Study of initial conditions in small systems at LHC energies with String Percolation Model.

Pablo Fierro* [1], Irais Bautista [2], J. Ricardo Alvarado [2], Miguel Ortiz [2], Alan Ruiz [2]

E-Mail: pablo.fierro.rojas@cern.ch

Instituto de Física Luis Rivera Terrazas, Benemérita Universidad Autónoma de Puebla [1]
Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla[2]

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Abstract

sing the Color String Percolation Model, a review is made of the results obtained for p-p and p-Pb collisions at Large Hadron Collider (LHC) energies. These results show the description of a state that presents common characteristics with the Quark Gluon Plasma (QGP) status formed in nuclear collisions. However, studies of this system in the framework of the string percolation model imply the presence of particularities that are not observed in the QGP system in nuclear collisions and that lead to an important conceptual differentiation of these states.

1 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.

$$\bar{N}^s = 2 + 4\frac{S_0}{S}\left(\frac{\sqrt{s}}{m_p}\right)^{2\lambda}, \tag{1.1}$$

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 $\xi_c \approx 1.2$, the critical string density, to classify the events the string density is defined as

$$\xi = \frac{S_0}{S}\bar{N}_s. \tag{1.2}$$

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]

$$\mu = \kappa F(\xi)\bar{N}^s, \tag{1.3a}$$

which has the form

$$F(\xi) = \sqrt{\left(1 - e^{-\xi}\right)/\xi}. \tag{1.3b}$$

2 Fits over the experimental data

Using the above equations, we parametrize $S(b) = \pi(R_p - b/2)\sqrt{R_p^2 - (b/2)^2}$ through the impact parameter b, we made a global fit over the minimum bias mutiplicity dependence of the center of mass energy experimental data [3-11].

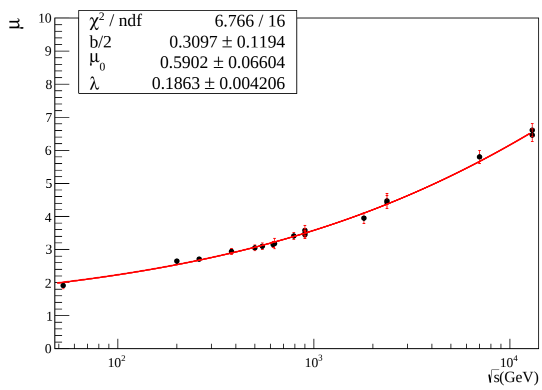

Figure 1: Multiplicity dependence of energy fit.

The transverse momentum distribution for charged pions behaves as the following power law

$$\left.\frac{1}{N}\frac{d^2N_{ch}}{d\eta dp_T}\right|_{\eta=0} \sim \frac{p_0^{\alpha-2}}{(p_T + p_0)^{\alpha-1}}, \tag{2.1}$$

In order to obtain p_0 and α, which are energy parameters, it is necessary to make a fit over the minimum bias transverse momentum distributions from data [12-14], as shown in the figure 1, the values of these parameters are shown in table 1.

	$\sqrt{s}$(TeV)	p_0(GeV)	α
p-Pb	5.02	2.780±0.171	9.937±1.716
p-p	13	2.478±1.862	9.980±0.297
	7	2.305±0.079	9.752±0.140
	2.76	2.032±0.074	9.448±0.147
	0.9	1.785±0.071	9.287±0.165
	0.2	1.98±0.1215	9.40 ± 1.80

Table 1: Model energy parameter values

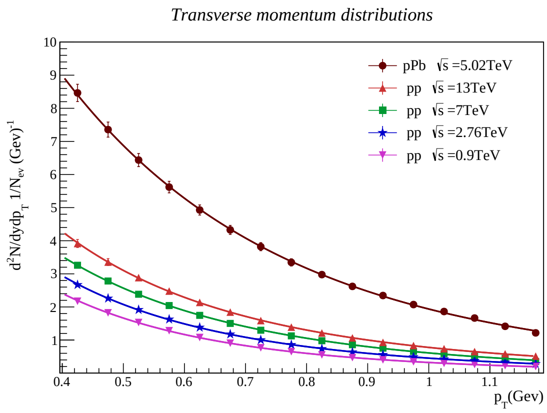

Figure 2: Fit of the equation (4) over the transverse moment distributions of charged pions in p-p collisions at energies of 0.9, 2.76, 7 and 13 TeV and p-Pb collisions at 5.02 TeV, in region 0.4 $< p_T <$1.175, data from the CMS collaboration [12-14].

We use the deviation between high multiplicity (ξ) and minimum bias events (ξ_0) through $p_0 \to p_0\sqrt{F(\xi_0)/F(\xi)}$. We use this relation in eq. (4) to make a new fit over the high multiplicity events obtaining the corresponding Color Reduction Factors for each multiplicity class.

To include the spectra of different hadron species H, we use the relation[15,16]

$$P(H) = \frac{1}{N}\frac{d^2N}{d\eta dp_T}\bigg|_H \sim \exp\left(\frac{-m_H^2 F(\xi_0)}{\langle p_T\rangle^2 + \langle p_H\rangle^2}\right)\frac{1}{N}\frac{d^2N}{d\eta dp_T}\bigg|_\pi . \tag{2.2}$$

The Λ_c/D^0 production ratio is obtained by fitting $P(\Lambda_c)/P(D^0)$ to the data [17]. Using $P_{HM} \sim F(\xi_{HM})\exp\left(\frac{-m_H}{\langle p_H \langle + p_T}\right)$ to obtain the different multiplicity class, with the corresponding string density parameter ξ_H, we make a prediction for the production ratio spectra behavior (fig 2).

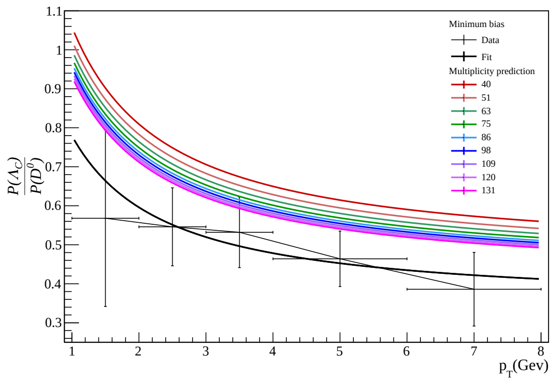

Figure 3: The figure shows the fit to the min bias data[8] and the prediction of the Λ_c/D^0 production for different multiplicity classes at $\sqrt{s}$ =7TeV.

3 Thermodynamical quantities

The stress of the macroscopic clusters in SMP fluctuates around their mean value due to chromeelectric 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 as:

$$T(\xi) = \sqrt{\langle p_T^2 \rangle_0 / 2F(\xi)}, \tag{3.1}$$

where $\sqrt{\langle p_T^2 \rangle_0}$ =190.25MeV obtained at $T(\xi_c) = T_c = 154$MeV[18].

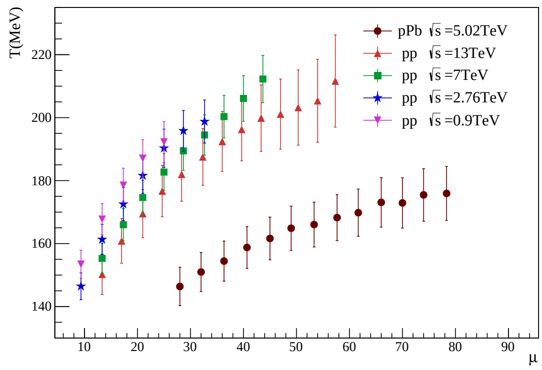

Figure 4: The figure shows the fit to the min bias data[8] and the prediction of the Λ_c/D^0 production for different multiplicity classes at $\sqrt{s}$ =7TeV.

The local order parameter of QCD phase transition is the energy density ε, which has a critical value ε_0, the relation of ε and ξ is directly proportional, where $\varepsilon_c/\xi_c \approx 0.56$ GeV/fm^3, obtained in [2].

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 $\eta_s/s = T\lambda_{\text{mfp}}/5$, where the mean free path is $\lambda_{\text{mfp}} = 1/(\sigma_{tr} n) = L/(1-e^{-\xi})$, so

$$\frac{\eta_s}{s} = \frac{TL}{5(1-e^{-\xi})}. \tag{3.2}$$

4 Bulk properties

Using thermodynamic identities we can write the adiabatic speed of sound as $c_s^2 = s\left(\frac{\partial T}{\partial \varepsilon}\right)_V$. With the fundamental relation $Ts = \varepsilon + P$, we obtain c_s^2 in terms of the model parameters:

$$c_s^2 = \frac{sT}{4\varepsilon}\left(1 - \frac{e^{-\xi}}{F(\xi)^2}\right), \tag{4.1}$$

this quantity behaves quite similar to the Lattice QCD results[19]. As a first approximation of the hydrodynamical expansion the increasing entropy is considered with a cylindrical expansion with one of the longitudinal dimensions, L, fixed. In this way, the dissipative speed of sound is defined as:

$$c_{sL}^2 = \left(\frac{\partial P}{\partial \varepsilon}\right)_L = \frac{P}{\varepsilon} + \frac{T^3\Delta}{3s} c_s^2, \tag{4.2}$$

where Δ is the expected value of the trace of the energy-moment tensor in QCD, $\langle T_\mu^\mu \rangle = \varepsilon - 3P$ weighted by T^4, that measures the deviation with respect to the conformal behavior and identifies the residual interactions in the medium. Qualitatively it has been verified that the behavior of this observable is inversely proportional to the η_s/s ratio. For the QGP system, we can consider soft equations of state and Gaussian-like initial profiles of the energy density given by the Bag Model[20], starting from the equation

$$P = c_s^2\varepsilon - \left(1 + c_s^2\right) B_Q, \tag{4.3}$$

where B_Q is the Bag constant[20], we calculate the liquid-like correction to the energy density:

$$\varepsilon = \frac{1}{3}\frac{T^4\Delta + \left(1 + c_s^2\right) B_Q}{\frac{1}{3} + c_S^2}. \tag{4.4}$$

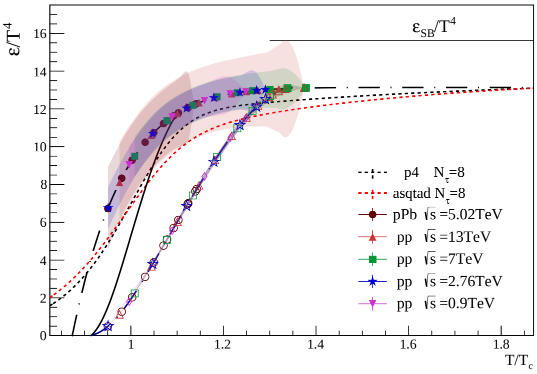

Figure 5: Behavior of ε/T^4 with T/T_c compared to Lattice QCD predictions for 2 + 1 flavors (two light and one heavy) using 8 lattices with p4 action in blue and asqtad action in red [19], the theoretical curve of the model is represented by the dashed black line, the liquid-like corrections from the Bag Model are represented by the non filled marks, and the continuos curve is the Bag Model correction with the dissipative speed of sound.

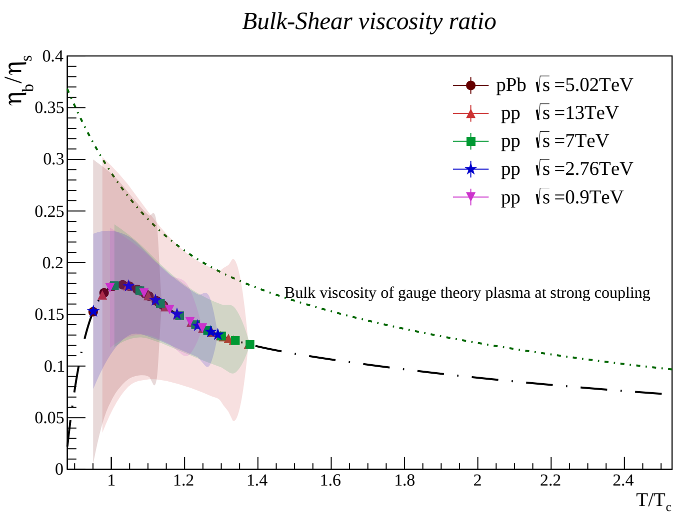

Figure 6: Figure shows the behavior of the shear viscosity over the bulk viscosity, which is well carried out causally using the modification for the speed of sound, the quotient between the two viscosities shows a change in the steep slope that suggests a second-order phase transition for these systems, the quotient is below of the dotted green line, that represents the result based on dual holography, where it is speculated that $\eta_b/\eta_s \geq 2(1/3 - c_2^s)$[22].

For the calculation of bulk viscosity, the projection operator's approach was considered to derive the microscopic formulas for the transport coefficients in Causal Dissipative Relativistic Fluid-dynamics that can be seen as a generalization of the Navier-Stokes equation[21]:

$$\frac{\eta_b}{s} = \left(\frac{1}{3} - c_{sL}^2\right)\tau_\Pi T - \frac{2T^4\tau_\Pi\Delta}{9s}. \tag{4.5}$$

5 Event by event $\langle p_T \rangle$ fluctuations

The event by event (EbE) fluctuations were proposed as a probe of the properties of the hot and dense matter generated in high-energy heavy-ion collisions. QGP phase transition goes along with the appearance of fluctuations of thermodynamic quantities that can be related to the EbE $\langle p_T \rangle$ fluctuations of final-state charged particles.

In the SPM we can understand EbE fluctuations as a superposition of partially independent particle-emitting sources [23]

- At low ξ: we have very little fluctuations
- Over critical ξ: we have no fluctuations
- Below critical ξ: fluctuations are maximal

$$F_{p_T} = \frac{1}{\sqrt{\langle z^2 \rangle}}\sqrt{\frac{\langle Z^2 \rangle}{\langle \mu \rangle}} - 1 \tag{5.1}$$

Experimentally, fluctuations of the $\langle p_T \rangle$ are measured though correlations between two particles rather than the variance of the $\langle p_T \rangle$ as in F_{p_T}, but the correlator is proportional to F_{p_T} [24]

$$C_m \simeq 2F_{p_T}\frac{var(p_T)}{\langle N \rangle} \tag{5.2}$$

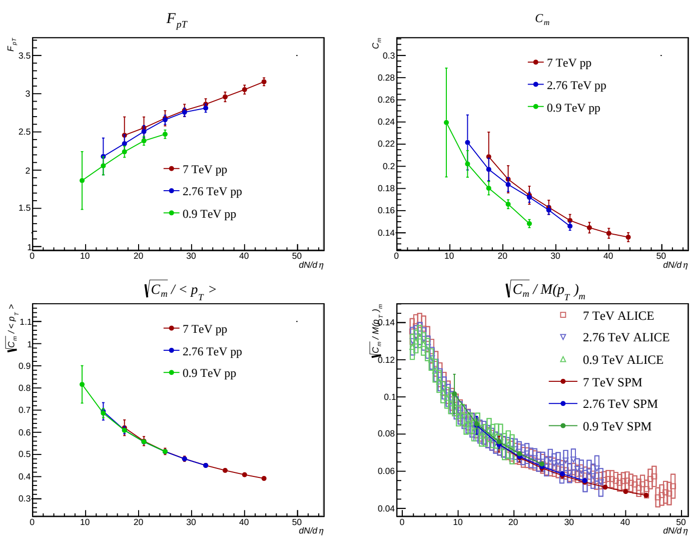

Figure 7: Fluctuation observable F_{p_T}, C_m and $\sqrt{C_m}/\langle p_T \rangle$ and comparing with experimental data from [24].

6 Temperature fluctuations

width, remove 'span=2' fluctuations of any observable of a system have two distinct origins, one quantum that has initial state fluctuations and classical thermodynamical fluctuations which occur after elapse of sufficient time after a collision. initial state fluctuations arise because of internal structures of the colliding nuclei and these appearas EbE fluctuations of energy density or Temperature [23].
Temperature fluctuations may also arise as fluctuations of p_T or it's correlations and are given by:

$$\frac{\Delta T}{\langle T_{eff} \rangle_{overall}} = \frac{\sum_i \langle T_{eff} \rangle - T_i}{\langle T_{eff} \rangle_{overall}} \tag{6.1}$$

If the initial state correlations can survive after the thermalization, teperature fluctuations are a good tool to see them and collect information about the initial state.

6.1 Tsallis model

The Tsallis model takes a more statistical approach, given that, we first define the p_T spectra as the standard distribution taken form the integration in the phase space [25].

$$\frac{1}{N}\frac{d^3N}{dp^3} = \frac{gV}{(2\pi)^3} E \left[\left(1 \pm \frac{q-1}{T}(E-\mu) \right)^{\pm 1/(q-1)} + S \right]^{-1} \tag{6.2}$$

the terms $E = \sqrt{p_T^2 + m_0^2}\cosh(\eta)$ and S indicates us of the statistic which will be taken, so for practical reasons we will take $S = 0$ which corresponds to the Maxwell statistics, in the sense that we want the particles to be distinguishable for this to correspond with the SPM. So we will have [26]:

$$\frac{1}{N}\frac{d^2N}{d\eta dp_T} = \frac{C_T p_T \sqrt{p_T^2 + m_0^2}\cosh(\eta)}{\left[\left(1 \pm \frac{q-1}{T}\left(\sqrt{p_T^2 + m_0^2}\cosh(\eta) - \mu\right) \right)^{\pm 1/(q-1)} \right]} \tag{6.3}$$

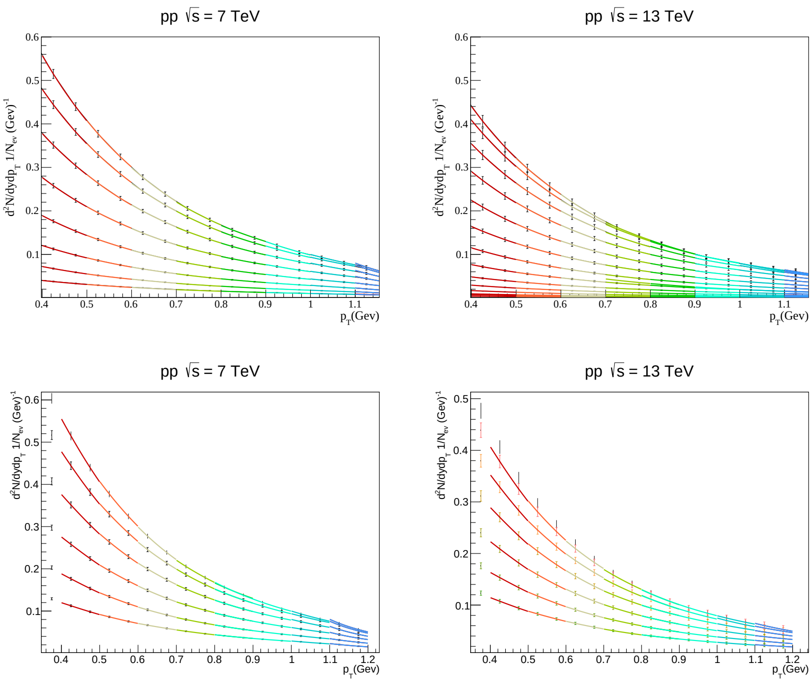

Figure 8: Fits to the p_T spectra [12] using the SPM (up) andT salis model (bottom) at 7 and 13 TeV.

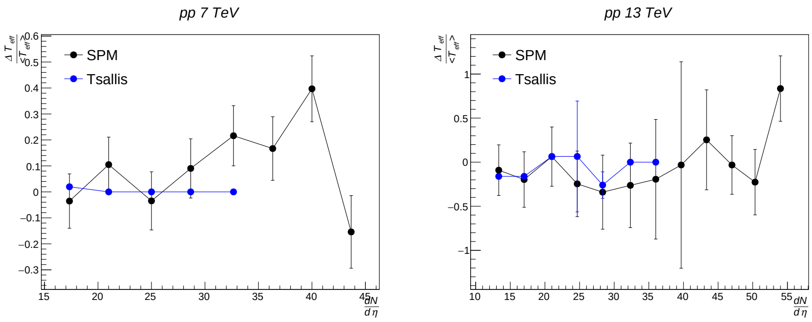

Figure 9: Temperature fluctuations on the SPM and Tsallis model from the fit on data from [12]. Where SPM shows higher fluctuations due to the picture of the internal structure of partons.

7 Conclusions

1. The model allows us to make good descriptions of the phenomena present in small collisions systems.
2. The signals observed show that perhaps these systems probably do not reach thermalization, which implies the bulk properties for these systems.
3. The fact of considering soft equations and dissipative properties allows us to obtain new physics results that are relevant.

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