Searches for lepton flavour and lepton number violation in K^+ and π^0 decays

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on behalf of the NA62 Collaboration

Outline:

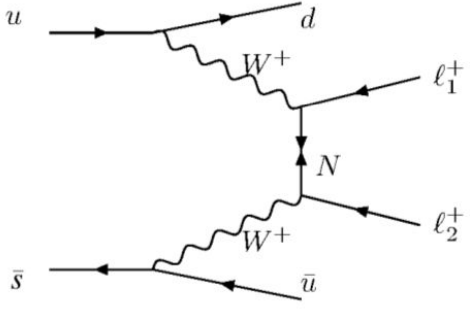
- Introduction
- The NA62 experiment
- Search for $K^+ \to \pi^\pm \mu^\mp e^+$ and $\pi^0 \to \mu^- e^+$ decays
- Summary

EPS-HEP Conference 2021 July 26-30 Hamburg, Germany (Online)

Lepton Number & Lepton Flavour violation in K^+ decay

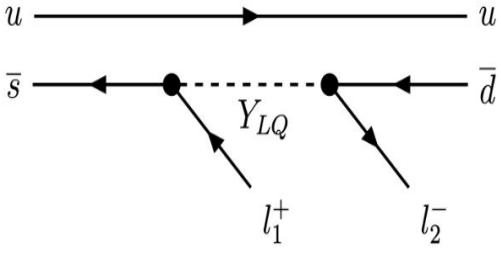
Lepton Number (**L**) and Lepton Flavour(**L_e**,**L_μ**,**L_τ**) are approximately conserved numbers within the SM: their conservation is not imposed by any local gauge symmetry → interesting to search for New Physics effects, exploring high mass scale $\mathcal{O}$(100 TeV).

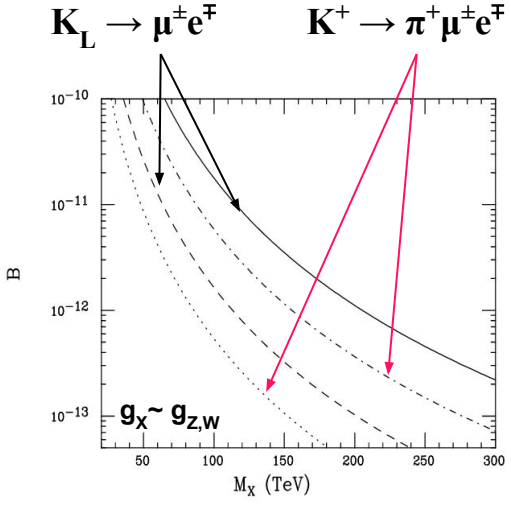
Lepton Number Violation



E.g: ***Type I see-saw mechanism***
ΔL = 2 via exchange of Majorana neutrinos
Indirect upper limit of few × 10^{-11} for $K^+ \to \pi^- \mu^+ e^+$

Lepton Flavour 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^+ and π^0 decay: State of the art

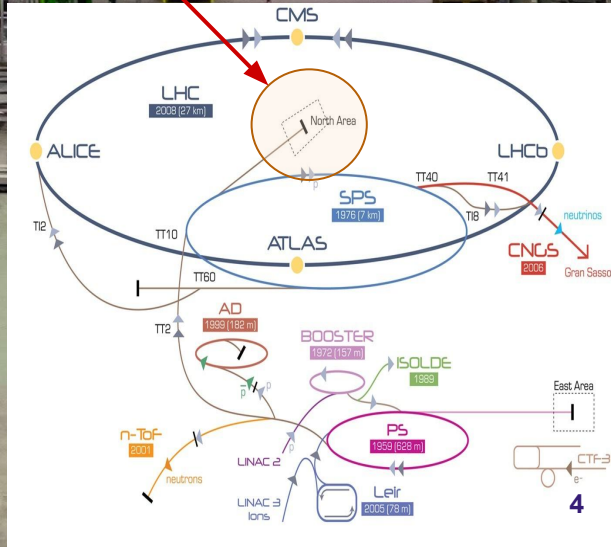
	UL @ 90% C.L
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11} E865 experiment at BNL
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10} E865 experiment at BNL
$\pi^0 \to \mu^-e^+$	3.4×10^{-9} E865 experiment at BNL
$\pi^0 \to \mu^+e^-$	3.8×10^{-10} E865 experiment at BNL

Lepton Flavour Violation

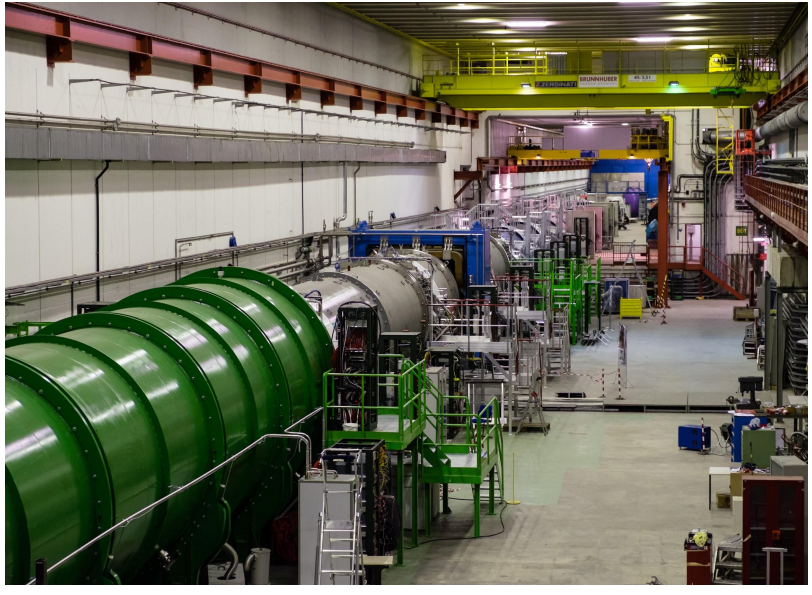
	UL @ 90% C.L
$K^+ \to \pi^-\mu^+\mu^+$	4.2×10^{-11} NA62 experiment at CERN
$K^+ \to \pi^-e^+e^+$	2.2×10^{-10} NA62 experiment at CERN
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10} E865 experiment at BNL
$K^+ \to e^-\nu\mu^+\mu^+$	no limits
$K^+ \to \mu^-\nu e^+e^+$	2.1×10^{-8} Geneva-Saclay experiment

Lepton Number Violation

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 :

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

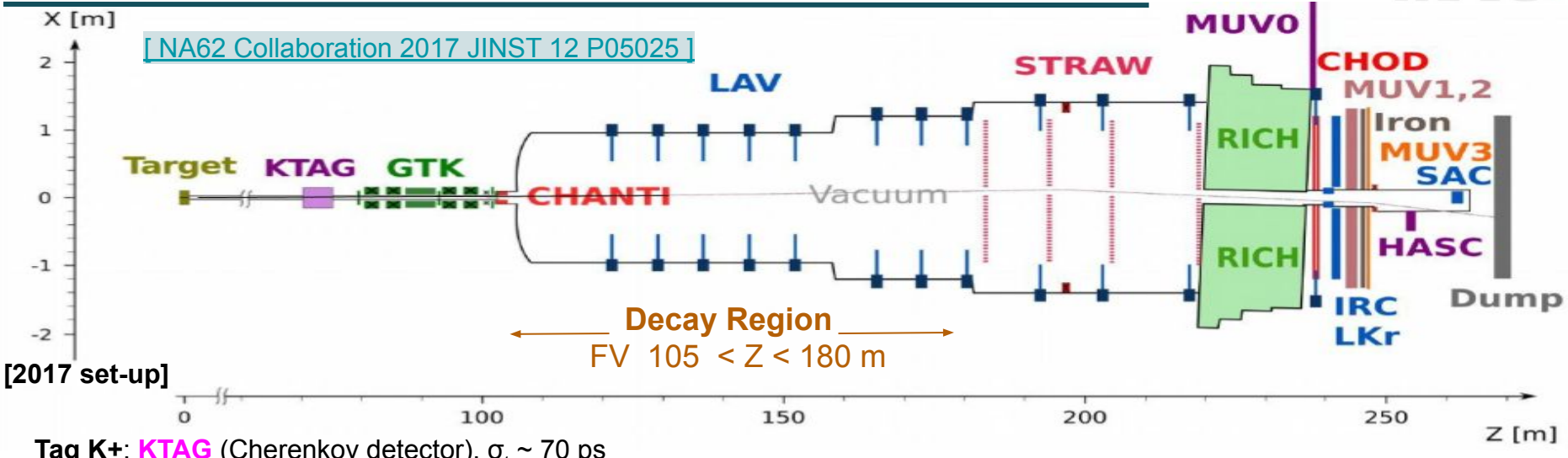
[Buras et al. JHEP 1511(2015)33]

Latest results → Talk by A.Romano

Broad physics program

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

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



[2017 set-up]

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

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

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

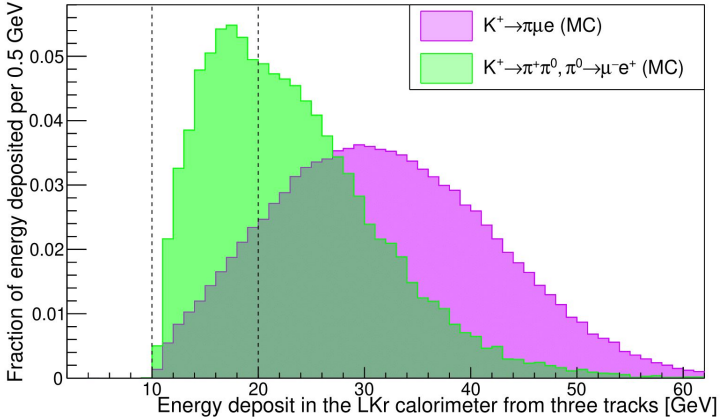
Trigger: L0 (hardware max 1MHz) + L1 (software max 10 kHz).
Rare+Exotics triggers taken simultaneously with $K^+ \to \pi^+ \nu\nu$ trigger

Search for $K^+ \to \pi^\pm \mu^\mp e^+$ and $\pi^0 \to \mu^- e^+$ decays at NA62

- **Blinded analysis strategy**
- **2017+2018 data:** Data analyzed = Logic OR of three trigger chains
- The invariant mass of the three selected tracks built under the $\pi-\mu-e$ hypothesis $\mathbf{M_{\pi\mu e}}$ **(σ_M~ 1.4 MeV),** is the **kinematic variable** used to **distinguish between signal and background**
- $K^+ \to \pi^+\pi^0$, $\pi^0 \to \mu^- e^+$ additional constraint on the mass of the two leptons: $\mathbf{M_{\mu e}}$ compatible with π^0 mass

Trigger chain	Description
Multi-Track D_{MT} = 100 ($K^+ \to \pi^+\pi^+\pi^-$ + **Signal**)	Min.bias 3-track trigger
Multi-Track μ $D_{\mu\text{-}MT}$ = 8 (**Signal**)	3 tracks + E_{LKr} > 10 GeV + ≥ 1μ (MUV3)
Multi Track e $D_{e\text{-}MT}$ = 8 (**Signal**)	3 tracks + E_{LKr} > 20 GeV

	$K^+ \to \pi^-\mu^+e^+$	$K^+ \to \pi^+\mu^-e^+$	$\pi^0 \to \mu^-e^+$
$\varepsilon_{LKr10} \times 10^2$	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
$\varepsilon_{MT} \times 10^2$	93.5 ± 0.5		

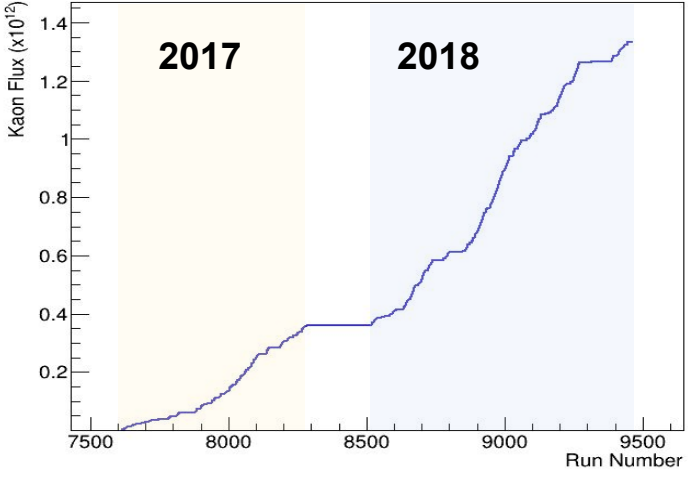


Single Event Sensitivity

Signals are normalized to the $K^+ \to \pi^+\pi^+\pi^-$ channel: $\mathcal{B}(K3\pi) = (5.583 \pm 0.024)\%$
→ 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 → kaon decays in the FV.
Account for the downscaling factor of the three triggers (D_{eff})



$$N_K = (1.33 \pm 0.02) \times 10^{12}$$

$$\mathcal{B}_{S.E.S} = \frac{1}{N_K \cdot A_s \cdot \varepsilon_{trig}}$$

Account for signal trigger efficiency
For $\pi^0 \to \mu^- e^+$ $\mathcal{B}_{S.E.S}$ divided by $\mathcal{B}(K^+ \to \pi^+\pi^0) = (20.67 \pm 0.08)\%$

$$A_s(K^+ \to \pi^-\mu^+e^+) = (4.90 \pm 0.02)\% \implies \mathcal{B}_{S.E.S} = (1.82 \pm 0.08) \times 10^{-11}$$
$$A_s(K^+ \to \pi^+\mu^-e^+) = (6.21 \pm 0.02)\% \implies \mathcal{B}_{S.E.S} = (1.44 \pm 0.04) \times 10^{-11}$$
$$A_s(K^+ \to \pi^+\pi^0, \pi^0 \to \mu^+e^+) = (3.11 \pm 0.02)\% \implies \mathcal{B}_{S.E.S} = (1.38 \pm 0.09) \times 10^{-10}$$

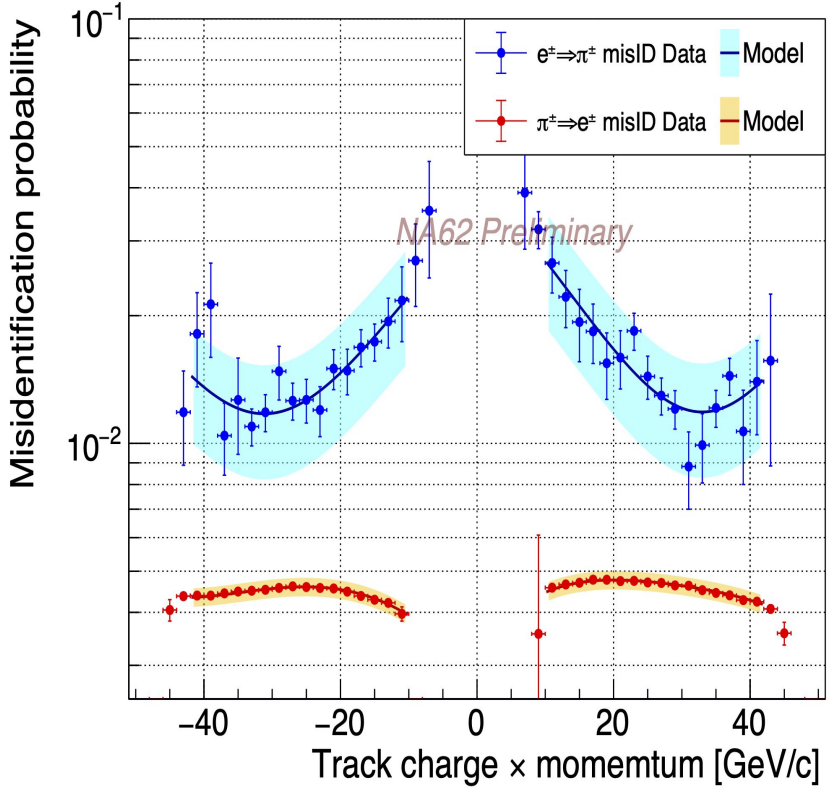
Background mechanism

1. Mis-identification (mis-ID)

Mis-ID probability measured from data

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

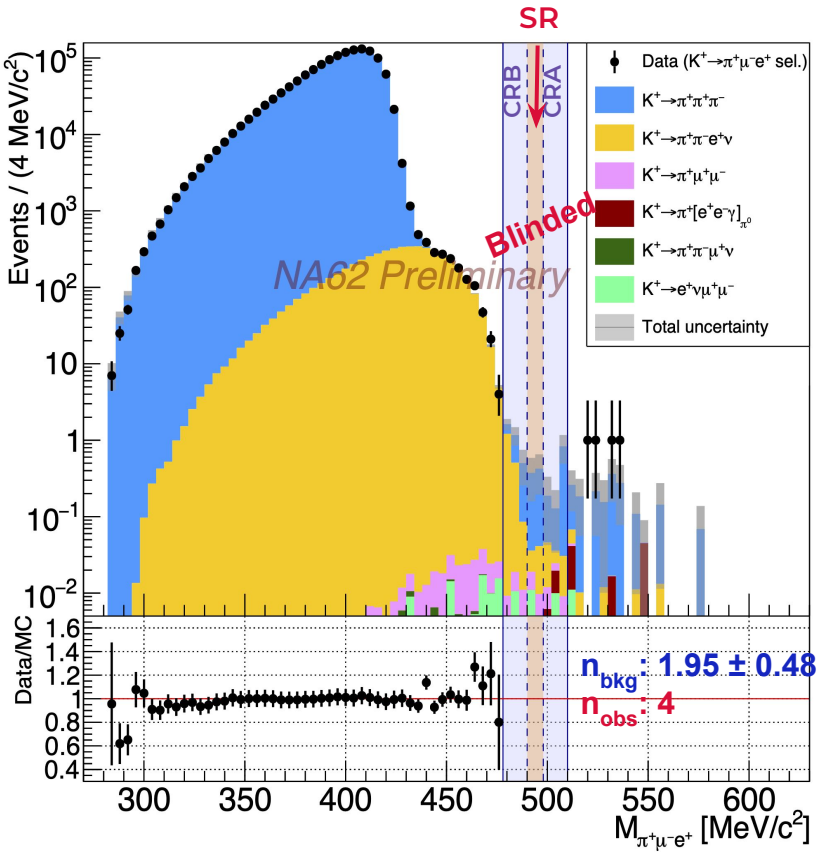


2. Decay-in-flight

$\pi^{\pm} \to \mu^{\pm}\nu_{\mu}$ 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 background contributions:

$K^+ \to \pi^+ \pi^+ \pi^-$ (decay upstream FV)

mis-ID → e^+ ; DIF → $\mu^-\nu_\mu$

$K^+ \to \pi^+ \pi^- e^+\nu_e$: DIF → $\mu^+\nu_\mu$

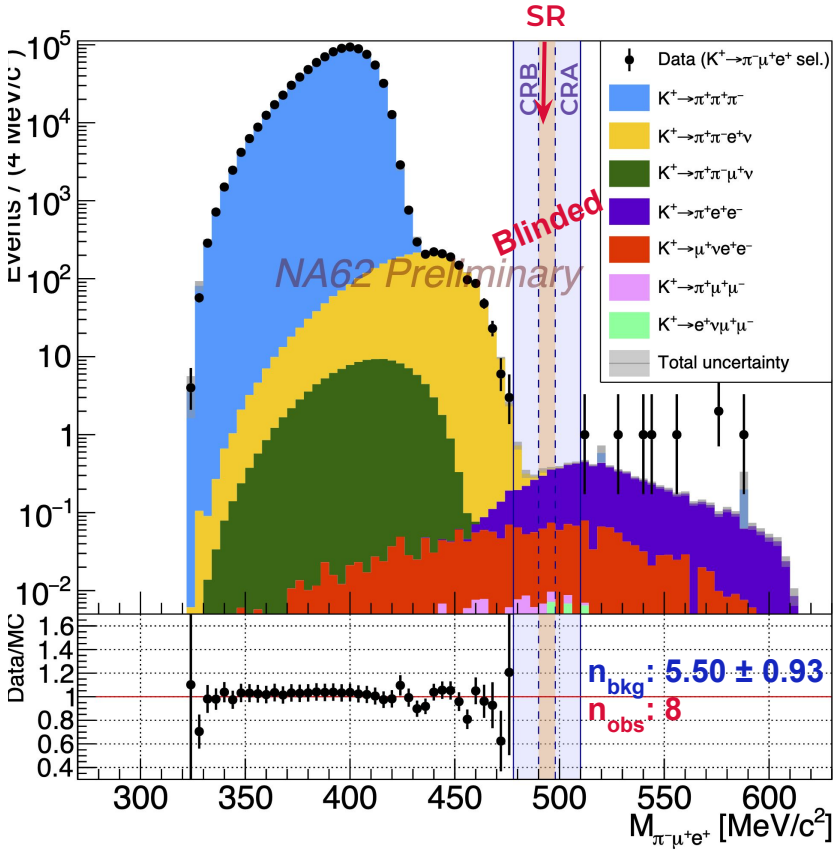
$K^+ \to \pi^+ \pi^- e^+\nu_e$: mis-ID → μ^+

	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 background contributions:

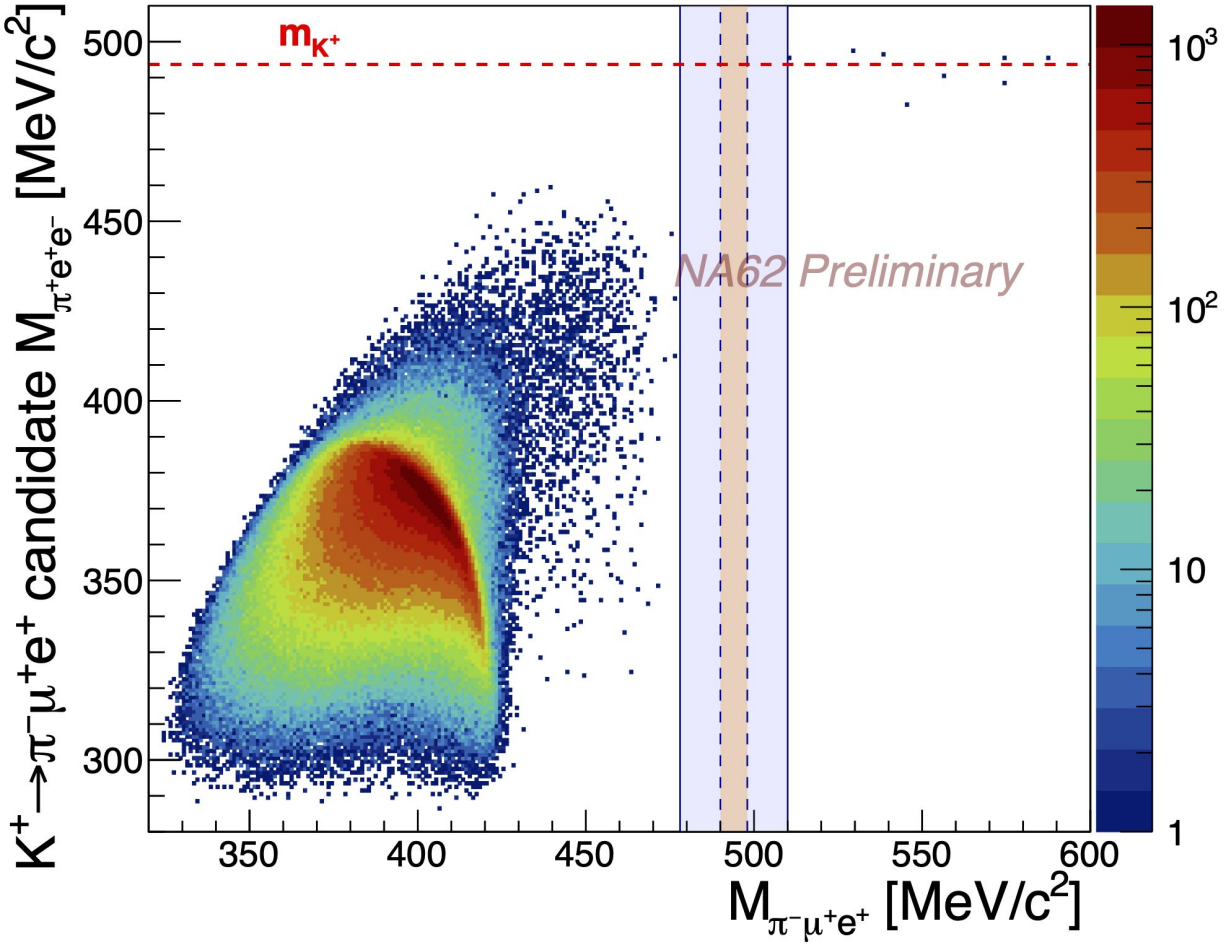
$K^+ \to \pi^+ e^+ e^-$ (DIF: $\mu^+\nu_\mu$; mis-ID: π^-)

$K^+ \to \mu^+\nu e^+ e^-$ (mis-ID: π^-)

$K^+ \to \pi^+ \pi^+ \pi^-$ (decay upstream FV) (mis-ID: e^+; DIF: $\mu^+\nu_\mu$)

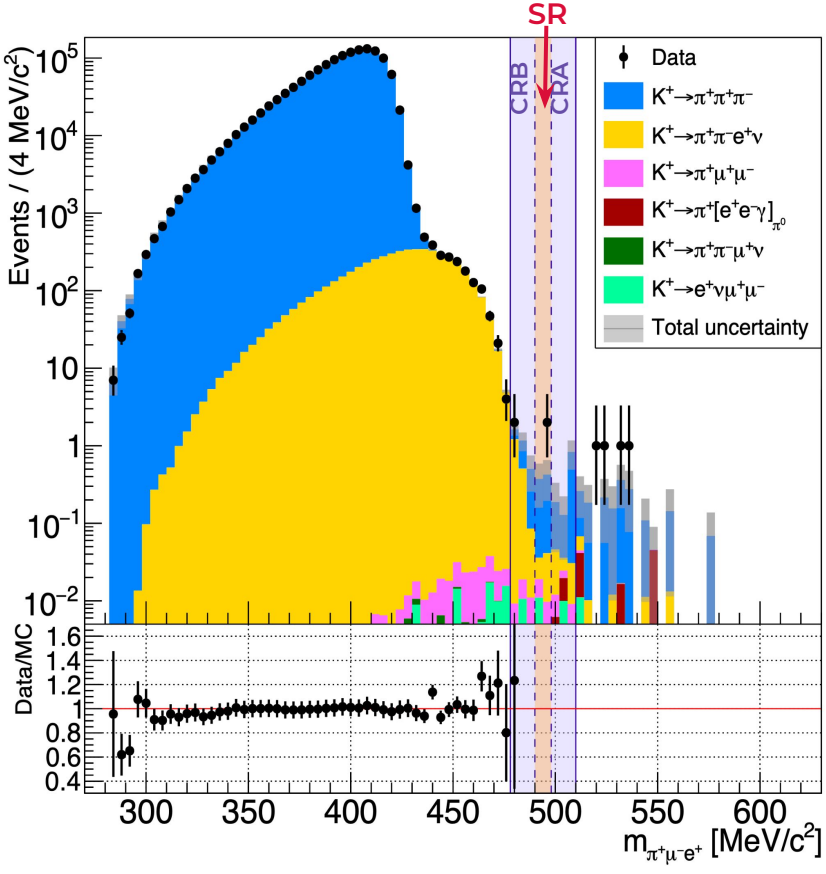
	N_{CRB}	N_{CRA}
Total bkg expected	1.68 ± 0.20	1.66 ± 0.26
Observed events	2	4
p-value	0.18	

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



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

(arXiv:2105.06759)



In signal region

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

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

For $K^+ \to \pi^+ \pi^0$, $\pi^0 \to \mu^- e^+$

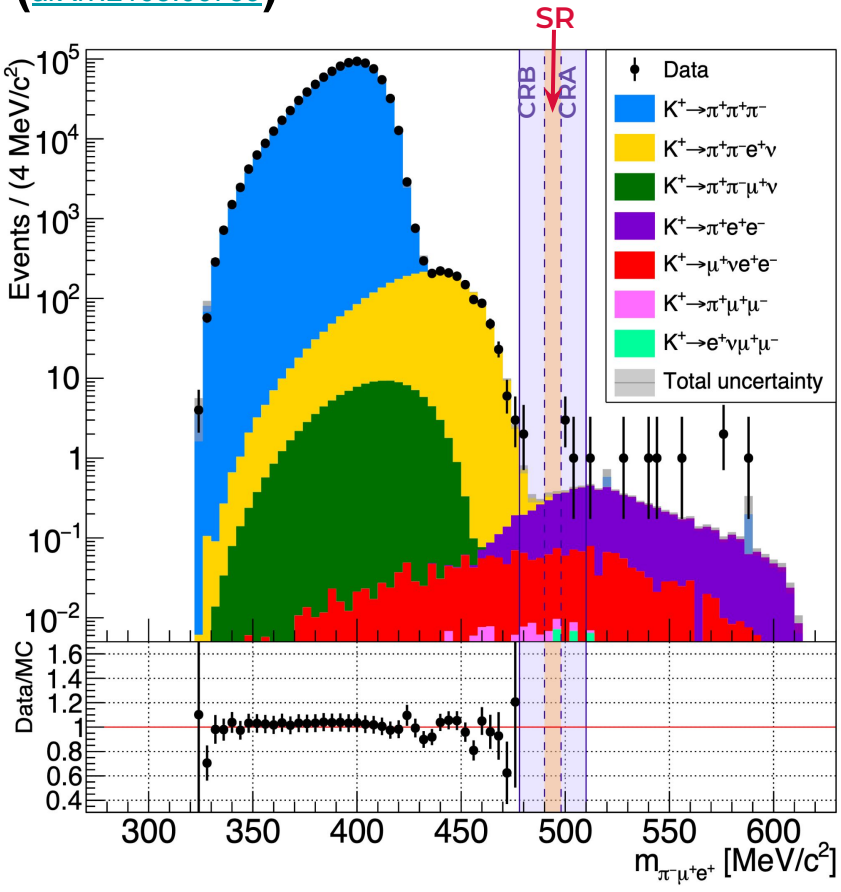
$n_{bkg} = 0.23 \pm 0.15, \quad n_{obs} = 0$

$$Br(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10} \ @ \ 90\% \ C.L$$

[Counting experiment, CLs treatment]

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

(arXiv:2105.06759)



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]

Summary: LN & LF violating searches at NA62

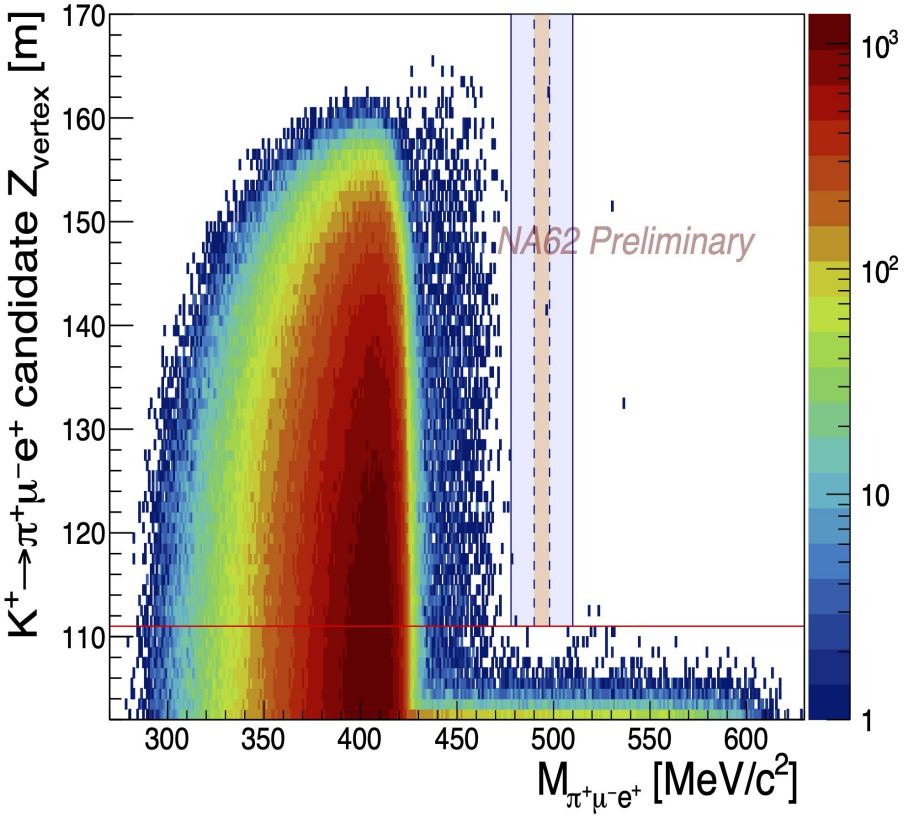
	Previous UL @ 90% C.L	NA62 UL @ 90% C.L		
$K^+ \to \pi^-\mu^+\mu^+$	8.6×10^{-11}	4.2×10^{-11}	2017 data → improved by factor 2	Phys. Lett. B 797 (2019) 134794
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	2.2×10^{-10}	2017 data → improved by factor 3	Phys. Lett. B 797 (2019) 134794
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	4.2×10^{-11}	2017+2018 data → improved by factor 12	arXiv:2105.06759 (submitted to PRL)
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	6.6×10^{-11}	2017+2018 data → improved by factor 8	arXiv:2105.06759 (submitted to PRL)
$\pi^0 \to \mu^-e^+$	3.4×10^{-9}	3.2×10^{-10}	2017+2018 data → improved by factor 13	arXiv:2105.06759 (submitted to PRL)
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	-	sensitivity similar to the previous search	
$\pi^0 \to \mu^+e^-$	3.8×10^{-10}	-	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 $S.E.S \sim 5 \times 10^{-11}$	

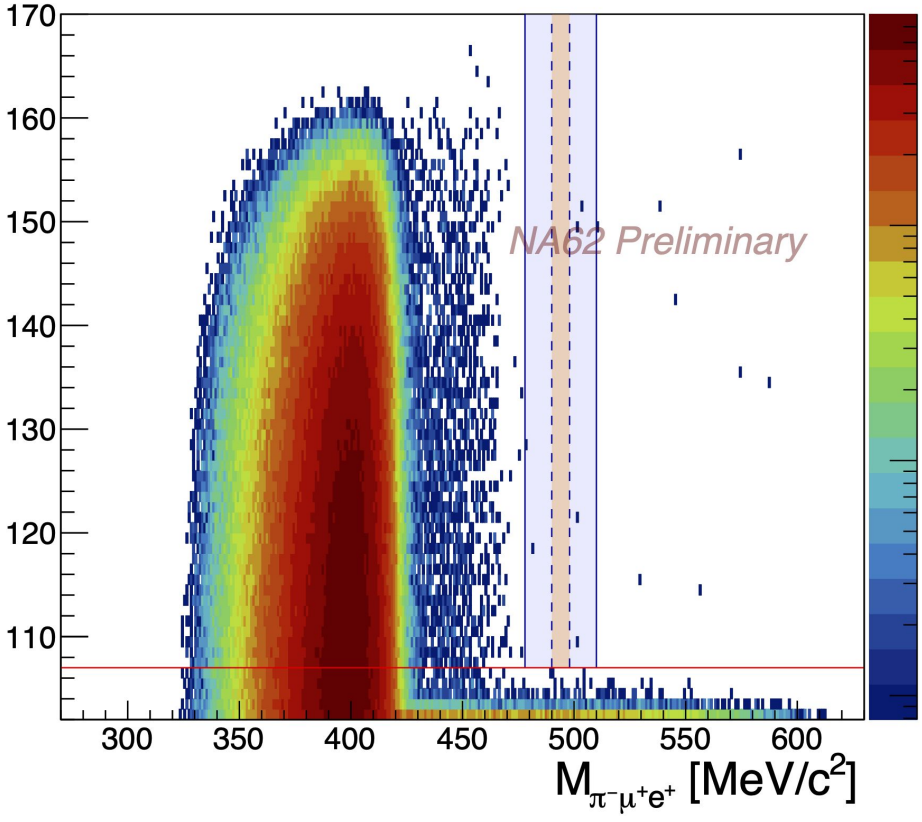
- Large improvements on most of the LN & LF violating K^+ and π^0 decays → sensitivity up to 10^{-11}
- NA62 will resume data taking in summer 2021 with higher beam intensity and new detectors

Thanks

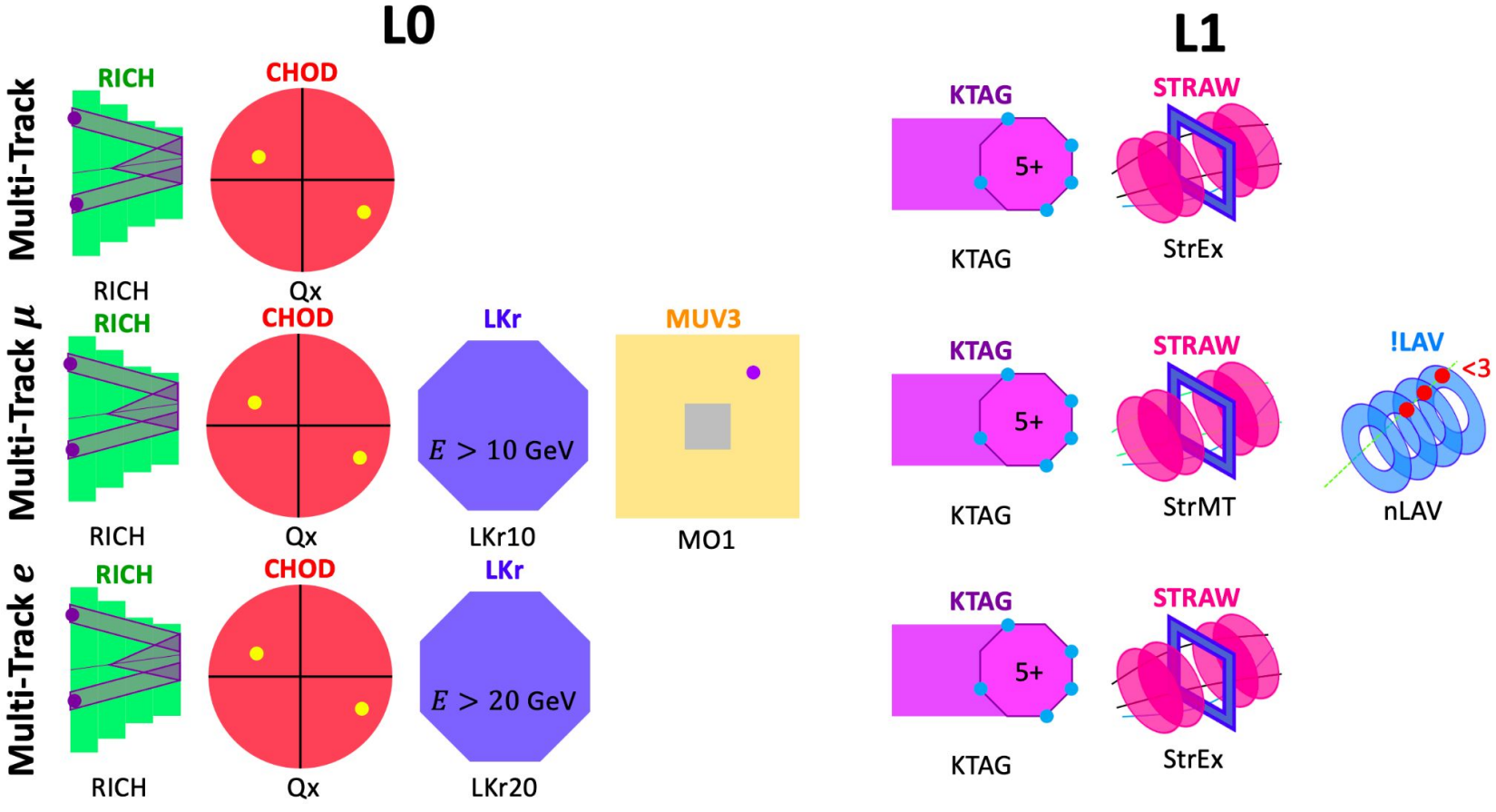
Backup slides

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

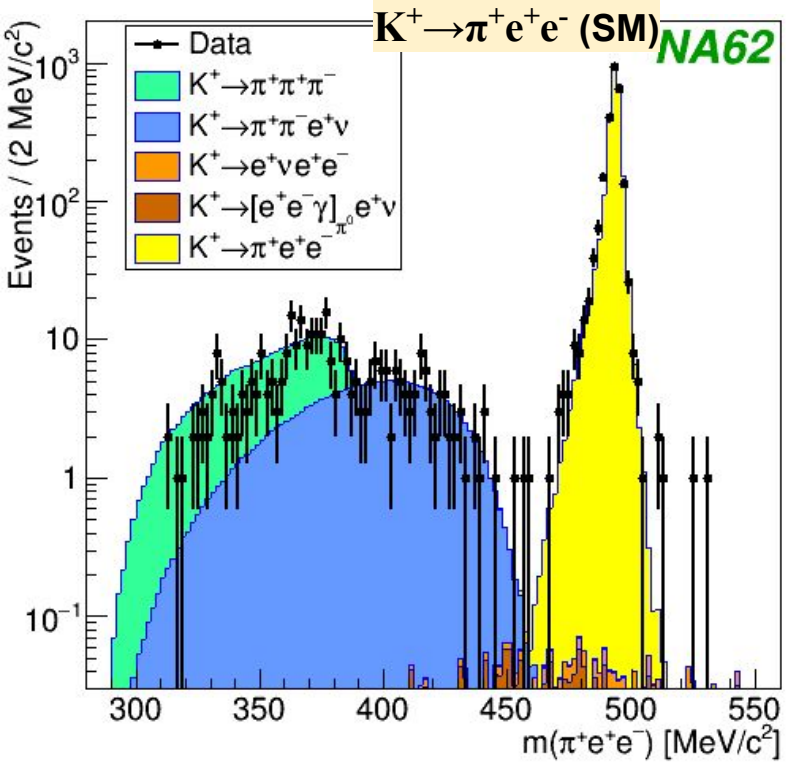


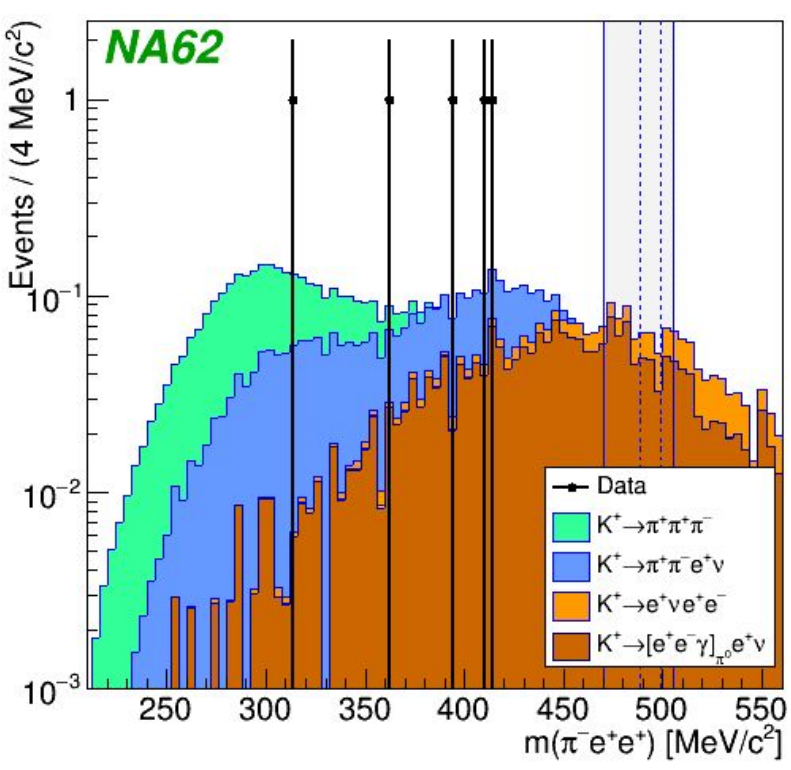


Trigger chains schematic illustration



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





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

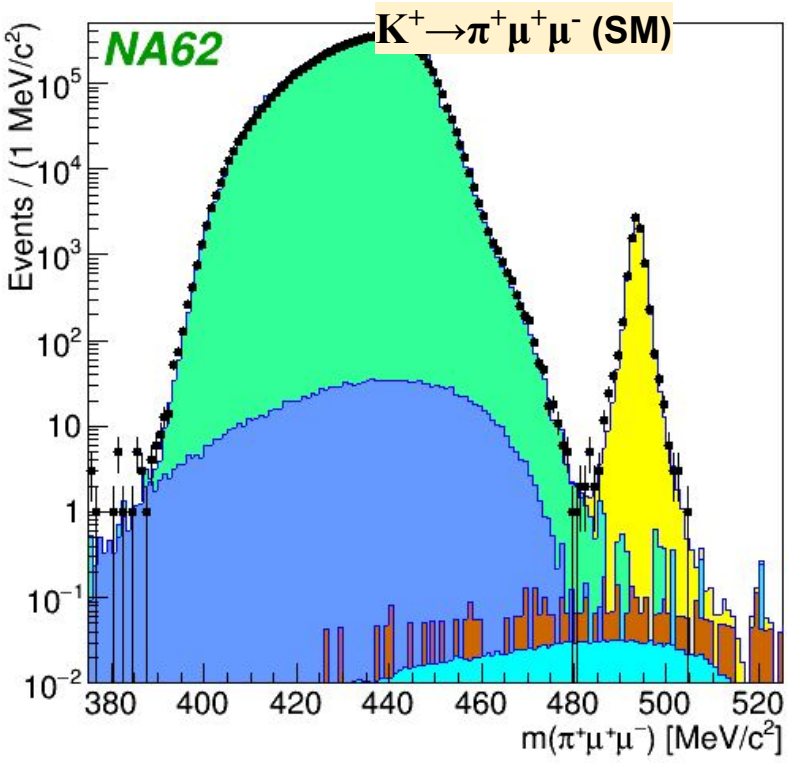
$N_K = (2.14 \pm 0.04_{stat} \pm 0.06_{ext}) \times 10^{11}$

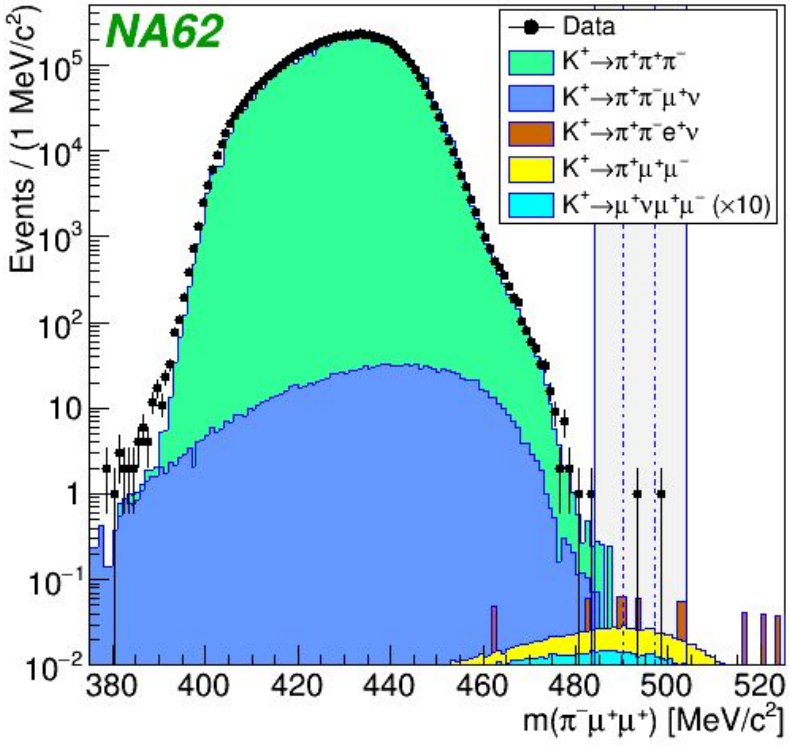
Additional RICH condition for π^+/e^+ separation

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

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

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





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

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

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

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