New results for searches of exotic decays with NA62 in beam-dump mode

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21st conference on Flavor Physics and CP violation; May 30, 2023

*On behalf of the NA62 Collaboration

Introduction

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)	decay ($m \lesssim 1$ GeV)
HNL (N_I)	fermion	$F_{\alpha I}(\bar{L}_\alpha H)N_I$	$\pi\ell(\nu)$,$\ell_1\ell_2(\nu)$
dark Higgs (S)	scalar	$(\mu S + \lambda S^2)H^\dagger H$	$\ell\ell$, $\pi\pi$
axion/ALP (a)	pseudoscalar	$(C_{aV}/\Lambda)aV_{\mu\nu}\tilde{V}^{\mu\nu}$ $(C_{af}/\Lambda)\partial_\mu a\bar{f}\gamma^\mu\gamma^5 f$	$\gamma\gamma$, $\ell\ell$, $2\pi\gamma$, 3π, $2\pi\eta$
dark photon (A'_μ)	vector	$-(\epsilon/2\cos\theta_W)F'_{\mu\nu}B^{\mu\nu}$	$\ell\ell$, $\pi\pi$, $\pi\pi\pi$

[1] See plenary talk by G. Ruggeiro this afternoon.

Introduction

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

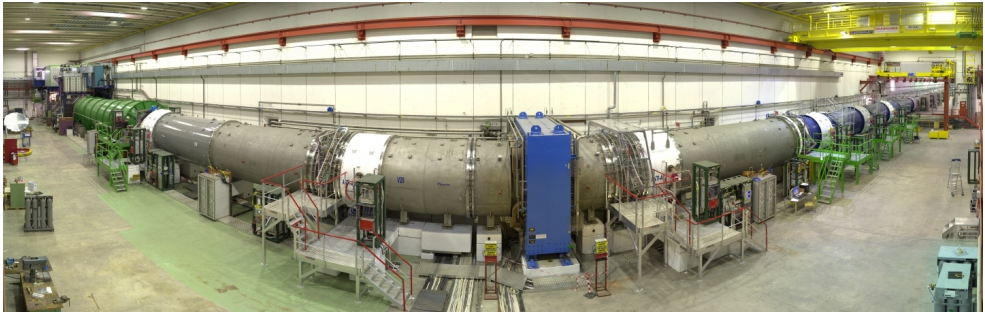
- NP particle decay to SM particles - reconstruction of original particle from the SM final states
- NP particle production in SM particle decays - reconstruction from both initial and final state particles

NA62 experiment can do both in two modes of operation - kaon mode[1] and **beam-dump mode**

[1] See plenary talk by G. Ruggeiro this afternoon.

NA62 experiment

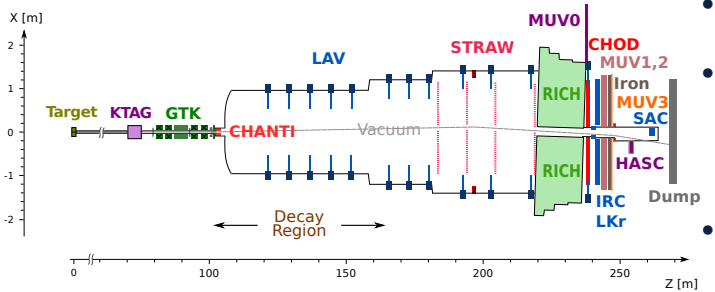
- Fixed-target experiment at CERN SPS (north area).
- Main goal: measure ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ with 10% precision,
  yet NA62 covers a broad kaon and beam-dump physics program.
- Data-taking period 2016-18 (Run 1): $K^+ \to \pi^+ \nu\bar{\nu}$ analysis of Run 1 data set published,[2]
  2021-25: Run 2 ongoing.



[2] 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)[3];

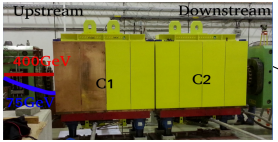


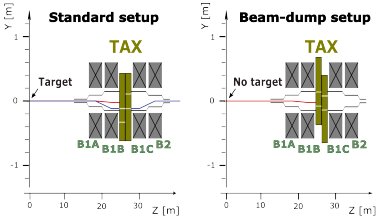
- K^+ tagged by **KTAG** and 3-mom. determined by **GTK**;
- Decay products' 3-mom. measured by **STRAW**, time measured by **CHOD** PID given by **LKr**, **MUV1**, **MUV2** and **RICH**;
  μ ID provided by **MUV3**;
- Photons can be vetoed by **LKr** and at large angles by 12 **LAV** stations or by **SAC**/**IRC** at small angles;
- Overall experimental time resolution reaches $\mathcal{O}(100)$ps

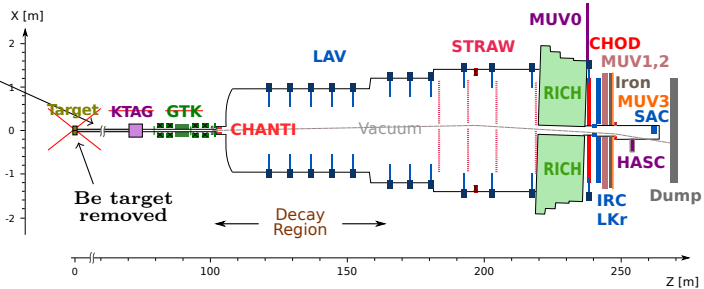
[3] The beam and detector of the NA62 experiment at CERN. NA62 Collaboration. 2017 *JINST* **12** P05025, [1703.08501]

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
  $\Rightarrow$ 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 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 $M \in \{\pi^0, \eta, \rho, \omega, ..\}$

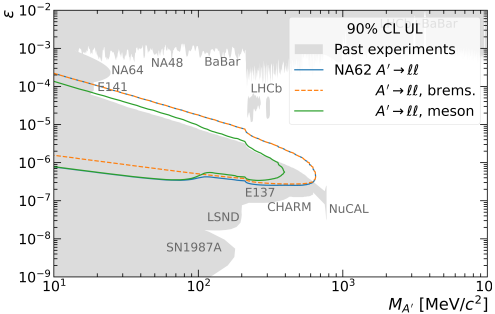


Figure: Sensitivity per production mechanism assuming 0 observed events in 1.4×10^{17} POT.

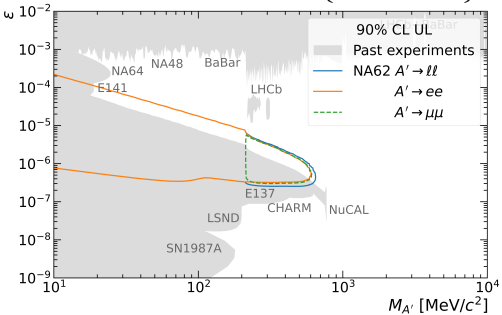


Figure: Sensitivity per decay mode assuming 0 observed events in 1.4×10^{17} POT.

Search for dark photons ($A' \to \mu\mu$)

Search strategy:

- $\mu^+\mu^-$ 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}

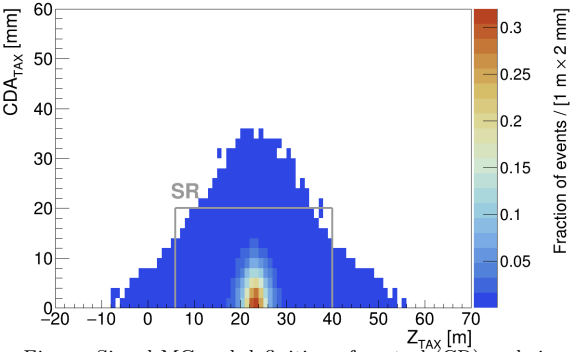


Figure: Signal MC and definition of control (CR) and signal regions (SR) for $A' \to \mu\mu$.

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

Search for dark photons ($A' \to \mu\mu$)

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

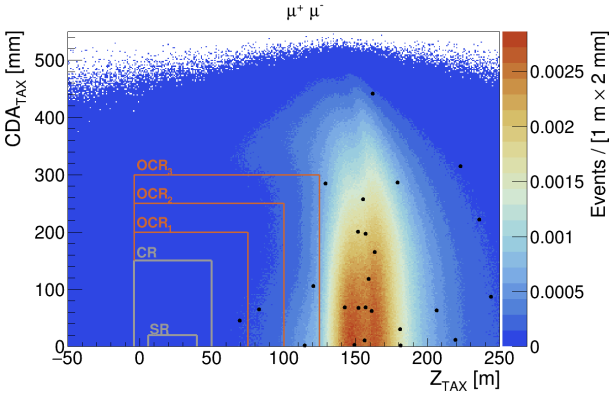


Figure: Data-MC comparison, SR closed.

	$N_{\text{exp}} \pm \delta N_{\text{exp}}$	N_{obs}	$p_{N \geq N_{\text{obs}}}$	$p_{L \leq L_{\text{obs}}}$
outside CR	26.3 ± 3.4	28	0.41	0.74
OCR3	1.70 ± 0.22	2	0.25	0.25
OCR2	0.58 ± 0.07	1	0.44	0.44
OCR1	0.29 ± 0.04	1	0.50	0.68
OCR1+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 ($A' \to \mu\mu$)

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

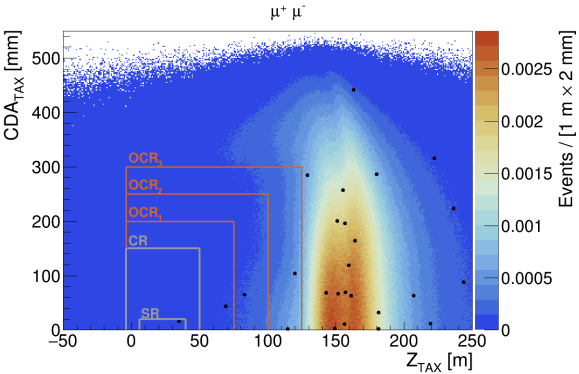


Figure: Data-MC comparison, CRs and SR open.

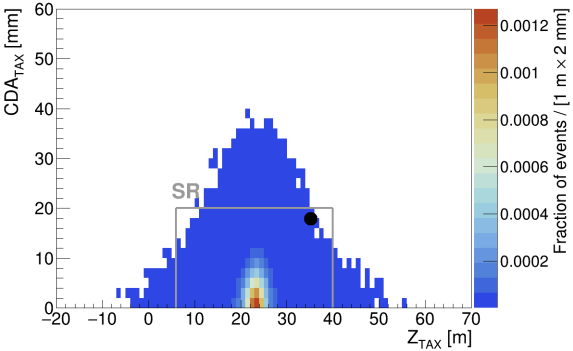


Figure: Signal MC - data: 1 event observed - counting experiment with 2.4σ significance. Signal shape not taken into account for the significance.

Search for dark photons ($A' \to \mu\mu$)

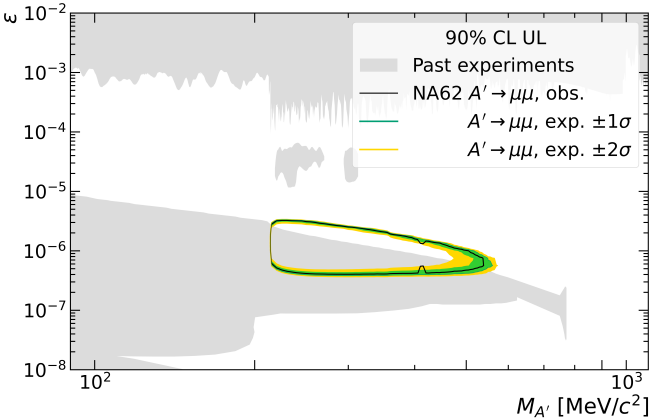


Figure: Final result with upper limit @90% CL[3].

[4]Search for dark photon decays to $\mu^+\mu^-$ at NA62. NA62 Collaboration. [2303.08666]

Search for exotic (pseudo)scalar

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

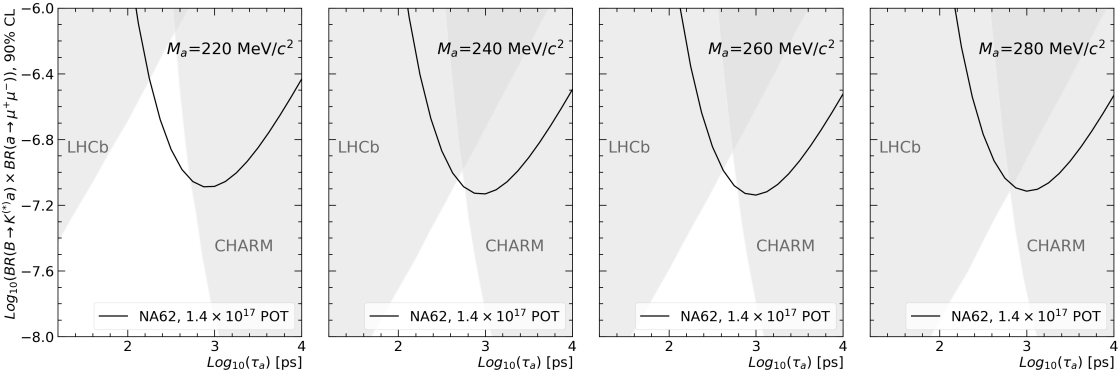


Figure: Resulting exclusion @90% CL for (pseudo)scalar a with mass M_a and lifetime τ_a.

Search for dark photons ($A' \to ee$)

Search strategy:

- e^+e^- vertex reconstructed in optimized FV;
- primary production vertex close to TAX.

Event selection:

- good quality tracks with timing in coincidence with each other and the trigger
- optimized particle ID with LKr and MUV3
- no in-time activity in LAV and ANTI0
- extrapolation of di-lepton momentum to TAX - definition of signal region (SR) in terms of primary vertex location: $\mathrm{CDA_{TAX}}$ and z_{TAX}

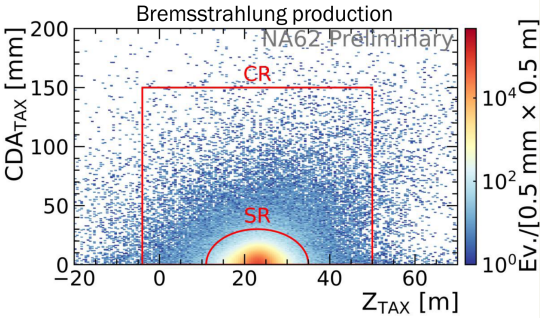


Figure: Signal MC and definition of control (CR) and signal regions (SR) for $A' \to ee$.

- SR:
  ellipse centered at $z_{\mathrm{TAX}} = 23$ m, $\mathrm{CDA_{TAX}} = 0$;
- both SR and CR kept masked during the analysis

Search for dark photons ($A' \to ee$)

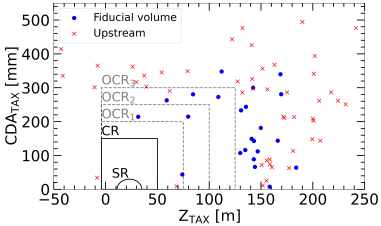


Figure: Data no LAV/ANTI0, CR/SR closed.

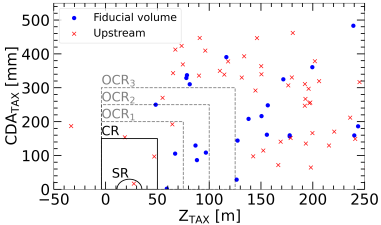


Figure: MC no LAV/ANTI0, CR/SR open.

Condition	$N_{\text{exp}} \pm \delta N_{\text{exp}}$	$1-\eta$
e^+e^- PID	59.9 ± 6.7	–
e^+e^- PID, LAV & ANTI0	0.72 ± 0.72	$0.012^{+0.020}_{-0.008}$
e^+e^- CR	0.51 ± 0.51	$0.008^{+0.018}_{-0.006}$
e^+e^- SR	0.47 ± 0.47	$0.008^{+0.018}_{-0.006}$

Expected number of events in CR and SR:

- $N_{\text{bkg}}^{\text{CR}} = 0.0097^{+0.049}_{-0.009}$ 90%CL
- $N_{\text{bkg}}^{\text{SR}} = 0.0094^{+0.049}_{-0.009}$ 90%CL

Search for dark photons ($A' \to \ell\ell$)

0 events observed in CR and SR:

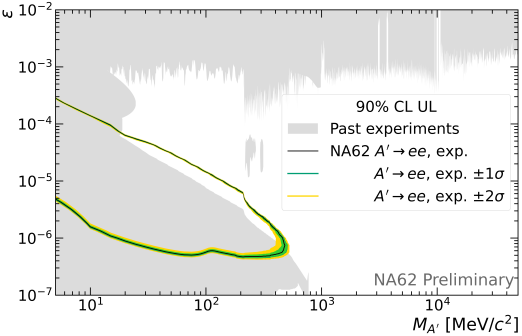


Figure: Final result with upper limit @90% CL.

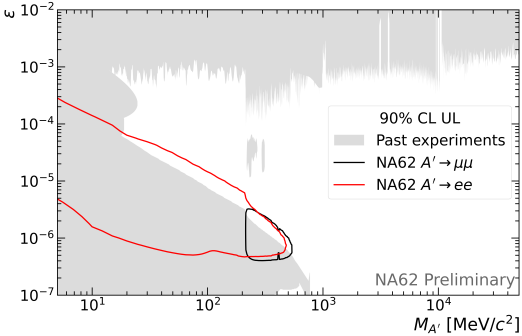


Figure: Overlay of upper limits @90% CL.

Statistical combination of $A' \to ee$ and $A' \to \mu\mu$ **in progress**

Search for Axion-like particles (ALP)

Phenomenological prospects (with 1.4×10^{17} POT) for ALPs coupled to SM gauge bosons:

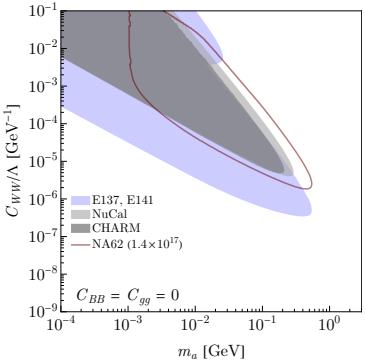


Figure: NA62 sensitivity (compared to past BD) from $a \to 2\gamma$ search for ALPs with C_{WW} coupling-only[4].

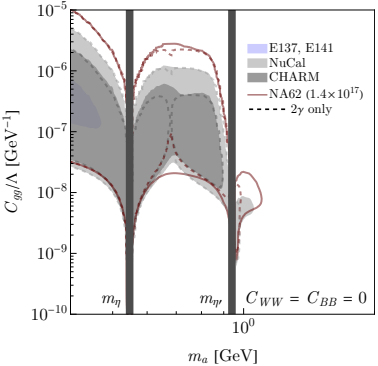


Figure: NA62 sensitivity from $a \to$ hadrons and $a \to 2\gamma$ search for ALPs with C_{GG} coupling-only[4].

[5] ALPINIST: Axion-Like Particles In Numerous Interactions Simulated and Tabulated. JJ, B. Döbrich, F. Ertas, F. Kahlhoefer, T. Spadaro, *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 searches for NP Particles
- A cut-based counting experiment blind analysis to search for $A' \to \ell^+\ell^-$ has been performed on the data collected in 2021 exploring new region of parameter space;
- Analyses of ALP decays to $\gamma\gamma$ and hadrons are in progress;
- Data-taking ongoing with expected 10^{18} POT in beam-dump mode by 2025 with interesting perspectives on dark photons, ALPs, dark scalars and HNLs.

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Thank you for your attention!

Backup slides

Search for $A' \to \mu\mu$ - 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 $\to$ 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 $A' \to \mu\mu$ - backgrounds details

ΔT of the tracks suggests two types of background mechanisms

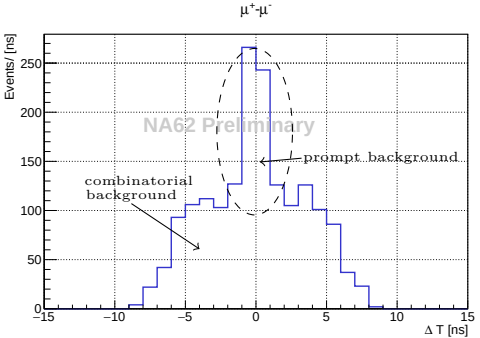


Figure: ΔT before LAV veto is applied (CR, SR masked).

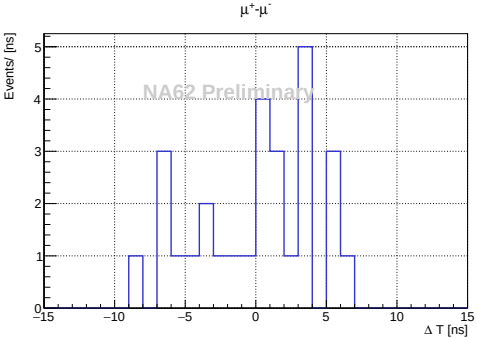
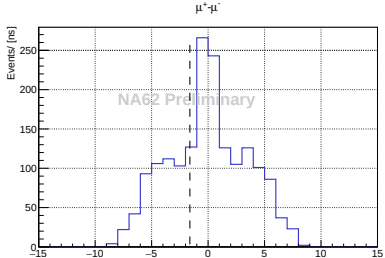
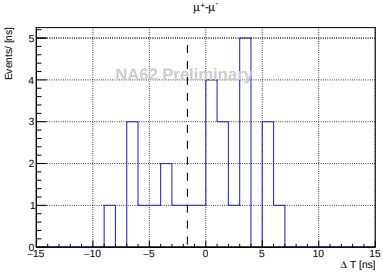


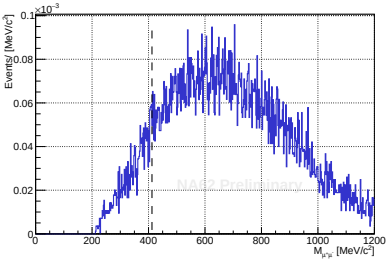
Figure: ΔT after full selection (CR, SR masked).

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

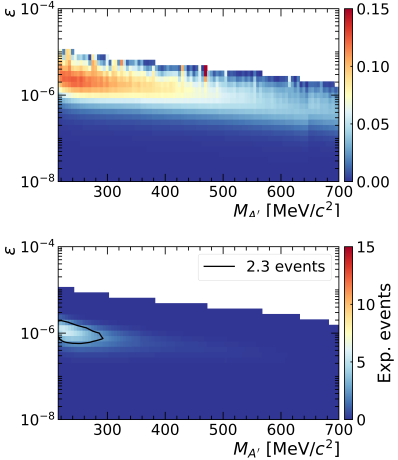




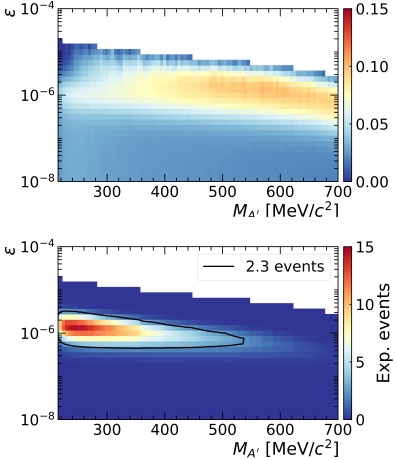


Search for $A' \to \mu\mu$ - selection efficiency and signal yield

Meson-mediated production:



Bremsstrahlung production:



Search for $A' \to ee$ - background details

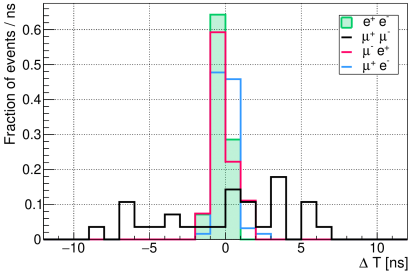
Combinatorial:

- Same technique as for $\mu\mu$ - negligible: $N_{\text{exp}} < 9 \times 10^{-4}$

Prompt:

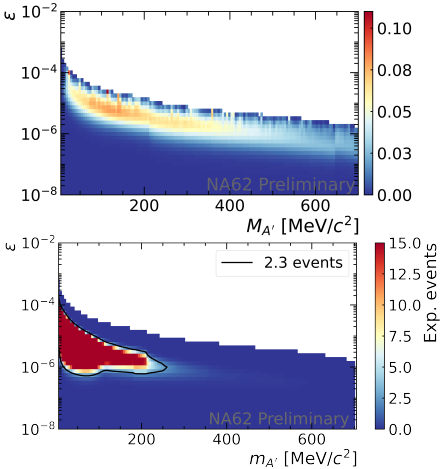
- Dominating for ee. Expected number of events estimated using rejection factors η for LAV, ANTI0, CR, SR obtained from dedicated MC.

Background before LAV veto (SR and CR masked)



Search for $A' \to ee$ - selection efficiency and signal yield

Meson-mediated production:



Bremsstrahlung production: