DECONFINEMENT IN pp COLLISIONS AT LHC ENERGIES*

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Recently, the CMS Collaboration has published identified particle transverse momentum spectra in high multiplicity events at LHC energies $\sqrt{s} =$ 0.9–13 TeV. In the present work, the transverse momentum spectra have been analyzed in the framework of the color fields inside the clusters of overlapping strings, which are produced in high-energy hadronic collisions. The initial temperature and shear viscosity-to-entropy density ratio η/s are obtained. For the higher multiplicity events at $\sqrt{s} = 7$ and 13 TeV, the initial temperature is above the universal hadronization temperature and is consistent with the creation of deconfined matter. In these small systems, it can be argued that the thermalization is a consequence of the quantum tunneling through the event horizon introduced by the confining color fields, in analogy to the Hawking–Unruh effect.

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1. Introduction

The observation of high total multiplicity, high transverse energy, non-jet and isotropic events led Van Hove [1] to conclude that high-energy density events are produced in high-energy $\bar{p}p$ collisions. In these events, the transverse energy is proportional to the number of low transverse momentum particles. This basic correspondence has been previously explored over a wide range of the charged particle pseudorapidity density $\langle \mathrm{d}N_{\mathrm{c}}/\mathrm{d}\eta \rangle$ in $\bar{p}p$ collisions at the center-of-mass energy of $\sqrt{s} = 1.8$ TeV [2]. The multiplicity independent freezout energy density ~ 1.1 GeV/fm^3 at a temperature of ~ 179 MeV further suggested deconfinement in $\bar{p}p$ collisions [3].

The objective of the present work is to obtain the initial temperature and the shear viscosity-to-entropy density ratio η/s of the matter created in

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pp collisions at LHC energies by analyzing the published CMS data [4, 5] on the transverse momentum spectra of pions using the framework of clustering of color sources.

2. Clustering of color sources

Multi-particle production at high energies is currently described in terms of color strings stretched between nucleons of the projectile and target, which decay into new strings through $q\bar{q}$ pairs production and, subsequently, hadronize to produce the observed hadrons [6]. Color strings may be viewed as small discs in the transverse space filled with the color field created by colliding partons. Particles are produced by the Schwinger mechanism, emitting $q\bar{q}$ pairs in this field [7]. With growing energy, the number of strings grows and starts to overlap and interact to form clusters in the transverse plane very much similar to discs in two-dimensional (2D) percolation theory [6, 8]. At a critical density, a macroscopic cluster appears that marks the percolation phase transition. The critical density corresponds to the value of $\xi_{\mathrm{c}} \geq 1.2$ [8, 9]. This is termed as the Color String Percolation Model (CSPM) [6]. Knowing the color charge, one can obtain the multiplicity μ_n and the mean transverse momentum squared $\langle p_{\mathrm{t}}^2\rangle_n$ of the particles produced by a cluster of n strings [6]

$$\mu_n = N_{\mathrm{S}} F(\xi)\mu_1 \,; \qquad \left\langle p_{\mathrm{t}}^2\right\rangle_n = \left\langle p_{\mathrm{t}}^2\right\rangle_1 / F(\xi)\,, \tag{1}$$

where μ_1 and $\langle p_{\mathrm{t}}^2\rangle_1$ are the mean multiplicity and transverse momentum squared of particles produced from a single string with a transverse area S_1 and S_n is the area covered by n strings. $F(\xi)$ is the color suppression factor and is related to the percolation density parameter ξ [6]

$$F(\xi) = \sqrt{\frac{1-e^{-\xi}}{\xi}}\,; \qquad \xi = \frac{N_{\mathrm{S}} S_1}{S_{\mathrm{N}}}\,, \tag{2}$$

where N_{S} is the number of strings formed in the collisions and S_{N} is the nuclear overlap area.

3. Determination of the color suppression factor $F(\xi)$

In our earlier work, $F(\xi)$ was obtained in Au+Au collisions by comparing the charged hadron transverse momentum spectra from pp and Au+Au collisions [6]. To evaluate the initial value of $F(\xi)$ from data for Au+Au collisions, a parameterization of the experimental data of p_{t} distribution in pp collisions $\sqrt{s} = 200$ GeV was used [6]. The charged particle spectrum is described by a power law [6]

$$\mathrm{d}^2 N_{\mathrm{c}} / \mathrm{d}p_{\mathrm{t}}^2 = a/(p_0 + p_{\mathrm{t}})^{\alpha}\,, \tag{3}$$

where a is the normalization factor, p_0 and α are fitting parameters with $p_0 = 1.98$ and $\alpha = 12.87$ [6]. This parameterization is used in high multiplicity pp collisions to take into account the interactions of the strings [6]

$$\frac{\mathrm{d}^2 N_\mathrm{c}}{\mathrm{d}p_\mathrm{T}^2} = \frac{a}{\left(p_0\sqrt{F(\xi)_{pp}/F(\xi)_{pp}^{\mathrm{mult}}} + p_\mathrm{T}\right)^\alpha}\,, \tag{4}$$

where $F(\xi)_{pp}^{\mathrm{mult}}$ is the multiplicity-dependent color suppression factor. In pp collisions, $F(\xi)_{pp} \sim 1$ at low energies due to the low overlap probability.

In the present work, we have extracted $F(\xi)$ in high multiplicity events in pp collisions using CMS data from the transverse momentum spectra of pions at $\sqrt{s} = 0.9$, 2.76, 7 and 13 TeV [4, 5]. The spectra were fitted using Eq. (4) in the softer sector with p_t in the range of 0.12–1.0 GeV/c. Figure 1 (a) shows the extracted value of $F(\xi)$ as a function of $N_{\mathrm{tracks}}/\Delta\eta$ scaled by the interaction area $S_\perp$ from CMS experiment for $\sqrt{s} = 0.9$–13 TeV. N_{tracks} is the total charged particle multiplicity in the region $|\eta| < 2.4$ with $\Delta\eta \sim 4.8$ units of pseudorapidity. The interaction area $S_\perp$ has been computed in the IP-Glasma model [10]. Figure 1 (a) also shows Au+Au results at $\sqrt{s_{NN}} = 200$ GeV. It is observed that $F(\xi)$ as a function of $\mathrm{d}N_\mathrm{c}/\Delta\eta$ scaled by the transverse interaction area falls on a universal scaling curve for hadron–hadron and nucleus–nucleus collisions.

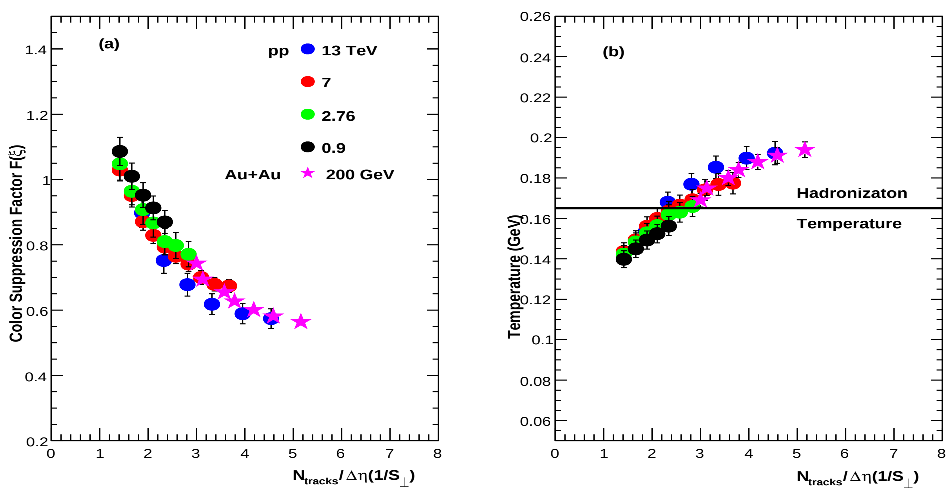

Fig. 1. (a) Color suppression factor $F(\xi)$ in pp, and Au+Au collisions *versus* $N_{\mathrm{tracks}}/\Delta\eta$ scaled by the transverse area $S_\perp$. (b) Temperature *versus* $N_{\mathrm{tracks}}/\Delta\eta$ scaled by $S_\perp$ from pp and Au+Au collisions.

4. Relation between $F(\xi)$ and temperature

The connection between $F(\xi)$ and the temperature $T(\xi)$ involves the Schwinger mechanism (SM) for particle production [6, 7]. The Schwinger distribution for massless particles is expressed in terms of p_{t}^2 [6]

$$\mathrm{d}n/\mathrm{d}p_{\mathrm{t}}^2 \sim e^{-\pi p_{\mathrm{t}}^2/x^2}\,, \tag{5}$$

where the average value of the string tension is $\langle x^2\rangle$. The tension of the macroscopic cluster fluctuates around its mean value because the chromo-electric field is not constant. The origin of the string fluctuation is related to the stochastic nature of the QCD vacuum. Such fluctuations lead to a Gaussian distribution of the string tension, which transforms SM into the thermal distribution [6, 11]

$$T(\xi) = \sqrt{\frac{\left\langle p_{\mathrm{t}}^2\right\rangle_1}{2F(\xi)}}\,; \qquad \left\langle x^2\right\rangle = \pi\left\langle p_{\mathrm{t}}^2\right\rangle_1/F(\xi)\,, \tag{6}$$

where $\langle p_{\mathrm{t}}^2\rangle_1$ is the average transverse momentum squared of particles produced from a single string. Figure 1 (b) shows a plot of temperature as a function of $N_{\mathrm{tracks}}/\Delta\eta$ scaled by $S_\perp$. The horizontal line at ~ 165 MeV is the universal hadronization temperature obtained from the systematic comparison of the statistical model parametrization of hadron abundances measured in high-energy e^+e^-, pp, and AA collisions [12]. In Fig. 1 (b), for $\sqrt{s} = 7$ and 13 TeV, higher multiplicity cuts show temperatures above the hadronization temperature and similar to those observed in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The temperatures obtained in higher multiplicity events are consistent with the creation of deconfined matter in pp collisions at $\sqrt{s} = 7$ and 13 TeV. The thermalization in pp collisions can occur through the existence of an event horizon caused by a rapid deceleration of the colliding nuclei [13, 14]. The thermalization in this case is due to the Hawking–Unruh effect [13, 15, 16]. In CSPM, the strong color field inside the large cluster produces deceleration of the primary $q\bar{q}$ pair which can be seen as a thermal temperature by means of the Hawking–Unruh effect [13].

5. Transport coefficient: shear viscosity

In the Color String Percolation Model (CSPM), the shear viscosity-to-entropy density ratio η/s was obtained in the framework of kinetic theory and the string percolation [6]. In this picture, the relevant parameter is the string density ξ. The following expression was obtained for η/s [6]:

$$\frac{\eta}{s} = \frac{TL}{5(1-e^{-\xi})}\,, \tag{7}$$

where T is the temperature and L is the longitudinal extension of the source $\sim$ 1–1.1 fm [6]. Figure 2 (a) shows η/s as a function of the temperature for pp collisions. The lower bound shown in Fig. 2 (a) is given by the AdS/CFT conjecture [17]. The results from Au+Au at 200 GeV and Pb+Pb at 2.76 TeV collisions are also shown in Fig. 2 (a). The results from pp collisions from $\sqrt{s}$ = 13 TeV show a very small η/s and that is 2.2 times the AdS/CFT conjectured lower bound $1/4\pi$.

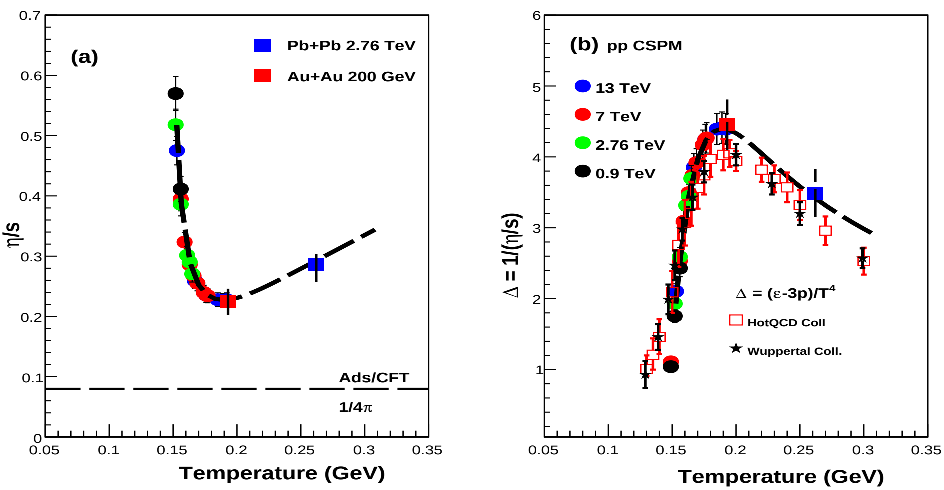

Fig. 2. (Color online) (a) η/s as a function of temperature T using Eq. (7) for $\sqrt{s}$ = 0.9, 2.76, 7 and 13 TeV. The lower bound shown is given by the AdS/CFT [17]. For comparison, the results from Au+Au and Pb+Pb at $\sqrt{s_{NN}}$ = 200 GeV and 2.76 TeV, respectively, are also shown as solid squares for 0–5% centrality [6]. (b) The trace anomaly $\Delta = (\varepsilon - 3p)/T^4$ *versus* temperature. Red open squares are from HotQCD Collaboration [19]. Black stars are from Wuppertal Collaboration [20]. The CSPM results are obtained as $\Delta = 1/(\eta/s)$ [6]. The black dotted line both in (a) and (b) corresponds to extrapolation from CSPM at higher temperatures.

The trace anomaly is the expectation value of the trace of the energy-momentum tensor, $\langle \Theta^{\mu}_{\mu} \rangle = (\varepsilon - 3p)$, which measures the deviation from conformal behavior and thus identifies the interaction still present in the medium [18]. The inverse of η/s also measures how strong are the interactions in the medium and, therefore, we expect a similar behavior as seen in the trace anomaly [6]. Figure 2 (b) shows $1/(\eta/s)$ and the dimensionless quantity, $(\varepsilon - 3p)/T^4$, obtained from lattice simulations [19]. We consider the Ansatz that the inverse of η/s is equal to the dimensionless trace anomaly $\Delta = (\varepsilon - 3p)/T^4$ [6]. The inverse of η/s is in quantitative agreement with Δ over a wide range of temperatures with the LQCD simulations [19]. The maximum in Δ corresponds to the minimum in η/s.

6. Summary and conclusions

We have analyzed the transverse momentum spectra of pions from pp collisions at LHC energies using CMS published data for temperature and the shear viscosity-to-entropy density ratio in the framework of clustering of color sources. The same universal scaling of the temperature is obtained for both pp and AA. For high multiplicity events at $\sqrt{s} = 7$ and 13 TeV, the temperature is above the universal hadronization temperature suggesting that the matter created is in the deconfined phase. The small η/s near the transition temperature also suggests the formation of strongly coupled matter.

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