String percolation and the first LHC data

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Dual year Russia-Spain 2011
Barcelona 8-11 Nov
Outline

- Brief description of string percolation
- $dn/dy$ in pp and Pb-Pb
- Rapidity long range correlations, Ridge in pp and AA
- Elliptic flow in percolation, comparison at RHIC and LHC
  Shear viscosity/entropy in percolation
• **Color strings** are stretched between the projectile and target

• **Strings = Particle sources:** particles are created via sea \( qq \) production in the field of the string

• **Color strings = Small areas** in the transverse space filled with color field created by the colliding partons

• With growing energy and/or atomic number of colliding particles, the number of sources grows

• So the elementary color sources start to **overlap**, **forming clusters**, very much like disk in the 2-dimensional percolation theory

• In particular, at a certain **critical density**, a macroscopic cluster appears, which marks the **percolation phase transition**
(N. Armesto et al., PRL77 (96); J. Dias de Deus et al., PLB491 (00); M. Nardi and H. Satz (98).

- How?: Strings fuse forming clusters. At a certain critical density $\eta_c$ (central PbPb at SPS, central AgAg at RHIC, central SS at LHC) a macroscopic cluster appears which marks the percolation phase transition (second order, non thermal).

$$\eta = N_{st} \frac{S_1}{S_A}, \quad S_1 = \pi r_0^2, \quad r_0 = 0.2 \text{ fm}, \quad \eta_c = 1.1 \div 1.2.$$
\[ \mu_n = \sqrt{\frac{nS_n}{S_1}} \mu_1 ; \quad < p_T^2 >_n = \sqrt{\frac{nS_1}{S_n}} < p_T^2 >_1 \]

Energy-momentum of the cluster is the sum of the energy-momentum of each string.

As the individual color field of the individual string may be oriented in an arbitrary manner respective to one another, \( Q_n^2 = nQ_1^2 \)
- At high densities

\[
< \mu >_n = n F(\eta) < \mu >_1 \quad < p_T^2 >_n = \frac{< p_T^2 >_1}{F(\eta)}
\]

- \( F(\eta) = \sqrt{\frac{1-e^{-\eta}}{\eta}} \), \( \eta = N_S \frac{\pi r_0^2}{S_A} \)

- \( r_0 \) is the transverse size of a single string \( \simeq 0.2 \) fm.
New data: multiplicities

[ALICE: arxiv:1011.3916]

\[\frac{dN_{ch}}{d\eta} \times (0.5/N_{\text{part}})\]

\[v s_{\text{NN}}^{0.15}\]

\[v s_{\text{NN}}^{0.11}\]
\[ \frac{1}{N_A} \frac{dn}{dy} |_{N_A N_A} = \frac{dn}{dy} |_{pp} [1 + \gamma(\sqrt{s}) \frac{F(\eta_{N_A})}{F(\eta_p)} (N_A^{1/3} - 1)] \]

at high energy \( \gamma \to 1 \)

\[ \frac{1}{N_A} \frac{dn}{dy} |_{N_A N_A} = \frac{dn}{dy} |_{pp} [1 + \left( \frac{N_A}{A} \right)^{1/22} \left( 1 - \frac{1}{N_A^{1/3}} \right)] \]

(The shape as a function of \( N_A \) is independent of energy)
Two-Particle Angular Correlations

First surprising result from the LHC:
Observation of Long-Range Near-Side Angular Correlations in pp Collisions

MinBias
(b) MinBias, 1.65GeV/c<\rho<3.0GeV/c

high multiplicity (N>110)
(d) N>110, 1.65GeV/c<\rho<3.0GeV/c

Figure 7
Why Protons?

In String Percolation...

\[ \eta_{AA} = \left( \frac{r}{R} \right)^2 \overline{N}^s = \frac{N_A^{4/3}}{N_A^{2/3}} \left( \frac{r}{R_p} \right)^2 \overline{N}_p^s \]

\[ \eta_{AA}(s) = N_A^{2/3} \eta_{pp}(s) \quad \text{and} \quad \overline{N} \sim s^{2/7} \]

\[ \eta_{PbPb}(\sqrt{s}) \approx 20 \text{GeV} \]

\[ \eta_c \approx 1.15 \]

\[ \eta_{pp}(\sqrt{s}) \approx 6 \text{TeV} \quad \text{LHC} \]
• As the string density in Au-Au peripheral collisions at 200GeV is the same as in pp high multiplicity events (three times m.b)
If there is a ridge structure in Au-Au at RHIC It should be seen the same structure in pp as it was seen CMS collaboration

L. Cunqueiro, J Dias de Deus and CP
LONG RANGE CORRELATIONS

• A measurement of such correlations is the backward–forward dispersion

\[ D^2_{\text{BF}} = \langle n_B \rangle \langle n_F \rangle - \langle n_B \rangle <n_F> \]

where \( n_B(n_F) \) is the number of particles in a backward (forward) rapidity

\[ D^2_{\text{BF}} = \langle N \rangle \left( \langle n_B n_F \rangle - \langle n_B \rangle \langle n_F \rangle \right) + \left( \langle N^2 \rangle - \langle N \rangle^2 \right) \langle n_F \rangle <n_B> \]

\[ \begin{array}{c}
| B | \\
\Delta \eta \\
| F | \\
\end{array} \]

\( <N> \) number of collisions: \( <n_{1B}> <n_{1F}> \) F and B multiplicities in one collision

• In a superposition of independent sources model, \( D^2_{\text{BF}} \) is proportional to the fluctuations(\( D^2_N \)) on the number of independent sources (It is assumed that Forward and backward are defined in such a way that there is a rapidity window \( \Delta \eta \geq 1.0 \) to eliminate short range correlations).
\[ < n_s > = a + b n_p \]

with
\[ b = \frac{D_{BF}^2}{D_{FF}^2} \]

- \( b \) in pp increases with energy. In hA increases with A also in AA, increases with centrality.
The dependence of \( b \) with rapidity gap is quite interesting, remaining flat for large values of the rapidity window.
Existence of long rapidity correlations at high density.
Correlation Parameter $b$

**Situation:** Symmetrica

\[
\frac{1}{K} \left(1 + \frac{K}{\langle n_F \rangle}\right)
\]

- $1/K$ is the squared normalized fluctuations on effective number of strings (clusters) contributing to both forward and backward intervals.

The height of the ridge structure is proportional to $n_k$. 


\[ b = \frac{l}{l + \frac{d}{\left(1 - e^{-\eta}\right)^{3/2}}} \]

low density \( b \to 0 \)

high density (energy) \( b \to \frac{l}{l + d} \)

CGC

\[ b = \frac{l}{l + \alpha^2 c} \]

high density (energy) \( b \to 1 \)
As the centrality or the energy increases, $Q_s$ increases, $\alpha_s$ decreases and $b$ increases

(N. Armesto, L. McLerran and C.P; N. Armesto, M. Braun and C.P)
\[ \eta_\varphi = \eta \left( \frac{R}{R_\varphi} \right)^2 \]

\[ v_2(p_T, y) = \frac{2}{\pi} \int_0^{\pi/2} d\varphi \cos(2\varphi)[1 + \frac{\partial \ln f(p^2_T, \eta, y)}{\partial R^2}(R_\varphi^2 - R^2)] \]

\[ = \frac{2}{\pi} \int_0^{\pi/2} d\varphi \cos 2\varphi \left( \frac{R_\varphi}{R} \right)^2 \left( \frac{e^{-\eta} - F(\eta)^2}{2F(\eta)^2} \right) \frac{F(\eta)p_T^2 / \langle p_T^2 \rangle_1}{1 + F(\eta)p_T^2 / \langle p_T^2 \rangle_1} \]

\[ v_2 = \frac{2}{\pi} \int_0^{\pi/2} d\varphi \cos(2\varphi) \left( \frac{R_\varphi}{R} \right) \left( \frac{e^{-\eta} - F(\eta)^2}{2F(\eta)^3} \right) \frac{R}{R - 1} \]
ALICE preliminary, Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV
centrality 10%-20%

- $\pi^\pm$, $v_2(2, |\Delta\eta|>1)$
- $K^\pm$, $v_2(2, |\Delta\eta|>1)$
- $\Xi^-$, $v_2(2, |\Delta\eta|>1)$

-- hydro LHC
(CGC initial conditions)
($\eta/s=0.2$)
\[ \eta \approx \frac{4}{15} \varepsilon(T) \lambda_{mpf} \approx \frac{1}{5} \frac{T}{\sigma_{tr}} \frac{s(T)}{n(T)} \]

\[ \varepsilon(T) = \frac{3}{4} T s \]

\[ \lambda_{tr} = \frac{1}{n \sigma_{tr}} \]

\[ \frac{n}{s} \approx \frac{T \lambda_{mpf}}{5} \]

\varepsilon \quad \text{Energy density}

s \quad \text{Entropy density}

n \quad \text{the number density}

\lambda_{mpf} \quad \text{Mean free path}

\sigma_{tr} \quad \text{Transport cross section}
\[
\eta \approx \frac{T \lambda_{mpf}}{s} \frac{1}{5}
\]

\[
\frac{\eta}{s} = \frac{1}{5} \frac{\langle pt^2 \rangle_1}{2F(\xi)} \frac{1}{n \sigma_{tr}}
\]

\[n = \frac{N_{sources}}{\pi R_A^2 L}\]

No of effective sources per unit volume

\[N_{sources} = \frac{(1-e^{-\xi})\pi R_A^2}{F(\xi) S_1}\]

\[n = (1-e^{-\xi})\frac{1}{F(\xi) S_1 L}\]

In percolation

\[T = \sqrt{\frac{\langle pt^2 \rangle_1}{2F(\xi)}}\]

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

\[S_1 \text{ Single string area}\]

\[N_{sources} \text{ Effective no of sources}\]

\[L = 1 \text{ fm Length of the string}\]

\[\sqrt{\langle pt \rangle_1^2}\]

Average transverse momentum of the single string
\[ \sigma_{tr} = S_1 F(\xi) \]

\[ \eta \approx \frac{T \lambda_{mpf}}{5} \]

\[ n = \left(1 - e^{-\xi}\right) \frac{1}{F(\xi)S_1L} \]

\[ \lambda_{mpf} = \frac{1}{n \sigma_{tr}} = \frac{F(\xi)S_1L}{1 - e^{-\xi}} \frac{1}{F(\xi)S_1} \]

\[ \eta \approx \frac{1}{s} \frac{L}{5 \left(1 - e^{-\xi}\right)} T \]

\[ \frac{\eta}{s} = \frac{1}{5\sqrt{2}} \frac{\sqrt{\langle pt \rangle^2 \xi^{1/4}}}{(1 - e^{-\xi})^{5/4}} L \]

\[ \sigma_{tr} \propto \frac{1}{T^2} \]
Conclusions

--- A good agreement with RHIC and LHC data, for dN/dy dependences on energy and centrality.

--- It was predicted rapidity long range correlations and ridge structure in pp at high multiplicity.

--- Good description of v2 at RHIC and LHC including the rapidity dependences.

--- Low ratio shear viscosity/entropy density in the whole energy range RHIC-LHC.