An Investigation of Charm Quark Jet Spectrum and Shape Modifications in Au+Au Collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV*

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Partons, *i.e.*, quarks and gluons, in heavy-ion collisions interact strongly with the Quark-Gluon Plasma (QGP), and hence have their energy and shower structure modified compared to those in vacuum, e.g., those produced in proton-proton collisions. Theoretical calculations predict that the radiative energy loss, which is the dominant mode of energy loss for gluons and light quarks in the QGP, is suppressed for heavy quarks, such as charm and bottom, at low transverse momenta (p_{T}). The excellent secondary vertex resolution provided by the Heavy Flavor Tracker in the STAR experiment at RHIC enables reconstruction of $D^0(c\bar{u})$ mesons at low p_{T} with high signal significance over the background.

In this proceeding, we report the first measurements of the D^0 meson tagged jet p_{T} spectra and the D^0 meson radial profile in jets reconstructed from Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, collected by the STAR experiment in 2014.

1. Introduction

Relativistic heavy ion collisions produce Quark-Gluon Plasma (QGP), as predicted by Quantum Chromodynamics (QCD). Internal probes involving hard scattering processes are useful in studying the properties of the QGP medium. One such probe, called jets, manifests as a collimated cluster of final state particles in the detector. The partons which give rise to these jets lose energy to the QGP medium, either through collisions, or through induced gluon *bremsstrahlung* - a phenomenon known as jet quenching [1]. The effects of jet quenching can be seen in measurements of energy-loss [2], and modifications to the jet-structure [3]. A study of heavy-flavor tagged jets can shed light on the mass and flavor dependence of the aforementioned

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parton energy loss and jet structure modifications. An important prediction of QCD, the dead-cone effect was measured for charm quarks in pp collisions at LHC [4], but remains elusive for heavy-ion collisions. Heavy flavor jets at LHC have also yet to reveal significant differences with their inclusive counterparts [5, 6], possibly due to having energies much higher than the parton masses. Therefore, such studies at the complementary RHIC energies, where lower energy jets are produced, could be key to better understanding the parton mass dependence. This proceeding will focus on the first set of such measurements from RHIC: Jet p_{T} spectra and D^0 meson radial profile in D^0 meson tagged jets from Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV.

2. Analysis Setup

This analysis uses '*minimum-bias*' triggered Au+Au collision events at nucleon-nucleon center of mass energy of $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, collected in 2014 by the STAR detector [7] at RHIC. The event selections for this analysis mimic the ones found in Ref. [8]. Tracks which pass standard quality cuts at STAR [9], are chosen within the STAR pseudorapidity acceptance of $|\eta| < 1$. The analysis is done in three centrality bins: 0-10 % (central), 10-40 %(mid-central), and 40-80 %(peripheral). $D^0(\bar{D}^0)$ mesons are reconstructed via the decay channel $D^0 \rightarrow K^- + \pi^+$ (and its charge conjugate) with a branching ratio of 3.89 % [10]. Several topological selections based on the decay geometry of $D^0(\bar{D}^0)$ are applied to the combinatorial $K\pi$ pairs in an event. That is possible due to the Heavy Flavor Tracker (HFT), which improves the resolution of tracking from 1 mm at Time Projection Chamber (TPC) to about 30 μm. A more thorough discussion on the selection criteria for the $D^0(\bar{D}^0)$ candidates is available in Ref. [8].

Jets are reconstructed from tracks and towers with $p_{\mathrm{T}} > 0.2$ GeV/c, and $E_{\mathrm{T}} > 0.2$ GeV respectively. The jets are defined using the anti-k_{T} clustering algorithm available in the FASTJET package [11], with a radius parameter of $R = 0.4$ in the $\eta - \phi$ space. The K and π daughter tracks are replaced with the corresponding $D^0(\bar{D}^0)$ candidate before the jets are reconstructed. A jet area based background subtraction is applied to nullify the effect of the soft background on the jets [12]. Jets with a $D^0(\bar{D}^0)$ constituent with $p_{\mathrm{T,D^0}} > 5$ GeV/c are considered for this analysis.

3. $D^0(\bar{D}^0)$ Jet Spectrum and Shape Modifications

To extract the raw yield of $D^0(\bar{D}^0)$ mesons, a method called $_s\mathcal{P}lot$ [13] is used. $_s\mathcal{P}lot$ calculates per event weights, called sWeights, from an unbinned likelihood fit to the $D^0(\bar{D}^0)$ invariant mass distribution over all kinematics. The weights classify how '*signal-like*' a $D^0(\bar{D}^0)$ candidate is. Figure 1 shows the invariant mass distribution of $K\pi$ candidates in the p_{T} region of 5–10 GeV/c for 0–80% minimum bias events. The raw yields are corrected for the tracking efficiencies and acceptances of TPC and HFT, topological cut efficiency, particle identification efficiency, and finite vertex resolution, based on the correction factors derived in the STAR study on $D^0(\bar{D}^0)$ production in heavy-ion collisions [8]. The invariant yields of $D^0(\bar{D}^0)$ tagged jets is

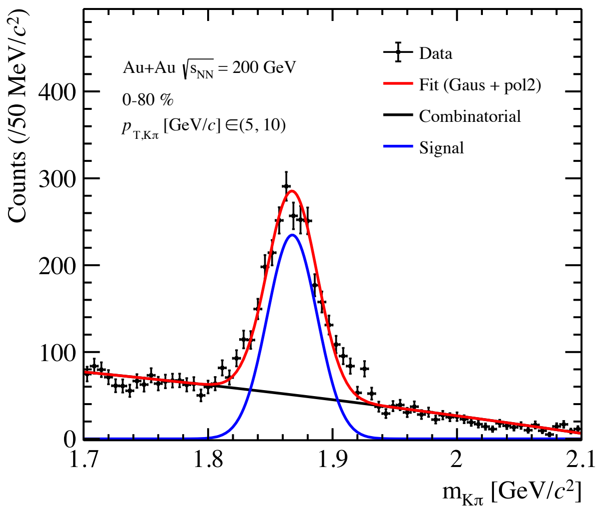

Fig. 1. The invariant mass distribution of $K\pi$ pairs with $p_{\mathrm{T}} \in (5, 10)$ GeV/c. The unlike sign $K\pi$ pairs distribution (*black*) is fit with a Gaussian plus second order polynomial (*red*) to estimate the $D^0(\bar{D}^0)$ meson yield. The signal after the removal of the background (*blue*) is also shown on the same scale.

represented by the formula:

$$\frac{d^2 N_{\mathrm{jet}}}{2\pi N_{\mathrm{evt}} p_{\mathrm{T,jet}} dp_{\mathrm{T,jet}} d\eta} = \frac{1}{\mathrm{B.R.}} \times \frac{N_{\mathrm{jet}}^{\mathrm{raw}}}{2\pi N_{\mathrm{evt}} p_{\mathrm{T,jet}} \Delta p_{\mathrm{T,jet}} \Delta\eta} \times \frac{1}{\epsilon_{\mathrm{corr}}} \tag{1}$$

where B.R. is the $D^0 \to K^-\pi^+$ decay branching ratio $(3.89 \pm 0.04\%)$, $N_{\mathrm{jet}}^{\mathrm{raw}}$ is the reconstructed $D^0(\bar{D}^0)$ tagged jets raw counts, N_{evt} is the total numbers of events used in this analysis, and ϵ_{corr} is the total correction factor described above. The nuclear modification factor R_{CP} is defined as the ratio of N_{coll}–normalized yields between central and peripheral collisions where N_{coll} is the number of the binary collisions for a centrality class.

The radial distribution of $D^0(\bar{D}^0)$ mesons in tagged jets is defined by the formula here:

$$\frac{1}{N_{\mathrm{jet}}}\frac{dN_{\mathrm{jet}}}{d\mathrm{r}} = \frac{1}{N_{\mathrm{jet}}}\frac{N_{\mathrm{jet}}|_{\Delta\mathrm{r}}}{\Delta\mathrm{r}} \tag{2}$$

where r $= \sqrt{(\eta_{\rm jet} - \eta_{\rm D^0})^2 + (\eta_{\rm jet} - \phi_{\rm D^0})^2}$ is the distance of the $D^0(\eta_{D^0}, \phi_{D^0})$ from the jet axis $(\eta_{\rm jet}, \phi_{\rm jet})$ in the $\eta - \phi$ plane, and $N_{\rm jet}|_{\Delta \rm r}$ is the number of jets with $D^0(\bar{D}^0)$ mesons in the Δr interval.

A Bayesian unfolding procedure [14], with a Monte-Carlo (MC) generated event sample, is used to account for the detector inefficiencies in jet reconstruction. A $D^0(\bar{D}^0)$-enriched sample pp collision events at $\sqrt{s} =$ 200 GeV is generated using PYTHIA v8.303, with the 'Detroit' tune [15], and propagated through the STAR detector using the GEANT3 package. The FONLL (Fixed Order + Next-to-Leading Logarithms) charm quark spectrum is used as a prior for the unfolding procedure. The charm jet fragmentation function is modeled using PYTHIA, and a systematic study of effects of its variation is in the outlook. Observables with an asterisk(*), found later in this proceeding, denote this underlying assumption.

The fluctuation due to the heavy-ion background is estimated by embedding 'single-particle' jets in '*minimum-bias*' Au+Au events, and then matching each embedded jet with a reconstructed jet. The quantity $\Delta p_{\rm T,SPjet} = p^{\rm det}_{\rm T,SPjet} - p^{\rm part}_{\rm T,SPjet}$ models this fluctuation. The superscript 'part' refers to particle-level jets, and 'det' refers to detector-level jets. For the D^0 meson radial profile, a two-dimensional Bayesian unfolding procedure is used to simultaneously correct Njet as a function of $p_{\rm T,jet}$ and Δr.

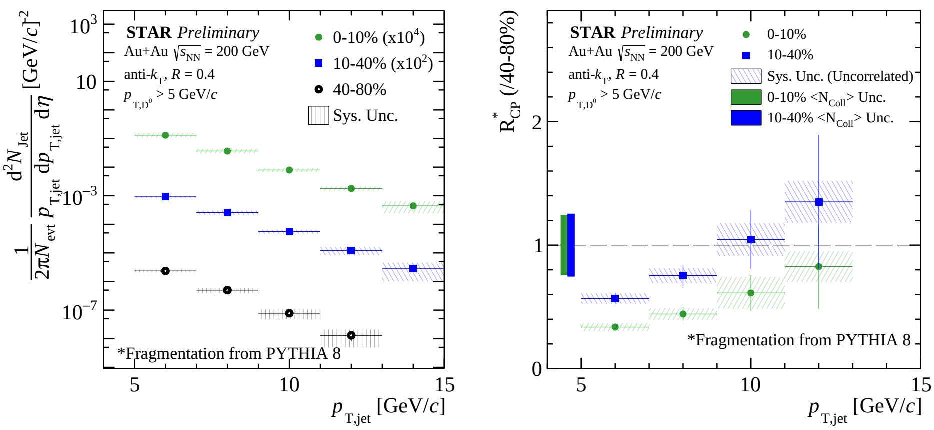

Fig. 2. **Left**: p_T spectra for $D^0(\bar{D}^0)$ jets with $p_{\rm T,D^0} > 5$ GeV/c in different centrality classes; **Right**: $R_{\rm CP}$ for $D^0(\bar{D}^0)$ jets

The systematic uncertainties across the bins in the reported observables are dominated by the following contributions: a) differences in the invariant yield of D^0 mesons calculated using the ${}_s\mathcal{P}lot$ method, and a like-sign background subtraction method, and b) systematics from $D^0(\bar{D}^0)$ reconstruction, available in Ref. [8]. Systematic variations related to the unfolding procedure are estimated by varying the following: a) the prior from FONLL to the jet distribution for D^0 tagged jets in pp collisions at $\sqrt{s} = 200$ GeV generated by PYTHIA, and b) the regularisation parameter.

The efficiency-corrected invariant yield of $D^0(\bar{D}^0)$ meson tagged jets with $p_{\mathrm{T,D^0}} > 5$ GeV/c is shown in Figure 2, as a function of $p_{\mathrm{T,jet}}$ in 0-10 %, 10-40 %, and 40-80% Au+Au collisions. The spectra in the first two centrality bins are scaled by arbitrary factors, and the last data point is omitted for the most peripheral centrality bin, because of a non-closure in the unfolding. The nuclear modification factor, R^*_{CP}, is shown for the central and the mid-central Au+Au collisions in Figure 2, with the 40-80 % centrality bin as the reference. The yield of $D^0(\bar{D}^0)$ jets is found to be more suppressed in central collisions than in mid-central collisions, with R^*_{CP} showing a strong suppression at low $p_{\mathrm{T,jet}}$ for both cases. R^*_{CP} also shows an increasing trend with $p_{\mathrm{T,jet}}$ for both centrality bins, which is qualitatively different from the R_{CP} for inclusive jets [2].

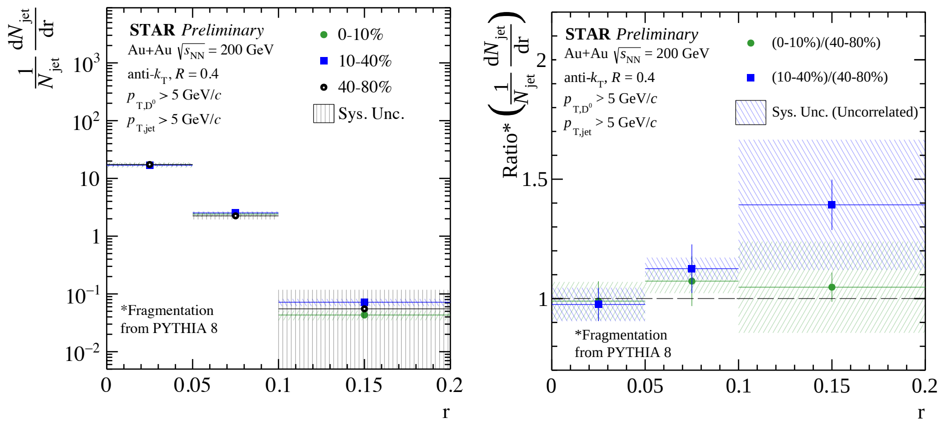

Fig. 3. **Left**: D^0 radial profile for $D^0(\bar{D}^0)$ jets with $p_{\mathrm{T,D^0}} > 5$ GeV/c in different centrality classes; **Right**: Ratio of D^0 radial profiles for central and mid-central events with respect to D^0 radial profile for peripheral events

The radial profile for $D^0(\bar{D}^0)$ mesons with $p_{\mathrm{T,D^0}} > 5$ GeV/c in the tagged jets is shown in Figure 3, as a function of the distance from the jet axis (r) in 0-10 %, 10-40 %, and 40-80% Au+Au collisions. The distribution is cut off at r = 0.2 to remove the non-closure bins. The ratio of the radial profiles for the central and mid-central events with the radial profile for peripheral events, shown in Figure 3, is found to be consistent with unity within the uncertainties.

4. Discussion

In this proceeding, the first measurements of D^0 meson tagged jet p_{T} spectra and D^0 meson radial profile is reported for $p_{\mathrm{T,D^0}} > 5$ GeV/c in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. The D^0 $p_{\mathrm{T,\,jet}}$ spectra is found to be suppressed for central and mid-central collisions, with the nuclear modification factor showing an interesting increasing trend with $p_{\mathrm{T,jet}}$, which is qualitatively different from inclusive jets. The radial profiles are found to be the same between different centrality bins, within large uncertainties dominated by limited statistics in the most peripheral centrality bin. Within the current uncertainties, no hint of differences in charm quark diffusion is observed in the presence of the QGP medium. A systematic study to understand the dependence of our unfolding procedure on the prior fragmentation function is underway. We also aim to extend our measurements to lower $p_{\mathrm{T,D^0}}$, accessible at STAR, to get closer to the charm quark mass. These measurements can constrain theoretical models on parton flavor and mass dependencies of jet energy loss.

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