Searches for hidden sectors and lepton flavor violation in kaon decays at the NA62 experiment

EPS-HEP 2025
Marseille, July 07-11

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INFN Perugia

NA62 experiment

NA62: fixed target experiment at CERN SPS

Technique:
Kaon decays in flight

Timeline:
- 2015: commissioning
- **2016-2018: Run 1**

- 2021-2026: Run 2

Primary goal:
Measure BR($K^+ \to \pi^+ \nu\nu$)

ECN3 hall at CERN

NA62 collaboration: ~300 participants, ~30 institutions

NA62 recent results

- $K^+ \to \pi^+ \nu \nu$
  - BR($K^+ \to \pi^+ \nu \nu$) JHEP 02 (2025) 191
  - spin-off: $K^+ \to \pi^+ X$ JHEP 03 (2021) 58 paper on Run1+2 analysis in preparation
- Precision measurements
  - $K^+ \to \pi^+ \gamma \gamma$ PLB 850 (2024) 138513
  - spin-off: $K^+ \to \pi^+ X$, $X \to \gamma \gamma$
- LFV/LNV decays
  - $K^+ \to \pi \mu e$ PRL 127 (2021) 131802
  - $K^+ \to \pi^- l^+ l^+$ PLB 797 (2019) 134794; PLB830 (2022) 137172
  - $K^+ \to \pi^- \pi^0 e^+ e^+$ PLB 830 (2022) 137172
  - $K^+ \to \mu^- \nu e^+ e^+$ PLB 838 (2023) 137679
  - $K^+ \to \pi^0 \pi \mu e$ PLB 859 (2024) 139122
- HNL production in kaon decays
  - $K^+ \to l^+ N$ PLB807 (2020) 135599, PLB816 (2021) 136259
- HNL production in pion decays
  - $\pi^+ \to e N$ Paper in preparation
- Beam dump searches for Hidden Sectors
  - $A' \to l^+ l^-$ PRL 133 (2024) 111802
  - $X \to$ hadronic states Eur. Phys. J. C85 (2025) 571
- Neutrino tagging PLB 863 (2025) 139345

This talk

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Talk by A. Romano

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- Beam dump searches for Hidden Sectors
  - $A' \to l^+ l^-$ PRL 133 (2024) 111802
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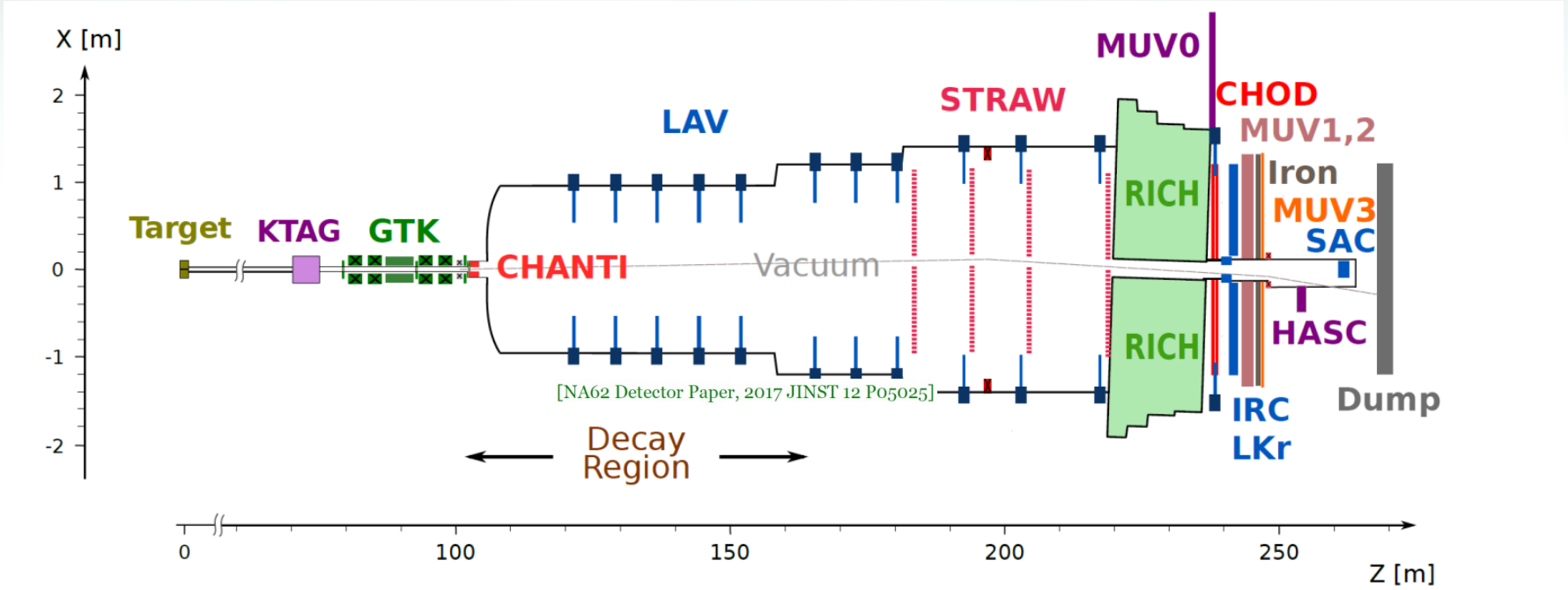
Talk by I. Rosa

- Neutrino tagging PLB 863 (2025) 139345

Talk by M. Perrin-Terrin

NA62 in the standard mode

[NA62 Detector Paper, 2017 JINST 12 P05025]



Primary beam:
- 400 GeV/c protons
- 3×10^{12} protons per spill

Secondary beam:
- 75 GeV/c (±1%)
- Beam angular spread < 100 μrad
- 70% pions, **6% K^+**, 24% protons

Key detectors:
- PID: KTAG, RICH, LKr, MUV1-2, MUV3
- Momentum: GTK, STRAW
- Time: GTK, KTAG, RICH, CHOD
- Photon veto: LAV, LKr, IRC, SAC

Hidden sector searches

Hidden sector paradigm

- Could explain Dark Matter
- Mediator particles: kinetic mixing with SM particles via portals
- Mass: MeV-GeV

Hidden sector searches @ NA62

- Production searches in K→π X, K →l X
- Decay searches in K→π X (X →ll, γγ)
- Decay searches in beam dump mode: X →ll, hadrons

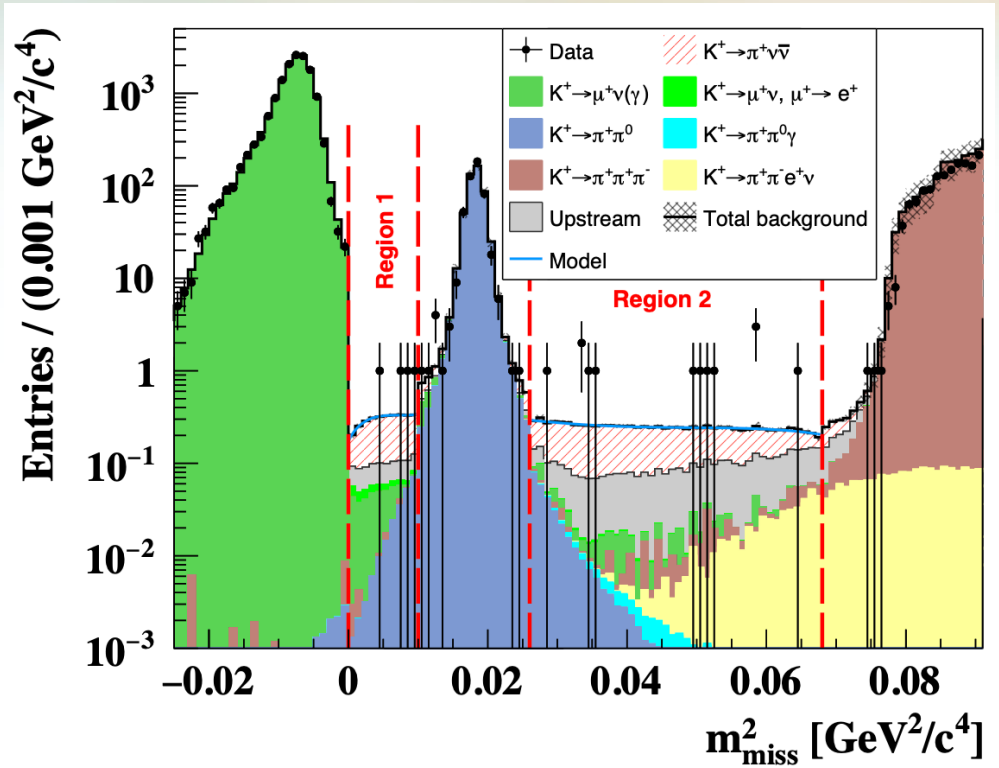
Dark sector portals and PBC scenarios

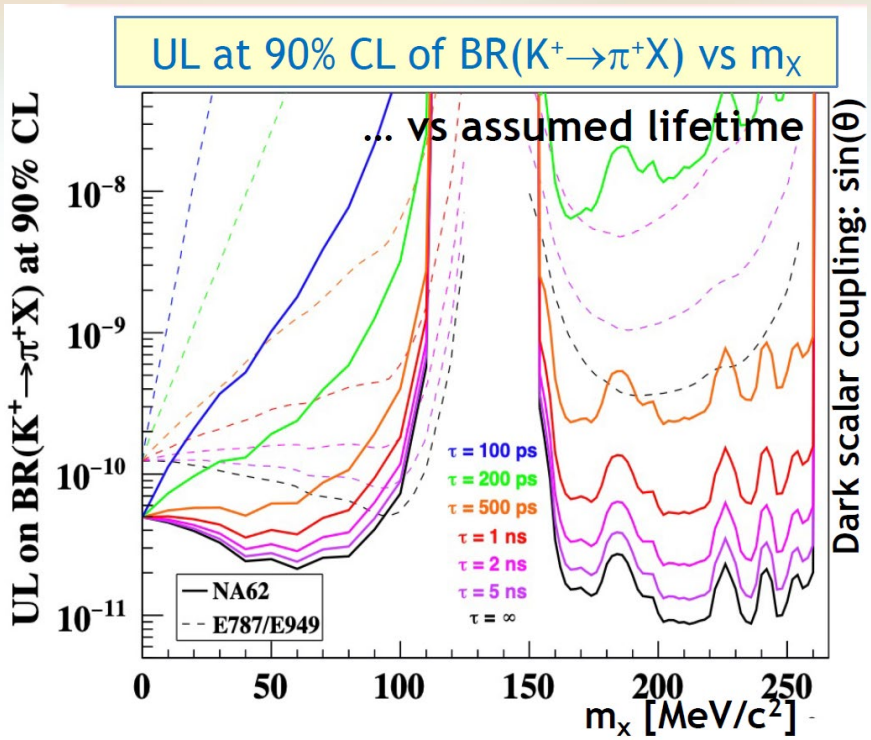
NP particle	Type	Minimal portal	Decay ($m \leq GeV$)	PBC*
Dark photon (A')	Vector	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$	$ll, 2\pi, 3\pi$	BC1-2
Dark scalar (S)	Scalar	$(\mu S + \lambda S^2) H^\dagger H$	$ll, 2\pi$	BC4-5
ALP (a)	Pseudoscalar	$\frac{C_{ff}}{\Lambda} \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f$, $\frac{C_{VV}}{\Lambda} a V_{\mu\nu} \tilde{V}^{\mu\nu}$	$\gamma\gamma, ll, 2\pi\gamma, 3\pi, 2\pi\eta$	BC10, BC9-11
HNL (N)	fermion	$F_{\alpha I} (\bar{L}_\alpha H) N_I$	$\pi l(\nu), l_1 l_2(\nu)$	BC6-8

*Physics Beyond Collider project at CERN [J. Phys. G47 (2020) 010501]

Searches for $K^+ \to \pi^+ X$ decays

$K^+ \to \pi^+$ X, X invisible





Data:
- Run 1 (2016-2018)

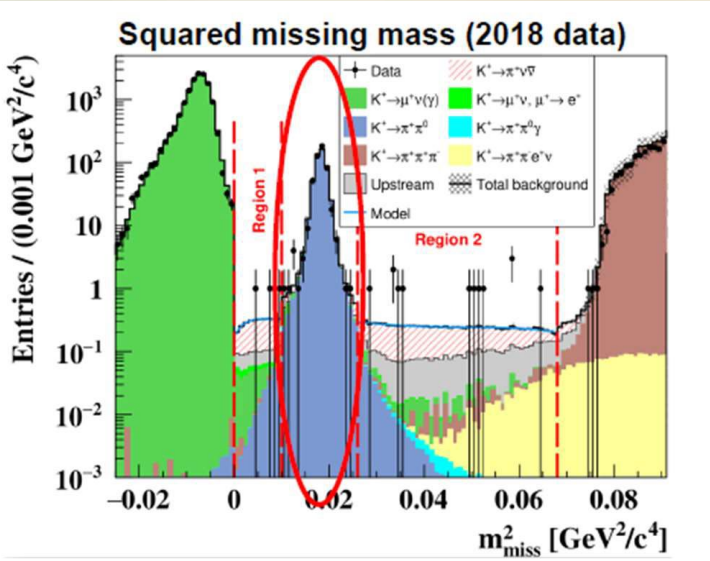
JHEP 03 (2021) 58

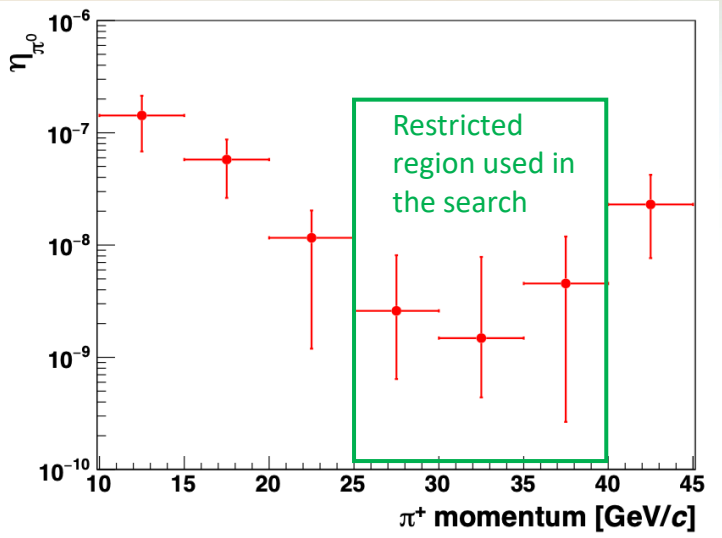
Main features
- Spin-off of the $K^+ \to \pi^+ \nu \nu$ analysis
- Observable: $m^2_{miss} = (p_K - p_\pi)^2$
- Mass/tau scan: 0-110 and 154-260 MeV and $\tau \geq 100$ ps
- Main bkg from $K^+ \to \pi^+ \nu \nu$

$K^+ \to \pi^+ \pi^0$, $\pi^0 \to$ invisible

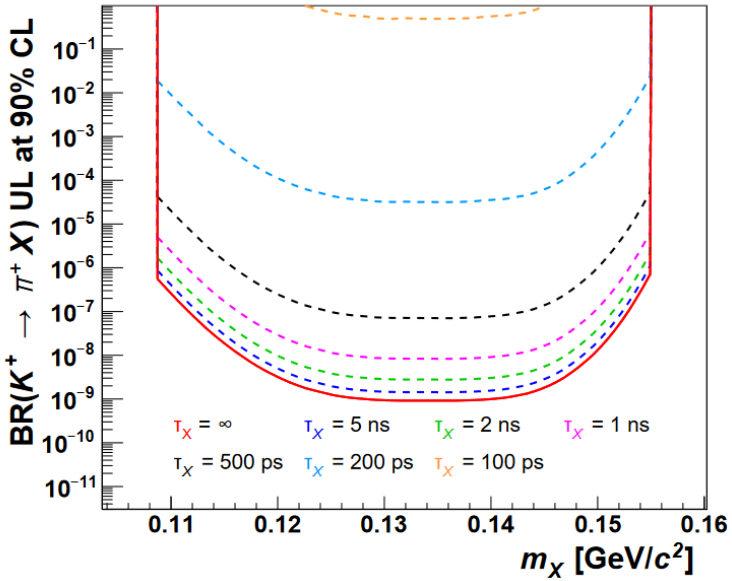
Data:
- 10% Run 1 (2017)

JHEP 02 (2021) 201





Main features
- Selection for the $K^+ \to \pi^+ \nu \nu$ analysis applied to $K^+ \to \pi^+ \pi^0$ region
- Observable: $m^2_{miss} = (p_K - p_\pi)^2$
- Main bkg from $K^+ \to \pi^+ \pi^0$: MC + single γ efficiency from data ($K^+ \to \pi^+ \pi^0$ decays), restricted region $p(\pi^+)$ = 25-40 GeV
- Mass/tau scan: 110-155 MeV, $\tau \geq 100$ ps

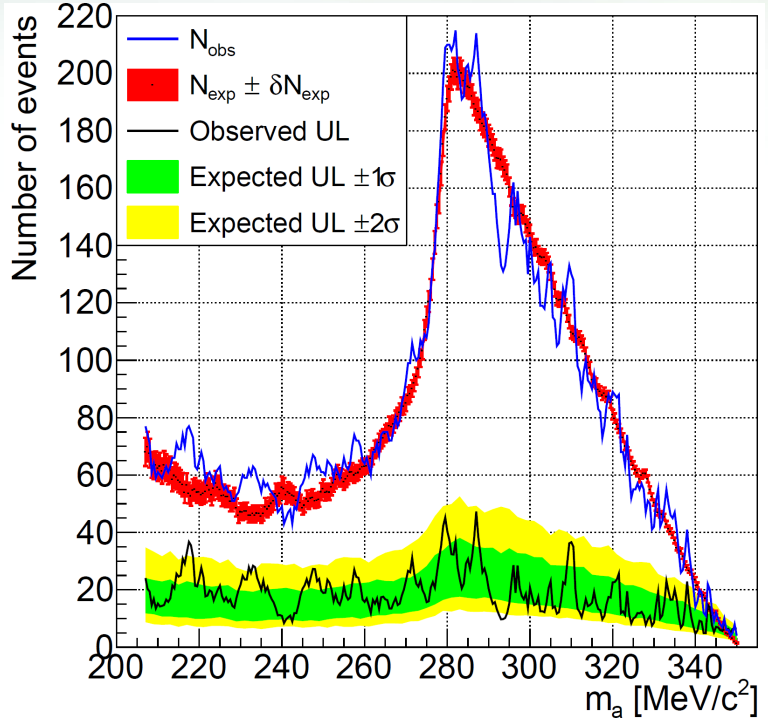


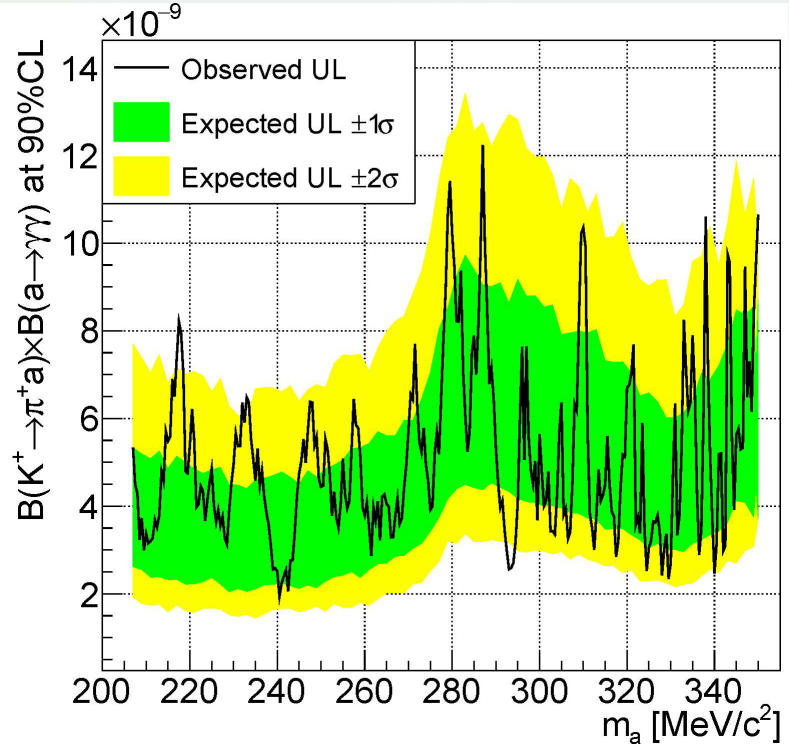
$K^+ \to \pi^+ X,\ X \to \gamma\gamma$

Data:
- Run 1 (2017-2018)

PLB 850 (2024) 138513

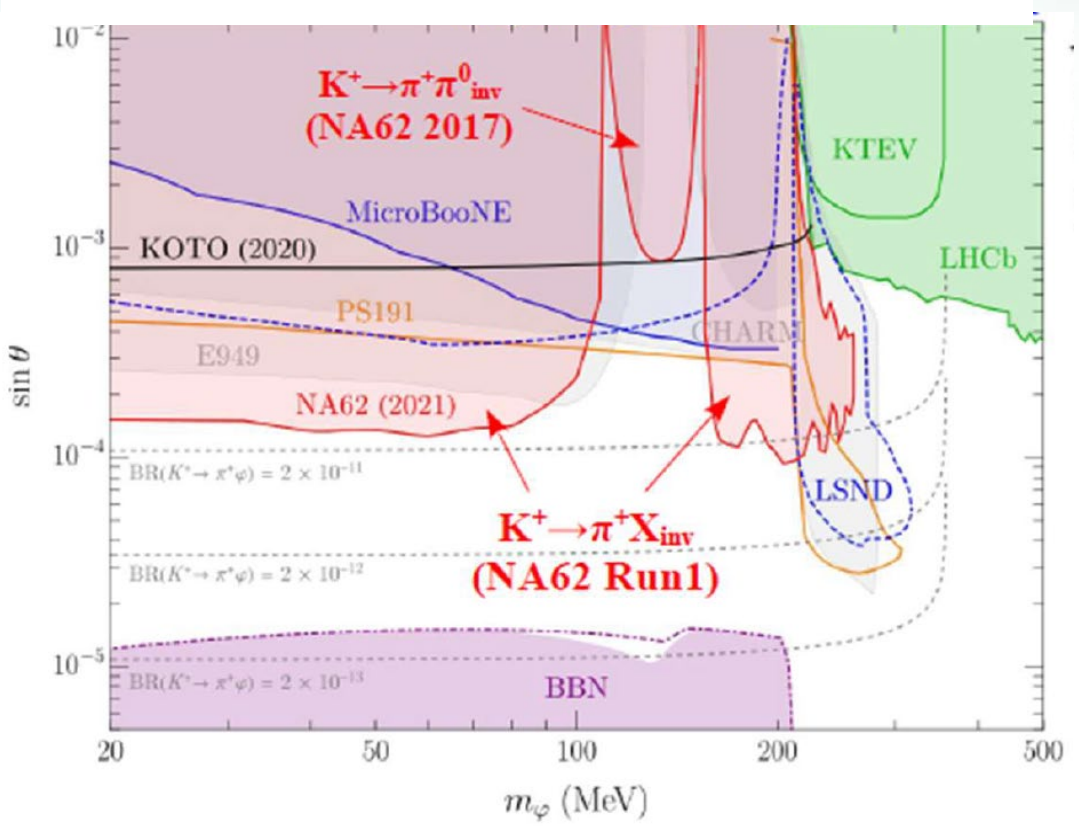
Main features
- Spin-off of the $K^+ \to \pi^+ \gamma\ \gamma$ analysis
- Prompt decays assumed for X
- Observable: $m_{miss} = \sqrt{(p_K - p_\pi)^2}$
- Mass scan: 207-350 MeV
- Main bkg from $K^+ \to \pi^+ \gamma\ \gamma$





$K^+ \to \pi^+ X$ interpretation

Dark scalar decaying to SM particles (BC4)



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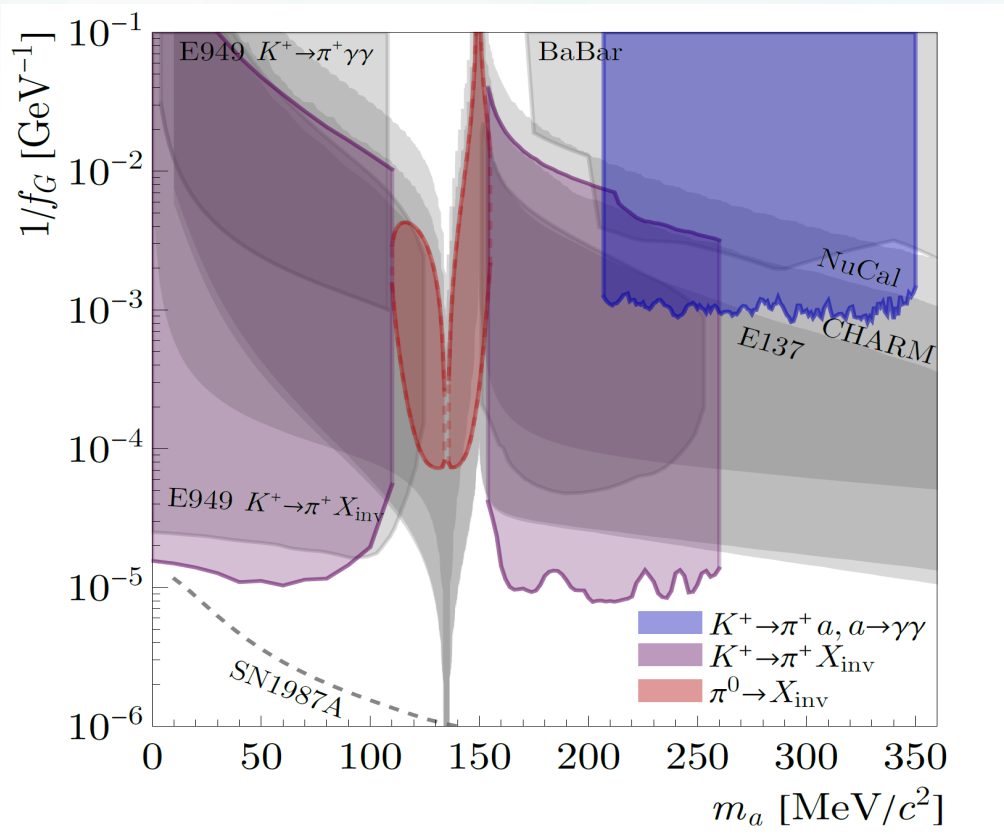
ALP with gluon coupling (BC11)



PLB 850 (2024) 138513

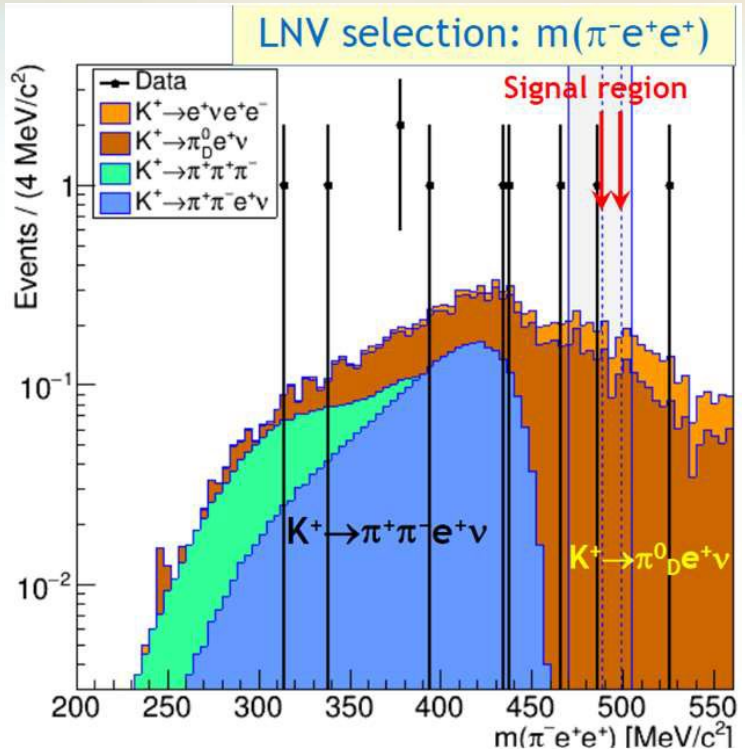
LFV/LNV decays

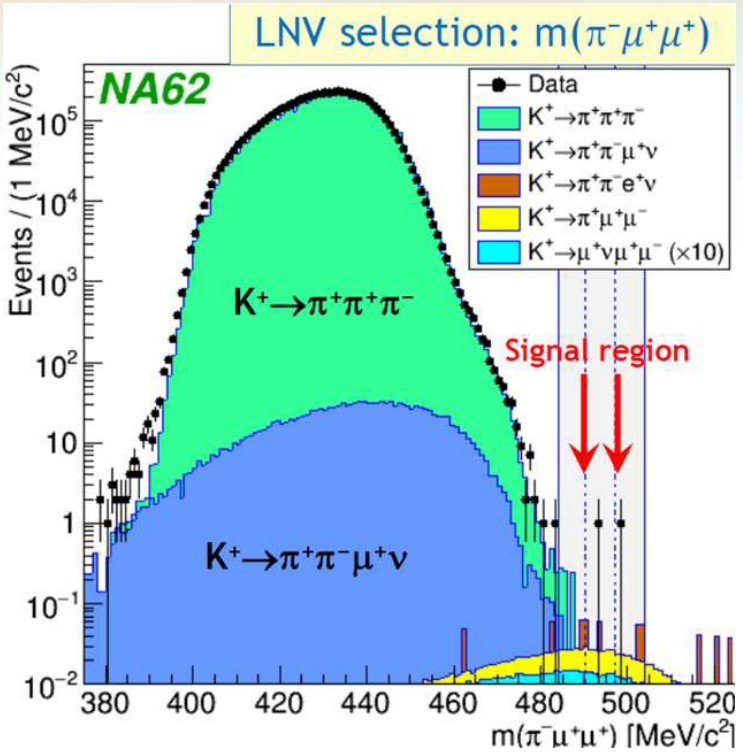
$K^+ \to \pi^- l^+ l^+$

Data:
- Run 1 (2016-2018) for K→πee
- 25% Run 1 (2017) for K→πμμ

PLB830 (2022) 137172

PLB797 (2019) 134794



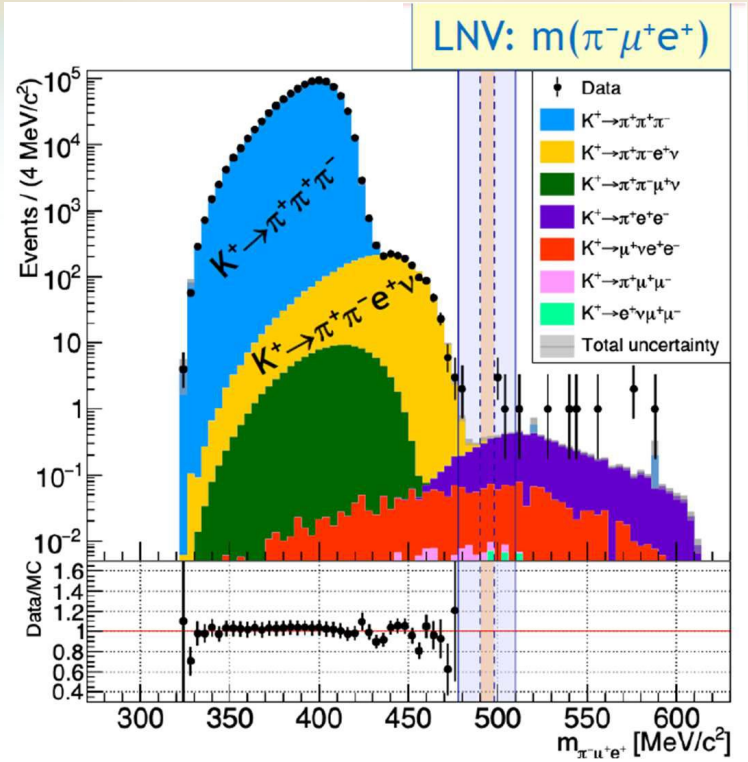


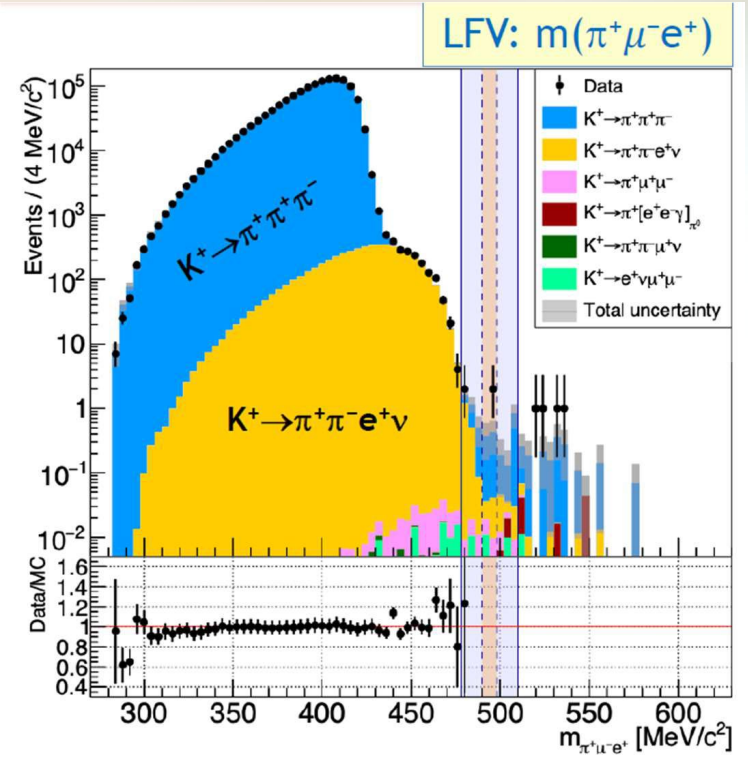
mode	Expected bkg	N(observed)	UL(BR) @ 90% CL
$K^+ \to \pi^- e^+ e^+$	0.43(9)	0	$5.3*10^{-11}$
$K^+ \to \pi^- \mu^+ \mu^+$	0.91(41)	1	$4.2*10^{-11}$

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

Data:
- Run 1 (2017-2018)

PRL 127 (2021) 131802





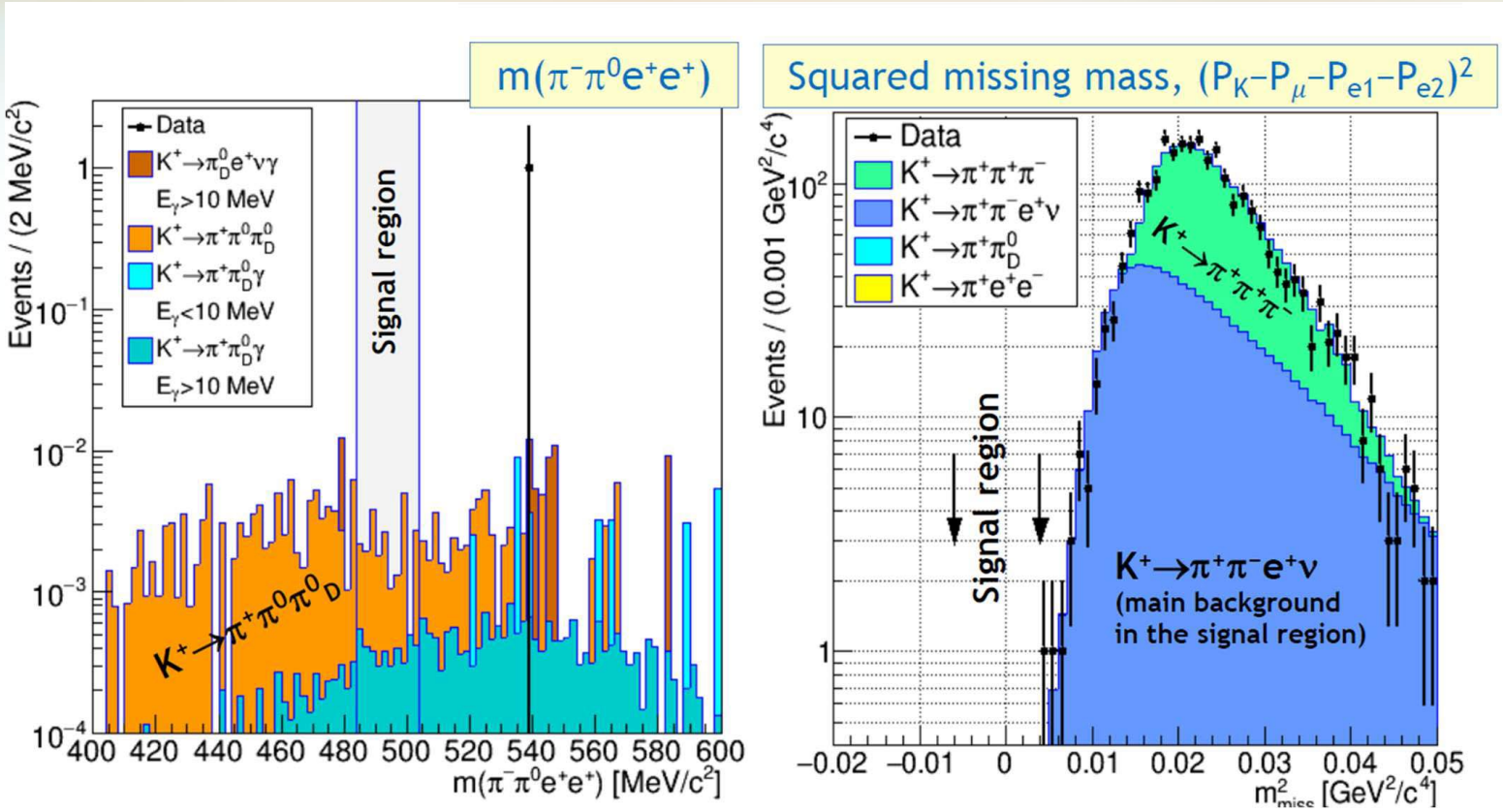
mode	Expected bkg	N(observed)	UL(BR) @ 90% CL
$K^+ \to \pi^- \mu^+ e^+$	1.07(20)	0	$4.2*10^{-11}$
$K^+ \to \pi^+ \mu^- e^+$ $\pi^0 \to \mu^- e^+$	0.92(34)	2	$6.6*10^{-11}$ $3.2*10^{-10}$

$K^+ \to \pi^- \pi^0 e^+ e^+$ and $K^+ \to \mu^- \nu e^+ e^+$

Data:
- Run 1 (2016-2018)

PLB 830 (2022) 137172

PLB 838 (2023) 137679

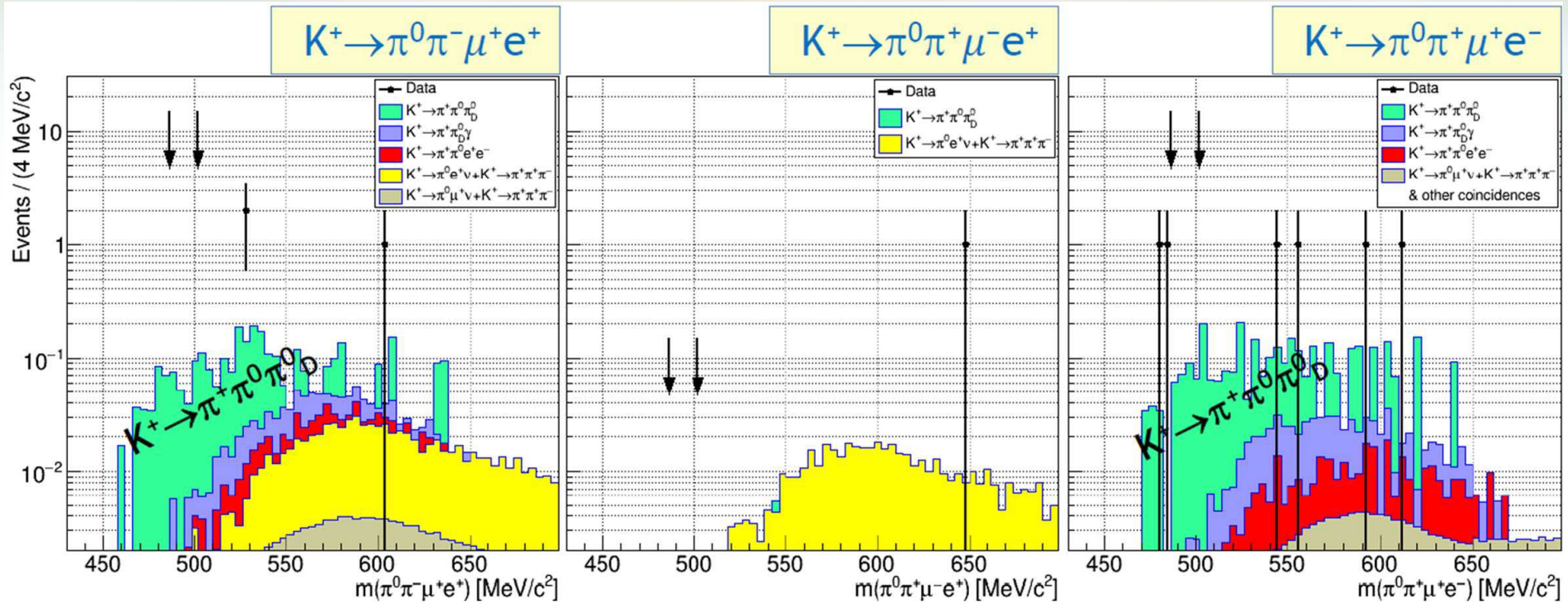


mode	Expected bkg	N(observed)	UL(BR) @ 90% CL
$K^+ \to \pi^- \pi^0 e^+ e^+$	0.044(20)	0	$8.5*10^{-10}$
$K^+ \to \mu^- \nu e^+ e^+$	0.26(4)	0	$8.1*10^{-11}$

Search for $K^+ \to \pi^0 \pi e \mu$

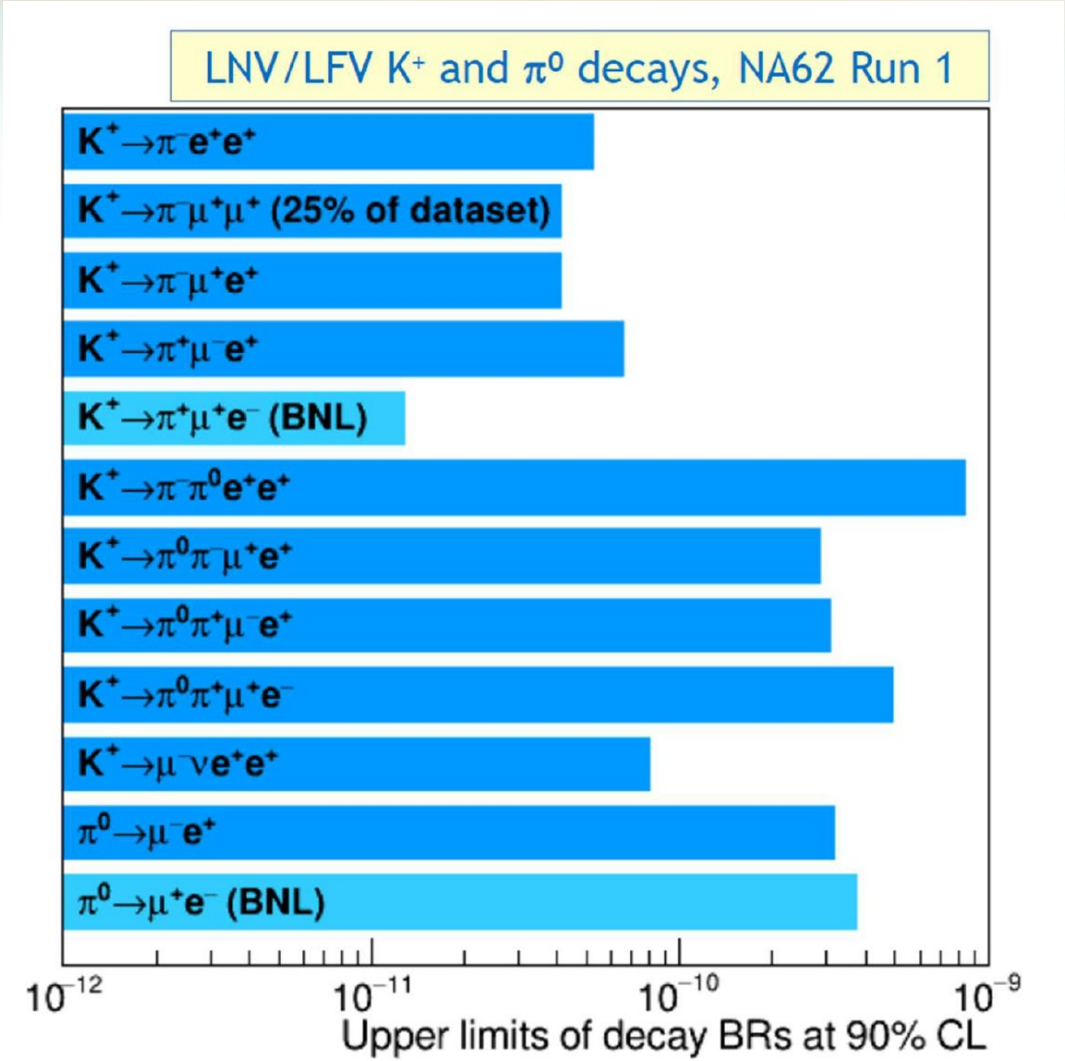
Data:
Run 1 (2016-2018)

PLB 859 (2024) 139122



Mode	Expected bkg	N(observed)	UL(BR) @ 90%CL
$K^+ \to \pi^0 \pi^- \mu^+ e^+$	0.33(7)	0	$2.9*10^{-10}$
$K^+ \to \pi^0 \pi^+ \mu^- e^+$	0.004(3)	0	$3.1*10^{-10}$
$K^+ \to \pi^0 \pi^+ \mu^+ e^-$	0.29(7)	0	$5.0*10^{-10}$

LFV/LNV decays @ NA62: state of the art



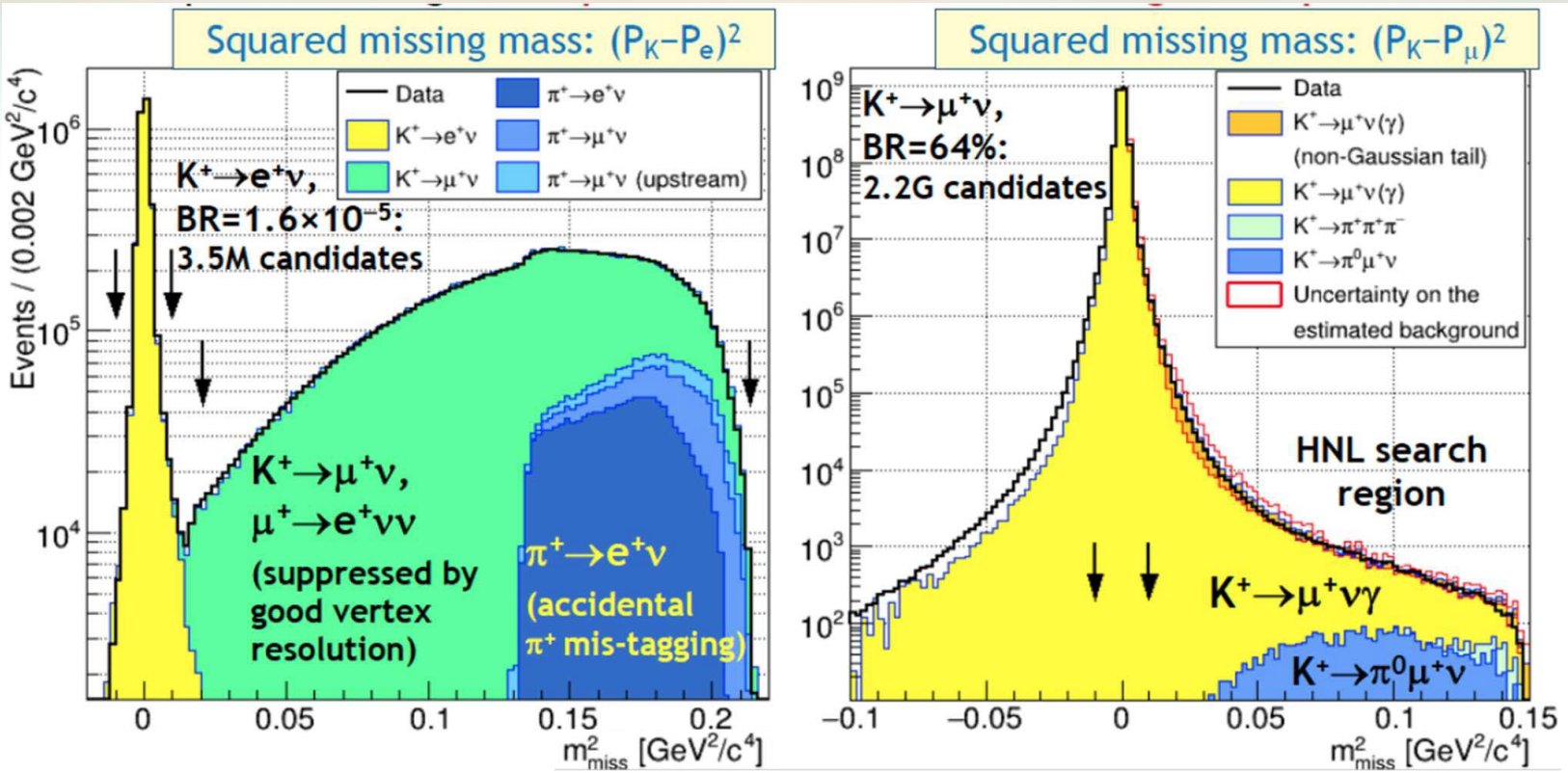
Searches for HNL in $K^+ \to l^+ N$ and $\pi^+ \to e^+ N$ decays

$K^+ \to l^+ N$

Data:
e: Run 1 (2017-2018)
μ: Run 1 (2016-2018)

PLB807 (2020) 135599
PLB816 (2021) 136259

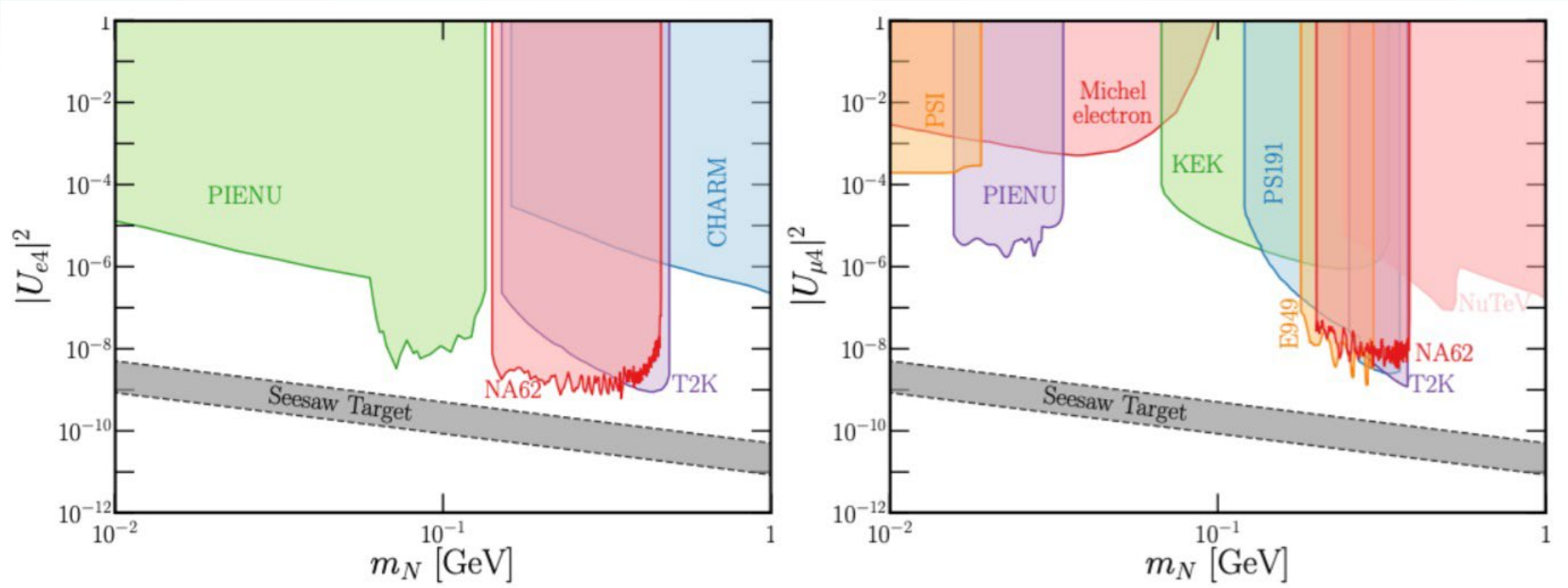
Main features
- Observable: $m^2_{miss} = (P_K - P_l)^2$
- Mass scan: expected bkg from sidebands, CLs to set UL(N)
- N lifetime > 50 ns



mode	N_K	Mass scan range	Main bkg
$K^+ \to e^+ N$	$3.5*10^{12}$	144-462 MeV	$K^+ \to \mu^+ \nu$ ($\mu^+\to e^+ \nu \nu$)
$K^+ \to \mu^+ N$	$4.3*10^9$ Downscaled min. bias trigger	200-384 MeV	$K^+ \to \mu^+ \nu \gamma$

HNL production in K decays

BC6,7: $|U_{\ell 4}|2$ limits vs m_{HNL} from production & decay searches



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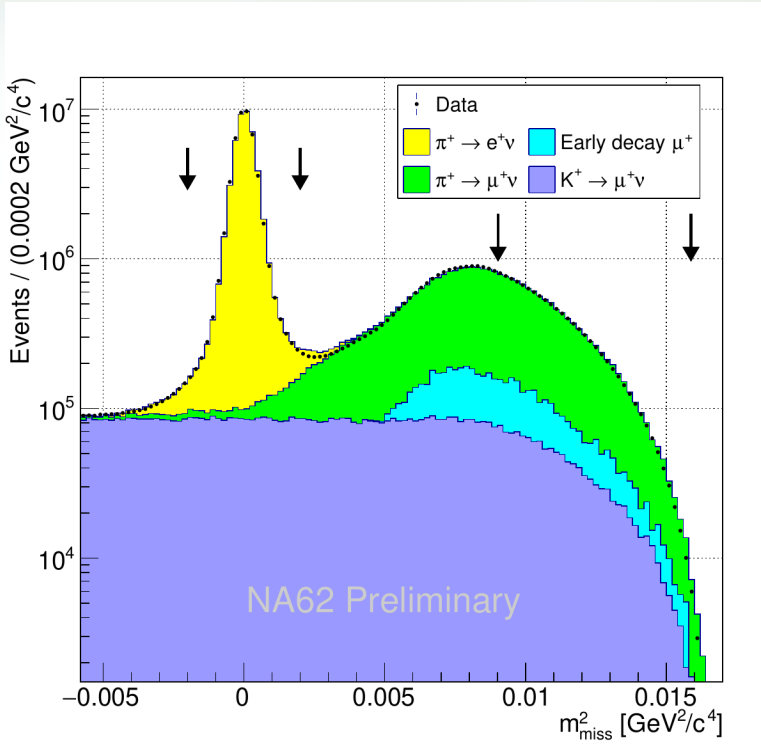
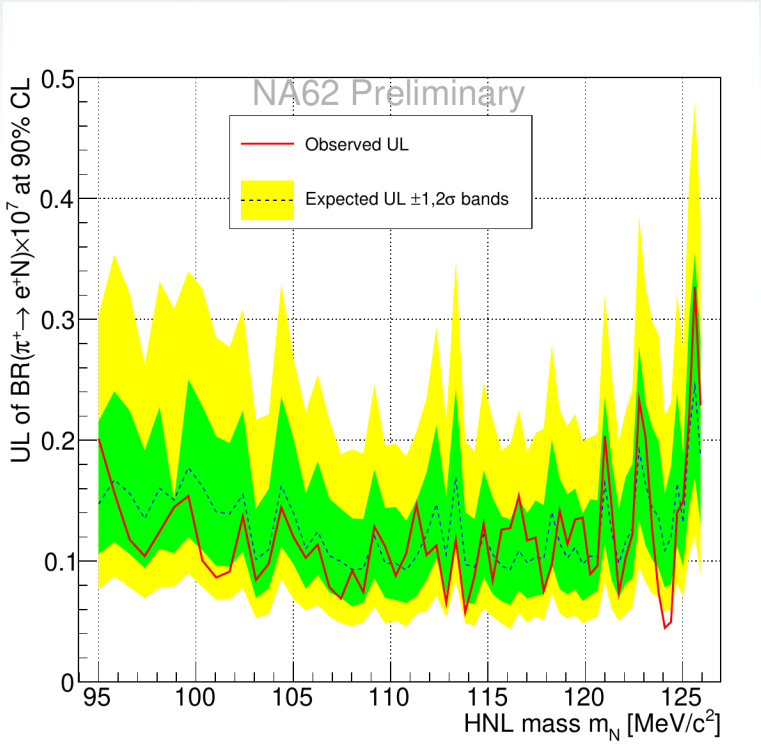
Search for HNL in $\pi^+ \to e^+$ N decays

Data:
- Run 1 (2016-2018)
- Run 2 (2021-2024)

Paper in preparation



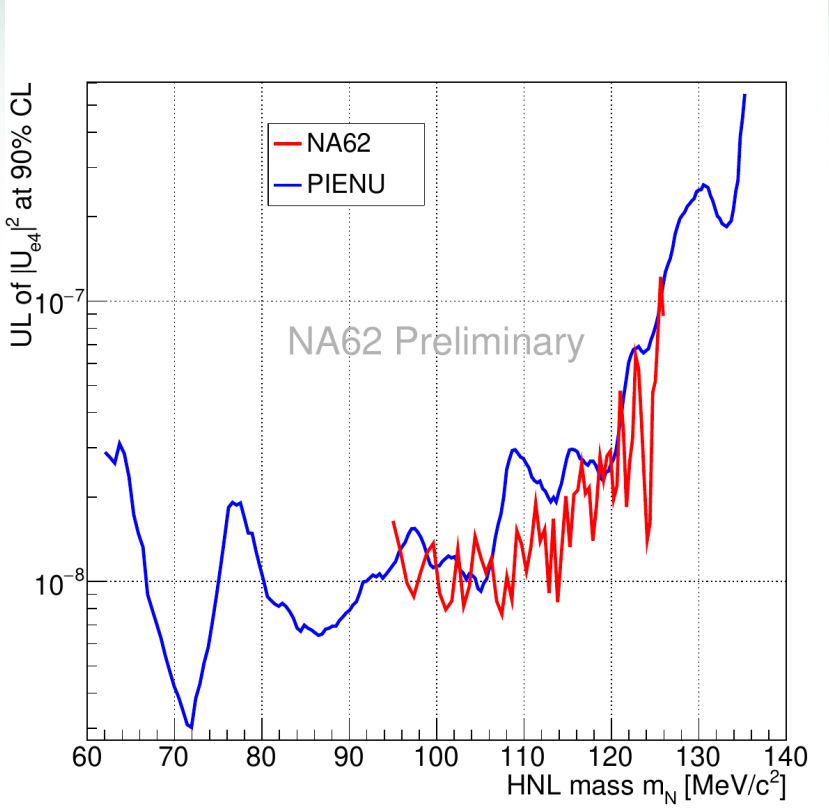


Main features
- Pion decays from pileup
- Observable: $m^2_{miss} = (P_\pi - P_e)^2$
- $N_\pi = 6.54(3) \times 10^{12}$
- Mass scan: 95-126 MeV, expected bkg from sidebands, CLs to set UL(N)
- Main bkg from $\pi^+ \to \mu^+ \nu$

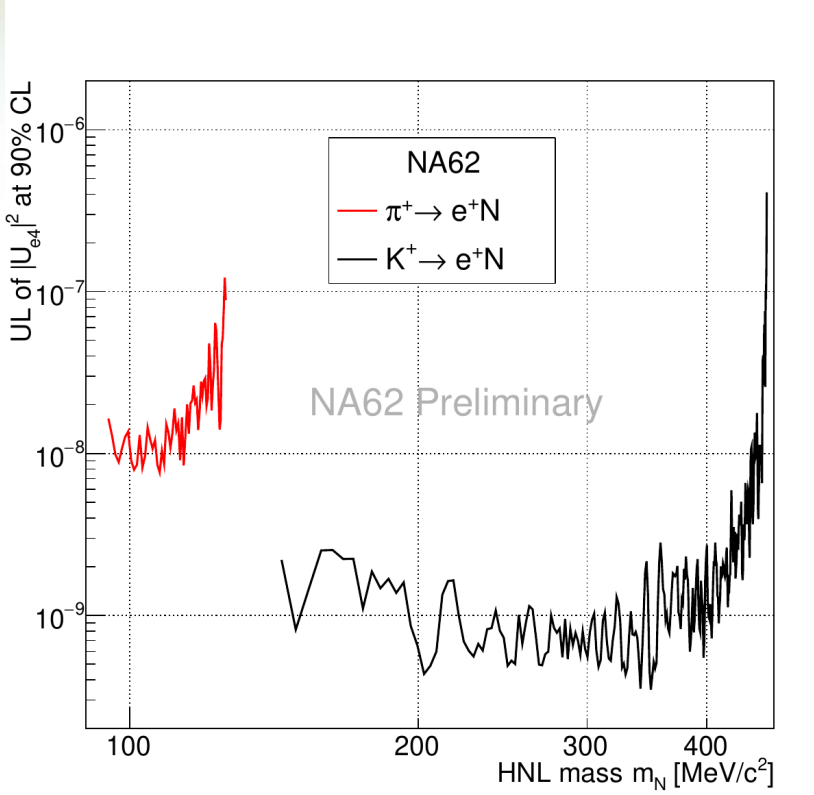
Normalisation:
- $\pi^+ \to e^+ \nu$
- bkg from K decays normalised to $K^+ \to e^+ \nu$

- For all mass hypotheses UL(BR) ~10^{-8}
- Local significance <3σ

HNL production in pion decays



- Limits comparable with PIENU



- Extension to lower masses wrt K decays

Paper in preparation

Conclusions

Search for hidden sectors

- $K^+ \to \pi^+ X$: dark scalar (BC4), ALP (BC10, 11)
- $K^+ \to l^+ X$, $\pi^+ \to e^+ X$: HNL(BC6, 7)

Search for LFV/LNV decays

- NA62 has already collected $N_K \sim O(10^{13})$
- Stringent limits UL(BR) with Run 1 data at $10^{-9} – 10^{-10}$

Future plans

- Collect data in 2025-2026 (both standard and beam dump mode)
- Improvement in sensitivity: factor $\sim N_K$ for small bkg signatures, $\sim\sqrt{N_K}$ for bkg dominated signatures

Spare

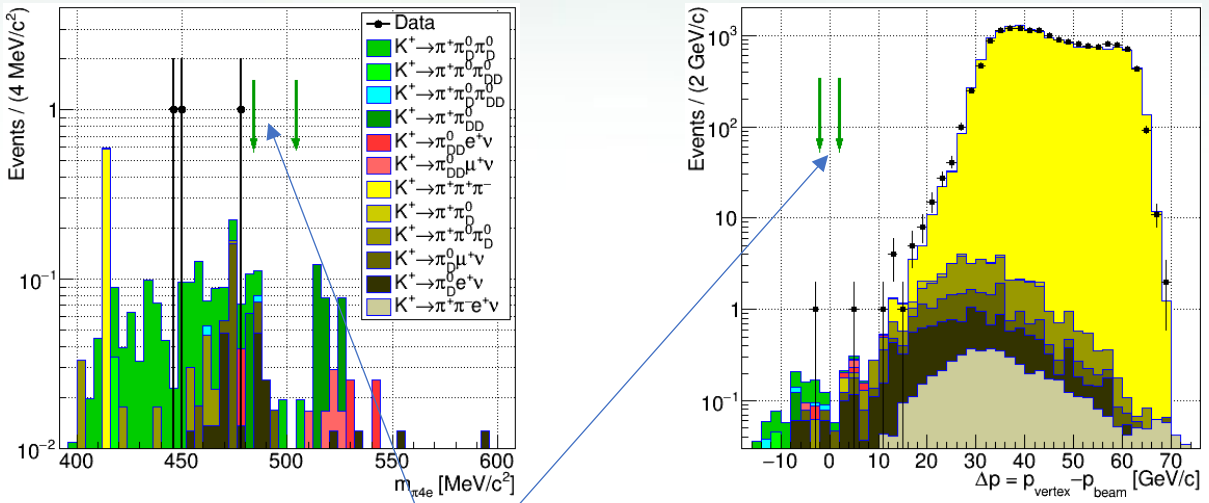
$K^+ \to \pi^+ e^+ e^+ e^- e^-$ analysis strategy

Data:

Run 1 (2017-2018)

Main features

- 5 tracks without PID, just kinematic cuts
- Kinematic variables: $m_{\pi 4e} = m(\pi eeee)$, $\Delta p = p(\pi eeee) - p_K$
- $|m_{eeee} - m_{\pi 0}| > 10$ MeV
- Masked signal region in terms of $m_{\pi 4e}$ and Δp
- $A(sig, SM) = 1.85 \times 10^{-4}$
- $N_K = 8.58(46) \times 10^{11}$



SR: $N_{observed} = 0$

Normalisation:

- $K^+ \to \pi^+ \pi^0$, $\pi^0 \to \gamma\gamma$, $\gamma \to e^+ e^-$
- $|m_{eeee} - m_{\pi 0}| < 10$ MeV
- $N(K^+ \to \pi^+ \pi^0$, $\pi^0 \to \gamma\gamma$, $\gamma \to e^+ e^-) = 2023$

Expected bkg:

N = 0.18(6)

$BR(K^+ \to \pi^+ e^+ e^- e^+ e^-) < 1.4 \times 10^{-8}$ (90% CL)

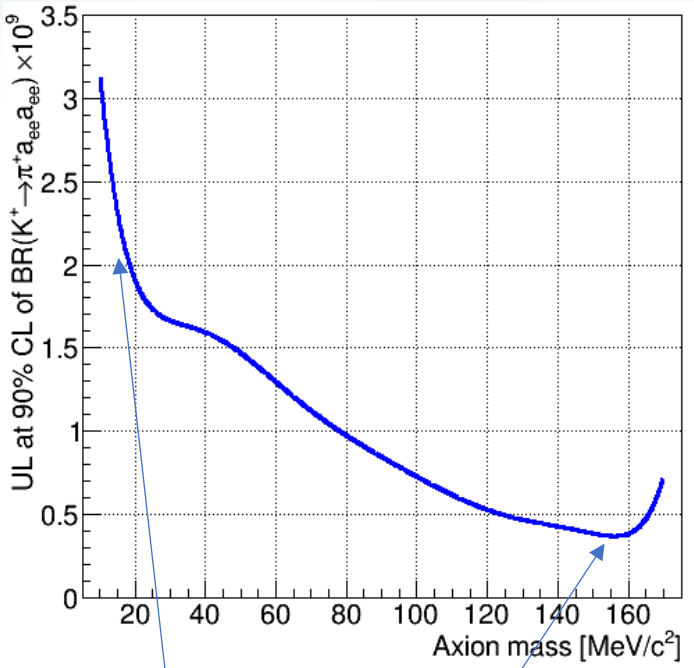
- First upper limit
- Factor of 200 far from BR(SM, expected) = 7.2×10^{-11}

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

Mass scan

- Multiple hypotheses tested
- $10 < m_a < 170$ MeV, 5 MeV step
- $20 < m_S < 340$ MeV and $10 < m_{A'} < 170$ MeV, 5 MeV step
- CLs to set UL(BR)

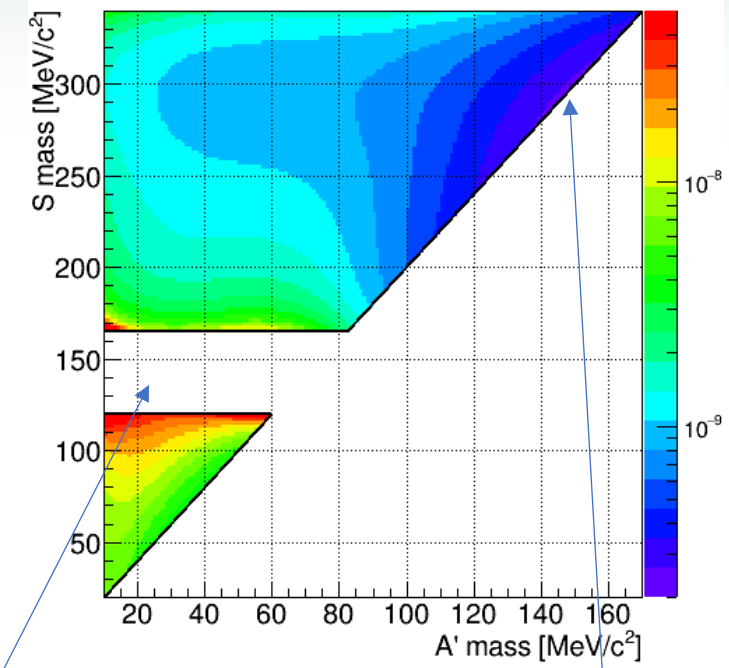
$K^+ \to \pi^+$ a a, a $\to e^+ e^-$



17 MeV anomaly
explanation with QCD axion excluded (UL = 2.1×10^{-9})

Best limit at 155 MeV
UL = 3.7×10^{-10}

$K^+ \to \pi^+$ S, S $\to$ A' A', A' $\to e^+ e^-$



$m_{\pi 0}$ region:

- low acceptance due to $|m_{eeee} - m_{\pi 0}| > 10$ MeV
- Excluded from the search

Best limit at $m_{A'} = 150$ MeV, $m_S = 300$ MeV
UL = 2.5×10^{-10}