Search for Lepton Number and Flavour Violation in K^+ and π^0 Decays

Lubos Bician

on behalf of the NA62 Collaboration

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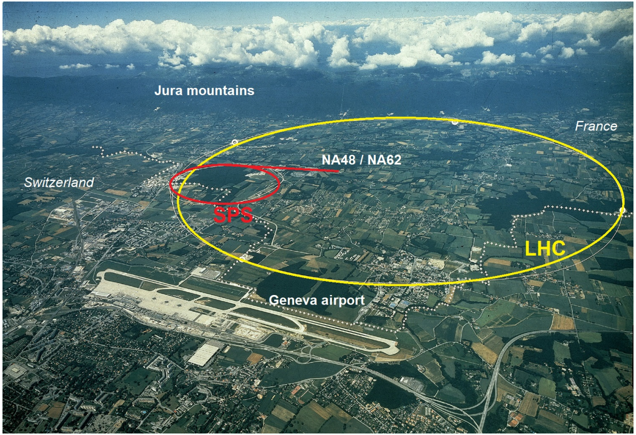
Kaon Experiments at CERN



NA62: ~ 200 participants, ~ 30 institutes

- **NA31**: 1980s, *beam:* K_L/K_S
  - *First evidence of direct CPV*
- **NA48**: 1997–2001, *beam:* K_L/K_S
  - *Discovery of direct CPV*
- **NA48/1**: 2002, *beam:* K_S/hyperons
  - *Rare decay studies*
- **NA48/2**: 2003–2004, *beam:* K^+/K^-
  - *Precision measurements*
- **NA62-R$_K$**: 2007–2008, *beam:* K^+/K^-
  - $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$
- **NA62**: since 2015, *beam:* K^+
  2015: commissioning run
  2016-2018: physics runs:
  - Main goal: $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$
  - Precision measurements (e.g. $K^+ \to \pi^+ \mu^+ \mu^-$)
  - Searches for HNL, axions, dark γ, LNV or LFV decays – **this talk**

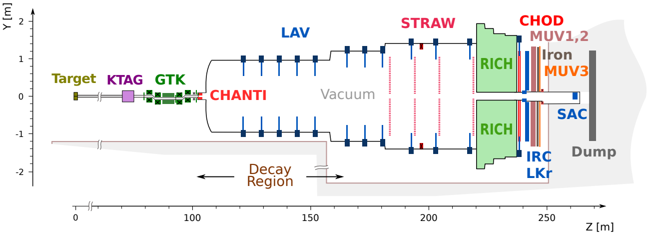
Motivation

- Observation of LNV or charged LFV processes would be a clear indication of BSM physics
- Previous LNV and/or LFV searches in π^0 and semileptonic K^+ decays:

Process	Previous UL on $\mathcal{B}$ @ 90% CL	
$K^+ \to \pi^-\mu^+\mu^+$	4.2×10^{-11}	NA62, 30% of Run 1 stat., [PLB 797 (2019) 134794]
$K^+ \to \pi^- e^+ e^+$	2.2×10^{-10}	NA62, 30% of Run 1 stat., [PLB 797 (2019) 134794]
$K^+ \to \pi^+\mu^+ e^-$	1.3×10^{-11}	BNL E865, [PDG]
$K^+ \to \pi^-\mu^+ e^+$	5.0×10^{-10}	BNL E865, [PDG], New NA62 result presented here
$K^+ \to \pi^+\mu^- e^+$	5.2×10^{-10}	BNL E865, [PDG], New NA62 result presented here
$\pi^0 \to \mu^- e^+$	3.4×10^{-9}	BNL E865, [PDG], New NA62 result presented here
$\pi^0 \to \mu^+ e^-$	3.8×10^{-10}	BNL E865, [PDG]

- The LNV decays could be mediated by Majorana neutrinos, [JHEP 0905 (2009) 030]
- The LFV decays could proceed via e.g. the exchange of leptoquarks, or a Z' boson, [JHEP 10 (2018) 148], [Rev. Mod. Phys. 81, 3 (2009)]

NA62: Beam and Detector



[JINST 12 (2017) P05025]

Beam parameters:

- **Beam momentum:** 75 GeV/c ($\pm 1\%$)
- **Nominal rate:** 750 MHz
- **Positive beam:** $\sim 6\%$ K$^+$

Main subdetectors:

- **Beam tracker:** GTK
- **Kaon tagger:** KTAG ($\sigma_t \sim 70$ ps)
- **Downstream tracker:** ($\pi/\mu/e$): Straw $\sigma_p/p = 0.3\% \bigoplus 0.005\% \cdot p$[GeV/$c$]
- **Photon veto detectors:** LAV, IRC, SAC
- **Cherenkov counter:** RICH
- **Trigger and timing:** CHOD ($\sigma_t \sim 1$ ns), NA48-CHOD ($\sigma_t \sim 200$ ps)
- **Electromagnetic calorimeter:** LKr $\sigma_E/E = 4.8\%/\sqrt{E} \bigoplus 11\%/E \bigoplus 0.9\%$, $[E] =$ GeV
- **Hadronic calorimeters:** MUV1,2
- **Muon detector:** MUV3 ($\sigma_t \sim 500$ ps)

Analysis Overview

- Improvement on ULs on $\mathcal{B}(K^+ \to \pi^\pm \mu^\mp e^+)$, and $\mathcal{B}(\pi^0 \to \mu^- e^+)$ with π^0 from $K^+ \to \pi^+ \pi^0$
  - Full 2017 + 2018 dataset used in the analysis
  - Blind analysis technique used in order to not bias the measurement
- All signal channels produce three charged tracks and nothing else
- This motivates the choice of the normalisation decay channel: $K^+ \to \pi^+ \pi^+ \pi^-$ $(K_{3\pi})$:
  - Abundant: $\mathcal{B}(K_{3\pi}) = 5.583(24)\%$, **[PDG]**
  - Allows for similar signal and normalisation event selections
- Three physics trigger streams used to collect signal and normalisation events in parallel:

Trigger	Downscale	Description	Use in this analysis
Multi-track (MT)	~ 100	Minimum-bias multi-track trigger	$K_{3\pi}$, $K^+ \to \pi^\pm \mu^\mp e^+$
μMT	~ 8	MT, $10+$ GeV in LKr, 1+ μ in MUV3	$K^+ \to \pi^\pm \mu^\mp e^+$
eMT	~ 8	MT, $20+$ GeV in LKr	$K^+ \to \pi^\pm \mu^\mp e^+$

- The effective number of kaon decays in $[105, 180]$ m region: $N_K = (1.33 \pm 0.02) \times 10^{12}$

Event Selections

Part common to both signal and normalisation event selections

- Event passes at least one of the three triggers from the previous slide
- Exactly one "good" in-time three-track (Straw) vertex is required
- At least one "good" in-time KTAG kaon is present

Part specific to the normalisation event selection

- Invariant mass $m(3\pi)$ of the three vertex tracks under $\pi^{\pm}$ mass hypotheses has to be consistent with the charged kaon mass m_K: $|m(3\pi) - m_K| < 3.5$ MeV$/c^2$

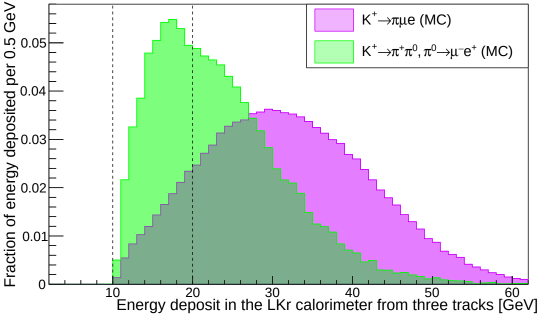
Part specific to the signal event selections

- Particle identification:
  - $\pi^{\pm}$: LKr $E/p < 0.9c$, and 0 associated in-time MUV3 muons
  - $\mu^{\pm}$: LKr $E/p < 0.2c$, and 1 associated in-time MUV3 muon
  - $e^{\pm}$: LKr $E/p \in [0.95, 1.05]c$, 1 associated in-time LKr cluster, and 0 associated in-time MUV3 muons
- $K^+ \to \pi^- \mu^+ e^+$: $Z_{\text{vertex}} > 107$ m, and Dalitz rejection cut (see next slides)
- $K^+ \to \pi^+ \mu^- e^+$: $Z_{\text{vertex}} > 111$ m
- $\pi^0 \to \mu^- e^+$: $K^+ \to \pi^+ \mu^- e^+$ selection, and $|m_{\mu e} - m_{\pi^0}| < 2$ MeV$/c^2$

Trigger efficiencies

- The efficiency of MT trigger: $\varepsilon_n = (93.2 \pm 0.05)\%$
- The MUV3 condition in the μMT has negligible inefficiency
- The efficiencies of LKr trigger conditions ($10+$ and $20+$ GeV) depend strongly on energy:

LKr ε [%]	$\varepsilon_{\text{LKr10}}$	$\varepsilon_{\text{LKr20}}$
$K^+ \to \pi^- \mu^+ e^+$	97.5 ± 1.3	74.1 ± 1.6
$K^+ \to \pi^+ \mu^- e^+$	97.5 ± 1.3	73.3 ± 1.6
$\pi^0 \to \mu^- e^+$	92.9 ± 1.2	45.3 ± 1.0



Signal selection acceptances assuming uniform phase-space densities [%]

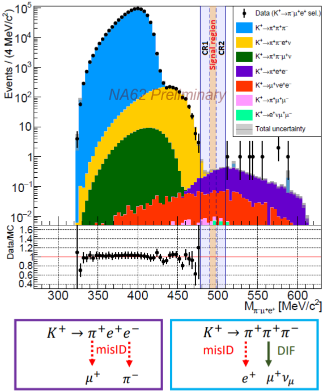
- $A(K^+ \to \pi^- \mu^+ e^+) = 4.90 \pm 0.02$, $A(K^+ \to \pi^+ \mu^- e^+) = 6.21 \pm 0.02$, $A(\pi^0 \to \mu^- e^+) = 3.11 \pm 0.02$

Background Mechanisms and Expectations

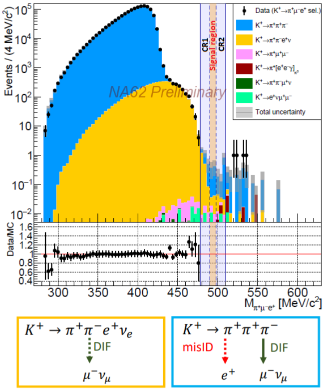
Two dominant background mechanisms:

- Particle misidentification (misID)
  - probabilities measured with data and applied to simulations as weights (forced misID)
- Decays in-flight (DIF):
  - $\pi^{\pm} \to \ell^{\pm}\nu_\ell, \quad (\ell \in \{e, \mu\})$
  - $K^+ \to \pi^+\pi^0$, $K^+ \to \pi^0\ell^+\nu_\ell$ followed by a Dalitz decay $\pi^0 \to e^+e^-\gamma$
    $\to$ suppressed by a dedicated cut in the $K^+ \to \pi^-\mu^+e^+$ selection on $m_{\pi^-,e^+}(m_e, m_e) > 140$ MeV$/c^2$

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



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



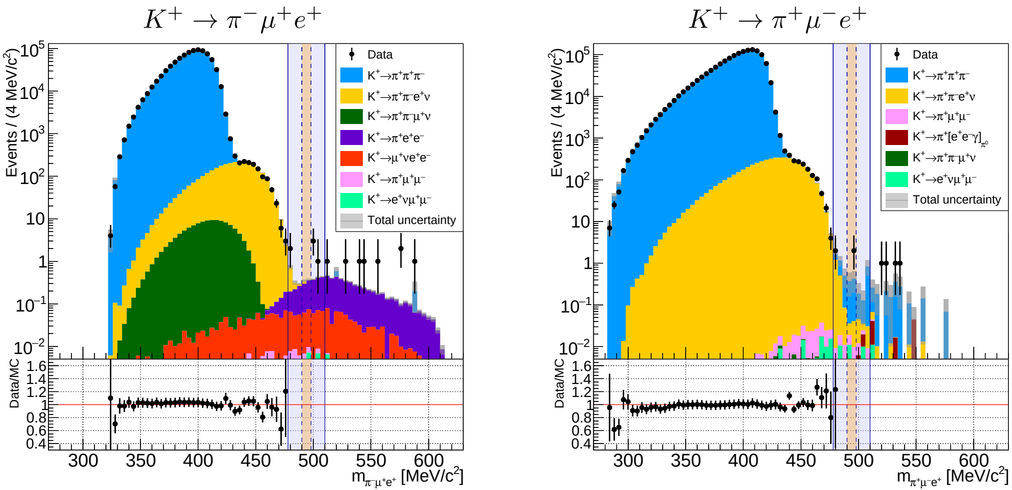
Background in control regions:

	$K^+ \to \pi^-\mu^+e^+$		$K^+ \to \pi^+\mu^-e^+$	
	CR1	CR2	CR1	CR2
Predicted	1.68 ± 0.20	1.66 ± 0.26	3.41 ± 0.54	1.27 ± 0.40
Observed	2	4	2	0

Bckgr. predictions in signal regions:

Source	$K^+ \to \pi^-\mu^+e^+$	$K^+ \to \pi^+\mu^-e^+$	$\pi^0 \to \mu^-e^+$
$K^+ \to \pi^+\pi^+\pi^-$	0.22 ± 0.15	0.84 ± 0.34	0.22 ± 0.15
$K^+ \to \pi^+e^+e^-$	0.63 ± 0.13	negl.	negl.
$K^+ \to \mu^+\nu_\mu e^+e^-$	0.13 ± 0.02	negl.	negl.
$K^+ \to \pi^+\pi^-e^+\nu_e$	0.07 ± 0.02	0.05 ± 0.03	0.01 ± 0.01
$K^+ \to \pi^+\mu^+\mu^-$	0.01 ± 0.01	0.02 ± 0.01	negl.
$K^+ \to e^+\nu_e\mu^+\mu^-$	0.01 ± 0.01	0.01 ± 0.01	negl.
Total	1.07 ± 0.20	0.92 ± 0.34	0.23 ± 0.15

Unblinding Signal Regions



Decay	Expected background	Observed events	UL on $\mathcal{B}$ @ 90% CL
$K^+ \to \pi^- \mu^+ e^+$	1.07 ± 0.20	0	4.2×10^{-11}
$K^+ \to \pi^+ \mu^- e^+$	0.92 ± 0.34	2	6.6×10^{-11}
$\pi^0 \to \mu^- e^+$	0.23 ± 0.15	0	3.2×10^{-10}

Summary

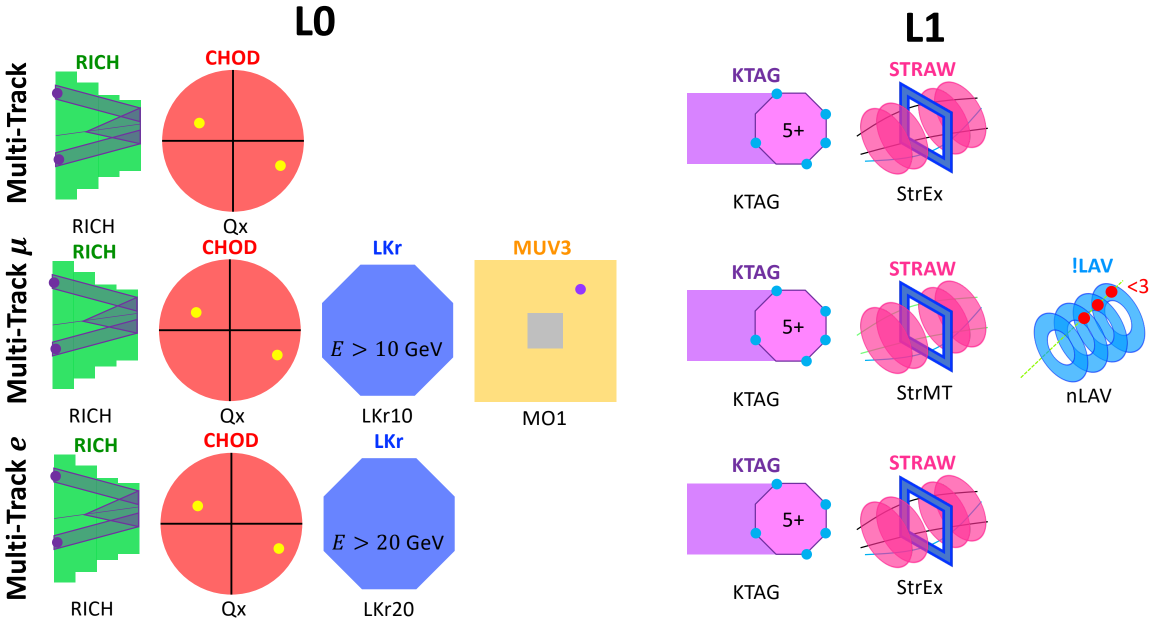
- Data collected in 2017 + 2018 were used to improve limits on $\mathcal{B}(K^+ \to \pi^\pm \mu^\mp e^+)$, and $\mathcal{B}(\pi^0 \to \mu^- e^+)$ with π^0 from $K^+ \to \pi^+ \pi^0$
- Presented results improve on previous results by one order of magnitude:

Process	Previous UL on $\mathcal{B}$ @ 90% CL BNL E865, [Phys. Rev. Lett. 85, 2877]	New UL on $\mathcal{B}$ @ 90% CL NA62, [arXiv:2105.06759]
$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11}
$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11}
$\pi^0 \to \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}

- Searches for other LNV or LFV decays at NA62 are ongoing e.g. $K^+ \to \mu^- \nu_\mu e^+ e^+$ or $K^+ \to e^- \nu_e \mu^+ \mu^+$
- NA62 resumes data taking this year at higher beam intensity, and will benefit from new and upgraded sub-detectors
- Stay tuned for more LNV or LFV searches and other results from NA62

Backup

Schematics of Trigger Conditions



PID: LKr Misidentification Probability