Insight into the thermodynamic activity of high-multiplicity hadronic collisions at LHC energy

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I. INTRODUCTION

In recent times, understanding the medium formation and its evolution in the hadronic collisions has become an exciting topic for the high energy and nuclear physics community. Both experimental and theoretical studies compel us to reexamine the traditional use of proton+proton (pp) collisions as a baseline to study the formation of quark-gluon plasma (QGP) in the heavy-ion collision (HIC). In this context of better understanding the dynamics of pp collisions, heavy-flavored hadrons are believed to be one of the best probes as they are produced during the early stages of collision, possess heavy mass and long relaxation time compared to QGP lifetime. Previous work [1] indicates the possibility of a thermal medium after a threshold multiplicity for a small system through some markers of thermalization. Also,ref. [1] uses experimental results of light and strange hadrons using at LHC. Furthermore, in the case of Monte-Carlo simulation, through various studies. It is established through various studies that multi-partonic interaction (MPI) along with color reconnection (CR) tune of PYTHIA8 could mimic the behavior of thermalization in pp collisions. This motivated us to study the thermalization effect in pp collision via charm hadrons namely Λ_c^+ and D^0 at $\sqrt{s} = 13$TeV using speed of sound, isothermal compressibility, Knudsen number.

II. METHODS AND RESULTS

Speed of sound (c_s), isothermal compressibility (κ_T), and Knudsen number(K_n) are obtained using the thermodynamic quantities like energy density (ϵ), and pressure (P) modified by thermodynamically consistent non-extensive distribution function. Using parameters of Tsallis distribution function, namely the effective temperature (T) and non-extensive parameter (q) as inputs from the ref. [2], the mathematical expression for ϵ and P using the Tsallis distribution function are given as

$$\epsilon = g\int \frac{d^3p}{(2\pi)^3}\sqrt{p^2+m^2}\left[1+(q-1)\frac{\sqrt{p^2+m^2}}{T}\right]^{\frac{-q}{q-1}} \quad (1)$$

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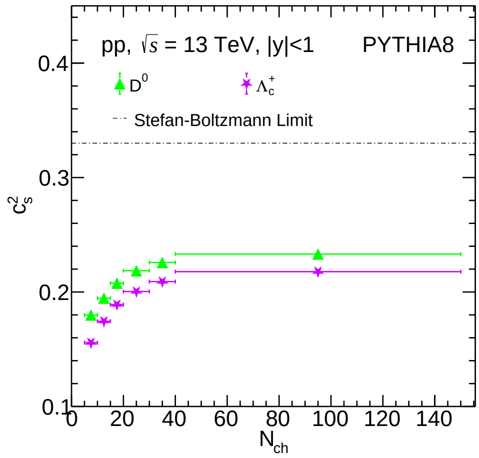

FIG. 1: (Color online) Variation of the squared speed of sound (c_s^2) with charged-particle multiplicity [2].

$$P = g\int \frac{d^3p}{(2\pi)^3}\frac{p^2}{3\sqrt{p^2+m^2}}\left[1+(q-1)\frac{\sqrt{p^2+m^2}}{T}\right]^{\frac{-q}{q-1}} \quad (2)$$

In an isentropic process, the squared speed of sound is defined as the change in pressure of the system with respect to a change in the energy density and is given as

$$c_s^2 = \left(\frac{\partial P}{\partial \epsilon}\right)_{isentropic} \quad (3)$$

In an isothermal process, compressibility (κ_T) is defined as the change in volume of the system with a change in pressure. Mathematically,

$$\kappa_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_{isothermal} \quad (4)$$

Knudsen number (K_n) is defined as the ratio of the mean free path (λ) of a particle to a spatial dimension of the system (R).

$$K_n = \frac{\lambda}{R} \quad (5)$$

Both speed of sound and isothermal compressibility describe the equation of state of the medium, while the Knudsen number describe the hydrodynamical evolution of the thermal medium.

Figure 1 shows the variation of c_s^2 with charged-particle multiplicity both for Λ_c^+ and D^0. We observed that c_s^2

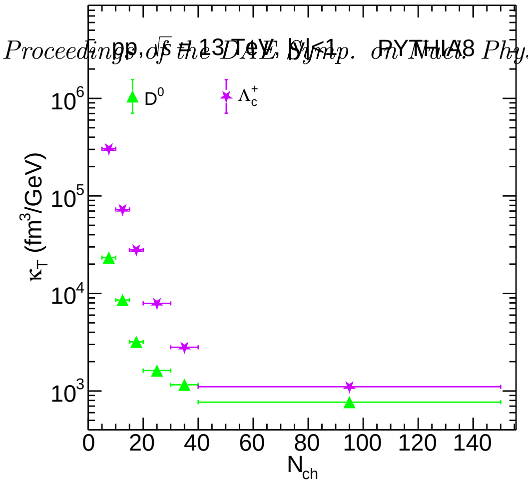

FIG. 2: (Color online) Variation of Isothermal compressibility (κ_T) with charged-particle multiplicity [2].

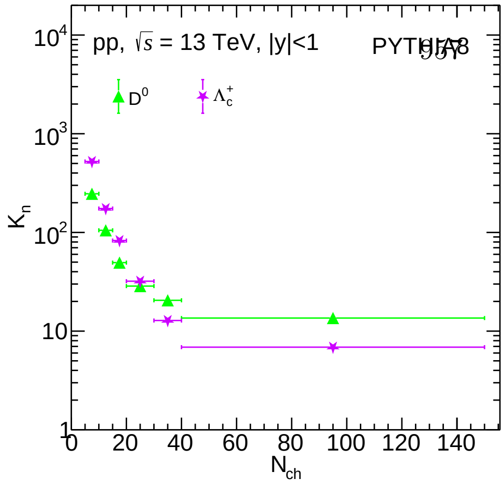

FIG. 3: (Color online) Variation of Knudsen number (K_n) with charged-particle multiplicity [2].

increases with multiplicity and approaches the massless non-interacting gas limit (1/3), towards the higher multiplicity classes. This observation indicates that the high-multiplicity medium is more thermal-like than the low-multiplicity environment. It is observed that the effect of interaction strength in the charm sector is in line with light and strange sectors. Further, it is also found that the mass ordering in the speed of sound is preserved in all multiplicity classes, i.e., massive particles (Λ_c^+) have less c_s^2 value as compared to D^0, which is relatively less massive.

Figure 2 shows the variation of κ_T with charged-particle multiplicity for Λ_c^+ and D^0. We observed that final state multiplicity is vital in describing the medium formation in hadronic collisions. In lower multiplicity classes, the value of isothermal compressibility is relatively high. It decreases with the increase in particle multiplicity until it attains a minimum value at the higher multiplicity classes. This observation shows that the system is more incompressible at higher multiplicities.

Further, the Knudsen number in fig. 3 is decreases with charged-particle multiplicity. This indicates that the system toward high-multiplicity events is in thermal equilibrium owing to interaction length being much smaller than system size and thereby hydrodynamical treatment is applicable. This result of K_n somewhat confirms the probability of a high-multiplicity class to be thermally equilibrated as indicated by the observation of c_s^2 and κ_T.

III. SUMMARY

1. It is observed that both for Λ_c^+ and D^0, squared speed of sound increases with charged-particle multiplicity following mass ordering and approaches to the ideal gas limit towards high-multiplicity events.
2. We observed that κ_T decreases with charged-particle multiplicity and attains a minimum at high multiplicity both for Λ_c^+ and D^0. This indicates that the system is more incompressible at high-multiplicity events.
3. It is also observed that the Knudsen number decreases with charged-particle multiplicity, indicating the possibility of thermal medium formation. This also points out that the hydrodynamic behavior is higher in high-multiplicity than in low-multiplicity events.
4. From the above three observations, it is clear that the system with higher final state multiplicity shows a tendency of thermalization and is of particular interest in the search for QGP in small system.

ACKNOWLEDGEMENT

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Reference

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[2] B. Sahoo, S. Deb and R. Sahoo, [arXiv:2208.10901 [hep-ph]].