Investigation of Ω_c^0 states decaying to $\Xi_c^+ K^-$ in pp collisions at $\sqrt{s} = 7$, 13 TeV

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The production of strange particles Ξ_c^+, K^- is simulated in pp collisions at $\sqrt{s} = 7$ TeV at mid-rapidity with $0.2 \leqslant p_T \leqslant 6$ GeV/c using the PACIAE model. The results are consistent with LHCb experimental data on Ξ_c^+ and K^- yield. Then, a dynamically constrained phase-space coalescence model plus PACIAE model was used to produce the $\Xi_c^+ K^-$ bound states and study the narrow excited Ω_c^0 states through $\Omega_c^0 \to \Xi_c^+ K^-$ in pp collisions at $\sqrt{s} = 7$ and 13 TeV. The yield, transverse momentum distribution, and rapidity distribution of the five new excited Ω_c^0 states of $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$ were predicted.

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I. INTRODUCTION

In the early 1960s, many strongly interacting particles were observed in particle and nucleon experiments, which were later named "hadrons" by Okun [1]. According to these observations, Gell-Mann and Zweig independently proposed the quark model, which is the classification scheme for hadrons [2,3]. The quark model achieves great success, and it is a milestone in the development of particle physics. A well-known example was that, after Ω had been predicted in 1961 independently by Gell-Mann [4] and Ne'eman [5], this particle was discovered in 1964 [6]. In the traditional quark model, hadrons can be categorized into two families: baryons made of three quarks and mesons made of one quark and one antiquark. Both mesons and baryons are color singlets. During the last four decades, baryons containing heavy quarks have been the focus of much attention, especially since the development of the efficient theory of heavy quarks and its application to baryons containing a single heavy quark. In recent years, a variety of theories and experiments have been proposed for the study of heavy flavor baryons. Heavy quarks provide a "flavor tag" that can be used as a window into the depths of the color confinement, or at least a window allowing us see further under the nonperturbative QCD layer than the light baryons do. In the process of establishing cognition of different energy scale QCD, a rich dynamical study on heavy flavor baryons and their properties is urgently needed.

In the past three decades, various phenomenological models have been used to study heavy baryons, including the relativized potential quark model [7], the Feynman-Hellmann theorem [8], the combined expansion in $1/m_Q$ and $1/N_c$ [9], the relativistic quark model [10], the chiral quark model [11], the hyperfine interaction [12,13], the pion induced reactions [14], the variational approach [15], the Faddeev approach [16], the constituent quark model [17], the unitarized dynamical model [18], the extended local hidden gauge approach [19], and the unitarized chiral perturbation theory [20]. There are also many lattice QCD studies [21,22].

Furthermore, there are numerous experimental groups to investigate heavy baryons. Some mass spectra, width, lifetime, decays, and form factors of heavy baryons have been reported but the spin and parity identification of some states are still missing. By now, all the ground state charmed baryons containing a single charmed quark have been well established both experimentally and theoretically [23]. The lowest-lying orbitally excited charmed states $\Lambda_c(2959)^0(J^P = 1/2^-)$, $\Lambda_c(2625)^0(J^P = 3/2^-)$, $\Xi_c(2790)^0(J^P = 1/2^-)$, and $\Xi_c(2815)^0(J^P = 3/2^-)$ have been well observed by several collaborations, which made the two SU(4) multiplets complete [24–28]. In addition to that, several P-wave charmed baryon candidates $\sum_c(2800)$, $\Xi_c(2980)$, and $\Xi_c(3080)$ were also well observed by the Belle and BABAR Collaborations [28–31]. In 2017, the LHCb Collaboration reported their observation of five new narrow excited Ω_c^0 states decaying to $\Xi_c^+ K^-$, based on samples of pp collision data corresponding to integrated luminosities of 1.0, 2.0, and 0.3 fb^{-1} at center-of-mass energies of 7, 8, and 13 TeV, respectively [32]. In the near future, the experiments at JPARC, PANDA [33], and LHCb are expected to give further information on charmed baryons.

These heavy baryons provide us an ideal platform to deepen our understanding of nonperturbative QCD. Therefore, people hope to fully understand their nature. In this paper, we study the $\Xi_c^+ K^-$ bound state to predict the properties of Ω_c^0 states decaying to $\Xi_c^+ K^-$ by simulating analysis. First, we generate pp collision events at $\sqrt{s} = 7$ and 13 TeV to obtain the hadrons of Ξ_c^+ and K^- using the parton and hadron

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cascade model (PACIAE) [34]. Then we use a dynamically constrained phase-space coalescence (DCPC) model [35–37] to produce $\Xi_c^+ K^-$ bound states for the study of Ω_c^0. Here, we mainly simulate and study five different excited resonance Ω_c^0 states of $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$, which is observed by LHCb experiment.

II. PACIAE MODEL AND DCPC MODEL

The parton and hadron cascade model PACIAE [34] is based on PYTHIA 6.4 to simulate various collisions, such as e^+e^-, pp, p-A, and A-A collisions. In general, PACIAE has four main physics stages, consisting of the parton initiation, parton rescattering, hadronization, and hadron rescattering. In the parton initiation, the string fragmentation is switched off temporarily in PACIAE and di(anti)quarks are broken into (anti)quarks. This partonic initial state can be regarded as quark-gluon matter (QGM) formed inside the parton initialization stage in the pp collisions. Then the parton rescattering in QGM is taken into account by the $2 \to 2$ LO-pQCD (leading-order perturbative QCD) parton-parton cross sections [38]. Their total and differential cross sections in the parton evolution are computed by the Monte Carlo method. In the hadronization process, the parton can be hadronized by the Lund string fragmentation regime and/or the phenomenological coalescence model [38]. The final stage is the hadron rescattering process happening between the created hadrons until the hadronic freeze-out.

In the theoretical papers, the yield of nuclei or bound states usually is calculated in two steps: First, the nucleons are calculated by the transport model. Then, the nuclei are calculated by the phase-space coalescence model based on the Wigner function [39,40] or by the statistical model [41]. We proposed a DCPC model to calculate the yield of bound states after the transport model simulations.

From quantum statistical mechanics [42], one cannot precisely define both position $\vec{q} \equiv (x, y, z)$ and momentum $\vec{p} \equiv (p_x, p_y, p_z)$ of a particle in six-dimensional phase space because of the uncertainty principle, $\Delta\vec{q}\Delta\vec{p} \sim h^3$. One can only say this particle lies somewhere within a six-dimensional quantum box or that the state of volume of the $\Delta\vec{q}\Delta\vec{p}$ volume element in the six-dimensional phase space corresponds to a state of the particle. Therefore, one can estimate the yield of a single particle [42] by

$$Y_1 = \int_{E_a \leqslant H \leqslant E_b} \frac{d\vec{q}d\vec{p}}{h^3}, \tag{1}$$

where E_a, E_b, and H denote energy threshold and the energy function of the particle, respectively. Furthermore, the yield of a cluster consisting of N particles is defined as follows:

$$Y_N = \int \cdots \int_{E_a \leqslant H \leqslant E_b} \frac{d\vec{q}_1 d\vec{p}_1 \cdots d\vec{q}_N d\vec{p}_N}{(h)^{3N}}. \tag{2}$$

Therefore, the yieldof a $\Xi_c^+ K^-$ cluster in the DCPC model can be calculated by

$$Y_{\Omega_c^0} = \int \dots \int \delta_{12} \frac{d\vec{q}_1 d\vec{p}_1 d\vec{q}_2 d\vec{p}_2}{h^6}, \tag{3}$$

$$\delta_{12} = \begin{cases} 1 & \text{if } 1 \equiv \Xi_c^+, 2 \equiv K^-;\ m_{\Omega_c^0} - \Delta m \leqslant m_{\text{inv}} \leqslant m_{\Omega_c^0} + \Delta m,\ q_{12} \leqslant D_0 \\ 0 & \text{otherwise,} \end{cases} \tag{4}$$

where

$$m_{\text{inv}} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}. \tag{5}$$

The variables $\vec{q}$ and $\vec{p}$ are the coordinates and momentum of the particle in the center-of-mass frame system at the moment after hadron rescattering. The $q_{12} = |\vec{q}_1 - \vec{q}_2|$ is the distance between the two particles (Ξ_c^+ and K^-), $m_{\Omega_c^0}$ denotes the mass of Ω_c^0, and Δm refers to its mass uncertainty. E_1, E_2 and $\vec{p}_1, \vec{p}_2$ denote the energies and momenta of the two particles (Ξ_c^+ and K^-). Here, we refer to Ref. [43] and compare the bound state ($\Xi_c^+ K^-$) with the structure of deuteron (pn) to choose the parameter $D_0 = 1.74$ fm. In PACIAE, the hadron rescattering phase is modeled in a way that all the created hadrons are transported based on the same time step. So we assign the time at the end of the hadron transport stage to all the hadrons in the final state. In that sense, all the hadrons are transported to the same time for further Ω_c coalescence.

In Eq. (1), the energy function H satisfies $H^2 = (\vec{p}_1 + \vec{p}_2)^2 + m_{\text{inv}}^2$ and the energy threshold satisfies $E_{a,b}^2 = (\vec{p}_1 + \vec{p}_2)^2 + (m \mp \Delta m)^2$. Thus, the dynamic constraint condition $m - \Delta m \leqslant m_{\text{inv}} \leqslant m + \Delta m$ in Eq. (3) is equivalent to $E_a \leqslant H \leqslant E_b$ in Eq. (1). So, we may use the constraint condition $m - \Delta m \leqslant m_{\text{inv}} \leqslant m + \Delta m$, instead of $E_a \leqslant H \leqslant E_b$, to estimate the yield of particle clusters by the phase-space integral.

III. RESULTS

We first simulate the pp collision events using the PACIAE model at $\sqrt{s} = 7$ and 13 TeV. The capability of PACIAE to describe the generation of the final state particles in pp collisions was detailed in Refs. [35–37,44–48]. In order to obtain a suitable set of model parameters, the results on the yield

TABLE I. The yield of Ξ_c^+ and K^- computed by PACIAE in midrapidity pp collisions at $\sqrt{s} = 7$ TeV with $0.2 \leqslant p_t \leqslant 6$ GeV/c and comparison with experimental data [49–53].

Particles	PACIAE	Experimental data
K^-	0.286	0.286 ± 0.016
Ξ_c^+	7.40×10^{-5}	$(7.47 \pm 0.14) \times 10^{-5}$

TABLE II. The total yield of five resonant Ω_c^0 states varies with Δm from 0.4 to 8 MeV in pp collisions at $\sqrt{s} = 7$ and 13 TeV with $|y| < 6$, $0 < p_T < 20$ GeV/c, computed by Ω_c^0 states decaying to $\Xi_c^+ K^-$ bound states using the PACIAE+DCPC model.

c.m. energy	Δm (MeV)	0.4	0.55	1.0	1.75	2.25	4.35	8.0
	$\Omega_c(3000)^0$	2.03×10^{-7}	2.69×10^{-7}	5.10×10^{-7}	8.83×10^{-7}	1.16×10^{-6}	2.24×10^{-6}	4.14×10^{-6}
	$\Omega_c(3050)^0$	2.90×10^{-7}	4.0×10^{-7}	7.22×10^{-7}	1.28×10^{-6}	1.62×10^{-6}	3.12×10^{-6}	5.71×10^{-6}
7 TeV	$\Omega_c(3066)^0$	3.15×10^{-7}	4.37×10^{-7}	7.65×10^{-7}	1.32×10^{-6}	1.72×10^{-6}	3.32×10^{-6}	6.06×10^{-6}
	$\Omega_c(3090)^0$	3.17×10^{-7}	4.37×10^{-7}	8.28×10^{-7}	1.46×10^{-6}	1.88×10^{-6}	3.58×10^{-6}	6.43×10^{-6}
	$\Omega_c(3119)^0$	3.66×10^{-7}	4.88×10^{-7}	8.54×10^{-7}	1.48×10^{-6}	1.92×10^{-6}	3.70×10^{-6}	6.79×10^{-6}
	$\Omega_c(3000)^0$	2.20×10^{-7}	2.95×10^{-7}	5.44×10^{-7}	9.61×10^{-7}	1.24×10^{-6}	2.44×10^{-6}	4.48×10^{-6}
	$\Omega_c(3050)^0$	3.21×10^{-7}	4.52×10^{-7}	7.98×10^{-7}	1.38×10^{-6}	1.78×10^{-6}	3.35×10^{-6}	6.10×10^{-6}
13 TeV	$\Omega_c(3066)^0$	3.48×10^{-7}	4.52×10^{-7}	8.15×10^{-7}	1.41×10^{-6}	1.82×10^{-6}	3.57×10^{-6}	6.53×10^{-6}
	$\Omega_c(3090)^0$	3.48×10^{-7}	4.68×10^{-7}	8.97×10^{-7}	1.52×10^{-6}	1.96×10^{-6}	3.70×10^{-6}	6.84×10^{-6}
	$\Omega_c(3119)^0$	3.70×10^{-7}	5.28×10^{-7}	9.57×10^{-7}	1.61×10^{-6}	2.06×10^{-6}	3.95×10^{-6}	7.35×10^{-6}

of Ξ_c^+ and K^- were roughly fitted to the LHCb data in pp collisions at $\sqrt{s} = 7$ TeV [49–53].

The simulation results with PACIAE agree well with the experimental results, as shown in Table I. It should be said that the yield of Ξ_c^+ for the experimental data in Table I is calculated by the ratio of the cross sections of Ξ_c^0 to the D_0 meson and the ratio of Ξ_c^0 to Ξ_c^+ according to the data in Refs. [50–53].

In this work, we assume that the narrow excited states [$\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$] are the $\Xi_c^+ K^-$ bound state generated through $\Omega_c^0 \to \Xi_c^+ K^-$, which is produced during the hadron evolution period. We use the PACIAE transport model to generate about two billion events of pp collision at $\sqrt{s} = 7$ and 13 TeV with $|y| < 6$, $0 < p_T < 20$ GeV/c, and input the final state particles Ξ_c^+ and K^- into the DCPC model to construct the clusters of $\Xi_c^+ K^-$, as in Eqs. (3) and (4). The results are shown in Table II and Fig. 1.

From Table II and Fig. 1, one can see the following:

(i) The yield of the five excited resonant Ω_c^0 states from the PACIAE+DCPC model increase with parameter Δm from 0.4 to 8 MeV. The values are on the order of 10^{-7} to 10^{-6}. There is a significant parameter dependence of the yield of Ω_c^0 on the uncertainty Δm; i.e, $\ln Y \sim \ln \Delta m$ presents a linear increasing distribution. The yield of Ω_c^0 in the pp collision of $\sqrt{s} = 13$ TeV is more than the yield of it at $\sqrt{s} = 7$ TeV.

(ii) When reaction energy increases from 7 to 13 TeV the yield of five resonant Ω_c^0 states from PACIAE+DCPC simulations increases ≈6%. The yield of Ω_c^0 increases with the increase of its mass at a given width of parameter Δm. This may be attributed to the stronger increase in available phase space for the heavier bound states $\Omega_c^0(\Xi_c K)$ production than for the lighter bound states production.

(iii) If we take half of the decay width of mass for excited Ω_c^0 states measured in the LHCb experiment [32,47,48] as the Δm parameter, i.e, $\Delta m = \Gamma/2$, then we may predict the total yields of the five new narrow excited Ω_c^0 states of $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$ in pp collisions at $\sqrt{s} = 7$ and 13 TeV with $|y| < 6$, $0 < p_T < 20$ GeV/c, as shown in Table III. However, the $\Xi_c^0 \bar{K}^0$ can also form Ω_c^0. If the decay from Ω_c^0 to $\Xi_c^0 \bar{K}^0$ is taken into account, this would increase the Ω_c^0 yield.

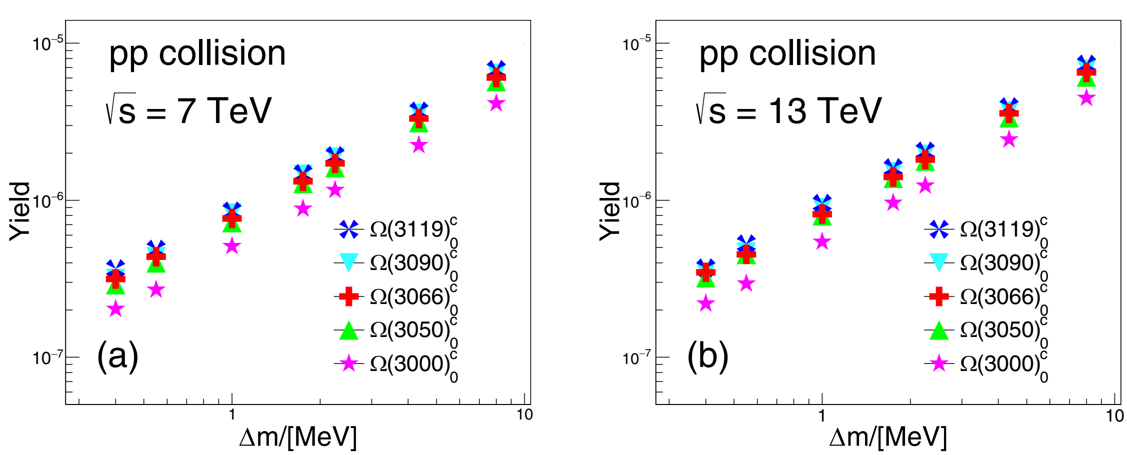

FIG. 1. Logarithmic distribution of the yields of the five narrow excited resonant Ω_c^0 states, as a function of Δm, in pp collisions with $|y| < 6$, $0 < p_T < 20$ GeV/c, at (a) $\sqrt{s} = 7$ TeV and (b) $\sqrt{s} = 13$ TeV. The data are calculated using the PACIAE+DCPC model as Ω_c^0 states decaying to $\Xi_c^+ K^-$ bound states.

TABLE III. The total yields of the five excited resonant Ω_c^0 states in pp collision at $\sqrt{s} = 7$ and 13 TeV, computed by the PACIAE+DCPC model, where $\Delta m = \Gamma/2$ [32,47,48].

Resonance	Δm (MeV)	Yield (7 TeV)	Yield (13 TeV)
$\Omega_c(3000)^0$	2.25	1.16×10^{-6}	1.24×10^{-6}
$\Omega_c(3050)^0$	0.40	2.90×10^{-7}	3.21×10^{-7}
$\Omega_c(3066)^0$	1.75	3.32×10^{-6}	3.57×10^{-6}
$\Omega_c(3090)^0$	4.35	1.46×10^{-6}	1.52×10^{-6}
$\Omega_c(3119)^0$	0.55	4.88×10^{-7}	5.28×10^{-7}

Figure 2 shows the transverse momentum p_T distributions of the five excited resonant Ω_c^0 states of $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$), and $\Omega_c(3119)^0$ in pp collisions at $\sqrt{s} = 7$ and 13 TeV. In each panel, the red dashed line and the blue solid line refer to the distribution in pp collisions at $\sqrt{s} = 7$ and 13 TeV, respectively. The peak of p_T distributions is about 1.35 GeV. It can be seen from this figure that all the transverse momentum distribution characteristics of the produced five excited resonant Ω_c^0 states are similar. These normalized p_T distributions for all five excited resonant Ω_c^0 states are the same within error at the same energy. But the transverse momentum distribution characteristics of the produced excited resonant Ω_c^0 states of $\sqrt{s} = 13$ TeV are slightly wider than that of 7 TeV. The strong fluctuation, which appears in Figs. 2(b) and 2(e), indicates that the two billion events are not enough for the p_T distribution of these excited resonant Ω_c^0 states.

We also predicted the rapidity distribution of excited resonant Ω_c^0 states of $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$ in pp collisions at $\sqrt{s} = 7$ and 13 TeV, which is symmetric distribution in the range of -6 to 6, shown in Fig. 3. From this figure, one can see that the global features of rapidity distributions are similar to the different excited resonant Ω_c^0 state particles. These normalized rapidity distributions for all five excited resonant Ω_c^0 states are the same within error at the same energy.

IV. CONCLUSIONS

In this paper, we simulate the generation of final state particles in pp collisions at $\sqrt{s} = 7$ and 13 TeV using the PACIAE model, and study the production of strange particles Ξ_c^+ and K^-, which are consistent with the data of LHCb. Then the Ξ_c^+ and K^- are input into the DCPC model to construct the clusters of $\Xi_c^+K^-$, and the production and the characteristics of the five narrow excited states of $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$ are studied, based on the Ω_c^0 states decaying to the $\Xi_c^+K^-$ bound state. It is found that the yield of these excited resonant particles increases as the reaction energy, the mass uncertainty parameters Δm, and the mass of excited resonant Ω_c^0 increases. We take half of the width of the mass decay measured in LHCb as mass uncertainty parameters Δm, it is predicted that the yields of the five narrow excited resonant states of $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$ computed using the PACIAE+DCPC model in pp collisions are 1.16×10^{-6}, 0.29×10^{-6}, 3.32×10^{-6}, 1.46×10^{-6}, and 0.488×10^{-6} at $\sqrt{s} = 7$ TeV, and 1.24×10^{-6}, 0.321×10^{-6}, 3.57×10^{-6}, 1.52×10^{-6}, and 0.528×10^{-6} at $\sqrt{s} = 13$ TeV, respectively. The transverse momentum

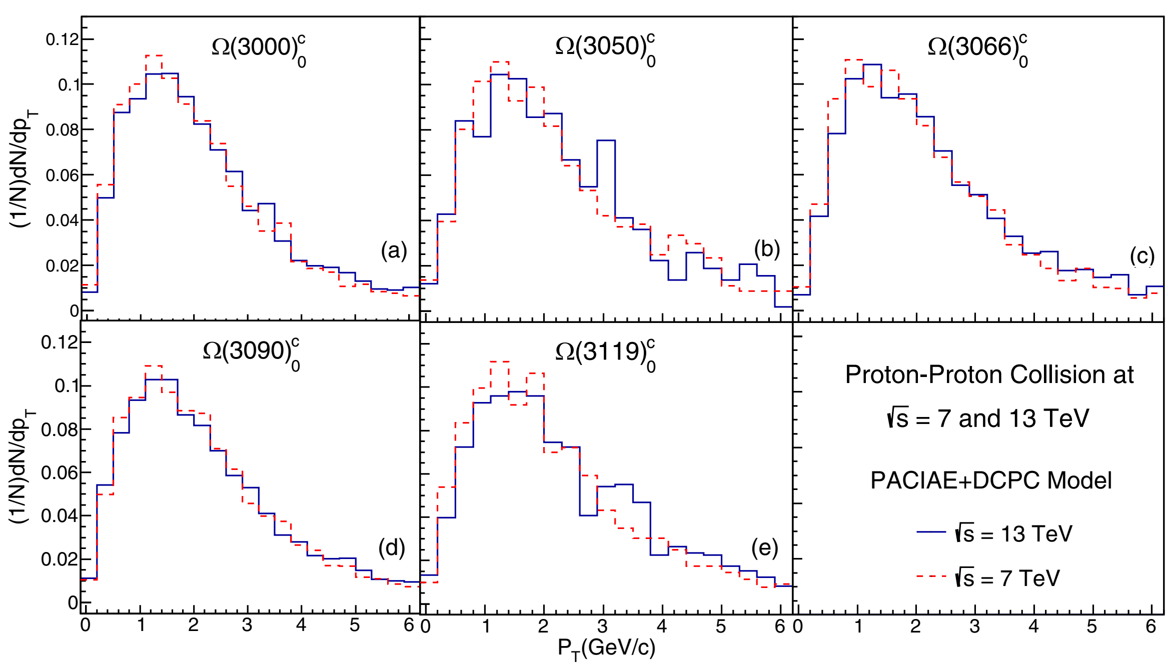

FIG. 2. Transverse momentum distributions of the five excited resonant Ω_c^0 states by the decay from $\Omega_c^0 \rightarrow \Xi_c^+K^-$ in pp collisions at $\sqrt{s} = 7$ (red dashed histograms) and 13 TeV (blue solid histograms) calculated by the final hadronic states in the PACIAE+DCPC model simulations with $\Delta m = \Gamma/2$, respectively.

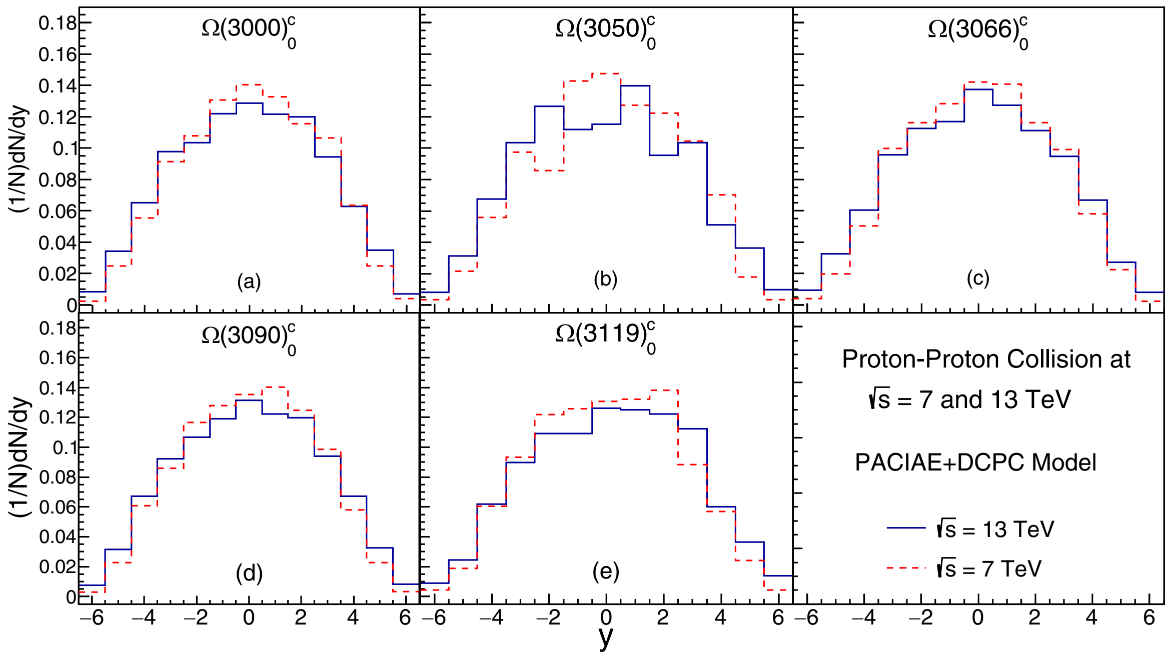

FIG. 3. Similar to Fig. 2, but for the rapidity distribution.

distribution and rapidity distribution of the five different excited resonant Ω_c^0 states in pp collisions at $\sqrt{s} = 7$ and 13 TeV were also predicted according to the PACIAE+DCPC model simulations.

The study of the new narrow excited Ω_c^0 states production in pp collisions is under way. One may expect more diverse results in pp or nucleus-nucleus collisions.

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[1] L. B. Okun, The theory of weak interaction, in *Proceedings, 11th International Conference, ICHEP'62, 4-11 July 1962* (Geneva, Switzerland, 1962), pp. 845–866.
[2] M. Gell-Mann, A schematic model of baryons and mesons, Phys. Lett. **8**, 214 (1964).
[3] G. Zweig, An SU(3) model for strong interaction symmetry and its breaking, Version 1 CERN-TH-401 (CERN, Geneva, 1964); G. Zweig, An SU3 model for strong interaction symmetry and its breaking; Version 2, CERN-TH-412 (1964).
[4] M. Gell-Mann, *The Eightfold Way: A Theory of Strong Interaction Symmetry* (Benjamin, New York, 1961).
[5] Y. Ne'eman, Derivation of strong interactions from a gauge invariance, Nucl. Phys. **26**, 222 (1961).
[6] V. E. Barnes *et al.*, Observation of a Hyperon with Strangeness Minus Three, Phys. Rev. Lett. **12**, 204 (1964).
[7] S. Capstick and N. Isgur, Baryons in a relativized quark model with chromodynamics, Phys. Rev. D **34**, 2809 (1986).
[8] R. Roncaglia, D. B. Lichtenberg, and E. Predazzi, Predicting the masses of baryons containing one or two heavy quarks, Phys. Rev. D **52**, 1722 (1995).
[9] E. E. Jenkins, Heavy baryon masses in the $1/m_Q$ and $1/N_c$ expansions, Phys. Rev. D **54**, 4515 (1996).
[10] D. Ebert, R. N. Faustov, and V. O. Galkin, Masses of excited heavy baryons in the relativistic quark model, Phys. Lett. B **659**, 612 (2008).
[11] X. H. Zhong and Q. Zhao, Charmed baryon strong decays in a chiral quark model, Phys. Rev. D **77**, 074008 (2008).
[12] L. A. Copley, N. Isgur, and G. Karl, Charmed baryons in a quark model with hyperfine interactions, Phys. Rev. D **20**, 768 (1979).
[13] M. Karliner, B. Keren-Zur, H. J. Lipkin, and J. L. Rosner, The quark model and b baryons, Ann. Phys. (Amsterdam) **324**, 2 (2009).
[14] S.-H. Kim, A. Hosaka, H.-C. Kim, H. Noumi, and K. Shirotori, Pion induced reactions for charmed baryons, Prog. Theor. Exp. Phys. **2014**, 103D01 (2014).
[15] W. Roberts and M. Pervin, Heavy baryons in a quark model, Int. J. Mod. Phys. A **23**, 2817 (2008).
[16] H. Garcilazo, J. Vijande, and A. Valcarce, Faddeev study of heavy baryon spectroscopy, J. Phys. G **34**, 961 (2007).
[17] P. G. Ortega, D. R. Entem, and F. Fernandez, Quark model description of the $\Lambda_c(2940)^+$ as a molecular D_N state and the possible existence of the $\Lambda_b(6248)^+$, Phys. Lett. B **718**, 1381 (2013).
[18] C. Garcia-Recio, J. Nieves, O. Romanets, L. L. Salcedo, and L. Tolos, Odd parity bottom-flavored baryon resonances, Phys. Rev. D **87**, 034032 (2013).
[19] W. H. Liang, C. W. Xiao, and E. Oset, Baryon states with open beauty in the extended local hidden gauge approach, Phys. Rev. D **89**, 054023 (2014).

[20] J. X. Lu, Y. Zhou, H. X. Chen, J. J. Xie, and L. S. Geng, Dynamically generated $J^P = 1/2^-(3/2^-)$ singly charmed and bottom heavy baryons, Phys. Rev. D. **92**, 014036 (2015).
[21] K. C. Bowler, R. D. Kenway, O. Oliveira, D. G. Richards, P. Ueberholz, L. Lellouch, J. Nieves, C. T. Sachrajda, N. Stella, and H. Wittig (UKQCD Collaboration), Heavy baryon spectroscopy from the lattice, Phys. Rev. D **54**, 3619 (1996).
[22] T. Burch, C. Hagen, C. B. Lang, M. Limmer, and A. Schafer, Excitations of single-beauty hadrons, Phys. Rev. D **79**, 014504 (2009).
[23] K. A. Olive *et al.* (Particle Data Group Collaboration), Review of particle physics, Chin. Phys. C **38**, 090001 (2014).
[24] H. Albrecht *et al.* (ARGUS Collaboration), Observation of a new charmed baryon, Phys. Lett. B **317**, 227 (1993).
[25] P. L. Frabetti *et al.* (E687 Collaboration), An Observation of an Excited State of the Λ_c^+ Baryon, Phys. Rev. Lett. **72**, 961 (1994).
[26] K. W. Edwards *et al.* (CLEO Collaboration), Observation of Excited Baryon States Decaying to $\Lambda_c^+\pi^+\pi^-$, Phys. Rev. Lett. **74**, 3331 (1995).
[27] J. P. Alexander *et al.* (CLEO Collaboration), Evidence of New States Decaying into $\Xi_c^*\pi$, Phys. Rev. Lett. **83**, 3390 (1999).
[28] R. Mizuk *et al.* (BELLE Collaboration), Observation of an Isotriplet of Excited Charmed Baryons Decaying to $\Lambda_c\pi$, Phys. Rev. Lett. **94**, 122002 (2005).
[29] B. Aubert *et al.* (BABAR Collaboration), Measurements of $\beta(\overline{B}^0 \to \Lambda_c^+\overline{P})$ and $\beta(B^- \to \Lambda_c^+\overline{P}\pi^-)$ and studies of $\Lambda_c^+\pi^-$ resonances, Phys. Rev. D **78**, 112003 (2008).
[30] R. Chistov *et al.* (BELLE Collaboration), Observation of New States Decaying into $\Lambda_c^+K^-\pi^+$ and $\Lambda_c^+K_s^0\pi^-$, Phys. Rev. Lett. **97**, 162001 (2006).
[31] B. Aubert *et al.* (BABAR Collaboration), A study of excited charm-strange baryons with evidence for new baryons $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$, Phys. Rev. D **77**, 012002 (2008).
[32] R. Aaij *et al.* (LHCb Collaboration), Observation of Five New Narrow Ω_c^0 States Decaying to $\Xi_c^+K^-$, Phys. Rev. Lett. **118**, 182001 (2017).
[33] B. Singh *et al.* (PANDA Collaboration), Feasibility studies of time-like proton electromagnetic form factors at PANDA at FAIR, Eur. Phys. J. A **52**, 325 (2016).
[34] B.-H. Sa, D.-M. Zhou, Y.-L. Yan, X.-M. Li, S.-Q. Feng, B.-G. Dong, and X. Cai , PACIAE 2.0: An updated parton and hadron cascade model (program) for the relativistic nuclear collisions, Comput. Phys. Commun. **183**, 333 (2012).
[35] Y.-L. Yan, G. Chen, X.-M. Li, D.-M. Zhou, M.-J. Wang, S.-Y. Hu, L. Ye, and B.-H. Sa, Predictions for the production of light nuclei in *pp* collisions at $\sqrt{s} = 7$ and 14 TeV, Phys. Rev. C **85**, 024907 (2012).
[36] G. Chen, Y.-L. Yan, D.-S. Li, D.-M. Zhou, M.-J. Wang, B.-G. Dong, and B.-H. Sa, Antimatter production in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. C **86**, 054910 (2012).
[37] G. Chen, H. Chen, J. Wu, D. S. Li, and M. J. Wang, Centrality dependence of light (anti)nuclei and (anti)hypertriton production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. C **88**, 034908 (2013).
[38] T. Sjostrand, S. Mrenna, and P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026.
[39] R. Mattiello, H. Sorge, H. Stöcker, and W. Greiner, Nuclear clusters as a probe for expansion flow in heavy ion reactions at $(10-15)A$ GeV, Phys. Rev.C **55**, 1443 (1997).
[40] S. Zhang, J. H. Chen, H. Crawford, D. Keane, Y. G. Ma, and Z. B. Xu, Searching for onset of deconfinement via hypernuclei and baryon-strangeness correlations, Phys. Lett. B **684**, 224 (2010).
[41] A. Andronic, P. Braun-Munzinger, J. Stachel, and H. Stöcker, Production of light nuclei, hypernuclei and their antiparticles in relativistic nuclear collisions, Phys. Lett. B **697**, 203 (2011).
[42] K. Stowe, *An Introduction to Thermodynamics and Statistical Mechanics* (Cambridge University Press, Cambridge, U.K., 2007); R. Kubo, H. Ichimura, T. Usui, and N. Hashitsume, *Statistical Mechanics: An Advanced Course with Problems and Solutions* (North-Holland, Amsterdam, 1965).
[43] T. W. Wu, M. Z. Liu, L. S. Geng, E. Hiyama, and M. P. Valderrama, DK, DDK, and DDDK molecules-understanding the nature of the $D_{s0}^*(2317)$, Phys. Rev. D **100**, 034029 (2019).
[44] G. Chen, H. Chen, J. L. Wang, and Z.-Y. Chen, Scaling properties of light (anti)nuclei and (anti)hypertriton production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, J. Phys. G: Nucl. Part. Phys. **41**, 115102 (2014).
[45] Z. J. Dong, Q. Y. Wang, G. Chen, Z.-L. She, Y.-L. Yan, F.-X. Liu, D.-M. Zhou, and B.-H. Sa, Energy dependence of light (anti)nuclei and (anti)hypertriton production in the Au-Au collision from $\sqrt{s_{NN}} = 11.5$ to 5020 GeV, Eur. Phys. J. A **54**, 144 (2018).
[46] Z. L. She, G. Chen, H.-G. Xu, T.-T. Zeng, and D.-K. Li, Centrality dependence of light (anti)nuclei and (anti)hypertriton production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Eur. Phys. J. A **52**, 93 (2016).
[47] P. Sittiketkorn, K. Tomuang, P. Srisawad, A. Limphirat, C. Herold, Y.-L. Yan, G. Chen, D.-M. Zhou, C. Kobdaj, and Y. Yan, Production of K^-P and $K^+\overline{P}$ bound states in *pp* collisions and interpretation of the $\Lambda(1405)$ resonance, Phys. Rev. C **96**, 064002 (2017).
[48] K. Tomuang, P. Sittiketkorn, P. Srisawad, A. Limphirat, Y.-L. Yan, G. Chen, D.-M. Zhou, C. Kobdaj, and Y. Yan, Production of K^-pp and $K^+\overline{pp}$ in *pp* collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. C **99**, 034002 (2019).
[49] J. Adam *et al.* (ALICE Collaboration), Measurement of pion, kaon and proton production in proton-proton collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C **75**, 226 (2015).
[50] S. Acharya *et al.* (ALICE Collaboration), Measurement of D-meson production at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C **77**, 550 (2017).
[51] S. Acharya *et al.* (ALICE Collaboration), First measurement of Ξ_c^0 production in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B **781**, 8 (2018).
[52] R. Aaij *et al.* (LHCb Collaboration), Precision measurement of the Λ_c^+, Ξ_c^+, Ξ_c^0 baryon lifetimes, Phys. Rev. D **100**, 032001 (2019)
[53] M. Tanabashi *et al.* (Particle Data Group Collaboration), Review of particle physics, Phys. Rev. D **98**, 030001 (2018).