Searches for LF/LN violation and other new physics at NA62

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Outline:

1) Introduction: $K^{\pm}$ decay experiments at CERN
2) Overview of NA62 physics programme
3) Status of LF/LN conservation tests in 3-track K^{+} decays
4) First results on HNL production search in K^{+} decays
5) Summary

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Rare kaon decay forum
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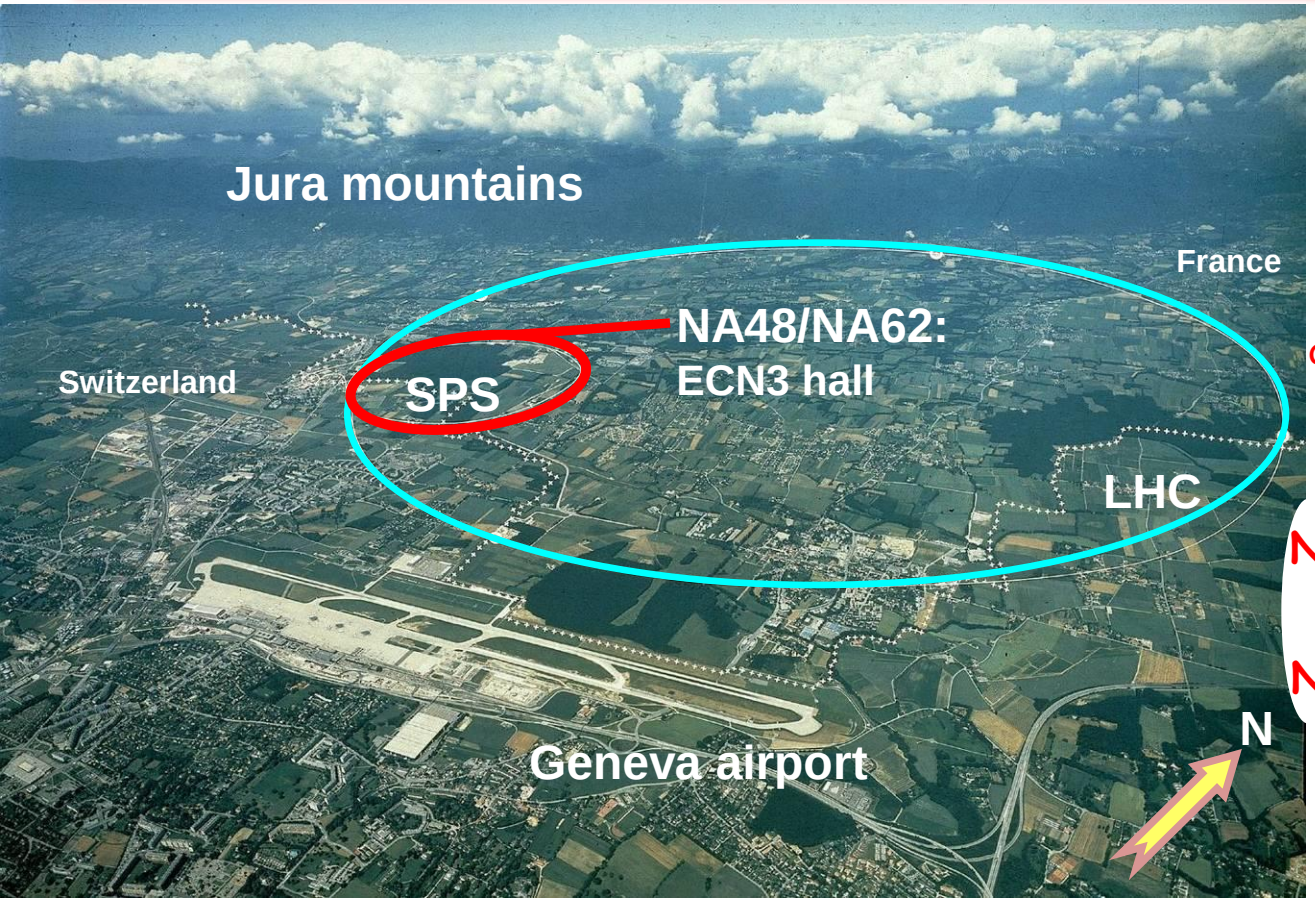
EXCELLENCE IN SCIENCE

Kaon programme at CERN



Kaon decay in flight experiments.
NA62: currently ~200 participants, ~30 institutions

Earlier: NA31

NA48 discovery of direct CPV
- 1997: ε'/ε: K_L+K_S
- 1998: K_L+K_S
- 1999: K_L+K_S | K_S HI
- 2000: K_L only | K_S HI
- 2001: K_L+K_S | K_S HI

NA48/1
- 2002: K_S/hyperons

NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

NA62 R_K run
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests

NA62
- 2015: commissioning
- 2016–: K^+ physics run

$K^{\pm}$ decay experiments at CERN

Experiment	NA48/2 ($K^{\pm}$)	NA62-R_K ($K^{\pm}$)	NA62 (K^{+})
Data taking period	2003–2004	2007	2016–2018
Beam momentum, GeV/c	60	74	75
RMS momentum bite, GeV/c	2.2	1.4	0.8
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV/c	120	265	270
$M(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-})$ resolution, MeV/c^2	1.7	1.2	0.8
K decays in fiducial volume	2×10^{11}	2×10^{10}	$\approx10^{13}$
Main trigger	Multi-track; $K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$	Minimum bias; $e^{\pm}$	$K_{\pi\nu\nu}$; lepton pairs

NA48 detector | NA62 detector

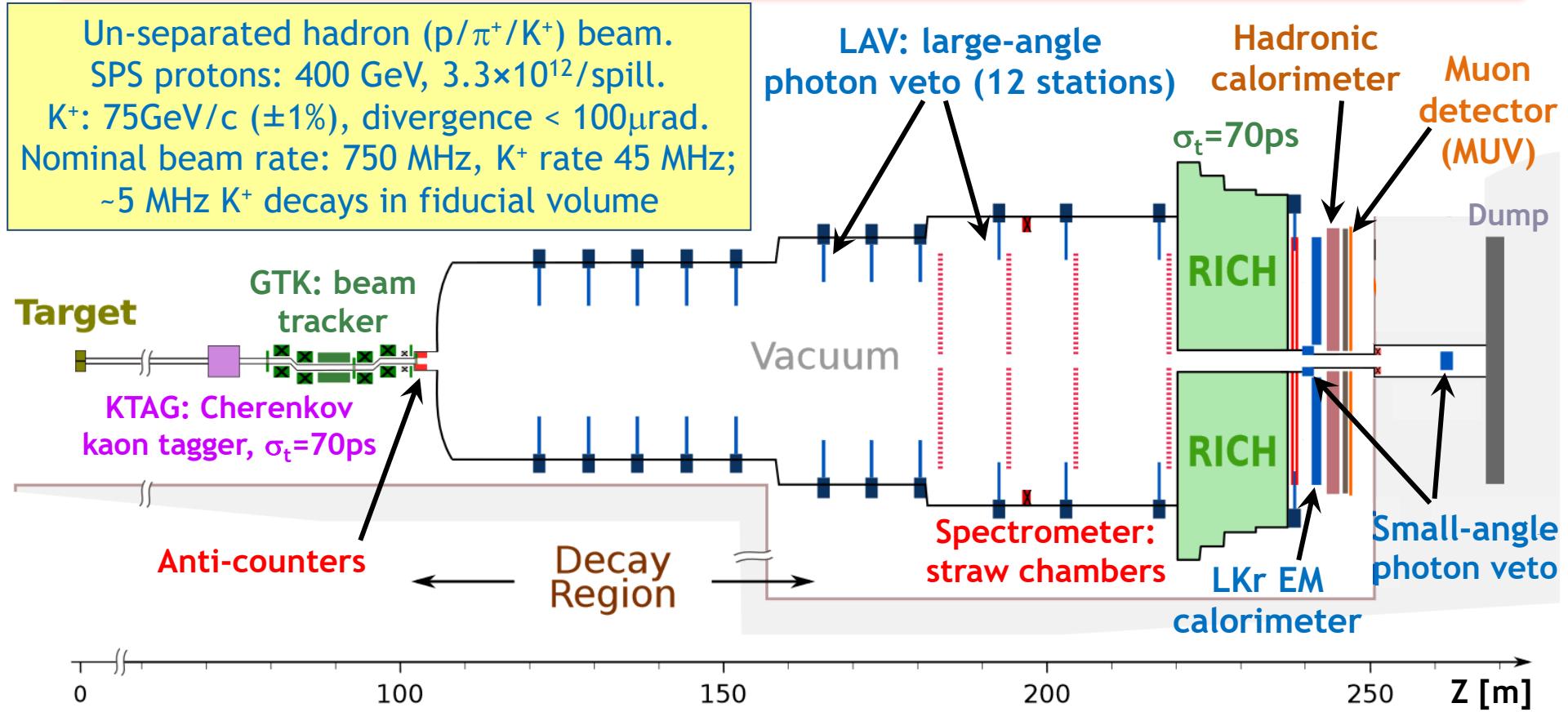
The NA62 experiment

- Main goal: collect up to 100 SM $K^{+}\to\pi^{+}\nu\nu$ decays, $BR_{SM}=(8.4\pm1.0)\times10^{-11}$.
  Buras et al., JHEP 1511 (2015) 033
- Current $K^{+}\to\pi^{+}\nu\nu$ experimental status: $BR = (1.73\,^{+1.15}_{-1.05})\times10^{-10}$ from 7 candidates with expected background of 2.6 observed by BNL-E949.
  PRL101 (2008) 191802

NA62 collaboration,
JINST 12 (2017) P05025

The NA62 detector

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, 3.3×10^{12}/spill.
K^+: 75GeV/c (±1%), divergence < 100μrad.
Nominal beam rate: 750 MHz, K^+ rate 45 MHz;
~5 MHz K^+ decays in fiducial volume



- Expected single event sensitivity for K^+ decays: BR~10^{-12}.
- Measured kinematic rejection factors (limited by beam pileup & MCS tails): 6×10^{-4} for $K^+\to\pi^+\pi^0$, 3×10^{-4} for $K\to\mu^+\nu$.
- Hermetic photon veto: measured $\pi^0\to\gamma\gamma$ decay suppression = 1.2×10^{-7}.
- Particle ID (RICH+LKr+HAC+MUV): ~10^{-7} muon suppression.

Overview of the NA62 physics programme

NA62 physics programme

❖ **NA62 Run 2016–2018**: focused on the "golden mode" $K^+ \to \pi^+ \nu\nu$.

- ✓ Trigger bandwidth for other physics is limited.
- ✓ Several measurements at **SES~10^{-12}**: $K^+ \to \pi^+ A'$ (**A'→invisible**), $\pi^0 \to \nu\nu$.
- ✓ Sensitivities to most rare/forbidden decays are behind $K^+ \to \pi^+ \nu\nu$ but still often world-leading (down to **~10^{-11}**).
- ✓ NA62 is designed for searches: precision measurements are difficult.
- ✓ But a few leading measurements with downscaled control triggers are possible (e.g. $K^+ \to \pi^+ \gamma\gamma$).

❖ **NA62 Run 2021–2023**: programme is under discussion.
[Physics Beyond Colliders workshops @ CERN: Sep 2016, Mar 2017, Nov 2017]

- ✓ Existing apparatus with improved trigger logic.
- ✓ Further data collection for $K^+ \to \pi^+ \nu\nu$ and rare/forbidden decays.
- ✓ A more selective trigger foreseen for forbidden decays.
- ✓ Beam dump with **~10^{18} POT** (=3 months of dedicated data collection): hidden sector (decays of long-lived HNL, DP, ALP).

Rare decay analyses

With downscaled control triggers

(a personal selection)

- Measurements of $K^+ \to e^+ \nu\gamma$ and $K^+ \to \mu^+ \nu\gamma$ decays.
  [BR~10^{-5}; world data: ~1k events in each SD mode]
- Measurements of $K^+ \to \pi^+\pi^-\mu^+\nu$ and $K^+ \to \pi^0\pi^0\mu^+\nu$ decays.
  [BR~10^{-5}; world data = 7 events published in $K^+ \to \pi^+\pi^-\mu^+\nu$ mode]
  [NA48/2 analysis in progress; improved vertex resolution at NA62 is instrumental]
- Measurement of the $K^+ \to \pi^+\gamma\gamma$ decay.
  [BR~10^{-6}; world data: ~400 events in total]

Precision measurements with main triggers: large data sets

- Measurement of $R_K = BR(K^+ \to e^+\nu)/BR(K^+ \to \mu^+\nu)$. [sub-percent precision]
  ["Extremely difficult": BR~10^{-5}; world data: ~200k decays]
- Measurements of $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^+e^+e^-$ decays.
  ["Very difficult": BR~10^{-7}; world data: ~4k and ~18k events]
- Measurement of the $\pi^0 \to e^+e^-$ decay.
  ["Difficult": BR~10^{-8}; world data: ~800 events]
- Measurement of the $K^+ \to \pi^+\gamma e^+e^-$ decay.
  ["Easier": BR~10^{-8}; world data: ~100 events]

Forbidden decay analyses

Forbidden K^+ decays with large datasets

Goal: improve over most existing limits (mainly from BNL E865, E777).

- Search for the LNV decay $K^+ \to \pi^- \mu^+ \mu^+$ [BR<8.6×10^{-11}, NA48/2@CERN]
- Search for the LNV decay $K^+ \to \pi^- e^+ e^+$ [BR<6.4×10^{-10}]
- Searches for LNV/LFV decays $K^+ \to \pi\mu e$, including $\pi^0 \to \mu e$.
  [BR($\pi^- \mu^+ e^+$)<5.0×10^{-10}; BR($\pi^+ \mu^- e^+$)<5.2×10^{-10}; BR($\pi^+ \mu^+ e^-$)<1.3×10^{-11}]
  [BR($\pi^0 \to \mu^\pm e^\mp$)<3.6×10^{-10}, kTeV@FNAL]
- Searches for $K^+ \to \mu^- \nu e^+ e^+$ and $K^+ \to e^- \nu \mu^+ \mu^+$ decays.
  [BR($\mu^- \nu e^+ e^+$)<1.9×10^{-8}: Geneva-Saclay, 1976]
- Searches for $\Delta S = \Delta Q$ violating decays $K^+ \to \pi^+ \pi^+ e^- \nu$ and $K^+ \to \pi^+ \pi^+ \mu^- \nu$.
  [BR($\pi^+ \pi^+ e^- \nu$)<1.3×10^{-8}; BR($\pi^+ \pi^+ \mu^- \nu$)<3.0×10^{-6}: ~50 years old]

Approximate statistical reach with the 2016–17 data sample:

(for searches not dominated by backgrounds)

- Di-muon stream: ~2×10^{12} K^+ decays; SES~10^{-11};
- Decays to μe and ee pairs: ~5×10^{11} K^+ decays; SES~10^{-10};
- Other 3-track decays: ~5×10^{10} K^+ decays; SES~10^{-9}.
- NA62 is competitive for most of the above decay modes.

Hidden sector searches in K^+ decay

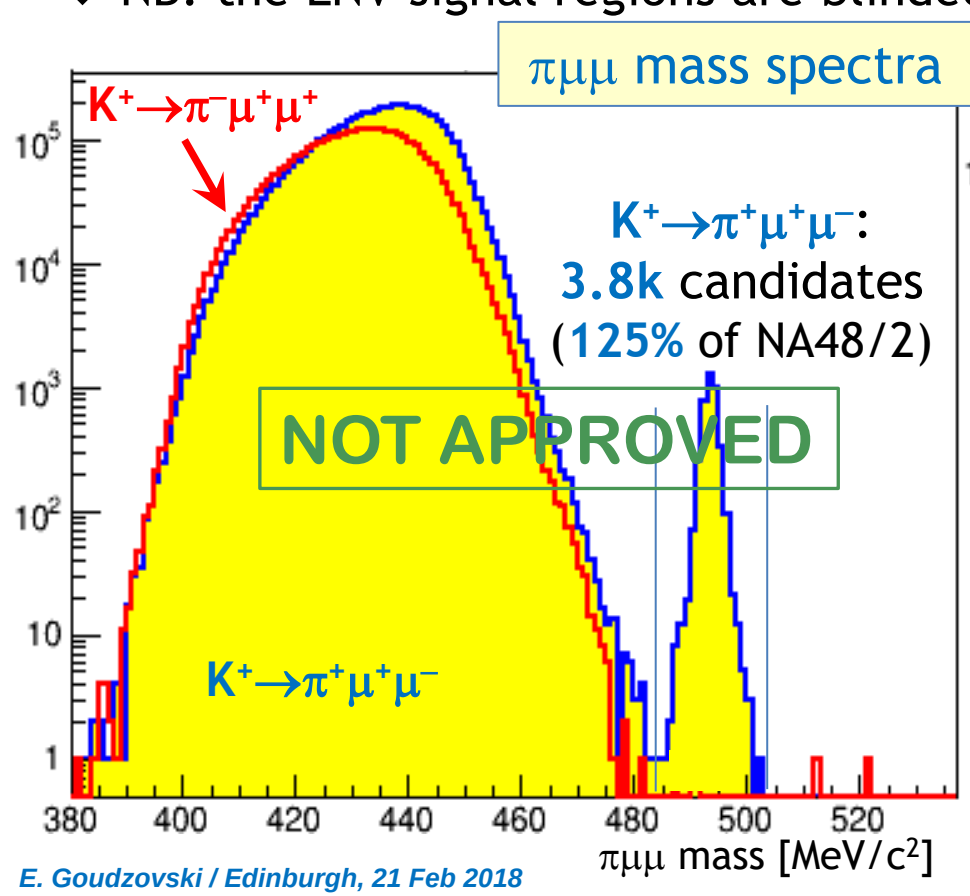
(Further discussion: talks by Karim Massri and Angela Romano)

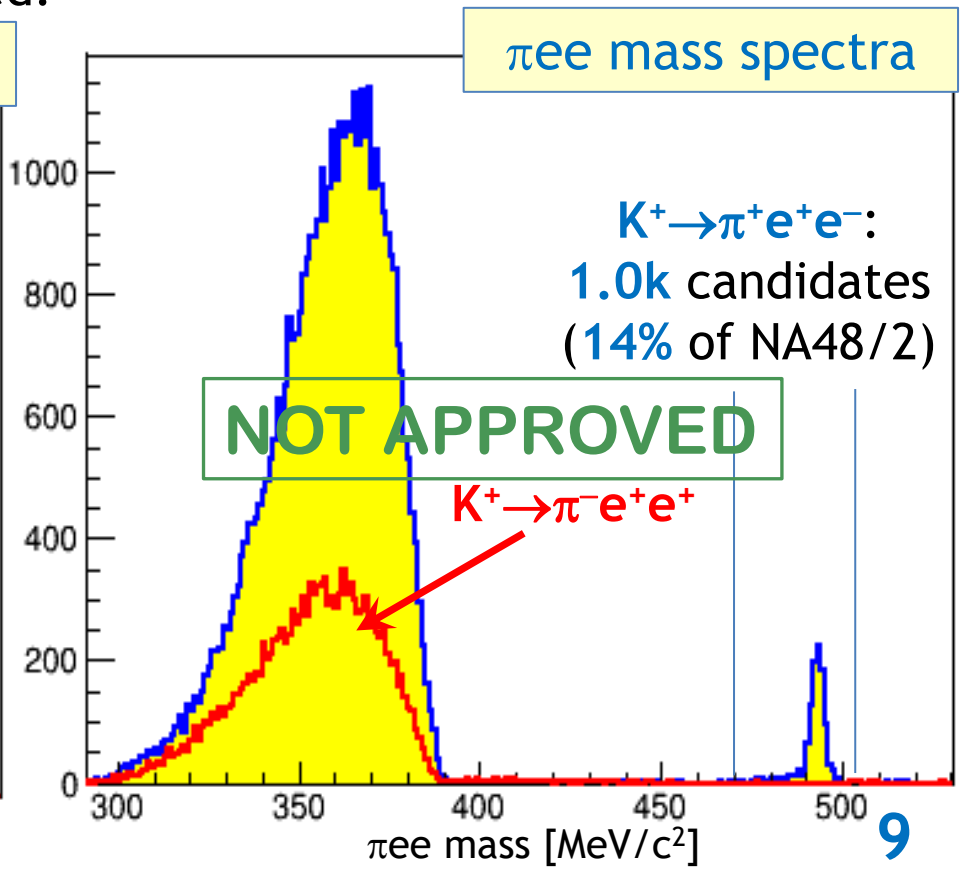
- Long-lived dark scalars: $K^+ \to \pi^+ X$, with $X \to e^+e^-$, $X \to \mu^+\mu^-$.
  [Bezrukov and Gorbunov, JHEP 05 (2010) 010]
- Short-lived dark photon, **O(10 MeV)** QCD axion: $K^+ \to \pi^+ X$, $X \to e^+e^-$.
  [Batell, Pospelov, Ritz, PRD80 (2009) 095024]
  [Alves and Weiner, arXiv:1710.03764]
- Short-lived dark vector/scalars in $K^+ \to \mu^+ \nu X$ and $K^+ \to \pi^+ \pi^0 X$, with $X \to e^+e^-$.
  [Barger et al., PRL 108 (2012) 081802]
- Long-lived heavy neutral lepton (HNL) production:
  $K^+ \to \ell^+ N$, possibly with by $N \to \pi \ell$.
  [Asaka et al., PLB631 (2005) 151]
  [First NA62 results on HNL production: PLB778 (2018) 137]
- Searches for $K^+ \to e^+ \nu X$ (X=invisible) and $K^+ \to e^+ \nu\nu\nu$ decays:
  an extension of the HNL production search ($K^+ \to e^+ N$).

$K^+ \to \pi \ell \ell$: FCNC and LNV decays

The 2016 data sample (~20% of total expected sample)

- Dedicated di-lepton trigger lines used.
- Clear FCNC signals observed; backgrounds to FCNC and LNV decays are small.
- Main background source: $K^+ \to \pi^+\pi^+\pi^-$, mainly outside signal regions.
- Mass resolutions very close to the nominal ones.
- NB: the LNV signal regions are blinded.



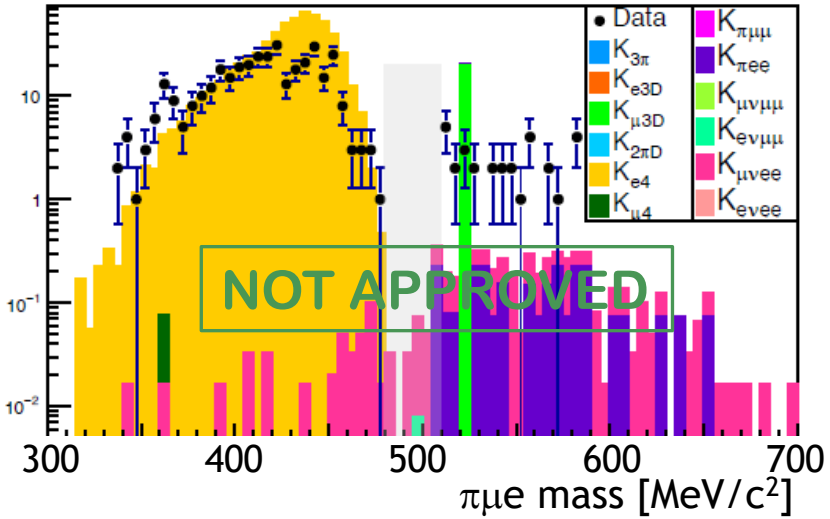


Search for $K^+ \to \pi\mu e$ decays

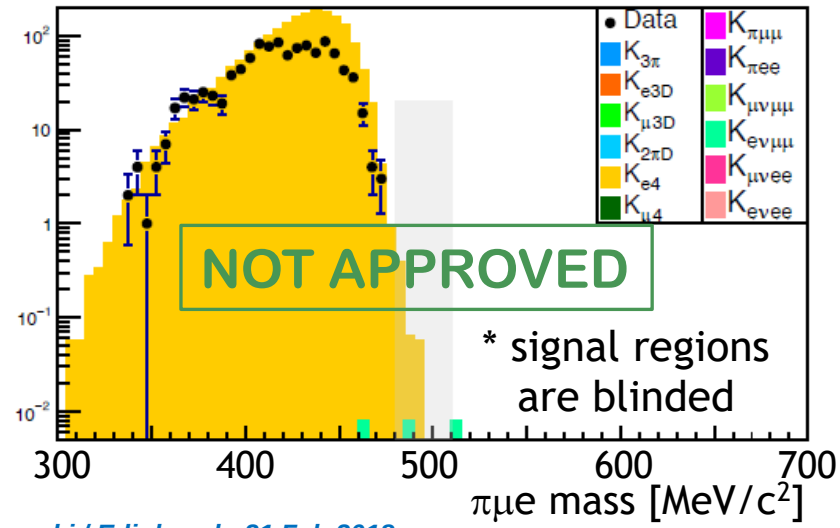
On-going analysis of a partial 2016–17 sample with 2.5×10^{11} kaon decays:

- Every analysis is individual as the NA62 setup is not charge-symmetric (including PID with the RICH detector).
- Multiple background sources to be considered in the $\pi^-\mu^+e^+$ and $\pi^+\mu^+e^-$ channels.
- Background contributions from $K_{3\pi}$, $K_{2\pi D}$, $K_{\mu 3D}$, K_{e4}, $K_{\mu 4}$, $K_{\pi ee}$, $K_{\mu\nu ee}$ decays identified.

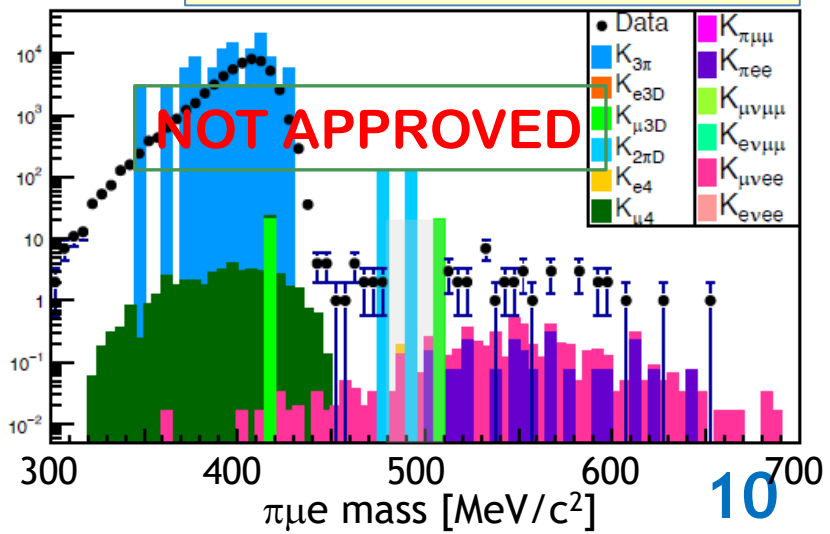
$\pi^-\mu^+e^+$ mass spectrum



$\pi^+\mu^-e^+$ mass spectrum



$\pi^+\mu^+e^-$ mass spectrum



(plots by Joel Swallow, University of Birmingham)

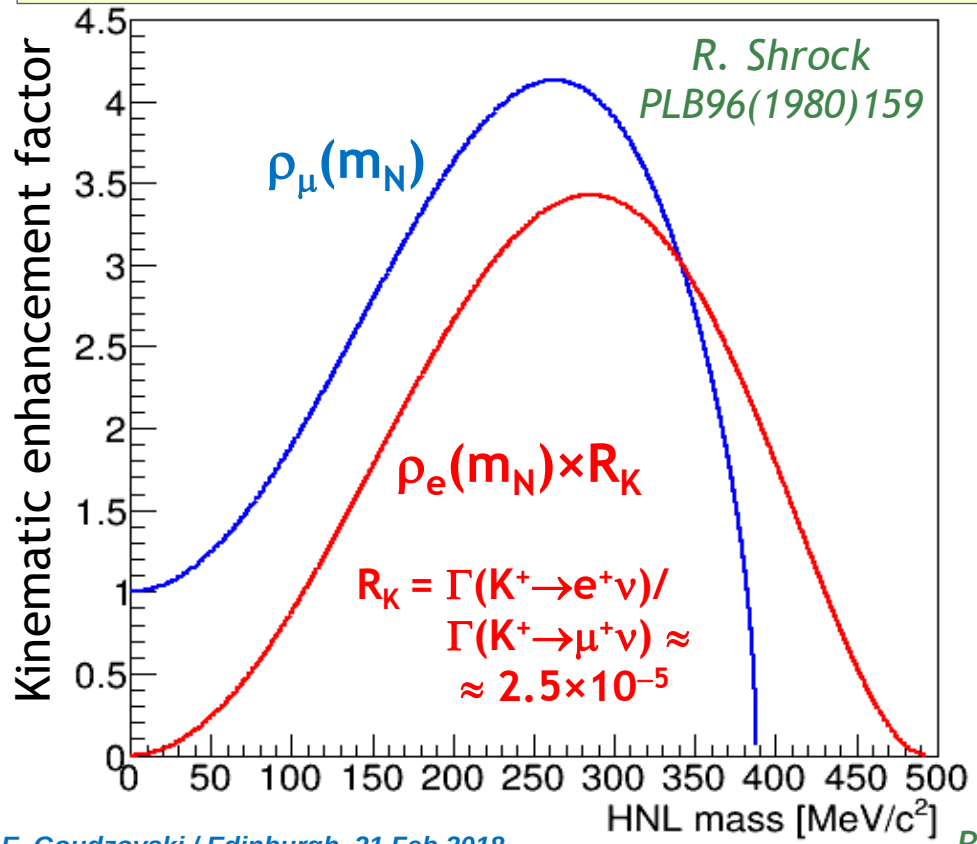
Searches for heavy neutral lepton production

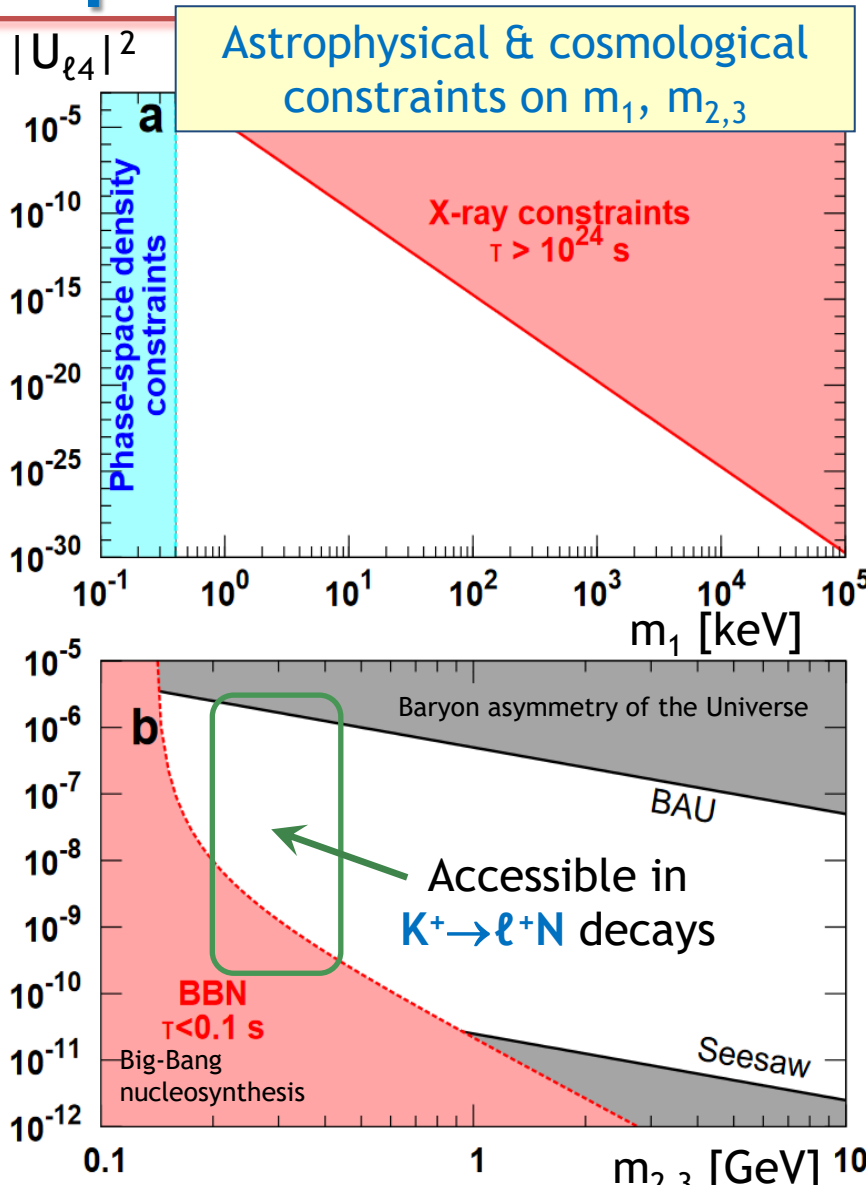
Result based on the 2015 data:
Phys. Lett. B778 (2018) 137

Heavy neutral leptons in νMSM

Neutrino minimal SM (**νMSM**) =
SM + 3 right-handed neutral heavy leptons.
[Asaka et al., PLB631 (2005) 151]
Masses: m_1~10 keV [DM candidate]; $m_{2,3}$~1 GeV.
HNLs observable via **production** and **decay**.

$$\Gamma(K^+\to\ell^+N) = \Gamma(K^+\to\ell^+\nu)\,\rho_\ell(m_N)\,|U_{\ell 4}|^2$$

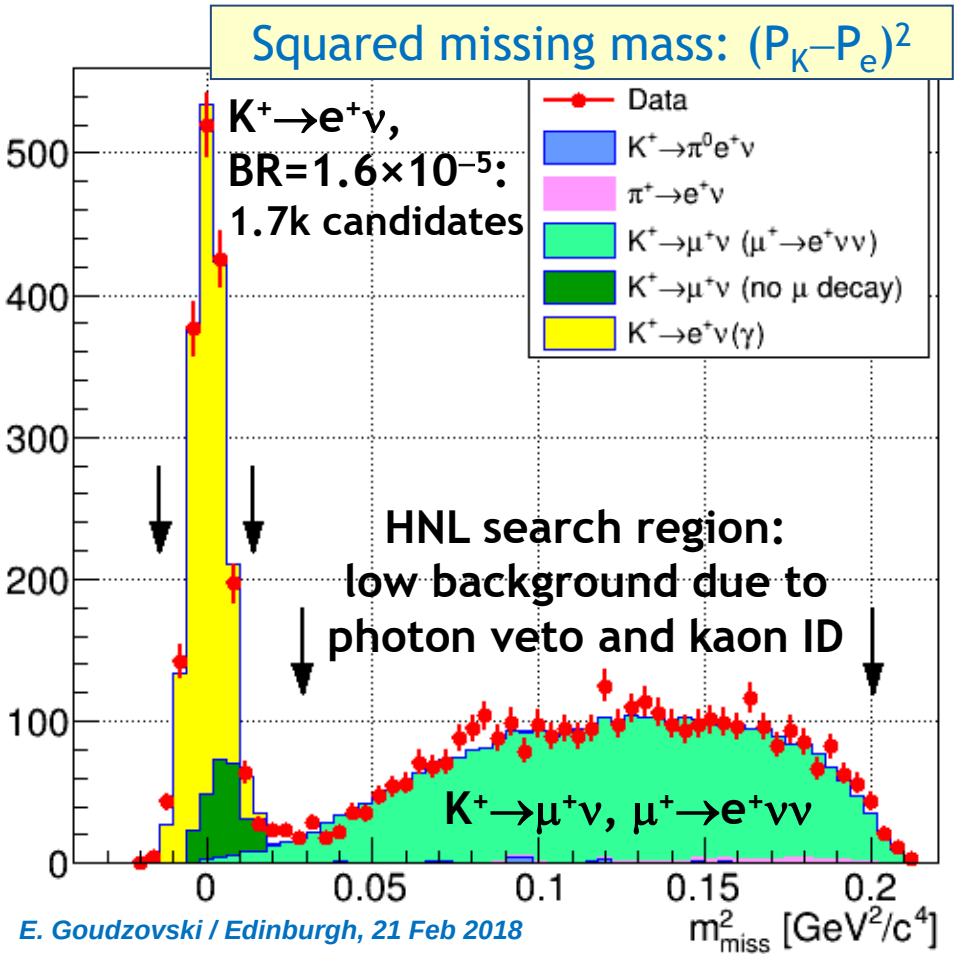


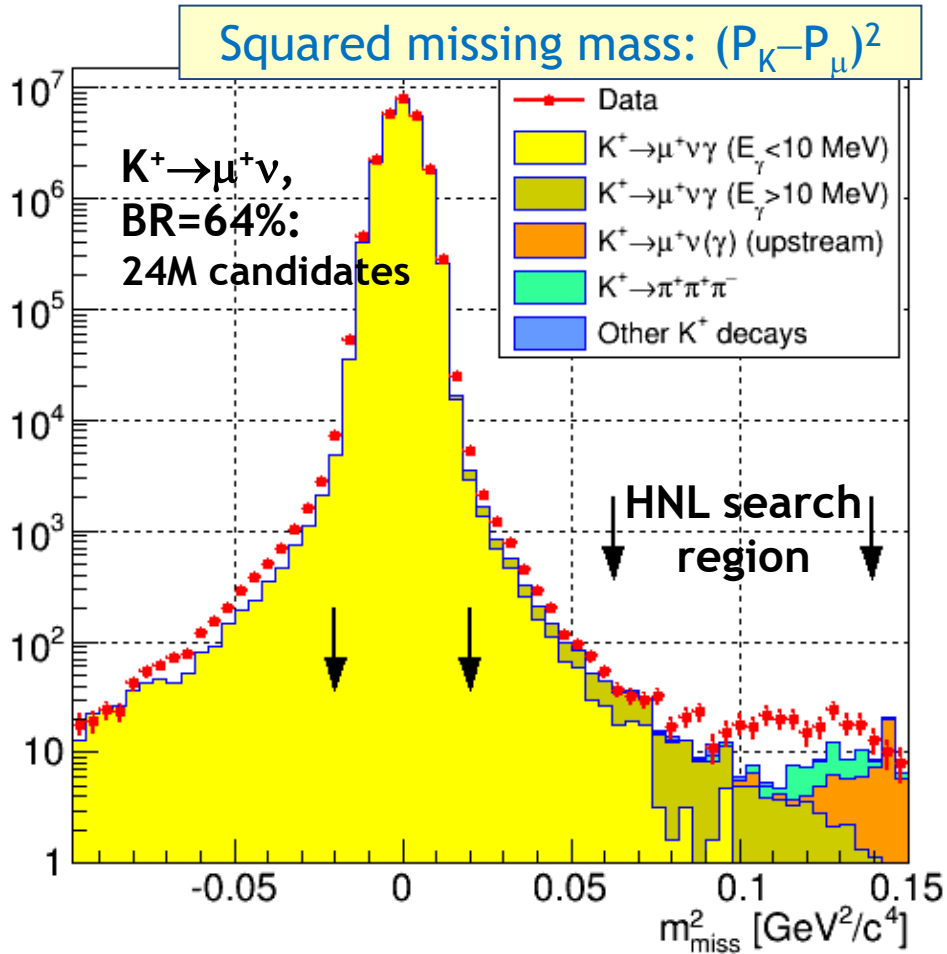


Shaposhnikov, JHEP 0808 (2008) 008
Boyarsky et al., Ann.Rev.Nucl.Part.Sci.59 (2009) 191

$K^+ \to \ell^+ N$ data samples

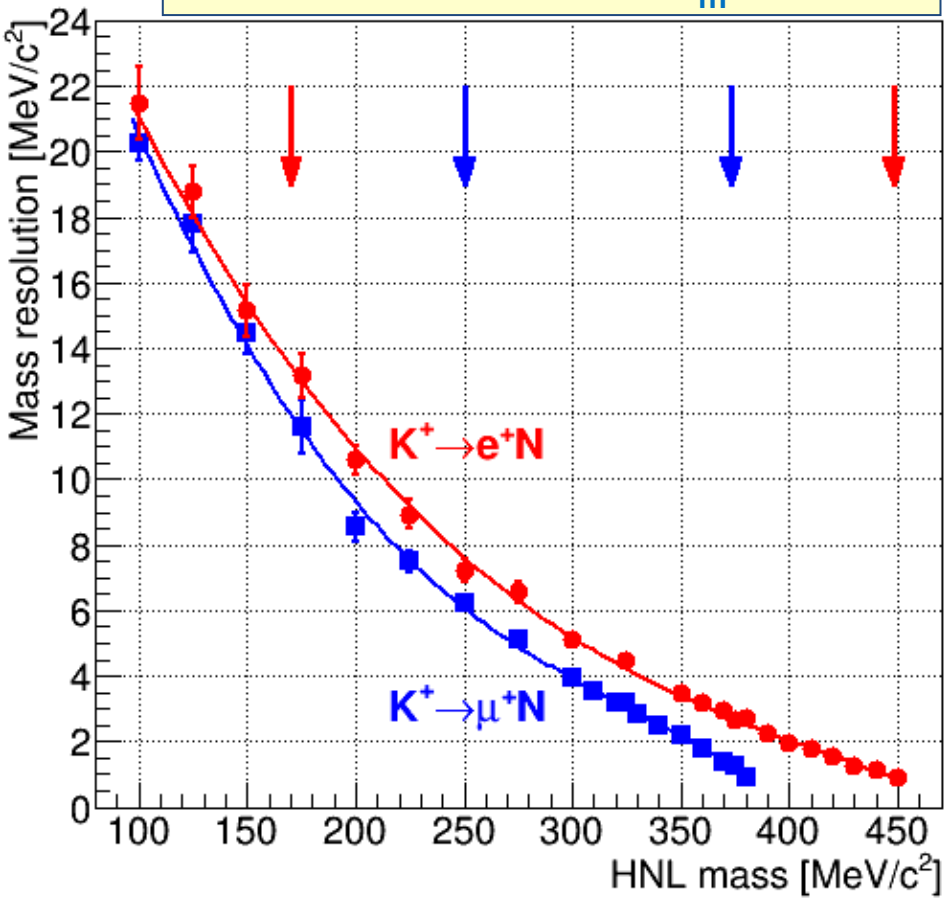
- Minimum bias data (1% intensity); 12k SPS spills (=5 days) in 2015.
- Numbers of K^+ decays in fiducial volume:
  $N_K = (3.01 \pm 0.11) \times 10^8$ in positron case; $N_K = (1.06 \pm 0.12) \times 10^8$ in muon case.
- Beam tracker not available: kaon momentum is estimated as the beam average.
- HNL production signal: **a spike above continuous missing mass spectrum**.



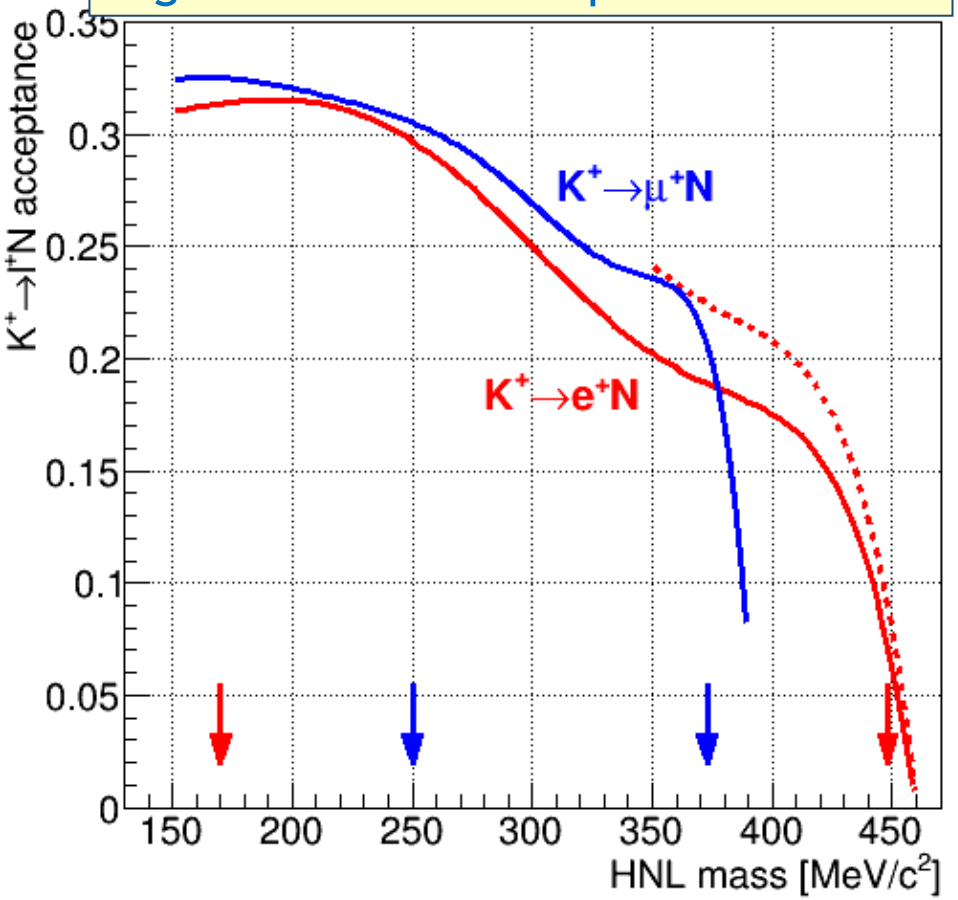


$K^+ \to \ell^+ N$: resolution & acceptance

HNL mass resolution σ_m vs mass



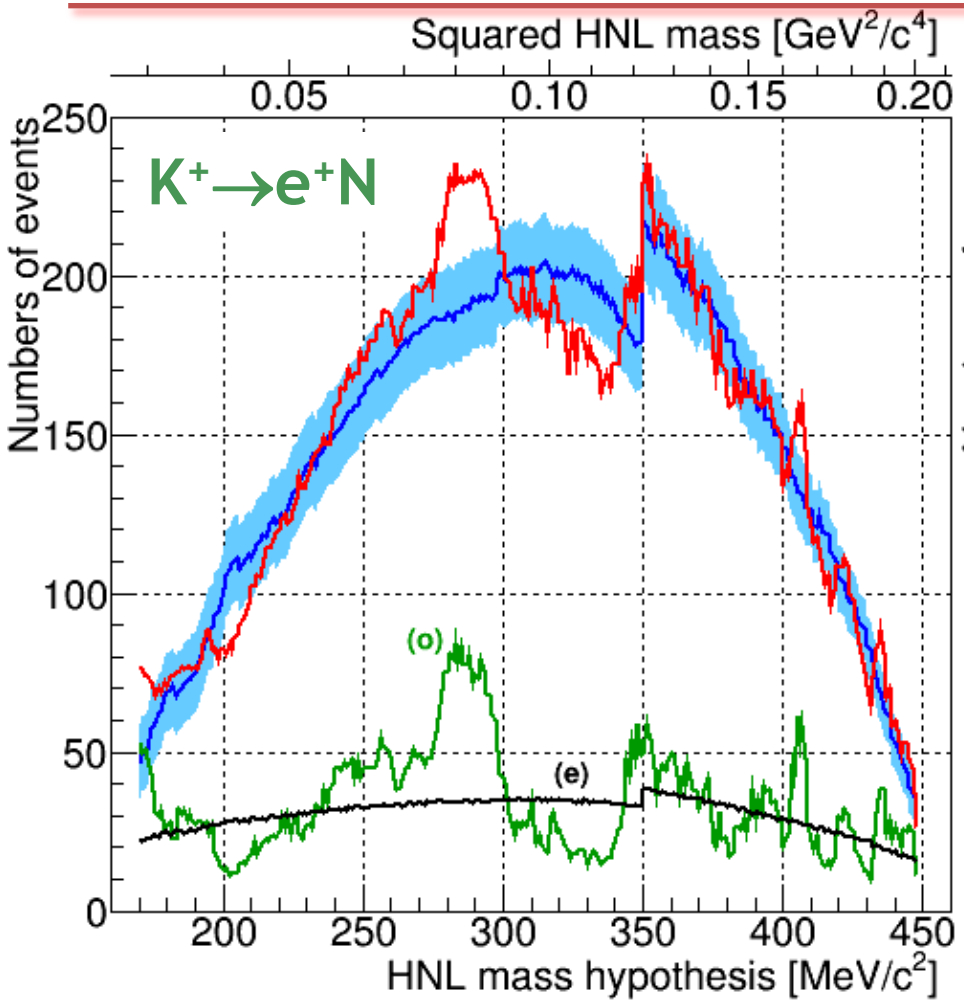
Signal selection acceptance vs mass

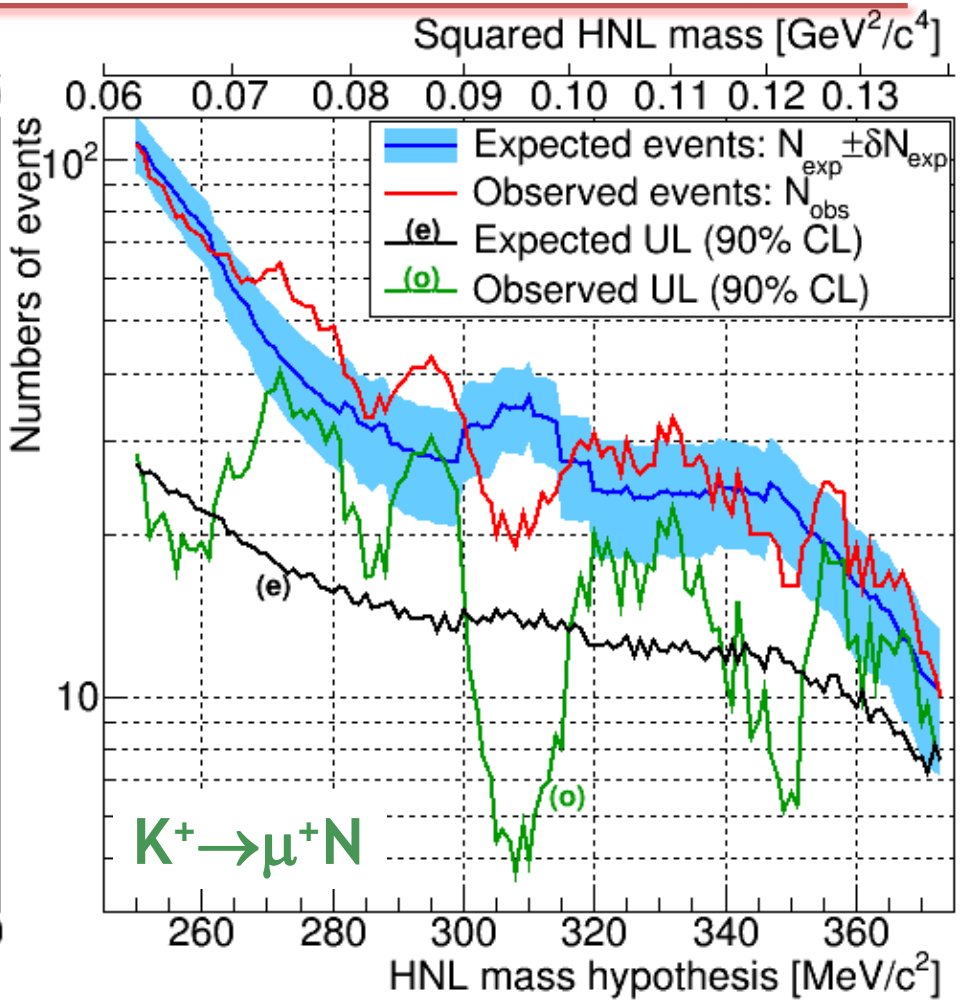


- Selection for each HNL mass hypothesis (m_{HNL}) includes the "mass window" condition: $|m - m_{HNL}| < 1.5\sigma_m$: background is proportional to mass resolution.
- Also, resolution is crucial to resolve possible HNL mass splitting

[Baryogenesis: 2 quasi-degenerate mass states; Canetti et al., PRD87(2013)093006]

Statistical analysis



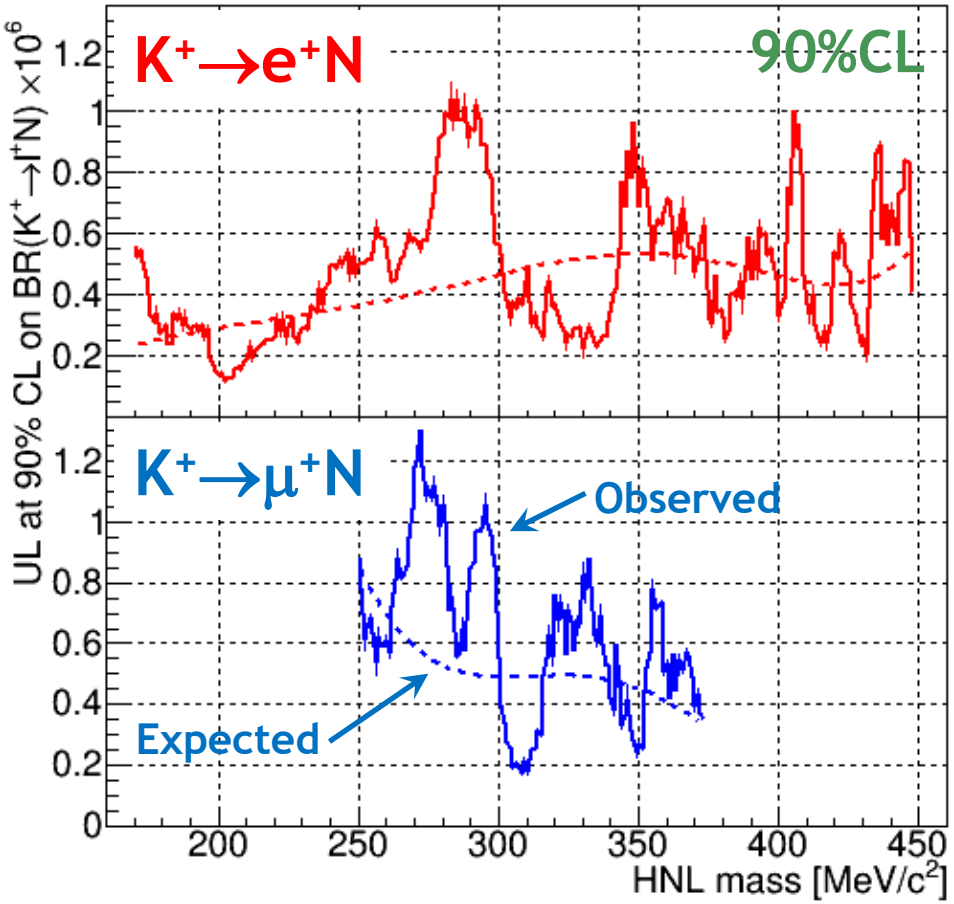


- Expected background (and stat.error) estimated from fits to the sidebands; numbers of observed and expected events converted into signal CI.
- Background simulations used to certify the absence of peaking structures.
- Full MC background estimate would allow a **measurement of $K^+ \to \ell^+ \nu\nu\nu$**.

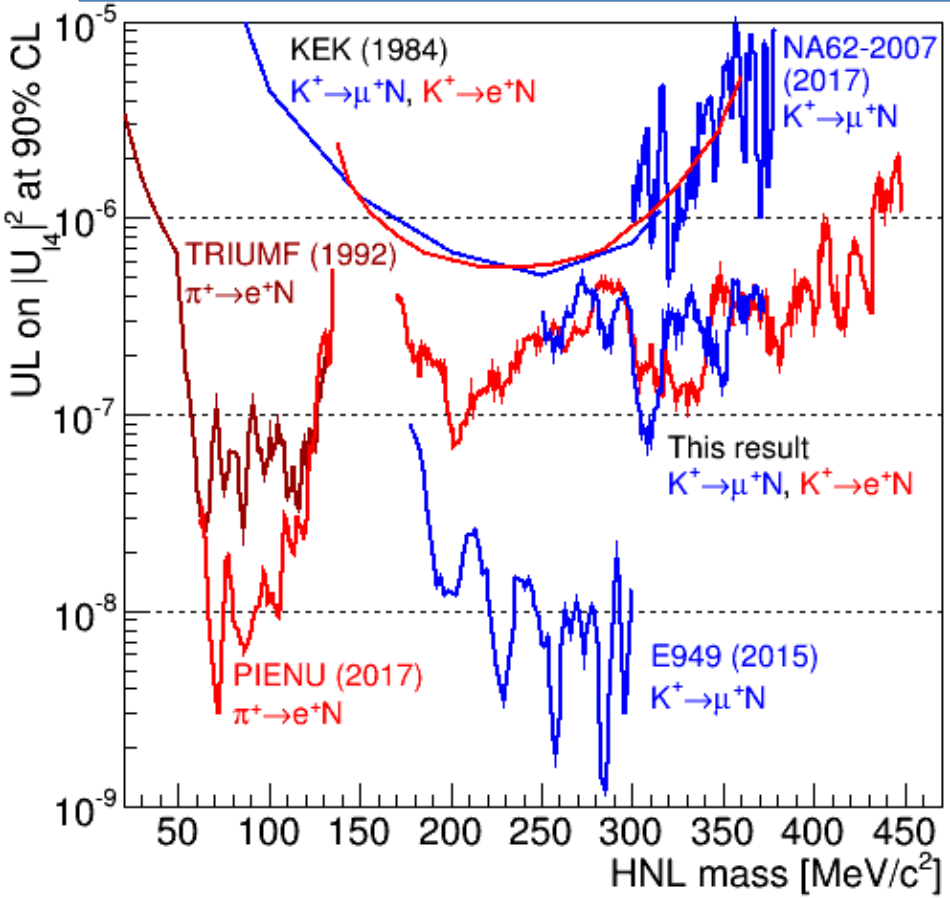
HNL production search: results

NA62 collaboration, Phys. Lett. B778 (2018) 137

Upper limits on BR($K^+ \to \ell^+ N$)



$|U_{\ell 4}|^2$ limits from production searches



- Local signal significance never exceeds 2.2σ: **no HNL signal** is observed.
- Reached 10^{-6}–10^{-7} limits for $|U_{\ell 4}|^2$ in the 170–448 MeV/c^2 mass range.

HNLs: prospects with full dataset

In comparison to the 2015 data set:

- Beam tracker (GTK) in operation:
  - ✓ a factor ~2 improved HNL mass resolution σ_m, therefore lower background and broader mass range is accessible;
  - ✓ a factor ~3 lower background in the $K^+ \to e^+ N$ mode ($K^+ \to \mu^+ \nu$, $\mu^+ \to e^+ \nu\nu$: muon decays in flight rejected geometrically);
  - ✓ lower background from upstream decays in the $K^+ \to \mu^+ N$ mode.
- Much larger datasets:
  - ✓ In the $K^+ \to e^+ N$ mode, the main $K^+ \to \pi^+ \nu\nu$ trigger can be used (with reduced signal acceptance: max calorimetric energy = 30 GeV): expect at least ~2×10^6 $K^+ \to e^+ \nu$ events, i.e. a factor ~1000 improvement.
  - ✓ In the $K^+ \to \mu^+ N$ mode, downscaled control trigger only (D=400): expect ~10^9 $K^+ \to \mu^+ \nu$ events, i.e. a factor ~100 improvement.

Expected sensitivities to $|U_{\ell 4}|^2$ with 2016–18 data:

~10^{-9} for $|U_{e4}|^2$, ~10^{-8} for $|U_{\mu 4}|^2$

Large data sets already collected; analysis is in progress

Summary

- First NA62 physics run (**2016–18**) is in progress:
  a large data sample collected; more data to be collected in **2018**.
- A discovery experiment focused on $K_{\pi\nu\nu}$ measurement (**SES~10^{-12}**):
  extreme beam intensity; sizeable trigger inefficiencies. Precision rare decay measurements are difficult; some are within reach.
- Searches for LF/LN violation in 3-track decays: analyses are in progress; aiming to reach **10^{-10}…10^{-11}** sensitivities,
  improving over the world limits.
- A programme of hidden sector searches in kaon decays is starting.
- First result: HNL production in **$K^+ \to \ell^+ N$** decays. *[PLB778 (2018) 137]*
  Sub-**10^{-6}** limits reached, expect **~2** orders of magnitude improvement.