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Baryon-to-Meson Ratios in Jets from Au+Au and p+p Collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV

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Abstract. Measurements at RHIC and the LHC show strongly enhanced inclusive hadron baryon-to-meson yield ratios at intermediate transverse momenta (p_{T}) in high-energy nuclear collisions compared to p+p baseline. This enhancement is attributed to strong hydrodynamic flow and parton recombination in the Quark-Gluon Plasma (QGP). Jet probes have been used extensively to gain insights into QGP properties, with substantial modifications to jet yields and internal structures seen across multiple measurements. Despite apparent medium-induced changes to jet fragmentation patterns, the LHC results indicate that in-jet baryon-to-meson ratios remain similar to that of p+p measurements and are significantly different from that of the QGP bulk. To explore this behavior with the STAR detector at RHIC, we employ jet-hadron correlation and particle identification to measure in-cone baryon-to-meson yield ratios associated with fully reconstructed jets from Au+Au and p+p collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. These in-jet ratios are studied as a function of jet radii, $R = 0.2, 0.3, 0.4$, with a jet constituent p_{T} selection of $p_{\mathrm{T}}^{\mathrm{const}} > 2.0$ GeV/c. Varying the jet radius allows us to probe jets with different levels of QGP interaction. The in-jet baryon-to-meson ratios are compared between Au+Au and p+p to examine what effect the presence of QGP has on the hadronization process in jets.

1 Introduction

Heavy-ion collisions provide a unique environment to study an exotic phase of matter, Quark-Gluon Plasma (QGP), in the laboratory setting. The existence of such a phase has been demonstrated in many ways, for example, through observation of collective partonic flow [1]. QGP properties can often be studied by comparing heavy-ion collisions to p+p collisions, in which QGP is not expected to be formed. Key signatures of QGP observed through such comparisons include significant modification of charged particle spectra, enhancement of relative baryon to meson production, and jet quenching. The observed differences in these observables demonstrate that the medium impacts charged particle production [2]. Jet quenching-related phenomena can also be studied through hadron production measurements at high transverse momenta or with fully reconstructed jets. Jets, collimated collections of particles produced by fragmentation and hadronization of hard-scattered partons, are present in both p+p and heavy-ion collisions. This makes them ideal in-situ probes to study QGP, as we can observe the differences in jet properties with and without the presence of the medium [3].

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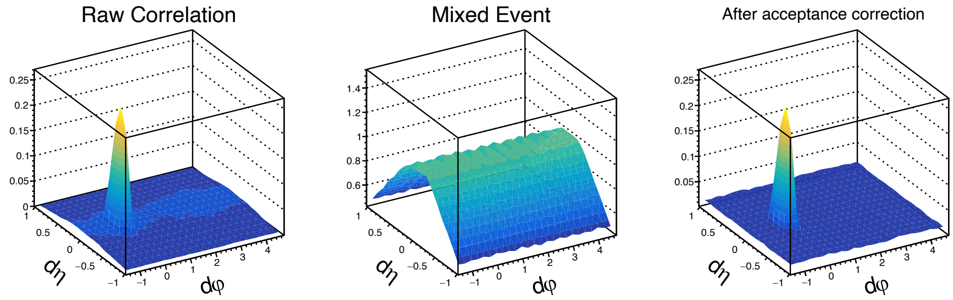

Figure 1. Jet-track correlations in $d\phi$ and $d\eta$. (left) a raw correlation is shown. (center) a correlation resulting from a mixed-event procedure. (right) a pair-acceptance corrected correlation distribution, resulting from dividing the signal by the mixed event correction.

In contrast with elementary collision systems, hard scattering is not the dominant source of particle production in heavy-ion collisions at intermediate transverse momenta, as demonstrated by an enhancement in baryon production relative to meson production [4]. This enhancement is attributed to the coalescence of partons from the medium. It remains unknown quantitatively to what extent the hard-scattered parton traversing the medium contributes to in-medium coalescence and if the QGP presence modifies the particle composition of the jet shower.

This analysis aims to further our understanding of how jets fragment in medium as well as QGP hadronization mechanisms. Recent AMPT simulations predict an enhanced in-jet baryon to meson ratio for heavy-ion collision simulations [5]. Using the STAR detector at RHIC, we combine the jet-track correlation technique and particle identification afforded by STAR subsystems to measure the in-jet baryon-to-meson ratios in Au+Au and p+p collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV.

2 Methods

A jet-track correlation technique is employed to find a sample of fully reconstructed jets with tracks identified by the STAR Time-of-Flight (ToF) and Time Projection Chamber (TPC) information to achieve Particle Identification (PID) in jets. Jets are reconstructed using the anti-k_{T} algorithm [6], with various radii parameters, $R = 0.2, 0.3, 0.4$. A constituent transverse momentum, $p_{\mathrm{T}}^{\mathrm{const}}$, minimum of 2.0 GeV/$c$ is imposed for all jet selections. All jets with a raw jet transverse momentum, $p_{\mathrm{T}}^{\mathrm{raw}}$, above 9 GeV/$c$ are considered. For each event, once an axis for such a jet is determined, correlations are constructed in η and ϕ for all charged particle tracks in the event, achieving a distribution in $d\eta$ and $d\phi$, where $d\eta = \eta_{\mathrm{jet}} - \eta_{\mathrm{track}}$ and $d\phi = \phi_{\mathrm{jet}} - \phi_{\mathrm{track}}$. Once this raw correlation signal is constructed, there is a latent geometric structure from pair acceptance that must be corrected. A mixed event method is employed for this correction. The mixed event distribution is constructed by correlating all tracks in an event with a jet axis from a different event of similar centrality and collision vertex position. The resulting distribution is normalized to unity at maximum. To implement the correction, the signal correlation is divided by the mixed event distribution. The result is a flat underlying event distribution in $d\eta$. Figure 1 shows each step of the pair acceptance correction process.

After pair acceptance correction is applied, a circular region with a radius equivalent to the anti-k_{T} R is selected around the jet axis as the jet signal, and a region of equal area away

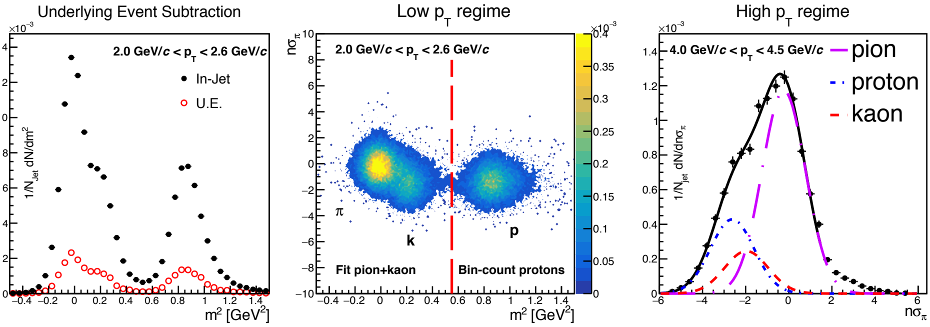

Figure 2. left) Overlay of in-jet and Underlying Event (U.E.) m^2 distribution for 2.0 GeV/c < p_T < 2.6 GeV/c. U.E. is subtracted from In-Jet for every p_T bin before PID. (center) In-Jet 2D PID distribution with 2.0 GeV/c < p_T < 2.6 GeV/c. In this regime we can directly bin count protons, using a cut in m^2, and fit the remaining Pion and Kaon distribution with a double Gaussian in $n\sigma_\pi$. (right) In-Jet $n\sigma_\pi$ distribution for 4.0 GeV/c < p_T < 4.5 GeV/c. In this regime ToF resolution is poor, so a triple Gaussian fit in $n\sigma_\pi$ is employed to identify all three particle species.

from the peak in $d\eta$ is selected as the underlying event (UE). The UE selection is constrained to the same region in $d\phi$ rather than dη to ensure an accurate assessment of the hadrochemistry sitting beneath the signal, as it has been shown that baryons and mesons exhibit different flow behavior in azimuth [1]. Histograms are constructed in dϕ, dη, m^2, and $n\sigma_\pi$ from these selections, and UE is subtracted from jet in all four parameters. The normalized energy loss is defined as $n\sigma_\pi = \frac{\ln(dE/dx)_\mathrm{measured} - \ln(dE/dx)^\pi_\mathrm{theory}}{\sigma(\ln(dE/dx))}$, where $(dE/dx)_\mathrm{measured}$ is the measured energy loss from the TPC, $(dE/dx)^\pi_\mathrm{theory}$ is the theoretical expectation for the energy loss of a pion, and $\sigma(\ln(dE/dx))$ is the resolution of the energy loss measurement. Mass squared is measured using β from ToF as $m^2 = p^2(1/\beta^2 - 1)$, where p is the measured track momentum. An overlay in m^2 is included in Fig. 2 as an example of the PID distributions corresponding to the jet and UE regions.

Particle identification is achieved using two key parameters: m^2 derived from ToF information, and energy loss per unit distance, dE/dx, derived from TPC tracking information. Two different methods are employed at the low and high p_T regimes, as shown in Fig. 2. In the low p_T regime, ToF resolution allows the proton yields to be directly bin-counted, given the clean separation of the proton peak. The remaining bins are then projected onto $n\sigma_\pi$ and fit with a double Gaussian to extract the pion yield. In the high p_T regime, ToF resolution deteriorates. However, at this point, there is improved separation in dE/dx between particle species, so the full distribution is fit with a triple Gaussian to extract both proton and pion yields simultaneously.

UE subtraction eliminates uncorrelated background contributions from the signal, however due to the use of jet reconstruction, there is also correlated background present that must be removed. There are two forms of correlated background introduced when reconstructing jets: preferential selection of upward fluctuation in the underlying event, and fully combinatorial jets. We use two different methods to measure these two contributions: pseudo-embedding and analysis of mixed constituent events, respectively.

An analysis of mixed constituent events (MCE) is used to identify the correlated background contribution from combinatorial jets. To create the sample of mixed constituent events, a distribution of number of tracks (N_tracks) per event is sampled from signal to determine how many tracks to place in MCE. A MCE is then created sampling each track from

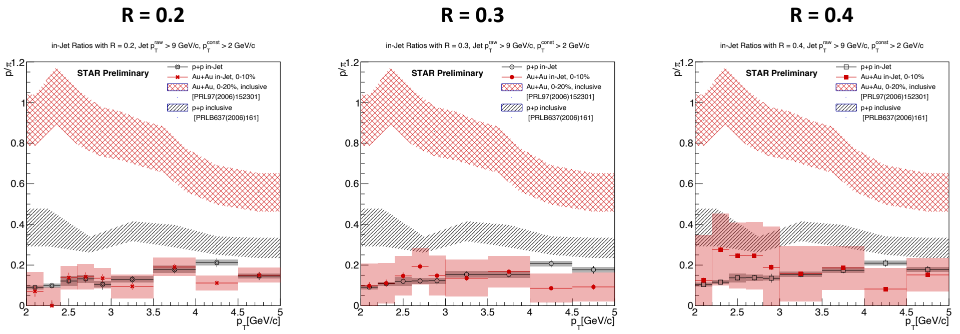

Figure 3. (left) In-jet p/π ratios for jets with $R = 0.2$ from p+p and 0 − 10% Au+Au collisions at $\sqrt{s}$, $\sqrt{s_{NN}}$ = 200 GeV compared against the published p/π ratio from inclusive charged hadrons for the same two systems [4, 7]. (center) In-jet p/π ratios for jets with $R = 0.3$ from p+p and 0 − 10% Au+Au collisions at $\sqrt{s}$, $\sqrt{s_{NN}}$ = 200 GeV. (right) In-jet p/π ratios for jets with $R = 0.4$ from p+p and 0 – 10% Au+Au collisions at $\sqrt{s}$, $\sqrt{s_{NN}}$ = 200 GeV. Jet selections use the anti-k_T algorithm and have jet $p_T^{raw} > 9$ GeV/c.

a separate event. The jetfinder is run over the MCE, accepting only jets with 2 or more constituent tracks. Jet-track correlation and uncorrelated background subtraction are performed as in signal on the resulting distributions. The correlations produced from this technique represent the contribution from fully combinatorial jets.

Pseudo-embedding is carried out by embedding events with jets from p+p into an Au+Au MCE. The jetfinder is run over the combined p+p ⊕ MCE event, and if the leading jet is matched in location to one of the p+p jet seeds, then correlations are performed with all tracks from the Au+Au MCE against the found jet axis. Uncorrelated background subtraction is performed on the resulting distribution identically to how it is performed in signal. The resulting correlations represent the upward fluctuations carried into the jet signal from Au+Au UE.

The final combinatorial jet distributions are scaled by the fake rate, the portion of jets in raw Au+Au signal that are fully combinatorial. This rate is determined using a two parameter template fit of the raw Au+Au jet spectra. The input of this fit is the spectra of p+p jets smeared with Au+Au background, and the spectra of combinatorial jets. The two parameters in the fit scale p+p and combinatorial spectra respectively to fit the overall Au+Au spectra. Integrating the yields of scaled combinatorial and scaled p+p jet spectra allows us to determine the fraction of our raw Au+Au signal that are combinatorial jets. We refer to this fraction as the fake rate. For Au+Au jets with anti-k_T $R = 0.3$, constituent $p_T^{const} > 2.0$ GeV/c, and jet $p_T^{raw} > 9$ GeV/c, this rate is found to be 39%. Both of these measures of correlated background are then subtracted from signal.

3 Results

The p/π ratio for jets in p+p collisions at $\sqrt{s}$ = 200 GeV is shown in Fig. 3 for three jet selections with $p_T^{const} > 2.0$ GeV/c: $R = 0.2$, $R = 0.3$, and $R = 0.4$. All jet selections have jet $p_T^{raw} > 9$ GeV/c and $p_T^{const} > 2.0$ GeV/c. There is a strong preference for pion production over proton production for all jets from p+p collisions. The observed in-jet ratio sits below that measured for inclusive p+p data, a measure of the full event rather than only within jet, in the low p_T regime. This feature is not unexpected, as data from ALICE shows that the inclusive hadron particle production at low $p_{\rm T}$ (around 3 GeV/c) cannot be described in a purely vacuum-like fragmentation framework, instead requiring Color Reconnection (CR) at the partonic level to describe the full particle production [8]. Our in-jet selection biases the yield towards fragmentation from hard scattering, removing the low $p_{\rm T}$ baryonic enhancement that results from CR. The selection of different radii allows us to study jets with different fragmentation processes. Broader jet selections (for the same $p_{\rm T}^{\rm raw}$) could have a higher fraction of gluon jets [10]. This effect may be subleading, given that at RHIC energies, QCD predicts predominantly quark jets [11]. The results in Fig. 3 left show that varying the anti-$k_{\rm T}$ R for jet collections in p+p collisions does not impact the resulting in-jet p/π ratio.

The p/π ratio for jets in 0-10% central Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV with $p_{\rm T}^{\rm const} > 2.0$ GeV/c, jet $p_{\rm T}^{\rm raw} > 9$ GeV/c, and $R = 0.2, 0.3, 0.4$ are shown in Fig. 3. These ratios show no significant deviation from the p/π ratio in p+p for the same jet selection criteria, indicating no measurable medium effect on the in-jet p/π ratio for this particular jet selection. Additionally, the p/π ratio is consistent within systematic uncertainty across all three measured jet radii, demonstrating no dependence on jet radius. Systematic uncertainty on Au+Au p/π ratios grows with an increase in jet R. This is a result of an increasing contribution from combinatorial jets to the measured jet signal. The percentage of measured jets that are combinatorial, or fake rate, for $R = 0.2$ is found to be 13%, for $R = 0.3$ it is 39%, and for $R = 0.4$ it is 63%. This fake rate has an uncertainty of ±3% from the spectral template fit. This variation translates to our leading systematic uncertainty on the final ratio. Work is underway to circumvent the necessity for a template fit and determine fake rate with a fully data-driven technique to improve systematic precision of this measurement.

4 Conclusion

The first measurement of in-jet relative baryon-to-meson production with jet R dependence from the STAR experiment is presented for p+p and central Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. The study of p+p data has shown that for multiple jet R selections, the p/π ratio demonstrates a strong preference for pion over proton production and is indistinguishable within the uncertainties for different jet selections considered. This ratio sits below the published inclusive ratio for p+p events of the same collision energy. Measurements reported for central Au+Au collisions show that anti-$k_{\rm T}$ jets with $R = 0.2, 0.3, 0.4$ and constituent $p_{\rm T} > 2.0$ GeV/c, the in-jet p/π ratio is significantly below the ratio reported for inclusive Au+Au collisions of the same centrality and shows no dependence on jet R. The in-jet p/π ratio is consistent within uncertainties between the two systems, indicating no in-jet baryon enhancement in Au+Au collisions compared to p+p collisions at $\sqrt{s_{\rm NN}} = 200$ GeV.

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