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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Proposal to search for QGP at the Fermi Lab CO Collider

The experiment was accepted as E-735 in 1983 $\bar{p}p$ At 1.8 TeV

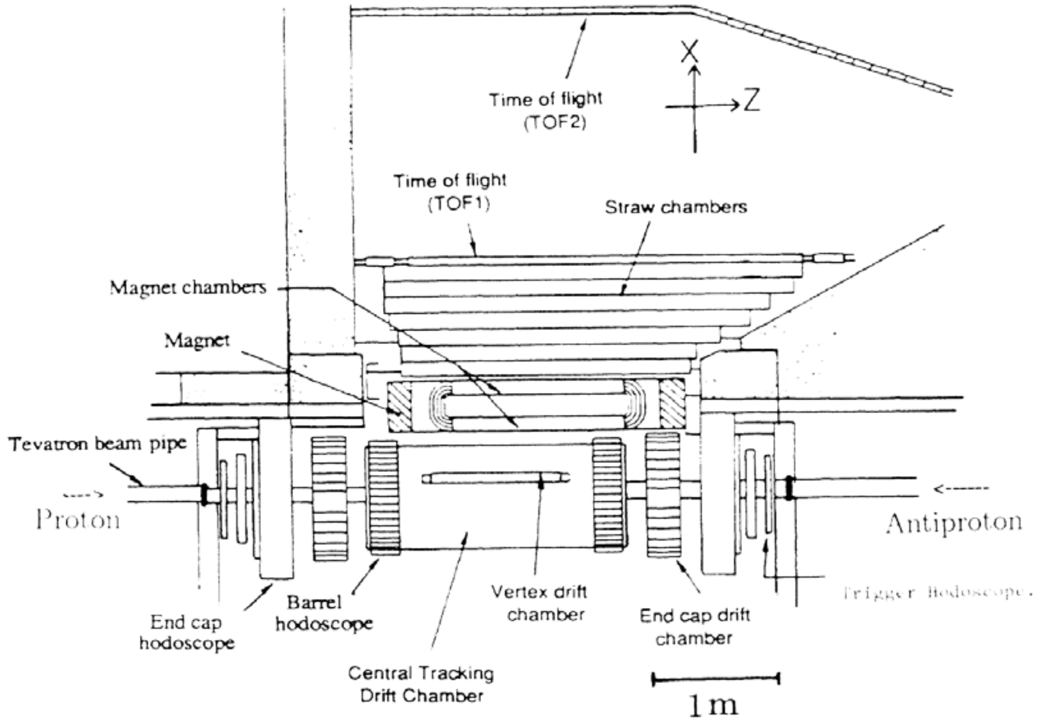


FIG. 1. Plan view of the E735 detector.

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 :π, K, p,** $\bar{p}$ **, d,** Λ
- **Freeze-out energy density**

Conclusion:
Evidence for de-confinement was published in 2002. The comparison was Made with Lattice QCD calculations.
Phys. Lett. B528, 43 (2002).

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 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:

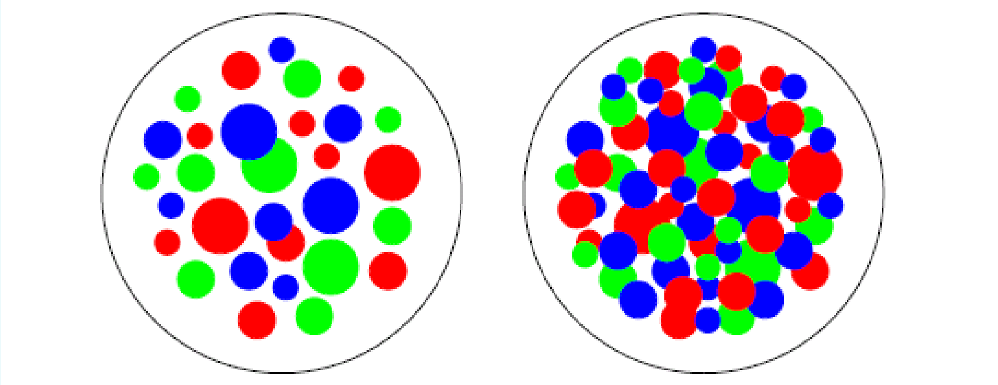
*** Transition from liquid to gas**
*** Normal conductor to a superconductor**
*** Paramagnet to ferromagnet**

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.



Clustering of Color Sources

De-confinement is thus related to cluster formation very much similar to cluster formation in percolation theory

Critical Percolation Density $\xi_c = 1.20$

Color Strings + Percolation = CSPM

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

Multiplicity (μ_n)

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

Average Transverse Momentum

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

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

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

= **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 percolation density parameter.

Complete description of CSPM has been published in
Phys. Rep. Sept. 2015
Braun, Deus, Hirsch, Pajares, Scharenberg, Srivastava

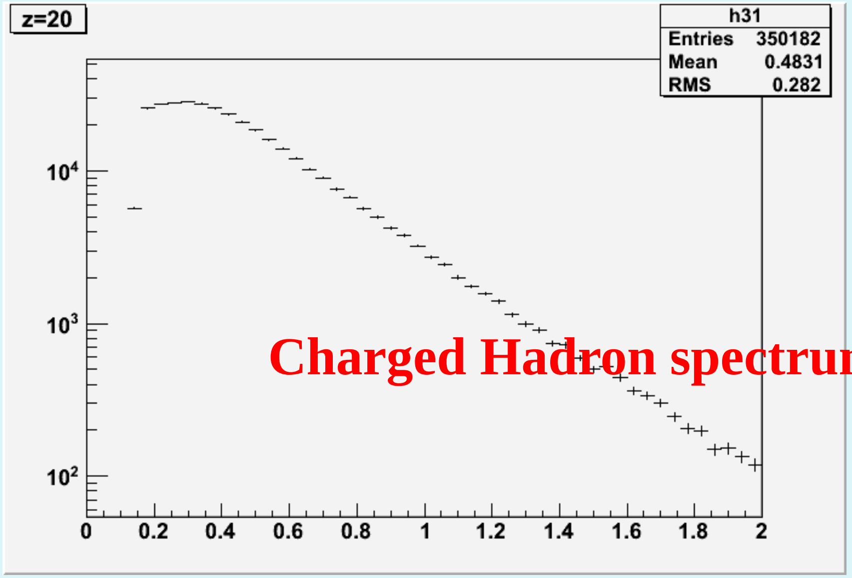
PURDUE UNIVERSITY

Using the p_T spectrum to calculate ξ

The experimental p_T distribution from pp data is used

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

$$\frac{d^2N}{dp_t^2}$$



p_t GeV/c

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 :

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

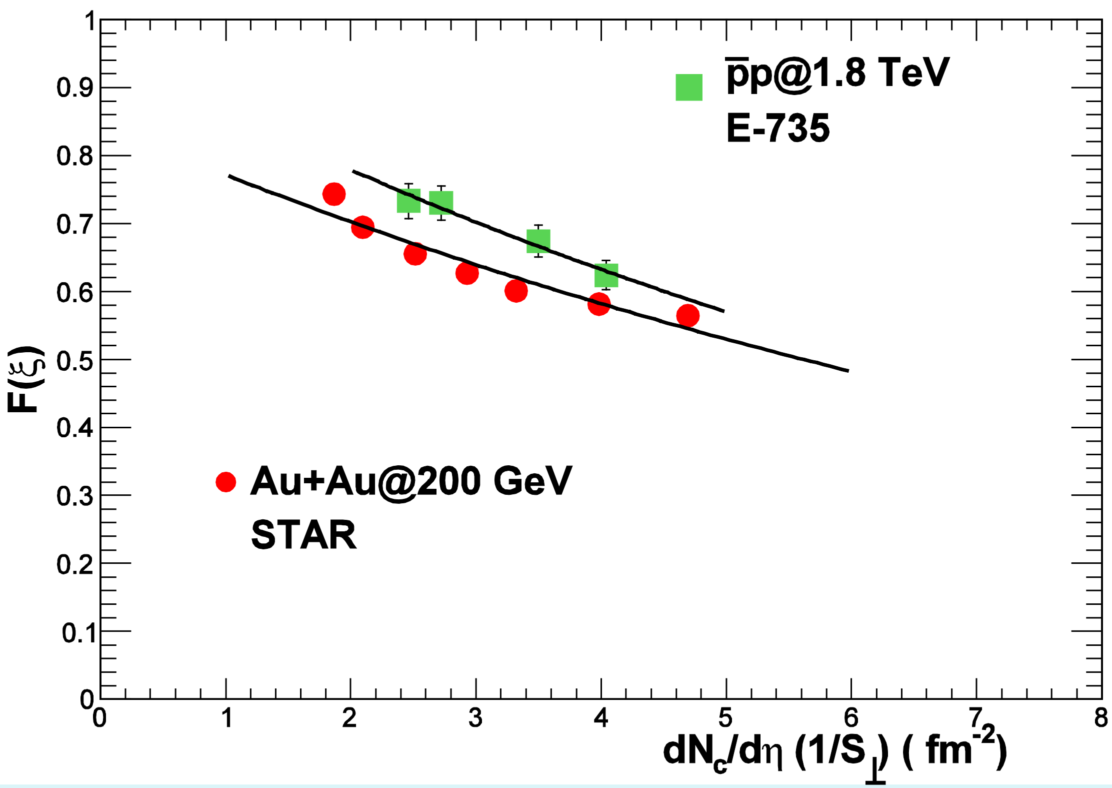
$$F(\xi)_{pp} = 1$$

$$F(\xi)_{AuAu} = 0.57$$

For central collisions

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].

N_c	$\langle dN_c/d\eta \rangle$	p_0	n
85	13.07	1.052±0.005	7.038±0.020
105	16.15	1.001±0.005	6.743±0.020
135	20.76	1.001±0.009	6.581±0.033
165	25.38	1.061±0.035	6.676±0.117



Schwinger Mechanism of Particle Production

p_t distribution of the produced quarks

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

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

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

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

Cluster /Initial Temperature

Temperature

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

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

$F(\xi)$ 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.

$\sqrt{\langle p_t^2 \rangle_1} = 207.2 \pm 3.3$ 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 ± 20 MeV
PRL 104, 132301 (2010)

Pb+Pb @ 2.76TeV for 0-5%
T ~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 ξ, initial temperature T, initial energy density ε and η/s for $\bar{p}p$ collisions at $\sqrt{s}$=1.8 TeV. The error on η/s is same as on temperature ∼4%.

$\langle dN_c/d\eta\rangle$	ξ	T (MeV)	$\varepsilon(GeV/fm^3)$	η/s
13.07	1.39±0.04	170.73±4.26	0.86±0.03	0.23
16.15	1.42±0.04	171.22±4.28	1.07±0.04	0.23
20.76	1.84±0.07	178.06±5.34	1.39±0.06	0.21
25.38	2.30±0.08	185.07±6.47	1.75±0.07	0.21

Energy Density

Bjorken 1D expansion

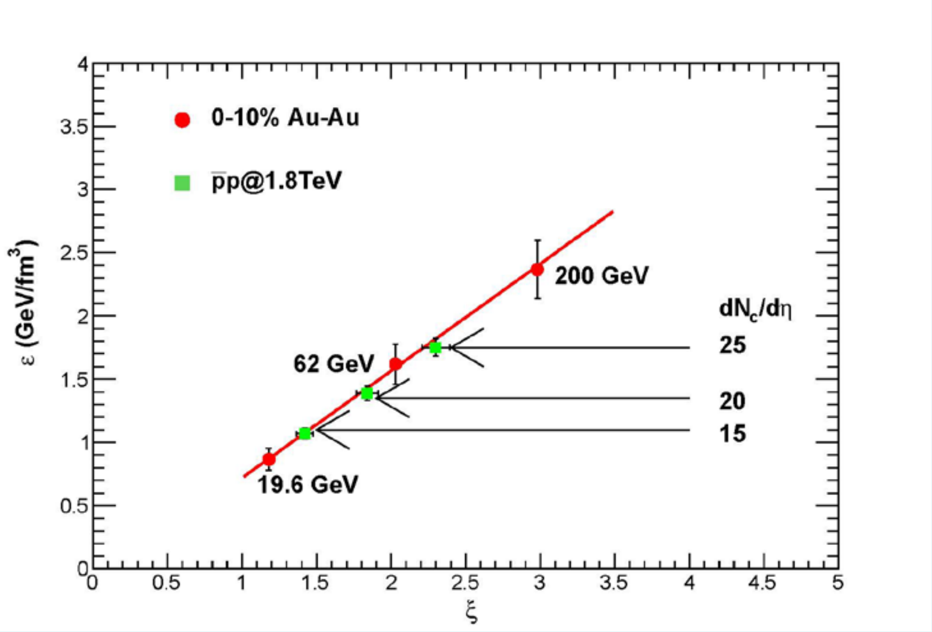
$$\varepsilon = \frac{3}{2}\frac{dN_c}{dy}\frac{<m_t>}{A}\frac{1}{\tau_{pro}} GeV/fm^3$$

Transverse overlap area

Proper Time

τ_{pro} **is the QED production time for a boson which can be scaled from QED to QCD and is given by**

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



$$\varepsilon \propto \xi$$

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)

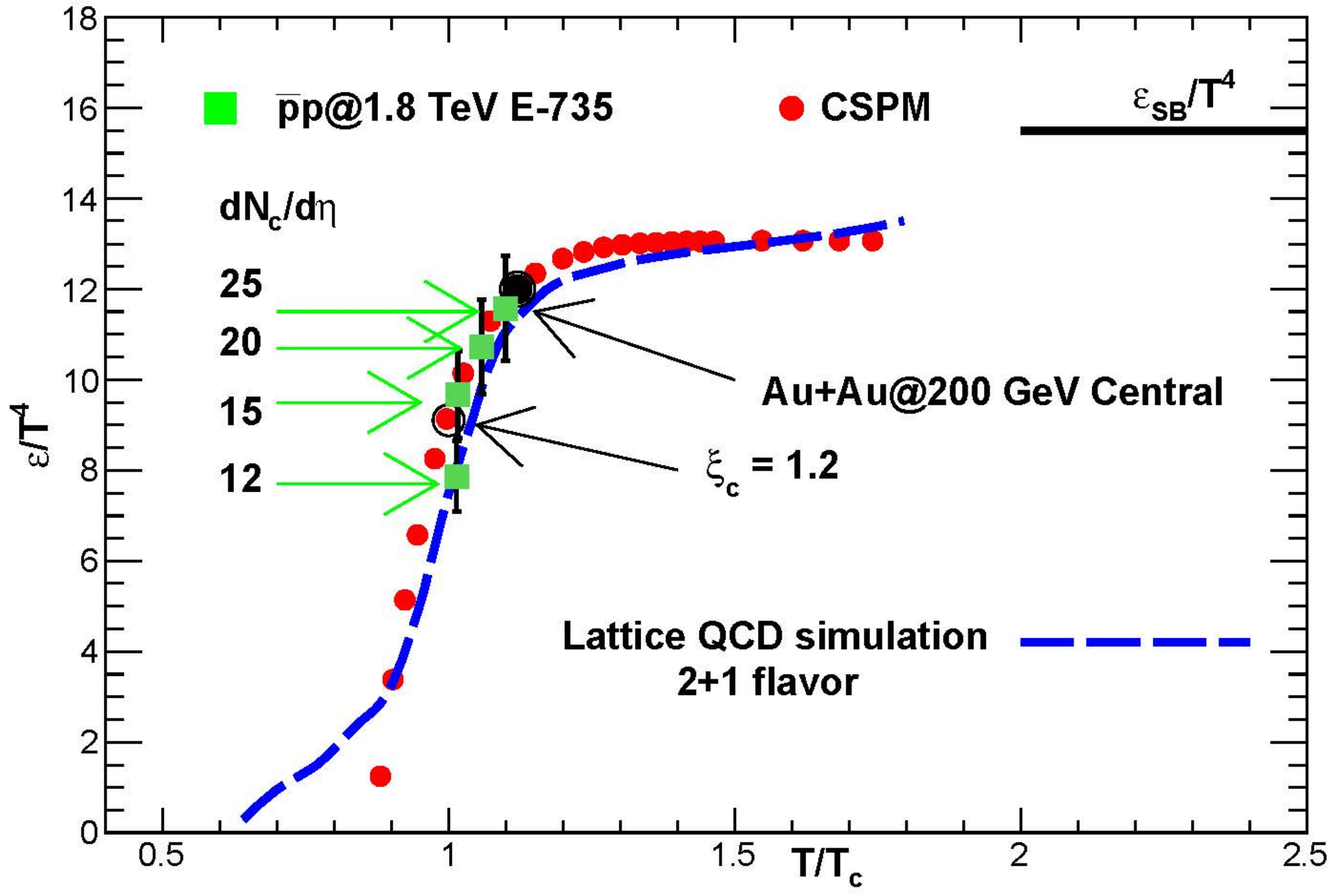
Having determined the initial temperature of the system from the data one would like to obtain the following quantities to understand the properties of QCD matter

$$\varepsilon / T^4$$

Shear Viscosity

Equation of State

Energy Density $/T^4$



The viscosity can be estimated from kinetic theory to be

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

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

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

$$\frac{\eta}{s} \approx \frac{T\lambda_{mfp}}{5}$$

Hirano & Gyulassy, Nucl. Phys. A769, 71(2006)

ε Energy density

s Entropy density

n the number density

λ_{mfp} **Mean free path**

σ_{tr} **Transport cross section**

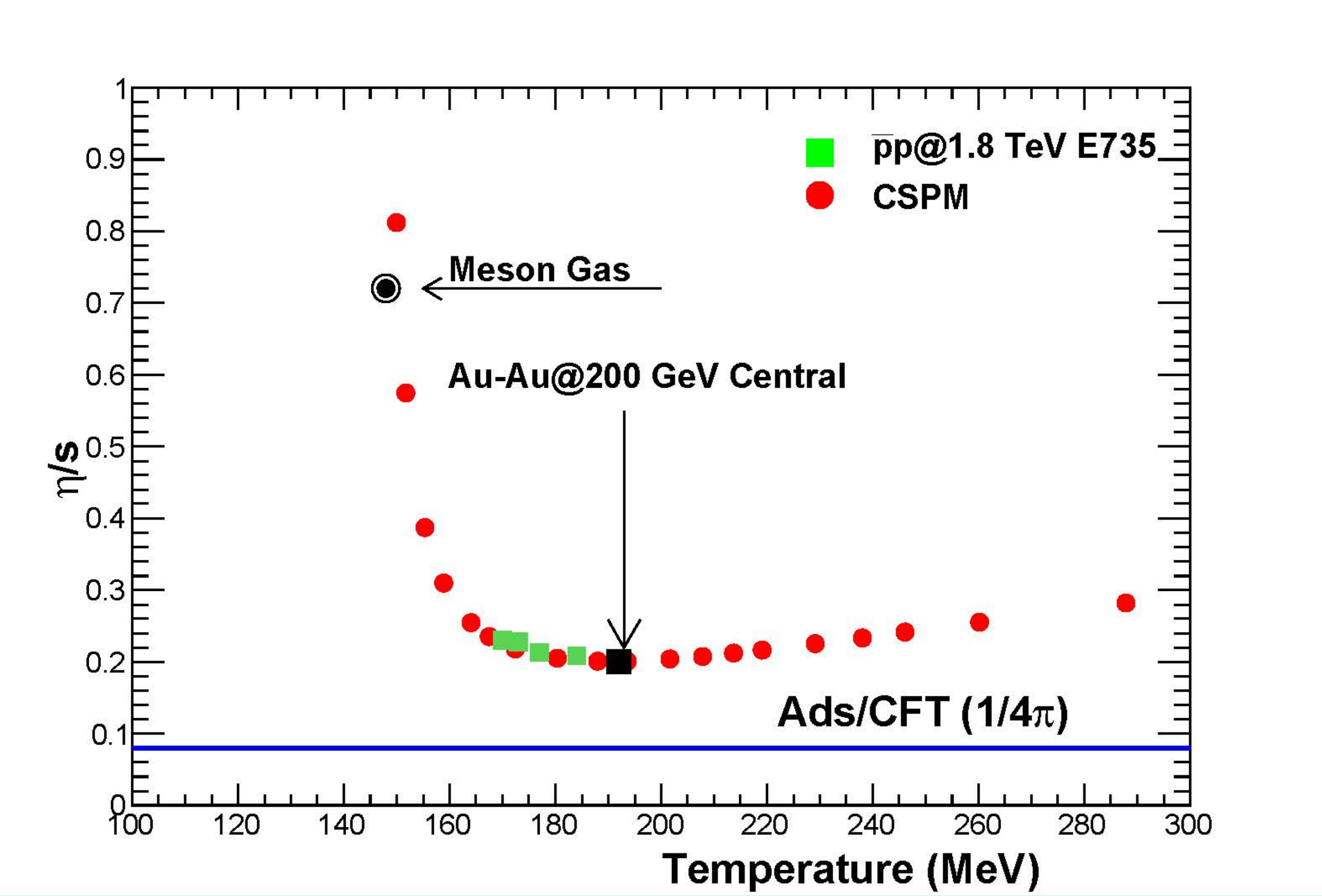
$\sqrt{\langle p_t \rangle_1^2}$ **Average transverse momentum of the single string**

L is Longitudinal extension of the source 1 *fm*

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

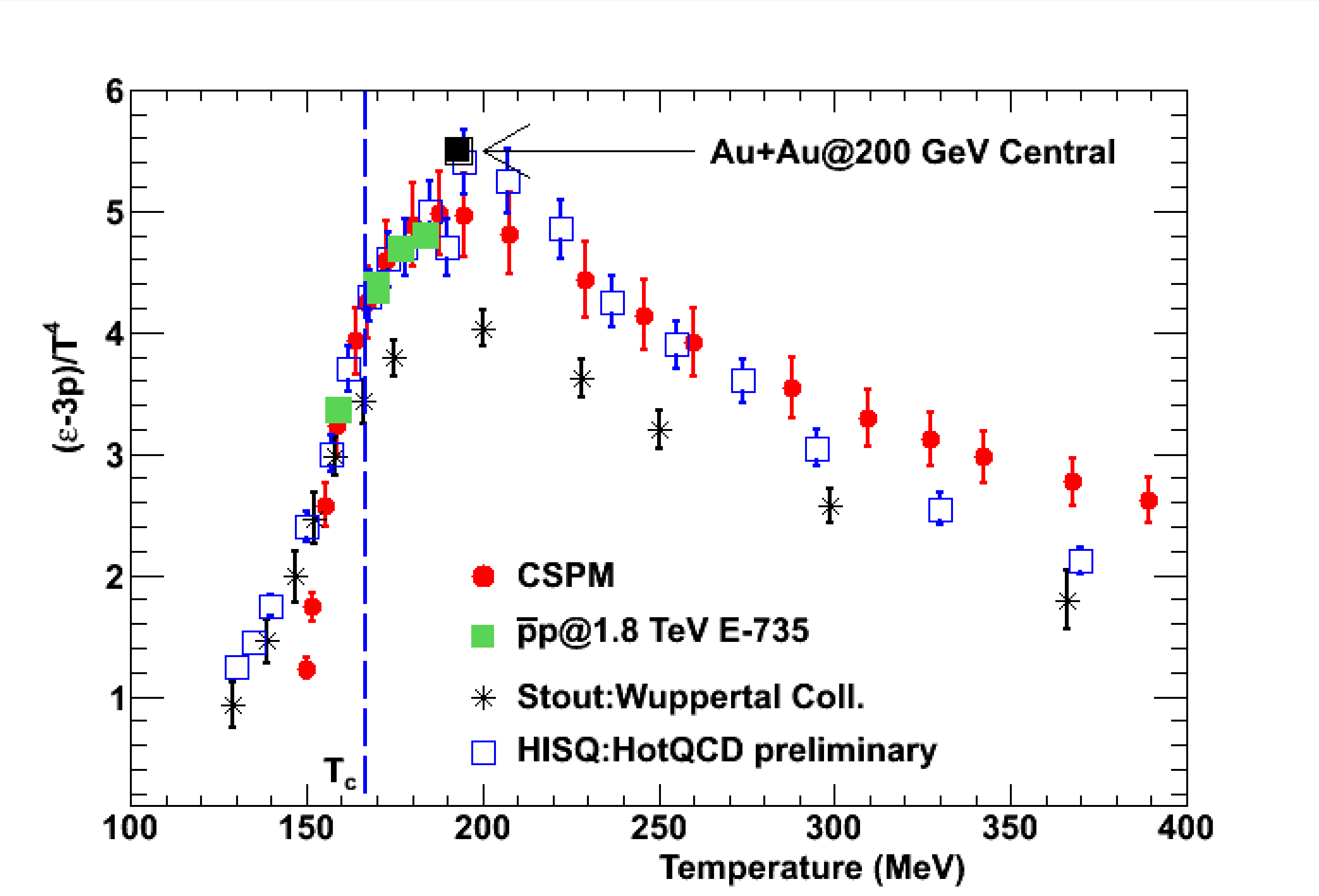
$$\frac{\eta}{s} \approx \frac{1}{5}\frac{L}{1-e^{-\xi}}T$$

Shear Viscosity to Entropy Density ratio



Trace Anomaly

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



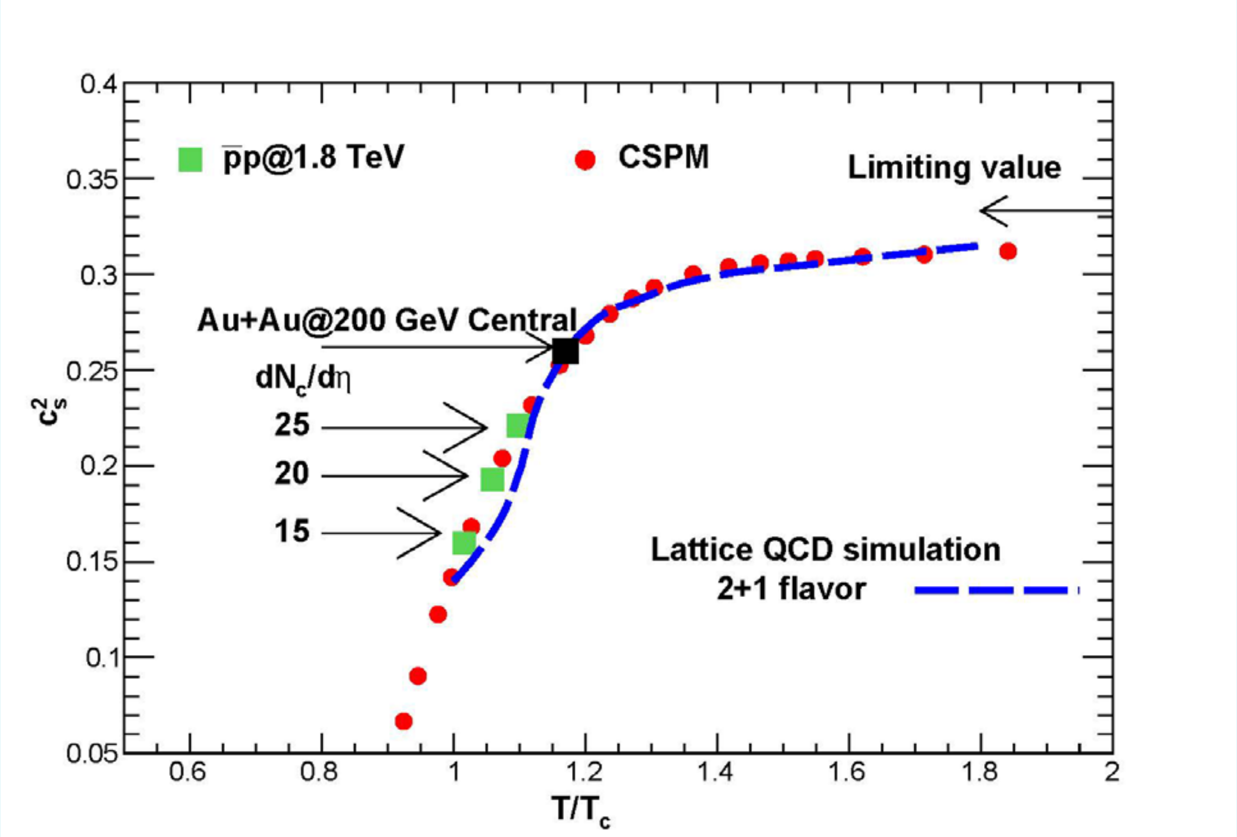
S/η (T) and Δ (T) have the same magnitude and temperature dependence.

Ansatz: we will use S/η (T) to correlate ε(T) and p(T) for $T>T_C$

Sound Velocity

$$\Delta = \frac{\varepsilon - 3p}{T^4}$$

$$C_s^2 = \frac{dp}{d\varepsilon} = \varepsilon \frac{dp/\varepsilon}{d\varepsilon} + \frac{p}{\varepsilon}$$



$$C_S^2 = (-0.33)\left(\frac{\xi e^{-\xi}}{1-e^{-\xi}} - 1\right) + 0.0191(\Delta/3)\left(\frac{\xi e^{-\xi}}{(1-e^{-\xi})^2} - \frac{1}{1-e^{-\xi}}\right)$$

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 provide 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 Δ represented by *s/η* 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 $\bar{p}p$ $\sqrt{s}$= 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

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   B. K. Srivastava , Nucl. Phys. A926, 142(2014)

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

** Deus, Hirsch, Pajares, Scharenberg and Srivastava

*** Scharenberg, Srivastava and Hirsch