De-Confinement in small systems: Clustering of color sources in high multiplicity \( \bar{p} p \) collisions at \( \sqrt{s} = 1.8 \) TeV

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in collaboration with  


ISMD 2015  
Oct. 4-9, 2015  
Wildbad Kreuth, Germany
The experiment was accepted as E-735 in 1983 $pp$ At 1.8 TeV

The Detector consisted of:

- Scintillator vertex hodoscope
- A Side arm magnetic spectrometer
- A time of flight system for particle identification
E-735 Measurements

- Temperature as a function of $\frac{dn}{d\eta}$
- Length of multiplicity involved
- Particle identity: $\pi$, K, p, $\bar{p}$, d, $\Lambda$
- Freeze-out energy density

Conclusion:
Evidence for de-confinement was published in 2002. The comparison was made with Lattice QCD calculations.

Here we present the results which come from reanalysis of the E-735 data using Color String Percolation Model. The results are also compared with Lattice QCD simulations.
Percolation: General

It is well known that the percolation problem on a large lattice displays the features of a system undergoing a second-order phase transition. For example:

* Transition from liquid to gas
* Normal conductor to a superconductor
* Paramagnet to ferromagnet

1. H. E. Stanley, Introduction to Phase Transitions and Critical Phenomena
2. D. Stauffer and A. Aharony, Introduction to Percolation Theory
Parton Percolation

Multiparticle production at high energies is currently described in terms of color strings stretched between the projectile and target. Hadronizing these strings produces the observed hadrons. The no. of strings grow with energy and the no. of participating nuclei and one expects that interaction between strings becomes essential.

De-confinement is thus related to cluster formation very much similar to cluster formation in percolation theory. Critical Percolation Density \( \xi_c = 1.20 \)
Multiplicity and \( <p_T^2> \) of particles produced by a cluster of \( n \) strings

\[
\mu_n = F(\xi) N^s \mu_1
\]

\[
\xi = \frac{N^s S_1}{S_N}
\]

\( \xi \) is the percolation density parameter.

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

Complete description of CSPM has been published in Phys. Rep. Sept. 2015
Braun, Deus, Hirsch, Pajares, Scharenberg, Srivastava
Using the $p_T$ spectrum to calculate $\xi$

The experimental $p_T$ distribution from $pp$ data is used

\[
\frac{d^2 N}{dp_t^2} = \frac{a}{(p_0 + p_t)^n} \quad \frac{d^2 N}{dp_t^2} = \frac{b}{p_0 \left( \sqrt{\frac{F(\xi_{pp})}{F(\xi_{AuAu})}} + p_t \right)^n}
\]

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

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

\[
F(\xi)_{pp} = 1 \quad \text{For central collisions}
\]

\[
F(\xi)_{AuAu} = 0.57
\]

Charged Hadron spectrum
Table 1. Number of tracks $N_c$ as measured by the E735 experiment in the pseudorapidity range $|\eta| < 3.25$, $\langle dN_c/d\eta \rangle$, and the fit parameters $p_0$ and $n$ to the invariant $p_t$ distribution [27, 28].

<table>
<thead>
<tr>
<th>$N_c$</th>
<th>$\langle dN_c/d\eta \rangle$</th>
<th>$p_0$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>13.07</td>
<td>1.052±0.005</td>
<td>7.038±0.020</td>
</tr>
<tr>
<td>105</td>
<td>16.15</td>
<td>1.001±0.005</td>
<td>6.743±0.020</td>
</tr>
<tr>
<td>135</td>
<td>20.76</td>
<td>1.001±0.009</td>
<td>6.581±0.033</td>
</tr>
<tr>
<td>165</td>
<td>25.38</td>
<td>1.061±0.035</td>
<td>6.676±0.117</td>
</tr>
</tbody>
</table>
Schwinger Mechanism of Particle Production

$p_t$ distribution of the produced quarks

\[ \frac{dn}{d^2 p_t} \sim \exp\left(-\frac{\pi p_t^2}{k}\right) \]

$k$ is the string tension

The tension of the macroscopic cluster fluctuates around its mean value because the chromoelectric field is not constant. Assuming a Gaussian form for these fluctuations one arrives at the probability distribution of transverse momentum.

**Thermal Distribution**

\[ \frac{dn}{d^2 p_t} \sim \exp\left(-\frac{\pi p_t}{T}\right) \]

**Cluster /Initial Temperature**

\[ T = \sqrt{\frac{\langle k \rangle}{2\pi}} \]

\[ T = \sqrt{\frac{\langle p_t^2 \rangle_1}{2F'(\xi)}} \]
Temperature

The connectivity or percolation threshold for the formation of the “spanning” cluster occurs when the string density is $\xi = 1.2$.

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

F($\xi$) at $\xi = 1.2$ and the Universal Hadronization Temperature $T = 167 \pm 2.2$ MeV are used to accurately calibrate the T($\xi$) scale. This accurately determines the single string momentum.

\[ \sqrt{\langle p_t^2 \rangle_1} = 207.2 \pm 3.3 \text{ MeV} \]

CSPM result:
For Au+Au@ 200 GeV (STAR data) 0-10% centrality $\xi = 2.88$ $T \sim 195$ MeV

PHENIX:
Temperature from direct photon Exponential (consistent with thermal) Inverse slope = $220 \pm 20$ MeV PRL 104, 132301 (2010)

Pb+Pb @ 2.76 TeV for 0-5% $T \sim 265$ MeV

ALICE : Direct Photon Measurement $T = 304 \pm 51$ MeV, QM 2012
Table 2. \( \langle dN_c/d\eta \rangle \), the measured percolation density parameter \( \xi \), initial temperature \( T \), initial energy density \( \varepsilon \) and \( \eta/s \) for \( \bar{p}p \) collisions at \( \sqrt{s}=1.8 \) TeV. The error on \( \eta/s \) is same as on temperature \( \sim 4\% \).

<table>
<thead>
<tr>
<th>( \langle dN_c/d\eta \rangle )</th>
<th>( \xi )</th>
<th>( T ) (MeV)</th>
<th>( \varepsilon ) (GeV/( fm^3 ))</th>
<th>( \eta/s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.07</td>
<td>1.39±0.04</td>
<td>170.73±4.26</td>
<td>0.86±0.03</td>
<td>0.23</td>
</tr>
<tr>
<td>16.15</td>
<td>1.42±0.04</td>
<td>171.22±4.28</td>
<td>1.07±0.04</td>
<td>0.23</td>
</tr>
<tr>
<td>20.76</td>
<td>1.84±0.07</td>
<td>178.06±5.34</td>
<td>1.39±0.06</td>
<td>0.21</td>
</tr>
<tr>
<td>25.38</td>
<td>2.30±0.08</td>
<td>185.07±6.47</td>
<td>1.75±0.07</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Energy Density

\[ \varepsilon = \frac{3}{2} \frac{dN_c}{dy} \frac{<m_t>}{A} GeV / fm^3 \]

Transverse overlap area

Proper Time

\[ \tau_{pro} \]

is the QED production time for a boson which can be scaled from QED to QCD and is given by

\[ \tau_{pro} = \frac{2.405\hbar}{<m_t>} \]

Introduction to high energy heavy ion collisions

C. Y. Wong


Having determined the initial temperature of the system from the data one would like to obtain the following quantities to understand the properties of QCD matter:

\[ \frac{\varepsilon}{T^4} \]

- **Shear Viscosity**
- **Equation of State**
Energy Density $/T^4$

- Data points for pp@1.8 TeV E-735 and CSPM.
- Lattice QCD simulation for 2+1 flavor.
- Au+Au@200 GeV Central with $\xi_c = 1.2$.
The viscosity can be estimated from kinetic theory to be

\[ \eta \approx \frac{4}{15} \varepsilon(T) \lambda_{mfp} \approx \frac{1}{5} \frac{T}{\sigma_{tr}} \frac{s(T)}{n(T)} \]

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

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

\[ \frac{\eta}{s} \approx \frac{T \lambda_{mfp}}{5} \]


- \( \varepsilon \) Energy density
- \( s \) Entropy density
- \( n \) the number density
- \( \lambda_{mfp} \) Mean free path
- \( \sigma_{tr} \) Transport cross section
- \( \sqrt{<p_{tr}^2>} \) Average transverse momentum of the single string
- \( L \) is Longitudinal extension of the source 1 fm

\[ \lambda_{mfp} = \frac{L}{1 - e^{-\xi}} \]

\[ \frac{\eta}{s} \approx \frac{1}{5} \frac{L}{1 - e^{-\xi}} T \]
Shear Viscosity to Entropy Density ratio

\[ \eta/s \]

Temperature (MeV)

pp@1.8 TeV E735
CSPM

Meson Gas

Au-Au@200 GeV Central

Ads/CFT (1/4\pi)
Trace Anomaly

COMPARE the trace anomaly Ansatz \((\eta/S)^{-1} = S/\eta\) with the trace anomaly from hot QCD \(\Delta(T) = (\varepsilon - 3p)/T^4\)

\(\frac{S}{\eta}(T)\) and \(\Delta(T)\) have the same magnitude and temperature dependence.

Ansatz: we will use \(\frac{S}{\eta}(T)\) to correlate \(\varepsilon(T)\) and \(p(T)\) for \(T > T_c\)
\[ \Delta = \frac{\varepsilon - 3p}{T^4} \]

\[ C_s^2 = \frac{dp}{d\varepsilon} = \varepsilon \frac{dp}{d\varepsilon} + \frac{p}{\varepsilon} \]

\[ C_s^2 = (-0.33) \left( \frac{\xi e^{-\xi}}{1 - e^{-\xi}} - 1 \right) + 0.0191(\Delta / 3) \left( \frac{\xi e^{-\xi}}{(1 - e^{-\xi})^2} - \frac{1}{1 - e^{-\xi}} \right) \]
Summary

- The $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV from the E735 experiment have been re-analyzed in using the clustering of color sources data based phenomenology.

- The Percolation framework provides us with a microscopic partonic structure which explains the early thermalization.

- The Bjorken ideal fluid description of the QGP, when modified by the color reduction factor and the trace anomaly $\Delta$ represented by $s/\eta$ is in remarkable agreement with the Lattice Quantum Chromo Dynamics (LQCD) simulations.

- These results prove that even in small systems at high energy and high multiplicity events, QGP formation is possible as seen in collisions at $\sqrt{s} = 1.8$ TeV.

- A further definitive test of clustering phenomena can be made at LHC energies by comparing $h-h$ and A-A collisions.
References

1. De-Confinement and clustering of color sources in nuclear collisions

2. Clustering of Color sources and shear viscosity to entropy density

3. Percolation of color sources and the equation of state of QGP....

4. The QGP EOS by measuring the color suppression factor at RHIC and LHC
   R. P. Scharenberg, CPOD 2013, 017 (2013)

5. Percolation approach to initial stage effects in high energy collisions

* Braun, Deus, Hirsch, Pajares, Scharenberg and Srivastava
** Deus, Hirsch, Pajares, Scharenberg and Srivastava
*** Scharenberg, Srivastava and Hirsch