Search for physics beyond the Standard Model at NA62

Michal Zamkovsky

CERN

August 26, 2024

Outline

Main goal of the NA62 experiment:

- Measurement of the Branching fraction of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay
  - Golden mode of the flavour physics, sensitive to BSM
  - Reinterpretation for $K^+ \to \pi^+ X$ search

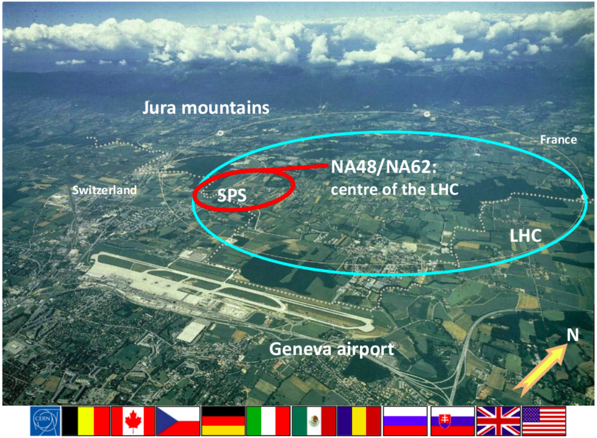
BSM searches in the kaon mode:

- Search for Heavy Neutral Leptons in $K^+ \to e^+ N$, $K^+ \to \mu^+ N$ decays
- LFV, LNV studies in $K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \mu^- \nu e^+ e^+$ and $K^+ \to \pi^0 \pi \mu e$ decays
- Search for $K^+ \to \pi^+ e^+ e^- e^+ e^-$ decay

BSM searches in the beam dump mode:

- Searches for $A' \to \ell^+ \ell^-$
- Searches for Dark Scalars and ALPs

NA62 experiment at CERN



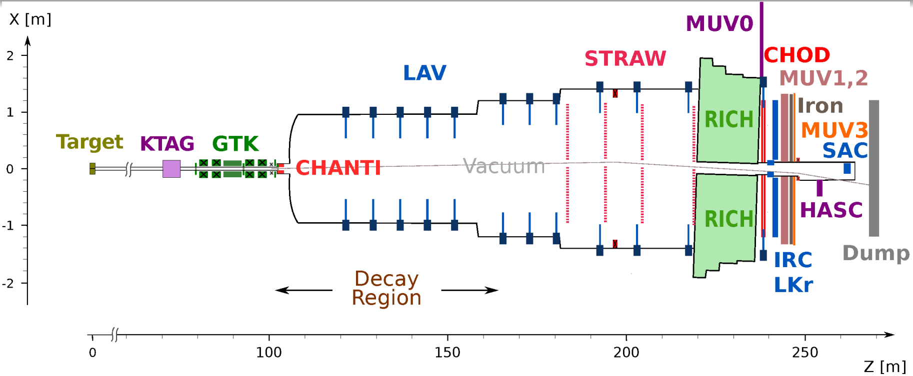
Kaon decay in flight experiments.

NA62: ~**300** participants, ~ **30** institutes

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 phase	2007: $K^\pm_{e2}/K^\pm_{\mu2}$	tests
	2008: $K^\pm_{e2}/K^\pm_{\mu2}$	tests
NA62	2014: pilot run	
	2015: commissioning run	
	2016 – 18 : $K^+\to\pi^+\nu\nu$ run	
	2021 – 24: $K^+\to\pi^+\nu\nu$ run	

NA62 Detector layout



SPS Beam:

- 400 GeV/c protons
- 1.9×10^{12} p/spill
- 3.5 s spill
- $\sim 10^{18}$ POT/year

Secondary beam:

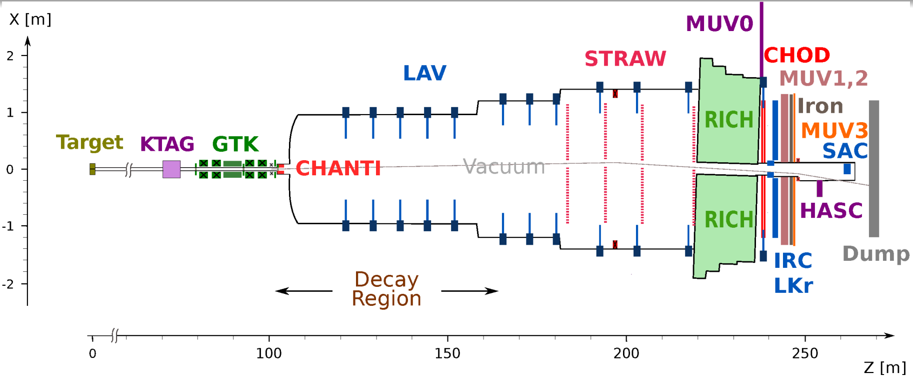
- 75 GeV/c momentum, 1% RMS
- 100 μrad divergence (RMS)
- 60×30 mm^2 transverse size
- $K^+(6\%)/\pi^+(70\%)/p(24\%)$
- 450 MHz of particles at GTK3

Decay Region

- 60 m long fiducial region
- ~ 3 MHz K^+ decay rate
- Vacuum $\mathcal{O}(10^{-6})$ mbar

[The NA62 Collaboration, JINST 12 (2017) P05025]

NA62 Detector layout



Upstream detectors (K^+)

- **KTAG:** differential Cherenkov counter for K^+ ID
- **GTK:** Si pixel beam tracker
- **CHANTI:** Anti-counter for inelastic beam-GTK3 interactions

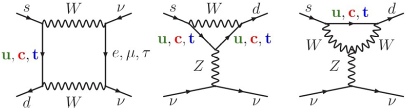
[The NA62 Collaboration, JINST 12 (2017) P05025]

Downstream detectors (π^+)

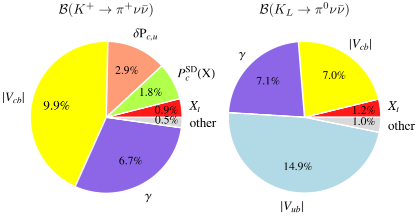
- **STRAW:** track momentum spectrometer
- **CHOD:** scintillator hodoscopes
- **LKr/MUV1/MUV2:** Calorimeters
- **RICH:** Cherenkov counter for $\pi/\mu/e$ ID
- **LAV/SAC/IRC:** Photon veto detectors
- **MUV3:** Muon detector

$K \to \pi\nu\bar{\nu}$: Theoretical motivation - Standard Model

- **FCNC loop process**
  - **s $\to$ d coupling** and highest CKM suppression (BR$\sim |V_{ts} \times V_{td}|^2$)



- **Very clean theoretically**
  - Short distance contribution and no hadronic uncertainties
  - Hadronic matrix element extracted from well-known decay $K^+ \to \pi^0 e^+ \nu$
  - Theoretical error budget dominated by CKM parameters



- **SM predictions**

[Buras et al., JHEP 1511 (2015) 033]

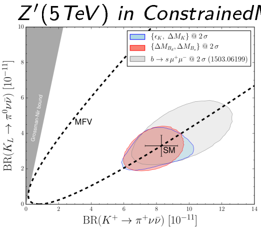
$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30)\cdot 10^{-11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (8.4 \pm 1.0)\cdot 10^{-11}$$

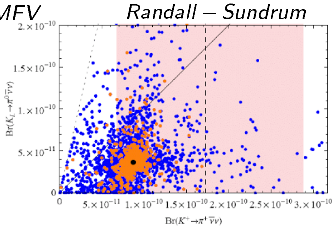
$$\mathrm{BR}(K_L^0 \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05)\cdot 10^{-11} \left(\frac{|V_{ub}|}{0.00388}\right)^{2} \left(\frac{|V_{cb}|}{0.0407}\right)^{2} \left(\frac{\sin\gamma}{\sin 73.2}\right)^{2} = (3.4 \pm 0.6)\cdot 10^{-11}$$

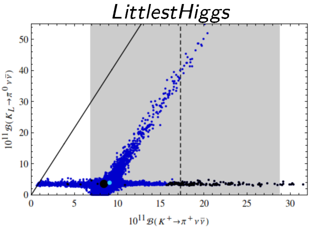
$K \to \pi\nu\bar{\nu}$: Theoretical motivation - Beyond the SM

- Simplified Z, Z' models *[Buras, Buttazzo,Knegjens, JHEP 1511 (2015) 166]*
- Littlest Higgs with T-parity *[Blanke, Buras, Recksiegel, EPJ C76 (2016) no.4 182]*
- Custodial Randall-Sundrum *[Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]*
- MSSM non-MFV *[Blazek, Matak Int.J.Mod.Phys.A29 (2014) 1450162; Isidori et al. JHEP 0608 (2006) 064]*
- LFU violation models *[Isidori et. al., Eur. Phys. J. C (2017) 77]*
- Leptoquarks *[S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]*

- Constraints from existing measurements (correlations model dependent):
  Kaon mixing and CPV, CKM fit, K,B rare meson decays, NP limits from direct searches
- $K \to \pi\nu\bar{\nu}$ **can discriminate among different new physics scenarios**

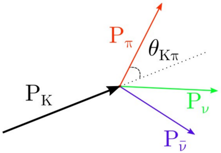


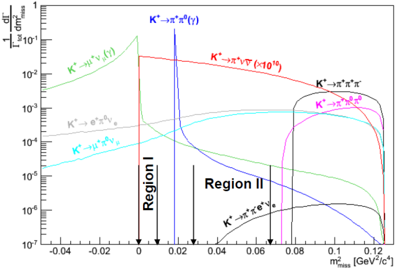




Kaon decays in flight

- **Signal:** Time and space $K^+ - \pi^+$ matching
- **Regions defined by:** $m^2_{miss} = (P_K - P_\pi)^2$
- The analysis is mostly cut based
- **Blind analysis:** Signal and background ctrl regions are kept blind throughout the analysis





Main background sources

Decay mode	BR	Main rejection tools
$K^+ \to \mu^+ \nu(\gamma)$	63%	μ−ID + kinematics
$K^+ \to \pi^+ \pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+ \pi^+ \pi^-$	6%	multi + kinematics
$K^+ \to \pi^+ \pi^0 \pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+ \nu_e$	5%	e−ID + γ-veto
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3%	μ−ID + γ-veto

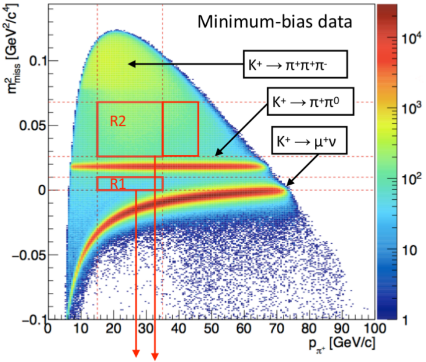
Requirements

- $\mathcal{O}(100)$ ps timing between sub-detectors
- $\mathcal{O}(10^4)$ background suppression with kinematics
- $\mathcal{O}(10^7)$ μ-suppression ($K^+ \to \mu^+ \nu$)
- $> (10^7)$ π^0-suppression ($K^+ \to \pi^+ \pi^0$,$\pi^0 \to \gamma\gamma$)

$K^+ \to \pi^+ \nu\bar{\nu}$: Event selection

Signal regions

- Three different ways to calculate m_{miss} to avoid mis-reconstruction:
  - $m^2_{miss} = (STRAW,\ GTK)$
  - $m^2_{miss} = (RICH,\ GTK)$
  - $m^2_{miss} = (STRAW,\ Beam)$



Kinematic cuts to define signal regions R1 and R2

Selection

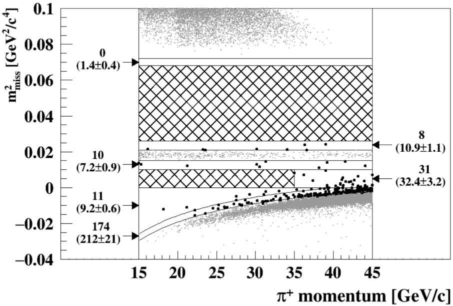
- Single track in final state topology matched with upstream K^+
- π^+ identification
- Photon rejection
- Multi-track rejection
- $105 < Z_{vertex} < 165$ m
- $15 < P_{\pi^+} < 35$ GeV$/c$ in R1
  $15 < P_{\pi^+} < 45$ GeV$/c$ in R2
  (best μ/π discrimination in RICH & to leave at least 30 GeV of E_{miss})

Performance

- $\varepsilon(\mu) = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
- $\varepsilon(\pi^0) = (1.4 \pm 0.1) \cdot 10^{-8}$
- $\sigma(m_{miss}) = 1 \cdot 10^{-3}$ GeV$^2/c^4$
- $\sigma(t) \sim \mathcal{O}(100)$ ps

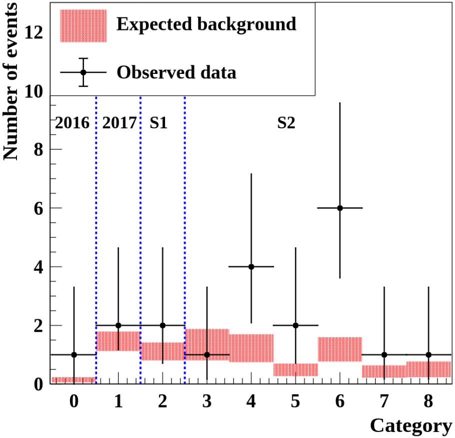
Background expectation validated using control regions.

Observed (expected) events in control regions. Signal Regions are masked!



Validation: expected vs observed background events in control regions in bins of π^+ momentum

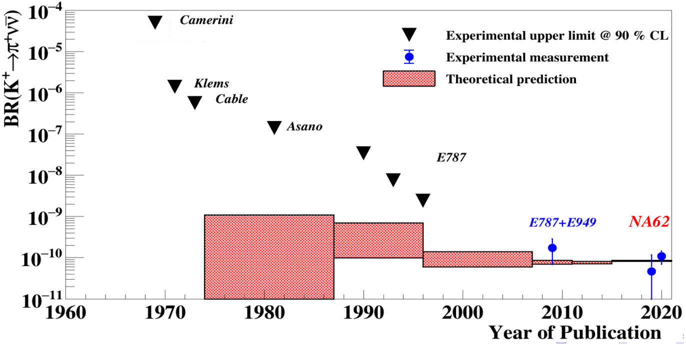
In 2018 collimator was replaced to remove early decays mechanism and data are split in subsets S1/S2 ($\sim$ 20%/80% of 2018 data).



$BR(K^+ \to \pi^+ \nu \bar{\nu})$: Run1 final result

	2016 data	2017 data	2018 S1 data	2018 S2 data
$SES \times 10^{10}$	3.15 ± 0.24	0.39 ± 0.02	0.54 ± 0.04	0.14 ± 0.01
$A_{\pi\nu\nu} \times 10^2$	4 ± 0.4	3 ± 0.3	4 ± 0.4	6.4 ± 0.6
Expected SM signal	0.27 ± 0.04	2.16 ± 0.13	1.56 ± 0.10	6.02 ± 0.39
Expected background	0.15 ± 0.090	1.46 ± 0.30	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
Observed events	1	2	2	15
	[PLB 791 (2019) 156-166]	*[JHEP 11 (2020) 042]*	*[JHEP 06 (2021) 093]*	

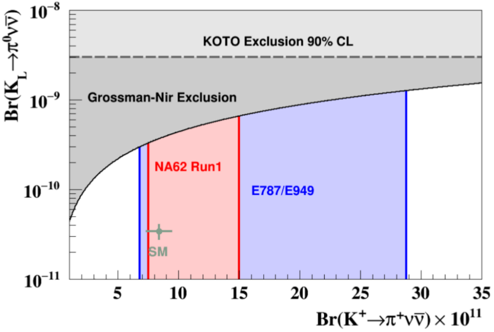
$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$ **(3.4σ significance)**

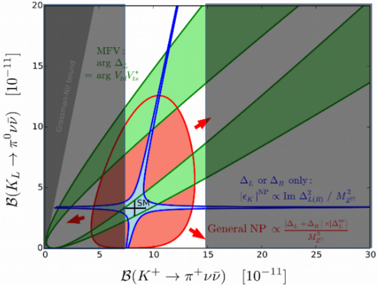


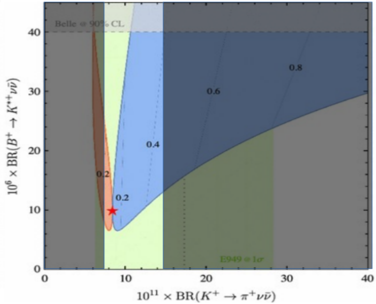
Interpretation of result

Large deviations from SM $BR(K^+ \to \pi^+ \nu \bar{\nu})$ are excluded

$\to$ high precision measurement needed





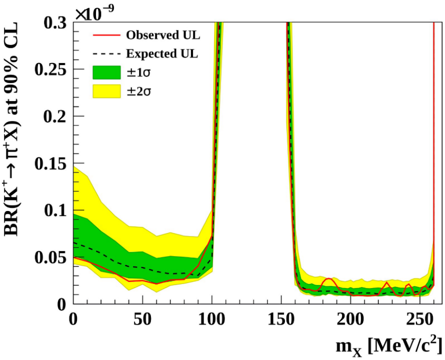


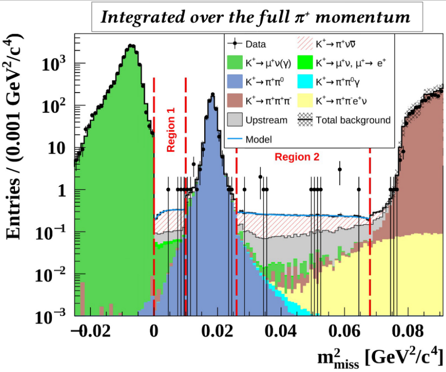
Grossman-Nir limit:

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) < 4.3 \cdot BR(K_L \to \pi^0 \nu \bar{\nu})$$

[Phys. Lett. B 398, 163 (1997)]

Search for $K^+ \to \pi^+ X(\text{invisible})$

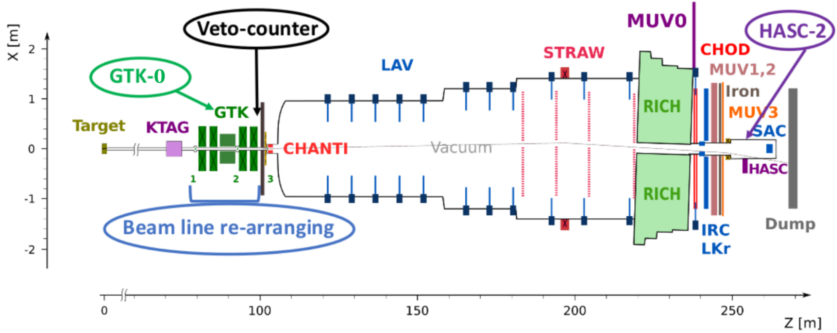




- Search for X particle production in $K^+ \to \pi^+ X$ decays
- Technique: peak searching using the m^2_{miss} observable for m_X in the 0-260 MeV$/c^2$ range
- Background shapes taken from the $K^+ \to \pi^+ \nu\bar{\nu}$ analysis including the shape of the SM $K^+ \to \pi^+ \nu\bar{\nu}$ process itself
- 90% Upper limits on BR($K^+ \to \pi^+ X$) in $(10^{-11} - 10^{-10})$ range

[JHEP 06 (2021) 093]

Run2 upgrade and Single Event Sensitivity (S.E.S.)



$$N^{exp}_{\pi\nu\nu} \approx N_{\pi^+\pi^0} \cdot \varepsilon_{RV} \cdot \varepsilon_{trigger} \cdot \frac{A_{\pi\nu\nu}}{A_{\pi^+\pi^0}} \cdot \frac{BR(\pi\nu\nu)}{BR(\pi^+\pi^0)} \quad \Rightarrow \quad S.E.S. = \frac{BR(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}}$$

- Normalization channel: $K^+ \to \pi^+\pi^0$
- ε_{RV} - Random Veto - efficiency loss due to accidental activity
- Ratio of $\pi\nu\nu$ and $\pi^+\pi^0$ acceptances allows cancellation of systematic effects
- Computation in bins of π^+ momentum and instantaneous beam intensity

$K^+ \to \pi^+ \nu\bar{\nu}$: Preliminary values for Run2

	2021 ($t > 2$ s)	2022	21+22	2018
$\varepsilon_{trigger}$	$(83.5 \pm 1.3)\%$	$(86.3 \pm 1.5)\%$	$(85.8 \pm 1.4)\%$	$(89.5 \pm 1)\%$
ε_{RV}	$(63.0 \pm 0.5)\%$	$(63.8 \pm 0.5)\%$	$(63.6 \pm 0.5)\%$	$(66 \pm 1)\%$
$A_{\pi^+\pi^0}$	$(13.525 \pm 0.005)\%$			$(11.77 \pm 0.18)\%$
$A_{\pi\nu\nu}$	$(7.7 \pm 0.2)\%$			$(6.4 \pm 0.6)\%$
$N_{\pi\nu\nu}^{SM,exp}$	1.80 ± 0.06	8.28 ± 0.24	10.07 ± 0.31	7.58 ± 0.40
$N_{\pi\nu\nu}^{SM,exp}$ per burst	1.7×10^{-5}	2.5×10^{-5}	2.3×10^{-5}	1.7×10^{-5}

- Improvements in LKr reconstruction
- "Bayesian" $K^+ - \pi^+$ matching
- Increased signal yield
- More precise $\varepsilon_{trigger}$ and ε_{RV} evaluation
- Checks ongoing about scaling of backgrounds with intensity

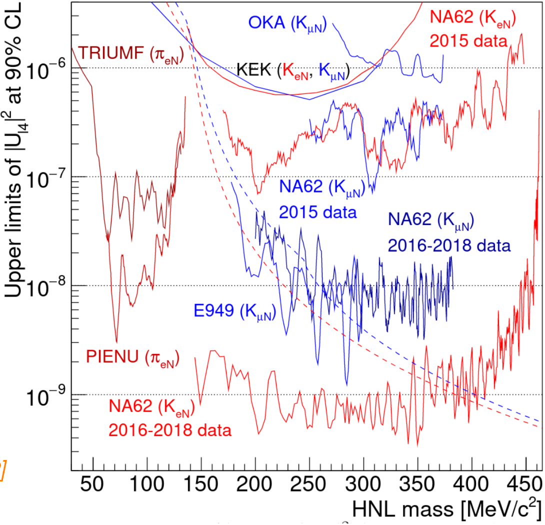
Background type	$N_{background}$
$K^+ \to \mu^+\nu$	0.86 ± 0.06
$K^+ \to \pi^+\pi^0$	0.93 ± 0.20
$K^+ \to \pi^+\pi^- e^+\nu$	$0.84^{+0.35}_{-0.28}$
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
$K^+ \to \pi^0\ell^+\nu$	< 0.001
Upstream	$8.0^{+2.2}_{-1.9}$
Total	$10.8^{+2.2}_{-1.9}$

Results of HNL search

- Improvement over earlier production searches by up to two orders of magnitude in terms of $|U_{\ell 4}|^2$.
- For $|U_{e4}|^2$, the BBN-allowed range excluded up to 350 MeV.

  [NPB 590 (2000) 562]
- For $|U_{\mu 4}|^2$, reached BNL-E949 sensitivity, and extended the HNL mass range to 384 MeV.
- New upper limit at 90% CL: $BR(K^+ \to \mu^+ \nu\nu\nu) < 1.0 \times 10^{-6}$. Similar limits on $BR(K^+ \to \mu^+ \nu X)$, with X = invisible.

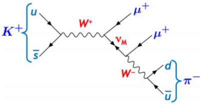
  [Theory: PRL 124 (2020) 041802]
- Full Run 1 data set.



[Phys. Lett. B 816 (2021) 136259]

- Search for Majorana neutrinos in LNV $K^+ \to \pi^- \ell^+ \ell^+$ decays

  [Asaka-Shaposhnikov model (νMSM) [PLB 620 (2005) 17]]



  - DM + Baryon Asymmetry + low mass of SM ν can be explained by adding three sterile Majorana neutrinos to the SM
  - Searches for LNV in 3-track decays:
    - LNV decays improving over PDG limits:

$$\mathrm{BR}(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11} @ \ 90\% \ \mathrm{CL}$$

[PLB 830 (2022) 137172]

$$\mathrm{BR}(K^+ \to \pi^- \pi^0 e^+ e^+) < 8.5 \times 10^{-10} @ \ 90\% \ \mathrm{CL}$$

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

[PLB 797 (2019) 134794]

$$\mathrm{BR}(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11} @ \ 90\% \ \mathrm{CL}$$

[PLB 838 (2023) 137679]

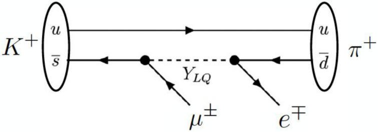
- Search for LNV/LFV in $K^+ \to \pi \mu e$, $K^+ \to \pi^0 \pi \mu e$ decays
  - Experimental signature: 3 charged tracks with $\pi^\pm \mu^\mp e^+$
  - BR measured relative to normalization channel $K^+ \to \pi^+ \pi^+ \pi^-$

$$\mathrm{BR}(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11}$$

$$\mathrm{BR}(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11}$$

$$\mathrm{BR}(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10}$$

[PRL 127 (2021) 131802]

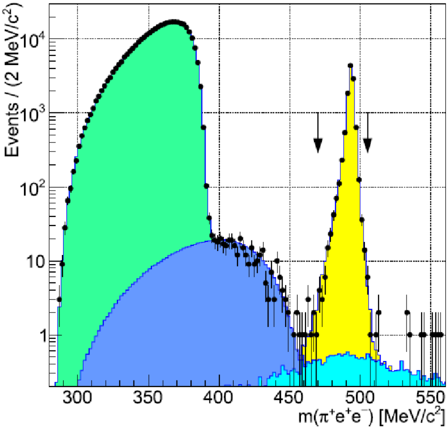


1 order of magnitude improvements compared to previous searches. Upper limits at 90% CL.

Normalisation selection

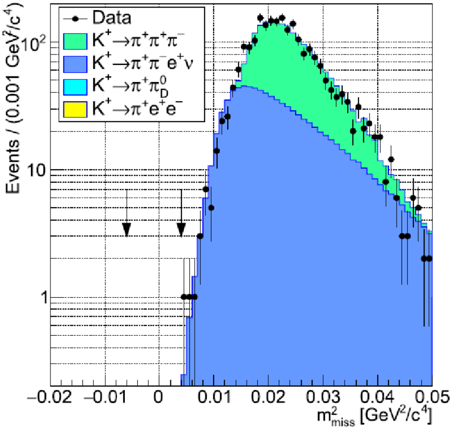
$N_{\pi ee} = 21401$

$N_K = 1.97(2)_{stat}(2)_{syst}(6)_{ext} \times 10^{12}$



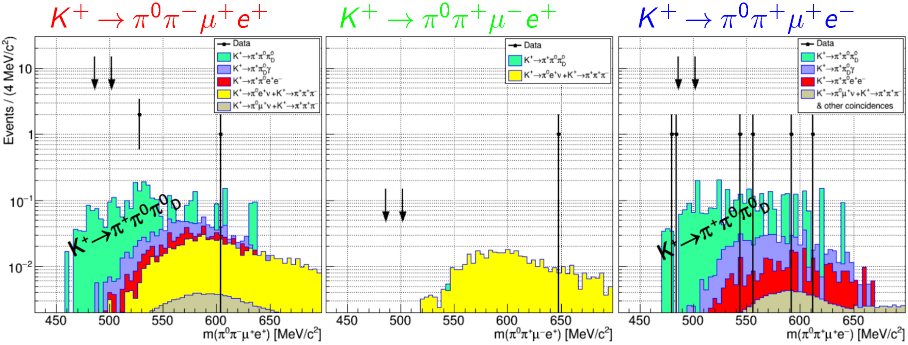
Signal selection (NB $= 0.26 \pm 0.04$)

No candidate observed in the signal region



$$\mathrm{BR}(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11} \text{ @90\% CL}$$

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

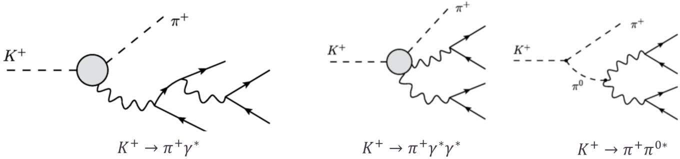


Decay mode	Expected bkg	Observed	UL of $\mathcal{BR}$ at 90% CL
$K^+ \to \pi^0 \pi^- \mu^+ e^+$	0.33 ± 0.07	0	2.9×10^{-10}
$K^+ \to \pi^0 \pi^+ \mu^- e^+$	0.004 ± 0.003	0	3.1×10^{-10}
$K^+ \to \pi^0 \pi^+ \mu^+ e^-$	0.29 ± 0.07	0	5.0×10^{-10}

[First presented at BEACH 2024, paper in preparation]

$K^+ \to \pi^+ e^+ e^- e^+ e^-$ $(K_{\pi 4e})$

- **Theory:**
  - SM allowed BR$= 7.2 \pm 0.7 \times 10^{-11}$ (outside π^0 pole)



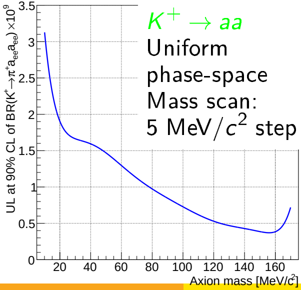
- **Dark sector probe:** [arXiv:2012.02142]
  - $K^+ \to aa$ with $a \to e^+e^-$ QCD axion, e.g. $m_a = 17$ MeV BR$= 1.7 \times 10^{-5}$
  - $K^+ \to \pi^+ S$, $S \to A'A'$ dark scalar and $A' \to e^+e^-$ dark photon $m_S > 2m_{A'}$

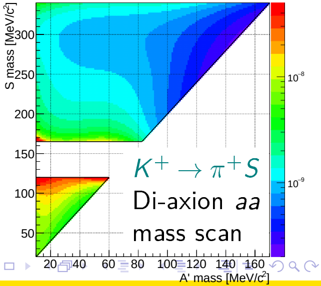
- **Procedure:**

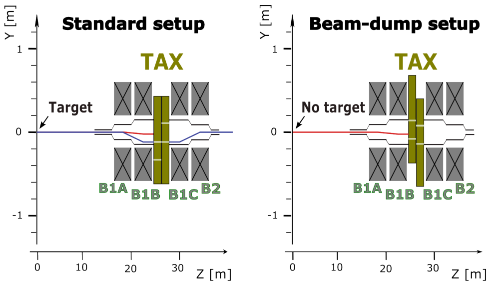
$K_{\pi 4e}$ SM:
Acceptance from MC
No candidate observed in SR

- **Result:** [PLB 846 (2023) 138193]

BR$(K_{\pi 4e}) < 1.4 \times 10^{-8}$ @90% CL







NA62 beam-dump setup:

- The Be target is lifted; the protons hit directly the 3.2 m Cu-Fe dump
- Primary proton beam operating at 1.7× nominal intensity

Data sample:

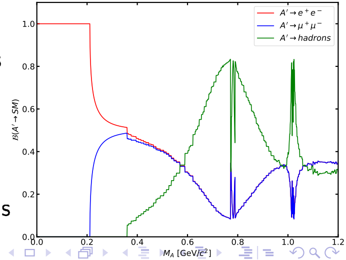
- Beam dump data from 2021
- Collected $(1.4 \pm 0.28) \times 10^{17}$ POT

Dark Photon A′ model:

- New vector field $F'_{\mu\nu}$ feebly interacting with SM fields
- Free parameters: mass $m_{A'}$, coupling ε
- For $m_A < 600$ MeV$/c^2$, $A' \to \ell^+\ell^-$ decays dominate

BSM physics models:

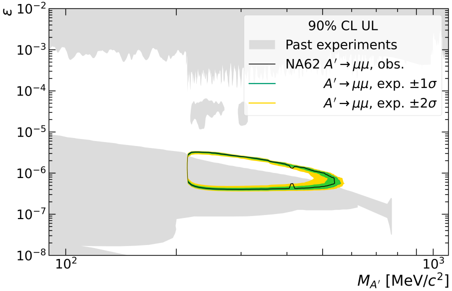
- New scalar S or pseudoscalar a coupled with SM fields
- Free parameters: masses and coupling constants



$A' \to \mu^+\mu^-$

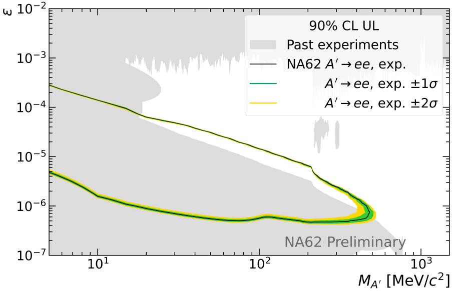
1 event observed in the SR

Corresponding to 2.4σ global significance



$A' \to e^+e^-$

0 events observed in the SR



Excluded new regions in the $m_{A'}, \varepsilon$ parameter space

[JHEP 09 (2023) 035], [2312.12055]

Searches for DS or ALP via Hadronic Decay Modes

Dark Scalar

Studied modes:

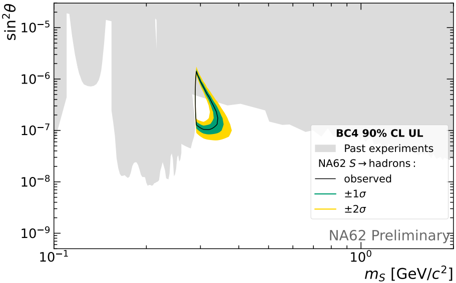
$\pi^+\pi^-$, $\pi^+\pi^-\pi^0\pi^0$, K^+K^-

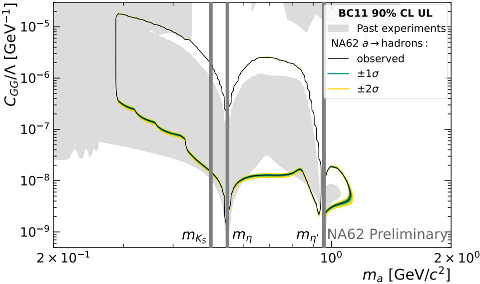
0 events observed in the SR

Axion-Like Particle

Studied modes: $\pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^0\pi^0$, $\pi^+\pi^-\eta$, $K^+K^-\pi^0$

0 events observed in the SR





Excluded new regions in the mass-coupling parameter space

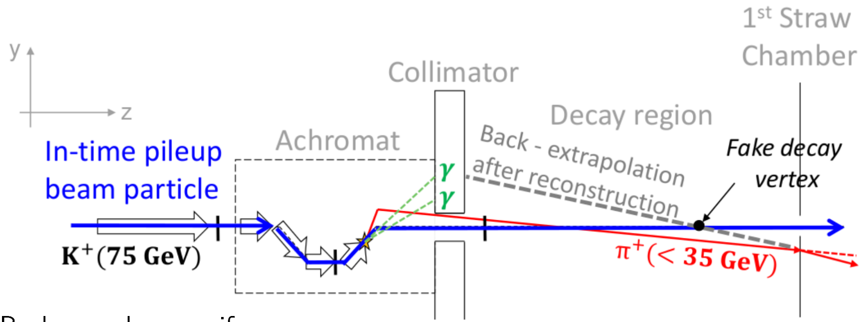
[Talk at Moriond EW 2024]

Conclusion

- Complete result for $K^+ \to \pi^+ \nu \bar{\nu}$ from Run 1 (2016+2017+2018):
  - observed: 20 events; expected background: ~ 7 events [JHEP 06 (2021) 093]
  - **BR**$(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$ **at 68% CL** (3.4σ)
- Run2 result of $K^+ \to \pi^+ \nu \bar{\nu}$ is coming soon!
  Expected signal to be doubled
- BSM physics in kaon decays:
  - Searches for $K^+ \to \ell^+ N$ and $K^+ \to \mu^+ \nu X$ decays [PLB 816 (2021) 136259]
  - LFV/LNV searches in $K^+ \to \pi^- \ell^+ \ell^+$, [PLB 830 (2022) 137172], [PLB 797 (2019) 134794]
    $K^+ \to \mu^- \nu e^+ e^+$& $K^+ \to \pi^0 \pi \mu e$ decays [PLB 838 (2023) 137679], [PRL 127 (2021) 131802]
  - $K^+ \to \pi^+ e^+ e^- e^+ e^-$ analysis & $K^+ \to aa$ $(a \to e^+ e^-)$ interpretation [PLB 846 (2023) 138193]
- BSM physics in beam-dump mode:
  - Studies of $A' \to \ell^+ \ell^-$ decays [JHEP 09 (2023) 035], [2312.12055]
  - Searches for Dark Scalar or Axion-Like Particle via Hadronic Decay Modes
  - Presented results obtained from data collected in 2021
  - Extended 90% CL exclusion regions in the mass–coupling parameter space
- Next steps:
  - Data taking on-going with upgraded detector
  - New data set in beam-dump mode already available

Spares

Upstream background



Background source if:

- a kaon decays upstream, and only a pion enters in the decay region;
- there is an in-time pileup beam particle (in KTAG and GTK);
- the upstream generated pion enters in the decay region and is scattered in the first STRAW chamber.

In 2018 collimator was replaced to remove early decays mechanism and data are split in subsets S1/S2 (Old/New collimator, $\sim$ 20%/80% of 2018 data). It allows to relax some cuts for S2, while keeping the S/B ratio same as for S1.

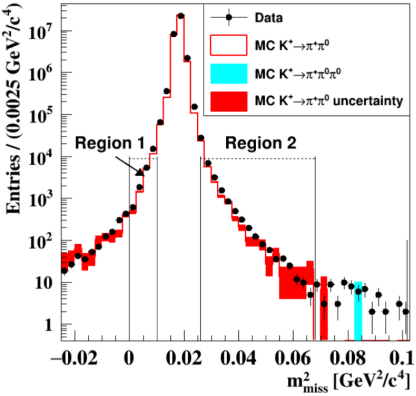
Background from kaon decays

Data in *bkg* region after $\pi\nu\nu$ selection:γ-rejection applied

$$N^{exp}_{bkg}(region) = N(bkg) \cdot f^{kin}(region); \;\; bkg = \pi^+\pi^0 \;\; \text{or} \;\; \mu^+\nu$$

Expected *bkg* in signal regions after $\pi\nu\nu$ selection

Fraction of *bkg* in signal region measured on control data



Control $K^+ \to \pi^+\pi^0$ data used to study the tails of the m_{miss^2} distribution