System Size and Multiplicity Dependence of Thermal Parameters in High Energy Collisions at LHC

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Abstract

The comprehensive study of chemical freeze-out parameters in high energy collisions at LHC is presented. The experimental data of light flavor particles are used to obtain the freeze-out parameters using the statistical thermal model. Three different ensembles are used in this study: the grand canonical ensemble, the canonical ensemble with exact strangeness conservation, and the canonical ensemble with exact baryon number, strangeness, and electric charge conservation. Chemical freeze-out temperature, Radius, and strangeness suppression factor are compared for different collision systems and energies. The multiplicity dependence of these parameters and thermodynamic limit in high multiplicity pp collisions at LHC are also discussed.

Introduction and Motivation

- Statistical thermal model has been quite successful in describing hadron yields in high energy collisions.
- The yields of produced hadrons have been fitted by mostly the Grand Canonical Ensemble (strangeness number, baryon number and charge number are conserved on an average) and Strangeness Canonical Ensemble (only baryon and charge number are conserved on average, strangeness is exactly conserved).
- In this study, we extend the application of statistical thermal model to the full canonical ensemble, where all quantum numbers are treated exact.
- In statistical mechanics, the system in the thermodynamic limit when the total number of particles N and the volume V becomes large but the ratio N/V remains finite. Thus, the microcanonical, canonical, and grand canonical ensembles become equivalent.
- ALICE experiment at LHC, CERN has collected large amount of data in various collision systems such as pp, p-Pb, and Pb-Pb etc. The large amount of data has made it possible to study differential measurements and multiplicity dependent measurements in small systems such as pp. One could test the thermodynamic limit in high energy collisions using these data. It would be first experimental verification of statistical thermodynamic limit if found.

Thermal Model

Grand Canonical Ensemble (GCE):

- The quantum numbers are conserved on average and the conservation is implemented by using chemical potentials.
- The partition function depends on thermodynamic quantities and the Hamiltonian in system of N hadrons

$$Z_{\rm GCE} = {\rm Tr}[e^{-(H-\mu N)/T}]$$

and is given by

$$\ln Z_{\rm GCE}(T,\mu,V) = \sum_i g_i V \int \frac{d^3p}{(2\pi)^3} \exp\left(-\frac{E_i-\mu_i}{T}\right)$$

g_i – degeneracy factor of hadron
V – volume of the system
μ_i – chemical potential associated with hadron I

From here the yield N_i can be obtained.

Strangeness Canonical Ensemble (SCE):

- The exact implementation of strangeness conservation.
- The partition function will not include chemical potential for strangeness:

$$Z_{\rm SCE} = {\rm Tr}\left[e^{-(H-\mu N)/T}\,\delta_{(S,\sum_i S_i)}\right]$$

This leads to

$$Z_{\rm SCE} = \frac{1}{(2\pi)}\int_0^{2\pi} d\phi\, e^{-iS\phi} Z_{\rm GCE}(T,\mu_B,\lambda_S)$$

Here the δ function imposes exact strangeness conservation.

Full Canonical Ensemble (FCE):

- The exact conservation of baryon, charge, and strangeness quantum numbers.
- The partition function is given by

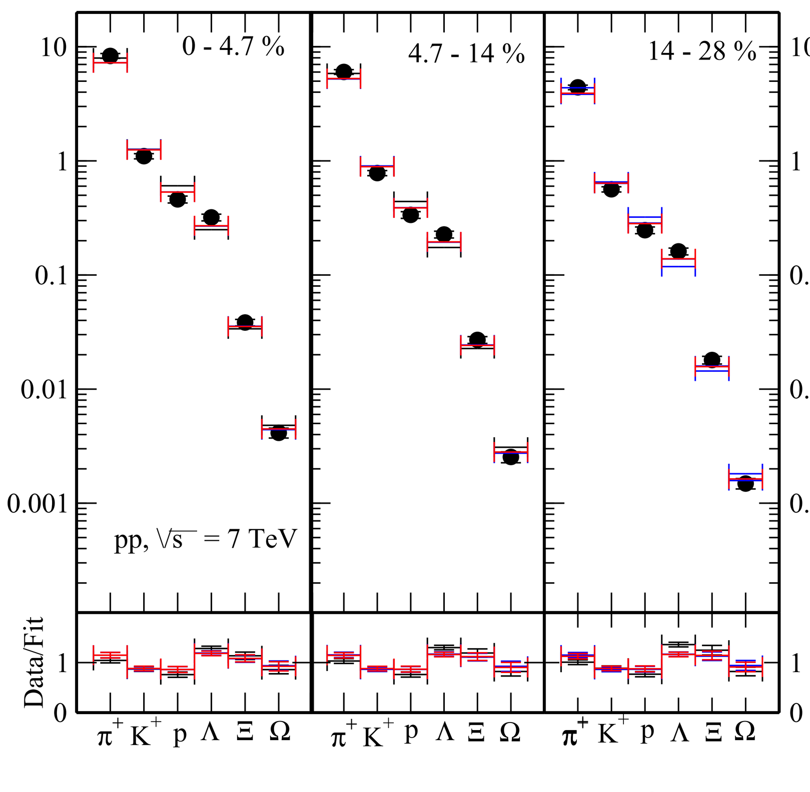
$$Z_{\rm FCE} = {\rm Tr}\left[e^{-H/T}\,\delta_{(B,\sum_i B_i)}\delta_{(Q,\sum_i Q_i)}\delta_{(S,\sum_i S_i)}\right]$$

which leads to

$$Z_{\rm FCE} = \frac{1}{(2\pi)^3}\int_0^{2\pi} d\alpha\, e^{-iB\alpha}\int_0^{2\pi} d\psi\, e^{-iQ\psi} \times \int_0^{2\pi} d\phi\, e^{-iS\phi} Z_{\rm GCE}(T,\lambda_B,\lambda_Q,\lambda_S)$$

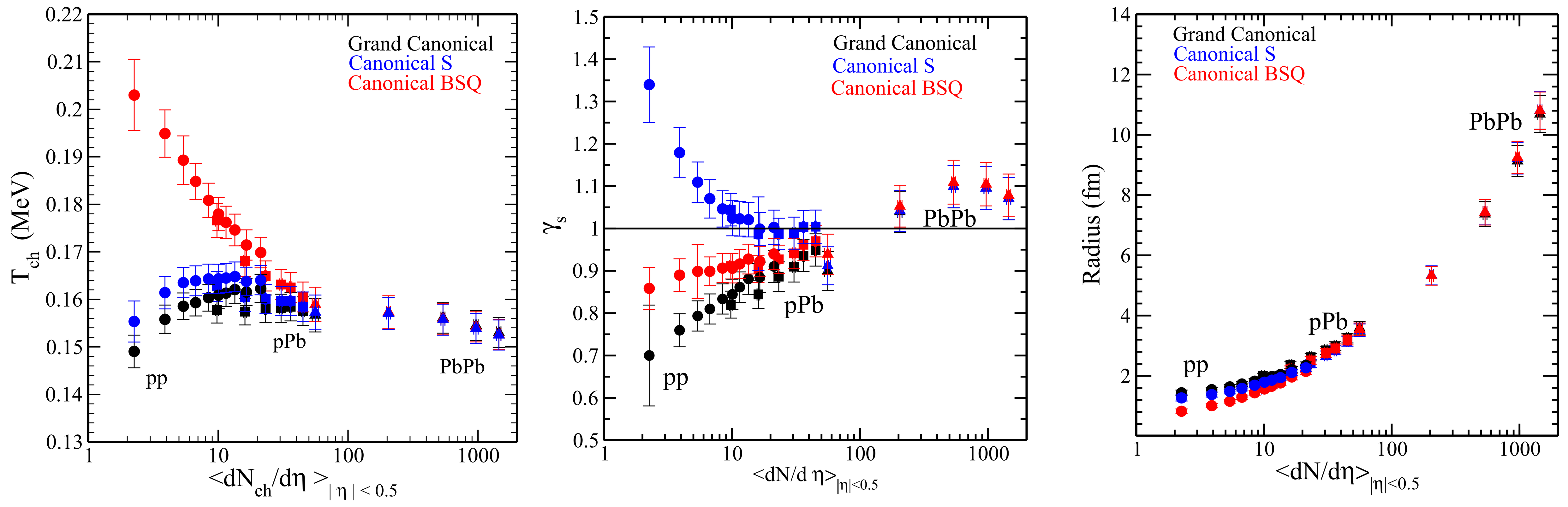
Results & Discussions

- Fit results for pp collisions at $\sqrt{s}$ = 7 TeV using three ensembles



Lower panels represent ratio of data over model

- Freeze-out parameters as a function of multiplicity for various systems pp, p-Pb and Pb-Pb using three ensembles



- T_{ch}, γ_S, and radius show smooth evolution as a function of multiplicity
- The three ensembles GSE, SCE, and FCE agree well for p-Pb and Pb-Pb but not for pp systems
- The three ensembles yield similar result for $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5} > 20$
- This could be the **first experimental evidence of thermodynamics limit** in high energy collisions

Summary

- Comparison of GCE, SCE, and FCE is done for various collision systems – pp, p-Pb, and Pb-Pb.
- The results from the three ensembles agree well for large systems such as p-Pb and Pb-Pb but show differences for pp collisions
- The three ensembles yield similar results for $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5} > 20$
- This could be the first experimental evidence of the thermodynamic limit.

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