HNL and LLP at NA62 (not only) beam-dump

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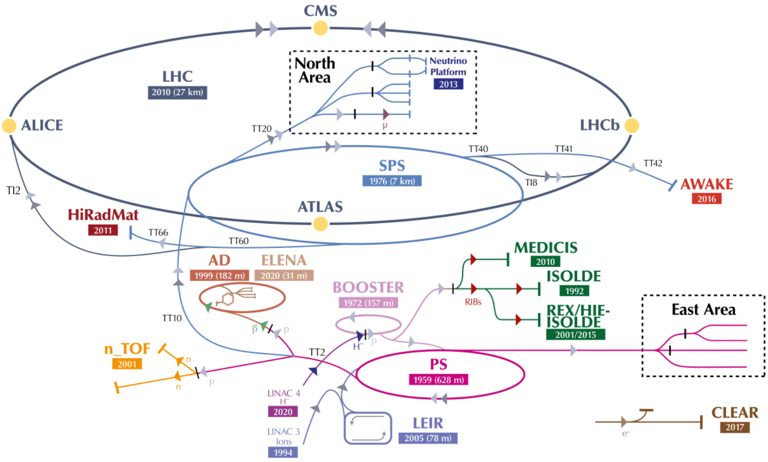
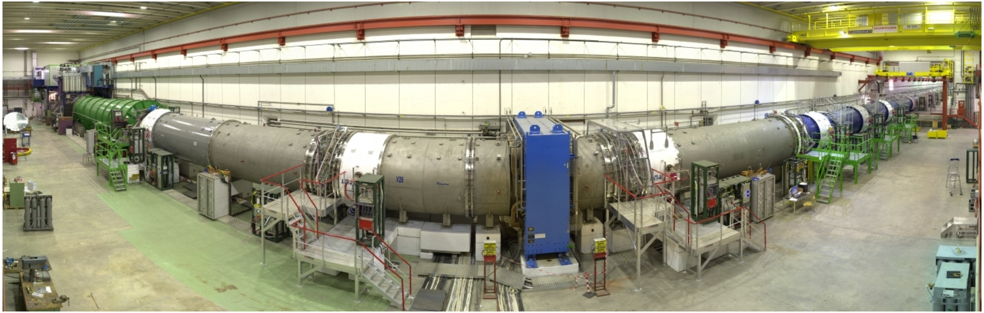
Introduction: NA62 experiment

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 period 2016-18 (Run 1): $K^+ \to \pi^+ \nu\bar{\nu}$ analysis of Run 1 data set published,[2]
  2021-LS3(2025): Run 2 ongoing.



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

Introduction: 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 ($m \lesssim 1\,$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	$(C_{VV}/\Lambda)aV_{\mu\nu}\tilde{V}^{\mu\nu}$ $(C_{ff}/\Lambda)\partial_\mu a\bar{f}\gamma^\mu\gamma^5 f$	9,11 10	$\gamma\gamma$, $\ell\ell$	$2\pi\gamma$, 3π, 4π, $2\pi\eta$, $2K\pi$

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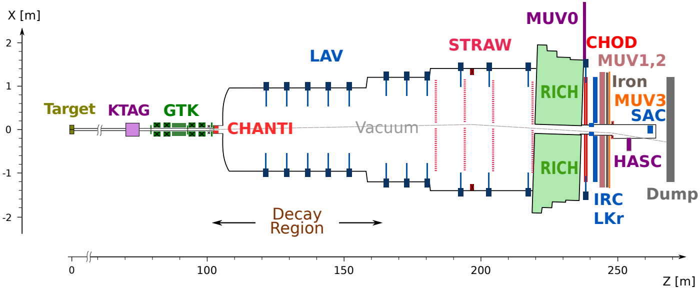
Two types of direct searches for NP particles at fixed-target experiments:

- 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)[3];



- 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

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

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

- 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 (search for an excess in $K_{\pi\nu\nu}$)

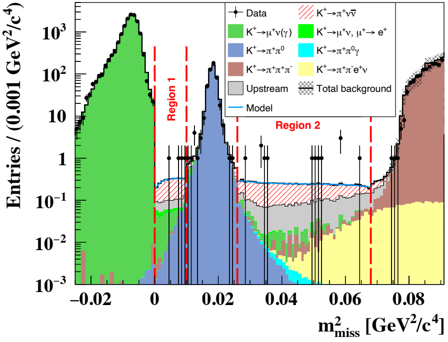


Figure: Expected and observed number of $K^+ \to \pi^+ \nu\bar{\nu}$ events in the 2018 data set.[4]

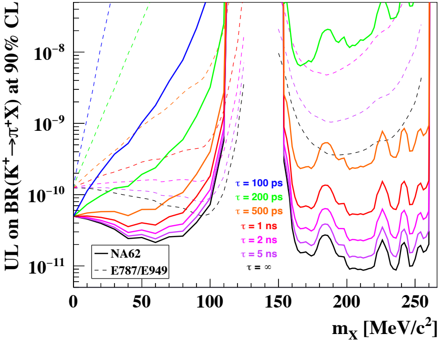


Figure: Bounds on the $K^+ \to \pi^+ X$ BR at 90% CL.

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

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

- Interpretation of $K^+ \to \pi^+ \nu\bar{\nu}$ result in terms of DS and ALP models:

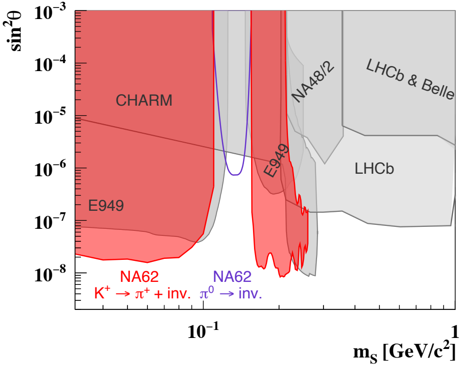


Figure: Bound on the dark scalar mixing angle.[5]

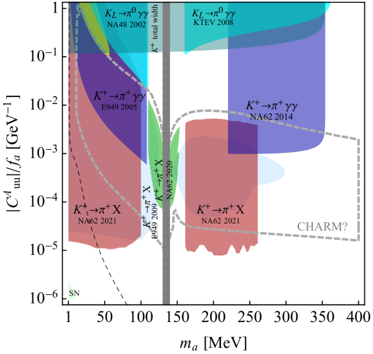


Figure: Bound on the ALP coupling to up quark.[6]

- Study in progress: $K^+ \to \pi^+\pi^0 a$ (ALP escaping)

[5] 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.*. *Rept. Prog. Phys.* 86 (2023) 1, 016201.

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

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

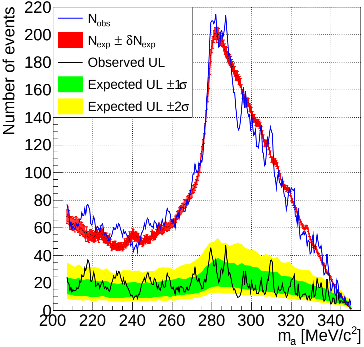


Figure: Number of expected and observed events.

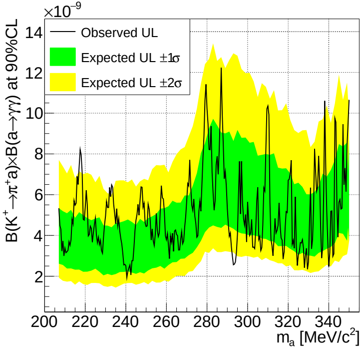


Figure: Upper limit at 90% CL on the BR.[7]

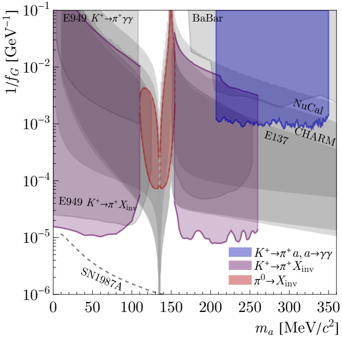


Figure: Exclusion bound for ALPs coupled to gluons.

[7] 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 $\text{BR}(K_{\pi 4e}) = 7.2 \times 10^{-11}$:

- no signal observed, $\text{BR}(K_{\pi 4e}) < 1.4 \times 10^{-8}$ 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

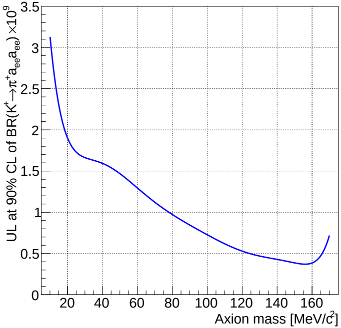


Figure: Upper limit at 90% CL on the ALP BR.[8]

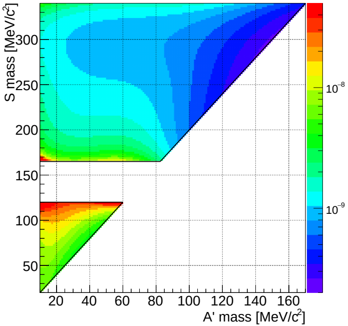


Figure: Bound on the combined BRs of the decay chain.

[8] 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

- Two analyses searching for a spike above the m^2_{miss} spectra of $K^+ \to e^+ X$ and $K^+ \to \mu^+ X$
- X = HNL (e- or μ-coupled): $\text{BR}_{K^+ \to \ell^+ N} = \text{BR}_{\text{SM}} \cdot \rho_\ell(m_N) \cdot |U_{l4}|^2$
- $K \to eN$: $m_N \in 144 - 462\,\text{MeV}/c^2$
  $K \to \mu N$: $m_N \in 200 - 384\,\text{MeV}/c^2$
- Reinterpretation for νX with $X = S/V$
- Search for $K^+ \to \mu^+ \nu_\mu X (X \to \gamma\gamma)$ in progress

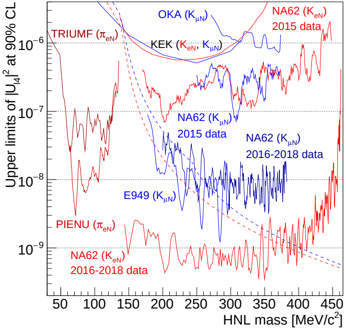


Figure: UL at 90% CL on $|U_{\ell 4}|^2$ from production searches, red: $|U_{e4}|^2$, blue: $|U_{\mu 4}|^2$.[9]

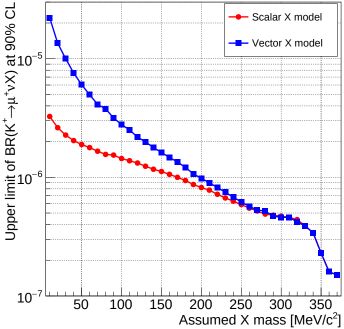


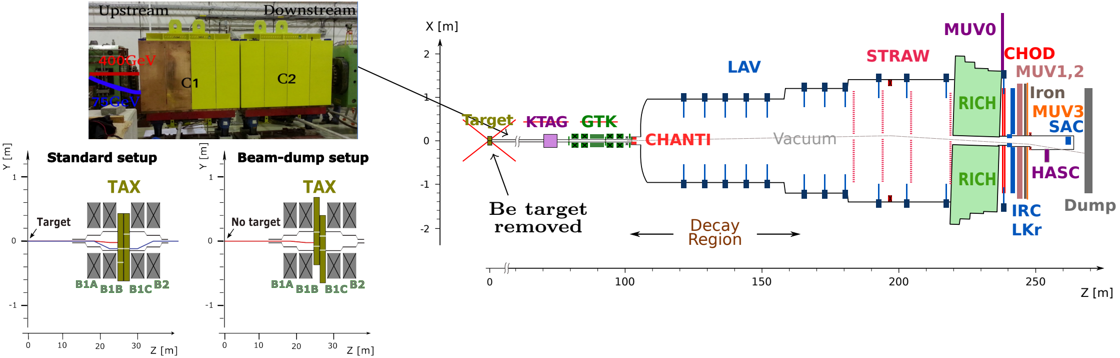
Figure: UL on $\text{BR}(K^+ \to \mu^+ \nu X)$, where X is scalar or vector.[10]

[9] Search for HNL production in K^+ decays to positrons. NA62 Collaboration. *Phys. Lett. B* 807 (2020) 135599.

[10] Search for K^+ decays to a muon and invisible particles. NA62 Collaboration. *Phys. Lett. B* 816 (2021) 136259.

NA62 experiment in beam-dump mode

- target removed and TAX closed, KTAG and GTK not used:



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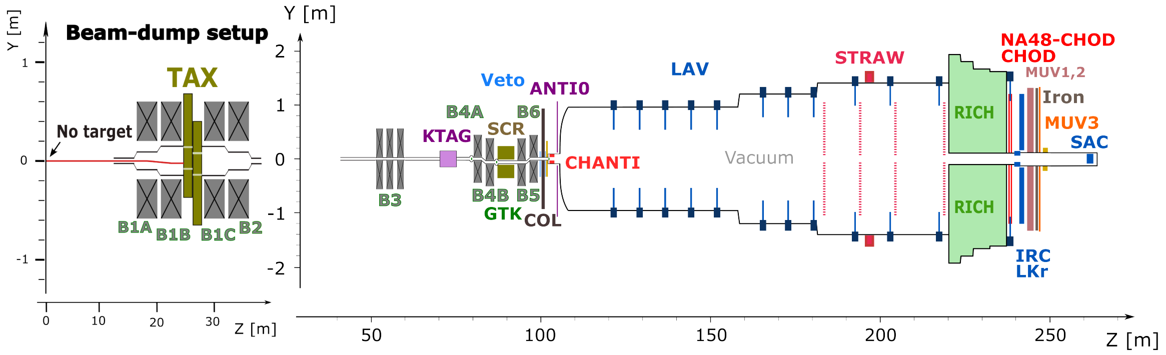

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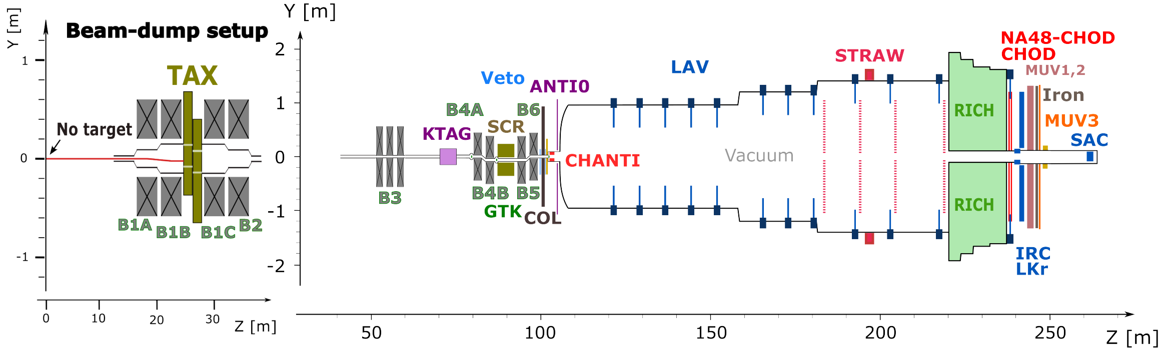

- two trigger lines for charged particles: Q1/20 (≥ 1 hits in CHOD), H2 (> 1 in-time hit in CHOD)
- $N_{\text{POT}} = (1.4 \pm 0.28) \times 10^{17}$ protons on target (POT) collected in 2021; plan: $N_{\text{POT}} = 10^{18}$ in Run 2
- NP searches with ee and $\mu\mu$ final states published;[4]; preliminary result on hadronic decays

[4] NA62 Collaboration *JHEP* 09 (2023) 035 [2303.08666]; [2312.12055]

Search for LLP decay to $\ell^+\ell^-$ in beam-dump mode (strategy)

An LLP X with $\ell^+\ell^-$ decay can be e.g. a DP, DS or ALP

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$\Rightarrow$ 6 combinations of production and decay channels $(e^+e^-, \mu^+\mu^-)$ considered:

- DP: p-Bremsstrahlung production $p + N \to A' + ..$
- DP: meson-mediated production $p + N \to P(V) + ..$; $P \to A'\gamma$ $(P = \{\pi^0,\eta,\eta'\})$, $V \to A'P$ $(V = \{\rho, \omega, \phi\})$
- ALP/DS: B-meson-mediated production: $B^{\pm,0} \to K^{\pm,0,(\star)}X$

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- ALP/DS: B-meson-mediated production: $B^{\pm,0} \to K^{\pm,0,(\star)}X$

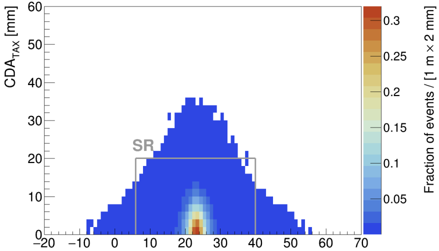
Search strategy:

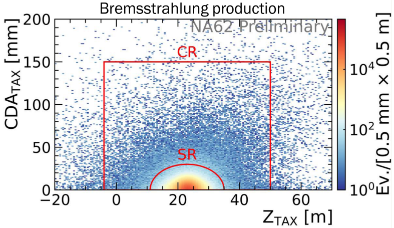
- selecting $\ell^+\ell^-$ tracks;
- $\ell^+\ell^-$ vertex reconstructed in FV $\Rightarrow$ reconstruction of p_X and m_X;
- search for primary production vertex close to TAX (where you expect LLP to be produced);
- blind analysis (signal and control regions defined around primary vertex location kept masked).

Search for LLP decay to $\ell^+\ell^-$ in beam-dump mode (selection)

Event selection:

- good quality tracks with timing in coincidence with each other and the trigger
- particle ID with LKr $E_{\mathrm{LKr}}/p \sim 0$ + MUV3 for $\mu^\pm$ and $E_{\mathrm{LKr}}/p \sim 1$ + !MUV3 for $e^\pm$
- no in-time activity in LAV (and ANTI0 for e)
- extrapolation of di-lepton momentum to TAX: definition of signal region (SR) in terms of primary vertex location $\mathrm{CDA}_{\mathrm{TAX}}$ and z_{TAX}
    - $\mu\mu$: SR is a box $6 < z_{\mathrm{TAX}} < 40$ m and $\mathrm{CDA}_{\mathrm{TAX}} < 20$ mm;
    - ee: SR is an ellipse centered at $z_{\mathrm{TAX}} = 23$ m and $\mathrm{CDA}_{\mathrm{TAX}} = 0$;



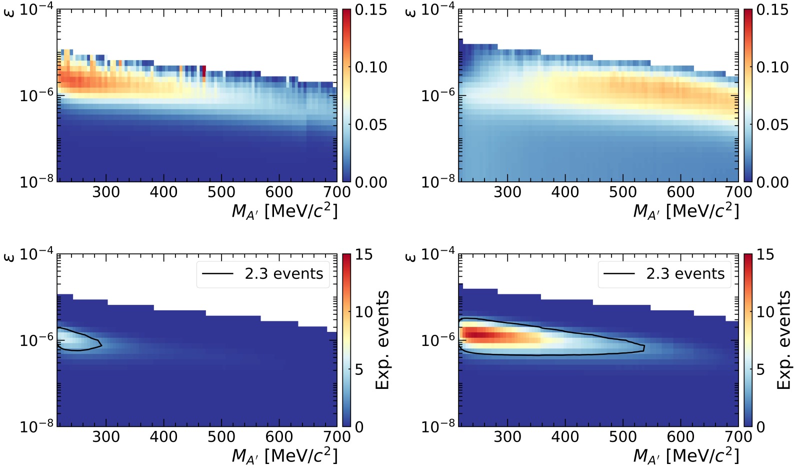


Search for LLP decay to $\mu^+\mu^-$ in beam-dump mode (acceptance)

$$N_{\text{exp}}(M_{A'}, \varepsilon) = N_{\text{POT}} \times \text{BR}_{A' \to \mu\mu} \times \chi_{pp \to A'} \times P_{\text{rd}}(\varepsilon) \times A_{\text{acc}} \times A_{\text{trig}}$$

- $\chi_{pp\to A'}$: LLP production probability
- P_{rd}: probability to reach NA62 FV and decay therein
- $A_{\text{acc}} \times A_{\text{trig}}$: signal selection and trigger efficiencies

Meson-mediated production: **Bremsstrahlung production:**



Search for LLP decay to e^+e^- in beam-dump mode (acceptance)

$$N_{\mathrm{exp}}(M_{A'}, \varepsilon) = N_{\mathrm{POT}} \times \mathrm{BR}_{A' \to ee} \times \chi_{pp \to A} \times P_{\mathrm{rd}}(\varepsilon) \times A_{\mathrm{acc}} \times A_{\mathrm{trig}}$$

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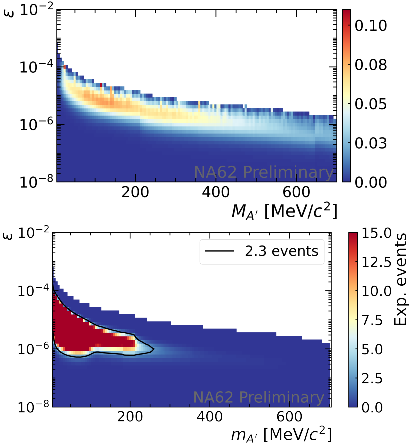
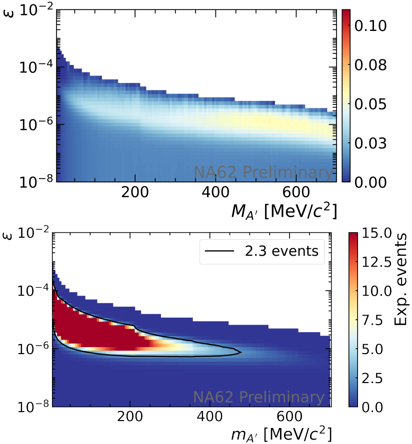


Bremsstrahlung production:



Search for LLP decay to $\ell^+\ell^-$ in beam-dump mode (background)

ΔT of the tracks suggests two types of background mechanisms:

Combinatorial:

- Background from random superposition of two uncorrelated upstream particles;
- Dominating for $\mu^+\mu^-$

Prompt:

- Background from secondaries of μ interactions with the traversed material (hadron photo-production);
- Dominating for ee.

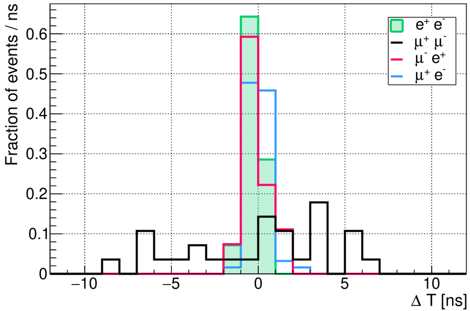


Figure: $X \to \ell^+\ell^-$ background before LAV veto (SR and CR masked).

Search for LLP decay to $\ell^+\ell^-$ in beam-dump mode (background)

Combinatorial background:

- 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;

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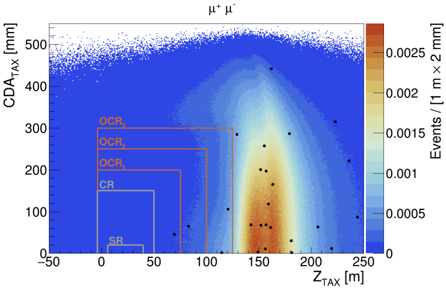
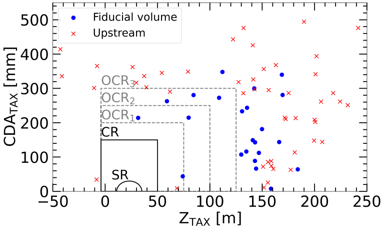
Prompt background:

- 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 $\sim 50\%$.

Search for LLP decay to $\ell^+\ell^-$ in beam-dump mode (background)





after LAV veto	$N_{\rm exp} \pm \delta N_{\rm exp}$	$N_{\rm obs}$	$p_{L \le L_{\rm obs}}$
$\mu^+\mu^-$ outside CR	26.3 ± 3.4	28	0.74
$\mu^+\mu^-$ OCR3	1.70 ± 0.22	2	0.25
$\mu^+\mu^-$ OCR2	0.58 ± 0.07	1	0.44
$\mu^+\mu^-$ OCR1	0.29 ± 0.04	1	0.68

- $N^{\rm CR}_{\rm exp,bkg}(\mu^+\mu^-) = 0.17 \pm 0.02$ 90%CL
- $N^{\rm SR}_{\rm exp,bkg}(\mu^+\mu^-) = 0.016 \pm 0.002$ 90%CL

before LAV, ANTI0 veto	$N_{\rm exp} \pm \delta N_{\rm exp}$	$N_{\rm obs}$	$p_{L \le L_{\rm obs}}$
e^+e^- PID, OCR	58.9 ± 30.2	81	0.50

- $N^{\rm CR}_{\rm exp,bkg}(e^+e^-) = 0.0097^{+0.049}_{-0.009}$ 90%CL
- $N^{\rm SR}_{\rm exp,bkg}(e^+e^-) = 0.0094^{+0.049}_{-0.009}$ 90%CL

Search for LLP decay to $\ell^+\ell^-$ in beam-dump mode (result)

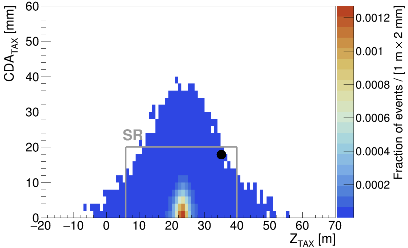


Figure: Signal MC - data: 1 event observed.

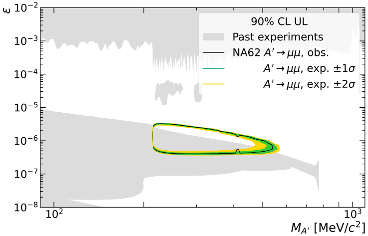
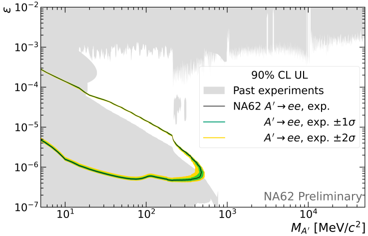
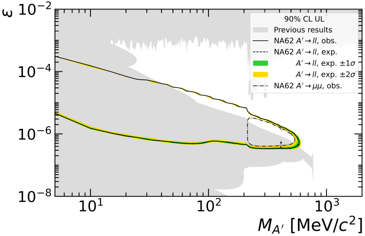


Figure: Bound for $A' \to \mu^+\mu^-$ @90% CL.





Search for LLP decay to $\mu^+\mu^-$ in beam-dump mode (result)

Interpretation of $A' \to \mu\mu$ analysis as a search for ALP/scalar a produced in $B \to K^{(\star)}a$ decay:

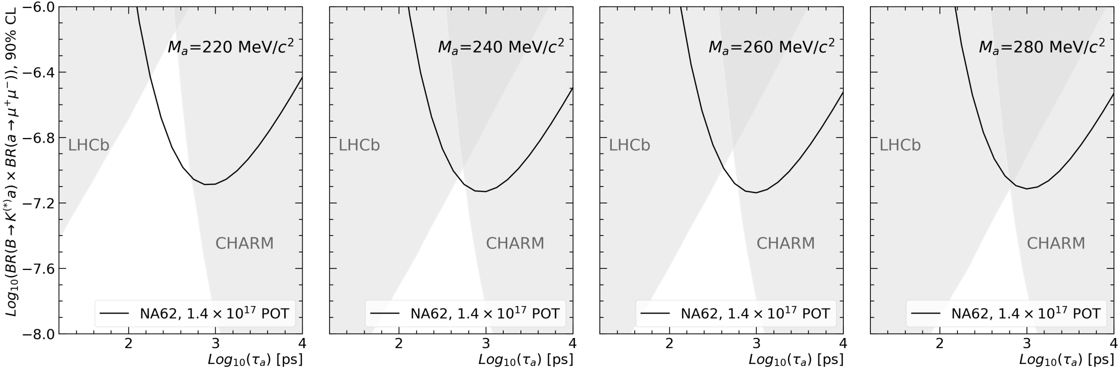


Figure: Resulting exclusion @90% CL for (pseudo)scalar a with mass M_a and lifetime τ_a.

Search for LLP decay to e^+e^- in beam-dump mode (result)

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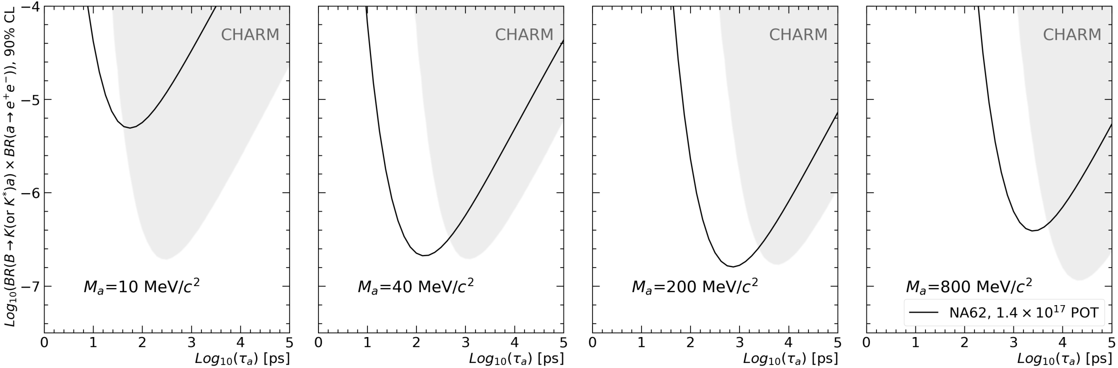

Figure: Resulting exclusion @90% CL for (pseudo)scalar a with mass M_a and lifetime τ_a.

Search for LLP decay to hadrons in beam-dump mode (strategy)

- Numerous possibilities for LLP X being a dark photon (DP), dark scalar (DS), axion-like particle (ALP), ..

Search for LLP decay to hadrons in beam-dump mode (strategy)

- Numerous possibilities for LLP X being a dark photon (DP), dark scalar (DS), axion-like particle (ALP), ..
- $\Rightarrow$ numerous production and decay channels:

DP	DS	ALP
$\pi^+\pi^-$	$\pi^+\pi^-$	$\pi^+\pi^-\gamma$
$\pi^+\pi^-\pi^0$		$\pi^+\pi^-\pi^0$
$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$
		$\pi^+\pi^-\eta$
K^+K^-	K^+K^-	
$K^+K^-\pi^0$		$K^+K^-\pi^0$

- ALP: Primakoff (on-, off-shell), mixing with $P = \{\pi^0, \eta, \eta'\}$, $B^{\pm,0} \to K^{\pm,0,(\star)}a$
- DP: Bremsstrahlung, $P \to A'\gamma$, $V \to A'P$ $(V = \{\rho, \omega, \phi\})$
- DS: $B^{\pm,0} \to K^{\pm,0,(\star)}S$

- Altogether 36 combinations of production and decay channels studied

Search for LLP decay to hadrons in beam-dump mode (selection)

2 hadronic track selection:

- 2 good quality tracks in coincidence with each other and the trigger
- BDT particle ID selecting hadrons (calo. and MUV3), RICH used for tagging K
- no in-time activity in LAV, SAV and ANTI0
- decay vertex reconstructed in FV;

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Search strategy:

- search neutral LKr clusters and reconstruction of γ, π^0, η based on time and opening angle;
- LLP p reconstructed from final states and extrapolation to TAX

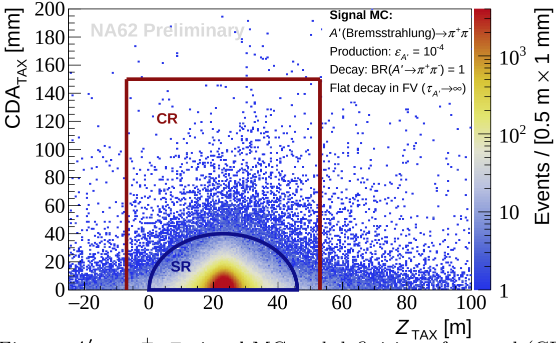

Figure: $A' \to \pi^+\pi^-$ signal MC and definition of control (CR, red) and signal regions (SR, blue).

- SR: ellipse centered at $\{Z_{\mathrm{TAX}}, \mathrm{CDA}_{\mathrm{TAX}}\} = \{23\,\mathrm{m}, 0\,\mathrm{mm}\}$ with semi-axes of 23 m and 40 mm
- CR: $\mathrm{CDA}_{\mathrm{TAX}} < 150\,\mathrm{mm}$ and $-7\,\mathrm{m} < Z_{\mathrm{TAX}} < 53\,\mathrm{m}$

Search for LLP decay to hadrons in beam-dump mode (acceptance)

- In model-independent case $X \to \pi^+\pi^-$ ($\mathrm{BR}_{X\to\pi^+\pi^-} = 1$): $N_{\mathrm{exp}}(M_X, \Gamma_X) = N_{\mathrm{POT}} \times \chi_{pp\to X}(C_{\mathrm{ref}}) \times P_{\mathrm{rd}} \times A_{\mathrm{acc}} \times A_{\mathrm{trig}}$
- $\chi_{pp\to X}(C_{\mathrm{ref}})$: LLP prod. probability for ref. coupling
- P_{rd}: probability to reach NA62 FV and decay therein
- $A_{\mathrm{acc}} \times A_{\mathrm{trig}}$: signal selection and trigger efficiencies

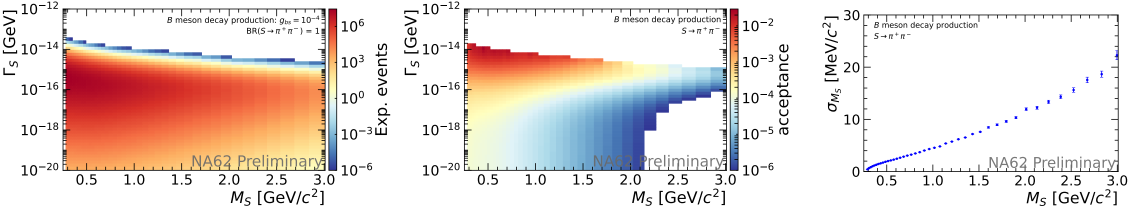

Figure: Left: expected $S \to \pi^+\pi^-$ yield after full selection, assuming $g_{bs} = 10^{-4}$ and BR = 1. Center: acceptance after full selection for LLPs that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

- Distributions above obtained for all 36 combinations of production and decay channels.

Search for LLP decay to hadrons in beam-dump mode (background)

After masking SR and CR and lifting vetoes, two $\pi\pi$ events observed in data:

- 1 event with vertex upstream of FV, vetoed by ANTI0
- 1 event with vertex inside FV, not vetoed by ANTI0, vetoed by LAV

Background estimations with MC:

- **combinatorial and neutrino-induced backgrounds**: negligible contributions
- **prompt background**: inelastic interaction of halo muons can produce hadrons
- **upstream background**: formed by particles that are collected by the GTK achromat

Search for LLP decay to hadrons in beam-dump mode (background)

- estimation using data-driven backward MC with measured μ halo + unfolding for correct kinematics
- MC stat. equivalent of $N_{\mathrm{POT}} = 1.53 \times 10^{17}$ (exceeding the data stat.)

- $\pi\pi$ **outside CR** (in ANTI0 acceptance + no vetoes applied):
  - $N_{\mathrm{exp}} = 1.8 \pm 1.4$ vs $N_{\mathrm{obs}} = 1$ (Upstream region)
  - $N_{\mathrm{exp}} = 0.20 \pm 0.15$ vs $N_{\mathrm{obs}} = 1$ (FV)

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- after applying full selection the prompt background expectations in CR and SR are below 10^{-4} in all channels

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

Channel	$N_{\mathrm{exp,CR}} \pm \delta N_{\mathrm{exp,CR}}$	$N_{\mathrm{exp,SR}} \pm \delta N_{\mathrm{exp,SR}}$
$\pi^+\pi^-$	$(5.7^{+18.5}_{-4.7}) \times 10^{-5}$	$(5.5^{+18.0}_{-4.5}) \times 10^{-5}$
$\pi^+\pi^-\gamma$	$(1.7^{+5.3}_{-1.4}) \times 10^{-5}$	$(1.6^{+5.2}_{-1.3}) \times 10^{-5}$
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$
K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$

Search for LLP decay to hadrons in beam-dump mode (background)

- 3 upstream background subcomponents observed in the control sample in the $Z_{\text{VTX}} - m_{\pi\pi}$ plane:
  - 19 upstream interactions
  - 2 $K_S \to \pi^+\pi^-$ candidates
  - 8 $K^+ \to \pi^+\pi^+\pi^-$ (6 identified as $\pi^+\pi^-$, 2 $\pi^+\pi^-\gamma$)

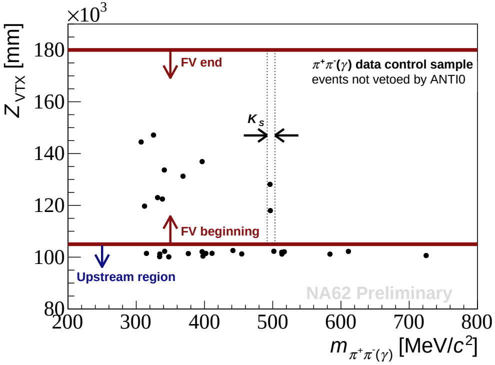

Figure: Events not in ANTI0 acceptance or not vetoed by ANTI0 in Z_{VTX} – invariant mass plane. Solid lines indicate the FV. Dashed lines indicate the K_S 3σ mass window.

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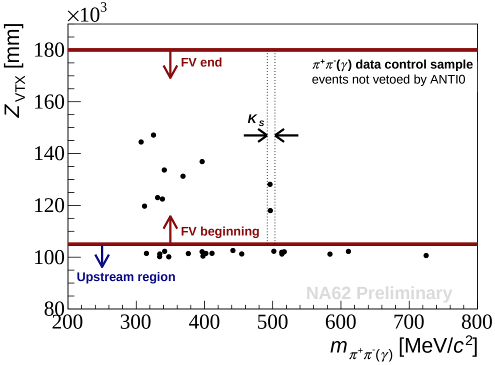

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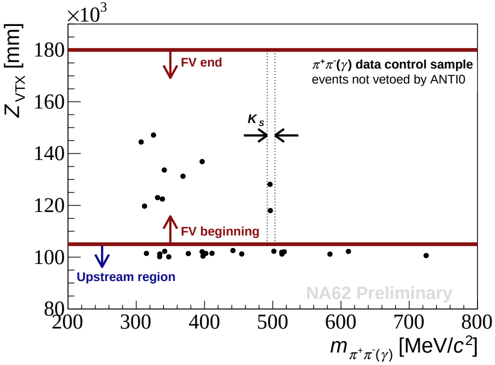

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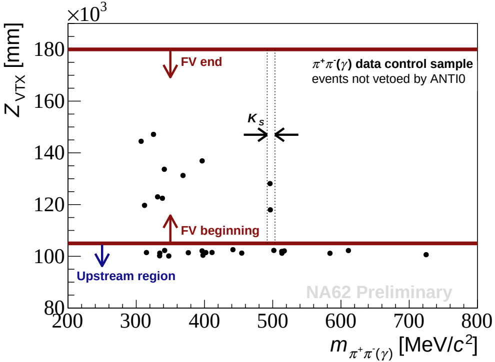
- upstream interactions vetoed by ANTI0 acceptance and vertex location
- for K_S 3σ window ($\pm 5.7\,\mathrm{MeV}/c^2$) around m_{K_S} kept masked
- K^+-induced background simulated using selected single track K^+ forced to decay as $K \to \pi^+\pi^+\pi^-$ in the FV



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Search for LLP decay to hadrons in beam-dump mode (background)

- Result outside CR/SR before ANTI0 acceptance:

Channel	$N_{\mathrm{exp}} \pm \delta N_{\mathrm{exp}}$	N_{obs}
$\pi^+\pi^-$	5.6 ± 2.8	6
$\pi^+\pi^-\gamma$	2.4 ± 1.2	2

- Result outside CR/SR after ANTI0 acceptance:

Channel	$N_{\mathrm{exp}} \pm \delta N_{\mathrm{exp}}$	N_{obs}
$\pi^+\pi^-$	0.68 ± 0.34	1
$\pi^+\pi^-\gamma$	0.31 ± 0.16	0

- Background expectation in SR and CR:

Channel	$N_{\mathrm{exp,CR}} \pm \delta N_{\mathrm{exp,CR}}$	$N_{\mathrm{exp,SR}} \pm \delta N_{\mathrm{exp,SR}}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004

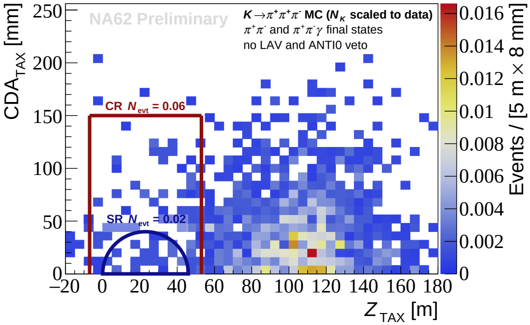

Figure: Obtained background distribution from $K_{3\pi}$ in the primary vertex Z and CDA plane before applying ANTI0 acceptance.

- Simulation performed also for K_{e4} and $K_{\mu4}$ decays $\Rightarrow$ negligible contributions

Search for LLP decay to hadrons 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. Needed number of observed events N_{obs} for p-value more than 5σ from background-only hypothesis in SR and SR+CR (global significance, flat background in m_{inv} assumption).

Channel	$N_{\text{exp,CR}} \pm \delta N_{\text{exp,CR}}$	$N_{\text{exp,SR}} \pm \delta N_{\text{exp,SR}}$	$N^{p>5\sigma}_{\text{obs,SR}}$	$N^{p>5\sigma}_{\text{obs,SR+CR}}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$	1	1
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$	1	1
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K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$	1	2
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$	1	1

- background-free hypothesis **not only** at $N_{\text{POT}} = 1.4 \times 10^{17}$ but also in the future full Run 2 dataset of $N_{\text{POT}} = 10^{18}$

Search for LLP decay to hadrons in beam-dump mode (result)

0 events observed in all control and signal regions

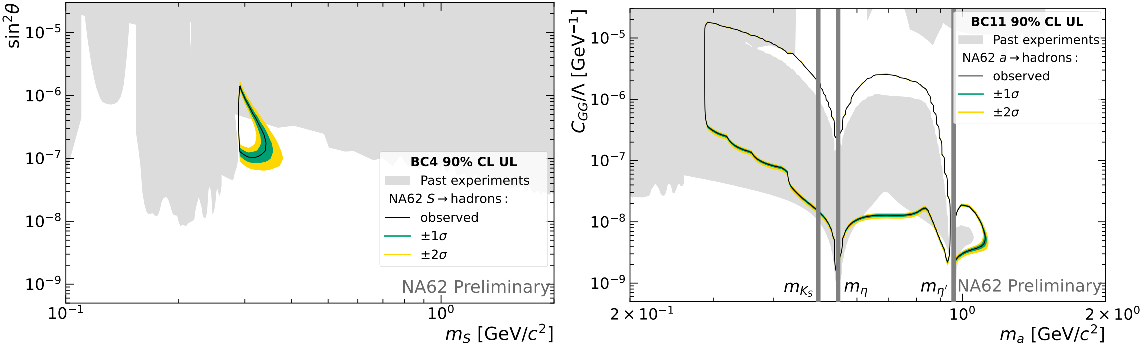
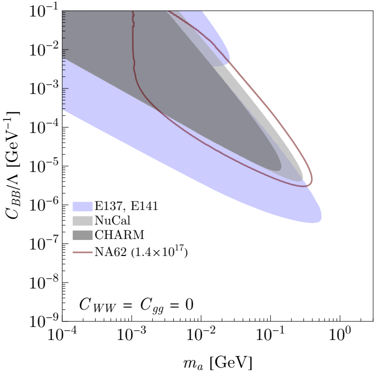


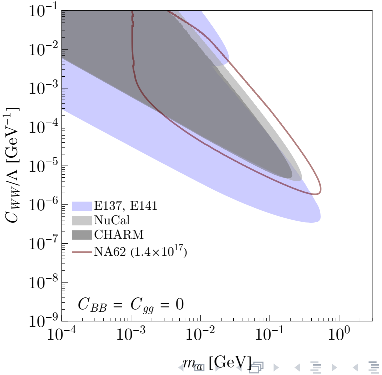
Figure: The observed 90% CL exclusion contours in BC4 (left) and BC11 (right) benchmarks together with the expected $\pm1\sigma$ and $\pm2\sigma$ bands (theory uncertainty not included). Public tool ALPINIST used for the combination of the results from the individual production and decay channels.[5] No standalone 90% CL exclusion for BC1 (dark photon).

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

Future prospects

- Data-taking ongoing, new BD sample collected in 2023, 10^{18} POT in beam-dump mode expected by the LHC LS3 ⇒ improvement in all channels shown before;
- Searches for LLPs decaying into semi-leptonic or di-gamma final states are in progress ⇒ interesting perspectives on ALPs and HNLs ($\gamma\gamma$ sensitivity estimated with a toy MC):





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 were presented;
- Blind analyses to search for LLP decays $X \to \ell^+\ell^-$ and $X \to$ hadrons have been performed on the data collected in 2021;
- New regions of LLP parametric spaces were probed with no NP signal observed;
- 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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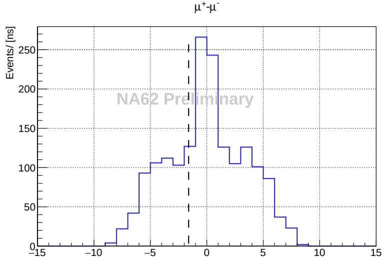
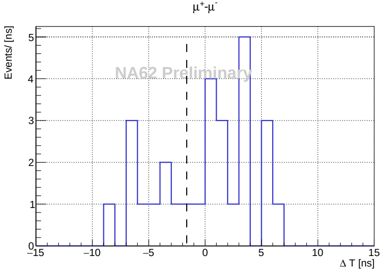
Thank you for your attention!

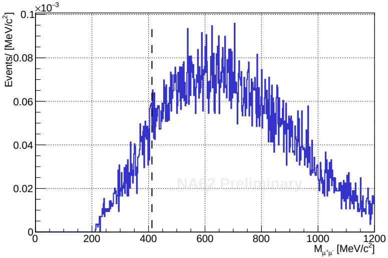
Backup slides

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
- $E/p(\mu^+) = 0.008$
- $E/p(\mu^-) = 0.018$







MC: DP (Brems) $\to \pi^+\pi^-$

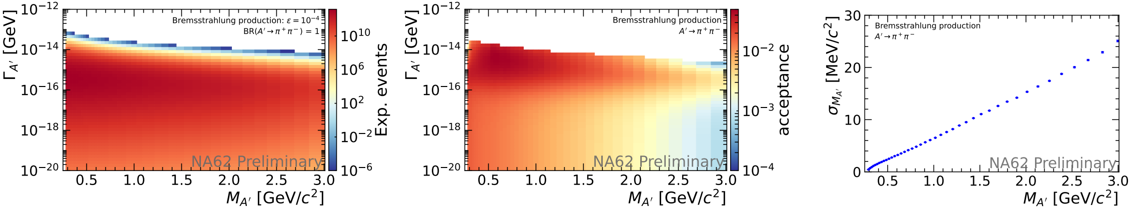


Figure: Left: expected yield after full selection, assuming $\epsilon = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: DP (Brems) $\to 3\pi$

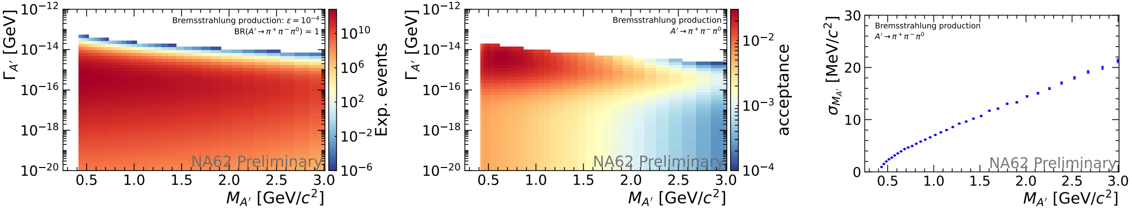
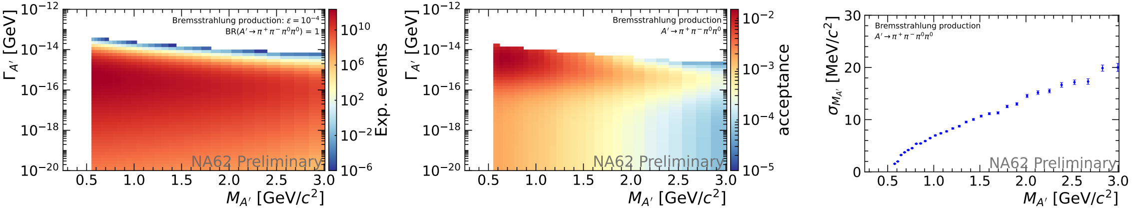


Figure: Left: expected yield after full selection, assuming $\epsilon = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: DP (Brems) $\to 4\pi$



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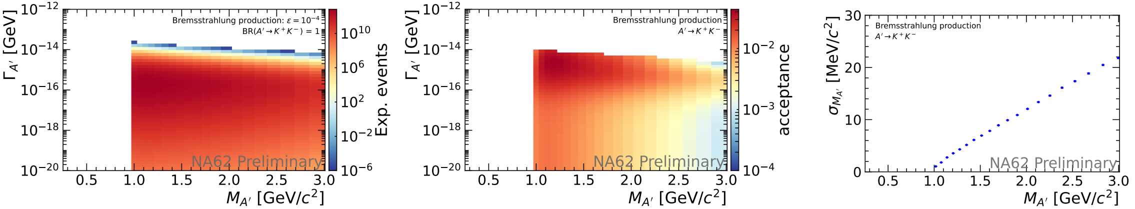

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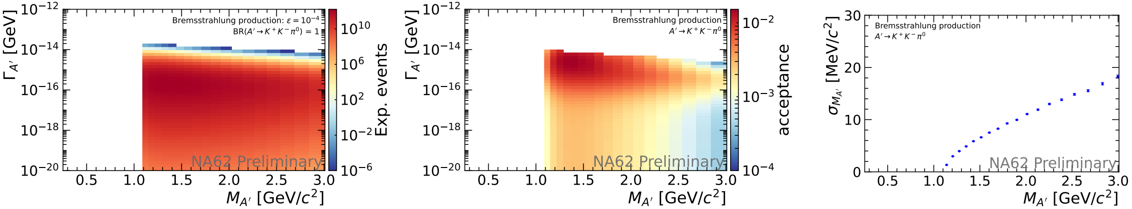

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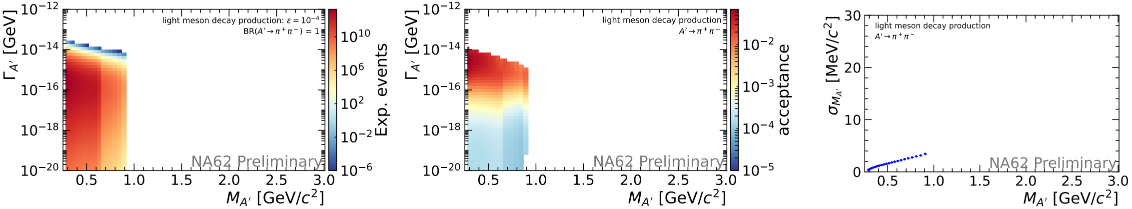

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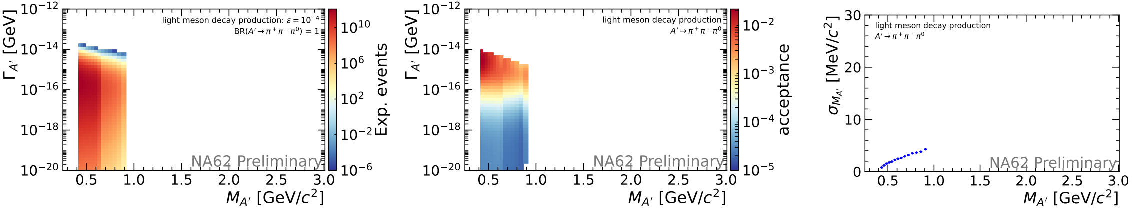

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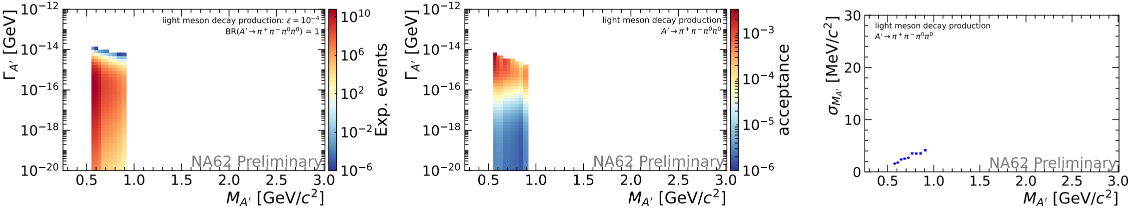


Figure: Left: expected yield after full selection, assuming $\epsilon = 10^{-4}$ and BR $= 1$. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: DS (B meson decay) $\to \pi^+\pi^-$

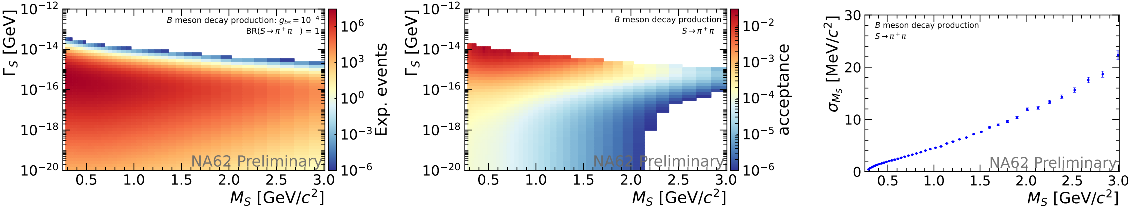
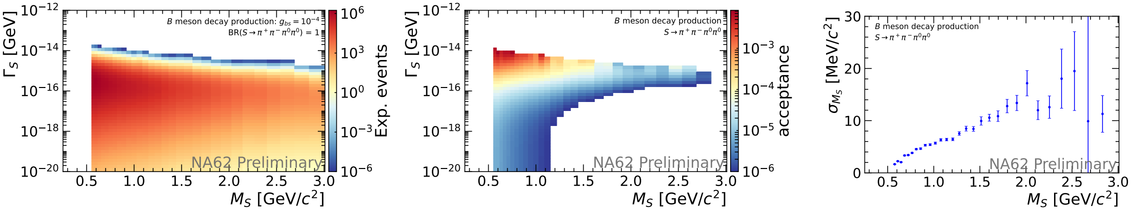


Figure: Left: expected yield after full selection, assuming $g_{bs} = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: DS (B meson decay) $\to 4\pi$



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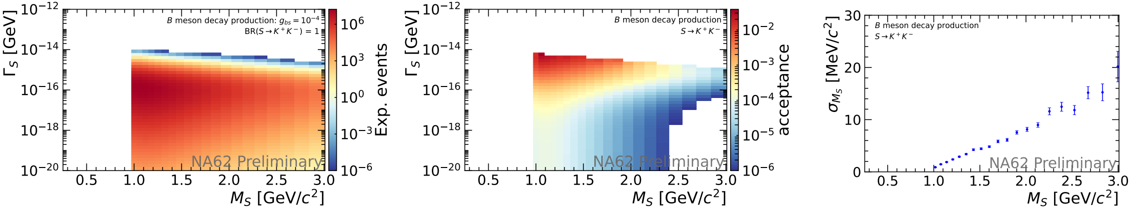

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MC: ALP (Primakoff) $\to \pi^+\pi^-\gamma$

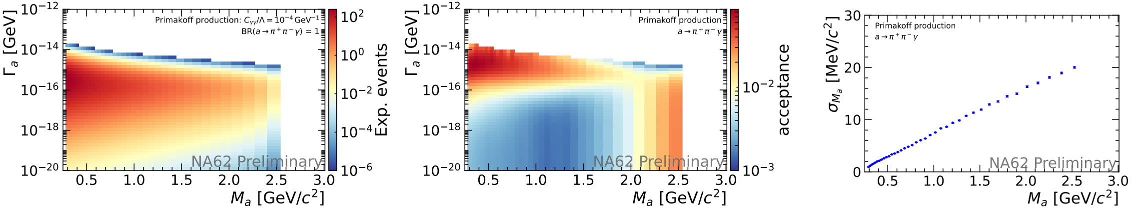

Figure: Left: expected yield after full selection, assuming $C_{\gamma\gamma}/\Lambda = 10^{-4}$ GeV^{-1} and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

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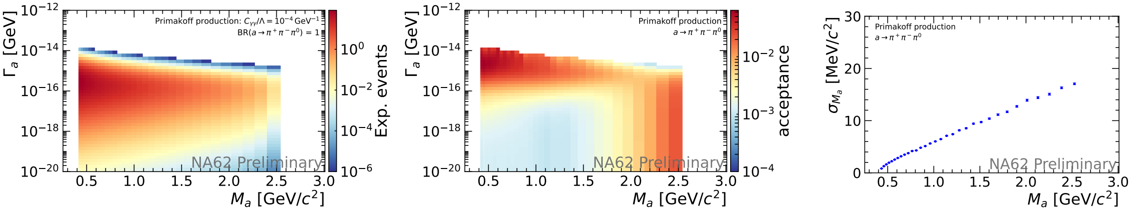

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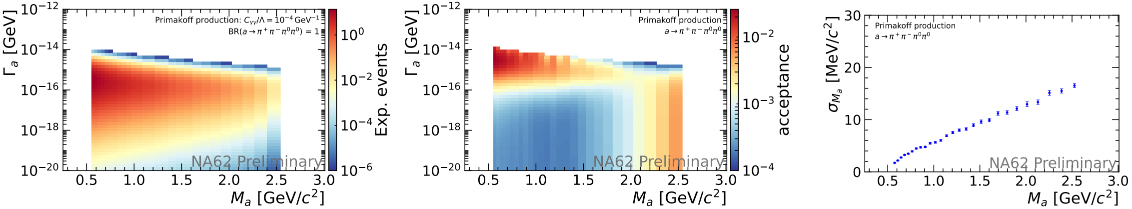

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MC: ALP (Primakoff) $\to \pi^+\pi^-\eta$

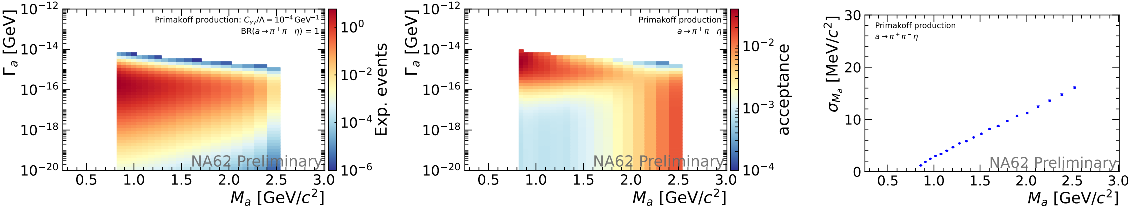


Figure: Left: expected yield after full selection, assuming $C_{\gamma\gamma}/\Lambda = 10^{-4}\,\mathrm{GeV}^{-1}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (Primakoff) $\rightarrow K^+K^-\pi^0$

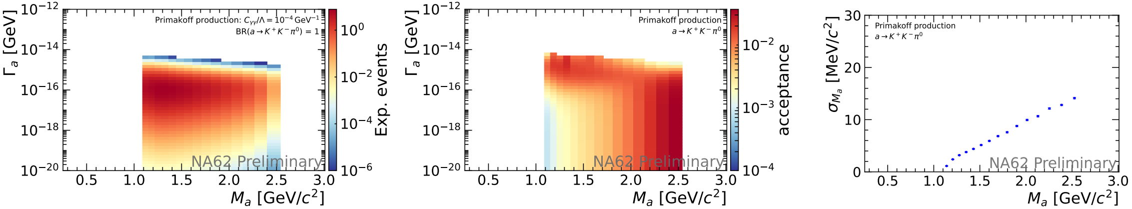


Figure: Left: expected yield after full selection, assuming $C_{\gamma\gamma}/\Lambda = 10^{-4}\,\mathrm{GeV}^{-1}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (B meson decay) $\to \pi^+\pi^-\gamma$

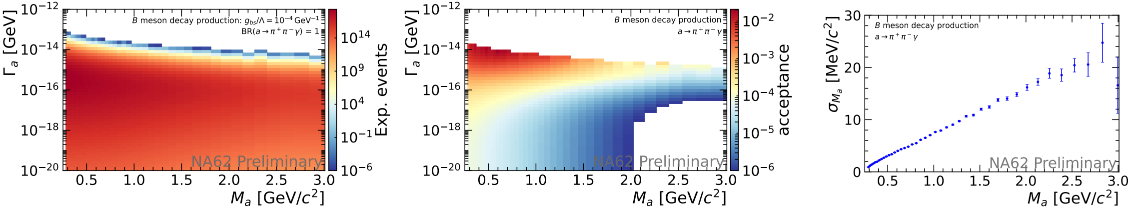


Figure: Left: expected yield after full selection, assuming $C_{bs}/\Lambda = 10^{-4}\,\text{GeV}^{-1}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (B meson decay) $\to 3\pi$

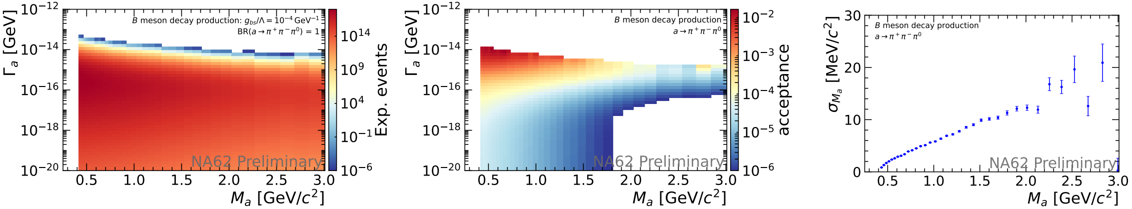


Figure: Left: expected yield after full selection, assuming $C_{bs}/\Lambda = 10^{-4}\,\text{GeV}^{-1}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (B meson decay) $\to 4\pi$

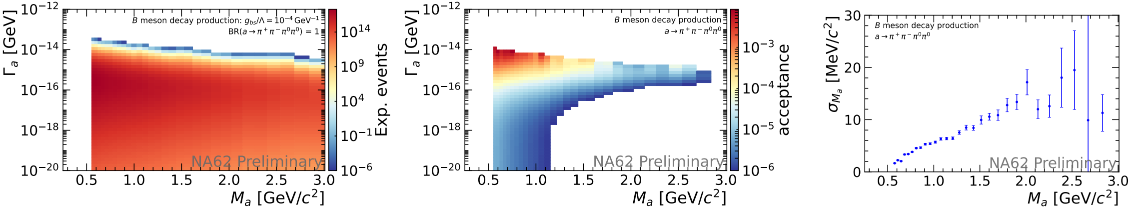


Figure: Left: expected yield after full selection, assuming $C_{bs}/\Lambda = 10^{-4}\,\mathrm{GeV}^{-1}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (B meson decay) $\to \pi^+\pi^-\eta$

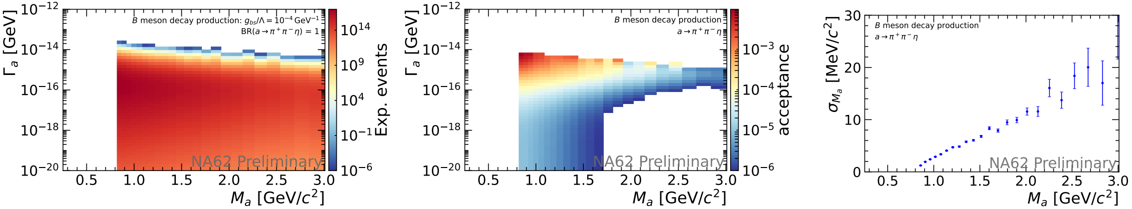


Figure: Left: expected yield after full selection, assuming $C_{bs}/\Lambda = 10^{-4}\,\mathrm{GeV}^{-1}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (B meson decay) $\to K^+K^-\pi^0$

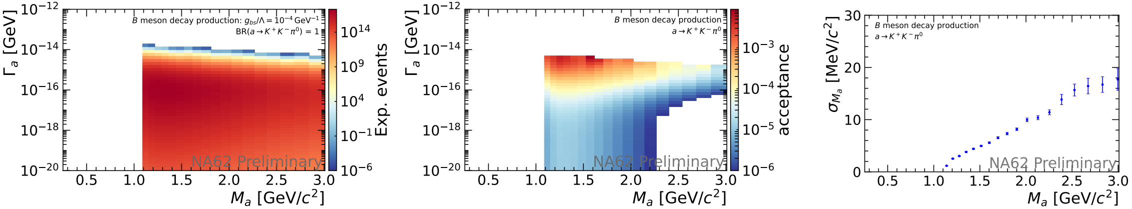


Figure: Left: expected yield after full selection, assuming $C_{bs}/\Lambda = 10^{-4}\,\mathrm{GeV}^{-1}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (π^0 mixing) $\to \pi^+\pi^-\gamma$

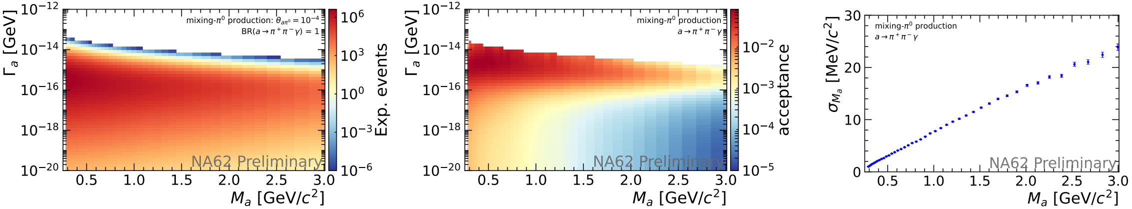


Figure: Left: expected yield after full selection, assuming $\theta_{a\pi^0} = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (π^0 mixing) $\to 3\pi$

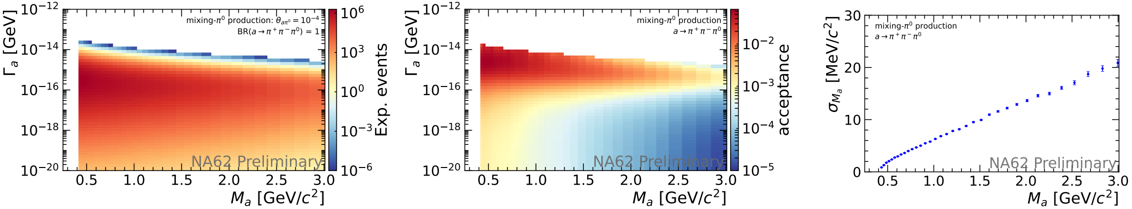
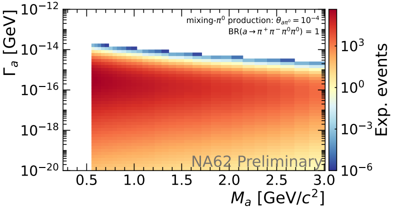
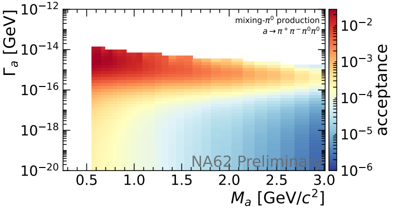


Figure: Left: expected yield after full selection, assuming $\theta_{a\pi^0} = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (π^0 mixing) $\rightarrow 4\pi$





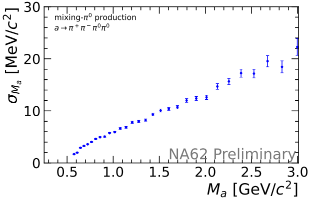


Figure: Left: expected yield after full selection, assuming $\theta_{a\pi^0} = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (π^0 mixing) $\rightarrow \pi^+\pi^-\eta$

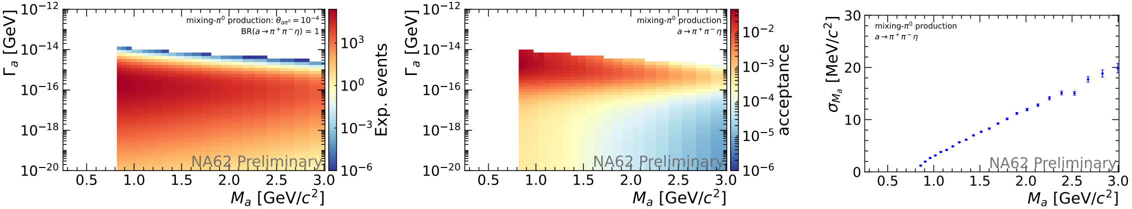


Figure: Left: expected yield after full selection, assuming $\theta_{a\pi^0} = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (π^0 mixing) $\to K^+K^-\pi^0$

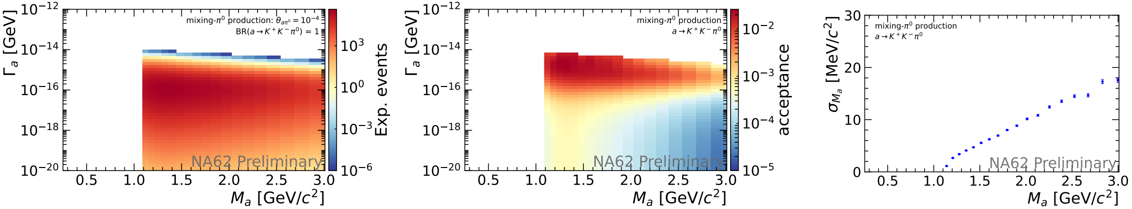


Figure: Left: expected yield after full selection, assuming $\theta_{a\pi^0} = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (η mixing) $\to \pi^+\pi^-\gamma$

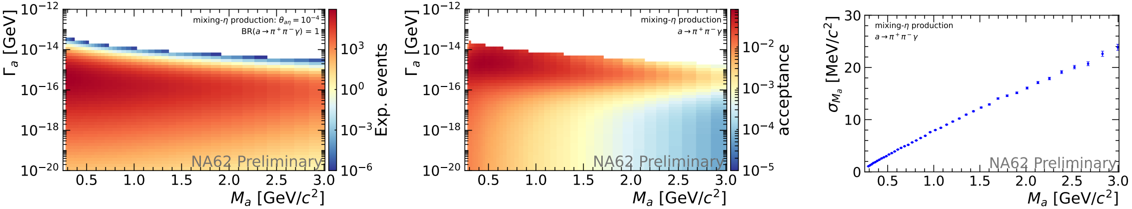


Figure: Left: expected yield after full selection, assuming $\theta_{a\eta} = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (η mixing) $\to 3\pi$

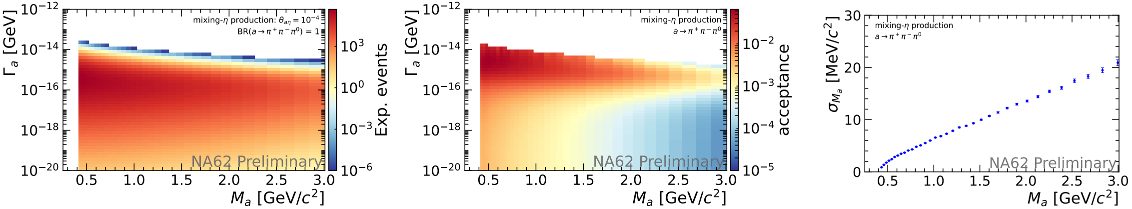
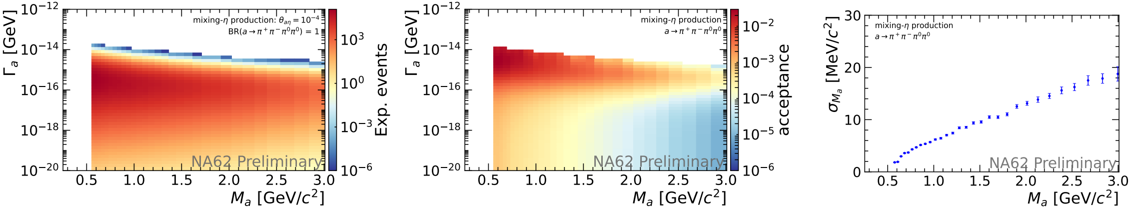


Figure: Left: expected yield after full selection, assuming $\theta_{a\eta} = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (η mixing) $\rightarrow 4\pi$



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MC: ALP (η mixing) $\to \pi^+\pi^-\eta$

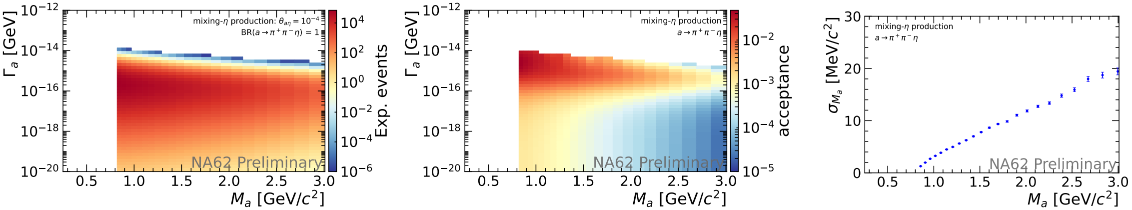


Figure: Left: expected yield after full selection, assuming $\theta_{a\eta} = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (η mixing) $\to K^+K^-\pi^0$

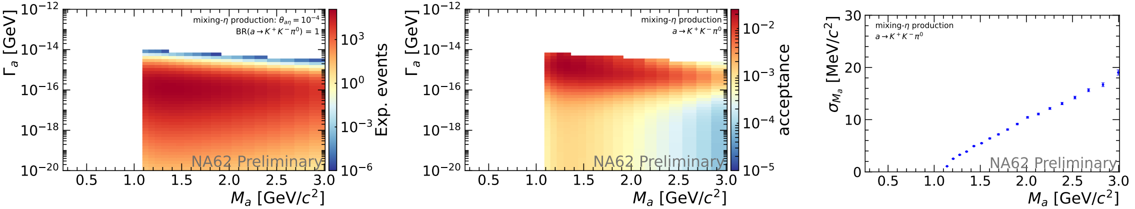


Figure: Left: expected yield after full selection, assuming $\theta_{a\eta} = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (η' mixing) $\rightarrow \pi^+\pi^-\gamma$

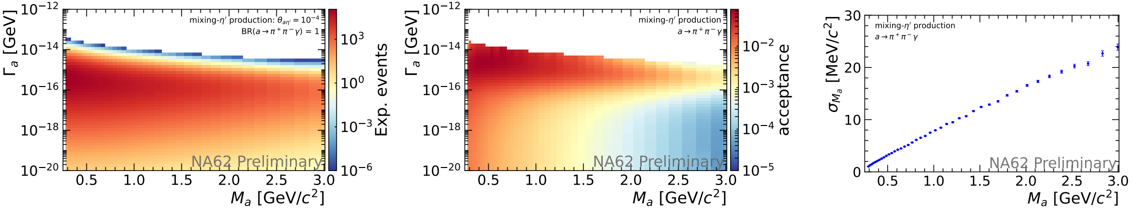
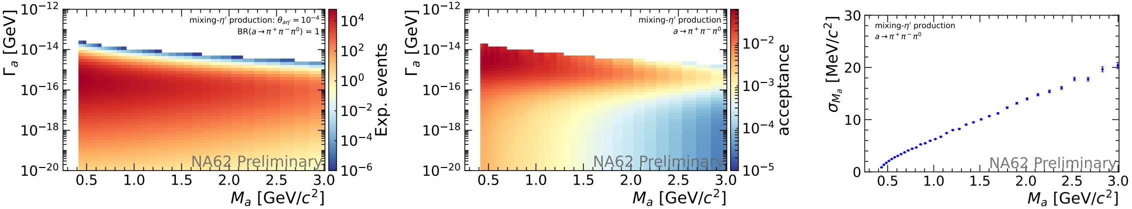


Figure: Left: expected yield after full selection, assuming $\theta_{a\eta'} = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

MC: ALP (η' mixing) $\to 3\pi$



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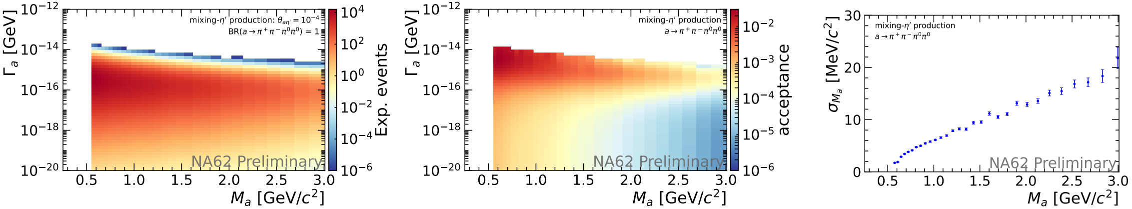

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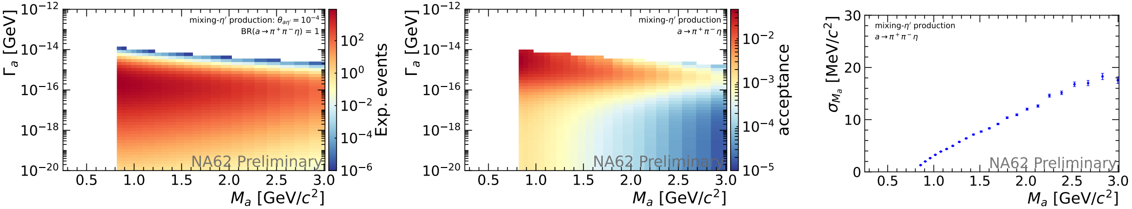

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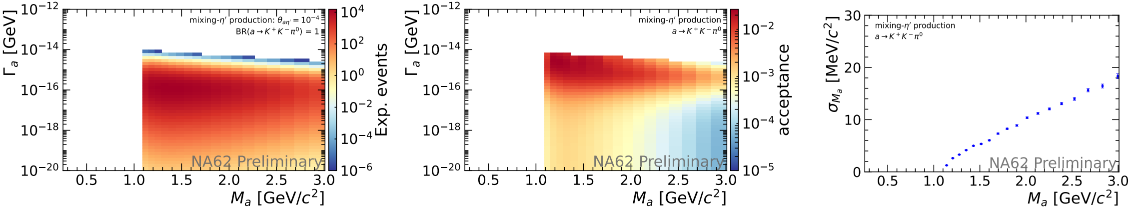

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