Collective effects on small systems

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Table of contents

Motivation

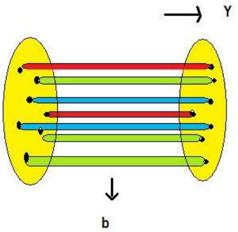
- Long range near side correlation in $(\Delta\eta)$ "Ridge" was observed by CMS experiment at 7 TeV high multiplicity p-p events.
- Phenomenological results from LHC for high multiplicity events allow us to study systems of different energy density created at high energy p-p collisions.
- Some studies had shown that high multiplicity event-classes in p-p collisions show indications of collectivity [1].
- The analysis of charge particle transverse momentum data E735 exhibits also flow velocity of mesons and anti-baryons [2].

  [1] Chatrchyan et al CMS EPJ C 72, 2164, ALICE Phys. Lett B 727 (2013) [2] arxiv:1504.08270 [ncl-th]

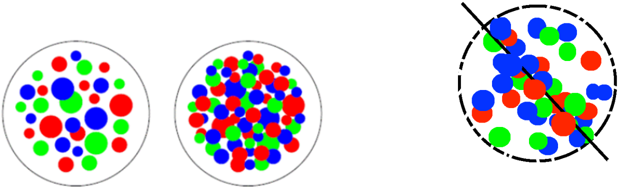
String Percolation Model

- Strings are supposed to describe confined QCD interactions in an effective way. They carry color charges at the ends, and an extended color field between the charges.
- Multi-particle production is described in terms of color strings stretched between the partons of the projectile and target that decay into new ones $q\bar{q}$, $qq-\bar{q}\bar{q}$.
- They emit particles by string breaking and pair creation.

- In the projected impact parameter plane strings look like discs.
- The area covered by a small disc connected to a single string is $S_1 = \pi r_0^2$, where we consider $r_0 \sim 0.25$ fm.
- The N_s grows with $\sqrt{s}$, N_{part}



- At critical density, the strings start to overlap and form clusters.
- A macroscopic cluster appears and marks the percolation phase transition.



- Due to the $SU(3)$ random summation of color charges, total changes make a reduction of the multiplicity and an increase in the string tension of the clusters (increase of $< p_T^2 >$).
- Particles are produced by the Schwinger mechanisms.

- The clusters behaves like discs in the continuum two dimensional percolation.
- Where the critical parameter is the transverse string density, given by:

  $\xi = N_s \frac{S_1}{S_A}$, $\xi_c = 1.1 - 1.5$ (depending on the profile function)
- For ξ larger than ξ_c a large cluster extend over the whole surface covering the fraction $1 - e^{-\xi}$ of the total area at which $\xi = \xi_c$
- We assume that a cluster of n strings behaves as a single string with higher color field, and momentum.
- In the large n limit one get the multiplicity and transverse momentum relations:

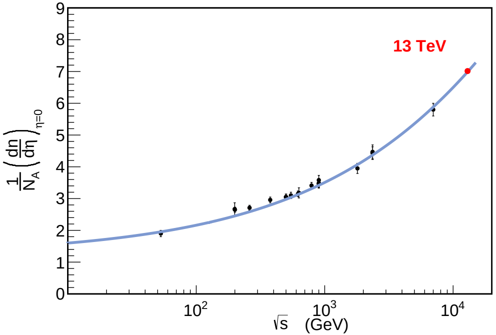
$$< \mu_n >= \sqrt{\frac{nS_n}{S_1}} < \mu_1 > \ , < p_{Tn}^2 >= \sqrt{\frac{nS_1}{S_n}} < p_{T1}^2 >$$

where $< \mu_1 >$ is the multiplicity and the transverse momentum $< p_{T1}^2 >$ corresponding to the value of a single string.

- The particle density dn/dy is related to the average number $\bar{N}_s$ of strings
  $\frac{dn}{dy} \sim F(\xi)\bar{N}_s$
  $F(\xi) = \sqrt{\frac{1-e^{-\xi}}{\xi}}$
  $N_p^s = 2 + 4\left(\frac{r_0}{R_p}\right)^2 \left(\frac{\sqrt{s}}{m_p}\right)^{2\lambda}$
- where m_p is the mass of the proton, R_p is the proton radius and $\lambda = .201$
- in pp collisions

$$\xi = N_p^s (\frac{r_0}{R_p})^2,$$

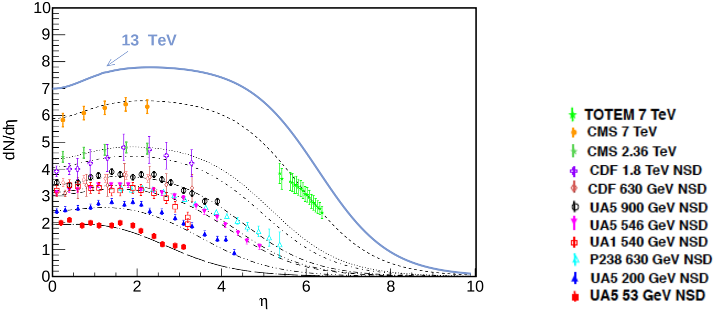
- $dn_{ch}^{pp}/dy|_{y=0} = \kappa F(\xi) N_p^s$ with $\kappa = .63$



Multiplicity dependence on $\sqrt{s}$. Data from $p-p$ PDG,

I. Bautista, J. G. Milhano, C. Pajares and J. Dias de Deus, Phys. Lett. B715, 230 (2012).

- $dn_{ch}^{pp}/d\eta|_{\eta} = \kappa' J F(\xi) N_p^s \frac{1}{\exp\left(\frac{\eta-(1-\alpha)Y}{\delta}\right)+1}$



Comparison of the results from the evolution of the $\frac{dn_{ch}}{d\eta}$ with dependence in pseudorapidity for $p-p$ collisions at different energies (lines).

I. Bautista,J. Dias de Deus, C. Pajares, Phys.Rev. C86 (2012) 034909.

- CMS collaboration has measured p_T-spectra of charged particles from pp collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV in the rapidity range $|y| < 1$ for different classes of events depending on mean number of charged particles, $\langle N_{ch} \rangle$ in the pseudo-rapidity interval, $|\eta| < 2.4$.
- The measured p_T - ranges are (0.1 to 1.2) GeV/c for $\pi^{\pm}$.

$$\frac{d^2N}{dp_T^2} = \omega(\alpha, p_0, p_T) = \frac{(\alpha-1)(\alpha-2)}{2\pi p_0^2} \frac{p_0^\alpha}{[p_0+p_T]^\alpha}$$

To determine the corresponding value of the string density, we fit the transverse momentum distributions for identified particles from different classes of high multiplicity events,

where $p_0 \to p_0\sqrt{\frac{F(\zeta)}{F(\zeta_{HM})}}$

$$\frac{d^2N}{dp_T^2} = \frac{(\alpha-1)(\alpha-2)(p_0\sqrt{\frac{F(\zeta_{pp})}{F(\zeta_{HM})}})^{\alpha-2}}{2\pi[p_0\sqrt{\frac{F(\zeta_{pp})}{F(\zeta_{HM})}}+p_T]^\alpha}$$ where ζ_{HM} is use for high multiplicity events (HM), leads to the expression,

$$\frac{1}{N}\frac{d^2N}{d\eta dp_T} = a'(\sqrt{s})\frac{dN}{d\eta}\Big|_{\eta=0}^{pp}(\sqrt{s})\omega(\alpha, p_0, p_T) = \frac{a(p_0\frac{F(\zeta_{pp})}{F(\zeta_{HM})})^{\alpha-2}}{[p_0\sqrt{\frac{F(\zeta_{pp})}{F(\zeta_{HM})}}+p_T]^{\alpha-1}}$$

In the case of pp collision with no high multiplicity data (min bias)

$$\frac{1}{N}\frac{d^2N}{d\eta dp_T} = \frac{a p_0^{\alpha-2}}{[p_0+p_T]^{\alpha-1}},$$

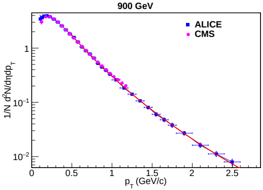


Figure: Fits to the transverse momentum distribution for energies $\sqrt{s} = 900$ GeV in $p-p$
Eur.Phys.J. C75 (2015) 226.

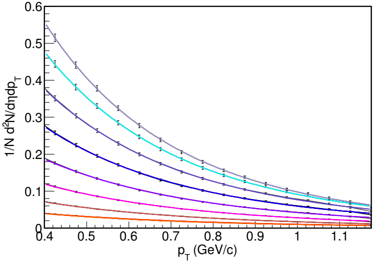


Figure: Fits to the transverse momentum distribution for energies $\sqrt{s} = 7$ TeV in $p-p$ collisions for different multiplicity classes from $N_{track} = 40$ grey line to $N_{track} = 131$ orange line. Data taken from http://hepdata.cedar.ac.uk/view/ins1123117 .

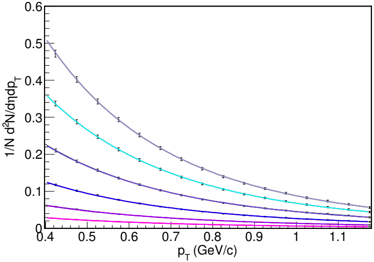


Figure: Fits to the transverse momentum distribution for energies $\sqrt{s} = 2.76$ TeV in $p-p$ collisions for different multiplicity classes from $N_{track} = 40$ grey line to $N_{track} = 98$ pink line. Data taken from http://hepdata.cedar.ac.uk/view/ins1123117 .

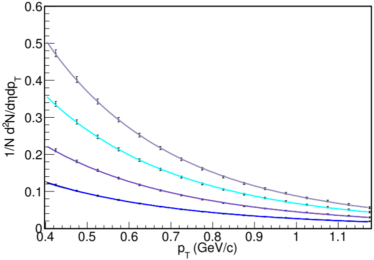


Figure: Fits to the transverse momentum distribution for energies $\sqrt{s} = 900$ GeV in $p-p$ collisions for different multiplicity classes from $N_{track} = 40$ grey line to $N_{track} = 75$ blue line. Data taken from http://hepdata.cedar.ac.uk/view/ins1123117 .

Color reduction factor $F(\zeta^t)$ with the corresponding $dn/d\eta$ respectively at different energies.

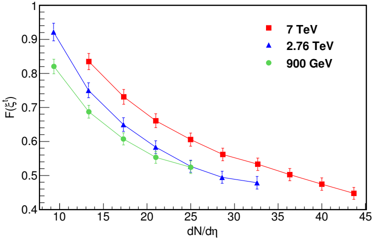


Figure: Color reduction factor at high multiplicities for different energies

The Schwinger mechanism for massless particles

$$\frac{dN}{dp_T} \sim e^{-\sqrt{2F(\zeta^t)}\frac{p_T}{\langle p_T \rangle_1}},$$

which can be related to the average value of the string tension

$$\langle x^2 \rangle = \pi \langle p_T^2 \rangle_1 / F(\zeta),$$

this value fluctuates around its mean value because the chromoelectric field is not constant, the fluctuations of the chromo electric field strength lead to a Gaussian distribution of the string tension that transform it into a thermal distribution.

The temperature is been given by the relation

$$T(\zeta^t) = \sqrt{\frac{\langle p_T^2 \rangle_1}{2F(\zeta^t)}}$$

We consider that the experimental, determined chemical freeze out temperature is a good mesure of the phase transition temperature T_c.
We calculate the effective temperature, T, from the equation, for each multiplicity class for a critical density $\zeta_c = 1.2$ and at the critical temperature $T_c = 154 \pm 9$ MeV, as obtained by the latest LQCD results [1], with the corresponding $\langle p_T \rangle_1 \sim 190.25 \pm 11.12$ MeV/c consistent with the measured of direct photon enhanced measured

[1] HotQCD: Phys. Rev. D85, 054503 (2012)

In the SPM the evolution of the mean transverse momentum can be described as an inverse function of the color reduction factor, since the distributions in transverse moment normalized for p-p collisions corresponds to $\frac{1}{N}\frac{d^2N}{dp_T^2} = \omega(\alpha, p_0, p_T) = \frac{(\alpha-1)(\alpha-2)}{2\pi p_0^2}\frac{p_0^\alpha}{(p_T+p_0)^\alpha}$ with $\langle p_T \rangle = p_0 \frac{2}{\alpha-3}$ taking again $p_0 \to p_0\sqrt{\frac{F(\zeta)}{F(\zeta_{HM})}}$ leads to

$$\langle p_T \rangle = p_0\sqrt{\frac{F(\zeta)}{F(\zeta_{HM})}}\frac{2}{\alpha-3}$$

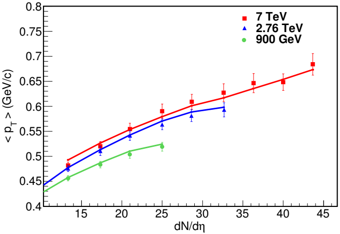


Figure: Mean transverse momentum at different energies data from http://hepdata.cedar.ac.uk/view/ins1123117

In SPM the energy density can be determined by a temperature at string level, by using the energy density from Bjorken $\varepsilon_i = \frac{3}{2}\frac{\frac{dN_c}{dy}\langle p_T \rangle}{S_N \tau_{pro}}$, where S_n is the nuclear overlap area, τ_{pro} is the production time for a boson gluon which we will replace by $\tau = 2.405\bar{h}/ < m_t >$ the propagation time of the parton given in fermis. The results are shown in Figure 6.

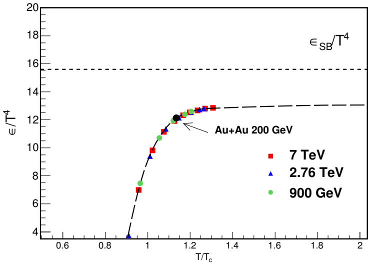
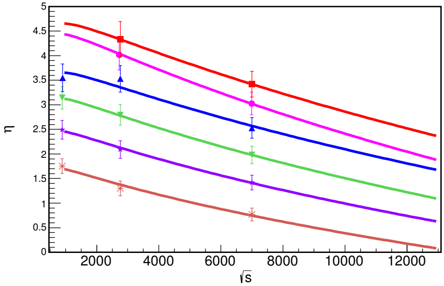


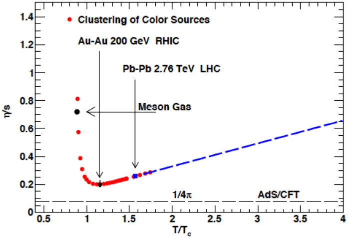
Figure: Energy density at different energies

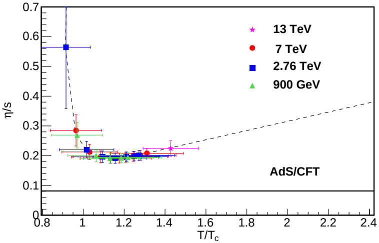
- The kinetic theory relation for shear viscosity and entropy density ratio is given by
- $\frac{\eta}{s} \simeq \frac{T\lambda_{fp}}{5}$ where T is temperature and $\lambda_{fp} \sim \frac{1}{n\sigma_{tr}}$ is mean free path, n the number density of an ideal gas of quarks and gluons and σ_{tr} the transport cross section.
- For SPM n is given by the effective number of sources per unit volume $n = \frac{N_{sources}}{S_N L}$ we consider $L = 1fm$ as the longitudinal extension of the source. $\frac{N_{sources}}{S_N L}\sigma_{tr} = (1 - e^{-\zeta^t})/L$

$$\frac{\eta}{s} = \frac{TL}{5(1 - e^{-\zeta^t})} \tag{1}$$



Extrapolation of ζ_{HM} for different multiplicity classes higher in red to lower in brown.





On the right Shear viscosity over entropy ratio for 7 TeV high multiplicity classes corresponding to $N_{track} = 40$ to $N_{track} = 131$, with the $T_c = 154 \pm 9$. In here we have plot the corresponding value corresponding to an approximate number of tracks $\sim 155 \pm 7$ corresponding to high multiplicity event in 13 TeV. Left side calculations the T_c value was taken as 167 MeV for heavy ion B. K. Srivastava, Eur. Phys. J. C72.

The model gives a clear indication of the geometrical phase transition for measured high multiplicity $p-p$ events, that may provide a explanation to the observed unexpected feature of the $p-p$ collision data at LHC energies.

More details see: I. Bautista, A. F. Tllez and P. Ghosh, Phys. Rev. D **92** (2015) 7, 071504

Thank you ..

$\sqrt{s}$ (TeV)	a	p_0	α
.9	23.29 ± 4.48	1.82 ± .54	9.40 ± 1.80
.9	20.6 ± 1.2	1.8 ± .22	8.2 ± .54
2.76	22.5± 4.2	1.5 ± .46	7.94± 1.41
7	33.12 ± 9.30	2.32 ± .88	9.78 ± 2.53

Table: Parameters of the transverse momentum distribution in pp collisions.

$\sqrt{s}$	7 (TeV)	2.76 (TeV)	900 (GeV)
$dN/d\eta$	ζ_{HM}	ζ_{MH}	ζ_{MH}
13.33	0.77 $\pm$ .13	1.30 $\pm$ .15	1.75 $\pm$ .15
17.33	1.42 $\pm$ .15	2.09 $\pm$ .18	2.49 $\pm$ .19
21.0	1.98 $\pm$ .18	.78 $\pm$ .21	3.13 $\pm$ .23
25	2.53 $\pm$ .21	3.52 $\pm$ .27	3.55 $\pm$ .28
28.67	3.02 $\pm$ .23	4.03 $\pm$ .31	
32.67	3.42 $\pm$ .26	4.33 $\pm$ .36	
36.33	3.89 $\pm$ .30		
40.	4.40 $\pm$ .36		
43.67	4.98 $\pm$ .40		

Table: Corresponding $dN/d\eta$ and ζ_{HM}, and R for the $\langle N_{track} \rangle$ in pp collisions high multiplicity clases

The single string average transverse momentum $\langle p_t \rangle_1$ is calculated at $\zeta_c = 1.2$ and $\zeta_c = 1.5$ with the universal chemical freeze out temperature of 167.7 ± 2.6 MeV and 154 ± 9 MeV both values corresponding to the old and new LQCD results from the HotLQCD collaboration. The values for the corresponding ζ^t and T_c obtained:

$p_{T1} = 190.25 \pm 11.12$ for $\zeta^t = 1.2$ and $T_c = 154 \pm 9$
$p_{T1} = 184.76 \pm 7.80$ for $\zeta^t = 1.5$ and $T_c = 154 \pm 9$
$p_{T1} = 207.18 \pm 3.21$ for $\zeta^t = 1.2$ and $T_c = 167.7 \pm 2.3$
$p_{T1} = 201.19 \pm 3.12$ for $\zeta^t = 1.2$ and $T_c = 167.7 \pm 2.3$.

We compare the obtained temperature T_i at the measured value of $\zeta = 2.88$ before the expansion of the QGP with the measured $T_i = 221 \pm 19_{stat} \pm 19_{sys}$ MeV from the enhanced direct photon experiment measured by PHENIX. All the values are consistent with the previously used value of ~ 200 MeV in the calculation of percolation transition of temperature with the exception of the one obtained at $T_c = 154$ with $\zeta_c = 1.5$.

A. Bazavov et al., Phys. Rev. D80, 014504 (2009). A. Adare et al., (PHENIX Collaboration), Phys. Rev. Lett. 104, 132301 (2010).