Searches for lepton flavor and lepton number violation in K+ decays

Elisa Minucci

on behalf of the NA62 Collaboration

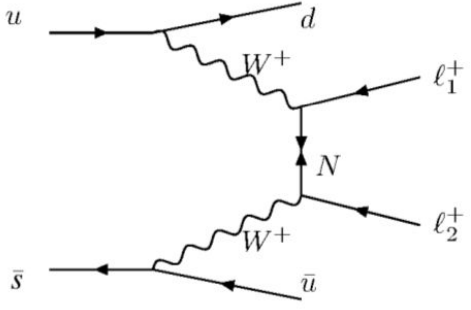
Outline:

- Introduction
- The NA62 experiment
- Search for $K^+ \to \pi^\pm \mu^\mp e^+$ decays
- Search for $K^+ \to \pi^- l^+ l^+$ decays
- Summary

Lepton Number & Lepton Flavor violation in K^+ decay

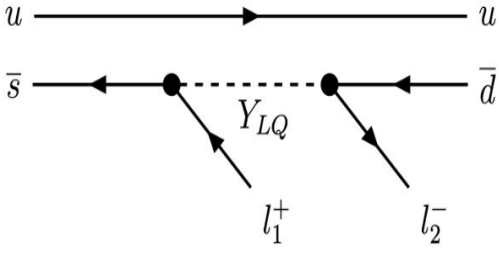
Lepton Number (**L**) and Lepton Flavor(**L_e**,**L_μ**,**L_τ**) are approximately conserved numbers within the SM: their conservation is not imposed by any local gauge symmetry → interesting to search for New Physics effects, exploring high mass scale.

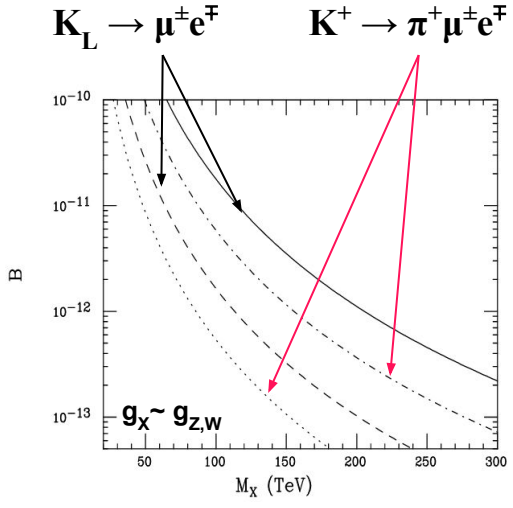
Lepton Number Violation



E.g: ***Type I see-saw mechanism***
ΔL = 2 via exchange of Majorana neutrinos

Lepton Flavor Violation





$\Delta L_i = 1$ & $\Delta L_j = 1$ i,j =[μ,e]
E.g mediated at three level by ***leptoquark*** that can couples with fermions of more than one families or by a ***new heavy Z' boson*** with family non-universal coupling

Searches in K decays are complementary to searches in B-physics and in pure leptonic processes as: μ → 3e

LNV & LFV in K^+ decay: State of the art

	Previous UL @ 90% C.L
$K^+ \to \pi^+\mu^+e^-$ (LF)	1.3×10^{-11} E865 experiment at BNL
$K^+ \to \pi^+\mu^-e^+$ (LF)	5.2×10^{-10} E865 experiment at BNL
$K^+ \to \pi^-\mu^+e^+$ (LF & LN)	5.0×10^{-10} E865 experiment at BNL

NA62 New Results

	Previous UL @ 90% C.L
$K^+ \to \pi^-\mu^+\mu^+$ (LN)	8.6×10^{-11} NA48/2 experiment at CERN
$K^+ \to \pi^-e^+e^+$ (LN)	6.4×10^{-10} E865 experiment at BNL

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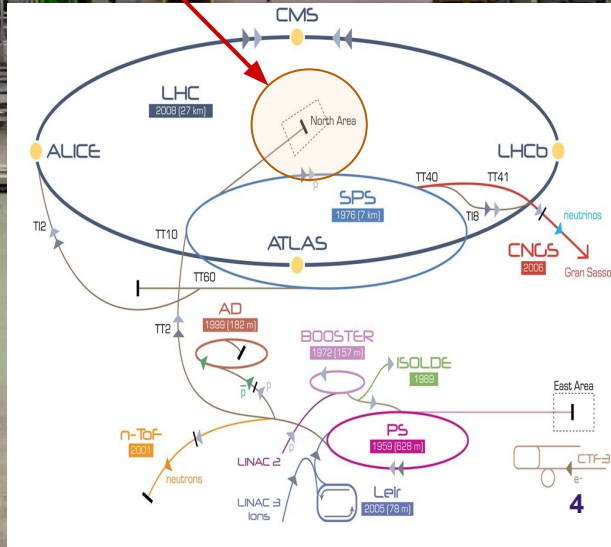
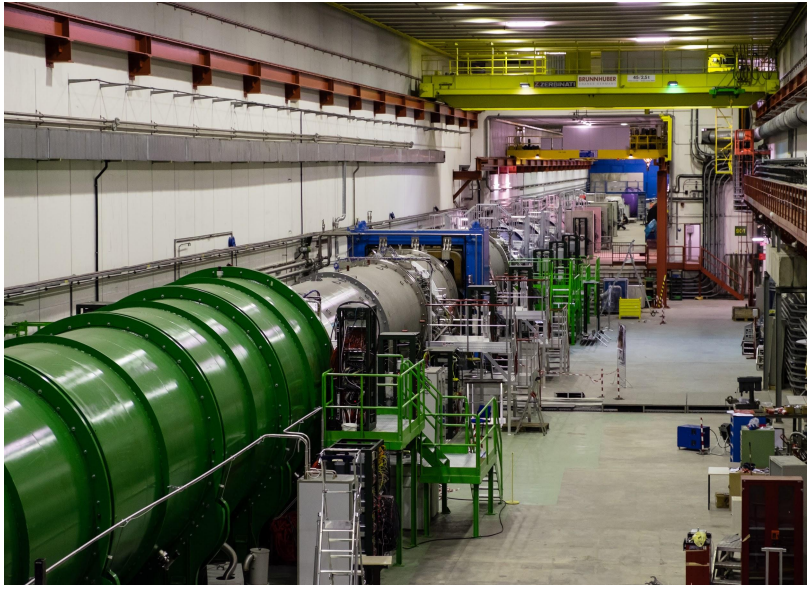
Ongoing analyses

	Previous UL @ 90% C.L
$K^+ \to e^-\nu\mu^+\mu^+$ (LN)	no limits
$K^+ \to \mu^-\nu e^+e^+$ (LN)	2.1×10^{-8} Geneva-Saclay experiment

The NA62 experiment at the CERN SPS



The NA62 experiment at the CERN SPS



- **Data taking: 2016-2018**
- **Fixed target experiment**
  (400 GeV/c proton from SPS onto a Beryllium target)
- **Unseparated secondary beam**
- **Kaon decay-in-flight technique**
  ~5 MHz K^+decay rate within the fiducial volume

Main goal:

Measure $Br(K^+ \to \pi^+ \nu\bar{\nu})$ **with O(10%) precision**

SM prediction :

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

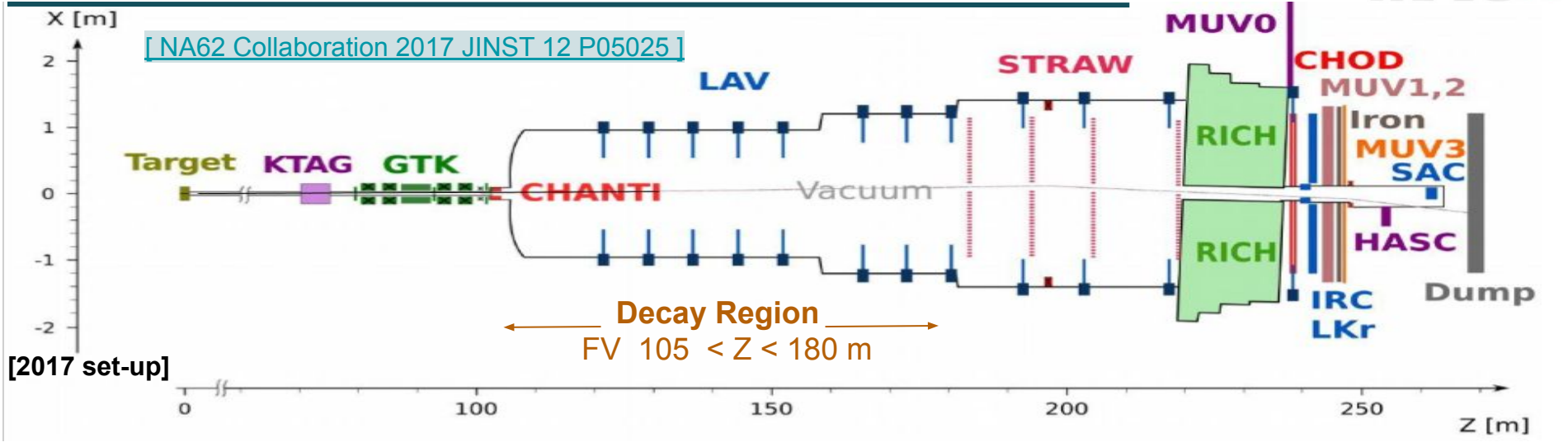
[Buras et al. JHEP 1511(2015)33]

Latest results → Talk by A. Antonelli

Broad physics program

- **Rare and forbidden decays :** LN and LF violation
- **Precision measurements of SM decays.**
  Talk by C. Parkinson
- **Exotics searches:** dark photon, heavy neutral leptons, axion-like particles → Talk by M.Corvino

The NA62 experiment & the $K^+ \to \pi^\pm l^\pm l'^\mp$



Tag K+: **KTAG** (Cherenkov detector), $\sigma_t \sim 70$ ps

Reconstruct momentum and direction of 3 charged tracks: STRAW

- Total momentum consistent with the K+ beam momentum
- Reconstruct vertex in **FV**

PID:

- **LKr:** E/P → E= energy deposited in calorimeter; P= reconstructed momentum
- **MUV3**: ID/veto muons
- **RICH:** ID positive charged particle: $\pi/\mu/e$ separation (used only in the $K^+ \to \pi^- e^+ e^+$ analysis)

Photon vetos: hermetic (0-50) mrad: **12LAVs**, 2SAVs (**IRC+SAC**), **LKr**

Track Timing: CHOD $\sigma_t \sim 200$ ps

Search for $K^+ \to \pi^\pm \mu^\mp e^+$ decays at NA62

- **Blinded analysis strategy** [2 independent analysis cross-checked]
- **2017+2018 data**
- The invariant mass of the three selected tracks built under the $\pi-\mu-e$ hypothesis **$M_{\pi\mu e}$ (σ_M~ 1.4 MeV),** is the **kinematic variable** used to **distinguish between signal and background**

Triggers:

- L0 (hardware) + L1 (software)
- Rare+Exotics triggers taken simultaneously with πνν trigger
- Data analyzed → Logic OR of three triggers

Trigger name	Downscaling	Description	Use in analysis
Multi-Track	D_{MT} = 100	Minimum bias 3-track trigger	**Collect $K^+ \to \pi^+\pi^+\pi^-$ + Signal events**
Multi-Track μ	$D_{\mu\text{-}MT}$ = 8	3 track + > 10 GeV in LKr + ≥ 1μ (MUV3)	**Collect Signal events**
Multi Track e	$D_{e\text{-}MT}$ = 8	3 track + > 20 GeV in LKr	**Collect Signal events**

Single Event Sensitivity

The $K^+ \to \pi^+ \mu^- e^+$ and $K^+ \to \pi^- \mu^+ e^+$ signals are normalized to the $K^+ \to \pi^+ \pi^+ \pi^-$ channel: Br = (5.583 ± 0.024)%
→ cancellation of systematic effects: trigger efficiency, intrinsic detector inefficiencies

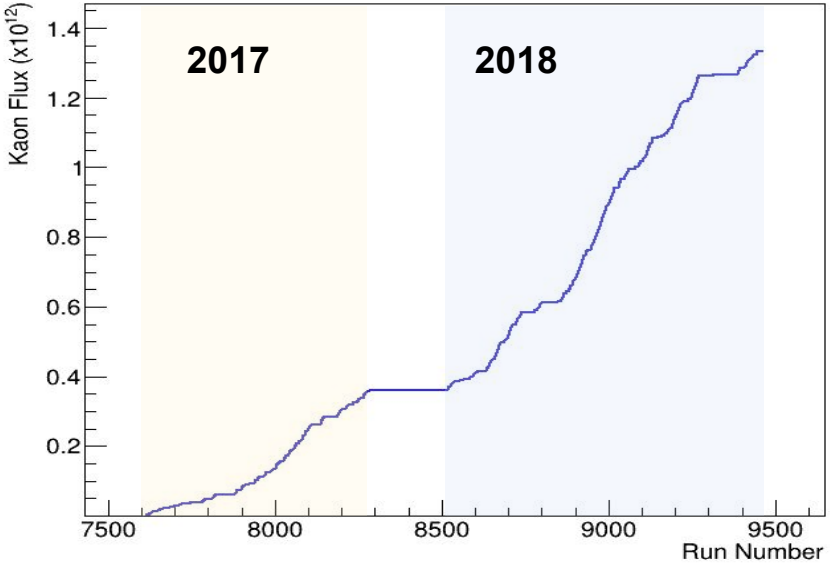
$$N_K = \frac{N_{K3\pi}}{Br_{K3\pi} \cdot A_n \cdot \epsilon_n} \frac{D_{MT}}{D_{eff}}$$

$$N_K = (1.32 \pm 0.01) \times 10^{12}$$

N_K = number of kaon decays in the FV.
Account for the downscaling factor of the three triggers (D_{eff})

$$S.E.S = \frac{1}{N_K \cdot A_s \cdot \epsilon_{trig}}$$

Account for signal trigger efficiency



$$A_s(K^+ \to \pi^- \mu^+ e^+) = (4.90 \pm 0.02)\% \implies S.E.S = (1.82 \pm 0.08) \times 10^{-11}$$
$$A_s(K^+ \to \pi^+ \mu^- e^+) = (6.21 \pm 0.02)\% \implies S.E.S = (1.44 \pm 0.05) \times 10^{-11}$$

Background mechanism

1. Mis-identification (mis-ID)

Measure the mis-ID probability from data
$\pi^{\pm}$: E/P < 0.9
$e^{\pm}$: 0.95 < E/P < 1.05

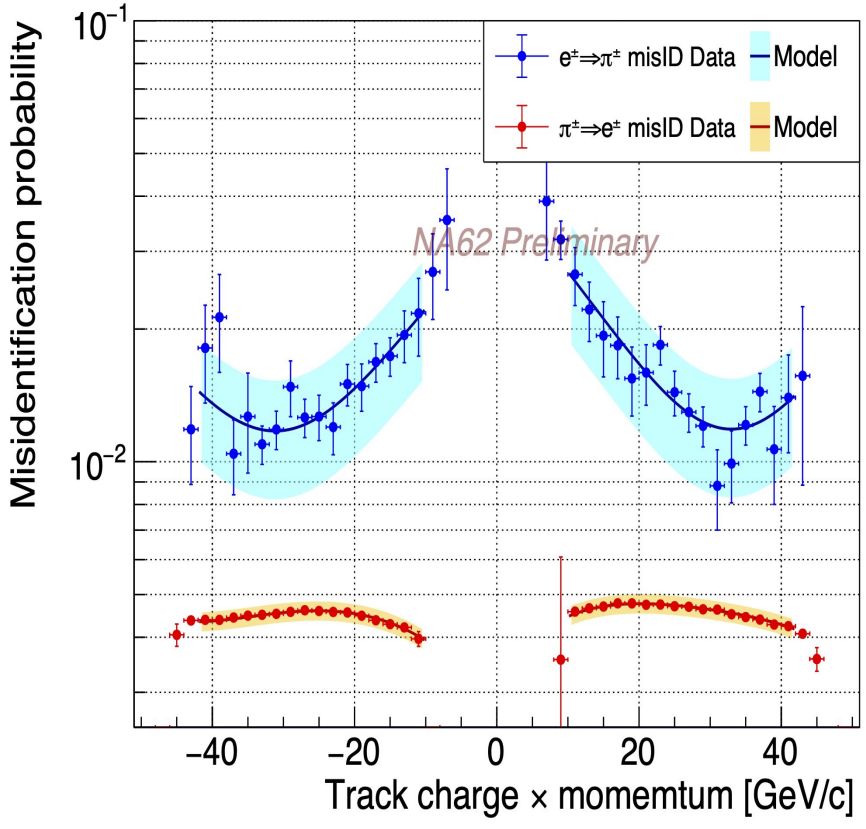
- $\pi^{\pm} \Rightarrow e^{\pm}$ from pure sample of $K^{+} \to \pi^{+}\pi^{+}\pi^{-}$
- $e^{\pm} \Rightarrow \pi^{\pm}$ from pure sample of $K^{+} \to \pi^{+}\pi^{0}$, $\pi^{0} \to e^{+}e^{-}\gamma$

Model applied to simulation→ boosts statistical power

Also $\pi^{\pm} \Rightarrow \mu^{\pm}$ and $\mu^{\pm} \Rightarrow e^{\pm}$ have been consider
(MUV3 accidentals)

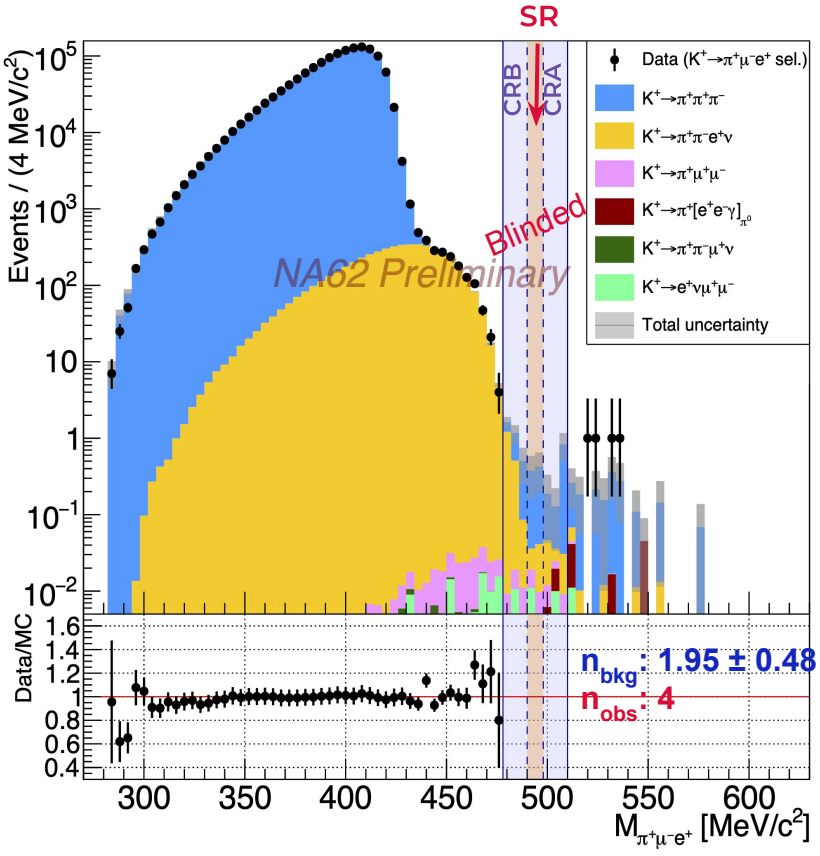
2. Decay-in-flight

$\pi^{\pm} \to \mu^{\pm}\nu_{\mu}$ or $\mu^{\pm} \to e^{\pm}\nu_{e}$
Dalitz decay : $\pi^{0} \to e^{+}e^{-}\gamma$



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

$$A_s(K^+ \to \pi^+ \mu^- e^+) = (6.21 \pm 0.02)\% \implies S.E.S = (1.44 \pm 0.05) \times 10^{-11}$$



Main sources of background in control and signal regions:

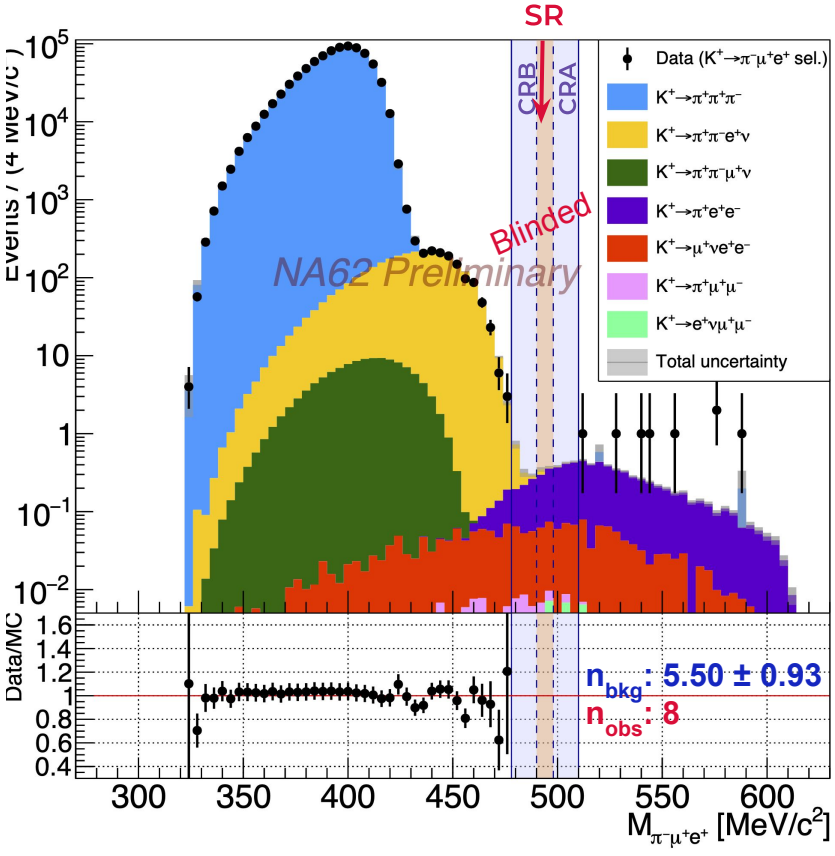
- ❑ **K3π upstream decay in flight + $\pi^+ \Rightarrow e^+$**
- ❑ **Ke4 with $\pi^\pm \to \mu^\pm \nu_\mu$ or $\pi^\pm \Rightarrow \mu^\pm$**

	N_{CRB}	N_{CRA}
Total bkg expected	**3.41 ± 0.54**	**1.27 ± 0.40**
Observed events	**2**	**0**
p-value	**0.99**	

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

$$A_s(K^+ \to \pi^- \mu^+ e^+) = (4.90 \pm 0.02)\% \implies S.E.S = (1.82 \pm 0.08) \times 10^{-11}$$

[dedicated cut to reject K^+ decays with $\pi^0 \to e^+e^-\gamma$ DIF]

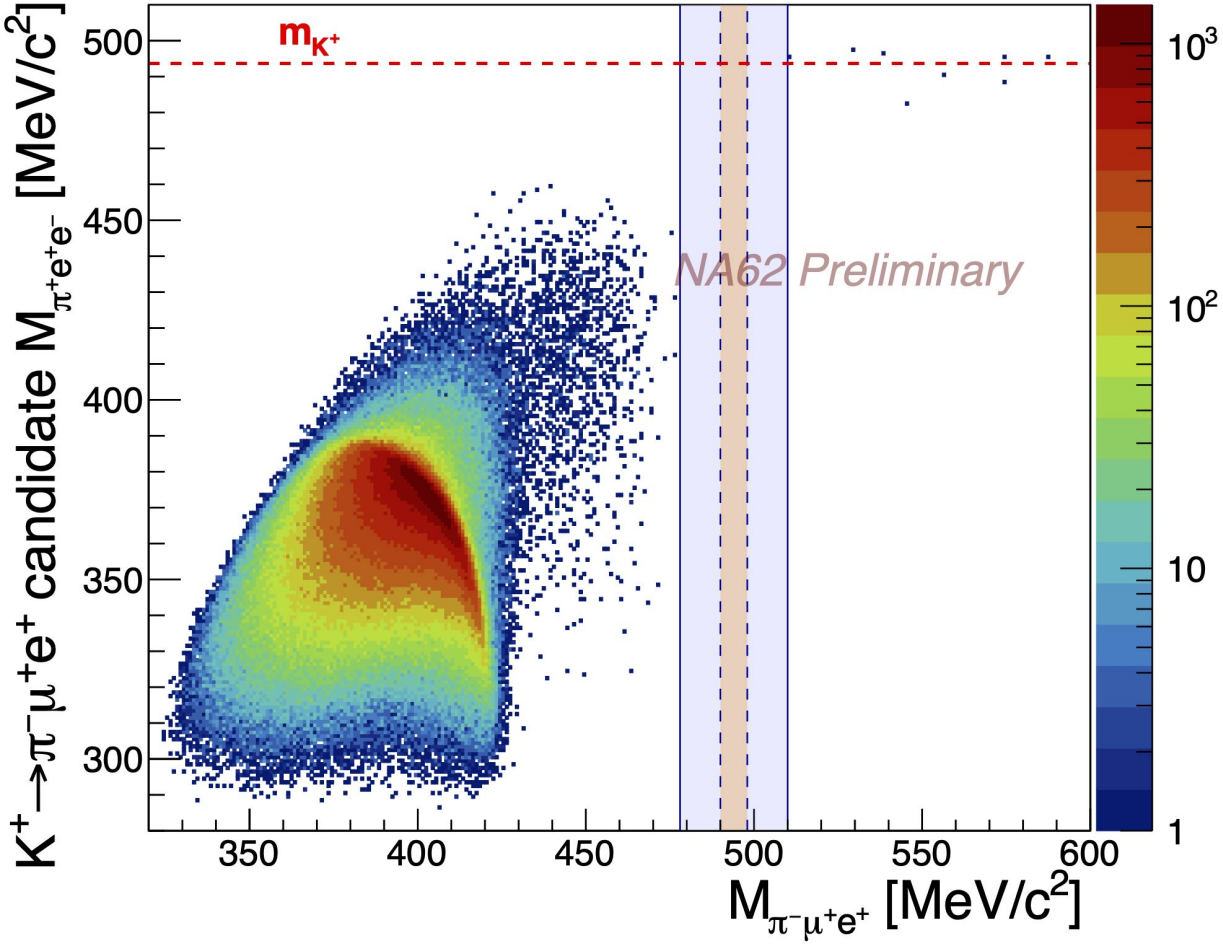


Main sources of background in control and signal regions:

- $K^+ \to \pi^+ e^+ e^-$ with $\pi^+ \to \mu^+\nu_\mu$ and $e^- \Rightarrow \pi^-$
- $K3\pi$ upstream decay in flight + $\pi^+ \Rightarrow e^+$
- $K^+ \to \mu^+\nu e^+ e^-$ with $e^- \Rightarrow \pi^-$

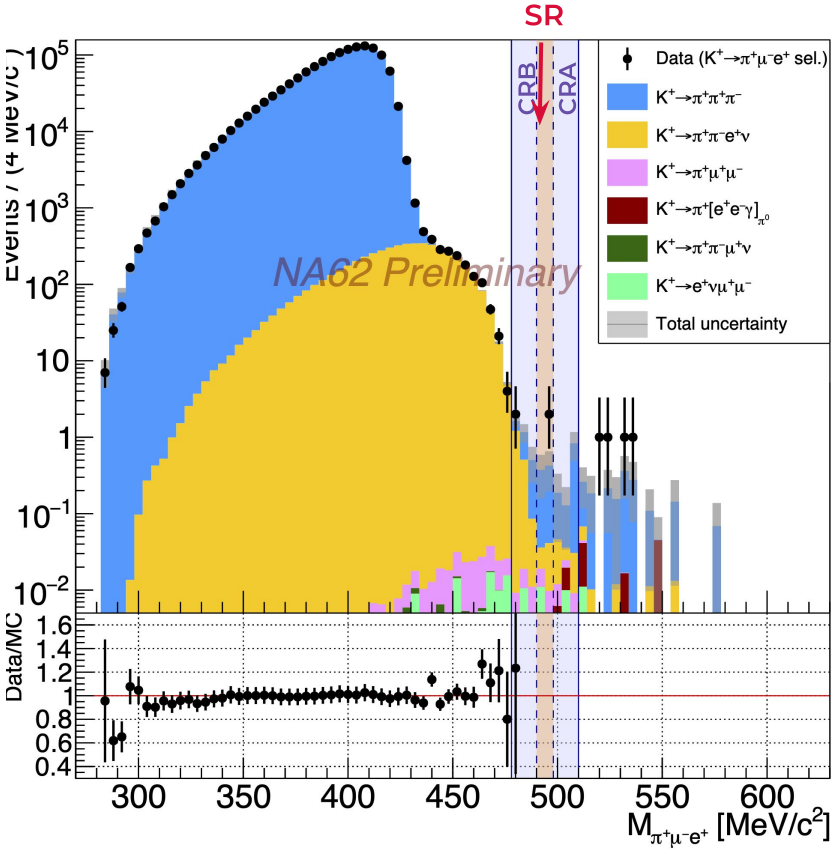
	N_{CRB}	N_{CRA}
Total bkg expected	**1.68 ± 0.20**	**1.66 ± 0.26**
Observed events	**2**	**4**
p-value	**0.18**	

$K^+ \to \pi^- \mu^+ e^+$ Analysis: $K^+ \to \pi^+ e^+ e^-$ background



$K^+ \to \pi^+ \mu^- e^+$ Analysis: Signal Region opened

$$A_s(K^+ \to \pi^+ \mu^- e^+) = (6.21 \pm 0.02)\% \implies S.E.S = (1.44 \pm 0.05) \times 10^{-11}$$



Main sources of background in control and signal regions:

- ❑ **K3π upstream decay in flight + $\pi^+ \Rightarrow e^+$**
- ❑ **Ke4 with $\pi^\pm \to \mu^\pm \nu_\mu$ or $\pi^\pm \Rightarrow \mu^\pm$**

In signal region

$$n_{bkg} = 0.92 \pm 0.34, \quad n_{obs} = 2$$

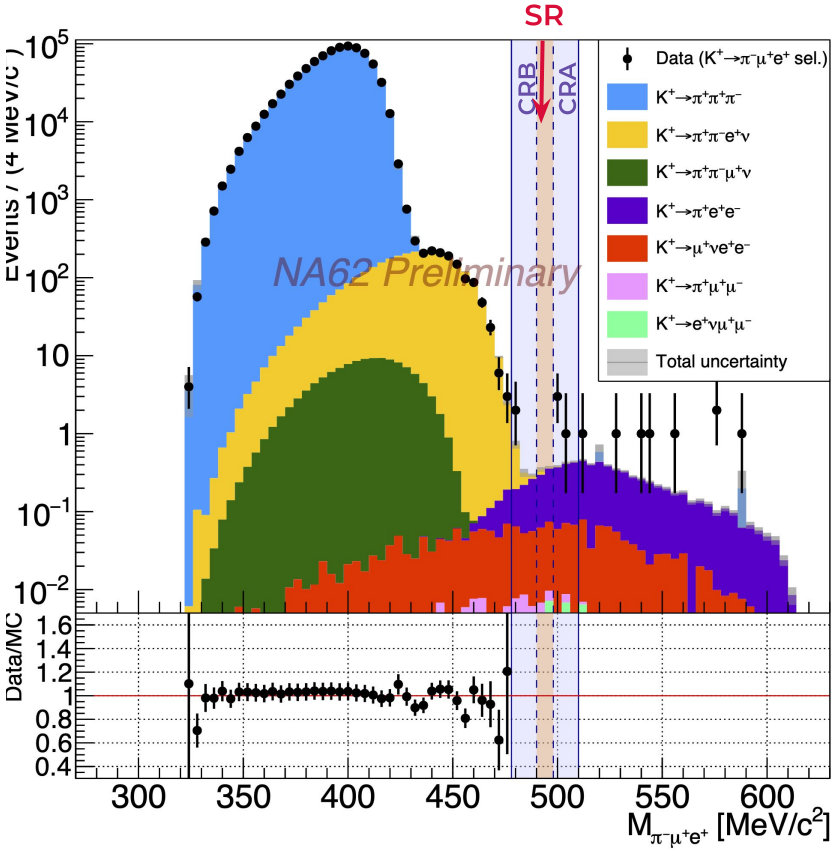
$$Br(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11} \ @ \ 90\% \ C.L$$

[Counting experiment, CLs treatment]

$K^+ \to \pi^- \mu^+ e^+$ Analysis: Signal Region opened

$$A_s(K^+ \to \pi^- \mu^+ e^+) = (4.90 \pm 0.02)\% \implies S.E.S = (1.82 \pm 0.08) \times 10^{-11}$$

[dedicated cut to reject K^+ decays with $\pi^0 \to e^+e^-\gamma$ DIF]



Main sources of background in control and signal regions:

- $K^+ \to \pi^+ e^+ e^-$ with $\pi^+ \to \mu^+\nu_\mu$ and $e^- \Rightarrow \pi^-$
- $K3\pi$ upstream decay in flight + $\pi^+ \Rightarrow e^+$
- $K^+ \to \mu^+\nu e^+ e^-$ with $e^- \Rightarrow \pi^-$

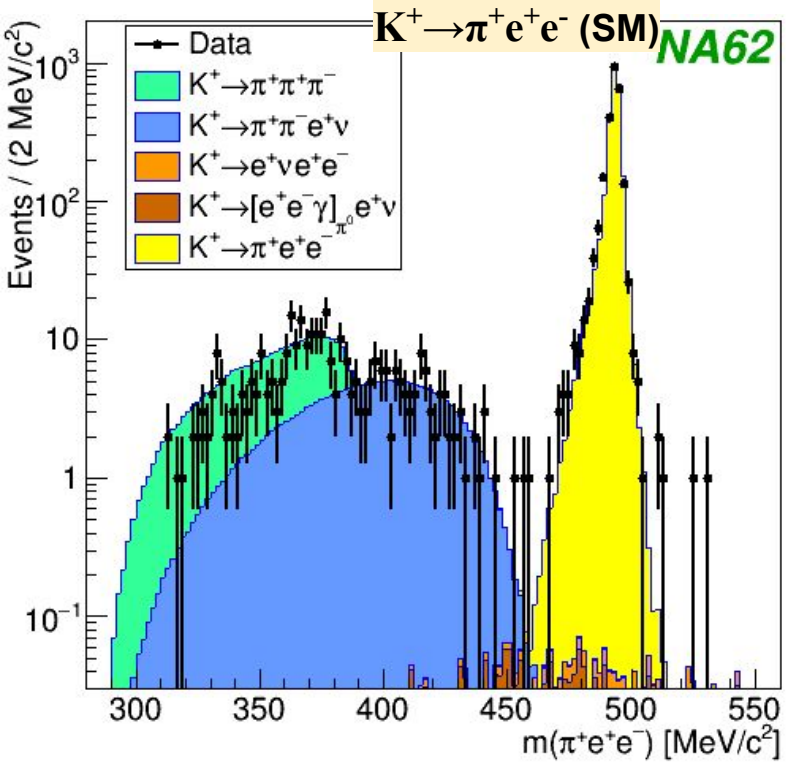
In signal region

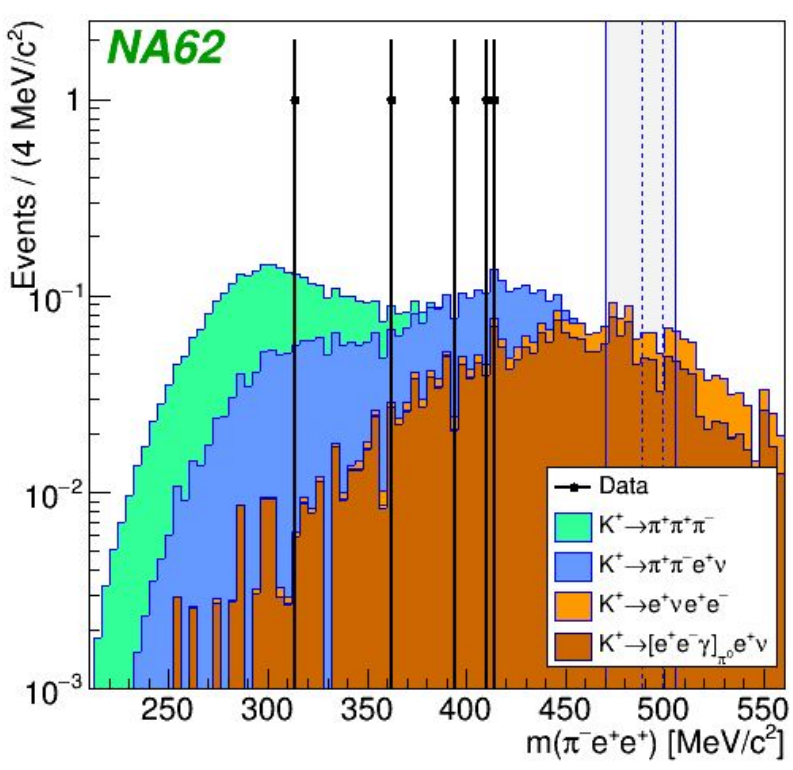
$$n_{bkg} = 1.06 \pm 0.20, \quad n_{obs} = 0$$

$$Br(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11} \ @ \ 90\% \ C.L$$

[Counting experiment, CLs treatment]

$K^+ \to \pi^- e^+ e^+$ Analysis (2017 data)





Normalization: $K^+ \to \pi^+ e^+ e^-$ **(SM)**

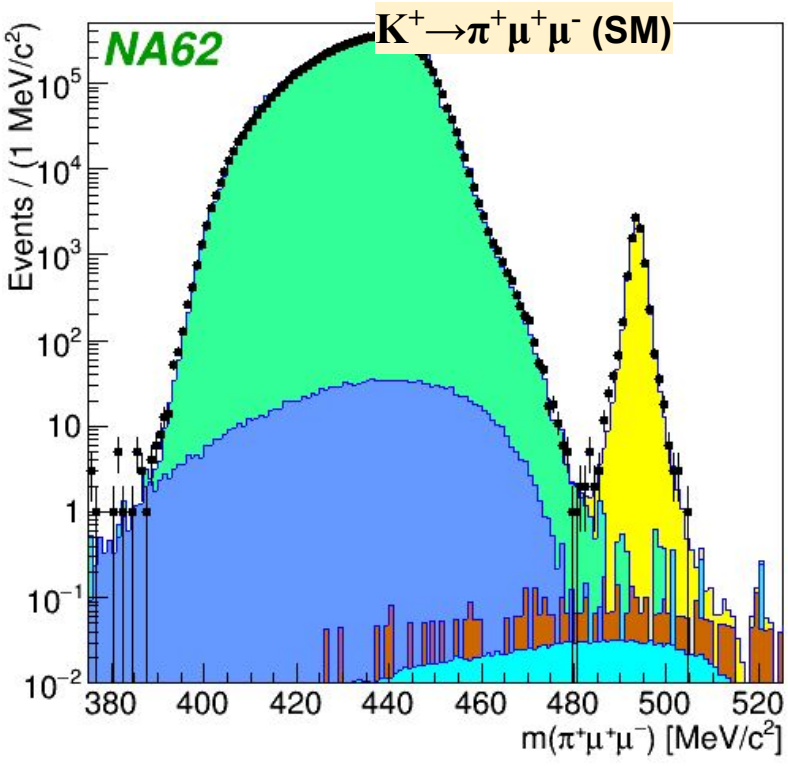
$N_K = (2.14 \pm 0.04_{stat} \pm 0.06_{ext}) \times 10^{11}$

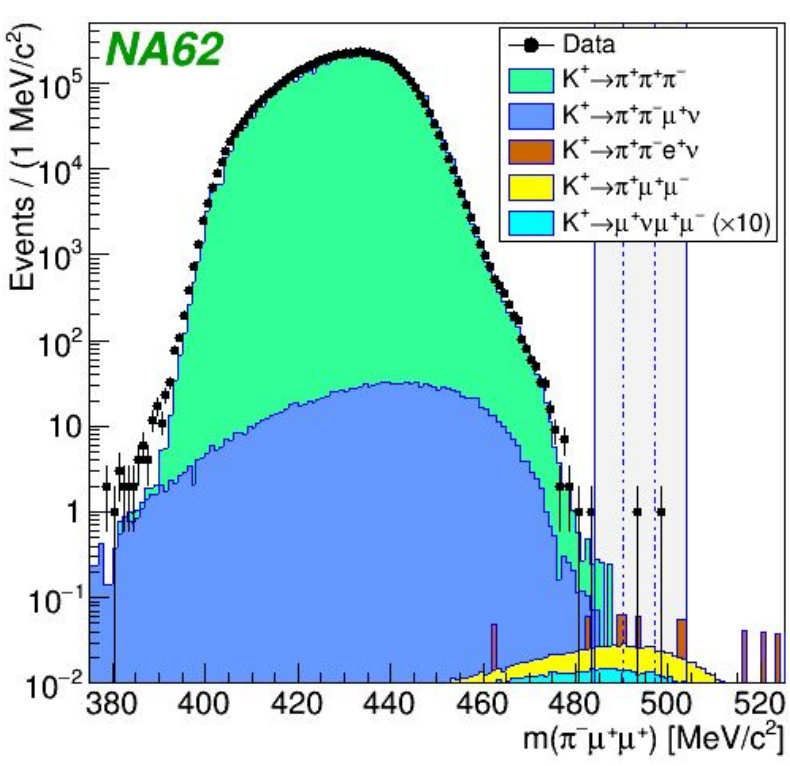
Additional RICH condition for π^+/e^+ separation

$$n_{bkg} = 0.16 \pm 0.03, \quad n_{obs} = 0$$

$$Br(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10} \ @ \ 90\% \ C.L$$

$K^+ \to \pi^- \mu^+ \mu^+$ Analysis (2017 data)





Normalization: $K^+ \to \pi^+ \mu^+ \mu^-$ (SM)

$N_K = (7.94 \pm 0.09_{stat} \pm 0.21_{ext}) \times 10^{11}$

$n_{bkg} = 0.91 \pm 0.41, \quad n_{obs} = 1$

$$Br(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11} \ @ \ 90\% \ C.L$$

Summary: LN & LF violating searches at NA62

	Previous UL @ 90% C.L	NA62 UL @ 90% C.L	
$K^+ \to \pi^-\mu^+\mu^+$	8.6×10^{-11}	4.2×10^{-11}	2017 data → improved by factor 2
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	2.2×10^{-10}	2017 data → improved by factor 3
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	4.2×10^{-11}	2017+2018 data → improved by factor 12
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	6.6×10^{-11}	2017+2018 data → improved by factor 8
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	-	sensitivity similar to the previous search
$K^+ \to \mu^-\nu e^+e^+$	2.1×10^{-8}	-	Ongoing analysis: 2017 data $S.E.S \sim 1 \times 10^{-10}$
$K^+ \to e^-\nu\mu^+\mu^+$	no limit	-	Ongoing analysis: 2017 data $S.E.S \sim 5 \times 10^{-11}$

- Large improvements on most of the LN & LF violating K^+ decays → sensitivity up to 10^{-11}
- NA62 will resume data taking after LS2

Thanks

Backup slides

$K^+ \to \pi^\pm \mu^\mp e^+$ Analysis: K3π Upstream background