Multiplicity dependence study of thermodynamic and transport properties of the matter formed in ultra-relativistic collisions at LHC using Color String Percolation Model

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- Summary
• What is color string percolation?
• Color strings are stretched between the partons of the target and the projectile
• Number of color string grows with growing energy and with increase in number of colliding partons
• String density increases
• After a critical percolation density, a macroscopic cluster appears, which marks the percolation phase transition**

Color String Percolation Model

• In CSPM, Schwinger’s string breaking mechanism produces color neutral quark-antiquark pairs

• They subsequently hadronize to form the final state particles

• We assume that a cluster of $N$ strings that occupies an area of $S_N$ behaves as a single-color source with a higher color field $\bar{Q}_N$ corresponding to the vector sum of the color charges of each individual strings $\bar{Q}_1$

• As $\bar{Q}_N^2 = (\sum_1^N \bar{Q}_1)^2$, and the individual string colors may be oriented in random manners, so we get $\bar{Q}_N^2 = N\bar{Q}_1^2$

• The multiplicity, $\mu_N = \sqrt{\frac{NS_N}{S_1}}\mu_1$ and the mean transverse momentum $\langle p_T \rangle_N = \sqrt{\frac{NS_1}{S_N}}\langle p_T \rangle_1$

• In the thermodynamic limit, we obtain the analytic expression**

$$\left\langle \frac{NS_1}{S_N} \right\rangle_N = \frac{\xi}{1 - e^{-\xi}} \equiv \frac{1}{F(\xi)^2}$$

where, $F(\xi)$ is the color suppression factor and $\xi$ is the percolation density parameter and is given by,

$$\xi = \frac{N_1S_1}{S_N}$$

In the thermodynamic limit, the color Suppression Factor can be expressed in terms of the string percolation density $\xi$ as

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

We fit the $p_T$ spectra of the lower energy pp collisions at $\sqrt{s} = 200$ GeV with the function,

$$d^2N_{ch}/dp_T^2 = \frac{a}{(p_0 + p_T)^\alpha}$$

where, $p_0$ and $\alpha$ are fitting parameters with the values $p_0 = 1.98$ and $\alpha = 12.87$

For higher energy pp collisions and heavy ion collisions, we update the parameter as,

$$p_0 \rightarrow p_0 \left( \frac{\langle NS_1/S_N \rangle_{pp, pA, AA}}{\langle NS_1/S_N \rangle_{pp, \sqrt{s}=200 \text{ GeV}}} \right)^{1/4}$$

Now the fitting function becomes,

$$d^2N_{ch}/dp_T^2 = \frac{a}{(p_0\sqrt{F(\xi)_{pp, \sqrt{s}=200 \text{ GeV}}}/F(\xi)_{pp, pA, AA} + p_T)^\alpha}$$

Color String Percolation Model

- The initial percolation temperature is related to the color suppression factor by the relation, \( T = \sqrt{\frac{\langle p_T \rangle}{2F(\xi)}} \).
- We observe that after \( \langle dN_{\text{ch}}/d\eta \rangle \approx 10 \), the temperature is higher than the hadronization temperature regardless of the collision systems.
- The percolation density parameter \( \xi \) is given by \( \xi = \frac{N_s S_1}{S_N} \).
- \( \xi \) is strongly dependent on the charged particle multiplicity, hinting that \( \xi \) is responsible for final state particle production.


Mean Free Path ($\lambda$) -

- Mean free path is inversely proportional to the number density and the scattering cross-section of the particles.
- In CSPM, the number density is given by the effective number of sources per unit volume, $n = \frac{N_{\text{sources}}}{S_N L}$.
- The effective number of sources is given by the total area occupied by the strings divided by the area of an effective string, $N_{\text{sources}} = \frac{(1 - e^{-\xi}) S_N}{S_1 F(\xi)}$.
- Finally, we get the mean free path as,

$$\lambda = \frac{1}{n \sigma} = \frac{L}{(1 - e^{-\xi})}$$

- We observe that after $\langle dN_{\text{ch}}/d\eta \rangle \geq 10 - 20$, the mean free path of the system approaches to a minimum value regardless of collision systems.

*Figures are from D. Sahu and R. Sahoo, [arXiv:2006.04185 [hep-ph]]*
Thermodynamic and Transport Properties

Speed of Sound ($c_s$) -

- Gives us a vivid picture about the dynamics of the systems and help us to have a proper idea about the equation of state.
- For massless ideal gas, the value is expected to be $1/3$ and for hadron gas it is $1/5$
- Using CSPM coupled to a 1D Bjorken expansion, the velocity of sound can be estimated
- We can express $c_s^2$ in terms of $\xi$ as,

$$c_s^2 = -0.33 \left( \frac{\xi e^{-\xi}}{1 - e^{-\xi}} - 1 \right) + 0.0191 \left( \frac{\xi e^{-\xi}}{(1 - e^{-\xi})^2} - \frac{1}{1 - e^{-\xi}} \right)$$

- We observe that for higher charged particle multiplicity, the speed of sound of the matter formed in the collisions approaches the ideal gas limit

*Figures are from D. Sahu and R. Sahoo, [arXiv:2006.04185 [hep-ph]]
Shear Viscosity to Entropy Density Ratio ($\eta/s$) -

- From the relativistic kinetic theory, the shear viscosity to entropy density ratio is given by,
  \[
  \frac{\eta}{s} \sim \frac{T \lambda}{5}
  \]

- Using the value of mean free path, we get the final expression of shear viscosity to entropy density ratio as,
  \[
  \frac{\eta}{s} \sim \frac{T L}{5(1 - e^{-\xi})}
  \]

- For the matter formed in ultra-relativistic collisions at LHC energies, the value of $\eta/s$ is the lowest as compared to any other known material

- We observe that $\eta/s$ approaches the KSS bound value and becomes minimum at $\langle dN_{ch}/d\eta \rangle \geq 10 - 20$

- This hints that the matter behaves almost like a perfect fluid

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Thermodynamic and Transport Properties

**Bulk Viscosity to Entropy Density Ratio (ζ/s)** -

- From the relaxation time approximation (RTA), the bulk viscosity of a system is given as, \[ \zeta = 15\eta \left( \frac{1}{3} - c_s^2 \right)^2 \]
- So, the bulk viscosity to entropy density ratio becomes, \[ \frac{\zeta}{s} = 15\frac{\eta}{s} \left( \frac{1}{3} - c_s^2 \right)^2 \]
- After \( <dN_{ch}/d\eta> \geq 10 - 20 \), the value of \( \frac{\zeta}{s} \) becomes minimum and approaches zero

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Thermodynamic and Transport Properties

Isothermal Compressibility ($\kappa_T$) -

- Defined as the relative change in the volume of the gas with respect to the change in pressure at constant temperature
- Expressed as,
  \[ \kappa_T = \frac{1}{V} \frac{\partial V}{\partial P} \]
- Tells us about the deviation of a real fluid from a perfect fluid
- Using CSPM framework, volume $V = S_N L$ and pressure $P = (\epsilon - \Delta T^4)/3$
  After simplification,
  \[ \kappa_T = \frac{1}{V} \frac{\partial V}{\partial S_N} \frac{\partial S_N}{\partial P} \implies \kappa_T = \frac{\tau_{pro} S_N}{(m_T) dN_{ch}/dy} \]
- We observe that after $\langle dN_{ch}/d\eta \rangle \geq 10 - 20$, the values become minimum and almost close to zero
- Further evidence for QGP being the closest to a perfect fluid

Thermodynamic and Transport Properties

Bulk Modulus (B) -

• Defined as the ratio of increase in pressure of the matter after changing the volume
• Inverse of isothermal compressibility
• Tells us how much resistant is the matter to compression
• Increases with increase in multiplicity

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Summary

• We have studied various thermodynamic and transport properties of the matter formed in high energy collisions by taking CSPM approach.
• QGP is closest to a perfect fluid found in nature.
• Observed a threshold of charged particle multiplicity \( \langle dN_{ch}/d\eta \rangle \geq 10 - 20 \) after which we see a change in the dynamics of the systems.
• Hints at possible formation of QGP droplets in high multiplicity pp collisions.
thank you