PHENO 2021 : 24th —26th May 2021

NA62 Searches for LNV/LFV in K^+ Decays

Overview

- The NA62 experiment at CERN.
- Searches for Lepton Number & Lepton Flavour Violation (LNV/LFV) in K^+ and π^0 decays.

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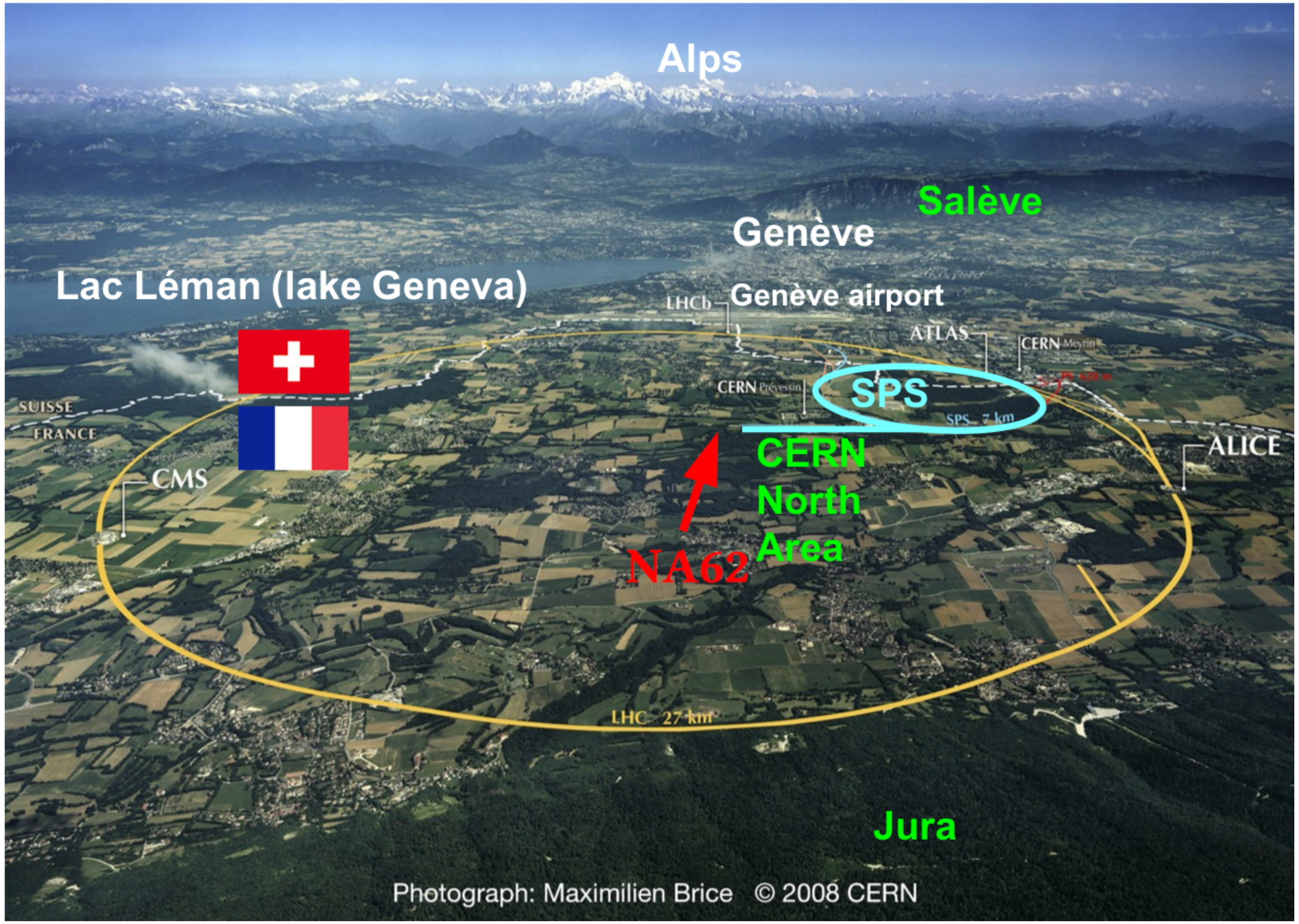
UNIVERSITY OF BIRMINGHAM

The NA62 Experiment at CERN

~200 collaborators from ~30 institutions :

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP) , Rome I, Rome II, San Luis Potosi, TRIUMF, Turin, Vancouver (UBC) .



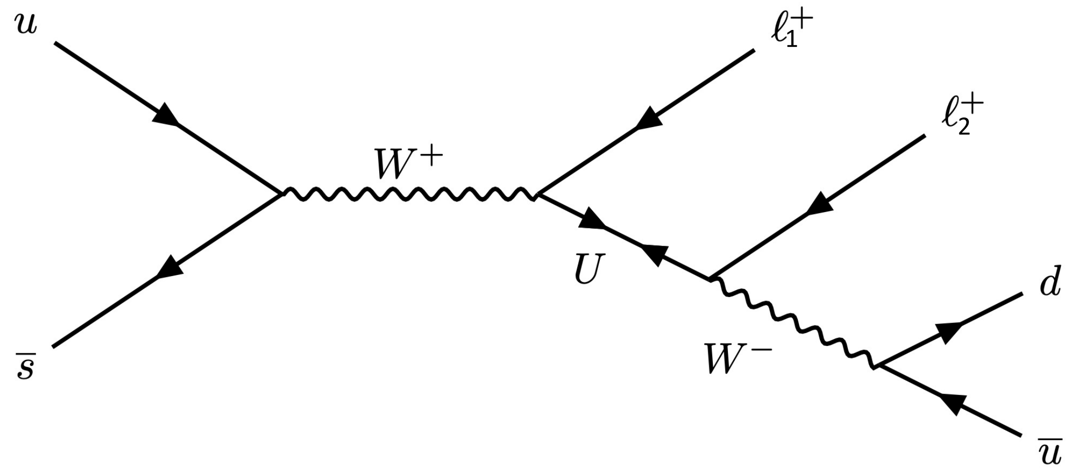
- **Primary goal:** Measurement of $BR(K^+ \to \pi^+\nu\bar{\nu})$.
- **New Technique:** K decay-in-flight.
- **Requirements:**
  - 10^{13} K^+ decays
  - Signal acceptance $\mathcal{O}(10\%)$
  - $\mathcal{O}(10^{12})$ Background rejection
- $\pi\nu\bar{\nu}$ **results** : [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [arXiv:2103.15389]
- **Broader Physics programme** : [SPSC NA62 (2021)]
  - Rare K^+ decays (e.g $K^+ \to \pi^+\mu^+\mu^-$ [ICHEP20]).
  - LNV/LFV K^+ decays (e.g $K^+ \to \pi^\pm l_1{}^\mp l_2{}^+$).
  - Exotics (e.g HNL: [PLB 807 (2020) 135599] [PLB 816 (2021) 136259]).
- **Data Taking**
  - 2016 Commissioning + Physics run (45 days).
  - 2017 Physics run (160 days).
  - 2018 Physics run (217 days).
  - 2021 resuming data taking.

} This talk

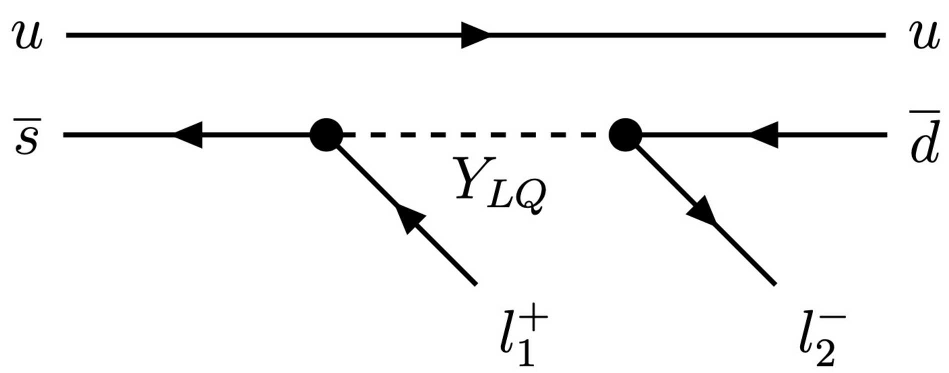
LFV & LNV in Kaon Decays

- Violation of L and L_e, L_μ, L_τ conservation is a clear indication of BSM physics:

E.g. $K^+ \to \pi^- \ell_1^+ \ell_2^+$: $\Delta L = 2$ via Majorana neutrinos U (analogue to $0\nu\beta\beta$ decays) [JHEP 0905 (2009) 030], [PLB 491 (2000) 285]



E.g. $K^+ \to \pi^\pm \mu^\mp e^+$ decays ($\Delta L = 2$ if π^- + $\Delta L_e = 1$ and $\Delta L_\mu = 1$) mediated by a leptoquark [JHEP 12 (2019) 089], [NPB 176 (1980) 135]



- Searches for LNV/LFV in Kaon decays are powerful probes of models beyond the SM at mass scales up to O(100 TeV).

$K^+ \to \pi^\pm \ell_1^+ \ell_2^\mp$ decays At NA62

This talk

LFU Test → [ICHEP20] → $K^+ \to \pi^+\mu^+\mu^-$

LFU Test → (NA48/2) → $K^+ \to \pi^+e^+e^-$

SM rare decays	LNV/LFV decays
$K^+ \to \pi^+\mu^+\mu^-$	$K^+ \to \pi^-\mu^+\mu^+$
$K^+ \to \pi^+e^+e^-$	$K^+ \to \pi^-e^+e^+$
	$K^+ \to \pi^-\mu^+e^+$
	$K^+ \to \pi^+\mu^-e^+$
	$K^+ \to \pi^+\pi^0, \pi^0 \to \mu^-e^+$
	$K^+ \to \pi^+\mu^+e^-$

$K^+ \to \pi^-\mu^+\mu^+$, $K^+ \to \pi^-e^+e^+$: PLB 797 (2019) 134794

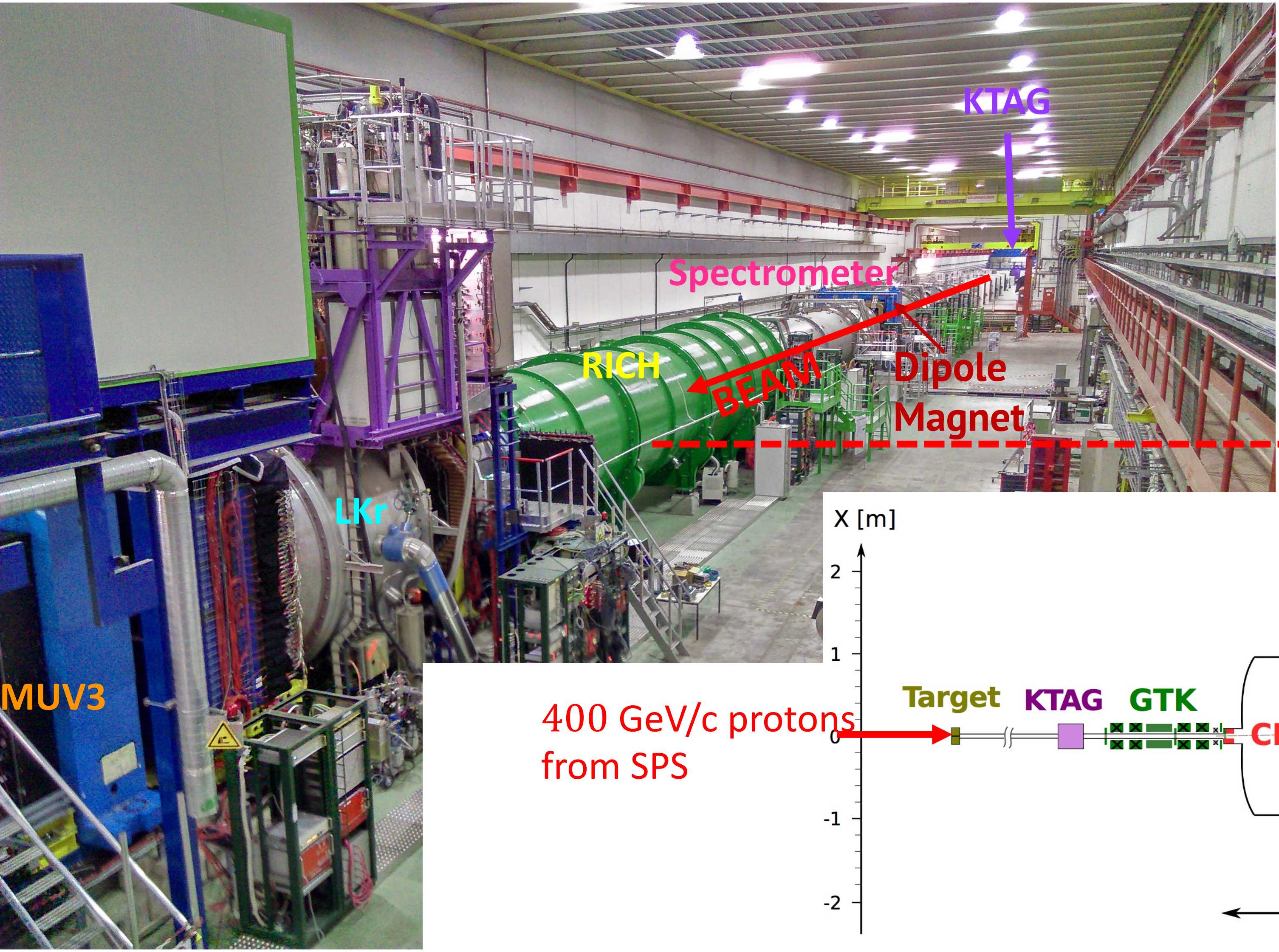
$K^+ \to \pi^-\mu^+e^+$, $K^+ \to \pi^+\mu^-e^+$, $K^+ \to \pi^+\pi^0, \pi^0 \to \mu^-e^+$: arXiv:2105.06759 (14th May 2021)

Experimental signature : 3 charged tracks with $\pi^\pm\ell_1^\mp\ell_2^\pm$ identities, consistent with closed kinematics K^+ decay.

To Study:

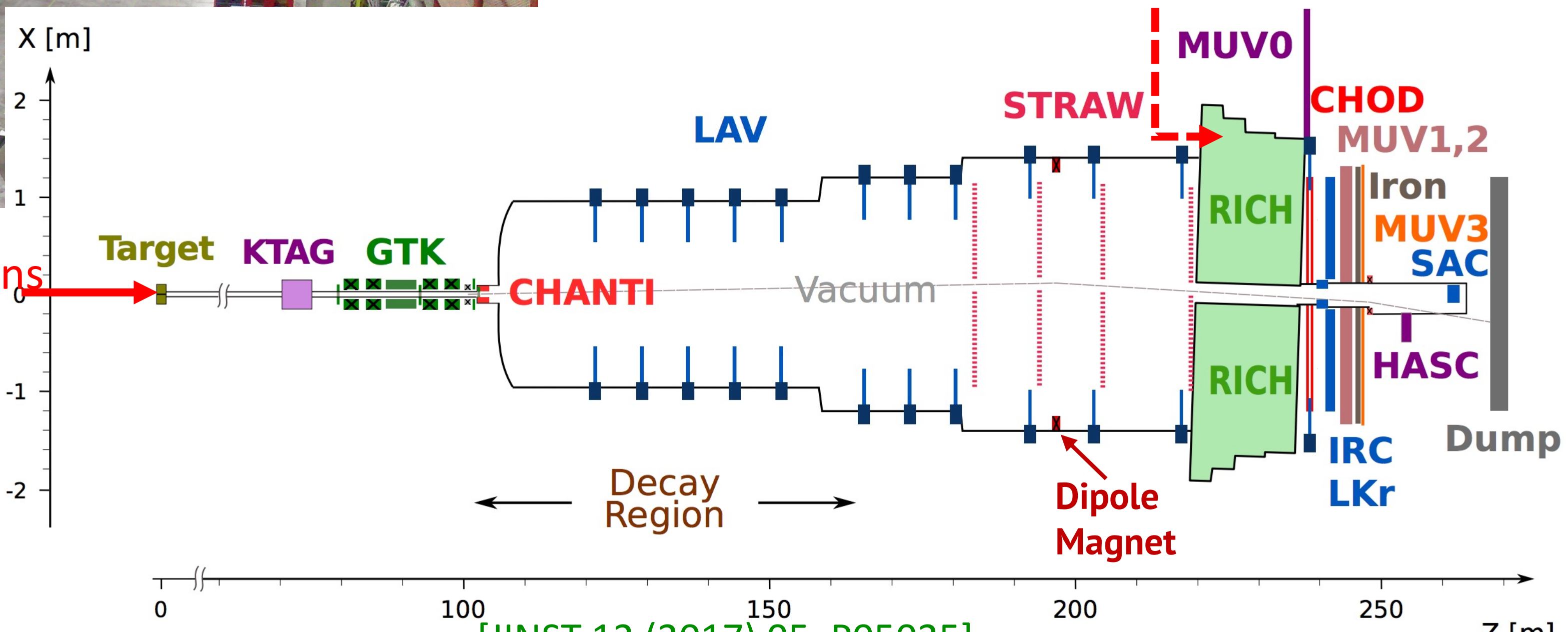
- Abundant source of K^+ decays (high intensity beam).
- Efficient trigger and reconstruction.
- Particle Identification (PID) – discriminate signal from background.
- Search for LFV $\pi^0 \to \mu^-e^+$: like $K^+ \to \pi^+\mu^-e^+$ search with $M_{\mu e}$ consistent with m_{π^0}

The NA62 Detector



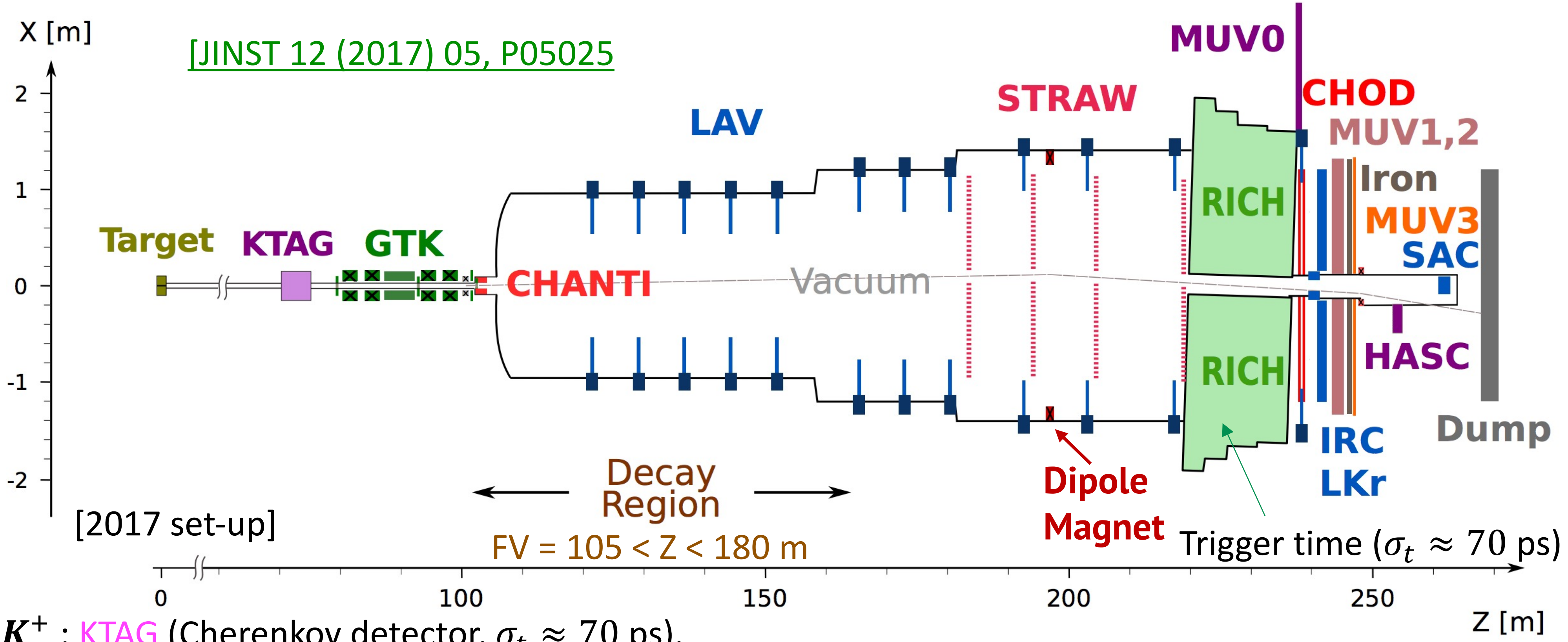
Unseparated secondary hadron beam

- Composition : $70\%\ \pi^{+}$, $24\%\ p$, $6\%\ K^{+}$
- $p_{K^{+}} = 75$ GeV/c.
- Mean K^{+} decay rate in the decay region of 3.7 MHz.



[JINST 12 (2017) 05, P05025]

The NA62 Detector & LNV/LFV Searches



- **Tag K^+** : KTAG (Cherenkov detector, $\sigma_t \approx 70$ ps).
- **Reconstruct 3 tracks with momentum measurement** : STRAW spectrometer.
  - Total momentum consistent with beam K^+, reconstruct decay vertex in FV.
- **PID :** use E/p : E = energy deposited in Calorimeter (LKr), p = track momentum **+** MUV3 to ID/veto muons + RICH
- **Photon Vetos** : (hermetic for $0-50$ mrad) 12LAVs, 2SAVs (IRC&SAC), LKr.
- **Tracks are in time :** CHOD.
- **Build invariant mass (**e.g. $\boldsymbol{M_{\pi\mu e}}$ with resolution $\approx 1.4\ MeV/c^2$).

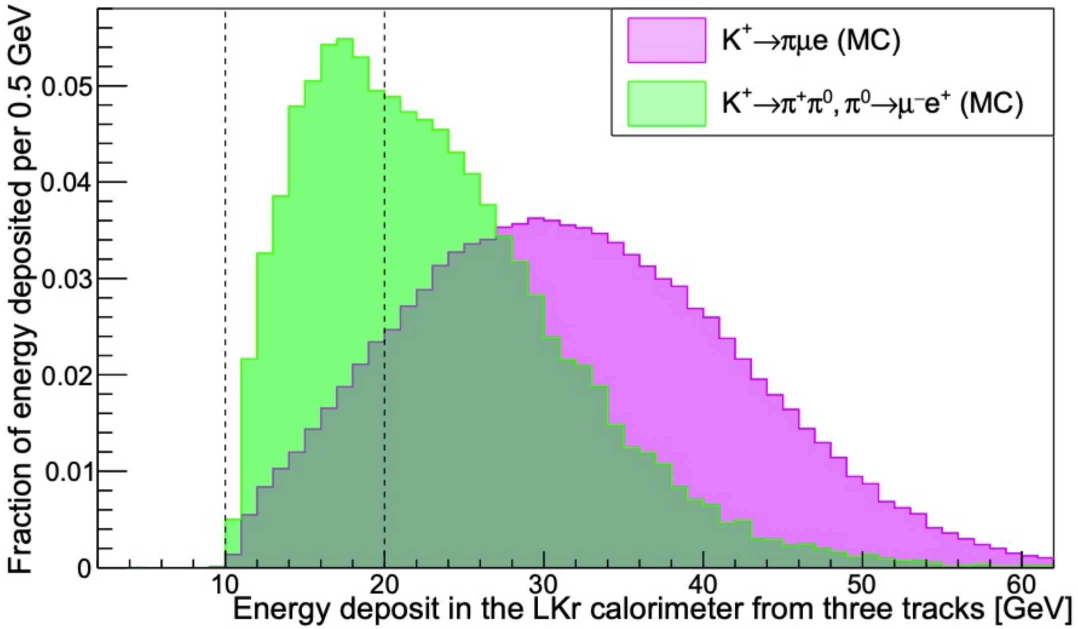
Searches for $K^+ \to \pi^\pm \mu^\mp e^+$ decays at NA62

- Search in 2017 + 2018 Data
- Blind analysis strategy [2 independent analyses cross-checked]
- Triggers :
  - Hardware L0 + software L1.
  - “Rare+Exotics” triggers downscaled (by factors ~ 100, ~ 8, ~ 8) & run simultaneously with $\pi\nu\bar{\nu}$ trigger
  - Account for trigger inefficiency effects.

Trigger Name	Description	Use in LNV/LFV Searches
Multi-Track	Minimum bias 3-track trigger	Collect SM $K^+ \to \pi^+\pi^+\pi^-$ & LNV/LFV $K^+ \to \pi^\pm \mu^\mp e^+$
Multi-Track μ	3 tracks + 10 GeV in LKr + ≥ 1 μ (MUV3) cand.	Collect LNV/LFV $K^+ \to \pi^\pm \mu^\mp e^+$
Multi-Track e	3 tracks with 20 GeV energy deposit in LKr	Collect LNV/LFV $K^+ \to \pi^\pm \mu^\mp e^+$

- Normalization :
  - Use SM $K^+ \to \pi^+\pi^+\pi^-$ decay, $BR = (5.583 \pm 0.024)\%$
  - Find $N_K^{eff} = (1.33 \pm 0.02) \times 10^{12}$ [Effective number of K^+ decays in FV of 105<z<180 m useful for the analysis]

Trigger Efficiencies & Background Studies

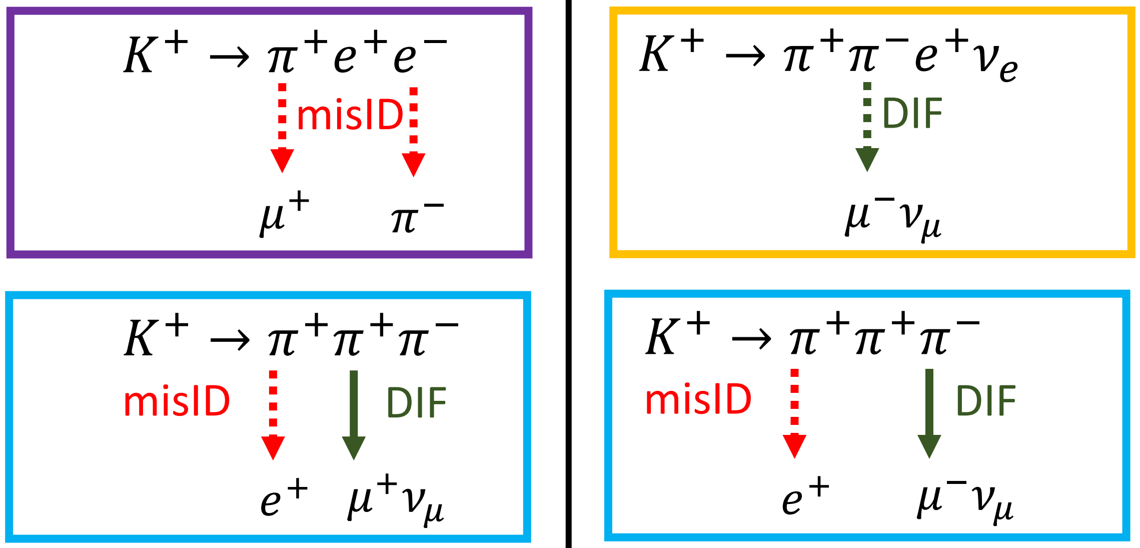


	$K^+ \to \pi^-\mu^+e^+$	$K^+ \to \pi^+\mu^-e^+$	$\pi^0 \to \mu^-e^+$
$A_s \times 10^2$	4.90 ± 0.02	6.21 ± 0.02	3.11 ± 0.02
$\varepsilon_{\mathrm{LKr10}} \times 10^2$	97.5 ± 1.3	97.5 ± 1.3	92.9 ± 1.2
$\varepsilon_{\mathrm{LKr20}} \times 10^2$	74.1 ± 1.6	73.3 ± 1.6	45.3 ± 1.0

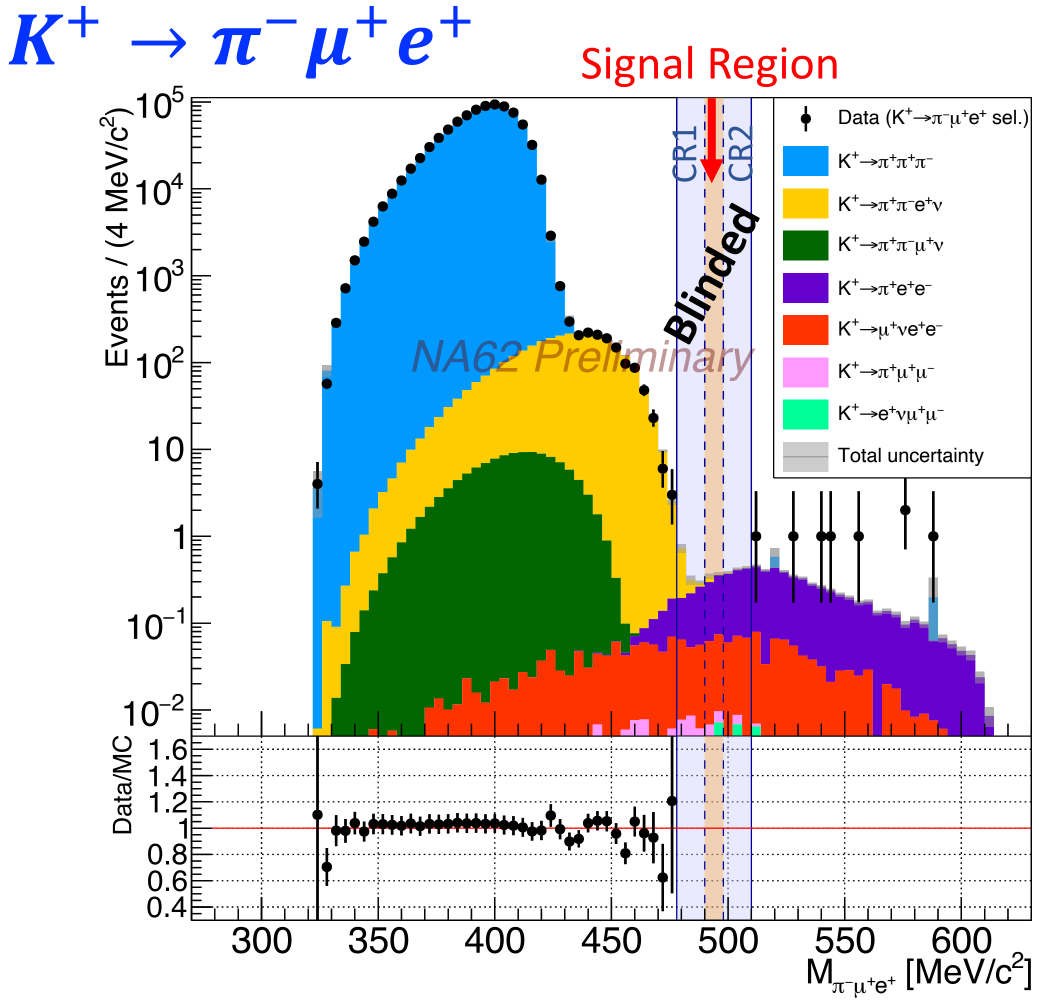
Background Mechanisms:

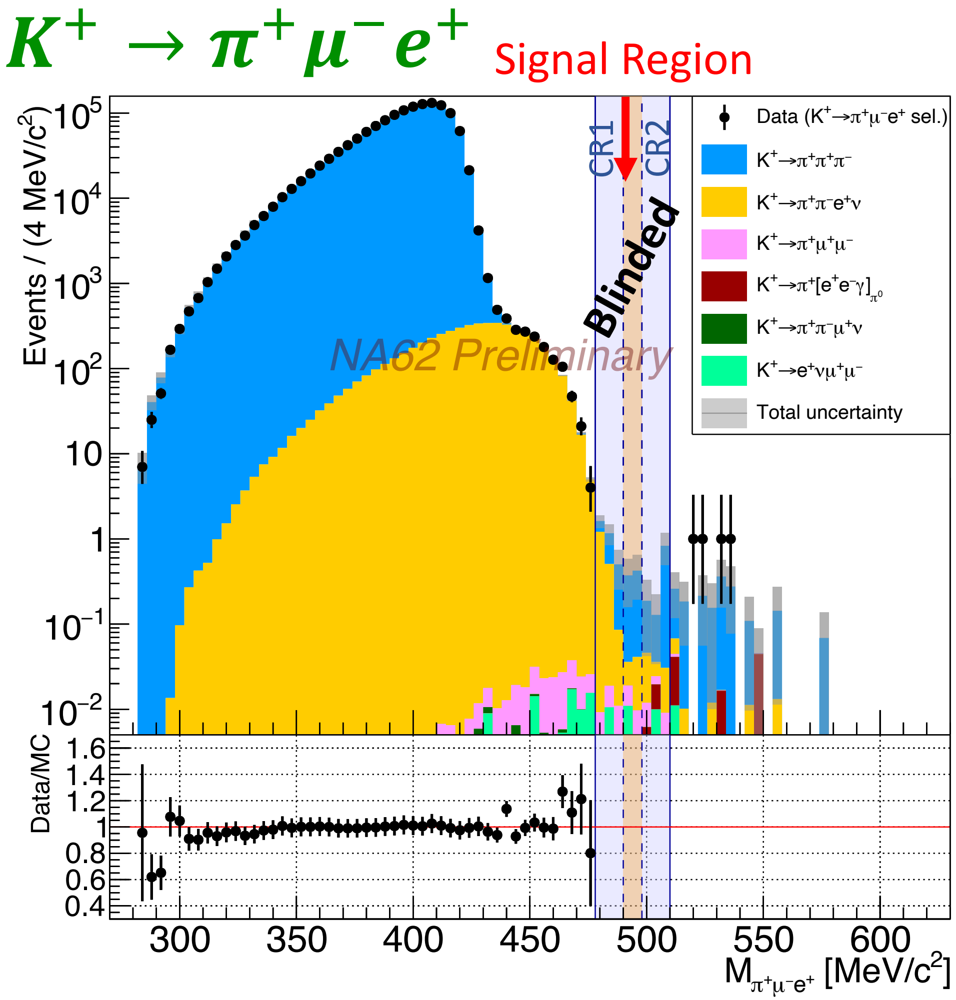
1. Misidentification (misID)
   - Measure with data and apply to simulations.
2. Decays in flight (DIF)
   - Dalitz decays: $\pi^0 \to e^+e^-\gamma$. Dedicated cut to reject in **π^- Channel** – reduces acceptance wrt. **μ^- Channel**.

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



Background Expectations





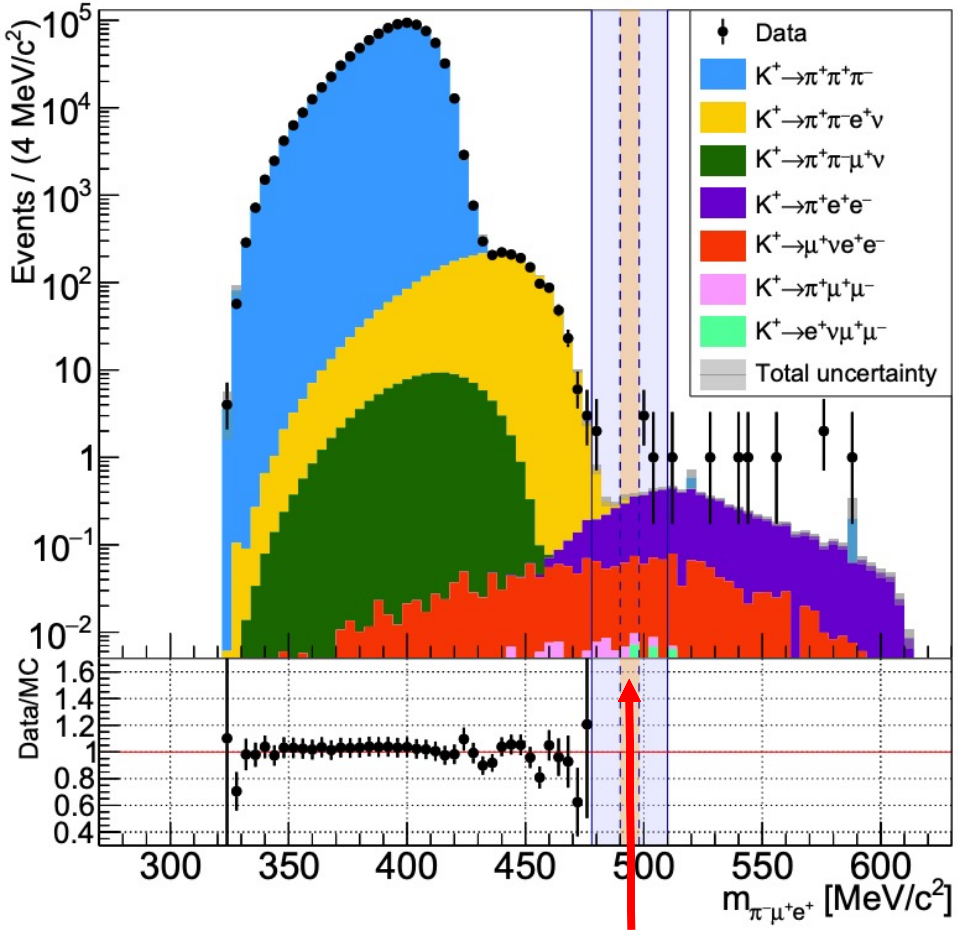
Control regions:

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

Open Signal regions

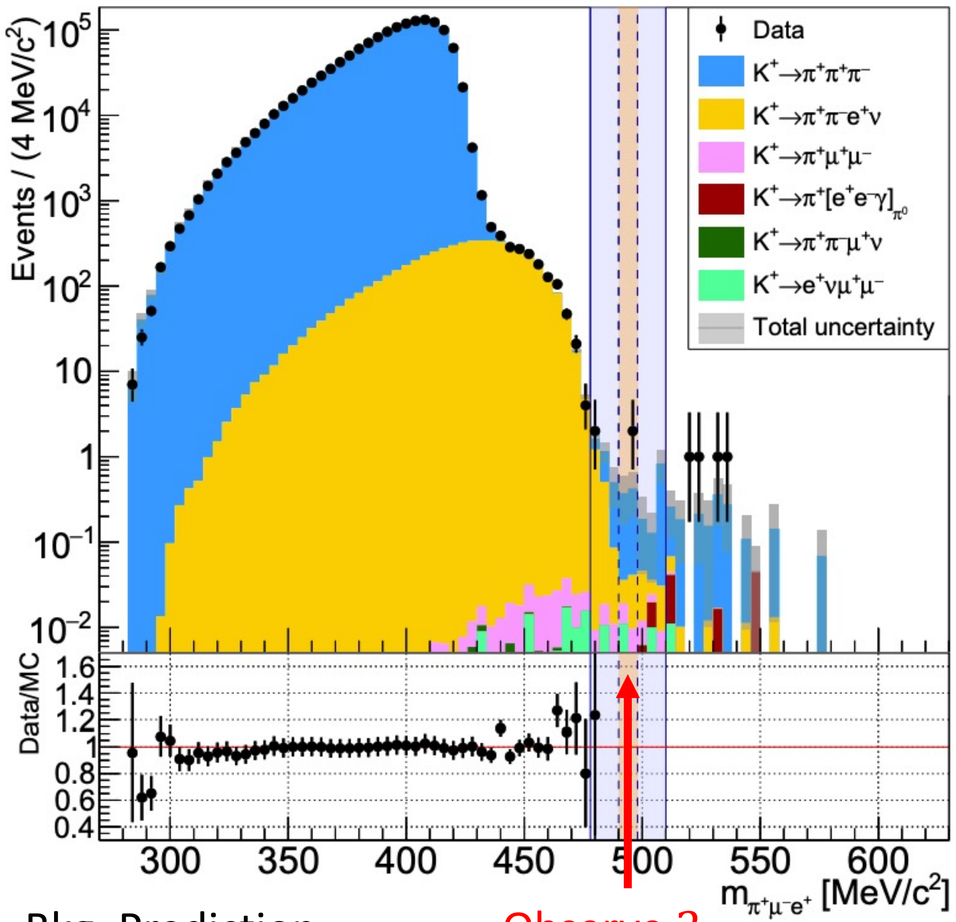
$BR(K^+ \rightarrow \pi^- \mu^+ e^+) < 4.2 \times 10^{-11}$ @ 90% CL

$BR(K^+ \rightarrow \pi^+ \mu^- e^+) < 6.6 \times 10^{-11}$ @ 90% CL



Bkg. Prediction:
$N_{SR}^{tot} = 1.07 \pm 0.20$

Observe 0 events in SR



Bkg. Prediction:
$N_{SR}^{tot} = 0.92 \pm 0.34$

Observe 2 events in SR

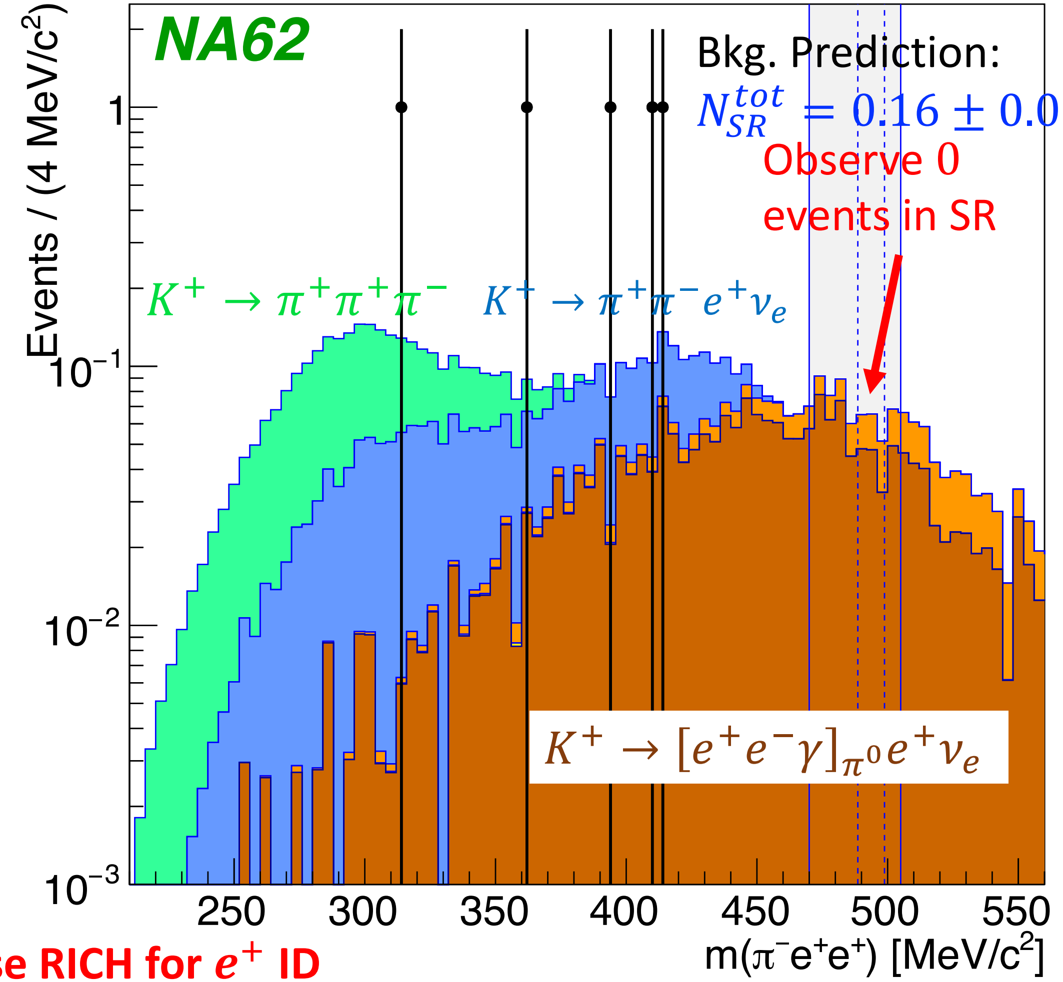
With 0 Events in $K^+ \rightarrow \pi^+\pi^0, \pi^0 \rightarrow \mu^- e^+$ signal region:

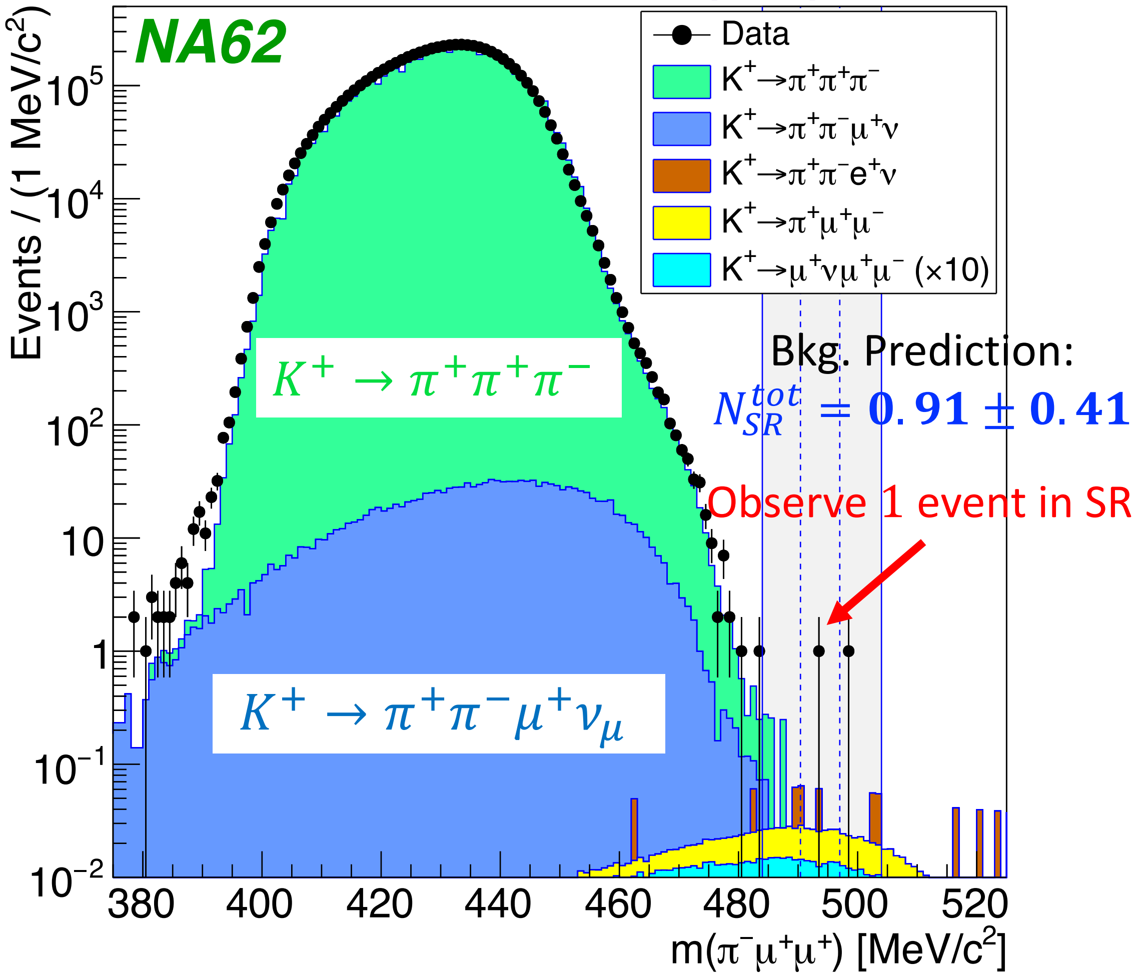
$BR(\pi^0 \rightarrow \mu^- e^+) < 3.2 \times 10^{-10}$ @ 90% CL

3 new upper limits: arXiv:2105.06759

NA62 searches for $K^+ \to \pi^- \ell^+ \ell^+ \; [\ell = \mu, e]$

$K^+ \to \pi^- e^+ e^+$ **PLB 797 (2019) 134794** $K^+ \to \pi^- \mu^+ \mu^+$





Use RICH for e^+ ID

$$BR(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10} \text{ @ } 90\% \, CL$$

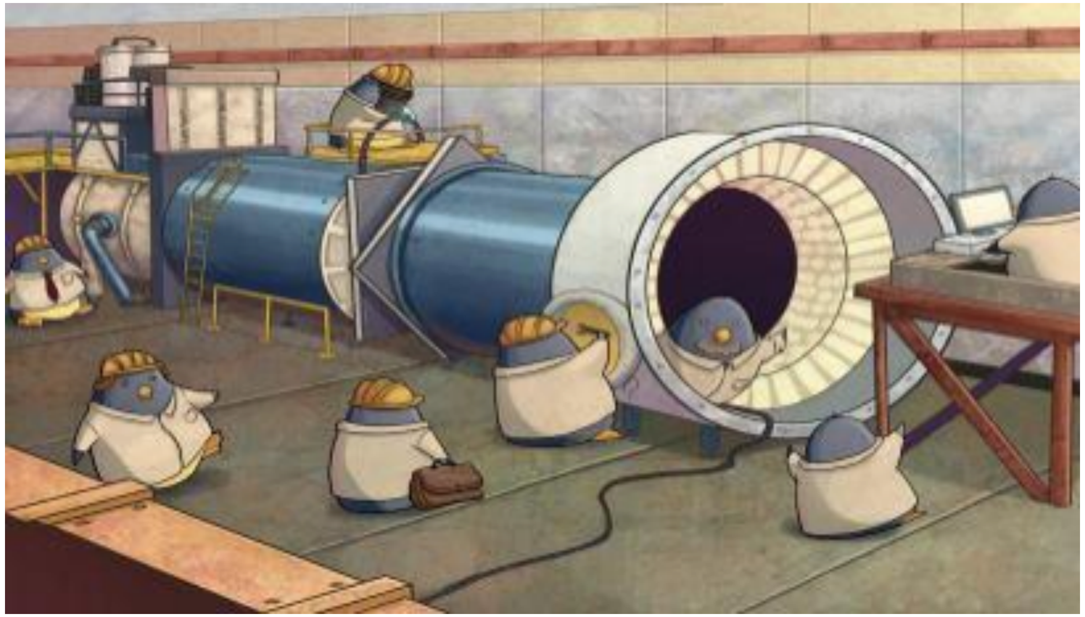
$$BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11} \text{ @ } 90\% \, CL$$

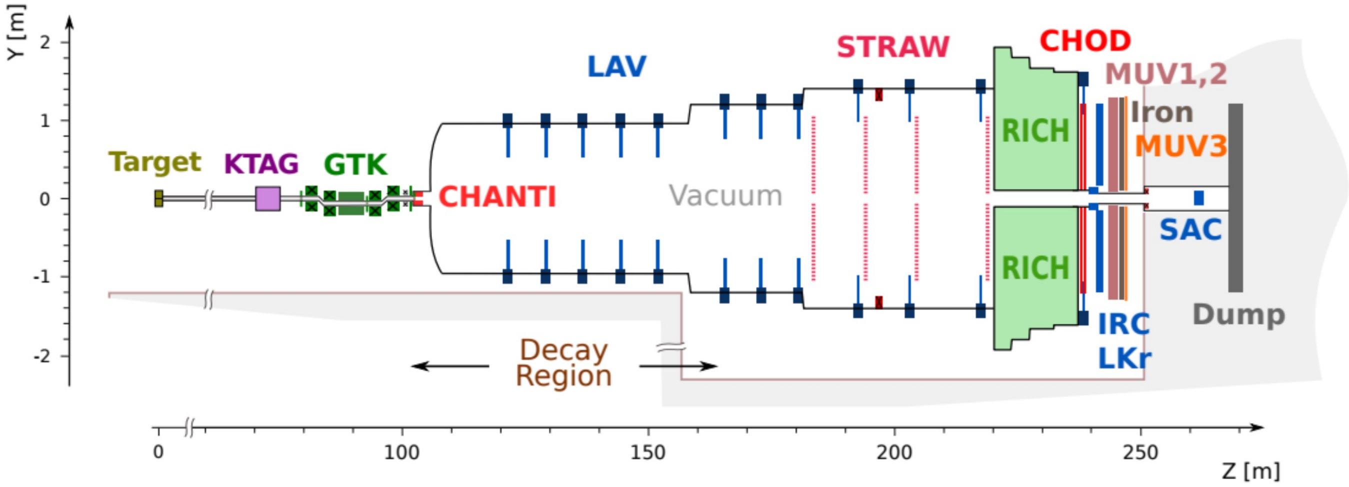
Conclusions And Outlook

Decay	Previous BR upper limit @ 90% CL [PDG]	NA62 BR upper limit @ 90% CL	
$K^+ \to \pi^-\mu^+\mu^+$	8.6×10^{-11}	4.2×10^{-11}	Improve by factor **2** with **30% of 2016-18 data** [PLB 797 (2019) 134794]
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	2.2×10^{-10}	Improve by factor **3** with **30% of 2016-18 data** [PLB 797 (2019) 134794]
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	4.2×10^{-11}	Improve by factor **12** with **2016-18 data** [arXiv:2105.06759]
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	6.6×10^{-11}	Improve by factor **8** with **2016-18 data** [arXiv:2105.06759]
$\pi^0 \to \mu^-e^+$	3.4×10^{-9}	3.2×10^{-10}	Factor 13 improvement on charge-specific result [arXiv:2105.06759]
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}		Not yet competitive with previous dedicated experiment
$K^+ \to \mu^-\nu e^+e^+$	2.1×10^{-8}		Stay tuned… $SES\sim1\times10^{-10}$ [2017 data]
$K^+ \to e^-\nu\mu^+\mu^+$	No previous limit…		Stay tuned… $SES\sim5\times10^{-11}$ [2017 data](first search)

- Alongside 'headline' $K^+ \to \pi^+\nu\bar{\nu}$ studies NA62 has a broad physics program with world-leading sensitivities to rare and forbidden K^+ decays.
  - See other NA62 talks at this conference : $K^+ \to \pi^+\nu\bar{\nu}$ results, Search for FIPs , Search for HNLs.
- NA62 resumes data-taking this year at higher intensity with new & upgraded detectors.
- Stay tuned for more LNV/LFV searches…

Supplemental





Background Expectations

arXiv:2105.06759

Control regions:

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

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

Results Summary

arXiv:2105.06759

- Observations consistent with background expectation therefore set upper limit on branching ratios
  - Counting experiment, CLs treatment

Single Event Sensitivity = $\mathcal{B}_{\mathrm{SES}}^{i} = \frac{1}{N_K^i A_{\mathrm{s}} \varepsilon_{\mathrm{s}}^i} = \mathcal{B}(K_{3\pi}) \frac{A_{\mathrm{n}} D_{\mathrm{eff}}^i}{A_{\mathrm{s}} N_{3\pi}^i D_{\mathrm{MT}}^i} \frac{\varepsilon_{\mathrm{n}}}{\varepsilon_{\mathrm{s}}^i}$

	$K^+ \to \pi^- \mu^+ e^+$	$K^+ \to \pi^+ \mu^- e^+$	$\pi^0 \to \mu^- e^+$
Signal acceptance	$(4.90 \pm 0.02)\%$	$(6.21 \pm 0.02)\%$	$(3.11 \pm 0.02)\%$
Single event sensitivity	$(1.82 \pm 0.08)\times10^{-11}$	$(1.44 \pm 0.05)\times10^{-11}$	$(13.9 \pm 0.9)\times10^{-11}$
Bkg. expectation in signal region	$\mathbf{1.07 \pm 0.20}$	$\mathbf{0.92 \pm 0.34}$	$\mathbf{0.23 \pm 0.15}$
Events observed	**0**	**2**	**0**
***BR* upper limit @ 90% CL**	$\mathbf{4.2\times10^{-11}}$	$\mathbf{6.6\times10^{-11}}$	$\mathbf{3.2\times10^{-10}}$
Previous world-best limits: [PRL 85 (2000) 2877]	5.0×10^{-10}	5.2×10^{-10}	3.4×10^{-9}

Summary: searches for $K^+ \to \pi^- \ell^+ \ell^+$ $[\ell = \mu, e]$

NA62

PLB 797 (2019) 134794

	$K_{\pi ee}$ analysis	$K_{\pi\mu\mu}$ analysis
SM candidates selected $N_{\pi\ell\ell}$	2484	8357
Background contamination f_ℓ	negligible	7×10^{-4}
Acceptance $A_{\pi\ell\ell}$	3.87%	10.93%
Acceptance $A_{\pi\ell\ell}^{\mathrm{LNV}}$	4.98%	9.81%
Branching fraction $\mathcal{B}_{\pi\ell\ell} \times 10^7$	3.00 ± 0.09 [6]	0.962 ± 0.025 [12]
Number of decays in FV $N_K^{\pi\ell\ell}/10^{11}$	$2.14 \pm 0.04_{\mathrm{stat}} \pm 0.06_{\mathrm{ext}}$	$7.94 \pm 0.09_{\mathrm{stat}} \pm 0.21_{\mathrm{ext}}$
Single event sensitivity $S_{\pi\ell\ell}$	$(0.94 \pm 0.03) \times 10^{-10}$	$(1.28 \pm 0.04) \times 10^{-11}$

$K^+ \to \pi^- e^+ e^+$ signal mass region

Process	Expected Background
$K^+ \to \pi_D^0 e^+ \nu_e$	$0.12 \pm 0.02_{stat}$
$K^+ \to e^+ \nu_e e^+ e^-$	$0.04 \pm 0.01_{stat}$
Total	$0.16 \pm 0.03_{stat}$

Table 2: Expected backgrounds in the $K^+ \to \pi^- \mu^+ \mu^+$ signal mass region with their statistical uncertainties.

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