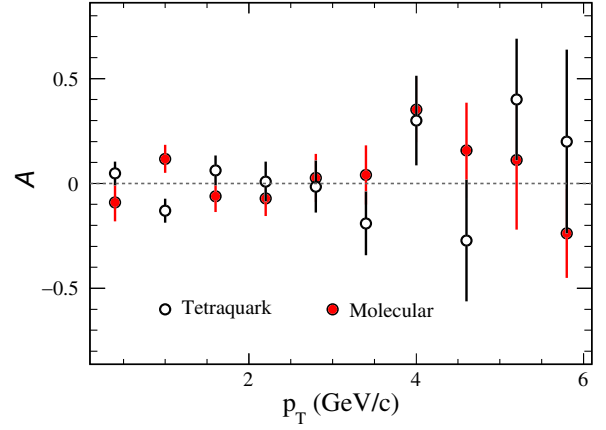


FIG. 3. The asymmetry of charged T_{cc} in pp collisions at $\sqrt{s} = 7$ TeV, for molecular and tetraquark picture, respectively, which defined in Eq. (7).

$$\mathcal{A} \equiv \frac{N_{T_{cc}^-} - N_{T_{cc}^+}}{N_{T_{cc}^-} + N_{T_{cc}^+}}, \quad (7)$$

where $N_{T_{cc}^+}$ and $N_{T_{cc}^-}$ represent the yield of T_{cc}^+ and T_{cc}^- , respectively.

When comparing in two pictures, i.e., molecular and tetraquark picture, the asymmetry is shown in Fig. 3. We can find that $\mathcal{A}$ presents a smaller production asymmetry in tetraquark state than in molecular state when it is in low p_T , and the asymmetry exhibits a larger production asymmetry in tetraquark states than in molecular states in high p_T . The $\mathcal{A}$ represents a significant discrepancy in two pictures, therefore, the $\mathcal{A}$ can be a valuable criterion to identify the molecular or tetraquark T_{cc} .

D. Coalescence parameter

In the coalescence framework [42,43], the production of a cluster is generally regarded as the result of coalescence of constituent particles that are spatially close and have similar velocities at the chemical freeze-out. This framework has been extensively and successfully applied to describe the production of light nuclei and antinuclei in pp and heavy-ion collisions [44,45], and we extend it to the study of exotic states $T_{cc}^\pm$ and $X(3872)$ in the present work to extract their coalescence parameters. For these exotic states, two distinct structural interpretations (loose molecular state and compact tetraquark state) are considered. The coalescence parameter serves as a robust probe to characterize both the correlation length and correlation volume between constituent particles, as well as the properties of the emission source. Notably, the magnitude of the coalescence parameter is closely related to the correlation volume: a larger coalescence parameter corresponds to a smaller correlation volume, and vice versa. This relation enables us to distinguish whether the exotic states are formed in the hadronic final state (HFS, for molecular

states) or the partonic final state (PFS, for tetraquark states) through the measured value of the coalescence parameter.

The invariant yield of a cluster is proportional to the product of the invariant yields of its constituent particles, which is quantitatively described by the general formula:

$$E_X \frac{d^3 N_X}{dp_X^3} = B_N \prod_{i=1}^N \left(E_i \frac{d^3 N_i}{dp_i^3} \right), \quad (8)$$

where N denotes the number of constituent particles of the cluster, $E_X \frac{d^3 N_X}{dp_X^3}$ is the invariant differential yield of the cluster [e.g., $T_{cc}^\pm$, $X(3872)$ in our work], and $E_i \frac{d^3 N_i}{dp_i^3}$ represents the invariant differential yield of the i th constituent particle (quarks for tetraquarks or mesons for molecular states in our work). The coalescence parameter B_N is inversely related to the correlation volume of the emitting source; a larger B_N indicates a more compact source with stronger correlations between constituents.

In general, the production of light nuclei and anti-nuclei can be described by coalescence parameter B_A , which has been used extensively and successfully in pp [44] and heavy ion [45] collisions. In the coalescence framework, the production of cluster is expected to be the result of the coalescence of the constituents that are nearby in space and have similar velocities at chemical freeze out of mesons or quarks constituents. To analyze the production of these exotic states, we introduce the coalescence parameters. We consider two distinct structural interpretations: the loose molecular and compact tetraquark state. For the molecular state, the coalescence parameters correspond to B_2 , which relates the invariant differential yield of exotic states to the one of mesons via the following equation:

$$B_2 = \left(\frac{1}{2\pi} \frac{dN^X}{p_T^X dp_T^X} \right) / \left[\left(\frac{1}{2\pi} \frac{dN^D}{p_T^D dp_T^D} \right) \cdot \left(\frac{1}{2\pi} \frac{dN^{D^*}}{p_T^{D^*} dp_T^{D^*}} \right) \right], \quad (9)$$

where the superscript X represents the exotic state [$X(3872)$ or T_{cc}^+ , T_{cc}^- in this work], D and D^* represent the constituent of molecular X , the D or D^* meson yield is measured at a value of half of the transverse momentum of exotic state, $p_T^{D/D^*} = \frac{1}{2} p_T^X$.

Similarly, in tetraquark picture, the invariant yield of exotic states is proportional to the invariant yield of quarks (the constituents of the tetraquark state), the coalescence parameter is noted as B_4 ,

$$B_4 = \left(\frac{1}{2\pi} \frac{dN^X}{p_T^X dp_T^X} \right) / \left[\left(\frac{1}{2\pi} \frac{dN^{Q_1}}{p_T^{Q_1} dp_T^{Q_1}} \right) \cdot \left(\frac{1}{2\pi} \frac{dN^{Q_2}}{p_T^{Q_2} dp_T^{Q_2}} \right) \cdot \left(\frac{1}{2\pi} \frac{dN^{q_1}}{p_T^{q_1} dp_T^{q_1}} \right) \cdot \left(\frac{1}{2\pi} \frac{dN^{q_2}}{p_T^{q_2} dp_T^{q_2}} \right) \right], \quad (10)$$

where the superscript X represents the exotic state, Q and q represent the quark constituents of X ($Q = Q_1 = Q_2 = c/\bar{c}$, $q = q_1 = q_2 = u/\bar{u}/d/\bar{d}$), the yield of quarks is calculated at a value of transverse momentum commensurate their mass, $p_T^{Q/q} = \frac{m^{Q/q}}{M} p_T^X$, ($M = m^{Q_1} + m^{Q_2} + m^{q_1} + m^{q_2}$).

Based on p_T of exotic states and their constituents, the coalescence parameter B_2 and B_4 are calculated as functions of p_T and shown in Fig. 4, respectively. Our results show a rising trend in the coalescence parameters with increasing p_T . Since a larger coalescence parameter corresponds to a more compact source, this trend implies that

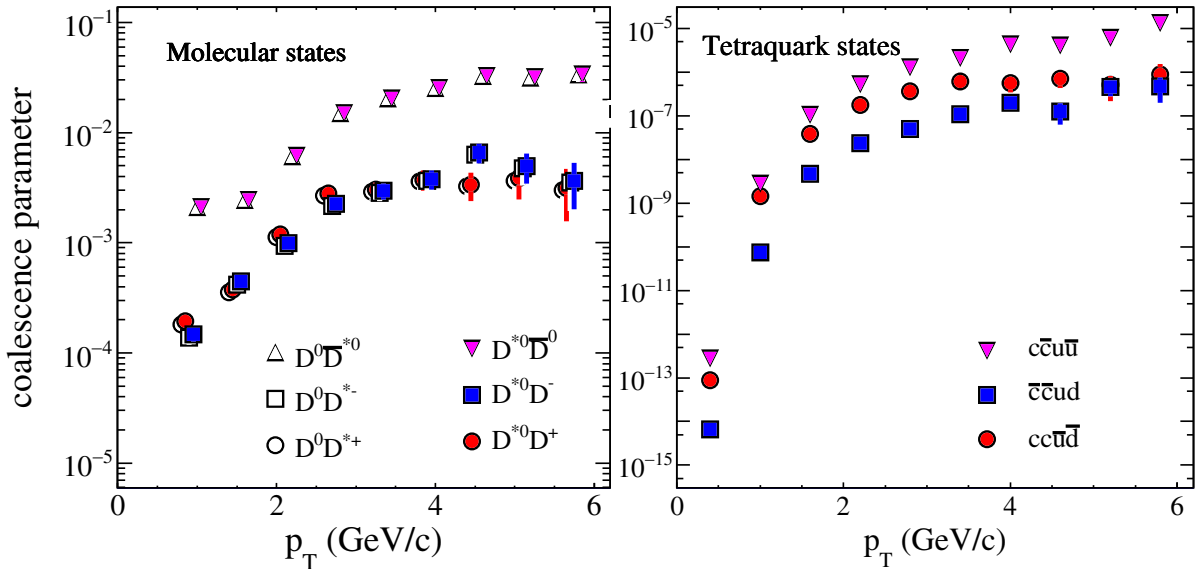


FIG. 4. Coalescence parameter defined in Eq. (9) and (10) of T_{cc} and $X(3872)$ as functions of p_T for molecular (left) and tetraquark (right) picture, respectively, in pp collisions at $\sqrt{s} = 7$ TeV. The vertical bars represent the statistical uncertainties.

the correlation volume decreases with increasing p_T . The observation is consistent with the principle that the coalescence is inversely proportional to the correlation volume of the emitting source.

IV. SUMMARY AND OUTLOOK

In this work, we simulated the production of T_{cc}^+ , T_{cc}^- , and $X(3872)$ states within both molecular and tetraquark frameworks in pp collision at $\sqrt{s} = 7$ TeV. Our comparison reveals that the yields of T_{cc} are consistently lower than those of $X(3872)$, which may be attributed to the “threshold” effect of the required double charm quarks for T_{cc} formation. Furthermore, the yields of the tetraquark states are found to be significantly larger than those for the molecular states. The analysis of the p_T spectral distribution shows distinct differences between the molecular and tetraquark state, suggesting that transverse momentum spectra can serve as an effective tool to discriminate between these internal structures in future high-statistics experiments. The production asymmetry $\mathcal{A}$ exhibits distinctly different behaviors between the molecular and

tetraquark scenarios for T_{cc}^+ and T_{cc}^- in different p_T regions. We also find that the coalescence parameter increases monotonically as a function of p_T . Interestingly, as shown in Fig. 4, no differences are found in the distribution shapes of a given state between different constituents.

Given the advantage of heavy ion collisions in producing an abundance of the charmed and doubly charmed exotic states, our future research will extend to this environment to explore the production and properties of these states.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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