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Di-hadron and three-particle correlations at RHIC

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We present the results from 2- and 3-particle azimuthal angle ($\Delta\phi$) and pseudorapidity ($\Delta\eta$) correlation with high-transverse momentum (p_T) trigger particles in Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV at RHIC experiment. The dihadron correlations with subtraction of v_2, v_3, and v_4 backgrounds are presented. The near-side ($\Delta\phi\sim0$) ridge is separated from jet-like contributions by exploiting the charge ordering properties between associated and trigger particles in 3-particle $\Delta\eta$-$\Delta\eta$ correlations. The results indicate that the correlation of ridge particles are uniform not only with respect to the trigger particle but also between themselves event-by-event in our measured $\Delta\eta$. The production of the ridge appears to be uncorrelated to the presence of the narrow jet-like component. The away-side ($\Delta\phi\sim\pi$) conical emission of the associated particles in ϕ with respect to a high p_T trigger particle in the data are found to be consistent with the Mach cone scenario.

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Correlations among the produced particles provide a powerful tool to study the properties of the medium created in ultrarelativistic heavy-ion collisions. The near-side "ridge" [1, 2], a long range pseudorapidity ($\Delta\eta$) correlation, and the away-side "cone" [1, 3] structures observed in the central Au+Au collision data has inspired various theoretical models to explain the particle production mechanism. Qualitatively most of the models give similar results when compared with the di-hadron correlations. Three-particle correlation [4, 5] analysis will allow us to distinguish among these models having different physics mechanisms for particle production. Recent model studies suggest, however, that triangular and other odd harmonics do not vanish because of initial geometry fluctuations [6]. A non-zero $v_3\{2\}$ from two-particle cumulant method has been measured [7]; $v_n\{2\} = \sqrt{V_{n\Delta}}$, $V_{n\Delta} \equiv \langle\cos(n\Delta\phi)\rangle$ where $\Delta\phi$ is the two-particle opening azimuthal angle. While a non-zero $v_3\{2\}$ itself is not a proof of finite hydrodynamic triangular flow because nonflow also contributes, the centrality and p_T dependences of the measured $v_3\{2\}$ do suggest that part of the $v_3\{2\}$ is of hydrodynamic origin, and this part should be subtracted from dihadron correlations. In this talk, we subtract v_n backgrounds and present the obtained dihadron correlations. We discuss possible implications of our results. We analyze the hadron pair densities from 3-particle correlation measurements in (($\Delta\eta_1$,$\Delta\eta_2$) and ($\Delta\phi_1$,$\Delta\phi_2$)), the pseudorapidity and azimuthal angle differences between two associated particles and a trigger particle, respectively. We also exploit charge combinations in an attempt to separate the jet-like and ridge components and study their distributions, without assuming the $\Delta\eta$ shape of the ridge. Jet fragmentation in vacuum should give a peak at ($\Delta\eta_1$,$\Delta\eta_2$)$\sim$(0,0) in 3-particle correlations, while particles from the ridge would produce structures that depend on its physics mechanism. Correlation between particles from jet fragmentation and the ridge would generate horizontal or vertical stripes ($\Delta\eta_1\sim0$ or $\Delta\eta_2\sim0$) in the 3-particle correlation measurement. The observation of off-diagonal structures on the away-side, symmetric about π, $\Delta\phi_1$-$\pi \approx \pi$-$\Delta\phi_2$, in $\Delta\phi$-$\Delta\phi$ correlations would indicate the production of Mach-cone in heavy-ion collisions. The 3-particle correlations results presented are not subtracted for the odd harmonic flow contributions.

1. Dihadron correlation relative to the event plane

Two-particle cumulant $v_n\{2\}$ measures the net effect of flow, flow fluctuations, and nonflow. Except the nonflow contamination, $v_n\{2\}$ is the most truthful background to dihadron correlation. However, if $v_n\{2\}$ is measured from the same pairs used in dihadron correlation analysis, then $v_n\{2\}$ will precisely describe the correlation function and the $v_n\{2\}$-subtracted signal will by definition be zero. It is thus important to measure $v_n\{2\}$ using pairs far removed in phase-space from those used in dihadron correlation analysis. An η-gap, $|\Delta\eta|>1$, was applied in the analysis to reduce the nonflow contributions from small-angle correlations, such as jet-like correlations, resonance decays, etc. Nonflow correlations beyond $|\Delta\eta|>1$ still remain. One likely contribution comes from away-side jet-like correlations because the away-side jet partner is uncorrelated to the near-side jet in η. Figure 1 shows the dihadron correlation signals in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by STAR after v_n subtraction. The trigger and associated p_T ranges are 3-6 GeV/c and 2-3 GeV/c, respectively. The $v_n\{2\}$ were measured with reference particles from $p_T^{\rm ref} < 2$ GeV/c, which is somewhat removed from the trigger and associated p_T regions. The blue data points show the results with v_2, v_3, and v_4 subtraction, while the black ones show those

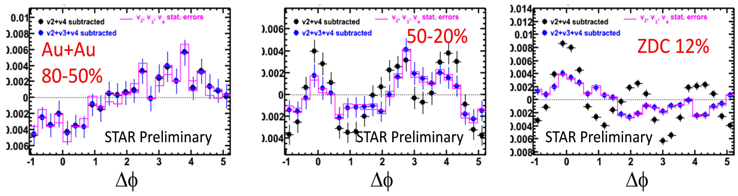

Figure 1: (Color online) v_n-subtracted dihadron correlations at $|\Delta\eta| > 1$ in Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV by STAR. Three centrality ranges are shown: 50-80% (left), 20-50% (middle), and ZDC top 12% (right). The trigger and associated p_T ranges are 3-6 GeV/c and 2-3 GeV/c, respectively. The subtracted $v_n\{2\}$ were measured by the two-particle cumulant method with $|\Delta\eta| > 1$ and reference particle $p_T^{\mathrm{ref}} < 2$ GeV/c. The background is normalized such that the average signal is zero.

with only v_2 and v_4 subtraction for comparison. In peripheral collisions, no visible signal remains besides a negative dipole. This may suggest that the subtracted v_n contain nonflow contributions comparable to the jet-like correlation between the trigger-associated pairs. In medium-central collisions, there seems finite correlation amplitude on the near side which may indicate a ridge contribution. In other words, the previously observed ridge may not be completely explained by v_3. On the away side, a broad correlation signal is still observed, however, the double-hump structure is weaker. In the most central collisions, no away-side correlation is visible, consistent with the "disapparence" of away-side high-p_T hadrons. The near-side correlation seems to indicate a finite peak consistent with remaining ridge contributions. Dihadron correlations as a function of the trigger particle azimuth relative to the event plane, $\phi_s = \phi_t - \psi_2$, have been analyzed in 20-60% Au+Au collisions by STAR [8]. The v_2 and v_4 backgrounds were subtracted. The v_2 was obtained from the average of two- and four-particle cumulant methods [9]. The v_4 was measured with respect to the v_2 harmonic event plane [9]. The effect of v_3 background was estimated and found to be insignificant [8]. In this talk we use for background subtraction the measured $v_2\{2\}$ ($|\Delta\eta| > 0.7$) and the parameterized $v_4\{\psi_2\} = 1.15 v_2\{2\}^2$ for v_4 correlated to ψ_2. The resultant dihadron correlations at $|\Delta\eta| > 0.7$ are shown in the black histograms in Fig. 2 and are consistent with the results in Ref. [8]. We further subtract the additional $v_3\{2\}$ and $v_4\{\mathrm{uncorr.}\} = \sqrt{v_4\{2\}^2 - v_4\{\psi_2\}^2}$ backgrounds (both uncorrelated to ψ_2): $2v_3^{\mathrm{trig}}\{2\}v_3^{\mathrm{assoc}}\{2\}\cos 3\Delta\phi + 2v_4^{\mathrm{trig}}\{\mathrm{uncorr.}\}v_4^{\mathrm{assoc}}\{\mathrm{uncorr.}\}\cos 4\Delta\phi$. The results are shown in Fig. 2 in the red histograms. The results again show that the effect of v_3 is insignificant; however, the reduction in the near-side correlation magnitude is noticeable.

2. 3-particle correlations

We have analyzed the 3-particle correlations data in d+Au and Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV [4, 5]. The trigger (t) and associated (a) particles are restricted to $|\eta|<1$. The p_T ranges for $\Delta\eta$-$\Delta\eta$ correlations are $1<p_T^{(a)}<3<p_T^{(t)}<10$ GeV/c and for $\Delta\phi$-$\Delta\phi$ correlations are $1<p_T^{(a)}<2$ and $3<p_T^{(t)}<4$ GeV/c. The 3-particle correlation raw signal in $\Delta\phi$ and $\Delta\eta$ are obtained from all triplet of one trigger and two associated particles from the same event. Details about background construction, systematic uncertainties and correction factors can be found in Ref. [4, 5]. Figure 3 shows the background subtracted dihadron $\Delta\eta$ correlation between associated and trigger particles on the near-side ($|\Delta\phi|<0.7$) in 0-12% Au+Au collisions. The correlation is separated for like-sign and unlike-sign pairs. At larger $|\Delta\eta|>0.7$, the ridge is similar for like- and unlike-sign trigger-associated pairs as shown in Fig. 3. Thus we expect the ridge con-

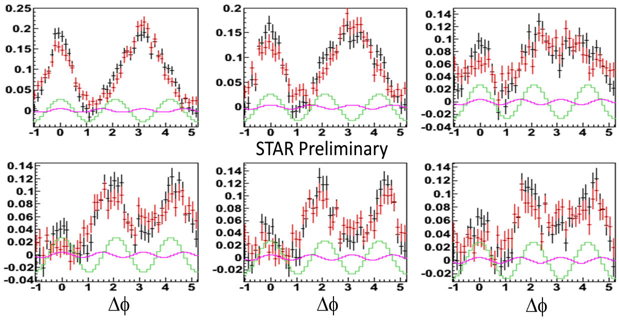

Figure 2: (Color online) v_n-subtracted dihadron correlations at $|\Delta\eta| > 0.7$ in 20-60% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by STAR. The correlations are shown, from upper left (in-plane) to lower right (out-of-plane) panel, in 15° steps in trigger particle azimuth relative to the event plane, ϕ_s. The trigger and associated p_T ranges are 3-4 GeV/c and 1-2 GeV/c, respectively. The subtracted v_n were measured by the two-particle cumulant method with $|\Delta\eta| > 0.7$ and reference particle $p_T^{\mathrm{ref}} < 2$ GeV/c. The subtracted v_3 background (uncorrelated to the event plane) and the uncorrelated portion of v_4 are shown in the green and pink histograms, respectively. The background is normalized by the ZYAM prescription.

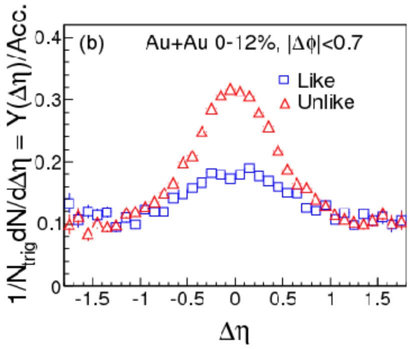

Figure 3: Background subtracted dihadron correlation in $\Delta\eta$ ($|\Delta\phi|<0.7$) corrected for $\Delta\eta$ acceptance in 0-12% Au+Au collisions for $3<p_\perp^{trig}<10$ GeV/c and $1<p_\perp^{assoc}<3$ GeV/c. The distributions are separated between like-sign (square) and unlike-sign (triangle) trigger-associated pairs.

tributions in the correlated pair density from 3-particle correlations to be the same in all charge combinations of trigger and associated particle pairs. Moreover, the probability to fragment into three same-sign hadrons at our energy scale is small [10], and hence the like-sign triplets from 3-particle correlations are dominated by ridge particles. Therefore, four times $A^\pm A^\pm T^\pm$ contains the total (with other charge combinations) ridge particle pair density ($\hat{P}_{rr} = 4 \times \frac{d^2N(A^\pm A^\pm T^\pm)}{d\Delta\eta_1 d\Delta\eta_2}$). The remaining jet-like signal (AAT - $4\times A^\pm A^\pm T^\pm$), where AAT is the charge-independent 3-particle correlations pair density. Both the jet-like and ridge signals should contain cross pairs of a jet-like and a ridge particle ($\hat{P}_{jr}$), larger in the former because of the larger unlike-sign contribution (see Fig. 3). We average the jet-like pair densities in $|\Delta\eta_{1(\mathrm{or}2)}|<0.7$ and $|\Delta\eta_{2(\mathrm{or}1)}|>0.7$ region and obtain -0.004 ± 0.025, the upper estimate of $\langle\hat{P}_{jr}\rangle/2$. The average pair densities for jet-jet ($\langle\hat{P}_{jj}\rangle$) and ridge-ridge pairs ($\langle\hat{P}_{rr}\rangle$) are 0.077±0.026 and 0.114±0.039, where the averages are taken within $|\Delta\eta_{1,2}|<0.7$ and $|\Delta\eta_{1,2}|>0.7$ regions, respectively. The comparison between $\langle\hat{P}_{jr}\rangle$ and $\sqrt{\langle\hat{P}_{jj}\rangle\langle\hat{P}_{rr}\rangle}$=0.094±0.023 (whose systematic uncertainties are strongly correlated) suggests that the production of the ridge and the jet-like particles may be uncorrelated. Figure. 4(a) shows the average ridge and jet-like signals as a function of $R=\sqrt{\Delta\eta_1^2+\Delta\eta_2^2}$. Because $\langle\hat{P}_{jr}\rangle\sim0$, the ridge and jet-like signals shown in Fig. 4(a) are essentially $\langle\hat{P}_{rr}\rangle$ and $\langle\hat{P}_{jj}\rangle$. The ridge pair density $\langle\hat{P}_{rr}\rangle$ is consistent with a constant 0.15±0.02(stat)±0.03(syst) (χ^2/ndf=6.2/7). Gaussian fits indicate a best fit value σ=$2.30^{+1.21}_{-0.01}$(syst) (χ^2/ndf=5.1/6), and σ>$1.48^{+0.33}_{-0.06}$(syst) with 84% confidence level. On the other hand, the jet pair density is narrow with a Gaussian (σ=$0.33^{+0.09}_{-0.07}$(stat)$^{+0.01}_{-0.02}$(syst) (χ^2/ndf=1.1/6)). In order to investigate possible structures in the ridge, we show in Fig. 4(b) the

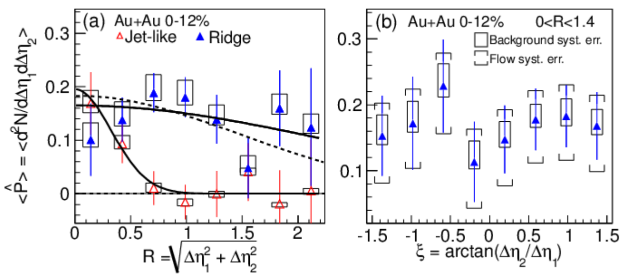

Figure 4: The average correlated hadron pair density per trigger particle in 0-12% Au+Au collisions (a) for the jet-like and ridge components as a function of R, and (b) for the ridge as a function of ξ within R<1.48. The solid curves are Gaussian fits. The dashed curve is a Gaussian fit with a fixed σ=1.48 to the ridge data.

average ridge particle pair density as a function of ξ=arctan$(\Delta\eta_2/\Delta\eta_1)$ within R<1.4. The data are consistent with a uniform distribution in ξ (χ^2/ndf=1.8/7). This suggests that the ridge particles are uncorrelated in $\Delta\eta$ not only with the trigger particle but also between themselves and appears

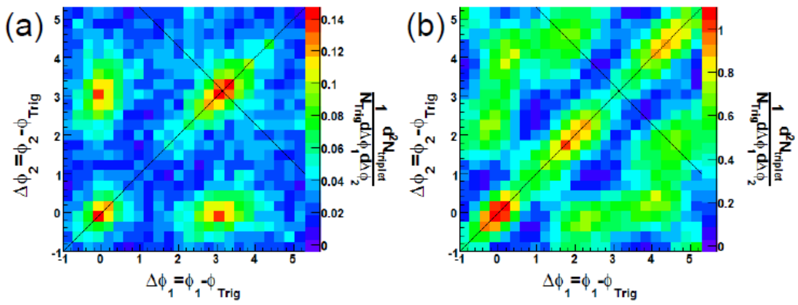

Figure 5: Background subtracted 3-particle $\Delta\phi$-$\Delta\phi$ correlations in (a) d+Au, and (b) Au+Au 0-12% central data.

Figure 5 shows background subtracted 3-particle $\Delta\phi$-$\Delta\phi$ correlations in d+Au and 0-12% Au+Au collisions. The details about the background subtraction can be found in ref [4]. Four distinct peaks are observed for each data set, corresponding to both correlated particles on the near-side ($\Delta\phi\sim$0), both on the away-side (around π) and one on each side. The away-side central peak is elongated along the diagonal, progressively from d+Au to Au+Au collisions. For central Au+Au collisions, additional peaks are observed in Fig. 5 on the away-side along the off-diagonal, indicating large opening angles between the away-side correlated pairs, symmetric about π, $\Delta\phi_1$-$\pi\approx\pi$-$\Delta\phi_2$ corresponding to each off-diagonal peak. The diagonal and off-diagonal projections for

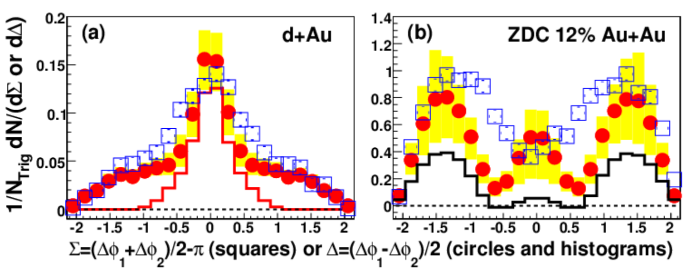

Figure 6: Projections of away-side 3-particle $\Delta\phi$-$\Delta\phi$ correlations along the diagonal Σ within 0 <Δ< 0.35 (squares) and along off-diagonal Δ within $|\Sigma|$<0.35 (points) in (a) d+Au and (b) 0-12% central Au+Au collisions. The shaded area indicates systematic uncertainties on the off-diagonal projections. The histogram in (a) is the near-side off-diagonal projections. The histogram in (b) is the away-side off-diagonal projection of our result with background normalization factors a=b=1.

d+Au and central Au+Au collisions are shown in Fig. 6. In central Au+Au, the diagonal projection displays a double peaked structure similar to what is seen on the away-side 2-particle correlations. The off-diagonal projection shows 3 peaks. A central peak and 2 symmetric side peaks. The side peaks are the signature for conical emission. These peaks can be fit with a Gaussian and the position of this Gaussian can be used to extract the conical emission angle. For 0-12% central Au+Au the observed angle is 1.37±0.02(stat)$^{+0.06}_{-0.07}$(syst) radian.

3. Summary

In summary, we have presented the 2-paricle correlation results with trigger $p_T^{(\mathrm{t})}$=3-6 GeV/c and associated $p_T^{(\mathrm{a})}$=2-3 GeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by STAR, with v_2, v_3, and v_4 background subtraction. A near-side 'ridge' peak seems to remain in non-peripheral collisions. The away-side correlation, while strongly suppressed in central collisions, is broad in medium-central collisions. The 3-particle correlation measurement are presented in $\Delta\phi$-$\Delta\phi$ and $\Delta\eta$-$\Delta\eta$ in d+Au and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. We found that same-sign associated pairs correlated with a same-sign trigger particle are dominated by the ridge. Unlike the correlation between particles in $\Delta\phi\sim 0$, the particles from the ridge appear to be uncorrelated in $\Delta\eta$ not only with the trigger particle, but also between themselves; they are uniform in our measured $\Delta\eta$ range event-by-event. No correlation is found between production of the ridge and production of the jet-like particles, suggesting the ridge may be formed from the bulk medium itself. Dijet structures are observed in $\Delta\phi$-$\Delta\phi$ correlations in d+Au and 0-12% Au+Au collisions, with a progressive diagonal elongation of the away-side central peak. Distinct peaks at θ=1.37±0.02(stat)$^{+0.06}_{-0.07}$(syst) from π are observed on the away-side in central Au+Au collisions, with correlated hadrons pairs far apart, symmetric about π. These structures are evidence of conical emission of hadrons correlated with high p_T particles.

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