Searches for lepton flavour and lepton number violating K^+ decays at the NA62 experiment

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on behalf of the NA62 collaboration

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NA62 experiment

NA62: fixed target experiment at CERN SPS

Technique:
Kaon decays in flight

Timeline:
- 2015: commissioning
- 2016-2018: physics runs

- 2021-2025: physics runs

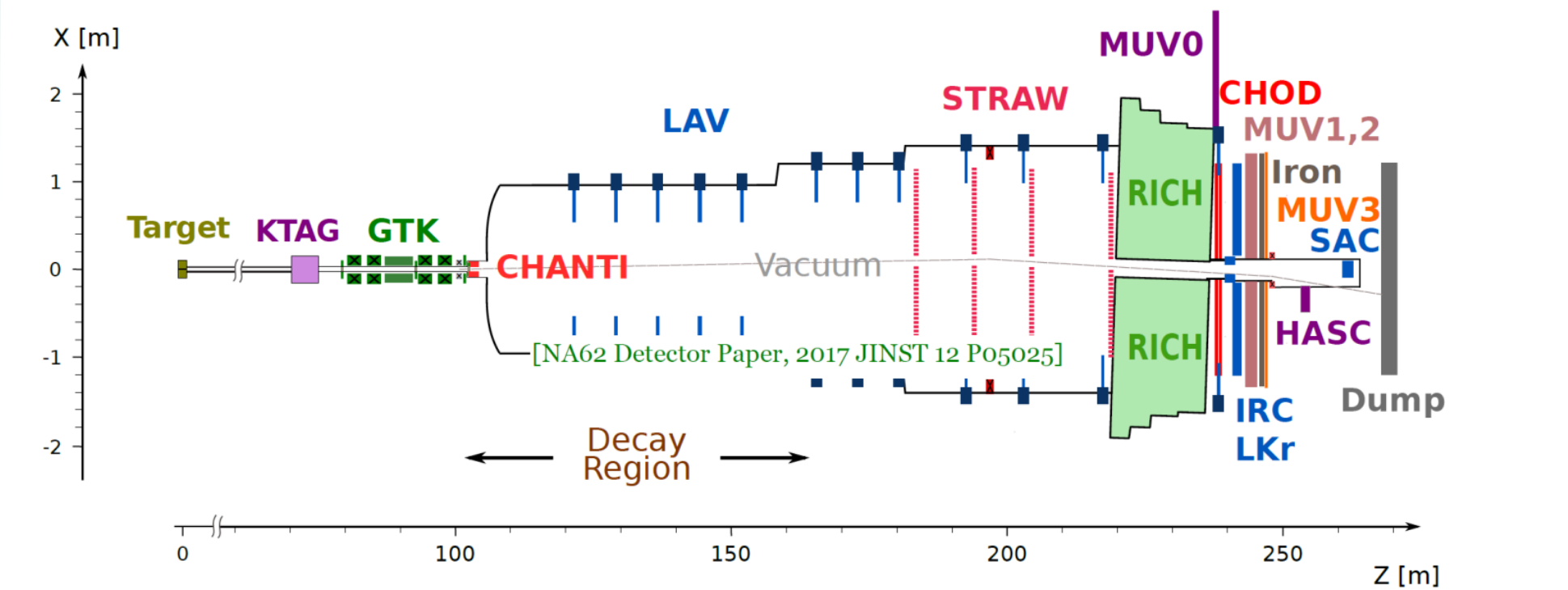
Primary goal:
Measure BR($K^+ \to \pi^+ \nu\nu$)

ECN3 hall at CERN

NA62 collaboration: ~300 participants, ~30 institutions

NA62 experimental setup

[NA62 Detector Paper, 2017 JINST 12 P05025]



Primary beam:
- 400 GeV/c protons
- 3×10^{12} protons per spill

Secondary beam:
- 75 GeV/c (±1%)
- Divergency < 100 μrad
- 70% pions, **6% K^+**, 24% protons

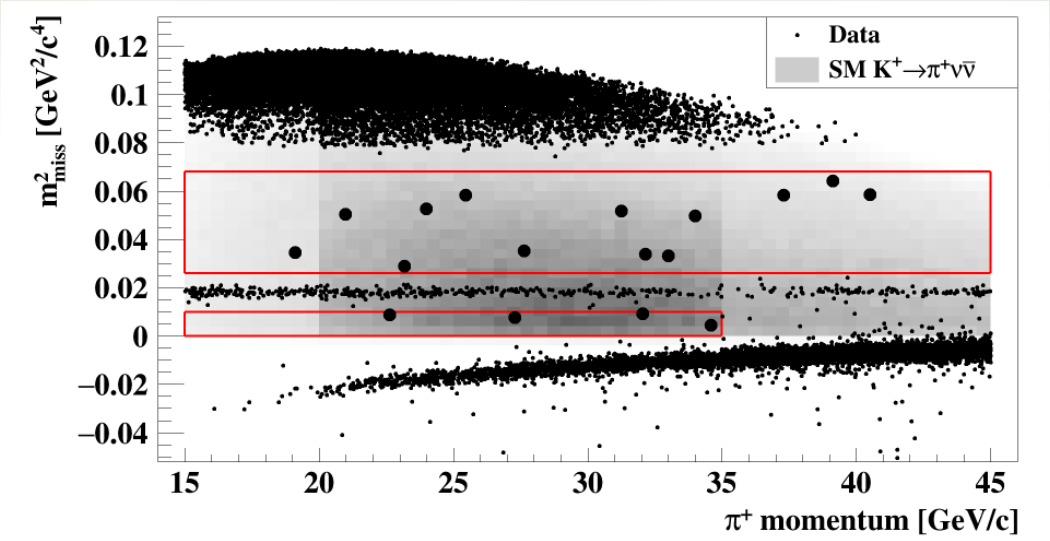
Key detectors:
- PID: KTAG, RICH, LKr, MUV1-2, MUV3
- Momentum: GTK, STRAW
- Time: GTK, KTAG, RICH, CHOD
- Photon veto: LAV, LKr, IRC, SAC

NA62 main goal: BR($K^+ \to \pi^+ \nu\nu$)

Run 1 (2016-2018) fully analysed

Data	N(K decays)	N($K^+ \to \pi^+ \nu\nu$ candidates)	publication
2016	2×10^{11}	1	PBL 791 (2019) 156
2017	2×10^{12}	2	JHEP 11 (2020) 042
2018	4×10^{12}	17	JHEP 06 (2021) 093

2018 data sample

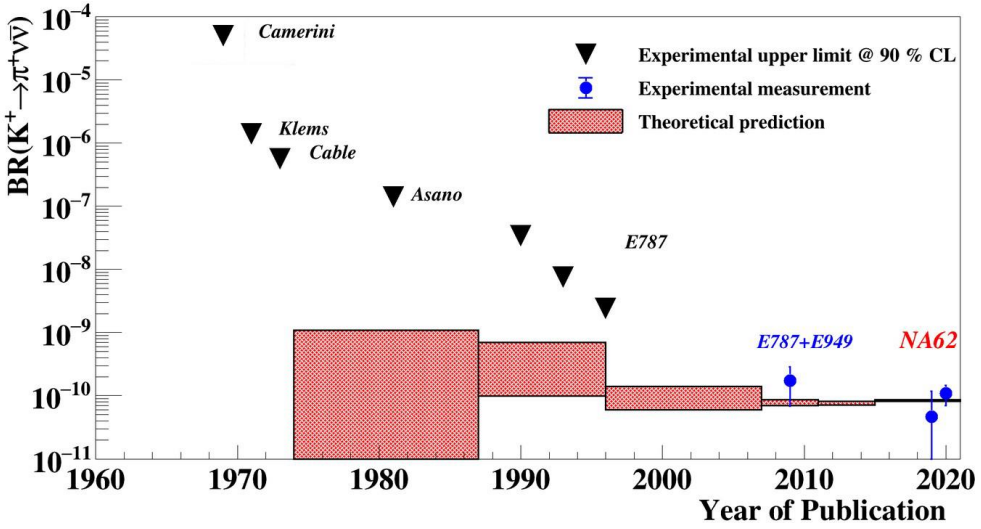


Combined result:

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

Statistical significance: p = 3.4×10^{-4} (3.4 σ)

First evidence of the decay



NA62 recent results

- $K^+ \to \pi^+ \nu \nu$
- Search for $K^+ \to \pi^+ X$ JHEP 06 (2021) 93; JHEP 03 (2021) 58
- LFV/LNV decays

  $K^+ \to \pi \mu e$ PRL 127 (2021) 131802

  $K^+ \to \pi^- l^+ l^+$ PLB797 (2019) 134794; PLB830 (2022) 137172

  $K^+ \to \pi^- \pi^0 e^+ e^+$ PLB830 (2022) 137172

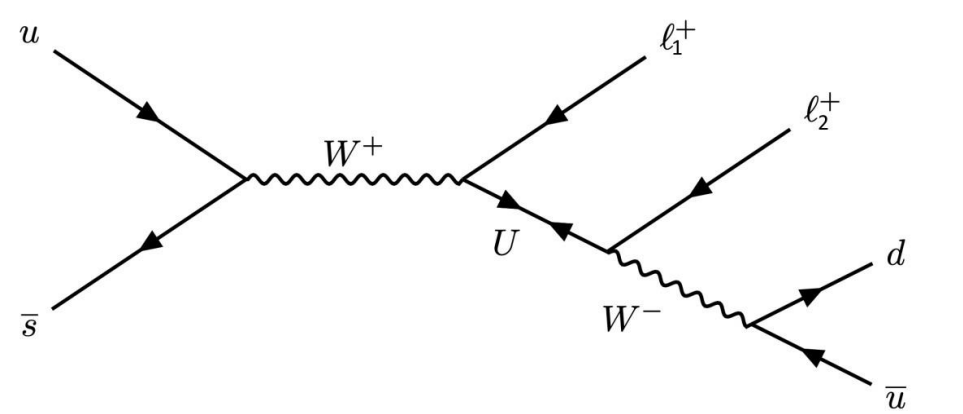
  $K^+ \to \mu^- \nu e^+ e^+$ new

  This talk
- Precise measurements

  $K^+ \to \pi^+ \mu^+ \mu^-$

  $K^+ \to \pi^0 e^+ \nu \gamma$
- HNL production in $K^+ \to l^+ N$ PLB 807 (2020) 135599; PLB 816 (2021) 136259
- Search for $\pi^0 \to$ invisible JHEP 02 (2021) 201

LFV and LNV in kaon decays

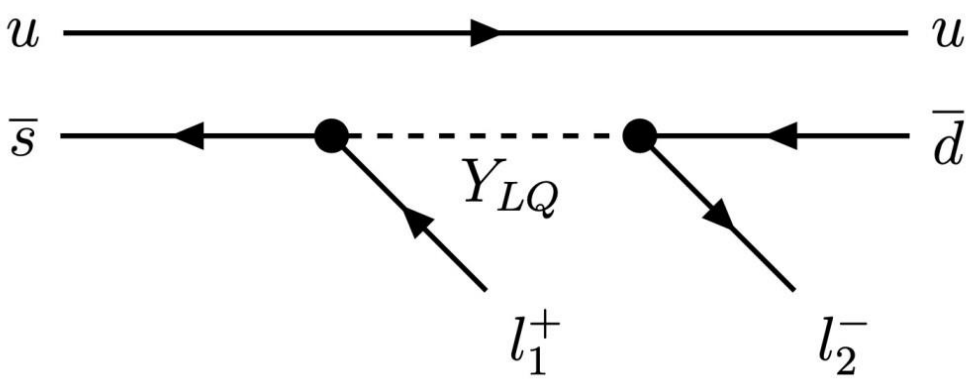


$K^+ \to \pi^- l^+ l^+$ ($l = e, \mu$)

- LNV: $\Delta L = 2$
- Mediated by Majorana neutrino U
- similar to $0\nu2\beta$ decays

NPB 176 (1980) 135

JHEP 12 (2019) 089



$K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^+ \mu^- e^+$

- LFV: $\Delta L_e = 1$, $\Delta L_\mu = 1$
- Mediated by a leptoquark

PLB 491 (2000) 285

JHEP 12 (2019) 089

Search for $K^+ \to \pi\, \mu\, e$

Data
- Run 1 (2017 + 2018)

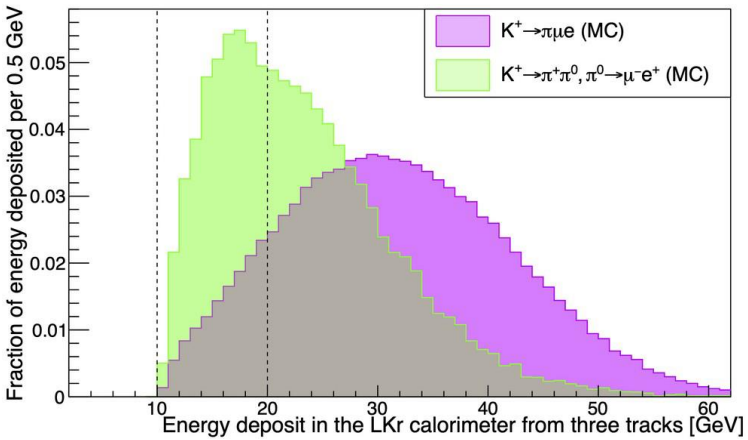
Relevant triggers (downscaled)
- MultiTrack / 100
- MultiTrack & LKr10 (E > 10 GeV) & MUV3 / 8
- MultiTrack & LKr20 (E > 20 GeV) / 8

Main features
- blind analysis (control and signal regions)
- Byproduct: search for $\pi^0 \to \mu\, e$ from $K^+ \to \pi^+ \pi^0$, $\pi^0 \to \mu\, e$
- Main background from misID and π decays in flight
- $M(\pi^- e^+) > 140$ MeV against $K^+ \to \pi^+ \pi^0$, $\pi^0 \to e^+ e^- \gamma$

Normalisation
- $K^+ \to \pi^+ \pi^+ \pi^-$, BR = 0.0558
- $N(K^+ \to \pi^+ \pi^+ \pi^-) = 2.73 \times 10^8$
- $N_K = 1.33(2) \times 10^{12}$

Number of K^+ decays in the fiducial volume ($105 < Z_{vertex} < 180$ m)

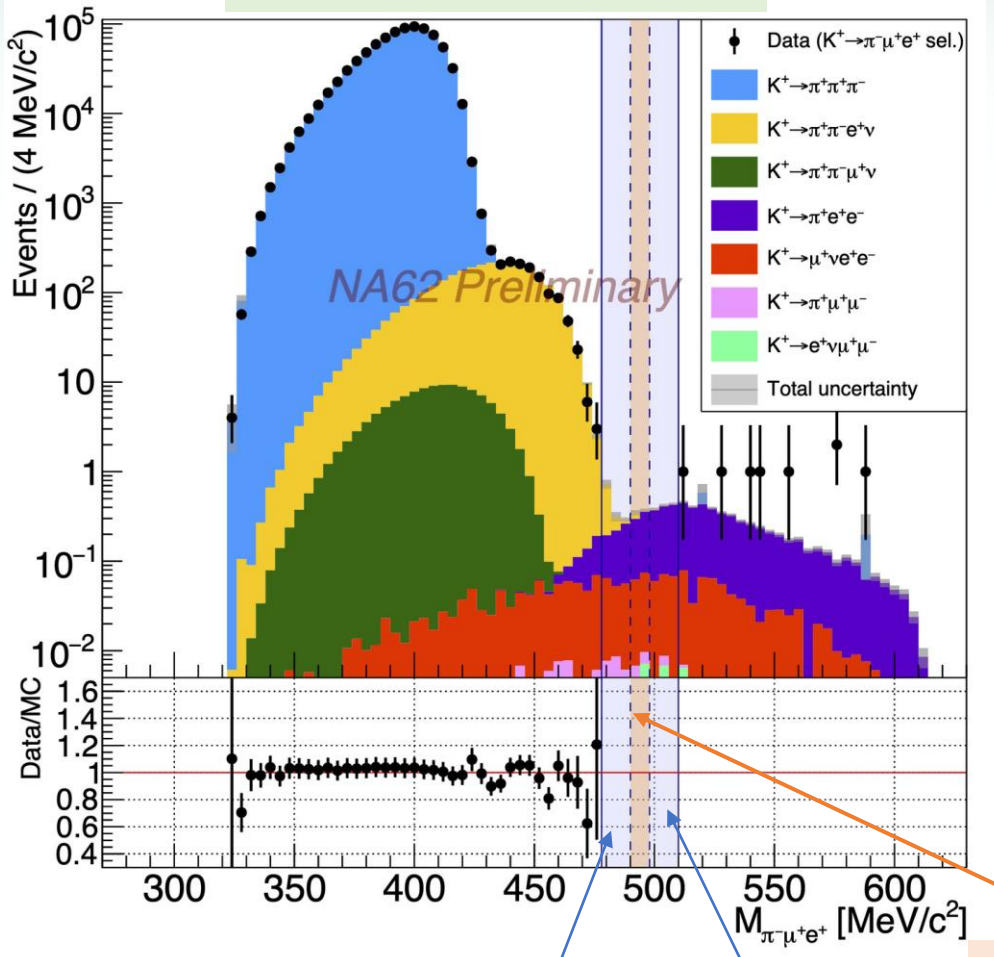
MultiTrack trigger
- MultiTrack = RICH & QX
- QX: hits in opposite quadrants of the hodoscope
- MultiTrack efficiency $\varepsilon = 93.2(5)$ %
- Runs in parallel with the $\pi\nu\nu$ trigger



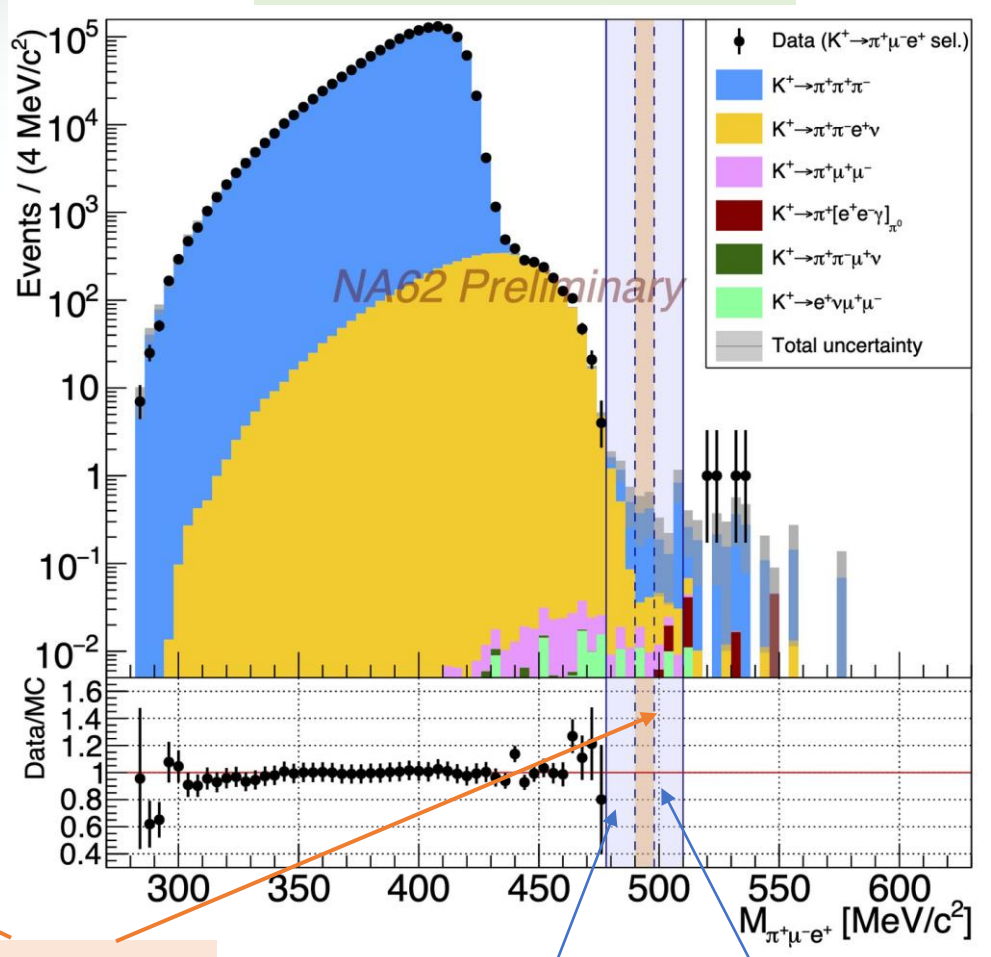
	$K^+ \to \pi^- \mu^+ e^+$	$K^+ \to \pi^+ \mu^- e^+$	$\pi^0 \to \mu^- e^+$
$A_s \times 10^2$	4.90 ± 0.02	6.21 ± 0.02	3.11 ± 0.02
$\varepsilon_{LKr10} \times 10^2$	97.5 ± 1.3	97.5 ± 1.3	92.9 ± 1.2
$\varepsilon_{LKr20} \times 10^2$	74.1 ± 1.6	73.3 ± 1.6	45.3 ± 1.0
$\mathcal{B}_{SES} \times 10^{11}$	1.82 ± 0.08	1.44 ± 0.05	13.9 ± 0.9

$K^+ \to \pi\ \mu\ e$: before unblinding

LNV: $M(\pi^-\ \mu^+\ e^+)$



LNV: $M(\pi^+\ \mu^-\ e^+)$



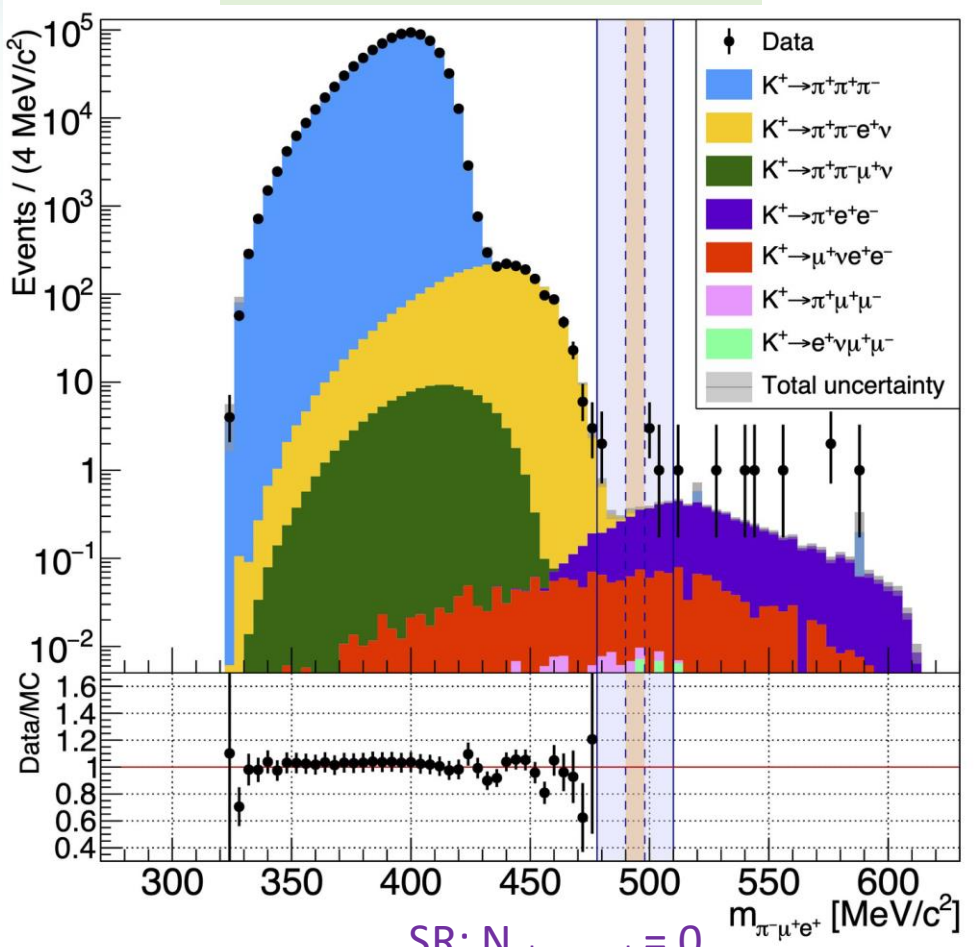
Signal region (SR)

Control regions

Control regions

$K^+ \to \pi\ \mu\ e$: after unblinding

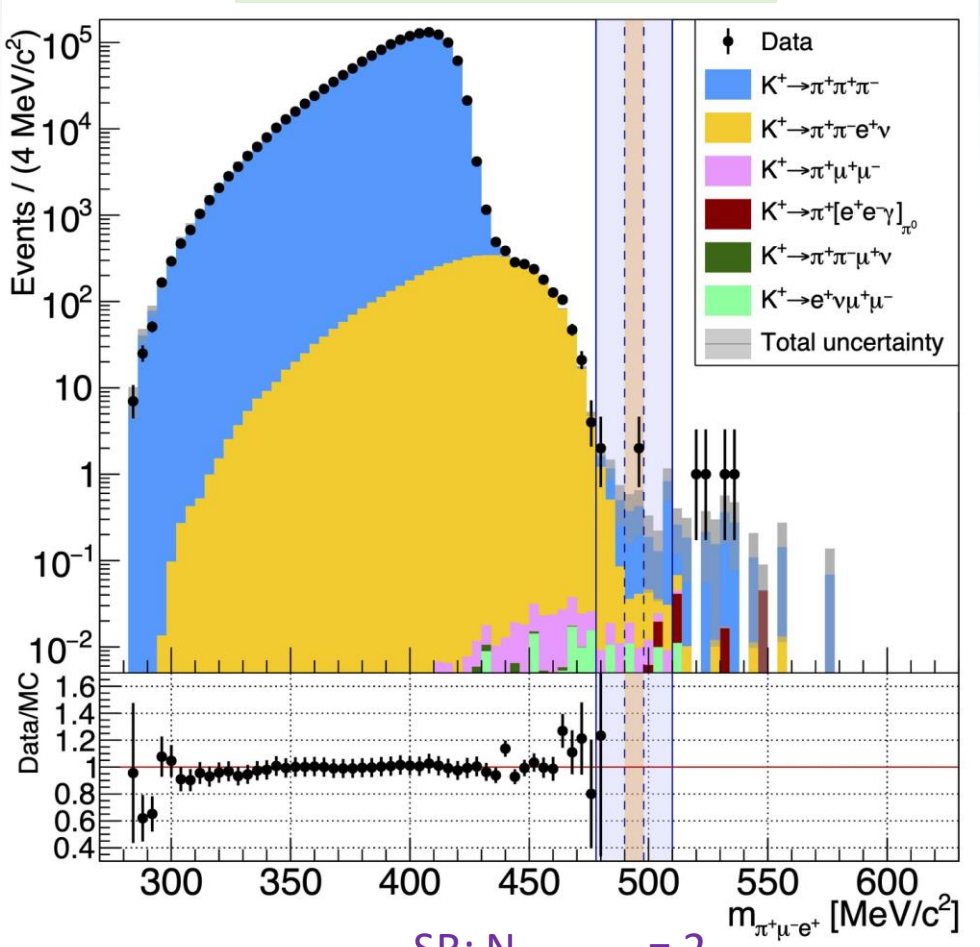
LNV: $M(\pi^-\ \mu^+\ e^+)$



SR: $N_{observed} = 0$

$BR(K^+ \to \pi^-\ \mu^+\ e^+) < 4.2 \times 10^{-11}$ (90% CL)

LNV: $M(\pi^+\ \mu^-\ e^+)$



SR: $N_{observed} = 2$

$BR(K^+ \to \pi^+\ \mu^-\ e^+) < 6.6 \times 10^{-11}$ (90% CL)

$K^+ \to \pi\ \mu\ e$: final results

	$K^+ \to \pi^- \mu^+ e^+$	$K^+ \to \pi^+ \mu^- e^+$	$\pi^0 \to \mu^- e^+$
Acceptance	4.90(2) %	6.21(2) %	3.11(2) %
SES	$1.82(8)\times10^{-11}$	$1.44(5)\times10^{-11}$	$13.9(9)\times10^{-11}$
Expected bkg	1.07(20)	0.92(34)	0.23(15)
$N_{observed}$	0	2	0
BR(UL) @ 90% CL	4.2×10^{-11}	6.6×10^{-11}	3.2×10^{-10}
Previous UL(BR)	5.0×10^{-10}	5.2×10^{-10}	3.4×10^{-9}

Factor of ~10 improvement wrt previous experiments

$K^+ \to \pi^+ \mu^+ e^-$, $\pi^0 \to \mu^+ e^-$: sensitivity similar to previous searches

Search for $K^+ \to \pi^- \mu^+ \mu^+$

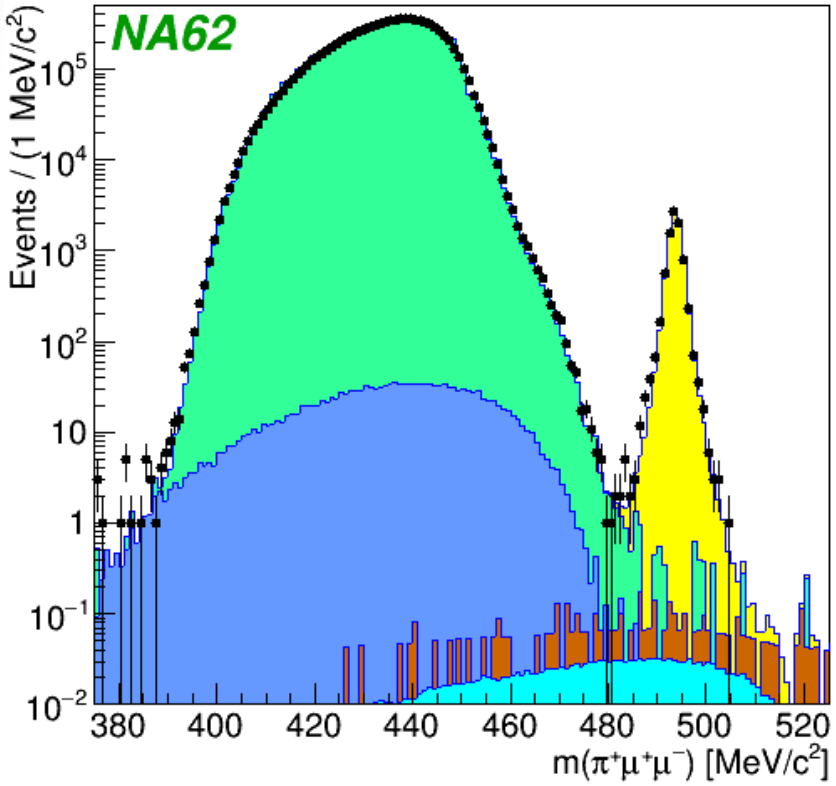
Data:
- partial Run 1 (2017)

Main features
- blind analysis
- A(sig) = 9.81%
- $N_K = 7.97(23) \times 10^{11}$
- SES = 1.28×10^{-11}

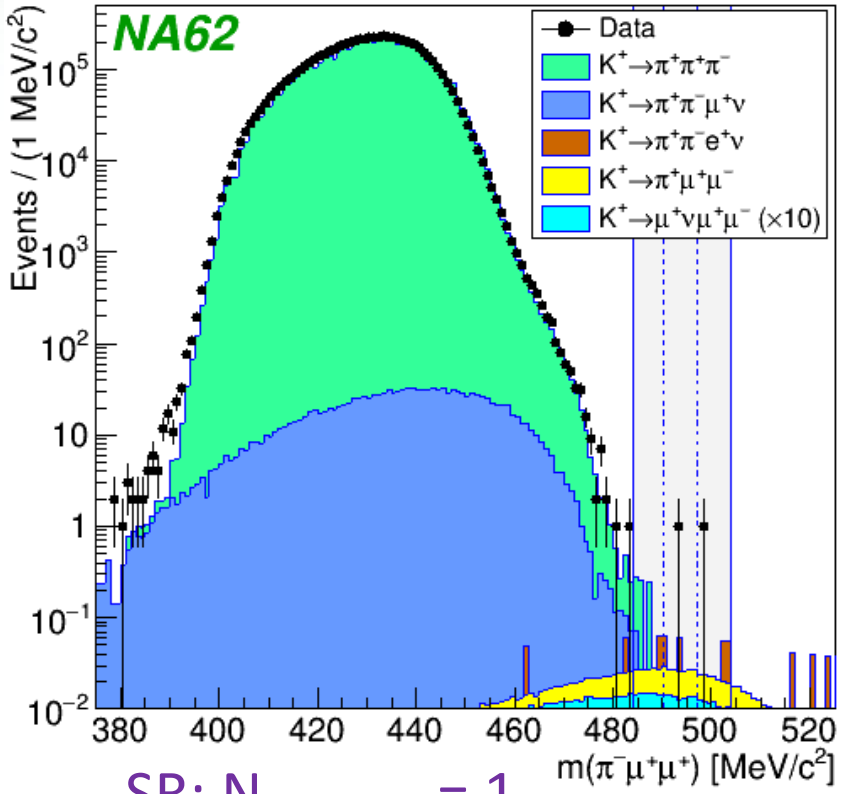
Normalisation:
- $K^+ \to \pi^+ \mu^+ \mu^-$
- $N(K^+ \to \pi^+ \mu^+ \mu^-) = 8357$

Expected bkg:
- N = 0.91(41)

SM: $M(\pi^+ \mu^+ \mu^-)$



LNV: $M(\pi^- \mu^+ \mu^+)$



SR: $N_{observed} = 1$

$BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ (90% CL)

Factor of 2 improvement wrt previous limit: $BR < 8.6 \times 10^{-11}$ (90% CL)

Search for $K^+ \to \pi^- e^+ e^+$

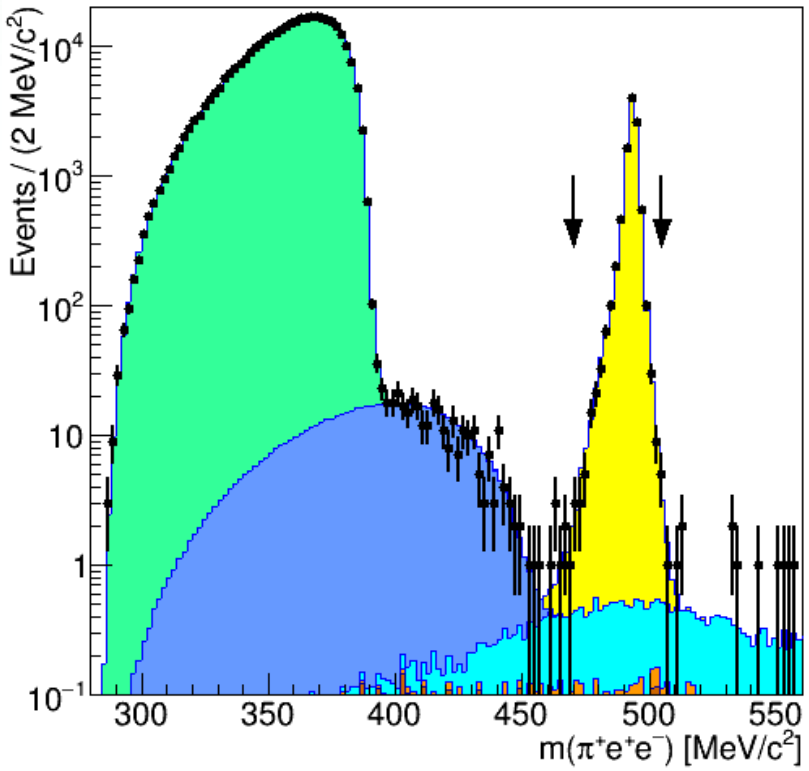
Data:
- Run 1 (2016-2018)

Main features
- blind analysis
- A(sig) = 4.23%
- $N_K = 9.79(31) \times 10^{11}$
- SES = 2.4×10^{-11}

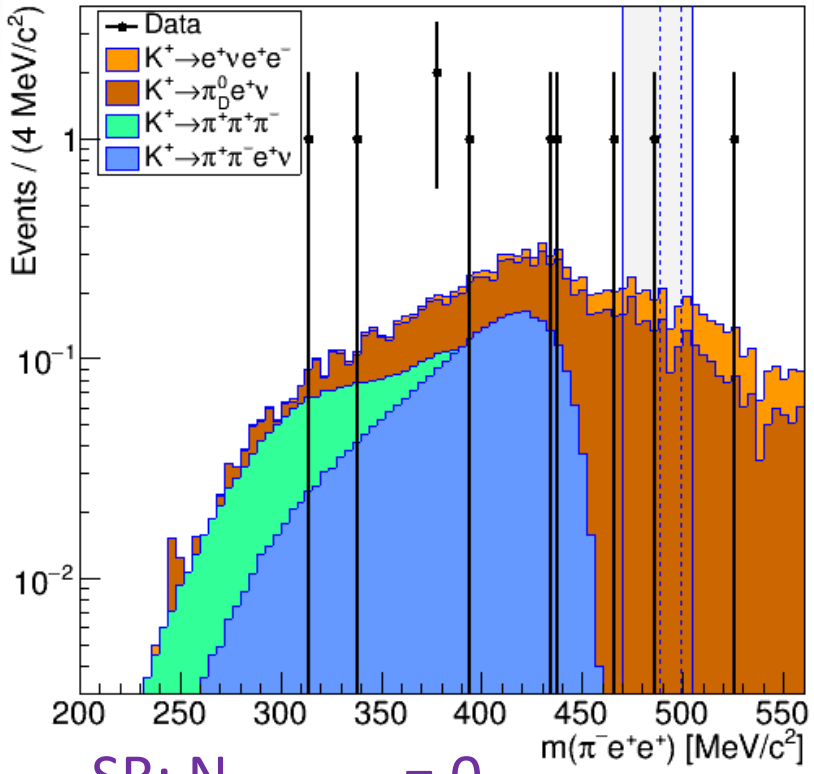
Normalisation:
- $K^+ \to \pi^+ e^+ e^-$
- $N(K^+ \to \pi^+ e^+ e^-) = 9483$

Expected bkg:
- N = 0.43(9)

SM: $M(\pi^+ e^+ e^-)$



LNV: $M(\pi^- e^+ e^+)$



SR: $N_{observed} = 0$

$BR(K^+ \to \pi^- \mu^+ \mu^+) < 5.3 \times 10^{-11}$ (90% CL)

Factor of 12 improvement wrt previous limit: $BR < 6.4 \times 10^{-10}$ (90% CL)

$K^+ \to \pi^- \pi^0 e^+ e^+$

LNV: $M(\pi^- \pi^0 e^+ e^+)$

Data:
- Run 1 (2016-2018)

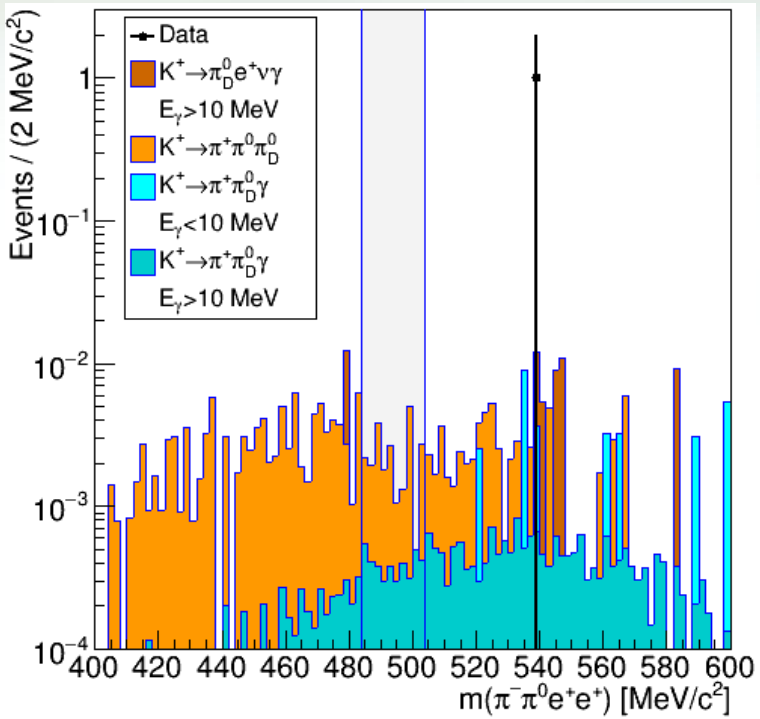
Main features
- blind analysis
- A(sig) = 0.27%
- $N_K = 9.79(31) \times 10^{11}$
- SES = 3.8×10^{-10}

Normalisation:
- $K^+ \to \pi^+ e^+ e^-$
- $N(K^+ \to \pi^+ e^+ e^-) = 9483$

Expected bkg:
- N = 0.044(20)

Expected bkg

Mode	Control region	Signal region
$K^+ \to \pi^+\pi^0\pi^0_D$	0.16 ± 0.01	0.019
$K^+ \to \pi^+\pi^0_D\gamma$	0.06 ± 0.01	0.004
$K^+ \to \pi^0_D e^+\nu\gamma$	0.05 ± 0.02	–
$K^+ \to \pi^+\pi^0 e^+e^-$	0.01	0.001
Pileup	0.20 ± 0.20	0.020 ± 0.020
Total	0.48 ± 0.20	0.044 ± 0.020
Data	1	0



SR: $N_{observed} = 0$

$BR(K^+ \to \pi^- \pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ (90% CL)

First search for this mode

Search for $K^+ \to \mu^- \nu e^+ e^+$

Data:

- Run 1 (2016-2018)

Main features

- blind analysis
- A(sig) = 1.44%
- $N_K = 1.97(7) \times 10^{12}$
- SES = 3.5×10^{-11}

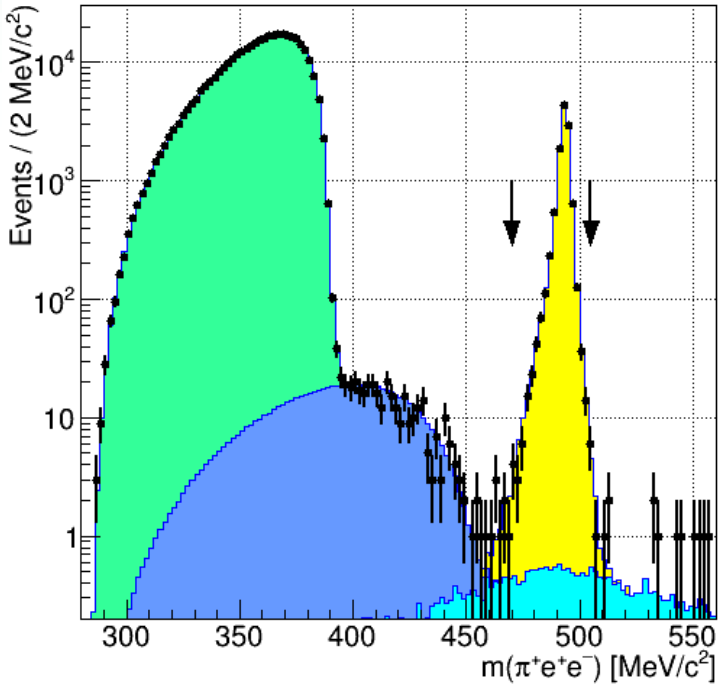
Normalisation:

- $K^+ \to \pi^+ e^+ e^-$
- $N(K^+ \to \pi^+ e^+ e^-) = 10975$

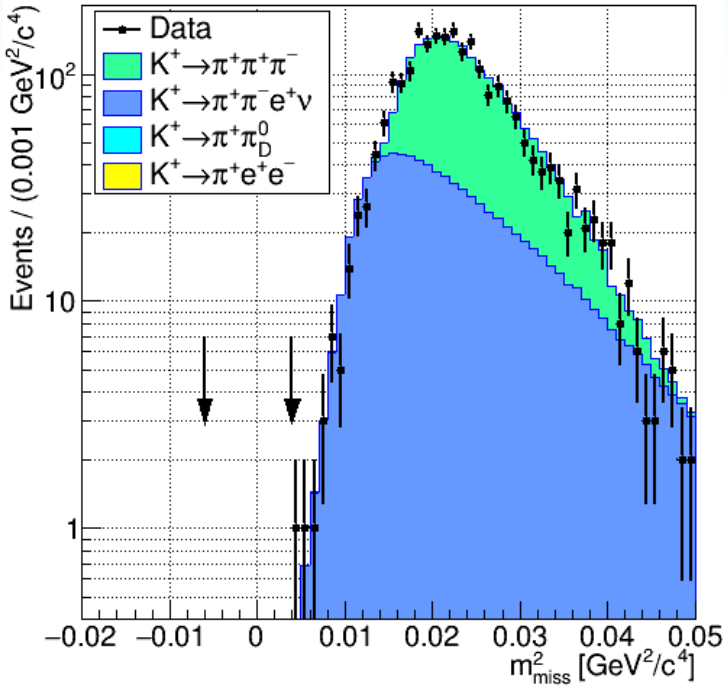
Expected bkg:

- N = 0.26(4)

SM: $M(\pi^+ e^+ e^-)$



LNV: $(P_K - P_{\mu-} - P_{e+} - P_{e+})^2$



SR: $N_{observed} = 0$

$BR(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11}$ (90% CL)

Factor of 250 improvement wrt previous limit: BR < 2.1×10^{-8} (90% CL)

Conclusions

- LFV/LNV searches at NA62: limits improved for several decay modes

Decay mode	Previous UL on BR (90% CL)	NA62 UL on BR (90% CL)	improvement
$K^+ \to \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	Factor of 2 (partial dataset)
$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}	5.3×10^{-11}	Factor of 12
$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11}	Factor of 12
$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11}	Factor of 8
$\pi^0 \to \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}	Factor of 13
$K^+ \to \pi^- \pi^0 e^+ e^+$	-	8.5×10^{-10}	First search
$K^+ \to \mu^- \nu e^+ e^+$	2.1×10^{-8}	8.1×10^{-11}	Factor of 250

NA62 LFV/LNV prospects

- Data taking ongoing (2022-2025)

Spare