STRING PERCOLATION AND THE GLASMA

C.Pajares
Dept Particle Physics and IGFAE
University Santiago de Compostela

CERN The first heavy ion collisions at the LHC
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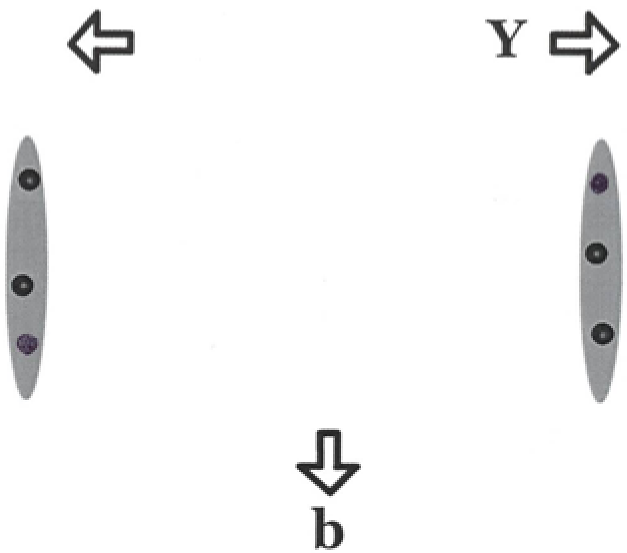
- Introduction to percolation of strings
- Results for some observables
- Similarities on rapidity distributions,and multiplicity distributions

. Behaviour of normalized width with energy or density

. Long range correlations

. EoS

J.Dias de Deus.EoS(B.Srisvastava,et al)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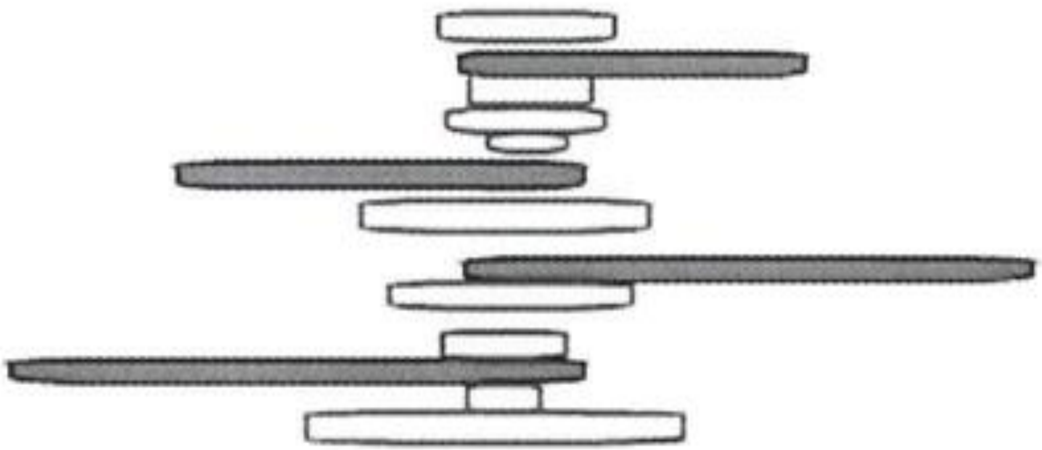
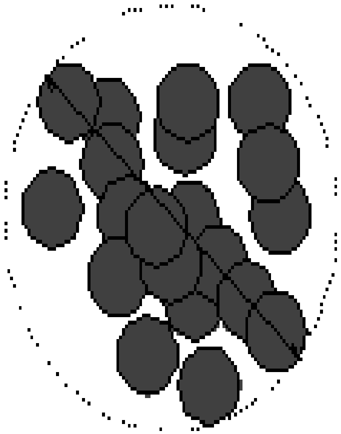


CLUSTERING OF COLOR SOURCES

- Color strings are stretched between the projectile and target
- Strings = Particle sources: particles are created via sea qqbar production in the field of the string
- Color strings = Small areas in the transverse space filled with color field created by the colliding partons
- With growing energy and/or atomic number of colliding particles, the number of sources grows
- So the elementary color sources start to overlap, forming clusters, very much like disk in the 2-dimensional percolation theory
- In particular, at a certain critical density, a macroscopic cluster appears, which marks the percolation phase transition

(N. Armesto et al., PRL77 (96); J.Dias de Deus et al., PLB491 (00); M. Nardi and H. Satz(98).

- How?: Strings fuse forming clusters. At a certain critical density η_c (central PbPb at SPS, central AgAg at RHIC, central pp at LHC) a macroscopic cluster appears which marks the percolation phase transition (second order, non thermal).



$$\eta = N_{st}\frac{S_1}{S_A}\,, \quad S_1 = \pi r_0^2, \quad r_0 = 0.2 \ \text{fm}, \quad \eta_c = 1.1 \div 1.2.$$

- Hypothesis: clusters of overlapping strings are the sources of particle production, and central multiplicities and transverse momentum distributions are little affected by rescattering.

$$\mu_n = \sqrt{\frac{nS_n}{S_1}}\mu_1 \; ; \; < p_T^2 >_n = \sqrt{\frac{nS_1}{S_n}} < p_T^2 >_1$$

Energy-momentum of the cluster is the sum of the energy-momentum of each string. As the individual color field of the individual string may be oriented in an arbitrary manner respective to one another, $\vec{Q}_n^2 = n\vec{Q}_1^2$

- At high densities
  - $< \mu >_n = nF(\eta) < \mu >_1 \;\; < p_T^2 >_n = \frac{< p_T^2 >_1}{F(\eta)}$
  - $F(\eta) = \sqrt{\frac{1-e^{-\eta}}{\eta}}$, $\eta = N_S \frac{\pi r_0^2}{S_A}$
  - r_0 is the transverse size of a single string $\simeq$ 0.2 fm.

$$\frac{< p_T^2 >}{< \mu >} = \frac{< p_T^2 >_1}{< \mu >_1} \; \frac{S_1}{S_n \;\; 1-e^{-\eta}}$$

E	0.2	0.9	2.36
dN/dy	2.75	3.48	4.47
Pt	0.40	0.46	0.50
Pt**2/dN/dy	0.058	0.060	0.056

LHC

- Scales of pp and AA

Why Protons?

In String Percolation…

$$\eta_{AA} = \left(\frac{r}{R}\right)^2 N^s = \frac{N_A^{4/3}}{N_A^{2/3}}\left(\frac{r}{R_p}\right)^2 N_p^s$$

$$\eta_{AA}(s) = N_A^{2/3}\eta_{pp}(s) \quad \text{and} \quad \overline{N} \sim s^{2/7}$$

$$\eta_c \approx 1.15 \begin{cases} \eta_{PbPb}(\sqrt{s}) \cong 20GeV - 200Gev \\ \eta_{pp}(\sqrt{s}) \cong 6TeV - 14Tev \longleftarrow \text{LHC} \end{cases}$$

Transverse size $r_0^2 F(\eta)$

CGC $1/Q_s^2$

Effective number of clusters

$$<N> = \frac{(1-\exp(-\eta))R_A^2}{F(\eta)\, r_0^2} = (1-\exp(-\eta))^{1/2}\sqrt{\eta}\left(\frac{R_A}{r_0}\right)^2$$

low density $\eta\left(\frac{R_A}{r_0}\right)^2, N_A^{4/3}, \exp(2\lambda y)$

high density $\sqrt{\eta}\left(\frac{R_A}{r_0}\right)^2, N_A, \exp(\lambda y)$

CGC $\frac{1}{\alpha_s} R_A^2 Q_s^2, N_A, \exp(\lambda y)$

rapidity extension

$\Delta y_H = \Delta y_r + 2 \ln N_s$, $\ln N_A, \ln s$

CGC $\frac{1}{\alpha_s}$ $\ln N_A, \ln s$

$$\kappa = \frac{< N >^2}{< N^2 > - < N >^2}$$

low density $k \to \infty$

high density $k \to \infty$

$$k = \frac{< N >}{(1 - exp(-\eta))^{3/2}}$$

high density $\sqrt{\eta}\left(\frac{R_A}{r_a}\right)^2, N_A, exp(\lambda \gamma)$

low density $\frac{1}{\sqrt{\eta}}\left(\frac{R_A}{r_a}\right)^2$

CGC $k = R_s^2 Q_s^2, N_A, exp(\lambda \gamma)$

MULTIPLICITY DISTRIBUTIONS

NEGATIVE BINOMIAL

$k = \langle N \rangle k_0$ (k_0, single effective string)

low density $k \to \infty,\ k_0 \to \infty$ Poisson

high density $k \to \infty,\ k_0 \to 1$ Bose-Einstein

CGC $k_0 = 1$ $B:E$, $k = \langle N \rangle$

$\boldsymbol{k}$ first decreases with density (energy)

Above an energy(density) k increases

$\Rightarrow$ Multiplicity distributions (normalized,

i.e. $\langle n \rangle P_n$ as a function of $n / \langle n \rangle$

will be narrower (Quantum Optical prediction)

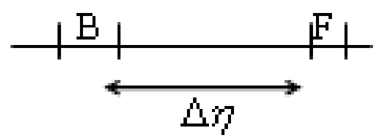
LONG RANGE CORRELATIONS

• A measurement of such correlations is the backward–forward dispersion

$$D^2_{FB} = <n_B n_F> - <n_B> <n_F>$$

where $n_B (n_F)$ is the number of particles in a backward (forward) rapidity

$$D^2_{FB} = <N> \left(<n_{1B} n_{1F}> - <n_{1B}><n_{1F}> \right) + \left(<N^2> - <N>^2 \right) <n_{1F}><n_{1B}>$$



$<N>$ number of collisions: $<n_{1B}>,<n_{1F}>$ F and B multiplicities in one collision

• In a superposition of independent sources model, D^2_{BF} is proportional to the fluctuations(D^2_N)on the number of independent sources (It is assumed that Forward and backward are defined in such a way that there is a rapidity window $\Delta_\eta \geq 1.0$ to eliminate short range correlations).

$$\langle n_B \rangle = a + b\, n_F$$

with

$$b \equiv D^2_{BF} / D^2_{FF}$$

- b in pp increases with energy. In hA increases with A also in AA,increases with centrality

The dependence of b with rapidity gap is quite interesting, remaining flat for large values of the rapidity window.

Existence of long rapidity correlations at high density

Correlation Parameter b

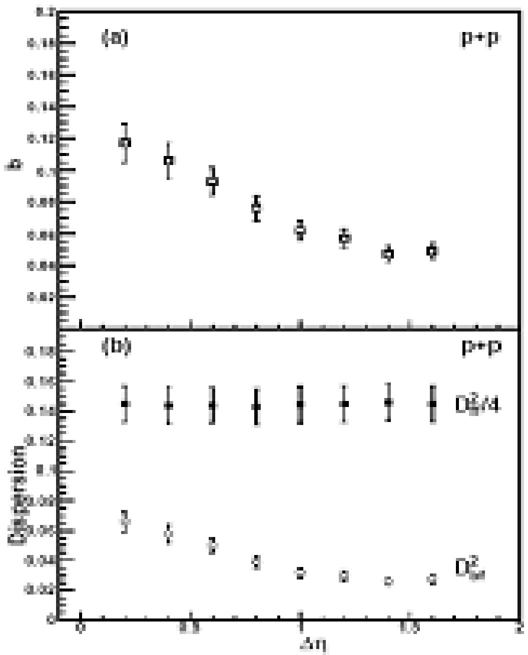
I Situation: Symmetrica

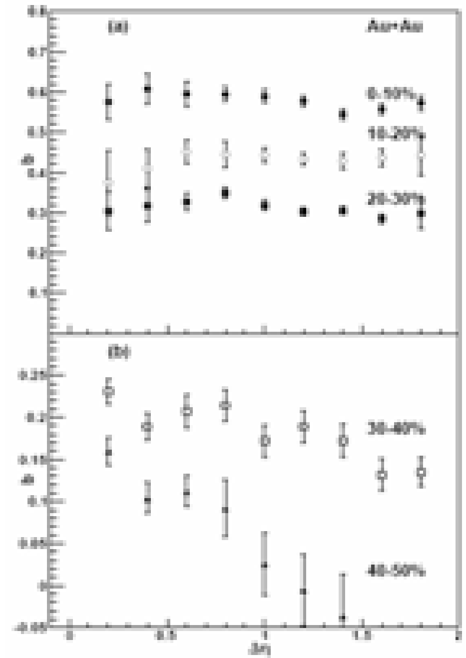
:

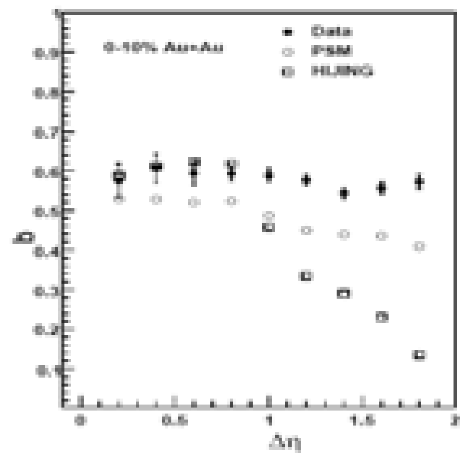
$$b \equiv \frac{1}{1 + \frac{K}{<n_F>}}$$

- 1/K is the squared normalized fluctuations on effective number of strings(clusters)contributing to both forward and backward intervals

The heigth of the ridge structure is proportional to n/k


(a)
p+p
(b)
p+p
Dispersion
Δη


(a)
Au+Au
0-10%
10-20%
20-30%
(b)
30-40%
40-50%
Δη


0-10% Au+Au
Data
PSM
HIJING
Δη

Comments

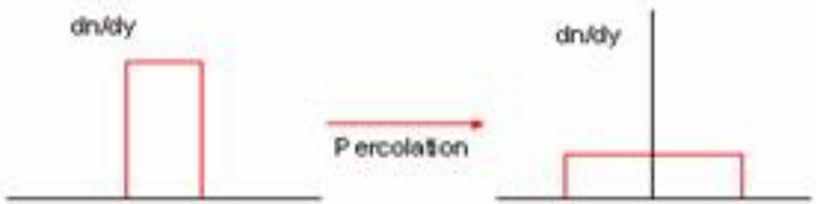
- Data (RHIC)
- FB Correlations YES: SO LONG?

Colour Flux Tube: OK

Strings : TOO SHORT

One String: $x^+ = x^- = x = 1/\sqrt{s} \Rightarrow \Delta y_1$

N^s Strings: $\Delta y_{N_s} = \Delta y_1 + 2\ln(N_s)$



$$b = \frac{1}{1 + \frac{d}{(1 - e^{-\tau})^{3/2}}}$$

low density $b \rightarrow 0$

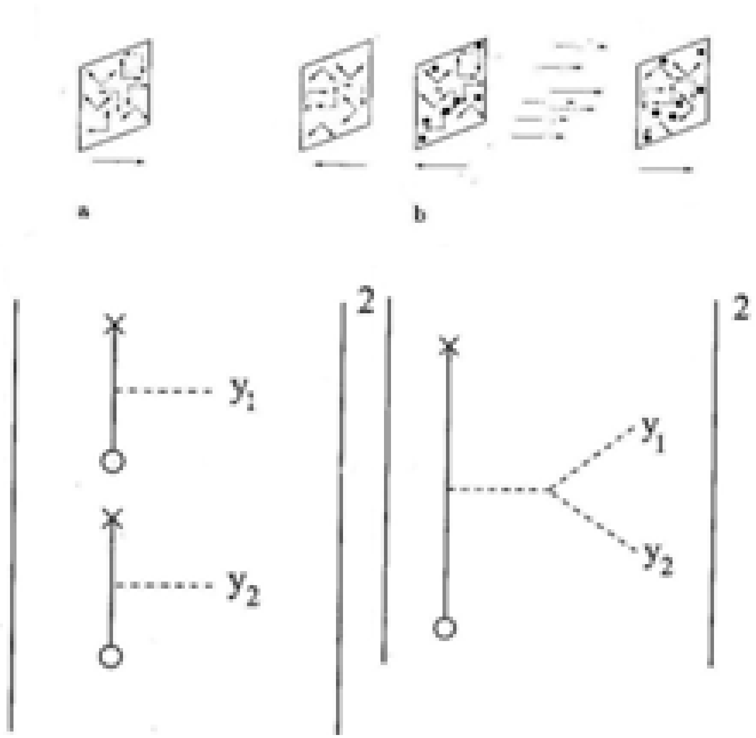
high density (energy) $b \rightarrow 1/(1 + d)$

CGC

$$b = \frac{1}{1 + \alpha_s^2 c}$$

high density (energy) $b \rightarrow 1$

Color Glass Condensate



$$\frac{dN}{dy} = \frac{1}{\alpha_s}\pi R^2 Q_{sat}^2$$

$$< \left(\frac{dN}{dy}\right)^2 > = \frac{1}{\alpha_s^2}\pi R^2 Q_{sat}^2$$

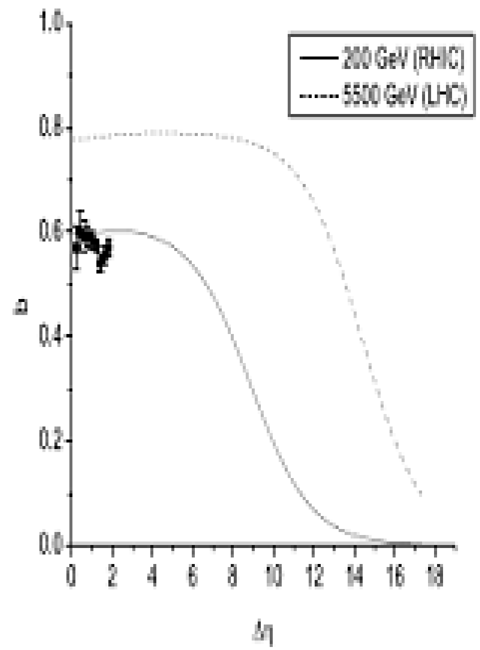
$$\sim \frac{1}{\alpha_s}\frac{dN}{dy}$$

$$< \frac{dN_{con}}{dy_1}\frac{dN_{con}}{dy_2} > = \alpha_s \pi R^2 Q_{sat}^4$$

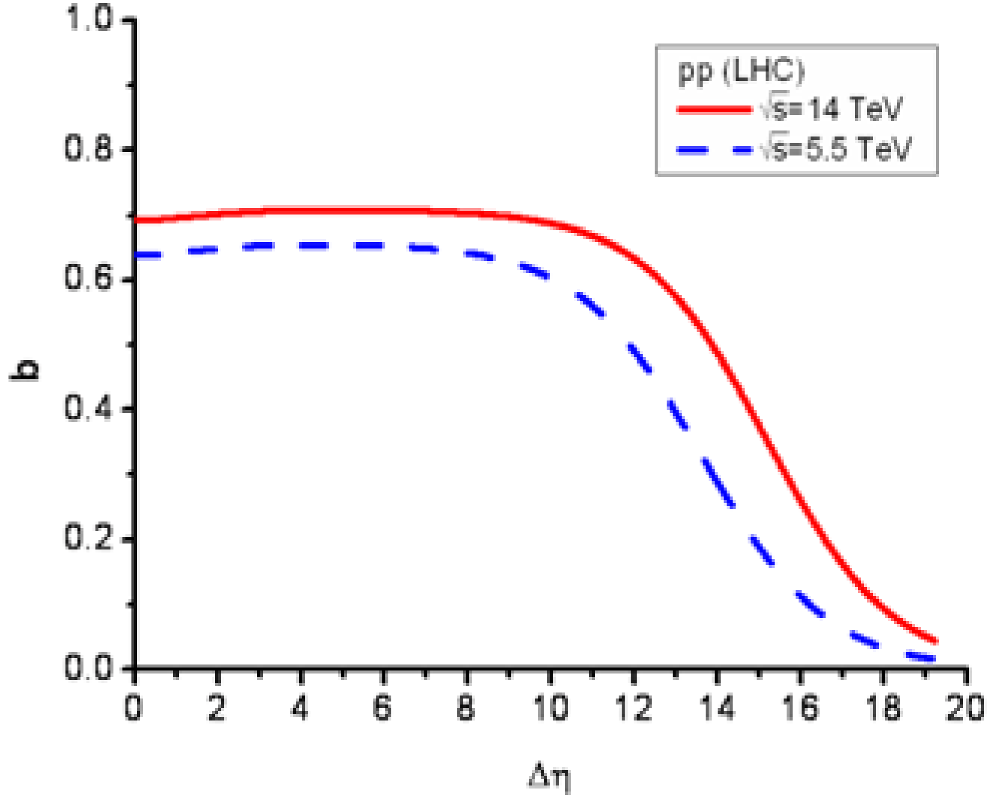
$$\sim \frac{dN_{con}}{dy} e^{-k|y_1 - y_2|}$$

$$b = \frac{1}{1 + \alpha_s^2 c}$$

As the centrality or the energy increases, Q_s increases, α_s decreases and b increases (N.Armesto,L.McLerran and C.P;N.Armesto,M.Braun and C.P)



200 GeV (RHIC)
5500 GeV (LHC)
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10
12
14
16
18
Δη



pp (LHC)
√s=14 TeV
√s=5.5 TeV
b
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
14
16
18
20
Δη

The STAR analysis of charged hadrons for 0 to 10% central Au+Au collisions at $\sqrt{s_{NN}}$ =200 GeV gives a value η =2.88 ± 0.09 [8]. Above the critical value of η the QGP in SPM consists of massless constituents (gluons). The connection between η and the temperature T(η) involves the Schwinger mechanism (SM) for particle production. In CSPM the Schwinger distribution for massless particles is expressed in terms of p_t^2

$$dn/dp_t^2 \sim e^{-\pi p_t^2/x^2} \quad (9)$$

with the average string tension value $\langle x^2 \rangle$. Gaussian fluctuations in the string tension around its mean value transforms SM into the thermal distribution [6]

$$dn/dp_t^2 \sim e^{-p_t/\sqrt{2\pi/\langle x^2\rangle}} \quad (10)$$

with $\langle x^2 \rangle = \pi \langle p_t^2 \rangle_1 / F(\eta)$. The temperature is given by

$$T(\eta) = \sqrt{\frac{\langle p_t^2 \rangle_1}{2F(\eta)}} \quad (11)$$

where F(η) and $\langle p_t^2 \rangle_1$ can be obtained from the data as described above.

The initial energy density ε_I above T_c is given by [7]

$$\varepsilon_I = 3/2 \frac{dN_C}{dy} \frac{\langle m_T \rangle}{A_N \tau_{PRO}} \quad (17)$$

To evaluate ε_I we use the charged pion multiplicity dN_c/dy at midrapidity and S_N values from STAR for 0-10% centrality [15]. The factor 3/2 in Eq.(17) accounts for the neutral pions. We can calculate $\langle p_t \rangle$ using the CSPM thermal distribution Eqs.(9) and (10). For $0.2 < p_t < 1.5$, $\langle p_t \rangle = 0.394 \pm 0.003$GeV, adding the extra energy required for the rest mass of pions at hadronization $\langle m_t \rangle = 0.42 \pm 0.003$GeV. The error is determined by the error on $T_i = 193.6 \pm 3.0$MeV.

[15] B.I. Abelev et al., (STAR Collaboration), Phys. Rev. C79 (2009) 34909.

The dynamics of massless particle production has been studied in QE2 quantum electrodynamics. QE2 can be scaled from electrodynamics to quantum chromodynamics using the ratio of the coupling constants. The production time τ_{pro} for a boson (gluon) is

$$\tau_{pro} = \frac{2.405 h/2\pi}{mc^2} \tag{18}$$

For mc^2 we use $\langle m_t \rangle$ and τ_{pro}= 1.128 ± 0.009 fm/c. This gives ε_i= 2.27±0.16 GeV/fm^3 at η =2.88. In SPM the energy density ε at y=0 is proportional to η. From the measured values of η and ε it is found that ε is proportional to η for the range 1.2 < η < 2.88 [8, 15].

$$\varepsilon_i = 0.788\ \eta$$

C Y. Wong, Introduction to high energy heavy ion collisions, 289 (1994).
J. Schwinger, Phys. Rev. 128, 2425 (1962).

This relationship (19) has been extrapolated to below $\eta = 1.2$ and above $\eta = 2.88$ for the energy and entropy density calculations. Figure 1 shows ε/T^4 obtained from SPM along with the LQCD calculations . The number of degrees of freedom G(T) are:

$$\varepsilon_i = \frac{G(T)\pi^2 T_i^4}{30(hc/2\pi)^3}$$

At T_i , $\varepsilon_i = 2.27 \pm 0.16$ GeV/fm^3

and 37.5 ± 3.6. DOF

At T_c, $\varepsilon_C = 0.95 \pm 0.07$ GeV/fm^3

and 27.7 ± 2.6 DOF.

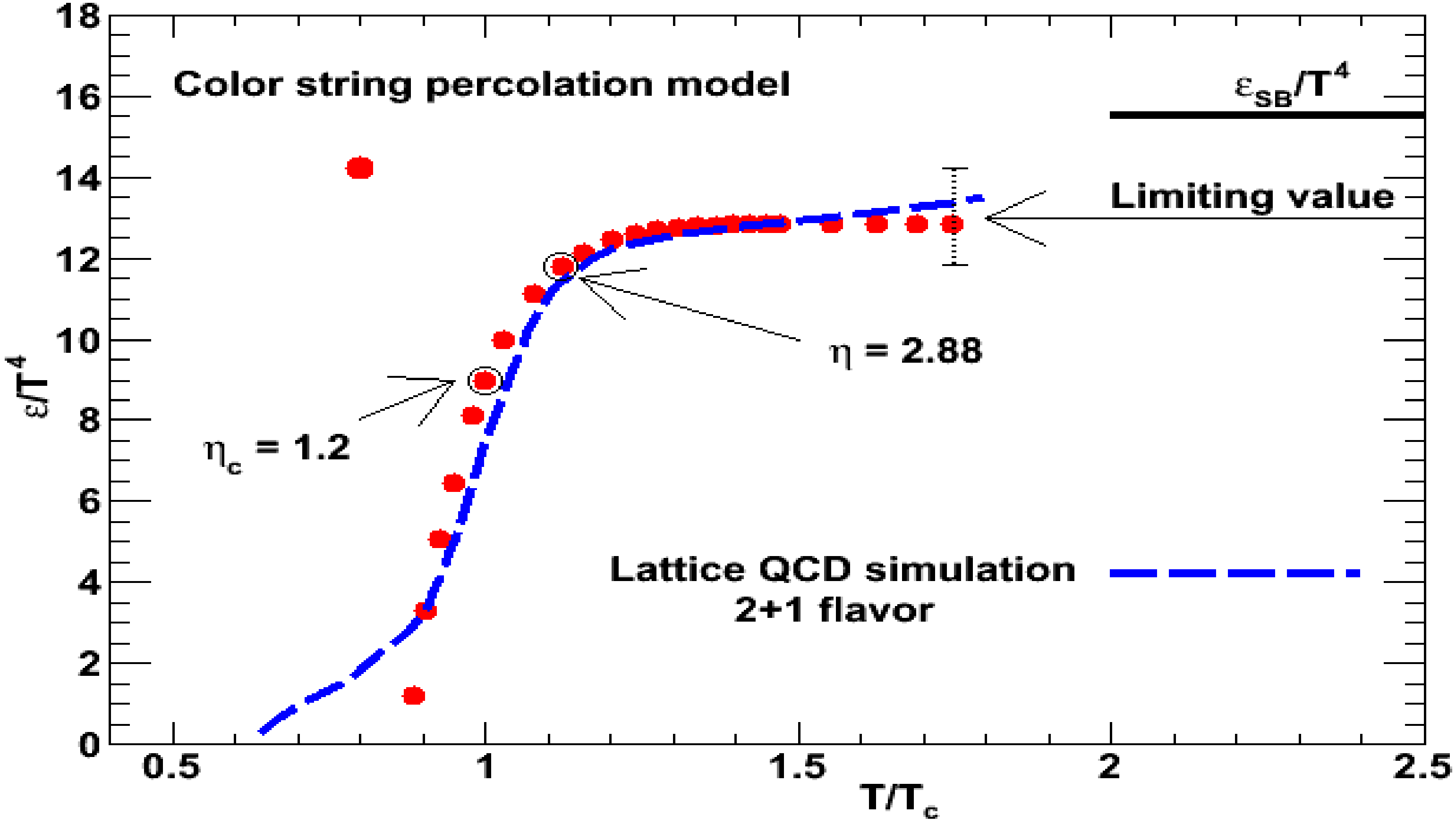


FIG: The energy density from SPM versus T/T_{SPM} (red circles) and Lattice QCD energy density vs T/T_{LQCD} (blue dash line) for 2+1 flavor and p4 action.

Bjorken 1D Expansion and the velocity of sound in the QGP

$$\frac{1}{T}\frac{dT}{d\tau} = -C_S^2/\tau \qquad (12)$$

$$\frac{dT}{d\tau} = \frac{dT}{d\varepsilon}\frac{d\varepsilon}{d\tau} \qquad (13)$$

$$\frac{d\varepsilon}{d\tau} = -\frac{Ts}{\tau} \qquad (14)$$

$$s = \left(1 + C_s^2\right)\frac{\varepsilon}{T} \qquad (15)$$

$$\frac{dT}{d\varepsilon}s = C_s^2 \qquad (16)$$

where ε is the energy density, s the entropy density, τ the proper time, and C_s the sound velocity. Above the critical temperature only massless particles are present in SPM.

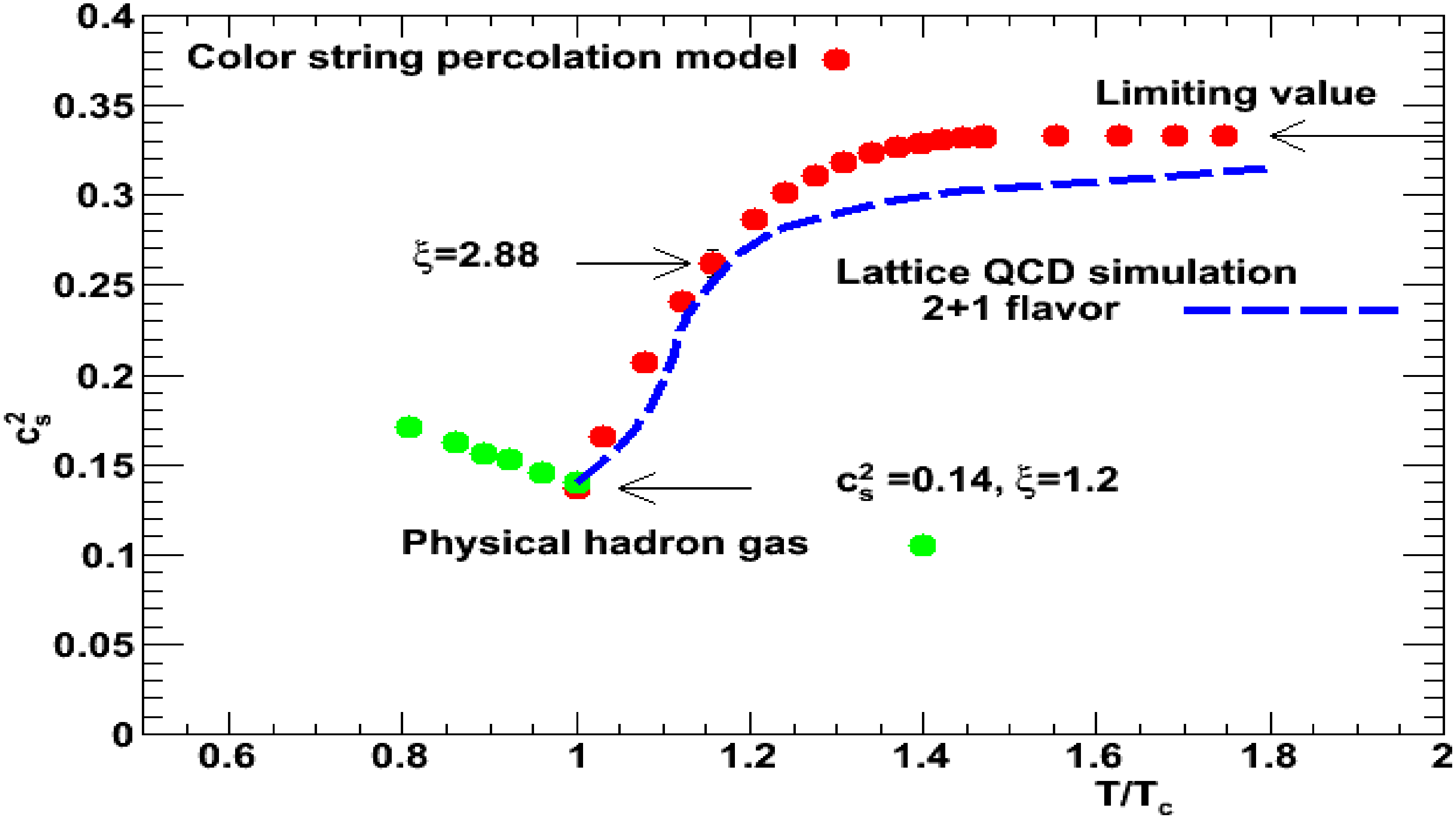


FIG: The speed of sound from SPM versus $T/T_{C\ CSPM}$ (red circles) and Lattice QCD-p4 speed of sound versus $T/T_{C\ LQCD}$ (blue dash line) . The physical hadron gas with resonance mass cut off M ≤ 2.5 GeV is shown (green circles).

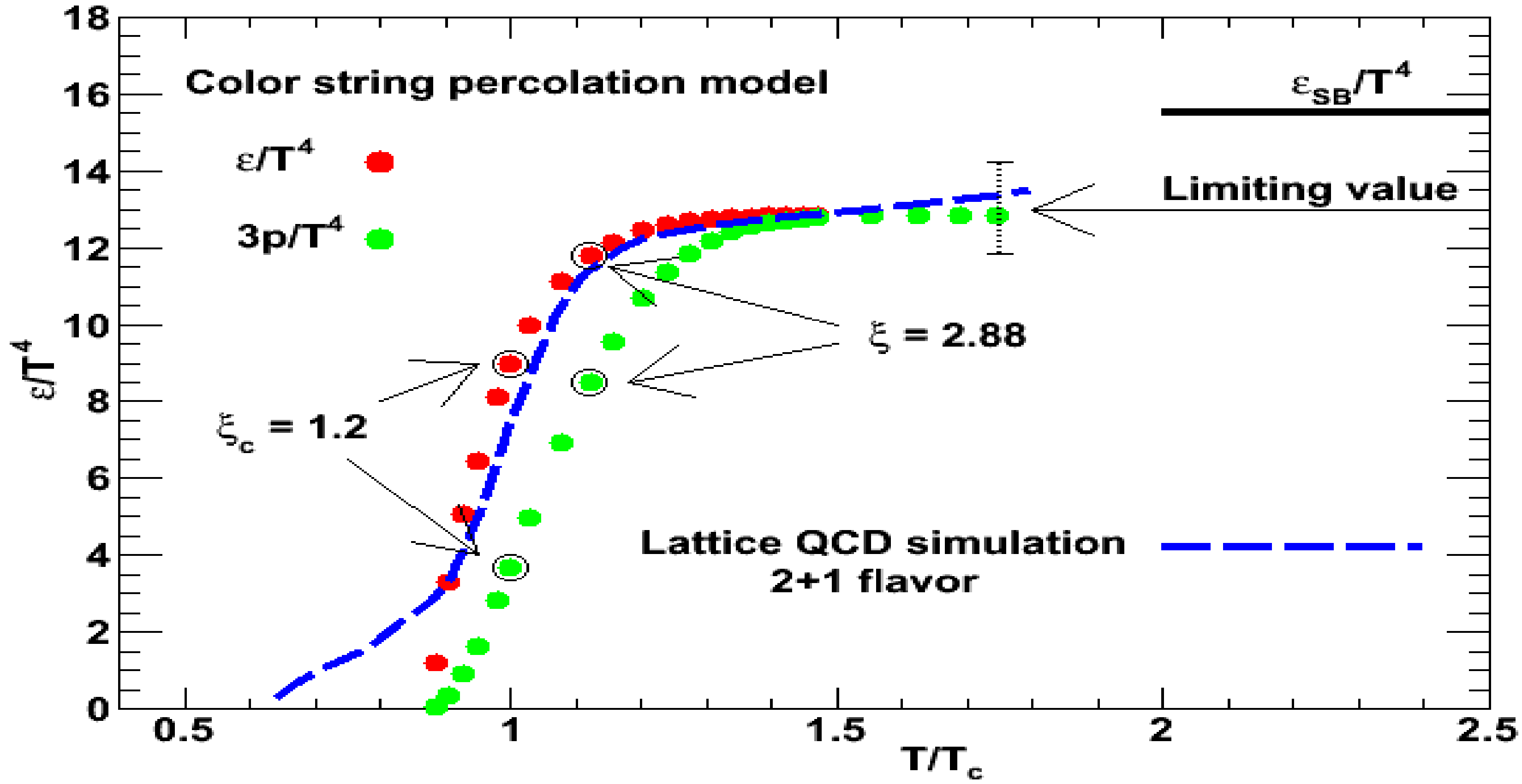


FIG. : The energy density from SPM versus T/T_{SPM} (red circles) and Lattice QCD energy density vs T/T_{LQCD} (blue dash line) for 2+1 flavor and p4 action. $3p/T^4$ is also shown for SPM (green circles).

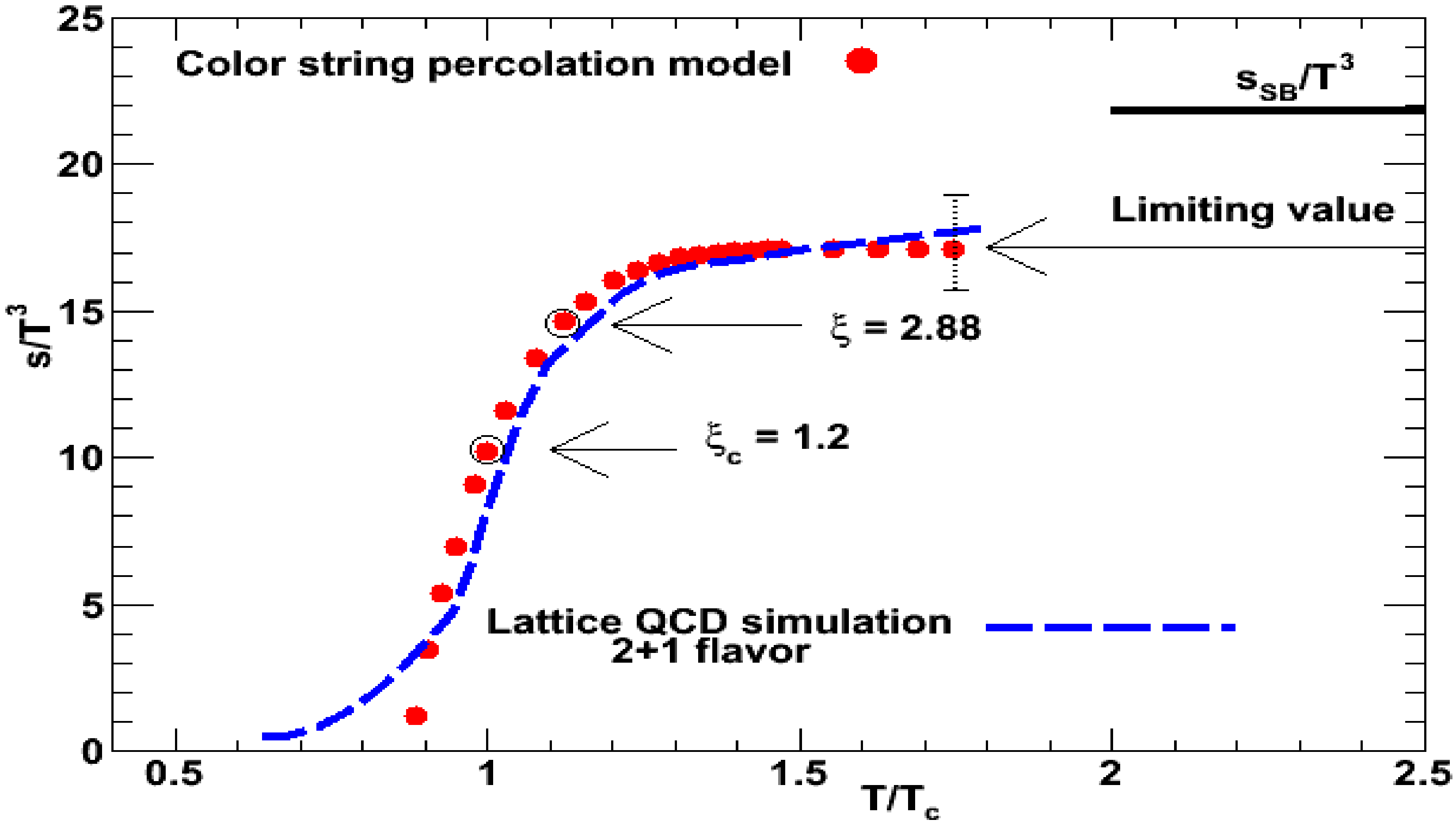


FIG. : The entropy density from SPM versus $T/T_{C\ CSPM}$ (red circle) and Lattice QCD entropy density versus $T/T_{C\ LQCD}$ (blue dash line) .

Nucl Phys. A769, 71 (2006)
Nucl-th/0506049 8 March 2006
Hirano and Gyulassy Eq. (1)

Weak coupling perturbative QCD estimates of the velocity of a wQGP were based on basic kinetic theory relations

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

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

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

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

ε Energy density

s Entropy density

n the number density

λ_{tr} Mean free path

σ_{tr} Transport cross section

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

$$\frac{\eta}{s} = \frac{1}{5}\frac{< pt >_1}{\sqrt{2F(\xi)}}\frac{1}{n\sigma_{tr}}$$

$$n = \frac{N_s}{\pi R_A^2 L}$$

$$N_s = \frac{(1-e^{-\xi})\pi R_A^2}{S_1}$$

$$\frac{\eta}{s} = \frac{1}{5\sqrt{2}}\frac{< pt >_1 \eta^{1/4}}{(1-e^{-\eta})^{5/4}} L$$

In percolation

$$T = \sqrt{\frac{< pt^2 >_1}{2F(\xi)}}$$

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

$\sigma_{tr} = S_1$ Single string area

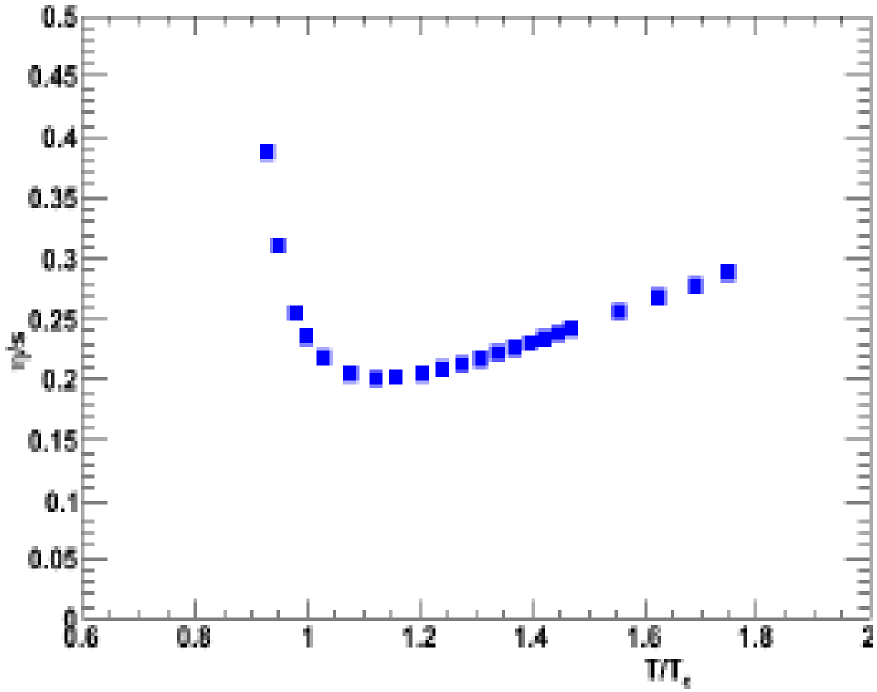
N_s No of overlapping strings

L Length of the string

$< pt >_1$ Average transverse momentum of the single string

The above equation is used for shear viscosity calculation

η/s



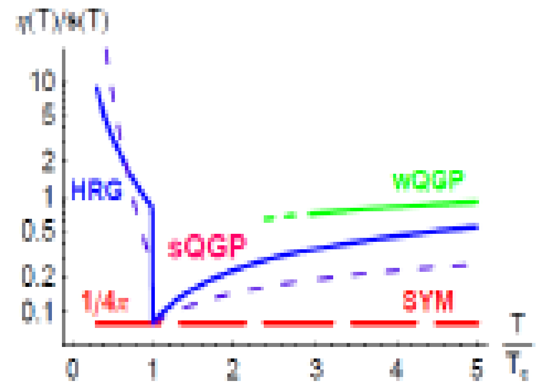


FIG. 2: Illustration of the rapid variation of the dimensionless ratio of the shear viscosity, $\eta(T)$, to the entropy density, $s(T)$. The sharp discontinuity illustrated is not due to a rapid change of the transport coefficient (see Fig. 1) but to the rapid increase of the entropy density in QCD near T_c. As in Fig. 1, we expect the discontinuity to be smeared into a rapid drop within $\Delta T_c/T_c \sim 0.1$. Solid (dashed) blue curve illustrates the change of η/s of a HRG with $c_H^2 = 1/3$ $(1/6)$, $s_Q/s_H = 10$ (3) into an approximate "perfect fluid" sQGP at T_c. The red long dashed curve is $(\eta/s)_{SYM} = 1/4\pi$. At $T \gg T_c$ asymptotic freedom gradually transforms the sQGP into an ordinary viscous fluid wQGP (green), here shown for $\alpha = \frac{1}{2}, 1$.

Conclusions

---For pp at LHC are predicted the same phenomena observed at RHIC in Au-Au

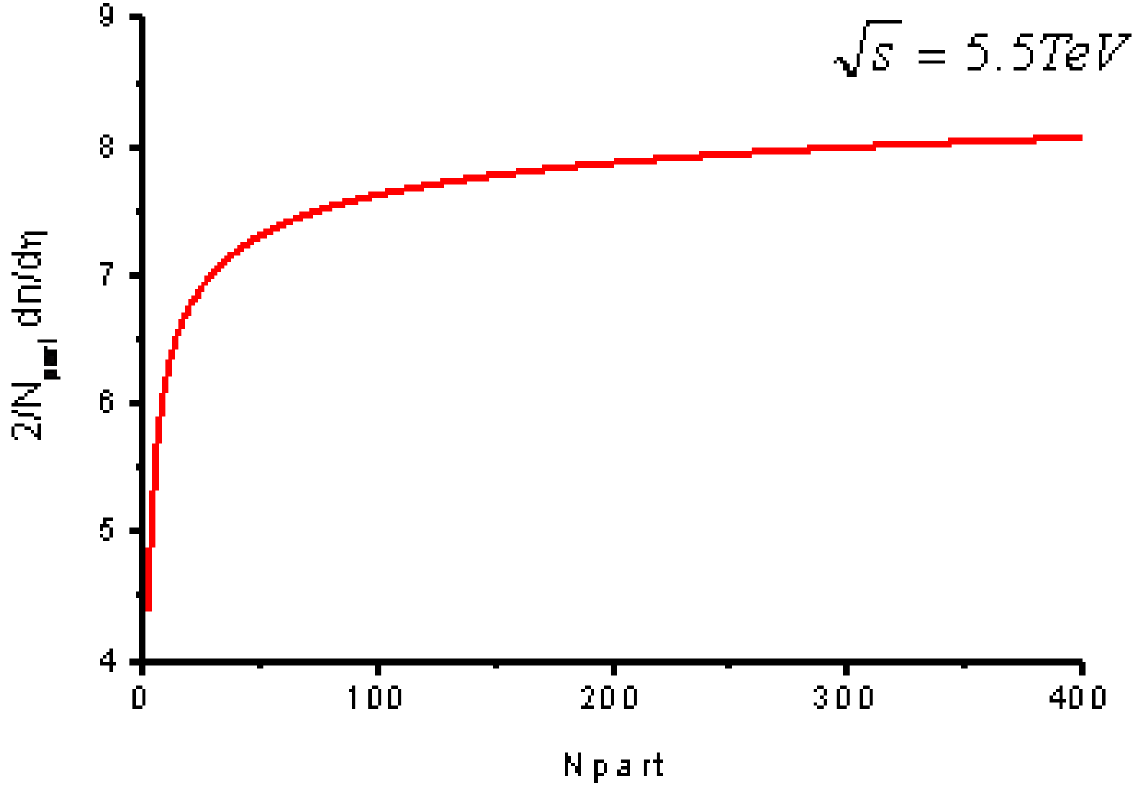
---Normalized multiplicity distributions will be narrower

---Long range correlations extended more than 10 units of rapidity at LHC.Large LRC in pp extended several units of rapidity.

---Large similarities between CGC and percolation of strings.Similar predictions corresponding to similar physical picture.Percolation explains the transition low density-high density

--The strings must be extended in both hemispheres,otherwise either they do not obtained LRC(Heijing)or they have to include parton interactions(PACIAE).PACIAE reproduces well b for central but not for peripheral

--Without parton interactions the length of the LRC is the same in pp than AA(modified wounded model of Bzdak)



$\sqrt{s} = 5.5TeV$
2/N_part dn/dη
Npart
0
100
200
300
400
4
5
6
7
8
9

The determination of the EOS of hot, strongly interacting matter is one of the main challenges of strong interaction physics (Hot QCD Collaboration) . Recently, Lattice QCD (LQCD) presented results for for the bulk thermodynamic observables, e.g. pressure, energy density, entropy density and for the sound velocity. We use SPM to calculate these quantities and compare them with the LQCD results. The QGP according to SPM is born in local thermal equilibrium because the temperature is determined at the string level. After the initial temperature $T_I > T_c$, SPM may expand according to Bjorken boost invariant 1D hydrodynamicS

A. Bazavov et al, Phys. Rev. D80 (2009) 014504

The sound velocity requires the evaluation of s and $dT/d\varepsilon$, which can be expressed in terms of η and F(η). With $q^{1/2} = F(\eta)$ one obtains:

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

Then C_S^2 becomes:

$$C_S^2 = (1+C_S^2)\,(-0.25)\left(\frac{\xi e^{-\xi}}{1-e^{-\xi}} - 1\right) \quad \text{for } \eta \geq \eta_C \qquad (22)$$

An analytic function of η for the equation of state of the QGP for $T \geq T_c$.

Figure shows the comparison of C_S^2 from SPM and LQCD. The LQCD values were obtained using the EOS of 2+1 flavor QCD at finite temperature with physical strange quark mass and almost physical light quark masses [14].

At $T/T_c=1$ the SPM and LQCD values agree with the $C_S^2 = 0.14$ value of the physical hadron gas with resonance mass truncation $M \leq 2.5$ GeV

P. Castorina et al, arXiv:hep-ph/0906.2289v1