

Baryon-to-Meson ratios in jets from Au+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV

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Abstract. Measurements at RHIC and the LHC show strongly enhanced baryon-to-meson yield ratios at intermediate transverse momenta (p_T) in high-energy nuclear collisions compared to a $p+p$ 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 at RHIC, we employ jet-hadron correlation and particle identification to measure in-jet proton-to-pion yield ratios for $p_T < 5.0$ GeV/c. We present the first in-cone baryon-to-meson yield ratios associated with fully reconstructed jets from Au+Au and $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV using the STAR detector at RHIC. The measured in-jet ratios are similar between the two systems for our selected kinematic regime, despite significant difference between the inclusive ratios for the same systems.

1 Introduction

Heavy-ion collisions provide a unique environment to study an exotic phase of matter, Quark-Gluon Plasma (QGP), consisting of deconfined quarks and gluons, in the laboratory setting. QGP properties can be studied by comparing heavy-ion collisions to $p+p$ collisions, in which QGP is not expected to be formed. Some key signatures of QGP observed through such comparisons include significant modification of charged particle spectra, jet quenching, and enhancement of relative baryon to meson production [1]. 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. Jet modification-related phenomena can be studied with fully reconstructed jets or, by proxy, through hadron production measurements at high transverse momenta, p_T . Employing these techniques, many measurements at the LHC and RHIC have demonstrated that jets are indeed modified in the presence of QGP [2, 3].

In contrast with elementary collision systems, hard scattering is not the dominant source of particle production in heavy-ion collisions at intermediate transverse momenta ($2.0 <$

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$p_T < 5.0$ GeV/c), as demonstrated by an enhancement in baryon production relative to meson production [4]. This enhancement is attributed to strong hydrodynamic flow and 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. Recent AMPT simulations predict modifications to the baryon-to-meson ratio in jets around the jet cone [5]. This study searches for modification in in-jet hadro-chemistry by combining jet-track correlation and particle identification to measure the proton to pion ratio in jets for both $p+p$ and 0 – 10% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

2 Analysis Procedure

The data employed in this analysis were collected by STAR in 2014 (for Au+Au collisions) and 2015 (for $p+p$ collisions) at $\sqrt{s_{NN}} = 200$ GeV. Charged-particle tracks are reconstructed in the Time Projection Chamber (TPC) [6] that provides momentum and energy loss, dE/dx . In addition, the Time of Flight detector (TOF) [7] provides the relativistic velocity, β , of tracks from the primary vertex to the TOF detector, which can be used to calculate mass. TOF-matching is required for all TPC tracks considered in the analysis. A Barrel Electromagnetic Calorimeter (BEMC) high tower trigger (HT2) requiring an energy of at least 3.4 GeV deposited in at least one tower is employed to provide a sample enriched with jets. For Au+Au events, we select only 0 – 10% central collisions.

Particle identification (PID) is achieved using normalized energy loss, $n\sigma_\pi$, and m^2 . $n\sigma_\pi$ is defined as $n\sigma_\pi = \frac{\ln(dE/dx)_{\text{measured}} - \ln(dE/dx)_{\text{theory}}^\pi}{\frac{\sigma(\ln(dE/dx))}{(dE/dx)_{\text{theory}}^\pi}}$, where $(dE/dx)_{\text{measured}}$ is the measured energy loss from the TPC, $(dE/dx)_{\text{theory}}^\pi$ 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 track velocity, β , from ToF as $m^2 = \frac{p^2}{c^2} \left(\frac{1}{\beta^2} - 1 \right)$, where p is the measured track momentum.

Two different PID methods are employed at the low and high p_T regimes. In the low p_T regime, $p_T < 3.0$ GeV/c, 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, $p_T > 3.0$ GeV/c, ToF resolution deteriorates, meaning the proton yield cannot be directly bin-counted in this regime. However, in this kinematic range, 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.

A jet-track correlation technique is employed to find a sample of fully reconstructed jets with charged-particle tracks. TPC and TOF information is preserved for all tracks throughout this process. The TPC has a pseudorapidity, η , coverage of $|\eta_{\text{track}}| < 1.0$. This cut is applied for all tracks in this analysis to ensure uniform acceptance for PID. Jets are reconstructed using the anti- k_T algorithm [8], with jet radius $R = 0.3$, and constituent transverse momentum, $p_T^{\text{cons}} > 2.0$ GeV/c. Jets with reconstructed transverse momentum, $p_T^{\text{raw}} > 9$ GeV/c, and $|\eta_{\text{jet}}| < 0.7$ are employed in the sample. For each event, once an axis for such a jet is determined, correlations are constructed in η and azimuthal angle, ϕ , for all charged particle tracks in the event, achieving a distribution in $\Delta\eta$ and $\Delta\phi$, where $\Delta\eta = \eta_{\text{jet}} - \eta_{\text{track}}$ and $\Delta\phi = \phi_{\text{jet}} - \phi_{\text{track}}$.

Once a 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 each track in an event with a jet axis from a different event in our sample. 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 $\Delta\eta$.

After pair acceptance correction is applied, a circular region centered around the jet axis with a radius equivalent to the jet resolution parameter, R , is selected from correlations as the jet signal, and a region of equal area away from the peak in $\Delta\eta$ is selected as the underlying event (UE). The UE selection is constrained to the same region in $\Delta\phi$ rather than $\Delta\eta$ 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 [9]. Histograms are constructed in $\Delta\phi$, $\Delta\eta$, m^2 , and $n\sigma_\pi$ from these selections, and UE is subtracted from jet in all four parameters.

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 (MCE).

An analysis of MCEs is used to identify the correlated background contribution from combinatorial jets. To create the sample of mixed constituent events, a distribution of N_{tracks} per event is sampled from our collection of high tower events, referred to as "signal" from here on out, to determine how many tracks to place in MCE. A MCE is then created sampling each track from a separate event. Exclusively minimum bias events are used to create these mixed events to minimize introduction of tracks from hard processes into the combinatorial background. The jet reconstruction algorithm 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.

Pseudo-embedding is carried out by embedding events with jets from $p+p$ into an Au+Au MCE. The jet reconstruction algorithm is run over the combined $p+p \oplus$ 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 N_{jet} per event rate as compared to the N_{jet} per event rate in signal. For Au+Au jets with anti- k_T $R = 0.3$, constituent $p_T^{\text{cons}} > 2.0$ GeV/ c , and jet $p_T^{\text{raw}} > 9$ GeV/ c , this rate is found to be 39%. Both of these measures of correlated background are then subtracted from the in-jet distributions constructed from signal.

The in-jet p/π ratio is studied as a function of p_T as well as Δr , defined as $\Delta r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2}$, for tracks with 2.0 GeV/ $c < p_T < 3.0$ GeV/ c . This momentum range was selected for the radial study as it posses the cleanest PID. The radial study is performed identically to the p_T dependent study for three integration radii around the jet axis, $\Delta r = 0.1, 0.2, 0.3$. The yields associated with each ring in Δr are obtained by subtracting inner radii from outer radii. Correlated background rates are obtained in the same fashion.

3 Results and Discussion

The p/π ratio for jets in $p+p$ collisions at $\sqrt{s} = 200$ GeV is shown in Fig. 1 for jets with $p_T^{\text{cons}} > 2.0$ GeV/ c , jet $p_T^{\text{raw}} > 9$ GeV/ c , and anti- k_T radius $R = 0.3$. There is a strong preference for pion production over proton production for jets from $p+p$ collisions. The observed

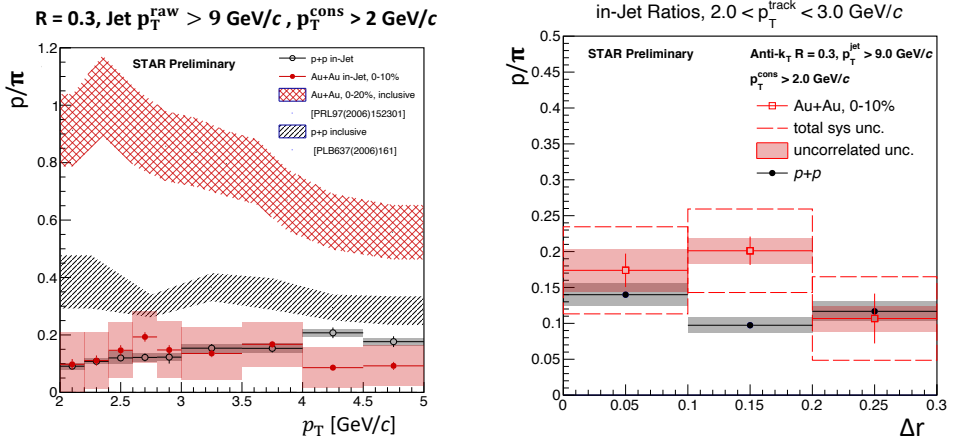


Figure 1. (left) In-jet p/π ratios are shown for $p+p$ and 0 – 10% central Au+Au collisions, with jet $p_T^{\text{raw}} > 9 \text{ GeV}/c$ and $p_T^{\text{cons}} > 2.0 \text{ GeV}/c$. Published inclusive p/π ratios are included for both systems [4, 10]. (right) In-jet p/π ratios from the same two samples presented as a function of Δr .

in-jet ratio is less than that measured for inclusive hadrons in $p+p$ collisions 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_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 [11]. Our in-jet selection biases the yield towards fragmentation from hard scattering, removing the low p_T baryonic enhancement that results from CR. The p_T^{cons} minimum provides a control on the hardness of fragmentation within the sample of jets.

The p/π ratio for jets in 0 – 10% central Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$ with $p_T^{\text{cons}} > 2.0 \text{ GeV}/c$, jet $p_T^{\text{raw}} > 9 \text{ GeV}/c$, and $R = 0.3$ are also shown in Fig. 1, as well as the previously published inclusive hadron result for central events from the same system and collision energy [4]. The Au+Au in-jet ratio shows no significant deviation from the p/π ratio in $p+p$ collisions for the same jet selection criteria, indicating no significant medium effect on the in-jet p/π ratio for this particular jet selection. The agreement between in-jet p/π ratios is striking given the significant enhancement in the Au+Au inclusive hadron measurement as compared to inclusive hadrons from $p+p$ collisions. This selection of leading jets with a narrow anti- k_T radius and a high p_T^{cons} minimum is biased toward the hardest scattering in the event collection. The collection of leading jets in central heavy-ion data may be subject to "survivor bias," that is, have the least interaction with the medium, which could explain the lack of modification found in p/π ratios from jets in Au+Au collisions. In Au+Au data, the p_T^{cons} minimum provides both a control on the hardness of the initial parton scattering as well as a control on how much correlated background is picked up by the jet finder algorithm.

Simulations from AMPT predict a qualitative linear trend in the difference between jet-associated p/π ratios from heavy-ion and $p+p$ collisions as a function of Δr [5]. To examine this feature in Au+Au and $p+p$ collisions, a radial extension of the study was performed for tracks with $2.0 < p_T < 3.0 \text{ GeV}/c$ in jets with $p_T^{\text{cons}} > 2.0 \text{ GeV}/c$, $R = 0.3$, and jet $p_T^{\text{raw}} > 9.0 \text{ GeV}/c$. The resulting in-jet radial evolution of the p/π ratio for both $p+p$

and 0 – 10% Au+Au collisions is shown in Fig. 1 (right). For the studied range in Δr , the predicted linear trend in the difference between Au+Au and $p+p$ collisions is not observed. Systematic uncertainty on the p/π ratio for this measurement has been separated into fully correlated and uncorrelated contributions. This is done to isolate the band that represents shape uncertainty in Au+Au from total uncertainty, given that the predicted trend relies on shape, rather than overall magnitude.

4 Summary and Conclusions

The first measurement of in-jet relative baryon-to-meson production from the STAR experiment is presented for $p+p$ and central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The study of the $p+p$ data sample has shown that the p/π ratio demonstrates a strong preference for pion over proton production for jets with anti- k_T $R = 0.3$, constituent $p_T^{\text{cons}} > 2.0$ GeV/ c , and jet $p_T^{\text{raw}} > 9$ GeV/ c . This ratio is smaller than the published inclusive ratio for $p+p$ events of the same energy. Measurements reported for 0 – 10% central Au+Au collisions show that for anti- k_T $R = 0.3$ jets with constituent $p_T^{\text{cons}} > 2.0$ GeV/ c there exists a similar preference for pion over proton production among jet fragments. The resulting p/π ratio shows no evidence of baryon enhancement and is significantly below the ratio reported for inclusive Au+Au collisions of the same centrality. Furthermore, the evolution of the in-jet p/π ratios of these two systems as a function of Δr demonstrates no significant divergence between the two systems.

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