Study of initial state of causal dissipative relativistic fluid expansion in p-p and p-Pb collisions at LHC energies with percolation color sources approach

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Abstract

By using the string percolation framework we study the shear and bulk viscosity over entropy ratio in addition to studying the mixed effect of the two viscosities in high multiplicity events in p-Pb and p-p collisions at the current LHC energies, where evidence on collective like effects has been found recently on data. Evidence of the formation of a strongly interacting medium similar to that obtained in nuclear collisions is shown. Moreover effects of non thermal equilibrium are shown to be significant.

The Model

The phase transition in QCD can be described from percolation theory by using critical orden parameters. In the String Percolation Model (SPM) we use the 2-dimensional percolation theory over the overlapping area of a collision, S, considering the chromodynamic interaction as color flux tubes stretched among the colliding partons of the proyectiles or targets. By the Schwinger mechanism more strings are created and more particles are produced, which are then identified by the detectors.

The number of initial strings, $\bar{N}^s$, depends on the energy of the collision, on the number of participants and, of course, on the centrality of the event.

$$\bar{N}^s = 2 + 4\frac{S_0}{S}\left(\frac{\sqrt{s}}{m_p}\right)^{2\lambda}, \tag{1}$$

where $m_p = 938.3$MeV is the mass of the proton and the power $\lambda = 0.186$ describes the multiplicity increase with the energy in p-p and A-A collisions. The transverse area of a string is $S_0 = \pi r_0^2$, with $r_0 = 0.25$fm[1]. As the multiplicity increases the string density will increase to and the strings will start to overlap to form macroscopic clusters, thus marking a phase transition defined by the percolation threshold ξ_c^t, the critical string density, to classify the events the string density is defined as

$$\xi^t = \frac{S_0}{S}\bar{N}_s. \tag{2}$$

The average multiplicity at central rapidity region, $\mu \equiv dN/d\eta$, for each energy is related to the average number of initial strings through the following geometrical scalling function of the string density[2]

$$\mu = \kappa F(\xi^t)\bar{N}^s, \tag{3a}$$

$$F(\xi^t) \equiv \sqrt{\left(1 - e^{-\xi^t}\right)/\xi^t}. \tag{3b}$$

The transverse momentum distribution behaves as the following power law

$$\frac{1}{N}\frac{d^2N_{ch}}{d\eta dp_T}\bigg|_{\eta=0} = a\frac{(p_0 b)^{\alpha-2}}{(p_T + p_0 b)^{\alpha-1}}, \tag{4}$$

To obtain a, p_0 and α, which are energy parameters, it is necessary to make a fit over the minimum bias transverse momentum distributions from data [3,4,5], as shown in the figure 1, the values of these parameters are shown in table 1.

	$\sqrt{s}$(TeV)	a	p_0(GeV)	α
p-Pb	5.02	85±3.40	2.780±0.171	9.937±1.716
p-p	13	30.77±1.23	2.478±1.862	9.980±0.297
	7	33±1.32	2.305±0.079	9.752±0.140
	2.76	27±1.08	2.032±0.074	9.448±0.147
	0.9	23±0.92	1.785±0.071	9.287±0.165

Table 1: Energy parameter values

In the thermodynamic limit

$$b \to \sqrt{F(\xi_0^t)/F(\xi^t)}, \tag{5}$$

that measures the deviation between high multiplicity (ξ^t) and minimum bias events (ξ_0^t). We use the relation (5) in eq. (4) to make a new fit over the high multiplicity events obtaining the corresponding Color Reduction Factors.

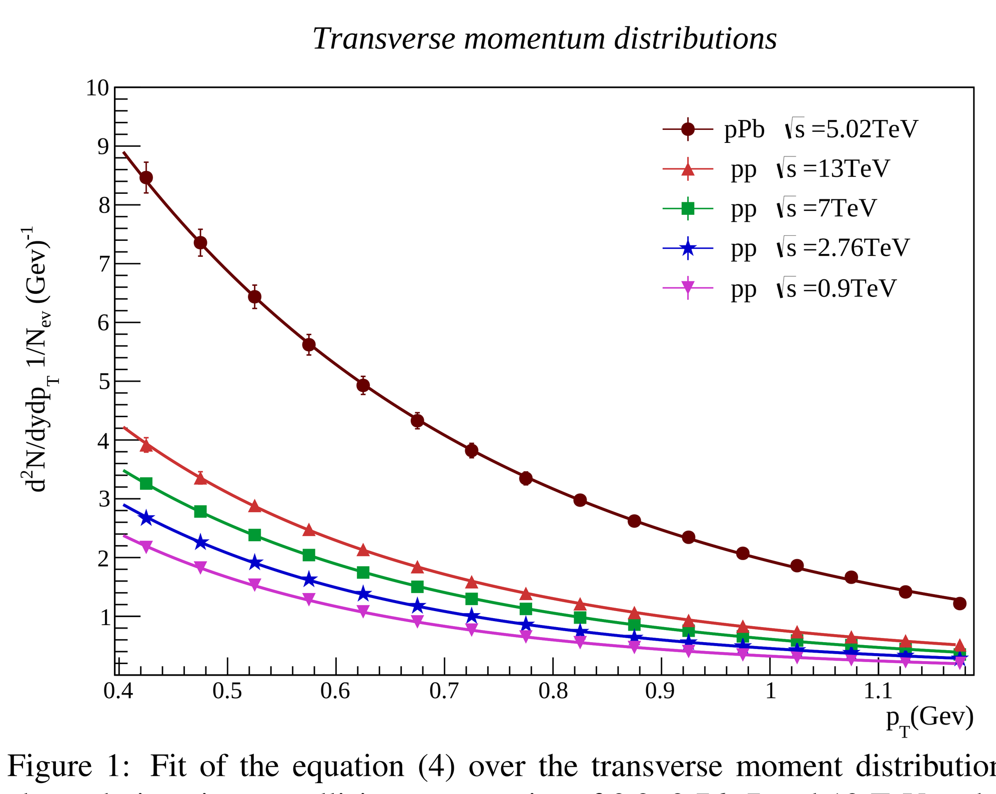

Figure 1: Fit of the equation (4) over the transverse moment distributions of charged pions in p-p collisions at energies of 0.9, 2.76, 7 and 13 TeV and p-Pb collisions at 5.02 TeV, in region $0.4 < p_T < 1.175$, data from the CMS collaboration [3,4,5].

Observables

The stress of the macroscopic clusters in SMP fluctuates around their mean value due to chrome-electric field fluctuations from the nature of the quantum vacuum in QCD. These fluctuations determine a Gaussian distribution in terms of the color reduction factor that is related to a thermal distribution. The average temperature of the system is proportional to the average moment of the produced particles, in this way a local temperature is defined, even in small systems, that is expressed as:

$$T(\xi^t) = \sqrt{\frac{\langle p_T^2\rangle_0}{2F(\xi^t)}}, \tag{6}$$

where $\sqrt{\langle p_T^2\rangle_0}$ =190.25 MeV, using $\xi_c^t = 1.2$ at critical temperature of 154MeV obtained from HotLQCD collaboration[6].

The string density is the local order parameter which determines the geometric phase transition of the system. In the case of the phase transition in QCD, the local order parameter is the energy density ε, for which there is also a critical value ε_0, the proposal is that the relationship between both order parameters is directly proportional:

$$\frac{\varepsilon}{\varepsilon_c} = \frac{\xi^t}{\xi_c^t}. \tag{7}$$

where $\varepsilon_c/\xi_c^t = 0.56010039$ GeV/fm^3, obtained in [2].

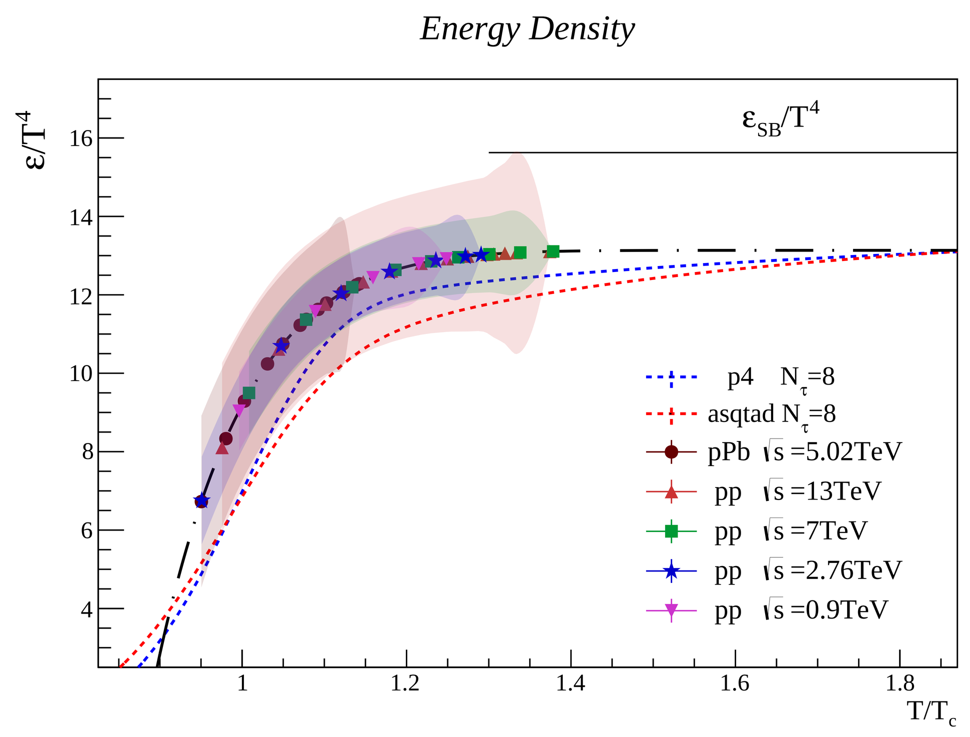

Figure 2: Behavior of ε/T^4 with T/T_c compared to Lattice QCD predictions for $2+1$ flavors (two light and one heavy) using 8 lattices with p4 action in blue and asqtad action in red [7], the curve of the model is represented by the dashed black line.

The behavior of the elliptic flow in nuclear collisions suggests that the matter created in these systems behaves like an almost perfect fluid, with a small contribution of viscosity, the indirect measurement of the Shear Viscosity over entropy density η_s/s was proposed as a measure of the fluidity of the medium; the relativistic kinetic theory for the viscosity establishes the relation $\eta_s/s = T\lambda_{\rm mfp}/5$, where the mean free path is $\lambda_{\rm mfp} = 1/(\sigma_{tr}n) = L/(1 - e^{-\xi^t})$, so

$$\frac{\eta_s}{s} = \frac{TL}{5(1 - e^{-\xi^t})}. \tag{8}$$

The trace anomaly is the expected value of the trace of the energy-moment tensor in QCD, $\langle T_\mu^\mu\rangle = \varepsilon - 3P$. This observable measures the deviation with respect to the conformal behavior and identifies the residual interactions in the medium. It is expected that this observable is related to the viscosity properties of the medium, qualitatively it has been verified that the behavior of this observable is inversely proportional to the η_s/s ratio:

$$\Delta \equiv \frac{\varepsilon - 3P}{T^4} \simeq \frac{s}{\eta_s}. \tag{9}$$

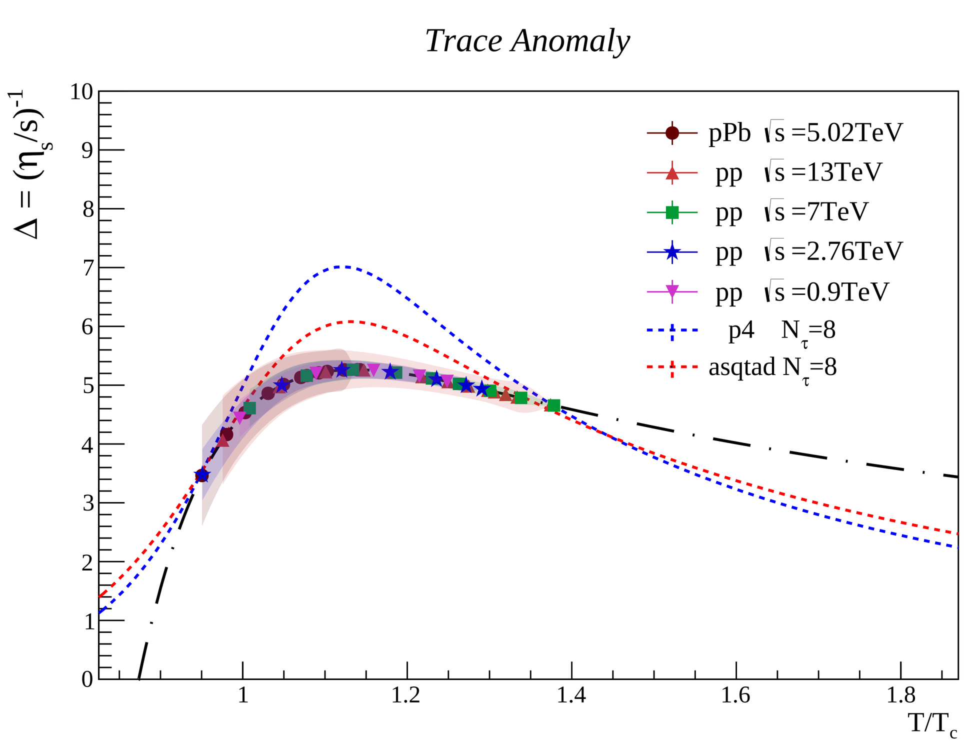

Figure 3: The plot shows the behavior of the trace anomaly approaching the inverse of η_s/s from eq (9), compared to the LQCD results for that observable.

The adiabatic speed of sound is a well defined quantity for a medium in thermal equilibrium, using thermodynamic identities can be written as follows

$$c_s^2 = \left(\frac{\partial P}{\partial\varepsilon}\right)_s = \left(\frac{\partial P}{\partial T}\right)_V\left(\frac{\partial T}{\partial\varepsilon}\right)_V = s\left(\frac{\partial T}{\partial\varepsilon}\right)_V, \tag{10}$$

with a fundamental relation $Ts = \varepsilon + P$, we can obtain in terms of the model:

$$c_s^2 = \frac{sT}{4\varepsilon}\left(1 - \frac{e^{-\xi^t}}{F(\xi^t)^2}\right), \tag{11}$$

this speed of sound has a behavior quite similar to that obtained in Lattice, as shown in Figure 4.

Results

There are reasons why compressibility functions as a well-defined concept, so it is necessary expand our definition of sound velocity to dissipative medium. The perfect fluids in the balance are translated into a specific type of heat and an increase in entropy, which is the communication in the reversible processes, this type of systems are useful to describe the hydrodynamic expansion of the systems in heavy ion collisions, where after a relaxation time τ_0, the system is thermalised. However, we must take into account the hydrodynamic expansion of the causal relativistic dissipative fluid in small collision systems that can present dissipative properties, for that reason it is necessary to introduce properties of "non-equilibrium", as a first approximation the increasing entropy is considered with a cylindrical expansion with one of the longitudinal dimensions, L, fixed:

$$c_{sL}^2 = \left(\frac{\partial P}{\partial\varepsilon}\right)_L = \frac{P}{\varepsilon} + \frac{T^3\Delta}{3s}c_s^2. \tag{12}$$

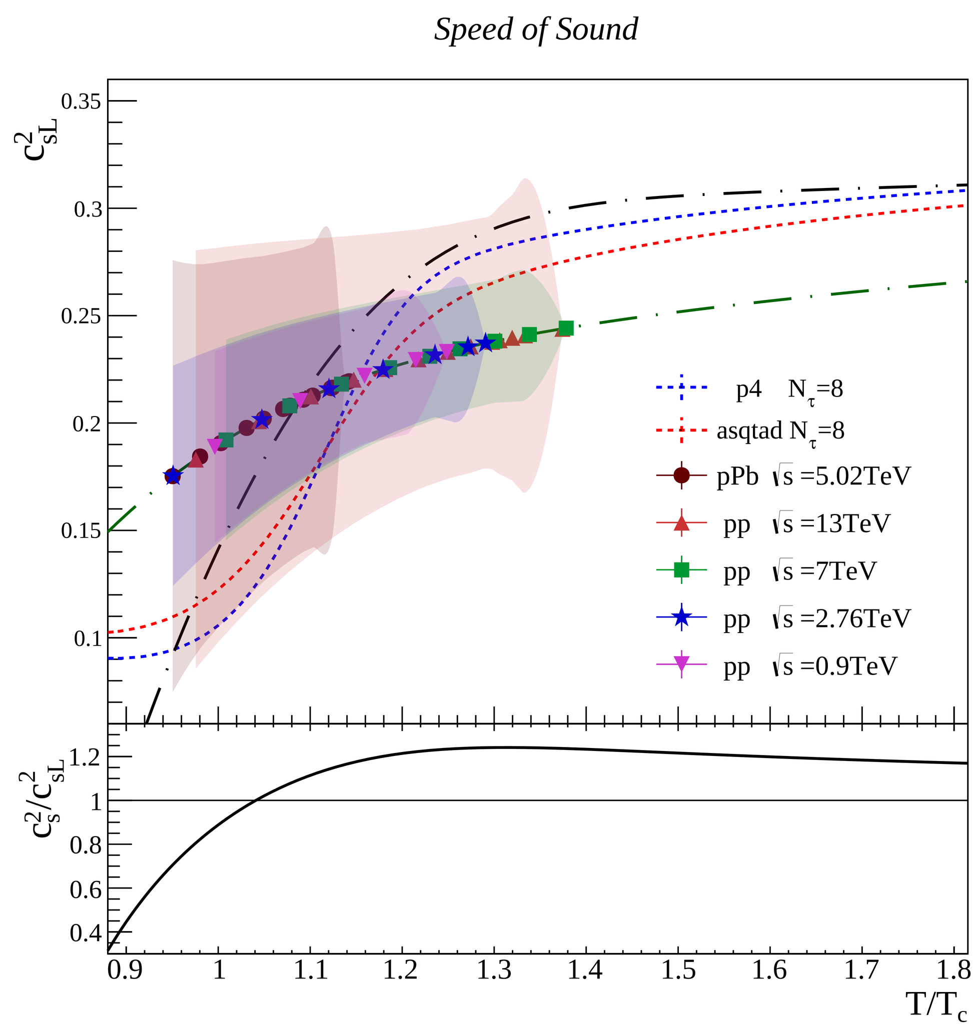

Figure 4: The upper graph shows the approximation of the behavior of the speed of sound in a dissipative medium, eq (12), whose curve is shown with green dotted line, the adiabatic speed of sound is shown with the black dotted line. The lower graph shows the comparison between the two calculated speeds, noting that equality occurs at very high temperatures.

The formulation of relativistic hydrodynamics is absolutely not trivial, since the inadequate implementation of dissipative formulas violates relativistic causality and leads to inconsistent behaviors in the property of stability, for the calculation of bulk viscosity, the projection operator's approach was considered to derive the microscopic formulas for the transport coefficients in CDRF that can be seen as a generalization of the Navier-Stokes equation. The consistency of this approach has been confirmed by comparing with the results obtained from the Boltzmann equation. In addition, it is verified that the formula satisfies the exact result obtained from the f-sum rule when applied to the diffusion process (generalized):

$$\frac{\eta_b}{s} = \left(\frac{1}{3} - c_s^2\right)\tau_\Pi T - \frac{2T^4\tau_\Pi\Delta}{9s}. \tag{13}$$

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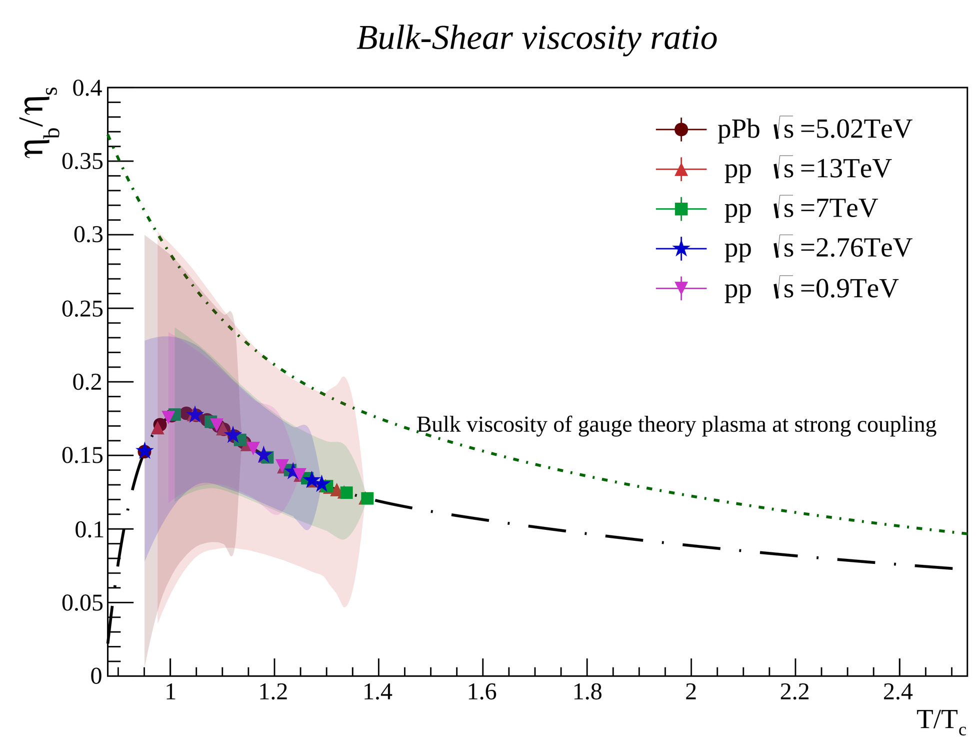

Figure 5: Figure shows the behavior of the shear viscosity over the bulk viscosity, which is well carried out causally using the modification for the speed of sound, the quotient between the two viscosities shows a change in the steep slope that suggests a second-order phase transition for these systems, the quotient is below of the organic curve, represented by the dotted green line, based on dual holography, where it is speculated that $\eta_b/\eta_s \geq 2(1/3 - c_2^s)$[9].

Conclusions

1. The signals observed in small collision systems show that perhaps these systems do not reach thermalization, which implies the bulk properties for these systems.
2. The fact of considering equations for dissipative media allows us to obtain new physics results that are relevant, since the QGP that is formed in collisions of small systems may be, rather, different to that found in nuclear collisions.

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