De-Confinement in high multiplicity proton-proton collisions at LHC energies

A. S. Hirsch\textsuperscript{1}, C. Pajares\textsuperscript{2}, R. P. Scharenberg\textsuperscript{1} and B. K. Srivastava \textsuperscript{1}

\textsuperscript{1}Department of Physics and Astronomy, Purdue University, West Lafayette, IN-47907, USA
\textsuperscript{2}Departamento de Física de Partículas, Universidade de Santiago de Compostela and Instituto Galego de Física de Altas Enerxías(IGFAE), 15782 Santiago, de Compostela, Spain

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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 non-Abelian nature is reflected in the coherence sum of the color fields which as a consequence gives rise to an enhancement of the transverse momentum and a suppression of the multiplicities relative to the non-overlapping strings. The initial temperature and shear viscosity to entropy density ratio $\eta/s$ 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 de-confined 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. The small shear viscosity to entropy density ratio $\eta/s$ near the critical temperature suggests that the matter is a strongly coupled Quark Gluon Plasma.

The observation of high total multiplicity, high transverse energy, non-jet and isotropic events led Van Hove \textsuperscript{[1]} to conclude that high energy density events are produced in high energy $pp$ 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 $\langle dN_{c}/d\eta \rangle$ in $pp$ collisions at center of mass energy $\sqrt{s} = 1.8$ TeV \textsuperscript{[2]}. The analysis of charged particle transverse momentum in $pp$ exhibits flow velocity of mesons and anti-baryons also indicating the possible evidence of QGP formation \textsuperscript{[3]}. The multiplicity independent freezeout energy density $\sim 1.1$ GeV/$fm^{3}$ at a temperature of $\sim 179$ MeV further suggested de-confinement in $pp$ collisions \textsuperscript{[4]}.

Collective hydrodynamics flow has been successful in describing the $A - A$ collisions at RHIC and LHC energies \textsuperscript{[5-10]}. Several interesting features related to the QGP formation e.g. long range rapidity correlations, the so called “ridge”, elliptic flow and strangeness enhancement seen in heavy ion collisions are also observed in high multiplicity $pp$ collisions at LHC energies \textsuperscript{[6,11-13]}. 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 \textsuperscript{[21]}. 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 \textsuperscript{[22]}.

With growing energy the number of strings grow and start to overlap and interact to form clusters in the transverse plane very much similar to discs in two dimensional (2D) percolation theory \textsuperscript{[23,25]}. At a critical density a macroscopic cluster appears that marks the percolation phase transition. The critical density corresponds to the value of $\xi_c \geq 1.2$ \textsuperscript{[28,29]}. This is termed as the Color String percolation Model (CSPM) \textsuperscript{[24,25]}. The interaction between strings occurs when they overlap and the general result, due to the $SU(3)$ random summation of color charges, is a reduction in the multiplicity and an increase in the string tension or equivalently an increase in the average transverse momentum squared, $\langle p_t^{2} \rangle$. In the $SU(3)$ lattice gauge theory the crossover de-confinement transition can be described by a percolation phase transition of second order \textsuperscript{[27]}

A cluster of $n$ strings that occupies an area of $S_n$ behaves as a single color source with a higher color field $\vec{Q}_n$, corresponding to the vectorial sum of the color charges of each individual string $\vec{Q}_1$. The resulting color field covers the area of the cluster. As $\vec{Q}_n = \sum_{1}^{n} \vec{Q}_1$, and the individual string colors may
be oriented in an arbitrary manner respective to each other, the average $Q_1^2 Q_{j1}^2$ is zero, and $Q_n^2 = n Q_1^2$. Knowing the color charge $Q_n$, one can obtain the multiplicity $\mu_n$ and the mean transverse momentum squared $\langle p_T^2 \rangle_n$ of the particles produced by a cluster of $n$ strings \[\mu_n = \sqrt{\frac{n S_n}{S_1}} \mu_0; \quad \langle p_T^2 \rangle_n = \sqrt{\frac{n S_1}{S_n}} \langle p_T^2 \rangle_1, \] \tag{1}

where $\mu_0$ and $\langle p_T^2 \rangle_1$ 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. In the thermodynamic limit Eq. \[1\], can be written as \[2\] \[25\]

\[\mu_n = N_s F(\xi) \mu_0; \quad \langle p_T^2 \rangle_n = \langle p_T^2 \rangle_1 / F(\xi). \] \tag{2}

$F(\xi)$ is the color suppression factor and is related to the percolation density parameter $\xi$ \[21\]

\[F(\xi) = \sqrt{1 - e^{-\xi}}; \quad \xi = \frac{N_s S_1}{S_N}, \] \tag{3}

where $N_S$ is the number of strings formed in the collisions and $S_N$ is the nuclear overlap area. It is worth noting that CSPM is a saturation model similar to the Color Glass Condensate (CGC), where $\langle p_T^2 \rangle_1 / F(\xi)$ plays the same role as the saturation momentum scale $Q_s^2$ in the CGC \[28\] \[29\].

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\[16\]. 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 \[16\]. The charged particle spectrum is described by a power law \[21\]

\[d^2 N_c / dp_T^2 = a / (p_0 + p_T)^\alpha, \] \tag{4}

where $a$ is the normalization factor, $p_0$ and $\alpha$ are fitting parameters with $p_0 = 1.98$ and $\alpha = 12.87$ \[16\]. This parameterization is used in high multiplicity $pp$ collisions to take into account the interactions of the strings \[21\]

\[d^2 N_c / dp_T^2 = \frac{a}{(p_0 \sqrt{F(\xi)_{pp} / F(\xi)^{mult}_{pp} + p_T})^\alpha}. \] \tag{5}

where $F(\xi)^{mult}_{pp}$ is the multiplicity dependent color suppression factor. In $pp$ collisions $F(\xi)^{pp} \sim 1$ at low energies due to the low overlap probability. Equation \[5\] is similar to Tsallis distribution \[30\] which can be obtained in the clustering of color sources frame by doing the convolution of the distribution of the different formed clusters size with the thermal distributions of the decay of each cluster.

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 \[11, 12\]. Figure \[1\] shows a transverse momentum spectra for two multiplicity cuts at $\sqrt{s} = 7$ TeV. For comparison purpose the spectra from $\sqrt{s} = 200$ GeV is also shown. The spectra becomes harder for higher multiplicity cuts. This is due to the fact that high string density color sources are created in high multiplicity events. The spectra were fitted using Eq. \[3\] in the softer sector with $p_0$ in the range $0.12-1.0$ GeV/c.

Figure \[2\] shows the extracted value of $F(\xi)$ as a function of $N_{tracks} / \Delta \eta$ 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 \[31\]. This is based on an impact parameter description of $pp$ collisions, combined with an underlying description of particle production based on the theory of Color Glass Condensate \[31\].

The results from FNAL (Fermi National Accelerator Laboratory) E735 experiment on $p \bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV is also shown in Fig. \[2\] \[32\]. In the E735 experiment the total charged particle multiplicity was $10 < N_c < 200$ in the pseudorapidity.
range $|\eta| < 3.25$ with $\Delta \eta \sim 6.5$ units of pseudorapidity. It is observed that the E735 results follow the trend as seen in CMS data. The decrease in $F(\xi)$ for high multiplicity events is due to the high string density created in these events.

Since the color suppression factor $F(\xi)$ is related with the string interaction area it is natural to compare it with the heavy ions. In our earlier work $F(\xi)$ was obtained in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for various centralities using STAR data [21]. Centrality is obtained using a cut on the charged particle multiplicity per unit pseudorapidity $dN_c/d\eta$. The results are shown in Fig. 2 along with $pp$ (CMS), $\bar{p}p$ (E735) collisions. It is observed that $F(\xi)$ as a function of $dN_c/\Delta \eta$ scaled by the transverse interaction area falls on a universal scaling curve for hadron-hadron and nucleus-nucleus collisions. $F(\xi)$ values in high multiplicity events in $pp$ collisions at $\sqrt{s} = 13$ TeV are similar to those obtained in most central events in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. This shows the importance of the string density in these collisions.

The connection between $F(\xi)$ and the temperature $T(\xi)$ involves the Schwinger mechanism (SM) for particle production [21, 22, 33].

The Schwinger distribution for massless particles is expressed in terms of $p_T^2$ [21, 33]:

$$dn/dp_T^2 \sim e^{-\pi p_T^2/x^2}$$

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 chromoelectric 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 [34].

$$T(\xi) = \sqrt{\frac{\langle p_T^2 \rangle_1}{2F(\xi)}}; \quad \langle x^2 \rangle = \pi \langle p_T^2 \rangle_1/F(\xi). \tag{7}$$

with $\langle p_T^2 \rangle_1$ is the average transverse momentum squared of particles produced from a single string.

![FIG. 2: Color Suppression Factor $F(\xi)$ in $pp$, $\bar{p}p$ and Au + Au collisions vs $N_{\text{tracks}}/\Delta \eta$ scaled by the transverse area $S_\perp$. For $pp$ and $\bar{p}p$ collisions $S_\perp$ is multiplicity dependent as obtained from IP-Glasma model [31].](image1)

![FIG. 3: Temperature vs $N_{\text{tracks}}/\Delta \eta$ scaled by $S_\perp$ from $pp$ and Au + Au collisions. The horizontal line $\sim 165$ MeV is the universal hadronization temperature [35].](image2)

Figure 3 shows a plot of temperature as a function of $N_{\text{tracks}}/\Delta \eta$ scaled by $S_\perp$. Temperature from hadron-hadron and nucleus-nucleus collisions fall on a universal curve when multiplicity is scaled by the transverse interaction area. The horizontal line at $\sim 165$ MeV is the universal hadronization temperature obtained from the systematic comparison of the statistical model parametrization of hadron abundances measured in high energy $pp$, $AA$ and $e^+e^-$ collisions [35]. In Fig. 3 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 hadronization temperature $\sim 165$ MeV also corresponds to the critical percolation density threshold $\xi_c \geq 1.2$ at which a spanning cluster appears and marks the percolation phase transition [20]. The temperatures obtained in higher multiplicity events are consistent with the creation of de-confined matter in $pp$ collisions at $\sqrt{s} = 7$ and 13 TeV.

The string percolation density parameter $\xi$ that characterizes the percolation clusters also deter-
mines the temperature of the system. In this way at $\xi_c = 1.2$ the connectivity percolation transition at $T(\xi_c)$ models the thermal de-confinement transition \[21, 20\].

The thermalization in $pp$ collisions can occur through the existence of an event horizon caused by a rapid deceleration of the colliding nuclei \[36, 37\]. The thermalization in this case is due the Hawking-Unruh effect \[36, 38, 39\]. 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 \[36\].

The trace anomaly $\Delta = (\varepsilon - 3p)/T^4$ over a wide range of temperatures with the LQCD results at $\sqrt{s} = 13$ TeV shows a very small $\eta/s$ and that is 2.2 times the AdS/CFT conjectured lower bound $1/4\pi$.

The trace anomaly is the expectation value of the trace of the energy-momentum tensor, $\langle \Theta_{\mu}^{\mu} \rangle = (\varepsilon - 3p)/T^4$, which measures the deviation from conformal behavior and thus identifies the interaction still present in the medium \[11\]. The inverse of $\eta/s$ also measures how strong are the interactions in the medium and therefore we expect a similar behavior as seen in the trace anomaly \[20\]. Figure 4(b) shows $1/(\eta/s)$ and the dimensionless quantity, $(\varepsilon - 3p)/T^4$, obtained from lattice simulations \[42\]. We consider the ansatz that the inverse of $\eta/s$ is equal to the dimensionless trace anomaly $\Delta = (\varepsilon - 3p)/T^4$ \[20\]. The inverse of $\eta/s$ is in quantitative agreement with $\Delta$ over a wide range of temperatures with the LQCD simulations \[42\]. The maximum in $\Delta$ corresponds to the minimum in $\eta/s$. Both $\Delta$ and $\eta/s$ describe the transition from a strongly coupled QGP to a weakly coupled QGP. This result is shown in Fig. 4(b).

We have analyzed the transverse momentum spectra of pions from $pp$ collisions at LHC energies for temperature and the shear viscosity to entropy density ratio $\eta/s$ was obtained in the framework of kinetic theory and the string percolation \[18\]. In this picture the relevant parameter is the string density $\xi$. The following expression was obtained for $\eta/s$ \[18\].

\[
\frac{\eta}{s} = \frac{TL}{5(1 - e^{-\xi})},
\]

where $T$ is the temperature and $L$ is the longitudinal extension of the source $\sim 1$ fm \[18\]. The temperature is given by Eq. (7) while $\xi$ is related to $F(\xi)$ through Eq. (3). Figure 4(a) shows $\eta/s$ as a function of the temperature \[18\]. The lower bound shown in Fig. 4(a) is given by the AdS/CFT conjecture \[40\]. The results from Au+Au at 200 GeV and Pb+Pb at 2.76 TeV collisions show that the $\eta/s$ value is 2.5 and 3.3 times the KSS bound \[40\]. The results from $pp$ collisions from $\sqrt{s} = 13$ TeV shows a very small $\eta/s$ and that is 2.2 times the AdS/CFT conjectured lower bound $1/4\pi$.

It is important to ask the question if matter created in high multiplicity $pp$ events is nearly a perfect fluid with a low shear viscosity as observed in heavy ion collisions \[21\] ? In the Color String Percolation Model (CSPM) the shear viscosity to entropy density ratio $\eta/s$ was obtained in the framework of kinetic theory and the string percolation \[18\]. The percolation framework provides us with a microscopic picture that correctly describes the crossover
phase transition between the QGP and hadronic matter.

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