

STAR Highlights

Hiroshi Masui for the STAR collaboration

Lawrence Berkeley National Laboratory, Nuclear Science Division, 1 Cyclotron Road, Berkeley, CA 94720

E-mail: HMasui@lbl.gov

Abstract. We report selected results from STAR collaboration at RHIC, focusing on jet-hadron and jet-like correlations, quarkonium suppression and collectivity, di-electron spectrum in both p + p and Au + Au, and higher moments of net-protons as well as azimuthal anisotropy from RHIC Beam Energy Scan program.

1. Introduction

The main goals at the STAR experiment for ultra-relativistic heavy ion collisions is to study the structure of QCD phase diagram. In order to achieve this question, the STAR experiment has two main programs in heavy ion collisions; study the medium properties and eventually identify the equation of state of partonic matter, and search for the QCD critical point through RHIC Beam Energy Scan (BES).

This article is organized as follows. In Section 2, recent results on jet-hadron and jet-like correlations are presented, which can be used to understand underlying mechanisms of jet-quenching and hadron productions at higher p_T . The suppression and collectivity for heavy flavors are discussed through the measurement of the transverse momentum p_T spectra, nuclear modification factor R_{AA} and azimuthal anisotropy v_2 in Section 3. In Section 4, the first STAR measurement of di-electron spectrum in both p + p and Au + Au are presented. Section 5 presents selected results from BES about higher moments of net-protons and second harmonic of azimuthal anisotropy v_2 for identified hadrons

2. Jet-hadron and jet-like correlations

Measurements of R_{AA} as well as di-hadron azimuthal correlations for high p_T inclusive charged hadrons have indicated large partonic energy loss in the medium at RHIC [1, 2]. Jet-hadron correlation with full jet reconstructions can provide direct access to the energy of partons in order to understand the underlying mechanisms how partons lose energy in the medium. Figure 1 (left) shows the away side ($\Delta\phi \sim \pi$) energy

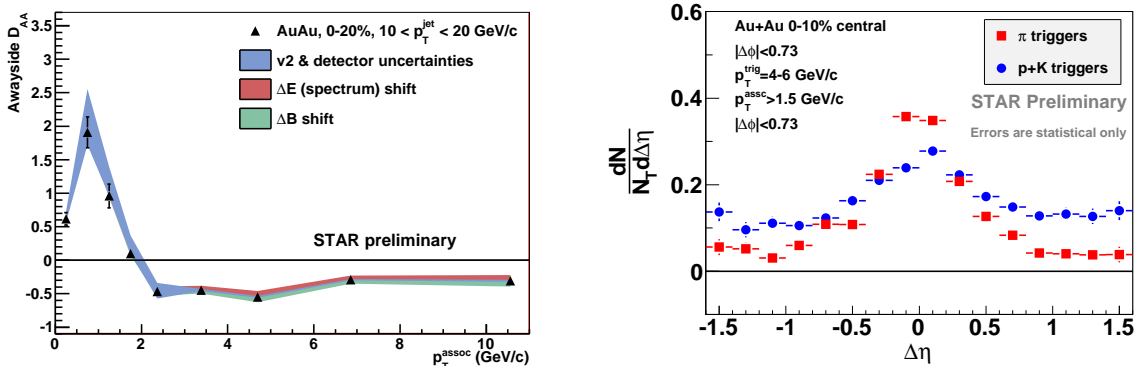


Figure 1. (Color online) (Right) Away side energy balance D_{AA} as a function of associated hadron p_T (p_T^{assoc}) in 0-20% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, where the bands represent systematic uncertainties arising from several different sources quoted in the figure. (Left) $\Delta\eta$ distributions for π (squares) and $p+K$ (circles) triggered hadron correlation in central 0-10% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Only statistical errors are shown.

balance D_{AA} as a function of associated hadron p_T^{assoc} in 0-20% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [3]. The D_{AA} is defined by

$$D_{AA}(p_T^{assoc}) = Y_{AA}(p_T^{assoc}) \cdot p_{T,AA}^{assoc} - Y_{pp}(p_T^{assoc}) \cdot p_{T,pp}^{assoc}, \quad (1)$$

where $Y(p_T^{assoc})$ denotes the away side jet yields. In central 0-20%, the away side jets are significantly enhanced at low p_T^{assoc} , and suppressed at high p_T^{assoc} . The integrated energy balance for the away side jets $\Delta B = 1.6_{-0.4}^{+1.6+0.5}$ GeV/c reveals a large part of high p_T^{assoc} suppression is balanced by low p_T^{assoc} enhancement. This result together with the observation of significant broadening of awayside jets in Au + Au compared to p + p seems to be consistent with the radiative energy loss picture.

The p/π ratio at intermediate p_T ($2 < p_T < 6$ GeV/c) have been qualitatively described by recombination models in the most central Au + Au collisions [2], which indicates that coalescence or recombination process would play an important role for hadron productions at intermediate p_T . More differential study by utilizing the di-hadron correlation with identified particles would provide further insights into the hadron production mechanisms at intermediate p_T . Figure 1 (right) shows the $\Delta\eta$ distributions for identified π and $p+K$ in $4 < p_T^{trig} < 6$ GeV/c associated with inclusive charged hadrons in $1.5 < p_T^{assoc} < p_T^{trig}$ GeV/c in the most central 0-10% Au + Au collisions [4], where η denotes the pseudorapidity. The π and $p+K$ are identified by their specific energy loss in the Time Projection Chamber (TPC). The shoulder structures in the large $\Delta\eta$ (ridge) is higher for $p+K$ trigger than that for π trigger. The near side peak is higher for π trigger compared to that for $p+K$ trigger, which is similar in both d + Au and Au + Au collisions. The similarity of near side peak in d + Au and Au + Au collisions pose a challenge to the naive recombination picture, where the dilution of near side peak with thermalized partons would be expected if the recombination is the dominant mechanism of hadron productions at intermediate p_T .

3. Heavy flavors

The suppression of J/ψ due to color screening of $c\bar{c}$ pairs is expected to be one of the unambiguous signature of QGP formation [5]. Measurements of nuclear modification factor R_{AA} for J/ψ in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions at RHIC show the similar suppression pattern as at SPS as a function of centrality [6], while the R_{AA} for high p_T ($p_T > 5$ GeV/c) J/ψ is consistent with no suppression in Cu + Cu collisions [7]. It has been reported that the suppression of Υ at RHIC could provide large sensitivity to color screening in the QGP because contributions from regeneration [8] and absorption by hadronic co-movers are negligible [9]. The quarkonium suppression would be one of the probes to study the properties of the QGP as well as to understand their production mechanisms.

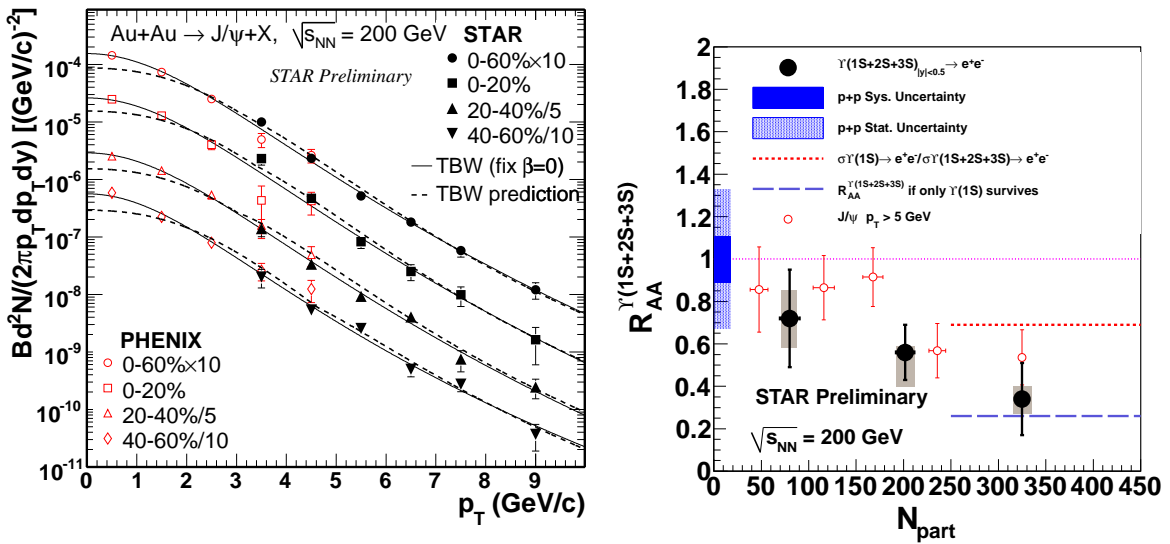


Figure 2. (Color online) (Right) Invariant yields of J/ψ as a function of p_T for several different centrality bins shown by solid symbols in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Open symbols are published PHENIX results for comparison [6]. Lines are calculations from Tsallis-Blast-Wave model [10]. (Left) $\Upsilon(1S+2S+3S)$ R_{AA} as a function of N_{part} compared to the J/ψ R_{AA} for $p_T > 5$ GeV/c in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The shaded bands at $N_{part} = 0$ represent statistical and systematic uncertainties in p + p measurements.

Figure 2 (left) shows the invariant yields of J/ψ as a function of p_T in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for several different centrality bins. High statistics data in year 2010 allows us to extend the p_T reach of J/ψ spectra out to 10 GeV/c [11]. Figure 2 (right) shows the R_{AA} for high p_T J/ψ ($p_T > 5$ GeV/c) and $\Upsilon(1S+2S+3S)$ as a function of number of participants N_{part} in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The high p_T J/ψ shows suppression in central collisions, while the magnitude of R_{AA} is higher in higher p_T compared to the measurements at low p_T from [6]. The $\Upsilon(1S+2S+3S)$ R_{AA} shows similar suppression pattern as high p_T J/ψ . The R_{AA} in the most central 0-10% indicates the suppression of Υ , which is more than 3 σ away from unity, with systematic

uncertainties in p + p [12].

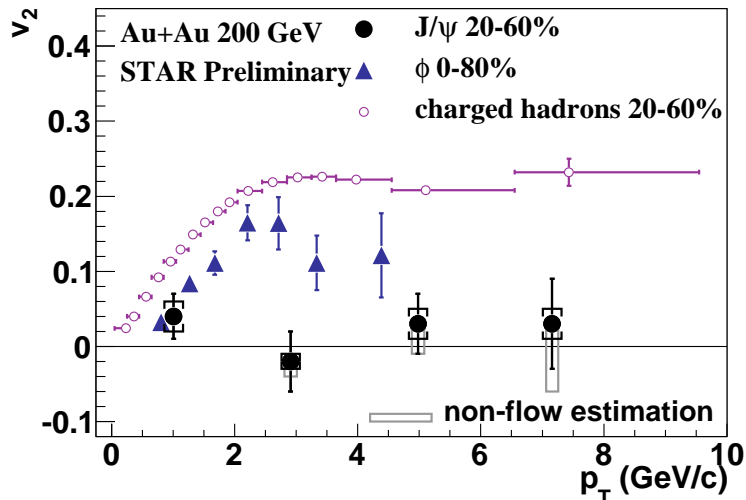


Figure 3. (Color online) J/ψ v_2 (solid circles) as a function of p_T in mid-central 20-60% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, where open boxes show systematic uncertainties from non-flow effects, and brackets show those from other sources. Open circles show result of inclusive charged hadrons in 20-60% [13] and solid triangles are the ϕ meson v_2 in 0-80% [14] for comparison.

It has been reported at RHIC that azimuthal anisotropy v_2 have shown universal scaling among light flavor mesons and baryons in intermediate p_T range suggested by parton coalescence and recombination models [14, 15, 16, 17]. The results are strong indication of partonic degrees of freedom in the early stage of heavy ion collisions. Measurements of charm quark collectivity could play a potential role to answer the thermalization of light flavors as well as to shed more lights on the production mechanisms of charm quarks in the medium. Figure 3 shows new measurements of J/ψ v_2 as a function of p_T in 20-60% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, up to $p_T = 8$ GeV/c [11]. Systematic errors from non-flow effects are evaluated with measurements of preliminary J/ψ -hadron correlation in p + p collisions by assuming that the non-flow effects are the same in p + p and Au + Au collisions. The J/ψ v_2 appears to be consistent with 0 within systematic uncertainties for $p_T > 2$ GeV/c, which seems to disfavor the coalescence scenario to form J/ψ with thermalized charm quarks.

4. Electromagnetic probes

Di-lepton productions are of particular interest among the observables to explore the early stage of heavy ion collisions. They directly probe the evolution of the medium and unaffected by final-state interactions in contrast to hadrons.

Figure 4 presents the recent measurements of STAR di-electron mass spectrum in both p + p (left) and Au + Au (right) collisions at $\sqrt{s_{NN}} = 200$ GeV after combinatorial

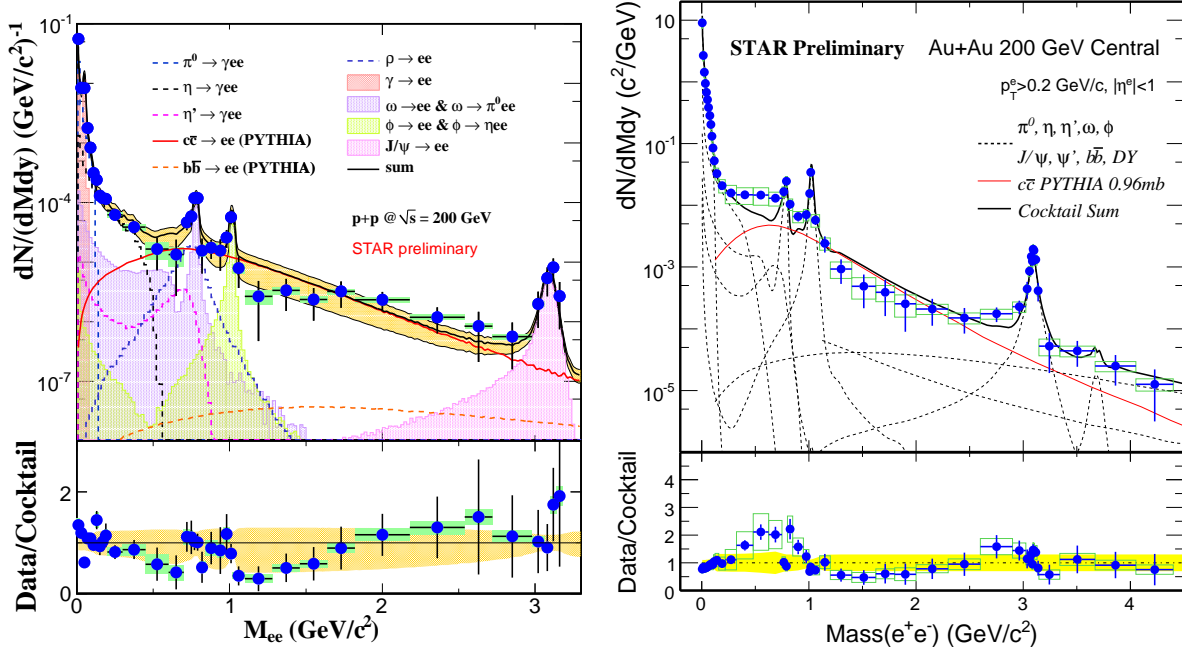


Figure 4. (Color online) Di-electron mass spectrum in $p + p$ collisions at $\sqrt{s} = 200$ GeV (left) and in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV (right) after combinatorial background subtraction. Solid circles show the data, the bars denote the statistical uncertainties and boxes around data points show systematic uncertainties. The dashed lines represent the individual hadronic source used in the cocktail simulations. Bottom panels show the ratio of data to cocktail simulation, where shaded bands around unity and the boxes around data points show the systematic uncertainties on cocktail and data, respectively.

background subtraction [18]. The result in $p + p$ collisions is consistent with the known hadronic sources by cocktail simulation within systematic uncertainties, which provides the baseline for the measurements in $Au + Au$ collisions. The result in central 0-5% $Au + Au$ collisions is also compared to the hadronic cocktail simulation as shown in the right panel. The data in $M(e^+e^-) < 1$ GeV/c^2 appears to be enhanced by a factor of $1.72 \pm 0.10(\text{stat}) \pm 0.50(\text{sys})$ compared to the cocktail simulation without ρ^0 contribution in the cocktail. Further study will be done to study the possible modification of ρ^0 in the low mass region and charm contributions in the intermediate mass region.

5. Beam Energy Scan

The goal of RHIC Beam Energy Scan is to search for the QCD critical point, onset of signature of QGP, and softening of equation of state. It has been started since year 2010, and STAR experiment collected the data at $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV in 2010, and 19.6 GeV in 2011.

Higher moments of fluctuations for conserved quantities, such as net-baryons, net-charge and so on, are expected to be more sensitive to the correlation length of the system, and thus to be a powerful tool to search for the critical point [19, 20]. Figure 5

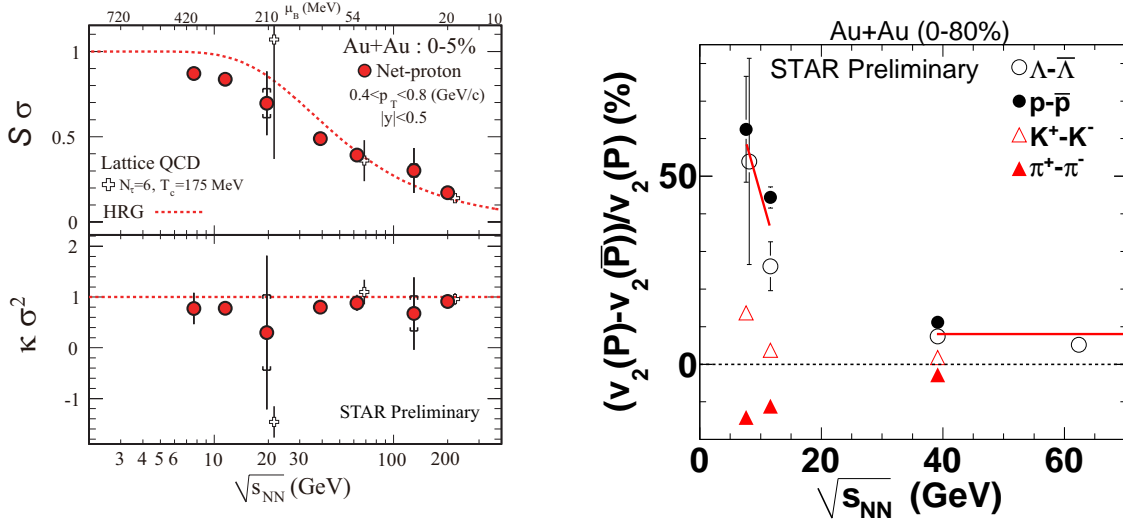


Figure 5. (Color online) (Left) Product of higher moments $S\sigma$ (top) and $\kappa\sigma^2$ (bottom) for net-protons as a function of $\sqrt{s_{NN}}$ in the most central Au + Au collisions. Dashed lines show the calculations from Hadron Resonance Gas model [22] and open crosses show the Lattice QCD calculations [23]. (Right) Difference of v_2 between particles and anti-particles normalized by particle v_2 as a function of $\sqrt{s_{NN}}$ in 0-80% Au + Au collisions for Λ (open circles), p (solid circles), K (open triangles) and π (solid triangles). The data points for Λ at $\sqrt{s_{NN}} = 62.4$ GeV are taken from [25]. Solid lines just guide eyes.

(left) shows the excitation function of the product of net-proton higher moments $S\sigma$ and $\kappa\sigma^2$ in the most central Au + Au collisions, where σ^2 , S and κ denote the variance, skewness and kurtosis, respectively [21]. The calculations from Hadron Resonance Gas (HRG) [22] model as well as Lattice QCD [23] are also shown for comparison. The data at $\sqrt{s_{NN}} = 62.4$ -200 GeV are consistent with both HRG and Lattice QCD results, while the results at $\sqrt{s_{NN}} = 7.7$ -39 GeV show deviation from the HRG model. The data at $\sqrt{s_{NN}} = 19.6$ GeV show the largest deviation with huge statistical uncertainty, which will be improved by using the new 19.6 GeV data with much higher statistics.

As discussed earlier, the number of quark scaling of v_2 could be the strong indication of partonic degrees of freedom at $\sqrt{s_{NN}} = 200$ GeV. The observed scaling can be used as a turn-off signature if the hadronic stage becomes dominant in lower energies at BES. Figure 5 (right) shows the excitation function of the difference of v_2 between particles and anti-particles normalized by particle v_2 in 0-80% Au + Au collisions at $\sqrt{s_{NN}} = 7.7$ -62.4 GeV [24]. The results at 62.4 GeV has shown about 5% difference of v_2 between Λ and $\bar{\Lambda}$ [25]. At $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV, the difference of v_2 is significantly larger $\sim 50\%$ for baryons than those at higher energies. The observed difference is similar for p and Λ . There are 5-10% difference on meson v_2 as well at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV.

6. Summary

We report recent results from STAR experiment at RHIC. The away side jets from jet-hadron correlation in Au + Au collisions show significant modifications as compared to that in p + p collisions. The results seem to be consistent with the radiative energy loss picture. The near side peak obtained by di-hadron correlation with identified π trigger is higher than that for $p + K$ trigger, which is similar in both d + Au and Au + Au collisions. This result appears to disfavor the expectations from naive coalescence of thermal partons. The high p_T J/ψ shows stronger suppression in more central collisions, while the magnitude of suppression is less compared to the results in lower p_T . The suppression of Υ is observed at 3σ level including p + p uncertainties at most central 0-10% collisions. The J/ψ v_2 appears to be consistent with 0 in $2 < p_T < 8$ GeV/c, which disfavors the scenario of naive coalescence for thermal charm quarks. The STAR new measurement of di-electron mass spectrum in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV is presented compared to that in p + p collisions. The result in p + p collisions is consistent with hadronic cocktail simulation, which provides the baseline for the measurements in Au + Au collisions. The enhancement of di-electron spectrum is observed below $M(e^+e^-) < 1$ GeV/c² in Au + Au collisions. Further investigation will be carried out to understand the possible modification of vector mesons as well as charm contributions. Excitation function of higher moments of net-protons are reported. The results are in good agreement with HRG model at higher energies, while they seem to deviate from the HRG model in $\sqrt{s_{NN}} = 7.7$ -39 GeV. Significant difference between baryon and anti-baryon v_2 is observed for p and Λ in $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV. Further studies will be performed with 19.6 and 27 GeV data in order to search for the QCD critical point and the onset of QGP.

References

- [1] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **91**, 172302 (2003)
- [2] C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **90**, 082302 (2003)
- [3] A. Ohlson [STAR Collaboration], these proceedings
- [4] K. Kauder [STAR Collaboration], these proceedings
- [5] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
- [6] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **98**, 232301 (2007)
- [7] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **80**, 041902 (2009)
- [8] L. Grandchamp, S. Lumpkins, D. Sun, H. van Hees and R. Rapp, Phys. Rev. C **73**, 064906 (2006)
- [9] Z. w. Lin and C. M. Ko, Phys. Lett. B **503**, 104 (2001)
- [10] Z. Tang *et al.*, arXiv:1101.1912 [nucl-ex].
- [11] Z. Tang [STAR Collaboration], these proceedings
- [12] R. Reed [STAR Collaboration], these proceedings
- [13] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **93**, 252301 (2004)
- [14] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **99**, 112301 (2007)
- [15] D. Molnar and S. A. Voloshin, Phys. Rev. Lett. **91**, 092301 (2003)
- [16] V. Greco, C. M. Ko and P. Levai, Phys. Rev. C **68**, 034904 (2003)
- [17] R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. C **68**, 044902 (2003)
- [18] J. Zhao [STAR Collaboration], these proceedings

- [19] M. A. Stephanov, Phys. Rev. Lett. **102**, 032301 (2009)
- [20] M. M. Aggarwal *et al.* [STAR Collaboration], Phys. Rev. Lett. **105**, 022302 (2010)
- [21] T. Tarnowsky [STAR Collaboration], these proceedings
- [22] F. Karsch and K. Redlich, Phys. Lett. B **695**, 136 (2011)
- [23] S. Gupta, X. Luo, B. Mohanty, H. G. Ritter and N. Xu, Science **332**, 1525 (2011)
- [24] A. Schmah [STAR Collaboration], these proceedings
- [25] B. I. Abelev *et al.* [the STAR Collaboration], Phys. Rev. C **75**, 054906 (2007)