TWO-PARTICLE CORRELATIONS IN HADRONIC e^+e^- COLLISIONS AT BELLE AND THEIR IMPLICATION*

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We present the measurement of two-particle correlations in hadronic e^+e^- collisions data collected by the Belle detector at KEKB. The clean e^+e^- collision system is conducive to the unambiguous investigation of the azimuthal anisotropy of final-state charged particles found in various heavy-ion and proton–proton collisions. High-statistics Belle datasets at the center-of-mass energies of $\sqrt{s} = 10.52$ GeV (89.5 fb^{-1}) and 10.58 GeV on the $\Upsilon(4S)$ resonance (333.2 fb^{-1}) are analyzed. The larger statistics also enable the study of very rare events of the multiplicity distribution tail. Measurements are reported as a function of the charged-particle multiplicity over the full relative azimuthal angle ($\Delta\phi$) and three units of pseudorapidity ($\Delta\eta$). Correlation functions calculated in two coordinate systems with respect to different reference axes — the conventional beam axis and the event thrust axis — are measured. The thrust-reference-axis coordinate is the more natural representation for e^+e^- annihilating into a quark–antiquark pair for providing sensitivity to the color activity emitted transversely to the diquark fragmentation. In this paper, we also present a qualitative understanding of the measured correlation structure based on the Monte Carlo simulations. We will discuss the correlations for jet fragmentation in this low-energy regime and for the special scenario of $b\bar{b}$ bound state decays.

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1. Introduction

Two-particle correlation studies in heavy-ion and proton–proton (pp) collision systems have long discovered a novel phenomenon — there is an excess of particle correlations in the close azimuth (often referred to as the "ridge correlation"). In this work, we work on understanding such anisotropy using the rather clean system colliding the elementary electron and positron. Following up on the first examination in e^+e^- annihilation events using the small archived ALEPH dataset [1], we report on the first measurement of two-particle angular correlation functions in high-multiplicity e^+e^- annihilation events at $\sqrt{s} = 10.52$ GeV and 10.58 GeV data recorded by the Belle detector, corresponding to about 89.5 fb^{-1} and 332.2 fb^{-1} of integrated luminosity, respectively. The $\sqrt{s} = 10.58$ GeV collision data is targeted at the $\Upsilon(4S)$ resonance and referred to as the "on-resonance data", with about one-fourth of the events decaying from $\Upsilon(4S)$ states into $B\bar{B}$ mesons. The other dataset is 60 MeV below the resonance, named "off-resonance data" in this analysis, and mostly composed of quark pairs fragmenting into hadrons. Those are tests of the existence of ridge-like signals without complications from initial states. In addition, we use simulations to better understand the correlation structure and a comparison of the expectations from different event generators, offering insights into the fragmentation models and a deeper look into the explanation of two-particle correlation. Comprehensive results are released in Ref. [2].

2. Detector and sample

The Belle experiment is configured with asymmetric 8 GeV electron and 3.5 GeV positron beams. Data are collected with the Belle detector [3, 4], which is a large-solid-angle magnetic spectrometer consisting of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprising CsI(Tl) crystals, all located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return surrounding the coil is instrumented to detect K_L^0 mesons and muons.

The EvtGen [5]- and PYTHIA 6 [6]-based Belle MC sample is used as the simulation of e^+e^- annihilation events, including hadronic $q\bar{q}$ ($q = u, d, s$, and c) fragmentation, $\Upsilon(4S)$ decays, radiative Bhabha events, low multiplicity $e^+e^- \to l^+l^-$ ($l = e$ or μ), and two-photon processes. This MC dataset is used to study reconstruction inefficiencies and to derive efficiency correction factors for the data.

3. Two-particle correlations

To measure two-particle correlation functions, we first perform a boost back into the e^+e^- center-of-mass frame. In this work, we measure two-particle correlations using the "beam axis coordinates" and the "thrust axis coordinates". The correlation results for the multiplicity range $N_{\rm trk}^{\rm rec} \geq 12$ are shown in figure 1. A projection of correlations to the particle pairs' azimuthal angle difference $\Delta\phi$ is also studied in three $\Delta\eta$ regions: short range ($|\Delta\eta| < 1$), middle range ($1 \leq |\Delta\eta| < 1.5$), and long range ($1.5 \leq |\Delta\eta| < 3.0$).

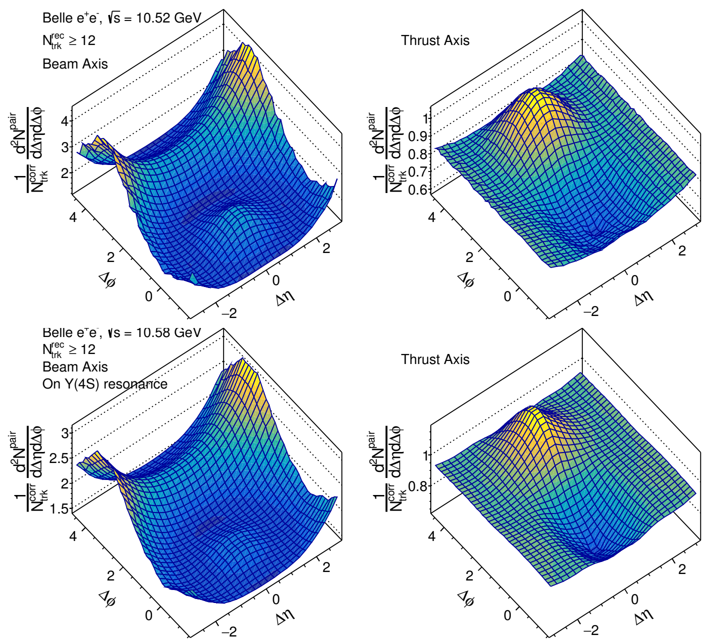
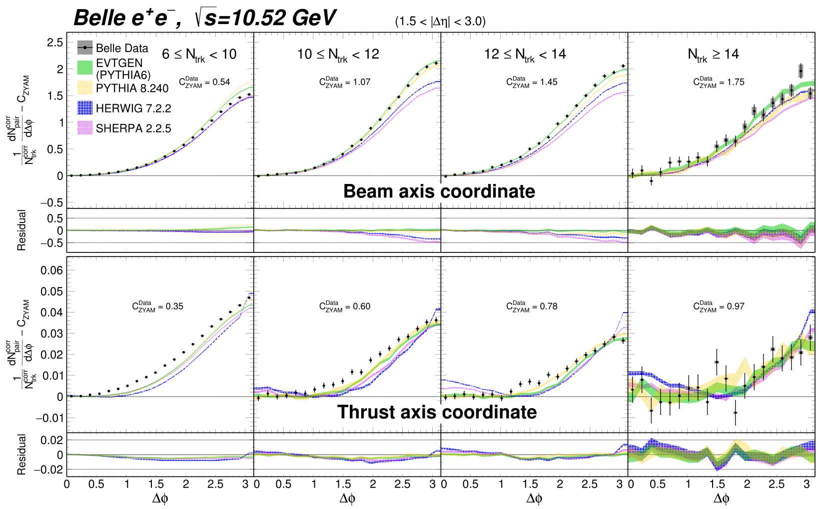


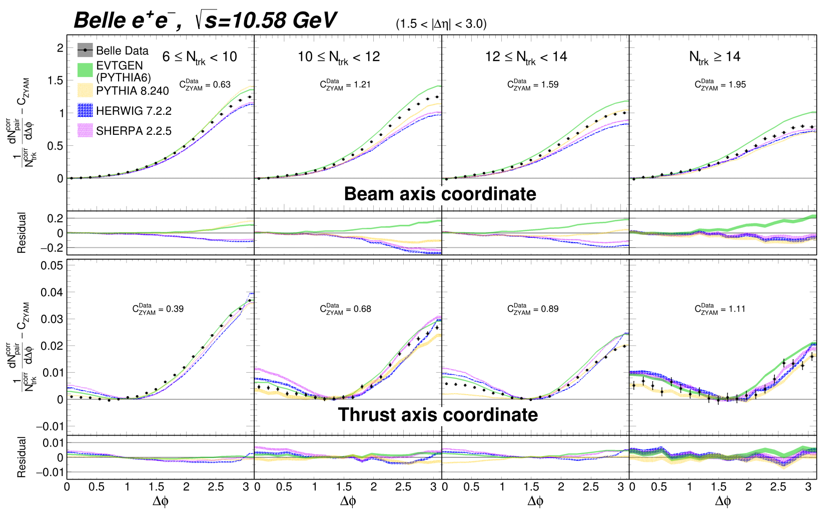
Fig. 1. Two-particle correlation functions for the off-resonance data (top) and the on-resonance data (bottom). For each result, the beam (left) and thrust (right) axis analyses with the multiplicity $N_{\rm trk}^{\rm rec} \geq 12$ are shown.

4. Studies with event generators

We provide the off-resonance and on-resonance results in full multiplicity analysis ranges comparing data with PYTHIA 6-based Belle MC, PYTHIA 8.240 [7], Herwig 7.2.2 [8], and Sherpa 2.2.5 [9] event generators for long-range azimuthal differential associated yields after subtracting off a flat correlation. Figure 2 displays the results.



(a) off-resonance



(b) on-resonance

Fig. 2. (Color online) Comparison of the azimuthal differential yields after subtracting off a flat correlation in the range of $1.5 \leq |\Delta\eta| < 3.0$ for beam (top) and thrust (bottom) axis analyses as a function of the charged-particle multiplicity in e^+e^- collisions at Belle. The colored bands show simulation predictions from PYTHIA 6 (green), PYTHIA 8 (yellow), Herwig (blue), and Sherpa (violet). Reconstruction effects on data (data points) are corrected, with error bars representing associated statistical uncertainties, and the gray boxes the systematic uncertainties. For visual purposes, the minimal statistical uncertainties of the MC correlation colored bands are set to be 0.4% of the plotting ranges, and residual panels have minimum thresholds of 3% of the plotting ranges.

The result with Belle data in the thrust axis analysis lacks a significant origin-peak correlation, as shown in figure 1. We study this behavior with the Sherpa event generator, simulating e^+e^- annihilation events with collision energies ranging from 10.52 GeV up to the Z-pole energy. The initial-state radiation is turned off in this simulation. A consistent evolving trend of the magnitude of the origin-peak correlation is seen with increasing collision energy for every multiplicity interval. Under the picture in the thrust axis analysis, the main contribution to the origin-peak correlation is from jets fragmenting in the transverse direction of the event thrust axis. Increasing the collision energy can also make these jets more energetic.

We observe an enhancement of long-range near-side correlations in the thrust-axis analysis with the on-resonance data, as shown in figure 2 (b). The MC simulation also reproduces a similar order of long-range near-side excess. However, the enhanced structures seen for these B-decay events (or the on-resonance sample) have an intrinsic difference in shape from those reported with heavy-ion collisions. Recall for the latter, the typical ridge structure is an elongated feature spanning a wide pseudorapidity range, but the enhancement seen in the B-decay event sample is only located in the long-range regions. To understand the long-range near-side enhancement in the B-decay events under the thrust axis analysis, a decomposition study of the correlation contribution among two B mesons is performed. We examine the correlation function with track pairs selected specifically from single B-meson decay products, and the cross-correlations between different B-mesons' decay products.

Distinct patterns in the two-particle correlation functions are observed under these two circumstances. The sizable enhancement in the long-range near-side region is seen exclusively in the correlation function calculated by track pairs from different B mesons. It is because the derived event thrust axis for the two-B-decay event has a large probability to lie in the plane formed by two B mesons' main decay directions. The special circumstances further make most of the constituents sit on either ϕ or $\pi + \phi$, yielding aggregated correlation at $\Delta\phi \approx 0$ or $\Delta\phi \approx \pi$. The sculpted ridge signal in the B-decay events (or the on-resonance sample) should be a consequence of the special event topology and thrust axis alignment in two B-meson decay systems.

5. Summary

We report on results of two-particle correlations in both the beam and thrust axis coordinate systems performed on datasets of e^+e^- to hadronic final states at $\sqrt{s} = 10.52$ GeV and $\sqrt{s} = 10.58$ GeV. The thrust-axis correlation function distribution is different from measurements in hadron collisions and high-energy e^+e^- collisions in its shape, with the significant near-side peak structure, interpreted as intra-jet correlation, not being seen. We further characterize the evolution of the near-side-peak correlation magnitude using the Sherpa event generator from low-energy collisions towards the high collision energies and understand the disappearance of the near-side-peak correlation.

The two-particle correlation measurement with the $\Upsilon(4S)$ on-resonance dataset is presented for the first time. A low-scaled long-range near-side enhancement is observed in data for the thrust-axis two-particle correlations. However, this enhancement is different from the more familiar elongated ridge structure over a broad $\Delta\eta$ range as reported in pp collisions and heavy-ion experiments. Monte Carlo simulations can qualitatively replicate these new features of the on-resonance correlation data. It is concluded that such a special topological arrangement within a decay system can give rise to such correlations.

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