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Study of a background reconstruction method for the measurement of D-meson azimuthal angular correlations

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Abstract We studied experimental background reconstruction methods for the measurement of the $D-\overline{D}$ correlation using PYTHIA simulation. The like-sign (LS) and side-band (SB) background methods, which are widely used in the experimental measurements of single D-meson production yields, were deployed for correlation study. It was found that the LS method, which describes the combinatorial background of single D^0 meson yields, fails to reproduce the correlated background in the $D^0-\overline{D^0}$ correlation measurement, while the SB background method yields a good description of the background for both single D^0 yields and the correlated background of the $D^0-\overline{D^0}$ correlation measurement. We further examined the validity of the correlation methods under different signal-to-background ratios, providing direct references for experimental measurements.

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1 Introduction

Quantum chromodynamics (QCD) is a theory that describes quarks, gluons, and the strong interaction between them. In QCD, heavy flavor quarks (c, b) are mostly produced through initial hard scattering in high-energy collisions of nucleons or nuclei. Because of their large masses, heavy quarks may offer a unique sensitivity for studying the cold and hot QCD medium created in these collisions [1–5]. In proton + proton ($p+p$) collisions, perturbative QCD (pQCD) calculations reproduce the inclusive heavy-flavor hadron-production cross-section data over a broad range of collision energies and rapidities [6–10]. The nuclear modification factor (R_{AA}) for charmed hadrons in heavy-ion collisions is significantly modified compared to the $p+p$ reference [11]. Several models with different energy-loss mechanisms can describe the experimental data [12, 13, 18, 19].

Recent research suggests that azimuthal correlations $\Delta\phi$ between heavy quark pairs offer a new insight about charm-medium interaction dynamics and therefore can help distinguish different energy-loss mechanisms in a hot QCD medium [14–17, 20]. The theoretical prediction indicates that pure radiative energy loss does not change the initial angular correlation function significantly, while pure collisional energy loss is more efficient at diluting the initial back-to-back charm pair correlation. Furthermore, the momentum broadening in the direction perpendicular to the initial quark momentum, which cannot be probed directly with traditional single-particle measurements (e.g.,

R_{AA} and elliptic flow parameter v_2), could be reflected in the azimuthal angle correlations [15, 21, 22].

In $p+p$ collisions, charm-quark pairs are produced through initial back-to-back hard scattering in leading order. In next-to-leading order, the angular correlation between charm-quark pairs widens. In particular, it will show a near-side peak at $\Delta\phi \sim 0$ if the charm pairs are produced through gluon splitting. The measurement of $D-\overline{D}$ correlations in $p+p$ collisions not only provides a baseline for measurements in heavy-ion collisions, but also offers a good constraint for pQCD calculations. D-mesons inherit most of the initial charm pair correlations, but weak decays smear the correlation significantly. Therefore, the measurement of $D-\overline{D}$ correlations should be the most sensitive probe for studying charm-quark pair correlations [23–25, 30].

The experimental reconstruction of the $D-\overline{D}$ azimuthal angular correlation is challenging. It requires the reconstruction of two charmed hadrons in a single event. Charmed hadrons must be reconstructed through their hadronic decay channels with small branching ratios. Furthermore, there is often a sizable background in each reconstructed charmed hadron. In single-charmed hadron yield measurements, for instance D^0 mesons through the $K^-\pi^+$ decay channel, several background methods, such as the like-sign (LS), side-band (SB), and mixed-event (ME) methods, were deployed by experimentalists [26, 27]. In the ME technique, background pairs are reconstructed using two daughter tracks from different events. Given that the tracks are produced in different events, the background reconstructed is uncorrelated with the foreground D^0 candidates. By mixing multiple events, this method has the advantage of reproducing the combinatorial background with good statistics. In the LS technique, the background is generated by pairing the daughter tracks with the same charge sign. It contains the produced background correlated in pairs with opposite charge signs in the same event. In the SB technique, opposite sign pairs with invariant masses away from the D^0 peak are used, two symmetric mass regions on both sides of the D^0 peak are usually selected, and the average of these regions is chosen to represent the background underneath the D^0 peak. Both LS and SB techniques can successfully reproduce the background in single D^0 yield measurements with reasonable precision.

In this study, we investigated these background reconstruction methods for the experimental measurement of $D-\overline{D}$ correlations. The ME technique misses the background correlation in the same event and typically needs to be normalized to either LS or SB distributions. In this study, we focused on the comparison of the LS and SB background techniques.

2 PYTHIA study for $D-\overline{D}$ correlations

The Monte Carlo event generator PYTHIA (version 8.168) was used in this study [28]. We focused on $p+p$ collisions at $\sqrt{s}$ = 500 GeV. The parameters were adjusted so that PYTHIA could reproduce the experimental data on the inclusive $c\bar{c}$ production cross section in $p+p$ collisions at 500 GeV, as measured by the STAR experiment at RHIC [29].

Figure 1 shows the $c\bar{c}$ production cross section as a function of the transverse momentum in PYTHIA in comparison with the STAR measurements. The modified PYTHIA parameters in this case were as follows: strong-interaction coupling constant (α_S) of the final parton shower (TimeShower:alphaSvalue) set to 0.15; minimum invariant transverse-momentum (p_T) threshold for hard QCD process (PhaseSpace:pTHatMin) set to 1.5 GeV/c. With this setting, PYTHIA properly describes both the magnitude and the p_T spectrum. It was also found that changing these two parameters has a negligible effect on charm correlations.

A sample of six-billion PYTHIA minimum bias events with this setting was generated for the $D^0-\overline{D^0}$ correlation study. D^0 mesons can be directly accessed in the PYTHIA simulation based on their particle identification number. To emulate the experimental measurement, D^0s were reconstructed by pairing the kaon and pion candidate pairs via the typical hadronic decay channel $D^0 \rightarrow K^- + \pi^+$ and its charge conjugate channel for $\overline{D^0}$. In a real experiment with a silicon vertex detector, many background tracks from the

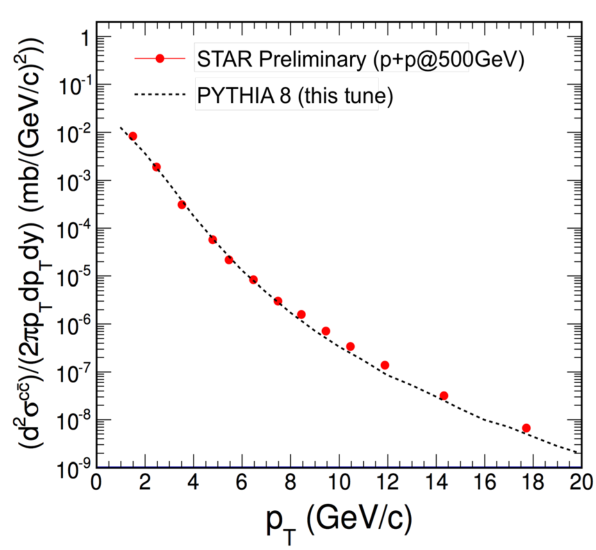

Fig. 1 (Color online) Charm-pair cross section as a function of transverse momentum in $p+p$ collisions at $\sqrt{s}$ = 500 GeV in PYTHIA (dashed line) compared with STAR measurements (solid circles)

primary collisions can be eliminated, but considerable background remains, particularly in the low p_T region.

In this study, we did not distinguish the secondary decay vertices in the D^0 reconstruction. Instead, we combined all kaons and pions at mid-rapidity ($|\eta| \leq 1$) in the final stage of the PYTHIA output. This allowed us to study the validity of the background reconstruction methods with different signal-to-background (S/B) ratios of the reconstructed D^0 candidates. The invariant masses of the unlike-sign (US) and (LS) kaon and pion pairs in the same event were calculated. A finite momentum resolution effect was included so that the reconstructed D^0 signal peak had the width observed in the experiment.

Figure 2 shows the $D^0(\overline{D^0})$ signal and the combinatorial background from the LS and SB methods. The LS and SB background regions are denoted by the blue and red hatched areas, respectively. The invariant mass distribution of $\overline{D^0}$ is almost identical to D^0 in both shape and magnitude. The background was found to be flat in PYTHIA within a relative wide invariant mass range. For simplicity, we denote $D^0(\overline{D^0})$ candidates from $K^-\ \pi^+(K^+\ \pi^-)$ pairs with unlike signs as 'US' candidates, and those from $K^-\ \pi^-$ or $K^+\ \pi^+$ pairs with same charge sign as 'LS' background. The SB background is denoted as 'SB'. Figure 2 shows that both the LS and SB methods can reasonably reproduce the real background underneath the reconstructed D^0 signals. For single-particle yield measurement, the D^0 and $\overline{D^0}$ counts were calculated from Eqs. 1 and 2 for the LS and SB background methods, respectively.

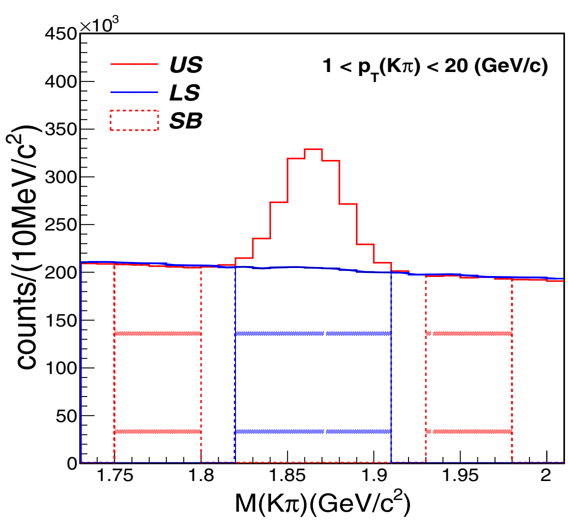

Fig. 2 (Color online) Invariant mass distribution of all final-stage kaon and pion pairs with opposite signs in PYTHIA data at mid-rapidity (shown by solid red line, US). The LS method reproduces the combinatorial background shown by the blue solid line. The blue shaded region shows the LS background within a $\pm 3\sigma$ window of the signal peak. The SB background regions are shaded in red

If the background methods work well for the $D^0 - \overline{D^0}$ correlation measurement, the correlation signal between D^0 and $\overline{D^0}$ can be derived using Eqs. 3 and 4. The asterisks (*) indicate the correlation functions between the pairs. We can also derive the $D^0 - \overline{D^0}$ correlation signal from the PYTHIA simulation directly and compare it to the reconstructed signals using these two background methods.

$$N_{\mathrm{LS}}^{D+\overline{D}} = \mathrm{US}(K^-\pi^+) + \mathrm{US}(K^+\pi^-) - \mathrm{LS}(K^-\pi^-) - \mathrm{LS}(K^+\pi^+) \quad (1)$$

$$N_{\mathrm{SB}}^{D+\overline{D}} = \mathrm{US}(K^-\pi^+) + \mathrm{US}(K^+\pi^-) - \mathrm{SB}(K^-\pi^+) - \mathrm{SB}(K^+\pi^-) \quad (2)$$

$$\begin{aligned} C_{\mathrm{LS}}^{D\overline{D}} = {} & \mathrm{US}(K^-\pi^+) * \mathrm{US}(K^+\pi^-) \\ & - \mathrm{LS}(K^-\pi^-) * \mathrm{US}(K^-\pi^+) \\ & - \mathrm{LS}(K^+\pi^+) * \mathrm{US}(K^+\pi^-) \\ & + \mathrm{LS}(K^-\pi^-) * \mathrm{LS}(K^+\pi^+), \end{aligned} \quad (3)$$

$$\begin{aligned} C_{\mathrm{SB}}^{D\overline{D}} = {} & \mathrm{US}(K^-\pi^+) * \mathrm{US}(K^+\pi^-) \\ & - \mathrm{SB}(K^+\pi^-) * \mathrm{US}(K^-\pi^+) \\ & - \mathrm{SB}(K^-\pi^+) * \mathrm{US}(K^+\pi^-) \\ & + \mathrm{SB}(K^-\pi^+) * \mathrm{SB}(K^+\pi^-), \end{aligned} \quad (4)$$

The di-hadron correlation measurements are usually plotted as a function of the azimuthal angle difference, i.e., $\Delta\phi = \phi_{D^0} - \phi_{\overline{D^0}}$. The upper panel in Fig. 3 shows the correlations between US candidates and the LS backgrounds as a function of $\Delta\phi$. The $p_T > 1.0$ GeV/c cut was set for both D^0 and $\overline{D^0}$ mesons, and the mass-window cuts for US, LS, and SB pairs are shown as colored bands in Fig. 2. The plot shows that the correlation between LS and LS background pairs (LS*LS) tends to peak at $\Delta\phi$ around 0 and that its magnitude is considerably larger than that between the LS background and US candidates (LS*US). The lower panel in Fig. 3 shows the results of the SB method with the same trigger p_T and *S/B* ratio as the LS method. The correlation between the SB background and US candidates lies between the other two correlation terms. The correlation between two SB background pairs shows a trend similar to that between the SB background and US candidates.

Figure 4 shows the reconstructed $D^0 - \overline{D^0}$ correlation signals with the LS and SB background methods in comparison with the real correlation signals from PYTHIA directly. Two sets of p_T cuts were imposed for the triggered and associated *D*-mesons, as shown in the upper and lower panels, respectively. Panels in two different columns show the comparisons with two different mass-window

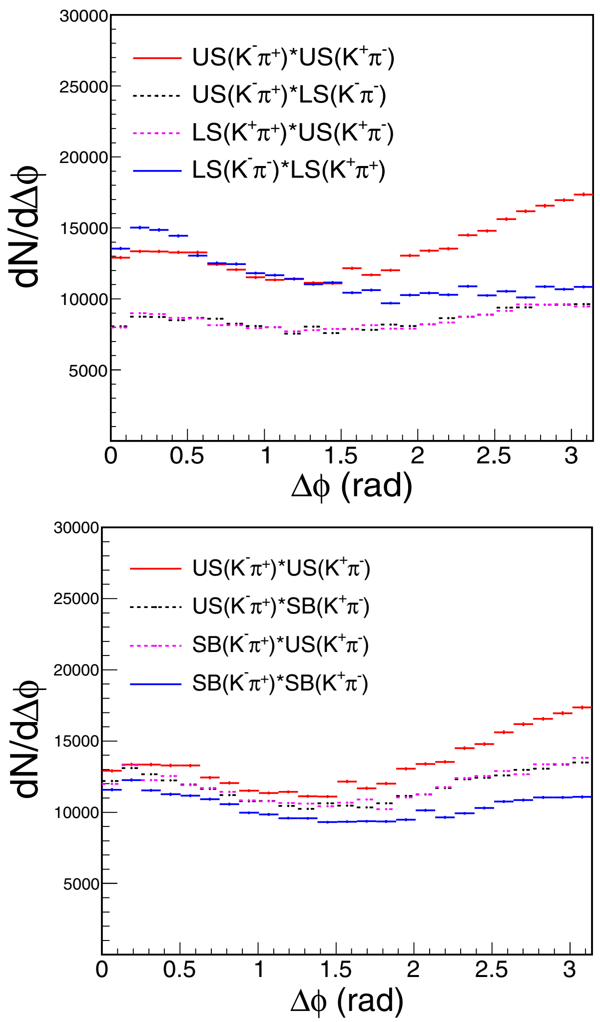

Fig. 3 (Color online) Upper Panel: cross-correlations of $D^0-\overline{D^0}$ from US candidates and LS backgrounds. The trigger and associated p_T cuts were both set to 1 GeV/c with a *S/B* ratio of approximately 0.3. Lower panel: similar results from the SB method

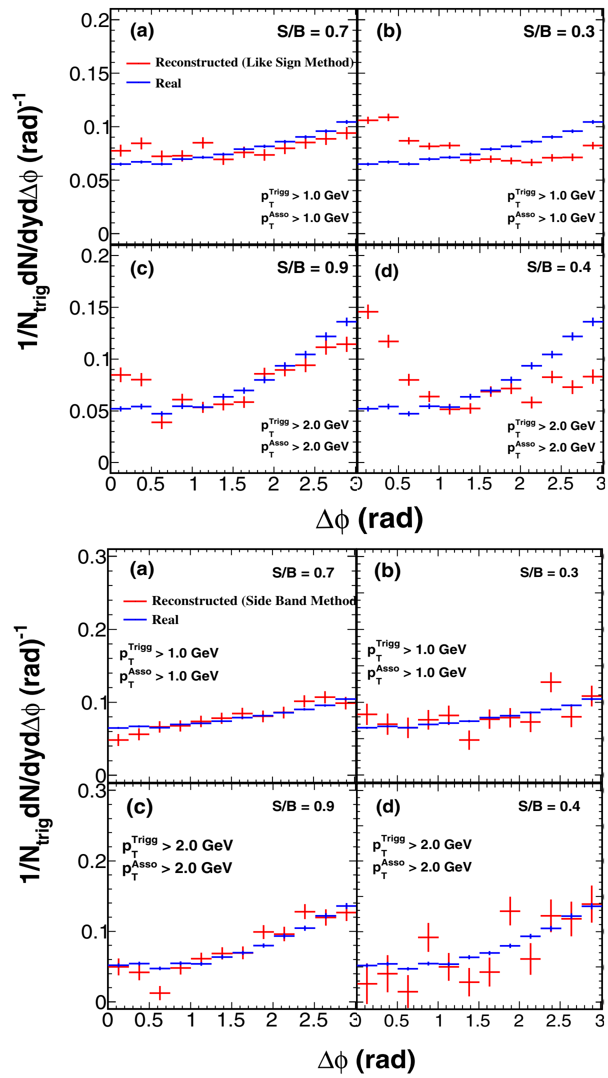

Fig. 4 (color online). $D^0-\overline{D^0}$ correlation as a function of the relative azimuthal angle $\Delta\phi$ in $p+p$ collisions at $\sqrt{s}$ = 500 GeV calculated using the LS method (upper panel) and SB method (lower panel) based on Eq. 3 in PYTHIA simulation. The transverse-momentum dependence is shown with p_T cuts applied to the triggered and associated D mesons. Panels (a)–(d) show correlations of reconstructed D^0 mesons under different *S/B* ratios in comparison with correlations of produced $D^0-\overline{D^0}$ pairs in PYTHIA

cuts, which result in different *S/B* ratios of the reconstructed D^0 candidates. The red data points represent the correlation signals from the reconstructed D^0 mesons, whereas the blue data points are the real D^0 correlations directly obtained from PYTHIA with the same kinematic cuts applied. Similar results from the SB method are presented in Fig. 4.

Note that the reconstructed correlations using the LS method are different from the real $D^0-\overline{D^0}$ signal from PYTHIA. In particular, the reconstruction correlations start to show an enhanced structure in the near-side region when the *S/B* ratio decreases. Reconstructed correlations using the SB method can reproduce the real $D^0-\overline{D^0}$ signal reasonably well in these kinematic and *S/B* ratio regions. In addition, the quality of the reproduction does not depend on the transverse-momentum cut. It depends on the *S/B* ratios of the D^0 candidates.

$$u_i = \left(\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi_i}\right)_{\mathrm{reco}}, \qquad v_i = \left(\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi_i}\right)_{\mathrm{real}} \tag{5}$$

$$\Delta P = \frac{1}{N}\sum_{i=1}^{k}\left|\frac{u_i - v_i}{v_i}\right|, \qquad \Delta E = \frac{1}{N}\sum_{i=1}^{k}\left|\frac{\sqrt{\sigma_{u_i}^2+\sigma_{v_i}^2}}{v_i}\right| \tag{6}$$

To better illustrate the performance of these two background methods in measuring the angular correlations of the $D-\overline{D}$ pairs, we introduced two variables to quantify the goodness of fit for the reconstructed correlation signals with respect to the real $D^0-\overline{D^0}$ correlations from PYTHIA. ΔP and ΔE are defined in Eq. 6 to describe the relative differences between the data points and the statistical errors from this sample. Note that u_i and v_i are the values of the number of i data points of the reconstructed and real correlation signals in each $\Delta\phi$ bin; N is the total number of data points in each correlation signal, assuming the same binning for the histograms. Figure 5 shows the corresponding results from the LS and SB methods, respectively. Note that ΔP in the LS results shows a large deviation from ΔE when the *S/B* ratio decreases, indicating that the LS method fails to reproduce the real correlation at relatively low S/B ratios. The SB method exhibits good performance throughout the entire *S/B* ratio region investigated. The increase in both ΔP and ΔE in the low *S/B* region for the SB method is due to the reduced statistics. We also studied the performance of the two background methods by considering D^0 from D^* decay and non-prompt D^0 from B-decay. The conclusions concerning the goodness of fit for both methods remain unchanged. Experimentally, as particle misidentification (Mis-PID) may affect the background reconstruction and cause double counting of the signals, we further evaluated such effects on the correlation reconstruction through a toy Monte Carlo simulation based on the PID criteria for $p+p$ collisions in STAR analysis [29]. We found that the mis-PID effect was significantly small ($<1\%$) in this case.

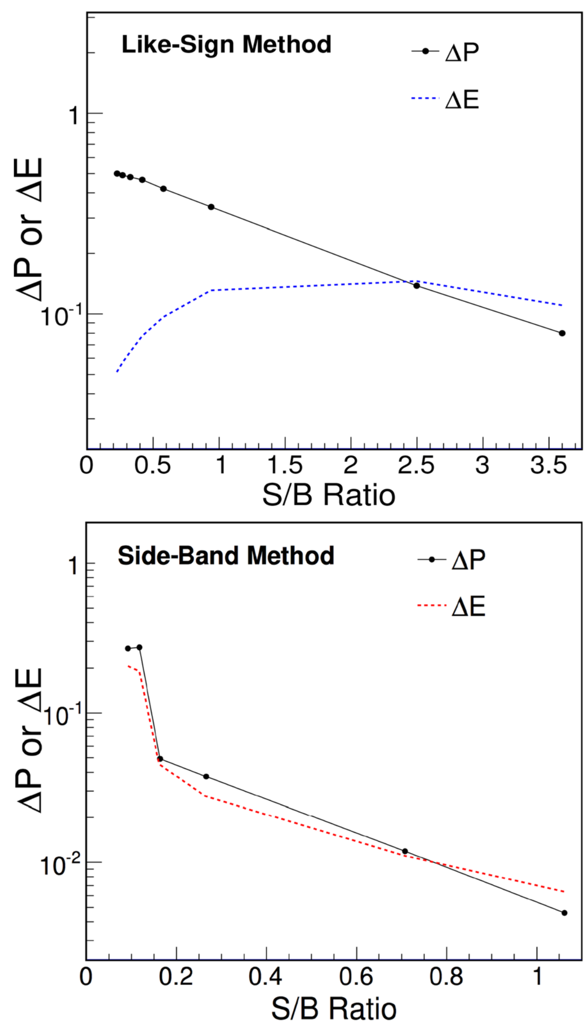

Fig. 5 (color online). Summary plots of the goodness of fit calculated using the LS method (upper panel) and SB method (lower panel) in the PYTHIA simulation. The estimator is shown as a function of the (*S/B*) ratio. The solid and dashed lines show ΔP and ΔE, respectively

In the LS method, when a $K^+\pi^+$ pair is selected, there is a higher probability of finding a $K^-\pi^-$ pair than another $K^+\pi^+$ pair because of local and global charge conservation. The reconstructed correlation signal after LS background subtraction from Eq. 3 should contain all correlations between $K^+\pi^-$ and $K^-\pi^-$ pairs, including the $D^0-\overline{D^0}$ correlation of interest, as well as the correlation due to charge conservation. To further demonstrate that the additional correlation observed in the LS method is related to the underlying event instead of the $D^0-\overline{D^0}$ signal, we turned off the D^0 hadronic decay process in the PYTHIA simulation and ran the same analysis.

Figure 6 shows the invariant mass distribution of pure $K\pi$ pairs without D^0 decay contribution. Cross-correlations between US/LS and LS/LS pairs are plotted in comparison with the US/US pair correlations in Fig. 7 with different cuts applied to the invariant mass region. Similarly, results

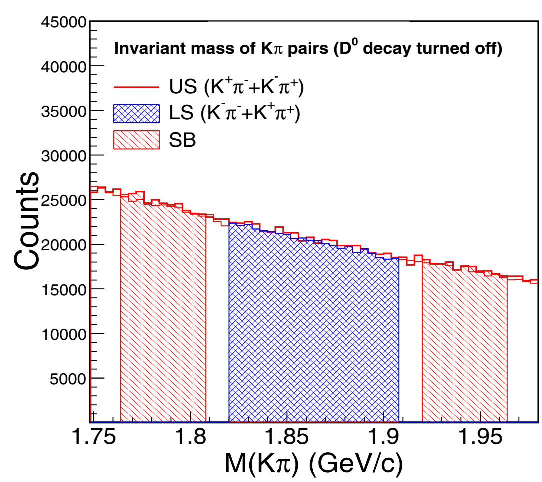

Fig. 6 (Color online) Invariant mass distribution of pure $K\pi$ pairs in PYTHIA. The $D^0\to K\pi$ hadronic decay process was turned off. Red line: US $K\pi$ pairs. Blue hatched area: LS $K\pi$ pairs within cut window. Red shaded area: SB $K\pi$ pairs within cut window

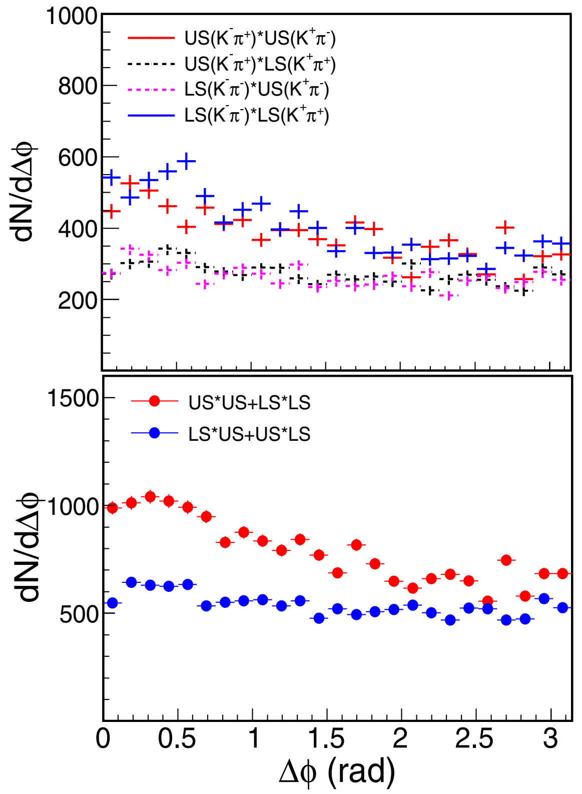

Fig. 7 (Color online) Cross-correlations of the pure LS and US $K\pi$ pairs in the LS method

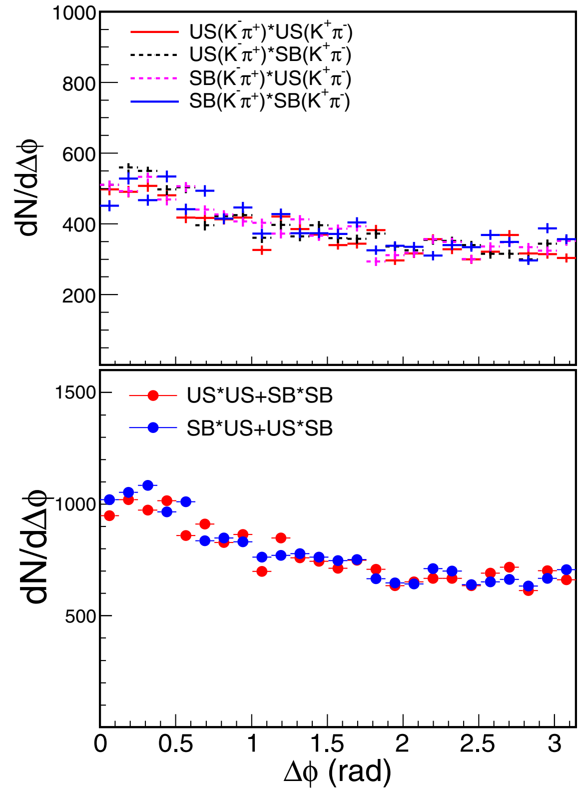

Fig. 8 (Color online) Cross-correlations of SB and US $K\pi$ pairs in the SB method

from the SB method are shown in Fig. 8. There is a large difference between the LS*US and US*US pair correlations, while there is very a small difference between LS*LS and US*US. This is consistent with our understanding that there is an additional correlation that is not originated from the $D^0-\overline{D^0}$ pairs.

The SB method is not affected by charge conservation. Note that all cross-correlations fall in the same trend, and there is no remaining $K^+\pi^-$–$K^-\pi^+$ correlation when the $D^0 \to K^+\pi^-$ decay is turned off.

3 Conclusion

In summary, we studied background reconstruction methods for azimuthal correlations between D^0 and $\overline{D^0}$ pairs using a PYTHIA simulation.

Both the LS and SB methods provide a good description of the background when reconstructing single D^0 yields. However, when reconstructing the correlation signal, the LS method fails to reproduce the $D^0-\overline{D^0}$ correlation. The residual correlation after the LS background subtraction mainly comes from the underlying event activity, likely due to local or global charge conservation. We demonstrate that the SB method performs well in describing the correlation background and therefore reproduces the original $D^0-\overline{D^0}$ correlation in the S/B rate regions investigated. The upcoming sPHENIX experiment at RHIC will explore the charm correlation in $p+p$ and Au+Au collisions by measuring the $D-\overline{D}$ azimuthal correlation with full reconstruction of D-mesons through their hadronic decay channels. Our study on correlation methods constitutes an important reference for future experimental measurements.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Long Ma. The first draft was written by Xin Dong. Revisions of the manuscript were made by Huan-Zhong Huang and Yu-Gang Ma. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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