Sudden increase in the degree of freedom in dense QCD matter

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Color Strings

- ✓ Multiparticle production at high energies is currently described in terms of color strings stretched between the projectile and target.
- ✓ These strings decay into new ones by $q-\bar{q}$ production and subsequently hadronize to produce the observed hadrons. Particles are produced by the Schwinger 2D mechanism.
- ✓ As the no. of strings grow with energy and or no. of participating nuclei they start to interact and overlap in transverse space as it happens for disks in the 2-D percolation theory

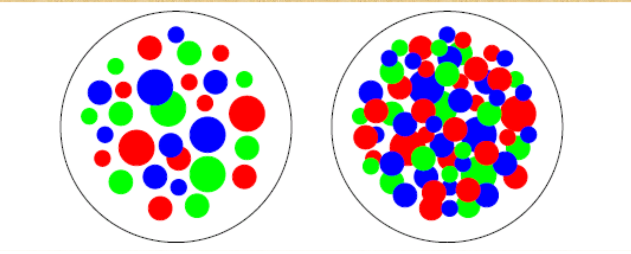
In the case of a nuclear collisions, the density of disks –elementary strings

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

N^s = # of strings
S_1 = Single string area
S_N = total nuclear overlap area

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.



Parton distributions in the transverse plane of nucleus- nucleus collisions

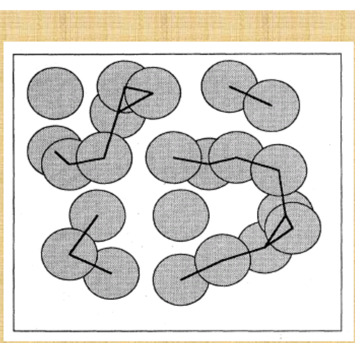
In two dimensions, for uniform string density, the percolation threshold for overlapping discs is:

$\xi_c = 1.18$

Critical Percolation Density

H. Satz, Rep. Prog. Phys. 63, 1511(2000).
H. Satz , hep-ph/0212046

Percolation : General



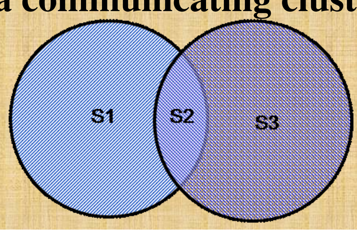
Percolation, statistical topography, and transport in random media
M. B. Isichenko
Reviews of Modern Physics, Vol. 64, No. 4, October 1992

$\xi = \pi n r^2$ **ξ is the percolation density parameter 'n' is the density and r the radius of the disc**

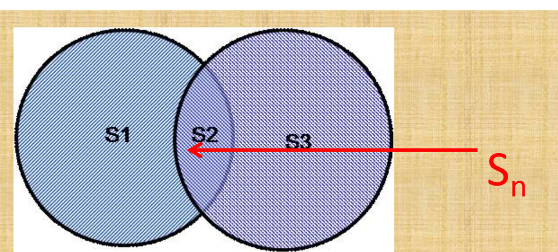
ϕ is the fractional area covered by the cluster $\phi = 1 - e^{-\xi}$

ξ_c is the critical value of the percolation density at which a communicating cluster appears

For example at ξ_c=1.2 , ϕ ~ 2/3
It means ~67% of the whole area is covered by the cluster
In the nuclear case it is the overlap area



Color Sources



The transverse space occupied by a cluster of overlapping strings split into a number of areas in which different no of strings overlap, including areas where no overlapping takes place.
A cluster of n strings that occupies an area S_n behaves as a single color source with a higher color field $\vec{Q}_n$ corresponding to vectorial sum of color charges of each individual string $\vec{Q}_1$:

$\vec{Q}_n^2 = n\vec{Q}_1^2$ If strings are fully overlap

$\vec{Q}_n^2 = n\frac{S_n}{S_1}\vec{Q}_1^2$ Partially overlap

Schwinger mechanism for the Fragmentation

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

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

Average Transverse Momentum
$\langle p_T^2 \rangle_n = \langle p_T^2 \rangle_1 / F(\xi)$

M. A. Braun et al, Eur.Phys. J. C16,349 (2000)
M. A. Braun et al, Phys. Rev. C65, 024907 (2002)

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

$$F(\xi) = \sqrt{\frac{1-e^{-\xi}}{\xi}}$$ = Color suppression factor (due to overlapping of discs)

N^s = # of strings
S_1 = disc area
S_N = total nuclear overlap area

ξ is the string density parameter

Percolation and Color Glass Condensate

Both are based on parton coherence phenomena: Percolation : Clustering of strings
CGC : Gluon saturation

- ✓ Many of the results obtained in the framework of percolation of strings are very similar to the one obtained in the CGC.
- ✓ In particular , very similar scaling laws are obtained for the product and the ratio of the multiplicities and transverse momentum.
- ✓ Both provide explanation for multiplicity suppression and $\langle p_t \rangle$ scaling with dN/dy.

Momentum Q_s establishes the scale in CGC with the corresponding one in percolation of strings

$$Q_s^2 = \frac{k\langle p_T^2 \rangle_1}{F(\xi)}$$

For large value of ξ

$$Q_s^2 \propto \sqrt{\xi}$$

The no. of color flux tubes in CGC and the effective no. of clusters of strings in percolation have the same dependence on the energy and centrality.
This has consequences in the Long range rapidity correlations and the ridge structure.

CGC : Y. V. Kovchegov, E. Levin, L McLerran, Phys. Rev. C 63, 024903 (2001).

Data Analysis

The experimental p_T distribution from pp data is used to extract F(ξ)

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

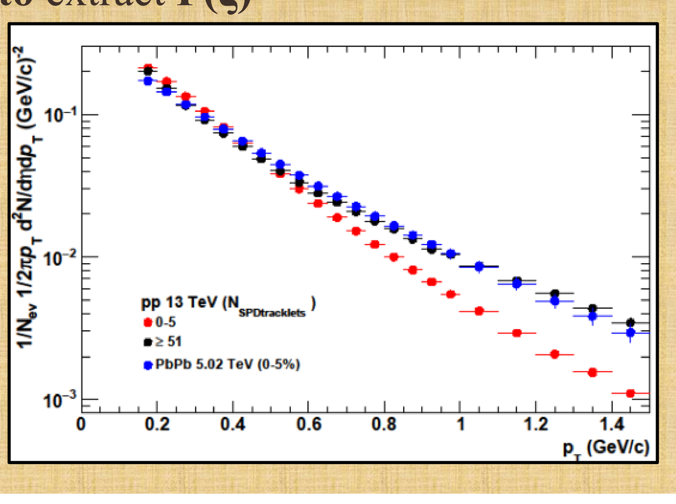
a, p_0 and n are parameters fit to the data.

This parameterization can be used for nucleus-nucleus collisions to account for the clustering :

$$\frac{d^2N}{dpt^2} = \frac{b}{\left(p_0\sqrt{\frac{F(\xi_{pp})}{F(\xi_{AuAu})}} + pt\right)^n}$$

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

Parametrization of STAR 200 GeV
p_0 = 1.982 and n = 12.877
Phys. Rep. 599 (2015) 1-50



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Data Analysis

Schwinger : p_t distribution of the produced quarks

$$\frac{dn}{d^2p_\perp} \sim \exp\left(-\frac{\pi p_t^2}{k^2}\right)$$

Thermal Distribution

$$\frac{dn}{d^2p_\perp} \sim \exp\left(-\frac{\pi p_t}{T}\right)$$

The Schwinger formula can be reconciled with the thermal distribution if the String tension undergoes fluctuations

$$P(k)dk = \sqrt{\frac{2}{\pi\langle k^2\rangle}}\exp\left(-\frac{k^2}{2\langle k^2\rangle}\right)dk$$

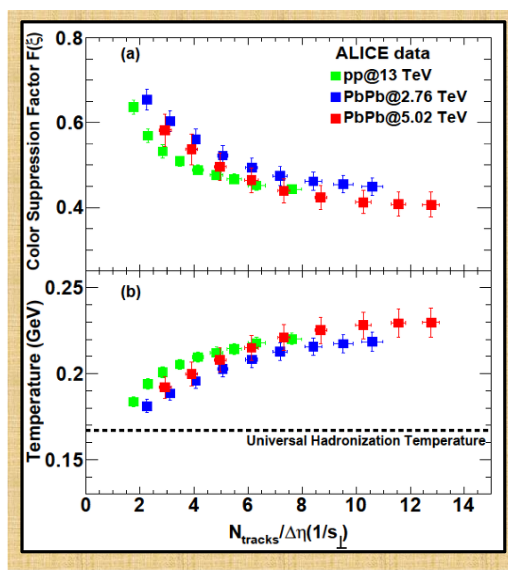
which gives rise to thermal distribution

$$\frac{dn}{d^2p_\perp} \sim \exp\left(-p_\perp\sqrt{\frac{2\pi}{\langle k^2\rangle}}\right)$$

$$T = \sqrt{\frac{\langle k^2\rangle}{2\pi}}$$

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

Results



- ✓ Color Suppression Factor $F(\xi)$ in Pb-Pb and pp collisions vs $N_{tracks}/\Delta\eta$ scaled by the transverse area $S_\perp$.
- ✓ N_{tracks} is the charged particle multiplicity in the pseudorapidity range $|\eta| < 0.8$ with $\Delta\eta$ = 1.6 units.
- ✓ For pp collisions $S_\perp$ is multiplicity dependent as obtained from IP-Glasma model.
- ✓ For Pb-Pb collisions the nuclear overlap area was obtained using the Glauber model.
- ✓ Temperature vs $N_{tracks}/\Delta\eta$ scaled by $S_\perp$ from Pb-Pb and pp collisions. The line ~ 165 MeV is the universal hadronization temperature.

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

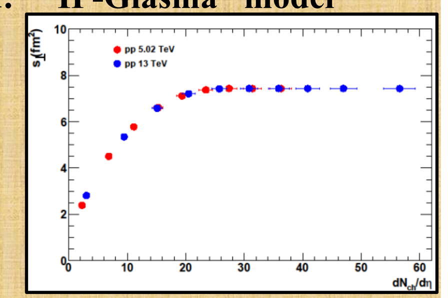
Transverse momentum of protons, pions and kaons in high multiplicity pp and pA collisions: Evidence for the color glass condensate?
Larry McLerran, Michal Praszalowicz, Björn Schenke
Nucl. Phys. A 916 (2013) 210-218

Interaction area is computed: IP-Glasma model

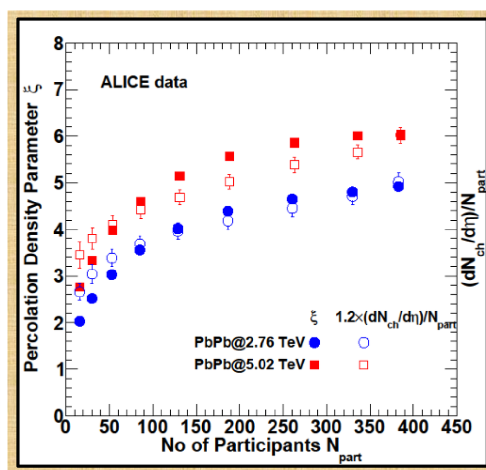
The gluon multiplicity can be approx. related to the no of tracks

$$\frac{dN_g}{dy} \approx K\frac{3}{2}\frac{1}{\Delta\eta}N_{track}$$

Transverse area : $S_{pp} = \pi R_{pp}^2$

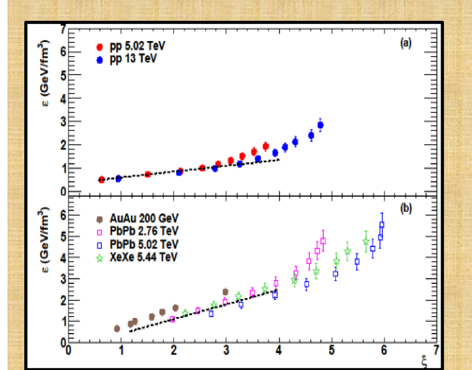


$R_{pp} = 1\text{ fm} \times f_{pp}(\sqrt[3]{dN_g/dy})$



- ✓ ξ as a function of N*part* for Pb-Pb collisions at 2.76 and 5.02 TeV. is also shown on the figure for comparison with ξ.
- ✓ It is observed that ξ rises slowly at higher *Npart*. This behavior is similar to measured $(dN_{ch}/d\eta)/N_{part}$ as shown in Figure (right y-axis).

Energy Density



Bjorken Phys. Rev. D 27, 140 (1983)

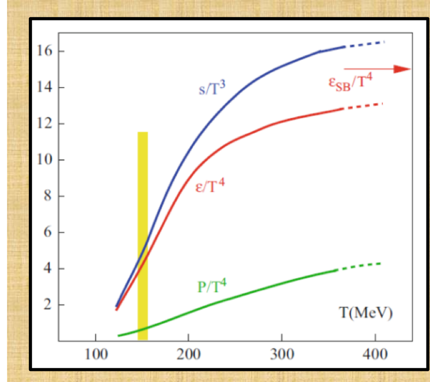
$$\varepsilon = \frac{3}{2}\frac{dN_c}{dy}\frac{\langle m_t\rangle}{A}\frac{1}{\tau_{pro}}GeV/fm^3$$

A = Transverse overlap area

τ_{pro} (proper time) is the QED production time for aboson which can be scaled from QED to QCD and is given by

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

Lattice Simulation results:

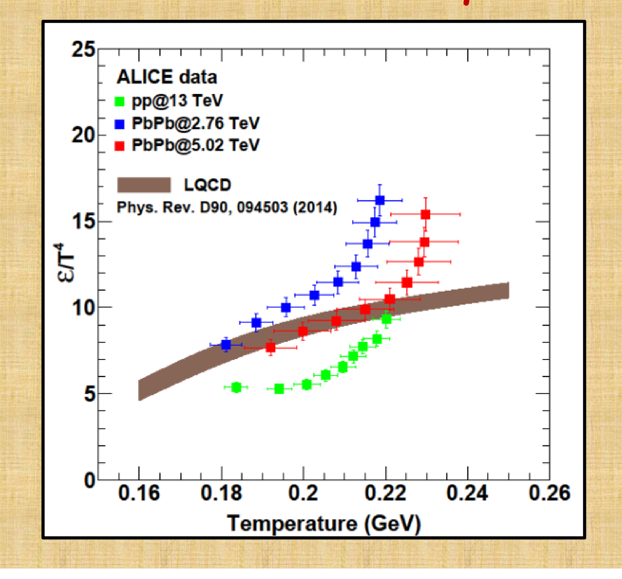


Energy density, entropy density and pressure in full QCD with (2+1) physiscal quarks. The ideal gas energy density is indicated by ε/T^4

$$\varepsilon/T^4 = \{(37/30)\pi^2 \approx 12\ for\ N_{f=2}$$
$$\{(47.5/30)\pi^2 \approx 16\ for\ N_{f=3}$$

H. Satz, Extreme states of matter in strong interaction physics. Lecture notes in physics 945, 2018

ALICE results and comparison with Lattice:



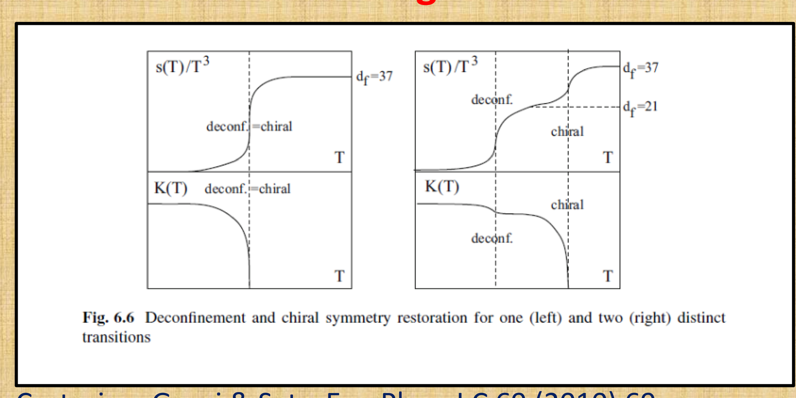
Degrees of Freedom (DOF):
DOF is obtained from Energy Density and Temperature

$$\frac{\varepsilon}{T^4} \sim g\,\pi^2/30$$

For ideal gas g ~ 47 corresponding to 3 quarks flavor.

Our results agree with LQCD results up to temperature of T~ 210 MeV.
Above 210 MeV CSPM $\frac{\varepsilon}{T^4}$ rises much faster and reaches the ideal gas value of 16.

It has been argued that QCD could lead to three – state phase structure as a function of temperature. In such a scenario, color deconfinement would result in a plasma of massive "dressed quarks". At still higher temperature this gluonic dressing of quarks would then " evaporate" , leading to a plasma of deconfined massless quarks and gluons : a "QGP".



Castorina, Gavai & Satz, Eur. Phys. J C 69 (2010) 69.

Results

- ✓ The Clustering of Color Sources produced by overlapping strings has been applied to both A-A and *pp* collisions.
- ✓ The most important quantity in this picture is the multiplicity dependent interaction area in the transverse plane
- ✓ The temperature from AA and *pp* scales as
- ✓ Quantum tunneling through color confinement leads to thermal hadron production in the form of Hawking-Unruh radiation. In QCD we have string interaction instead of gravitation.
- ✓ We observe for the first time a two-step behavior in the increase of DOF.

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