De-Confinement in $pp$ Collisions at LHC Energies

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MULTIPLICITY DEPENDENCE OF $p_t$ SPECTRUM AS A POSSIBLE SIGNAL FOR A PHASE TRANSITION IN HADRONIC COLLISIONS

L. VAN HOVE
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It is argued that the flattening of the transverse momentum ($p_t$) spectrum for increasing multiplicity $n$, observed at the CERN proton–antiproton collider for charged particles in the central rapidity region, may serve as a probe for the equation of state of hot hadronic matter. We discuss the possibility that this $p_t$ versus $n$ correlation could provide a signal for the deconfinement transition of hadronic matter.

1. Experiments at the CERN $p\bar{p}$ collider (c.m. energy $\sqrt{s} = 540$ GeV) have shown that the charged particles produced in the central region of rapidity ($|y| \leq y_0 = 2.5$) have the following properties:
   (a) The multiplicity per unit of rapidity, $dn/dy$, continues to grow above ISR energies ($\sqrt{s} = 30–60$ GeV) [1,2].
   (b) There is a clear dependence of the $p_t$ spectrum on the central multiplicity.
Transverse Baryon Flow as Possible Evidence for a Quark-Gluon-Plasma Phase

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(Received 13 March 1991)

In order to investigate the coupling between the collective flow of nucleons and pions in hot pion-dominated hadronic matter, we calculate the pion-nucleon drag coefficient in linearized transport theory. We find that the characteristic time for flow equalization is longer than the time scale of the expansion of a hadronic fireball created in high-energy collisions. The analysis of transverse-momentum data from \(p + \bar{p}\) collisions at \(\sqrt{s} = 1.8\) TeV reveals the same flow velocity for mesons and antinucleons. We argue that this may be evidence for the formation of a quark-gluon plasma in these collisions.

E-735 Experiment
The yields and average transverse momenta of pions, kaons, and antiprotons produced at the Fermilab \( \bar{p}p \) collider at \( \sqrt{s} = 300, 540, 1000, \) and \( 1800 \) GeV are presented and compared with data from the energies reached at the CERN collider. We also present data on the dependence of average transverse momentum \( \langle p_t \rangle \) and particle ratios as a function of charged particle density \( dN_c/d\eta \); data for particle densities as high as six times the average value, corresponding to a Bjorken energy density \( 6 \) GeV/fm\(^3\), are reported. These data are relevant to the search for quark-gluon phase of QCD.
E735: QGP?

Evidence for hadronic deconfinement in $\bar{p}-p$ collisions at 1.8 TeV

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W. D. Walker$^{(6)}$

Physics Letters B 528 (2002) 43–48

Abstract

We have measured deconfined hadronic volumes, $4.4 < V < 13.0$ fm$^3$, produced by a one dimensional (1D) expansion. These volumes are directly proportional to the charged particle pseudorapidity densities $6.75 < dN_c/d\eta < 20.2$. The hadronization temperature is $T = 179.5 \pm 5$ (syst) MeV. Using Bjorken’s 1D model, the hadronization energy density is $\epsilon_F = 1.10 \pm 0.26$ (stat) GeV/fm$^3$ corresponding to an excitation of $24.8 \pm 6.2$ (stat) quark-gluon degrees of freedom.
De-Confinement and Clustering of Color Sources In Nuclear Collisions
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.

In two dimensions, for uniform string density, the percolation threshold for overlapping discs is: \( \xi_c = 1.18 \)

H. Satz, Rep. Prog. Phys. 63, 1511(2000).
H. Satz, hep-ph/0212046
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 \( \vec{Q}_1 \)

\[
\vec{Q}_n^2 = n\vec{Q}_1^2 \quad \text{If strings are fully overlap}
\]

\[
\vec{Q}_n^2 = n \frac{S_n}{S_1} \vec{Q}_1^2 \quad \text{Partially overlap}
\]
Schwinger mechanism for the Fragmentation

Multiplicity and $<p_T^2>$ of particles produced by a cluster of $n$ strings

**Multiplicity ($\mu_n$)**

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

**Average Transverse Momentum**

$$< p_T^2 >_n = < p_T^2 >_1 / F(\xi)$$

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

$\xi$ = the string density parameter

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

N$^s$ = # of strings
S$^s_1$ = disc area
S$^N_1$ = total nuclear overlap area

M. A. Braun and C. Pajares, Eur.Phys. J. C16, 349 (2000)
M. A. Braun et al, Phys. Rev. C65, 024907 (2002)
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 $<p_t>$ scaling with $dN/dy$.

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

$$Q_s^2 = \frac{k <p_t^2>}{F(\xi)}$$

For large value of $\xi$

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

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).
| Color String Percolation Model for Nuclear Collisions from SPS-RHIC-LHC |
|---|
| Elementary partonic collisions |
| Formation of Color String |
| SU(3) random summation of charges |
| Reduction in color charge |
| Increase in the string tension |
| String breaking leads to formation of secondaries |
| Probability rate $\rightarrow$ Schwinger |
| Fragmentation proceeds in an iterative way |

1. Multiplicity
2. $pt$ distribution
3. Particle ratios
4. Elliptic flow
5. Suppression of high $pt$ particles $R_{AA}$
6. $J/\psi$ production
7. Forward-Backward Multiplicity Correlations at RHIC
Thermodynamic and Transport Properties

Determination of the Color Suppression Factor $F(\xi)$ from the Data

Thermodynamics

- Temperature
- Energy Density
- Shear viscosity to Entropy density ratio
- Equation of State
Data Analysis

Using the $p_T$ spectrum to extract $F(\xi)$

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

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

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

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

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

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

Parametrization of UA1 data from 200, 500 and 900 GeV $\bar{pp}$

ISR 53 and 23 GeV $pp$

$p_0 = 1.71$ and $n = 12.42$

Nucl. Phys. A698, 331 (2002)
Now the aim is to connect $F(\xi)$ with Temperature and Energy density.

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

**Au+Au @200 GeV**

STAR data

Phys. Rev. C 79, 034909(2009)

Using ALICE charged particle multiplicity

Phys. Rev. Lett. 106, 032301 (2011).

Extrapolation
Schwinger: $p_t$ distribution of the produced quarks

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

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

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

\[
\sqrt{\langle p_t^2 \rangle} = \sqrt{\frac{\langle k^2 \rangle}{\pi}} = \sqrt{\frac{\langle p_t^2 \rangle}{2F(\xi)}}
\]

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

Initial temperature

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

- The origin of the string fluctuation is related to the stochastic picture of the QCD vacuum. Since the average value of color field strength must vanish, it cannot be constant and must vanish from point to point. Such fluctuations lead to the Gaussian distribution of the string.
  
  H. G. Dosch, Phys. Lett. 190 (1987) 177
  A. Bialas, Phys. Lett. B 466 (1999) 301

- The fast thermalization in heavy ion collisions can occur through the existence of event horizon caused by rapid deceleration of the colliding nuclei. Hawking-Unruh effect encountered in black holes and for accelerated objects.

D. Kharzeev, E. Levin, K. Tuchin, Phys. Rev. C75, 044903 (2007)
H. Satz, Eur. Phys. J. 155, (2008) 167
Temperature

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

At the critical percolation density
\[ \xi_c = 1.2 \quad T_c = 167 \text{ MeV} \]
For Au+Au @ 200 GeV
0-10% centrality \( \xi = 2.88 \quad T \sim 195 \text{ MeV} \)

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

Pb+Pb @ 2.76 TeV for 0-5%
\[ T = 262 \pm 13 \text{ MeV} \]

Temperature has increased by 35% from Au+Au @ 0.2 TeV
First Results from Pb+Pb Collisions @ 2.76 TeV at the LHC
Muller, Schukraft and Wyslouch, Ann. Rev. Nucl. Sci. Oct. 2012

ALICE: Direct Photon Measurement
\[ T = 304 \pm 51 \text{ MeV} \quad \text{QM2 2012} \]
\[ T = 297 \pm 12 \pm 41 \text{ MeV} \quad \text{Phys. Lett. B 754, 235 (2016)} \]
Summary : Heavy Ion

- The Clustering of Color Sources leading to the Percolation Transition may be the way to achieve de-confinement in High Energy collisions.

- This picture provide us with a microscopic partonic structure which explains the early thermalization. The relevant quantity is transverse string density \( \xi = \frac{N^s S_1}{S_N} \)

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

Braun, Dias de Deus, Hirsch, Pajares, Scharenberg and Srivastava
Phys. Rep. 599 (2015) 1-50
Application of Clustering Picture to Small System

\( \bar{pp} \) at 1.8 TeV E-735 experiment at FNAL

\( pp \) at LHC energies 0.9, 2.76, 7 and 13 TeV

Determination of the Color Suppression Factor F (\( \xi \)) using transverse momentum spectra of pions in high multiplicity events

Temperature

Comparison between AA and \( pp \)
De-confinement in small systems: Clustering of color sources in high multiplicity $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV

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

A further definitive test of clustering phenomena can be made at LHC energies
Study of the inclusive production of charged pions, kaons, and protons in pp collisions at $\sqrt{s} = 0.9, 2.76$, and $7$ TeV

The CMS Collaboration

Eur. Phys. J. C (2012) 72:2164

Table 6  Relationship between the number of reconstructed tracks ($N_{\text{rec}}$) and the average number of true tracks ($\langle N_{\text{tracks}} \rangle$) in the 12 multiplicity classes considered

| $N_{\text{rec}}$ | 0–9  | 10–19 | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 | 70–79 | 80–89 | 90–99 | 100–109 | 110–119 |
|------------------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------|---------|
| $\langle N_{\text{tracks}} \rangle$ | 7    | 16    | 28    | 40    | 52    | 63    | 75    | 86    | 98    | 109    | 120      | 131     |

Measurement of charged pion, kaon, and proton production in proton-proton collisions at $\sqrt{s} = 13$ TeV

arXiv:1706.10194, Phys. Rev. D 96 (2017) 112003

Table 3: Relationship between the number of reconstructed tracks ($N_{\text{rec}}$) and the average number of corrected tracks ($\langle N_{\text{tracks}} \rangle$) in the region $|\eta| < 2.4$ in the 18 multiplicity classes considered.

| $N_{\text{rec}}$ | 0–9 | 10–19 | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 | 70–79 | 80–89 | 90–99 | 100–109 | 110–119 | 120–129 | 130–139 | 140–149 | 150–159 | 160–169 | 170–179 |
|------------------|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------|---------|----------|----------|----------|----------|----------|----------|----------|
| $\langle N_{\text{tracks}} \rangle$ | 7   | 16    | 28    | 40    | 51    | 63    | 74    | 85    | 97    | 108   | 119      | 130     | 141      | 151      | 162      | 172      | 183      | 187      |
Analysis of CMS data to extract Color Suppression Factor $F(\xi)$ from the transverse momentum spectra of pions at 0.9, 2.76, 7 and 13 TeV as a function of multiplicity ($N_{\text{track}}$)

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

Pseudorapidity coverage for CMS: $|\eta| < 2.4$
E735: $|\eta| < 3.25$
$F(\xi)$ from AA and $pp$

Fixed interaction cross section for all multiplicities in $pp$
Interaction area is computed: IP-Glasma model

The gluon multiplicity can be approx. related to the no of tracks seen in the CMS experiment

\[
\frac{dN_g}{dy} \approx K \frac{3}{2} \frac{1}{\Delta \eta} N_{\text{track}}
\]

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

\[
R_{pp} = 1 \text{ fm} \times f_{pp}\left(\sqrt[3]{dN_g/dy}\right)
\]
Scaling with the transvers interaction area $S_\perp$
$S_\perp$ varies with the multiplicity and is obtained using the methodology described by CGC.

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

E735 and Au+Au at 200 GeV are also shown in the plot. It scales with the Transverse overlap area.
Temperature

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

Universal hadronization temperature

Eur. Phys. J C66, 377 (2010)

Becattini et al.
Hadronization conditions in relativistic nuclear collisions and the QCD pseudo-critical line

Francesco Becattini, Jan Steinheimer, Reinhard Stock, Marcus Bleicher

Fig. 2. (Color online.) Reconstructed LCEPs (red squared dots) vs plain chemical freeze-out fitted points (blue round dots) in the \((\mu_B, T)\) plane. The solid lines are the 4 points quadratic fits quoted in Table 6; the dashed line is the 5 point quadratic fit including the lowest energy AGS point.

Figure 6: Strangeness suppression \(\gamma_s(T)\) as function of the initial temperature \(T\).

Strangeness Production and Color Deconfinement

P. Castorina, S. Plumari, and H. Satz
The viscosity can be estimated from kinetic theory to be

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

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

\[ \lambda_{mfp} = \frac{1}{(n\sigma_{tr})}, \sigma_{tr} = S_1 F(\xi) \]

\[ n = \frac{N_{\text{sources}}}{S_N L}, N_{\text{sources}} = \frac{(1 - e^{-\xi}) S_N}{S_1 F(\xi)} \]

\[ \eta \approx \frac{T \lambda_{mfp}}{s} \approx \frac{1}{5} \frac{L}{1 - e^{-\xi}} T \]

- \( \varepsilon \) Energy density
- \( s \) Entropy density
- \( n \) the number density
- \( \lambda_{mfp} \) Mean free path
- \( \sigma_{tr} \) Transport cross section
- \( \sqrt{< pt >^2} \) Average transverse momentum of the single string

L is Longitudinal extension of the source 1 fm

Hirano & Gyulassy, Nucl. Phys. A769, 71(2006)
 shear viscosity to entropy density ratio

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

\( \eta/s \) as a function of temperature for pp collisions at 0.9, 2.76, 7 and 13 TeV. The lower bound is given by the Ads/CFT.
Summary

- 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 $S_\perp$.

- The temperature both from AA and pp scales as $\frac{dN_c}{d\eta} \left( \frac{1}{S_\perp} \right)$.

- 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.

Question: Is Clustering of Color Sources the new Paradigm for producing QGP both in pp and A-A in high energy collisions?

Thank You
Extras
Energy Density

\[ \varepsilon = \frac{3}{2} \frac{dN_c}{dy} \frac{<m_t>}{A} \frac{1}{\tau_{pro}} \text{ GeV} / \text{fm}^3 \]

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

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

STAR Coll., Phys. Rev. C 79, 34909 (2009)

Introduction to high energy heavy ion collisions
C. Y. Wong

J. Dias de Deus, A. S. Hirsch, C. Pajares , R. P. Scharenberg , B. K. Srivastava
Eur. Phys. J. C 72, 2123 (2012)
Having determined the initial temperature of the system from the data one obtains the thermodynamic and transport properties of QCD matter.

Energy Density

Shear viscosity to entropy density ratio

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

Scharenberg, Srivastava, Hirsch
Eur. Phys. J. C 71, 1510 (2011)

Dias de Deus, Hirsch, Pajares, Scharenberg, Srivastava, Eur. Phys. J. C 72, 2123 (2012)