PROCEEDINGS OF SCIENCE

Study of fragmentation functions in e^+e^- annihilation process at Belle

Marko Bračko[*†,a], **Ralf Seidl**[b]
[a] *University of Maribor, Maribor, and Jožef Stefan Institute, Ljubljana, Slovenia*
[b] *RIKEN, Wakoshi, Japan*
E-mail: marko.bracko@ijs.si, rseidl@riken.jp

The e^+e^- annihilation process provides an access to the fragmentation functions due to its clean environment. In this report we give a short overview of selected fragmentation studies, which were performed on the data sample accumulated by the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The main part of this document focuses on the description of the recent unpolarized di-hadron fragmentation study, where preliminary di-hadron cross sections for various hadron and charge combinations were extracted as a function of the fractional energies z of the two hadrons from a data sample of 655 fb^{-1} collected with the Belle detector. The study indicates that the hadron pairs detected in the same hemisphere of the detector predominantly come from the fragmentation of a single parton, while opposite hemisphere di-hadrons appear to be from different partons. We also present comparisons of these preliminary cross-section measurements to various PYTHIA tunes.

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[*] Speaker.
[†] On behalf of the Belle Collaboration.

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1. Introduction

Fragmentation functions (FFs) describe the process in which high-energetic, asymptotically free partons fragment into confined, final state hadrons. Since fragmentation functions have to absorb some long-distance physics effects of the strong interaction, QCD, the FFs are by definition non-preturbative quantities, and can not be calculated from first principles. Instead, information about FFs needs to be extracted from measurements. Preferably this is done by a global QCD analysis, which combines results obtained in different processes, like electron-positron annihilations, proton-proton collisions and semi-inclusive deep-inelastic lepton-nucleon scattering.

The most straightforward way to gather information on FFs comes from the inclusive single-hadron cross sections extracted in electron-positron annihilations, as there are no hadrons in the initial state of those processes. Such measurements were performed at various energies, recently also at the B-factories [1, 2], yielding high-precision measurements also at high values of relative hadron energy with respect to a center-of-mass energy, $z = 2E_h/\sqrt{s}$. These precise measurements from B-factories were used recently in a new, comprehensive global analysis of parton-to-pion fragmentation at next-to-leading-order accuracy [3].

However, there is some information, which is difficult to access via measurements of single-hadron cross sections at electron-positron annihilation. As any quark-antiquark pair with an invariant mass below the center-of-mass energy $\sqrt{s}$ can be produced at the e^+e^- annihilations, the flavor dependence of fragmentation functions can not be directly obtained in these measurements. Moreover, it is also not possible to determine whether the measured hadron originated from the fragmentation of a quark or an antiquark. Some flavor dependent information can be gathered from semi-inclusive deep-inelastic scattering and proton-proton collision measurements by using the reasonable knowledge on parton distributions functions but due to the proton in the initial state one is generally most sensitive to up-quark type fragmentation.

2. Measurement of unpolarized di-hadron fragmentation in e^+e^- annihilation

With a new approach, which follows the method used to access the spin-dependent fragmentation functions at Belle [4, 5], some of the above limitations can be overcome. This is possible by studies of the pairs of detected hadrons—especially in opposite hemispheres, as defined by the thrust axis $\hat{n}$, which maximizes the event shape variable thrust $T = \max\{\sum_h |\mathbf{p}_h^{CMS} \cdot \hat{\mathbf{n}}| / \sum_h |\mathbf{p}_h^{CMS}|\}$. Favored fragmentation describes the fragmentation into a hadron with a valence (anti-)quark similar to the initial (anti-)quark[1], such as $u \to \pi^+$, $\overline{d} \to \pi^+$, while disfavored fragmenation refers to the opposite fragmentation processes, such as $u \to \pi^-$, $\overline{d} \to \pi^-$. For example, from initial $u\overline{u}$ or $d\overline{d}$ pairs two charged pions with opposite charge can be created either in two favored fragmentation processes or two disfavored fragmentation processes. On the other hand, from the same quark pairs, when same-sign charged pion pars are selected, one of these two pions has to be created through favored fragmenation while the other through disfavored fragmentation. In order to extract as much fragmentation information as possible, all six distinctive combinations of charged pion and kaon pairs were therefore studied separately in the analysis reported here.

[1]Throughout the document, charge-conjugated modes are included in all decays, unless explicitly stated otherwise.

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2.1 Analysis details

A data set of 655 fb^{-1}, collected with the Belle detector at the center-of-mass energy of 10.58 GeV was analyzed for the di-hadron cross sections. Events were selected, if at least three charged tracks were found in the Belle detector and a total visible energy of more than 7 GeV was seen in order to reduce $e^+e^- \to \tau^+\tau^-$ events. In order to select hadron pairs, pions and kaons in the Belle barrel acceptance were identified using the information from the central drift chamber, the time-of-flight and the aerogel Čerenkov counters as well as resisitive plate counters in the return yoke. These detectors as well as the rest of the Belle detector are in more detail described elsewhere [6]. The identities of selected charged particles were determined from particle identification (PID) detectors, and then corrected for mis-identification using particle mis-identification matrices. These matrices were determined with a fine-binning in both, laboratory momentum and polar angle of particles, which were studied in decays where the particle type could be inferred without the use of the PID information from the dedicated detectors. The resulting raw yields for all distinctive di-hadron combinations were binned in 16×16 ($z_1 \times z_2$) bins, defined in the interval between 0.2 and 1.0 for each of the fractional momenta z_1 and z_2. Yields for three hemisfere combinations were studied separately, depending on whether the two hadrons were found in the same or the opposite hemisphere as given by the thrust axis in the events with the value of thrust $T > 0.8$; and irrespective of the thrust axis in all other events. Momentum smearing was corrected for by using GEANT simulations and unfolding the momentum smearing matrices by a Single Value Decomposition (SVD) unfolding technique [7].

As the next step in the correction chain from the raw yields to the final di-hadron cross sections, the contributions not originating from initial quark-antiquark pairs were removed. The relevant processes are $e^+e^- \to \tau^+\tau^-$ production, resonant $\Upsilon(4S)$ production and two-photon processes $e^+e^- \to e^+e^-q\bar{q}$. The contributions were obtained from dedicated simulations and amount to up to $\sim 20\%$ at low-z values due to the Υ decays—especially for kaon combinations—and up to 50% for pions at high-z values due to τ-pair production. Several acceptance and reconstruction inefficiencies also required some corrections. Those were separated into one within the barrel detector acceptance region, and are predominantly due to reconstruction and pre-selection efficiency, the total acceptance in 4π space angle, and an extrapolation towards small polar angles, which was not perfectley described in generated MC simulations. At intermediate z-values, the overall correction is relatively flat at around a factor of 2-3, while increasing substantially towards high-z values, where the reconstruction efficiency drops substantially due to the requirement of at least three tracks. Weak decay can be removed based on the MC information; however, these decays are still kept in the results shown below. As a last correction, the effects of initial state radiation are addressed by evaluating in the MC sample the fraction of di-hadron events where the initial state radiation removes more than 0.5% of the nominal center-of-mass energy. Only the fraction of events with less initial-state radiation are then used to obtain the final di-hadron cross sections. Several addtional systematic tests were performed to see: whether cross sections with same physics content are consistent with each other, that variations between running periods are consistent between different cross sections as well and that non-diagonal z bins are consistent between pairs of the same hadron type. Also the cross sections taken at the center-of-mass energy of the $\Upsilon(4S)$ resonance and 60 MeV below were compared and found to be consistent.

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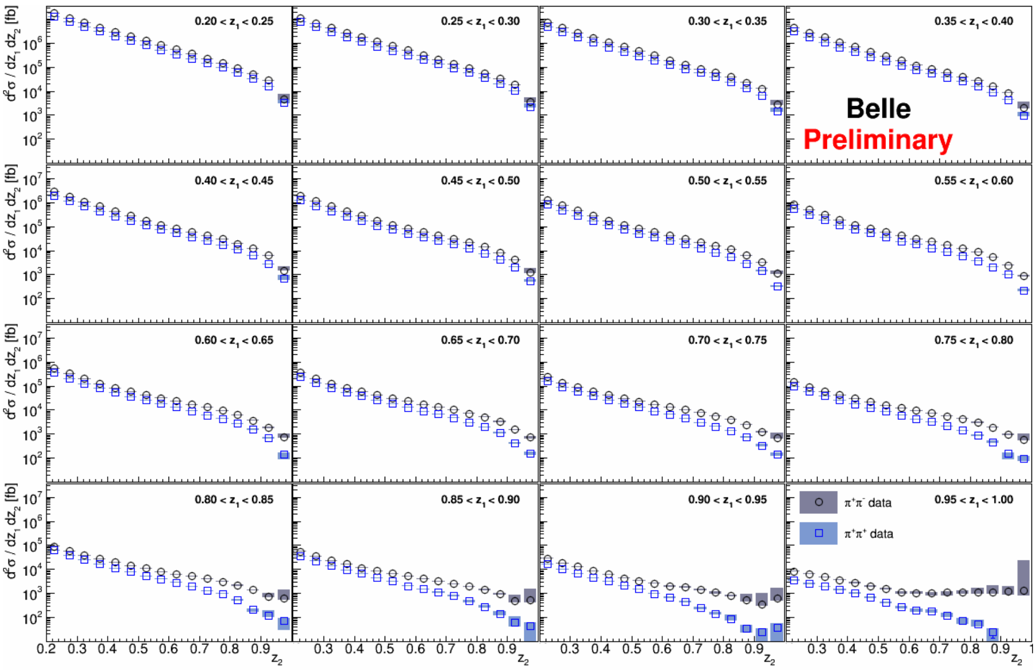

Figure 1: Preliminary results for the same-charge (blue squares) and opposite-charge (black circles) pion pairs as a function of fractional momenta of both pions, z_1 and z_2.

2.2 Results and discussion

Detailed description of the analysis and obtained results can be found in [8]. Here we show in Fig. 1 the final results for the cross session for pion pairs without hemisphere assignment as an example. As argued in the introduction, same-sign charged pion pairs contain at least one disfavored fragmentation and therefore should be suppressed at higher-z values with respect to oppositely-charged pion pairs where both of the pions can originate from favored fragmentation. This behavior can be seen as the differences between the two cross sections increase towards increasing z values.

It is also interesting to compare whether di-hadrons originate predominantly from quark and antiquark separately, or if both hadrons actually originate from the same parton. Fig. 2 displays the stacked contributions from the same- and opposite-hemispheres di-hadrons for diagonal z_1, z_2 bins. The sum of fractional energies of two hadrons originating from the same parton cannot exceed the total energy of that parton and thus need to be below unity. This is mostly fulfilled in case of same-hemisphere pions, for which the cross sections indeed drop to zero at z_1, z_2 values of around 0.5, while for the opposite-hemisphere hadron pairs contributions extend substantially further. As such one can assume that the majority of higher-z hadron pairs indeed originated from different partons. At small-z values there is a small difference between the same- and opposite-hemisphere sum and the cross sections without hemisphere assignment. The difference originates from the thrust $T > 0.8$ selection, required to well-define hemispheres, which is not applied in the cross-section measurements without the hemispehere assignment.

Finally, the diagonal z_1, z_2 cross sections for all six distinctive hadron flavor and charge combinations are compared to the yields for various MC tunes as used at various energies and collision

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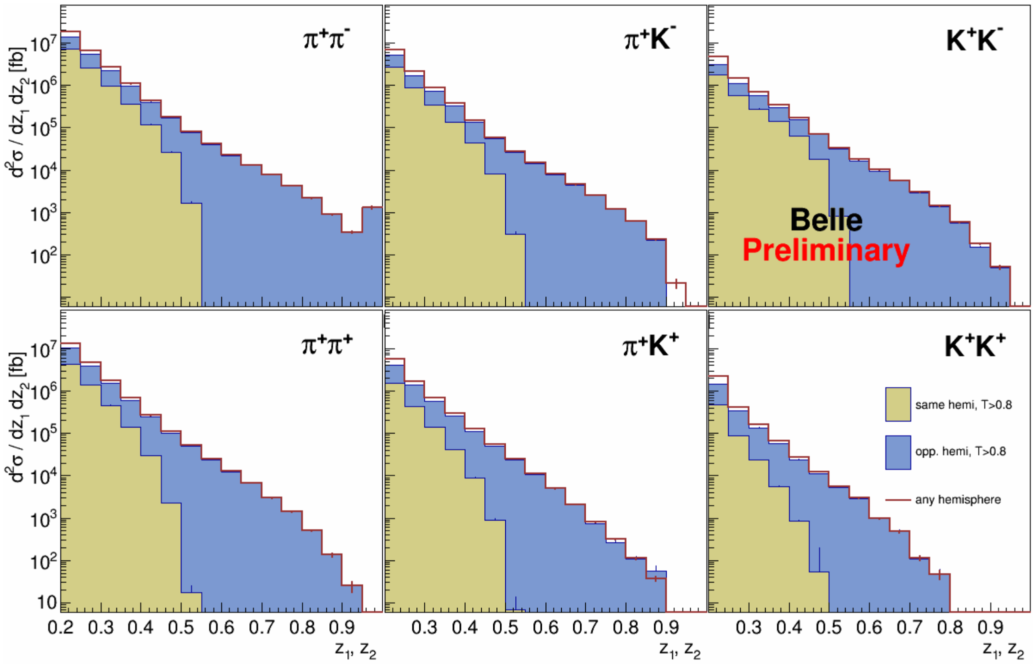

Figure 2: Stacked, preliminary contributions for hadron pairs from same- (grey areas) and opposite-hemisphere (blue areas) as a function of the diagonal fractional momentum z_1, z_2 bins. The cross sections without hemisphere assignment are also displayed (red lines). (Systematic uncertainties are not shown here.)

systems. As shown in Fig. 3, it seems that the current Belle setting, which are close to the PYTHIA default settings, describe the measured data best, while other tunes either overshoot or undershoot the data substantially at higher-z values.

3. Summary, conclusions and prospects

The additional information from the recent di-hadron cross section measurements is expected to further improve the results of global QCD analysis in the future. Together with other measurements of di-hadron cross sections at Belle, which were not reported in this document, all efforts should lead to substantially improved understanding of fragmentation functions, especially when distinction between favored and disfavored fragmentation is concerned.

It is worth noting that the rich experimental program of studies of fragmentation functions at B-factories is expected to continue in the future, at the Belle II experiment [9].

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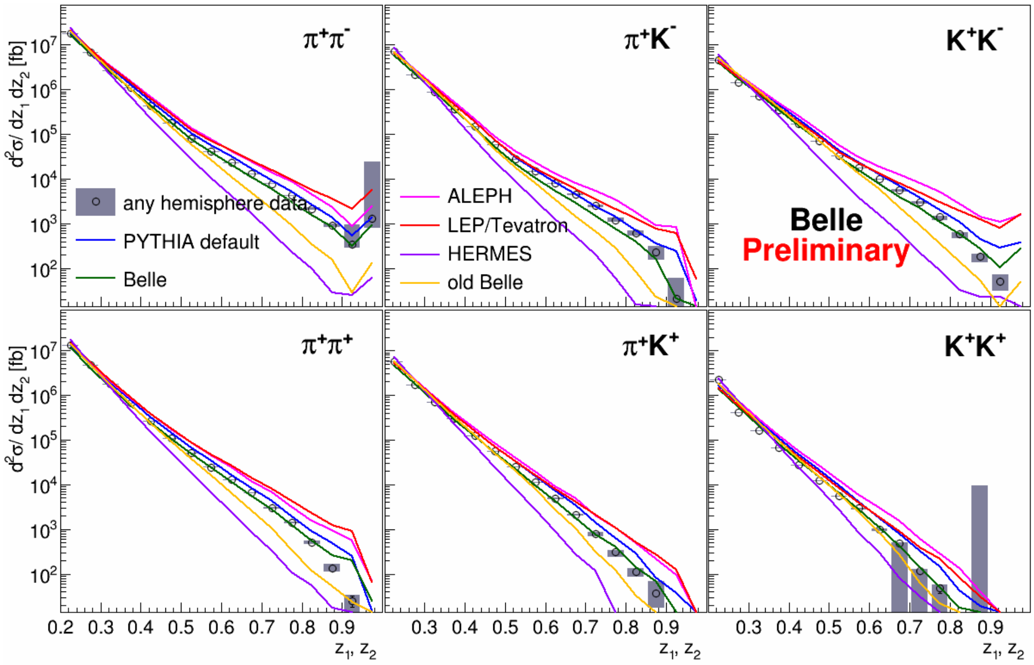

Figure 3: Preliminary cross sections for various hadron pairs as a function of the diagonal z_1, z_2 bins compared to various PYTHIA tunes.

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