De-Confinement in *pp* Collisions at LHC Energies

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Probing the Phase Structure of Strongly interacting Matter
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MULTIPLICITY DEPENDENCE OF p_t SPECTRUM AS A POSSIBLE SIGNAL FOR A PHASE TRANSITION IN HADRONIC COLLISIONS

L. VAN HOVE
CERN, Geneva, Switzerland

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 ($|y| \leqslant y_0 = 2.5$) 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

UA5

UA1

VOLUME 67, NUMBER 12 PHYSICAL REVIEW LETTERS 16 SEPTEMBER 1991

Transverse Baryon Flow as Possible Evidence for a Quark-Gluon-Plasma Phase

Péter Lévai[(a)] and Berndt Müller

Department of Physics, Duke University, Durham, North Carolina 27706

(Received 13 March 1991)

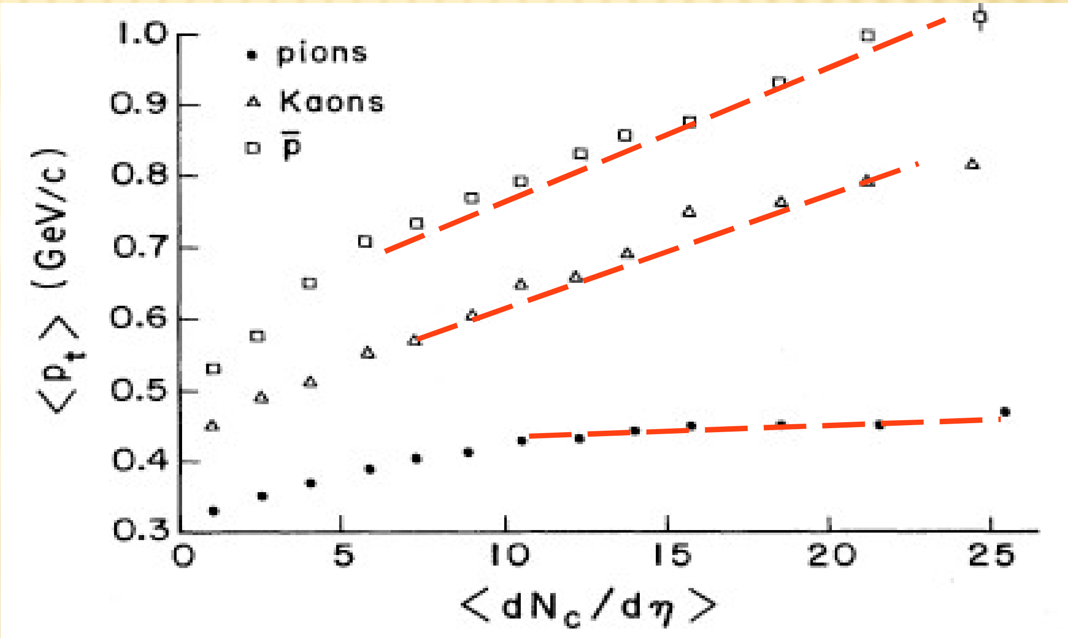
In order to investigate the coupling between the collective flow of nucleons and pions in hot pion-dominated hadronic matter, we calculate the pion-nucleon drag coefficient in linearized transport theory. We find that the characteristic time for flow equalization is longer than the time scale of the 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

E735 DATA

T. Alexopoulos, PRD48, 984 (1993)

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

T. Alexopoulos,[1*] E. W. Anderson,[2] A. T. Bujak,[3] D. D. Carmony[3] A. R. Erwin,[1] L. J. Gutay,[3] A. S. Hirsch,[3] K. S. Nelson,[1**] N. T. Porile,[4] S. H. Oh,[6] R. P. Scharenberg,[3] B. K. Srivastava,[4] B. C. Stringfellow,[3] F. Turkot,[7] J. Warchol,[5] 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 ± 6.2 (stat) quark-gluon degrees of freedom.

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De-Confinement and Clustering of Color Sources In Nuclear Collisions

Color Strings

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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

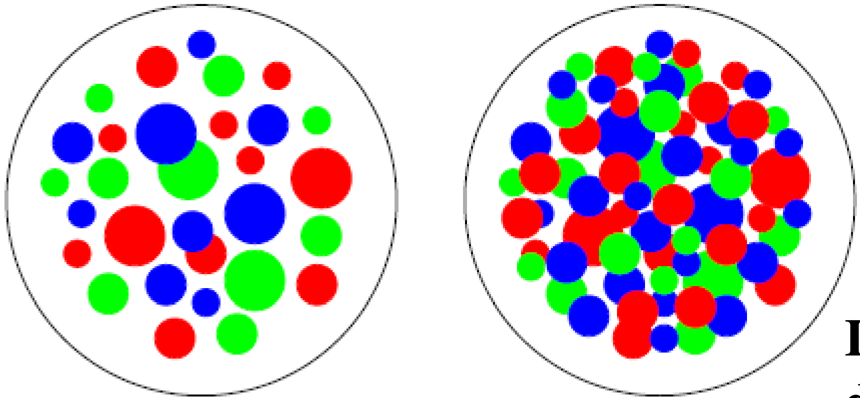
S_1 = Single string area

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.



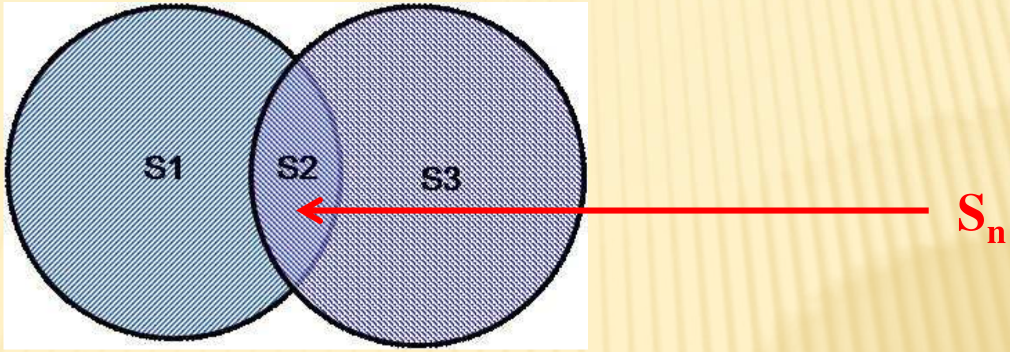
Parton distributions in the transverse plane of nucleus-nucleus collisions

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

Critical Percolation Density

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 $\vec{Q}_1$

$\vec{Q}_n^2 = n\vec{Q}_1^2$ **If strings are fully overlap**

$\vec{Q}_n^2 = n\frac{S_n}{S_1}\vec{Q}_1^2$ **Partially overlap**

Schwinger mechanism for the Fragmentation

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 string density parameter

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

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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

$$Q_s^2 = \frac{k < p_t^2 >_1}{F(\xi)}$$

For large value of ξ

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

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

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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 ->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/ψ production
7. Forward-Backward Multiplicity Correlations at RHIC

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Thermodynamic and Transport Properties

Determination of the Color Suppression Factor F(ξ) 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(ξ)

The experimental p_T distribution from pp data is used

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

Parametrization of UA1 data
from 200, 500 and 900 GeV $\bar{p}p$
ISR 53 and 23 GeV ***pp***

p_0 = 1.71 and n = 12.42

Nucl. Phys. A698, 331 (2002)

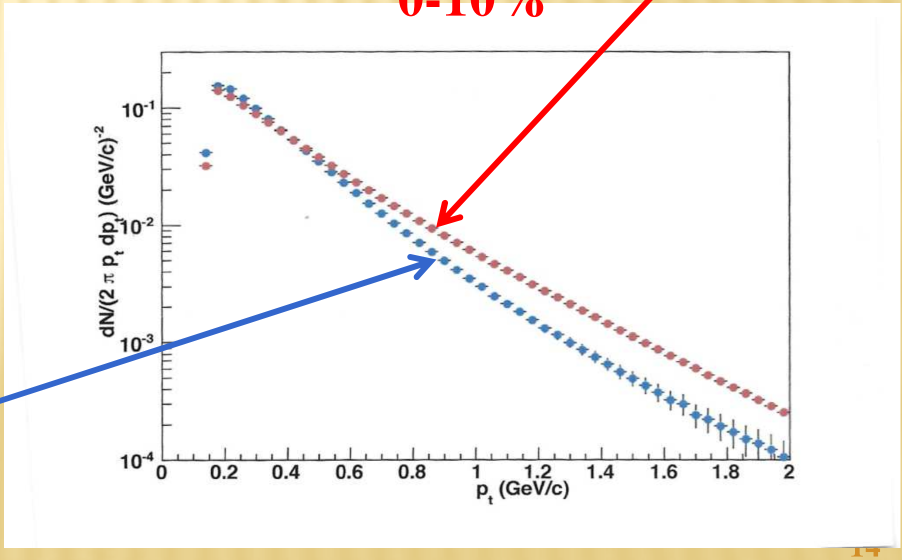
a, p_0 and n are parameters fit to the data.

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

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

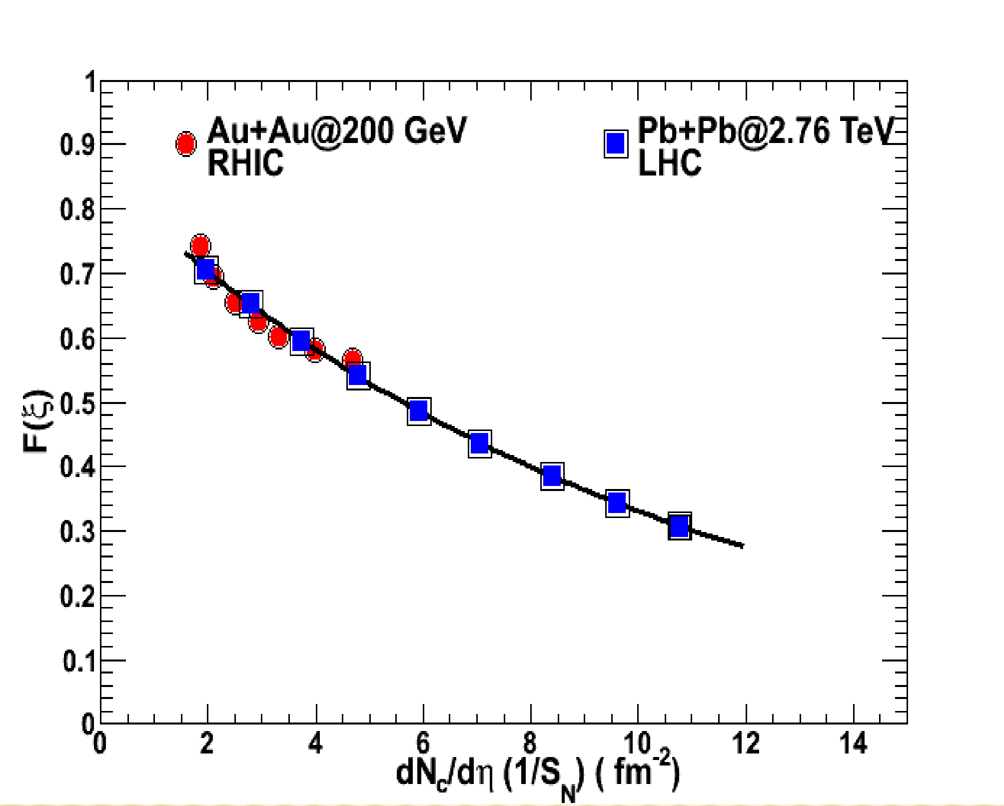
$$F(\xi)_{pp} = 1$$

Au+Au@200 GeV 0-10%



pp@200 GeV

Color Suppression Factor F(ξ)



Au+Au @200 GeV
STAR data
Phys. Rev. C 79, 034909(2009)

Using ALICE charged particle multiplicity
Phys. Rev. Lett. , 106, 032301 (2011).
Extrapolation

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

Now the aim is to connect F(ξ) with Temperature and Energy density

Energy Density

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Bjorken Phys. Rev. D 27, 140 (1983)

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

Transverse overlap area

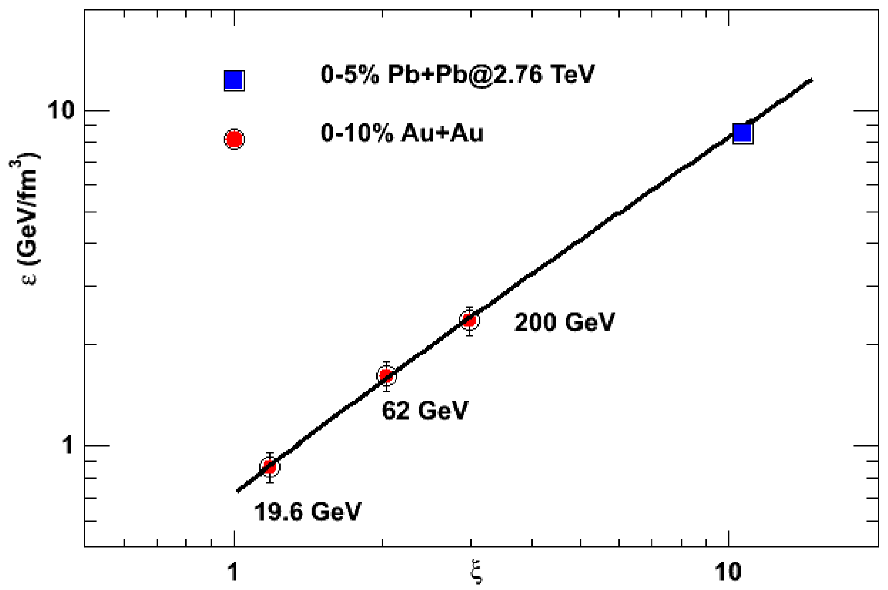
Proper Time

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

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

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

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



$$\varepsilon \propto \xi$$

J. Dias de Deus, A. S. Hirsch, C. Pajares, R. P. Scharenberg, B. K. Srivastava
Eur. Phys. J. C 72, 2123 (2012)

Schwinger : p_t distribution of the produced quarks

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

Thermal Distribution

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

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

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

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

Initial temperature

$$\sqrt{<p_t^2>} = \sqrt{\frac{<k^2>}{\pi}} = \sqrt{\frac{<p_t^2>_1}{F(\xi)}}$$

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

Thermalization

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- 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

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

For Au+Au@ 200 GeV
0-10% centrality $\xi = 2.88$
T = 193±3.5 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 =262 ± 13 MeV

ALICE : Direct Photon Measurement
T = 297 ± 12 ± 41MeV Phys. Lett. B 754 , 235 (2016)

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Mod. Phys. Lett A 34, 1950034 (2019)

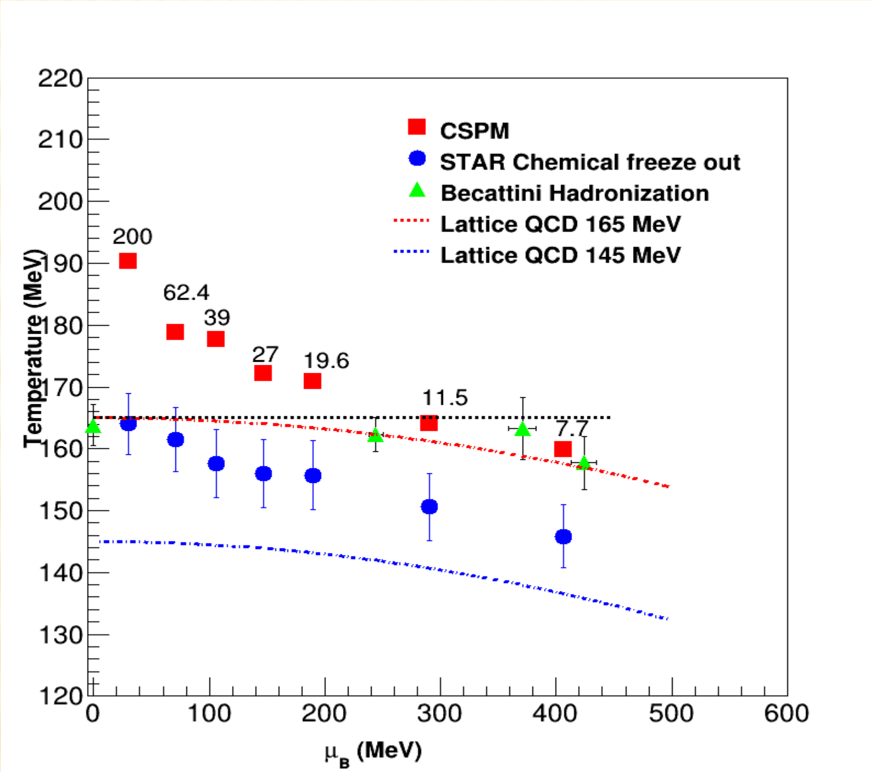
BES STAR

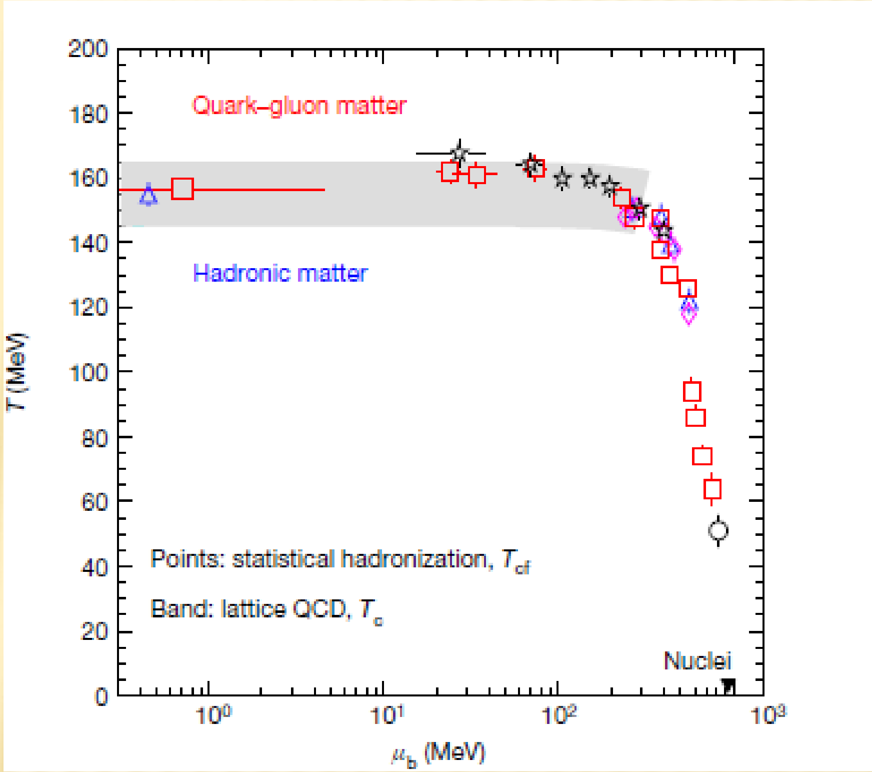
Pragati et al.

Naure 561, 322 (2018)

Decoding the phase structure ….

Andronic, Braun-Munzinger, Redlich , Stachel





Chemical freeze-out : 156.5 ± 1.5 MeV

LQCD (Bazavov et al.) : 154 ± 9

LQCD (Borsanyi et al.) : 156 ± 9

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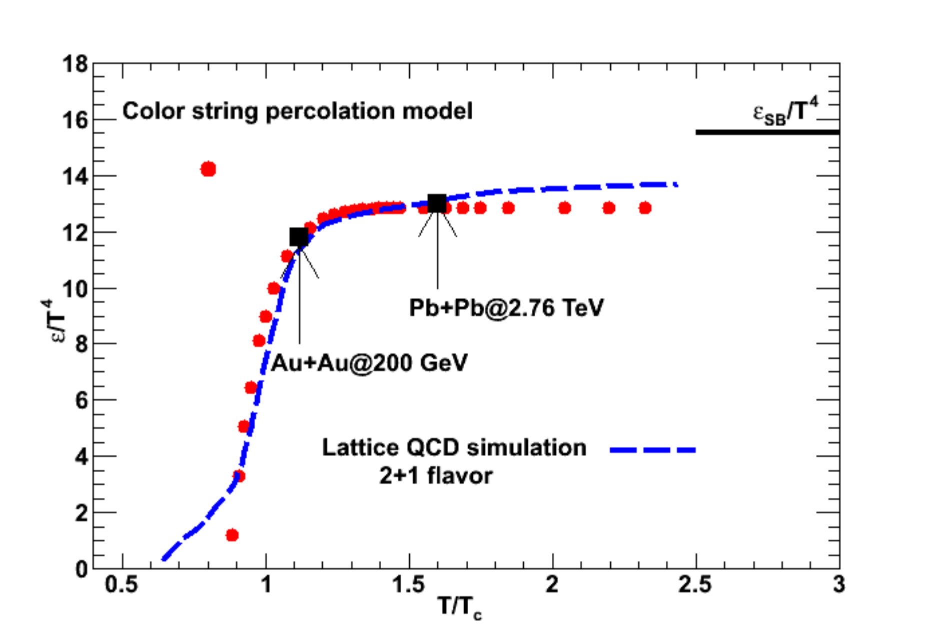
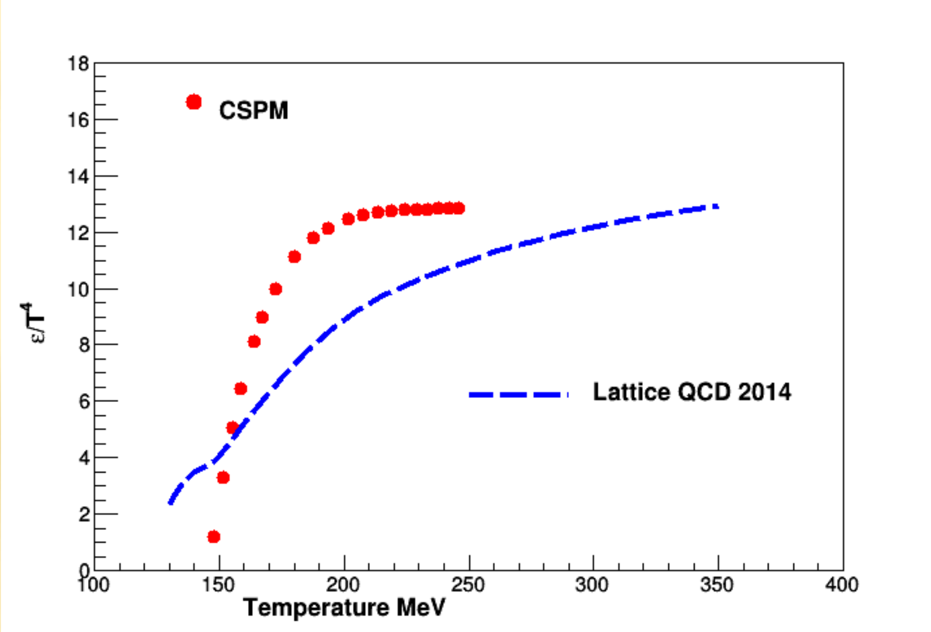
Having determined the initial temperature of the system from the data one obtains the thermodynamic and transport properties of QCD matter

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

Energy Density





2+1 flavor HISQ

HotQCD: Bazavov et al
Phys. Rev. D 80, 014504 (2009)

HotQCD: Bazavov et al
Phys. Rev. D 90, 094503 (2014)

The viscosity can be estimated from kinetic theory to be

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

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

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

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

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

ε Energy density
s Entropy density
n the number density
λ_{mfp} **Mean free path**

σ_{tr} **Transport cross section**

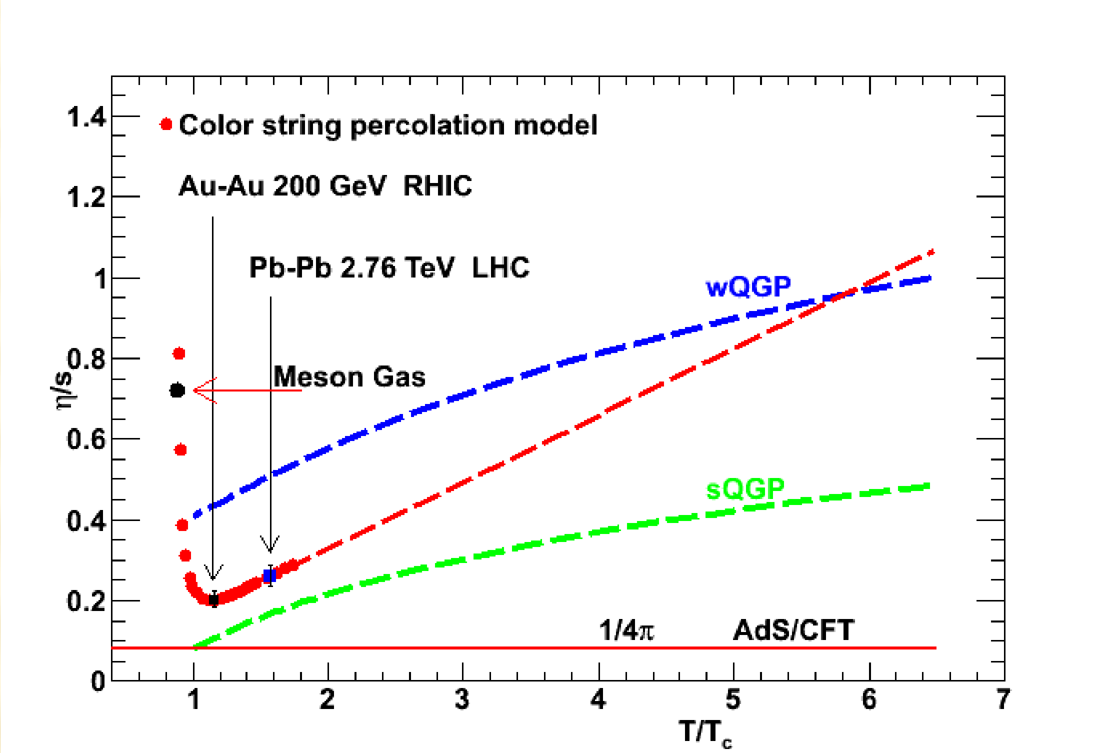
$\sqrt{< pt >_1^2}$ **Average transverse momentum of the single string**

L is Longitudinal extension of the source 1 *fm*

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

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

Shear viscosity to entropy density ratio



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

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

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

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Application of Clustering Picture to Small System

pp at LHC energies 0.9, 2.76, 7 and 13 TeV

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

↓

Temperature

↓

Comparison between AA and *pp*

CMS Collaboration

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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_{rec}) and the average number of true tracks ($\langle N_{tracks} \rangle$) in the 12 multiplicity classes considered

N_{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
$\langle N_{tracks} \rangle$	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_{rec}) and the average number of corrected tracks ($\langle N_{tracks} \rangle$) in the region $|\eta| < 2.4$ in the 18 multiplicity classes considered.

N_{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
$\langle N_{tracks} \rangle$	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(ξ) from the transverse momentum spectra of pions at 0.9, 2.76 , 7 and 13 TeV as a function of multiplicity (N_{track})

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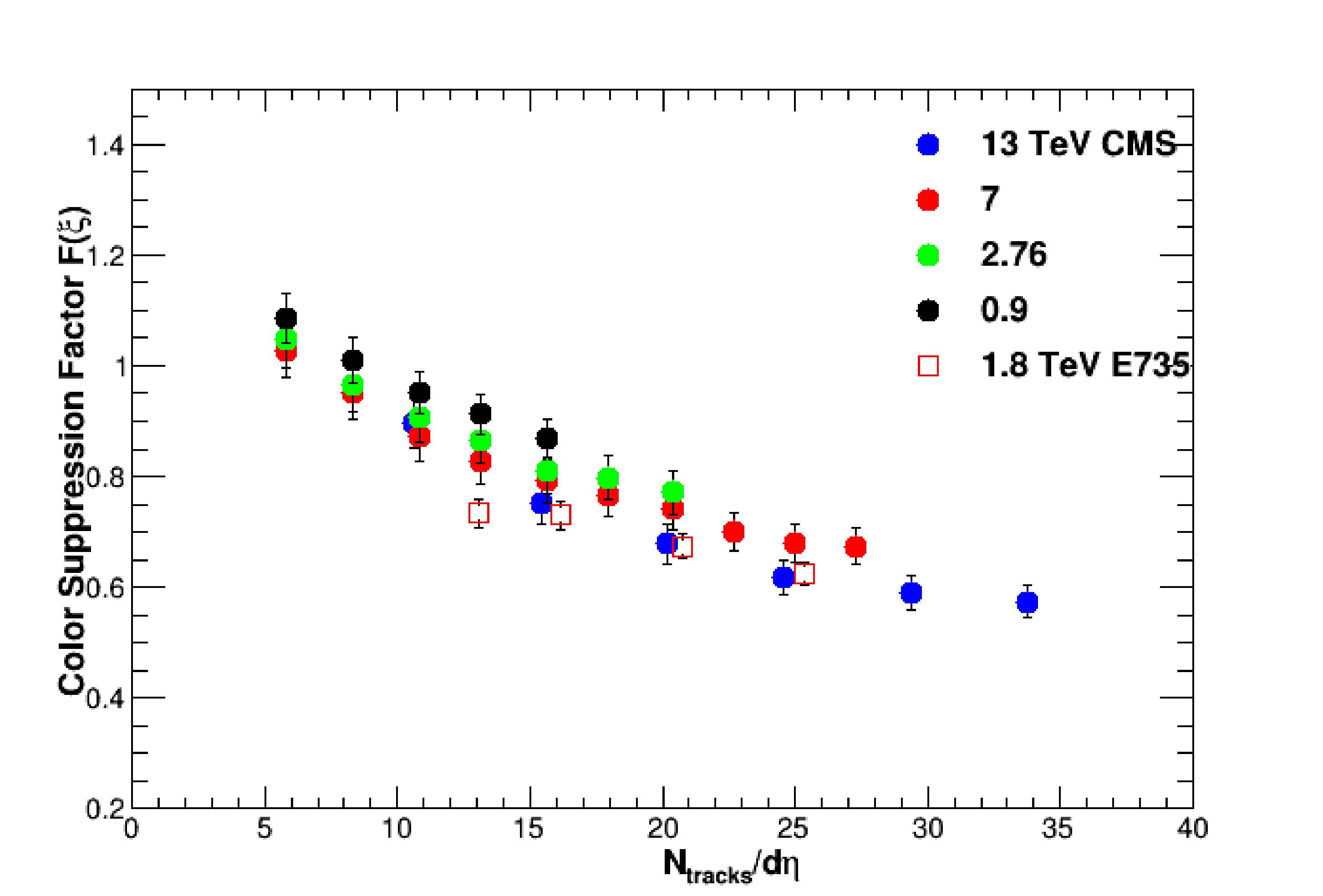
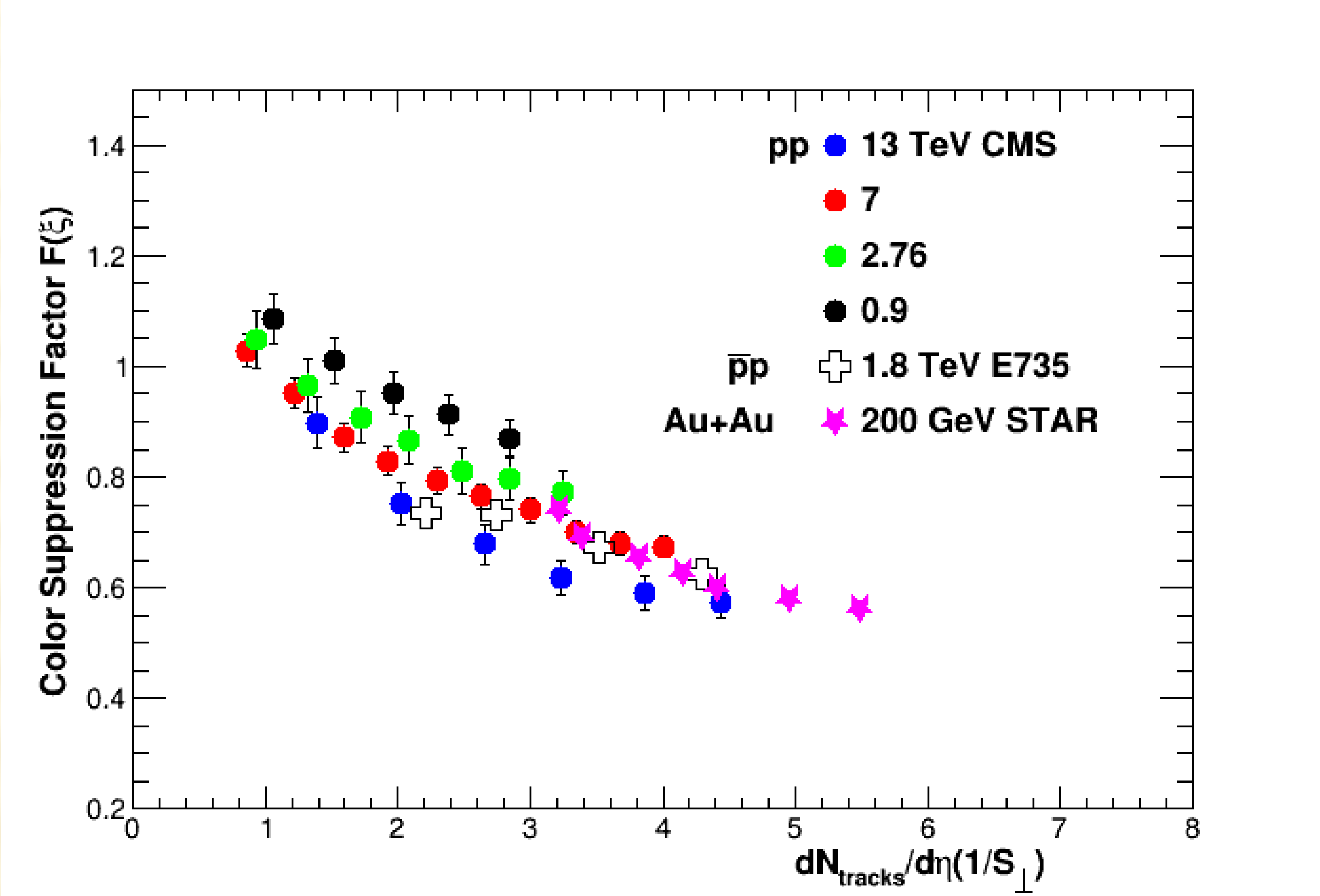


$$F(\xi) = \sqrt{\frac{1-e^{-\xi}}{\xi}}$$

Pseudorapidity coverage for CMS : |η| < 2.4

E735: |η| < 3.25

F(ξ) from AA and *pp*



Fixed interaction cross section for all multiplicities in *pp*

Nucl. Phys A 916 (20130 210-218

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Transverse momentum of protons, pions and kaons in high multiplicity pp and pA collisions: Evidence for the color glass condensate?

Larry McLerran [a,b,c], Michal Praszalowicz [d], Björn Schenke [a,*]

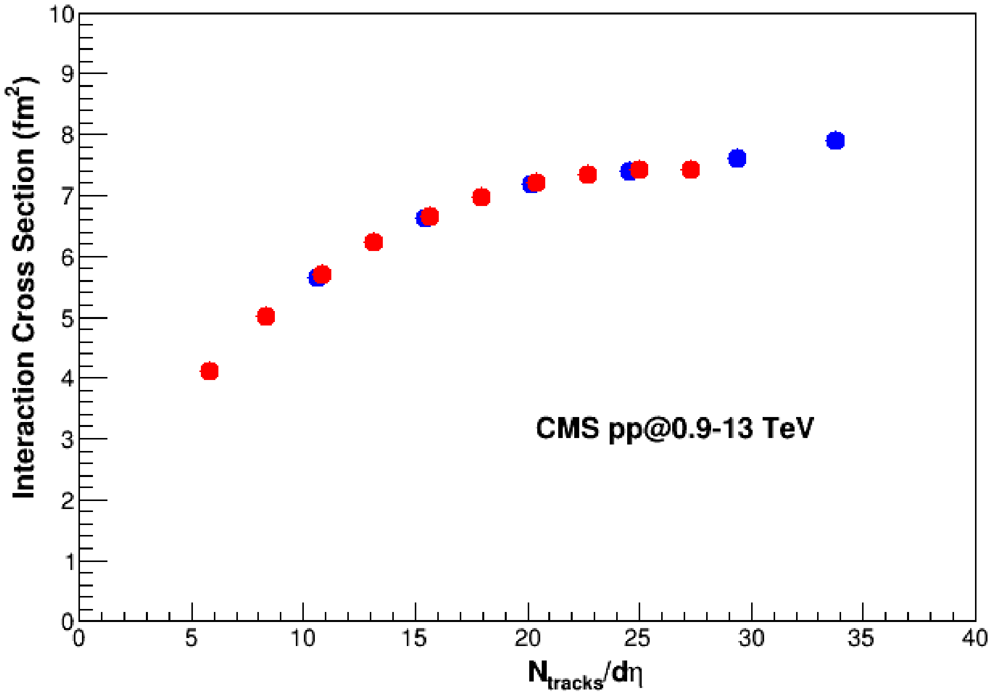
Interaction area is computed: IP-Glasma model

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

$$\frac{dN_g}{dy} \approx K \frac{3}{2} \frac{1}{\Delta\eta} N_{track}$$

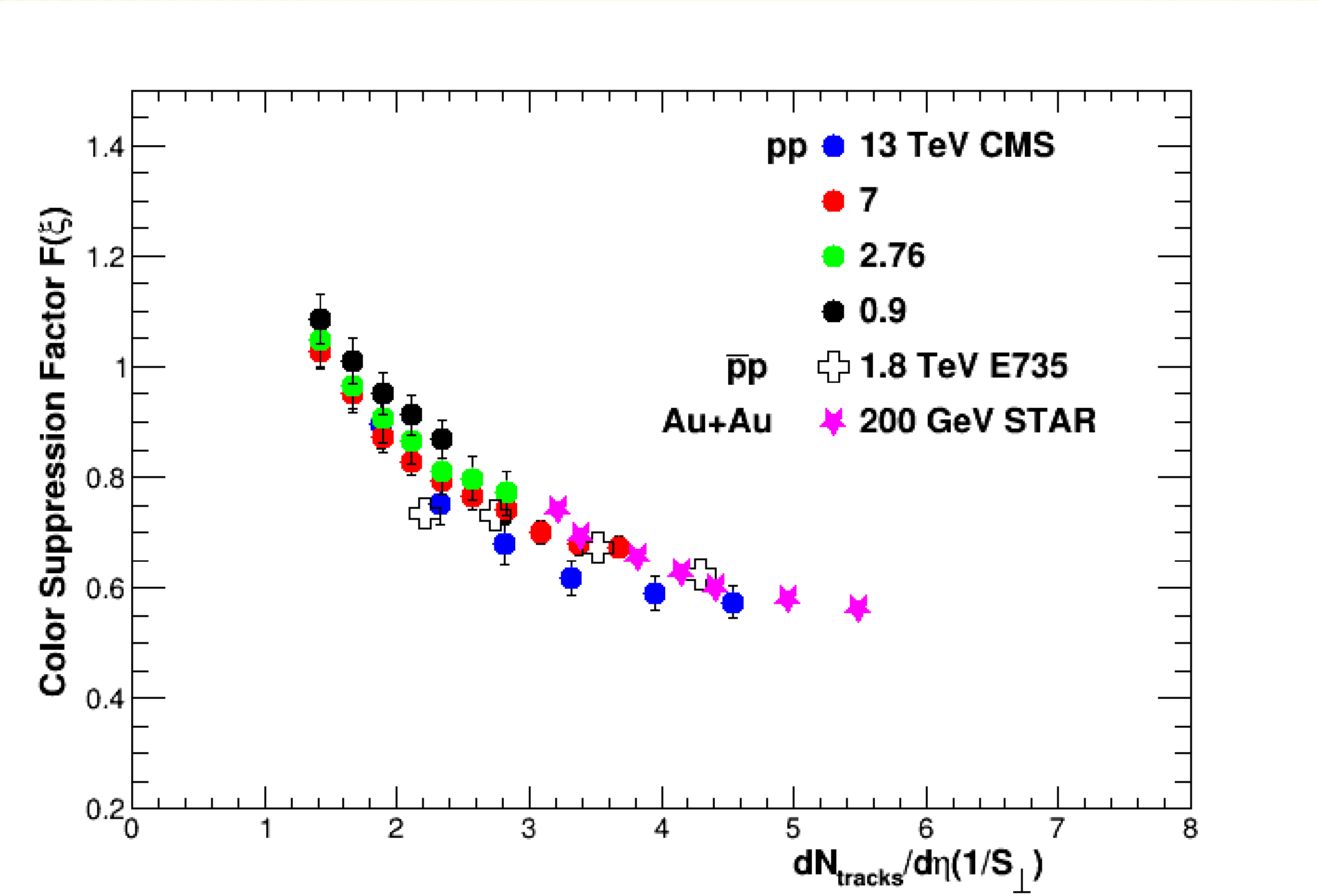
Transverse area : $S_{pp} = \pi R_{pp}^2$

$$R_{pp} = 1\ \text{fm} \times f_{pp}\left(\sqrt[3]{dN_g/dy}\right)$$



Scaling with the transvers interaction area $S_\perp$

$S_\perp$ varies with the multiplicity and is obtained using the methodology Described by CGC



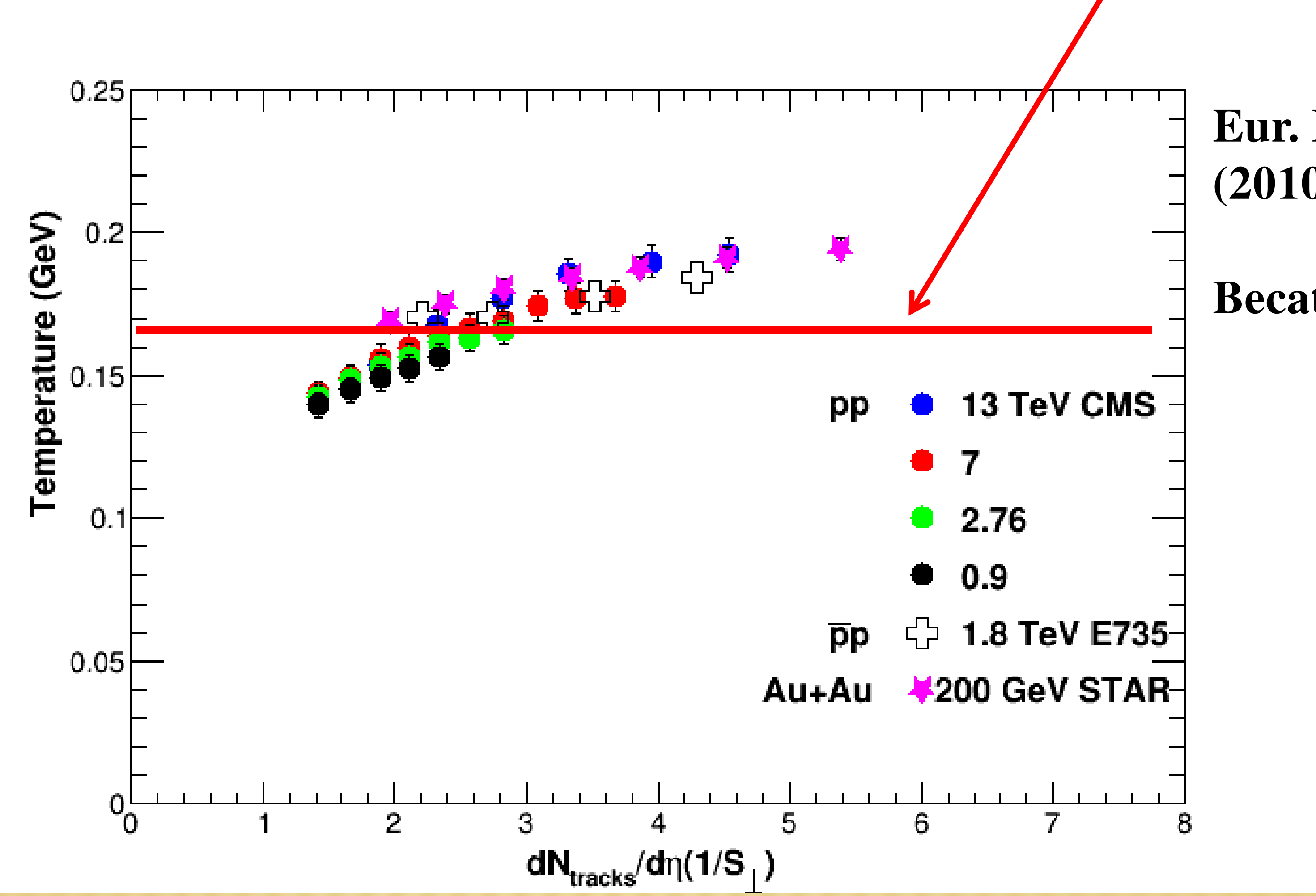
$$F(\xi) = \sqrt{\frac{1 - e^{-\xi}}{\xi}}$$

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

Temperature

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

Universal hadronization temperature



Eur. Phys. J C66, 377 (2010)

Becattini et al.

Shear viscosity to entropy density ratio

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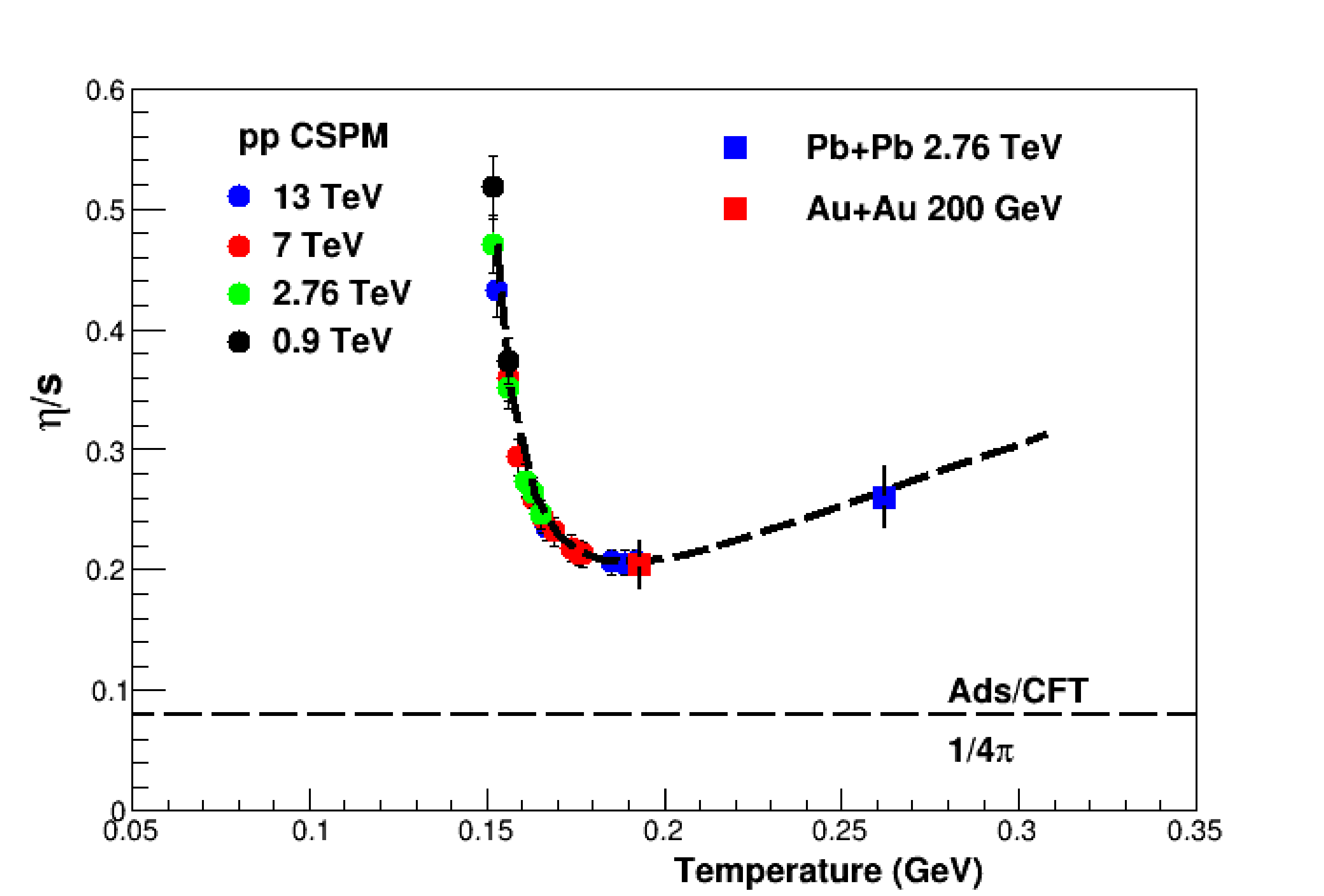

$$\frac{\eta}{s} \approx \frac{1}{5} \frac{L}{1-e^{-\xi}} T$$

η/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

Trace Anomaly from Lattice QCD Calculation

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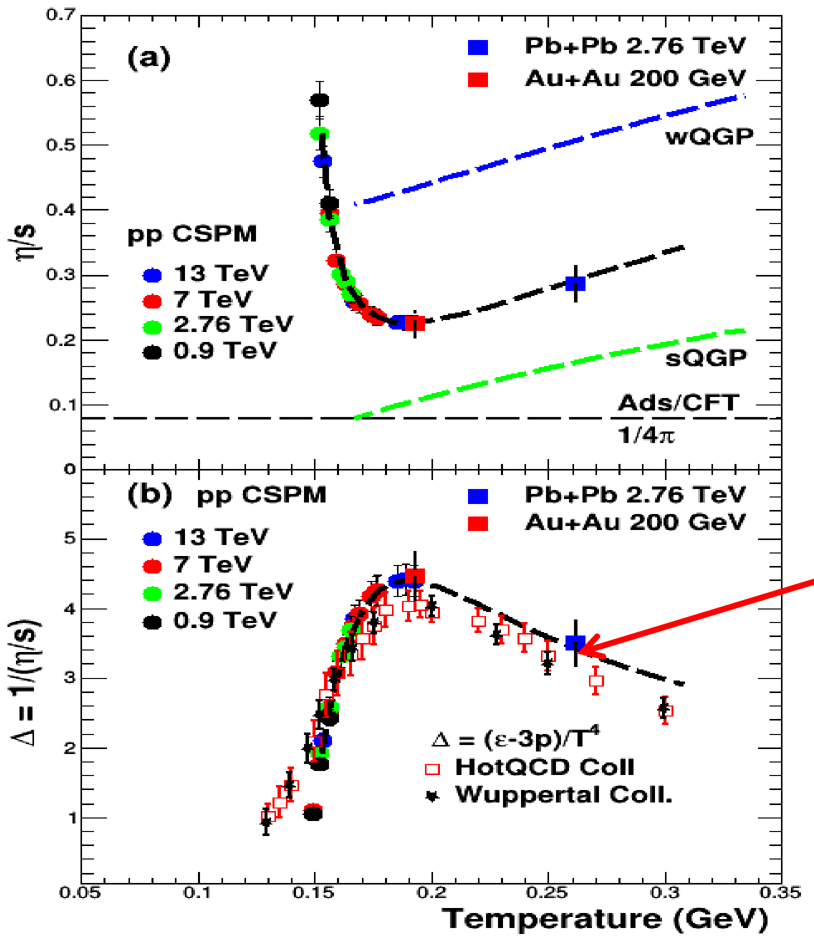
Trace Anomaly (Δ) is the expectation value of the energy-momentum tensor $\langle \Theta^{\mu}_{\mu} \rangle = (\varepsilon - 3p)$ which measures the deviation from conformal behavior.



Ansatz : $\Delta = 1/(\eta/s)$

Magnitude and functional dependence same as in LQCD

1/T dependence

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

Equation of State

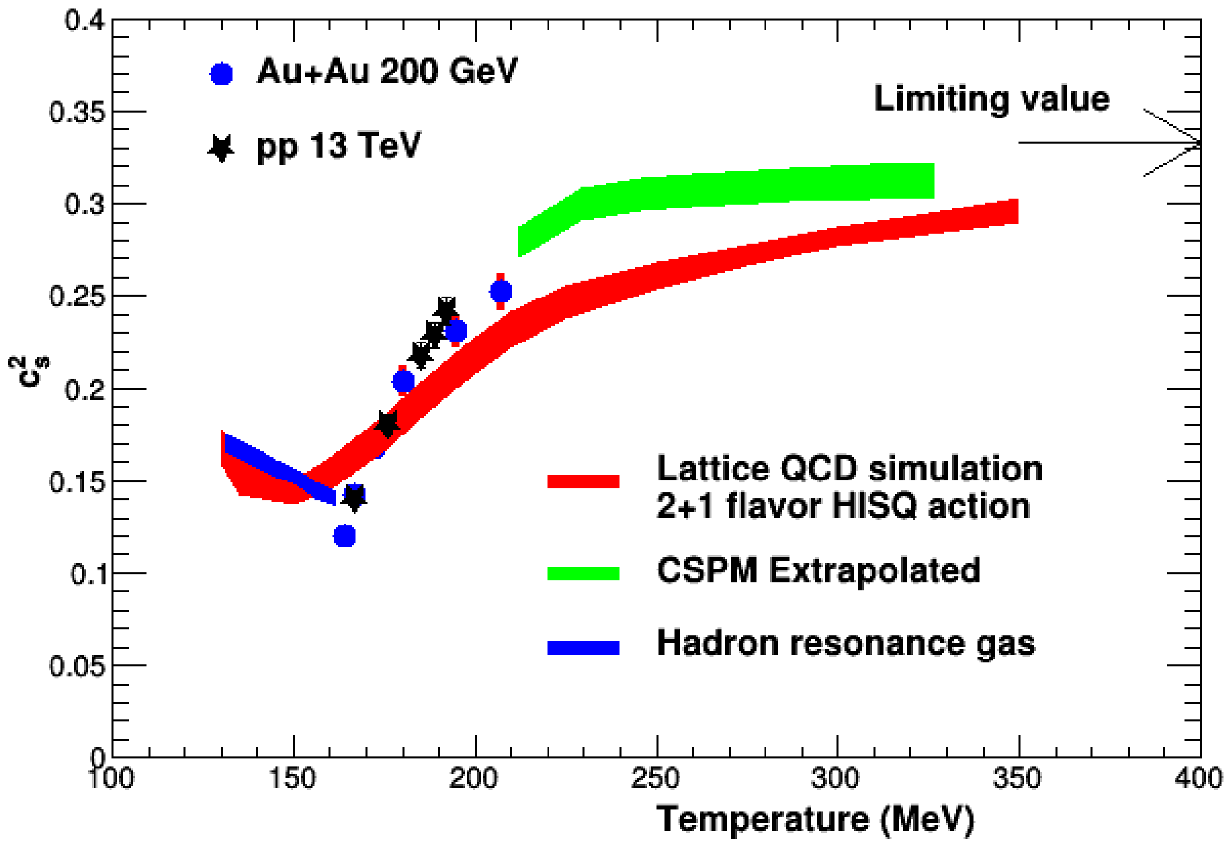
Bjorken 1D expansion gives the sound velocity

$$c_s^2 = \frac{dT}{d\varepsilon} s$$

$$\frac{dT}{d\varepsilon} = \frac{dT}{dq}\frac{dq}{d\xi}\frac{d\xi}{d\varepsilon}$$

$$s = \frac{\varepsilon + p}{T} = \frac{1}{T}\left(\frac{4}{3}\varepsilon - \frac{\Delta T^4}{3}\right), \Delta = \frac{\varepsilon - 3p}{T^4}$$

$$c_s^2 = \left(\frac{\xi e^{-\xi}}{1 - e^{-\xi}} - 1\right)\left(-\frac{1}{3} + \frac{\Delta}{12}\frac{1}{N}\right)$$


Au+Au 200 GeV
pp 13 TeV
Limiting value
c_s^2
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100
150
200
250
300
350
400
Temperature (MeV)
Lattice QCD simulation
2+1 flavor HISQ action
CSPM Extrapolated
Hadron resonance gas

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 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.

ALICE data : pp@0.9-13 TeV, Pb+Pb@2.76 and 5.02 TeV, Xe+Xe@5.44 TeV

G. Paic, A. N. Mishra and E. C. Flores
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Thank You

Extras

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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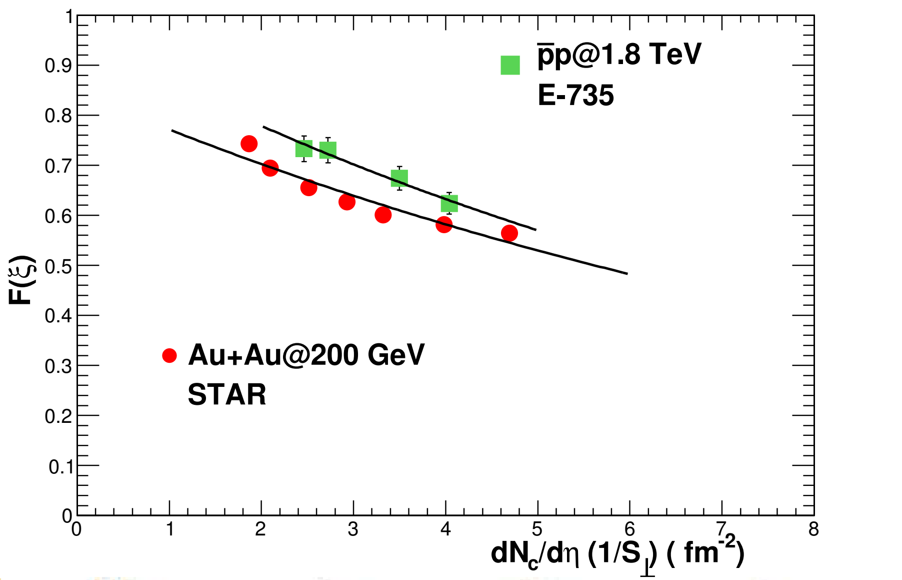
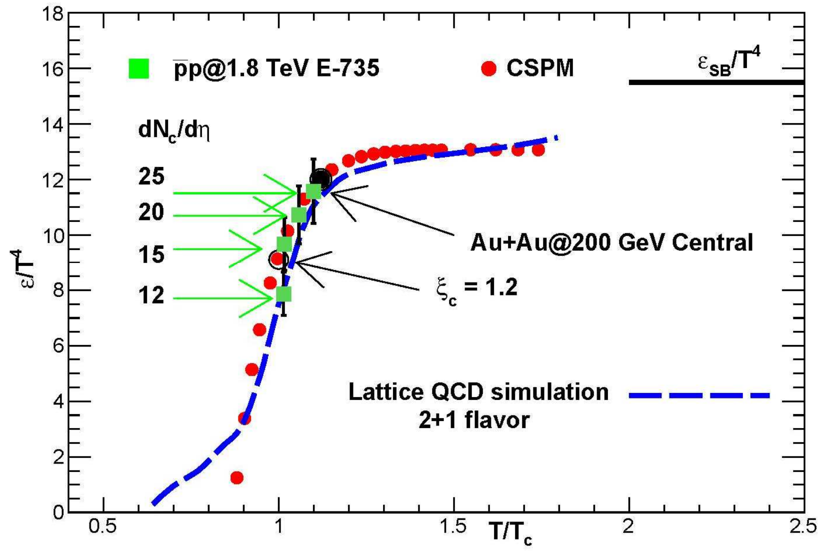
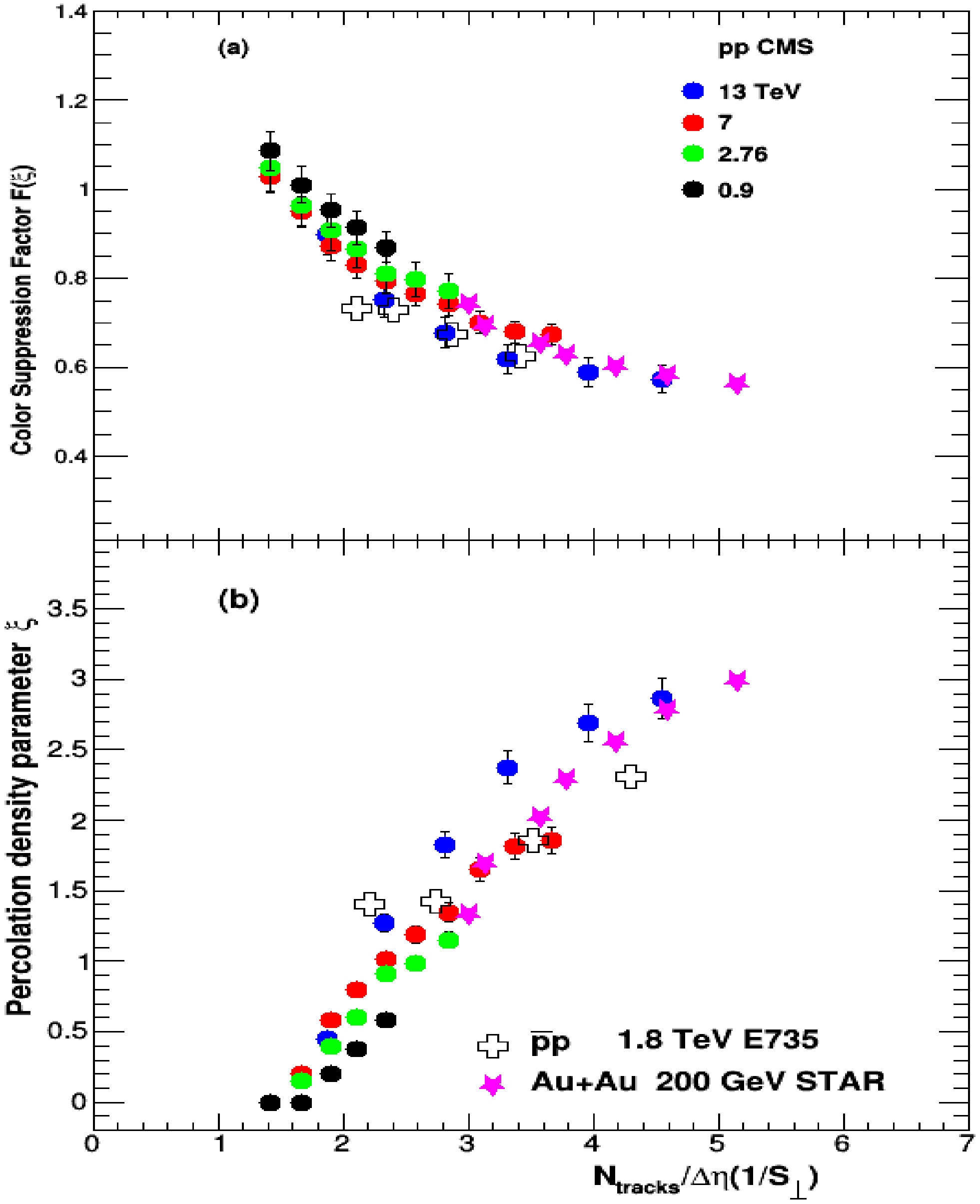
L. J. Gutay, A. S. Hirsch, R. P. Scharenberg and B. K. Srivastava and C. Pajares





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



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