European Physical Society
Conference on High Energy Physics

10 -17 July 2019, Ghent, Belgium

Searches for lepton flavour and lepton number violation in K^+ decays at NA62

Angela Romano (University of Birmingham)
on behalf of the NA62 Collaboration

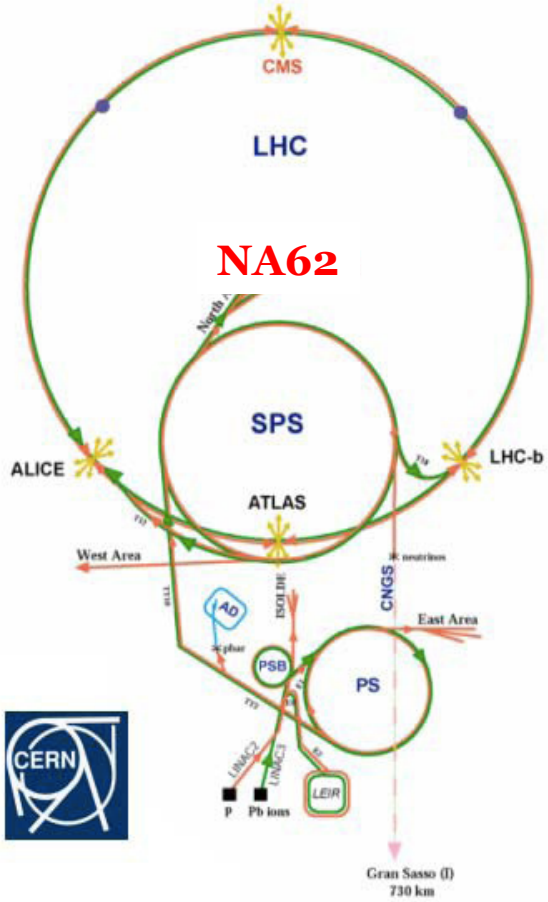
Outline:

- The NA62 experiment at CERN SPS
- Results on LFV-LNV searches
- Conclusions and Prospects

The NA62 experiment

High precision fixed-target Kaon experiment at CERN SPS

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax GMU, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosí, TRIUMF, Turin, Vancouver UBC.

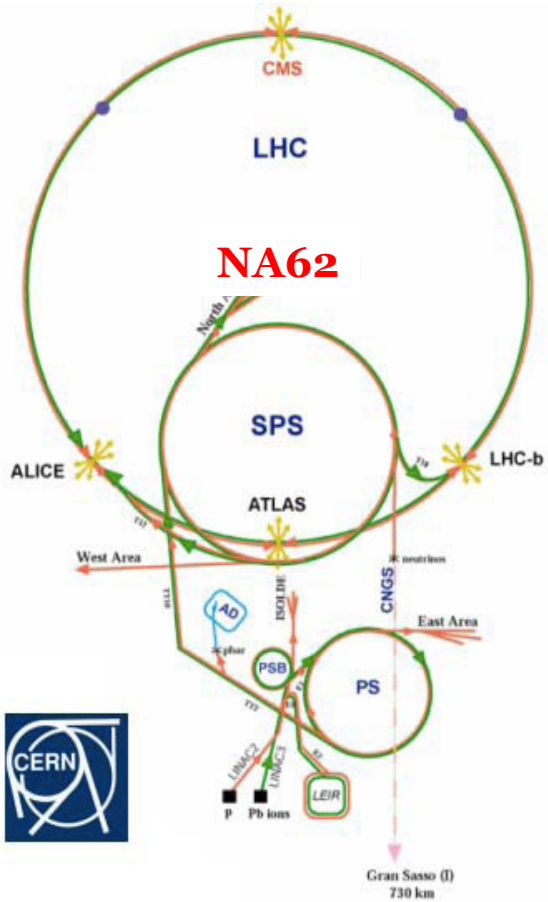


NA62 Beam line & detectors

The NA62 experiment

High precision fixed-target Kaon experiment at CERN SPS

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax GMU, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosí, TRIUMF, Turin, Vancouver UBC.



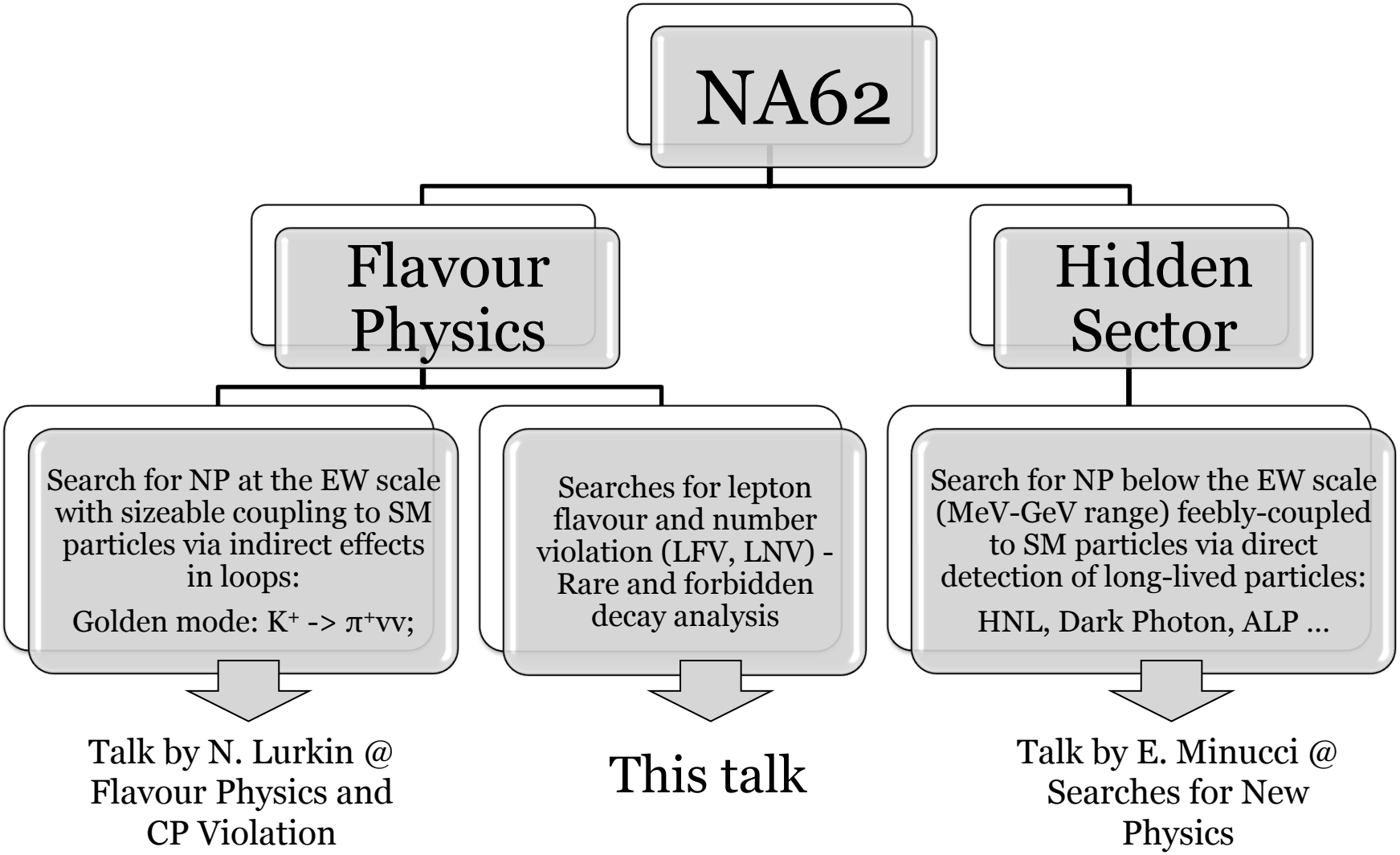
NA62 Timeline

- **Dec 2008 - NA62 Approval**
- **2009 - 2014: Detector R&D, Installation**
- **2015 Commissioning**
  2016-2017-2018: Physics Runs
- **2021 - 2023 Next Physics Runs (TBA)**

NA62 primary goal: Measure BR($K^+ \to \pi^+ \nu\bar{\nu}$)

New: K^+ decay-in-flight technique

NA62: a general purpose experiment



NA62 Programme with K^+ decays beyond $K \rightarrow \pi\nu\nu$

- **Standard Kaon Physics:**
  - Measurements of the BR of all the main K^+ decay modes
  - χPT: $K^+ \rightarrow \pi^+\gamma\gamma$, $K^+ \rightarrow \pi^+\pi^0 e^+e^-$, $K^+ \rightarrow \pi^0(^+)\pi^0(^-)l^+\nu$
  - Lepton Universality: $R_K = \Gamma(K^+ \rightarrow e^+\nu_e)/(K^+ \rightarrow \mu^+\nu_\mu)$

- **Rare/forbidden K^+ and π^0 decays at SES ~10^{-12}:**
  - **K^+** physics: **$K^+ \rightarrow \pi^+\ell^+\ell^-$, $K^+ \rightarrow \pi^+\gamma\ell^+\ell^-$, $K^+ \rightarrow \ell^+\nu\gamma$,**
  - **LFV/LNV** searches: $K^+ \rightarrow \pi^+\mu^\pm e^\mp$, $K^+ \rightarrow \pi^-\mu^+e^+$, $K^+ \rightarrow \pi^- l^+ l^+$, ...
  - **π^0** physics: $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow e^+e^-$, $\pi^0 \rightarrow e^+e^-e^+e^-$, $\pi^0 \rightarrow \gamma\gamma\gamma(\gamma)$, ...

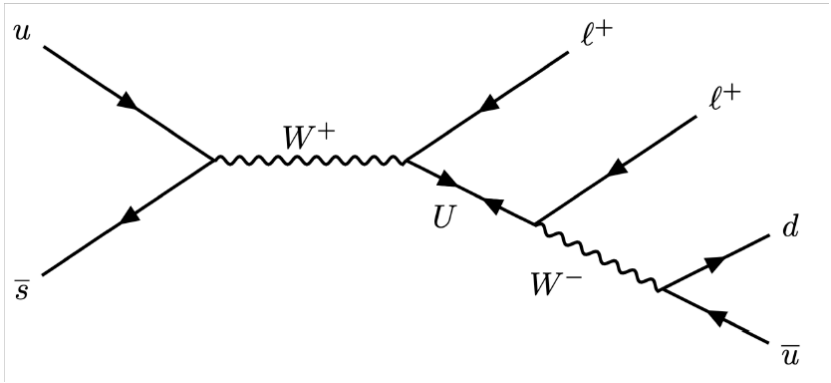
NEW Results

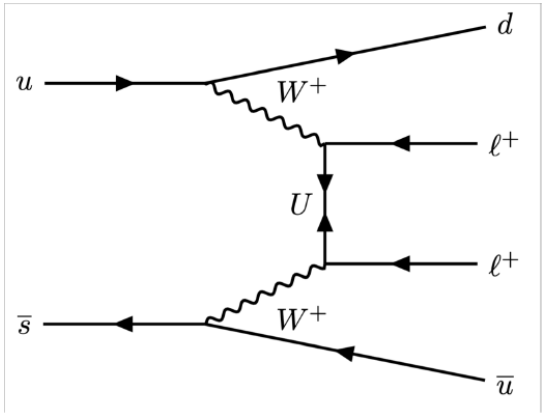
- **Exotics searches**
  - Heavy Neutral Lepton (HNL) production from $K^+ \rightarrow l^+\nu_h$
  - Dark Photon (A') $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow$ invisible

LFV/LNV $K^+ \to \pi^- \ell^+ \ell^+$

Violation of lepton flavour/number conservation laws is predicted in BSM models:

- $K^+ \to \pi^- \ell^+ \ell^+$: $\Delta L = 2$ and $\Delta L\mu = 2$ or $\Delta Le = 2$ ($\ell = \mu/e$) via Majorana neutrinos U [JHEP 0905 (2009) 030], [PL B491 (2000) 285-290]





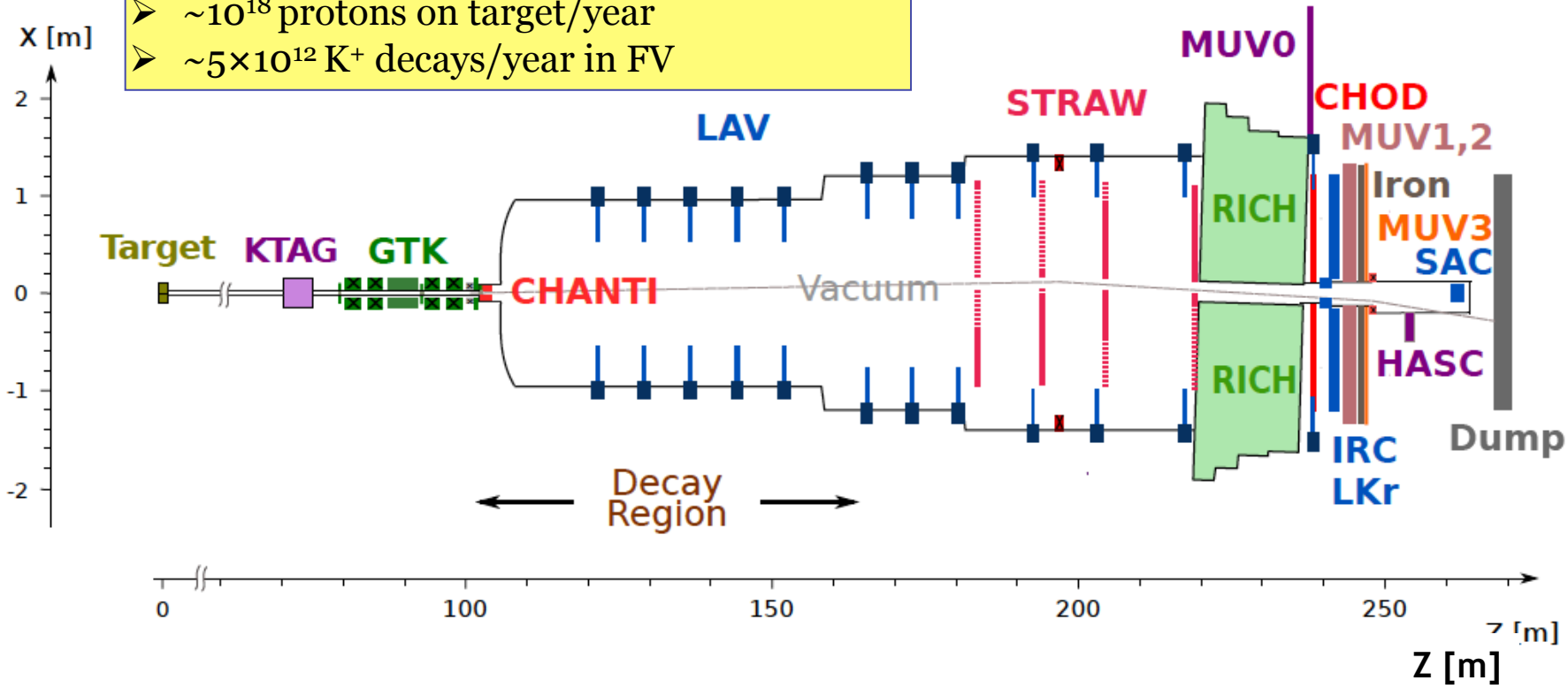
Experimental Status (results at 90% C.L):

- **BR ($K^+ \to \pi^- e^+ e^+$) < 6.4 x 10^{-10}** [BNL E865, PRL 85 (2000) 2877]
- **BR($K^+ \to \pi^- \mu^+ \mu^+$) < 8.6 x 10^{-11}** [CERN NA48/2, PL B769 (2017) 67]

The NA62 Detector

Nominal SPS proton beam on Be target:
- 400 GeV/c, 3×10^{12}/spill
- ~10^{18} protons on target/year
- ~5×10^{12} K^+ decays/year in FV

[NA62 Detector Paper, 2017 JINST 12 P05025]



- Secondary un-separated hadron beam: π^+(70%)/**K^+(6%)**/p(24%)
- **K^+: 75GeV/c** (±1%), divergence < 100μrad
- Intensity (2017): ~2×10^{12} protons/SPS spill
- Beam rate (2017): **~500MHz @GTK**

Talk by A. Kleimenova @ Detector R&D and Data Handling

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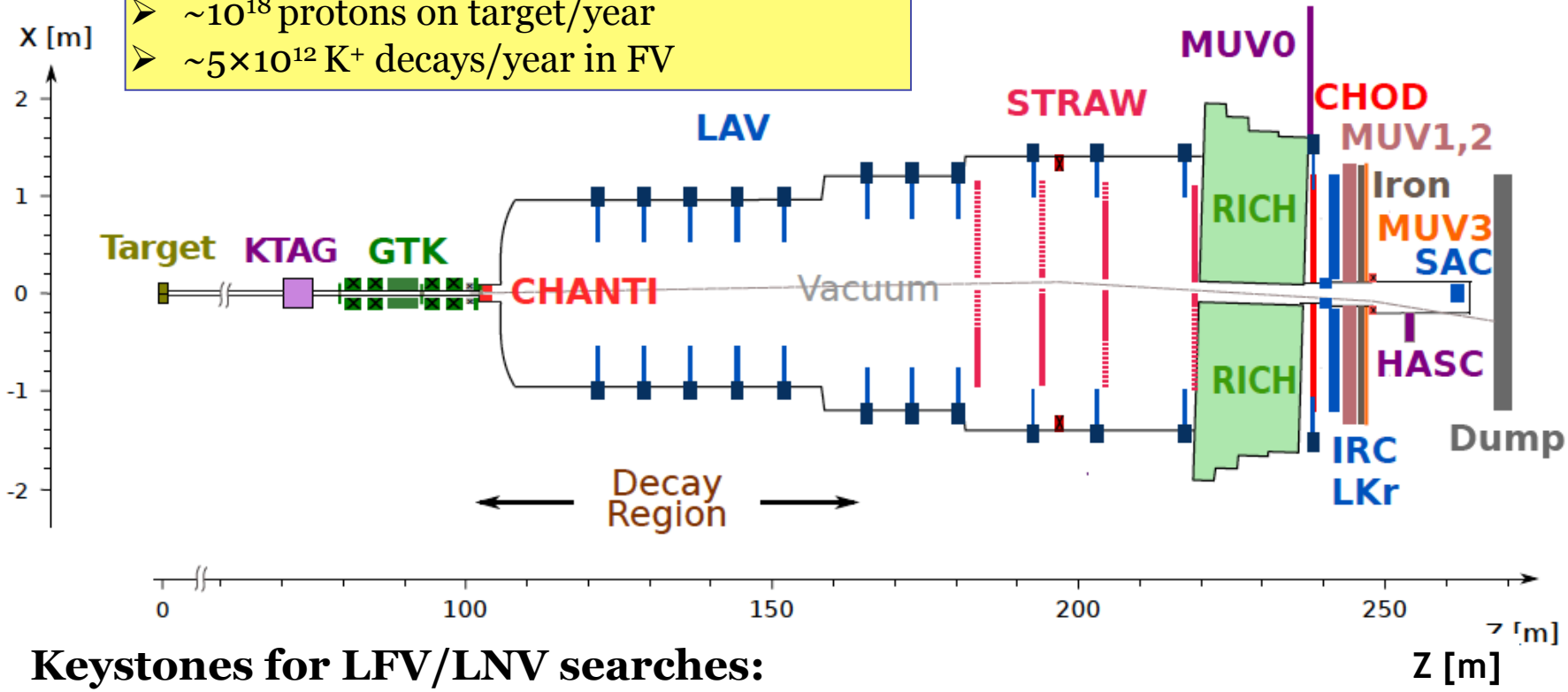


Keystones for LFV/LNV searches:

- Downstream 3 tracks reconstruction: **STRAW** spectrometer
- PID with Cherenkov detectors: **KTAG** (K^+), **RICH** (π/e separation)
- PID (via E/p) with ECal: **LKr** (π/μ/e separation)
- Photon vetoes: **LAV**, **LKr**, **SAV**; Muon ID/veto: **MUV3**

LFV/LNV Searches @ NA62

- Subset of 2017 data: ~3 months of data taking
- Blind analysis procedure
- Dedicated trigger lines: multi-track final states with $e^{\pm}$ or $\mu^{\pm}$

Trigger line	Requirements	Data Samples
Di-Muon	3 tracks, 2 muon candidates	SM $K^+ \rightarrow \pi^+\mu^+\mu^-$ & LNV $K^+ \rightarrow \pi^-\mu^+\mu^+$
Multi-Track e	3 tracks, 20GeV deposit in LKr	SM $K^+ \rightarrow \pi^+e^+e^-$ & LNV $K^+ \rightarrow \pi^-e^+e^+$
Multi-Track	3 tracks, minimum bias	Control samples for background studies

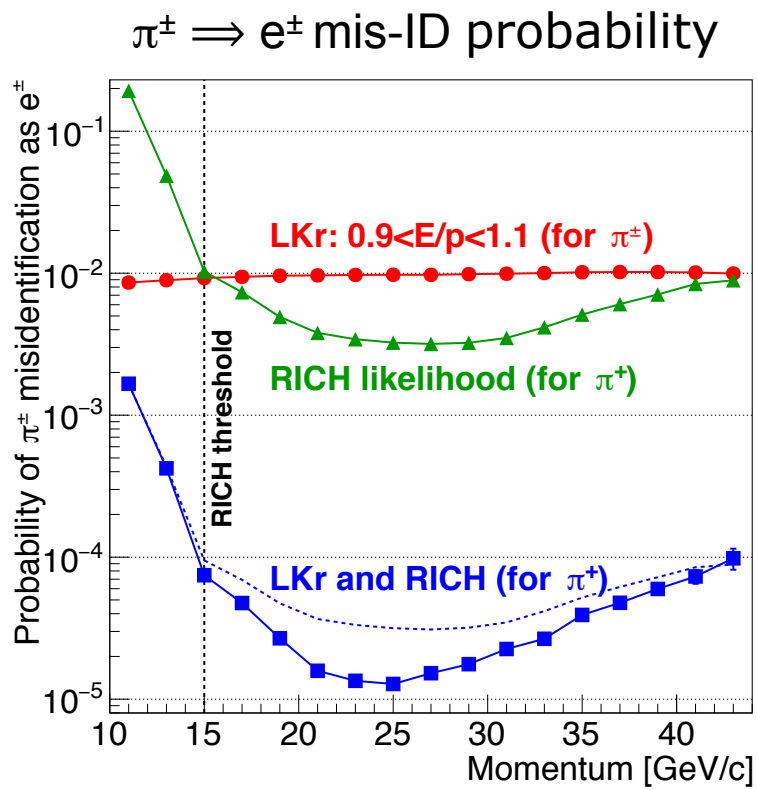
- **Corresponding SM channels used for normalisation**
  - Common event selection (differs mostly by charge)
  - Main systematic uncertainties cancel (trigger/detector efficiency/pileup)
- **BR ($K^+ \rightarrow \pi^+e^+e^-$) = (3.00 ± 0.09) x 10^{-7}** [PL B677 (2009) 246]
- **BR($K^+ \rightarrow \pi^+\mu^+\mu^-$) = (0.962 ± 0.025) x 10^{-7}** [PL B697 (2011) 107]

Backgrounds and PID

Main background from $K^+ \to \pi^+\pi^+\pi^-$ [dominant 3-track K^+ decay] BR = 5.6%

Mechanisms:

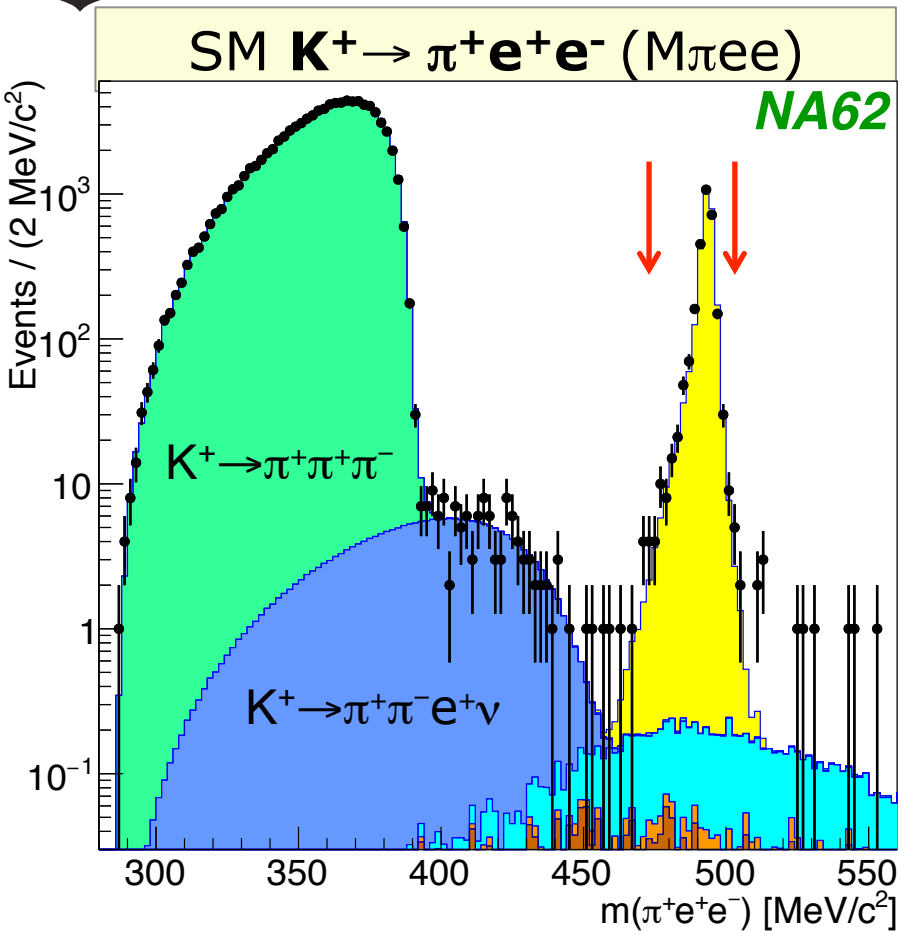
- Single/double mis-identification:
  - $\pi^\pm \Longrightarrow e^\pm$, $\pi^\pm \Longrightarrow \mu^\pm$
- Pion decay in flight (9% probability):
  - $\pi^\pm \to \mu^\pm$ (99.9%)
  - $\pi^\pm \to e^\pm$ (1.2×10^{-4})

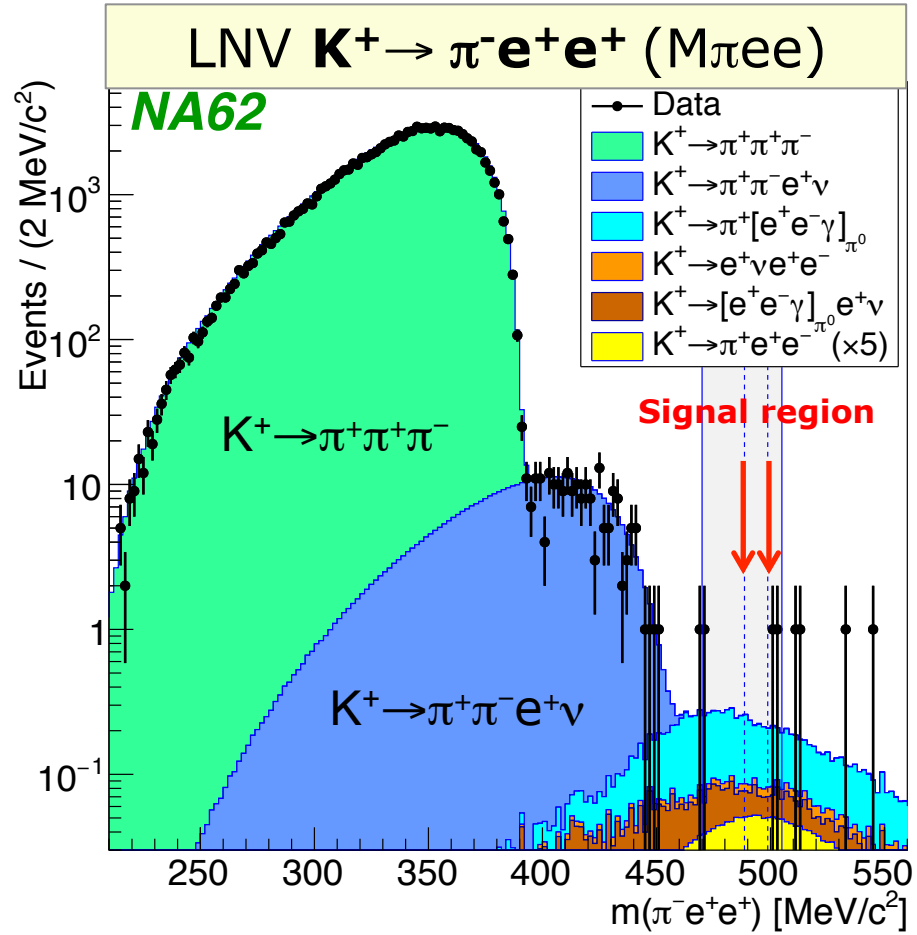


Study techniques:

- Force particle mis-ID and assign weight $P(\pi^\pm \Longrightarrow l^\pm)$
- Special $\pi^\pm$ decay enriched MC
- Data-driven: $K \to \pi\pi\pi$ control sample obtained by inverting PID criteria

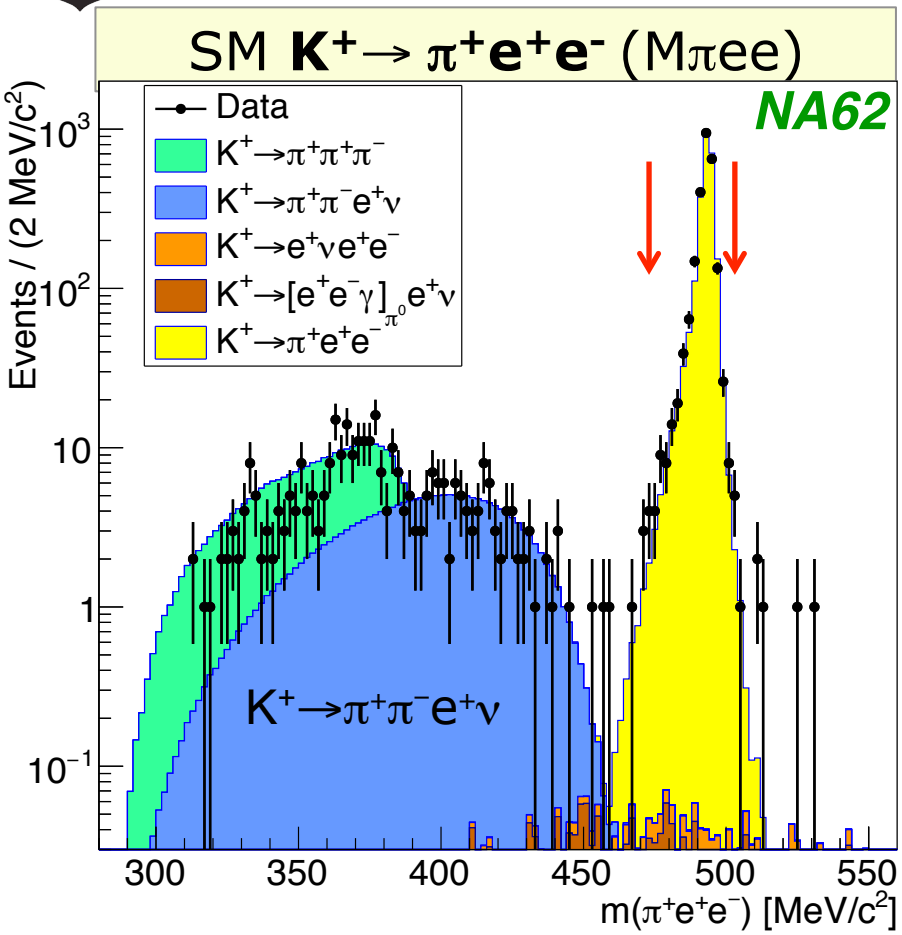
$K^+ \to \pi^- e^+ e^+$: auxiliary selection

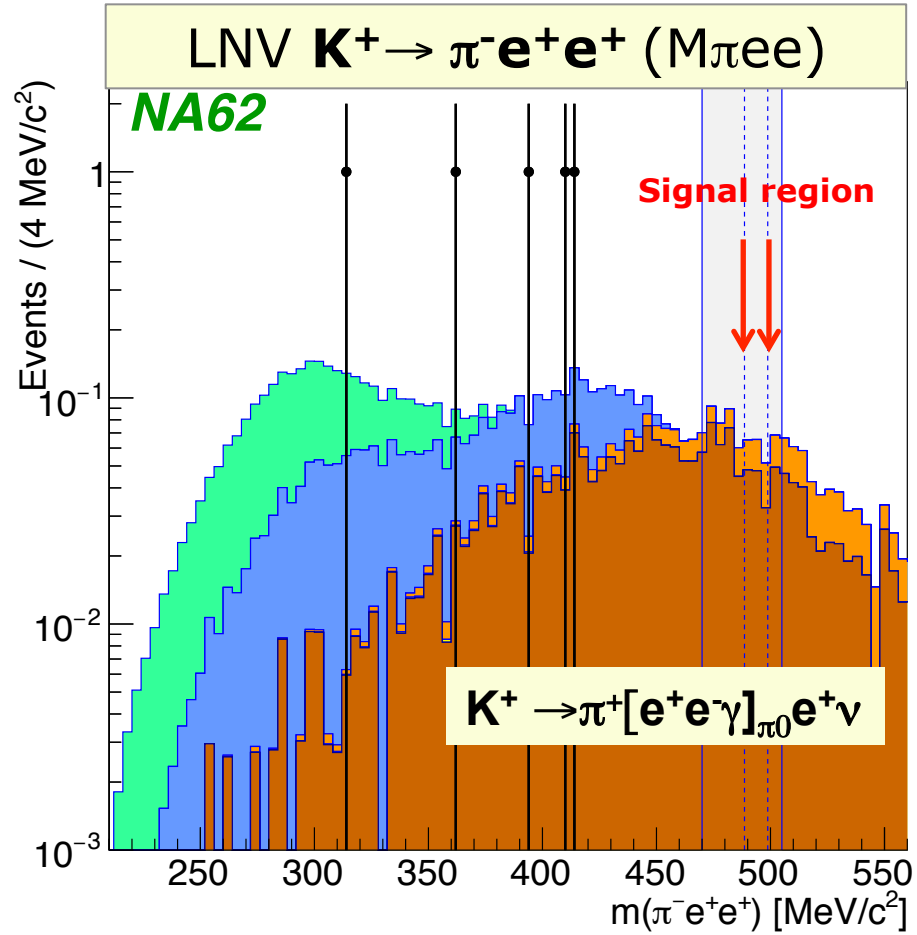




- **Auxiliary: LKr only used for pion/electron ID**
- Validation of background estimates in control mass regions
- **LNV sensitivity limited** by $K^+ \to \pi^+[e^+e^-\gamma]_{\pi 0}$ background

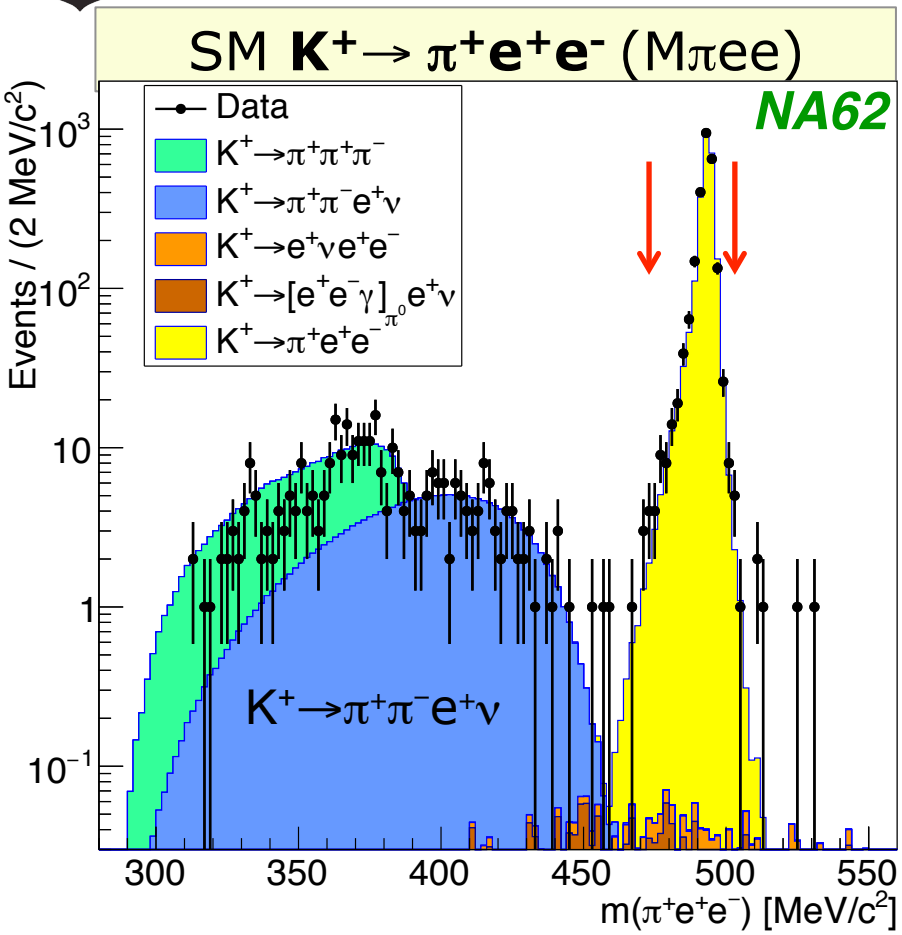
$K^+ \to \pi^- e^+ e^+$: standard selection

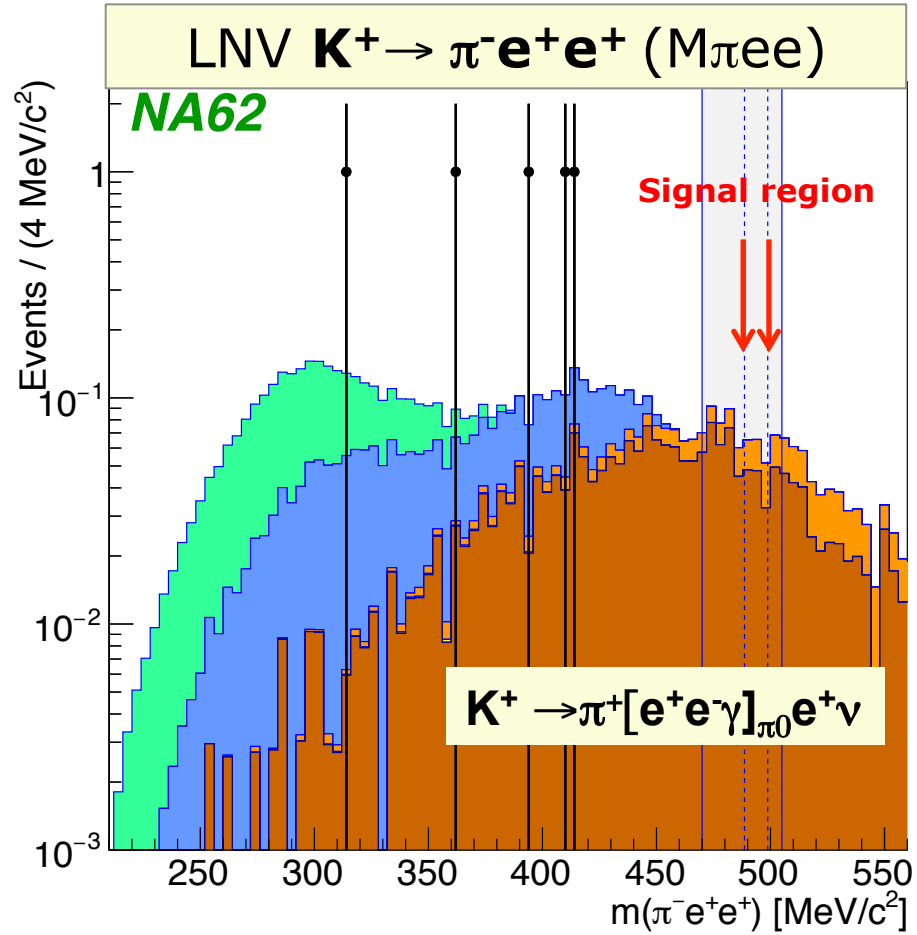




- **Standard: LKr + RICH used for pion/electron ID**
- About 10% loss of SES, ~6 times lower background
- **Better discovery potential for LNV**

$K^+ \to \pi^- e^+ e^+$: normalisation





SM $K^+ \to \pi^+ e^+ e^-$ observed candidates: 2,484

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

K^+ decays in FV: $N_K = (2.14 \pm 0.07) \times 10^{11}$

$K^+ \to \pi^- e^+ e^+$: Results

Using $N_K = (2.14 \pm 0.07) \times 10^{11}$

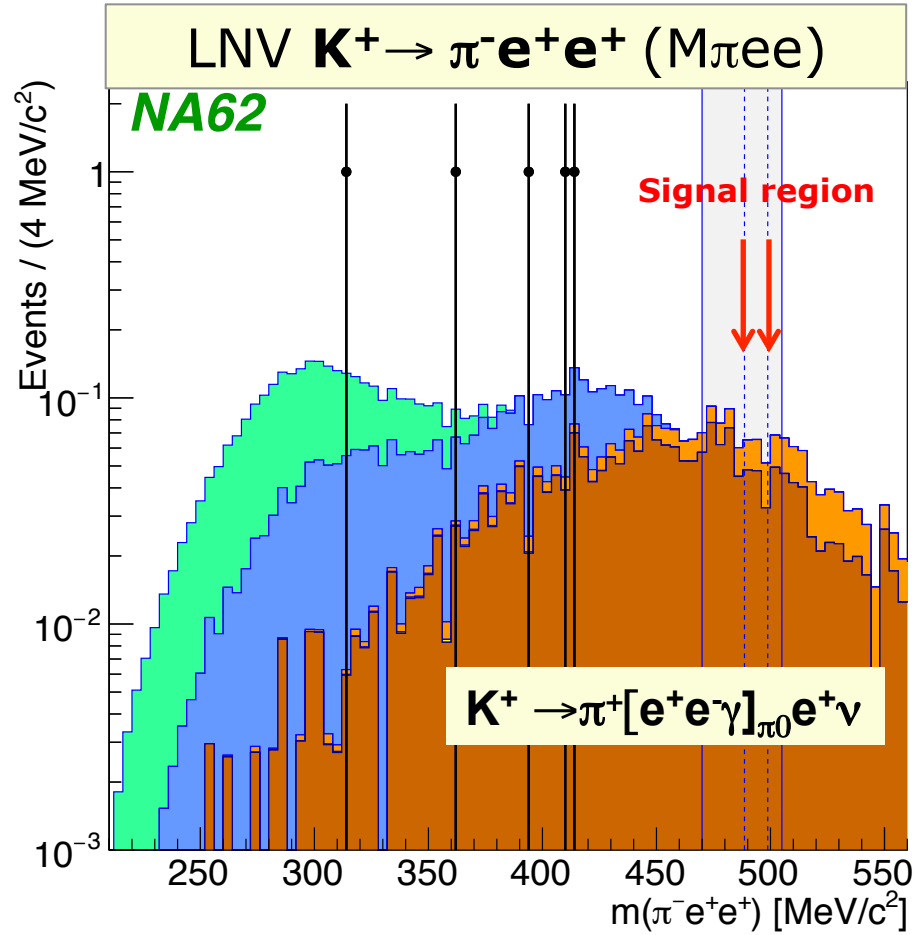
Signal Acceptance: 4.98%

SES = $(0.94 \pm 0.03) \times 10^{-10}$

Expected background in signal region:

Process	Sig. Reg.
$K^+ \to e^+\nu e^+ e^-$	0.12 ± 0.02
$K^+ \to [e^+e^-\gamma]_{\pi^0} e^+\nu$	0.04
Total	0.16 ± 0.03

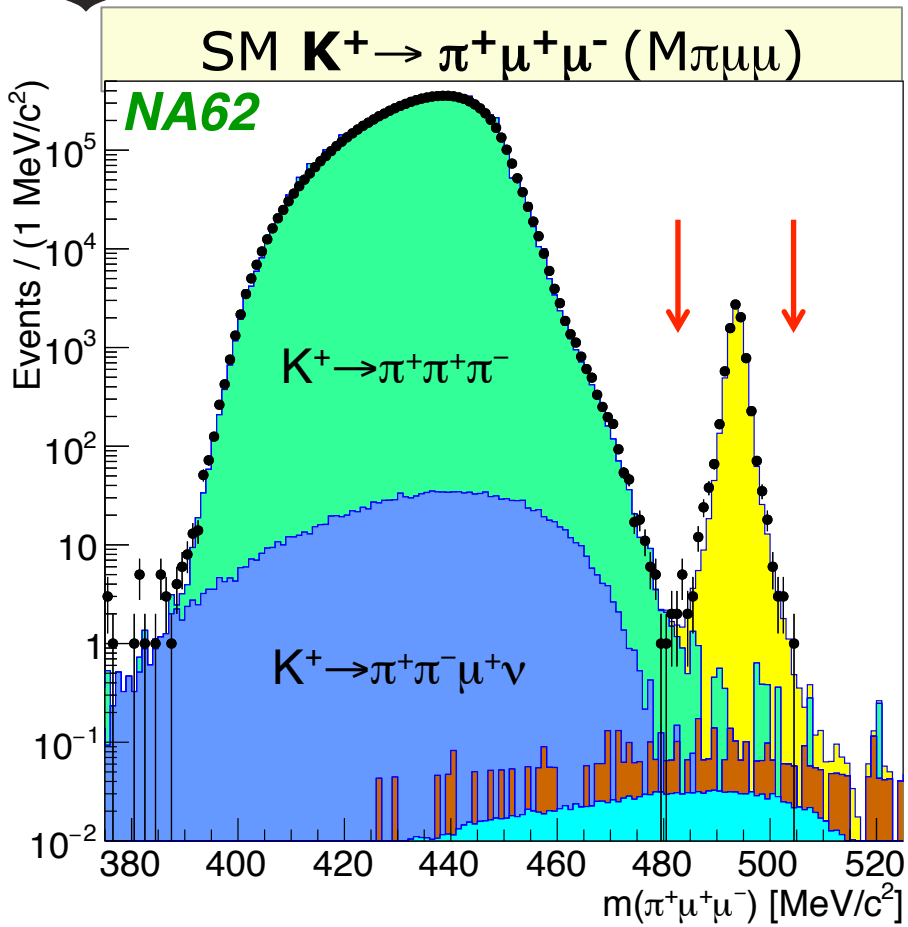
Observed candidates: 0

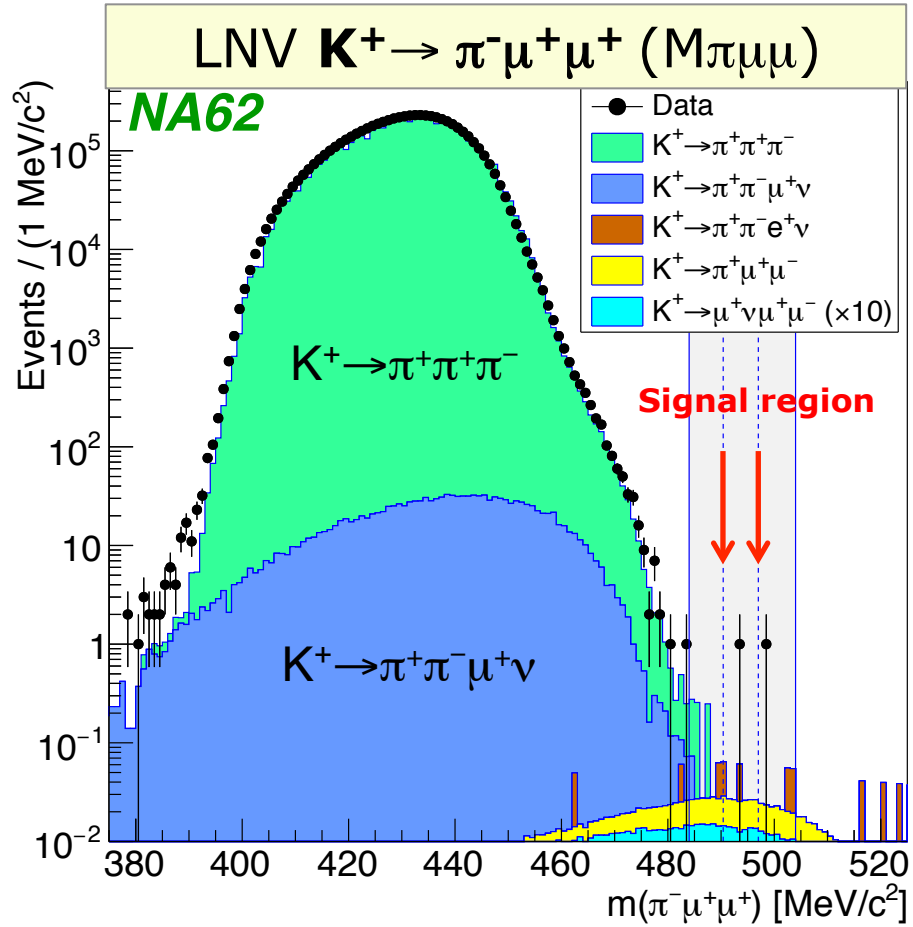


Set upper limit on BR using CLs statistical treatment:

BR($K^+ \to \pi^- e^+ e^+$) < 2.2×10^{-10} at 90% CL

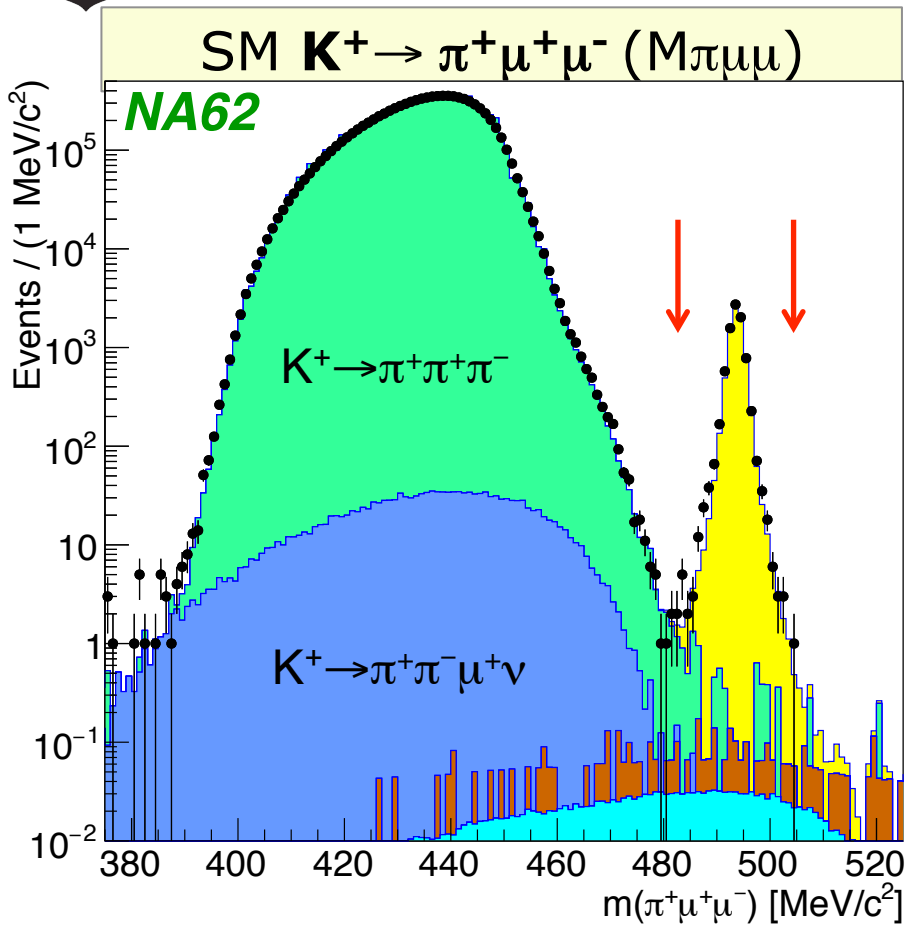
$K^+ \to \pi^- \mu^+ \mu^+$ Search

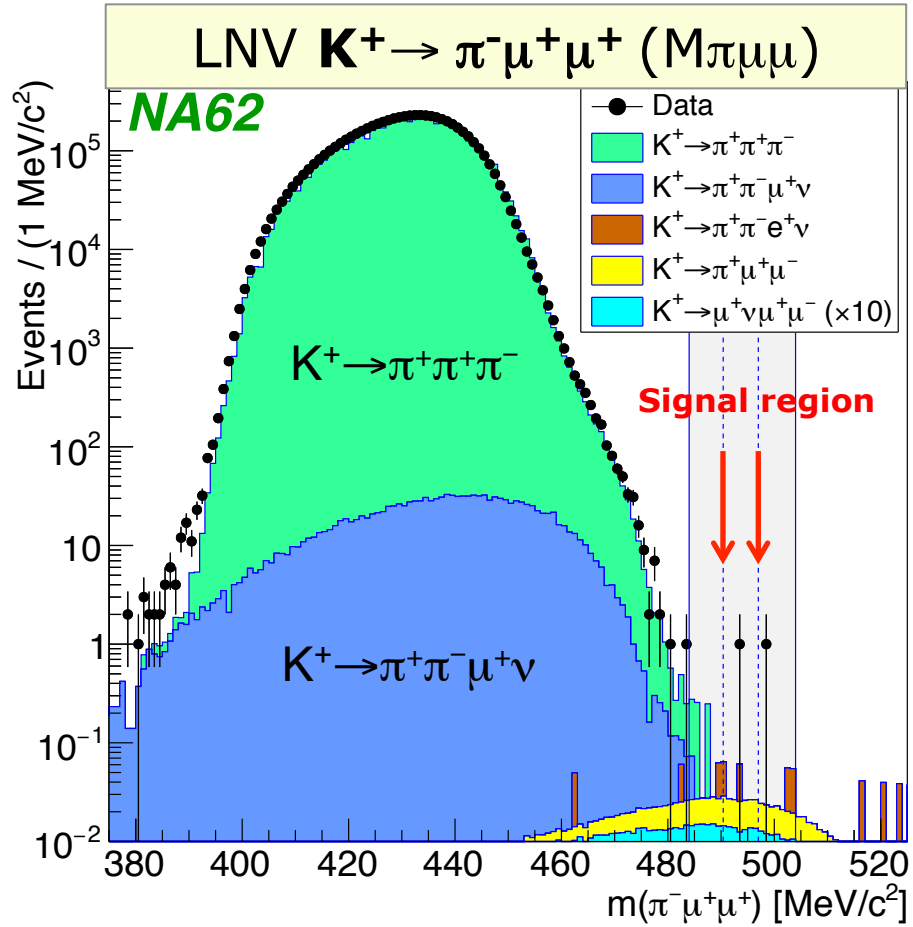




- **Standard: LKr + MUV3 used for pion/muon ID**
- Background in SM signal mass region: 0.07%
- Background to LNV due to pion in-flight decays and $\pi^\pm \Rightarrow \mu^\pm$ mis-ID

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





SM $K^+ \to \pi^+\mu^+\mu^-$ observed candidates: 8,357

$BR(K^+ \to \pi^+\mu^+\mu^-) = (0.962 \pm 0.025) \times 10^{-7}$

K^+ decays in FV: $N_K = (7.94 \pm 0.23) \times 10^{11}$

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

Using $N_K = (7.94 \pm 0.23) \times 10^{11}$

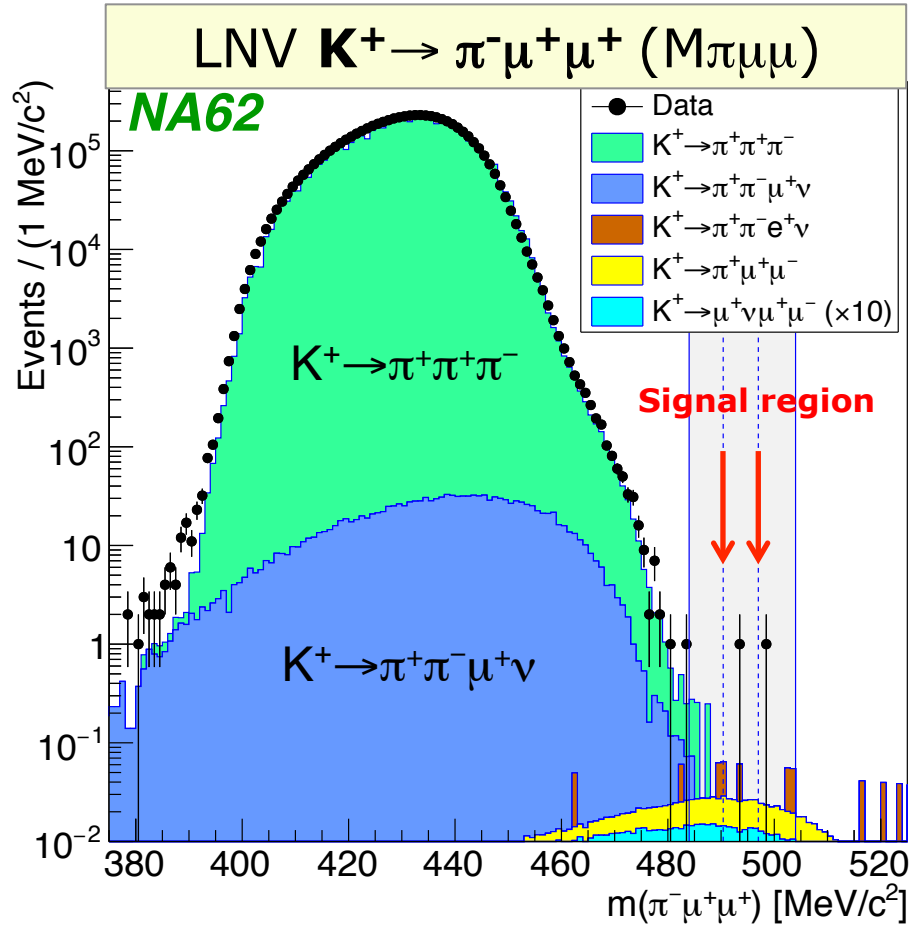
Signal Acceptance: 9.81%

SES = $(1.28 \pm 0.04) \times 10^{-11}$

Expected background in signal region:

Process	Exp. in Signal Region
$K^+ \to \pi^+\pi^+\pi^-$	0.70 ± 0.40
$K^+ \to \pi^+\pi^-\ell^+\nu$	$0.06(7) \pm 0.05\ \mu(e)$
$K^+ \to \pi^+\mu^+\mu^-$	0.08 ± 0.02
$K^+ \to \mu^+\nu\mu^+\mu^-$	0.01
Total	0.91 ± 0.41

Observed candidates: 1



Set upper limit on BR using CLs statistical treatment:

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

LFV-LNV: Results and Prospects

Upper Limits set with 80% of the 2017 NA62 data set:

- **BR ($K^+ \to \pi^- e^+ e^+$) < 2.2 x 10^{-10} @90% CL**
- **BR($K^+ \to \pi^- \mu^+ \mu^+$) < 4.2 x 10^{-11} @90% CL**

[arXiv:1905.07770]

Factor 2-3 improvement over previous results [NA48/2 and BNL-E865]

LFV-LNV: Results and Prospects

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[arXiv:1905.07770]

Factor 2-3 improvement over previous results [NA48/2 and BNL-E865]

Competitive SES achieved with 2017 data for:

ANALYSES IN PROGRESS

- $K^+ \to \pi^- \mu^+ e^+$ [LNV] & $K^+ \to \pi^+ \mu^- e^+$ [LFV]

  → **SES ~5 x 10^{-11}** (factor ~5 improvement on BNL-E865)

- $K^+ \to e^- \nu \mu^+ \mu^+$ [LFV]

  → **SES ~5 x 10^{-11}** (first search for this mode)

- $K^+ \to \mu^- \nu e^+ e^+$ [LFV]

  → **SES ~1 x 10^{-10}** (factor 100 improvement on PDG)

Available data set is not competitive yet for $K^+ \to \pi^+ \mu^+ e^-$ and $\pi^0 \to \mu^\pm e^\mp$

Conclusions

The NA62 experiment at CERN has a vast and unique physics program including searches of LFV/LNV processes.

NA62 has improved world limits on LNV processes:

- **BR ($K^+ \to \pi^- e^+ e^+$) < 2.2 x 10^{-10} @90% CL**
- **BR($K^+ \to \pi^- \mu^+ \mu^+$) < 4.2 x 10^{-11} @90% CL**

[arXiv:1905.07770]

with 2017 data set (di-lepton triggered data)

More data analyses are ongoing on same data - improvements are expected for several LNV/LFV channels.

Full NA62 data set (2016-2018) is ~3 times the size of 2017 data - results to be updated soon using larger data sets.

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SPARES

Angela Romano (University of Birmingham)
on behalf of the NA62 Collaboration

$K^+ \to \pi^- \ell^+ \ell^+$ Result Summary

Single Event Sensitivity: $SES = \frac{1}{N_K A}$

Decay	(N_K) Kaon Decays $[\times 10^{11}]$	Acceptance (A) [LNV]	SES$[\times 10^{-11}]$
$K^+ \to \pi^- e^+ e^+$	$2.14 \pm 0.04_{stat} \pm 0.06_{ext}$	4.98%	9.4 ± 0.3
$K^+ \to \pi^- \mu^+ \mu^+$	$7.94 \pm 0.09_{stat} \pm 0.21_{ext}$	9.81%	1.28 ± 0.04

Background predictions & Observed Events (Signal Region)

Decay	N(SR) [Predicted]	N(SR) [Observed]
$K^+ \to \pi^- e^+ e^+$	0.16 ± 0.03	0
$K^+ \to \pi^- \mu^+ \mu^+$	0.91 ± 0.41	1

For $K^+ \to \pi^- e^+ e^+$ use of RICH for e^+ ID reduces the background to LNV signal by a factor of 6.

- New branching ratio upper limits at 90% CL (CLs method):

Decay	BR UL @ 90% CL	PDG (2018) UL @ 90% CL
$K^+ \to \pi^- e^+ e^+$	2.2×10^{-10}	6.4×10^{-10}
$K^+ \to \pi^- \mu^+ \mu^+$	4.2×10^{-11}	8.6×10^{-11}

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

Process	Expected background
$K_{3\pi}$ (no $\pi^\pm$ decays)	0.007 ± 0.003
$K_{3\pi}$ (one $\pi^\pm$ decay)	0.25 ± 0.25
$K_{3\pi}$ downstream (at least two $\pi^\pm$ decays)	0.20 ± 0.20
$K_{3\pi}$ upstream (at least two $\pi^\pm$ decays)	0.24 ± 0.24
$K^+ \to \pi^+ \mu^+ \mu^-$	0.08 ± 0.02
$K^+ \to \pi^+ \pi^- \mu^+ \nu$	0.05 ± 0.05
$K^+ \to \pi^+ \pi^- e^+ \nu$	0.07 ± 0.05
$K^+ \to \mu^+ \nu \mu^+ \mu^-$	0.01 ± 0.01
Total	0.91 ± 0.41

Data-driven estimates (inversion of PID criteria)

Special fast simulations with forced pion decays: dominated by pion decays in the spectrometer

Full MC simulations tuned using the measured misID probabilities and measured pileup rates

One candidate observed

Upper limit with 2017 data set:

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