Study of the $K^+ \to \pi^0 e^+ \nu \gamma$ decay with NA62 experiment at CERN

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Abstract

I performed different measurements of $K^+ \to \pi^0 e^+ \nu \gamma$ decay (Ke3γ) branching ratio normalized to $K^+ \to \pi^0 e^+ \nu$ decay (Ke3) with the NA62 experiment at CERN. For $E^*_\gamma > 10 MeV$ and $\theta^*_{e,\gamma} > 10°$, 12242 candidate events have been selected, with the estimated fraction of background at the level of $(3.5 \pm 1.4)\%$, and I obtained $\frac{BR(Ke3\gamma)}{BR(Ke3)} = (1.95 \pm 0.04)\%$. With the same selection the asymmetry $A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$ of the T-odd observable $\xi = \frac{[\overrightarrow{p_\gamma} \cdot (\overrightarrow{p_e} \times \overrightarrow{p_\pi})]}{M_K^3}$ has been computed, and I measured $A_\xi = (0.016 \pm 0.017)$. The measurements are still dominated by statistical uncertainties, and they can be improved collecting and analysing more data.

I. The $Ke3\gamma$ decay and T-asymmetry

The $K^+ \to \pi^0 e^+ \nu \gamma$ decay (Ke3γ) is one of the radiative kaon's decays, with an average branching ratio computed by the PDG [1] of: $BR(Ke3\gamma) = (2.56 \pm 0.16) \cdot 10^{-4}$.

There are two processes for this decay at one-loop level described by the Feynman diagrams reported in fig. 1, corresponding to two different radiative photon emission modes: Direct Emission (a) and Inner Bremsstrahlung (b). The interference between these two processes also contributes to the decay.

The kinematics of this decay has been studied in [2, 3]; a divergent amplitude can be observed for small radiative photon energies or for small angle between radiative photon and positron in the kaon rest frame, due to the Inner Bremsstrahlung component (fig. 2).

This decay gives the opportunity to study the Standard Model symmetry violation sector, thanks to a T-odd variable, defined in [4, 5]:

$$\xi = \frac{[\overrightarrow{p_\gamma} \cdot (\overrightarrow{p_e} \times \overrightarrow{p_\pi})]}{M_K^3} \tag{1}$$

Its asymmetry can be computed defining the observable:

$$A_\xi = \frac{N_+ - N_-}{N_+ + N_-} \tag{2}$$

where N_+ is the number of events with $\xi > 0$, while N_- with $\xi < 0$. The Standard Model prediction for this asymmetry is [4, 5]:

$$A_\xi^{SM} = -0.59 \cdot 10^{-4} \tag{3}$$

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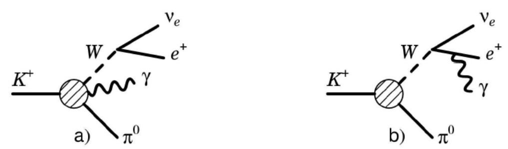

Figure 1: Feynman diagrams for Ke3γ decay at one-loop level: Direct Emission (a), Inner Bremsstrahlung (b).

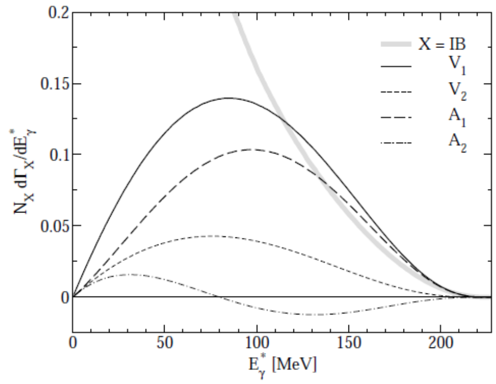

Figure 2: Radiative photon energy distributions in Ke3γ decay[3].

The non-zero value of the asymmetry is only due to radiative corrections on the one-loop level diagrams shown in fig. 1.

The main goal of this analysis is to understand if it is possible to perform an A_ξ measurement, competitive with the existing ones [6], with the data collected by NA62.

A_ξ measurement has already been performed by the *ISTRA+* experiment in 2006 [6], obtaining a result of $A_\xi^{ISTRA+} = -0.015 \pm 0.021$, with ξ defined with the opposite sign of eq. 1. This measurement is consistent with zero due to the big experimental error.

ISTRA+ performed also different measurements of the Ke3γ branching ratio normalized to $K^+ \to \pi^0 e^+ \nu$ decay (Ke3), changing the kinematic cuts in the kaon rest frame, obtaining the results reported in tab. 1. The branching ratio value strongly depends on the kinematic cuts, due to the

E_γ CUT	$\theta_{e,\gamma}$ CUT	$\frac{BR(Ke3\gamma)}{BR(Ke3)}$
$E_\gamma > 10 MeV$	$0.6 < \cos\theta_{e,\gamma} < 0.9$	$(0.47 \pm 0.02 \pm 0.03) \cdot 10^{-2}$
$E_\gamma > 30 MeV$	$\theta_{e,\gamma} > 20°$	$(0.63 \pm 0.02 \pm 0.03) \cdot 10^{-2}$
$E_\gamma > 10 MeV$	$\theta_{e,\gamma} > 10°$	$(1.81 \pm 0.03 \pm 0.07) \cdot 10^{-2}$

Table 1: *Ke*3γ branching ratio measurements performed by the ISTRA+ experiment *[1, 6].*

divergent amplitude at low photon energies.

II. Event reconstruction and selection

I analysed data collected by NA62 experiment in 2016 [7]. The full description of the NA62 setup and the trigger conditions can be found in [7, 8]; a schematic representation of the detector is

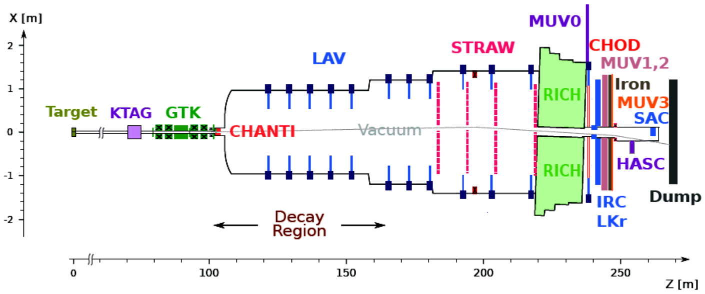

Figure 3: Schematic representation of the NA62 detector.

shown in fig. 3.

In particular I processed the events selected by the so-called *Mask0* trigger (which requires at least one hit in RICH, NewCHOD, five sectors in the KTAG and no hits in MUV3) of Runs n. 6300, 6303, 6318, 6319, 6355, 6356, 6365, 6368, 6371, 6501, 6582, 6566, 6673, with a total of $4.2 \cdot 10^8$ collected events.

In order to reconstruct the Ke3γ events, the following detectors have been used:

- KTAG to identify the kaon before its decay;
- GTK to measure the kaon momentum;
- STRAW to measure the positron momentum and direction;
- LKr to measure energies and positions of positron and photons;
- RICH for particles identification.

I reconstructed the position of the K^+ decay vertex computing the *Closest Distance of Approach (CDA)* between positron direction (STRAW) and kaon direction (GTK). This vertex position has been used together with the energy and the position of the photons in the LKr to compute the π^0 and radiative photon 4-momenta.

I used several cuts to select Ke3γ events and reject the background. To study the efficiency of the single cuts and of the selection, for signal and background, I analysed Monte Carlo samples. Tighter trigger conditions have been applied by the selection, in order to maximize the trigger efficiency, except for the MUV3. The most relevant cuts I applied are:

- one track in STRAW, with associated signals in KTAG, GTK, RICH, NewCHOD, LKr, and no associated signal in MUV3, in order to select decay processes with track multiplicity exactly;
- four clusters in LKr at least with $E > 2GeV$ and one pair of clusters with an invariant mass consistent with π^0 mass (due to the $\pi^0 \to \gamma\gamma$ decay), in the range $m_{\pi^0} \pm 10MeV$ (fig. 4), in order to identify correctly the clusters coming from the π^0 and the one coming from the radiative photon;
- vertex decay Z coordinate in the range $110\,m < Z_{vertex} < 180\,m$, that correspond to the kaon decay fiducial region;
- positron E/p ratio (E: energy of the corresponding cluster measured in the LKr; p: momentum measured by the STRAW) in the range $0.9 < E/p < 1.1$ (fig. 5) and one ring in RICH with radius grater than 180 mm, in order to identify positrons and reject muons and pions;
- $E_\gamma > 10MeV$ and $\theta_{e,\gamma} > 10°$ in the kaon rest frame, in order to cure the Ke3γ amplitude divergence (fig. 6);
- $|m^2_{miss}| < 10000MeV^2/c^4$ (fig. 7) in order to insure the good quality of the kinematic reconstruction;

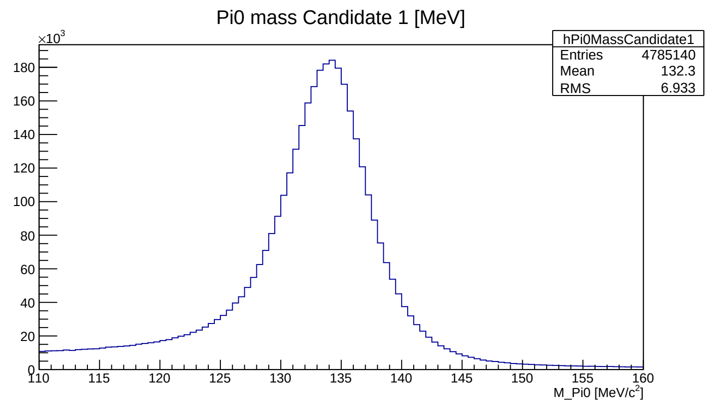

Figure 4: Closest clusters pair invariant mass in LKr to $mass_{\pi^0}$, before applying cuts.

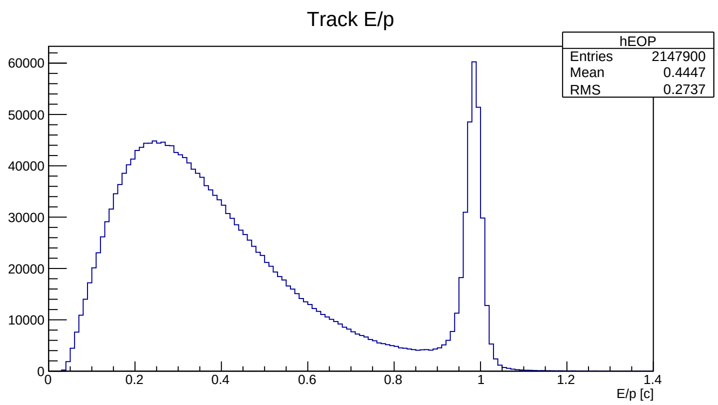

Figure 5: E/p for charged particle before applying cuts.

- all signals in time coincidence (3 ns);
- $|t_{GTK} - t_{event}| < 600ps$ where t_{event} (event time) has been defined as the average between LKr, RICH, KTAG times, in order to maximize the resolution.

The acceptance of the selection, measured with Monte Carlo Simulation, for signal and background, is shown in tab. 2.

In order to perform the branching ratio measurement using Ke3 as normalization channel, I selected these events too, requesting the same conditions, except for the the ones related to the radiative photon. The acceptance of Ke3 selection is shown in tab 3.

III. Branching ratio measurement

The normalized branching ratio is defined as:

$$\frac{BR(Ke3\gamma)}{BR(Ke3)} = \frac{\#SelectedEvents(Ke3\gamma)}{\#SelectedEvents(Ke3)} \cdot \frac{\epsilon_{acc}(Ke3)}{\epsilon_{acc}(Ke3\gamma)} \cdot \frac{\epsilon_{trig}(Ke3)}{\epsilon_{trig}(Ke3\gamma)} \quad (4)$$

First of all, thanks to the requested conditions, I observed that the trigger efficiency is the same for the two selections, and the inefficiencies are only due to random effects, that, by definition,

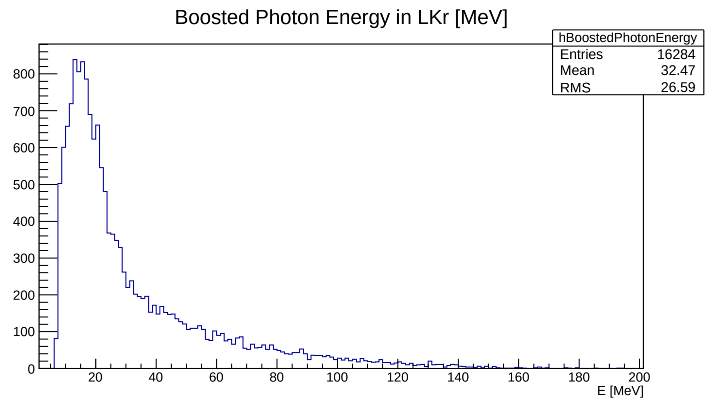

Figure 6: Radiative photon in kaon rest frame before applying cuts.

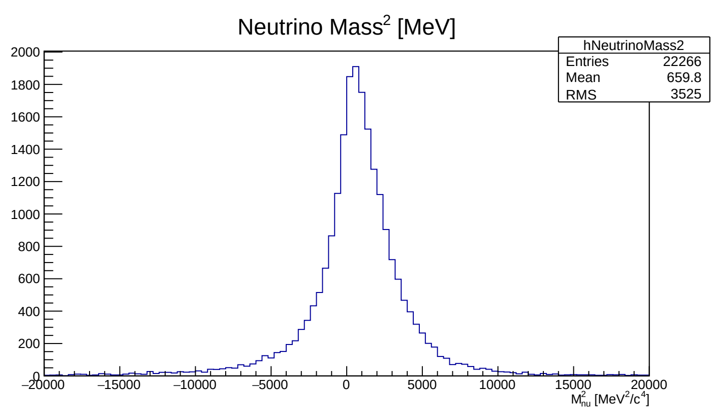

Figure 7: Square missing mass before applying cuts.

DECAY CHANNEL	SIMULATED EVENTS	SELECTED EVENTS	ACCEPTANCE EFFICIENCY
$K^+ \to \pi^0 e^+ \nu\gamma$	182294	5277	$(2.89 \pm 0.04)\%$
$K^+ \to \pi^0 e^+ \nu$	1188925	6	$(0.5 \pm 0.2) \cdot 10^{-5}$
$K^+ \to \pi^+ \pi^0 \pi^0$	1116770	0	$< 2.7 \cdot 10^{-6}$ 95% C.L.
$K^+ \to \pi^+ \pi^0$	1031844	0	$< 2.9 \cdot 10^{-6}$ 95% C.L.
$K^+ \to \pi^0 \mu^+ \nu$	1668931	0	$< 1.8 \cdot 10^{-6}$ 95% C.L.

Table 2: Ke3γ selection acceptance, for signal and background channels.

DECAY CHANNEL	SIMULATED EVENTS	SELECTED EVENTS	ACCEPTANCE EFFICIENCY
$K^+ \to \pi^0 e^+ \nu$	1188925	128683	$(10.82 \pm 0.03)\%$
$K^+ \to \pi^0 e^+ \nu\gamma$	252744	5870	$(2.32 \pm 0.03)\%$
$K^+ \to \pi^+ \pi^0 \pi^0$	1116770	1	$(0.9 \pm 0.9) \cdot 10^{-6}$
$K^+ \to \pi^+ \pi^0$	1031844	146	$(1.4 \pm 0.1) \cdot 10^{-4}$
$K^+ \to \pi^0 \mu^+ \nu$	1668931	4	$(2.4 \pm 1.2) \cdot 10^{-6}$

Table 3: Ke3 selection acceptance, for signal and background channels.

do not depend on the selection once the same time cuts are used. Indeed the trigger requests do not take into account any multiplicity, but only one signal by a charged particle is asked, so the presence of the radiative photon (that can convert in a electron-positron pair) can only increase the number of tracks, without any effects on the trigger. With an off-line trigger reconstruction I noticed that in Monte Carlo simulations (where there are no random effects) the efficiency is 100%, while in the data almost all the trigger inefficiency is caused by muon random veto in MUV3 detector. The extra radiative photon in the signal channel cannot affect the MUV3 trigger request in any way. Therefore in the eq. 4 the trigger efficiencies can be simplified. Even if it is not necessary for the branching ratio measurement, I measured this value of trigger efficiency (with Ke3 channel because of the better statistics): $\epsilon_{trig} = (93 \pm 1)\%$, consistent with the already known random muon veto rate.

In tab. 4 the numbers of selected events are reported, with the expected background value to be subtracted, computed according to the the acceptances reported in tab 2 and 3, and the relative average branching ratios [1].

SELECTION CHANNEL	SELECTED EVENTS	BACKGROUND VS SIGNAL
Ke3γ	12242	$(3.5 \pm 1.4)\%$
Ke3	2280352	$(0.64 \pm 0.04)\%$

Table 4: Number of selected events and background vs signal ratio.

With all this elements the result of the branching ratio measurement I performed is:

$$\frac{BR(Ke3\gamma)}{BR(Ke3)}(E_\gamma > 10MeV, \theta_{e,\gamma} > 10^\circ) = (1.95 \pm 0.04)\% \tag{5}$$

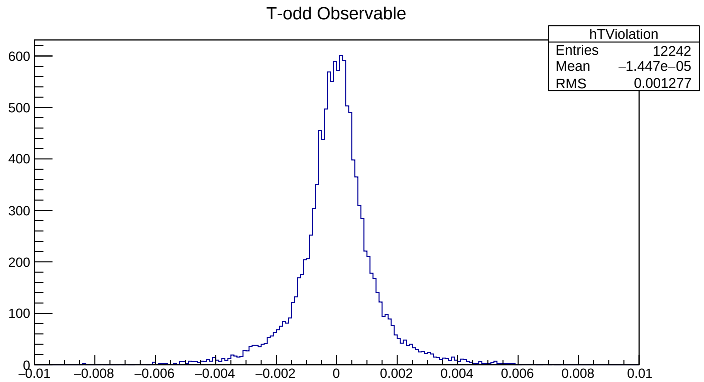

Figure 8: T-odd observable ξ.

where for the error all the following uncertainties sources have been taken into account: statistical errors on selected events numbers, measurements of the selections acceptances, expected background. This result is consistent within *ISTRA+* measurement with one sigma of confidence level. I also performed the same measurement changing the kinematic cuts, as *ISTRA+* experiment did. The comparison between the results is shown in tab. 5.

E_γ CUT	$\theta_{e,\gamma}$ CUT	ISTRA+ $\frac{BR(Ke3\gamma)}{BR(Ke3)}$	NA62 $\frac{BR(Ke3\gamma)}{BR(Ke3)}$
$E_\gamma > 10 MeV$	$0.6 < \cos\theta_{e,\gamma} < 0.9$	$(0.47 \pm 0.02 \pm 0.03) \cdot 10^{-2}$	$(0.57 \pm 0.02) \cdot 10^{-2}$
$E_\gamma > 30 MeV$	$\theta_{e,\gamma} > 20^\circ$	$(0.63 \pm 0.02 \pm 0.03) \cdot 10^{-2}$	$(0.68 \pm 0.03) \cdot 10^{-2}$
$E_\gamma > 10 MeV$	$\theta_{e,\gamma} > 10^\circ$	$(1.81 \pm 0.03 \pm 0.07) \cdot 10^{-2}$	$(1.95 \pm 0.04) \cdot 10^{-2}$

Table 5: $Ke3\gamma$ branching ratio measurements performed by the ISTRA+ experiment and the current analysis.

These results show the good quality of the Ke3γ events selection, and allow us to perform the T-asymmetry measurement with this data sample.

IV. T-asymmetry measurement

With the same selected events I computed the T-odd observable, defined in eq. 1; its distribution is shown in fig. 8.

Measuring the A_ξ variable defined in eq. 2, I obtained:

$$A_\xi = (0.005 \pm 0.009) \tag{6}$$

where only the statistical error is computed, and, according to the binomial distribution, it is: $\sigma_{A_\xi} \simeq \frac{1}{\sqrt{N}}$ where N is the number of selected events, in our case N = 12242.

I also evaluated the off-set introduced by our selection and our detector on the A_ξ variable, computing with Monte Carlo simulations the difference between the generated A_ξ and the reconstructed A_ξ, whose value is: (-0.010 ± 0.014). This off-set must be subtracted to the measurement shown in eq. 6. According to that, I obtained the following final results for T-asymmetry:

$$A_\xi = (0.016 \pm 0.017) \tag{7}$$

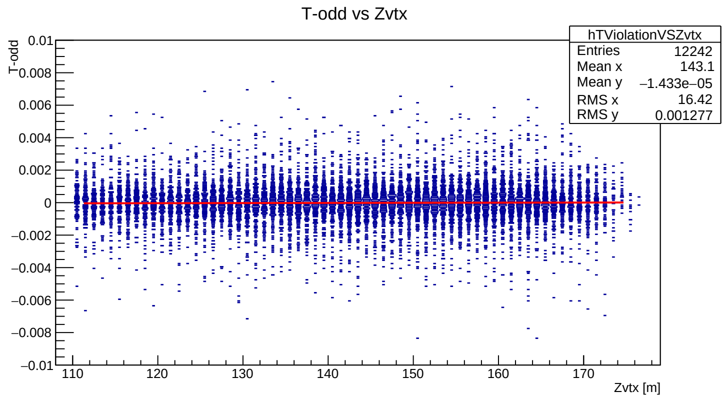

Figure 9: T-odd observable ξ with respect to decay vertex Z coordinate.

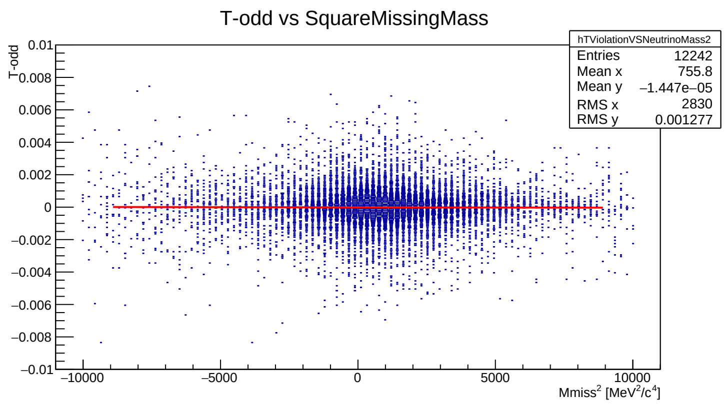

Figure 10: T-odd observable ξ with respect to squared missing mass.

I estimated possible systematic errors, plotting the T-odd observable ξ with respect to several physics quantities characterizing the decay, but in all the cases they appear flat (the fit parameters are consistent with a flat distribution). Three examples are shown in fig. 9, 10, 11. So I conclude that at this level of the analysis the systematic error is negligible with respect to statistical one.

V. Conclusions and outlook

Studying the Ke3γ decay with the NA62 experiment I performed branching ratio measurements. I also performed a first attempt to measure the T-violation parameter A_ξ; the measurement is consistent with zero within the statistical error.

Both the measurements are already competitive with the existing ones.

I estimated that with all the NA62 data taken in 2016 and 2017 the statistics could be increased by a factor 10, and so the statistical error could be reduced just by a factor 3. Taking data with the NA62 apparatus and an appropriate trigger mask could give the possibility to reduce the statistical error up to 10^{-3} and to perform a very interesting and competitive measurement of T-asymmetry in the weak interactions field.

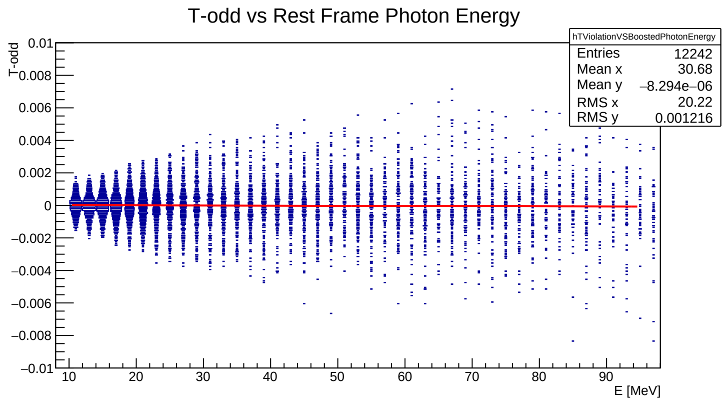

Figure 11: T-odd observable ξ with respect to radiative photon energy in kaon rest frame.

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