Particle Ratios on the Near and Away-Side of Jets at RHIC

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Abstract. We measure the relative abundances of strange mesons, baryons, and anti-baryons correlated with high-$p_T$ trigger particles in $^{197}$Au + $^{197}$Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Particle yields and ratios are extracted on the near-side and away-side of the trigger particle. The associate-particle ratios are studied as a function of the angle relative to the trigger particle azimuth $\Delta \phi$. Such studies should help elucidate the origin of the previously observed correlations and their strong modifications in Au+Au collisions relative to p+p collisions. We discuss how these measurements might be related to several scenarios for interactions of fast partons with the medium in Au+Au collision.

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1. Introduction

The observation of large collective flows [1,2] and jet-quenching [4,7] indicates that a dense medium is created in Au+Au collisions at RHIC [3]. Studies of two particle azimuthal correlations have revealed detailed information about jet interactions with this medium [4,5,6]. These measurements can be used to infer properties of the medium such as its temperature, density, and viscosity.

First measurements of di-hadron correlations show that when using a high $p_T$ hadron to trigger on jets, in central Au+Au collisions the away-side jet (as detected from hadrons with $p_T > 2.5$ GeV/c) disappears [4,7]. Later it was shown that the remnants of the away-side jet are recovered at lower $p_T$ values [8]. The distribution of these remnants in $\Delta \phi$ is highly modified in comparison to $p+p$ collisions: the away-side correlation is no longer peaked at $\Delta \phi = \pi$ but instead has two peaks shifted to either side of $\pi$ [9]. Several scenarios have been proposed to account for this splitting. These include: 1) the development of a shock-wave around a fast parton traversing the medium [10,11]. 2) the deflection of the away-side
parton as it traverses a flowing medium [12], and 3) the radiation of gluons at large angles from a fast parton traversing the medium [13]. Determining the origin of the splitting phenomenon is experimentally challenging. Analysis of tri-hadron correlations is being pursued as one method to distinguish between scenarios 2 and 1 or 3 [14, 15].

More information may be obtained about the interaction of fast partons with the medium by studying the particle-type composition of the di-hadron correlations. An increase in the ratio of baryons to mesons has been observed in Au+Au collisions [16]. The larger baryon-to-meson ratio in the in-plane direction compared to the out-of-plane direction seems to indicate that this increase is related to the density of the system. Models incorporating hadron formation through coalescence of co-moving dressed quarks successfully describe much of the observed phenomena. By extension, one might expect a larger baryon-to-meson ratio for intermediate $p_T$ hadrons on the away-side due to the coalescence of quenched fragments with each other or with constituents from the medium. Studies of the $p/\pi$ ratio show evidence for such an effect [17].

Information about the relative contribution of quarks and gluons may also be inferred from the antibaryon-to-baryon ratio: the fragmentation of gluon jets yields a larger antibaryon-to-baryon ratio than the fragmentation of quark jets [18]. For this reason, if the splitting of the away-side jet is linked to large-angle gluon radiation, then the antibaryon-to-baryon ratio should increase at angles away from $\Delta \phi = \pi$. The presence of these gluons may also contribute to an increase in the baryon-to-meson ratio: a recent study found that the baryon density is largest in collision processes involving gluons (i.e. $qg$, $gg$, $q\bar{g}$, or $g g$) [19]. For these reasons, measurements of the baryon-to-meson ratio and the antibaryon-to-baryon ratio on the near- and away-side of jets should be useful for understanding the interaction of fast partons with the medium.

In this talk we present measurement of di-hadron correlations using unidentified trigger hadrons and identified $K^0_S$, $\Lambda$, or $\bar{\Lambda}$ associated partners. We study mid-central Au+Au collisions (10%–40%). For this analysis, a trigger hadron is any charged track with $3 < p_T < 6$ GeV/c while associated partners are taken from $1 < p_T < 4$ GeV/c. We extract the baryon-to-meson and antibaryon-to-baryon ratios of associated partners on the near-side and away-side. We study the dependence of these ratios on $\Delta \phi$ and find that the double ratio — the away-side particle ratios over the near-side particle ratios — seems to cancel dominant sources of systematic uncertainty. We discuss our measurements and their relationship to coalescence models, mach-cones or conical flow, and Cherenkov radiation.

2. Analysis method

Our analysis is carried out using charged tracks detected in the STAR TPC [20]. We select track with pseudo-rapidity $|\eta| < 1$. $K^0_S$, $\Lambda$, and $\bar{\Lambda}$ candidates are selected according to the invariant mass ($m_{inv}$) for track pairs. For each trigger and associate
particle pair, we fill a 3-dimensional histogram with \( \Delta \phi, \Delta \eta, \) and \( m_{inv} \) \( (\Delta \phi = \phi_{trig} - \phi_{asso} \) and \( \Delta \eta = \eta_{trig} - \eta_{asso} \)). We then sum over entries in a given \( \Delta \eta \) range (Fig. 1 left panel). Then we fit the \( m_{inv} \) distribution in each \( \Delta \phi \) bin (Fig. 1 right panel) to get the yield \( dN/d\Delta \phi \) for \( K_0^0, \Lambda \) and \( \bar{\Lambda} \) as a function of \( \Delta \phi \). The same procedure is carried out on a mixed event sample to obtain a background distribution used to correct for imperfect detector acceptance. These effects are small because of the \( 2\pi \) azimuthal coverage of the STAR TPC. We scale the real event \( dN/d\Delta \phi \) distribution by the normalized mixed event distribution. Finally, a \( v_2 \) modulated background distribution is subtracted from the corrected \( dN/d\Delta \phi \) distribution. This subtraction accounts for the correlations from \( v_2 \) and the combinatorial background. The level of the background is adjusted so that the subtracted \( dN/d\Delta \phi \) distribution has zero-yield at the minimum (ZYAM) [21] or zero-yield at \( \Delta \phi = 1 \) (ZYA1). Efficiency corrections for the associated particles are then applied to the resulting \( dN/d\Delta \phi \) distribution. The following form is used to describe the \( v_2 \) modulated combinatorial background [1, 21]:

\[
B(\Delta \phi) = b_0(1 + 2\langle v_A^2 \times v_B^2 \rangle \cos(2\Delta \phi)).
\]

The background subtraction is the source of three major systematic uncertainties: 1) uncertainty in the value of \( v_2 \) and \( v_2 \) fluctuations [24] \( (\langle v_A^2 \times v_B^2 \rangle \neq \langle v_A^2 \rangle \times \langle v_B^2 \rangle) \), 2) uncertainty in the assumption that the correlations can be factorized into a jet-like component and a combinatorial background (the two-component model), and 3) the model dependent assumption that the \( dN/d\Delta \phi \) distribution should have zero-yield at some specified \( \Delta \phi \) value (ZYAM, ZYA1 etc.). These uncertainties lead to large systematic errors in our analysis. The nominal \( v_2 \) for the charged hadron trigger particle is taken as the average of \( v_2 \) from an event plane analysis \( (v_2\{EP\}) \) and \( v_2 \) from a 4-particle cumulant analysis \( (v_2\{4\}) \) [22]. \( v_2\{EP\} \) and \( v_2\{4\} \) are used as upper and lower bounds respectively for the allowed \( v_2 \). For the associated \( K_0^0, \Lambda \) and \( \bar{\Lambda} \) [27], the same procedure is followed except that \( v_2\{LYZ\} \) [23] is used as the lower bound instead of \( v_2\{4\} \) [25, 26].
3. Results

The acceptance, efficiency, and background subtracted di-hadron $dN/d\Delta\phi$ distributions are shown in Fig. 2. The data are from the 10%–40% centrality interval of $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions. All data is from the $\eta$ window $|\eta| < 1.0$. The left panel shows the hadron-$K^0_S$, and the hadron-$(\Lambda + \bar{\Lambda})$ $dN/d\Delta\phi$ distributions. The right panel shows the hadron-$\Lambda$ and hadron-$\bar{\Lambda}$ correlations separately. The yellow band around zero represents the systematic uncertainties. For all particle combinations a strong correlation is seen on the near-side of the charged hadron trigger ($\Delta\phi < 1.1$) as would be expected from fragmentation of a fast parton or jet. The correlation structure on the away-side of the trigger hadron is very broad and may even exhibit a minimum at $\Delta\phi = \pi$ where typically a maximum would exist. These features are similar to those already observed for unidentified di-hadron distributions which have much better statistics [21].

![Fig. 2. Hadron-$K^0_S$, -$\Lambda+\bar{\Lambda}$ (left panel) and hadron-$\Lambda$, -$\bar{\Lambda}$ (right panel) correlation function in the centrality bin 10%–40% in $^{197}$Au + $^{197}$Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The trigger particles $p_T$ range is $3.0 < p_T < 6.0$; the associate $K^0_S$, $\Lambda$, or $\bar{\Lambda}$ particles $p_T$ range is $1.0 < p_T < 4.0$. The yellow band around the zero is the systematic errors.](image)

![Table 1. Ratios of identified partner particles ($1 < p_T < 4$ GeV/c) associated with a charged hadron trigger particle ($p_T > 3.0$ GeV/c).](table)

| Particle Ratios | Near-Side (Stat. Sys.) | Away-Side (Stat. Sys.) |
|-----------------|------------------------|------------------------|
| $(\Lambda + \bar{\Lambda})/K^0_S$ | $0.765 \pm 0.120 \pm 0.175$ | $1.71 \pm 0.321 \pm 0.589$ |
| $\bar{\Lambda}/\Lambda$ | $0.916 \pm 0.200 \pm 0.200$ | $0.894 \pm 0.173 \pm 0.368$ |

We extract the conditional yields of identified $K^0_S$, $\Lambda$ and $\bar{\Lambda}$ particles on the near-side ($0. < \Delta\phi < 0.35\pi$) and away-side ($0.35\pi < \Delta\phi < \pi$) of the trigger hadron. In Table 1 we present the resulting $(\Lambda + \bar{\Lambda})/K^0_S$ and the $\bar{\Lambda}/\Lambda$ ratios on the near- and away-side along with the systematic and statistical errors.
In Fig. 3 we compare our results for the \((\Lambda + \bar{\Lambda})/K_S^0\) ratio to other measurements of the baryon-to-meson ratio. The left panel shows the \(\bar{p}/\pi^-\) ratio measured in \(e^+ + e^-\) \([28]\), \(p + p\) \([29]\), and \(Au + Au\) \([17, 30]\) collisions (these measurements are not conditional yields). The right panel shows the \(\Lambda/K_S^0\) ratio for \(p + p\), mid-peripheral \(Au + Au\) \([31]\), and central \(Au + Au\) collisions scaled by 0.5. In central \(Au+Au\) collisions, \(\bar{p}/\pi^-\) reaches a maximum value of nearly 1 at \(p_T \approx 3\) GeV/c. The measurements of the \(\bar{p}/\pi^-\) ratio made for particles associated with a trigger hadron \((p_T > 2.5)\) from PHENIX are also shown in the left panel while our results from Tab. 1 are shown in the right panel. We find that both STAR and PHENIX measurements are consistent with a larger baryon-to-meson ratio on the away-side than on the near-side. In addition, on the near-side the baryon-to-meson ratio is closer to values measured in \(p+p\) collisions while on the away-side the ratio is closer to that measured in central or mid-central \(Au+Au\) collisions. This observation may indicate that the larger density of matter traversed by the away-side jet leads to an enhancement in baryon production. Such an effect is expected if the baryon enhancement in the intermediate \(p_T\) region observed in \(Au+Au\) collisions is due to multi-parton interactions such as gluon junction \([32]\) or quark coalescence \([33]\).

Table 1 gives the particle ratios integrated over wide regions of \(\Delta \phi\) (i.e. the near- and away-side). More information can be obtained from the distributions in Fig. 2 by examining how the ratios depend on \(\Delta \phi\): e.g. the ratios of the conditional yields on the away-side can help us better understand the source of the correlations.
that appear at large angles away from $\Delta \phi = \pi$. It has been speculated that the enhanced correlations at wide angles may be related to large angle gluon radiation [13, 33], deflection of the away-side jet by the flowing medium [12], or a shock wave that is induced in the medium by a fast moving parton [10, 11]. We expect the dependence of the particle ratios on $\Delta \phi$ to differ in the three above scenarios: e.g. gluons radiated at large angles may lead to a larger antibaryon-to-baryon ratio in that region. A recent study also found that the presence of these gluons may also lead to an enhanced baryon-to-meson ratio [19]. Alternatively, the higher density that would be associated with a shock-wave could lead to an increase in the baryon-to-meson ratio via coalescence of co-moving partons. It has also been argued that since a shock wave should be moving at the speed of sound in the medium, the particles produced from such a shock should not be very fast particles. For a slow particle to satisfy the $p_T$ cut in our analysis it would have to be massive. For this reason, one might expect the correlation at large angles to have a larger number of massive particles and consequently a larger baryon-to-meson ratio. Detailed calculations of particle ratios from the above scenarios have not been made but are being pursued [35].

**Fig. 4.** Left panel: The baryon-to-meson ratio on the away-side vs. $\Delta \phi$ scaled by the same ratio in the near-side jet-cone. Data are for 10%−40% Au+Au collisions at 200 GeV. This double ratio appears to be insensitive to the background subtraction method. Right panel: the same for $\Lambda/\Lambda$. Fig. 4 shows the particle ratios (ratios of the conditional yields) on the away-side as a function of $\Delta \phi$. The ratios are normalized by the corresponding ratio measured in the near-side jet-cone so that unity corresponds to the case where the away-side particle composition is the same as that in the near-side jet cone. We find that this double ratio is largely independent of the elliptic flow used in the background subtraction indicating that such an analysis is able to reduce systematic uncertainties. The left panel shows the baryon-to-meson, away-side-to-near-side double ratio and the right panel shows the antibaryon-to-baryon, away-side-to-near-side double ratio. In both cases the data from $\Delta \phi < \pi$ (closed symbols) has been reflected to $\Delta \phi > \pi$ (open symbols). The uncertainty on both measurements remains large.
and precludes strong conclusions about the shape or magnitude of the ratios. We see some indication that both the $\bar{\Lambda}/\Lambda$ and $(\bar{\Lambda} + \Lambda)/K_S^0$ ratios are large at large angles than they are at $\Delta\phi = \pi$. This would be consistent, for example, with gluon radiation at large angles as discussed above.

The uncertainty in our measurements can be reduced in several ways. First, a more precise determination of $\langle v_A^2 \times v_B^2 \rangle$ can eliminate that source of error entirely. These measurements are currently being pursued in STAR. Second, greater statistics can reduce the uncertainty in the background normalization via ZYAM or ZYA1. Greater statistics will become available in upcoming runs at RHIC so we expect to be able to improve the precision of our measurements in the near future. Other uncertainties in our analysis due to the ZYAM assumption and the two-component, jet+flow background model may be un-reducible.

4. Summary

We measured di-hadron azimuthal angle correlations in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Charged hadrons ($3.0 < p_T < 6.0$ GeV/c) are used as the trigger particle; $K_S^0$s, $\Lambda$s and $\bar{\Lambda}$s ($1.0 < p_T < 4.0$ GeV/c) are used as the associated particles. A correlation is observed between the trigger hadrons and $K_S^0$s, $\Lambda$s and $\bar{\Lambda}$s. We extracted the conditional yields of identified associate particles on the near- and away-side of the jet trigger and calculated the near and away-side particle ratios. The systematic uncertainty from $v_2$ and the background normalization are large. These uncertainties can be reduced with more data to reduce the error on the level of the background and a better understanding of $v_2$ to reduce uncertainty on the shape of the background. Both STAR and PHENIX results are consistent with a larger baryon-to-meson ratio on the away-side than the near-side. We studied the shape of away-side particle ratios and find that this shape is insensitive to several sources of systematic uncertainty. These measurements should help elucidate how fast partons interact with the matter created in Au+Au collisions at RHIC.

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