ESTIMATION OF THE ENERGY DENSITY OF THE FORMED MEDIUM IN SMALL COLLISION SYSTEMS AT THE LHC ENERGIES*

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Results on small collision systems are still under study to characterize whether a strongly interacting perfect fluid is formed or not. In this work, we present an estimate of the initial-state energy density on small collision systems. Results consider effects of initial state fluctuations on geometry and finite volume in the clustering of color sources framework. The results are compared with Lattice QCD calculations. This work presents a perspective of how high-energy densities can be reached in such small collision systems at the LHC energies. The results give a collective description of the system.

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1. Introduction

Since the T.D. Lee and G. Wick proposal in 1974 of finding new physics by distributing the density of nuclear matter or energy in a finite volume, restoring broken symmetries of the vacuum physical and creating abnormal states of dense nuclear matter [1], it was found that the asymptotic freedom in QCD implies the existence of a very dense form of nuclear matter made up of unconfined quarks and gluons [2–4], which was later called Plasma of Quarks and Gluons (QGP) [5].

The Bjorken energy density was proposed by J.D. Bjorken in 1983 as a means of estimating the energy density produced in high-energy heavy-ion collisions (HIC) [6]. It provides a useful measure of the amount of energy that is available for the creation of the QGP. The higher the energy density, the more likely it is that the QGP will be created, and the more detailed information can be obtained about the properties of the QGP.

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In this contribution, we report on the estimation of energy density from a phenomenological point of view and compare it with Lattice QCD calculations [7].

We introduce the phenomenology of the String Percolation Model (SPM) in Section 2, which is the percolation theory-based model for non-perturbative heavy-ion physics [8, 9], and its modifications in the cases far from the thermodynamic limit. In Section 3, we describe the method we use to extract information on thermodynamic properties from experimental data, and, subsequently, we fit the transverse momentum distribution of *pp* collisions at the LHC energies. Finally, in Section 4, we introduce the SPM energy density approximation applying its relation with the percolation parameter found in [9, 10]. With the SPM results, we can discuss the properties of the medium formed in the case of small collision systems at the LHC energies.

2. Percolation color sources

The percolation theory is closely associated with phase transition phenomena [11–13], so that SPM has described successfully the collective effects on HIC's medium formed at the RHIC and LHC energies [8, 9, 14–20].

The interaction between nuclei in a collision is effectively represented by stretched Lund model-like strings [21] which have physical properties. We consider the projection area of strings in the overlapping area S in the impact parameter plane. The small discs (transverse strings) have area $S_0 = \pi r_0^2$ (~ 3.5 mb from parton–parton cross section [22, 23]).

We characterize the system by a density parameter that depends on the area fraction occupied by a determined number of strings

$$\xi = \frac{S_0}{S} N_{\mathrm{s}} \,, \tag{1}$$

where N_{s} is the number of initial strings, which for a minimum bias distribution escalates with energy as a power law [24].

In *pp* collisions, the areas S and S_0 can be described in terms of the radius of a single disc $r_0 \simeq 0.2385$ fm [25–28] and the proton radius $R_p \simeq 1$ fm.

Given an initial number of percolating strings, the multiplicity density $\mathrm{d}N/\mathrm{d}\eta \equiv \mu$ is expressed as [24]

$$\mu = \mu_0 F(\xi) N_{\mathrm{s}} \,, \tag{2}$$

where μ_0 was reported in previous works [8, 9].

The geometric scaling function $F(\xi)$, namely the color reduction factor, emerges from cluster formation [8, 9], and increases with the string tension of the cluster and the average momentum fraction of the partons $\langle p_{\mathrm{T}}^2 \rangle$. $F(\xi)$ is expressed as [8, 9, 29]

$$F(\xi)=\sqrt{\frac{1-\mathrm{e}^{-\xi}}{\xi}} \tag{3}$$

in the thermodynamic limit.

2.1. Maximum deviation from thermodynamic behavior

We propose a modification to the color reduction factor to describe the maximum deviation from the thermodynamic limit reported in [30, 31] as

$$F_{\mathrm{s}}(\xi)=F(\xi)\left(m+c\sqrt{\coth\left(\frac{\xi}{2}\right)}\right), \tag{4}$$

where $m = 0.7714731 \pm 0.01468$ and $c = 0.0609589 \pm 0.007527$, similar to previously reported [31].

3. Transverse momentum distribution

The initial-state properties can be derived from $F_{\mathrm{s}}(\xi)$. The temperature involves the Schwinger mechanism for non-massive particles, the strings with higher tension x will break producing quark pairs which later on hadronize. Thus, the transverse momentum distribution of charged particles is given by a p_{T}-exponential [32]. The string tension describes a Gaussian distribution that convolutes with the Schwinger mechanism and a thermal-like distribution appears [9, 25]

$$\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}^{2}}\sim\exp\left(-p_{\mathrm{T}}\sqrt{\frac{2F_{\mathrm{s}}(\xi)}{\langle p_{\mathrm{T}}^{2}\rangle_{0}}}\right), \tag{5}$$

with $\langle p_{\mathrm{T}}^{2}\rangle_{0}=\langle x^{2}\rangle F(\xi)/\pi$ the mean square transverse momentum of a single string from where we can extract the local temperature as

$$T(\xi)=\sqrt{\frac{\langle p_{\mathrm{T}}^{2}\rangle_{0}}{2F_{\mathrm{s}}(\xi)}}\,. \tag{6}$$

As in [24, 33], we consider the critical temperature $T_{\mathrm{c}}=T(\xi_{\mathrm{c}})=154\pm 9$ [34] in terms of critical string density $\xi_{\mathrm{c}}=1.128$ [35], thus

$$\frac{T}{T_{\mathrm{c}}}=\sqrt{\frac{F(\xi_{\mathrm{c}})}{F(\xi)}}=\frac{0.879947816}{\sqrt{F(\xi)}}\,. \tag{7}$$

3.1. Fit over experimental data

We fit Eq. (5) over the ALICE Collaboration results of transverse momentum distribution at 5.02 and 13 TeV [36], in $0.15 < p_{\mathrm{T}} < 1.15$ GeV/c range, the 13 TeV fit is shown in Fig. 1.

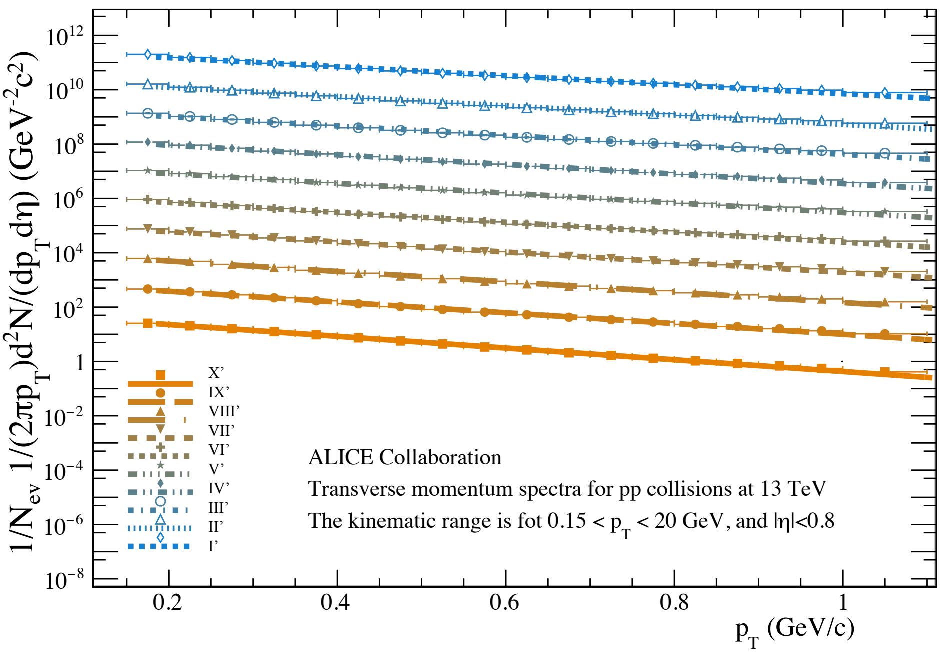

Fig. 1. p_{T}-exponential fit over the transverse momentum spectra as a function of the event multiplicity estimated with the signal in the VZERO detector for *pp* collisions at 13 TeV.

4. Energy density

The order parameter in the phase transition to QGP is the energy density [9, 10, 37] which is found to be proportional to the model main parameter ξ. Thus, we use the relation

$$\varepsilon = \varsigma\xi\,, \tag{8}$$

where $\varsigma = \varepsilon_{\mathrm{c}}/\xi_{\mathrm{c}} = 0.5601$ GeV/fm^3 [10].

In Fig. 2, we present the energy density estimation by using Eq. (3) in the thermodynamic limit and Eq. (4) as the maximum deviation found by the MC estimation [31]. Our estimation of energy density for *pp* collisions has the same behavior as the Lattice QCD calculations [7].

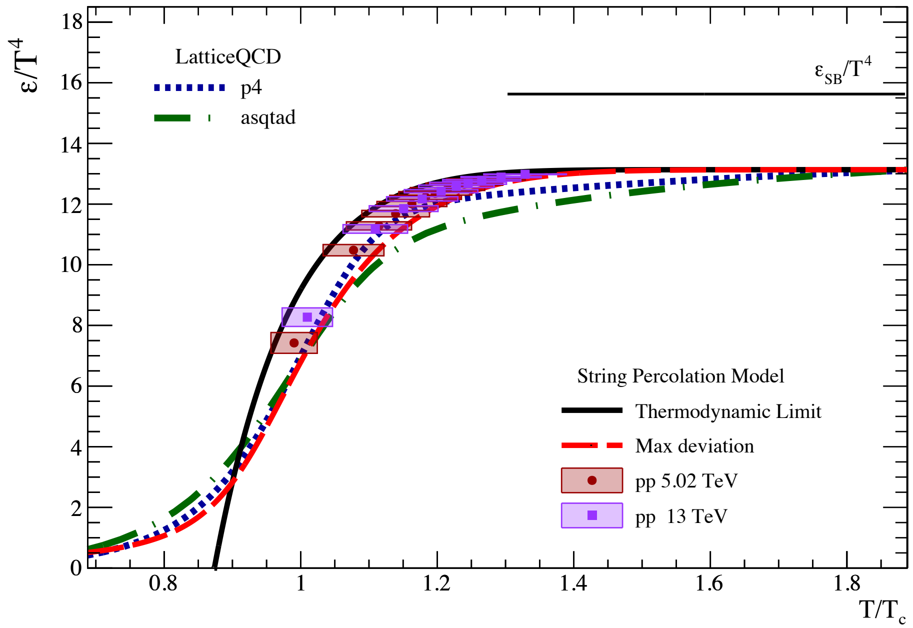

Fig. 2. (Color online) Energy density over T^4 behavior. The red dashed line shows the energy density computed with the maximum deviation from the thermodynamic limit, Eq. (4), while the black solid line is the calculation using $F(\xi)$, Eq. (3) [9]. The energy density of *pp* multiplicity classes for (circles) $\sqrt{s} = 5.02$ TeV, and (squares) $\sqrt{s} = 13$ TeV are shown with their corresponding error represented by the boxes. We include a comparison with Lattice QCD computations using p4 and asqtad actions [7].

5. Conclusions

We have presented the calculation of energy density corresponding to the formed medium in small collisions systems based on LHC data, by including size and initial geometry fluctuation effects.

The results indicate a clear phase transition which is consistent with the recent collective effects measured for high multiplicity events in small collision systems.

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