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Heavy Ion results from RHIC-BNL

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Abstract. Recent results from heavy ion collision experiments from RHIC at BNL are presented and discussed in terms of Quark Gluon Plasm properties, such as partonic collectivity and partonic energy loss. The experimental results with direct photons and heavy quarks have given important additional insights of the plasma on top of what has been known with light hadrons. Higher order event anisotropies and the related results have provided the geometrical, temporal and dynamical information of the plasma. The beam energy dependence of the various measurements could reveal the structure of QCD phase diagram and possibly the critical point in the diagram, where the properties of phase transition are expected to change drastically.

1 Introduction

Quark Gluon Plasma (QGP), which is supposed to exist in early universe or inside neutron stars, is currently being studied with high energy nucleus-nucleus collisions at $\sqrt{s_{NN}} = 200\ AGeV$ in Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and at 2.76 $ATeV$ in Large Hadron Collider (LHC) at European Organization for Nuclear Study (CERN). A large elliptic event anisotropy and its quark number scaling as well as a large partonic energy loss of high p_T hadrons and jets have been observed at RHIC energies and they are considered as possible indications of QGP. The properties of QGP at higher temperature region in QCD phase diagram are further investigated at the highest energy in the world at LHC, while the beam energy scan program is also in progress at RHIC in order to find a signature from the critical point, which is expected at higher density in the phase diagram.

The recent results from RHIC (STAR and PHENIX experiments) with direct photons and heavy quarks are discussed in Sect.2, the higher order event anisotropies and their related topics are discussed in Sect.3 and some selected results from beam energy scan program are discussed in Sect.4.

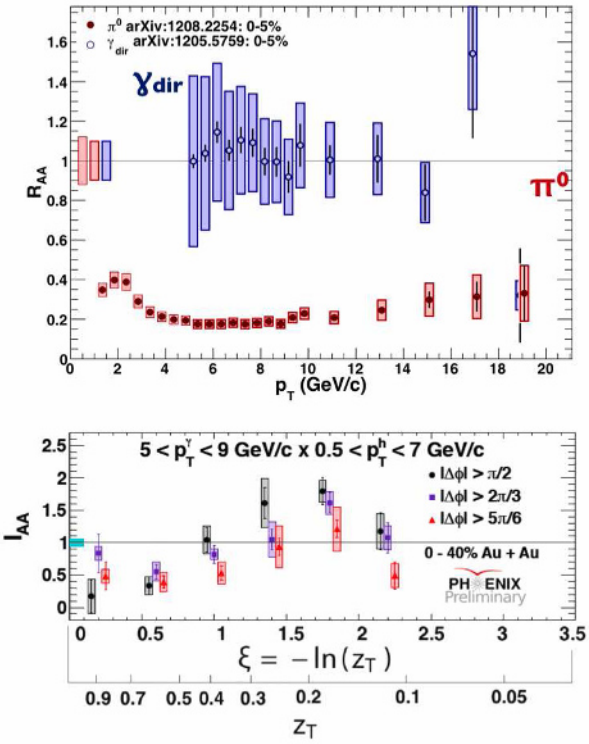

Figure 1. Top: π^0 and direct γ nuclear modification factor R_{AA} as a function of transverse momentum p_T in central Au+Au collisions at $\sqrt{s_{NN}} = 200\ AGeV$ [1, 2]. Bottom: Ratio I_{AA} Au+Au over p+p, for associate hadron yield per trigger direct γ as a function of z_T, which is defined as hadron p_T relative to the trigger direct γ p_T [3].

2 Plasma properties probed by direct photons and heavy quarks

Jet quenching and large elliptic flow of hadrons are the two major discoveries as signatures of QGP at RHIC experiments, several controlled measurements have provided further insights of the discoveries using the penetrating probes like direct photons and leptons as well as with

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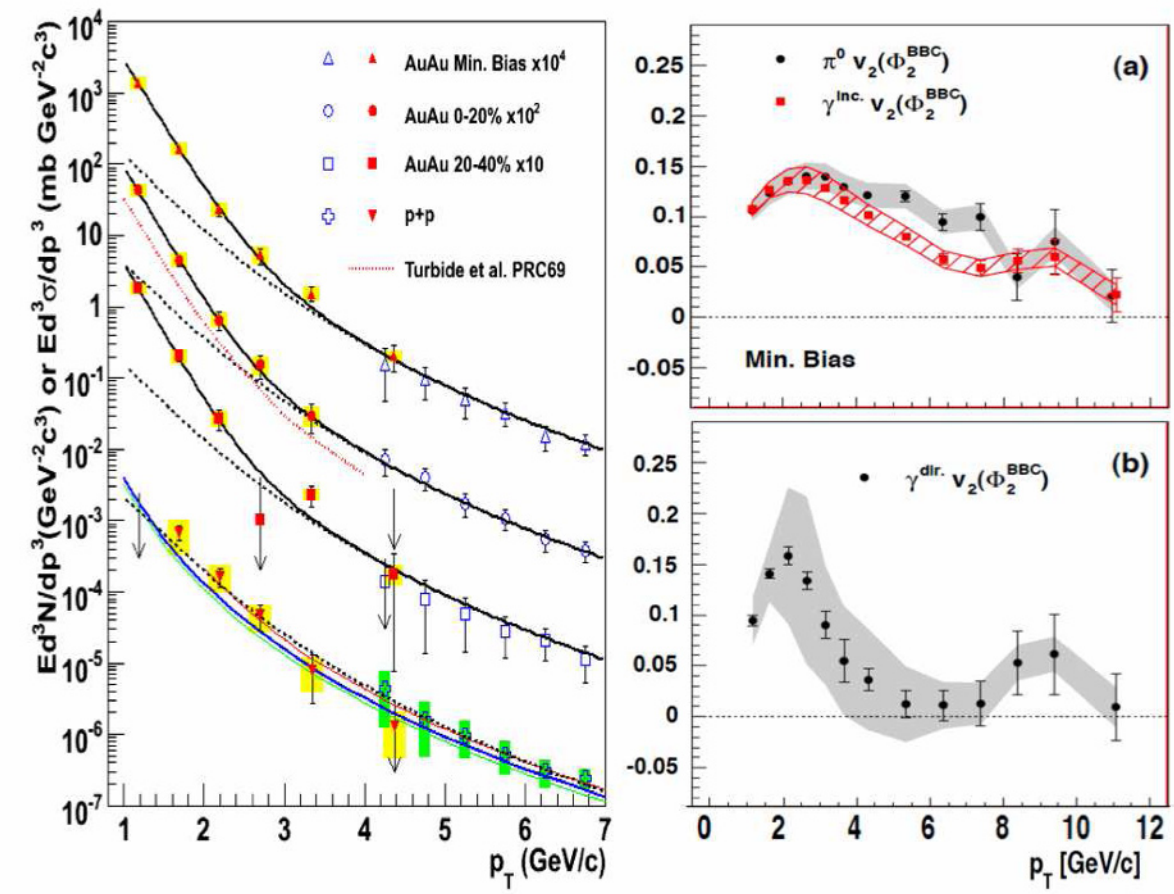

Figure 2. Left: Direct γ p_T spectra at p+p and Au+Au at 200 GeV [4]. Right-top: π^0 and inclusive γ v_2 and Right-bottom: direct γ elliptic event anisotropy parameter v_2 as a function of p_T in minimum bias Au+Au collisions [5].

d+Au collisions to disentangle the possible additional effect from the cold nuclear matter. Striking difference between strong suppression of π^0 and no suppression of direct γ are shown in the top panel of Fig.1, which are attributed to the large energy loss of parton inside QGP and the penetration of high p_T direct prompt γ from the initial hard scattering. The high p_T direct γ is used as trigger particle to study the correlated hadron distribution in opposite azimuthal angle region with respect to the triggered direct γ, where the penetration property of direct γ provides a measure of initial energy of recoil jet, which is observed as the correlated final hadrons, therefore this gives us the modification of the fragmentation function of jet inside the QGP. The presented I_{AA} data in the bottom panel of Fig.1 show a suppression of fragmentation function at high p_T and an enhancement at low p_T especially at wide angle, which tells us the partonic energy loss and re-distribution of lost energy.

On the other hand at low p_T region, direct thermal γ from the hot and dense matter have been clearly observed to be enhanced in heavy ion collision above the QCD prompt γ expected from the measured p+p data as shown in left panel of Fig.2. The measured temperature of thermal γ is slightly above the expected phase transition temperature, however the extracted initial temperature from this measurement can be much higher according to the extrapolation by hydro-dynamic calculation. The difference of elliptic event anisotropy parameters v_2 between π^0 and inclusive γ, shown in the right-top panel of Fig.2, as well as the relative direct γ yield over total inclusive γ, have been used to extract the elliptic event anisotropy v_2 of direct γ as shown in the right-bottom panel of Fig.2. The high p_T direct γ v_2 is small as expected from the penetration property ($R_{AA} \sim 1$) of direct prompt γ at high p_T, however v_2 of direct thermal γ at low p_T has been found to be comparable to the hadron v_2. This would tell us the thermal photons are dominated from the later stage of collision, after the elliptic expansion has already been developed, surprisingly without any significant contribution from the early stage.

R_{AA} and v_2 of single electron from heavy quarks are shown in left panel of Fig.3. These data indicate that heavy quarks, which are dominated by charm quarks at low p_T and bottom quarks at high p_T, have similar partonic energy loss and similar elliptic expansion comparable to the other light quarks such as up, down and strangeness quarks in spite of the quite large mass difference. This has been confirmed by the suppression of directly reconstructed D-meson as shown in right-top panel of Fig.3. Because of these observations of energy loss and collective flow of

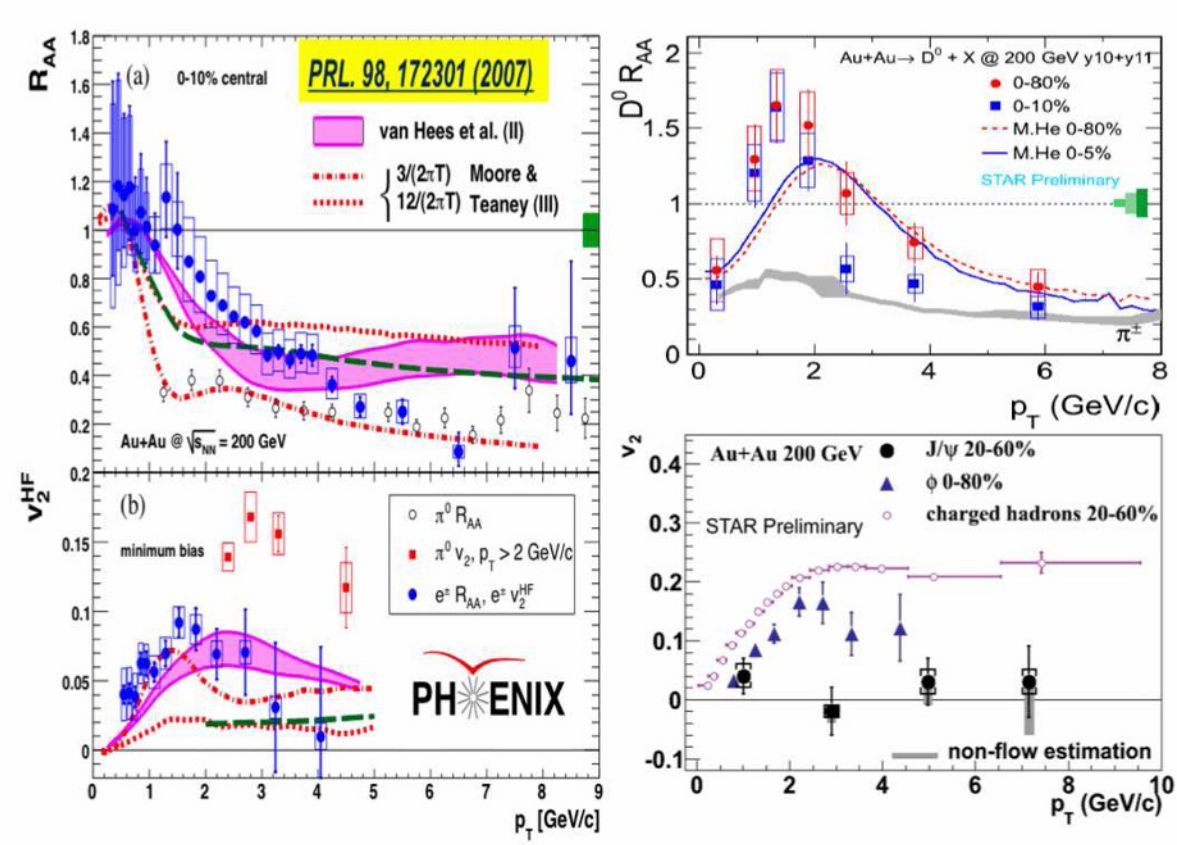

Figure 3. Left: R_{AA} and v_2 of single electron from heavy quarks as a function of p_T at 200 GeV Au+Au collisions [6] Right-top: D-meson R_{AA} and Right-bottom: J/ψ v_2 as a function of p_T at 200 GeV Au+Au collisions [7]

heavy quarks, the strongly interacting sQGP is considered as the property of the hot and dense matter created at RHIC energy. However, since the J/ψ v_2 is found to be much smaller than the light hadrons and open-charms, the recombination scenario for J/ψ production is disfavored at RHIC energies, which could be different with enhanced charm production at LHC energies.

3 Higher order event anisotropy and related topics

The higher order event anisotropy is supposed to be originated from the initial geometrical shape of the participants region, where the initial overlapped region is mainly dominated as elliptic shape in an non-central heavy ion collision, while the higher harmonic order anisotropies also arise in a central collision, because of statistical fluctuation of initial participant positions followed by hydro-dynamic expansion of the system. Simultaneous description of different order event anisotropies have been found to give a good constraint on determining the hydro-dynamic properties like share viscosity over entropy ratio such as η/S as well as initial conditions like the shape of initial energy density distribution. The measured higher order event anisotropy parameters $v_2\{\Psi_2\}$, $v_3\{\Psi_3\}$, $v_4\{\Psi_4\}$ and $v_4\{\Psi_2\}$ are shown for three different particle species $\pi^{+/-}$, $K^{+/-}$, p and $\bar{p}$ in Fig.4 at 200 GeV Au+Au collisions. When

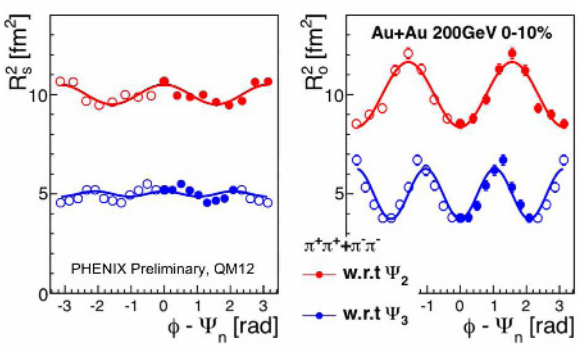

Figure 5. Extracted sideward size (left: perpendicular to the pair direction) and outward size (right: parallel to the pair direction) in transverse radius of QGP at freeze-out from two-particle interferometry measurement as a function of azimuthal angle of the pair with respect to the elliptic event plane Ψ_2 and the triangular event plane Ψ_3. The average radii are fixed at 10 fm^2 and 5 fm^2, respectively [3].

the quark number scaled v_n are shown as a function of the quark number scaled transverse kinetic energy, the v_n differences in hadron mass and the number of constituent quarks as a function of p_T are found to be scaled and minimized for each harmonic order as seen in the Fig.4,

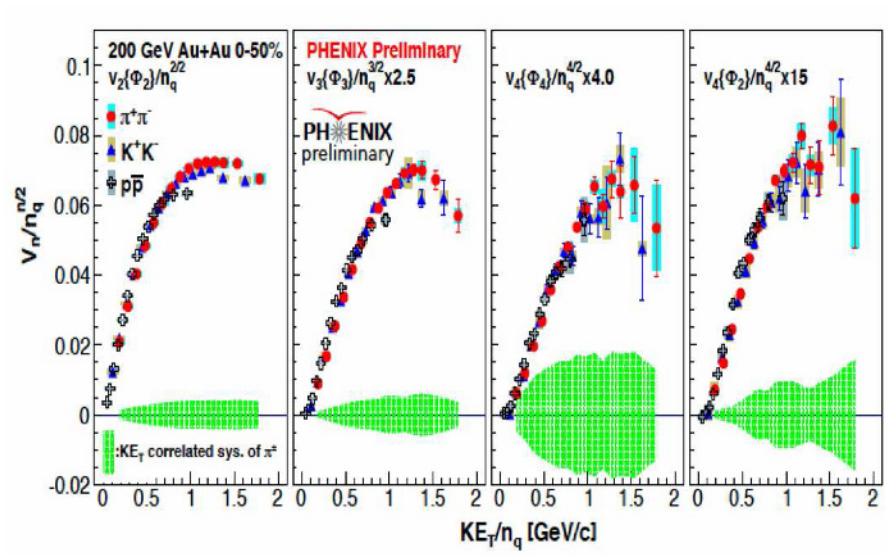

Figure 4. Number of quark scaled higher order event anisotropy parameters $v_n\{\Psi_m\}$ as a function of number of quark scaled transverse kinetic energy. From left to right: $v_2\{\Psi_2\}$, $v_3\{\Psi_3\}$, $v_4\{\Psi_4\}$ and $v_4\{\Psi_2\}$ [3]

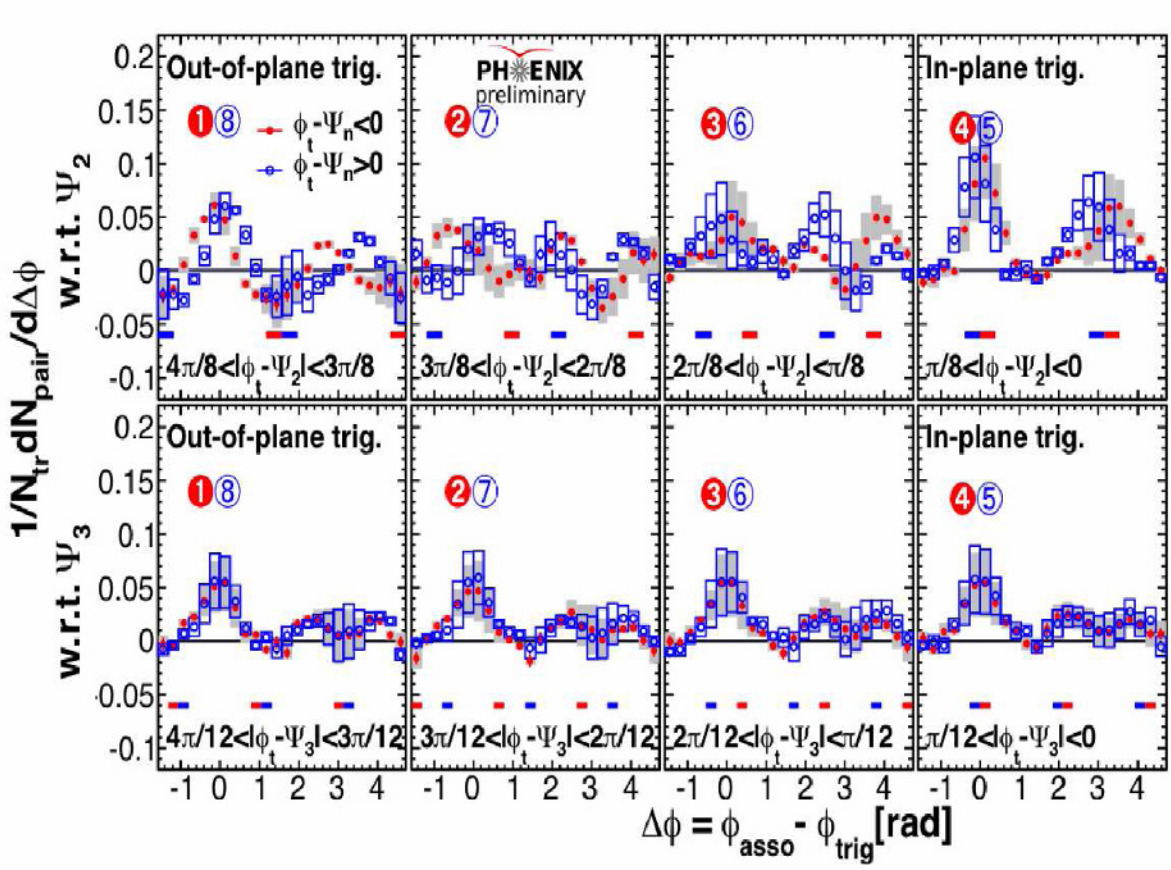

Figure 6. Two-particle correlation functions normalized as associate particle yield distribution per trigger particle as a function of relative azimuthal angle between associate and trigger particles, where the azimuthal angle of trigger particle are selected into 8 different trigger classes from out-of-plane to in-plane with respect to the 2nd order event plane Ψ_2 for top panels and to the 3rd order event plane Ψ_3 for the bottom panels. The data are from 200 GeV Au+Au collisions at centrality of 40 $\sim$ 50 % with trigger and associate p_T selections of $p_T^{Trig} = 2 \sim 4\ GeV/c$ and $p_T^{Asso} = 1 \sim 2\ GeV/c$. The red points (trigger classes 1 $\sim$ 4) are for left side trigger relative to the event plane and the blue points (trigger classes 5 $\sim$ 8) are for right side trigger selections. The small horizontal tick marks indicate the Ψ_2 or Ψ_3 directions in each panels [3].

which could be taken as an indication that the higher order harmonic collectivity is already formed during the pre-hadronic quark phase at top RHIC energy.

The higher order event anisotropy signals v_n define the higher order event planes direction Ψ_n for each harmonic order, the higher order event plane angles Ψ_n have been utilized to measure the geometrical event shape of QGP at the end of freeze-out stage via two-particle quantum interferometry method called as HBT. The measured two transverse sizes as a function of the azimuthal pair angle with respect to the higher order event planes Ψ_2 and Ψ_3 are shown in Fig.5 for both sideward and outward directions as explained in the figure caption. The phase and magnitude of the measured of oscillation would tell us the orientation and the eccentricity for the 2nd order (the triangularity for the 3rd order) of the geometrical shape with respect to the defined event planes. The measured orientation indicates that the major axis of elliptic event shape is still perpendicular to the reaction plane, even after the strong elliptic expansion in the minor axis from the pressure gradient of initial elliptic density distribution. The similar effects can been seen for the 3rd order plane Ψ_3 dependence. It is also remarkable to observe that the outward radii, which are considered to include the both depth and temporal spread of the freeze-out region, show larger amplitude of oscillation than the sideward radii in central Au+Au collisions at 200 GeV.

The higher order event planes are also used to test the geometrical dependence of jet-medium interaction with two-particle jet-like azimuthal distribution. The two-particle distributions are separated by the azimuthal angle of trigger particle with respect to the higher order event plane angle Ψ_n, the distributions are corrected for the back ground expected from the single particle flow correlation with event planes and the back ground subtracted distributions are shown in Fig.6 for Ψ_2 dependences in the top panels and for Ψ_3 dependences in the bottom panels. The extracted trigger-associate correlations show rather strong Ψ_2 dependences and left-right asymmetry but weak Ψ_3 dependences. This indicates that there is strong interplay between the jet-medium interaction and elliptic event geometry and/or elliptic expansion.

4 Beam energy scan program and critical point

Significant high p_T suppression of hadron has been observed at Au+Au $\sqrt{s_{NN}}$ = 200 $AGeV$, which is taken as an indication of possible QGP signature as partonic energy loss, while the suppression has not been seen at SPS energy around 20 $AGeV$. Therefore the beam energy scan program has been carried out at RHIC in order to find the onset of suppression as well as any other possible indication of phase transition. The beam energy dependence of charged particle R_{CP} from 7.7 $AGeV$ up to 200 $AGeV$ as a function of p_T are presented in Fig.7. The R_{CP} extracted from central-peripheral ratio clearly shows a strong energy dependence, where the suppression pattern seen in the highest RHIC beam energy changes into the enhancement pattern at the low RHIC beam energy. The crossing point from suppression to enhancement is found be around 30 $AGeV$, where the QGP phase transition could have been occurred, although the transition seems to be gradually monotonic.

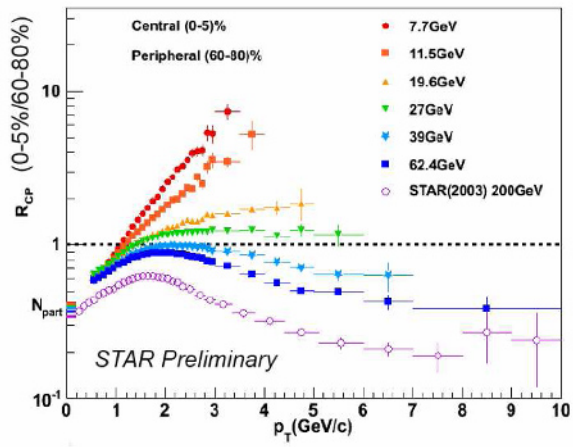

Figure 7. Beam energy dependence of nuclear modification factor R_{CP} measured via central-peripheral yield ratio for charged particles as a function of p_T [7]

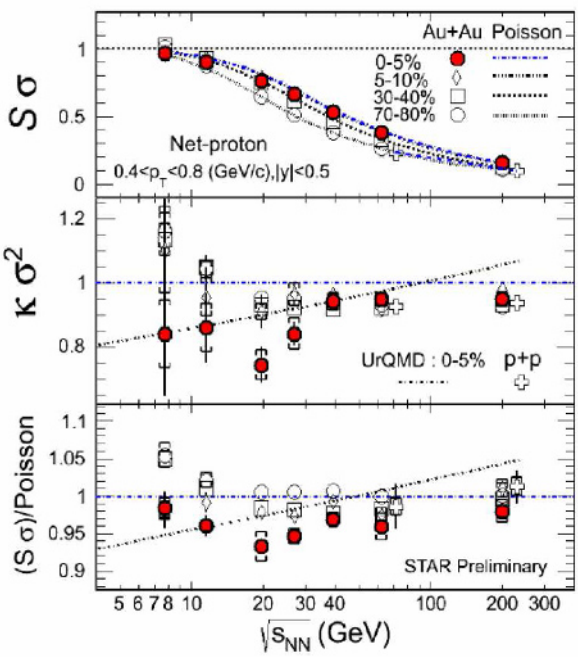

Figure 8. Beam energy dependence of products of higher moments (top: skewness times sigma, middle: kurtosis times sigma squared, bottom: normalized skewness times sigma relative to the Poisson expectation), where the higher moments are measured by multiplicity distribution of net-proton [7]

The critical point is expected on the QCD phase diagram along the phase boundary, which is somewhat away from the temperature axis into the high density region. However the exact location of the point is not well known,

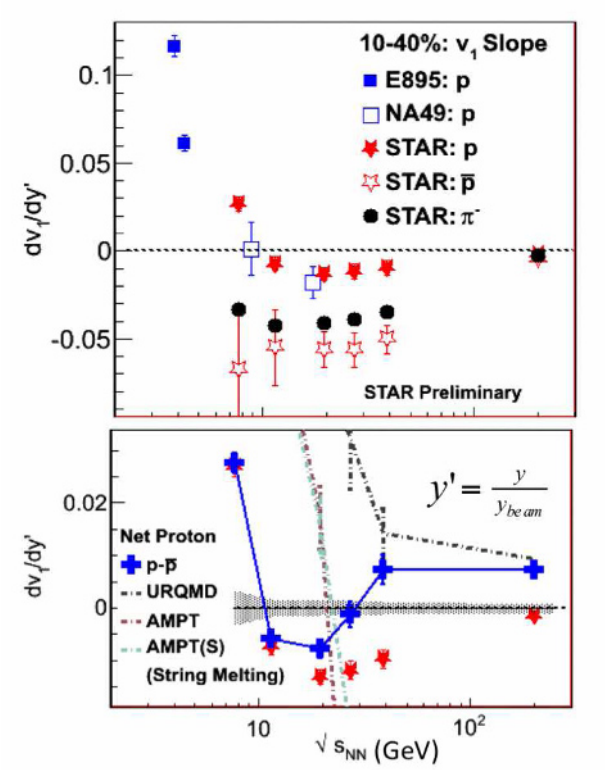

Figure 9. Beam energy dependence of v_1 slope with respect to the normalized rapidity for protons, anti-protons and π^- in the top panel and for p-pbar in the bottom panel [7]

this is also one of the reason of the RHIC beam energy scan program in order to find the existence and the location of the critical point on the phase diagram. The fluctuation of the conserved quantities is suggested as a signal from the critical point, because the correlation length would diverge so that the fluctuation could increase, if the system is very close to the critical point. The high density side of phase boundary beyond the critical point is also expected to be the 1st order (discrete) phase transition in stead of 2nd order (cross over) transition at the low density side close to the temperature axis. The net-proton multiplicity distribution as a measure of conserved net-baryon number is experimentally measured and the higher order moments of the multiplicity distribution are extracted, the products of 2nd (σ: sigma), 3rd (S: skewness) and 4th (κ: kurtosis) order moments are shown in Fig.8 as a function of beam energy, where the bottom panel is normalized by the expected signal from Poisson fluctuation. There might be some indication of possible non-monotonic behavior around 20 $\sim$ 30 GeV, however the signal is not yet significant enough to claim the signal from the critical point.

The directed event anisotropy v_1 of protons and anti-protons and their slopes with respect to normalized rapidity dv_1/dy' would reflect the ratio of system compression between transverse and longitudinal directions as well as the system response, therefore the beam energy dependence of the v_1 slope dv_1/dy' is expected to provide a sensitivity on the property of high density matter. The measured v_1 slopes dv_1/dy' from the RHIC beam energy scan are shown in the top panel of Fig.9 for proton, anti-proton and π^-. Since the energy dependence of baryon stopping and transport would play an important role in this measurement, the net-proton data are also shown in the bottom panel of Fig.9, where there could be an indication of non-monotonic behavior around 10 $\sim$ 30 GeV, which may be related with the critical point, while there could also be other possible scenarios to explain the observed dependence.

5 Summary and conclusion

Recent results about the property of hot and dense matter created in high energy heavy ion collisions from RHIC experiments are presented. The several indications of quark gluon plasma have been observed such as partonic collectivity and partonic energy loss especially with probes of direct photons and heavy quarks. Higher order anisotropy and related topics are also shown in order to discuss the geometrical, temporal and dynamical information of QGP. The RHIC beam energy scan program and several selected results are presented with some possible indications of phase transition close to the critical point near the phase boundary.

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