XIV International Conference on Beauty, Charm and Hyperon Hadrons

Latest results on rare decays at the NA62 experiment at CERN

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on behalf of NA62 Collaboration

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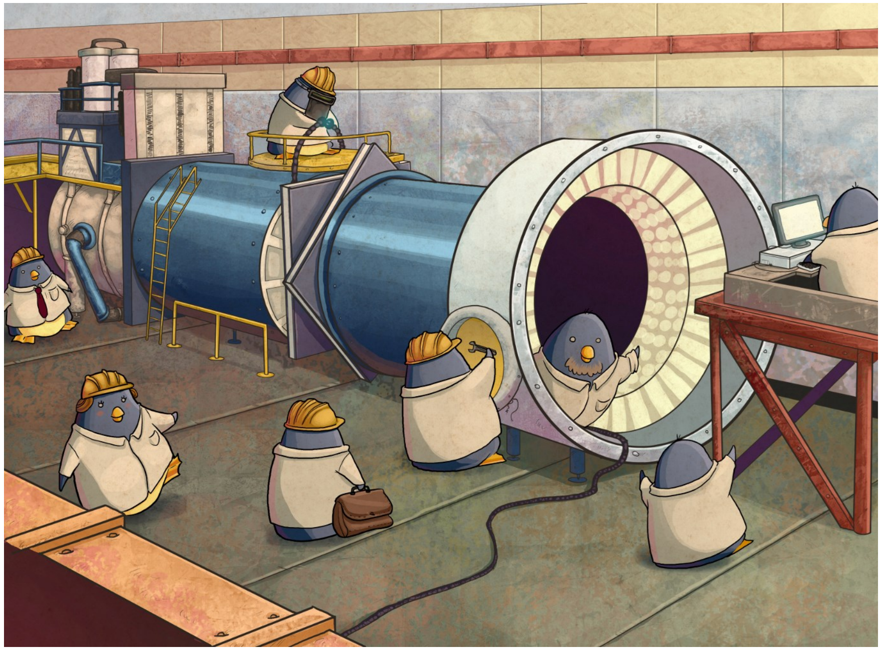
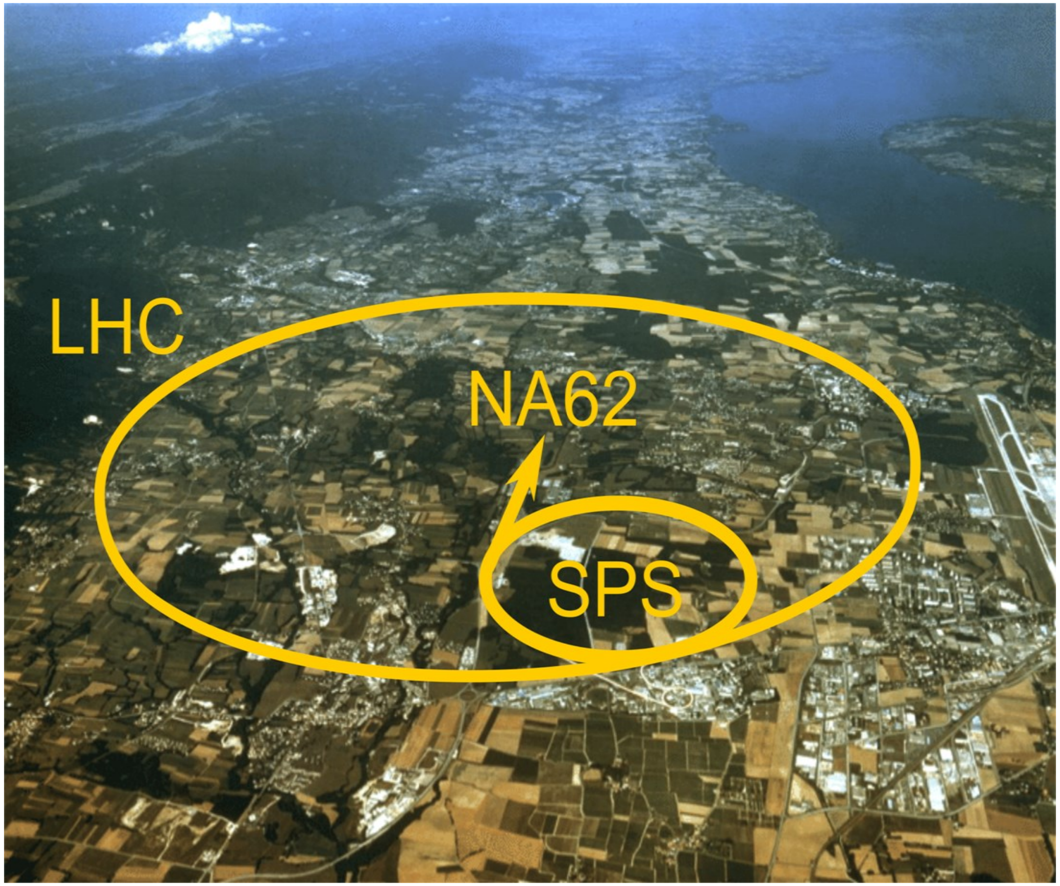
Outline

- Overview of the NA62 experiment
- Lepton Flavour/Number Violating decays
- Heavy Neutral Leptons (HNL) searches:
  - HNL production: $K^+ \to e^+N, K^+ \to \mu^+N$
- $K^+ \to \mu^+\nu\nu\nu, K^+ \to \mu^+\nu X$
- Summary



The NA62 experiment



~30 institutes, ~200 participants from:
Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

NA62 is a fixed-target experiment at CERN SPS

Main goal: measure $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ with 10% precision using novel kaon-in-flight technique

Current theoretical prediction:

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

[Buras et al., JHEP11(2015)033]

Experimental values:

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$$

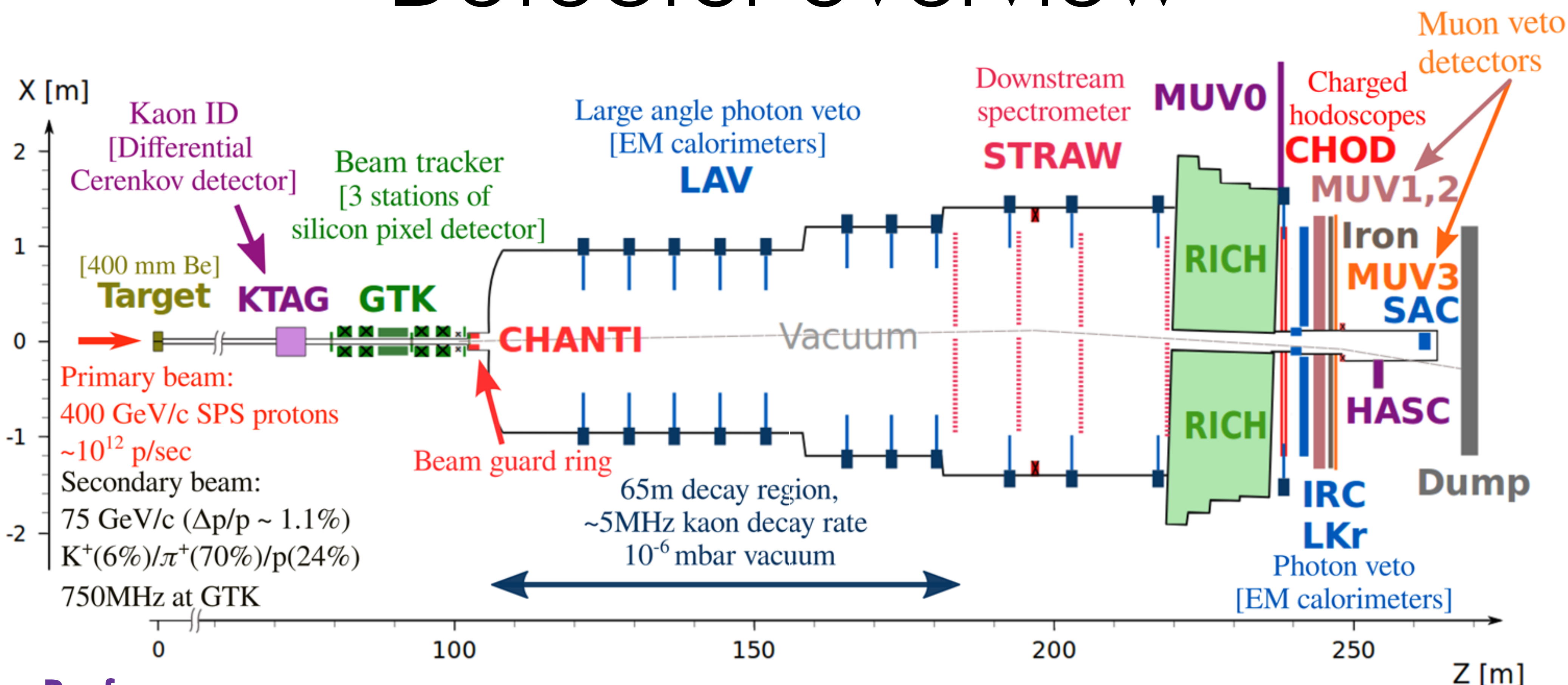
E949/E787[Phys. Rev D 79, 092004 (2009)]

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = \left(10.6^{+4.0}_{3.4}{}_{stat} \pm 0.9_{syst}\right) \times 10^{-11}$$

NA62[JHEP06 (2021) 093]

Broader physics programme:
- **Rare/forbidden** kaon decays
- Searches for **exotic particles** in kaon decays and in beam dump mode

Detector overview

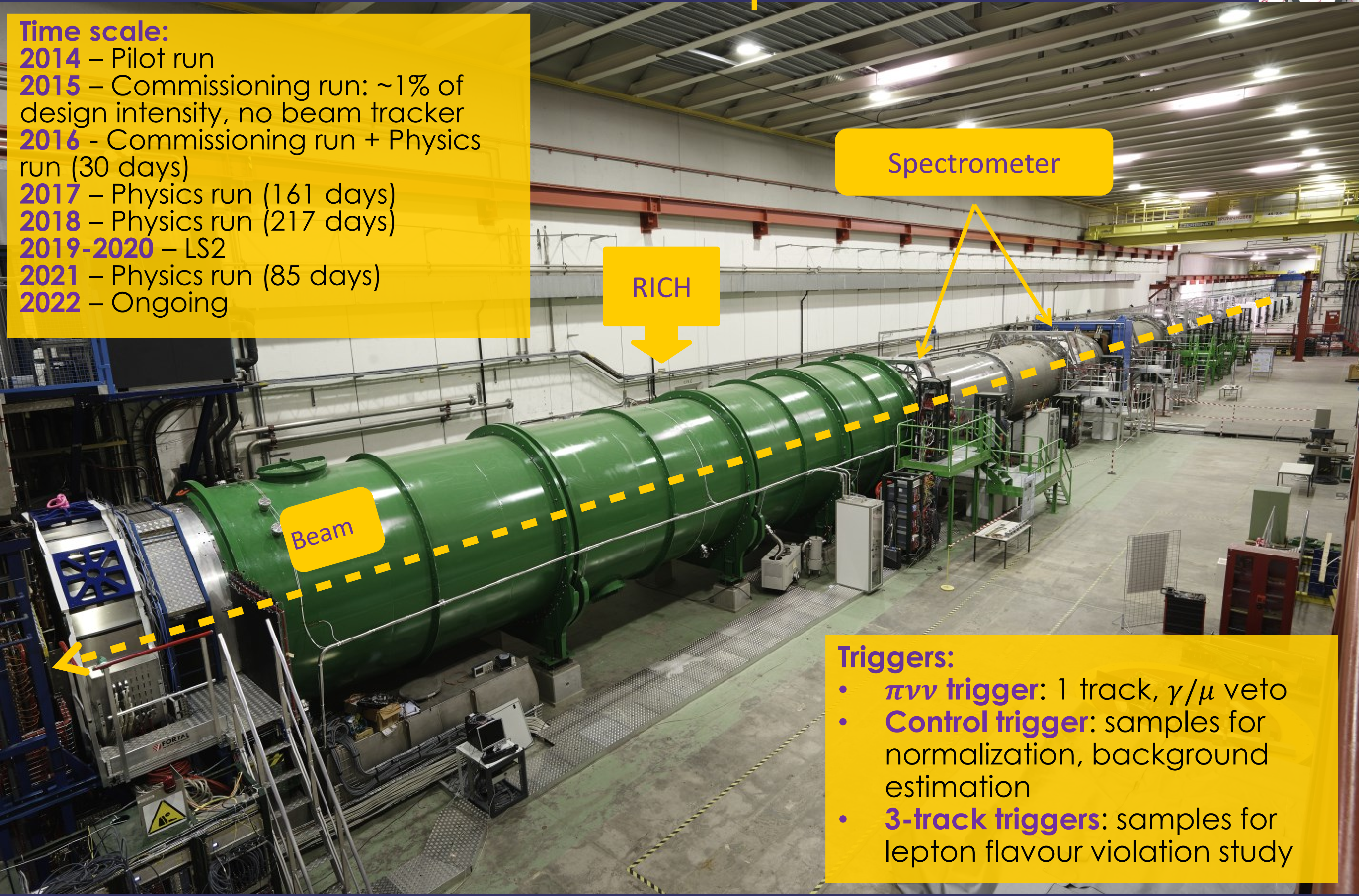


Performances:

- GTK-KTAG-RICH time resolution: $\mathcal{O}(100\ \text{ps})$
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $\mathcal{O}(10^7)$ muon rejection for 15 <p(π^+)< 35 GeV
- $\mathcal{O}(10^8)$ π^0 rejection of for E(π^0)> 40 GeV

[NA62 Detector Paper, JINST 12 (2017), P05025]

The NA62 experiment



Time scale:

2014 – Pilot run
2015 – Commissioning run: ~1% of design intensity, no beam tracker
2016 - Commissioning run + Physics run (30 days)
2017 – Physics run (161 days)
2018 – Physics run (217 days)
2019-2020 – LS2
2021 – Physics run (85 days)
2022 – Ongoing

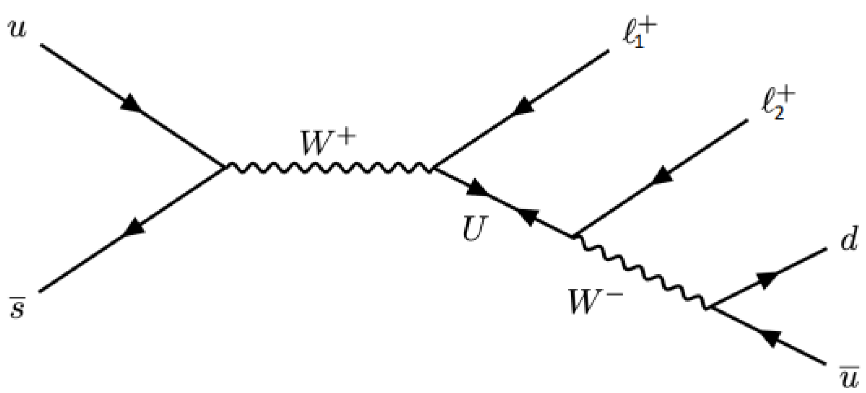
Triggers:

- **$\pi\nu\nu$ trigger**: 1 track, γ/μ veto
- **Control trigger**: samples for normalization, background estimation
- **3-track triggers**: samples for lepton flavour violation study

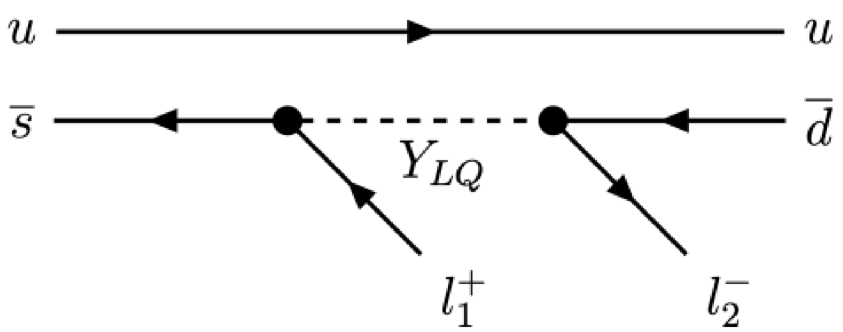
Lepton Number/Flavour violation

- Lepton number (L) and lepton flavour (L_e, L_μ, L_τ) are conserved quantities in the Standard Model
- Violation of these quantities is a clear indication of Physics Beyond the Standard Model

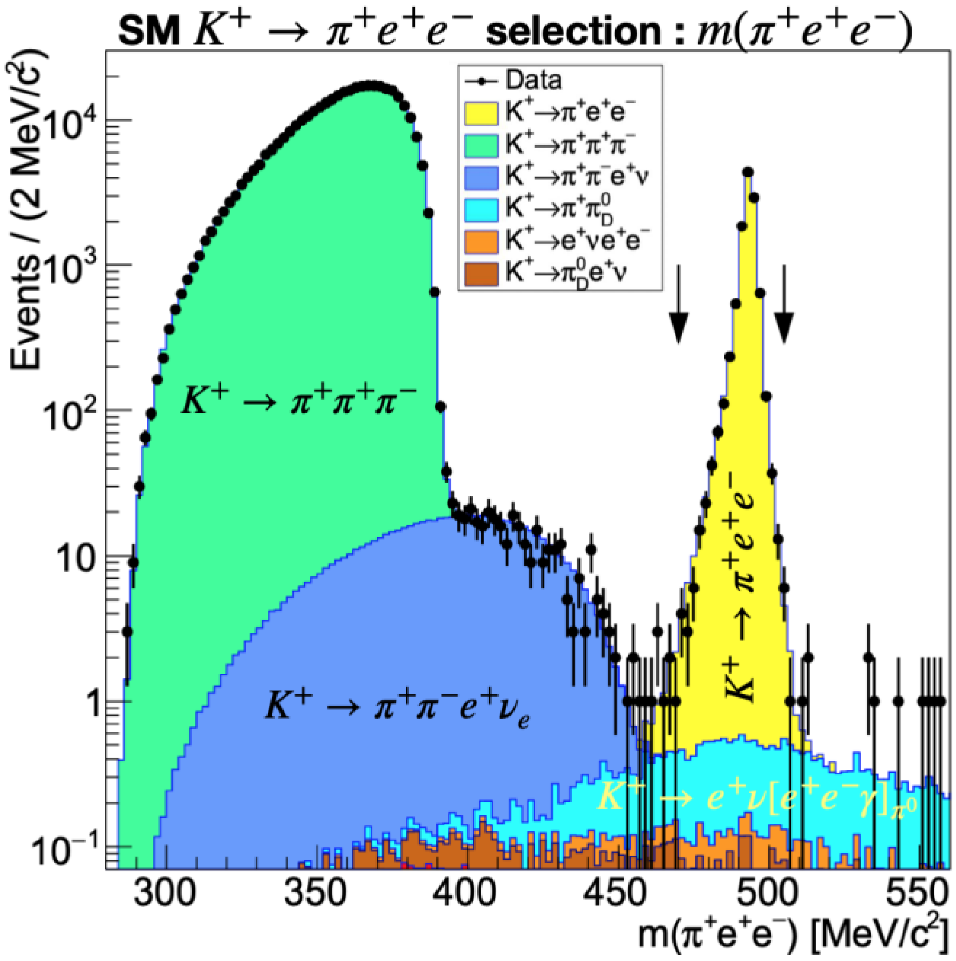
Seesaw mechanism provides a source of LNV through the exchange of Majorana neutrinos as in 0νββ decay [JHEP 0905 (2009) 030]



LFV processes can occur via the exchange of leptoquarks, of a Z' boson, or in SM extensions with light pseudoscalar bosons [JHEP 10 (2018) 148, Rev. Mod. Phys. 81, 1199 (2009), JHEP 01 (2020)158]



Searches for $K^+ \to \pi^-(\pi^0)e^+e^+$



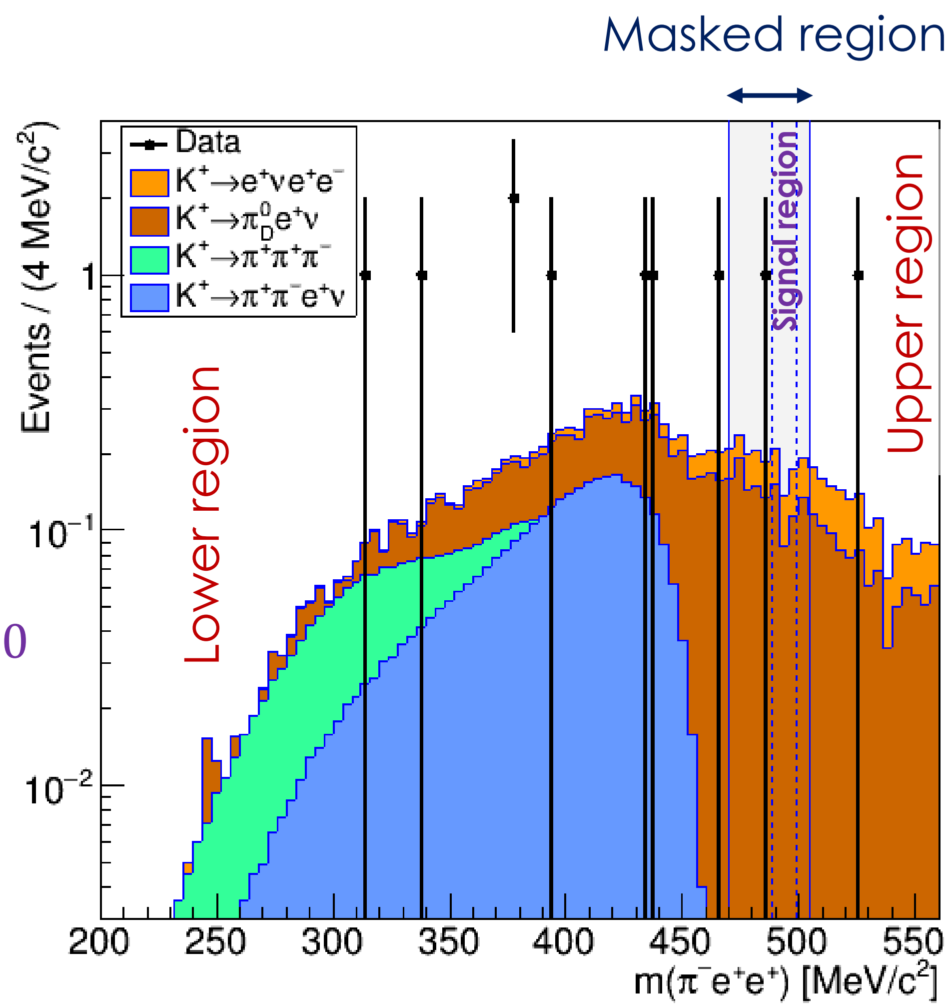
- Normalisation to the SM $K^+ \to \pi^+e^+e^-$, $\mathcal{B}(K^+ \to \pi^+e^+e^-) = (3.00 \pm 0.09) \times 10^{-7}$.
- 11041 candidates are found – world's largest sample

[PLB830 (2022)137172]

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

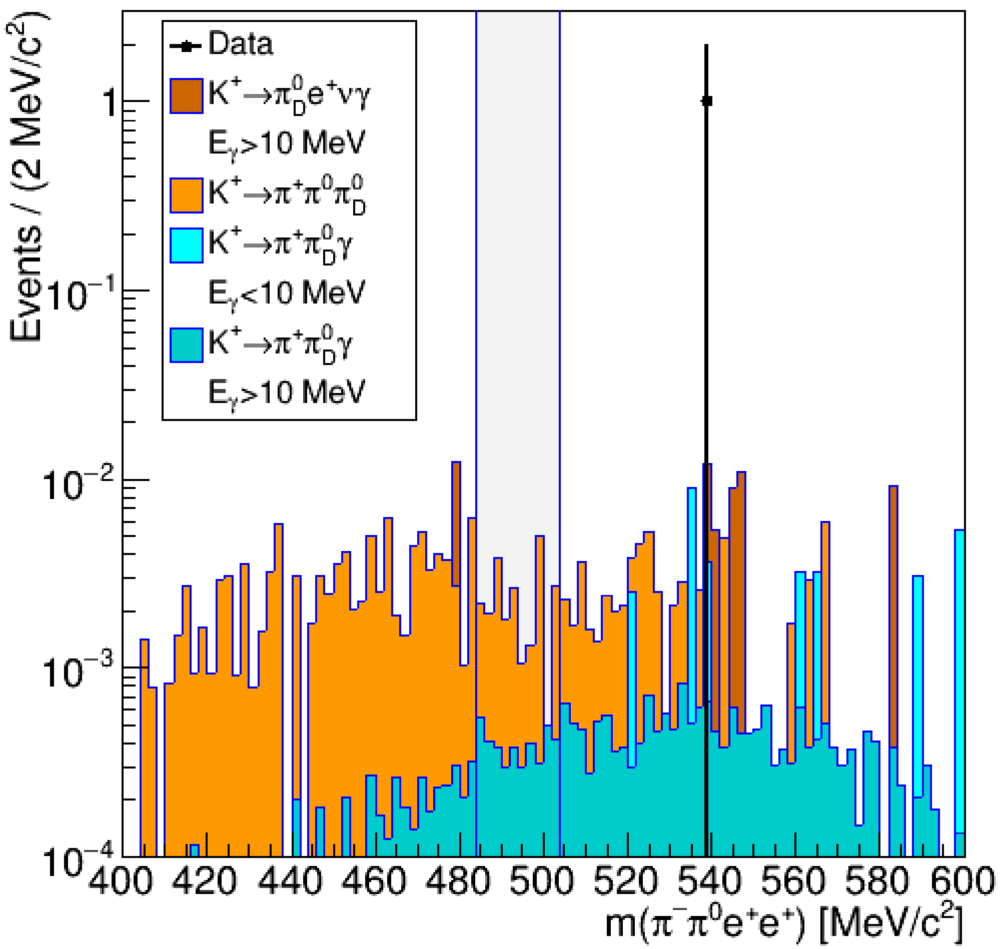
Mode	Lower region	Upper region	Masked region	Signal region
$K^+ \to \pi^+\pi^+\pi^-$	0.9	–	–	–
$K^+ \to \pi^+\pi^- e^+\nu$	3.3	–	–	–
$K^+ \to \pi^+\pi^0_D$	–	0.02	0.01	–
$K^+ \to \pi^0_D e^+\nu$	3.7 ± 0.7	1.20 ± 0.24	1.23 ± 0.25	0.29 ± 0.06
$K^+ \to e^+\nu e^+ e^-$	0.7 ± 0.1	0.76 ± 0.15	0.47 ± 0.09	0.14 ± 0.03
Total	8.6 ± 0.9	1.98 ± 0.39	1.71 ± 0.34	0.43 ± 0.09
Data	8	1	1	0

- Blind analysis method – validate background estimation in control regions.
- In signal region $n_{exp} = 0.43 \pm 0.09$, $n_{obs} = 0$
- Set upper limit: $\mathcal{B}(K^+ \to \pi^- e^+ e^+) < 5.3\ \times 10^{-11}$ at 90% CL
- A factor of 4 improvement with respect to previous NA62 result with partial data set (2017 only): [PLB 797 (2019) 13479]



[PLB830 (2022)137172]

Result for $K^+ \to \pi^- \pi^0 e^+ e^+$

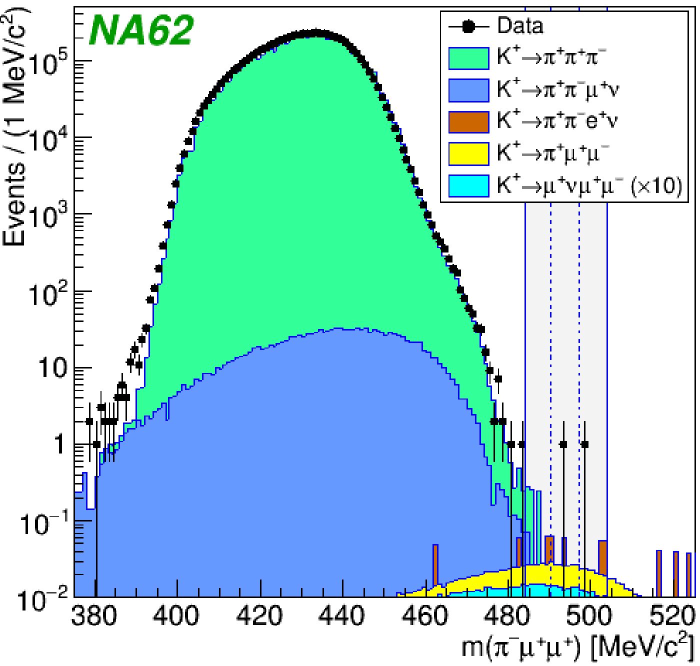


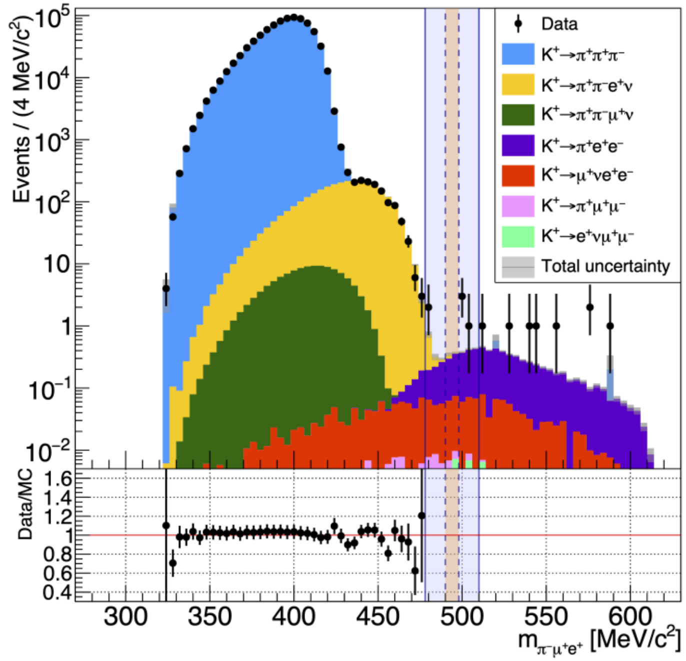
Mode	Control region	Signal region
$K^+ \to \pi^+\pi^0\pi^0_D$	0.16 ± 0.01	0.019
$K^+ \to \pi^+\pi^0_D\gamma$	0.06 ± 0.01	0.004
$K^+ \to \pi^0_D e^+\nu\gamma$	0.05 ± 0.02	–
$K^+ \to \pi^+\pi^0 e^+ e^-$	0.01	0.001
Pileup	0.20 ± 0.20	0.020 ± 0.020
Total	0.48 ± 0.20	0.044 ± 0.020
Data	1	0

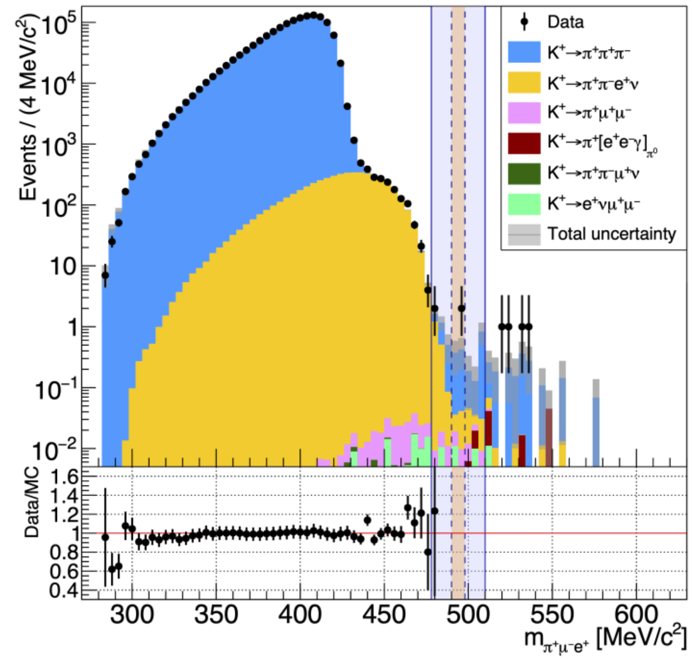
- Blind analysis method – validate background estimation in control regions.
- In signal region $n_{exp} = 0.044 \pm 0.020$, $n_{obs} = 0$
- Set upper limit: $\mathcal{B}(K^+ \to \pi^- \pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ at 90% CL
- First search for this LNV decay!

[PLB830 (2022)137172]

Other LNV/LFV decays







LNV: $K^+ \to \pi^-\mu^+\mu^+$
Data: 2017 sample, $N_K = (7.94 \pm 0.23) \times 10^{11}$ (di-μ trigger)
Expected background: 0.91 ± 0.41
Observed: 1
UL [PLB 797(2019)134794] : $\mathcal{B}(K^+ \to \pi^-\mu^+\mu^+) < 4.2 \times 10^{-11}$ @ 90%CL
Factor 2 of improvement on NA48/2 [PLB 769 (2017) 67]

LNV/LFV: $K^+ \to \pi^-\mu^+e^+$
Data: 2017+2018 samples, $N_K = (1.33 \pm 0.02) \times 10^{12}$ (combination of 3 triggers)
Expected background: 1.07 ± 0.2
Observed: 0
UL [PRL 127 (2021) 131802] : $\mathcal{B}(K^+ \to \pi^-\mu^+e^+) < 4.2 \times 10^{-11}$ @ 90%CL

LNV:$K^+ \to \pi^+\mu^-e^+$
Data: same as for $K^+ \to \pi^-\mu^+e^+$
Expected background: 0.91 ± 0.34
Observed: 2
UL [PRL 127 (2021) 131802] : $\mathcal{B}(K^+ \to \pi^+\mu^-e^+) < 6.6 \times 10^{-11}$ @ 90%CL
From $K^+ \to \pi^+\pi^0, \pi^0 \to \mu^-e^+$: $\mathcal{B}(\pi^0 \to \mu^-e^+) < 3.2 \times 10^{-10}$ @ 90%CL

NA62 LNV/LFV summary

	Previous UL @ 90% CL	NA62 UL @ 90%CL		
$K^+ \to \pi^- \mu^+ \mu^+$	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}	5.3×10^{-11}	Run1 data → improved by factor 12	**Phys. Lett. B 830 (2022) 137172**
$K^+ \to \pi^- \pi^0 e^+ e^+$	no limit	8.5×10^{-10}	Run1 data	
$K^+ \to \pi^- \mu^+ e^+$	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	PRL 127 131802 (2021)
$\pi^0 \to \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}	2017+2018 data → improved by factor 13	
$K^+ \to \pi^+ \mu^+ e^-$	1.3×10^{-11}	-	sensitivity similar to previous search	
$\pi^0 \to \mu^+ e^-$	3.8×10^{-10}	-	sensitivity similar to previous search	
$K^+ \to \mu^- \nu e^+ e^+$	2.1×10^{-8}	-	**Analysis in progress**	
$K^+ \to e^- \nu \mu^+ \mu^+$	no limit		**Analysis in progress**	

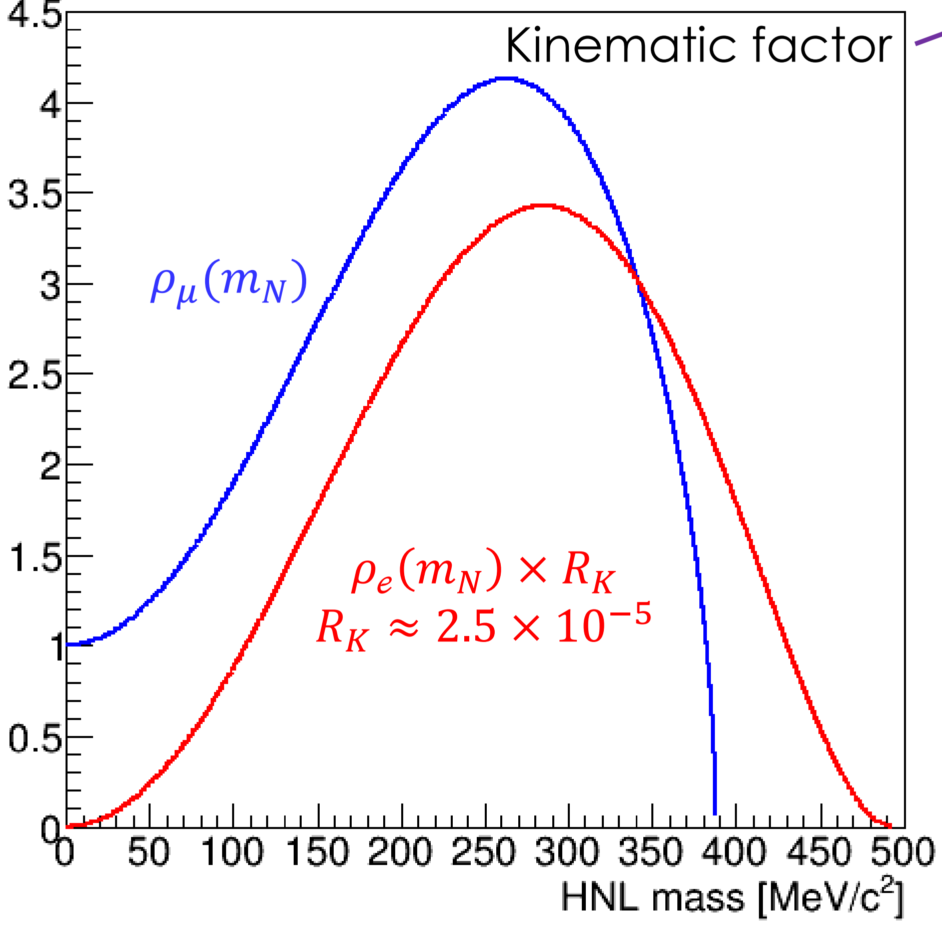
Heavy Neutral Leptons (HNL)

- The νMSM ([Asaka et al., Phys.Lett.B 620(2005)17]) is an extension of the SM to explain simultaneously neutrino oscillations, dark matter and baryon asymmetry of the Universe.
  - SM + 3 right-handed sterile neutrinos:
    - N_1: m_1 ~10 keV – dark matter candidate
    - $N_{2,3}$: $m_{2,3}$ ~100MeV – 100 GeV – baryon asymmetry
- GeV-scale HNLs can be observed via their production and decay (both searches are possible at NA62)

HNL production in K^+ decays

$$\Gamma(K^\pm \to l^\pm N) = \Gamma(K^\pm \to l^\pm \nu_l)\rho(m_N)|U_{l4}|^2$$

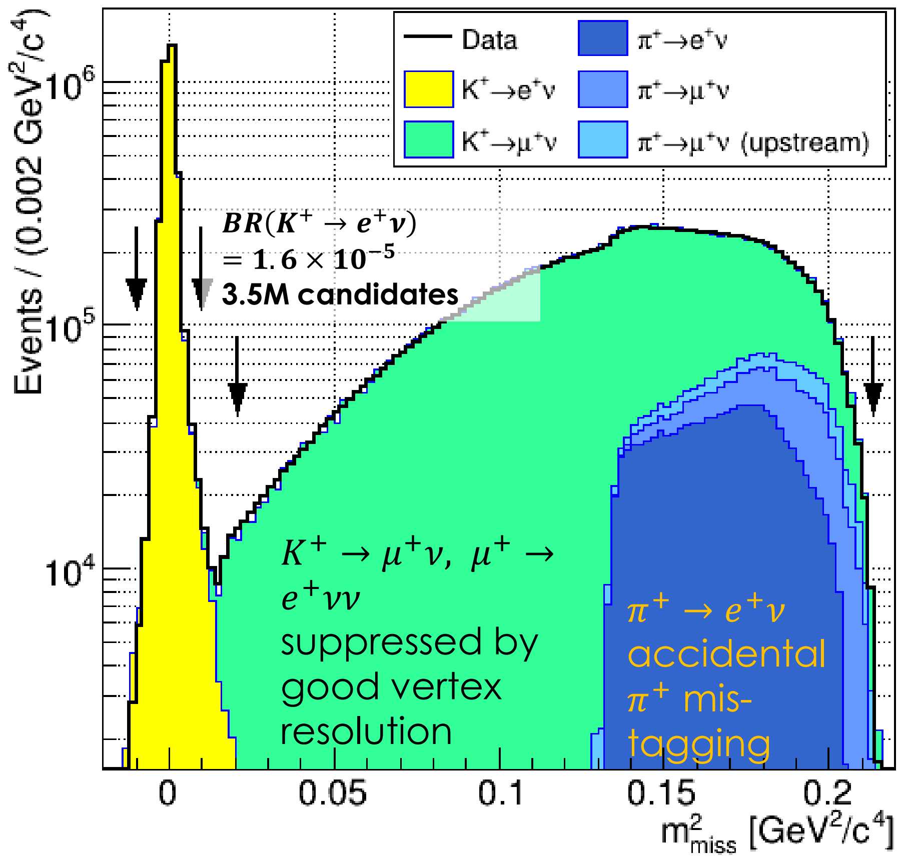
[R. Shrock PLB96 (1980) 159]

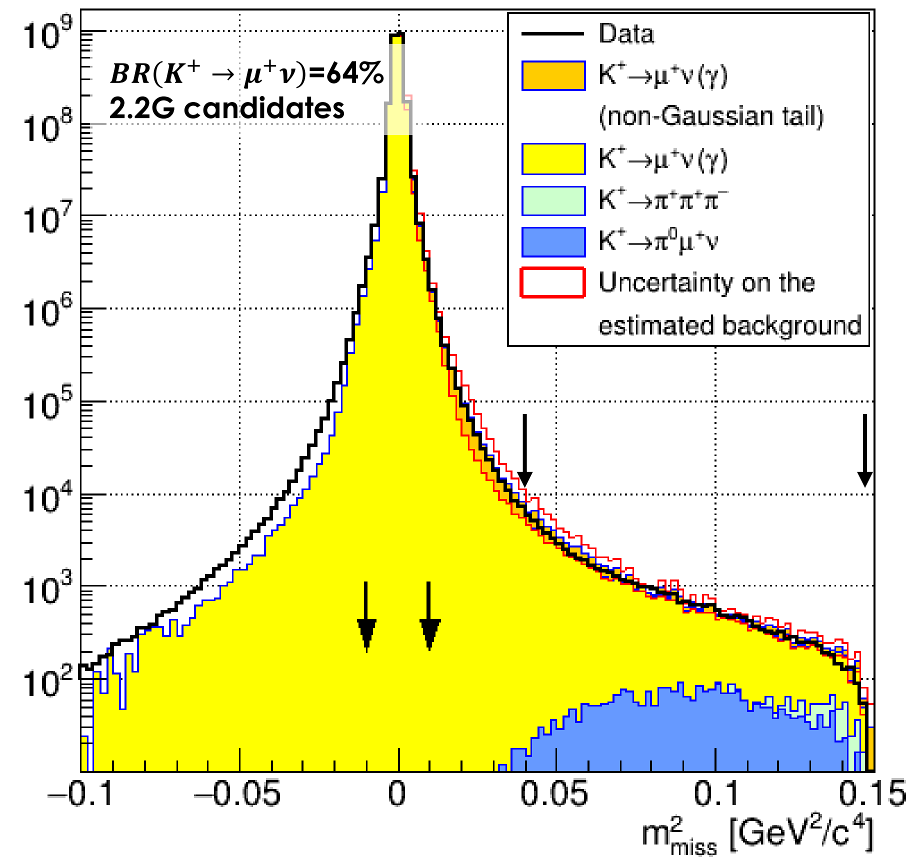


- HNL production is enhanced compared to SM decays
- Large $f \sim 10^5$ enhancement in the $K^+ \to e^+ N$ case: helicity suppression is relaxed.

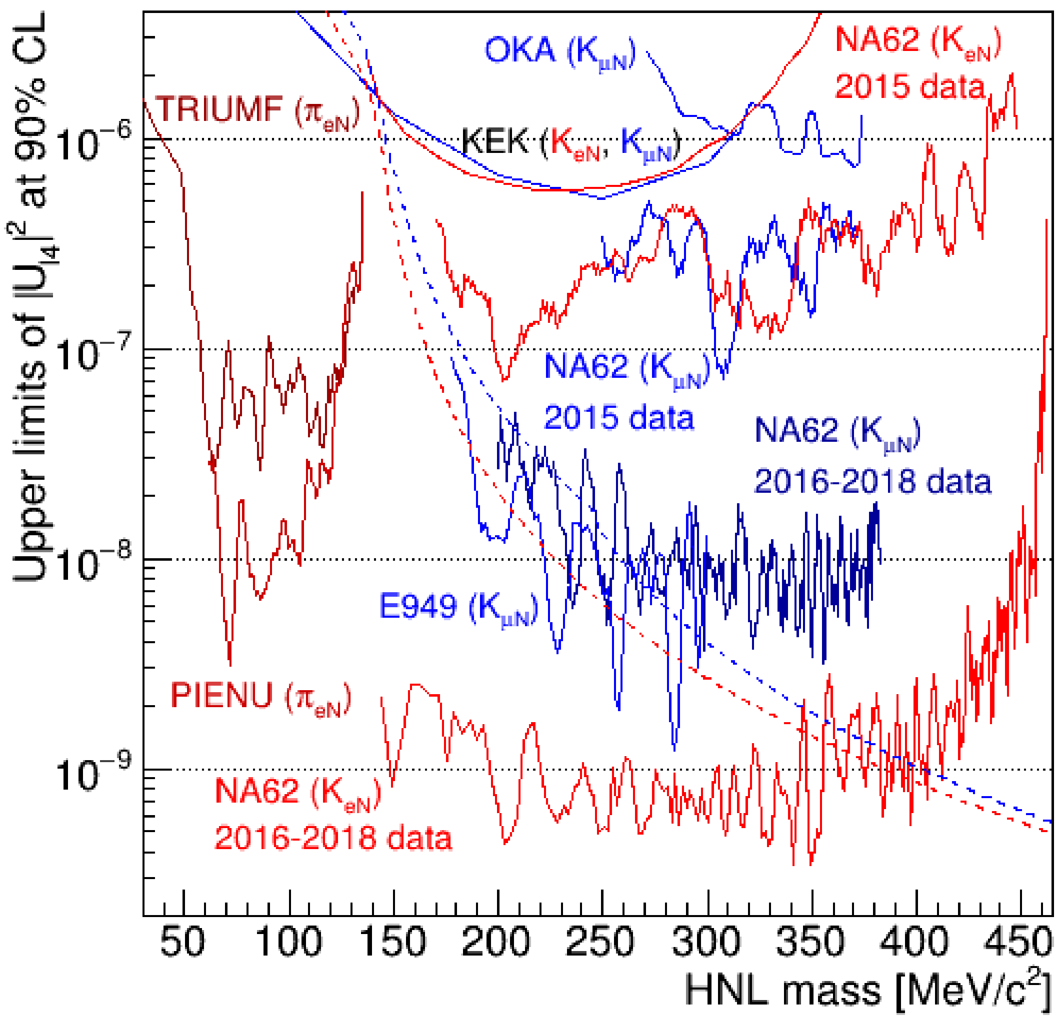
Heavy Neutral Leptons (HNL)

Triggers used: the main $K_{\pi\nu\nu}$ for $K^+ \to e^+N$; Control (min bias)/400 for $K^+ \to \mu^+N$.
Numbers of K⁺ decays in the fiducial volume: $N_K = (3.52 \pm 0.02) \times 10^{12}$ in positron case; $N_K = (1.14 \pm 0.02) \times 10^{10}$ in muon case.
Peak searches in the squared missing mass: $m^2_{miss} = (P_K - P_l)^2$, where P_K is kaon 4-momentum measured using GTK, and P_l is lepton 4-momentum measured using STRAW.





HNL Results



- No signal observed
- Full 2016-18 (Run I) data set is analyzed
- Close related study: $K^+ \to l^+\nu\nu\nu$ and $K^+ \to l^+\nu X$, X is invisible: predict background from MC simulation

$K^+ \to \mu^+\nu\nu\nu$ and $K^+ \to \mu^+\nu X$

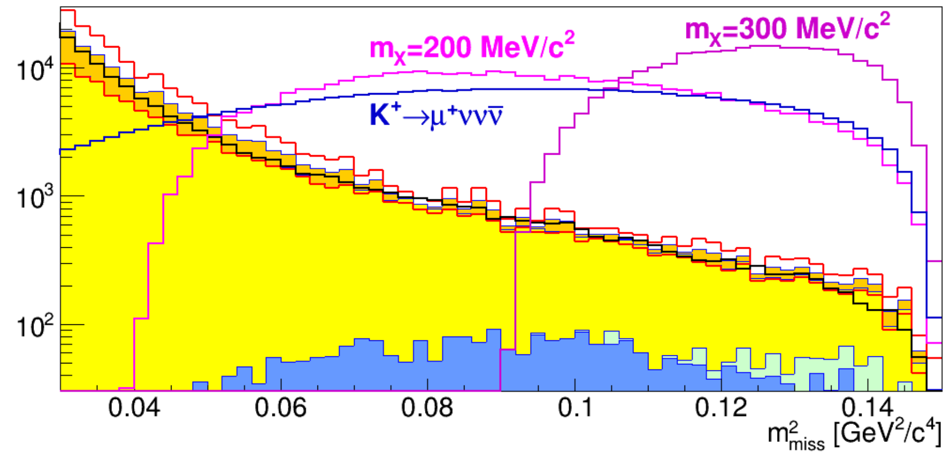
$K^+ \to \mu^+\nu\nu\nu$:

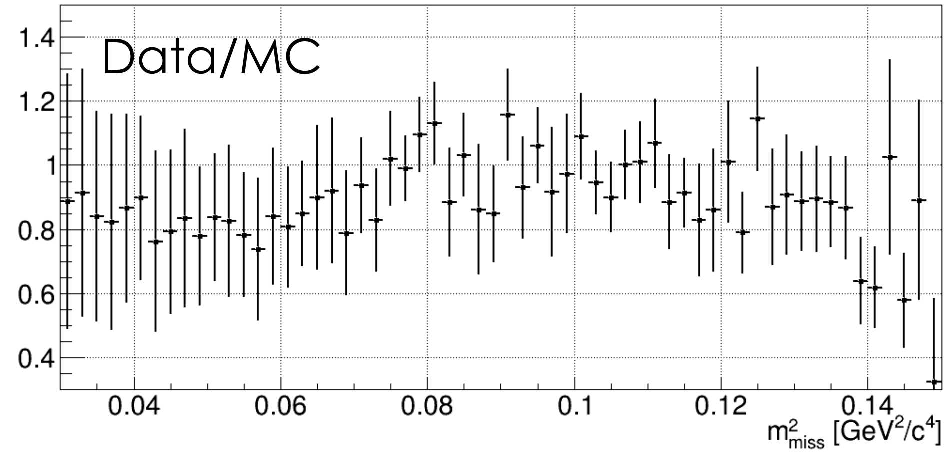
- Very rare in the Standard Mode: $\mathcal{B}(K^+ \to \mu^+\nu\nu\nu) = 1.6 \times 10^{-16}$ [JHEP1610 (2016) 039]
- The current limit: $< 2.4 \times 10^{-6}$ [E949, PRD94 (2016) 032012]
- Search region $m^2_{miss} > 0.1\ GeV^2/c^4$ (optimized to extract strongest limit):
  - Observed events: 6894
  - Expected from MC: 7549±928
  - Set upper limit: 1.0×10^{-6} at 90%CL in the SM framework

$K^+ \to \mu^+\nu X$, X is scalar or vector:

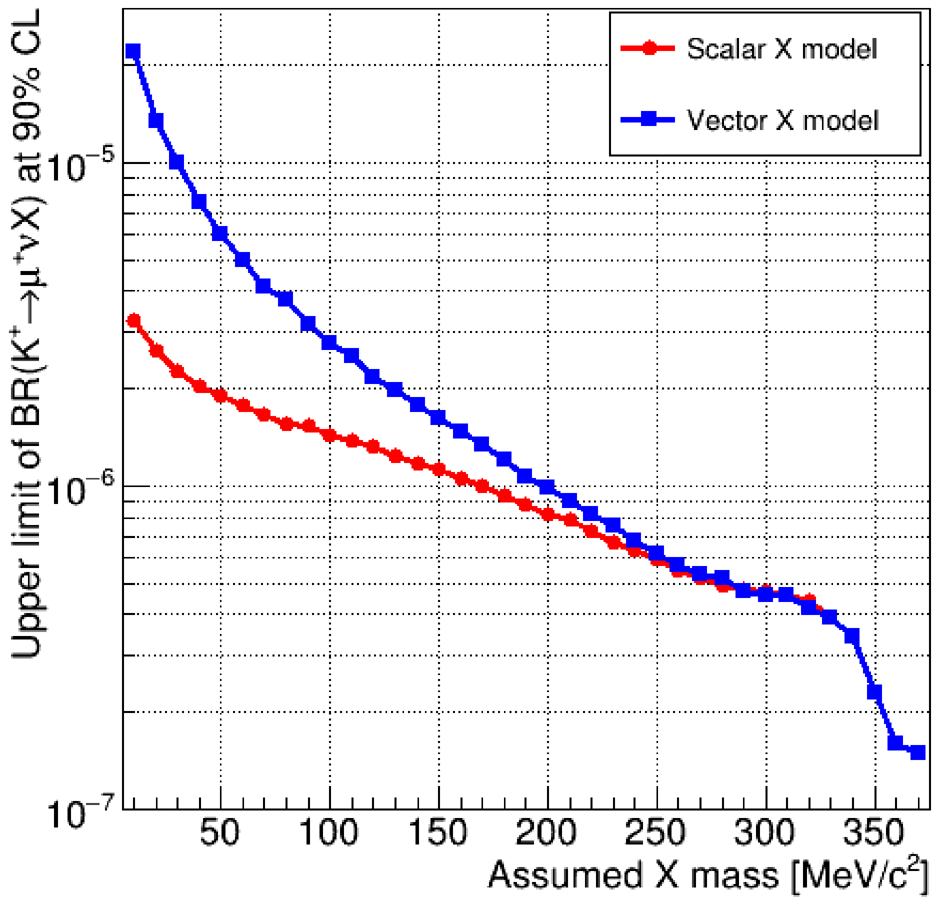
- [PRL124 (2020) 041802]
- Mass range $10 - 370\ MeV/c^2$
- Compare expected and observed number of event for each mass hypothesis and extract limit

Zoom from slide 14, right plot



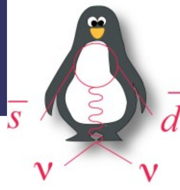


$K^+ \to \mu^+ \nu X$ results



$K^+ \to \mu^+ \nu X$, X is scalar or vector

- No signal observed
- The limits obtained in the scalar model are stronger than those in the vector model due to larger mean m^2_{miss} value.



Summary

- The NA62 experiment is a powerful laboratory to make searches for exotic particles/processes
- World best upper limits on LNV/LFV kaon decays have been set
- World best upper limits on HNL mixing parameters have been set
- World best upper limit on $\mathcal{B}(K^+ \to \mu^+ \nu\nu\nu)$ has been set
- NA62 will continue to take data until Long Shutdown 3 (LS3) – resumed in 2021


Thank you!