Estimation of smallest system size of Quark-Gluon Plasma in p-Pb collisions at 5.02 TeV

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Here we attempt to find an approximate estimate of the smallest size of QGP volume that can be modelled with second-order hydrodynamics using the JETSCAPE framework. For this we consider a small system of p-Pb collisions at 5.02 TeV. We match the simulated system with the experimental data for the soft sector observables. Following the proposition by Paul Romatschke [1] about breakdown of hydrodynamics due to contribution of non-hydrodynamic mode, we found the smallest volume of QGP in p-Pb system to be approximately a sphere of diameter 3 fm.

I. INTRODUCTION

Second-order Hydrodynamics has been widely successful in modelling the QGP phase of heavy-ion collisions. There are indications that the gradient expansion of the energy-momentum tensor which is typically deployed in fluid dynamics is divergent. But this divergent gradient expansion is Borrel resummable, which in turn can be decomposed into a hydrodynamic and non-hydrodynamic mode parts as,

$$T^{\mu\nu}_{\text{borrel}} = \langle \hat{T}^{\mu\nu} \rangle_{\text{hydro}} + \langle \hat{T}^{\mu\nu} \rangle_{\text{non-hydro}}. \quad (1)$$

To study how this divergence manifests, one can analyse the collective modes of energy-momentum tensor using the linear response theory. For this a small perturbation around equilibrium value of energy-momentum tensor is considered,

$$\delta\langle T^{\mu\nu}\rangle(t,\mathbf{x}) = \int dt\, d^3x\, G^{\mu\nu,\gamma\delta}(t,\mathbf{x})\, S_{\gamma\delta}. \quad (2)$$

Here, the correlator $G_R^{\mu\nu,\alpha\beta}$ when expressed in Fourier space has complex singularity. The real part of the singular frequency is associated with excitation of equilibrium plasma, also called hydrodynamic mode frequency. The complex part of frequency is associated with the dissipative effects. This complex part of frequency happens to be dependent on the second-order transport coefficient called shear relaxation time. Paul Romatschke [1] predicted that large deviation in elliptic flow for extreme values of shear relaxation time in peripheral collisions would indicate breakdown of second-order hydrodynamic description of QGP phase. A previous work [2] was an attempt to find this threshold for peripheral Pb-Pb and Au-Au collisions. In the ongoing work, a small part of which is presented here, we use the same concept to find the smallest QGP size in p-Pb collisions at 5.02 TeV with a modified system.

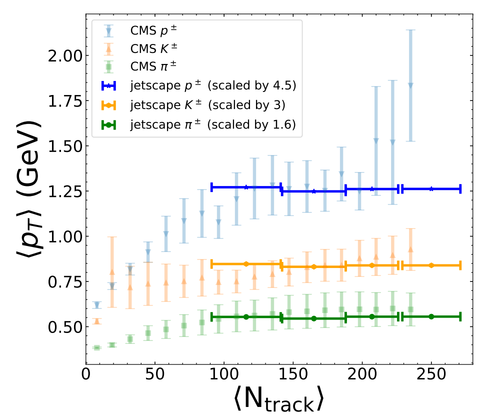

FIG. 1. Average transverse momentum as a function of the number of tracks for charged pions, kaons and protons compared with the corresponding experimental data.

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II. MODEL FRAMEWORK

To simulate p-Pb collisions at 5.02 TeV, we used the JETSCAPE framework [3] which involves T_{R}ENTo initial condition, *Freestreaming* as pre-equilibrium stage model, MUSIC for hydrodynamics stage of QGP and (iSS & SMASH) models for hadron after-burner stage. Temperature dependant shear and bulk viscosity to entropy density ratios has been used whose parametrization is given in Ref. [3]. We matched the simulated system with the experimental setup of p-Pb collision, using light particles observables like p_T-spectra and rapidity spectra. Fig. (1) shows the average transverse momentum as a function of the number of tracks for charged pions, kaons and protons compared with the corresponding experimental data.

The shear relaxation time (τ_π) is given by the expression: $\tau_\pi(T) = (b_\pi/T)(\eta/s)$. We independently varied shear relaxation time through varying b_π as well as using variation of $(\eta/s)(T)$ allowed by the Bayesian study. Small variations of shear relaxation time normalizaiton ($b_\pi = 3.5$ to 5.5) was found to have negligible effect on elliptic flow (Sec. VIII-C of [3]). We qualitatively find an abrupt increase in elliptic flow fluctuation when plotted for extreme values of shear relaxation time ($b_\pi = 2, 8$) as a function of dN/dy. This increase in fluctuation was noticed at apporximately $dN/dy = 8$, which roughly lie close to the centrality percent bin of 70-80%. Fig. (2) shows the x-τ temperature contour plot of system evolution at hydrodynamic stage for the 65-75%, 70-80% and 75-85% centralities respectively. We clearly see that the lifetime of a system decreases as we go towards peripheral collisions. The contour is marked for temperature value of 156 MeV which is the pseudo-critical temperature. From the contour plot of 70-80%, we find that the approximate system size of QGP which adequately show agreement with second-order hydrodynamics is a volume of diameter 3 fm.

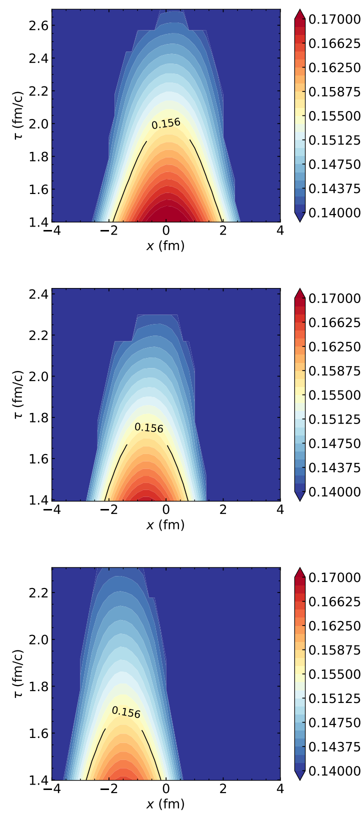

FIG. 2. Temperature contour as a function of evolution time and transverse x-coordinate of system for 65-75%(upper), 70-80%(middle) and 75-85%(lower) centrality percentile values.

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[3] D. Everett et al. (JETSCAPE Collaboration), Phys. Rev. C **103**, 054904 (2021).