STUDY OF MULTIPLICITY (CENTRALITY) DEPENDENT THERMODYNAMIC AND TRANSPORT PROPERTIES AT LHC WITHIN COLOR STRING PERCOLATION MODEL

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Introduction:

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- The color string percolation model (CSPM) describes the initial collision of two heavy ions in terms of color strings stretched between the projectile and target. Color strings may be viewed as small discs in the transverse space filled with the color field created by colliding partons.
- ➤ These strings decay into new ones by $q \overline{q}$ production and subsequently hadronize to produce the observed hadrons. Particles are produced by the Schwinger 2D mechanism.
- With the growing energy and size of the colliding nuclei the number of strings grow and start to overlap to form clusters in the transverse plane.
- At a certain critical string density a macroscopic cluster appears, which defines the percolation phase transition.
- The CSPM has been successfully used to describe the initial stages in the soft region of the high energy heavy-ion collisions.

Introduction: Clustering of Color Sources

- De-confinement is expected when the density of quarks and gluons becomes so high that it no longer makes sense to partition them into color-neutral hadrons, since these would overlap strongly.
- ➤ We have clusters within which color is not confined : De-confinement is thus related to cluster formation very much similar to cluster formation in percolation theory and hence a connection between percolation and de-confinement seems very likely.



In two dimensions, for uniform string density, the percolation threshold for overlapping discs is:



Parton distributions in the transverse plane of nucleus-nucleus collisions Aditya Nath Mishra(WIGNER RCP)

Critical Percolation Density

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Introduction: Schwinger mechanism for the **Fragmentation**

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Multiplicity and $\langle p_T^2 \rangle$ of particles produced by a cluster of *n* strings

Multiplicity (m_n) $\mu_n = F(\xi) N^s \mu_1$

Average Transverse Momentum

$$< p_T^2 >_n = < p_T^2 >_1 / F(\xi)$$

Color suppression factor can be defined as

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

(due to overlapping of discs).

Here, ξ is the string density parameter defined as

 $N^{s} = #$ of strings $S_{1} = disc$ area $S_{N} = total$ nuclear overlap area

$$\xi = \frac{N^s S_1}{S_N}$$

Methodology:

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Experimental p_T spectra are used to extract $F(\xi)$ by fitting spectra with following function

$$\frac{d^2 N}{dpt^2} = \frac{a}{\left(p_0 + pt\right)^n}$$

a, p_0 and n are parameters fit to the data.

Parameterization is done using (pp collisions data):

- UA1 data from 200, 500 and 900 GeV
- ISR 53 and 23 GeV

 $p_0 = 1.71$ and n = 12.42 (Nucl. Phys. A698, 331 (2002))

This parameterization can be used for highmultiplicity pp and nucleus-nucleus collisions to account for the clustering.



$$F(\xi)_{pp} = 1$$

(No percolation at low energy pp collisions)



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Results: $F(\xi)$ and ξ

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 $F(\xi)$ and ξ as a function of $<dN_{ch}/d\eta>$

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Results: Temperature



• This shows that the p_T spectrum is exponentially distributed and the inverse slope parameter is the thermalized temperature

$$T = \sqrt{\frac{\left\langle p_t^2 \right\rangle_1}{2F(\xi)}}$$

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0.1

0.12

0.1

100

150

200

STAR

250

🖧 AuAu 200 GeV

350

400

300

No of Participants N

Results: Energy Density

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The QGP according to CSPM is born in local thermal equilibrium because the temperature is determined at the string level. After the initial temperature T>Tc the CSPM perfect fluid may expand according to Bjorken boost invariant 1D hydrodynamics

$$\varepsilon = \frac{3}{2} \frac{\frac{dN_c}{dy} < m_T >}{s_n \tau_{\mathbf{pro}}}$$

where ϵ is the energy density, S_n nuclear overlap area, m_T transverse mass and τ_{pro} the production time for a boson (gluon)

$$\tau_{\mathbf{pro}} = \frac{2.405\hbar}{\langle m_T \rangle}$$

Results: Energy Density vs ξ





- a slow rise of ε for low values of ξ followed by a faster rise later.
- \triangleright ϵ is proportional to ξ in the range $1.2 < \xi < 5.0$
- A possible explanation for the sharp rise in the energy density could be that at such high degree of overlapping the gluons are seen naked without interaction and thus the coherence of the color fields of the overlapping strings is lost and thus recover the independence of the strings.

Results: Energy Density vs Temperature





As the surface covered by strings is $(1 - \exp(-\xi))S \perp$, the mean distance between strings d is

$$d = \left[\frac{N}{(1 - exp(-\xi))S_{\perp}}\right]^{-1/2} = F(\xi)\sqrt{\pi}r_0$$

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Results: Two Temperature

➢ For small ξ, d > r₀ → overlapping between strings is very peripheral, covering only the edges(corona) of the strings.

Ex: at the critical percolation density $\xi c = 1.2$, $d = 1.34r_0$. This corresponds to the hadronization temperature of ~ 166 MeV.

In order to penetrate the core the overlapping should be larger in such a way that d < r₀. In fact, for d ~ 0.8 – 0.9r0, F (ξ) ~ 0.45 – 0.51 corresponding to the temperature of ~ 208-220 MeV. This is the temperature at which our result starts deviating from LQCD. These two temperatures can be seen, related to the confinement-deconfinement and possibly chiral symmetry restoration respectively.

Results: Degree of Freedom

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The energy densities obtained in full QCD with different numbers of quark flavour are given by

$$\varepsilon/T^4 \simeq (37/30)\pi^2 \simeq 12, N_f = 2.$$

$$\varepsilon/T^4 \simeq (47.5/30)\pi^2 \simeq 16, N_f = 3.$$

- At T ~ 210 MeV, ε/T4 ~ 11 → ~ 33 DOF
- while at T ~ 230 MeV ϵ /T4 almost touches Stefan-Boltzmann limit \rightarrow ~ 47 DOF.
- For Xe-Xe collisions at 5.44 TeV ~ 44 DOF
- In pp collisions at 13 TeV only \sim 33 DOF are reached.

Our results are in agreement with the conclusions obtained studying the trace anomaly in a quasi particle gluonic model. In this model the DOF of the free gluons are also obtained for T $\simeq 1.3$ Tc (Tc ≈ 165 MeV). Aditya Nath Mishra(WIGNER RCP) Zimányi School 2021 12 December 2021

Summary

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- We have used the Color String Percolation Model (CSPM) to explore the initial stage in pp, Xe-Xe, and Pb-Pb collisions at LHC energies and determined the thermalized initial temperature of the hot nuclear matter at an initial time ~ 1 fm/c.
- ➢ For the first time the temperature and the energy density of the hot nuclear matter, from the measured charged particle spectra using ALICE data for pp collisions at 5.02 and 13 TeV have been obtained.
- > An almost universal scaling in the temperature is obtained for both pp and AA collisions.
- The dimensionless quantity $\epsilon/T4$ is evaluated to obtain the number of degrees of freedom (DOF) of the deconfined phase.
- The existence of two temperature ranges in the behavior of the AA system DOF, and a clear departure from the LQCD results regarding the maximum number of DOF, which reaches values in agreement with the Stephan Boltzmann limit for an ideal gas of quarks and gluons.
- ► In case of pp collisions at s = 5.02 we reach only $\varepsilon/T \sim 8$ corresponding to ~ 24 DOF, while at 13 TeV ~ 30 DOF is obtained.





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