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Studies of Heavy Flavor Jets Using D^0-Hadron Correlations in Azimuth and Pseudorapidity in Au + Au Collisons at 200 GeV at the STAR Experiment †

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Abstract: Heavy flavor (HF) quarks (charm, bottom) are important probes of the medium produced in relativistic heavy-ion collisions because they are formed in the early stage and propagate throughout the lifetime of the system. HF-meson spectra and azimuthal anisotropy (v_2) measurements have been reported by experiments at RHIC and the LHC, and they suggest strong interactions of HF quarks with the medium. D^0-hadron correlations on relative pseudorapidity and azimuth ($\Delta\eta, \Delta\phi$) provide a method for disentangling correlation structures on ($\Delta\eta, \Delta\phi$)—allowing for separation of structures related to jets and bulk phenomena directly, with the D^0 serving as a proxy for a charm jet. In these proceedings, we present 2D D^0-hadron angular correlations as a function of centrality in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. These data reveal a jet-like, peaked structure at ($\Delta\eta, \Delta\phi$) = (0, 0) (near-side), and a $\Delta\eta$-independent azimuthal harmonic modulation. Here, we focus on the evolution of the near-side peak's yield and widths on ($\Delta\eta, \Delta\phi$) as a function of centrality and compare them to results from light flavor correlations.

Keywords: heavy-flavor; jets; charm; correlations

1. Introduction

Heavy flavor (HF) quarks are formed in the early stage of the collision between ultra-relativistic heavy ions. HF quarks rapidly hadronize, and then decay outside the deconfined partonic medium, or quark-gluon plasma (QGP). This means that HF quarks and their hadrons sample the entire evolution of the QGP.

Recently, measurements of the nuclear modification factor, R_{AA}, by the STAR and ALICE collaborations show significant differences between light flavor (LF) mesons and HF mesons at low transverse momentum for mid- to very-central heavy-ion collisions [1–3]. However, at higher values of p_T, the R_{AA} of the LF and HF mesons are consistent with each other. Furthermore, the STAR collaboration has measured the D^0 meson azimuthal anisotropy, v_2, and seen that it is consistent with the v_2 of LF mesons as a function of transverse kinetic energy ($m_T - m_0$) at 10–40% centrality [4]. While no measurements can currently disentangle the effects of collisional and radiative energy loss, two-particle correlations can yield additional information from the net effects of interactions in the QGP.

Two-particle correlations allow for the study of the complicated underlying dynamics of heavy-ion collisions. In particular, correlations on both relative azimuth ($\Delta\phi$) and pseudorapidity ($\Delta\eta$) using a D^0 meson as a trigger provide access to both jet-like physics—with the D^0 serving as a proxy for a charm jet—and to flow harmonics dependent on $\Delta\phi$, which allows for simultaneous extraction of the evolution of the jet-like peak, as well as v_2, using a multi-parameter fit. In these proceedings, we focus on correlations at small $\Delta\phi$ ($|\Delta\phi| < \pi/2$; near-side or NS) and $\Delta\eta$, which provide access to the charm jet interactions with the medium.

2. D^0-Hadron Correlations

The analysis presented in these proceedings was carried out using around 900 million minimum-bias events collected by the STAR detector [5] at the Relativistic Heavy-Ion Collider (RHIC) in 2014. Particle trajectories (tracks) were reconstructed using the Time Projection Chamber (TPC) [6] and the Heavy Flavor Tracker (HFT) [7], where the TPC is used for extraction of particle momenta. The HFT is used for precise calculation of secondary decay vertices displaced from the primary collision vertex (PV) by ~ 100 µm, enabling reconstruction of HF hadrons via rejection of combinatorial background coming from particles originating at the PV.

The TPC and HFT both have full 2π coverage in azimuth, and both have pseudorapidity coverage of $|\eta| < 1$. The D^0 meson was reconstructed via the hadronic decay channel ($D^0(\bar{D}^0) \rightarrow K^{\mp} + \pi^{\pm}$), with $2 < p_{T,D^0} < 10$ GeV/c, with the range based on experimental constraints and statistics. The reconstruction of the D^0 uses five topological cuts mostly based on the distance of closest approach (DCA) of tracks, which are detailed in Figure 1. The associated hadron tracks used in this analysis require hits in both the TPC and the HFT detectors with acceptance cuts $|\eta| < 1$ and $p_T > 0.15$ GeV/c.

After being identified, the trigger D^0 and associated hadrons from the same-event (SE) are binned on $(\Delta\eta, \Delta\phi)$. In order to correct for detector acceptance effects, D^0 candidates are paired with associated hadrons from different events, or *mixed-events* (ME), with a similar event multiplicity and z-coordinate of the PV. The correlation is defined as a Pearson's correlation coefficient, as seen in [8], with $corr. = \frac{(SE - \alpha ME)}{\alpha ME}$, where α is defined as the ratio of the total number of counts in the SE distribution to the total number of counts in the ME distribution. This same correlation quantity is calculated for D^0 candidates from the signal region of the invariant mass distribution, as well as from sidebands (SB) of the invariant mass distribution to estimate the correlations from background Kπ pairs, with these regions illustrated in Figure 1. Additionally, a correlation is calculated for D^0-π pairs, where the invariant mass of the pair is within the invariant mass region of the charged, excited D-meson state ($D^{*\pm}$). The $D^* \rightarrow D^0 + \pi$ decay happens outside the medium, and is restricted to small opening angle due to the kinematics of the decay. The π from this decay adds an associated hadron not originating from medium interactions, thereby increasing the NS associated yield. The final correlation equation including all of these contributions is derived as

$$\frac{C_{D^0+h}}{(\alpha ME)_{D^0+h}} = \frac{S+B}{S}\frac{(SE - \alpha ME)_{\text{sig}}}{(\alpha ME)_{\text{sig}}} - \frac{B}{S}\frac{(SE - \alpha ME)_{\text{SB}}}{(\alpha ME)_{\text{SB}}} - \frac{S+B}{S}\frac{(\alpha ME)_{D^0+\pi}}{(\alpha ME)_{\text{sig}}}\frac{(SE - \alpha ME)_{D^0+\pi}}{(\alpha ME)_{D^0+\pi}}, \quad (1)$$

where S and B are the signal and background yields of the D^0 invariant mass signal region, respectively.

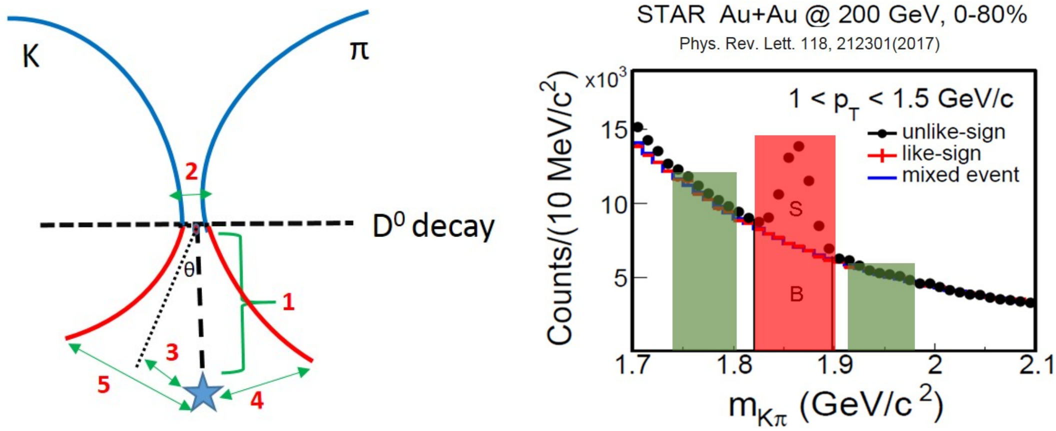

Figure 1. Left panel: Cartoon sketch of the D^0 decay to an unlike-sign Kπ pair. The decay components are enumerated as follows: (1) decay length of the mother D^0, (2) DCA Kπ daughters, (3) DCA of D^0 to PV, (4) DCA of π to PV, and (5) DCA K to PV. Right panel: D^0 invariant mass distributions with the signal region highlighted in red and the SB highlighted in green.

3. Results

The final D^0-hadron correlations are shown in Figure 2. Extraction of the underlying physics from the correlations is facilitated by fitting the data with a model that describes the visible features in the correlation structures. We assume a NS 2D Gaussian centered at $(\Delta\eta, \Delta\phi) = (0, 0)$, an away-side (AS) 2D Gaussian centered at $(0, \pi)$, a $\Delta\eta$-independent quadrupole, and an overall constant offset. Both 2D Gaussians are required to be periodic on $\Delta\phi$. The model is given by

$$F(\Delta\eta, \Delta\phi) = A_0 + 2A_{\rm Q}\cos(2\Delta\phi) + A_{\rm NS}e^{-\frac{1}{2}\left[(\Delta\eta/\sigma_{\Delta\eta,NS})^2+(\Delta\phi/\sigma_{\Delta\phi,NS})^2\right]} \\ + A_{\rm AS}e^{-\frac{1}{2}\left[(\Delta\eta/\sigma_{\Delta\eta,AS})^2+((\Delta\phi-\pi)/\sigma_{\Delta\phi,AS})^2\right]} + \text{periodicity}, \tag{2}$$

where near-side Gaussian terms at $\Delta\phi = \pm 2\pi$, etc. and AS Gaussians at $\Delta\phi = -\pi, \pm 3\pi$, etc. are not listed but are included in the model (periodicity). Additional and/or alternate model elements, such as a sextupole (v_3), were included in the study of systematic uncertainties. Additionally, when the away-side Gaussian width approaches $\sim$1, it mathematically limits to a dipole ($\cos(\Delta\phi)$) due to periodicity. This method has been employed previously in [8] to describe centrality trends of correlation structures from unidentified hadrons in heavy-ion collisions.

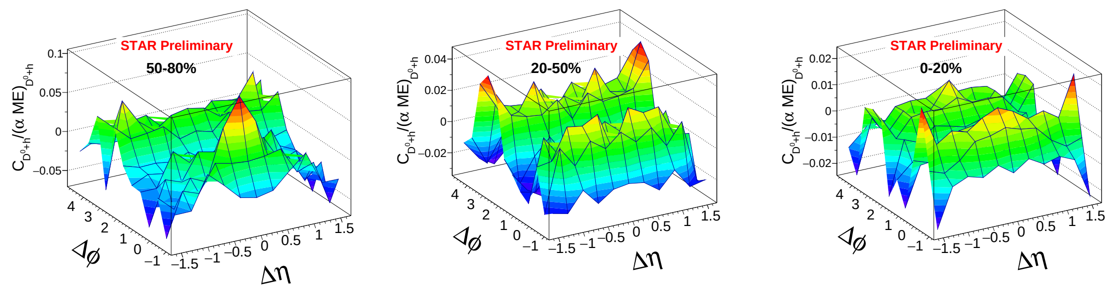

Figure 2. D^0-hadron correlations from Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV collisions at STAR. The left-most plot is most-peripheral (50–80%), the center is mid-central (20–50%) and the right-most plot is most-central (0–20%).

Using the extracted information on the NS widths, the associated yield of hadrons per trigger D^0 is given by

$$Y_{\rm NS,peak}/N_{D^0} = \frac{dN_{\rm ch}}{2\pi d\eta}\left(1 - \frac{1}{2N_{\Delta\eta}}\right)\int_{\Delta\eta\ \rm accep} d\Delta\eta \int d\Delta\phi F_{\rm NS-peak}(\Delta\eta, \Delta\phi), \tag{3}$$

where $\frac{dN_{\rm ch}}{2\pi d\eta}$ is calculated from [8], and the integrals are over the 2D Gaussian, NS peak using the fit parameters from the fitting procedure. The results of the fitting and calculation of the associated yield are shown in Figure 3.

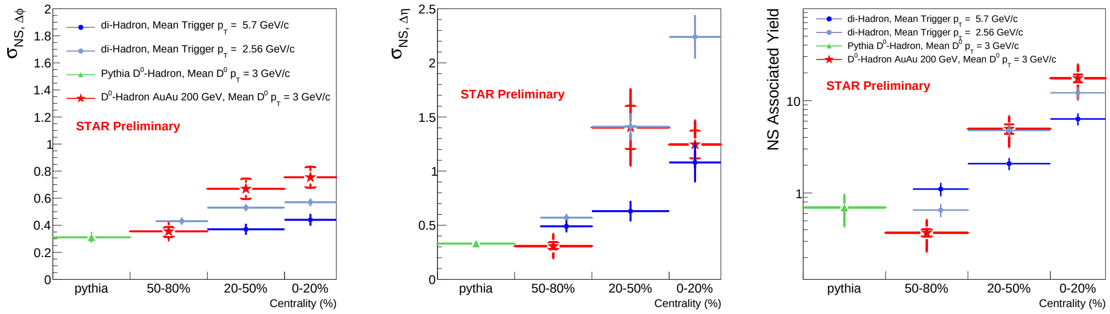

Figure 3. Extracted NS widths on $\Delta\eta$ and $\Delta\phi$ and associated yields from D^0-hadron correlations (red stars). The light and dark blue data points are from [9] and are LF di-hadron correlations with mean p_T of 2.56 and 5.7 GeV$/c$, respectively. The green data points are from correlations calculated using PYTHIA 8.23 (tune: [10]).

4. Discussion and Conclusions

These proceedings present the first measurement of D^0-hadron correlations on $(\Delta\eta, \Delta\phi)$ in heavy-ion collisions as a function of centrality. Two-particle correlations using a D^0 meson as a trigger allow for the study of jet-like phenomena involving charm quarks by studying the evolution of the widths of the near-side peak on $(\Delta\eta, \Delta\phi)$ and the NS associated yield per trigger as a function of centrality. The widths of the jet-like peak broaden from peripheral to central collisions, exhibiting behavior similar to what is seen in correlations with LF mesons at a similar mean-p_T. The NS yield increases by an order of magnitude from peripheral to central collisions, indicating significant interactions of the charm quark with the QGP. The widths and yields of D^0-hadron correlations calculated with PYTHIA are consistent with what is measured in the peripheral centrality bin of the present analysis, indicating minimal interactions of the charm-containing jet with the QGP in peripheral heavy-ion collisions.

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