Dark sector searches at NA62

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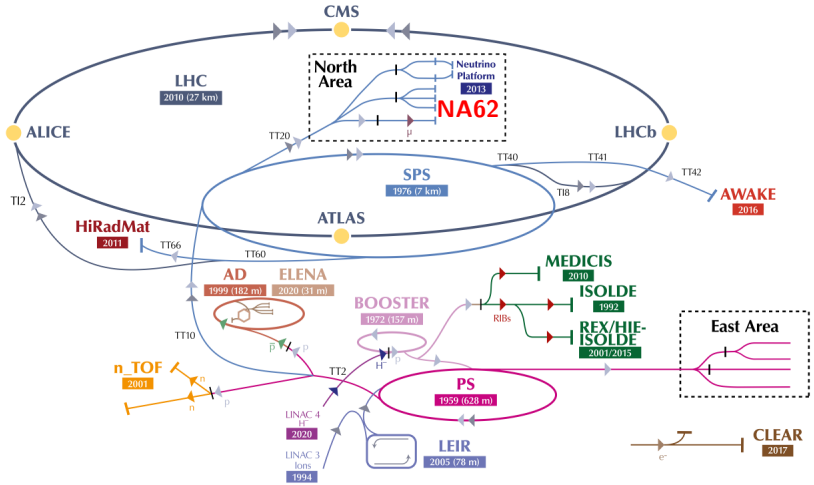
Max Planck Institute for Physics

Light Dark Matter @ Accelerators; April 10, 2025

European Research Council
Established by the European Commission

Introduction: NA62 experiment

Fixed-target experiment at CERN SPS (north area - ECN3 experimental cavern)



Introduction: NA62 experiment

- Main goal: study of ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay, yet NA62 covers:
  broad kaon physics program (precision measurements, LFV/LNV decays, LLP searches)
  beam-dump physics (LLP searches) program + more exotic searches (neutrino tagging, ..)
- Data-taking periods 2016-18, 2021-26: $K^+ \to \pi^+ \nu\bar{\nu}$ analysis of 2016-22 data published[1] (5σ obs)

[1] Observation of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay and measurement of its branching ratio. NA62 Collaboration [2412.12015]

Introduction: Long-lived particles (LLPs)

Search for New Physics (NP) at intensity frontier with fixed-target experiments:

- Complementary to energy frontier (LHC) and indirect searches (precision measurements, LNV, etc.);
- Smaller masses (typically MeV-GeV scale) but much lower couplings accessible (large statistics);
- Dark Sector (SM-DM) portals typically probed:

NP Particle	type	SM portal (dim ≤ 5)	PBC	**decay channels** ($m \lesssim 1\,\text{GeV}$)	
HNL (N_I)	fermion	$F_{\alpha I}(\bar{L}_\alpha H)N_I$	6-8	$\pi\ell$,$K\ell$,$\ell_1\ell_2\nu$	
dark photon (A'_μ)	vector	$-\epsilon/(2\cos\theta_W)F'_{\mu\nu}B^{\mu\nu}$	1-2	$\ell\ell$	2π, 3π, 4π, $2K$, $2K\pi$
dark Higgs (S)	scalar	$(\mu S + \lambda S^2)H^\dagger H$	4-5	$\ell\ell$	2π, 4π, $2K$
axion/ALP (a)	pseudoscalar	$(C_{VV}/\Lambda)gaV_{\mu\nu}\tilde{V}^{\mu\nu}$ $C_{ff}/(2\Lambda)\partial_\mu a\bar{f}\gamma^\mu\gamma^5 f$	9,11 10	$\gamma\gamma$, $\ell\ell$	$2\pi\gamma$, 3π, 4π, $2\pi\eta$, $2K\pi$

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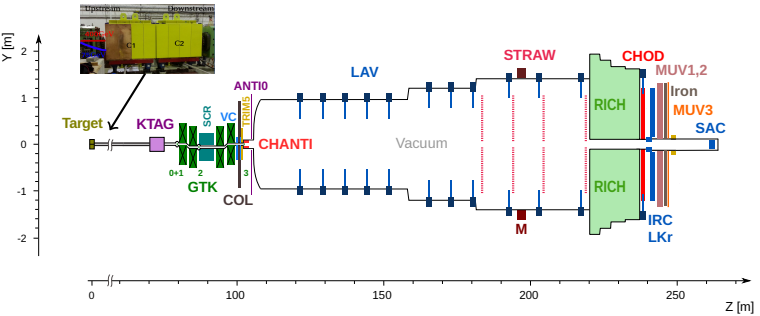
Two types of direct searches for NP particles at fixed-target experiments:

- NP particle production in SM particle decays - reconstruction from both initial and final state particles
- NP particle decay to SM particles - reconstruction of original particle from the SM final states

NA62 experiment can do both in two modes of operation - kaon mode and beam-dump mode

NA62 experiment in kaon mode

- 400 GeV/c primary p^+ beam impinges Be target,
  75 GeV/c secondary beam selected ($\sim 6\%$ of K^+) using **TAX** collimators
- K^+ decay in flight in 60 m long fiducial volume (FV)[2];



[2]The beam and detector of the NA62 experiment at CERN. NA62 Collaboration. 2017 *JINST* **12** P05025, [1703.08501]

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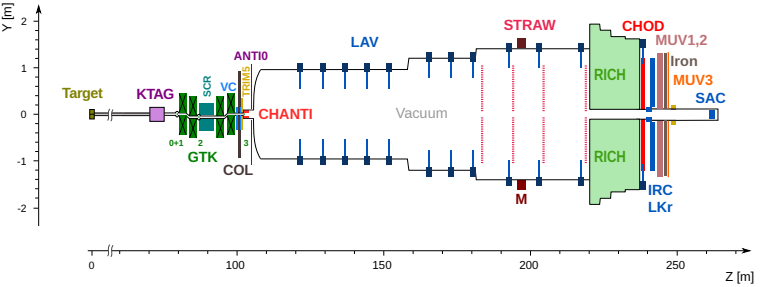

- K^+ tagged by **KTAG**;
  $\vec{p}_K$ measured by **GTK**;

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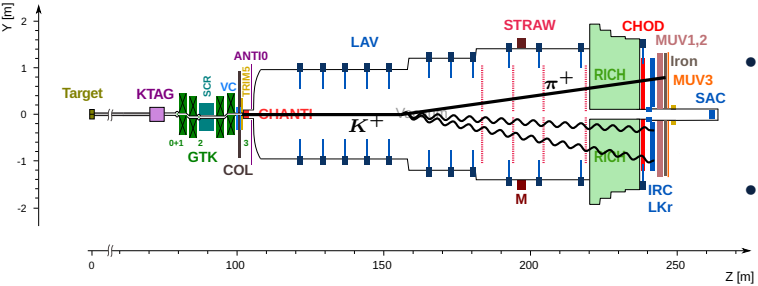

- Overall experimental time resolution reaches $\mathcal{O}(100)$ps

- K^+ tagged by **KTAG**;
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- Decay products' $\vec{p}$ from **STRAW**;
  time measured by **CHOD**;
  PID given by **LKr**, **MUV12**, **RICH**;
  + μ ID provided by **MUV3**;
- Photons can be vetoed by **LKr**
  + at large angles by 12 **LAV** stations
  + at small angles **SAC**/**IRC**;

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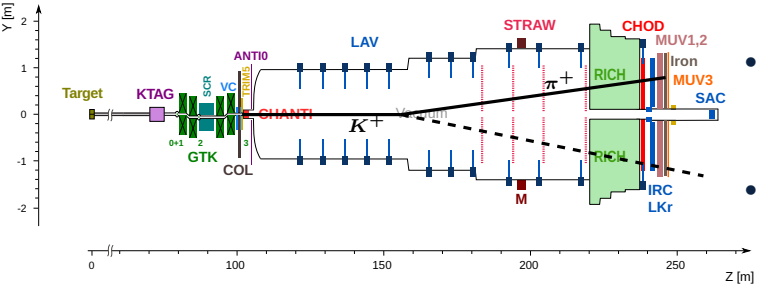

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Search for LLP (escaping detection) in $s \to d$ transition

- DP, DS or ALP with C_{WW}, C_{GG}, C_{qq} can be produced in FCNC decays
- $K^+ \to \pi^+ \nu\bar{\nu}$ has the same signature as $K^+ \to \pi^+ X(X)$ with X escaping (similarly $K_{2\pi}$, $\pi^0 \to$ invis.)

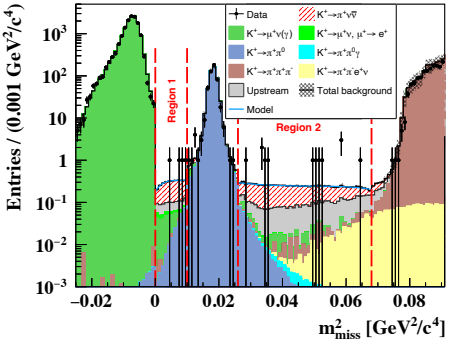


Figure: Expected and observed number of $K^+ \to \pi^+ \nu\bar{\nu}$ events in the 2018 data set.[3]

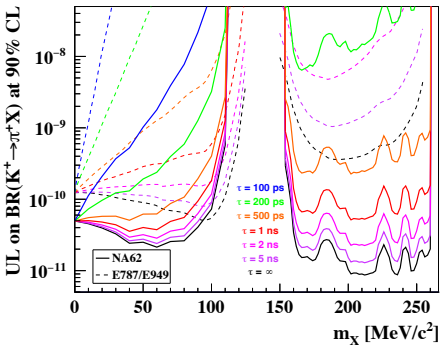


Figure: Bounds on the $K^+ \to \pi^+ X$ BR at 90% CL.

[3] Measurement of the very rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay. NA62 Collaboration. *JHEP* 06 (2021) 093, [2103.15389]

Search for LLP (decaying inside FV) in $s \to d$ transition

- Reinterpretation of precision measurement $K^+ \to \pi^+\gamma\gamma$ as $K^+ \to \pi^+ a(a \to \gamma\gamma)$:

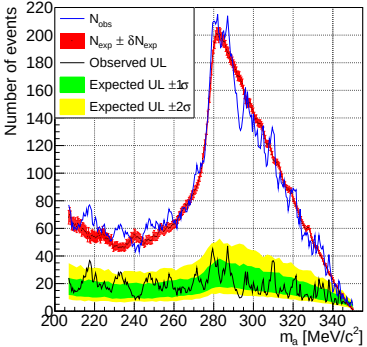


Figure: Number of expected and observed events.

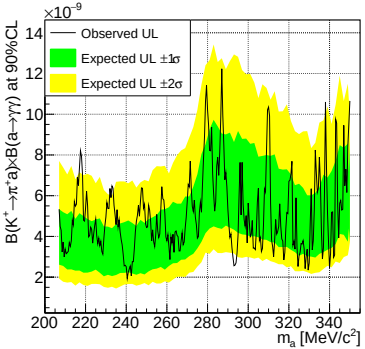


Figure: Upper limit at 90% CL on the BR.[4]

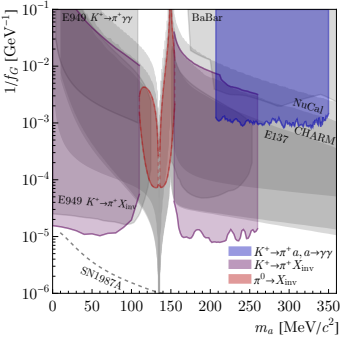


Figure: Exclusion bound for ALPs coupled to gluons.

[4] Measurement of the $K^+ \to \pi^+\gamma\gamma$ decay. NA62 Collaboration. *Phys.Lett.B* 850 (2024) 138513, [2311.01837]

Search for LLP (decaying inside FV) in $s \to d$ transition

Reinterpretation of search for the ultra-rare $K^+ \to \pi^+ e^+ e^- e^+ e^-$ decay $\mathrm{BR}(K_{\pi 4e}) = 7.2 \times 10^{-11}$:

- no signal observed, $\mathrm{BR}(K_{\pi 4e}) < 1.4 \times 10^{-8}$ at 90% CL
- $K^+ \to \pi^+ aa(a \to e^+ e^-)$ or $K^+ \to \pi^+ S(S \to A'A', A' \to e^+ e^-)$ interpretation
- QCD axion excluded as a possible explanation of the 17 MeV anomaly

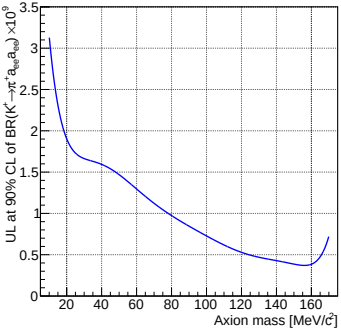


Figure: Upper limit at 90% CL on the ALP BR.[5]

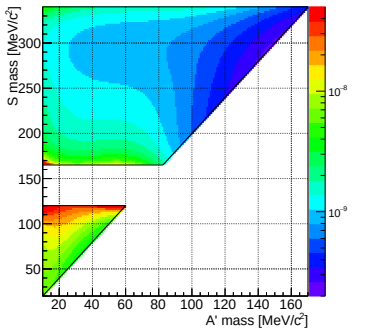


Figure: Bound on the combined BRs of the decay chain.

[5] Search for K^+ decays into the $\pi^+ e^+ e^- e^+ e^-$ final state. NA62 Collaboration. *Phys. Lett. B* 846 (2023) 138193, [2307.04579]

Search for LLP in $K^+ \to \ell^+ X$ decay

- X = HNL (e- or μ-coupled):
  $\mathrm{BR}_{K^+ \to \ell^+ N} = \mathrm{BR}_{\mathrm{SM}} \cdot \rho_\ell(m_N) \cdot |U_{l4}|^2$
- $K \to eN$: $m_N \in 144 - 462\,\mathrm{MeV}/c^2$
  $K \to \mu N$: $m_N \in 200 - 384\,\mathrm{MeV}/c^2$
- Reinterpretation for νX with
  $X = S/V$

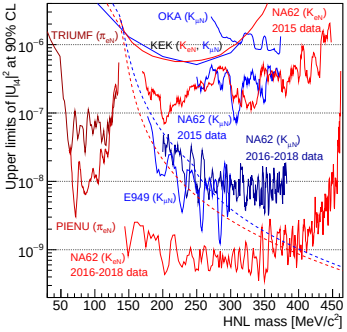


Figure: UL at 90% CL on $|U_{\ell 4}|^2$ from production searches, red: $|U_{e4}|^2$, blue: $|U_{\mu 4}|^2$.[6]

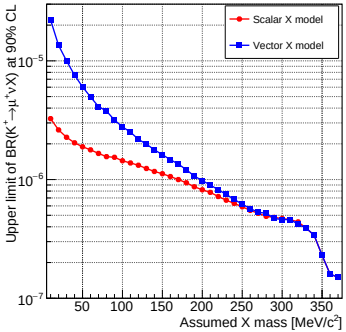


Figure: UL on BR($K^+ \to \mu^+ \nu X$), where X is scalar or vector.[7]

[6] Search for HNL production in K^+ decays to positrons. NA62 Collaboration. *Phys. Lett. B* 807 (2020) 135599.
[7] Search for K^+ decays to a muon and invisible particles. NA62 Collaboration. *Phys. Lett. B* 816 (2021) 136259.

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

- New preliminary result using 2016-2024 data;
- $\mathrm{BR}_{\pi^+ \to e^+ N} = \mathrm{BR}_{\mathrm{SM}} \cdot \rho_e(m_N) \cdot |U_{e4}|^2$
- Search in range: $m_N \in 95 - 126\,\mathrm{MeV}/c^2$

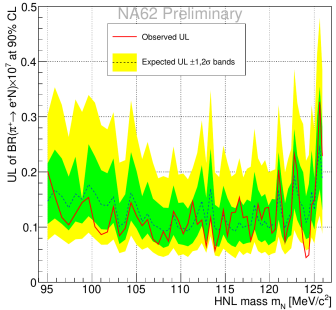


Figure: UL on $\mathrm{BR}(\pi^+ \to e^+ N)$.

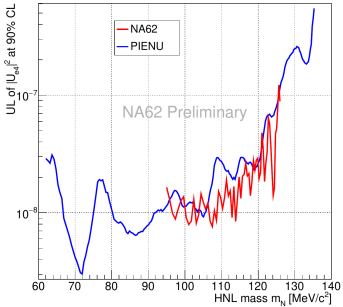
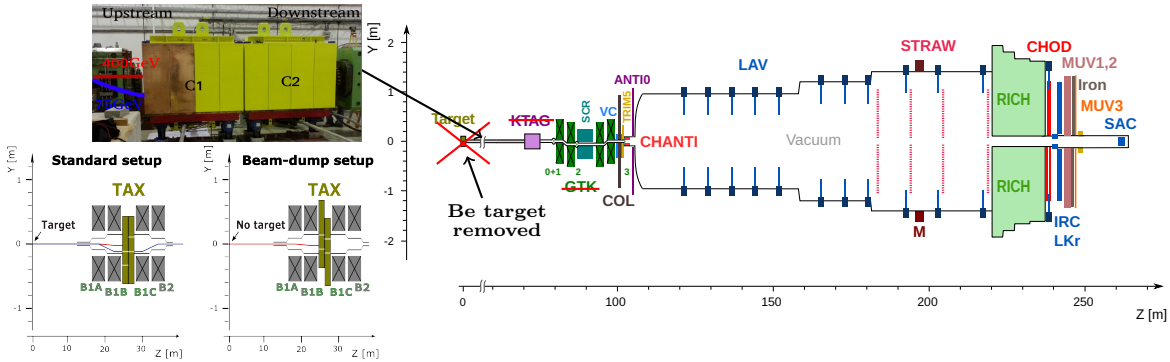


Figure: UL at 90% CL on $|U_{e4}|^2$ compared with the result from the PIENU experiment[8].

[8] Improved search for heavy neutrinos in the decay $\pi \to e\nu$. PIENU Collaboration. *Phys. Rev. D* 97 (2018) 7, 072012

NA62 experiment in beam-dump mode

- target removed and TAX closed; KTAG and GTK not used; ANTI0 used as an upstream veto:



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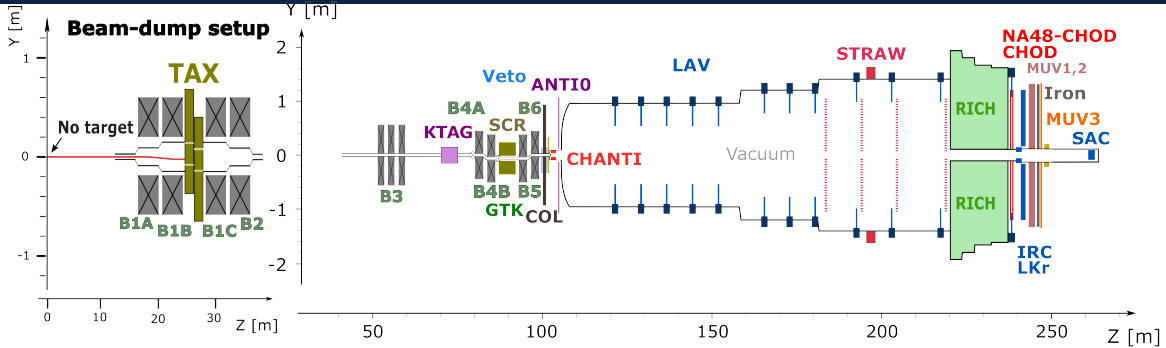

[9] NA62 Collaboration *JHEP* 09 (2023) 035 [2303.08666]; *PRL* 133 (2024) 11 [2312.12055]; accepted by *EPJC* [2502.04241]

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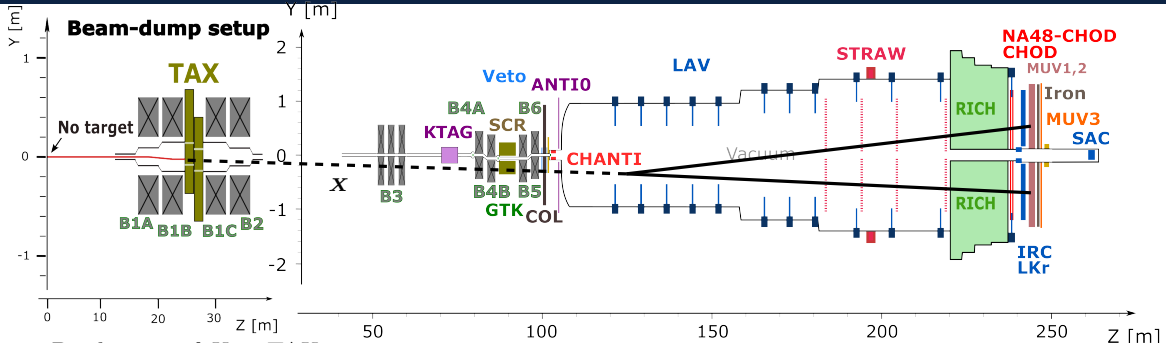

- Production of X in TAX:
  - DS/DP: p-Brems. $pN \to X + ..$; ALP mixing with $P = \{\pi^0, \eta, \eta'\}$; DP mixing with $V = \{\rho, \omega, \phi\}$
  - ALP/DS/DP: meson decays: $B \to KX$; $P \to A'\gamma$ and $V \to A'P$; ALP Primakoff

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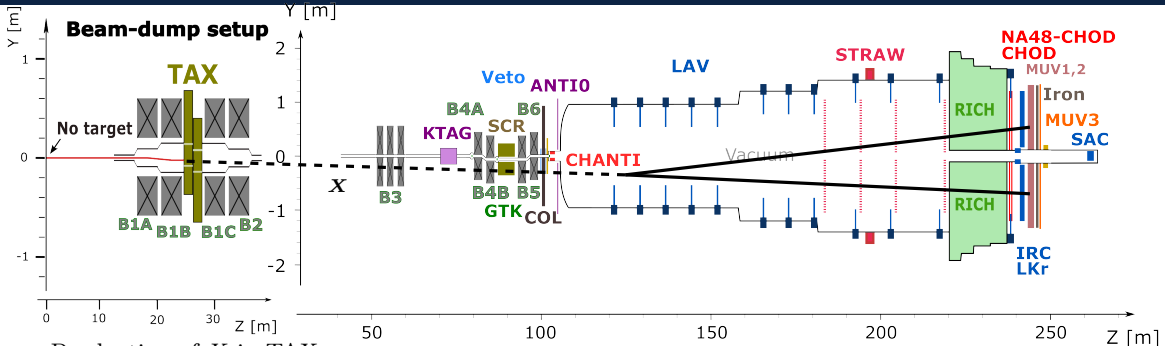

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- $N_{\rm POT} = (1.4 \pm 0.3) \times 10^{17}$ protons on target (POT) collected in 2021; plan: $N_{\rm POT} \simeq 10^{18}$ by LS3
- NP searches with $\mu\mu$, ee and hadronic $\pi^+\pi^-(\gamma, \pi^0, \eta, 2\pi^0), K^+K^-(\pi^0)$ final states published[9]

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Search for LLP decays in beam-dump mode (selection)

Search strategy:

- selecting two oppositely charged tracks + PID $\Rightarrow$ reconstructing their $\vec{p}$ and m;
- tracks forming a vertex in FV (+ search for additional photons) $\Rightarrow$ reconstructing $\vec{p}_X$ and m_X;
- search for primary production vertex close to TAX (where you expect LLP to be produced);
- blind analysis (signal and control regions defined around primary vertex location kept masked).

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Vetoes:

- $\mu^{\pm}$: no in-time activity in LAV
- $e^{\pm}$: + no geometrically associated ANTI0 signal
- hadrons: + no signal in SAV

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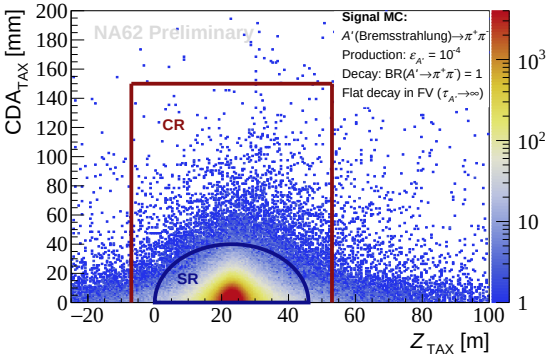

Signal and control regions (SR, CR):

- extrapolation of $\vec{p}_X$ from vertex to TAX: definition of SR and CR in terms of primary vertex location
  - $\mu^+\mu^-$: SR is a box $6 < Z_{\mathrm{TAX}} < 40$ m and $\mathrm{CDA}_{\mathrm{TAX}} < 20$ mm; CR is a box surrounding SR;
  - e^+e^- and hadrons: SR is an ellipse centered at $Z_{\mathrm{TAX}} = 23$ m and $\mathrm{CDA}_{\mathrm{TAX}} = 0$; box CR;

Search for LLP decays in beam-dump mode (acceptance)

In model-independent case ($C^i = C^i_{\text{ref}}$, $\text{BR}^f = 1$): $N^{if}_{\text{exp}}(m_X, \Gamma_X) = N_{\text{POT}} \times \chi^i_{pp\to X}(C^i_{\text{ref}}) \times P^i_{\text{rd}} \times A^{if}_{\text{acc}}$

- $\chi_{pp\to X}(C_{\text{ref}})$: LLP prod. probability for ref. coupling
- P_{rd}: probability to reach NA62 FV and decay therein
- A_{acc}: signal selection and trigger acceptance

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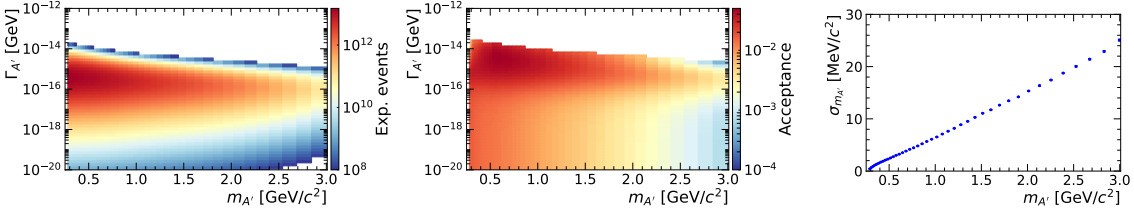

Figure: Left: expected $A' \to \pi^+\pi^-$ yield after full selection, assuming $\varepsilon = 1$ and BR = 1. Center: acceptance after full selection for LLPs that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

- Distributions above obtained for all 61 combinations of production and decay channels
- All available on HepData: `https://doi.org/10.17182/hepdata.156981.v1`

Search for LLP decays in beam-dump mode (background)

ΔT of the tracks suggests two types of background mechanisms for $X \to \ell^+\ell^-$:
Combinatorial:

- Background from random superposition of two uncorrelated upstream particles;
- Dominating for $\mu^+\mu^-$;
- Simulation based on single tracks selected in data artificially overlaid to emulate a random superposition.

Prompt:

- Background from secondaries of μ interactions with the traversed material (hadron photo-production);
- Dominating for e^+e^-.
- Simulation based on backwards MC using single muons from the data + unfolding.

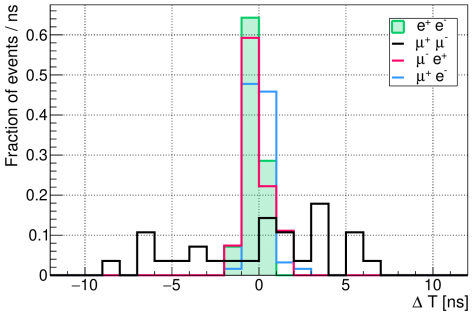

Figure: $X \to \ell^+\ell^-$ background before LAV veto (SR and CR masked).

Search for LLP decays in beam-dump mode (background)

Kaon decays:

- Background from upstream kaons entering the FV via non-instrumented ANTI0 hole;
- Dominating for hadrons;
- Simulation based on single kaons selected in data and forced to decay in the FV.

Neutrino-induced background:

- Interactions of ν_μ from TAX in detector material;
- Negligible for all final states.

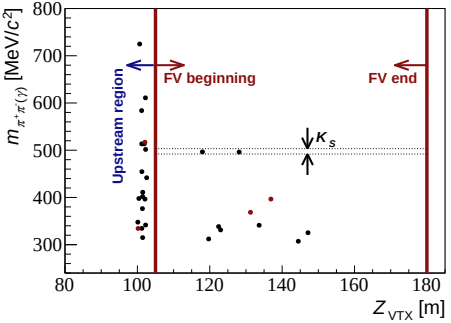

Figure: $\pi^+\pi^-(\gamma)$ events in Z_{VTX} – invariant mass plane after inverting ANTI0 veto. Solid lines indicate the FV. Dashed lines indicate the K_S 3σ mass window.

Search for LLP decays in beam-dump mode (background)

Table: Summary of total expected number of background events at 68% CL for all studied decay channels in CR and SR after full selection.

Channel	$N_{\text{exp,CR}} \pm \delta N_{\text{exp,CR}}$	$N_{\text{exp,SR}} \pm \delta N_{\text{exp,SR}}$
$\mu^+\mu^-$	0.17 ± 0.02	0.016 ± 0.002
e^+e^-	$0.0097^{+0.049}_{-0.009}$	$0.0094^{+0.049}_{-0.009}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$
K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$

Background-free hypothesis **not only** at $N_{\text{POT}} = 1.4 \times 10^{17}$ but also for $N_{\text{POT}} = 10^{18}$ and beyond

Search for LLP decays in beam-dump mode (result)

- 0 events observed in all CRs;
- 1 event observed in $\mu^+\mu^-$ SR (2.4σ global significance); 0 events observed in e^+e^- and hadronic SRs;

[10] ALPINIST: Axion-Like Particles In Numerous Interactions Simulated and Tabulated. *JHEP* 07 (2022) 094, [2201.05170]

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- Public tool ALPINIST[10] used for the model-dependent interpretation: $N_{\rm exp}(m_X, C_X) = \sum_{if} \mathrm{BR}^f(m_X, C_X) \times (C^i/C^i_{\rm ref})^2 \times \times N^{if}_{\rm exp}(m_X, \Gamma_X = \Gamma_X(m_X, C_X))$
- Observed 90% CL contours obtained using the $\mathrm{CL_s}$ method.

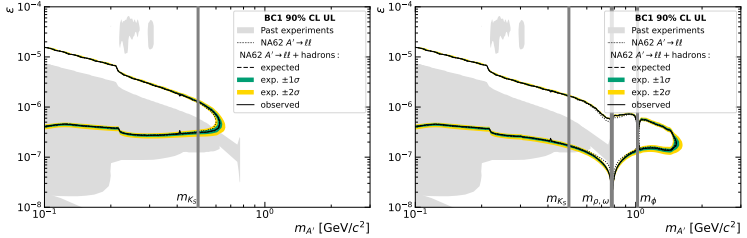

Figure: The observed 90% CL exclusion contours in BC1 (dark photon) benchmark together with the expected $\pm1\sigma$ and $\pm2\sigma$ bands (theory uncertainty not included). Left: Bremsstrahlung production without resonant enhancement. Right: Bremsstrahlung production with resonant enhancement.

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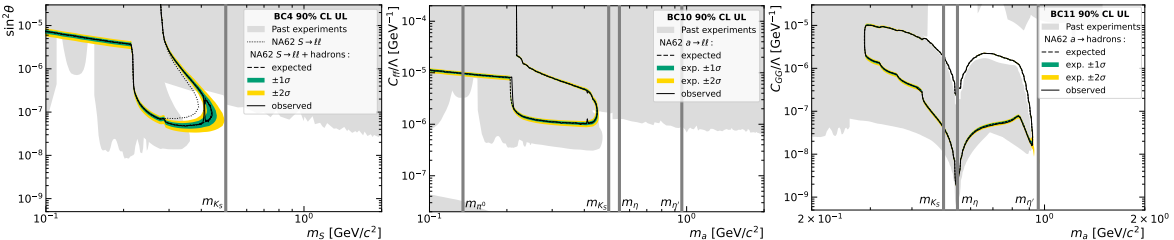

Figure: The observed 90% CL exclusion contours in BC4 (left), BC10 (center) and BC11 (right) benchmarks together with the expected $\pm 1\sigma$ and $\pm 2\sigma$ bands (theory uncertainty not included).

Summary

- NA62 is a multipurpose experiment allowing search for LLP in beam-dump mode and in kaon decays;
- Searches for LLP in $K^+ \to \pi^+$, $K^+ \to \mu^+$ and $K^+ \to e^+$ decays using 2016-2018 dataset and $\pi^+ \to e^+$ using 2016-2024 dataset were presented;
- Blind analyses searching for LLP decays $X \to \ell^+\ell^-$ and $X \to$ hadrons have been performed on the beam-dump data collected in 2021;
- New regions of LLP parametric spaces were probed with no NP signal observed;
- Much more data already collected, plan to collect $\simeq 10^{18}$ POT in beam-dump mode by LS3;
- Several new searches for LLPs in kaon decays and semi-leptonic or di-gamma final state decays in beam-dump mode are in progress.

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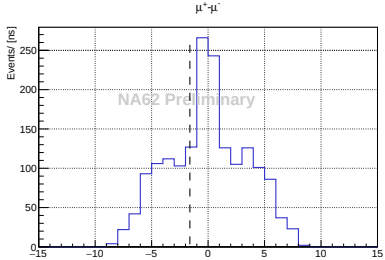
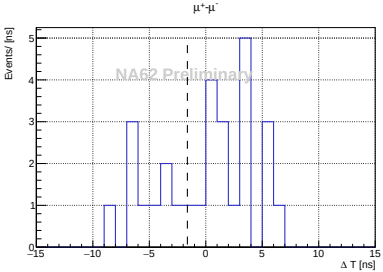
Thank you for your attention!

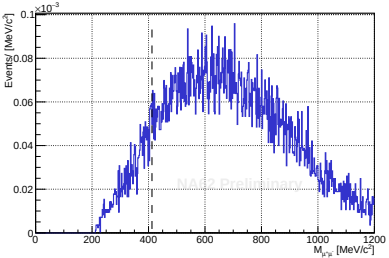
Backup slides

Search for $A' \to \mu\mu$ - details on observed event

- invariant mass: $m_{\mu\mu} = 411$ MeV
- time difference: $\Delta T = -1.69$ ns
- momenta:
  - $P(\mu^+) = 99.5$ GeV/c
  - $P(\mu^-) = 39.6$ GeV/c
- $z_{\mathrm{FV}} = 157.8$ m
- $\mathrm{CDA}_{\mathrm{FV}} = 382$ mm
- $z_{\mathrm{TAX}} = 17$ mm
- $E/p(\mu^+) = 0.008$
- $E/p(\mu^-) = 0.018$

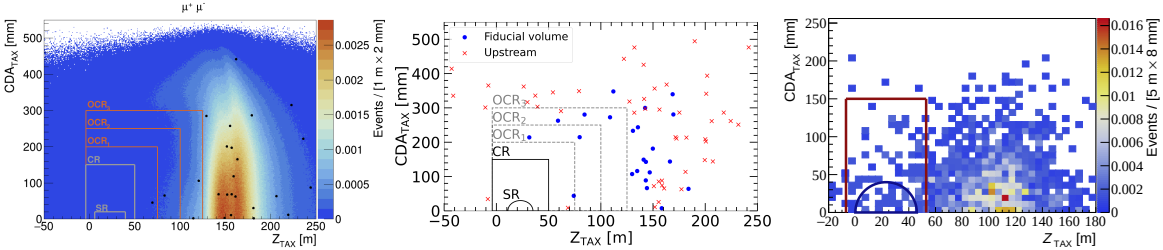






Search for LLP decays in beam-dump mode (background)

Distributions of the simulated background events in the (Z_{VTX}, $\mathrm{CDA}_{\mathrm{VTX}}$) plane for $\mu^+\mu^-$, e^+e^- and $\pi^+\pi^-(\gamma)$ final states:



Search for LLP decays in beam-dump mode (PID)

- $\mu^{\pm}$: $E_{\mathrm{LKr}}/p \sim 0$ + MUV3;
- $e^{\pm}$: $E_{\mathrm{LKr}}/p \sim 1$ + !MUV3;
- $h^{\pm}$ ($\pi^{\pm}$ and $K^{\pm}$):
  - LKR+MUV12 BDT classifier $p_{\pi} > 80\%$ + !MUV3;
  - $K^{\pm}$: $h^{\pm}$ with K^{+} selected by RICH (else $\pi^{\pm}$);
  - search neutral LKr clusters and reconstruction of γ, π^0, η based on opening angle wrt decay vertex;