Clustering of color sources and the shear viscosity of the QGP in heavy ion collisions at RHIC and LHC energies

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Abstract We present our results on the shear viscosity to entropy ratio (η/s) in the framework of the clustering of the color sources of the matter produced at RHIC and LHC energies. The onset of de-confinement transition is identified by the spanning percolating cluster in 2D percolation. The relativistic kinetic theory relation for η/s is evaluated using the initial temperature (T) and the mean free path (λmfp). The analytic expression for η/s covers a wide temperature range. At T ≈ 150 MeV below the hadron to QGP transition temperature of ~168 MeV, with increasing temperatures the η/s value drop sharply and reaches a broad minimum η/s ~ 0.20 at T ~ 175–185 MeV. Above this temperature η/s grows slowly. The measured values of η/s are 0.204 ± 0.020 and 0.262 ± 0.026 at the initial temperature of 193.6 ± 3 MeV from central Au + Au collisions at √sNN = 200 GeV (RHIC) and 262.2 ± 13 MeV in central Pb + Pb collisions at √sNN = 2.76 TeV (LHC). These η/s values are 2.5 and 3.3 times the AdS/CFT conjectured lower bound 1/4π but are consistent with theoretical η/s estimates for a strongly coupled QGP.

1 Introduction

The observation of the large elliptic flow at RHIC in non-central heavy ion collisions suggest that the matter created is a nearly perfect fluid with a very low shear viscosity [1–4]. Recently, attention has been focused on the shear viscosity to entropy density ratio η/s as a measure of the fluidity [5–8]. The observed temperature averaged η/s, based on viscous hydrodynamics analyses of RHIC data, are suggestive of a strongly coupled plasma [9, 10]. The effect of the bulk viscosity is expected to be negligible. It has been conjectured, based on infinitely coupled super-symmetric Yang–Mills (SYM) gauge theory using the correspondence between Anti de-Sitter(AdS) space and conformal field theory (CFT), that the lower bound for η/s is 1/4π and is the universal minimal viscosity to entropy ratio even for QCD [11]. However, there are theories in which this lower bound can be violated [12]. In this work, we use the color string percolation model (CSPM) [13, 14] to obtain η/s as a function of the temperature above and below the hadron to QGP transition. The measured η/s values are for Au + Au collisions at √sNN = 200 GeV at RHIC and for Pb + Pb collisions at √sNN = 2.76 TeV at LHC.

2 Clustering of color sources

Multiparticle production is currently described in terms of color strings stretched between the projectile and the target, which decay into new strings and subsequently hadronize to produce observed hadrons. Color strings may be viewed as small areas in the transverse plane filled with color field created by colliding partons. With growing energy and size of the colliding system, the number of strings grows, and they start to overlap, forming clusters, in the transverse plane very much similar to disks in two dimensional percolation theory. At a certain critical density a macroscopic cluster appears that marks the percolation phase transition. This is the Color String Percolation Model (CSPM) [13, 14]. The interaction between strings occurs when they overlap and the general result, due to the SU(3) random summation of charges, is a reduction in multiplicity and an increase in the string tension hence increase in the average transverse momentum squared, ⟨pT²⟩. We assume that a cluster of n strings that occupies an area of Sn behaves as a single color source with a higher color field Qn corresponding to the vectorial sum of the color charges of each individual string Q1.
The resulting color field covers the area of the cluster. As \( Q_n = \sum_{1}^{n} Q_1 \), and the individual string colors may be oriented in an arbitrary manner respective to each other, the average \( Q_{11} = Q_1 \) is zero, and \( Q_n^2 = n Q_1^2 \).

Knowing the color charge \( Q_n \), one can obtain the multiplicity \( \mu \) and the mean transverse momentum squared \( \langle p_t^2 \rangle \) of the particles produced by a cluster of \( n \) strings [14]

\[
\mu_n = \frac{n S_n}{S_1} \mu_0; \quad \langle p_t^2 \rangle_n = \frac{n S_1}{S_n} \langle p_t^2 \rangle_1
\]

where \( \mu_0 \) and \( \langle p_t^2 \rangle_1 \) are the mean multiplicity and \( \langle p_t^2 \rangle \) of particles produced from a single string with a transverse area \( S_1 = \pi r_0^2 \). For strings just touching each other \( S_n = n S_1 \), and \( \mu_n = n \mu_0 \). \( \langle p_t^2 \rangle_n = \langle p_t^2 \rangle_1 \). When strings fully overlap, \( S_n = S_1 \) and therefore \( \mu_n = \sqrt{n} \mu_0 \) and \( \langle p_t^2 \rangle_n = \sqrt{n} \langle p_t^2 \rangle_1 \), so that the multiplicity is maximally suppressed and the \( \langle p_t^2 \rangle_n \) is maximally enhanced. This implies a simple relation between the multiplicity and transverse momentum \( \mu_n \langle p_t^2 \rangle_n = n \mu_0 \langle p_t^2 \rangle_1 \), which means conservation of the total transverse momentum produced.

In the thermodynamic limit, one obtains an analytic expression [13, 14]

\[
\frac{n S_1}{S_n} = \frac{\xi}{1 - e^{-\xi}} = 1 \frac{F(\xi)}{F(\xi)^2}
\]

(2)

where \( F(\xi) \) is the color suppression factor. With \( F(\xi) \rightarrow 1 \) as \( \xi \rightarrow 0 \) and \( F(\xi) \rightarrow 0 \) as \( \xi \rightarrow \infty \), where \( \xi = \frac{n S_1}{S_n} \) is the percolation density parameter. Equation (1) can be written as \( \mu_n = n F(\xi) \mu_0 \) and \( \langle p_t^2 \rangle_n = \langle p_t^2 \rangle_1 / F(\xi) \). The critical cluster which spans \( S_N \), appears for \( \xi \geq 1.2 \) [15]. It is worth noting that CSPM is a saturation model similar to the Color Glass Condensate (CGC), where \( \langle p_t^2 \rangle_1 / F(\xi) \) plays the same role as the saturation momentum scale \( Q_s^2 \) in the CGC model [16–18].

### 3 Experimental determination of the color suppression factor \( F(\xi) \)

The suppression factor is determined by comparing the \( pp \) and \( A + A \) transverse momentum spectra. To evaluate the initial value of \( \xi \) from data for \( Au + Au \) collisions, a parameterization of \( pp \) events at 200 GeV is used to compute the \( p_t \) distribution [19–21]

\[
dN_c/dp_t^2 = \alpha/\left( p_0 + p_t \right)^\alpha
\]

(3)

where \( \alpha \) is the normalization factor. \( p_0 \) and \( \alpha \) are parameters used to fit the data. This parameterization also can be used for nucleus–nucleus collisions to take into account the interactions of the strings [14]

\[
dN_c/dp_t^2 = \frac{\alpha'}{(p_0 \sqrt{F(\xi_{pp})/F(\xi)} + p_t)^\alpha'}
\]

(4)

The color suppression factor \( F(\xi) \) is related to the percolation density parameter \( \xi \).

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

(5)

In \( pp \) collisions \( F(\xi) \sim 1 \) at these energies due to the low overlap probability.

In this way the STAR analysis of charged hadrons obtained the preliminary results for the percolation density parameter, \( \xi \) at RHIC for several collisions systems as a function of centrality [19]. Figure 1 shows a plot of \( F(\xi) \) as a function of charged particle multiplicity per unit transverse area \( dN_c/d\eta /S_N \) for \( Au + Au \) collisions at 200 GeV for various centralities for the STAR data [20, 21]. The error on \( F(\xi) \) is \( \sim 3 \% \). \( F(\xi) \) decreases in going from peripheral to central collisions. The \( \xi \) value is obtained using Eq. (5), which increases with the increase in centrality. The fit to the \( Au + Au \) points has the functional form

\[
F(\xi) = \exp[-0.165 - 0.094 dN_c/d\eta /S_N]
\]

(6)

The STAR results for \( Au + Au \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) can be used to estimate \( F(\xi) \) values for \( Pb + Pb \) collisions at different centralities using the fit function given by Eq. (6) for \( Au + Au \). Recently, the ALICE experiment at LHC published the charged-particle multiplicity density data as a function of centrality in \( Pb + Pb \) collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) [22]. The ALICE data points are shown in Fig. 1. For central 0–5 % in \( Pb + Pb \) collisions \( \xi = 10.56 \) as compared to \( \xi = 2.88 \) for central \( Au + Au \) collisions at 200 GeV. For \( Au + Au \) central collisions we have found that the Bjorken energy density \( \varepsilon \) in the collision is proportional to \( \xi \). To evaluate \( \varepsilon \) the charged pion multiplicity at mid rapidity and the Schwinger QED2 production time

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**Fig. 1** Color suppression factor \( F(\xi) \) as a function of \( dN_c/d\eta /S_N \) (fm$^{-2}$). The **solid red circles** are for \( Au + Au \) collisions at 200 GeV (STAR data) [19]. The error is smaller than the size of the symbol. The **line** is fit to the STAR data. The **solid blue squares** are for \( Pb + Pb \) at 2.76 TeV.
were used [21, 23]. Figure 2 shows a plot of energy density as a function of $\xi$, $\epsilon = 0.788 \xi$ for the range $1.2 < \xi < 2.88$. The extrapolated value of $\epsilon$ for central Pb + Pb collision at 2.76 TeV is 8.32 GeV/fm$^3$ as shown in Fig. 2.

### 4 Determination of the temperature

The connection between the measured $\xi$ and the temperature $T(\xi)$ involves the Schwinger mechanism (SM) for particle production. The Schwinger distribution for massless particles is expressed in terms of $P^2_f$ [24, 25]

$$\frac{dn}{dp^2_f} \sim e^{-\pi p^2_f/x^2}$$  \hspace{1cm} (7)

where the average value of the string tension is $\langle x^2 \rangle$. The tension of the macroscopic cluster fluctuates around its mean value because the chromo-electric field is not constant.

The origin of the string fluctuation is related to the stochastic picture of the QCD vacuum. Since the average value of the color field strength must vanish, it can not be constant but changes randomly from point to point [26]. Such fluctuations lead to a Gaussian distribution of the string tension for the cluster, which transforms SM into the thermal distribution [26]

$$\frac{dn}{dp^2_f} \sim e^{-(p^2_f \sqrt{2\beta})}$$  \hspace{1cm} (8)

with $\langle x^2 \rangle = \pi (p^2_f)_1 / F(\xi)$.

The temperature is expressed as [27]

$$T(\xi) = \sqrt{\frac{(p^2_f)_1}{2F(\xi)}}$$  \hspace{1cm} (9)

Recently, it has been suggested that fast thermalization in heavy ion collisions can occur through the existence of an event horizon caused by a rapid de-acceleration of the colliding nuclei [28]. The thermalization in this case is due to the Hawking–Unruh effect [29, 30]. In CSPM the strong color field inside the large cluster produces de-acceleration of the primary $q\bar{q}$ pair which can be seen as a thermal temperature by means of the Hawking–Unruh effect. The string percolation density parameter $\xi$ which characterizes the percolation clusters measures the initial temperature of the system.

Since this cluster covers most of the interaction area, this temperature becomes a global temperature determined by the string density. In this way at $\xi_c = 1.2$ the connectivity percolation transition at $T(\xi_c)$ models the thermal deconfinement transition.

We adopt the point of view that the experimentally determined universal chemical freeze-out temperature ($T_f$) is a good measure of the phase transition temperature, $T_c$ [31]. $(p^2_f)_1$ is evaluated using Eq. (9) at $\xi = 1.2$ with $T_f = 167.7 \pm 2.6$ MeV [32]. This gives $\sqrt{(p^2_f)_1} = 207.2 \pm 3.3$ MeV which is close to $\sim 200$ MeV used in a previous calculation of the percolation transition temperature [27]. This calibrates the CSPM temperature scale. The dynamics of massless particle production has been studied in QED2 quantum electrodynamics. QED2 can be scaled from electrodynamics to quantum chromodynamics using the ratio of the coupling constants. Here the production time for a boson (gluon) is $t_{pro} = \frac{m_c^2}{\Delta N}$ [25]. This gives $t_{pro} \sim 1.13$ fm for central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The temperature obtained using Eq. (9) was $\sim 193.6$ MeV for Au + Au collisions. For Pb + Pb collisions the temperature is $\sim 262.2$ MeV for 0–5 % centrality, which is expected to be $\sim 35$ % higher than the temperature from Au + Au collisions [21]. A recent summary of the results from Pb + Pb collisions at the LHC has mentioned that the initial temperature increases at least by 30 % as compared to the top RHIC energy [33]. Table 1 gives the CSPM values $\xi$, $T$, $\epsilon$ and $\eta/s$ at $T/T_c = 0.88, 1, 1.16$ and 1.57.

One way to verify the validity of extrapolation from RHIC to LHC energy is to compare the energy density expressed as $\epsilon / T^4$ with the available lattice QCD results. Figure 3 shows a plot of $\epsilon / T^4$ as a function of $T/T_c$. The latt-
CSPM results are available for lattice agreement with the lattice QCD results. The lattice and observed that at LHC energy the CSPM results are in excellent agreement with the lattice QCD results. The lattice and CSPM results are available for $T/T_c < 2$.

5 Shear viscosity

The relativistic kinetic theory relation for the shear viscosity over entropy density ratio, $\eta/s$ is given by [9, 35]

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

(10)

where $T$ is the temperature and $\lambda_{mfp}$ is the mean free path given by

$$\lambda_{mfp} \sim \frac{1}{n \sigma_r}$$

(11)

$n$ is the number density of an ideal gas of quarks and gluons and $\sigma_r$ the transport cross section for these constituents.

After the cluster is formed it behaves like a free gas of constituents. Equation (10) can be applied to obtain the shear viscosity. In CSPM the number density is given by the effective number of sources per unit volume

$$n = \frac{N_{\text{sources}}}{SN_L}$$

(12)

$L$ is the longitudinal extension of the source, $L = 1 \text{ fm}$ [27]. The area occupied by the strings is related to $\xi$ through the relation $(1 - e^{-\xi})S_N$. Thus the effective no. of sources is given by the total area occupied by the strings divided by the effective area of the string $S_1 F(\xi)$.

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

(13)

In general $N_{\text{sources}}$ is smaller than the number of single strings. $N_{\text{sources}}$ equals the number of strings $N_s$ in the limit of $\xi = 0$. The number density of sources from Eqs. (12) and (13) becomes

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

(14)

In CSPM the transport cross section $\sigma_r$ is the transverse area of the effective string $S_1 F(\xi)$. Thus $\sigma_r$ is directly proportional to $F(\xi)$ and hence to $\frac{1}{T}$. The mean free path is given by

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

(15)

For a large value of $\xi$ the $\lambda_{mfp}$ reaches a constant value. $\eta/s$ is obtained from $\xi$ and the temperature

$$\frac{\eta}{s} = \frac{T L}{5(1 - e^{-\xi})}$$

(16)

Well below $\xi_c$, as the temperature increases, the string density increases and the area is filled rapidly and $\lambda_{mfp}$ and $\eta/s$ decrease sharply. Above $\xi_c$, more than $2/3$ of the area are already covered by strings, and therefore the area is not filling as fast and the relatively small decrease of $\lambda_{mfp}$ is compensated by the rising of temperature, resulting in a smooth increase of $\eta/s$. The behavior of $\eta/s$ is dominated by the fractional area covered by strings. This is not surprising because $\eta/s$ is the ability to transport momenta at large distances and that has to do with the density of voids in the matter.

6 Results and discussion

Figure 4 shows a plot of $\lambda_{mfp}$, $T$ and $\lambda_{mfp} \times T$ as a function of $\xi$. Thus the product $T(\xi) \times \lambda_{mfp}$ will have a minimum in $\eta/s$. It has been shown that $\eta/s$ has a minimum at the critical point for various substances for example helium, nitrogen and water [10]. Thus the measurement of $\eta/s$ as a function of temperature can indicate the critical point in the QCD phase diagram with $T \sim 175-185 \text{ MeV}$.

Figure 5 shows a plot of $\eta/s$ as a function of $T/T_c$. The estimated value of $\eta/s$ for Pb + Pb is also shown in Fig. 5 at $T/T_c = 1.57$. The lower bound shown in Fig. 5 is given by AdS/CFT [11]. These results from STAR and ALICE data show that the $\eta/s$ value is 2.5 and 3.3 times the KSS bound [11].

The theoretical estimates of $\eta/s$ has been obtained as a function of $T/T_c$ for both the weakly (wQGP) and strongly (sQGP) coupled QCD plasma are shown in Fig. 5 [9]. It is seen that at the RHIC top energy $\eta/s$ is close to the sQGP. Even at the LHC energy it follows the trend of the sQGP. By extrapolating the $\eta/s$ CSPM values to higher temperatures it is clear that $\eta/s$ could approach the weak coupling limit near $T/T_c \sim 5.8$. The CSPM $\eta/s$ value for the

| System     | $\xi$  | $T$ (MeV) | $\varepsilon$ (GeV/fm$^3$) | $\eta/s$ |
|------------|--------|-----------|-----------------------------|---------|
| Meson Gas  | 0.22   | 150.0     | -                           | 0.76    |
| Hadron to QGP | 1.2   | 167.7 ± 2.6 | 0.94 ± 0.07                | 0.240 ± 0.012 |
| Au + Au    | 2.88 ± 0.09 | 193.6 ± 3.0 | 2.27 ± 0.16                 | 0.204 ± 0.020 |
| Pb + Pb    | 10.56 ± 1.05 | 262.2 ± 13.0 | 8.32 ± 0.83                 | 0.260 ± 0.026 |
hadron gas is in agreement with the calculated value using measured elastic cross sections for a gas of pions and kaons [37]. \( \eta/s \) has also been obtained in several other calculations for pure glue matter [38], in the semi quark gluon plasma [39] and in quasiparticle description [40]. In pure SU(3) gluodynamics a conservative upper bound for \( \eta/s \) was obtained \( \eta/s = 0.134(33) \) at \( T = 1.65T_c \) [41]. In the quasiparticle approach also low \( \eta/s \sim 0.2 \) is obtained for \( T > 1.05T_c \) and rises very slowly with the increase in temperature [42]. In CSPM also \( \eta/s \) grows with temperature as \( 0.16T/T_c \).

The CSPM model calculations have also successfully described the elliptic flow and the nuclear modification factor at RHIC and LHC energies [43]. In addition CSPM has determined the equation of state of the QGP and the bulk thermodynamic value of \( \varepsilon/T^4 \) and \( s/T^3 \) in excellent agreement with Lattice Gauge calculations [21]. This emphasizes the quantitative nature of the CSPM when applied to the data at \( \sim 1 \) TeV scale.

### 7 Summary

In summary the relativistic kinetic theory relation for shear viscosity to entropy density ratio \( \eta/s = \frac{1}{5} T \lambda_{\text{mfp}} \) was evaluated as a function of the temperature using the measured transverse momentum spectra and the Color String Percolation Model. The color suppression factor \( F(\xi) \) was extracted from the transverse momentum spectrum of charged hadrons. We found \( \eta/s = 0.204 \pm 0.020 \) at \( T/T_c = 1.15 \) (RHIC) and \( \eta/s = 0.260 \pm 0.020 \) at \( T/T_c = 1.57 \) (LHC). In the phase transition region \( \eta/s \) is 2–3 times the conjectured quantum limit for RHIC to LHC energies. The whole picture is consistent with the formation of a fluid with a low shear to viscosity ratio. The percolation framework provides us with a microscopic picture which predicts the early thermalization required for hydrodynamical calculations.

The minimum in \( \eta/s \) can be studied as a function of the beam energy at RHIC that could locate the critical point/crossover in the QCD phase diagram seen in substances like helium, nitrogen and water [6, 10]. The accurate determination of \( \eta/s \) is also important for the evaluation of another transport coefficient, the jet quenching parameter \( \hat{q} \) [44, 45].

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### References

1. I. Arsene et al. (BRAHAMS Collaboration), Nucl. Phys. A 757, 1 (2005)
2. B.B. Back et al. (PHOBOS Collaboration), Nucl. Phys. A 757, 28 (2005)
3. J. Adams et al. (STAR Collaboration), Nucl. Phys. A 757, 102 (2005)
4. K. Adcox et al. (PHENIX Collaboration), Nucl. Phys. A 757, 184 (2005)
5. D. Teaney, Phys. Rev. C 68, 034913 (2003)
6. T. Schafer, D. Teaney, Rep. Prog. Phys. 72, 126001 (2009)
7. R.A. Lacey et al., Phys. Rev. Lett. 98, 092301 (2007)
8. P. Romatschke, U. Romatschke, Phys. Rev. Lett. 99, 272301 (2007)
9. T. Hirano, M. Gyulassy, Nucl. Phys. A 769, 71 (2006)
10. L.P. Csernai, J.I. Kapusta, L.D. McLerran, Phys. Rev. Lett. 97, 152303 (2006)
11. P.K. Kovtun, D.T. Son, A.O. Starinets, Phys. Rev. Lett. 94, 111601 (2005)
12. A. Buchel, R.C. Myers, A. Sinha, J. High Energy Phys. 03, 084 (2009)
13. M.A. Braun, C. Pajares, Eur. Phys. J. C 16, 349 (2000)
14. M.A. Braun, F. del Moral, C. Pajares, Phys. Rev. C 65, 024907 (2002)
15. H. Satz, Rep. Prog. Phys. 63, 1511 (2000)
16. L. McLerran, R. Venugopalan, Phys. Rev. D 49, 2233 (1994)
17. L. McLerran, R. Venugopalan, Phys. Rev. D 49, 3352 (1994)
18. J. Dias de Deus, C. Pajares, Phys. Lett. B 695, 455 (2011)
19. B.K. Srivastava, R.P. Scharenberg, T. Tarnowsky (STAR Collaboration), Nukleonika 51, s109 (2006)
20. B.I. Abelev et al. (STAR Collaboration), Phys. Rev. C 79, 3409 (2009)
21. R.P. Scharenberg, B.K. Srivastava, A.S. Hirsch, Eur. Phys. J. C 71, 1510 (2011)
22. K. Aamodt et al. (ALICE Collaboration), Phys. Rev. Lett. 106, 032301 (2011)
23. J.D. Bjorken, Phys. Rev. D 27, 140 (1983)
24. J. Schwinger, Phys. Rev. 128, 2425 (1962)
25. C.Y. Wong, Introduction to High Energy Heavy Ion Collisions (1994), p. 289
26. A. Bialas, Phys. Lett. B 466, 301 (1999)
27. J. Dias de Deus, C. Pajares, Phys. Lett. B 642, 455 (2006)
28. D. Kharzeev, E. Levin, K. Tuchin, Phys. Rev. C 75, 044903 (2007)
29. S.W. Hawking, Commun. Math. Phys. 43, 199 (1975)
30. W.G. Unruh, Phys. Rev. D 14, 870 (1976)
31. P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B 596, 61 (2004)
32. F. Becattini, P. Castorina, A. Milov, H. Satz, Eur. Phys. J. C 66, 377 (2010)
33. B. Muller, J. Schukraft, W. Wyslouch, arXiv:1202.3233 [hep-exp]
34. A. Bazavov et al., Phys. Rev. D 80, 014504 (2009)
35. P. Danielewicz, M. Gyulassy, Phys. Rev. D 31, 53 (1985)
36. D. Teaney, in QGP4, ed. by R.C. Hwa, X.N. Wang (World Scientific, Singapore, 2010), p. 207
37. M. Prakash et al., Phys. Rep. 227, 321 (1993)
38. A.S. Khvorostukhin, V.D. Toneev, D.N. Voskresensky, Phys. Rev. C 83, 035204 (2011)
39. Y. Hidaka, R.D. Pisarski, Phys. Rev. D 81, 076002 (2010)
40. M. Bluhm, B. Kämpfer, K. Redlich, arXiv:1011.5634 [hep-ph]
41. H.B. Meyer, Phys. Rev. D 76, 101701(R) (2007)
42. A. Peshier, W. Cassing, Phys. Rev. Lett. 94, 172301 (2005)
43. I. Bautista, J. Dias de Deus, C. Pajares, arXiv:1102.3837 [hep-ph]
44. A. Majumder, B. Muller, X.-N. Wang, Phys. Rev. Lett. 99, 192301 (2007)
45. J. Casalderrey-Solana, X.-N. Wang, Phys. Rev. C 77, 024902 (2008)