

# Measurement of the absolute branching ratio of the $K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$ decay with the KLOE detector

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**Abstract.** The absolute branching ratio of the  $K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$  decay, inclusive of final-state radiation, has been measured using  $\sim 17$  million tagged  $K^+$  mesons collected with the KLOE detector at DAΦNE, the Frascati  $\phi$ -factory. The result is:

$$BR(K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)) = 0.05565 \pm 0.00031_{stat} \pm 0.00025_{syst}$$

## 1. Introduction

The measurement of the branching ratio (BR) of  $K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$  decay completes the KLOE program of precision measurements of the dominant kaon branching ratios, fully inclusive of radiation effects. The most recent  $BR(K^\pm \rightarrow \pi^\pm\pi^+\pi^-)$  measurement, based on 2330 events from a sample of  $\sim 10^5$  kaon decays, dates back to 1972 and gives no information on the radiation cut-off:  $BR(K^\pm \rightarrow \pi^\pm\pi^+\pi^-) = (5.56 \pm 0.20)\%$  [1].

The measurement of the absolute  $BR(K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma))$  has been performed with the KLOE detector using data corresponding to an integrated luminosity  $\int \mathcal{L} dt \simeq 174 \text{ pb}^{-1}$  collected at DAΦNE, the Frascati  $\phi$ -factory[2]. DAΦNE is an  $e^+e^-$  collider operated at the energy of 1020 MeV, the mass of the  $\phi$ -meson. The beams collide at the interaction point (IP) with a crossing angle  $\theta_x \simeq 25 \text{ mrad}$ , producing  $\phi$ -mesons with a small momentum of  $\sim 12.5 \text{ MeV}/c$  in the horizontal plane. The  $\phi$ -mesons decay in anti-collinear and monochromatic neutral (34%) and charged (49%) kaon pairs. The unique feature of a  $\phi$ -factory is the tagging: detection of a  $K^\pm$  (the tagging kaon) tags the presence of a  $K^\mp$  (the tagged kaon) with known momentum and direction. The selection of the  $K^\pm$  beams is done reconstructing the two-body decays  $K^\pm \rightarrow \mu^\pm\nu(\gamma)$  ( $K_{\mu 2}$  tags) and  $K^\pm \rightarrow \pi^\pm\pi^0(\gamma)$  ( $K_{\pi 2}$  tags) which provide two independent samples of pure kaons for the signal selection useful also for systematic uncertainties evaluation. These decays are easily identified as clear peaks in the distribution of  $p_{m\pi}^*$ , the momentum of the charged secondary track in the kaon rest frame evaluated using the pion mass [3].

The KLOE detector consists of a large cylindrical drift chamber (DC) [4], surrounded by a lead scintillating fiber electromagnetic calorimeter (EMC) [5] both embedded in an axial 0.52 T magnetic field produced by a superconducting coil.

The DC tracking system has 25 cm internal radius, 4 m diameter and 3.3 m length, with a total of  $\sim 52000$  wires, of which  $\sim 12000$  are sense wires arranged in a stereo geometry. In order to minimize the multiple scattering and  $K_L$  regeneration, and to maximize the detection efficiency for low energy photons, the DC works with a helium-based gas mixture and its walls are made

32 of light materials, mostly carbon fiber composites. Spatial resolutions are  $\sigma_{xy} \simeq 150 \mu\text{m}$  and  
 33  $\sigma_z \simeq 2 \text{ mm}$  and the transverse momentum resolution is  $\sigma(p^T)/p^T \leq 0.4\%$ .  
 34 The calorimeter covers 98% of the solid angle and is composed by a barrel and two endcaps.  
 35 For each impinging particle the calorimeter information consists of energy, position of impact  
 36 point and arrival time, with corresponding accuracy of  $\sigma_E/E = 5.7\%/\sqrt{E} \text{ (GeV)}$ ,  $\sigma_z = 1.2$   
 37  $\text{cm}/\sqrt{E} \text{ (GeV)}$ ,  $\sigma_\phi = 1.2 \text{ cm}$ , and  $\sigma_t = 57 \text{ ps}/\sqrt{E} \text{ (GeV)} \oplus 100 \text{ ps}$ .  
 38 The trigger [6] is based on energy deposits in the calorimeter and on hit multiplicity in the  
 39 drift chamber. Only events triggered by the calorimeter have been used in the present analysis.  
 40 The trigger system includes a second-level veto for cosmic-ray muons (cosmic-ray veto or CRV)  
 41 based on energy deposits in the outermost layers of the calorimeter and followed by a third-level  
 42 software trigger. A software filter (SF), based on the topology and multiplicity of energy clusters  
 43 and drift chamber hits, is applied to filter out machine background. Both CRV and SF may be  
 44 sources of events loss, and their effects on the BR measurement have been studied.

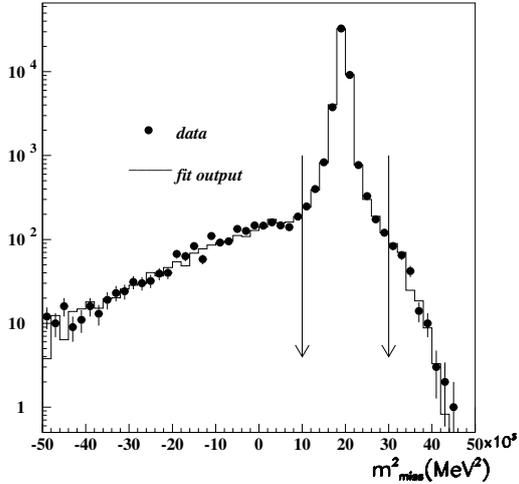
## 45 2. The analysis

46 To minimize the impact of the trigger efficiency on the signal side, we choose as normalization  
 47 sample  $K_{\mu 2}$  and  $K_{\pi 2}$  tags providing the trigger of the event. The residual dependence of the  
 48 signal sample on the tag selection, which we refer to as tag bias, has been evaluated for the BR  
 49 measurement. Moreover, to avoid systematics due to kaon nuclear interaction, we use  $K^-$  as the  
 50 tagging kaon ( $K_{\mu 2}$  or  $K_{\pi 2}$ ) and  $K^+$  as the tagged kaon (signal), since the nuclear cross section  
 51 for positive kaons with momenta  $\simeq 100 \text{ MeV}$  is lower by a factor of  $\sim 10^3$  with respect to that  
 52 of negative kaons [7].

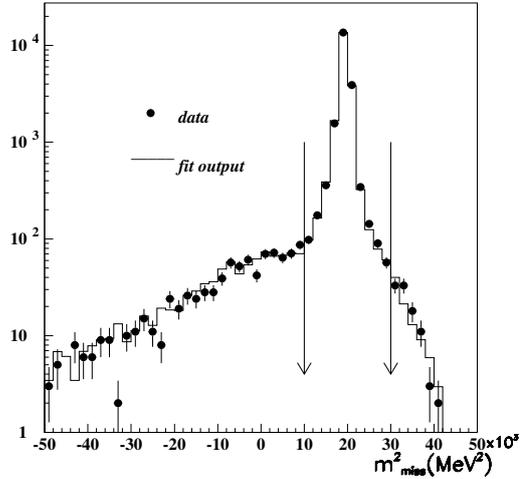
53 The track of the tagging kaon is backward extrapolated from its first hit in the DC to the IP.  
 54 We use the momentum of the tagging kaon at the IP,  $\mathbf{p}_{K^-}^{IP}$ , and the momentum of the  $\phi$ -meson  
 55 measured run by run with Bhabha scattering events,  $\mathbf{p}_\phi$ , to evaluate the momentum of the  
 56 tagged kaon at the IP,  $\mathbf{p}_{K^+}^{IP} = \mathbf{p}_\phi - \mathbf{p}_{K^-}^{IP}$ . Finally we extrapolate  $\mathbf{p}_{K^+}^{IP}$  inside the DC (signal  
 57 kaon path).

58 The kaon and the three charged pions from its decay have low momenta, less than  $\sim 200$   
 59 MeV, and curl up in the KLOE magnetic field; this increases the probability to have poorly  
 60 reconstructed tracks broken in more segments. We significantly improve the quality of the  
 61 reconstruction requiring the  $K^+$  decay to occur before it reaches the DC sensitive volume, i.e.  
 62 inside a cylindrical fiducial volume centered at the IP and with a transverse radius  $\rho_{xy} \leq 26 \text{ cm}$ .  
 63 In this way only the pion tracks are reconstructed, and we extrapolate only two of them to search  
 64 for a vertex along the signal kaon path. The decay vertices are selected cutting on the distance  
 65 of closest approach between each extrapolated tracks and the signal kaon path,  $\text{DCA} < 3 \text{ cm}$ ,  
 66 and on the distance of closest approach between the two selected tracks,  $\text{DCA}_{12} < 3 \text{ cm}$ . To  
 67 remove the background due to the two-body decays, each selected track must have a momentum  
 68 in the kaon rest frame  $p_{m_\pi}^* < 190 \text{ MeV}/c$ . After this selection, a residual background, mainly  
 69 due to broken kaon tracks, is removed cutting almost collinear tracks,  $|\cos(\theta_{12})| < 0.90$ , where  
 70  $\theta_{12}$  is the opening angle between the two selected tracks.

71 To extract the number of  $K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$  we fit the missing mass spectrum  $m_{miss}^2 =$   
 72  $E_{miss}^2 - (\mathbf{p}_{K^+} - \mathbf{p}_1 - \mathbf{p}_2)^2$  where  $\mathbf{p}_1$  and  $\mathbf{p}_2$  are the momenta of the selected tracks, with  
 73 MC-predicted shapes for the signal and the background. Fig 1 and Fig 2 show the results of the  
 74 fits of the missing mass distributions compared to data for both  $K_{\mu 2}^-$  and  $K_{\pi 2}^-$  tagged samples.  
 75 The signal selection efficiency,  $\epsilon_{sel}$ , is related to the track reconstruction efficiency of two charged  
 76 secondaries from  $K^+$  decays. We evaluate the selection efficiency from MC, and then we correct  
 77 it to take into account data-MC differences in the track reconstruction. To this aim we select,  
 78 both on data and MC, a control sample of  $K^+ \rightarrow \pi^- X$  decays (for signal events X corresponds  
 79 to  $\pi^+\pi^+$ ) with a background contamination of  $\simeq 10.7\%$ , to measure the efficiency corrections as  
 80 function of the total transverse momentum  $p_X^T$ , and of the total longitudinal momentum  $p_X^L$  of



**Figure 1.**  $K_{\mu 2}^{-}$  tagged sample: fit of the missing mass spectrum superimposed with data points,  $\chi^2/\text{ndf} = 44.8/46$  ( $P(\chi^2) = 0.52$ ). The arrows show the missing mass window for signal counting, where the signal over background ratio is  $S/B \simeq 88$ .



**Figure 2.**  $K_{\pi 2}^{-}$  tagged sample: fit of the missing mass spectrum superimposed with data points,  $\chi^2/\text{ndf} = 42.9/45$  ( $P(\chi^2) = 0.56$ ). The arrows show the missing mass window for signal counting, where the signal over background ratio is  $S/B \simeq 84$ .

**Table 1.** Corrections to  $\text{BR}(K^+ \rightarrow \pi^+\pi^-\pi^-(\gamma))$  measurement.

corrections	$K_{\mu 2}^{-}$ tags	$K_{\pi 2}^{-}$ tags
cosmic ray veto $C_{CRV}$	$1.00125 \pm 0.00002$	$1.00049 \pm 0.00001$
software filter $C_{SF}$	$1.0144 \pm 0.0013$	$1.0003 \pm 0.0005$
tag bias $C_{TB}$	$0.839 \pm 0.001$	$0.802 \pm 0.002$

81 the  $\pi^+\pi^+$  pair. The selection efficiency, is finally obtained folding the MC selection efficiency  
 82 with the measured corrections:  $\epsilon_{sel} = 0.0842 \pm 0.0003$  for the  $K_{\mu 2}^{-}$  tagged sample, and  $\epsilon_{sel} =$   
 83  $0.0866 \pm 0.0005$  for the  $K_{\pi 2}^{-}$  tagged sample.

84 The corrections  $C_{CRV}$  and  $C_{SF}$  have been measured with data taken without the cosmic-ray veto  
 85 and the software filter, respectively. The correction for the tag bias,  $C_{TB}$ , has been evaluated  
 86 using MC. All correction values are reported in Table 1.

87 The sources of systematic uncertainties and the corresponding values are listed in Table 2.

### 88 3. The result

89 With a sample of  $K^- \rightarrow \mu^- \bar{\nu}(\gamma)$  tagging events  $N_{tag} = 12065087$  we found  $N_{K \rightarrow 3\pi} = 48032 \pm 286$   
 90 signal events (the errors accounting for data and MC statistics), corresponding to:

$$BR(K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma))|_{TagK_{\mu 2}} = 0.05552 \pm 0.00034_{stat} \pm 0.00034_{syst}.$$

91 With a sample of  $K^- \rightarrow \pi^-\pi^0(\gamma)$  tagging events  $N_{tag} = 5171239$  we found  $N_{K \rightarrow 3\pi} = 20063 \pm 186$   
 92 signal events, corresponding to:

**Table 2.** Summary table of the fractional systematic uncertainties.

Source of systematic uncertainties	$K_{\mu 2}^-$ tags (%)	$K_{\pi 2}^-$ tags (%)
DCA, DCA <sub>12</sub> , cos( $\theta_{12}$ ) cuts	0.52	0.41
$p_{m_\pi}^*$ cut	0.08	0.11
$m_{miss}^2$ cut	0.05	0.14
fiducial volume	0.11	0.10
selection efficiency estimate	0.16	0.16
tag bias	0.16	0.32
$K^\pm$ lifetime	0.12	0.12
Total fractional systematic uncertainty	0.60	0.59

$$BR(K^+ \rightarrow \pi^+ \pi^- \pi^+ (\gamma))|_{TagK_{\pi 2}} = 0.05587 \pm 0.00053_{stat} \pm 0.00033_{syst}.$$

93 Averaging these two results, accounting for correlations, we obtain:

$$BR(K^+ \rightarrow \pi^+ \pi^- \pi^+ (\gamma)) = 0.05565 \pm 0.00031_{stat} \pm 0.00025_{syst}.$$

94 This absolute branching ratio measurement is fully inclusive of final-state radiation and has a  
 95 0.72% accuracy [8], a factor  $\simeq 5$  better with respect to the previous measurement [1].

## 96 References

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