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Measurement of the branching ratio for the decay $K^\pm \to \pi^\pm\pi^0\pi^0$ with the KLOE detector

The KLOE Collaboration

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Abstract

A new measurement of the absolute branching ratio BR($K^{\pm} \to \pi^{\pm}\pi^0\pi^0$) with the KLOE detector at the DAΦNE e^+e^- collider is presented, based on a sample of $\sim 3.3 \times 10^7$ charged kaons tagged events, produced in the reaction $e^+e^- \to \phi \to K^+K^-$. The value BR($K^{\pm} \to \pi^{\pm}\pi^0\pi^0$) $= (1.781 \pm 0.013_{stat} \pm 0.016_{syst})\%$ has been obtained.

The study of the non leptonic three pions decays of $K^{\pm}$ has been subject of a new both theoretical and experimental interest in the recent years. Actually, given the large theoretical uncertainties in the calculation of ε'/ε, additional experimental information is needed to better understand the issue of $\mathcal{CP}$ violation in $\Delta S = 1$ transitions. In this respect, an analysis of these decays in terms

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of Dalitz plot parameters can provide an interesting class of observables for testing the prediction of the Standard Model, as well as of its Supersymmetric extensions, about direct $\mathcal{CP}$ violation [1]. Moreover, due to the small phase space available in the reaction, $K \to 3\pi$ is an ideal process where to apply the notion of the Goldstone-boson nature of the pseudoscalar mesons, by testing the prediction obtained from the chiral lagrangian realization of the $\Delta S = 1$ weak interactions [2]. From the experimental point of view, the $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ (τ') is the least investigated among the fully hadronic $K^{\pm}$ decays; the most accurate measurement to date of BR($K^{\pm} \to \pi^{\pm}\pi^0\pi^0$) , performed on a sample of ~ 1300 K^+ decays in flight [3,4], has a relative accuracy of 3.3% and dates back to more than thirty years ago. The KLOE experiment [5] at DAΦNE [6], the Frascati e^+e^- accelerator operating at $\sqrt{s} = m_{\phi} \sim$ 1020 MeV, has excellent possibilities for studying charged kaon decays, since the ϕ mesons decay in K^+K^- pairs in $\sim 49\%$ of the times. Moreover, being the ϕ produced almost at rest (the momentum has a small transverse component in the horizontal plane, $p_{\phi} \sim 13\,\mathrm{MeV}/c$), K^+ and K^- are produced almost back-to-back in the laboratory and from the detection of one of the two charges one can automatically infer the existence of the opposite one in the event (tag). The measurement of the branching ratio BR($K^{\pm} \to \pi^{\pm}\pi^0\pi^0$) $= \Gamma(\pi^{\pm}\pi^0\pi^0)/\Gamma$ described here is based on a sample of data collected at the ϕ peak during the KLOE 2001-2002 data taking periods, corresponding to an integrated luminosity of 441 pb^{-1} and to $\sim 1.5 \times 10^9$ produced ϕ mesons.

The KLOE detector consists of a large cylindrical drift chamber surrounded by a lead-scintillating fiber sampling calorimeter. A superconducting coil outside the calorimeter provides a 0.52 T field. The drift chamber [7], 4 m in diameter and 3.3 m long, has 12582 all-stereo sense wires and 37746 aluminium field wires. The chamber shell is made of carbon fiber-epoxy composite and the gas used is a 90% helium, 10% isobutane mixture. These features maximize transparency to photons and reduce the effect of multiple Coulomb scattering on the low momentum tracks produced in kaon decays. The position resolutions are $\sigma_{xy} \sim 150\,\mu$m and $\sigma_z \sim 2$ mm. The momentum resolution is $\sigma(p_T)/p_T \leq 0.4\%$. Vertices are reconstructed with a spatial resolution of $\sim$3 mm. The calorimeter [8], divided into a barrel and two endcaps, covers 98% of the solid angle. The readout granularity is $\sim 4.4 \times 4.4$ cm^2 and 2440 "cells" are arranged in layers five-deep. Cells close in time and space are grouped into a "calorimeter cluster" and, for each cluster, the energy is the sum of the single cell energies, while the time and the position are calculated as energy-weighted averages over the fired cells. The energy resolution is $\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$ and the time resolution is $\sigma_t = 54\,\mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 50\,\mathrm{ps}$. The trigger [9] uses calorimeter and chamber information. For the present analysis, the trigger strategy is based on calorimeter detection, asking for two local energy deposits in the calorimeter above threshold (50 MeV in the barrel, 150 MeV in the endcaps). Cosmic-ray events are identified by the trigger as events with two energy deposits above

30 MeV threshold in the outermost calorimeter plane and rejected (cosmic veto). The trigger time has a large spread with respect to the bunch crossing time. It is synchronized with the machine RF divided by 4, $T_{\rm sync} = 10.8\,{\rm ns}$, with an accuracy of 50 ps. The time T_0 of the bunch crossing producing an event is determined after the event reconstruction.

Decays in the two channels $\mu^\pm\nu_\mu$ and $\pi^\pm\pi^0$ are the most abundant charged kaons decays, with branching fractions greater than 63% and 21%, respectively. Since they present a two-body signature, the $\mu^\pm$ or $\pi^\pm$ track from the decay vertex can be easily identified by its well defined momentum in the kaon rest frame. These two decays have been used to tag the production of $\pi^\pm\pi^0\pi^0$ and required to be responsible for triggering the event. Signal events have been selected from this tagged ("self-triggered") sample. A charged kaon two-body decay is recognized by looking for a two same charged track vertex with: a radial distance from the beam axis between 40 and 150 cm, a candidate kaon track with momentum between 70 and 130 MeV/c and point of closest approach to the beam axis within 10 cm in the plane orthogonal to it (x-y) and 20 cm in z from the interaction point, a candidate daughter track with momentum in the kaon frame between 180 and 270 MeV/c (in pion mass hypothesis). A $K^\pm \to \pi^\pm\pi^0$ tag is identified as a charged kaon two-body decay vertex in which the daughter track has a momentum in the K rest frame compatible with what expected for the $\pi^\pm$ from kinematics ($\sim$ 205 MeV/c) and a pair of neutral clusters, with energy above 15 MeV and times of flight which indicate that they are both produced in that vertex ("on-time" clusters, as defined in the following), have 85 $MeV/c^2 < m_{\gamma\gamma} <$ 185 MeV/c^2. A $K^\pm \to \mu^\pm\nu_\mu$ tag is identified as charged kaon two-body decay vertex in which the daughter track has a momentum in the K rest frame as expected for the muons ($\sim$ 236 MeV/c); moreover the missing mass m_m, computed from the missing energy and momentum in the vertex, is required to satisfy the cut: $|m_m^2| <$ 5000 MeV^2/c^4, in order to reject the residual background due to $\pi^\pm\pi^0$ decays. The main background in the two tag samples comes from the remaining charged kaons decays, like $K^\pm_{e3}$ or $K^\pm_{\mu3}$, especially in the case of $\pi^\pm\pi^0$ tag, and it has been evaluated from Monte Carlo and data: $\xi^{\pi^\pm\pi^0}_{bckg} = (0.37\pm0.02)\%$, $\xi^{\mu^\pm\nu}_{bckg} = (0.21 \pm 0.02)\%$, where the quoted error includes statistical and systematic contributions. The main advantage in requiring the "self-triggering tag" and in normalizing signal events to these tag events for computing the branching ratio is that in the ratio the tag efficiency, which contains as factors the trigger and the event filter algorithm efficiencies, cancels out provided that the tag is responsible of triggering and classifying the event.

The selection of $K^\pm \to \pi^\pm\pi^0\pi^0$ (τ') events is based on a search, in each tagged event, of another charged kaons vertex, different from the tagging one, in which the candidate kaon track is selected with similar criteria as described above. To this vertex only one charged track apart from the kaon and at least four neutral clusters with energy above 15 MeV and on-time, have to belong.

Both the track and all clusters are different from those already assigned to the tag in the opposite hemisphere. Since the maximum allowed momentum in the $K^{\pm}$ frame for the charged pions coming from a $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ decay is $p_{max} = 132.95\ MeV/c$, a cut on this momentum has been applied: $|\vec{p}_{\pi^{\pm}}| < 135\ MeV/c$. The on-time requirement has been imposed by computing the difference in time between all the possible pairs of clusters j and k related to the signal vertex and weighting it with the appropriate time resolution, σ_t:

$$\Delta t_{jk} = \Big[(t_j - t_k) - \frac{1}{c} \cdot \Big(|\vec{r}_{Vj}| - |\vec{r}_{Vk}|\Big)\Big] \Big/ \sqrt{\sigma_t(E_j)^2 + \sigma_t(E_k)^2}\ . \tag{1}$$

In equation (1) $\vec{r}_{Vi}$ is the distance between the centroid of the cluster i and the signal vertex V. Then $|\Delta t_{jk}| < 4 \quad \forall\ i, j = 1, 2, 3, 4\ (i < j)$ has been required. Accidental clusters surviving the cut on energy are powerfully rejected by applying this cut. Events with more than four on-time clusters in the final signal sample, apart from the rare radiative decay $K^{\pm} \to \pi^{\pm}\pi^0\pi^0\gamma$ ($BR < 10^{-5}$) get a residual contribution from accidentals or from clusters left unmerged by the clustering procedure. Finally, a cut on the total energy of the four most energetic clusters has been imposed: $E_{tot} \equiv \sum_{i=1}^{4} E_i < 450\ MeV$, to take into account that the typical energy of charged kaons passing through the drift chamber inner walls doesn't exceed $E_K \simeq 505\ MeV$. In order to minimize statistical errors and their correlations on the final measurement of the branching ratio, from the whole amount of data collected by the experiment a subsample corresponding to 188 pb^{-1}, extracted from 2001 and 2002 KLOE data, has been used for the signal selection, while the rest of the data has been split in three subsamples and used for the efficiency evaluations. In 188 pb^{-1}, 52253 and 30798 events, respectively for the $\mu^{\pm}\nu_{\mu}$ and $\pi^{\pm}\pi^0$ tags, pass all of the above criteria.

The most relevant sources of background in $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ candidates are the main $K^{\pm}$ decays (mostly $K^{\pm} \to \pi^{\pm}\pi^0$ and $K^{\pm} \to \text{e}^{\pm}\pi^0\nu_e$), rare radiative $K^{\pm}$ decays like $K^{\pm} \to \pi^{\pm}\pi^0\gamma$, in which a "spurious" cluster in the calorimeter has been paired with the cluster of the radiated γ (the probability for this to happen has been estimated from a $K^{\pm} \to \pi^{\pm}\pi^0$ data sample to be $\sim 8\%$), events in which a nuclear interaction of a charged kaon (mainly K^-) with the materials before the drift chamber produces secondary particles which simulate the signal topology and, finally, $K^{\pm} \to \text{e}^{\pm}\pi^0\pi^0\nu_e$ (K'_{l4}) decays. The relative contribution of these background sources has been estimated using Monte Carlo, while the total amount of background events has been determined from a fit of the missing mass spectrum in the data to the sum of the simulated signal and background spectra. The value obtained from pure Monte Carlo had to be corrected by a factor 1.13 ± 0.07. After applying this correction we find that the total background fraction is $\xi_{bckg}^{\tau'} = (0.75 \pm 0.11)\%$ where the quoted error includes the contributions from the finite statistics of the MC spectra and from the fit. Contaminations from other decays not originated from $K^\pm$, have been estimated to be negligible.

The overall signal selection efficiency $\varepsilon_{sel}^{\tau'}$ is given by the product $\varepsilon_{sel}^{\tau'} = \varepsilon_K \varepsilon_v \varepsilon_{\gamma' s}$ where ε_K is the identification efficiency for the charged kaon from which the decay has been originated, ε_v includes the efficiency to reconstruct the $K^\pm$-$\pi^\pm$ vertex and the efficiency of the cut on the pion momentum and $\varepsilon_{\gamma' s}$ is the efficiency for observing at least four photons in the calorimeter fulfilling the requirements on energy and timing described above. Each term has been measured, separately for $\mu^\pm\nu_\mu$ and $\pi^\pm\pi^0$ tags, by using special control samples [10] extracted from data taken in run periods close in time but different from the one used for signal selection. In general, control samples selected by using calorimeter variables have been used to compute the efficiencies involving the drift chamber, and vice-versa. The obtained values of the efficiencies have been corrected to take into account the contamination of the relative control sample, as estimated by Monte Carlo. For all control samples, Monte Carlo has estimated purities $> 96\%$. The efficiency $\varepsilon_K = 0.466 \pm 0.001_{stat} \pm 0.002_{syst}$ is dominated by the geometrical acceptance (more than one third of the charged kaons decay before reaching the drift chamber) and includes also the effect of the nuclear interaction of $K^\pm$ in the materials in front of the chamber. The efficiency to reconstruct the $K^\pm$-$\pi^\pm$ vertex has been parametrized as a function of the charged pion momentum, as shown in Fig. 1 (left). The overall value $\varepsilon_v = 0.539 \pm 0.003_{stat} \pm 0.002_{syst}$ is obtained, using the expected pion momentum distribution for the signal and the relative systematic error takes into account small differences between the two tags. For each single cluster, the probability to be detected, evaluated from a control data sample and corrected by using Monte Carlo to take into account the effects of accidental clusters is shown in Fig. 1 (right) parameterized as a function of its energy. The only appreciable difference in $\varepsilon_{\gamma' s}$ between the two tags has been found for the on-time clusters requirement and the obtained values are: $\varepsilon_{\gamma' s} = 0.592 \pm 0.003_{stat} \pm 0.004_{syst}$ ($0.554 \pm 0.002_{stat} \pm 0.004_{syst}$) in the case of $\mu^\pm\nu_\mu$ ($\pi^\pm\pi^0$) tag. Finally, $\varepsilon_{sel}^{\tau'} = 0.1487 \pm 0.0011 \pm 0.0013$ ($0.1392 \pm 0.0010 \pm 0.0013$) for $\mu^\pm\nu_\mu$ ($\pi^\pm\pi^0$) tag.

In principle, the tag efficiency cancels out in the ratio of the number of selected signal decays $N_{tag}^{\tau'}$ and all tag events N_{tag} in the hypothesis that this efficiency is independent of the decay mode in the non-tag hemisphere and requiring the self-triggering condition, which ensures the cancellation of the trigger contributions to it. In practice, due to the high cluster multiplicity in the event, it could be possible to observe a small "interference" between the tag and the rest of the event, especially in the $\pi^\pm\pi^0$ case. This effect has been analized by studying the sensitivity of the quantity $R = \frac{N_{tag}^{\tau'}}{N_{tag} \cdot \varepsilon_{\gamma' s}}$ to different definitions and cuts on the clusters associated to the required photons in the event and, finally, has been considered as a source of systematic error on $\varepsilon_{\gamma' s}$. Residual effects due to other contributions to the tag efficiency, like the cos-

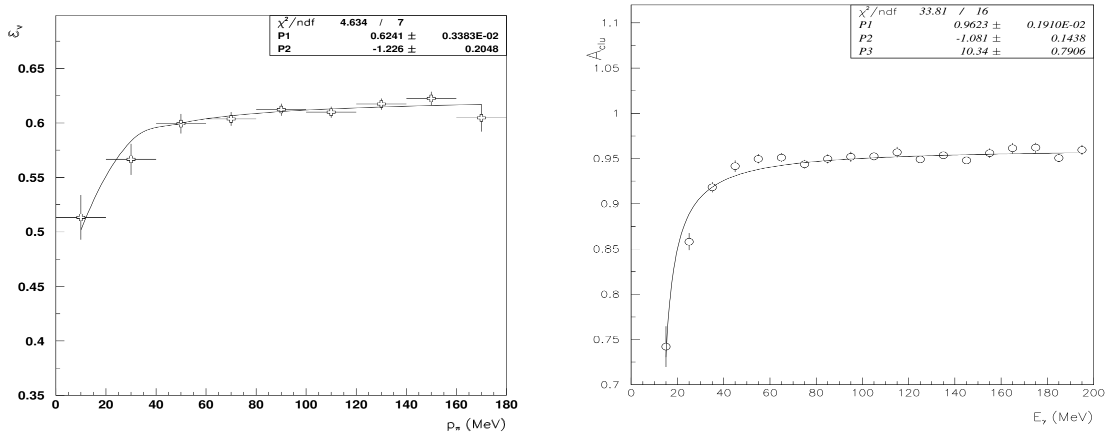

Fig. 1. Vertex efficiency as a function of the pion momentum in the lab frame (left). Single cluster acceptance corrected as described in the text as a function of the photon energy (right).

mic veto filter efficiency, have been studied and estimated to give a corrective factor $\Lambda = 0.999 \pm 0.001$ on the branching ratio.

The BR($K^{\pm} \to \pi^{\pm}\pi^0\pi^0$) has been computed as the weighted average of the two values obtained for the two differently tagged samples from:

$$BR(K^{\pm} \to \pi^{\pm}\pi^0\pi^0) = \frac{N_{tag}^{\tau'}}{N_{tag}} \cdot \frac{1-\xi_{bckg}^{\tau'}}{1-\xi_{bckg}^{tag}} \cdot \frac{1}{\varepsilon_{sel}^{\tau'}} \cdot \frac{\Lambda}{[BR(\pi^0 \to \gamma\gamma)]^2} \tag{2}$$

using the present experimental value for $BR(\pi^0 \to \gamma\gamma)$ [3]. We measure:

$$BR(K^{\pm} \to \pi^{\pm}\pi^0\pi^0) = (1.781 \pm 0.013_{stat} \pm 0.016_{syst}) \cdot 10^{-2} \ .$$

The stability of the obtained value has been verified by performing the measurement on different subsamples, corresponding to various periods of data taking. The efficiencies described above have been evaluated on statistically uncorrelated data cotrol samples. In Fig. 2 the BR($K^{\pm} \to \pi^{\pm}\pi^0\pi^0$) measured by KLOE is compared with previously published measurements. All the contributions to the total uncertainty are listed in table 1, from where it can be observed that the main error sources come from the knowledge of the efficiencies, due to the limited statistics of the data control samples used in their evaluations.

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Source of uncertainty	Relative error (10^{-3})
$N_{tag}^{\tau'}$ statistics	3.5
N_{tag} statistics	0.2
Charged kaon reconstruction/identification efficiency	5.2
Vertex reconstruction efficiency	6.6
Cluster algorithm efficiency	2.3
Four clusters acceptance	3.6
On-time requirement for clusters	5.1
Total energy cut	1.4
Background subtraction	1.1
Cosmic-ray trigger veto	1.0

Table 1
Summary of all the contributions to the total error on $BR(K^{\pm} \to \pi^{\pm}\pi^0\pi^0)$.

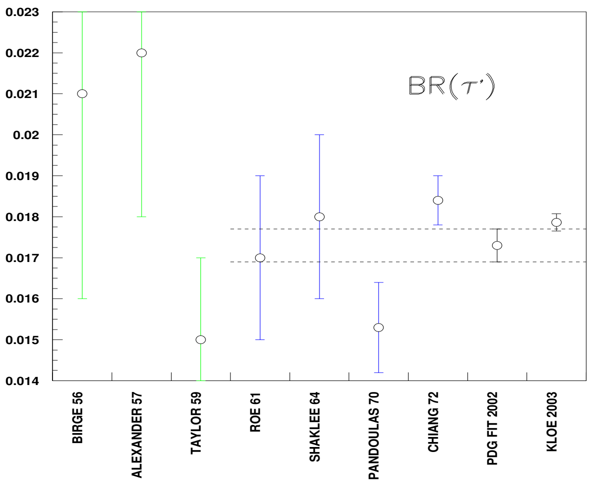

Fig. 2. Comparison between the measurement of BR($K^{\pm} \to \pi^{\pm}\pi^0\pi^0$) obtained in this analysis and previously published results: the dashed lines delimit the error of the 2002 PDG fit.

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