

Effect of α clusters on particle production in O-O and p -O collisions at energies available at the CERN Large Hadron Collider

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In the present work, O-O collisions at $\sqrt{s_{NN}} = 7$ TeV and p -O collisions at $\sqrt{s_{NN}} = 9.9$ TeV are studied using the PYTHIA8/Angantyr model for heavy-ion collisions. The theoretically predicted α -cluster structure of oxygen nucleus is implemented in the model to investigate the effect of the initial configuration of the oxygen nucleus on final state observables. The results obtained from the α -cluster structure are compared with those obtained from Woods-Saxon nuclear charge density distribution. The Angantyr model simulation showed that the radial distribution of the oxygen nucleus in α -cluster configuration is more compact in comparison to the Woods-Saxon distribution. The results on charged and identified particle pseudorapidity distribution are obtained in the two initial state configurations of the oxygen nucleus. The results demonstrated that the effect of initial geometrical configuration is more distinct in the noncentral collisions in comparison to the central collisions for both O-O and p -O collisions.

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I. INTRODUCTION

Over the last two decades, the experiments at the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC) have provided a wealth of information on the properties of the deconfined state of quarks and gluons, known as quark gluon plasma (QGP), formed in ultrarelativistic heavy-ion collisions [1–5]. These experiments have revealed that the QGP evolves hydrodynamically as a near perfect fluid with low viscosity to entropy density ratio (η/s) [6–8]. These experiments have also revealed heavy-ion like particle production patterns in small systems like p - p and p -A collisions at the RHIC and the LHC energies [9–15]. The recently started LHC Run-3 will enhance our understanding about the observation of QGP-like effects in small systems by providing data on various colliding systems with different center-of-mass energies. Most importantly, the data on oxygen-oxygen (O-O) and proton-oxygen (p -O) collisions at 7 TeV and 9.9 TeV center-of-mass energies, respectively, will shed light on the emergence of collective phenomenon and presence of partonic energy loss in small systems. Moreover,

p -O collisions will provide constraints on nuclear parton distribution functions and small- x studies [16] along with aiding the cosmic ray modeling by providing valuable hadronic data which might provide solutions to the muon puzzle in ultrahigh energy air showers and the ambiguity in the cosmic ray mass composition [17].

Apart from comprehending the physics and bridging the gap between small and large system dynamics, the oxygen collisions will also provide a unique opportunity to test the existence of the α -cluster model of the oxygen nucleus [18,19]. The existence of an α -cluster structure in elements having $4n$ nucleons, e.g., ^8Be , ^{12}C , ^{16}O , etc., was first conceived by Gamow in 1930 [20] due to the fact that α particles are highly stable with a large binding energy. The α -cluster model for $4n$ -type nuclei has been further investigated by several authors [21] as an alternative to suitably describe the energy level structures which were not well explained by the shell model theories [22]. However, the configuration of α clusters in the oxygen nucleus and other light nuclei is still not well understood. Several model calculations support linear chain structure with four α clusters in the oxygen nucleus [23]. A few model calculations suggest a tetrahedral structure of oxygen above the ground state [24,25]. Few other studies based on chiral nuclear effective field theory [26], skyrme energy density functional theory [27], and an algebraic cluster model [28] support the presence of tetrahedral α configuration in the ground state of oxygen. The consequences of square and kite shaped α -cluster configurations in light nuclei has also been discussed in the literature [29,30].

It has already been established through the collisions of deformed nuclei, such as ^{238}U and ^{129}Xe , that the initial geometry of the colliding nuclei plays a crucial role in the final state effects [31–37]. The nuclear charge distribution affects the initial energy density deposited at the collision

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vertex, which in turn affects the particle production in the final state. Thus, the presence of α clusters in the oxygen nucleus will manifest itself into the final state observables in collisions of the oxygen nucleus. Some recent studies indicate towards imaging the shapes of atomic nuclei through collective flow assistance [38], and a selection of events based on $\langle p_T \rangle$ to isolate body-body collisions in deformed nuclei [39] will allow to understand the initial conditions and evolution of nuclear structure in high energy collisions. In this article, we investigate whether the initial state α clustering in the ^{16}O nucleus can leave detectable imprints on the final state observables in O-O and p -O collisions at $\sqrt{s_{NN}} = 7$ TeV and 9.9 TeV, respectively, using the PYTHIA/Angantyr event generator. We geometrically incorporate α clusters in tetrahedral configuration in the oxygen nucleus in the PYTHIA/Angantyr event generator. To realize the consequences of α clusters on particle production, we compare the particle production in the O-O and p -O collisions without α clusters using a standard Woods-Saxon nuclear charge density distribution. Since the Angantyr model does not include hydrodynamic evolution, it provides a suitable framework for isolating purely geometric effects on final state observables. In this study, we focus on observables such as charged particle multiplicity and the transverse momentum spectra of identified particles to investigate the effects of α clustering in O-O and p -O collisions at LHC energies. Our primary goal is not to claim direct evidence for clustering, but rather to examine how the initial state nuclear structure influences final state observables even in the absence of a thermalized medium. The rest of the article is organized as follows. Section II concisely describes the PYTHIA/Angantyr model and the implementation of α -cluster structure in an oxygen nucleus. Section III presents the results and discussions, and Sec. IV concludes the article.

II. MODEL DESCRIPTION

A. Angantyr model

The Angantyr model is an extension of the PYTHIA8 event generator from p - p collisions to simulate nucleon-nucleus (p -A) and nucleus-nucleus (A-A) collisions without considering the formation of QGP matter [40]. The nucleon positions within the colliding nuclei are randomly sampled from the Woods-Saxon nuclear charge density distribution. The number of nucleon interactions and binary nucleon-nucleon (NN) collisions are obtained using the Glauber formalism [41,42]. The formalism is based on the eikonal approximation in impact parameter space with the assumption that the projectile nucleons travel in straight lines and experience multiple subcollisions with the target nucleons. The Glauber-Gribov color fluctuation model is used to incorporate diffractive excitation corrections due to fluctuations in the nucleon substructure and extended to include cross-section fluctuations in target and projectile nucleon for p -A and A-A collisions.

The contribution from each nucleon-nucleon interaction to the final state is obtained using the Fritiof model based on both nondiffractively and diffractively wounded nucleons which contribute to soft particle production. The events with multiple NN nondiffractive subcollisions are further characterized into

primary nondiffractive and secondary nondiffractive interactions based on impact parameters. The Angantyr model uses full multiparton interaction (MPI) machinery in PYTHIA8 to generate nondiffractive, diffractive, and elastic p - p interactions. Later, all multiple subcollisions are stacked together as color singlet Lund strings which are then hadronized to produce a heavy-ion collision event.

PYTHIA8 model using the microscopic rope hadronization mechanism and quantum chromodynamics (QCD)-based color reconnections (CR) for multiparton interactions properly describes the production and enhancement of (multi)strange hadrons in p - p collisions [43]. The Angantyr model used in the current study uses MPI-based color reconnection without any implementation of rope hadronization mechanism. In the present scenario, for the color reconnection mechanism, the color dipoles that form the strings from different subcollisions do not interact with each other. Albeit, recent studies implemented the QCD-based color reconnection at a hadronic level to understand naively the phenomenology of its effect on inter-sub-collisions [44]. Additionally, the rope hadronization mechanism has also been employed to understand the enhanced strange meson and baryon production in heavy-ion collisions [45].

B. α -cluster structure implementation in ^{16}O

^{16}O nucleus consists of eight protons and eight neutrons which makes it doubly magic providing an exceptional nuclear stability. In light nuclei, such as ^{16}O , the nucleons might rearrange themselves in a way to form α clusters and the nuclear mean field is not strong enough to break the clusters [21,46,47]. The tetrahedral structure with four α clusters in the oxygen nucleus has been provided by extended quantum molecular dynamics (EQMD) with the effective Pauli potential [48]. According to EQMD, the four α clusters are located at the vertices of a tetrahedron with the side length of 3.42 fm such that the rms radius is 2.699 fm, which is in agreement with the experimental data of 2.6991 fm [49].

The α -cluster structure of the ^{16}O nucleus is incorporated in the Angantyr model geometrically by creating a regular tetrahedron with a side length of 3.42 fm. For sampling the nucleon positions within the α clusters, the Woods-Saxon nuclear charge density is parameterized using a three-parameter Fermi (3pF) distribution. The 3pF distribution is given by

$$\rho(r) = \frac{\rho_0 \left(1 + w \left(\frac{r}{R}\right)^2\right)}{1 + \exp\left(\frac{r-R}{a}\right)}, \quad (1)$$

where r is the radial distance of the nucleon from the center of the nucleus, ρ_0 is the nuclear density at $r = 0$, R is the nuclear radius, a is the diffuseness parameter, and w is the skin thickness parameter. For each α cluster, $R = 0.964$ fm, $a = 0.322$ fm, and $w = 0.517$ fm are used to obtain the nuclear charge density distribution [50]. The position of nucleons are randomized by applying three successive Euler rotations on an event-by-event basis for the oxygen nucleus. To avoid overlapping, the minimum distance between two nucleons inside the same oxygen nucleus is kept larger than 0.9 fm which is the default hard core radius defined in

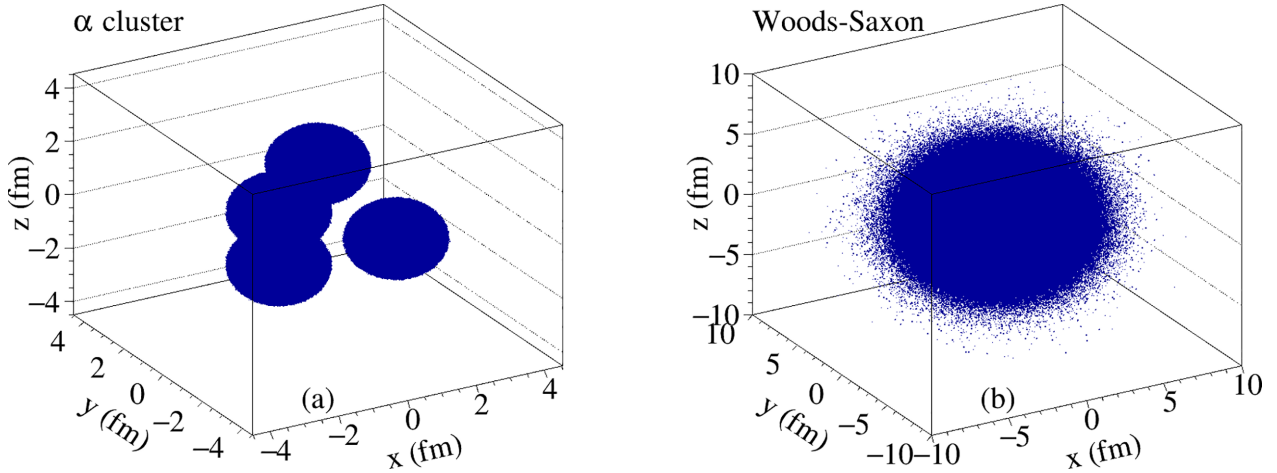


FIG. 1. A three-dimensional view of the (a) α -cluster structure and (b) Woods-Saxon nuclear charge density distribution for the ^{16}O nucleus.

the Angantyr model. Using this configuration in the Angantyr model, a rms radius of 2.257 ± 0.098 is obtained, which is a bit smaller than the predictions of EQMD. The discrepancy in the rms radius is probably due to the intrinsic differences in the treatment of nucleon spatial distributions. EQMD employs explicit nucleon wave packets combined with effective interactions that sustain extended α -cluster structures, leading to more diffuse nucleon densities and larger radii. In contrast, Angantyr, built on the PYTHIA8 string fragmentation model and Glauber nuclear geometry, treats nucleons as point-like sources sampled from a 3pF distribution, without explicit cluster wave functions. Consequently, nucleon configurations are more compact, resulting in a smaller rms radius.

C. Woods-Saxon distribution

In order to compare the effects of α -cluster structure on particle production in O-O and p -O collisions, the 3pF Woods-Saxon nuclear charge density distribution given in Eq. (1) is

used for the oxygen nucleus. Here, $R = 2.608$ fm, $a = 0.513$ fm, and $w = -0.051$ fm are used to obtain a charge density profile for the oxygen nucleus from which the nucleon positions are sampled [51]. Figure 1 shows the three-dimensional view of the nucleon positions for ^{16}O nucleus obtained from α -cluster structure as well as the Woods-Saxon distribution.

The distribution of nucleons in the x - y plane for α -cluster structure (left panel) and Woods-Saxon nuclear charge density distribution (right panel) for the ^{16}O nucleus is shown in Fig. 2. It can be observed that the nucleons are more localized at the vertices of the tetrahedron in an α -cluster structure in comparison to the Woods-Saxon nuclear charge density distribution where nucleons are localized at the center of the oxygen nucleus. Figure 3 shows the probability density of finding a nucleon inside the oxygen nucleus as a function of radial distance for α -cluster structure and Woods-Saxon nuclear charge density distribution. The radial profile is more succinct for an α -cluster structure in comparison to a Woods-Saxon nuclear charge density distribution which has a more

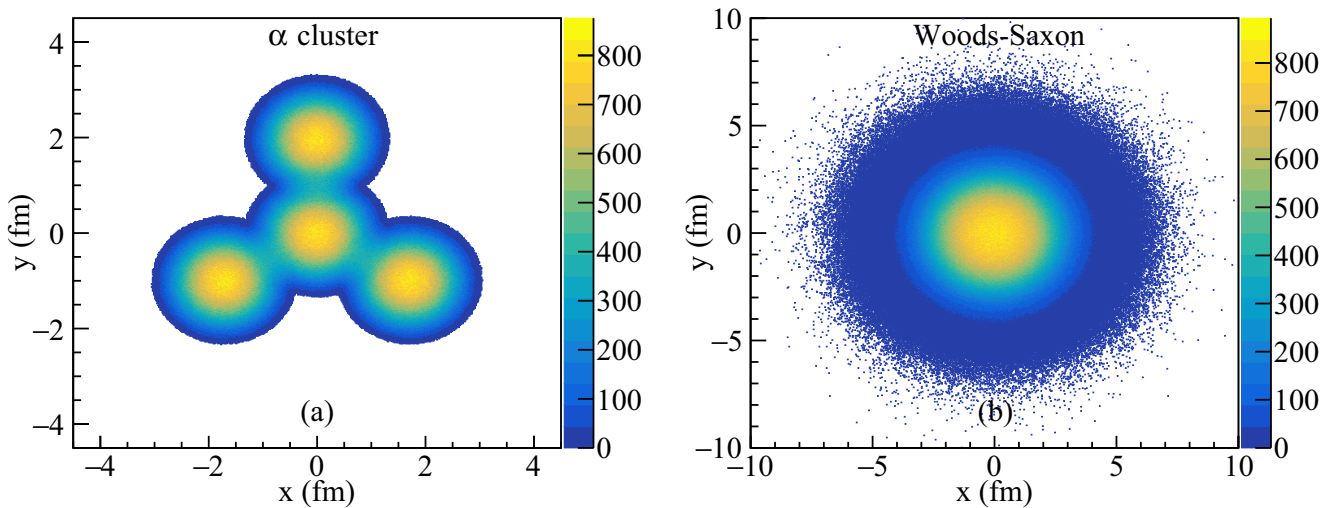


FIG. 2. Distribution of nucleons in the transverse (x - y) plane for (a) α -cluster structure and (b) Woods-Saxon nuclear charge density distribution for the ^{16}O nucleus.

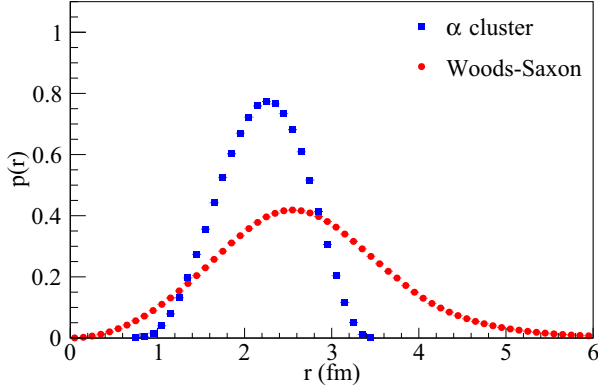


FIG. 3. Radial profile for distribution of the nucleons in the ^{16}O nucleus for α -cluster structure and Woods-Saxon nuclear charge density distribution.

smear radial distribution. The radial profile shows that the probability density is maximum at the nuclear radius for both α -cluster and Woods-Saxon distributions and the height of the probability distribution peak at the nuclear radius is about two times larger for α -cluster structure in comparison to Woods-Saxon distribution.

III. RESULTS AND DISCUSSIONS

In this section, the results obtained for the pseudorapidity (η) and transverse momentum (p_T) distributions of identified particles produced in O-O and p -O collisions at $\sqrt{s_{NN}} = 7$ TeV and $\sqrt{s_{NN}} = 9.9$ TeV, respectively, are presented and discussed. The results for the α -cluster structure of the oxygen nucleus are compared with the 3pF Woods-Saxon nuclear charge density distribution for 0–5%, 20–40%, and 60–80% centrality intervals. The centrality intervals are determined using the impact parameter of the colliding nuclei. Table I shows the values of impact parameter and average number of participating nucleons for O-O and p -O collisions at $\sqrt{s_{NN}} = 7$ TeV and 9.9 TeV, respectively, in different centrality intervals for α -cluster and Woods-Saxon distributions.

TABLE I. The impact parameter and average number of participating nucleons for O-O and p -O collisions at $\sqrt{s_{NN}} = 7$ TeV and 9.9 TeV, respectively, in different centrality intervals for α -cluster and Woods-Saxon distributions.

Centrality (%)	O-O, $\sqrt{s_{NN}} = 7$ TeV						p -O, $\sqrt{s_{NN}} = 9.9$ TeV					
	Woods-Saxon			α cluster			Woods-Saxon			α cluster		
	$b_{\min}$ (fm)	$b_{\max}$ (fm)	$\langle N_{\text{part}} \rangle \pm$ rms	$b_{\min}$ (fm)	$b_{\max}$ (fm)	$\langle N_{\text{part}} \rangle \pm$ rms	$b_{\min}$ (fm)	$b_{\max}$ (fm)	$\langle N_{\text{part}} \rangle \pm$ rms	$b_{\min}$ (fm)	$b_{\max}$ (fm)	$\langle N_{\text{part}} \rangle \pm$ rms
0-5	0	1.40	26.14 ± 2.53	0	1.04	27.37 ± 2.34	0	0.84	5.44 ± 2.64	0	0.74	5.47 ± 2.66
5-10	1.40	2.00	23.75 ± 2.71	1.04	1.48	25.86 ± 2.50	0.84	1.19	5.12 ± 2.48	0.74	1.06	5.22 ± 2.52
10-20	2.00	2.84	20.34 ± 3.11	1.48	2.13	23.50 ± 2.79	1.19	1.70	4.67 ± 2.26	1.06	1.51	4.86 ± 2.35
20-40	2.84	4.11	14.44 ± 3.80	2.13	3.16	18.84 ± 3.45	1.70	2.46	3.84 ± 1.93	1.51	2.21	4.13 ± 2.05
40-60	4.11	5.17	8.37 ± 3.45	3.16	4.10	12.92 ± 3.70	2.46	3.14	2.95 ± 1.55	2.21	2.82	3.28 ± 1.70
60-80	5.17	6.29	4.66 ± 2.58	4.10	5.14	7.71 ± 3.47	3.14	3.92	2.32 ± 1.24	2.82	3.53	2.58 ± 1.38
80-100	6.29	19.95	2.69 ± 1.54	5.14	11.00	3.76 ± 2.35	3.92	13.41	1.90 ± 0.95	3.53	10.76	2.01 ± 1.04

A. Pseudorapidity distributions

Figure 4 shows the η distributions of charged particles produced in O-O collisions at $\sqrt{s_{NN}} = 7$ TeV for 0–5%, 20–40%, and 60–80% centrality intervals. It can be clearly seen that the nuclear density has a significant effect on the η distribution of charged particles produced in O-O collisions at $\sqrt{s_{NN}} = 7$ TeV for all the centrality intervals. The charged particle pseudorapidity density for α -cluster structure is higher than the Woods-Saxon nuclear charge density distribution for all the centrality intervals. The difference becomes more pronounced as we move from central to peripheral collisions. The observation of higher values of charged particle density for α -cluster structure in comparison to the Woods-Saxon profile for O-O collisions is quite evident from $\langle N_{\text{part}} \rangle$ values shown in Table I. The $\langle N_{\text{part}} \rangle$ values for α -cluster structure are consistently higher than the Woods-Saxon nuclear charge density distribution for all the centrality intervals in O-O collisions. As seen from Fig. 2, the nucleons are more localized at the vertices of the tetrahedron in α -cluster structure in comparison to the Woods-Saxon nuclear charge density distribution where nucleons are localized at the center of the oxygen nucleus. Therefore, even in noncentral collisions, the collision system has a larger nucleonic density in the α cluster with respect to the Woods-Saxon profile. In context of the Angantyr model, this indicates that the α clustering in oxygen nucleus results in a higher string density concentrated within a smaller volume compared to the Woods-Saxon nuclear charge density distribution of the oxygen nucleus in the initial state. The higher string density manifests in larger production of particles in the final state.

Similar studies using a multiphase transport model (AMPT) [52] and relativistic hydrodynamics simulations [50] have observed an opposite trend in the pseudorapidity distributions of charged particles as a function of centrality. Their results show a large difference in the α -cluster structure and Woods-Saxon nuclear charge density distribution for central collisions and relatively smaller difference for peripheral collisions. They also show that the α -cluster structure and Woods-Saxon density profile has almost no dependence on charged particle pseudorapidity distribution at forward pseudorapidities. Notably, the results obtained from

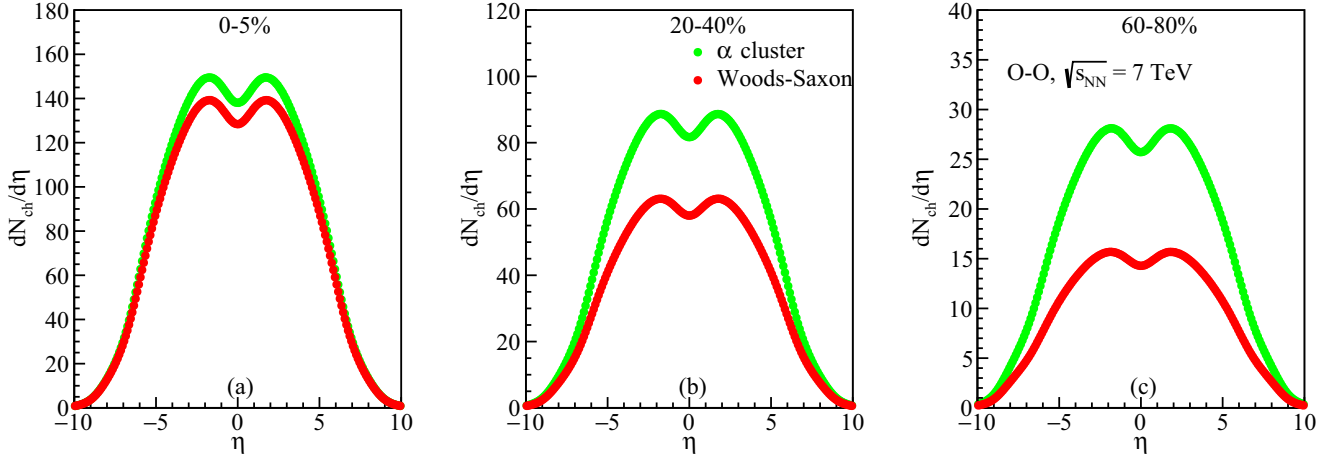


FIG. 4. Pseudorapidity distribution of charged particles produced in O-O collisions at $\sqrt{s_{NN}} = 7$ TeV for (a) 0–5%, (b) 20–40%, and (c) 60–80% centrality intervals for α -cluster structure and Woods-Saxon nuclear charge density distribution.

the PYTHIA/Angantyr model show a significant difference in the charged particle pseudorapidity distribution at forward pseudorapidities for α -cluster structure and Woods-Saxon nuclear charge density distribution for noncentral collisions. These differences may arise from model-specific treatments of the initial geometry of the oxygen nucleus. The AMPT model [52] employs HIJING to generate initial conditions based on the Glauber model, followed by hadronization through a spatial coalescence mechanism and subsequent evolution via a relativistic transport approach. In contrast, the relativistic hydrodynamics simulation [50] uses the TRENTO model to generate the initial entropy density for the α -cluster structures, which is then evolved through the CLVisc model to simulate the QGP expansion. The Angantyr model, on the other hand, treats the collision as a superposition of independent nucleon-nucleon interactions without hydrodynamic evolution. The absence of collective medium dynamics in Angantyr may contribute to the observed differences in centrality trends compared to other models. The precise origin of this discrepancy, however, remains unclear within the current Angantyr framework and warrants further investigation in future studies.

Figure 5 shows the pseudorapidity distributions of charged particles produced in p -O collisions at $\sqrt{s_{NN}} = 9.9$ TeV for 0–5%, 20–40%, and 60–80% centrality intervals. It is observed that the charged particle pseudorapidity distribution for 0–5% centrality interval is almost independent of initial nuclear density profile. The observation is consistent with the $\langle N_{part} \rangle$ values, which are nearly the same for both the α -cluster structure and Woods-Saxon distribution in 0–5% centrality interval. It also indicates that the string density for both the configuration of oxygen nucleus is almost similar in central p -O collisions. 20–40% and 60–80% centrality intervals show a significant difference in the pseudorapidity distribution for the α -cluster structure and the Woods-Saxon nuclear charge density distribution. The $\langle N_{part} \rangle$ values, as can be seen in Table I, are higher for the α -cluster structure relative to the Woods-Saxon distribution in noncentral p -O collisions. Larger $\langle N_{part} \rangle$ corresponds to a higher initial string density, resulting in a relatively large particle production in noncentral collisions for

α -cluster structure. A clear asymmetry in the charged particle pseudorapidity distribution is observed around $\eta = 0$ for α -cluster structure and Woods-Saxon nuclear charge density distribution for central and midcentral collisions. This is due to the fact that projectile proton probes a denser volume of the target oxygen nucleus, increasing the particle yield in an oxygen-going direction. In peripheral collisions, the charged particle pseudorapidity distribution for the α -cluster structure and Woods-Saxon nuclear charge density becomes more symmetric around $\eta = 0$. It may be due to the smaller number of participating nucleons and less dense interaction volume in the peripheral collisions, the situation becomes similar to the symmetric p - p collisions.

B. Transverse momentum distributions

Figure 6 shows the transverse momentum distributions of pions ($\pi^+ + \pi^-$), kaons ($K^+ + K^-$), and protons ($p + \bar{p}$) produced in O-O collisions at $\sqrt{s_{NN}} = 7$ TeV for 0–5%, 20–40%, and 60–80% centrality intervals in $|\eta| < 0.8$ for α -cluster structure and Woods-Saxon charge density profile. The bottom panel of the figure shows the ratio of transverse momentum distributions of the α -cluster to Woods-Saxon profile. It can be observed that, in central collisions, the p_T spectra of pions, kaons, and protons are similar for both the α -cluster structure and Woods-Saxon nuclear charge density distribution as evident from the ratio which is consistent with unity. For noncentral collisions, the p_T spectra of pions, kaons, and protons hardens slightly for α -cluster structure with respect to Woods-Saxon nuclear charge density distribution. In the Angantyr model, hadron production at all centralities is treated as a superposition of independent NN interactions with the p_T -spectra primarily determined by string fragmentation and multiparton interactions. In central collisions, 0–5% centrality interval, the nuclei overlap almost completely and nearly all nucleons participate. The number of participants for α -cluster structure is only about 4.70% higher relative to Woods-Saxon distribution, indicating a saturated overlap zone in which contributions from many overlapping

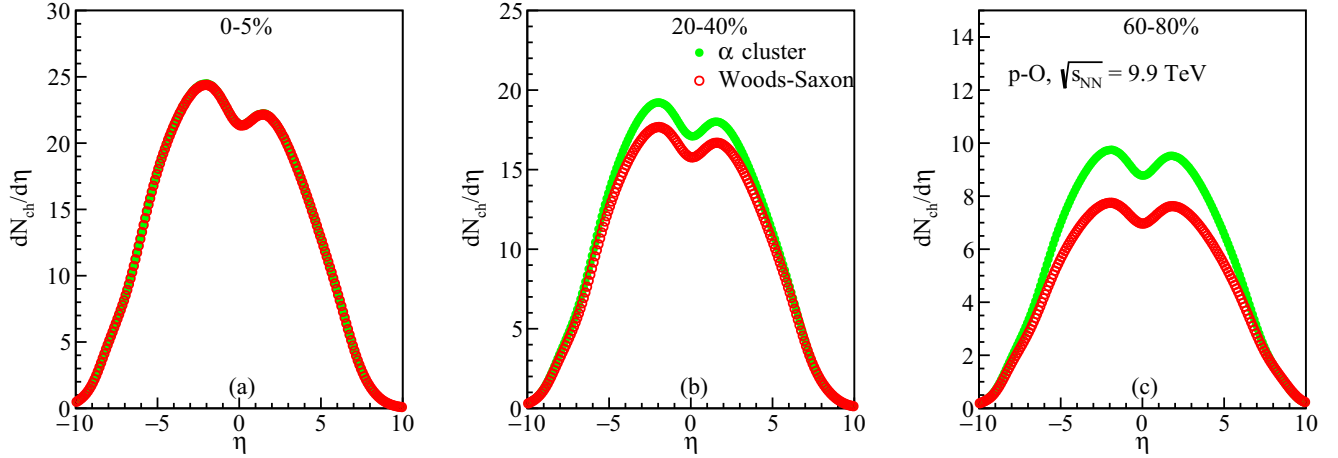


FIG. 5. Pseudorapidity distribution of charged particles produced in p -O collisions at $\sqrt{s_{NN}} = 9.9$ TeV for (a) 0–5%, (b) 20–40%, and (c) 60–80% centrality intervals for α -cluster structure and Woods-Saxon nuclear charge density distribution.

α clusters wash out local density variations. As a result, the p_T spectra of pions, kaons, and protons remain similar for both configurations. In noncentral collisions at 20–40% and 60–80% centrality intervals, the α -cluster structure has more participating nucleons than the Woods-Saxon distribution, approximately 30.50% and 65.50% higher, respectively. From Table I, it can be inferred that in the 20–40% centrality interval, roughly half of the clusters from each nucleus participate in the collision, while in the 60–80% centrality interval participation is dominated by approximately one cluster from each nucleus. In these noncentral events, the

reduced number of clusters in the overlap region means that the individual density peaks from each α cluster are no longer fully overlapped by others. Fewer overlapping clusters leave these local density variations intact, allowing them to persist in the participant density profile. These surviving localized density enhancements result in higher local parton densities for the α -cluster configuration compared to the smoother Woods-Saxon distribution. The enhancement in local parton densities allows geometry differences to begin influencing the system. Moreover, the increased local parton density enhances the number of multiparton interactions resulting in higher

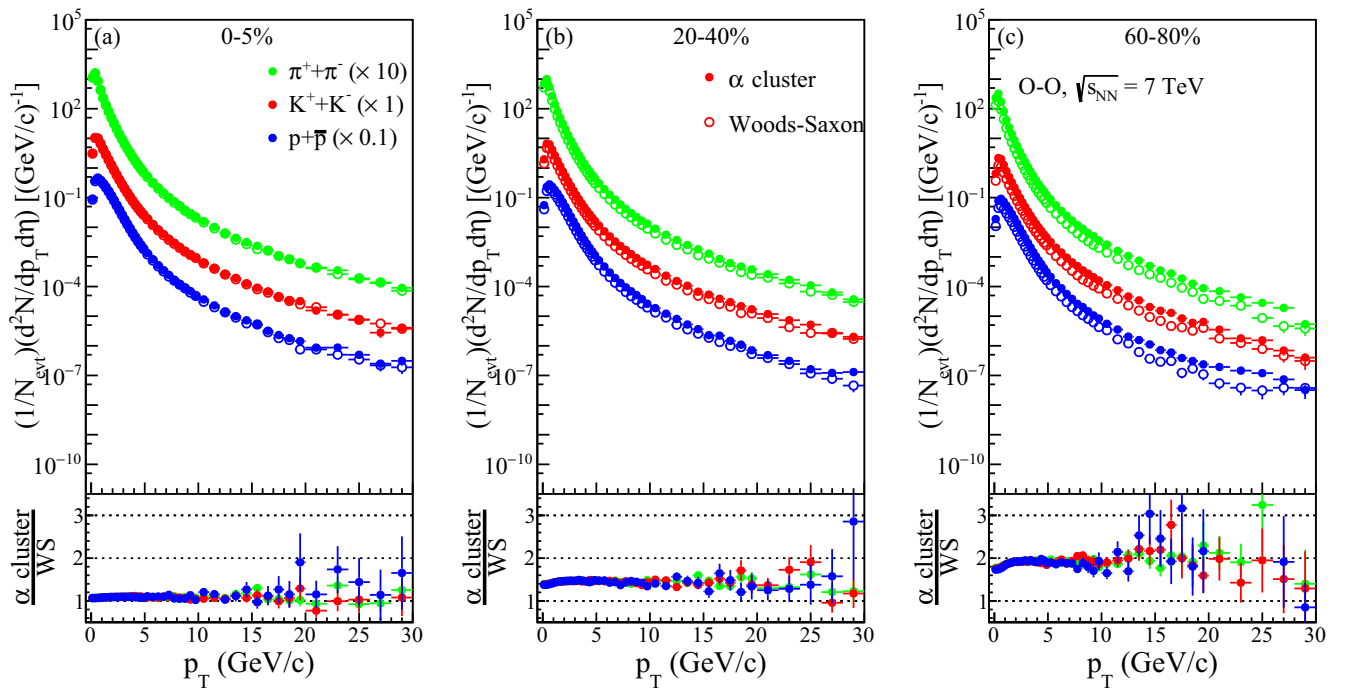


FIG. 6. p_T spectra of pions, kaons, and protons in O-O collisions at $\sqrt{s_{NN}} = 7$ TeV in (a) 0–5%, (b) 20–40%, and (c) 60–80% centrality intervals for α -cluster and Woods-Saxon distribution.

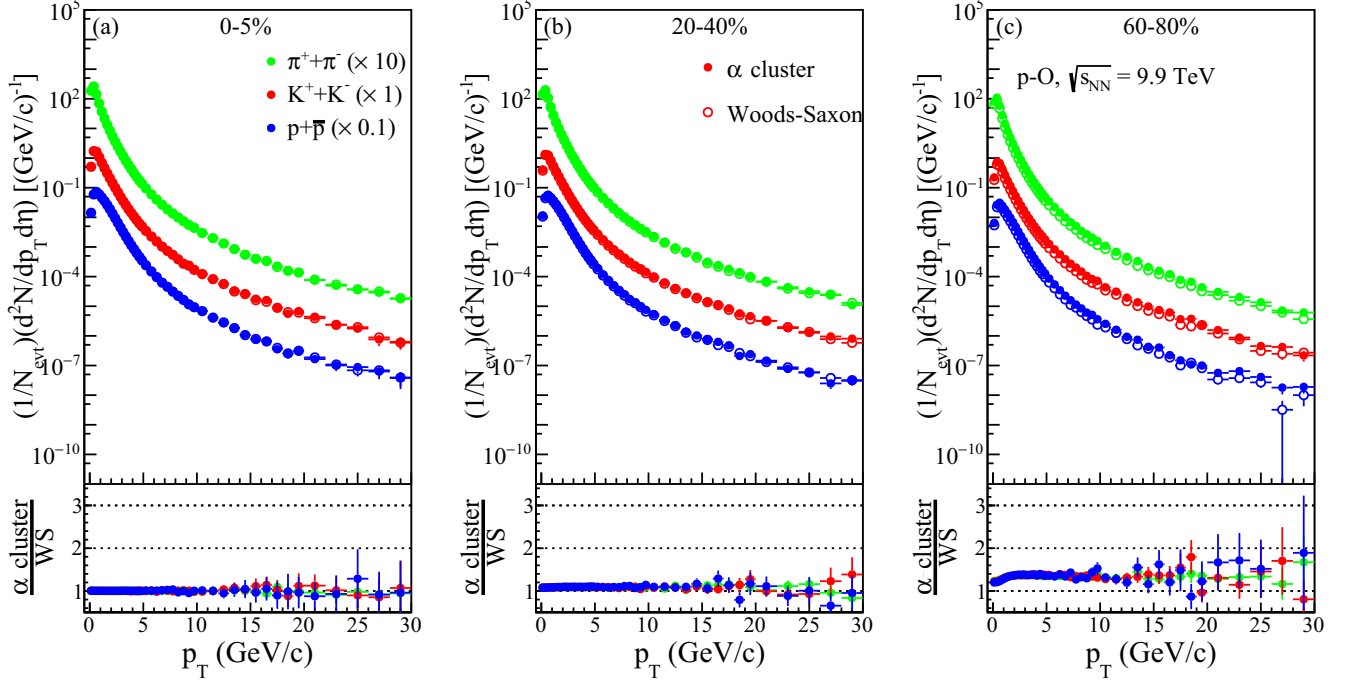


FIG. 7. p_T spectra of pions, kaons, and protons in p -O collisions at $\sqrt{s_{NN}} = 9.9$ TeV in (a) 0–5%, (b) 20–40%, and (c) 60–80% centrality intervals for α -cluster and Woods-Saxon distribution.

effective string tension which produces harder hadron spectra via string fragmentation. The magnitude of this effect increases toward peripheral collisions due to the larger relative increase in $\langle N_{part} \rangle$ for the α -cluster structure compared to the Woods-Saxon distribution.

Figure 7 shows the p_T spectra of pions ($\pi^+ + \pi^-$), kaons ($K^+ + K^-$), and protons ($p + \bar{p}$) produced in p -O collisions at $\sqrt{s_{NN}} = 9.9$ TeV for 0–5%, 20–40%, and 60–80% centrality intervals in $|\eta| < 0.8$. The results for both α -cluster structure and Woods-Saxon charge density profile are shown for comparison. The bottom panel of the figures show the ratio of α -cluster to Woods-Saxon p_T spectra for pions, kaons, and protons. It can be seen that the p_T spectra for pions, kaons, and protons show no visible difference for α -cluster structure and Woods-Saxon nuclear charge density distribution for central and semicentral collisions. For peripheral collisions, a slight hardening of the p_T spectra is observed for α -cluster structure with respect to Woods-Saxon nuclear charge density distribution for all the considered particles.

The transverse momentum distribution of strange hadrons from the Angantyr model with MPI-based CR in O-O and p -O collisions at $\sqrt{s_{NN}} = 7$ TeV and 9.9 TeV are obtained to understand the effect of initial density profile. Figures 8 and 9 show the p_T spectra of K_s^0 , $\Lambda + \bar{\Lambda}$, $\Xi^- + \bar{\Xi}^+$, and $\Omega^- + \bar{\Omega}^+$ for O-O and p -O collisions, respectively, in different centrality intervals. The results obtained with α -cluster structure are compared with the Woods-Saxon distribution. An observation similar to Figs. 6 and 7 is observed with higher particle yield and hardening of p_T spectra for noncentral collisions in α -cluster structure of oxygen in comparison to Woods-Saxon distribution for both the collision systems.

Production of strange hadrons (and light hadrons) in PYTHIA basically depends on the effective tunneling mechanism with string tension (κ) during hadronization through Lund fragmentation function. In the absence of QCD-based CR and rope hadronization mechanisms, Angantyr will not be able to provide sufficient string tension to enhance the production of strange mesons and baryons in heavy-ion collisions. The inclusion of both these mechanisms, which are sensitive to string density and overlap geometry, might significantly influence the strangeness production in α -cluster configuration compared to Woods-Saxon distribution, especially in noncentral collisions where localized string overlap is more pronounced.

Unlike the light quarks, the heavy quarks in PYTHIA8 are produced only in the hard scatterings and the partons showers [53]. The hard scattering processes like $qq \rightarrow Q\bar{Q}$ and $gg \rightarrow Q\bar{Q}$ are primary responsible for heavy quark production along with weak decay, Higgs decay, and top and bottom quark decay. The parton showers mainly produce heavy quarks through pair creation, flavour excitation or gluon splitting. The heavy quark masses are used for the perturbative description of their production which affects the matrix elements, splitting kernels, and the phase space of the heavy quark production cross section. Figures 10 and 11 show the p_T spectra of $D^{*+} + D^{*-}$, $D^0 + \bar{D}^0$, and $D_s^+ + D_s^-$ obtained for α -cluster structure and Woods-Saxon distribution in O-O and p -O collisions at $\sqrt{s_{NN}} = 7$ TeV and 9.9 TeV, respectively, for different centrality intervals. Here, also, an enhancement in the D-meson yields and slight hardening of spectra in noncentral collisions is observed in α -cluster configuration relative to Woods-Saxon distribution for both the collision systems.

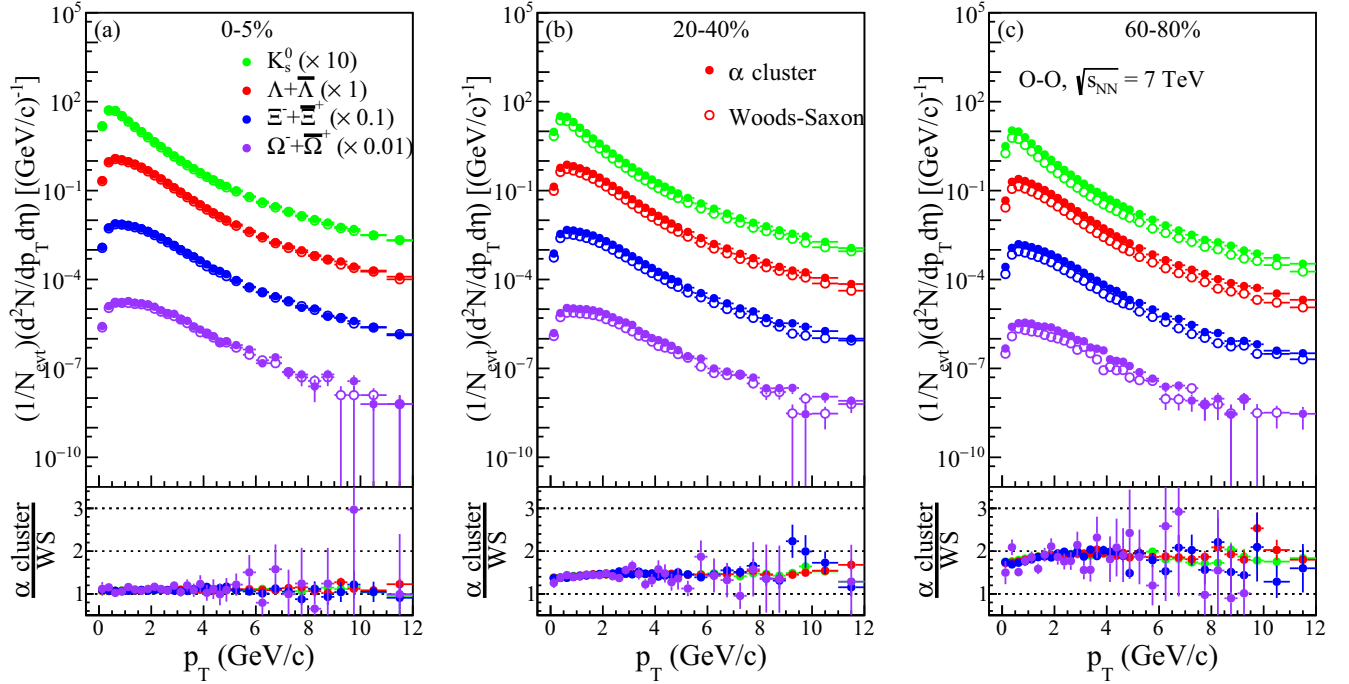


FIG. 8. p_T spectra of K_s^0 , Λ , Ξ , and Ω in O-O collisions at $\sqrt{s_{NN}} = 7$ TeV in (a) 0–5%, (b) 20–40%, and (c) 60–80% centrality intervals for α -cluster and Woods-Saxon distribution.

IV. CONCLUSIONS

In this article, the effects of initial geometrical configuration of oxygen nucleus on the final state multiparticle production in O-O and p -O collisions at $\sqrt{s_{NN}} = 7$ TeV and

9.9 TeV is explored under the framework of the Angantyr model for heavy-ion collisions. The nucleons in the oxygen nucleus are expected to have a α -cluster structure with four ${}^4\text{He}$ (α) nuclei sitting at each vertex of regular tetrahedron.

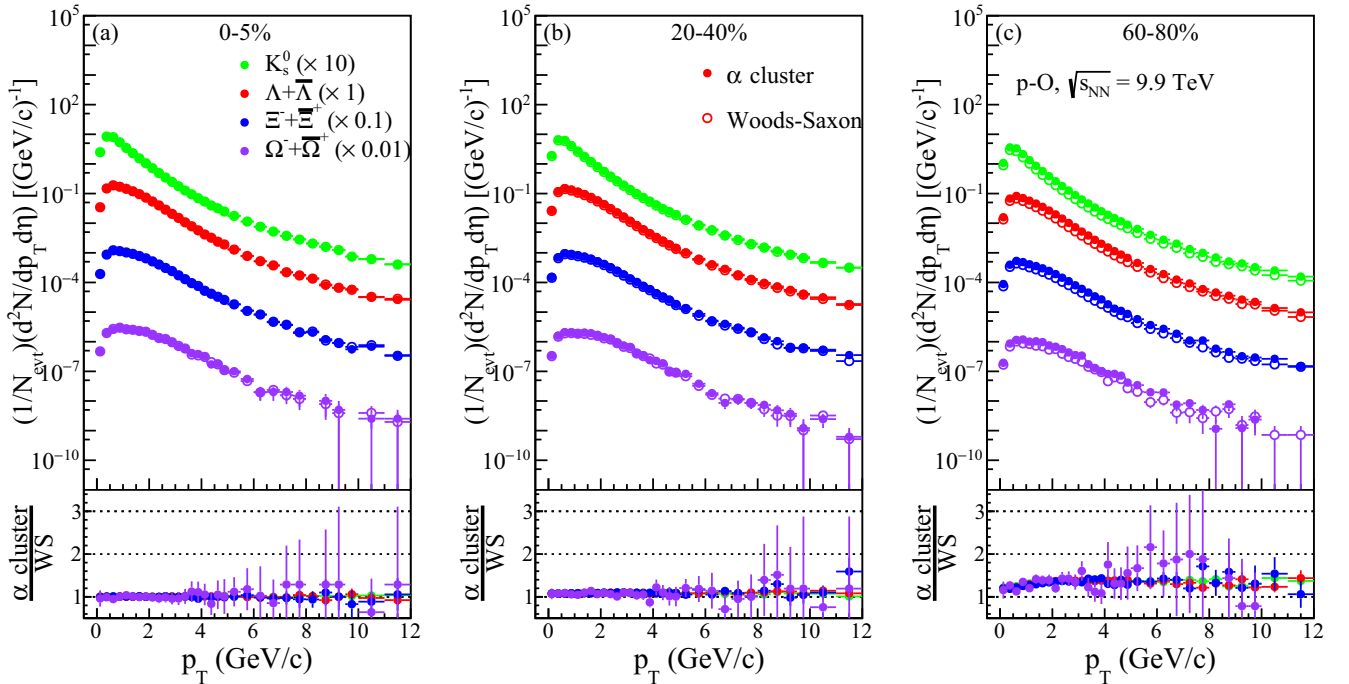


FIG. 9. p_T spectra of K_s^0 , Λ , Ξ , and Ω in p -O collisions at $\sqrt{s_{NN}} = 9.9$ TeV in (a) 0–5%, (b) 20–40%, and (c) 60–80% centrality intervals for α -cluster and Woods-Saxon distribution.

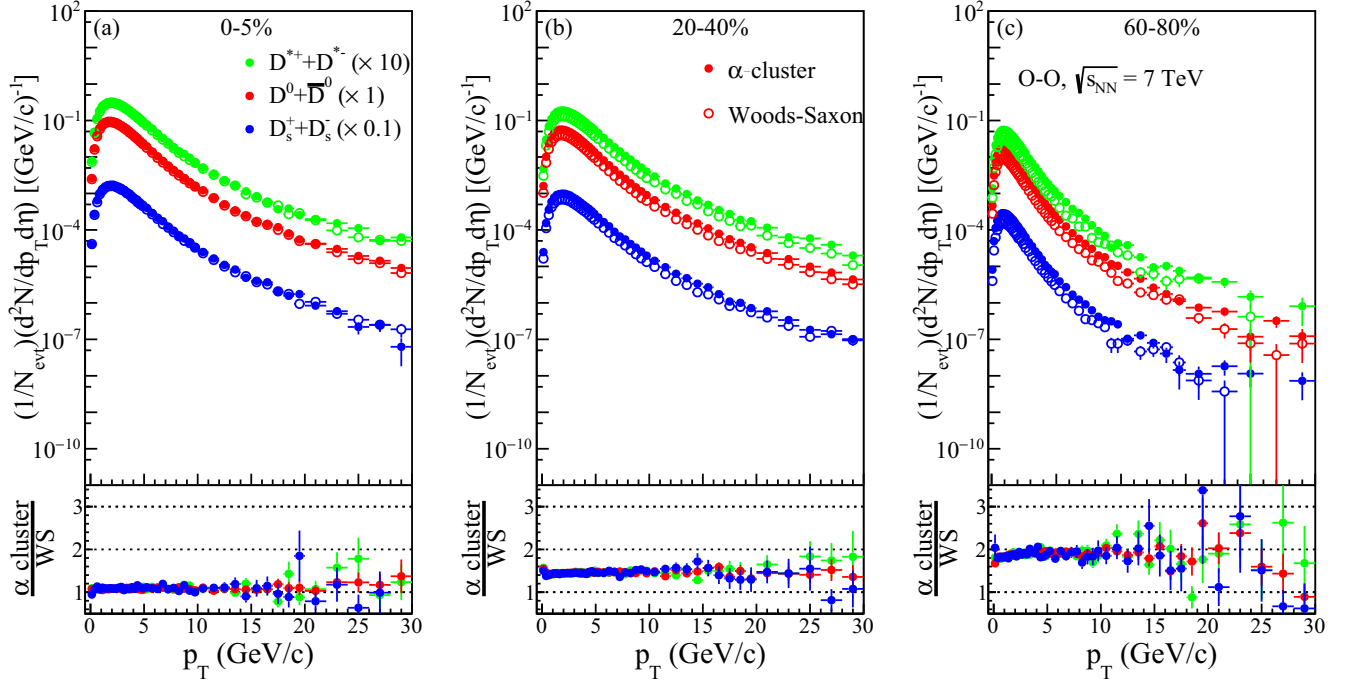


FIG. 10. p_T spectra of D^* , D^0 , and D_s in O-O collisions at $\sqrt{s_{NN}} = 7$ TeV in (a) 0–5%, (b) 20–40%, and (c) 60–80% centrality intervals for α -cluster and Woods-Saxon distribution.

The α -cluster configuration of oxygen is implemented geometrically in the Angantyr model and final state observables like pseudorapidity distribution of charged particles and transverse momentum distribution of identified particles, such as final state charged particle, strange hadron and open heavy

flavors are obtained. In order to realize the consequences of α clusters on final state observables, the commonly used 3pF Woods-Saxon charge density distribution in heavy-ion collisions is also utilized in the initial state of the Angantyr model. It is observed that the effect of α clusters is more pronounced

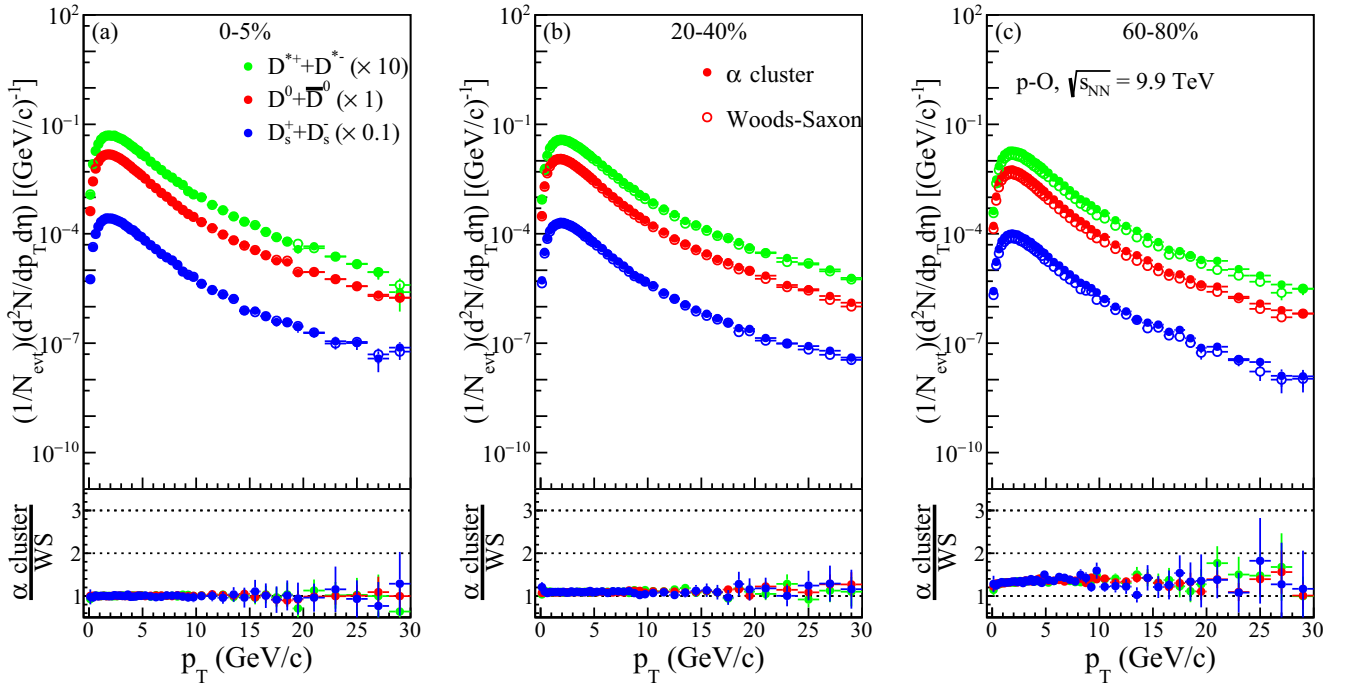


FIG. 11. p_T spectra of D^* , D^0 , and D_s in p-O collisions at $\sqrt{s_{NN}} = 9.9$ TeV in (a) 0–5%, (b) 20–40%, and (c) 60–80% centrality intervals for α -cluster and Woods-Saxon distribution.

in noncentral collisions around mid- and forward rapidities in comparison to the Woods-Saxon distribution for both O-O and p -O collisions. It indicates that the study of particles at forward rapidities, such as J/ψ , Υ , beam remnants, etc., may provide a better understanding of gluon saturation other QCD phenomena including the information about QGP and cold nuclear matter effects and most importantly the information about the structure of oxygen nucleus in the initial state.

The transverse momentum distribution of identified particles shows an increase in particle yield and slight hardening of the particle spectra in noncentral collisions for α clusters in comparison to Woods-Saxon distribution of the oxygen nucleus. The observed differences between the Woods-Saxon distribution and the α -cluster oxygen geometry are direct consequences of spatial variation in the initial NN collision density. The tetrahedral arrangement of α clusters results in localized regions of enhanced nucleon density, which in turn produce more frequent NN interactions with increased MPI activity. These differences arise even without hydrodynamic

evolution, highlighting the role of nuclear geometry in shaping final-state particle production. The distinction between the two initial configurations on the final state observables may become more evident upon incorporating the QCD-based color reconnection mechanism, and rope hadronization for string fragmentation in the Angantyr model. The effect of these mechanisms on particle production in O-O and p -O collisions will be explored in our future work.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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