Searches for hidden sector physics with the NA62 experiment

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*On behalf of the NA62 Collaboration

Introduction

Direct 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);
- Not a direct search for Dark Matter (DM) particles but for a SM-DM mediator (hidden sector portal):

NP Particle	type	SM portal (dim ≤ 5)
HNL (N_I)	fermion	$F_{\alpha I}(\bar{L}_\alpha H)N_I$
dark photon (A'_μ)	vector	$-(\epsilon/2\cos\theta_W)F'_{\mu\nu}B^{\mu\nu}$
dark Higgs (S)	scalar	$(\mu S + \lambda S^2)H^\dagger H$
axion/ALP (a)	pseudoscalar	$(C_{aX}/\Lambda)aX_{\mu\nu}\tilde{X}^{\mu\nu}$, $(C_{af}/\Lambda)\partial_\mu a\bar{f}\gamma^\mu\gamma^5 f$

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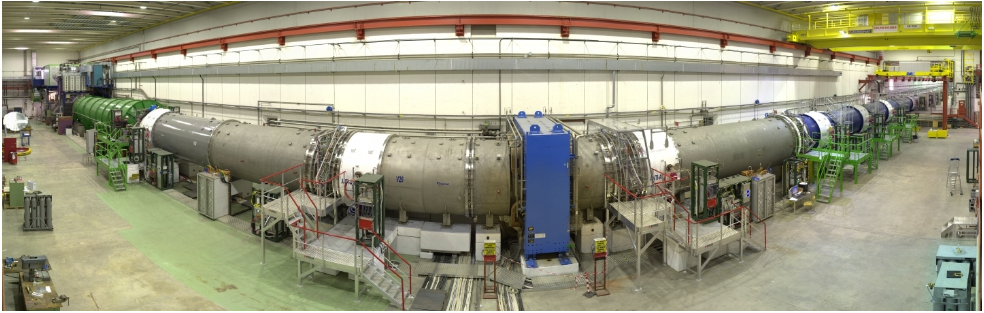
Two types of direct searches for NP particles at fixed-target experiments:

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

NA62 experiment can do both in two modes of operation - kaon mode and **beam-dump** mode
+ indirect searches from testing the SM predictions at NA62

NA62 experiment

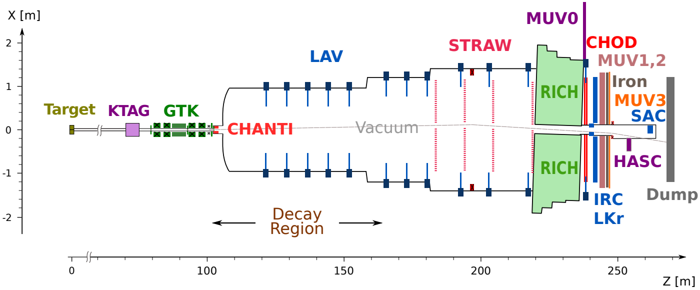
- Fixed-target experiment at CERN SPS (north area), ~ 300 participants (~ 30 institutions);
- Main goal: measure ultra-rare $K^+ \to \pi^+ \nu \bar{\nu}$ with 10% precision, yet NA62 covers a broad kaon and beam-dump physics program;
- Data-taking period 2016-18 (Run 1): $K^+ \to \pi^+ \nu \bar{\nu}$ analysis of Run 1 data set published,[1] 2021-LS3(2025): Run 2 ongoing.



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

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];



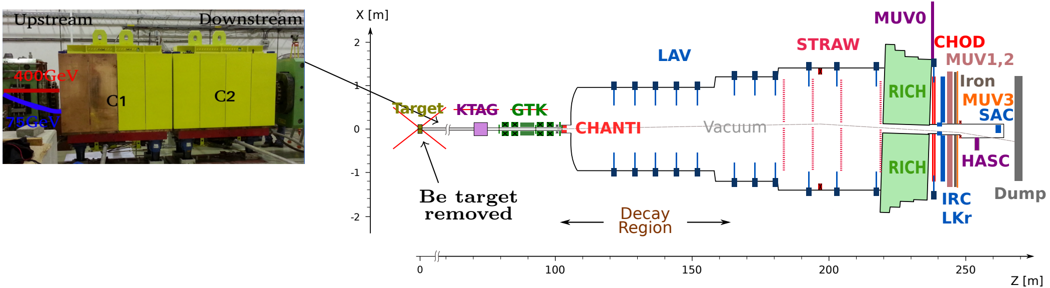
- K^+ tagged by **KTAG** and 3-mom. determined by **GTK**;
- Decay products' 3-mom. measured by **STRAW**, time measured by **CHOD** PID given by **LKr**, **MUV1**, **MUV2** and **RICH**;
  μ ID provided by **MUV3**;
- Photons can be vetoed by **LKr** and at large angles by 12 **LAV** stations or by **SAC**/**IRC** at small angles;

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

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

NA62 experiment in beam-dump mode

- target removed and TAX closed;



- KTAG and GTK not used;
- improved sweeping from magnets between TAX and FV to reduce muon halo background;
- beam intensity $\times 1.5$ of nominal;
- two trigger lines for charged particles: Q1/20 (≥ 1 hits in CHOD), H2 (> 1 in-time hit in CHOD)
- $(1.4 \pm 0.28) \times 10^{17}$ protons on target (POT) collected in 2021 from 10^{18} POT to be collected in Run 2;

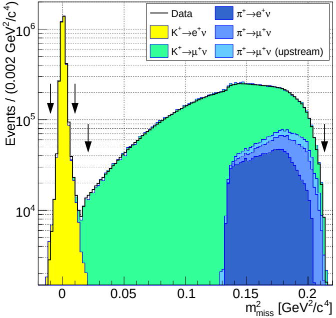
Search for heavy neutral leptons (HNL)

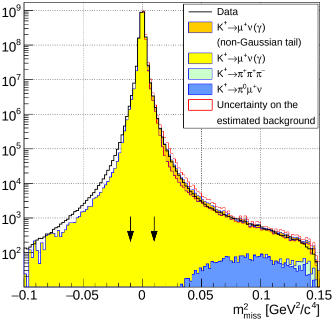
General form of the portal: $\mathcal{L} \supset F_{\alpha I}(\bar{L}_\alpha H)N_I$

- from diagonalizing mass terms for neutrinos $\Rightarrow$ mixing $\nu_\alpha - N_I$, which can be parametrized by $U_{\alpha I}$

Search for N production in K^+ decays: $\mathcal{B}(K^+ \to \ell^+ N) = \mathcal{B}(K^+ \to \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_{l4}|^2$, ρ_ℓ .. kin. factor

- assuming lifetime of N exceeds 50 ns (can be considered detector-stable)
- strategy: search for a spike above a continuous missing mass spectrum $m^2_{\text{miss}} = (P_K - P_\ell)^2$
  - scan m_N in steps of $\mathcal{O}(1)$ MeV/c^2 in range m_N:
  144–462 MeV/c^2 for $K^+ \to e^+ N$ [3]
  200–384 MeV/c^2 for $K^+ \to \mu^+ N$ [4]





[3] Search for heavy neutral lepton production in K^+ decays to positrons. NA62 Collaboration. *Phys.Lett.B* 807 (2020) 135599, [2005.09575]

[4] Search for K^+ decays to μ and invisible particles. NA62 Collaboration. *Phys.Lett.B* 816 (2021) 136259, [2101.12304]

Search for heavy neutral leptons (HNL)

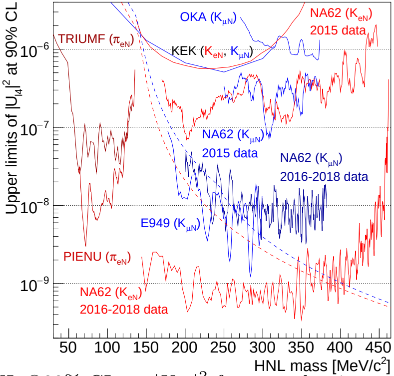


Figure: UL @90% CL on $|U_{\ell 4}|^2$ from production searches[4], red: $|U_{e4}|^2$, blue: $|U_{\mu 4}|^2$.

- For $|U_{e4}|^2$: UL at the level 10^{-9}
- For $|U_{\mu 4}|^2$, UL at the level 10^{-8}

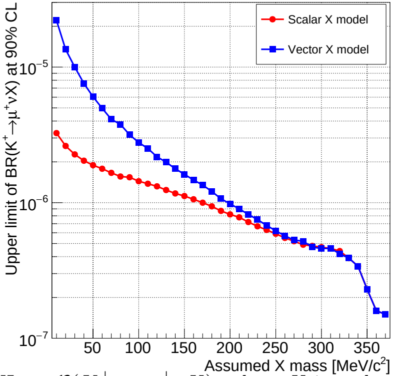


Figure: UL on $\mathcal{B}(K^+ \to \mu^+ \nu X)$, where X is scalar or vector.

- Search for $K^+ \to \mu^+ \nu X$ decay performed at the same dataset obtaining UL on the BR for various m_X hypotheses assuming X is scalar or vector.
- New UL: $\mathcal{B}(K^+ \to \mu^+ \nu \nu \bar{\nu}) < 1.0 \times 10^{-6}$

Search for heavy neutral leptons (HNL)

Search for HNL decay in beam-dump mode:[5]

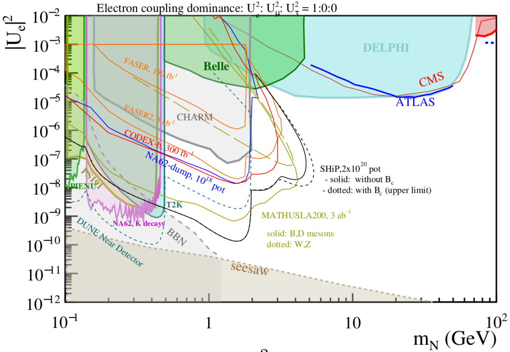


Figure: UL @90% CL on $|U_{e4}|^2$ comparison with beam-dump searches. Blue contour: projected NA62 sensitivity at 10^{18} POT.

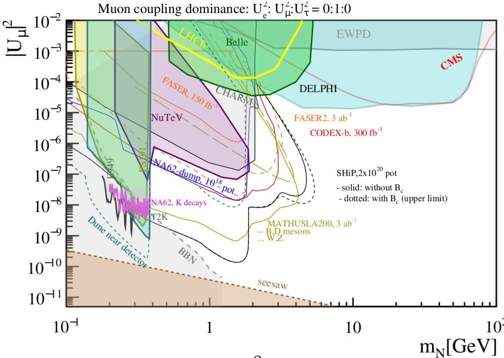


Figure: UL @90% CL on $|U_{\mu4}|^2$ comparison with beam-dump searches. Blue contour: projected NA62 sensitivity at 10^{18} POT.

[5] Feebly-interacting particles: FIPs 2020 workshop report. Prateek Agrawal et al., *Eur.Phys.J.C* 81 (2021) 11, 1015, [2102.12143]

Search for dark photons (DP)

Model of DP A' with kinetic mixing with the SM hypercharge: $\mathcal{L} \supset -\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu} \Rightarrow$

Two DP production mechanisms in the beam-dump setup (in TAX):

- Bremsstrahlung production: $p + N \to X + A'$
- meson-mediated production: $p + N \to X + M$, $M \to A' + \gamma(\pi^0)$, where $M \in \{\pi^0, \eta, \rho, \omega, ..\}$

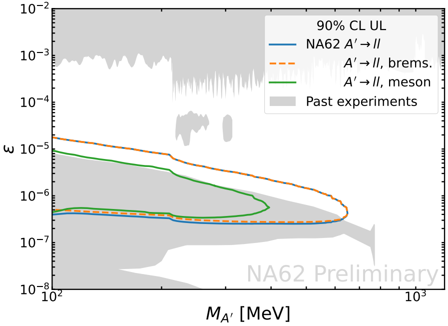


Figure: Sensitivity per production mechanism assuming 0 observed events in 1.4×10^{17} POT.

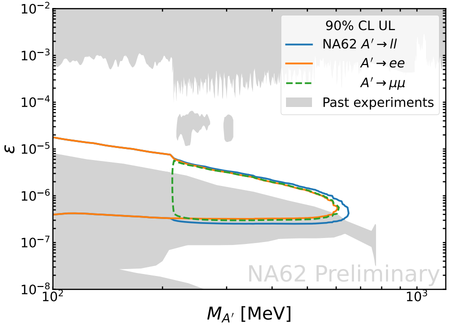


Figure: Sensitivity per decay mode assuming 0 observed events in 1.4×10^{17} POT.

Search for dark photons (DP)

Search strategy:

- $\ell^+\ell^-$ vertex reconstructed in FV;
- primary production vertex close to TAX.

Event selection:

- good quality tracks with timing in coincidence with each other and the trigger
- particle ID with LKr and MUV3
- no in-time activity in LAV
- extrapolation of di-lepton momentum to TAX - definition of signal region (SR) in terms of primary vertex location: $\mathrm{CDA_{TAX}}$ and z_{TAX}

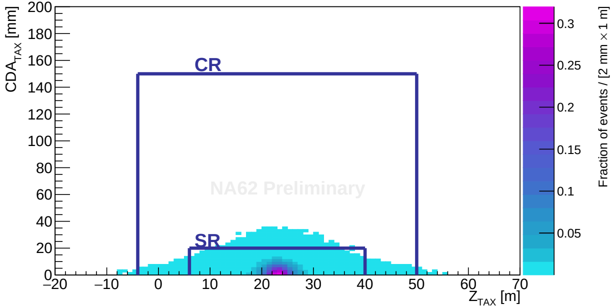


Figure: Signal MC and definition of control (CR) and signal regions (SR).

- SR: $6 < z_{\mathrm{TAX}} < 40$ m and $\mathrm{CDA_{TAX}} < 20$ mm;
- both SR and CR kept blinded during the analysis

Search for dark photons (DP)

Search for $A' \to \mu^+\mu^-$ decay - data and MC comparison, CRs opened:

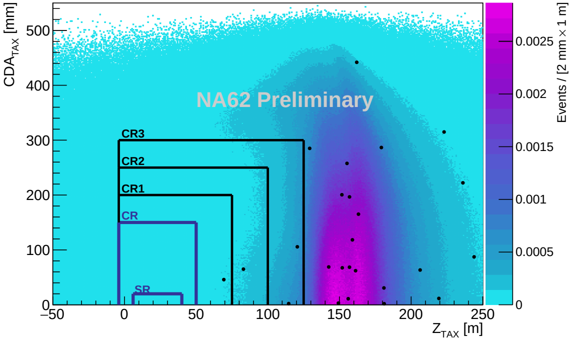


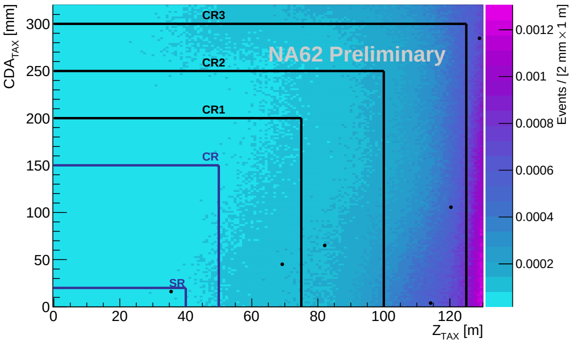
Figure: Data-MC comparison, CRs open, SR closed.

	$N_{\rm exp} \pm \delta N_{\rm exp}$	$N_{\rm obs}$	$p_{N \geq N_{\rm obs}}$	$p_{L \leq L_{\rm obs}}$
outside CR	26.3 ± 3.4	28	0.41	0.74
CR3	1.70 ± 0.22	2	0.25	0.25
CR2	0.58 ± 0.07	1	0.44	0.44
CR1	0.29 ± 0.04	1	0.50	0.68
CR1+2+3	2.57 ± 0.33	4	0.26	0.24
CR	0.17 ± 0.02	0	1.0	1.0
SR	0.016 ± 0.002	-	-	-

- probability to observe 1 or more events in SR is 1.59%

Search for dark photons (DP)

Search for $A' \to \mu^+\mu^-$ decay - data and MC comparison, CRs and SR opened:



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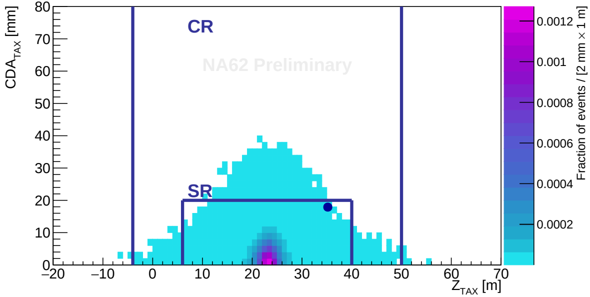

Figure: Signal MC - data: 1 event observed - counting experiment with 2.4σ significance. Signal shape not taken into account for the significance.

Search for dark photons (DP)

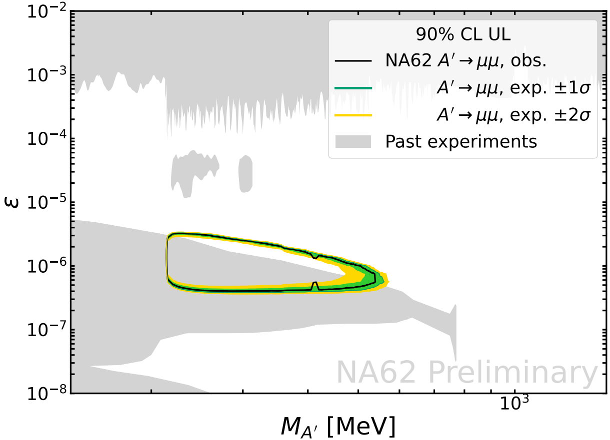

Figure: Final result with upper limit @90% CL.

Search for dark scalars (DS)

Scalar portal: $\mathcal{L} \supset (\mu S + \lambda S^2) H^\dagger H$

- minimal scenario: $\lambda = 0 \Rightarrow$ no pair production

Below EW scale:

- H is substituted by $(v + h)/\sqrt{2}$
- non-zero $\mu \Rightarrow S$-h mixing: $\sin\theta \simeq \theta = \dfrac{\mu v}{m_h^2 - m_S^2}$

At loop level, S production in FCNC transitions:

- $B \to KS$, $K \to \pi S \Rightarrow$ Search at NA62 for a bump above the $K^+ \to \pi^+ \nu\bar{\nu}$ spectrum

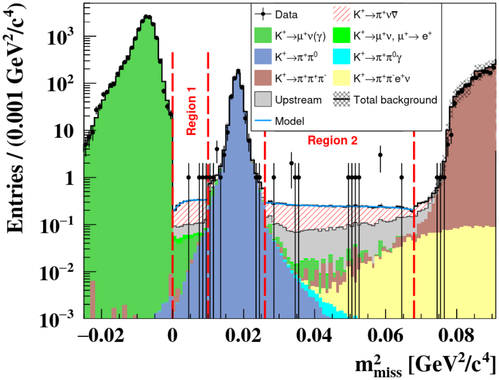

Figure: Expected and observed number of $K^+ \to \pi^+\nu\bar{\nu}$ events as a function of the reconstructed m^2_{miss} for the 2018 data set.[1]

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

[6] New Physics Searches at Kaon and Hyperon Factories. E. Goudzovski et al., [2201.07805]

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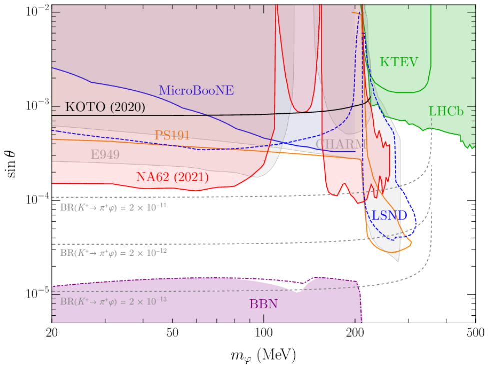

Figure: Excluded regions of $(\sin\theta, m_S)$ parameter space for S decaying only to visible SM particles. Red: exclusion from $K^+ \to \pi^+ +$ inv. and $\pi^0 \to$ inv. decays.[6]

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

[6] New Physics Searches at Kaon and Hyperon Factories. E. Goudzovski et al., [2201.07805]

Search for dark scalars (DS)

Probing higher m_S with the beam-dumps:

- search for charged 2-body decays ($S \to ee$, $\mu\mu$, $\pi\pi$) can be performed at NA62 with 10^{18} POT statistics

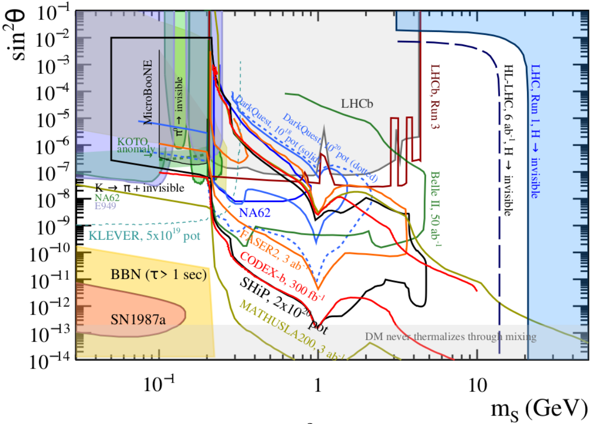

Figure: Excluded regions in the $(\sin^2\theta, m_S)$ parametric space, including beam-dump searches. Blue: projection for NA62 10^{18} POT $S \to \mu\mu$.[5]

[5] Feebly-interacting particles: FIPs 2020 workshop report. Prateek Agrawal et al., *Eur.Phys.J.C* 81 (2021) 11, 1015, [2102.12143]

Search for Axion-like particles (ALP)

Pseudoscalar (ALP) portals:

- gauge boson coupling: $\frac{C_{aX}}{\Lambda} a X_{\mu\nu} \tilde{X}^{\mu\nu}$, $X \in \{B, W, G\}$
- fermionic coupling: $\frac{C_{af}}{\Lambda} \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f$, $f \in \{q, \ell\}$

At loop level, FCNC decays for $C_{aq}, C_{aG}, C_{aW} \neq 0$:

- ALP production in $B \to K^{(\star)} a$, $K \to \pi a$
- At NA62 kaon mode: re-interpretation of $K^+ \to \pi^+ \nu \bar{\nu}$ decay

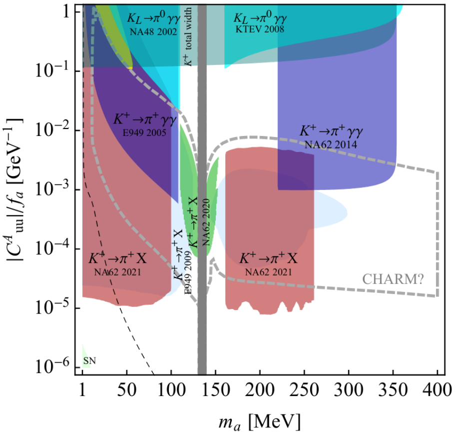

Figure: Bounds on flavor-diagonal pseudoscalar quark couplings: coupling of ALP to up quarks.[6]

[6] New Physics Searches at Kaon and Hyperon Factories. E. Goudzovski et al., [2201.07805]

Search for Axion-like particles (ALP)

NA62 sensitivity in beam-dump mode (10^{18} POT) in various coupling scenarios:

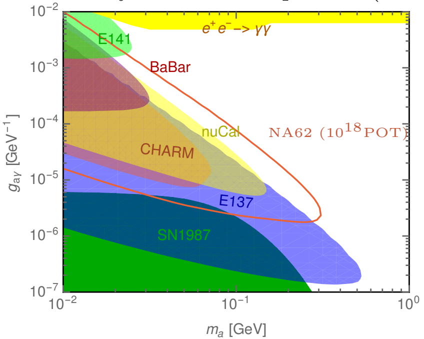

Figure: NA62 Run2 sensitivity w.r.t. past exclusions from $a \to 2\gamma$ search for $g_{a\gamma} = C_{a\gamma}/\Lambda$ coupling scenario[7].

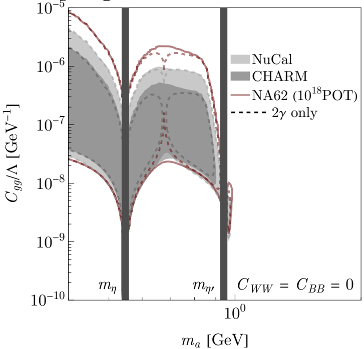

Figure: NA62 Run2 sensitivity (compared to past proton BD) from $a \to$ hadrons and $a \to 2\gamma$ search for C_{aG} coupling-only[8].

[7] Light in the beam dump – ALP production from decay photons in proton beam-dumps. B. Döbrich et al., *JHEP* 05 (2019) 213, [1904.02091]

[8] ALPINIST: Axion-Like Particles In Numerous Interactions Simulated and Tabulated. J.J., B. Döbrich et al., *JHEP* 07 (2022) 094, [2201.05170]

Conclusion

- NA62 is a **multipurpose experiment**: besides the main goal ($K_{\pi\nu\bar{\nu}}$, precision measurements, etc.), it covers a wide program of direct searches for NP particles in both kaon and beam-dump mode
- NA62 can probe new regions in Hidden Sector mass-coupling parametric spaces many years before dedicated facilities are built - **data being collected right now**:
  - data-taking ongoing with many software and hardware updates and increased beam intensity

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Thank you for your attention!

Backup slides

Search for dark photons - backgrounds details

Combinatorial background:

- background from random superposition of two uncorrelated halo muons;
- selected single tracks in a data sample orthogonal to the one used for the analysis;
- track pairs are artificially built to emulate a random superposition;
- each track pair weighted to account for the 10 ns time window $\rightarrow$ independent on the intensity;
- powerful statistical accuracy from combinatorial enhancement;

Prompt background:

- background from secondaries of muon interactions with the traversed material (hadron photo-production);
- muon kinematic distributions extracted from selected single muons in data (backwards MC);
- to correct the spread induced by the backward-forward process (straggling, MS), an unfolding technique is applied to better reproduce the data distributions;
- relative uncertainty of MC expectation $\sim 100\%$.

Prompt background negligible with respect to combinatorial (UL @90% CL is 30% of combinatorial)

Search for dark photons - backgrounds details

ΔT of the tracks suggests two types of background mechanisms

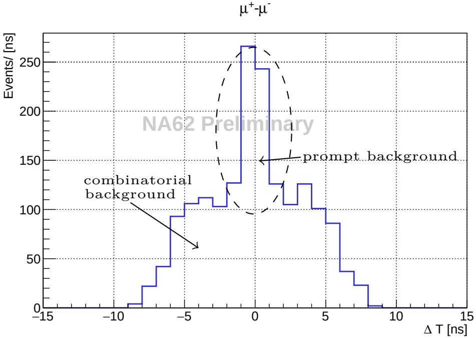


Figure: ΔT before LAV veto is applied (CR, SR blinded).

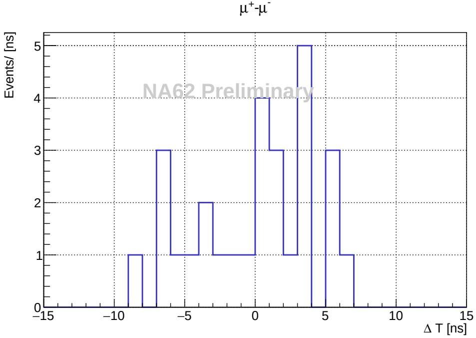
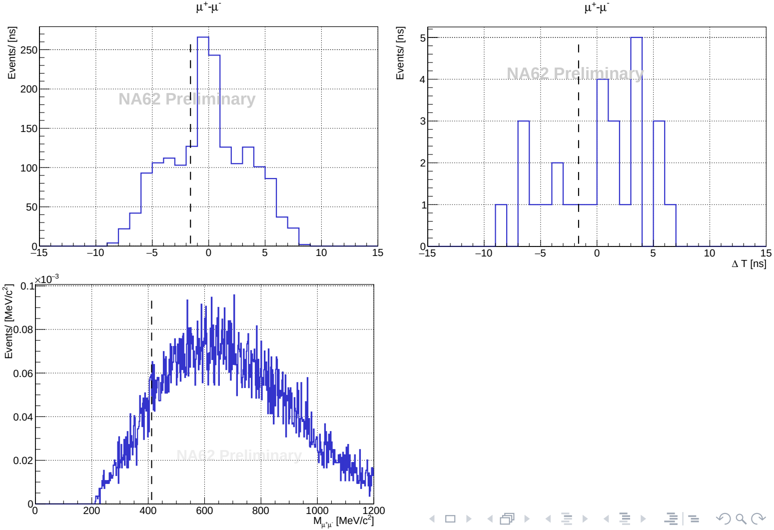


Figure: ΔT after full selection (CR, SR blinded).

Search for dark photons - 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 HNL - selection details

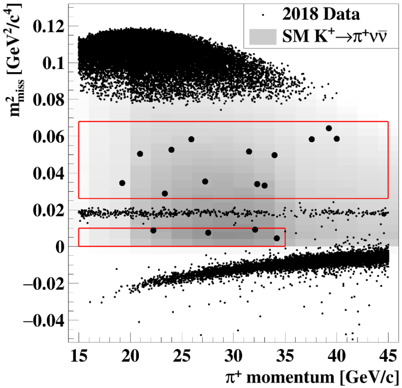
- triggers used: $K_{\pi\nu\nu}$ for $K^+ \to e^+ N$ and control/400 (hit in CHOD) for $K^+ \to \mu^+ N$
- number of K^+ decays:
  - $N_K = (3.52 \pm 0.02) \times 10^{12}$ in $K^+ \to e^+ N$ case[3]
  - $N_K = (1.14 \pm 0.02) \times 10^{10}$ in $K^+ \to \mu^+ N$ case[4]
- event selection:
  - good quality track, decay vertex reconstructed as the point of closest distance of approach (CDA) of STRAW track with original K^+ track
  - particle ID based on E/p (LKr/STRAW), RICH pattern matching signal and associated hit in MUV3 (required for μ, veto for e)
  - additional veto conditions to suppress multibody K^+ decays

[3] Search for heavy neutral lepton production in K^+ decays to positrons. NA62 Collaboration. *Phys.Lett.B* 807 (2020) 135599, [2005.09575]

[4] Search for K^+ decays to μ and invisible particles. NA62 Collaboration. *Phys.Lett.B* 816 (2021) 136259, [2101.12304]

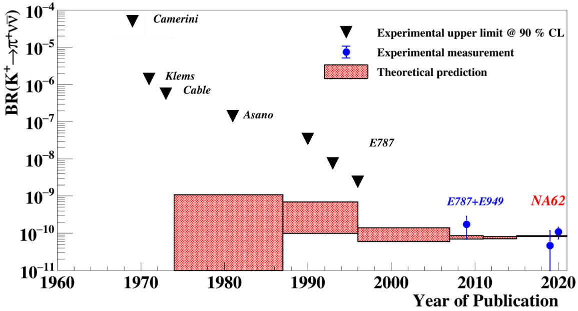
$K^+ \to \pi^+ \nu \bar{\nu}$ 2018

Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^- e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$



$K^+ \to \pi^+ \nu\bar{\nu}$ full Run 1

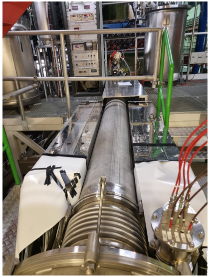
- Single event sensitivity: $(0.839 \pm 0.053_{\text{syst}}) \times 10^{11}$
- Expected SM events: $10.01 \pm 0.42_{\text{syst}} \pm 1.19_{ext}$
- Expected background events: $7.03^{+1.05}_{-0.82}$
- Observed events: 20
- $\mathcal{B}(K_{\pi\nu\bar{\nu}}) = (10.6^{+4.0}_{-3.8}|_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-11}$



Changes for Run 2 (2021-LS3)

- Beam intensity increased by $\sim 30\%$;
- Detectors:
  - Fourth GTK station;
  - Second HASC station;
  - VetoCounter - for detecting upstream kaon decays;
  - ANTI0 - for vetoing halo entering the decay volume;

HASC



VetoCounter

ANTI0

Future - HIKE

- HIKE = *High-Intensity Kaon Experiments* - rare kaon decay programme at SPS (operation of fixed-target at SPS foreseen until at least 2038)[5];
- Series of K^+ and K_{L} decay experiments in the NA62 hall;
- Beam intensity in the kaon mode $\times 6$ of NA62 ($\sim 1.5 \times 10^{19}$ POT/year) and 5×10^{19} POT to be collected in the beam-dump mode;
- 3 phases:
  1. A multi-purpose high-intensity K^+ experiment (main aim to measure $K^+ \to \pi^+ \nu \bar{\nu}$ at $\sim 5\%$ precision);
  2. A multi-purpose K_{L} experiment with charged particle detection (precision measurements of rare K_{L} decays and characterization of the neutral beam for the next phase)
  3. $K_{\mathrm{L}} \to \pi^0 \nu \bar{\nu}$ measurement with $\sim 20\%$ precision

[5] LoI to be submitted soon to the SPSC