New physics searches at the NA62 experiment

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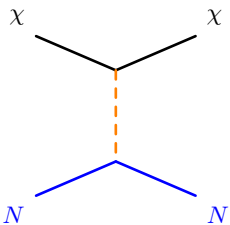
Laboratoire de Physique des Hautes Energies (LPHE), EPFL
TeVPA, Tendō, Japan, 30th August – 2nd September 2026

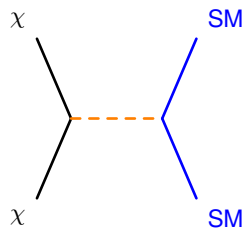
Dark matter

- The Standard Model only describes $< 20\%$ of matter in the universe.
- Evidence of dark matter from gravitational observations.
- Open questions: What is dark matter made of? How does it interact with SM particles?
- Experimental searches:

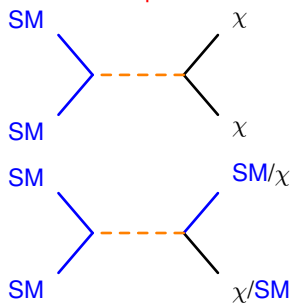
Direct detection
with nuclear recoil



Indirect detection
of annihilation products

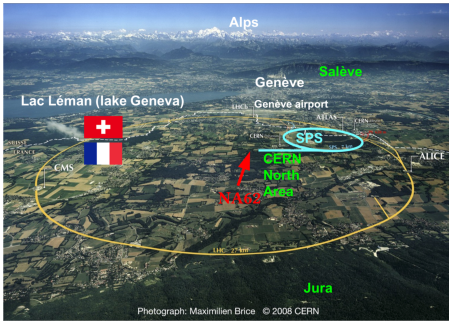


Dark matter production
from SM particles



The NA62 experiment

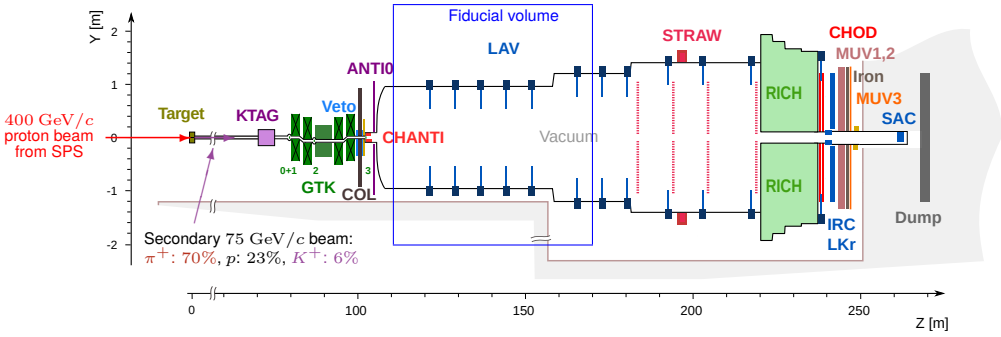
~200 collaborators from 35 institutions



High-precision kaon experiment at CERN SPS:

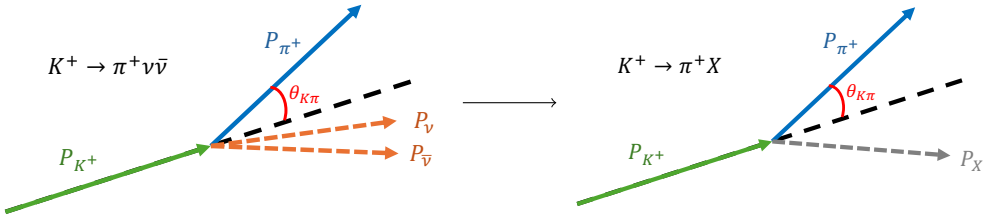
- **Technique**: Fixed target & decay-in-flight
- **Primary goal**: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ measurement:
  - latest result with NA62 2016–2024 dataset: $\mathcal{B}^{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (9.6^{+1.9}_{-1.8}) \times 10^{-11}$ [arXiv:2607.16413]
- **Broader physics program** [see backup for references]:
  - Precision measurements of kaon and pion decays;
  - LNV/LFV searches in kaon decays;
  - **Hidden sector searches with kaon and pion decays**;
  - **Hidden sector searches in beam dump mode**;
  - Neutrino tagging.

The NA62 detector



- **Particle tracking**: GTK - beam particle, STRAW - downstream tracks
- **PID**: Cherenkov detectors (KTAG - K^+, RICH - π^+), calorimeters (LKr, MUV1,2), muon (MUV3)
- **Comprehensive veto system**:
  - Upstream: VetoCounter (early decays), CHANTI (beam interactions), ANTI0 (halo particles)
  - Downstream: LAV, LKr, IRC, SAC (photon), MUV0 (multiplicity), HASC (photon conversion)

Dark sector searches in NA62 kaon mode

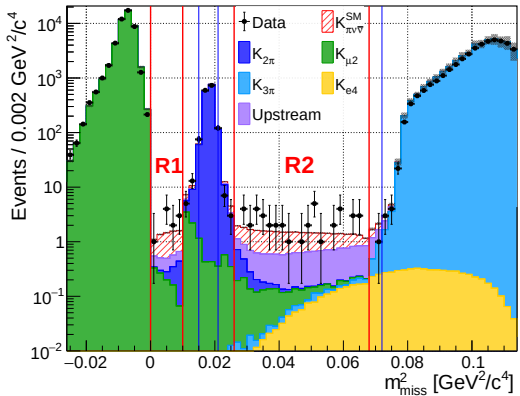


- $K^+ \to \pi^+ \nu\bar{\nu}$:
  - one incoming track (K^+)
  - one outgoing track (π^+)
  - no other activity
  - missing energy in $m^2_{miss} \equiv (P_K - P_\pi)^2$
- Dark matter searches: missing energy of $\nu\bar{\nu}$
  $\Rightarrow$ missing energy of a dark matter particle

Dark sector searches in NA62 kaon mode: $K^+ \to \pi^+ X$

[JHEP 11 (2025) 143]

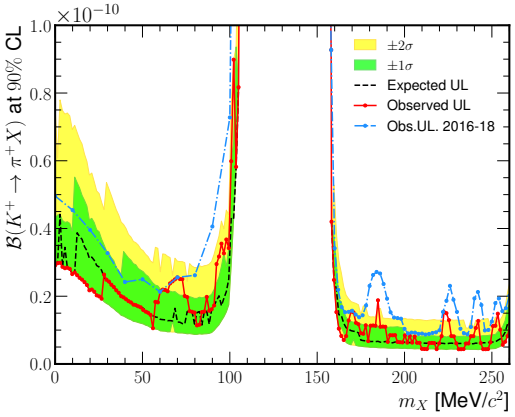
- Using the NA62 2016–2022 dataset
- Identical signature as $K^+ \to \pi^+ \nu\bar{\nu}$
- The same backgrounds as in $K^+ \to \pi^+ \nu\bar{\nu}$ analysis + $K^+ \to \pi^+ \nu\bar{\nu}$ itself (assumed to be SM here)
- Perform a peak search in the m^2_{miss} distribution

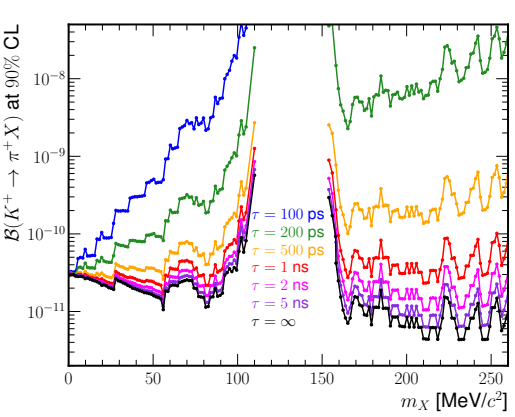


Dark sector searches in NA62 kaon mode: $K^+ \to \pi^+ X$

[JHEP 11 (2025) 143]

Model independent upper limit on $\mathcal{B}(K^+ \to \pi^+ X)$:



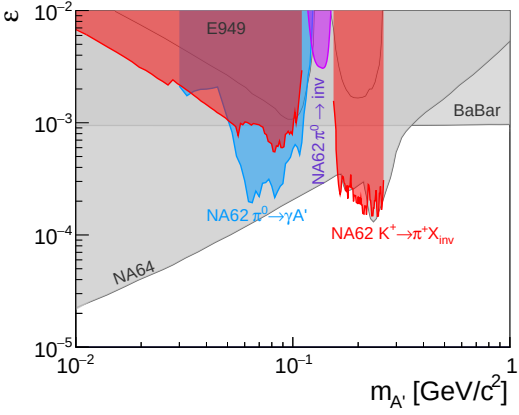


Dark sector searches in NA62 kaon mode: $K^+ \to \pi^+ X$

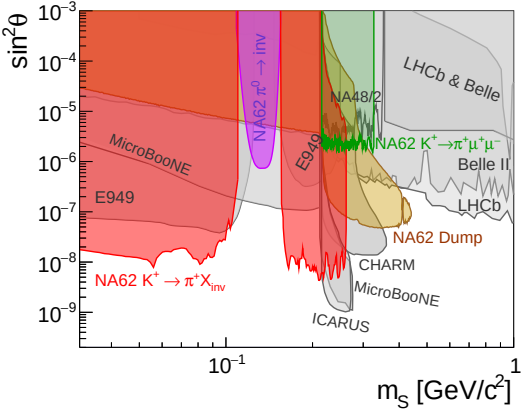
[JHEP 11 (2025) 143]

- Interpretation in models of hidden sector portals:

Benchmark 2: dark photon (A', vector)



Benchmark 4: dark scalar (S)

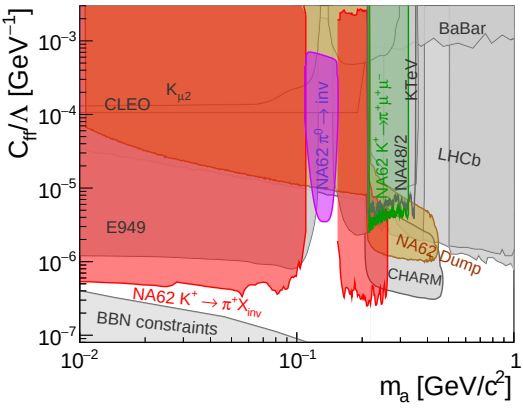


Dark sector searches in NA62 kaon mode: $K^+ \to \pi^+ X$

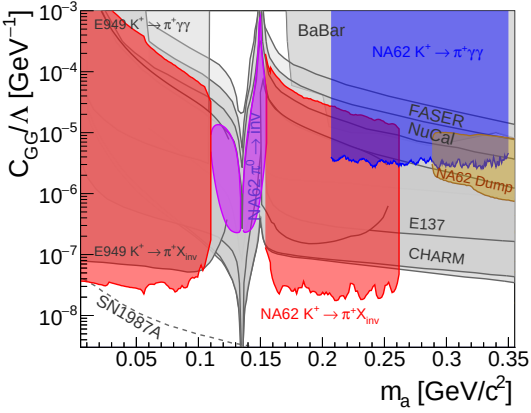
[JHEP 11 (2025) 143]

- Interpretation in models of hidden sector portals:

Benchmark 10: ALP (a, coupling to fermions)



Benchmark 11: ALP (a, coupling to gluons)



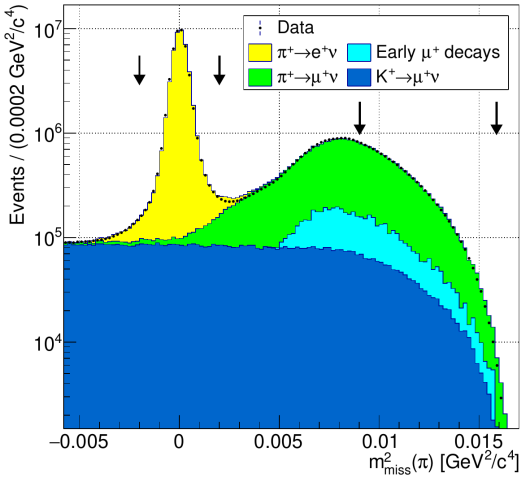
Dark sector searches in NA62 kaon mode: $\pi^+ \to e^+ N$

[PLB 872 (2026) 140119]

- $\pi^+ \to e^+ N$ with N a heavy neutral lepton

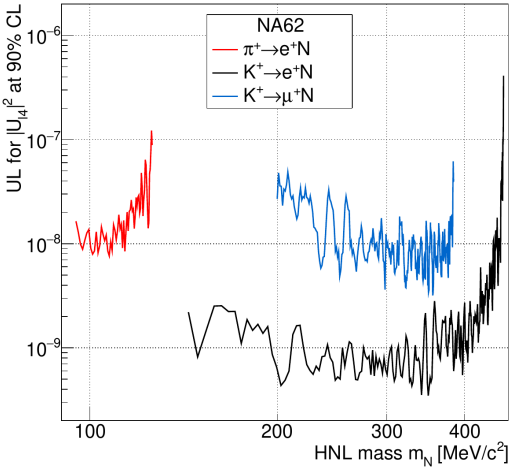
  $\mathcal{B}(\pi^+ \to e^+ N) = \mathcal{B}(\pi^+ \to e^+ \nu_e) \cdot \rho(m_N) \cdot |U_{e4}|^2$

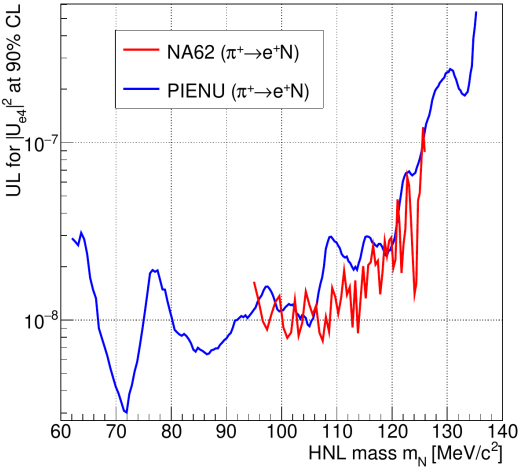
- Sensitive to the HNL mixing parameter U_{e4}
- Use pileup beam π^+s from 2017–2024 data
- Normalization channel: $\pi^+ \to e^+ \nu_e \Rightarrow$ 6.5×10^{12} π^+s
- Peak search in $m^2_{miss}(\pi) \equiv (P_\pi - P_e)^2$ for HNL mass $95 < m_N < 126\,\mathrm{MeV}/c^2$



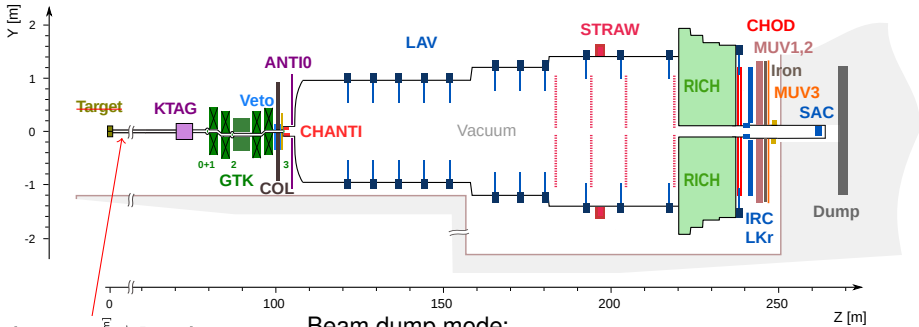
Dark sector searches in NA62 kaon mode: $\pi^+ \to e^+ N$

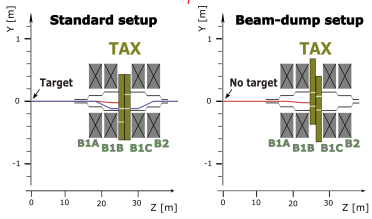
[PLB 872 (2026) 140119]





NA62 at beam dump mode



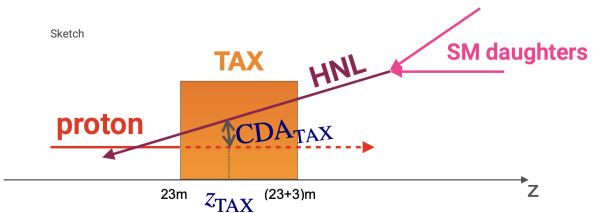


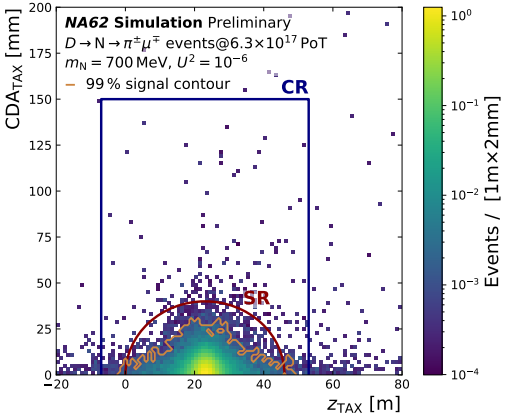
Beam dump mode:

- Remove the kaon production target.
- Close the TAX collimator ($19.6\lambda_I$) to dump mode.
- Searches with ee, $\mu\mu$, and hadronic final states[JHEP 09 (2023) 035, PRL 133 (2024) 111802, EPJC 85 (2025) 571].
- **Preliminary result on searches in semi-leptonic final states.**

Dark sector searches in NA62 beam dump mode: $h^{\pm}\ell^{\mp}$ final states

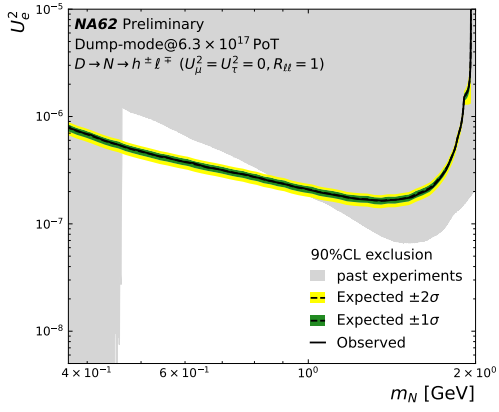
- NA62 2021–2024 beam dump dataset
- $(6.3 \pm 1.3) \times 10^{17}$ protons on target
- HNL from D-meson decays
- Search for HNL decays to $h^{\pm}\ell^{\mp}$:
  $h^{\pm} \in (\pi^{\pm}, \pi^{\pm}\pi^0, \pi^{\pm}2\pi^0, K^{\pm})$ and $\ell \in (e, \mu)$
- Backtrack the HNL to its likely point of production
- Signal Region defined in these coordinates

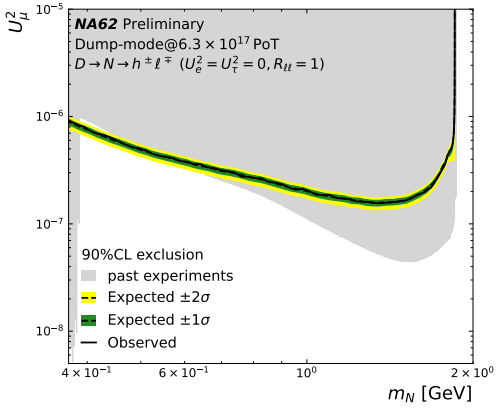




Dark sector searches in NA62 beam dump mode: $h^{\pm}\ell^{\mp}$ final states

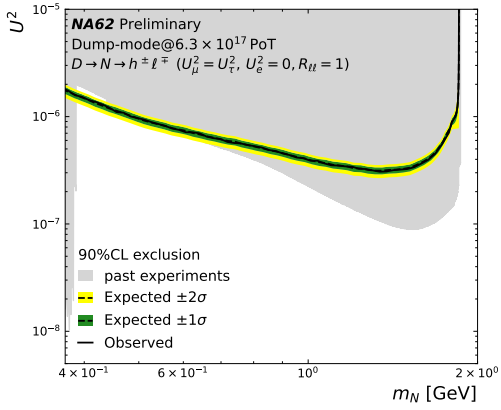
- Analysis essentially **background free**: $N_{bg}^{exp} < 0.01$
- **No event observed** across all signal categories
- 90% CL exclusion for various HNL coupling scenarios U_{α}:

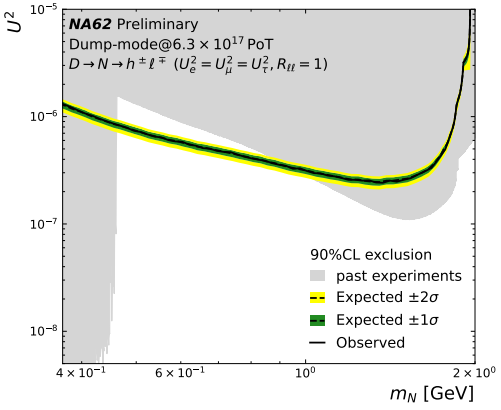




Dark sector searches in NA62 beam dump mode: $h^{\pm}\ell^{\mp}$ final states

Interpretation of results with phenomenologically relevant coupling structures [EPJC 82(2022)12,1176]:





* Here $U^2 \equiv \sum_\alpha U_\alpha^2$.

Conclusion

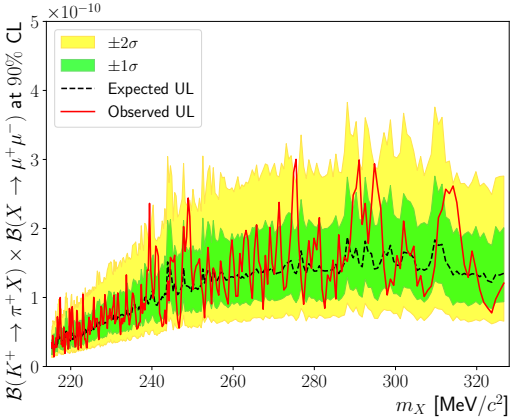
- Complementary dark matter searches at high energy particle physics experiments.
- NA62 kaon mode:
  - $K^+ \to \pi^+ X$: new excluded parameter spaces in hidden sector portals;
  - $\pi^+ \to e^+ N$: upper limit on $|U_{e4}|^2$ established at $\mathcal{O}(10^{-8})$.
- NA62 beam dump mode:
  - $h^\pm \ell^\mp$ final states: new limits on HNL couplings at $\mathcal{O}(\mathrm{GeV})$ mass scale.
- NA62 has concluded its data-taking in August 2026:
  - kaon mode: 2025–2026 sample contributes $\sim 1/3$ of the full NA62 2016–2026 dataset;
  - beam dump mode: $\sim 10^{18}$ proton on target in 2021–2026 dataset.
- New results are coming!

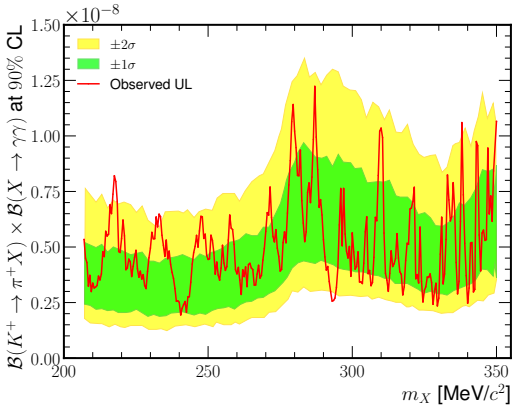
Backup slides

Dark sector searches in NA62 kaon mode: $K^+ \to \pi^+ X$

[JHEP 11 (2025) 143]

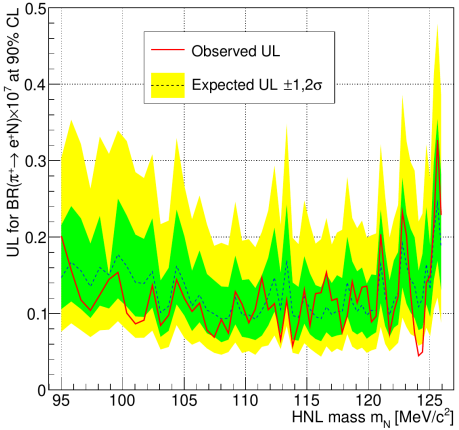
$K^+ \to \pi^+ X$ with $X \to \mu^+\mu^-$ or $X \to \gamma\gamma$:





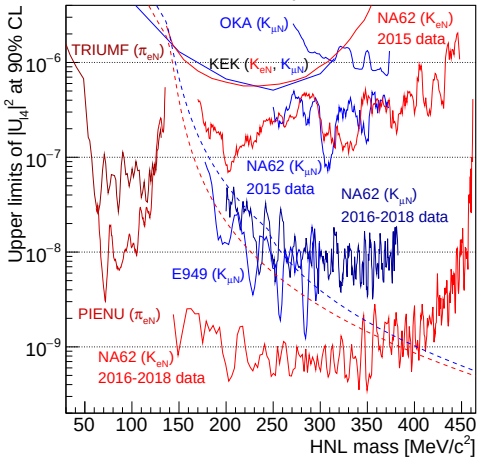
Dark sector searches in NA62 kaon mode: $\pi^+ \to e^+ N$

Model independent upper limit on the branching ratio



[PLB 872 (2026) 140119]

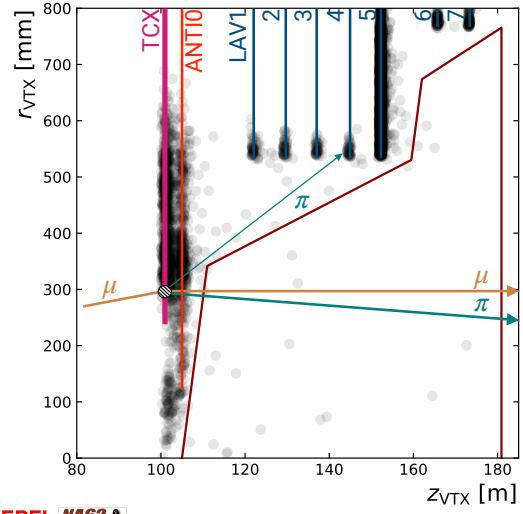
Limits from other experiments

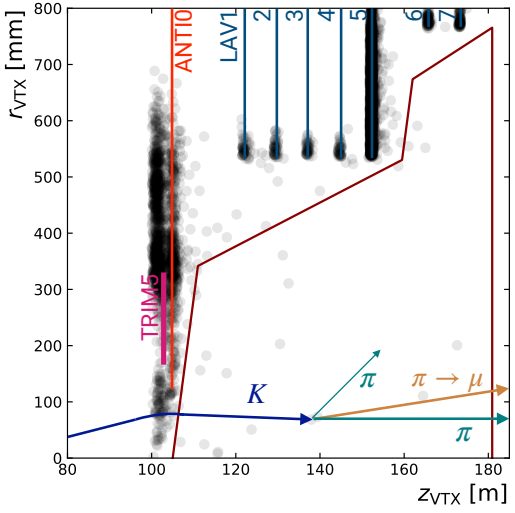


[PLB 816 (2021) 136259]

Dark sector searches in NA62 beam dump mode: $h^{\pm}\ell^{\mp}$ final states

Background mechanisms





Dark sector searches in NA62 beam dump mode: $h^{\pm}\ell^{\mp}$ final states

Estimated backgrounds

channel	$N_{\rm exp}^{\rm CR} \pm \delta N_{\rm exp}^{\rm CR}$	$N_{\rm exp}^{\rm SR} \pm \delta N_{\rm exp}^{\rm SR}$
$\pi^{\pm}\mu^{\mp}$	$(1.1^{+0.8}_{-0.6}) \times 10^{-2}$	$(9.3^{+7.4}_{-5.3}) \times 10^{-3}$
$\pi^{\pm}\mu^{\mp}\pi^0$	$(2.0^{+1.9}_{-1.2}) \times 10^{-6}$	$(1.4^{+1.2}_{-0.8}) \times 10^{-6}$
$\pi^{\pm}\mu^{\mp}2\pi^0$	$(1.0^{+2.5}_{-0.8}) \times 10^{-7}$	$(2.0^{+6.0}_{-1.7}) \times 10^{-8}$
$K^{\pm}\mu^{\mp}$	$(5.6^{+6.5}_{-3.5}) \times 10^{-6}$	$(2.8^{+2.9}_{-1.8}) \times 10^{-6}$
$\pi^{\pm}e^{\mp}$	$(2.6^{+2.7}_{-1.7}) \times 10^{-3}$	$(2.9^{+3.4}_{-2.0}) \times 10^{-3}$
$\pi^{\pm}e^{\mp}\pi^0$	$(3.2^{+3.9}_{-2.2}) \times 10^{-5}$	$(3.5^{+4.7}_{-2.5}) \times 10^{-5}$
$\pi^{\pm}e^{\mp}2\pi^0$	$(1.5^{+4.3}_{-1.3}) \times 10^{-9}$	$(3.0^{+10.1}_{-2.6}) \times 10^{-10}$
$K^{\pm}e^{\mp}$	$(5.9^{+8.8}_{-4.3}) \times 10^{-7}$	$(6.0^{+10.5}_{-4.7}) \times 10^{-7}$

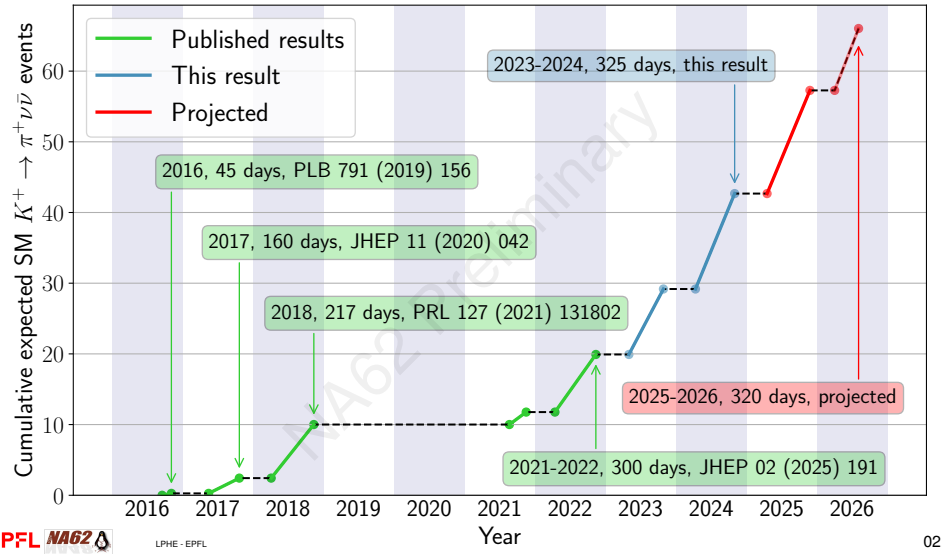
Expected number of signal events in Control and Signal Regions.

Validation of background estimation

channel	$N_{\rm exp} \pm \delta N_{\rm exp}$	$N_{\rm obs}$	$p(L < L_{\rm obs})$
$\pi^{\pm}\mu^{\mp}$	$9.4 \pm 2.0\vert_{\rm stat}{}^{+4.4}_{-3.5}\vert_{\rm syst}$	8	0.93
$\pi^{\pm}\mu^{\mp}\pi^0$	$(3.4 \pm 0.5\vert_{\rm stat}{}^{+2.2}_{-1.5}\vert_{\rm syst}) \times 10^{-2}$	0	> 0.99
$\pi^{\pm}\mu^{\mp}2\pi^0$	$(2.9 \pm 0.3\vert_{\rm stat}{}^{+3.6}_{-1.9}\vert_{\rm syst}) \times 10^{-3}$	0	> 0.99
$K^{\pm}\mu^{\mp}$	$0.14 \pm 0.01\vert_{\rm stat}{}^{+0.08}_{-0.05}\vert_{\rm syst}$	0	> 0.99
$\pi^{\pm}e^{\mp}$	$2.0 \pm 0.1\vert_{\rm stat}{}^{+1.0}_{-0.9}\vert_{\rm syst}$	2	> 0.99
$\pi^{\pm}e^{\mp}\pi^0$	$(2.9 \pm 0.3\vert_{\rm stat}{}^{+1.4}_{-1.3}\vert_{\rm syst}) \times 10^{-2}$	0	> 0.99
$\pi^{\pm}e^{\mp}2\pi^0$	$(2.8 \pm 0.9\vert_{\rm stat}{}^{+1.3}_{-1.1}\vert_{\rm syst}) \times 10^{-4}$	0	> 0.99
$K^{\pm}e^{\mp}$	$(8.5 \pm 2.0\vert_{\rm stat}{}^{+3.8}_{-3.5}\vert_{\rm syst}) \times 10^{-3}$	0	> 0.99

Expected number of opposite sign hadron decay and prompt events and number of observed events in validation sideband in FV

Prospects


Published results
This result
Projected
2016, 45 days, PLB 791 (2019) 156
2017, 160 days, JHEP 11 (2020) 042
2018, 217 days, PRL 127 (2021) 131802
2021-2022, 300 days, JHEP 02 (2025) 191
2023-2024, 325 days, this result
2025-2026, 320 days, projected
NA62 Preliminary
Cumulative expected SM $K^+ \to \pi^+ \nu\bar{\nu}$ events
Year
0
10
20
30
40
50
60
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026

Broader physics program

Precision measurements & rare decays:

- $K^+ \to \pi^+\mu^+\mu^-$: [JHEP 11 (2022) 011]
- $K^+ \to \pi^0 e^+ \nu_e \gamma$: [JHEP 09 (2023) 040]
- $K^+ \to \pi^+ e^+ e^- e^+ e^-$: [PLB 846 (2023) 138193]
- $K^+ \to \pi^+ \gamma\gamma$: [PLB 850 (2024) 138513]
- $\pi^0 \to e^+ e^-$: [MORIOND2024]
- $K^+ \to \mu^+ \nu_\mu \mu^+ \mu^-$: [KAON2025]
- $K^+ \to e^+ \nu_e \gamma$: [KAON2025]
- $K^+ \to \pi^+ \pi^+ \pi^- \gamma$: [KAON2025]

Forbidden decays:

- $K^+ \to \pi^- \ell^+ \ell^+$: [PLB 797 (2019) 134794]
- $K^+ \to \pi\mu e^+$ & $\pi^0 \to \mu^- e^+$: [PRL 127 (2021) 131802]
- $K^+ \to \pi^-(\pi^0) e^+ e^+$: [PLB 830 (2022) 132172]
- $K^+ \to \mu^- \nu e^+ e^+$: [PLB 838 (2023) 137679]
- $K^+ \to \pi^0 \pi\mu e$: [PLB 859 (2024) 139122]

Invisible particle search:

- $\pi^0 \to \gamma A'$: [JHEP 05 (2019) 182]
- $K^+ \to e^+ N$: [PLB 807 (2020) 135599]
- $\pi^0 \to$ inv.: [JHEP 02 (2021) 201]
- $K^+ \to \mu^+ +$ inv.: [PLB 816 (2021) 136259]
- $K^+ \to \pi^+ +$ inv.: [JHEP 11 (2025) 143]
- $\pi^+ \to e^+ N$: [PLB 872 (2026) 140119]

Dark sector in dump mode:

- $\mu^+\mu^-$ final state: [JHEP 09 (2023) 035]
- e^+e^- final state: [PRL 133 (2024) 111802]
- Hadrons final state: [EPJC 85 (2025) 571]

Neutrino tagging: [PLB 863 (2025) 139345]