International Conference on New Frontiers in Physics

23rd August to 2nd September 2021

Search for lepton number and flavour violation in K^+ and π^0 decays at NA62

Tom Bache (University of Birmingham, UK)

On behalf of the NA62 Collaboration

thomas.bache@cern.ch

Outline

Introduction to NA62 and kaon physics

- History of kaon physics
- NA62 beam and detector layout
- NA62's physics programme

Introduction to searches for LFV/LNV decays at NA62

- Theory
- Data taking

Search for LFV/LNV in $K^+ \to \pi^{\mp}\mu^{\pm}e^+$ and $\pi^0 \to \mu^-e^+$

- Background studies
- Opened signal regions

Search for LFV/LNV in $K^+ \to \pi^-l^+l^+$

- Opened signal regions

Conclusions and the future of NA62

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Conclusions and the future of NA62

NA62 and kaon physics at CERN

~200 participants, 30 institutes, 14 countries

1980s — NA31
First evidence of direct CPV

1997-2001 — NA48
Discovery of direct CPV

2002 — NA48/1
Rare decay studies

2003-2004 — NA48/2
Precision measurements

2007-2008 — NA62-$\boldsymbol{R_K}$
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$

2015-2018 — NA62 Run 1
(2015-2018)

2021-LS3 — NA62 Run 2
(2021-LS3)

Main goal: $B(K^+ \to \pi^+ \nu\bar{\nu})$
LNV/LFV searches, HNL…
Precision measurements

K_L/K_S beam

K_S/hyperon beam

K^+/K^- beam

K^+ beam

Run 1 searches in this talk!

Other NA62 talks

See the other ICNFP 2021 talks by NA62:

- 25th July -> P. Massarotti (Search for K+ decays to a lepton and invisible particles)
- 27th July (later this session) -> A. Bizzeti (Measurement of the very rare K+ to pi+ nu nubar decay)
- 30th July -> G. Lamanna (New measurement of radiative decays at the NA62 Experiment at CERN)

[JINST 12 (2017) P05025]

NA62 beam and detector layout

- KTAG (upstream Cherenkov detector) tags kaons in the beam ($\sigma_T \sim 70$ps)
- GTK (silicon pixel spectrometer) tracks the beam
- STRAW (magnetic spectrometer) tracks K^+ decay products
- RICH (downstream Cherenkov detector) provides PID ($\pi^+/\mu^+/e^+$) and timing ($\sigma_T \sim 70$ps)
- LKr (ECAL) provides PID and photon veto
- LAV, IRC and SAC provide additional photon veto to achieve hermetic acceptance (0-50 mrad) of photons
- Hadronic calorimetry provided by MUV1/2
- MUV3 provides muon detection/veto
- CHOD and NA48-CHOD used for trigger and timing ($\sigma_T \sim 200$ps)

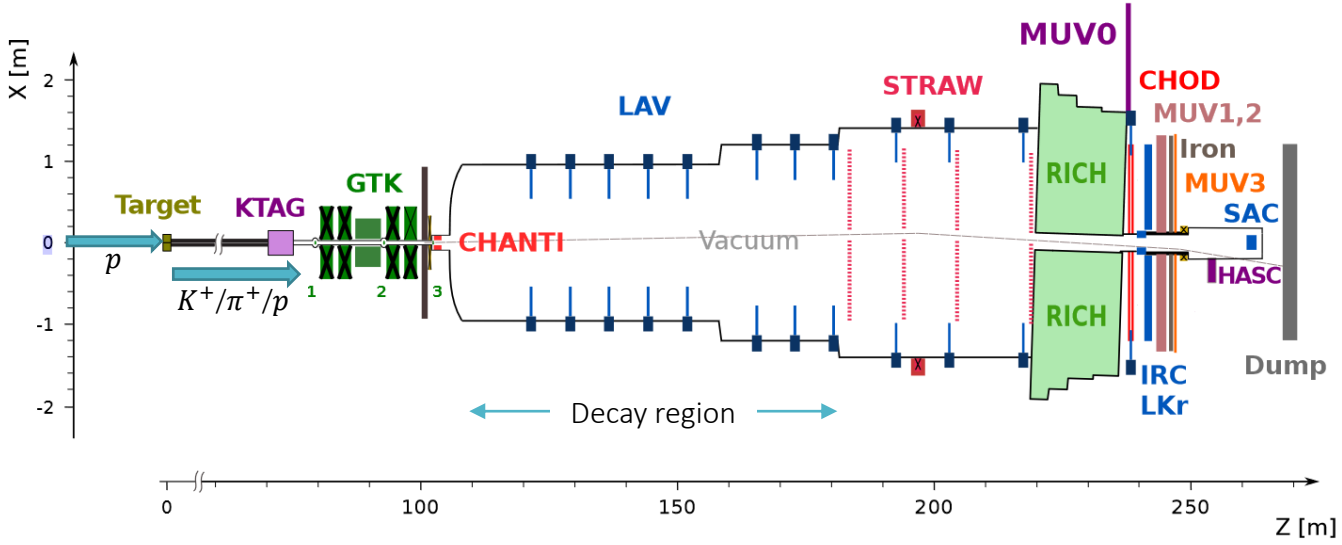
Protons from CERN SPS impinge on beryllium target.

Leads to an unseparated beam consisting of K^+, π^+ and protons entering NA62.

6% of the beam is K^+.

Beam rate ~500 MHz at decay region entrance
$\Rightarrow K^+$ decay rate ~5 MHz in the decay region.

Beam momentum = 75 GeV/c ($\pm 1\%$)



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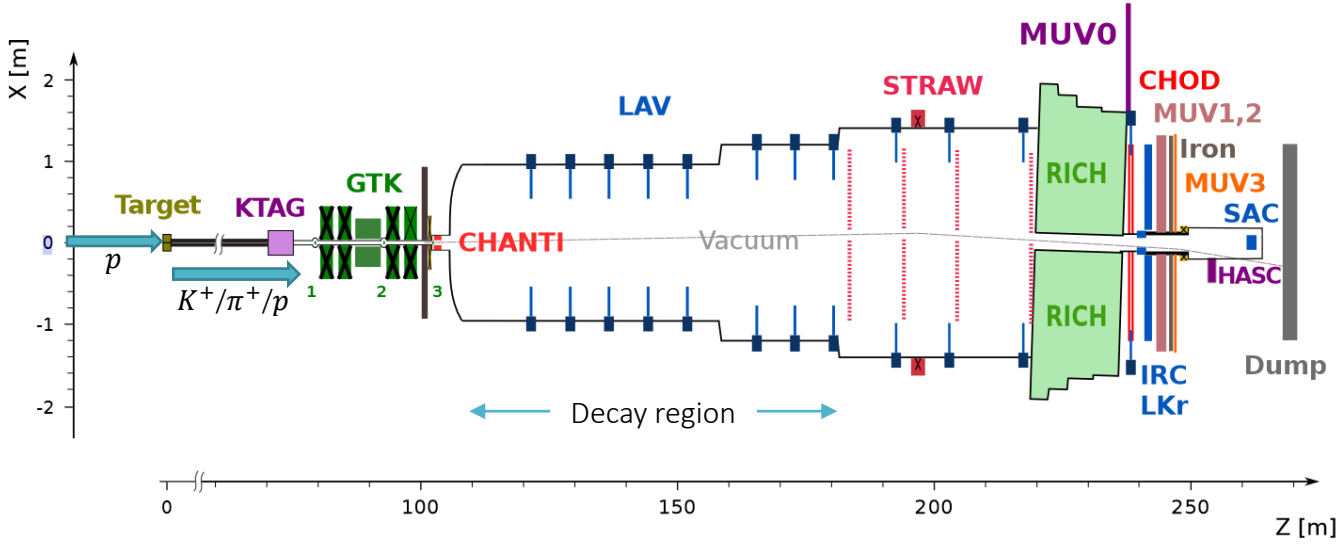
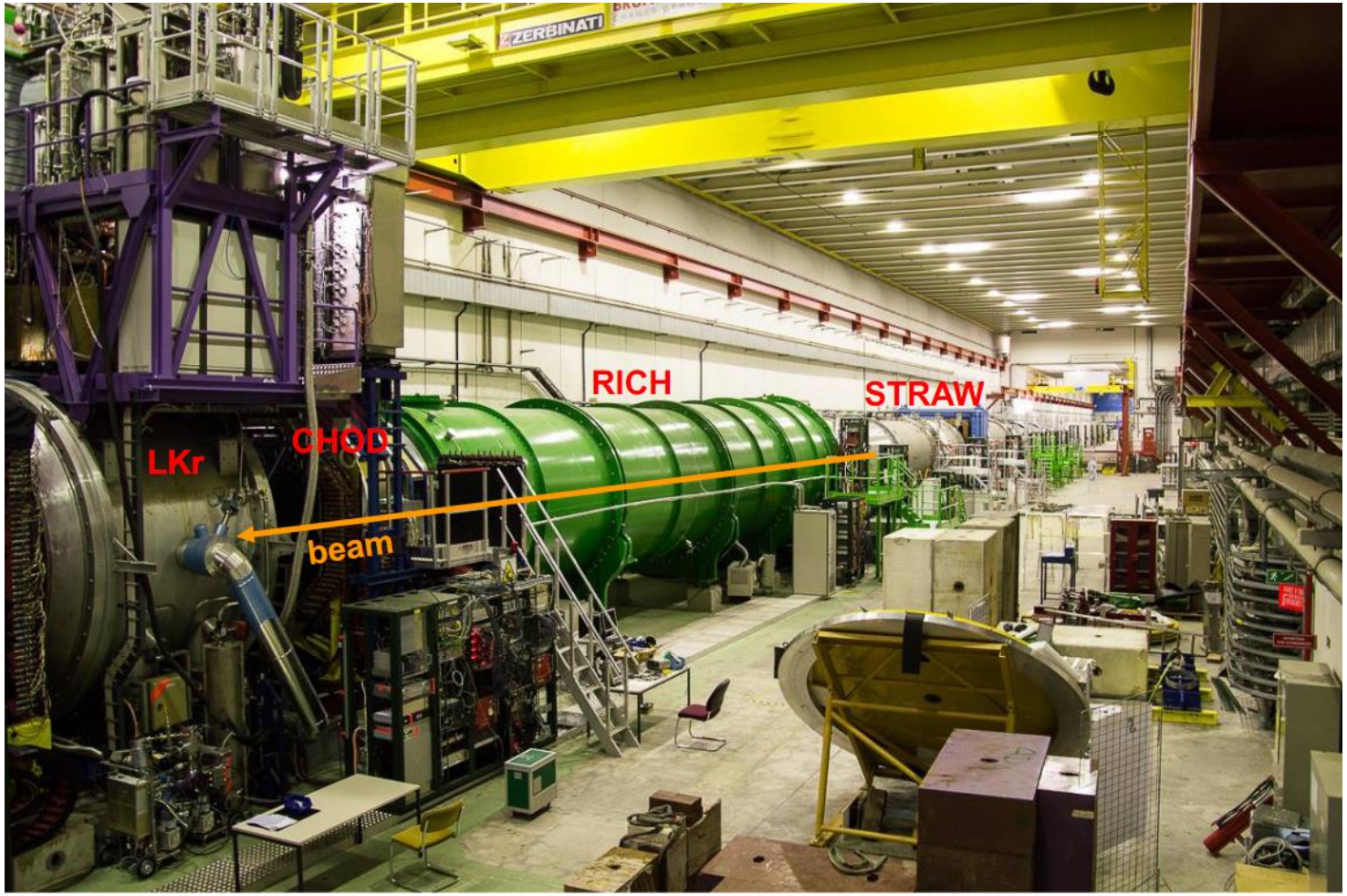
Key performance parameters:

- Very good timing resolution O(100ps).
- Kinematic rejection O(10^4) of $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$.
- Particle ID to suppress muons from $K^+ \to \mu^+\nu > 10^7$.
- Photon veto to suppress $\pi^0 \to \gamma\gamma$ from $K^+ \to \pi^+\pi^0 > 10^7$.



NA62 beam and detector layout



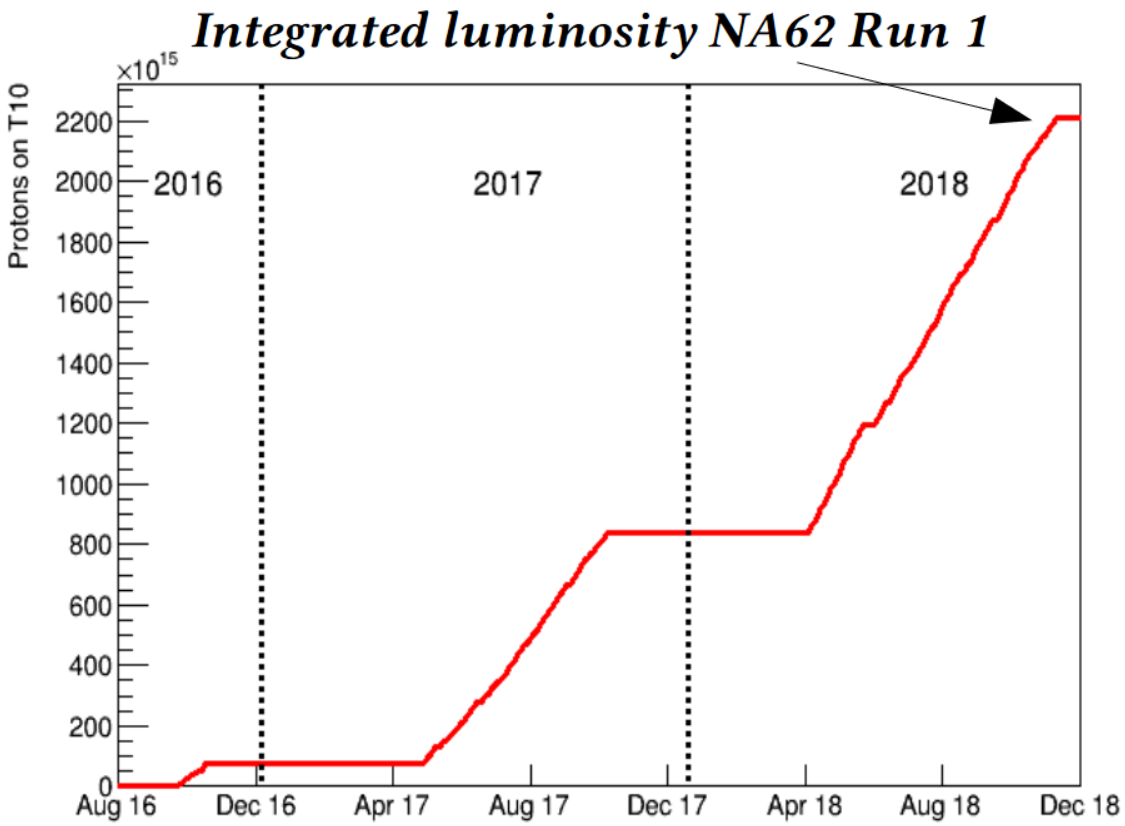
NA62 data taking periods

Run 1 comprises of 3 years of data taking between 2016 and 2018.

- 408 days in total.
- $\sim 6 \times 10^{12}$ K^+decays.

Run 2 started in July 2021 and will continue until 2023.

- Expect to collect $O(10^{13})$ K^+decays.



NA62's varied physics programme

Main goal of NA62 is to measure $K^+ \to \pi^+ \nu\bar{\nu}$, a decay with branching ratio $\sim 10^{-10}$

- Aiming for O(10%) precision.
- 20 candidates observed in Run 1 (6×10^{12} K^+ decays in flight, collected between 2016 and 2018), corresponding to a signal significance of 3.4σ [JHEP 06 (2021) 093].
- Data taking in Run 2 restarted in July 2021!

Large variety of other measurements have been/are being conducted:

- Rare decay and precision measurements (e.g. $K^+ \to \pi^+ \mu^+ \mu^-$ which has branching ratio $\sim 10^{-7}$ [ICHEP 2020 proceedings]).
- Exotic searches of e.g. HNL in $K^+ \to l^+ N$ [PLB 807 (2020) 135599, PLB 816 (2021) 136259].
- Searches for forbidden decays (e.g. LFV and LNV in $K^+ \to \pi^\pm \mu^\mp e^+$ and $K^+ \to \pi^- l^+ l^+$).
  - ➢ This talk!

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Conclusions and the future of NA62

Searches for forbidden LFV/LNV decays

Conservation of lepton flavour and lepton number is not required during construction of the standard model.

Observation of LFV or LNV would suggest BSM physics was at play.

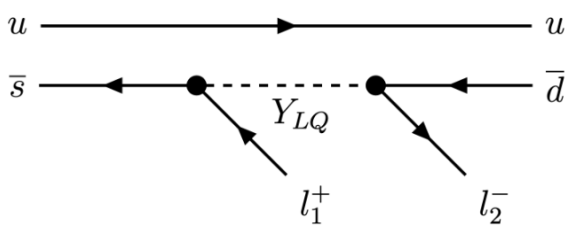
Five decays shown in this talk:

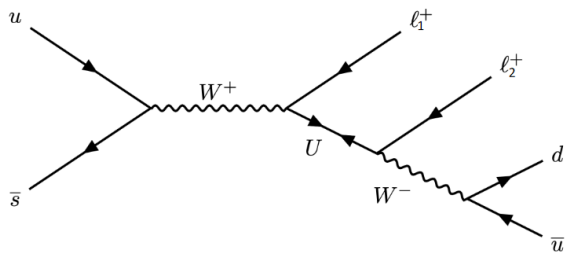
$K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^+ \mu^- e^+$ } $K_{\pi\mu e}$ $\quad \Delta L = 2$ if π^- and $\Delta L_e = \Delta L_\mu = 1$

$K^+ \to \pi^+ [\mu^- e^+]_{\pi^0}$ $\quad \Delta L_e = \Delta L_\mu = 1$ for $\pi^0 \to \mu^- e^+$

$K^+ \to \pi^- \mu^+ \mu^+$, $K^+ \to \pi^- e^+ e^+$ } $K_{\pi ll}$ $\quad \Delta L = 2$

All analyses were blinded until the backgrounds were validated.





Searches for forbidden LFV/LNV decays

Four different triggers used to collect data for these analyses:

Trigger	L0 definition	L1 definition	Downscaling (at L0)
Multi-track (MT)	RICH + 2 CHOD signals	KTAG + STRAW	100
Muon multi-track (μMT)	RICH + 2 CHOD signals + MUV3 signal	KTAG + STRAW	8
Dimuon multi-track ($2\mu MT$)	RICH + 2 CHOD signals + 2 MUV3 signals	STRAW	2
Electron multi-track (eMT)	RICH + 2 CHOD signals + 20 GeV energy in LKr	KTAG + STRAW	8

Triggers used for each mode:

$K^+ \to \pi^- \mu^+ e^+$
$K^+ \to \pi^+ \mu^- e^+$
$K^+ \to \pi^+ [\mu^- e^+]_{\pi^0}$
} $MT + \mu MT + eMT$

$K^+ \to \pi^- \mu^+ \mu^+$ $\quad 2\mu MT$
$K^+ \to \pi^- e^+ e^+$ $\quad MT + eMT$

All analyses were blinded until the backgrounds were validated.

Use $K^+ \to \pi^+ \pi^+ \pi^-$ as normalisation for $K_{\pi\mu e}$ (collected with the MT trigger).

Use the SM equivalent decays for $K_{\pi ll}$ normalisation (collected with the same triggers):
$K^+ \to \pi^+ \mu^+ \mu^-$
$K^+ \to \pi^+ e^+ e^-$

All chosen as kinematically similar ⇒ systematics cancelation.

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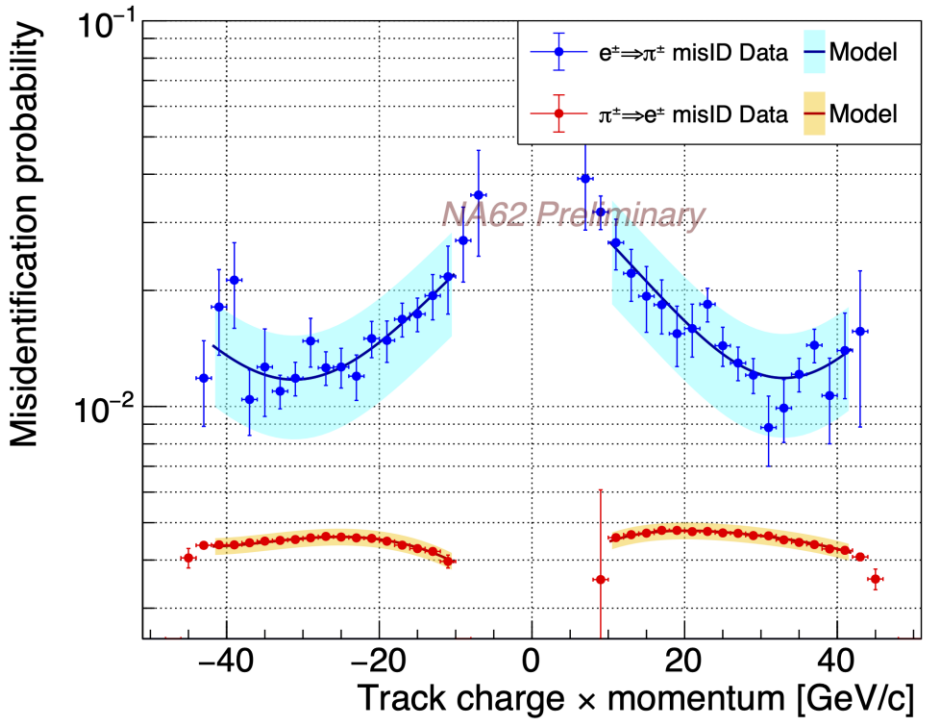
Conclusions and the future of NA62

arXiv:2105.06759

$K_{\pi\mu e}$ background studies

Main background decays:
- $K^+ \to \pi^+\pi^+\pi^-$ and $K^+ \to \pi^+e^+e^-$

Backgrounds arise from two mechanisms:
- Mis-ID
  - Selection uses the energy deposited in the LKr and the momentum measurement by STRAW for PID:
    $\pi^\pm \to E/p < 0.9$
    $e^\pm \to 0.95 < E/p < 1.05$
  - But…simulation constraints mean data-driven corrections are needed to account for mis-ID.
  - Mis-ID of π/e as μ due to accidental activity in MUV3 also accounted for.
- Decays in flight
  - Charged pion decays: $\pi^+ \to \mu^+\nu$ and $\pi^+ \to e^+\nu$
  - Neutral pion decays: $\pi^0 \to e^+e^-\gamma$



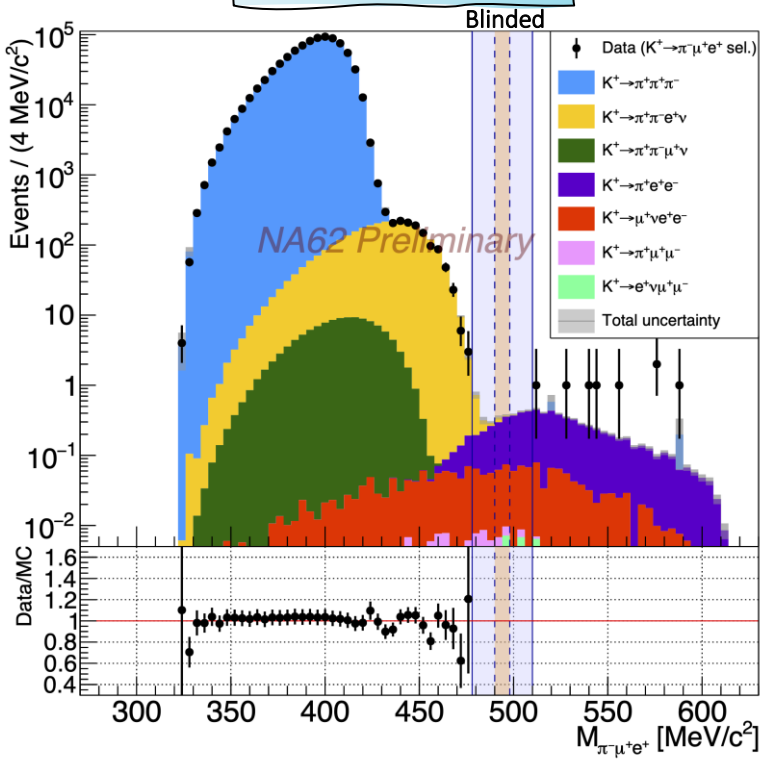
Mis-ID accounted for by measuring probabilities using data (see plot) and reweighting MC.

Pion decay in flight well simulated but reduced by using dedicated cuts (photon veto, vertex quality, kinematic…) in the selection.

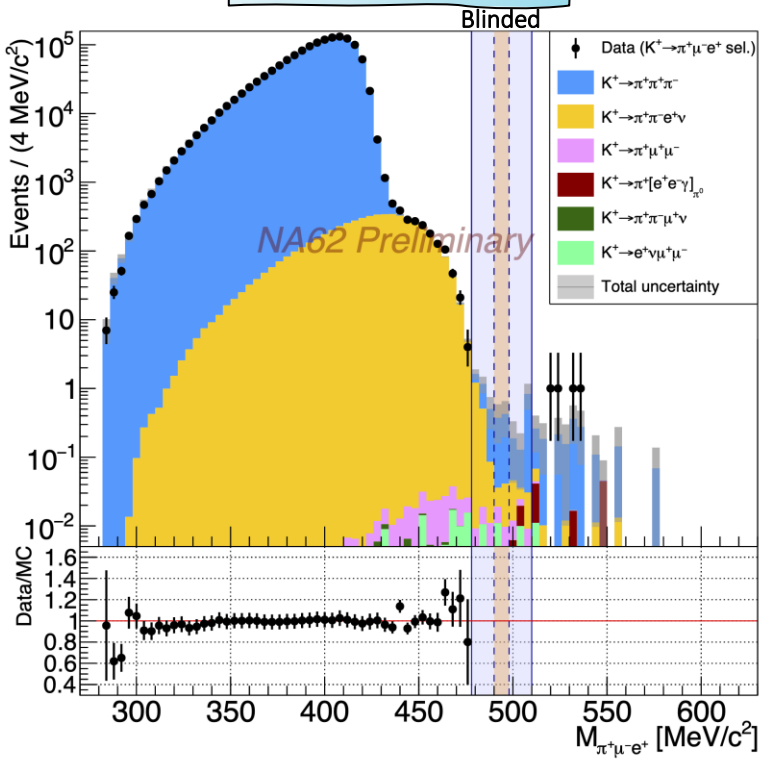
arXiv:2105.06759

$K_{\pi\mu e}$ background studies

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



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



Backgrounds validated in control regions either side of signal region before unblinding (CR1 below and CR2 above).

After unblinding CRs:

$K^+ \to \pi^-\mu^+e^+$	CR1	Signal region	CR2
Expected	1.68 ± 0.20	1.06 ± 0.20	1.66 ± 0.26
Observed	2	BLIND	4

$K^+ \to \pi^+\mu^-e^+$	CR1	Signal region	CR2
Expected	3.41 ± 0.54	0.92 ± 0.34	1.27 ± 0.40
Observed	2	BLIND	0

Signal acceptances and SES:

	Acceptance, A_s	SES
$K^+ \to \pi^-\mu^+e^+$	$(4.90 \pm 0.02)\%$	$(1.82 \pm 0.08) \times 10^{-11}$
$K^+ \to \pi^+\mu^-e^+$	$(6.21 \pm 0.02)\%$	$(1.44 \pm 0.05) \times 10^{-11}$

$$SES = \frac{1}{N_K^{eff} A_S \epsilon_{trigger}}$$

arXiv:2105.06759

$K^+ \to \pi^\pm \mu^\mp e^+$ - opening signal regions

Run 1 dataset used.

Results:

$\boldsymbol{B(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11}}$ **@ 90% CL**

$\boldsymbol{B(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11}}$ **@ 90% CL**

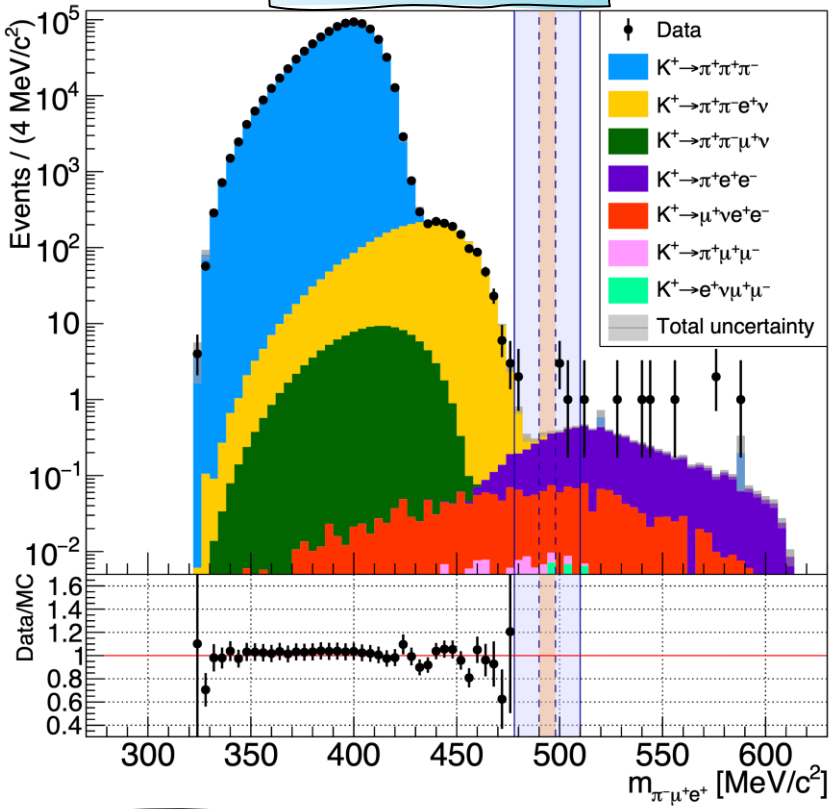
Both results are an order of magnitude improvement on the PDG. Accepted for publication in Phys. Rev. Lett.

Also altered the selection used for the $K^+ \to \pi^+ \mu^- e^+$ channel search to look for the LFV decay $\pi^0 \to \mu^- e^+$ from $K^+ \to \pi^+ \pi^0$.

Find $N_{bkg} = 0.23 \pm 0.15$ and $N_{obs} = 0$, leading to another result that is an order of magnitude improvement on the PDG:

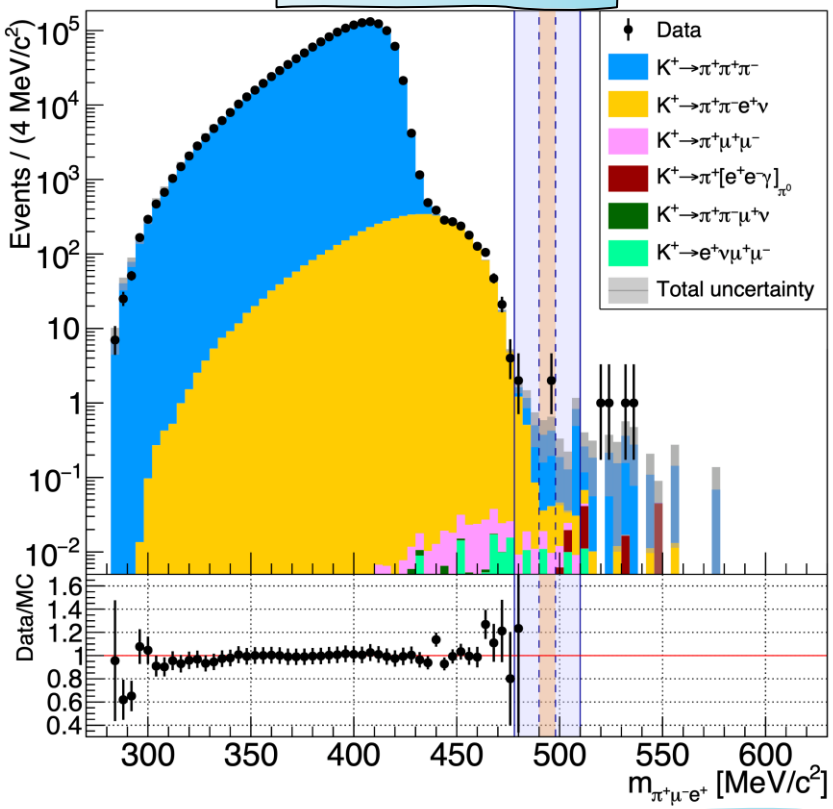
$\boldsymbol{B(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10}}$ **@ 90% CL**

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



0 events in SR.
Background prediction: $N_{bkg} = 1.06 \pm 0.20$

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



2 events in SR.
Background prediction: $N_{bkg} = 0.92 \pm 0.34$

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$K^+ \to \pi^- l^+ l^+$

Two lepton number violating decays studied:

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

Main backgrounds present in the signal region differ in each case:

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

- $K^+ \to e^+ \nu [e^+ e^- \gamma]_{\pi^0}$
- $K^+ \to e^+ \nu e^+ e^-$

} e^- mis-ID as π^- (probability of $\sim 1\%$).

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

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

} π^+ decay in flight and $\pi \leftrightarrow \mu$ mis-ID (probability of $0.4 - 0.5\%$).

- Normalisation done relative to $K^+ \to \pi^+ l^+ l^-$ (similar decay but under SM).
- Backgrounds validated in control regions (without the RICH in $K_{\pi ee}$ case to increase statistics).

$K^+ \to \pi^- l^+ l^+$ - opening signal regions

~30% of total Run 1 dataset used.

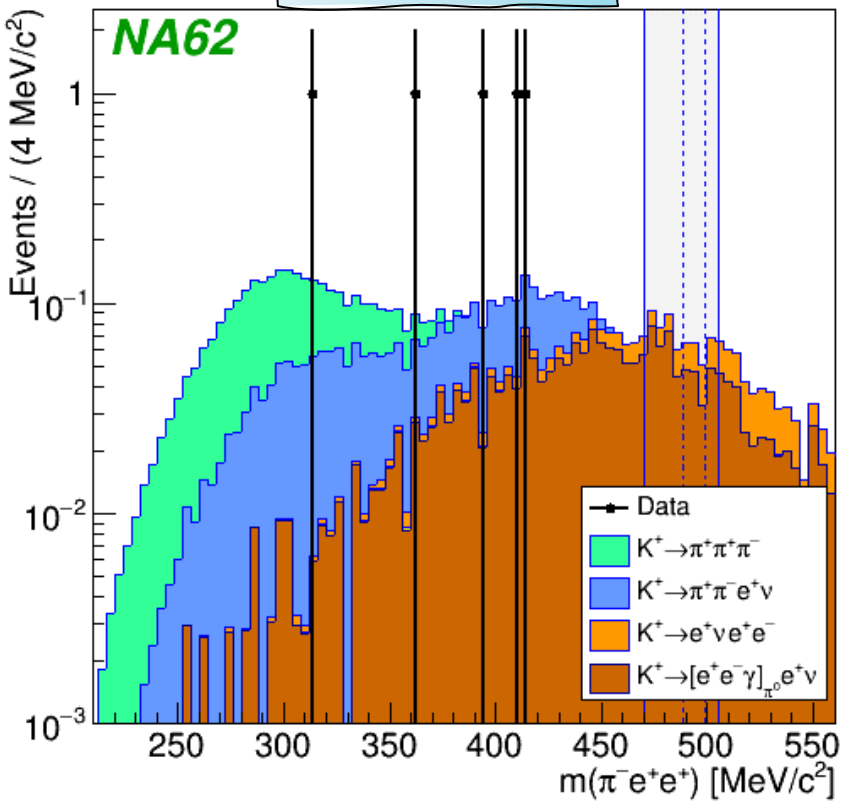
Final results:

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

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

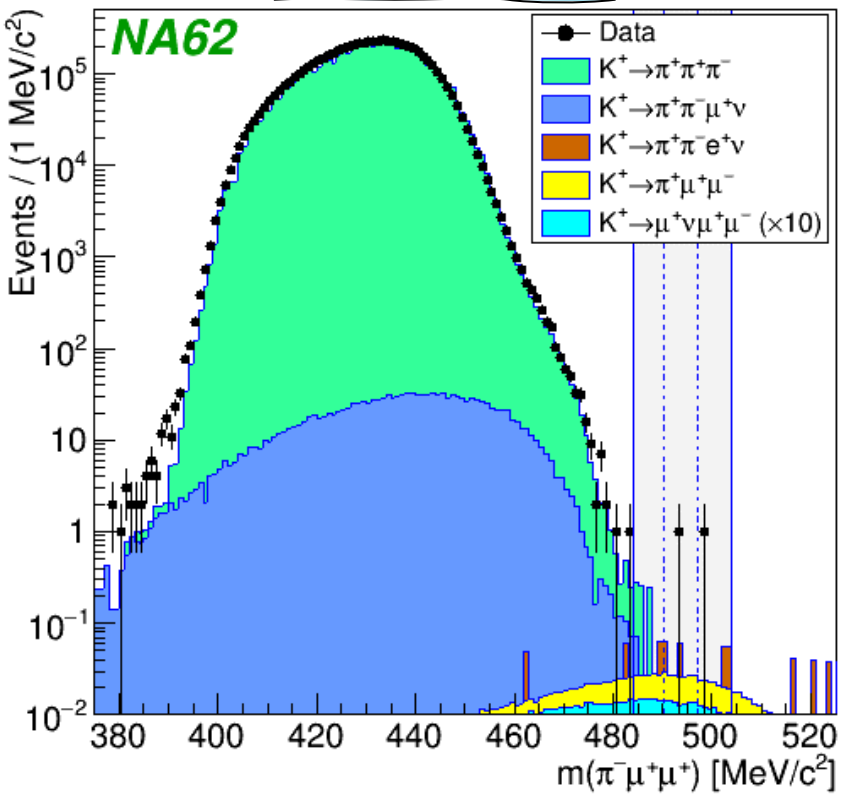
Both results are a factor 2-3 improvement on the PDG.

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



0 events in SR.
Background prediction: $N_{bkg} = 0.16 \pm 0.03$

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



1 events in SR.
Background prediction: $N_{bkg} = 0.91 \pm 0.41$

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Conclusions

NA62 has collected 6×10^{12} K^+ decays in flight during Run 1, with multiple world leading analyses taking place.

Only time to discuss searches for LNV/LFV during this talk:

- Order of magnitude improvement on upper limit of $B\left(K^+ \to \pi^{\pm}\mu^{\mp}e^+\right)$ and $B(\pi^0 \to \mu^- e^+)$.
- Factor 2-3 improvement on upper limit of $B(K^+ \to \pi^- l^+ l^+)$.

Other interesting analyses recently published/made public:

- $K^+ \to \pi^+ \nu\bar{\nu}$ [JHEP 06 (2021) 093], $K^+ \to \pi^+ \mu^+ \mu^-$ [ICHEP 2020 proceedings], $K^+ \to l^+ N$ [PLB 807 (2020) 135599, PLB 816 (2021) 136259], $K^+ \to \pi^+ X$ [JHEP 03 (2021) 058].

NA62 Run 2 started in July 2021 and will continue until LS3. Improvements relative to Run 1:

- Higher intensity (70% -> 100%).
- 4th GTK station added.
- Three new veto counters placed upstream or downstream of decay region.

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