EXPLORING THE QGP PHASE IN HIGH MULTIPLICITY PP AND A-A COLLISIONS USING COLOR STRING PERCOLATION MODEL AT LHC ENERGIES

Aditya Nath Mishra

WIGNER RCP

Budapest, Hungary

Collaboration with Guy Paic, Carlos Pajares, Rolf P Scharenberg, and Brijesh K Srivastava

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Outline:

- ❑ **Introduction : Color String Percolation Model**
- ❑ **Methodology**
- ❑ **Result and Discussions**
- ❑ **Summary**

Data Analysed:

- ALICE pp collisions at 5.02 and 13 TeV
- ALICE PbPb collisions at 2.76 and 5.02 TeV
- ALICE XeXe collisions at 5.44 TeV

Event multiplicity classes based on the number of tracklets ($N_{SPDtacklets}$) within $|\eta| < 0.8$

Introduction: CSPM

- 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.

- Particles are produced by the Schwinger mechanism, emitting $q\bar{q}$ pairs in this field.

- With the growing collision energy and/or size of the colliding nuclei the number of strings grow and start to overlap to form clusters in the transverse plane. This procedure is very much like discs in the 2-dimensional percolation theory, a non-thermal second order phase transition.

- At a certain critical string density ($\xi_c \sim 1.2$) a macroscopic cluster appears, which defines the percolation phase transition.

- The critical density of percolation is related to the effective critical temperature and thus percolation may provide the information of the deconfinement in the heavy-ion collisions and high multiplicity pp collisions.

Introduction: CSPM

- In CSPM, the Schwinger barrier penetration mechanism for particle production, the fluctuations in the associated string tension and the quantum fluctuations of the color fields make it possible to define a temperature. Consequently the particle spectrum is produced with a thermal distribution.

- The CSPM has been successfully used to describe the initial stages in the soft region of the high energy heavy-ion collisions[1-7].

[1]M.A. Braun et al. Phys. Reports. 509, 1 (2015).
[2] P. Sahoo et al., Eur. Phys. J. A 54 (2018) 136.
[3] P. Sahoo et al., Phys. Rev. D 98 (2018) 054005.
[4] P. Sahoo et al., Mod. Phys. Lett. A 34 (2019) 1950034.
[5] A. N. Mishra aty al., Eur. Phys. J. A 57 (2021) 245.
[6] M. A. Braun and C. Pajares, Eur. Phys. J. C 16 (2000) 349.
[7] M. A. Braun, F. del Moral and C. Pajares, Phys. Rev. C 65 (2002) 024907.
and many more

Introduction: CSPM

- In CSPM, the hadron multiplicity (μ_n) reduces as the interactions of strings increase and the mean transverse momentum squared, $\langle p^2_T \rangle_n$ of these hadrons increases, to conserve the total transverse momentum.

- The multiplicity, μ_n and the mean transverse momentum squared $\langle p^2_T \rangle_n$ of the particles produced by a cluster of ***n*** strings is defined as

$$\mu_n = \sqrt{\frac{nS_n}{S_1}}\mu_0 \qquad \langle p_T^2 \rangle_n = \sqrt{\frac{nS_1}{S_n}}\langle p_T^2 \rangle_1$$

- The percolation density parameter (ξ) can be written as:

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

N^s is the number of strings
S_1 is the transverse area of a single string
μ_0 is the multiplicity of hadrons due to single string
$\langle p^2_T \rangle_1$ is the average transverse momentum squared of particles produced from a single string
$\langle p^2_T \rangle_1$ is calculated at critical temperature, Tc = 165 ± 2.76 MeV and ξc = 1.2: 207.2 ± 3.3 MeV.

Methodology

- ξ is evaluated by fitting p_T spectra with a parametrise power law function given by

$$\frac{d^2N}{dp_T^2} = \frac{a}{(p_0 + p_T)^n}$$

a is the normalization factor

$p_0 = 1.98$ and $n = 12.87$ are fitting parameters[1,2]. (For independent string)

- This parameterization is used in high multiplicity pp collisions to take into account the interactions of the strings

$$p_0 \rightarrow p_0 \left(\frac{\langle nS_1/S_n \rangle_{pp}^{HM}}{\langle nS_1/S_n \rangle_{pp}} \right)^{1/4}$$

- Since in minimum bias pp collisions at 200 GeV, we get $\langle nS_1/S_n \rangle \sim 1.0 \pm 0.1$ due to low string overlap probability : we use it for parametrisation.

[1] M. A. Braun and C. Pajares, Eur. Phys. J. C16,349 (2000)
[2] M. A. Braun et al, Phys. Rev. C65, 024907 (2002)

Methodology

- Using thermodynamic limit, i.e. n and $S_n \rightarrow \infty$ and keeping ξ fixed, we get

$$\langle \frac{nS_1}{S_n} \rangle = \frac{1}{F^2(\xi)}$$

- F(ξ) is the color suppression factor and connected to string density ξ via following relation

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

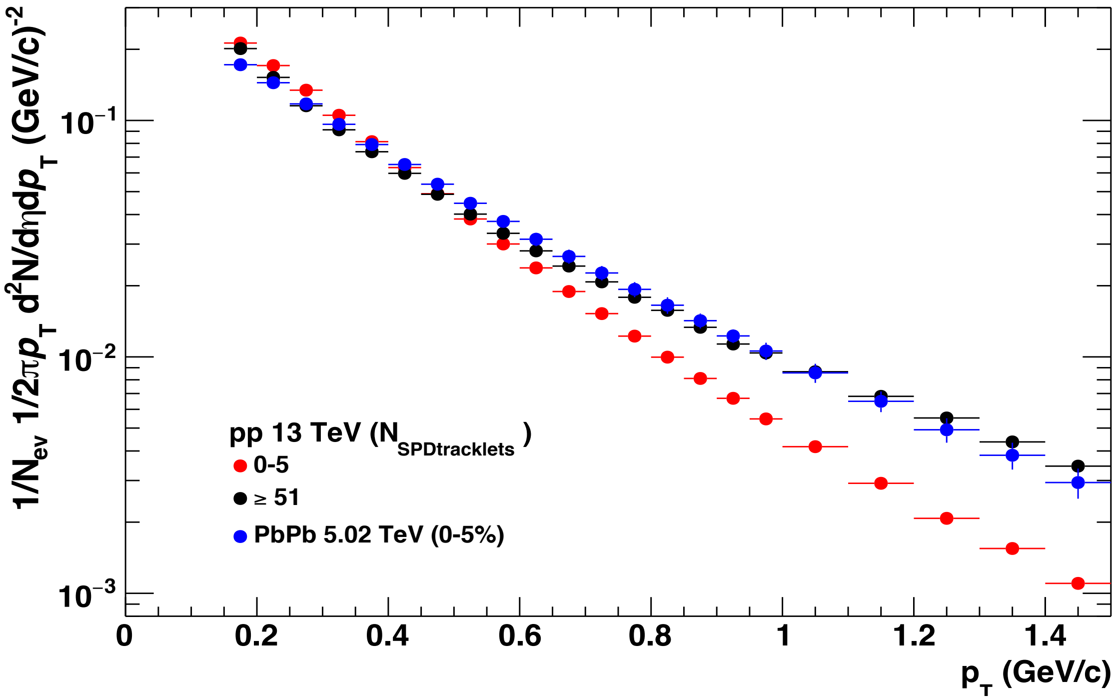
- Therefore, parameterised fitting function becomes

$$\frac{d^2N}{dp_T^2} = \frac{b}{\left(p_0 \sqrt{\frac{F(\xi_{pp})}{F(\xi_{pp})_{HM}}} + p_T \right)^n}$$

Here

$$F(\xi_{pp}) = 1$$

Methodology

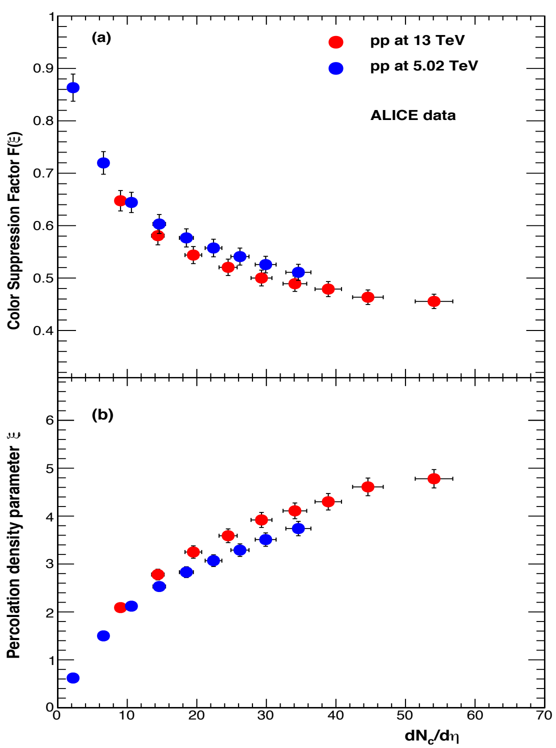


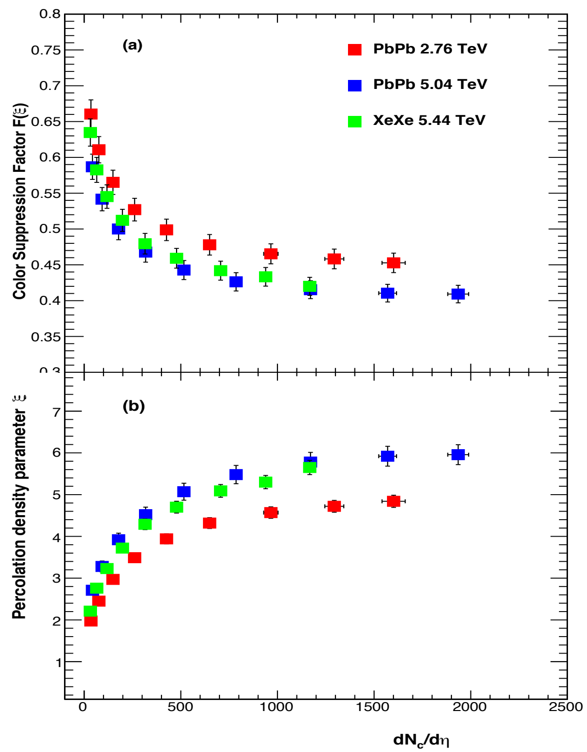
- p_T spectra for two multiplicity cuts at 13 TeV in pp collisions and Pb-Pb at 5.02 TeV.
- spectra becomes harder for higher multiplicity cut.

This is due to the fact that high string density color sources are created in the higher multiplicity events

Results: Color Suppression Factor F(ξ) & Percolation Density (ξ)

we have extracted ξ and F(ξ) at mid-rapidity for different multiplicity/centrality classes using the transverse momentum spectra of charged particles in pp and AA collisions.

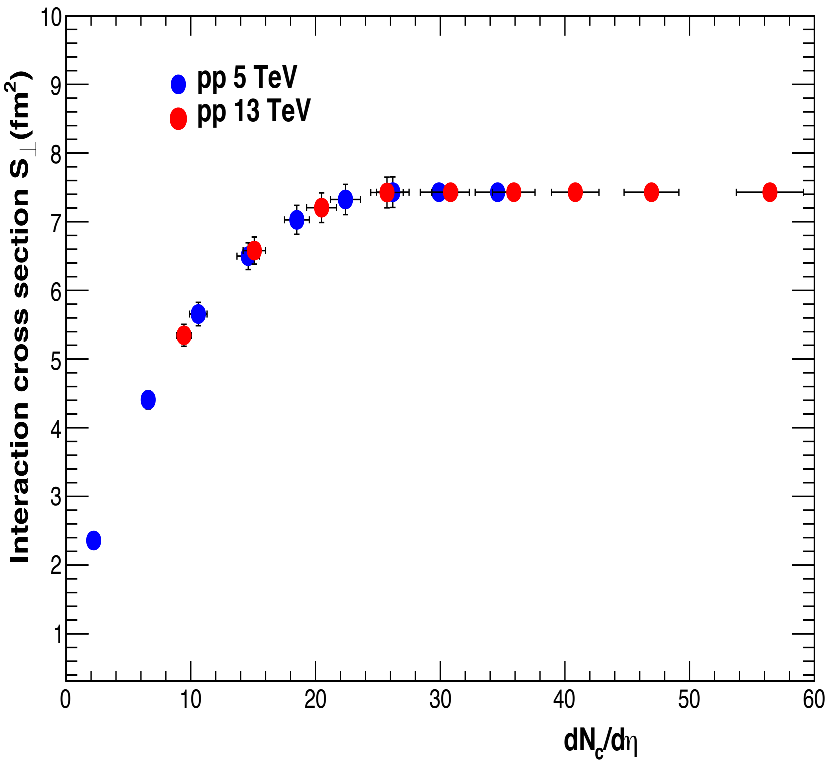


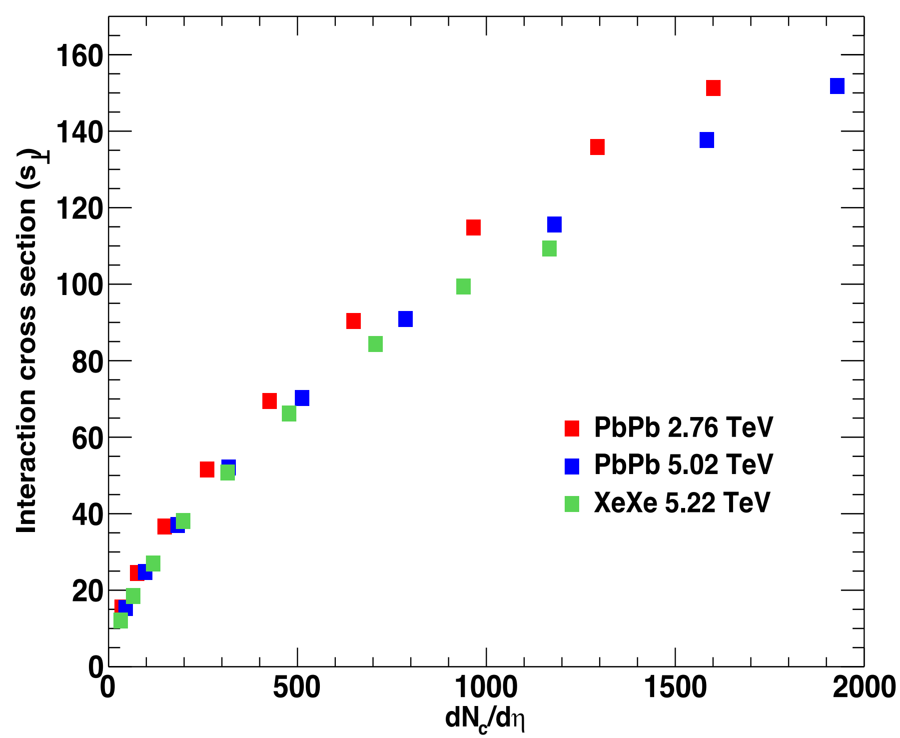


$$F(\xi) = \sqrt{\frac{1-e^{-\xi}}{\xi}}$$

Color Suppression Factor and Percolation Density Parameter as a function of multiplicity

Results: F(ξ) & (ξ) scaled with interaction area ($S_\perp$)



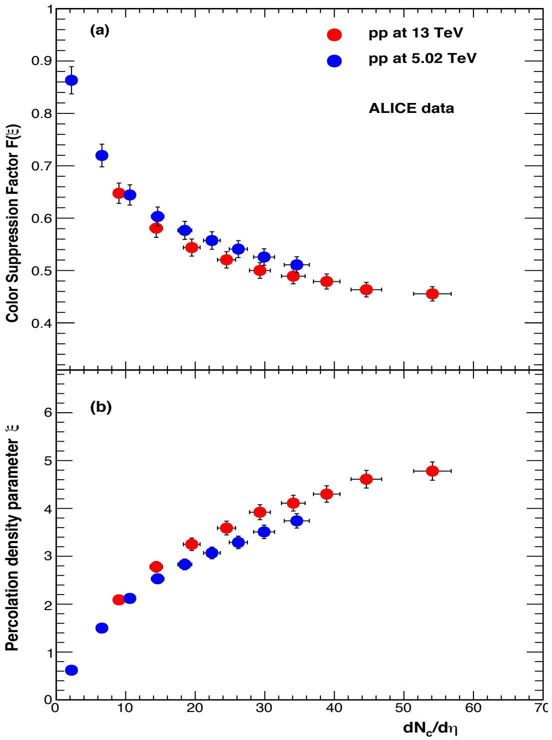


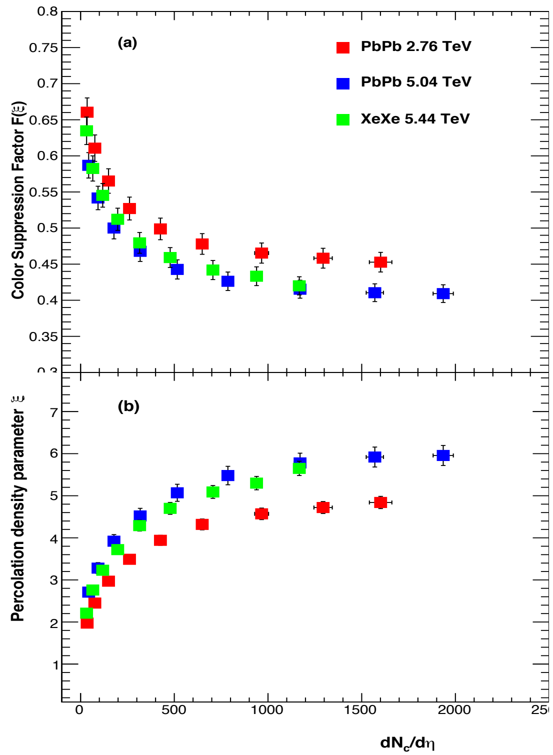
For pp: $S_\perp$ has been computed in the IP-Glasma model [1]

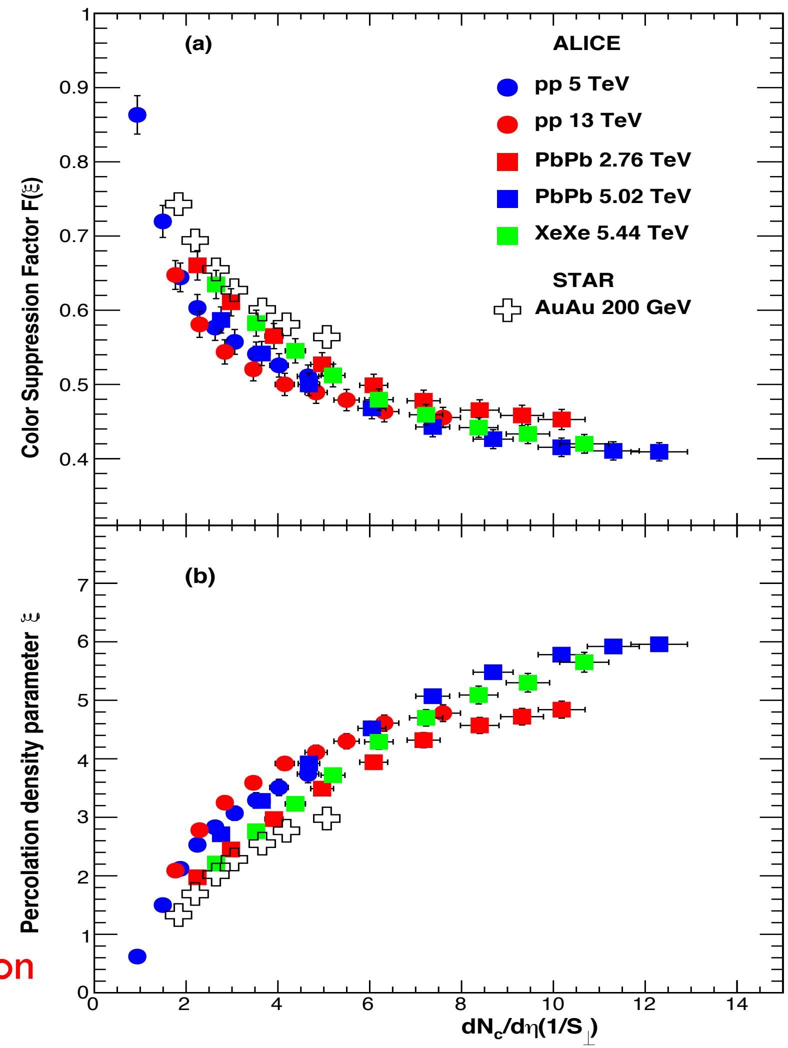
For AA: $S_\perp$ has been obtained using the Glauber model [2]

[1] L. McLerran, M. Praszalowicz and B. Schenke, Nucl. Phys. A 916 (2013) 210.
[2] C. Loizides, Phys. Rev. C 94 (2016) 024914.

Results: $F(\xi)$ & (ξ) scaled with interaction area ($S_\perp$)







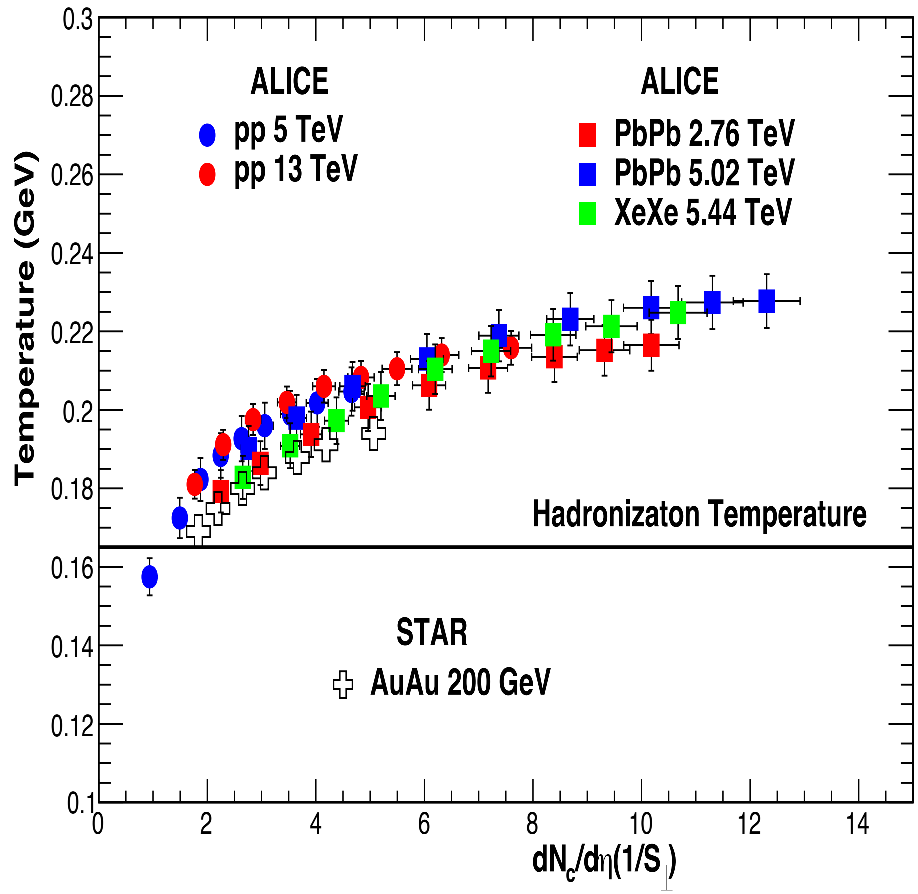
A universal scaling behavior is observed in hadron-hadron and nucleus-nucleus collisions.

Results: Connection between F (ξ)/ ξ and Temperature

In CSPM, the temperature is expressed as

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

- Temperature from both pp and AA collisions fall on a universal curve when multiplicity is scaled by $\mathbf{S}_\perp$.
- For pp collisions at 5.02 and 13 TeV: Higher multiplicity cuts show temperatures above the hadronization temperature[1].
- The hadronization temperature ~ 165 MeV also corresponds to the critical percolation density threshold ξc ≥ 1.2 at which a spanning cluster appears and marks the percolation phase transition.
- The temperatures obtained in higher multiplicity events are consistent with the creation of deconfined matter in pp collisions.

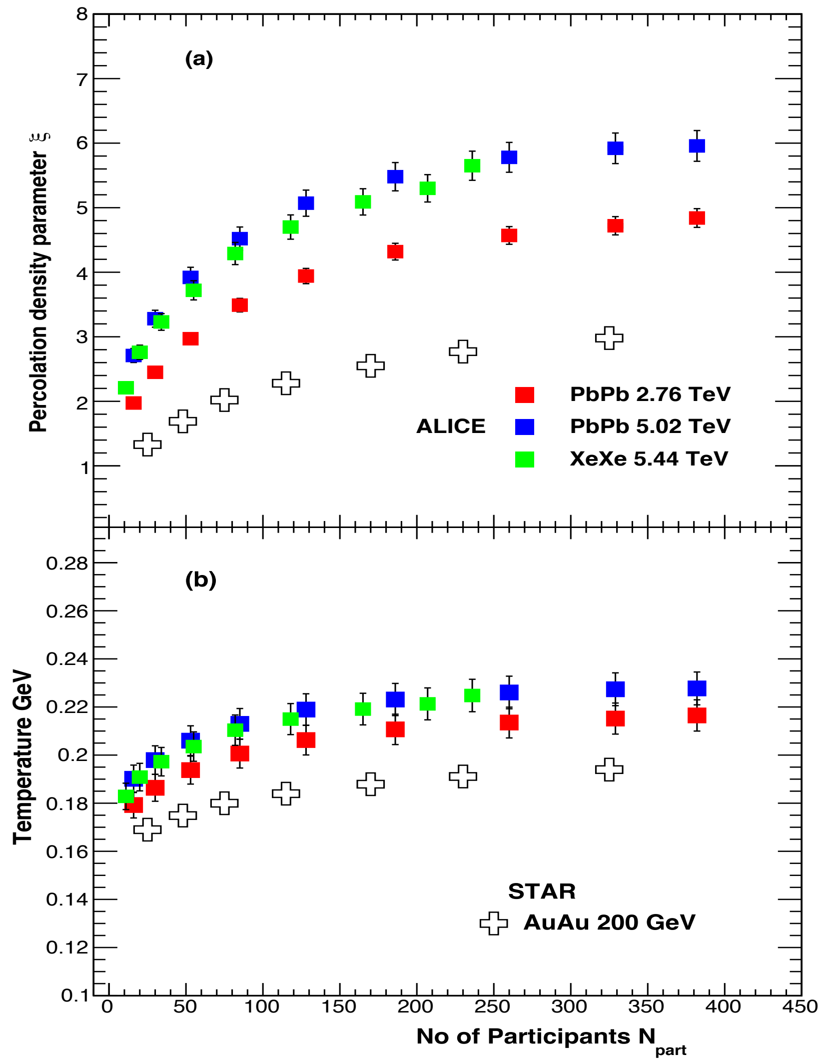


[1] F. Becattini et al., Eur. Phys. J. C 66, 377 (2010).

Results: Connection between F (ξ)/ ξ and Temperature

Only heavy-ion data are shown here to see the direct connection between ξ and the obtained Temperature

The string density ξ is collision energy dependent for the same number of participants.



Results: Energy density

In CSPM, the energy density (ε) can be given by

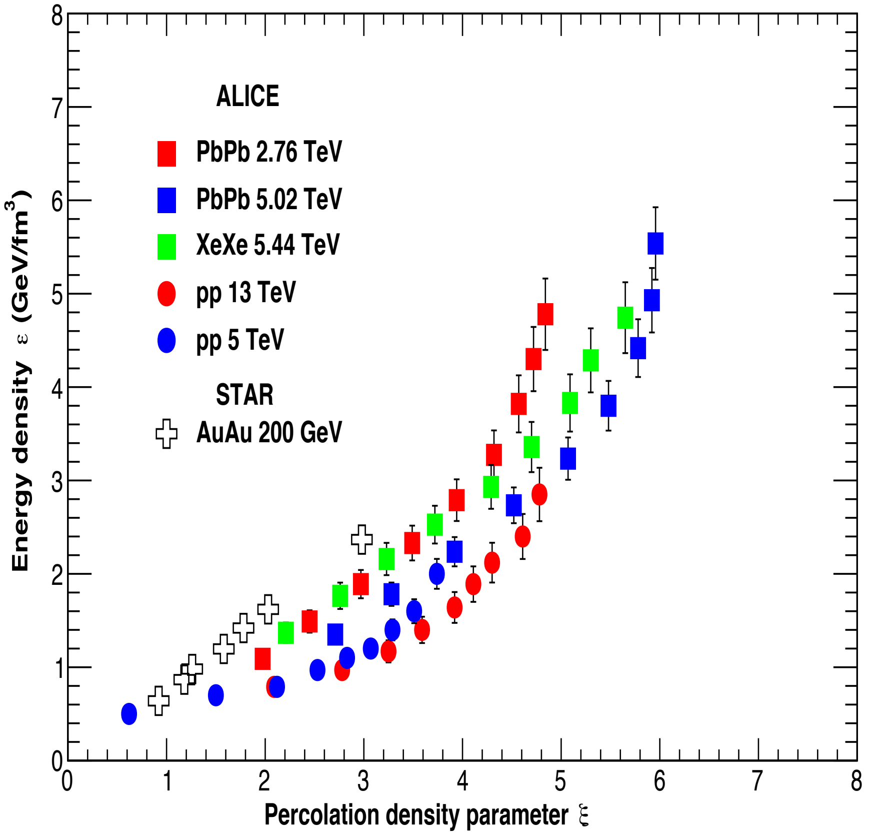
$$\varepsilon = \frac{3}{2}\frac{\frac{dN_c}{dy}\langle m_T\rangle}{S_n \tau_{pro}}$$

Where, τ_{pro} is the production time for boson (gluon) and is given by

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

- Slow rise of ε for low values of ξ followed by a faster rise later.
- For the range $1.2 < \xi < 5.0$: ε is proportional to ξ.
- Above $\xi \sim 5$ the energy density ε rises much faster.

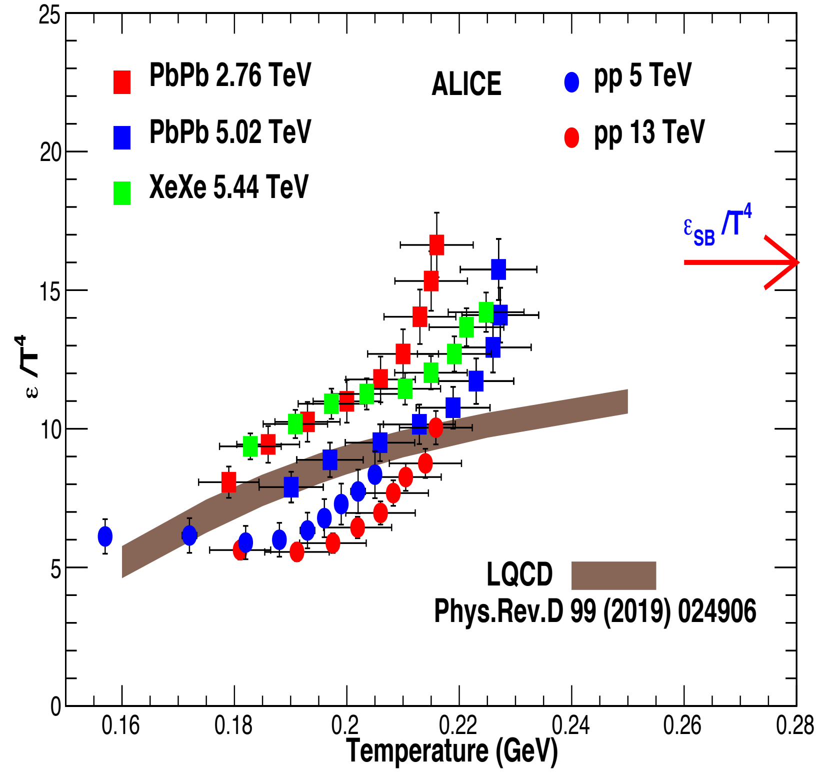
- A possible explanation for the sharp rise: At such high degree of overlapping the gluons are seen naked without interaction and thus the coherence of the color fields of the overlapping strings is lost and thus recover the independence of the strings.



This means that instead of a dependence on N_{part} it would be $N_{part}^{4/3}$.

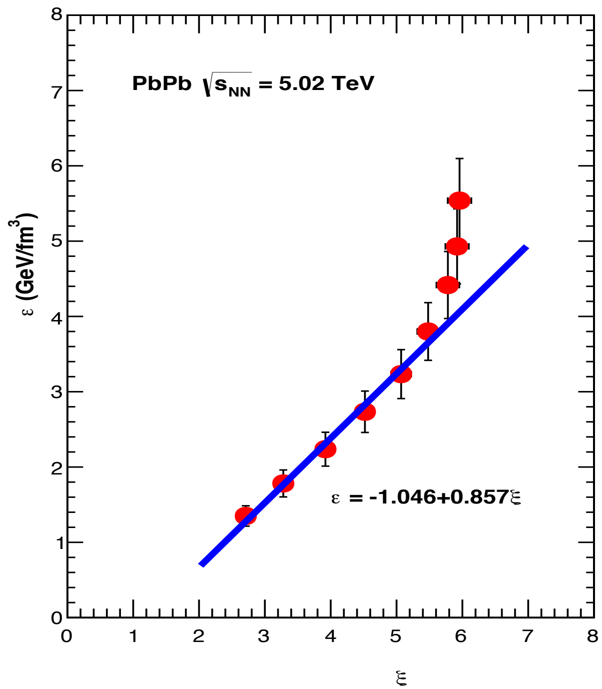
Results: Energy density

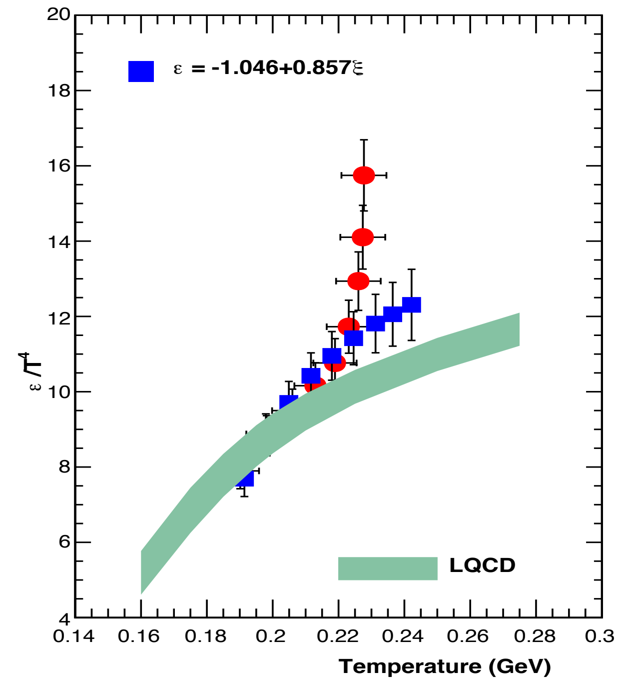
- Dimensionless quantity ε/T^4 as a function of temperature both from CSPM and LQCD.
- CSPM results similar trend with LQCD results up to the temperature of T ~ 210 MeV.
- Beyond this temperature the ε/T4 in CSPM rises much faster and reaches the ideal gas value of ε/T4 ~ 16 at T ~ 230 MeV.
- In this region, there is a strong screening due to the large degree of overlapping of the strings, producing a faster approach to the quark gluon gas limit.



To understand the deviation of ε/T^4 above ~ 210 MeV, one has to look at the energy density as a function of string density.

Results: Energy density





- The deviation form linear behavior starts ~ ξ = 5.
- CSPM values above T ~ 210 MeV have been obtained by extrapolating the linear fit to ε vs ξ.
- We find that obtained ε/T4 values follows the LQCD trend.

Results: Two temperatures

In CSPM, the mean distance between strings d is given by

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

- For small ξ , $d > r_0$ for example at the critital percolation density $\xi c = 1.2$, $d = 1.34r_0$.

⇓

Overlapping between strings is very peripheral, covering only the edges (corona) of the strings. This corresponds to the hadronization temperature of ~ 165 MeV.

To penetrate the core the overlapping should be larger in such a way that $d < r_0$.

- For $d \sim 0.8 - 0.9r_0$, $F(\xi) \sim 0.45 - 0.51$ 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

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

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

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

- Stefan-Boltzmann is also shown at ε/T^4, which corresponds to ~ 48 DOF
- In PbPb collisions: At T ~ 210 MeV, ε/T^4 ~ 11 ⟶ ~ 33 DOF while
  at T ~ 230 MeV, ε/T^4 ~ 16 ⟶ ~ 47 DOF
- In XeXe collisions at 5.44 TeV: ⟶ ~ 44 DOF.
- In pp collisions at 13 TeV : ⟶ ~ 33 DOF (only).

Our results are in agreement with the conclusions obtained studying the trace anomaly in a quasi particle gluonic model [1,2]. In this model the DOF of the free gluons are also obtained for T ≃ 1.3Tc (Tc ≈ 165 MeV).

[1] P. Castorina and M. Mannarelli, Phys. Lett. B 644 (2007) 336.
[2]P. Castorina and M. Mannarelli, Phys. Rev. C 75 (2007) 054901.

Summary

- ☑ Color String Percolation Model (CSPM) is used 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.

- ☑ A universal scaling in the temperature is obtained for both pp and A − A and are well above the universal hadronization temperature indicating that the matter created is in the deconfined phase.

- ☑ We observe:
  - existence of two temperature ranges in the behavior of the A-A 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.

- ☑ Our results show that the chiral symmetry restoration occurs ~ 210 MeV. Beyond this temperature the ε/T^4 rises much faster and reaches the Stefan-Boltzmann limit $\varepsilon/T^4 \sim 16$ at T ~ 230 MeV.

Thanks

for

your kind attention