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Charge-integrated pion and kaon multiplicities from Belle e^+e^--annihilation data

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High-precision charge-integrated pion and kaon multiplicities were extracted from e^+e^--annihilation data collected with the Belle detector. These data were taken at the KEKB e^+e^- collider at a center-of-mass energy of $\sqrt{s} = 10.52$ GeV. The multiplicities provide the cleanest access to spin-independent fragmentation functions, which describe the hadronization of quarks into final-state hadrons. The low center-of-mass energy and the multiplicity extraction beyond $z = 0.7$ extend the kinematic region covered by earlier measurements. This, in combination with the high-precision of the extraction, will allow an improved determination of the gluon fragmentation function.

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1. Fragmentation functions and multiplicities

The fragmentation of a quark into a final-state hadron is described by fragmentation functions. These non-perturbative, universal objects can be probed in various reaction processes, e.g., semi-inclusive deep-inelastic scattering, proton-proton collisions, and positron-electron (e^+e^-) annihilation. In the latter process, an electron and positron annihilate into a virtual photon or Z boson, which in turn creates a pair of quarks and anti-quarks that subsequently fragment into final-state hadrons. This channel provides the cleanest access to fragmentation functions, since contrary to the other two processes, no other non-perturbative objects are involved. However, e^+e^- annihilation does not allow for the possibility to separate between the fragmentation of quarks and anti-quarks, thus complementary information from semi-inclusive deep-inelastic scattering and proton-proton collisions is necessary.

At present, various measurements sensitive to different fragmentation functions were performed. In e^+e^- annihilation, azimuthal asymmetries providing access to the Collins fragmentation function, describing the fragmentation of a transversely polarized quark into an unpolarized hadron, were extracted [1,2]. In combination with measurements from deep-inelastic scattering [3], they allowed a first extraction of the transversity distribution, describing the distribution of a transversely polarized quark in a transversely polarized nucleon, and of the Collins fragmentation function [4]. In addition, azimuthal asymmetries providing access to interference-fragmentation functions were analyzed in e^+e^- annihilation [5]. These fragmentation functions describe the hadronization of a transversely polarized quark into two final-state hadrons, whereby the transverse spin of the fragmenting quark is transferred to the relative orbital angular momentum of the created hadron pair. In combination with data from semi-inclusive deep-inelastic scattering [6], these measurements again allow access to the transversity distribution and the interference-fragmentation function [7].

For spin-independent fragmentation functions various measurements and extractions are available. Here typically the z dependence, where z represents the fractional hadron energy with respect to the fragmenting-quark energy, of the fragmentation functions is probed. In addition, fragmentation functions depend, through QCD evolution, on the energy scale Q^2 of the process. Based on e^+e^--annihilation data only, an extraction of the spin-independent fragmentation functions was presented in Ref. [8], the first extraction containing both theoretical and experimental uncertainties. The authors from Ref. [9] included in addition data from proton-proton collisions for the parametrization of the fragmentation functions. In Ref. [10, 11] data from e^+e^- annihilation, proton-proton collisions, and semi-inclusive deep-inelastic scattering were used as combined input. All these parametrizations suffer, however, from large uncertainties in the large-z region. The reason lies in the limited availability of data in this z region. In addition, the gluon fragmentation function exhibits large uncertainties over the entire z region, which is due to the limited data at different energy scales.

The here presented experimental results cover the z region from 0.2 up to very large z, and thus will allow an improved parametrization of the fragmentation functions. In addition, contrary to the majority of available data, the data analyzed here are collected at a low energy scale, therefore allowing a better constraint of the gluon fragmentation function.

Spin-independent fragmentation functions can be accessed in e^+e^- annihilation through experimentally extracted multiplicities $M^h(z, Q^2 = s)$:

$$\begin{aligned} M^h(z,Q^2) &= \frac{1}{\sigma_{tot}} \frac{d\sigma(e^+e^- \to hX)}{dz} && (1.1) \\ &\overset{LO}{\propto} \sum_{i=q} e_i^2 D_i^h(z,Q^2) && (1.2) \\ &\overset{NLO}{\propto} \sum_{i=q,g} C_i^{NLO}(z,\alpha_s) \otimes D_i^h(z,Q^2), && (1.3) \end{aligned}$$

where σ_{tot} represents the total hadronic cross section, $d\sigma(e^+e^- \to hX)/dz$ the differential cross section for the production of a hadron, e_i the quark charge, $D_i^h(z,Q^2)$ the fragmentation function, and $C_i^{NLO}(z,\alpha_s)$ a QCD calculable coefficient function, with α_s the strong-coupling constant. In leading-order (LO) approximation the sum runs over all active quark (and anti-quark) flavors, whereas at next-to-leading order (NLO) also gluons contribute. Combining data collected at high- and low-energy scales allows access to the gluon fragmentation function.

2. Multiplicities extracted from Belle data

Data collected at the Belle experiment, located at the asymmetric e^+e^- KEKB accelerator in Tsukuba (Japan), were analyzed. The Belle detector consisted of a silicon-vertex detector, a central drift chamber, and a 1.5 T superconducting solenoid for track reconstruction, while the identification of pions, kaons, protons, electrons, and muons was performed by the central drift chamber, an aerogel Cherenkov counter, a time-of-flight counter, an electromagnetic calorimeter, and a series of glass-electrode resistive plate chambers alternated with iron absorption plates. In total 68 fb^{-1} of data acquired at a center-of-mass energy $\sqrt{s} = 10.52$ GeV were used in the present measurement of charged-pion and charged-kaon multiplicities. From these data raw pion and kaon yields were extracted in bins of $\Delta z = 0.01$ in the z range between 0.2 and 0.98 for pions, and 0.2 and 0.97 for kaons. To these yields various corrections were applied in order to, after normalization, obtain the charge-integrated pion and kaon multiplicities.

A primary correction concerns particle misidentification. Since particle misidentification amounts from 10% up to 50%, depending of the considered laboratory polar angle and momentum, the extracted yields need to be corrected accordingly. In order to evaluate the misidentification of pions and kaons, the D^* decay products were analyzed; for the misidentification of pions and protons, information from Λ decay was collected; finally, for the misidentification of electrons and muons, the J/ψ decay channel was employed. The extracted particle-misidentification probabilities were supplemented with information from Monte-Carlo simulations in the regions affected by limited statistics. The finally obtained particle-misidentification matrix, with 8 bins in laboratory polar angle and 16 bins in laboratory momentum, was used to correct the extracted yields.

A second correction relates to the subtraction of hadron yields that do not originate from a quark-anti-quark pair from e^+e^- annihilation. These mostly originate from e^+e^- annihilation into a $\tau^+\tau^-$ pair and to a lesser extend from two-photon events with creation of a quark-anti-quark pair. The evaluation of such contributions was based on a two-photon Monte-Carlo simulation and a QED Monte-Carlo simulation. The correction is small in the low-z region, but increases to up to 30% (10%) for pions (kaons) at large z values.

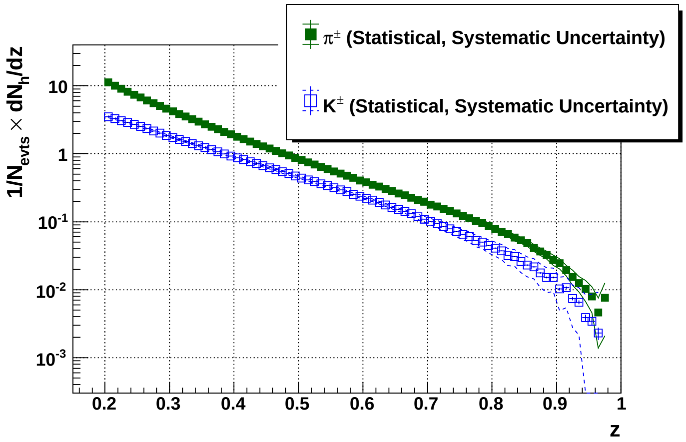

Figure 1: Charge-integrated pion (closed green symbols) and kaon (open blue symbols) multiplicities as a function of z. Statistical uncertainties are given by the error bars, while systematic uncertainties are delimited by the continuous and dashed lines. Not indicated is an additional 1.4% normalization uncertainty.

The obtained yields were in a third step corrected for finite detector resolution. This was done based on Monte-Carlo simulations by the construction of a smearing matrix, which relates the reconstructed z value to the generated z value, for z ranging from 0.08 (0.12) to 0.98 (0.97) for pions (kaons). The effect of this correction is imperceptible on the central yield values, but its effect is included in the systematic uncertainty, as discussed later.

Additional corrections concern the loss of pions and kaons due to decay-in-flight. Pions and kaons created in weak decay are, however, not removed, but included in the final, extracted multiplicities. Furthermore, hadronic detector interactions, event- and track-selection cuts, and the finite detector acceptance are accounted for. Finally, the effect of initial- and final-state photon radiation is taken into account by excluding hadrons from events where a photon radiated by the initial beam lepton or by the created quark had an energy larger than 1.0% of the center-of-mass energy. This correction was based on a Belle Monte-Carlo simulation, with in addition eleven different JETSET/PYTHIA parameter sets for the evaluation of the systematic uncertainty.

3. Results

The charge-integrated pion and kaon multiplicities are shown in figure 1. They exhibit a very large statistical precision, and are dominated by systematic uncertainties, which rise with increasing z values. At small z values the main systematic uncertainty arises from initial- and final-state radiation, followed by the combined contribution from decay-in-flight, detector interactions, and track-selection cuts. In the intermediate-z region, initial- and final-state radiation governs the systematic uncertainty, while at large-z values the finite detector resolution, particle-misidentification, and the combined contribution from decay-in-flight, detector interactions, and track-selection cuts dominate.

A comparison of these multiplicities with multiplicities obtained from e^+e^- annihilation at other experiments [12–20] is shown in figure 2. The data sets are scaled with different, but constant factors for improved visibility. The here presented results represent the first precision mea-

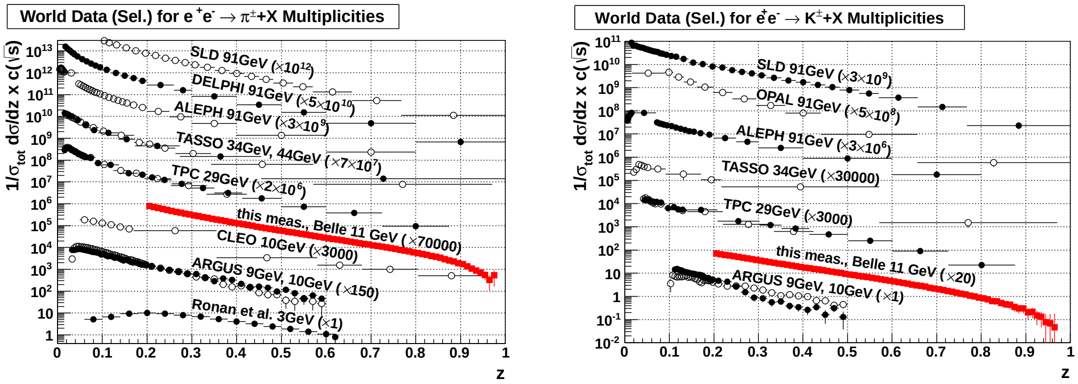

Figure 2: Comparison of the pion (left) and kaon (right) Belle multiplicities with multiplicities obtained from other e^+e^--annihilation measurements [12–20]. The data sets are scaled with different, but constant factors. All data sets have their statistical, systematic, and scale uncertainties added in quadrature.

surements at $z > 0.7$, and will thus allow for a better constraint of the fragmentation functions (in this large-z region). In addition, they complement the high-energy scale measurements well, which in particular will lead to an improved determination of the gluon fragmentation function.

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