Study of the $K^+ \to \pi^0 e^+ \nu \gamma$ decay: preliminary results from the NA62 experiment

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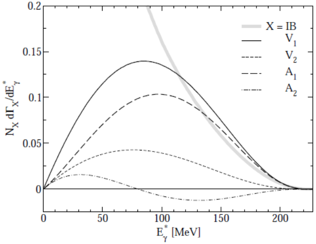
$K^+ \to \pi^0 e^+ \nu\gamma$ decay: state of the art

DE (a) + IB (b) + INT

Divergent decay amplitude for
$E_\gamma \to 0$ and $\theta_{e,\gamma} \to 0$
due to IB component.

[Kubis et al., EPJ C 50, 557]



$$R_j = \frac{\mathcal{B}(Ke3\gamma^j)}{\mathcal{B}(Ke3)} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \mid E^j_\gamma,\, \theta^j_{e,\gamma})}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma))}$$

	E_γ cut (*)	$\theta_{e,\gamma}$ cut (*)	$O(p^6)$ ChPT [EPJ C 50, 557]	ISTRA+	OKA
R_1 $(\times 10^2)$	$E_\gamma > 10$ MeV	$\theta_{e,\gamma} > 10^\circ$	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	$\theta_{e,\gamma} > 20^\circ$	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	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

Most recent theoretical calculation [Khriplovich et al., PAN 74, 1214]:

$$R_2 = (0.56 \pm 0.02)\%$$

(*) in the kaon rest frame

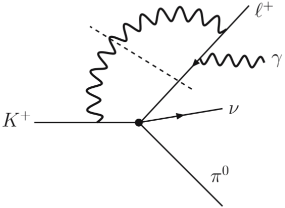
$K^+ \to \pi^0 e^+ \nu\gamma$ decay: T-asymmetry

T-odd observable ξ
(in the kaon rest frame):

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

Non-zero A_ξ values due to NLO (one-loop) electromagnetic corrections

[Muller et al., EPJ C 48, 427]

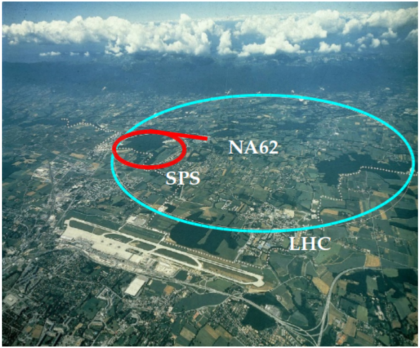


State of the art:

- $|A_\xi^{SM\ and\ beyond}| < 10^{-4}$
- $A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$
- No measurements provided for R_1 and R_2

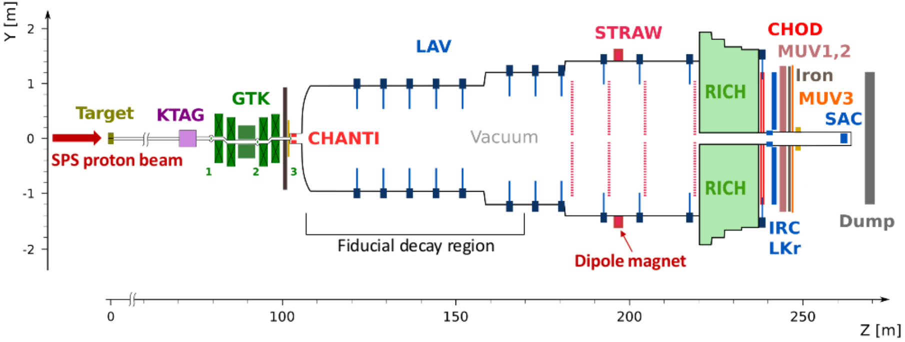
The NA62 experiment at CERN

- Main goal: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ measurement; NA62 programme covers the full K^+ physics.
- Detector installation completed in 2016.
- Physics runs in 2016, 2017 and 2018.
- Measurement of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ from full 2016+2017+2018 (run 1) data set published: [JHEP 06 (2021) 093].
- Data taking resumed in July 2021 (run2), approved up to CERN LS3 (until 2025).



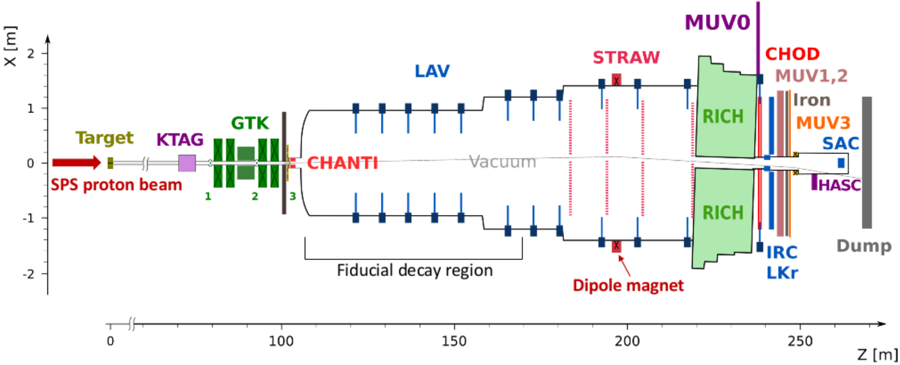
NA62 is located at CERN in the *North Area*, exploiting a 400 GeV/c proton beam extracted from the SPS accelerator.

NA62 beam *[2017 JINST 12 P05025]*



- SPS beam: 400 GeV/c proton on beryllium target
- Secondary hadron 75 GeV/c beam
- 70% pions, 24% protons, 6% kaons
- Nominal beam particle rate (at GTK3): 750 *MHz*
- Average beam particle rate during 2018 data-taking: 450 – 500 *MHz*

NA62 detector *[2017 JINST 12 P05025]*



- KTAG: Cherenkov threshold counter;
- GTK: Si pixel beam tracker;
- CHANTI: stations of plastic scintillator bars;
- LAV: lead glass ring calorimeters;
- STRAW: straw magnetic spectrometer;
- RICH: Ring Imaging Cherenkov counter;
- MUV0: off-acceptance plane of scintillator pads;
- CHOD: planes of scintillator pads and slabs;
- IRC: inner ring shashlik calorimeter;
- LKr: electromagnetic calorimeter filled with liquid krypton;
- MUV1,2: hadron calorimeter;
- MUV3: plane of scintillator pads for muon ID;
- HASC: near beam lead–scintillator calorimeter;
- SAC: small angle shashlik calorimeter.

Measurement of R_j: strategy

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

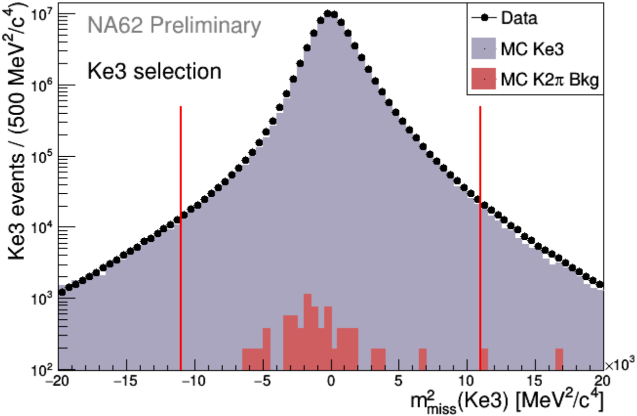
- Background estimation performed using both data and MC.
- Acceptances: evaluated by MC.
- Signal (Ke3γ) and normalization (Ke3) channels share most of the selection criteria (except for the radiative photon): first-order-cancellation of systematics effects.
- Trigger efficiencies: measured with data. Almost equal for signal and normalization (within per mill precision) since trigger conditions refer to the presence of the e^+ only.
- Only statistical uncertainty of $N^{obs}_{Ke3\gamma^j}$ and N^{obs}_{Ke3} is propagated as statistical uncertainty to the R_j measurement, all the rest is considered as systematic.
- Full 2017 and 2018 data sets have been analyzed.

Ke3γ selection criteria

- K^+ reconstructed in GTK and associated to KTAG, e^+ reconstructed in STRAW and associated to CHOD, RICH and LKr detectors
- $\pi^0 \to \gamma\gamma$ identified selecting two energy clusters in LKr, applying kinematic conditions on photons pair invariant mass
- Radiative γ identified selecting an in-time and isolated energy cluster in LKr
- e^+ PID (μ^+ and π^+ rejection) using RICH ring radius and LKr-STRAW E/p
- In-time extra activity in LKr, LAV, IRC and SAC not allowed, in order to rejec t$K^+ \to \pi^0\pi^0 e^+\nu$ (Ke4n) background
- In-time signal in MUV3 not allowed for further rejection of μ^+
- Anti-coincidence between the position of the radiative photon cluster in LKr and the extrapolation of track at the LKr plane, to reject $K^+ \to \pi^0 e^+\nu$ events with a photon emitted by the positron interaction with the detector material (bremsstrahlung)
- Dedicated kinematic conditions to reject $K^+ \to \pi^+\pi^0\pi^0$ (K3π0) and $K^+ \to \pi^+\pi^0$ (K2π) backgrounds
- Kinematic selection using the two main observables:

$$m^2_{miss}(Ke3\gamma) = (P_K - P_e - P_{\pi^0} - P_\gamma)^2 = m^2(\nu)$$
$$m^2_{miss}(Ke3) = (P_K - P_e - P_{\pi^0})^2 = m^2(\nu\gamma)$$

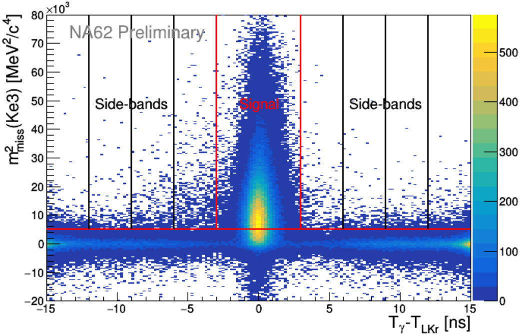
Normalization selected events (Ke3)



- Same selection as for the signal apart from the radiative photon
- $66M$ selected events
- Almost background free: $B/S \sim 10^{-4}$

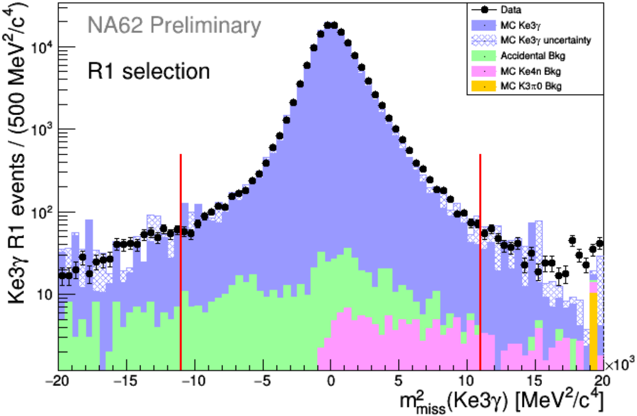
Main background source of Ke3γ selection: *accidentals*

Accidental event: $K^+ \to \pi^0 e^+ \nu$ decay (or K2π with π^+ mis-ID) $+$
additional LKr cluster that mimics the radiative photon



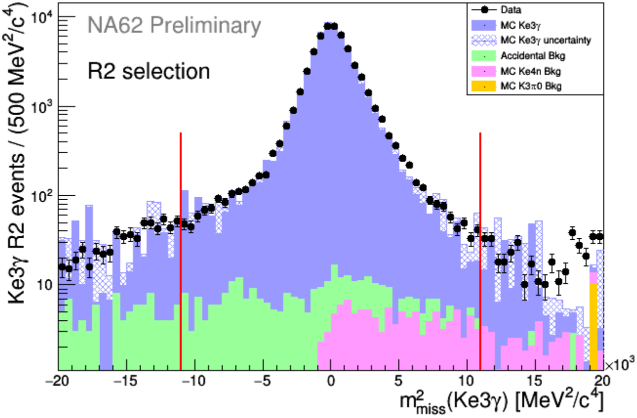
- Dedicated cut in signal selection using $m^2_{miss}(Ke3)$ observable
- Background in signal region estimated with data from the out-of-time side-bands

Signal selected events (Ke3γ - R_1)



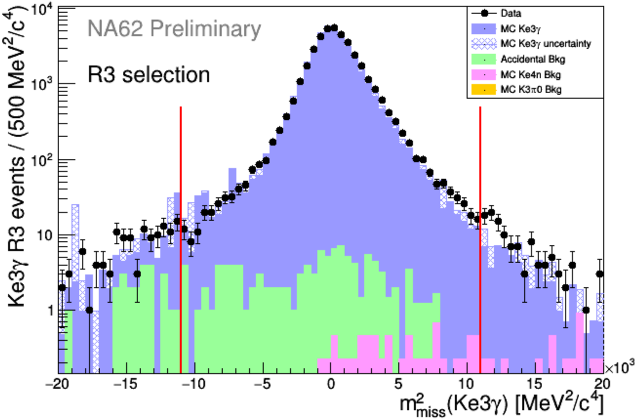
- $130K$ selected events in R_1
- Background contamination: $B/S \simeq 0.5\%$

Signal selected events (Ke3γ - R_2)



- $54K$ selected events in R_2
- Background contamination: $B/S \simeq 0.6\%$

Signal selected events (Ke3γ - R_3)



- $39K$ selected events in R_3
- Background contamination: $B/S \simeq 0.3\%$

Number of observed events (preliminary)

Selection	N^{obs}	Statistical relative uncertainty
$Ke3$	$66.378 \cdot 10^6$	0.01%
$Ke3\gamma(R_1)$	$129.6 \cdot 10^3$	0.3%
$Ke3\gamma(R_2)$	$53.6 \cdot 10^3$	0.4%
$Ke3\gamma(R_3)$	$39.1 \cdot 10^3$	0.5%

These statistical uncertainties on R_j measurements
improve the state of the art by a factor $\simeq 3$

Summary of signal selections backgrounds (preliminary)

Bkg source	R1	R2	R3
Accidentals	$(4.9 \pm 0.2 \pm 1.3) \cdot 10^2$	$(2.3 \pm 0.2 \pm 0.3) \cdot 10^2$	$(1.1 \pm 0.1 \pm 0.5) \cdot 10^2$
$K^+ \to \pi^0\pi^0 e^+\nu$	$(1.1 \pm 1.1) \cdot 10^2$	$(1.1 \pm 1.1) \cdot 10^2$	$(0.07 \pm 0.07) \cdot 10^2$
$K^+ \to \pi^+\pi^0\pi^0$	< 20	< 20	< 20
$K^+ \to \pi^+\pi^0\gamma$	< 2	< 2	< 2
Total	$(5.9 \pm 1.7) \cdot 10^2$	$(3.4 \pm 1.1) \cdot 10^2$	$(1.1 \pm 0.6) \cdot 10^2$
B/S	0.46%	0.64%	0.29%

- $B/S < 1\%$
- The contribution of the uncertainty of the background estimation is small when propagated to the final R_j measurements (0.2% relative in the worst case)

Acceptances measurements (preliminary)

Selection	A [%]	Relative uncertainty
$Ke3$	3.839 ± 0.002	0.06%
$Ke3\gamma(R_1)$	0.443 ± 0.001	0.2%
$Ke3\gamma(R_2)$	0.513 ± 0.002	0.4%
$Ke3\gamma(R_3)$	0.431 ± 0.002	0.4%

Uncertainties given only by the limited statistics of MC samples

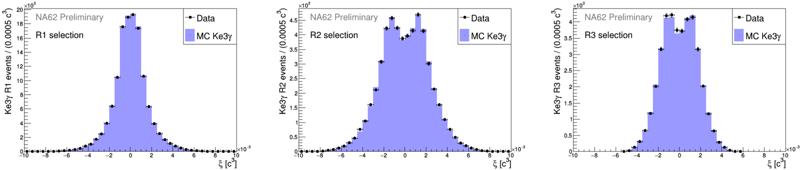
NA62 preliminary R_j measurements

	$O(p^6)$ *ChPT*	ISTRA+	OKA	**NA62 preliminary**
R_1 $(\times 10^2)$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.684 \pm 0.005 \pm 0.010$
R_2 $(\times 10^2)$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.599 \pm 0.003 \pm 0.005$
R_3 $(\times 10^2)$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.523 \pm 0.003 \pm 0.003$

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 stat+syst	0.7%	1.0%	0.8%

- Achieved precision on R_j measurements equal/better than 1% relative
- State of the art improved by a factor between 2.0 and 3.6 in terms of relative precision
- Relative discrepancy with theory of 6-7% in all three measurements
- NA62 result for R_2 is half way between the two latest theoretical predictions [Kubis et al., EPJ C 50, 557] and [Khriplovich et al., PAN 74, 1214]

NA62 preliminary A_ξ measurements



$$A_\xi = A_\xi^{Data} - (A_\xi^{MCreco} - A_\xi^{MCgene}) \simeq A_\xi^{Data} - A_\xi^{MCreco}$$

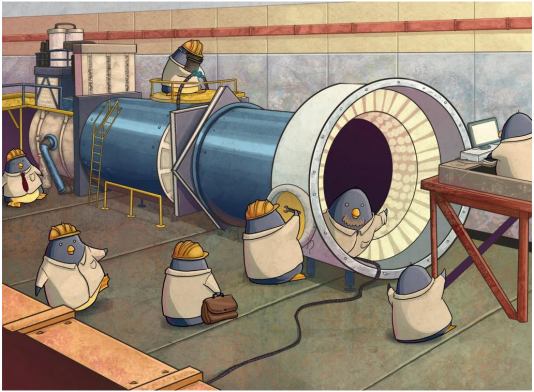
	R_1 selection	R_2 selection	R_3 selection
A_ξ^{Data} $(\times 10^2)$	0.2 ± 0.3	0.1 ± 0.4	-0.6 ± 0.5
A_ξ^{MCgene} $(\times 10^2)$	-0.01 ± 0.01	0.00 ± 0.02	-0.01 ± 0.02
A_ξ^{MCreco} $(\times 10^2)$	0.3 ± 0.2	0.4 ± 0.3	0.3 ± 0.5
A_ξ $(\times 10^2)$	$-0.1 \pm 0.3_{stat} \pm 0.2_{MC}$	$-0.3 \pm 0.4_{stat}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

- R_3 T-asymmetry precision improved by a factor greater than 3: $A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$
- First measurements ever performed for R_1 and R_2 T-asymmetry

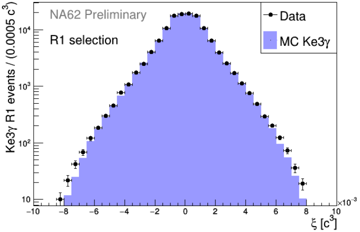
Conclusions

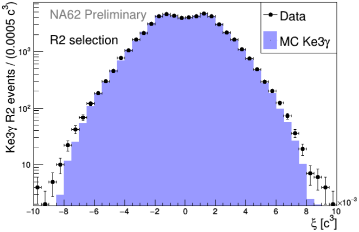
- New results (preliminary) from the NA62 experiment on the study of the $K^+ \to \pi^0 e^+ \nu\gamma$ process using 2017 and 2018 data sets
- Measurements of Ke3γ branching fraction ratio (R_j) have been performed, showing 6-7% relative discrepancy with *ChPT* $O(p^6)$ calculations
- Experimental relative precision of R_j measurements improved by a factor between 2.0 and 3.6, relative uncertainties $\leq 1\%$
- T-asymmetry measurements have been performed: still compatible with zero, experimental sensitivity far from the theoretical expectations
- First T-asymmetry measurements for R_1 and R_2, improvement by a factor greater than 3 for R_3

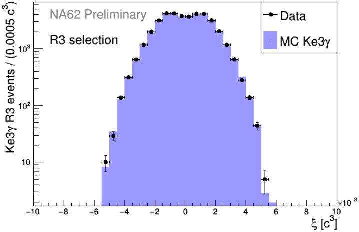
SPARES



T-odd observable







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