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LFV/LNV searches at the NA62 experiment

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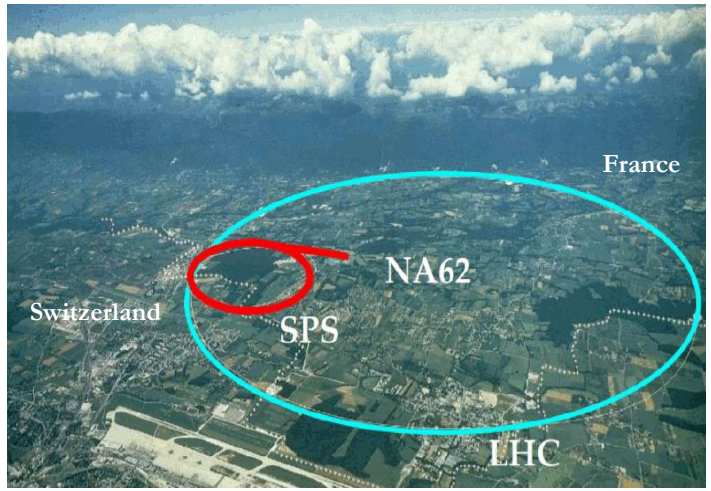
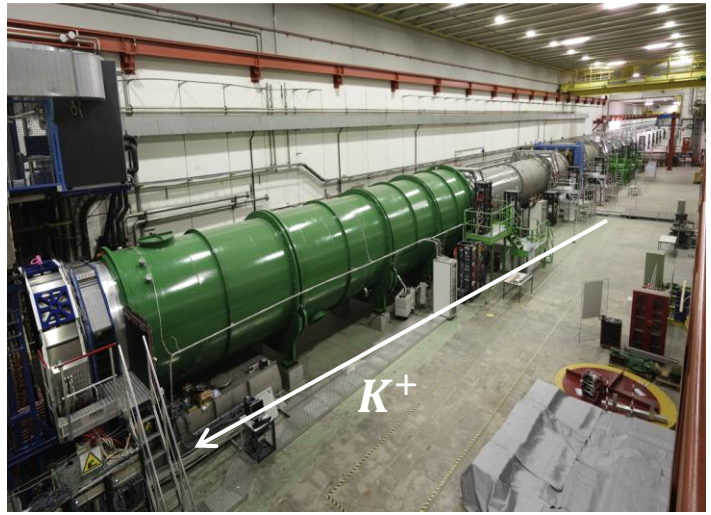
SEZIONE DI FIRENZE

NA62 P326

The NA62 experiment at CERN





- **High-intensity fixed target kaon** experiment at CERN SPS

2008 Approval	2009 → 2015 Detector R&D and commisioning	**Run1: 2016 - 2017- 2018** physics runs	LS2 upgrades	**Run2: 2021 - 2022 2023 - 2024 - 2025 -** 2026 physics runs	LS3

- **K^+ decay-in-flight technique**
- **Primary goal: study of the ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay**
  - $BR_{2016-2022}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(13.0^{+3.0|}_{-2.7|stat}\ ^{+1.3|}_{-1.3|sys}\right) \times 10^{-11}$ ($> 5\sigma$ significance) [JHEP 02 (2025) 191] → Silvia M. talk
- **Broader physics programme both in flavour physics…**
  - test of low-energy hadronic theories : e.g. $K^+ \to \pi^+ \gamma\gamma$ [Phys.Lett.B 850 (2024) 138513]
  - **searches for LFV/LNV decays → This talk**
  - …
- **…and in hidden sector searches** (Dark photon (A'), Dark scalars(S), ALP (a), HNL (N)…)
  - in kaon mode: e.g. $K^+ \to \pi^+ X$ [arXiv.2507.17286[hep-ex], submitted to JHEP], $\pi^+ \to e^+ N$, [arXiv.2507.07345[hep-ex] , submitted to Phys.Lett.B]
  - in a dedicated beam dump programme: eg. $X \to hadrons$ [Eur. Phys. J. C 85 (2025) 571]

The NA62 beam line & detector layout

(designed and optimised for the $K^+ \to \pi^+ \nu\bar{\nu}$ study)

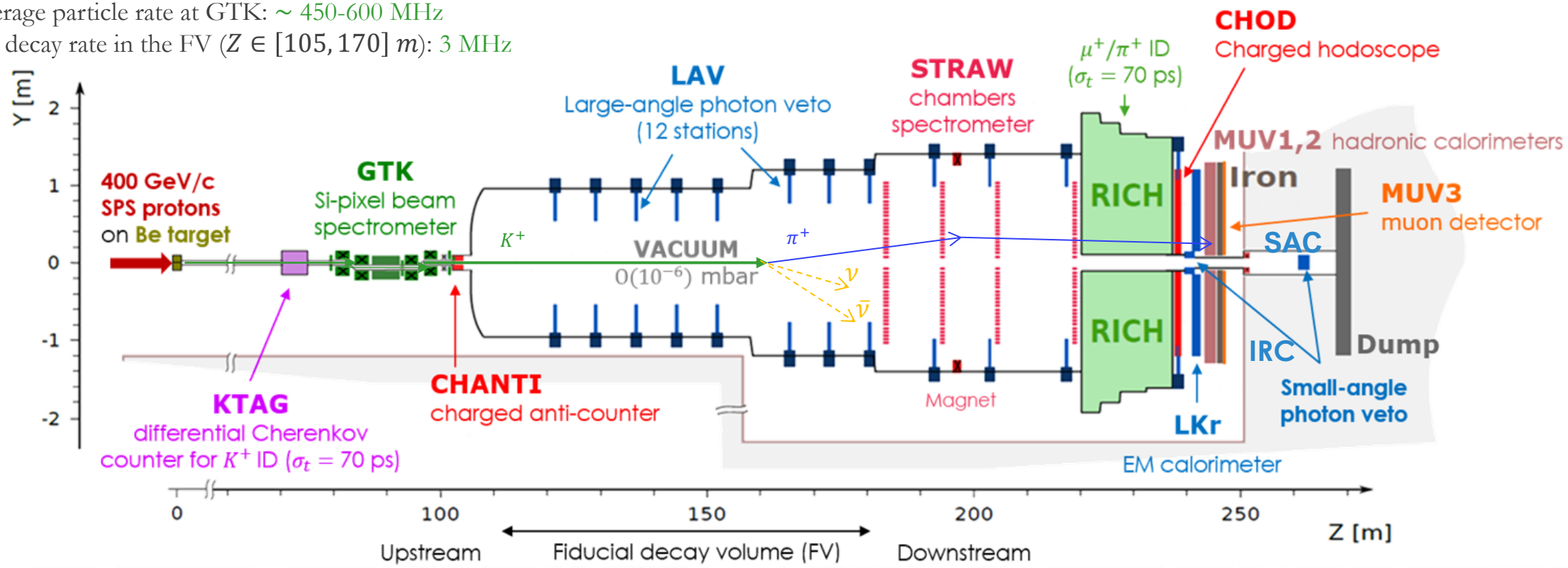
[JINST 12 (2017) P05025]

Primary beam:

- 400 GeV/c protons from the SPS

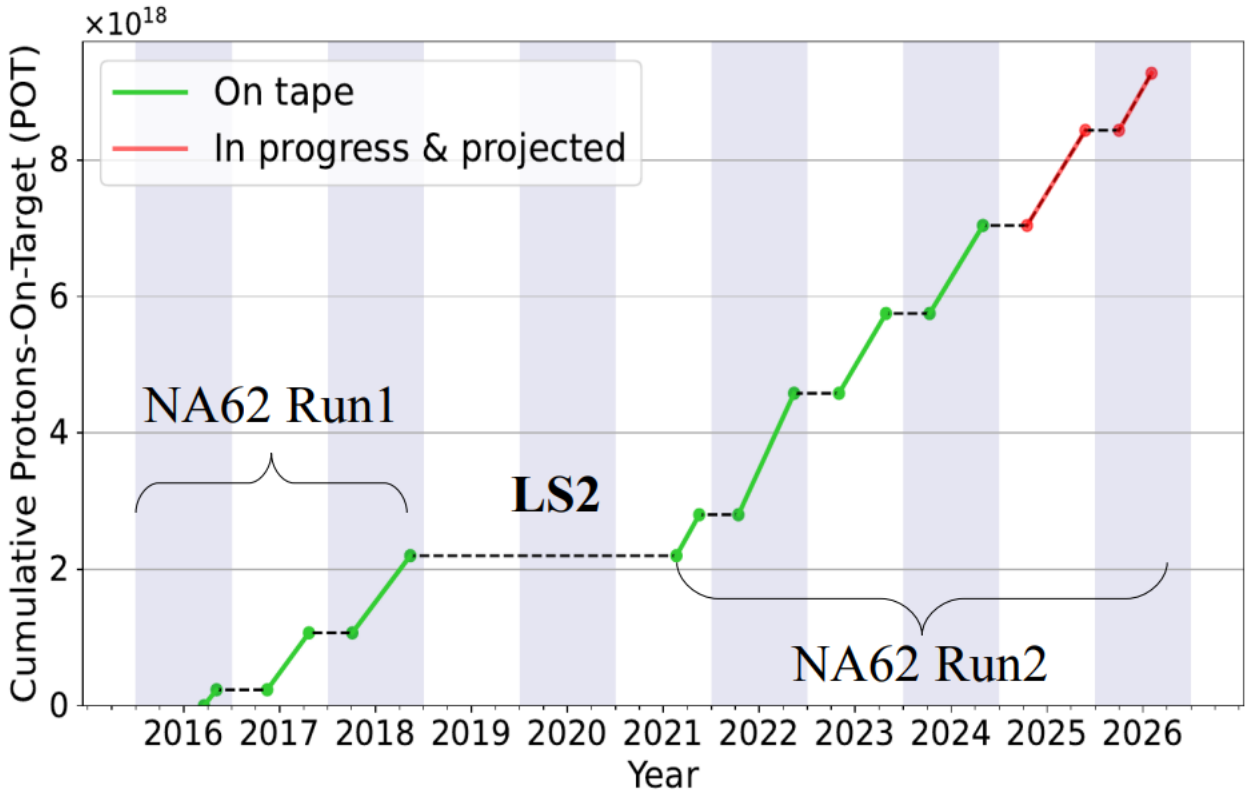
Secondary beam:

- unseparated $(70\%)\pi^+, (23\%)p, (6\%)K^+$ beam with 75 GeV/c momentum ($\pm 1\%$)
- Average particle rate at GTK: ~ 450-600 MHz
- K^+ decay rate in the FV ($Z \in [105, 170]\ m$): 3 MHz



LAV, LKr, IRC, SAC: hermetic coverage of polar angles up to 50 mrad from the beam axis, for photons emitted, for instance, in the $K^+ \to \pi^+\pi^0(\pi^0 \to \gamma\gamma)$ decay

The NA62 data samples in kaon mode



2016-2018: ~ **2.2×10^{18} POT were delivered**

- ~ **6.2×10^{12} K^+** decays collected by the main trigger line + dedicated trigger streams collecting single-track or multi-track final state events [JHEP 2303 (2023) 122]

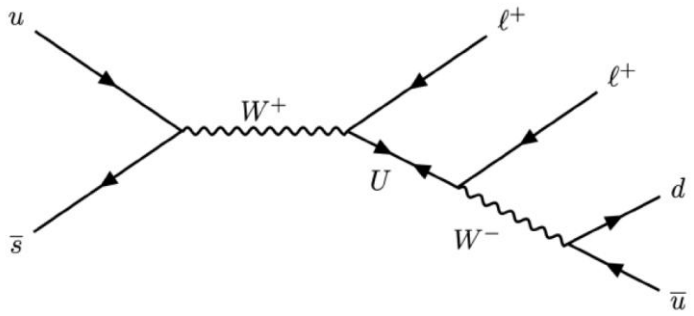
Since 2021: **Proton intensity +35% wrt 16-18 data**

- average beam intensity: 20×10^{11} (in 2018) → 30×10^{11} protons per pulse on target
- Matched by improvements to the trigger configuration

LFV/LNV searches in kaon decays: motivations

- Lepton Number ($\boldsymbol{L}$) and Lepton Flavor ($\boldsymbol{L_e, L_\mu, L_\tau}$) are accidentally conserved quantities within the SM.
- Violation of these conservation laws is a clear indication of BSM physics. Neutrino oscillation: first evidence of LFV
- **Searches for LNV and LFV kaon decays are powerful probes of BSM theories at mass scales up to $\boldsymbol{O}$(100 TeV)**
- Kaons are competitive in searches for LFV/LNV:
  - copious production (high statistics) and simple decay topologies (clean experimental signatures)
  - tagged π^0 via $K^+ \to \pi^+\pi^0$ (for e.g.): precision π^0 decay physics

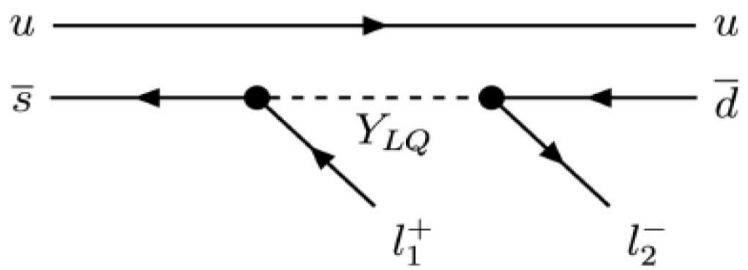
Lepton number violation (LNV)



$\boldsymbol{K^+ \to \pi^- l^+ l^+ \quad \Delta L = 2}$

Seesaw mechanism provides a source of LNV through the exchange of Majorana neutrinos (U) as in $0\nu\beta\beta$ decay [JHEP 05 (2009) 030]

Lepton flavor violation (LFV)



$\boldsymbol{K^+ \to \pi^+ l_1^+ l_2^- \quad \Delta L_1 = 1, \Delta L_2 = 1}$

LFV processes can occur via exchange of leptoquarks (Y_{LQ}), Z' boson or in SM extensions with light pseudoscalar bosons [Rev. Mod. Phys. 81, 1199 (2009), Rep. Prog. Phys. 86 (2023) 016201 JHEP 01 (2020)158]

LFV&LNV at NA62

$K^+ \to \pi^-\mu^+\mu^+, K^+ \to \pi^-(\pi^0)e^+e^+, K^+ \to \pi^\pm\mu^\mp e^+, K^+ \to \mu^-\nu e^+e^+, K^+ \to \pi^-\pi^0\mu^+e^+, K^+ \to \pi^+\pi^0\mu^\mp e^\pm$

- World's leading sensitivity to most LFV/LNV K^+ decays thanks to **dedicated di-lepton trigger lines**
- ***BRs* measured relative to** a SM decay with a similar topology **(normalisation channel)**
- **Main (common) steps of the event selection**
  - Track selection: momentum and direction (STRAW), time (CHOD or RICH)
  - 3-track events forming a Q=+1 vertex in the FV
  - vertex momentum $\left(\left|\sum_{final\ state} \vec{p}_f\right|\right)$ consistent with beam (i.e. K^+) average momentum
  - **LKr** (E/p) and **MUV3** detectors **to distinguish between e^+, μ^+ and π^+;** LAV for low energy photon veto
- **Expected background and selection acceptances from MC**
  - Primary bkg mechanisms from misidentification
  - Data sample used to account for discrepancy between data and MC PID probabilities

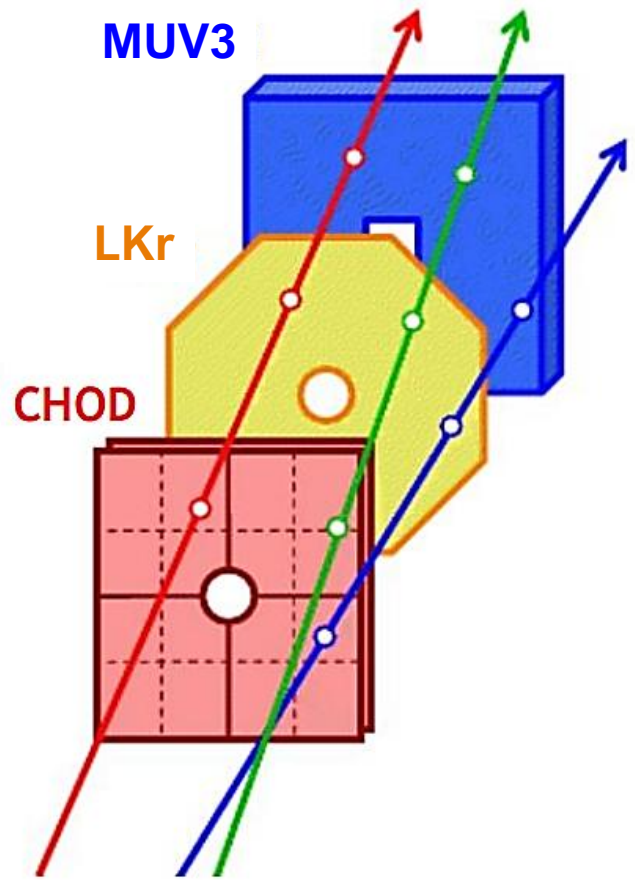
$\pi^\pm \to e^\pm$ misID: $(4-5)\times10^{-3}$	$e^\pm \to \pi^\pm$ misID: $(1-3)\times10^{-2}$
$\pi^\pm \to \mu^\pm$ misID: $(2-3)\times10^{-3}$	$\mu^\pm \to \pi^\pm$ misID: 1.5×10^{-3}

E.g. from $K^+ \to \pi^\pm\mu^\mp e^+$ searches

- **Discriminating kinematic variable and blind analysis strategy**
  - Signal region (SR) kept closed until final bkg validation in control regions

Di-lepton trigger lines (Run1)

[JHEP 2303 (2023) 122]



Lepton pair collection ($\sim 1/4$ of trigger bandwidth):
equivalent of $\mathcal{O}(10^{12})$ kaon decays in Run 1

L0 trigger primitives (firmware):
- QX: two diagonally-opposite CHOD quadrants;
- E10/20: at least 10/20 GeV deposit in LKr;
- MO2: at least two signals in outer MUV3 tiles.

L1 trigger conditions (software):
- KTAG: in-time signals from a beam K^+;
- STRAW: a negatively-charged STRAW track.

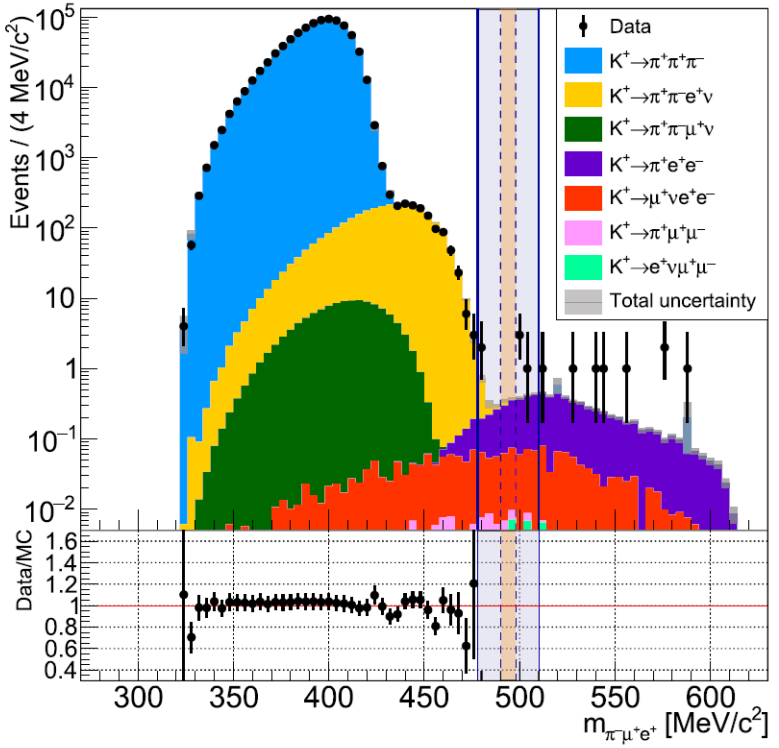
Trigger line		L0 trigger conditions	Downscaling (D)
MT	(generic) multi-track	$RICH \cdot QX$	100
$2\mu MT$	di-muon multi-track	$RICH \cdot QX \cdot MO2$	2
eMT	electron multi-track	$RICH \cdot QX \cdot E20$	8
μMT	Muon multi-track	$RICH \cdot QX \cdot MO1 \cdot E10$	5

LNV $K^+ \to \pi^-\mu^+e^+$ and LFV $K^+ \to \pi^+\mu^-e^+$

[Phys. Rev. Lett. 127 (2021) 131802]

- NA62 2017+2018 data samples.
- $K^+ \to \pi^-\pi^+\pi^+$ as normalisation channel. K^+ decays in the FV: $(1.30 \pm 0.02) \times 10^{12}$
- **Invariant mass $m_{\pi\mu e}$** used to distinguish between signal and bkg.
- Bkg from K^+ decays due to:
  - Particle misID
  - $\pi^\pm \to l^\pm \nu_l$ $(l = \mu, e)$ decays in flight
- **LFV $\pi^0 \to \mu^- e^+$ process is also investigated via $K^+ \to \pi^+\pi^0(\pi^0 \to \mu^- e^+)$**. Additional constraint: consistency of the reconstructed mass $m_{\mu^- e^+}$ with the π^0 mass.

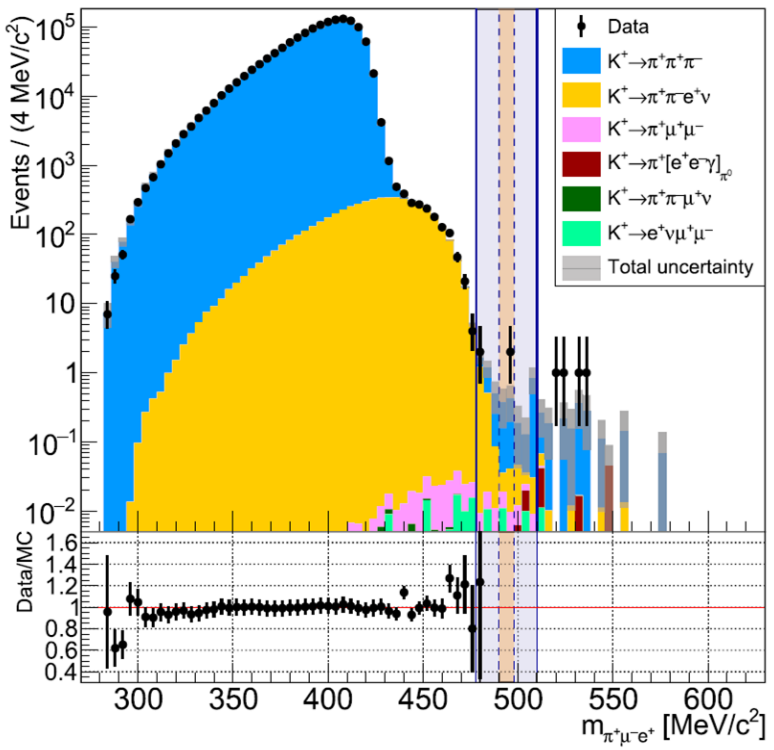
LNV $K^+ \to \pi^-\mu^+e^+$ selection: $m(\pi^-\mu^+e^+)$



Expected bkg events in SR: 1.07 ± 0.20
Observed events in SR: 0

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

LFV $K^+ \to \pi^+\mu^-e^+(\pi^0 \to \mu^-e^+)$ selection: $m(\pi^+\mu^-e^+)$



Exp. bkg in SR: $0.92 \pm 0.34 (0.23 \pm 0.15)$
Observed events in SR: 2 (0)

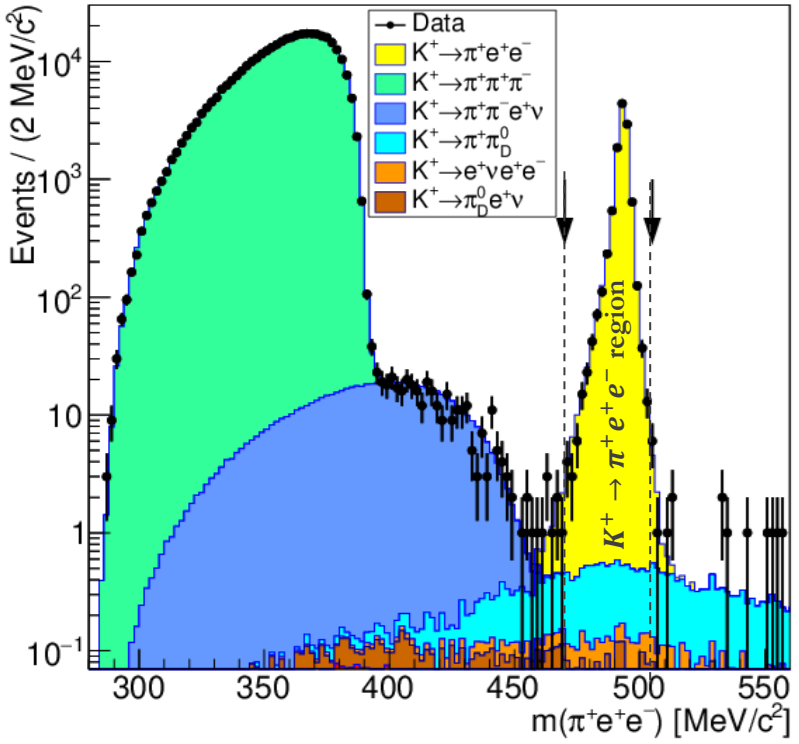
$BR(K^+ \to \pi^+\mu^-e^+) < 6.6 \times 10^{-11}$ at 90%CL
$BR(\pi^0 \to \mu^-e^+) < 3.2 \times 10^{-10}$ at 90%CL

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

[Phys. Lett. B 830 (2022) 137172]

- Whole NA62 Run1 data set analysed.
- **SM $K^+ \to \pi^+ e^+ e^-$** to normalise.
- **Invariant mass $m_{\pi^- e^+ e^+}$** used to distinguish between the LNV $K^+ \to \pi^- e^+ e^+$ signal ($\sigma_m = 1.7$ MeV/c^2) and the bkgs.
- LNV selection: (LKr+RICH)-based e^+ ID to suppress the otherwise dominant $K^+ \to \pi^+ \pi^0_D (\pi^0_D \to e^+ e^- \gamma)$ and $K^+ \to \pi^+ e^+ e^-$ decays with $\pi^+ \to e^+$ and $e^- \to \pi^-$ misID

Nomalisation selection: $m(\pi^+ e^+ e^-)$



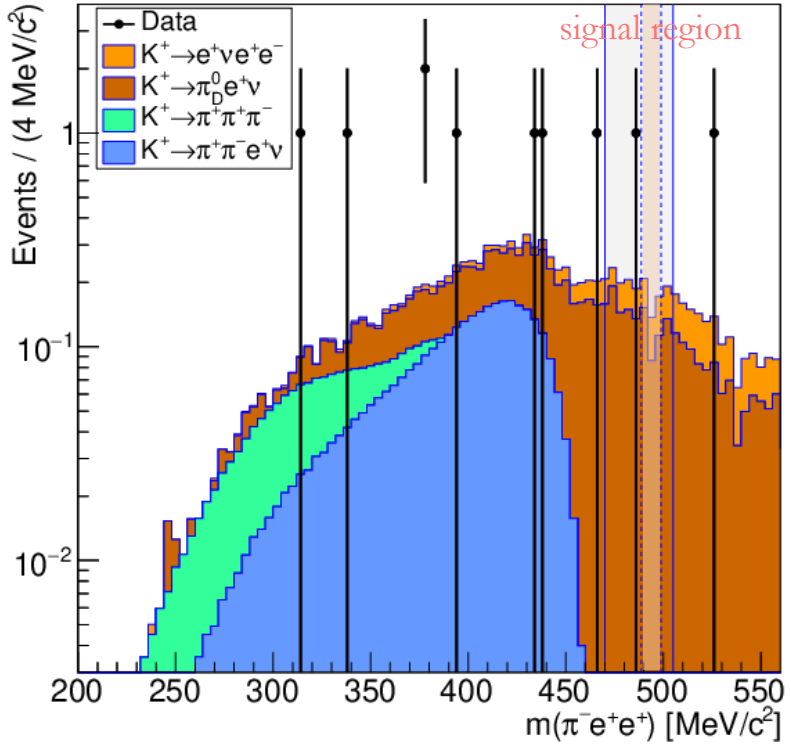
Observed $K^+ \to \pi^+ e^+ e^-$ candidates: 11041

$BR(K^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^{-7}$

Number of K^+ decays in the FV:

$(1.015 \pm 0.010_{stat} \pm 0.030_{ext}) \times 10^{12}$

LNV selection: $m(\pi^- e^+ e^+)$



Expected bkg events in SR: 0.43 ± 0.09

Observed events in SR : 0

$BR(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$

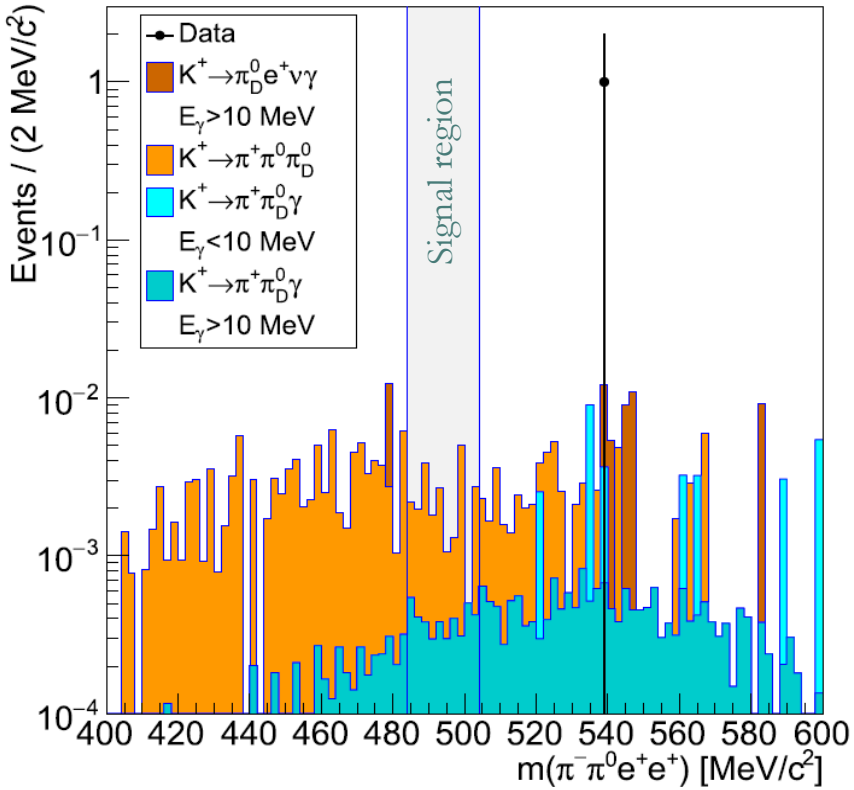
at 90% CL

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

[Phys. Lett. B 830 (2022) 137172]

- Whole NA62 Run1 data set analysed.
- **SM $K^+ \to \pi^+ e^+ e^-$** as normalisation channel (same selection as for the LNV $K^+ \to \pi^- e^+ e^+$ search).
  K^+ decays in the FV: $(1.015 \pm 0.010_{stat} \pm 0.030_{ext}) \times 10^{12}$
- **Invariant mass $m_{\pi^-\pi^0 e^+ e^+}$** used to distinguish between signal ($\sigma_m = 1.9$ MeV/c^2) and bkgs.
- π^0 reconstructed in LKr calorimeter via the $\pi^0 \to \gamma\gamma$ decay.
- Common selection to the LNV $K^+ \to \pi^- e^+ e^+$ but sample bkg free with LKr PID only.

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



Exp. bkg events in SR: 0.044 ± 0.020

Observed events in SR: 0

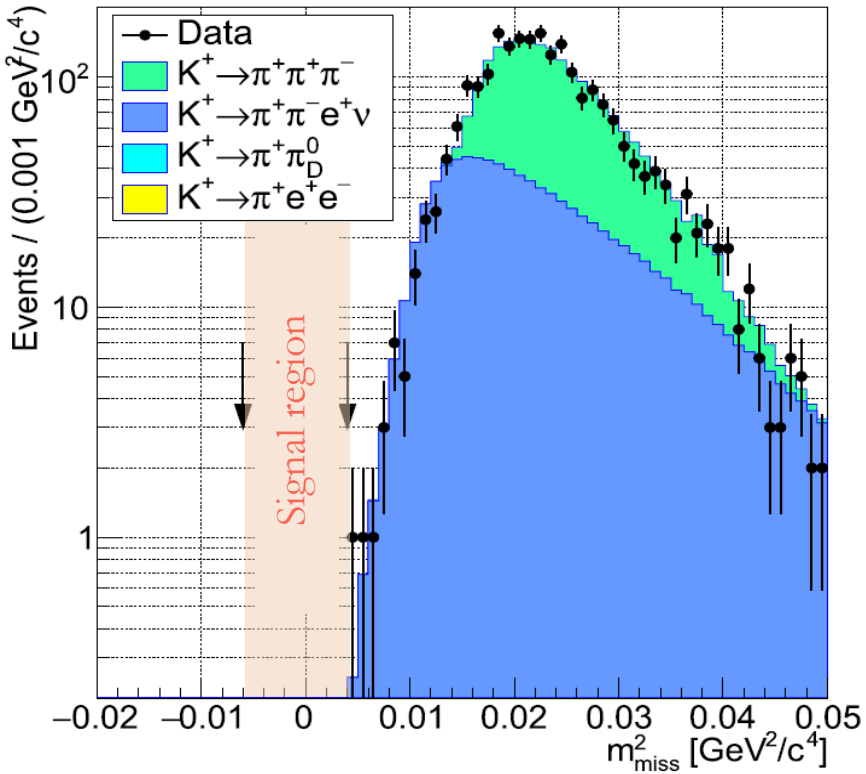
$BR(K^+ \to \pi^-\pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ at 90% CL

LFV/LNV $K^+ \to \mu^- \nu e^+ e^+$

[Phys. Lett. B 838 (2023) 137679]

- Whole NA62 Run1 data set.
- LFV or LNV depending on neutrino flavor.
- $K^+ \to \pi^+ e^+ e^-$ used as normalisation channel. K^+ decays in the FV: $\left(1.97 \pm 0.02_{stat} \pm 0.02_{sys} \pm 0.06_{ext}\right) \times 10^{12}$.
- **Squared missing mass** $m^2_{miss} \equiv \left(P_K - \left(P_\mu + P_{e1} + P_{e2}\right)\right)^2$ used to distinguish between signal ($\sigma_{m^2_{miss}} = 1.4 \times 10^{-3}\ \mathrm{GeV}^2/\mathrm{c}^4$) and bkg.
- Dominant bkgs due to $K^+ \to \pi^- \pi^+ \pi^+$ and $K^+ \to \pi^- \pi^+ e^+ \nu_e$ **with** $\pi^- \to \mu^- \nu_\mu$ **decay-in-flight and** $\pi^+ \to e^+$ **misID.**

LNV/LNV selection: m^2_{miss}



Expected bkg events in SR : 0.26 ± 0.04

Observed events in SR: 0

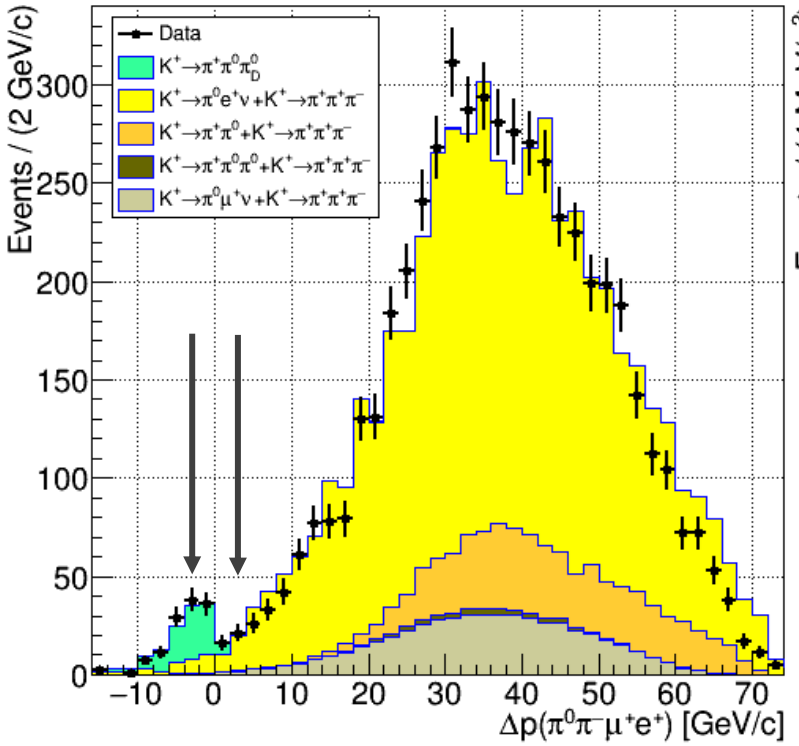
$BR(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11}$ @90% CL

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

[Phys. Lett. B 859 (2024) 139122]

- Whole NA62 Run1 data set analysed.
- $K^+ \to \pi^+e^+e^-$ as normalisation channel. Number of K^+ decays in the FV: $(1.97 \pm 0.02_{stat} \pm 0.02_{sys} \pm 0.06_{ext}) \times 10^{12}$
- **Invariant mass $m_{\pi^0\pi^-\mu^+e^-}$** used to distinguish between signal ($\sigma_m = 1.3$ MeV/c^2) and bkg.
- π^0 reconstructed in LKr calorimeter via the $\pi^0 \to \gamma\gamma$ decay
- Main bkg in the SR from $K^+ \to \pi^+\pi^0\pi^0_D$:
  - $\pi^+ \to \mu^+\nu_\mu$ decay-in-flight
  - $\pi^0_D \to e^+e^-\gamma$ with undetected soft photon and $e^- \to \pi^-$ misID

LNV loose selection:
$\Delta p(\pi^0\pi^-\mu^+e^+)$

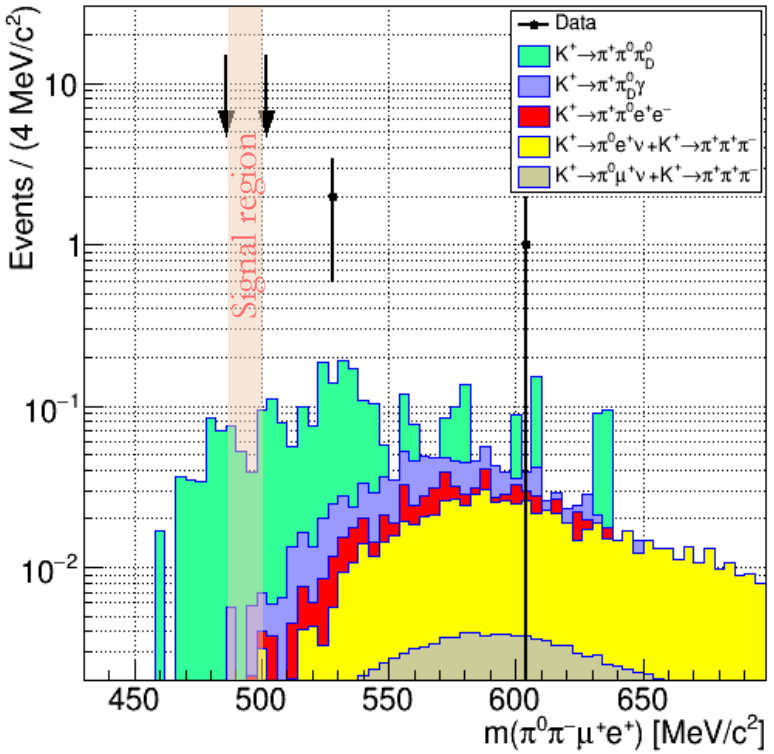


$\Delta p = p_{\pi^0\pi\mu e} - p_{beam}$

tot final state reco momentum

Average beam momentum measured from data

LNV full selection:
$m(\pi^0\pi^-\mu^+e^+)$



Expected bkg in SR : 0.33 ± 0.07
Observed events in SR: 0

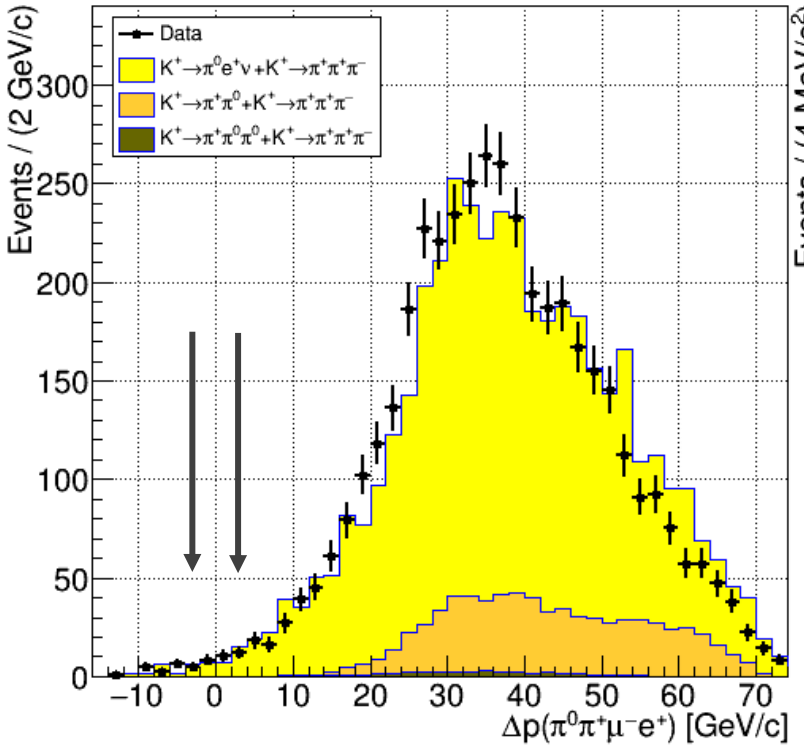
$BR(K^+ \to \pi^0\pi^-\mu^+e^-) < 2.9 \times 10^{-10}$ @90% CL

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

[Phys. Lett. B 859 (2024) 139122]

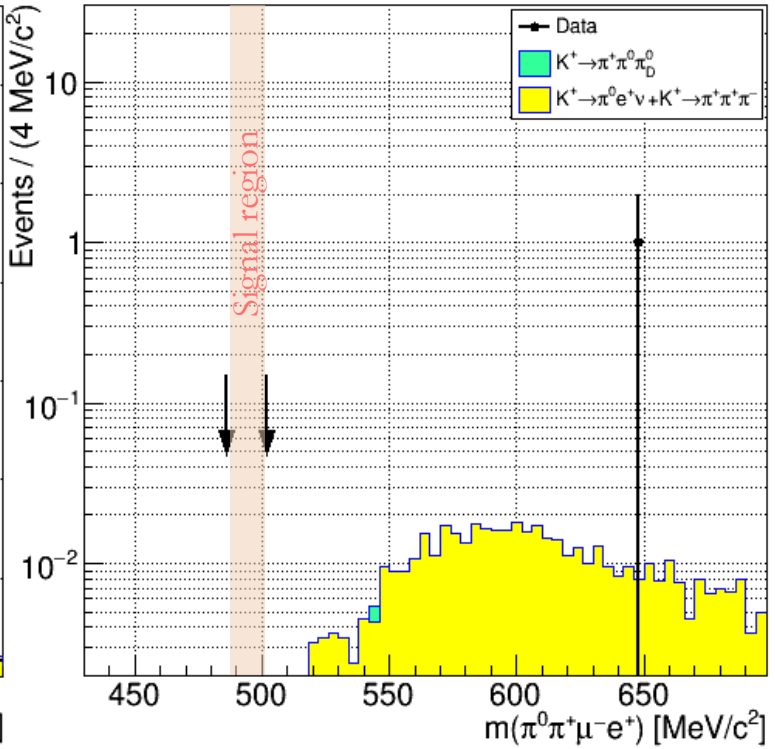
- Whole NA62 Run1 data set analysed.
- $K^+ \to \pi^+e^+e^-$ as normalisation channel. Number of K^+ decays in the FV: $(1.97 \pm 0.02_{stat} \pm 0.02_{sys} \pm 0.06_{ext}) \times 10^{12}$
- **Invariant mass $m_{\pi^0\pi^+\mu^-e^+}$** used to distinguish between signal ($\sigma_m = 1.3$ MeV/c^2) and bkg.
- Same selection as in the search for the LNV $K^+ \to \pi^0\pi^-\mu^+e^+$ decay
- Main bkg in the SR from **concurrent $K^+ \to \pi^+\pi^-\pi^+$** (with $\pi^- \to \mu^-\nu_\mu$ and one undetected π^+) **and $K^+ \to \pi^0e^+\nu_e$ decays**

LFV loose selection:
$\Delta p(\pi^0\pi^+\mu^-e^+)$



$\Delta p = (p_{\pi^0\pi\mu e} - p_{beam}) > 10$ GeV/c
used to validate bkgs from combination of pairs of decays

LFV full selection:
$m(\pi^0\pi^+\mu^-e^+)$



Expected bkg in SR : 0.004 ± 0.003
Observed events in SR: 0

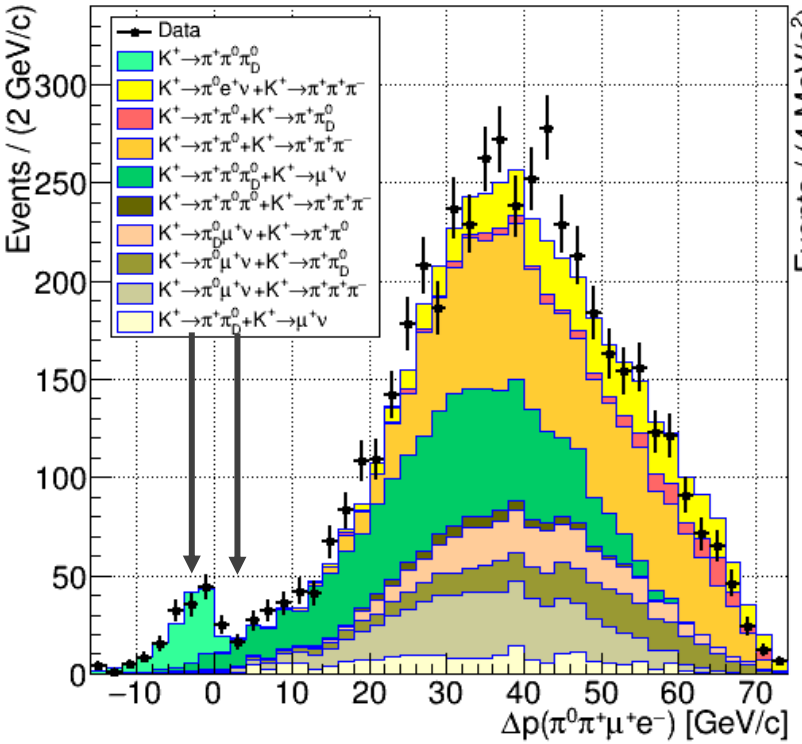
$BR(K^+ \to \pi^0\pi^+\mu^-e^+) < 3.1 \times 10^{-10}$ @90% CL

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

[Phys. Lett. B 859 (2024) 139122]

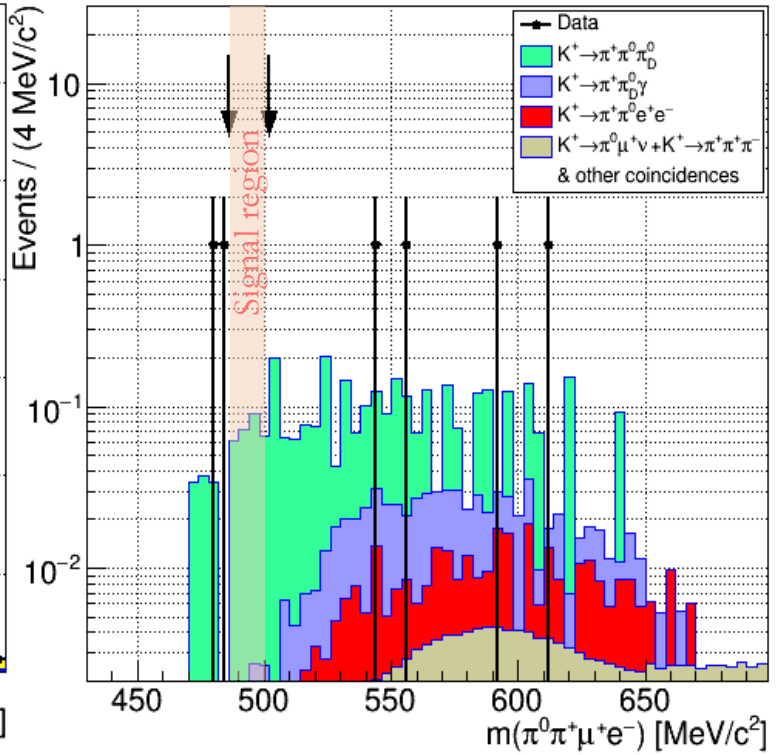
- Whole NA62 Run1 data set analysed.
- $K^+ \to \pi^+e^+e^-$ as normalisation channel. Number of K^+ decays in the FV: $(1.97 \pm 0.02_{stat} \pm 0.02_{sys} \pm 0.06_{ext}) \times 10^{12}$
- **Invariant mass $m_{\pi^0\pi^+\mu^+e^-}$** used to distinguish between signal ($\sigma_m = 1.3$ MeV/c^2) and bkg.
- Same selection as in the search for the LNV $K^+ \to \pi^0\pi^-\mu^+e^+$ decay
- Main bkg in the SR from $K^+ \to \pi^+\pi^0\pi^0_D$:
  - $\pi^+ \to \mu^+\nu_\mu$ decay-in-flight
  - $\pi^0_D \to e^+e^-\gamma$ with undetected soft photon and $e^+ \to \pi^+$ misID

LFV loose selection: $\Delta p(\pi^0\pi^+\mu^+e^-)$



Included combinations of pairs of decays having product of BR as low as $\mathcal{O}(10^{-6})$

LFV full selection: $m(\pi^0\pi^+\mu^+e^-)$



Expected bkg in SR : 0.29 ± 0.07
Observed events in SR: 0

$$BR(K^+ \to \pi^0\pi^+\mu^+e^-) < 5.0 \times 10^{-10}$$
@90% CL

LFV&LNV at NA62: RUN1 analysis programme in context

		Previous UL @ 90% CL	NA62 UL @ 90% CL	
LNV	$\mathrm{BR}(K^+ \to \pi^- \mu^+ \mu^+)$	$< 8.6 \times 10^{-11}$	$< 4.2 \times 10^{-11}$	**improved by factor 2** (30% Run1 sample)
	$\mathrm{BR}(K^+ \to \pi^- e^+ e^+)$	$< 6.4 \times 10^{-10}$	$< 5.3 \times 10^{-11}$	**improved by factor 12**
	$\mathrm{BR}(K^+ \to \pi^- \pi^0 e^+ e^+)$	none	$< 8.5 \times 10^{-10}$	**first limit**
	$BR(K^+ \to \pi^- \pi^0 \mu^+ e^+)$	none	$< 2.9 \times 10^{-10}$	**first limit**
	$\mathrm{BR}(K^+ \to \pi^- \mu^+ e^+)$	$< 5.0 \times 10^{-10}$	$< 4.2 \times 10^{-11}$	**improved by factor 12**
LFV	$\mathrm{BR}(K^+ \to \pi^+ \mu^- e^+)$	$< 5.2 \times 10^{-10}$	$< 6.6 \times 10^{-11}$	**improved by factor 8**
	$\mathrm{BR}(\pi^0 \to \mu^- e^+)$	$< 3.4 \times 10^{-9}$	$< 3.2 \times 10^{-10}$	**improved by factor 11**
	$BR(K^+ \to \pi^+ \pi^0 \mu^- e^+)$	none	$< 3.1 \times 10^{-10}$	**first limit**
	$BR(K^+ \to \pi^+ \pi^0 \mu^+ e^-)$	none	$< 5.0 \times 10^{-10}$	**first limit**
	$BR(K^+ \to \pi^+ \mu^+ e^-)$	$< 1.3 \times 10^{-11}$	-	sensitivity similar to previous search with Run1
	$BR(\pi^0 \to \mu^+ e^-)$	$< 3.8 \times 10^{-10}$	-	sensitivity similar to previous search with Run1
LFV/LNV depending on ν flavor	$\mathrm{BR}(K^+ \to \mu^- \nu e^+ e^+)$	$< 2.1 \times 10^{-8}$	$< 8.1 \times 10^{-11}$	**improved by factor $> O(10^2)$**

Conclusions and prospects

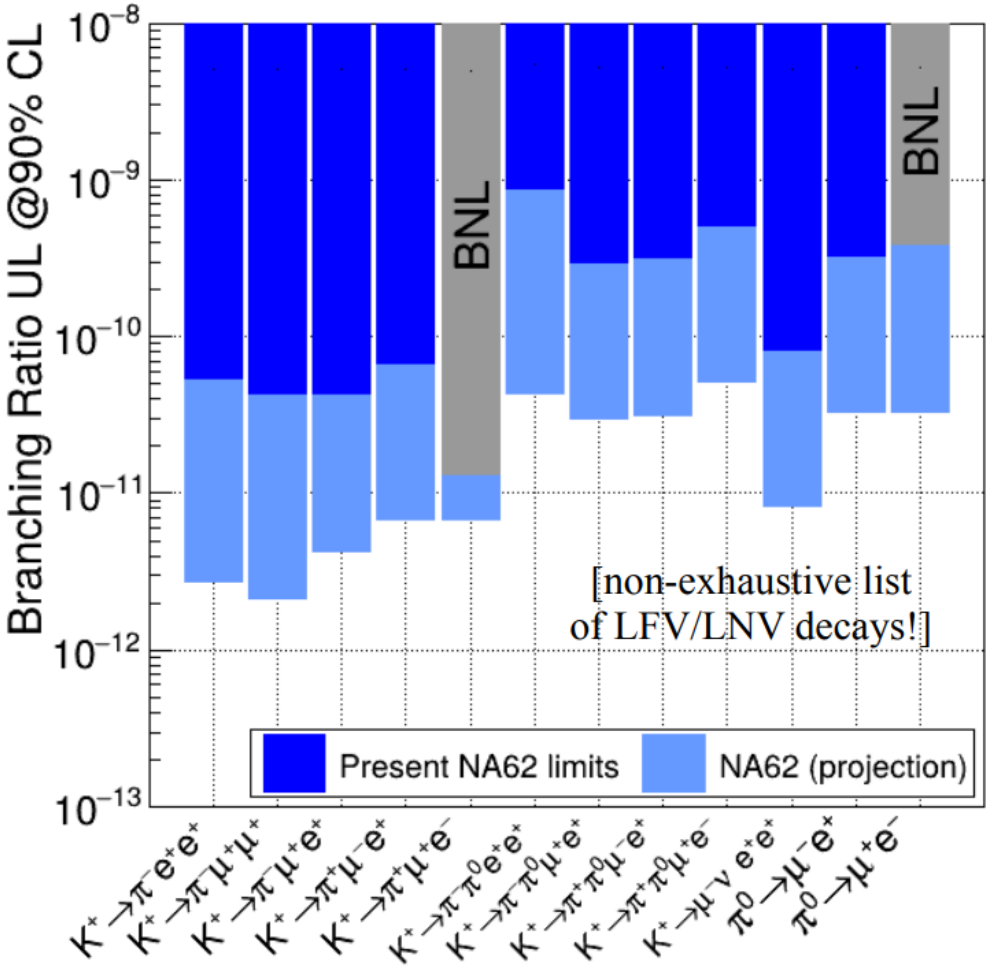
Run1 dataset (2016-2018)

- World-leading limits established for 10 LFV/LNV decay modes
- Sensitivity not limited by backgrounds

Run1 + Run2 dataset (2016-2026)

- To cope with beam intensity increase in Run2: di-lepton trigger upgrades including LKr clustering at L0 and improved L1-STRAW reconstruction
  → **downscaling factors set to D=1 in late 2023**
- 2016-2026 di-lepton datasets are expected to be equivalent to $O(10^{13})$ collected kaon decays
  → **an order of magnitude improvement in sensitivity**
- Further decay modes to be added

NA62 prospects for Run1+Run2 UL on BRs of LFV/LNV K^+ and π^0 decays: $\boldsymbol{O(10^{-11} - 10^{-12})}$



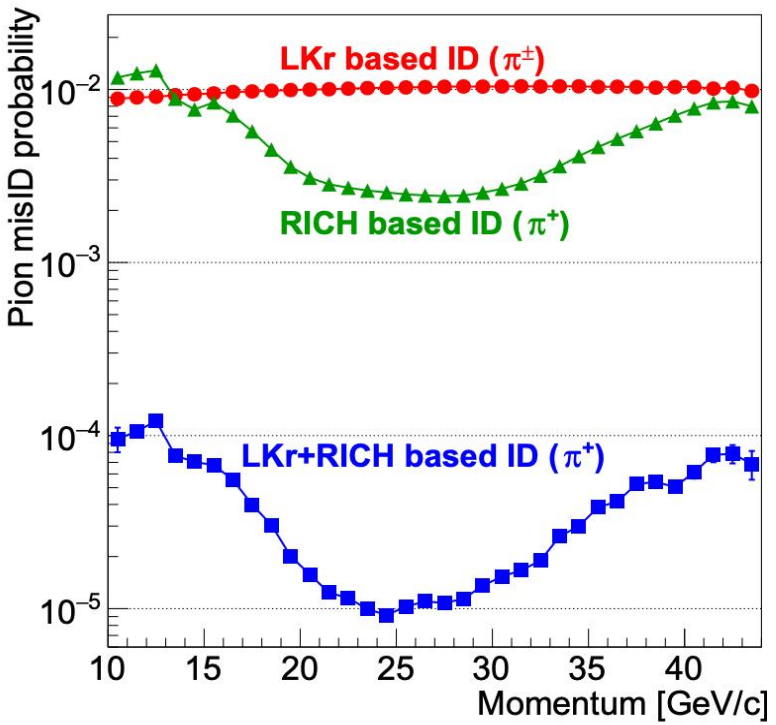
Supplemental material

Backgrounds and PID studies

from $K^+ \to \pi^-(\pi^0)e^+e^+$ analysis [Phys. Lett. B 830 (2022) 137172]

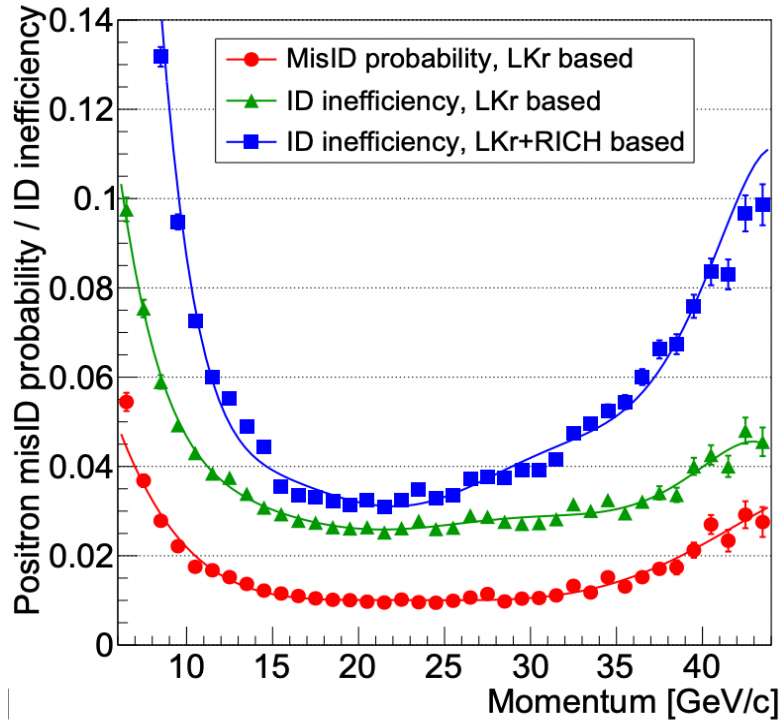
- Primary bkg mechanisms from misidentification but limited simulation accuracy of PID probabilities
- Dedicated data driven models from data (polynomial fits in the plots)
- Measured PID probabilities applied as weights to MC event
- Validated using control samples

π misidentification into e



Measured from a $K^+ \to \pi^+\pi^-\pi^+$ sample from data

e^+ misidentification into π^+



Measured from a $K^+ \to e^+\nu_e\pi^0$ sample from data