PROCEEDINGS OF SCIENCE

Search for long range flow-like correlation in hadronic e^+e^- collisions with Belle

Cheng-Wei Lin,[a] **Yu-Chen Chen,**[a,†,*] **Yen-Jie Lee**[a,b] **and Paoti Chang**[a]

[a] *National Taiwan University, Taipei, Taiwan*

[b] *Massachusetts Institute of Technology, Cambridge, USA*

E-mail: willylin@hep1.phys.ntu.edu.tw, janicechen@hep1.phys.ntu.edu.tw, yenjie@mit.edu, pchang@phys.ntu.edu.tw

The enhancement of charged-particle pairs with large pseudorapidity difference and small azimuthal angle difference, often referred to as the "ridge signal", is a phenomenon widely observed in high multiplicity proton-proton, proton-ion and deutron-ion collisions, which is not yet fully understood. In heavy-ion collisions, the hydrodynamic expansion of the Quark-Gluon Plasma is the most popular explanation of the ridge signal. Measurements in the e^+e^- collision system, without the complexities introduced by hadron structure in the initial state, can be a new opportunity to examine the formation of a ridge signal. The first measurement of two-particle angular correlation functions in high multiplicity e^+e^- collisions at $\sqrt{s} = 10.52$ GeV is reported. About 31.5 fb^{-1} hadronic e^+e^- annihilation data collected by the Belle detector at KEKB are used in this study. Two-particle angular correlation functions are measured over the full azimuth and large pseudorapidity intervals which are defined by either the electron beam axis or the event thrust as a function of charged particle multiplicity. The measurement in the event thrust analysis, with mostly quark and anti-quark pairs determining the reference axis, is sensitive to soft gluon emissions associated with the outgoing (anti-)quarks. No significant ridge signal is observed with analyses performed in either coordinate system. Near-side jet correlations appear to be absent in the thrust axis analysis. The measurements are compared to predictions from various e^+e^- event generators and expected to provide new constraints to the phenomenological models in the low collision energy regime.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

*Speaker
†For the Belle collaboration.

PoS(ICHEP2020)541

The measurement of two-particle angular correlation functions is a well-established observable for the study of Quark-Gluon Plasma (QGP) formation in nucleus-nucleus collisions [1–4]. A ridge-like structure for particle pairs having large differences in pseudorapidity ($\Delta\eta$, where $\eta = -\ln\tan\theta/2$ with the polar angle θ defined relative to the counterclockwise beam), but small differences in azimuthal angle ($\Delta\phi$), has been observed in such collisions. For nucleus-nucleus collisions, this signal is interpreted as the consequence of the hydrodynamical expansion of the QGP with fluctuations of the initial density, or the initial azimuthal anisotropy of the fireball in non-central events [5, 6]. The ridge-like signal was also observed in high charged-particle multiplicity events in proton-proton, proton-nucleus, deuteron-nucleus and helium-nucleus collisions [7–15]. However, the physical origin of the ridge signal in these smaller collision systems is not yet understood [16, 17]. In hadron-initiated collision systems, the complexity introduced by initial states cannot be easily factored out. A large number of theoretical models based on different underlying mechanisms such as partonic initial state correlations [18], final-state interactions [19, 20] and hydrodynamic medium expansion [21] have been proposed to explain the observed ridge-like signal in small collision systems. The measurement of high charged-particle multiplicity events originating from the two-quark system could offer significant insights into the origin of the ridge-like signal [22]. Recently, experimental studies have been extended to even smaller collision systems such as electron-ion [23] and electron-position (e^+e^-) [24] collisions. No significant ridge-like signal was observed in these measurements. Taking advantage of the clean environment in e^+e^- collisions and high-statistics data collected with the Belle detector at KEKB, the analysis is performed for the first time at a center-of-mass energy of $\sqrt{s} = 10.52$ GeV, which is 60 MeV lower than the $\Upsilon(4S)$ resonance.

In this study, a data sample of 31.5 fb^{-1} collected by the Belle detector [25] is analyzed. Hadronic event selections [26], including requirements on event multiplicity and energy sum in the electromagnetic calorimeter, are adopted to suppress contaminations from two-photon, radiative Bhabha and other QED events. Particles used in the calculation of the correlation functions are primary charged-particle tracks, defined as prompt tracks or decay products of intermediate particles with proper lifetime $\tau < 1$ cm$/c$. The corresponding requirement on real data is $V_r < 1$ cm, where V_r is the distance in the transverse plane of the decay vertex from the primary vertex.

To eliminate the effects of the nonuniform detection efficiency and misreconstruction bias, efficiency correction factors are derived with the EvtGen [27] and pythia [28] based Belle Monte Carlo (MC) samples, which include simulated hadronic $q\bar{q}$ ($q = u, d, s, c$) fragmentation as well as low multiplicity $e^+e^- \to \tau^+\tau^-$ and two-photon processes. The details of particle selection treatments and analysis scheme are described in [29]. Intervals of offline multiplicities, denoted $N_{\mathrm{Trk}}^{\mathrm{Offline}}$, in which results are classified, and their corresponding average multiplicities after efficiency correction $\langle N_{\mathrm{Trk}}^{\mathrm{Corr}}\rangle$ are listed in Table 1.

The two-particle correlation function is explored in two coordinate systems – beam and thrust axis coordinates in the e^+e^- center-of-mass frame. In the viewpoint of relativistic fluid dynamics [30], conventional measurements in beam axis coordinates are sensitive to their transverse directions, probing any anisotropic behaviour in the QCD medium, which are widely studied as the phenomena of elliptic or triangular flow [6, 31, 32]. In the e^+e^- annihilation process, when the interacting system is located in between or along the color string connecting the $q\bar{q}$, measuring with a coordinate system defined by the event thrust axis provides a more direct picture. In Fig. 1, correlation functions with offline charged particle multiplicity $N_{\mathrm{Trk}}^{\mathrm{Offline}} \geq 12$ are shown for both

Table 1: Average multiplicities and corrected multiplicities of different $N_{\mathrm{Trk}}^{\mathrm{Offline}}$ intervals.

$N_{\mathrm{Trk}}^{\mathrm{Offline}}$ interval	Fraction of data (%)	$\langle N_{\mathrm{Trk}}^{\mathrm{Offline}} \rangle$	$\langle N_{\mathrm{Trk}}^{\mathrm{Corr}} \rangle$
$6 \leq N_{\mathrm{Trk}}^{\mathrm{Offline}} < 10$	43.56	6.97	7.05
$10 \leq N_{\mathrm{Trk}}^{\mathrm{Offline}} < 12$	2.58	10.26	10.12
$12 \leq N_{\mathrm{Trk}}^{\mathrm{Offline}} < 14$	0.28	12.20	11.88
$N_{\mathrm{Trk}}^{\mathrm{Offline}} \geq 12$	0.29	12.32	11.99
$N_{\mathrm{Trk}}^{\mathrm{Offline}} \geq 14$	0.02	14.22	13.72

beam and thrust axis coordinates. In the beam axis coordinate view, the peak near the origin $(\Delta\eta, \Delta\phi) = (0, 0)$ has contributions from pairs originating in the same jet, while the structure at $\Delta\phi \approx \pi$ is from back-to-back correlations. The particles in e^+e^- collisions mainly come from dijet-like $q\bar{q}$ events. In contrast, for the thrust axis coordinates, the dominant structure is the hill-like bump near $(\Delta\eta, \Delta\phi) \approx (0, \pi)$, while a sizeable near-side correlation is lacking. Investigations by simulations tuned from $\sqrt{s} = 10.52$ GeV to 50 GeV show the magnitude of the near-side peak in the correlation function is strongly correlated with the collision energy when presented under thrust axis coordinates.

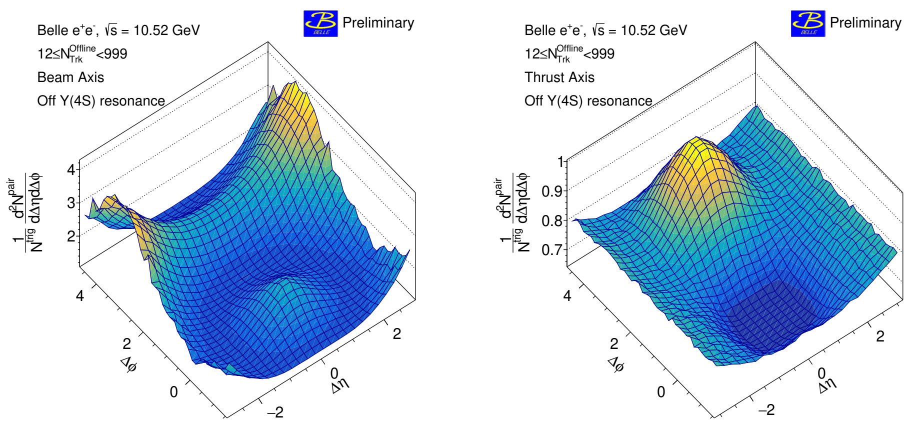

Figure 1: Two-particle correlation functions for beam (left) and thrust (right) axis analyses with offline multiplicity $N_{\mathrm{Trk}}^{\mathrm{Offline}} \geq 12$.

Fig. 2 shows the measurement of projected correlation $Y(\Delta\phi)$ in the long-range region $(1.5 \leq |\Delta\eta| < 3.0)$ after the "zero yield at minimum"(ZYAM) method [33], along with the comparison of predictions from PYTHIA 6.205 based Belle MC, HERWIG 7.1.5 [34] and SHERPA 2.2.5 [35] event generators. In the beam axis coordinates, all generator expectations are consistent with data in the near-side ridge region, but deviate in the away-side region. Under the thrust axis analysis, the Belle simulation, with specific tunes subjected to Belle data, gives a better description of data. A larger discrepancy from data is seen in the HERWIG simulation, especially in the near-side ridge-prone region and away-side region, hence a conclusion similar to that reported in [24] based on the analysis of ALEPH archived data.

Since no significant ridge yield is observed in either beam or thrust axis analysis, a bootstrap

PoS(ICHEP2020)541

procedure [36] is implemented and the 95% confidence limit of the integrated ridge yield is reported. For results with scarce ridge signal, an over 5σ significance level for measuring less than 10^{-7} ridge yield is quoted, instead. The upper limits as a function of $\langle N^{\rm Corr}_{\rm Trk}\rangle$ are shown in Fig. 3.

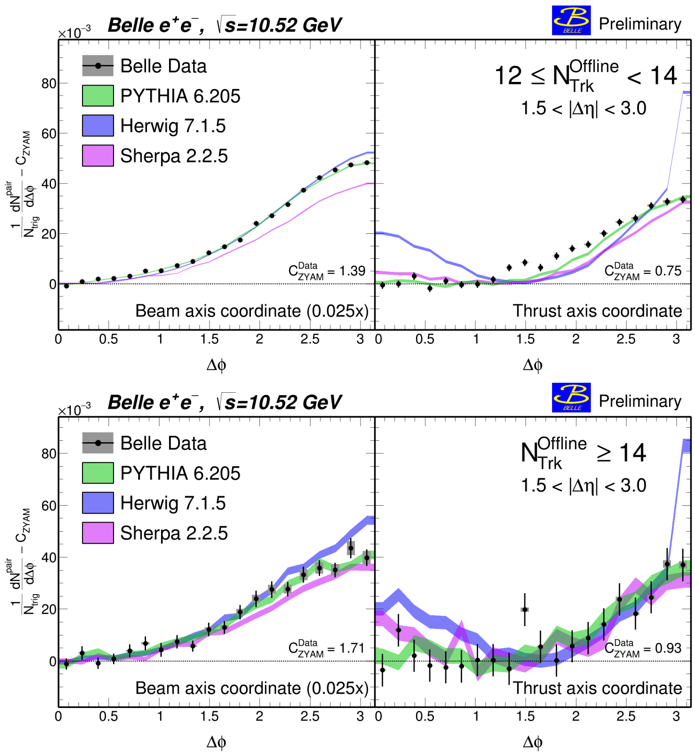

Figure 2: Comparison of ZYAM-subtracted $Y(\Delta\phi)$ in the range $1.5 \leq |\Delta\eta| < 3.0$ for beam (left) and thrust (right) axis analyses. The colored bands show simulation predictions from PYTHIA (green), HERWIG (blue) and SHERPA (violet). The error bars on the data represent the statistical uncertainties, and the gray boxes are systematic uncertainties.

In summary, the first measurement of two-particle correlation function in hadronic e^+e- collisions at $\sqrt{s} = 10.52$ GeV is reported. No significant ridge-like structure in either beam or thrust axis analysis is observed in the Belle dataset. Similar to the conclusion from the previous analysis with ALEPH archived data, the results in this study are found to be better described by PYTHIA and SHERPA than HERWIG.

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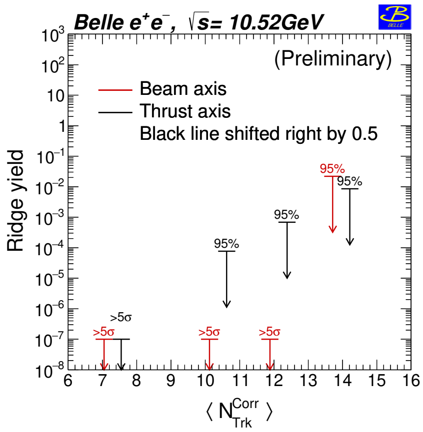

Figure 3: Upper limits on the ridge yield as a function of $\langle N_{\mathrm{Trk}}^{\mathrm{Corr}} \rangle$ in beam axis coordinate (red) and thrust axis coordinate (black) frames. Thrust axis data have been shifted right by 0.5 for presentation purposes. The label "$> 5\sigma$" indicates the 5σ confidence level upper limit.

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PoS(ICHEP2020)541