JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin Laboratory of High Energy Physics

FINAL REPORT ON THE
SUMMER STUDENT PROGRAM

Improvements on the $K^+ \rightarrow \pi^0 e^+ \nu \gamma$ analysis of the NA62 Experiment

Supervisor:
Dmitry Madigozhin

Student:
Francesco Brizioli
University of Perugia and INFN

Participation period:
September 9 – October 7, 2018

Dubna, October 2018

The project of the JINR Summer Student Programme of Francesco Brizioli has been aimed on improving the analysis of the $K^+ \rightarrow \pi^0 e^+ \nu \gamma$ decay already started in the Collaboration of the NA62 Experiment at CERN.

The report consist in a scientific note that illustrates the state of the art of the analysis, achieved at the end of the Summer Student Programme.

The analysis will be continued with the collaboration between Francesco Brizioli and the NA62 Group of JINR, in particular with the supervisor Dmitry Madigozhin.

Francesco Brizioli wants to thanks all the NA62 Group of Dubna for giving him this opportunity, for the hospitality and the kindness shown to him.

JINR SSP report

Study of the $K^+ \to \pi^0 e^+ \nu \gamma$ decay: BR and T-Violation measurements

Francesco Brizioli *

October 22, 2018

Abstract

A sample of 190K events of $K^+ \to \pi^0 e^+ \nu \gamma$ decay (Ke3γ) has been selected on the data collected by the NA62 Experiment at CERN in 2016 and 2017 runs.

Different measurements of the Ke3γ branching ratio normalized to $K^+ \to \pi^0 e^+ \nu$ decay (Ke3) have been performed.

With the same selection of Ke3γ events, 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.

The uncertainties on the preliminary results of the branching ratio measurements are dominated by the systematic contribution given by the comparison between data and Monte Carlo simualtions. This aspect must be improved: investigations are ongoing.

The uncertainties on the preliminary results of the T-Violation parameter measurement are dominated by the statistics of the collected data and the Monte Carlo samples.

All the performed measurements are already consistent and competitive with the state of the art.

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

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

There are two tree level processes of this decay 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).

Different Ke3γ branching ratio calculations (normalized to $K^+ \to \pi^0 e^+ \nu$ decay, Ke3) as a function of the lower limits imposed on the radiative photon energy and on the angle between radiative photon and positron in the kaon rest frame are performed in [3], using the *Chiral Perturbation Theory* in the Standard Model; some of them are reported in tab. 1.

ISTRA+ performed different measurements of the Ke3γ branching ratio normalized to $K^+ \to \pi^0 e^+ \nu$ decay (Ke3), changing the lower limits imposed on the radiative photon energy and on the angle between radiative photon and positron in the kaon rest frame [4], obtaining the results reported in tab. 1. The branching ratio value strongly depends on the kinematic cuts, due to

*University of Perugia and INFN - Italy

E_γ CUT	$\theta_{e,\gamma}$ CUT	$\frac{BR(Ke3\gamma)}{BR(Ke3)}$ SM	$\frac{BR(Ke3\gamma)}{BR(Ke3)}$ $ISTRA+$
$E_\gamma > 10MeV$	$0.6 < \cos\theta_{e,\gamma} < 0.9$	$(0.559 \pm 0.006) \cdot 10^{-2}$	$(0.47 \pm 0.02 \pm 0.03) \cdot 10^{-2}$
$E_\gamma > 30MeV$	$\theta_{e,\gamma} > 20^\circ$	$(0.640 \pm 0.008) \cdot 10^{-2}$	$(0.63 \pm 0.02 \pm 0.03) \cdot 10^{-2}$
$E_\gamma > 10MeV$	$\theta_{e,\gamma} > 10^\circ$	$(1.804 \pm 0.021) \cdot 10^{-2}$	$(1.81 \pm 0.03 \pm 0.07) \cdot 10^{-2}$

Table 1: *Ke*3γ branching ratio: theoretical calculations in the Standard Model ([3]) and measurements performed by ISTRA+ experiment[1, 4].

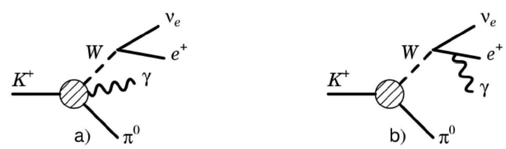

Figure 1: Feynman diagrams for Ke3γ decay at tree level: Direct Emission (a), Inner Bremsstrahlung (b).

the divergent amplitude at small photon energies and small angles between the photon and the positron.

The Ke3γ decay gives the opportunity to study the Standard Model symmetry violation sector, thanks to a T-odd physics quantity, defined in [5, 6]:

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

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 [5, 6]:

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

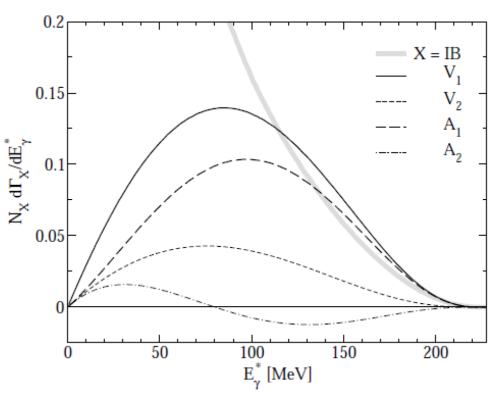

Figure 2: Radiative photon energy distributions in Ke3γ decay[3].

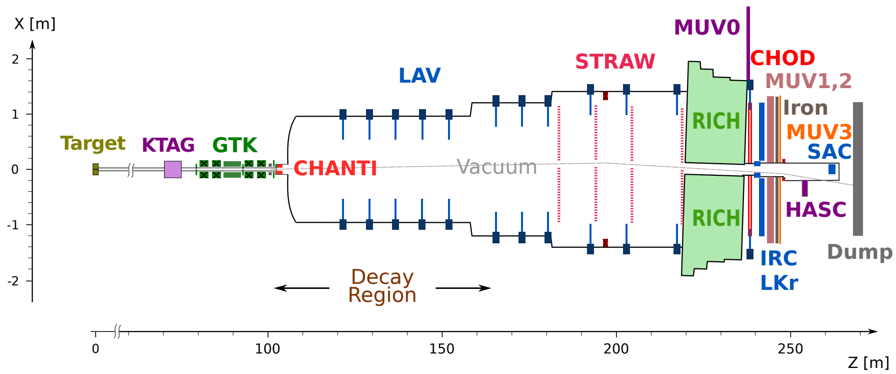

Figure 3: *Schematic layout of the NA62 detector in the xz plan [7].*

The non-zero value of the asymmetry in the Standard Model is only due to radiative corrections at the one-loop level.

A_ξ measurement has already been performed by the *ISTRA*+ Experiment [4], obtaining

$$A_\xi^{ISTRA+} = 0.015 \pm 0.021 \tag{4}$$

This measurement is consistent with zero due to the big experimental uncertainty.

The main goal of this analysis is to explore the possibility to perform an A_ξ measurement, competitive with the state of the art [4], with the data collected by NA62.

II. The NA62 Experiment

The NA62 Experiment is installed in the CERN North Area using a 400 GeV proton beam from the SPS accelerator colliding on a beryllium target, aimed to study the physics of the charged kaon meson. From the collisions a secondary hadronic beam with a momentum of 75 GeV, whose composition is 70% pions, 24% protons, 6% kaons, and the nominal particle rate is 750 MHz, is selected, and enters in the NA62 detector, shown in fig. 3.

The KTAG is a differential Cherenkov detector with the aim to identify the kaons into the beam. After it there is the Gigatracker (GTK) detector: three silicon pixel stations whose goal is tracking and measuring the momentum of the beam particles before entering in the fiducial decay region. The CHANTI detector, installed after the Gigatracker, is used as a veto for particles producted by the hadronic interaction between the beam particle and the material of the last GTK station. After the fiducial decay region, the magnetic spectrometer (STRAW) made of four straw chambers and a dipole magnet between the second and third chamber measures the momentum of the charged particles coming from the K^+ decay. A Ring Imaging Cherenkov detector (RICH) is placed after the spectrometer for the charged particle identification (π^+, μ^+, e^+). A system of scintillators (CHOD), together with the RICH, measure the time of charged particles. An electromagnetic calorimetr (LKr) and two hadronic calorimeters (MUV1 and MUV2), together with a scintillator array (MUV3) installed after an iron wall, provide further charged particle identification. A set of photons vetoes (LAVs, LKr, IRC, SAC) hermetically reject extra electromagnetic activity.

A full description of the NA62 Experiment is provided in [7] and [8].

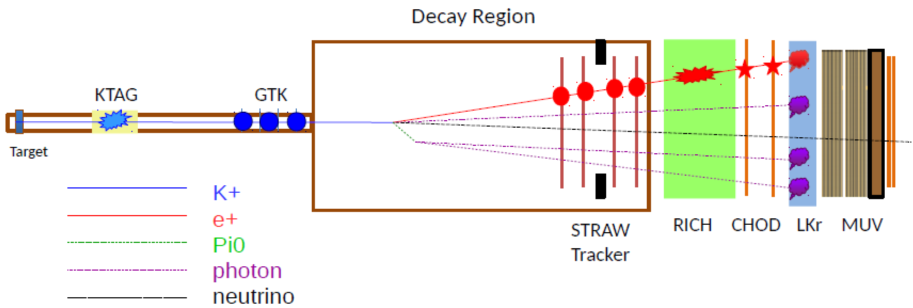

Figure 4: *Reconstruction of the Ke3γ event in the NA62 detectors.*

III. The event reconstruction

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 and direction (4-momentum);
- STRAW to measure the positron momentum and direction (4-momentum);
- LKr to measure energies and positions of positron, the photon pair coming from the π^0 and the radiative photon;
- RICH, the calorimeters and the MUV3 for particles identification.

The position of the K^+ decay vertex has been reconstructed computing the *Closest Distance of Approach (CDA)* between positron direction (STRAW) and kaon direction (GTK). The 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. Only the $\pi^0 \to \gamma\gamma$ decay has been considered for the neutral pion.

A graphic representation of the reconstruction of the Ke3γ event in the NA62 detector is provided in fig. 4. The kinematics of all the particles involved in the decay are reconstructed (4-momenta), except for the neutrino.

IV. The event selection

The following data samples collected by NA62 experiment in the 2016 and 2017 runs have been analyzed: 2016-A, 2017-A, 2017-B. Cause there are not relevant differences between the results obtained in each data sample, they have been merged and they will be shown all together.

The trigger conditions used for this analysis are:

- the *Not Muon* trigger (*Mask0*), which requires signal coincidence in RICH, NewCHOD and KTAG detectors, and anticoincidence in MUV3 detector;
- the *Minimum Bias* trigger (*Control*), which requires signal in CHOD detector.

The two exploited trigger conditions are strongly downscaled: a factor 400 is applied on the *Minimum Bias* trigger, and a factor 200 is applied on the *Not Muon* trigger for the largest part of the data taking.

Different conditions (*cuts*) on several physics quantities have been applied to select Ke3γ events (signal) and reject the background.

Tighter conditions have been applied in the selection with respect to the trigger, in order to maximize the trigger efficiency.

The most relevant applied conditions are reported below.

1 *good* track requested. A track is considered good if is in geometrical acceptance with: Straw, RICH, CHOD, NewCHOD, LKr, MUV1, MUV2, MUV3, has $Q = +1$, momentum in $[8 - 60]$ GeV/c, the fit of the reconstruction gives $\chi^2 < 5$.

A signal in the following detectors must be associated to the track projection (in time and space): RICH, CHOD, NewCHOD, LKr. For MUV1, MUV2, and MUV3 detector the same condition is requested in anticoincidence.

The association between the tracks in Straw and GTK is requested with a time matching of 500 *ps* and must give the following results and for the Z coordinate of the decay vertex (fiducial decay region) and for the *CDA*: $110\ m < Z_{vtx} < 170\ m$; $CDA < 10\ mm$.

In order to reconstruct the $\pi^0 \to \gamma\gamma$, 2 LKr clusters not associated with the track with a minimum energy of 4 GeV and in time with the track (3 ns) are requested. Then, a kinematic check, observing the invariant mass of the photons pair, is done asking $|M_{\gamma\gamma} - M_{\pi^0}| < 10\ MeV/c^2$ and no others clusters pairs with $|M_{\gamma\gamma} - M_{\pi^0}| < 18\ MeV/c^2$.

In order to reconstruct the radiative photon, one LKr cluster not associated with the track and the π^0, with a minimum energy of 2 GeV and in time with the track (2 ns, that corresponds to 3σ of the Δt distribution) is requested. Clusters with an energy smaller than 2 GeV or not in time are not taken into account, while events with more clusters with energy grater than 2 GeV and in time with the track are rejected.

The charged particle identification (positrons against muons and pions) is done by several physics quantities adn detectors. Anticoincidence in MUV1, MUV2, MUV3 is requested. The ratio between the energy of the track cluster in the LKr and the momentum measured by the Straw spectrometer (i.e. E/p) must be in $[0.9 - 1.1]$ (natural units). A BDT classifier using energy, energy sharing, clusters shape in LKr, MUV1 and MUV2 is asked to give a probability for the positron hypothesis grater than 0.9. Moreover, thanks to the RICH detector, the reconstructed radius of the Cherenkov ring must be grater than 180 *mm*, the absolute value of the reconstructed mass of the charged particle (combining the radius in the RICH and the moementum in the Straw) must be smaller than 80 MeV/c^2, and a track driven Likelihood discriminant computed with the hits in the RICH must give the greatest value for the positron hypothesis, and the ratio between all the other hypotheses values and the positron hypothesis value must be smaller than 0.8.

In order to avoid the possibility of misidentifing the radiative photon with accidental clusters or Bremsstrahlung photons emitted by the positron, in addition to the conditions on the timing and the minimum energy of the cluster, a minumum distance of 20 *cm* between all the clusters is requested, and the distance between the radiative photon cluster and track extrapolation at the LKr plane must be grater than 5 *cm*.

From the kinematics point of view the sum of the momenta of the positron, the neutral pion and the radiative photon in the final state must be smaller than the 0.95% of the momentum of the kaon in the initial state, and its ortogonal component with respect to the kaon direction (i.e. transverse momentum) must be grater than 40 MeV/c. Moreover, the so called squared missing mass of the Ke3γ reconstructed event must satisfy: $|M^2_{miss}| < 0.01\ GeV^2/c^4$, where $M^2_{miss} = (P_K - P_{e^+} - P_{\pi^0} - P_\gamma)^2$ and P_i are the 4-momenta of the reconstructed particles in the initial and final state of the decay. The distribution of the M^2_{miss}, before applying the cuts, is shown in fig. 5.

Finally, the lower limits on the radiative photon energy and on the angle between radiative photon and positron in the kaon rest frame have been imposed, applying the values reported in tab. 1. The lighter lower limits applied are $E_\gamma > 10\ MeV, \theta_{e,\gamma} > 10^\circ$. The distributions of the the

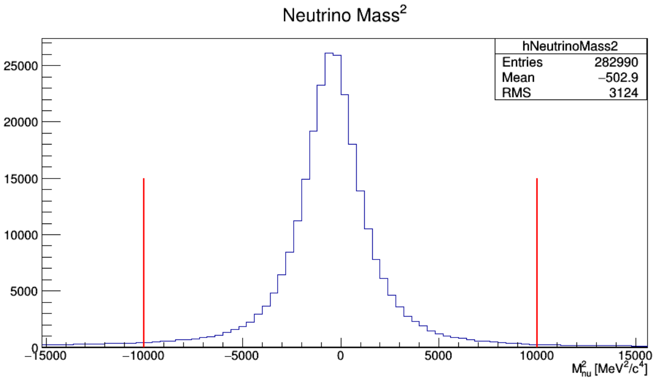

Figure 5: Square missing mass before applying cuts.

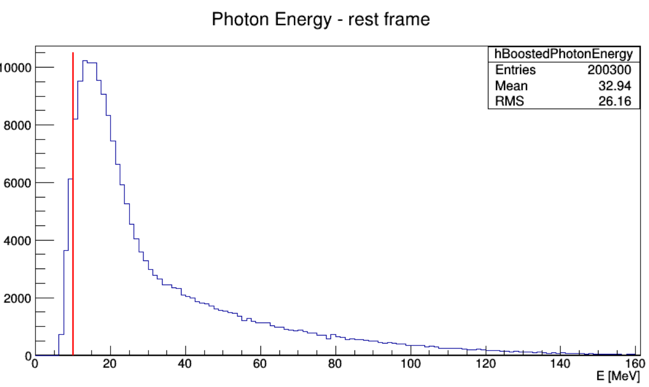

Figure 6: Radiative photon energy in the kaon rest frame before applying cuts.

two physics quantities, before applying the cuts, are reported in fig. 6 and 7.

In order to perform the branching ratio measurements using the Ke3 decay as normalization channel, a Ke3 selection has been implemented, requiring the same conditions of the Ke3γ selection, except for the the ones related to the radiative photon. In the Ke3 event selection also the radiative corrections are included, so the Ke3γ events (signal) are a subset of the Ke3 events (normalization).

V. Results and acceptances of the selections

The numbers of selected events are reported in tab. 2, with the estimation of the signal acceptance and the expected ratio *background*/*signal*, computed according to the background acceptances and the known branching ratios of the normalization and the background channels [1].

SELECTION	SELECTED EVENTS	ACCEPTANCE	*background*/*signal*
Ke3γ	$190K$	$(2.360 \pm 0.007)\%$	$(1.75 \pm 0.25)\%$
Ke3	$34.5M$	$(7.66 \pm 0.01)\%$	$(0.0014 \pm 0.0004)\%$

Table 2: Number of selected events, signal acceptance and *background*/*signal* ratio.

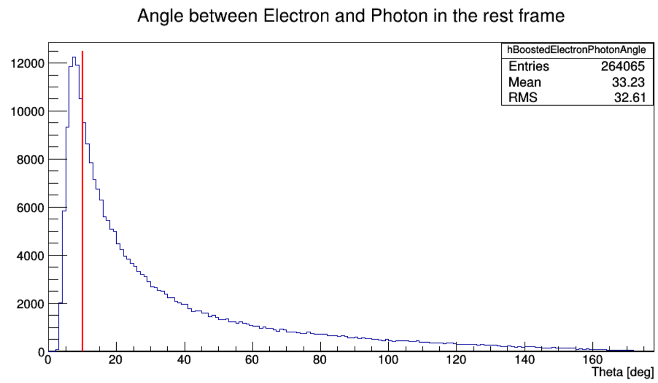

Figure 7: Angle between the radiative photon and the positron in the kaon rest frame before applying cuts.

To study the acceptance of the single cuts and of the global selections, for signal and background, Monte Carlo samples have been used. In particular for the signal channel a Monte Carlo generator provided by B. Kubis et al. [3] has been used. In this generator both the Direct Emission and the Inner Bremsstrahlung components (including their interference) are taken into account.

The decay channels considered as potencial background are: $K^+ \to \pi^0 e^+ \nu$, $K^+ \to \pi^+ \pi^0 \pi^0$, $K^+ \to \pi^+ \pi^0$, $K^+ \to \pi^0 \mu^+ \nu$, $K^+ \to \pi^0 \pi^0 e^+ \nu$, including the radiative corrections.

The acceptances have been defined as the ratio between the number of selected events and the number of the generated events in the decay fiducial region and (only for the Ke3γ channel) with the imposed lower limits on the the radiative photon energy and on the angle between radiative photon and positron in the kaon rest frame.

The trigger efficiencies has been directly measured from the data, exploiting the two indipendent triggered samples (*Not Muon* trigger and *Minimum Bias* trigger). The trigger efficiencies are greater than 98% and are equal for the signal and the normalization selections, so they will not affect the normalized branching ratio measurements:

$$\frac{\epsilon_{trig}(Ke3)}{\epsilon_{trig}(Ke3\gamma)} = 1.0035 \pm 0.0004 \tag{5}$$

VI. Comparison between Data and Monte Carlo

The Monte Carlo simulations, used to measure the acceptances of the selections, should exactly reproduce what is found in the data, otherwise a disagreement leads to a systematic error in the acceptances measurements, therefore in all the measurements in which acceptances are involved.

In order to check the agreement, the squared missing mass (M^2_{miss}) has been chosen as the most significative observable, cause it contains the convolution of all the kinematics of the decay in both its initial and final state, and of all the reconstructed particles.

The distributions of the M^2_{miss} for the Ke3 selection are shown in fig. 8: there are not significant disagreements between data and Monte Carlo simulation.

The distributions of the M^2_{miss} for the Ke3γ selection are shown in fig. 9: in this case there is a relevant disagreement in the tails of the distributions.

Cause the disagreement is present only in the Ke3γ selection and not in the Ke3 selection, the most probable hypothesis is that it is due to the radiative photon simulation.

In particular, it must be underlined that there are not kinematic constraint on the cluster tagged as the radiative photon one, but there are only the minimum energy (2 GeV), the time coincidence

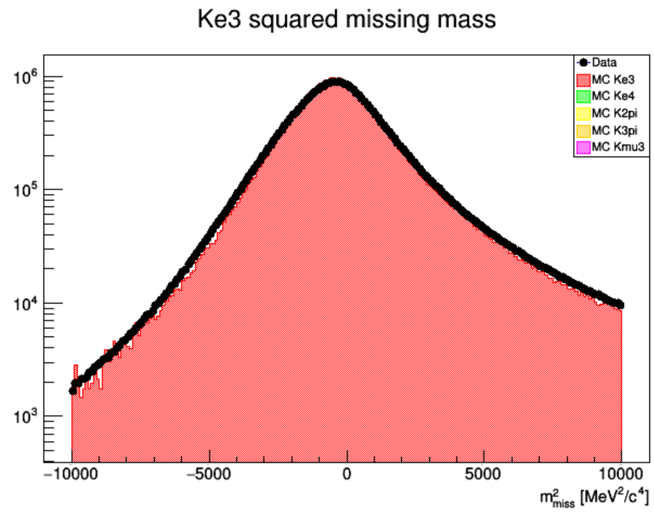

Figure 8: The M^2_{miss} observable in the data and in the Monte Carlo simulation for the Ke3 selected events.

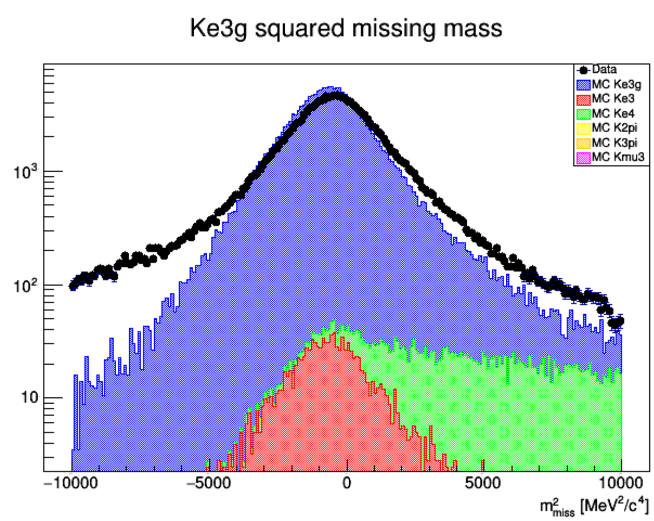

Figure 9: The M^2_{miss} observable in the data and in the Monte Carlo simulation for the Ke3γ selected events.

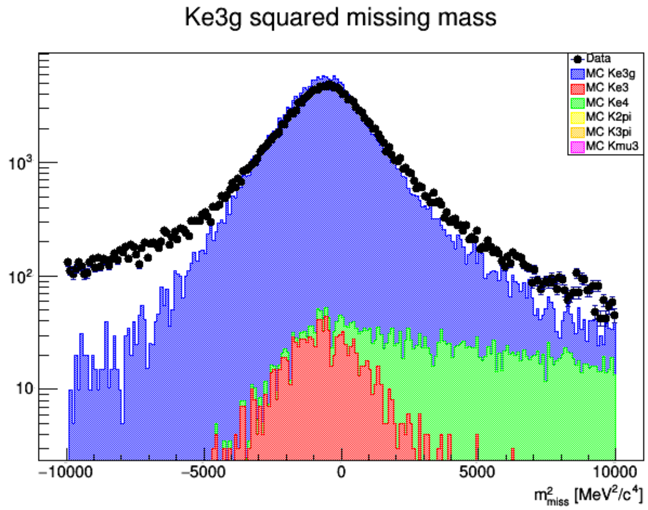

Figure 10: The M^2_{miss} observable in the data and in the Monte Carlo simulation for the Ke3γ events selected with stricter cuts on on the minimum energy (up to 4 GeV) and on the minumim clusters distance (up to 40 cm).

(2 ns) and the minimum clusters distance (20 cm) conditions. Therefore one of the possible causes of the excess of events in the data with respect to the Monte Carlo simulation, in the negative tail of the distributions, is the presence of an accidental cluster, in time and with an energy greater than 2 GeV, in a Ke3 event, that is tagged as a radiative photon cluster.

It is not possible to apply a stricter cut on the time coincidence (now set at 2 ns, that correspond to 3σ of the Δt distribution), because it is not simulated in the Monte Carlo (where by definition all the hits are assumed to be in time), and there should be a decreasing of the signal acceptance not simulated, so not taken into account in the acceptance measurement.

While stricter cut have been applied on the minimum energy (up to 4 GeV) and on the minumim clusters distance (up to 40 cm). The distributions of the M^2_{miss} for the event selected with such stricter conditions are shown in fig. 10: there is not any improvement with respect to the previous selection, therefore the *accidental cluster* hypothesis to explain the data - Monte Carlo disagreement on the M^2_{miss} distributions can be discarded.

Analyzing the single physics quantities that contribute to the M^2_{miss} computation, it emerges that there are not relevant disagreements between data and Monte Carlo simulation (to give an example, the distributions of radiative photon energy in the kaon rest frame are shown in fig. 11), except for the angle between the positron and the radiative photon in the kaon rest frame: its distributions are shown in fig. 12.

This evidence could imply that the disagreement between data and Monte Carlo simulation is due to a wrong generation of the radiative photon emitted at big angles with respect to the positron. In that region the Direct Emission component dominates the Inner Bremsstrahlung one (fig. 1, so the problem could be in the Direct Emmission component generation in the Ke3γ Monte Carlo generator, described in [3].

The fact that (at least) one reason of the disagreement in the M^2_{miss} distributions is the wrong simulation of radiative photon emitted at big angles with respect to the positron is confirmed by the plot in fig. 13, that shows the M^2_{miss} distributions in the data and in the Monte Carlo simulation for the Ke3γ events selected with the conditions $E_\gamma > 10 MeV$, $0.6 < \cos\theta_{e,\gamma} < 0.9$ (i.e. $26° < \theta_{e,\gamma} < 53°$): the agreement is definitely better than the distributions shown in fig. 9, even if

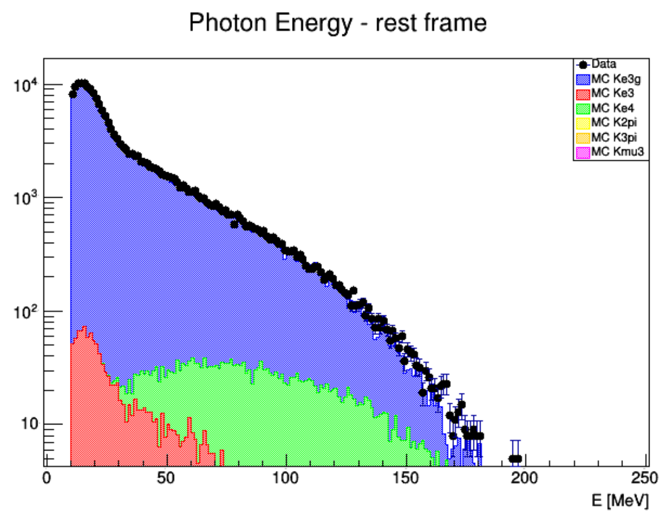

Figure 11: Radiative photon energy in the kaon rest frame in the data and in the Monte Carlo simulation for the Ke3γ selected events.

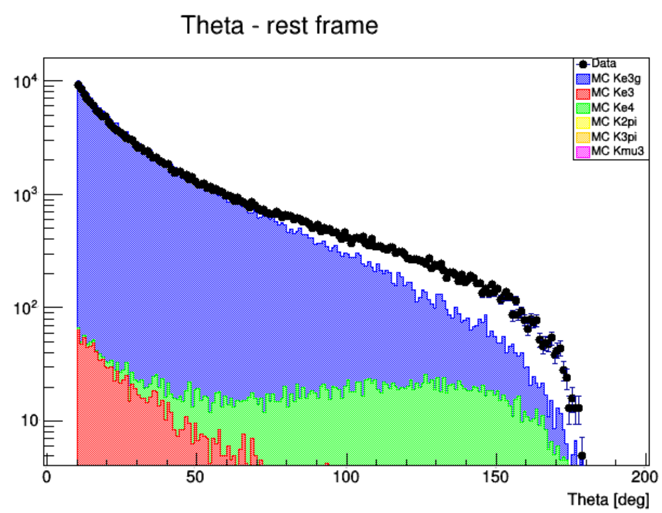

Figure 12: Angle between the radiative photon and the positron in the kaon rest frame in the data and in the Monte Carlo simulation for the Ke3γ selected events.

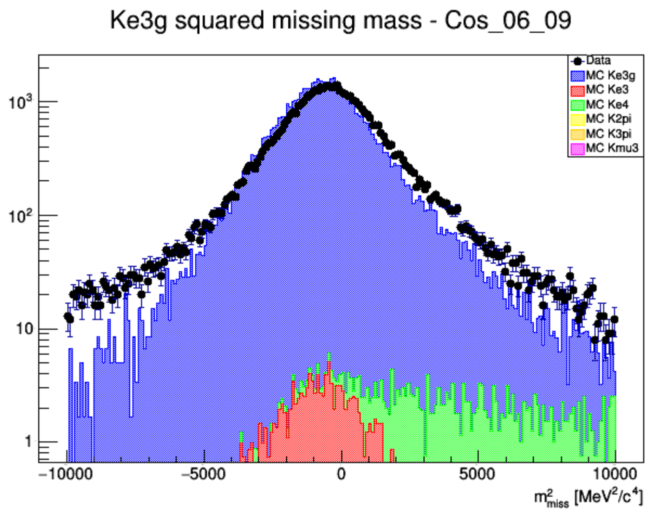

Figure 13: The M^2_{miss} observable in the data and in the Monte Carlo simulation for the Ke3γ selected events with the conditions $E_\gamma > 10MeV$, $0.6 < \cos\theta_{e,\gamma} < 0.9$.

still not perfect.

In order to understand if the problem is related to the Monte Carlo generator, an other independent generator could be useful for comparison: a sample producted with the Monte Carlo generator provided by C. Gatti, described in [9], has already been scheduled for the production, and will be tested as soon as it will be ready.

An other possible reason to explain the disagreement is the presence of other background sources not yet taken into account.

To reduce the systematic error, one possibility could be applying stricter cuts on the M^2_{miss} observable, e.g. $|M^2_{miss}| < 0.005\ GeV^2/c^4$, that basically discard all the regions where data and Monte Carlo do not agree, and lead to a loosing of signal statistic of $\simeq 8\%$.

The disagreement between data and Monte Carlo simulations has been quantitatively evaluated with the following procedure:

$$\frac{\sqrt{\sum_{k=1}^{N_{bins}} (MC_k - D_k)^2}}{\sum_{k=1}^{N_{bins}} D_k} = 2.4\% \tag{6}$$

where k is the bin index, N_{bins} is the number of the bins, MC_k is the number of Monte Carlo events in each bin, D_k is the number of data events in each bin.

At the moment, using a conservative approach, the value obtained for the evaluation of the disagreement between data and Monte Carlo simulations, has been assigned as systematic error to the branching ratio measurements. More studies are needed to improve this aspect and are still ongoing.

VII. Branching ratio measurements

The normalized branching ratio is defined as:

$$\frac{BR(Ke3\gamma)}{BR(Ke3)} = \frac{Signal\ Events(Ke3\gamma)}{Signal\ Events(Ke3)} \cdot \frac{\epsilon_{acc}(Ke3)}{\epsilon_{acc}(Ke3\gamma)} \cdot \frac{\epsilon_{trig}(Ke3)}{\epsilon_{trig}(Ke3\gamma)} \tag{7}$$

where *signal events* is the difference between the number of selected events and the number of expected background according to the tab. 2.

The result of the performed branching ratio measurement with all these elements is:

$$\frac{BR(Ke3\gamma)}{BR(Ke3)}(E_\gamma > 10\,MeV, \theta_{e,\gamma} > 10°) = (1.759 \pm 0.006 \pm 0.042)\% \quad (8)$$

where the statistical error is only due to the uncertainties on the signal events numbers, while the systematic error is due to the uncertainties on the selections acceptances and the trigger efficiency measurements, and the most relevant effect due the disagreement between data and Monte Carlo simulations, that has already been discussed.

In tab. 3 all the single contributions to the relative error on the branching ratio measurement are reported.

MEASUREMENT	RELATIVE ERROR
$Signal\ Events(Ke3\gamma)$	0.3%
$Signal\ Events(Ke3)$	0.02%
$\epsilon_{acc}(Ke3\gamma)$	0.3%
$\epsilon_{acc}(Ke3)$	0.3%
ϵ_{trig}	0.04%
$System.\ Monte\ Carlo$	2.4%
$\frac{BR(Ke3\gamma)}{BR(Ke3)}$	2.4%

Table 3: Single contributions to the relative error on the branching ratio measurement.

Two more measurements have been performed applying stricter lower limits on the the radiative photon energy and on the angle between radiative photon and positron in the kaon rest frame, as *ISTRA+* experiment did. The results are shown in tab. 4, and can be compared with the state of the art reported in tab. 1.

E_γ CUT	$\theta_{e,\gamma}$ CUT	SELECTED EVENTS	$\frac{BR(Ke3\gamma)}{BR(Ke3)}$ $NA62$
$E_\gamma > 10MeV$	$0.6 < \cos\theta_{e,\gamma} < 0.9$	$54K$	$(0.519 \pm 0.002 \pm 0.012) \cdot 10^{-2}$
$E_\gamma > 30MeV$	$\theta_{e,\gamma} > 20°$	$49K$	$(0.651 \pm 0.007 \pm 0.015) \cdot 10^{-2}$
$E_\gamma > 10MeV$	$\theta_{e,\gamma} > 10°$	$190K$	$(1.759 \pm 0.006 \pm 0.042) \cdot 10^{-2}$

Table 4: $Ke3\gamma$ branching ratio measurements performed by the current analysis on the NA62 data.

VIII. T-asymmetry measurement

With the same sample of Ke3γ selected events ($E_\gamma > 10MeV$, $\theta_{e,\gamma} > 10°$), the T-odd observable ξ, defined in eq. 1 has been computed, and its distribution is shown in fig. 14.

Measuring the A_ξ asymmetry defined in eq. 2, the following result has been obtained:

$$A_\xi^{raw} = -0.0002 \pm 0.0023 \quad (9)$$

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 this case N = 190K.

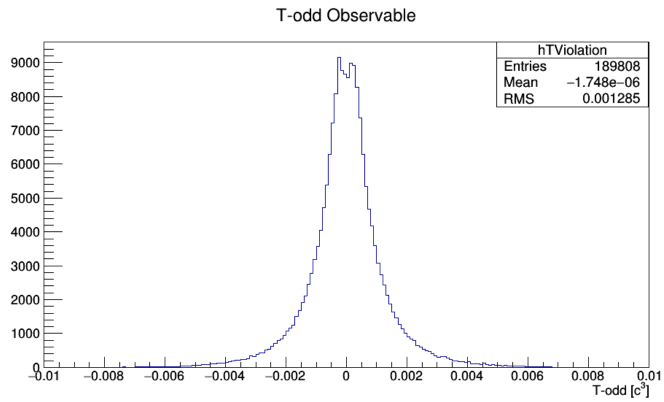

Figure 14: T-odd observable ξ.

The offset introduced by the selection and the detector on the A_ξ variable has also been evaluated, computing with Monte Carlo simulations the difference between the generated A_ξ and the reconstructed A_ξ, whose value is:

$$A_\xi^{offset} = -0.002 \pm 0.003 \tag{10}$$

This offset has been subtracted to the *raw* measurement shown in eq. 9, and its error, that is only due to the number of simulated events, has been considered a systematic error on the final measurement. Therefore the following final result for T-asymmetry has been obtained:

$$A_\xi = A_\xi^{raw} - A_\xi^{offset} = 0.002 \pm 0.002 \pm 0.003 \tag{11}$$

The systematic error due to the number of simulated events can be virtually reduced to zero, only generating more Monte Carlo events.

Other possible systematic errors have been estimated, plotting the T-odd observable ξ as a function of several physics quantities characterizing the decay, but in all the cases the distributions appear flat (the χ^2 of the fits show they are consistent with a flat distribution). An examples is shown in fig. 15. Even the agreement between data and Monte Carlo simulation is good for the ξ distribution, as shown in fig. 16.

It means that at this level of the analysis other possible systematic errors are negligible with respect to the statistical one.

IX. Conclusions and outlook

The Ke3γ decay has been studied with the NA62 experiment, selecting the largest Ke3γ sample ever collected: 190K events.

Branching ratio measurements have been performed. The systematic error due to the disagreement between data and Monte Carlo simluation is the most relevant contribution to the uncertainties.

A first attempt to measure the T-violation parameter A_ξ has also been performed; the measurement is consistent with zero within the errors. The uncertainties are dominated by the statistical ones. In particular, even assuming that the NA62 experiment will collect a factor 10 more of data useful for this analysis, the statistical uncertainty on the T-violation measurement could be reduce

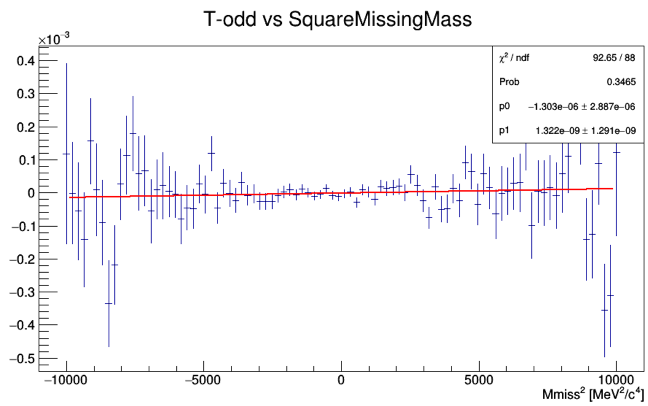

Figure 15: The T-odd observable ξ af a function of the squared missing mass.

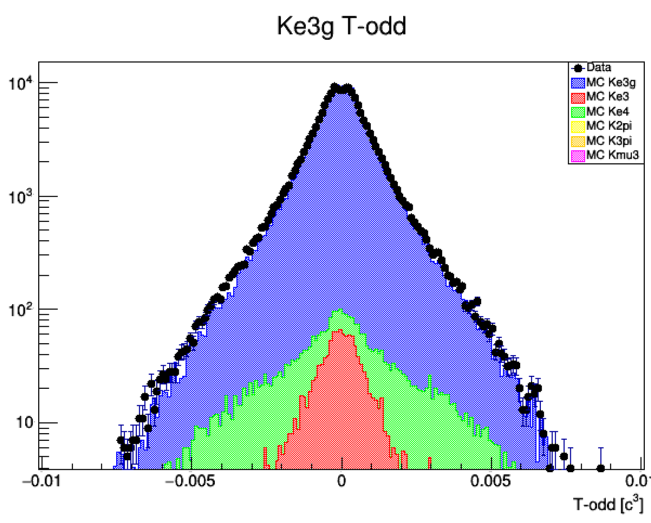

Figure 16: The T-odd observable ξ in the data and in the Monte Carlo simulation.

by only a factor 3. Anyway the uncertainty that NA62 will be able to reach is definitely smaller than the state of the art.

All the performed measurements are already consistent and competitive with the existing ones.

More investigations on the agreement between data and Monte Carlo simulations are needed to complete the analysis, and are indeed ongoing.

References

[1] C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016)

[2] J. Bijnens, G. Ecker and J. Gasser, *Radiative semileptonic Kaon decays*, Nucl.Phys.B396:81-118, 1993

[3] B. Kubis et al., *Aspects of radiative K^+_{e3} decays*, Eur.Phys.J.C50:557-571, 2007

[4] S.A. Akimenko et al., *Study of $K^- \to \pi^0 e^- \nu\gamma$ decay with ISTRA+ setup.*, PoSKAON:029, 2008

[5] V.V. Braguta et al., *T-odd correlation in the $K_{l3\gamma}$ decay*, Physical Review D, Vol. 65, 054038, 20.02.2002

[6] B. Kubis et al., *T-odd correlations in radiative K^+_{l3} decays and chiral perturbation theory*, Eur.Phys.J.C48:427-440, 2006

[7] The NA62 Collaboration, *The beam and detector of the NA62 experiment at CERN*, 2017 JINST 12 P05025 (May 2017)

[8] The NA62 Collaboration,*2018 NA62 Status Report to the CERN SPSC*, CERN-SPSC-2018-010 / SPSC-SR-229.

[9] C. Gatti, *Monte Carlo simulation for radiative kaon decays*, Eur. Phys. J. C 45, 417-420 (2006).