PROCEEDINGS OF SCIENCE

Preliminary results of the $K^+ \to \pi^0 e^+ \nu\gamma$ decay study at the NA62 experiment

Francesco Brizioli[a,*]

[a] *Istituto Nazionale di Fisica Nucleare, sezione di Perugia*
Via A. Pascoli, Perugia, Italy

E-mail: francesco.brizioli@cern.ch

The $K^+ \to \pi^0 e^+ \nu\gamma$ decay process has been studied by the NA62 experiment with the data collected in 2017 and 2018 runs. The preliminary results with measurements of the branching fraction (normalized to $K^+ \to \pi^0 e^+ \nu$ channel) and of the T-violation, that improve the experimental state of the art, are presented.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

*Speaker, for the NA62 Collaboration: A. Akmete, R. Aliberti, F. Ambrosino, R. Ammendola, B. Angelucci, A. Antonelli, G. Anzivino, R. Arcidiacono, T. Bache, A. Baeva, D. Baigarashev, L. Bandiera, M. Barbanera, J. Bernhard, A. Biagioni, L. Bician, C. Biino, A. Bizzeti, T. Blazek, B. Bloch-Devaux, P. Boboc, V. Bonaiuto, M. Boretto, M. Bragadireanu, A. Briano Olvera, D. Britton, F. Brizioli, M.B. Brunetti, D. Bryman, F. Bucci, T. Capussela, J. Carmignani, A. Ceccucci, P. Cenci, V. Cerny, C. Cerri, B. Checcucci, A. Conovaloff, P. Cooper, E. Cortina Gil, M. Corvino, F. Costantini, A. Cotta Ramusino, D. Coward, G. D'Agostini, J. Dainton, P. Dalpiaz, H. Danielsson, M. D'Errico, N. De Simone, D. Di Filippo, L. Di Lella, N. Doble, B. Dobrich, F. Duval, V. Duk, D. Emelyanov, J. Engelfried, T. Enik, N. Estrada-Tristan, V. Falaleev, R. Fantechi, V. Fascianelli, L. Federici, S. Fedotov, A. Filippi, R. Fiorenza, M. Fiorini, J. Fry, J. Fu, A. Fucci, L. Fulton, E. Gamberini, L. Gatignon, G. Georgiev, S. Ghinescu, A. Gianoli, M. Giorgi, S. Giudici, F. Gonnella, K. Gorshanov, E. Goudzovski, C. Graham, R. Guida, E. Gushchin, F. Hahn, H. Heath, J. Henshaw, Z. Hives, E.B. Holzer, T. Husek, O. Hutanu, D. Hutchcroft, L. Iacobuzio, E. Iacopini, E. Imbergamo, B. Jenninger, J. Jerhot, R.W. Jones, K. Kampf, V. Kekelidze, D. Kerebay, S. Kholodenko, G. Khoriauli, A. Khotyantsev, A. Kleimenova, A. Korotkova, M. Koval, V. Kozhuharov, Z. Kucerova, Y. Kudenko, J. Kunze, V. Kurochka, V. Kurshetsov, G. Lanfranchi, G. Lamanna, E. Lari, G. Latino, P. Laycock, C. Lazzeroni, M. Lenti, G. Lehmann Miotto, E. Leonardi, P. Lichard, L. Litov, P. Lo Chiatto, R. Lollini, D. Lomidze, A. Lonardo, P. Lubrano, M. Lupi, N. Lurkin, D. Madigozhin, I. Mannelli, A. Mapelli, F. Marchetto, R. Marchevski, S. Martellotti, P. Massarotti, K. Massri, E. Maurice, A. Mazzolari, M. Medvedeva, A. Mefodev, E. Menichetti, E. Migliore, E. Minucci, M. Mirra, M. Misheva, N. Molokanova, M. Moulson, S. Movchan, M. Napolitano, I. Neri, F. Newson, A. Norton, M. Noy, T. Numao, V. Obraztsov, A. Okhotnikov, A. Ostankov, S. Padolski, R. Page, V. Palladino, I. Panichi, A. Parenti, C. Parkinson, E. Pedreschi, M. Pepe, M. Perrin-Terrin, L.Peruzzo, P. Petrov, Y. Petrov, F. Petrucci, R. Piandani, M. Piccini, J. Pinzino, I. Polenkevich, L. Pontisso, Yu. Potrebenikov, D. Protopopescu, M. Raggi, M. ReyesSantos, M. Romagnoni, A. Romano, P. Rubin, G. Ruggiero, V. Ryjov, A. Sadovsky, A. Salamon, C. Santoni, G. Saracino, F. Sargeni, S. Schuchmann, V. Semenov, A. Sergi, A. Shaikhiev, S. Shkarovskiy, M. Soldani, D. Soldi, M. Sozzi, T. Spadaro, F. Spinella, A. Sturgess, V. Sugonyaev, J. Swallow, A. Sytov, G. Tinti, A. Tomczak, S. Trilov, P. Valente, B. Velghe, S. Venditti, P. Vicini, R.Volpe, M. Vormstein, H. Wahl, R. Wanke, V. Wong, B. Wrona, O. Yushchenko, M. Zamkovsky, A. Zinchenko.

PoS(EPS-HEP2021)553

1. The $K^+ \to \pi^0 e^+ \nu\gamma$ decay: state of the art

The $K^+ \to \pi^0 e^+ \nu\gamma$ decay is described in the framework of the *Chiral Perturbation Theory (ChPT)*. Branching ratio calculations are provided in [1–4]. The ratio between $K^+ \to \pi^0 e^+ \nu\gamma$ ($Ke3\gamma$) and the $K^+ \to \pi^0 e^+ \nu$ ($Ke3$) branching fractions is defined as follows:

$$R_j = \frac{\mathcal{B}(Ke3\gamma^j)}{\mathcal{B}(Ke3)} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \mid E_\gamma^j,\ \theta_{e,\gamma}^j)}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma))}, \tag{1}$$

where E_γ^j and $\theta_{e,\gamma}^j$ represent restrictions to the phase space in terms of the radiative photon energy E_γ and the angle $\theta_{e,\gamma}$ between the radiative photon and the charged lepton, due to the divergent decay amplitude for $E_\gamma \to 0$ and $\theta_{e,\gamma} \to 0$. The most commonly used definitions for the R_j kinematic regions in the kaon rest frame are given in Table 1, together with the corresponding recent theoretical and experimental results. The most recent theoretical calculation [4] provides an absolute branching ratio for the R_2 kinematic region only, that corresponds to $R_2 = (0.56 \pm 0.02) \cdot 10^{-2}$.

	E_γ^j	$\theta_{e,\gamma}^j$	$O(p^6)$ *ChPT*	ISTRA+	OKA
$R_1 \times 10^2$	$E_\gamma > 10\ MeV$	$\theta_{e,\gamma} > 10°$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
$R_2 \times 10^2$	$E_\gamma > 30\ MeV$	$\theta_{e,\gamma} > 20°$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$
$R_3 \times 10^2$	$E_\gamma > 10\ MeV$	$0.6 < \cos\theta_{e,\gamma} < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

Table 1: R_j definitions in terms of E_γ and $\theta_{e,\gamma}$ in the kaon rest frame, and respective expectations from the $O(p^6)$ *ChPT* calculations [3] and results of the measurements performed by the ISTRA+ [5] and the OKA [6] experiments.

Possible T-violation effects in $K^+ \to \pi^0 e^+ \nu\gamma$ process can be studied using the T-odd observable ξ and the corresponding asymmetry A_ξ (see Equation 2):

$$\xi = \frac{\overrightarrow{p_\gamma} \cdot (\overrightarrow{p_e} \times \overrightarrow{p_\pi})}{M_K^3}\ ;\ A_\xi = \frac{N_+ - N_-}{N_+ + N_-}, \tag{2}$$

where N_+ (N_-) is the number of events with positive (negative) value of ξ.

Different theoretical calculations of A_ξ (Standard Model and beyond) [2, 4, 7, 8] give values in the range $[-10^{-4}, -10^{-5}]$, while the current experimental sensitivity is two orders of magnitude worse [5], and it refers only to the range R_3: $A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \cdot 10^{-2}$ [1].

2. The $K^+ \to \pi^0 e^+ \nu\gamma$ decay at NA62

The NA62 experiment at CERN is designed to measure the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio [9]; the beam and the detector are described in [10]. Thanks to auxiliary trigger chains [11], the NA62 physics program comprises most of the K^+ decay channels, including the $K^+ \to \pi^0 e^+ \nu\gamma$ process.

The data collected in 2017 and 2018 are analyzed, together with Monte Carlo (MC) simulations samples for the signal and the main background channels.

[1] In [5] the result is reported with an opposite sign, since the observable ξ is there defined with an opposite sign with respect to Equation 2, that is consistent with the theoretical papers, e.g. the most recent: [4].

PoS(EPS-HEP2021)553

The only difference between the $K^+ \to \pi^0 e^+ \nu\gamma$ (signal channel) and the $K^+ \to \pi^0 e^+ \nu$ (normalization channel) selections is the treatment of the third photon in the event (see below), ensuring a first-order cancellation of several systematic effects. The kaon and the positron tracks are reconstructed and associated taking into account both space and time coincidences, reconstructing the decay vertex inside the fiducial decay volume. The RICH detector and the electromagnetic calorimeter (LKr) are used for μ^+ and π^+ rejection. The $\pi^0 \to \gamma\gamma$ process is identified selecting two energy clusters in the LKr calorimeter, compatible with the π^0 decay kinematics. An additional in time and spatially isolated energy cluster in the LKr is interpreted as a radiative photon, in the $K^+ \to \pi^0 e^+ \nu\gamma$ selection only. In-time extra activity is not allowed, in order to reject background, mainly coming from $K^+ \to \pi^0 \pi^0 e^+ \nu$ decays. Kinematic constraints are applied, using as main observables:

$$\begin{aligned} m^2_{miss}(Ke3\gamma) &= (P_K - P_e - P_{\pi^0} - P_\gamma)^2, \\ m^2_{miss}(Ke3) &= (P_K - P_e - P_{\pi^0})^2, \end{aligned} \tag{3}$$

where $P_{particle}$ are the four-momenta of the reconstructed particles. The cuts corresponding to the three R_j kinematic regions are finally applied to the measured E_γ and $\theta_{e,\gamma}$ values, in the $K^+ \to \pi^0 e^+ \nu\gamma$ selection only.

3. R_j measurements

The normalized branching ratio R_j is determined in the following way:

$$R_j = \frac{\mathcal{B}(Ke3\gamma^j)}{\mathcal{B}(Ke3)} = \frac{N^{obs}_{Ke3\gamma^j} - N^{bkg}_{Ke3\gamma^j}}{N^{obs}_{Ke3} - N^{bkg}_{Ke3}} \cdot \frac{A_{Ke3}}{A_{Ke3\gamma^j}} \cdot \frac{\epsilon^{trig}_{Ke3}}{\epsilon^{trig}_{Ke3\gamma^j}}, \tag{4}$$

where $N^{obs}_{Ke3\gamma\ (Ke3)}$ and $N^{bkg}_{Ke3\gamma\ (Ke3)}$ are respectively the number of observed signal and expected background events in the signal (normalization) selection, $A_{Ke3\gamma\ (Ke3)}$ is the acceptance measured with MC simulations and $\epsilon^{trig}_{Ke3\gamma\ (Ke3)}$ is the trigger efficiency, measured with data, for the signal (normalization) selection.

For the normalization channel, $66.4 \cdot 10^6$ are selected; for the signal, $129.6 \cdot 10^3$ events are selected for R_1, $53.6 \cdot 10^3$ events for R_2, $39.1 \cdot 10^3$ events for R_3. The distributions of $m^2_{miss}(Ke3)$, for the selected normalization events, and of $m^2_{miss}(Ke3\gamma)$, for the signal events (R_1), are shown in Figure 1, comparing the data with the expected signal and background.

3.1 Background estimation

For the normalization selection the largest background contribution is given by $K^+ \to \pi^+ \pi^0$ events with π^+ misidentified as a positron, that is estimated to be about 10^{-4} in relative terms.

The main background contribution to the selected $K^+ \to \pi^0 e^+ \nu\gamma$ sample (signal) is represented by $K^+ \to \pi^0 e^+ \nu$ events with one more cluster coming from accidental (pile-up) activity in the LKr that mimics the radiative photon (so-called *accidental* background) and by $K^+ \to \pi^+ \pi^0$ events with the misidentification of the charged pion. The *accidental* contamination in the signal sample is measured from the data, extrapolating from the out-of-time side-bands, shown in Figure 2. An additional contribution to the background contamination in the signal sample is given by

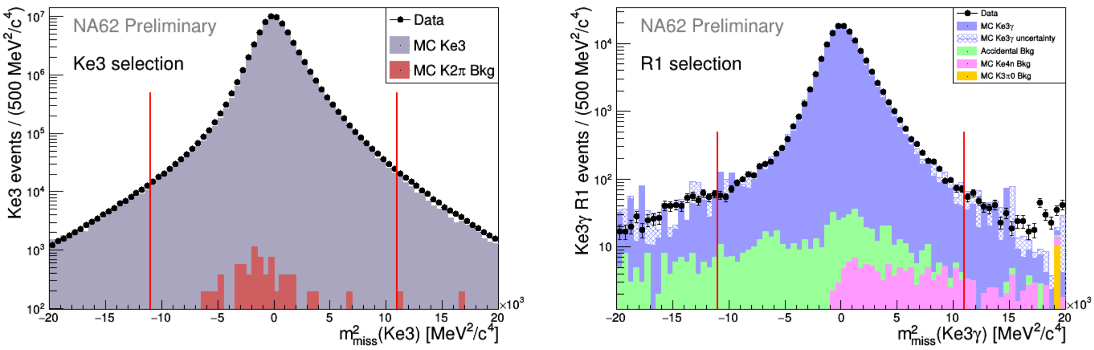

Figure 1: Left: $m^2_{miss}(Ke3)$ for the selected $K^+ \to \pi^0 e^+ \nu$ events in data (points), compared with the expected signal and background (histograms). Right: $m^2_{miss}(Ke3\gamma)$ for the selected $K^+ \to \pi^0 e^+ \nu\gamma$ (R_1) events in data (points), compared with the expected signal and all the background sources (histograms); the "MC Ke3γ uncertainty" histogram represents the maximum deviation of the signal MC distribution caused by LKr response distortion, that is allowed by data (used for LKr-response-related uncertainty evaluation). The red lines correspond to the cuts applied in the selections.

$K^+ \to \pi^0 \pi^0 e^+ \nu$ events with one photon, coming from $\pi^0 \to \gamma\gamma$ decays, not detected. It is estimated using MC simulation. The ratio between the expected total background and signal is 0.46% for R_1, 0.64% for R_2, 0.29% for R_3.

3.2 Preliminary results

Two main additional sources of systematic uncertainties are studied: the response of the electromagnetic calorimeter (LKr) and the theoretical model used in the MC simulation of the $K^+ \to \pi^0 e^+ \nu\gamma$ channel, based on $ChPT$ $O(p^6)$ from [3], for which a comparison with an other generator [12] (that includes only IB component for the radiative correction) is exploited.

The preliminary results of the measurements of R_j, obtained with data collected by NA62 in 2017 and 2018 runs, are reported in Equation 5, while the error budget is shown in Table 2.

$$
\begin{aligned}
R_1 &= (1.684 \pm 0.005 \pm 0.010) \cdot 10^{-2}, \\
R_2 &= (0.599 \pm 0.003 \pm 0.005) \cdot 10^{-2}, \\
R_3 &= (0.523 \pm 0.003 \pm 0.003) \cdot 10^{-2}.
\end{aligned}
\tag{5}
$$

4. A_ξ measurements

The T-asymmetry is measured using the $K^+ \to \pi^0 e^+ \nu\gamma$ samples selected for each R_j. The distributions of the ξ observable for the selected $K^+ \to \pi^0 e^+ \nu\gamma$ events are reported in Figure 3, both for data and MC.

A raw measurement of A_ξ is obtained applying the formula of Equation 2 directly on the selected data sample: A_ξ^{Data}. It is then corrected by the offset introduced by the reconstruction and the selection, that is measured with the $K^+ \to \pi^0 e^+ \nu\gamma$ MC sample, comparing the generated and the

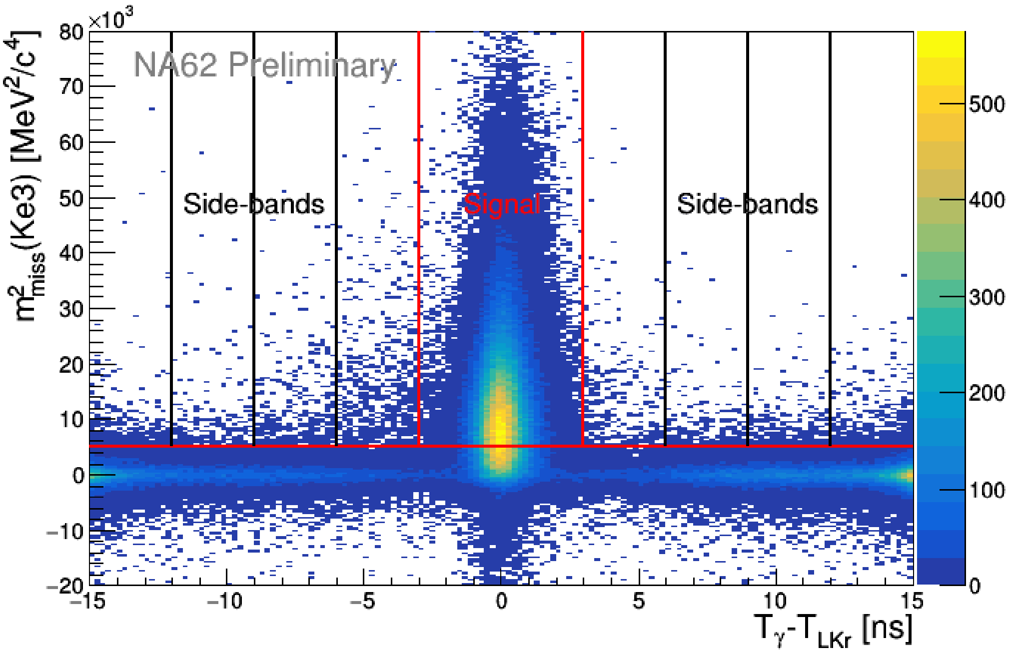

Figure 2: Reconstructed $m^2_{miss}(Ke3)$ vs the difference between the radiative photon cluster time (T_γ) and the average time of e^+ and π^0 clusters in LKr (T_{LKr}), in the $K^+ \to \pi^0 e^+ \nu\gamma$ selection. The cut on $m^2_{miss}(Ke3)$ applied in the selection is shown (red horizontal line), together with the time windows used for the radiative photon selection (in red) and the side-bands (in black) used for the estimation and the validation of the *accidental* background.

reconstructed values of the asymmetry: $A_\xi^{Offset} = A_\xi^{MCreco} - A_\xi^{MCgene}$. The final measurement is therefore obtained as: $A_\xi = A_\xi^{Data} - A_\xi^{Offset}$. The preliminary results are reported in Table 3.

5. Conclusions

Analyzing data collected by NA62 in 2017 and 2018 runs, preliminary measurements of $K^+ \to \pi^0 e^+ \nu\gamma$ branching ratio normalized to $K^+ \to \pi^0 e^+ \nu$ channel (R_j) have been performed, together with preliminary measurements of the A_ξ asymmetry.

The precision of the R_j preliminary measurements is improved by a factor between 2 and 3 with respect to the state of the art: the total relative uncertainty achieved is equal or better than 1%. The central values of all the R_j preliminary measurements from NA62 are about 6−7% smaller than the theoretical calculations provided in [3]. Considering also the most recent theoretical calculation for R_2 provided in [4], the NA62 preliminary result is half way between the two calculations.

The A_ξ preliminary measurements are upper limits since they are compatible with absence of T-asymmetry, and their precision is still two orders of magnitude far from the theoretical expectation. The preliminary measurement in the range R_3 improves the experimental state of the art by a factor of 3 in terms of precision, while the two others represent the first preliminary measurements ever performed for these physical quantities.

Uncertainty source	$\delta R_1/R_1$	$\delta R_2/R_2$	$\delta R_3/R_3$
Statistical	0.3%	0.5%	0.6%
Acceptances from MC	0.2%	0.4%	0.4%
Background estimation	0.1%	0.2%	0.1%
LKr response modeling	0.5%	0.6%	0.5%
Theoretical model	0.1%	0.5%	0.1%
Total systematic	0.6%	0.9%	0.6%
Total (statistical + systematic)	0.7%	1.0%	0.8%

Table 2: Relative uncertainties of the NA62 preliminary measurements of R_j.

	R_1 selection	R_2 selection	R_3 selection
A_ξ^{Data} $(\times 10^2)$	0.2 ± 0.3	0.1 ± 0.4	-0.6 ± 0.5
A_ξ^{MCgene} $(\times 10^2)$	-0.01 ± 0.01	0.00 ± 0.02	-0.01 ± 0.02
A_ξ^{MCreco} $(\times 10^2)$	0.3 ± 0.2	0.4 ± 0.3	0.3 ± 0.5
A_ξ $(\times 10^2)$	$-0.1 \pm 0.3_{stat} \pm 0.2_{MC}$	$-0.3 \pm 0.4_{stat} \pm 0.3_{MC}$	$-0.9 \pm 0.5_{stat} \pm 0.4_{MC}$

Table 3: Preliminary results from NA62 of the A_ξ measurements, for the three different kinematic regions of the $K^+ \to \pi^0 e^+ \nu\gamma$ process.

References

[1] J. Bijnens, G. Ecker, J. Gasser, *Radiative semileptonic kaon decays*, *Nucl. Phys. B* **396** (1993) 81.

[2] V. V. Braguta, A. A. Likhoded, A. E. Chalov, *T-odd correlation in the $K_{l3\gamma}$ decay*, *Phys. Rev. D* **65** (2002) 054038.

[3] B. Kubis, E. H. Muller, J. Gasser, M. Schmid, *Aspects of radiative K^+_{e3} decays*, *Eur. Phys. J. C* **50** (2007) 557.

[4] I. B. Khriplovich, A. S. Rudenko, *$K^+_{l3\gamma}$ decays revisited: branching ratios and T-odd momenta correlations*, *Phys. Atom. Nucl.* **74** (2011) 1214.

[5] S. A. Akimenko et al. (ISTRA+ Collaboration), *Study of $K^- \to \pi^0 e^- \bar{\nu}_e \gamma$ Decay with ISTRA+ Setup*, *Phys. Atom. Nucl.* **70** (2007) 702.

[6] A. Y. Polyarush et al. (OKA Collaboration), *Study of $K^+ \to \pi^0 e^+ \nu\gamma$ decay with OKA setup*, *Eur. Phys. J. C* **81** (2021) 161.

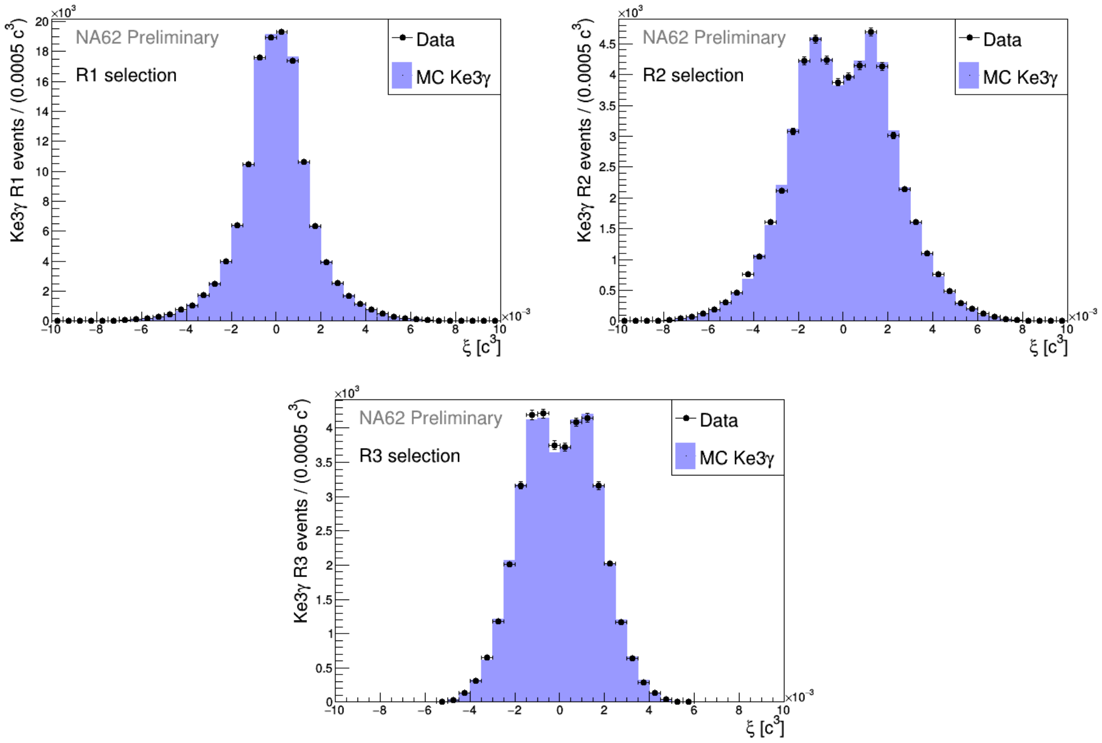

Figure 3: Distributions of the ξ observable for the selected $K^+ \to \pi^0 e^+ \nu\gamma$ events, in data (points) and in MC (histograms).

[7] V. V. Braguta, A. A. Likhoded, A. E. Chalov, *T-odd correlation in the $K^+ \to \pi l \nu\gamma$ decays beyond the standard model*, Phys. Rev. D **68** (2003) 094008.

[8] E. H. Muller, B. Kubis, Ulf-G. Meissner, *T-odd correlations in radiative K^+_{l3} decays and chiral perturbation theory*, Eur. Phys. J. C **48** (2006) 427.

[9] E. Cortina Gil et al. (NA62 Collaboration), *Measurement of the very rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay*, JHEP **06** (2021) 093.

[10] E. Cortina Gil et al. (NA62 Collaboration), *The beam and detector of the NA62 experiment at CERN*, JINST **12** (2017) P05025.

[11] R. Ammendola et al., *The integrated low-level trigger and readout system of the CERN NA62 experiment*, Nucl. Instrum. Meth. A **929** (2019) 1.

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