The study of exotic state $Z_c^{±}(3900)$ decaying to $J/ψπ^±$

in the $pp$ collisions at $\sqrt{s} = 1.96$, 7, and 13 TeV

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A dynamically constrained phase-space coalescence model plus PACIAE model was used to predict the exotic resonant state $Z_c^±(3900)$ yield, transverse momentum distribution, and the rapidity distribution with $|y| < 6$ and $p_T < 10$ GeV/c in $pp$ collisions at $\sqrt{s} = 1.96, 7$ and 13 TeV, respectively. The yield of the $Z_c^±(3900)$ is estimated to be around $10^{-6}$ to $10^{-5}$. We also present the energy dependence of the transverse momentum distributions and rapidity distributions for $Z_c^+(3900)$ and $Z_c^-(3900)$. The production of $Z_c^+(3900)$ and its anti-particle $Z_c^-(3900)$ is found to be quite similar to each other.

Key-words: $Z_c^±(3900)$, PACIAE+DCPC model, exotic state hadrons

I. INTRODUCTION

Particle physicists believe that quarks are the building blocks for the matter in our viable universe. Due to the color confinement of strong interaction, quarks are bounded in the color neutral hadrons with different configurations. Mesons consisting of quark antiquark pairs and baryons made of three quarks are the most common hadrons observed in high energy collision experiments. However, other unconventional configurations with more quarks or gluons are also allowed to exist in the quark model framework, for example, the multi-quark state $[1−3]$ composed of 4 or more quarks, the molecular state $[4−6]$ of hadrons bound together by hadrons and hadrons, the hybrid state $[7, 8]$ composed of quarks and gluons, and the gluon-ball composed of gluons. These unconventional hadrons are usually called the exotic state hadrons.

In 2013, the BESIII $[9−11]$ analyzed the invariant mass spectrum of $π^±J/ψ$ in the process $e^+e^- → π^±π^−J/ψ$ at $\sqrt{s} = 4.26$ GeV, and found there was a resonance structure around 3.9 GeV/$c^2$, whose decay width is $46 ± 10 \pm 20$ MeV. BESIII named it $Z_c^{±}(3900)$ $[12−14]$, and in the later experiment, its spin and parity were found to be $J^{PC} = 1^+$ [15]. This observation has also been confirmed by Belle and CELIO-c experiments $[16, 17]$.

It is speculated based on the experimental data that $Z_c^{±}(3900)$ consists of at least four quarks: $c\bar{u}d\bar{u}$ or $c\bar{u}d\bar{d}$, and can either be a four-quark state $[9, 16]$ or a weakly bounded molecular state considering that the mass of $Z_c^{±}(3900)$ is slightly higher than the open-charm $D^+\bar{D}$ threshold.

The D0 experiment $[18−20]$ speculates that $Z_c^{±}(3900)$ might be produced by these two processes $H_b → Y(4260) + h$ and $Y(4260) → Z_c^{±}(3900)π^±$, where $h$ is any particle other than $Y(4260)$ that produced by the decay of $b$-flavored hadrons $[21]$. By studying the data collected in the $pp$ collision, the D0 experimental group found the resonance state $Z_c^±(3900)$ in the invariant mass spectrum of $π^±J/ψ$, and confirmed $[22]$ the correlation between the resonance state and $J/ψπ^±π^−$ with the invariant mass within the range of $4.2 - 4.7$ GeV, in which $J/ψ$ $[23, 24]$ was derived from the $b$-flavored hadron decay. This shows that there is an intermediate state in the decay of $b$-flavored hadron, and then it decays into a resonant state $Z_c^±(3900)$. These observations suggest a more exclusive on the property of the exotic hadrons can be of great help for us to understand the formation of exotic hadron states and the nature of the strong force.

In this paper, we treat the $Z_c^±(3900)$ as a molecular state consisting of $J/ψπ^±$ and provide a systematic study on its production in $pp$ collisions based on a Monte Carlo simulation approach. First, event samples of multiparticle final states in $pp$ collisions at $\sqrt{s} = 1.96, 7$ and 13 TeV are generated using the parton and hadron cascade model (PACIAE) $[25]$, including the hadrons of $J/ψπ^±π^−$. Then the bound states $J/ψπ^±π^−$ are produced using a dynamically constrained phase space coalescence model (DCPC) $[26]$ to study $Z_c^{±}(3900)$.

II. THE PACIAE AND DCPC MODEL

The PACIAE model $[25]$, also known as the parton and hadron cascade model, which is based on PYTHIA model $[27]$, is a theoretical model to describe various high-energy collisions. In this paper, the PACIAE model was used to simulate the $pp$ collision. The PACIAE model divides high-energy collisions into four stages: parton initiation, parton rescattering, hadronization, and hadron rescattering.

In the first stage, the initial parton conditions are obtained by breaking down the PYTHIA strings created in hard scattering and parton shower into quarks and glu-
ons. After that, further parton-parton rescatterings can happen in the quark-gluon system to model the evolution of the deconfined quark matter state. A $K$ factor is allowed to account for higher order effects in hard scattering and parton-parton rescatterings. With all parton rescatterings finished, the final state partons are converted to hadrons via the Lund string fragmentation model [27] or the coalescence model [25]. The last stage is hadron rescattering, and the method of two-body collision [28] is used to rescat the hadronic matter until hadronic freeze-out. We refer to [25] for more details.

In this paper, the yield of nuclei or bound states is calculated in two steps: First, the hadrons are calculated by the PACIAE model. Then, the bound states or exotic state are calculated by the DCPC model, which has been successfully applied to calculate the yield of particles in Pb-Pb [29], Au-Au [26, 30–32] and $pp$ collisions [33].

According to quantum statistical mechanics [34], the yield of particles can be estimated by uncertain principle. The single particle’s yield can be calculated in the following integral:

$$ Y_1 = \int \frac{d\vec{q}d\vec{p}}{h^3}. $$

where $H$ is the Hamiltonian and $E$ is the energy of the particle. In the same way, the yield of a cluster consisting of $N$ particles can be calculated as following:

$$ Y_N = \int \cdots \int \frac{d\vec{q}_1d\vec{p}_1 \cdots d\vec{q}_N d\vec{p}_N}{h^{3N}}. $$

Thus, the yield of a $J/\psi$ cluster in the DCPC model can be calculated by

$$ Y_{Z^\pm}(3900) = \int \cdots \int \delta_{12} \frac{d\vec{q}_{12}d\vec{p}_{12}d\vec{q}_{J/\psi}d\vec{p}_{J/\psi}}{h^6}. $$

$$ \delta_{12} = \begin{cases} 1 & \text{if } 1 \equiv \pi^\pm, 2 \equiv J/\psi; \\ m_0 - \Delta m \leq m_{\text{inv}} \leq m_0 + \Delta m; \\ \bar{q}_{12} \leq R_0; \\ 0 & \text{otherwise} \end{cases} $$

$$ m_{\text{inv}} = (E_{\pi^\pm} + E_{J/\psi})^2 + (p_{\pi^\pm} + p_{J/\psi})^2)^{1/2} $$

where $m_0$ represent the rest mass of $Z^\pm(3900)$, $m_0 = 3887.2$ MeV/c$^2$ according to PDG [35], and $\Delta m$ refers to its mass uncertainty. $R_0$ is the effective radius of the possible combination of $\pi^\pm$ and $J/\psi$ to form $Z^\pm(3900)$, and $|\bar{q}_{12}| = |\bar{q}_1 - \bar{q}_2|$ represent the distance between $\pi^\pm$ and $J/\psi$.

### III. Calculations and Results

Firstly we use the PACIAE model to produce the final state particles. The model parameters were fixed on the default values given in the PYTHIA model, except for the $K$ factor and the parameters of $\text{parj}(1), \text{parj}(2),$ and $\text{parj}(3)$ which are determined by fitting to the LHC data in $pp$ collisions at $\sqrt{s} = 7$ TeV. The yields of $\pi^\pm$ and $J/\psi$ are shown in Table I, where the yields of particles are calculated with $|y| < 0.5, 0.1 < p_T < 3$ GeV/c for $\pi^\pm$ and $2.0 < y < 4.5, 0 < p_T < 14$ GeV/c for $J/\psi$, respectively. Here, $\text{parj}(1)$ is the suppression of diquark-antidiquark pair production compared with the quark-antiquark pair production, $\text{parj}(2)$ is the suppression of strange quark pair production compared with up (down) quark pair production, $\text{parj}(3)$ is the extra suppression of strange diquark production compared with the normal suppression of a strange quark. We choose $\text{parj}(1) = 0.10, \text{parj}(2) = 0.20, \text{parj}(3) = 0.90$. A comparison to the experimental data [36, 37] is listed in Table I. It can be seen from Table I that the PACIAE model results agree with the LHC data within uncertainties.

| Particle | LHC [36, 37] | PACIAE |
|----------|--------------|--------|
| $J/\psi$ | $(1.60 \pm 0.01 \pm 0.023) \times 10^{-5}$ | $(1.60 \pm 0.03) \times 10^{-5}$ |
| $\pi^+$  | $2.26 \pm 0.10$ | $2.26 \pm 0.01$ |
| $\pi^-$  | $2.23 \pm 0.10$ | $2.25 \pm 0.03$ |

Then, the event samples of multiparticle final states are generated by PACIAE model in $pp$ collisions at $\sqrt{s} = 1.96, 7, 13$ TeV with $|y| < 6, 0 < p_T < 10$ GeV/c, respectively. Next, we input these final state particles $J/\psi$ and $\pi^\pm$ into DCPC model to construct the clusters of $J/\psi\pi^\pm$, the molecular state of the $Z^\pm(3900)$. Here, we assume that the $Z^\pm(3900)$ are generated through the combination of $J/\psi$ and $\pi^\pm$ during the hadron evolution period. It should be noted that the production of $J/\psi$ can be divided into three types in $pp$ collisions [38–40]: the first is direct production, the second is produced by the decay of heavy charmonium, and the third is produced by the decay of $b$ hadrons. $J/\psi$ from $b$ decay and $\pi^\pm$ are involved in the reconstruction of $Z^\pm(3900)$.

Table II shows the yield of exotic state $Z^+_c(3900)$ and $Z^-_c(3900)$ in $pp$ collision at $\sqrt{s} = 1.96, 7$ and 13 TeV with parameter $\Delta m$ from 8 MeV to 40 MeV when the fixed radius parameter is 1.74 fm. In Fig.1(a), the distribution of $Z^+_c(3900)$ dependent on $\Delta m$ is also provided. From the Tab.II, we can see that the yield of the exotic $Z^+_c(3900)$ states computed by PACIAE+DCPC model increases with parameter $\Delta m$ from $10^{-6}$ to $10^{-5}$ in a linear way. When the center of mass energy increases from 1.96 TeV to 13 TeV, the yield of exotic $Z^+_c(3900)$ states calculated by PACIAE+DCPC increases.

Similarly, Table III presents the yield of exotic state $Z^+_c(3900)$ and $Z^-_c(3900)$ in $pp$ collision at $\sqrt{s} = 1.96, 7$ and 13 TeV with parameter $R$ from 1.0 fm to 2.75 fm.
one can see that the yield of the exotic
resonant states $Z_{+}^{*}(3900)$ in pp collisions at $\sqrt{s} = 1.96, 7, 13$ TeV, respectively. (a) as a function of mass uncertainty $\Delta m$, (b) as a function of radius parameter $R_0$. The data are calculated using PACIE+DCPC model as $Z_{+}^{*}(3900)$ states decaying to $J/\psi \pi^\pm$ bound states.

**TABLE II.** The yields ($10^{-6}$) of exotic resonant states $Z_{+}^{*}(3900)$ and $Z_{-}^{*}(3900)$ varies with parameter $\Delta m$ from 8 MeV to 40 MeV in pp collision at $\sqrt{s} = 1.96, 7$ and 13 TeV, computed by $Z_{+}^{*}(3900)$ states decaying to $J/\psi \pi^\pm$ bound states using PACIE+DCPC model with the value of radius parameter $R_0 = 1.74$ fm.

| $\Delta m$ (MeV) | 1.96 TeV | 7 TeV | 13 TeV |
|------------------|---------|-------|--------|
| 8                | $0.57 \pm 0.03$ | $0.55 \pm 0.03$ | $2.10 \pm 0.01$ | $2.02 \pm 0.05$ | $3.59 \pm 0.09$ | $3.51 \pm 0.08$ |
| 10               | $0.72 \pm 0.02$ | $0.66 \pm 0.03$ | $2.63 \pm 0.03$ | $2.54 \pm 0.07$ | $4.46 \pm 0.11$ | $4.38 \pm 0.09$ |
| 14.1             | $0.99 \pm 0.07$ | $0.93 \pm 0.05$ | $3.63 \pm 0.05$ | $3.58 \pm 0.05$ | $6.19 \pm 0.14$ | $6.11 \pm 0.05$ |
| 23               | $1.61 \pm 0.10$ | $1.51 \pm 0.02$ | $6.02 \pm 0.10$ | $5.92 \pm 0.20$ | $10.13 \pm 0.19$ | $9.95 \pm 0.10$ |
| 28               | $1.97 \pm 0.11$ | $1.87 \pm 0.04$ | $7.29 \pm 0.10$ | $7.21 \pm 0.16$ | $12.32 \pm 0.27$ | $12.16 \pm 0.10$ |
| 32               | $2.24 \pm 0.09$ | $2.14 \pm 0.05$ | $8.30 \pm 0.07$ | $8.26 \pm 0.15$ | $14.06 \pm 0.32$ | $13.94 \pm 0.18$ |
| 37               | $2.56 \pm 0.13$ | $2.48 \pm 0.06$ | $9.58 \pm 0.08$ | $9.50 \pm 0.11$ | $16.21 \pm 0.40$ | $16.13 \pm 0.13$ |
| 40               | $2.78 \pm 0.11$ | $2.66 \pm 0.08$ | $10.38 \pm 0.12$ | $10.25 \pm 0.10$ | $17.52 \pm 0.39$ | $17.40 \pm 0.09$ |

**TABLE III.** The yields ($10^{-6}$) of exotic resonant states $Z_{+}^{*}(3900)$ and $Z_{-}^{*}(3900)$ varies with parameter radius from 1 fm to 2.75 fm in pp collision at $\sqrt{s} = 1.96, 7$ and 13 TeV, computed by $Z_{+}^{*}(3900)$ states decaying to $J/\psi \pi^\pm$ bound states using PACIE+DCPC model with the value of parameter $\Delta m = 14.1$ MeV.

| $R_0$ (fm) | 1.96 TeV | 7 TeV | 13 TeV |
|------------|---------|-------|--------|
| 1.00       | $0.27 \pm 0.04$ | $0.23 \pm 0.02$ | $0.94 \pm 0.02$ | $0.92 \pm 0.03$ | $1.66 \pm 0.05$ | $1.65 \pm 0.02$ |
| 1.25       | $0.48 \pm 0.01$ | $0.47 \pm 0.02$ | $1.70 \pm 0.02$ | $1.71 \pm 0.04$ | $2.93 \pm 0.06$ | $2.99 \pm 0.04$ |
| 1.50       | $0.75 \pm 0.02$ | $0.70 \pm 0.03$ | $2.63 \pm 0.02$ | $2.62 \pm 0.06$ | $4.54 \pm 0.16$ | $4.54 \pm 0.05$ |
| 1.74       | $0.99 \pm 0.07$ | $0.93 \pm 0.05$ | $3.63 \pm 0.05$ | $3.58 \pm 0.05$ | $6.19 \pm 0.14$ | $6.11 \pm 0.05$ |
| 2.00       | $1.26 \pm 0.02$ | $1.18 \pm 0.02$ | $4.75 \pm 0.23$ | $4.67 \pm 0.11$ | $8.06 \pm 0.10$ | $7.94 \pm 0.10$ |
| 2.25       | $1.50 \pm 0.03$ | $1.42 \pm 0.03$ | $5.74 \pm 0.24$ | $5.73 \pm 0.12$ | $9.80 \pm 0.17$ | $9.67 \pm 0.17$ |
| 2.50       | $1.71 \pm 0.01$ | $1.61 \pm 0.03$ | $6.56 \pm 0.24$ | $6.55 \pm 0.12$ | $11.25 \pm 0.30$ | $11.10 \pm 0.15$ |
| 2.75       | $1.88 \pm 0.01$ | $1.79 \pm 0.06$ | $7.26 \pm 0.20$ | $7.29 \pm 0.10$ | $12.47 \pm 0.38$ | $12.27 \pm 0.21$ |

at a given width of parameter $\Delta m = 14.1$ MeV. In the Fig.1(b), the distribution of yield of exotic states $Z_{+}^{*}(3900)$ vs parameter $R_0$ is given. From the TableIII, one can see that the yield of the exotic $Z_{+}^{*}(3900)$ states also increase with parameter $R_0$ from 1.0 fm to 2.75 fm at a given value of parameter $\Delta m = 14.1$ MeV. The distribution, $Y \sim R_0$, presents a linear scale characteristic. If we take half of the decay width of mass for ex-
FIG. 2. The ratio distribution of $Z_c^-$ (3900) to $Z_c^+$ (3900) in $pp$ collisions at $\sqrt{s} = 1.96, 7$ and 13 TeV with the value of radius parameter $R_0 = 1.74$ fm, as a function of mass uncertainty $\Delta m$.

The transverse momentum distribution of $Z_c^\pm$ (3900) in $pp$ collisions at $\sqrt{s} = 1.96, 7$ and 13 TeV are shown in Fig. 3. In each panel, the dashed line and the solid line refers to the distribution of antiparticles $Z_c^-$ (3900) and particles $Z_c^+$ (3900), respectively. Here, mass uncertainty parameter is taken as $\Delta m = \Gamma/2 = 14.1$ MeV [35], and radius parameter is taken $R_0 = 1.74$ fm. It can be seen from this figure that the transverse momentum distribution characteristics of antiparticles $Z_c^-$ (3900) is the same as that of positive particles $Z_c^+$ (3900) at the same center of mass energy. But the transverse momentum distribution of the exotic resonant states $Z_c^\pm$ (3900) becomes wider and the peak value shifts to the right with the increase of the collision energy. The values of average transverse momentum is $2.46 \pm 0.16, 2.89 \pm 0.06, 3.05 \pm 0.04$ GeV/c for $Z_c^+$ (3900) and $2.50 \pm 0.04, 2.80 \pm 0.06, 3.06 \pm 0.03$ GeV for $Z_c^-$ (3900) in $pp$ collision at $\sqrt{s} = 1.96, 7$ and 13 TeV, respectively.

The rapidity distribution of $Z_c^\pm$ (3900) was also calculated by PACIAE+DCPC model which is shown in Fig. 4. It can be seen from this figure that the rapidity distribution characteristics of antiparticles $Z_c^-$ (3900) is the same as that of positive particles $Z_c^+$ (3900) at the same center of mass energy. But the rapidity distribution of the exotic resonant states $Z_c^\pm$ (3900) becomes wider with the growing of the collision energy.

IV. SUMMARY

In this paper, we study the production of $Z_c$(3900) in PACIAE+DCPC model at $\sqrt{s} = 1.96, 7$, and 13 TeV based on its $J/\psi \pi^\pm$ bound state. First, we study the parameter dependence of $Z_c^\pm$ (3900) generation on mass uncertainty parameters $\Delta m$ from 8 to 40 MeV and radius parameters $\Delta R_0$ from 1.0 to 2.75 fm. The results showed that the yield of $Z_c^\pm$ (3900) increased linearly with the increase of parameter $\Delta m$ and $R_0$. If the parameters are chosen as $\Delta m = \Gamma/2 = 14.1$ MeV and $R_0 = 1.74$ fm, we can predict that the yields of $Z_c^+(3900)$ and $Z_c^-(3900)$ are $(0.99 \pm 0.07)E-6, (3.63 \pm 0.05)E-6, (6.19 \pm 0.14)E-6,$ and $(0.93 \pm 0.05)E-6, (3.58 \pm 0.05)E-6, (6.11 \pm 0.05)E-6$ under three different energies of 1.96, 7, 13 GeV in $pp$ collisions, respectively. These yields of $Z_c^\pm$ (3900) calculated in the PACIAE+DCPC model agree with Ref [42]. Next, the energy dependence of rapidity and transverse momentum distribution of exotic state $Z_c^\pm$ (3900) are studied. The width of these distributions become larger and their peaks value get smaller with the increase of energy from 1.96 TeV to 13 TeV. In addition, it is also found that the yield ratio of antiparticle $Z_c^-$ (3900) to $Z_c^+$ (3900) is less than 1, although their distribution of rapidity and transverse momentum are the same in $pp$ collisions at different energies.

The study of the exotic resonant state $Z_c^\pm$ (3900) productions in $pp$ collisions is under way. To obtain further insight and understanding of the nature of the exotic resonant state $Z_c^\pm$ (3900), we therefore suggest measurements of their production rates in $pp$ and heavy-ion collisions by the LHCh experiments.

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FIG. 3. The transverse momentum distribution of exotic state $Z^+_c(3900)$ (the solid line) and $Z^-_c(3900)$ (dashed line) calculated by PACIAE+DCPC model simulations with $\Delta m = 14.1$ MeV and $R_0 = 1.74$ fm in $pp$ collision at $\sqrt{s} = 1.96, 7$ and 13 TeV, respectively.

FIG. 4. Similar to Fig. 3 but for the rapidity distribution.
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