First NA62 search for long-lived new physics particle hadronic decays

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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, LF&NV, etc.);

See talks by A.T. Akmete and R. Fiorenza, 18/7

➔ Sensitive to low masses at MeV - GeV scale and low couplings accessible (large statistics)

➔ Dark Sector (SM-DM) portals typically probed:

NP particle	type	SM portal (dim ≤ 5)	PBC	Decay channels (m ≲ 1GeV)	
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 Higgs (S)	scalar	$(\mu S + \lambda S^2) H^\dagger H$	4 - 5	$\ell\ell$	$2\pi, 4\pi, 2K$
axion/ALP (a)	pseudoscalar	$(C_{VV}/\Lambda)\, a V_{\mu\nu}\tilde{V}^{\mu\nu}$ $(C_{ff}/\Lambda)\, \partial_\mu a \bar{f}\gamma^\mu\gamma^5 f$	9, 11 10	$\gamma\gamma, \ell\ell$	$2\pi\gamma, 3\pi, 4\pi, 2\pi\eta, 2K\pi$
dark Photon (A'_μ)	vector	$-(\varepsilon/2\cos\theta_W)\, F'_{\mu\nu} B^{\mu\nu}$	1 - 2	$\ell\ell$	$2\pi, 3\pi, 4\pi, 2K, 2K\pi$

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Two type modes for NP particle searches at NA62 Experiment:

➔ **Beam-Dump mode**: Search NP particles into the Final States composed of SM particles;

➔ **K mode**: Search NP particles in SM particle decays.

The NA62 Experiment

- Fixed-target experiment @ CERN North Area (SPS)
- Main goal is to measure ultra-rare $K^+ \to \pi^+ \nu \bar{\nu}$ decay with high precision;
  the experiment additionally covers a broad Kaon and Beam-Dump physics program.
- Two data-taking period Run-I (2016-2018) and Run-II (2021-2025); Run-I paper: *JHEP 06 (2021) 093*; Run-II is ongoing!

The NA62 Experiment in kaon mode

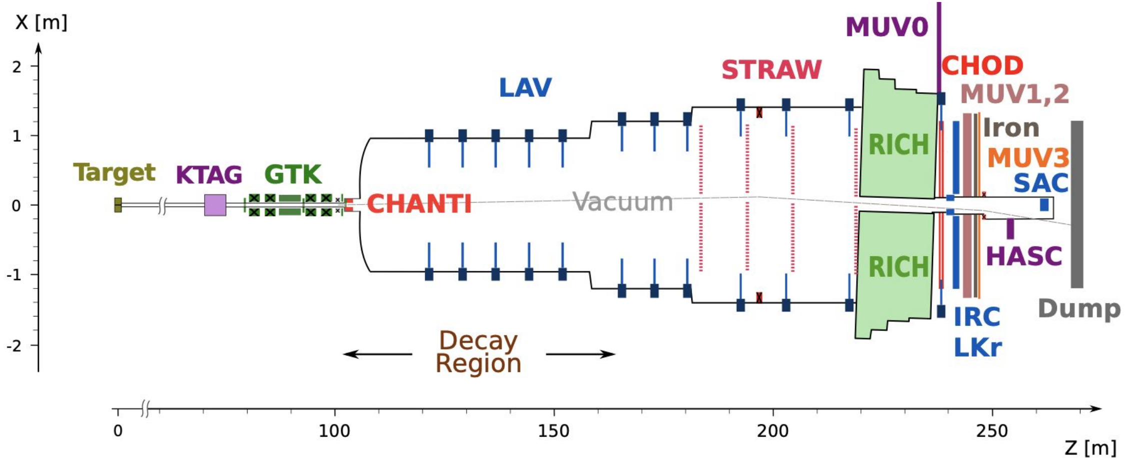
➔ 400 GeV/c primary p^+ beam collides *Be* target with ~10^{12} proton/s on spill; 75 GeV/c secondary beam (~6% of K^+) selected using **TAX** collimators.

➔ K^+ (~5MHz) decay-in-flight in 60 m long fiducial volume (FV)[1];

➔ 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**;

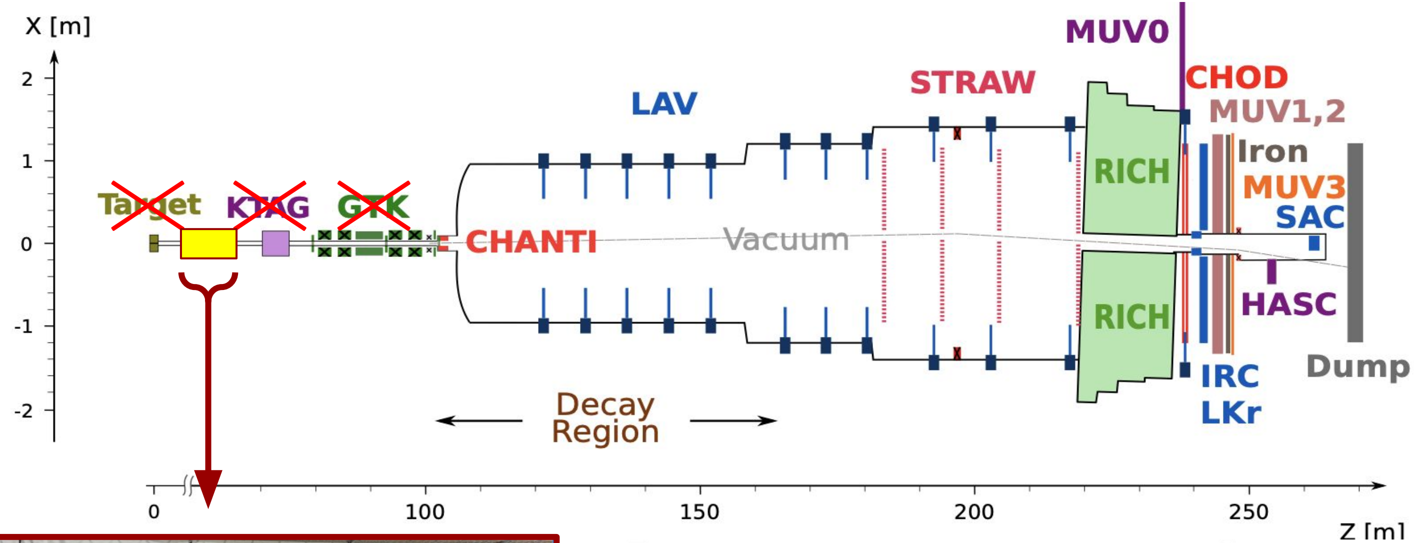
➔ Photons can be vetoed by **LKr** and at large angles by 12 **LAV** stations or by **SAC**/**IRC** at small angles;

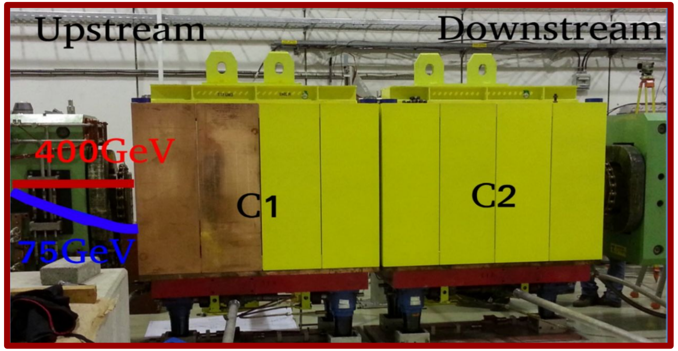


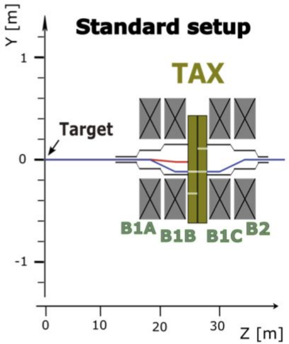
➔ Overall experimental time resolution reaches $\mathcal{O}$(100) ps

[1] The Beam and Detector of NA62 Experiment at CERN [*JINST* 12 (2017) 05, P05025].

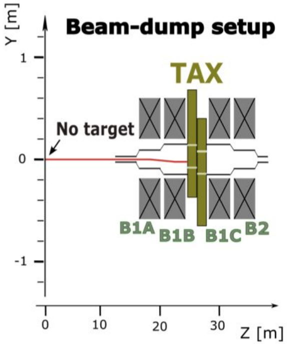
The NA62 Experiment in beam-dump mode - I -







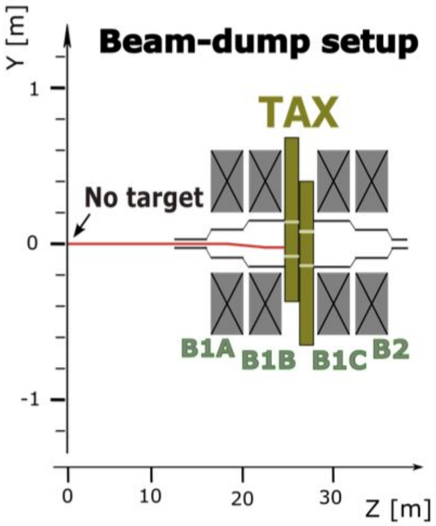
TAX closed

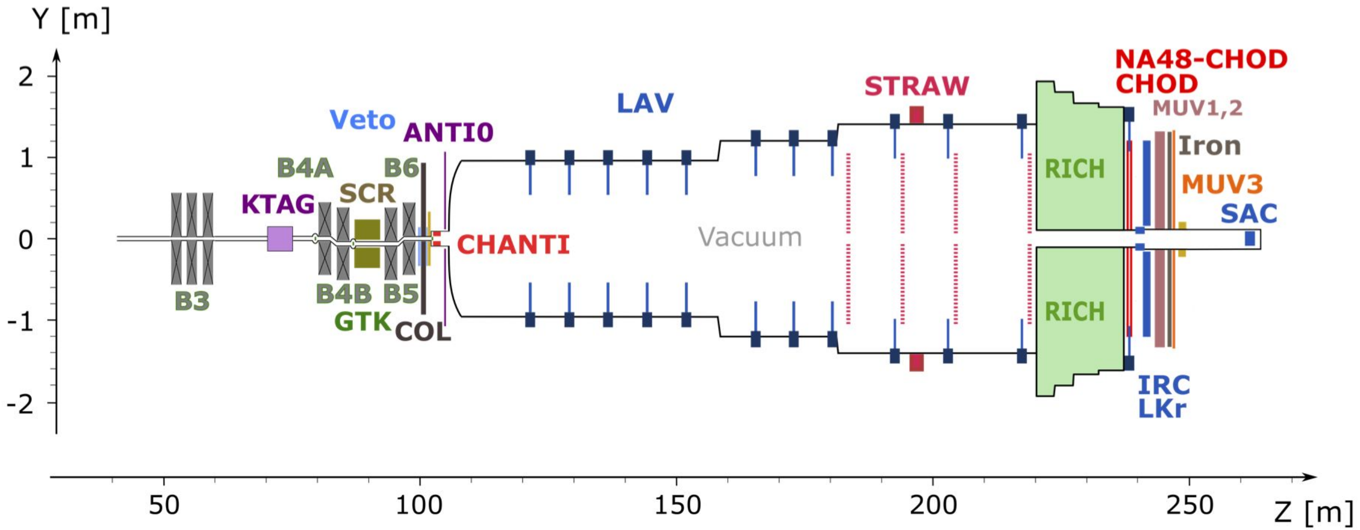


The NA62 Experiment in beam-dump mode - II -

➔ reduced background from penetrating particles through improved sweeping from magnets downstream of the TAX;

➔ increase proton beam intensity ~1.5xNominal;





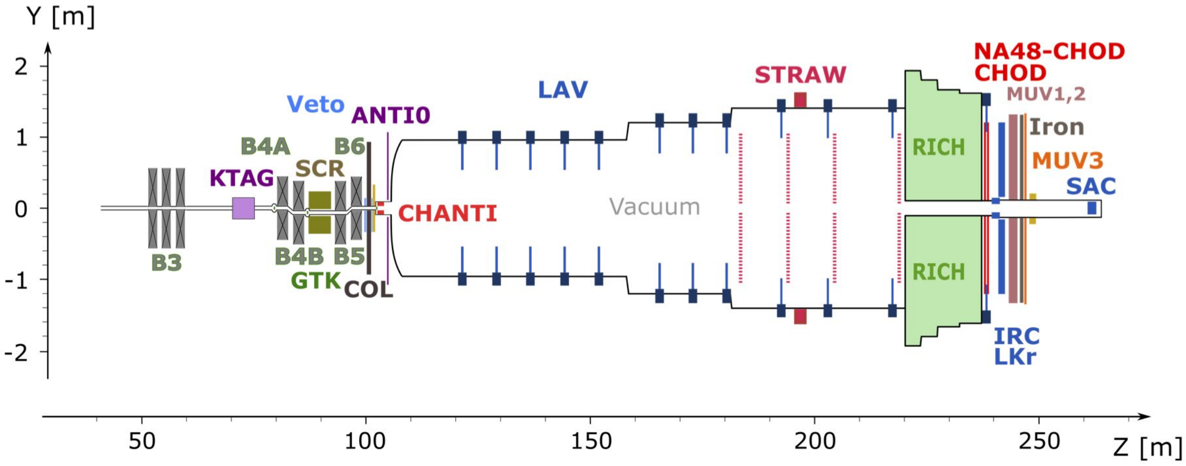
The NA62 Experiment in beam-dump mode - III -

➔ trigger lines for charged particles;

- Q1/20: $n_{hits} \geq 1$ in CHOD;
- H2: $n_{hits} \geq 2$ in-time in CHOD;

➔ $N_{POT} = (1.4 \pm 0.28) \times 10^{17}$ Protons On Target (POT) collected in 2021; target is $N_{POT} \cong 10^{18}$ during Run-II;

➔ *NP* searches into ***ee*** and ***μμ***, two lepton final states using NA62 2021 BD data published[2]; **today let's look into hadronic decays**



[2] NA62 Collaboration [*JHEP 09 (2023) 035*].

The Signal Monte Carlo in the dark side

- ➔ Various possibilities for exotic particle X: dark photon (DP), dark scalar (DS), axion-like particle (ALP), etc.;
- ➔ Various production mechanism and final states:
  - ◆ DP: Bremsstrahlung, $P \to A'\gamma$, $V \to A'P$
    $V = \{\rho, \omega, \phi\}$
  - ◆ DS: $B^{\pm,0} \to K^{\pm,0,(*)}S$
  - ◆ ALP: Primakoff (on-, off-shell); mixing with
    $P = \{\pi^0, \eta, \eta'\}$, $B^{\pm,0} \to K^{\pm,0,(*)}a$

model	production channels	decay channels
DP	Bremsstrahlung	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
		K^+K^-
		$K^+K^-\pi^0$
	light meson decay	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
DS	B meson decay	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0\pi^0$
		K^+K^-
ALP	Primakoff mixing $(\pi^0/\eta/\eta')$ B meson decay	$\pi^+\pi^-\gamma$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
		$\pi^+\pi^-\eta$
		$K^+K^-\pi^0$

- ➔ A total of 36 production and decay channel combinations studied.

What is the next? Maybe in another conference :)

The Analysis Strategy

Selection criteria for two charged hadrons:

- ➔ 2 good quality tracks in coincidence with each other and the trigger
- ➔ Selecting hadrons with PID by LKr and MUV1-3; K^+ tagging by RICH
- ➔ No in-time activity in LAV, SAV and ANTI0
- ➔ Decay vertex reconstructed in fiducial volume.

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Search strategy:

- ➔ Using time and opening angle, reconstruct π^0, γ, and η by checking neutral LKr clusters.
- ➔ Exotic particle reconstructed from the decay vertex and backward-extrapolation to the TAX and definition of signal region (SR) in terms of primary vertex: CDA_{TAX} vs Z_{TAX} .

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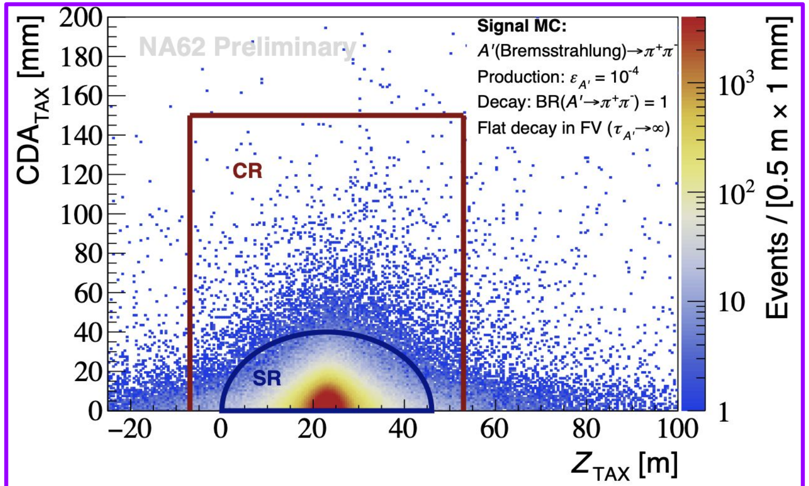

$A' \rightarrow \pi^+\pi^-$ signal MC and definition of signal and control region

- ➔ **SR**: { CDA_{TAX}, Z_{TAX}} = {0 mm, 23.07 m} with semi-axes 40 mm on CDA_{TAX} and 23 m on Z_{TAX}.
- ➔ **CR: CDA_{TAX} < 150 mm and -7 m < Z_{TAX} < 53 m**
- ➔ **During the analysis, both SR and CR were kept masked.**

The Background overview

Just 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 in FV, not vetoed by **ANTI0** but vetoed by **LAV**

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Background estimation with MC:

➔ **Combinatorial & neutrino induced BKG:** negligible contributions

➔ **Prompt BKG:** μ-halo inelastic interactions with negligible contributions

➔ **Upstream BKG:** Consisting of particles collected by the GTK achromat

The Background overview - Prompt -

- Estimation based on data-driven backward MC of μ-halo, and correct kinematics through unfolding
- MC statistics correspond to $N_{POT} = 1.53 \times 10^{17} >$ data statistics
- $\pi\pi$ **outside CR**, with ANTI0 acceptance, but no vetoes applied:
  - $N_{exp} = 1.8 \pm 1.4$ vs $N_{obs} = 1$; with vertex **upstream** of FV;
  - $N_{exp} = 0.20 \pm 0.15$ vs $N_{obs} = 1$; with vertex in FV;

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

The Background overview - Upstream - I -

In the control samples (no veto by ANTI0), 3 subcomponents observed in the Z_{vtx} - $m_{\pi\pi}$ plane;

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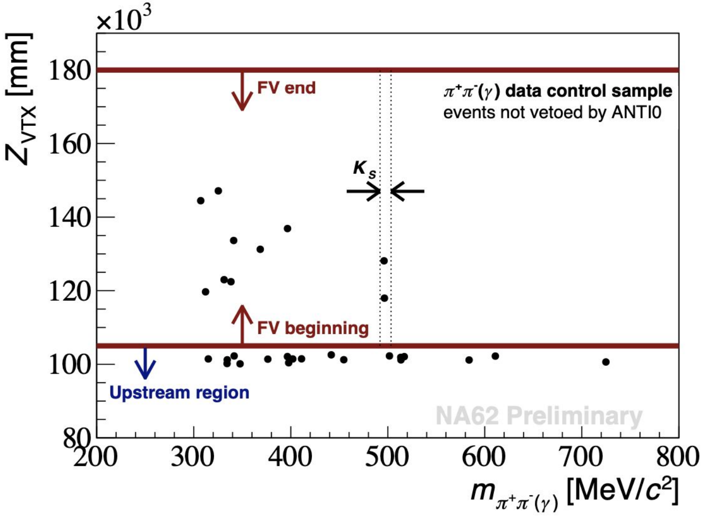

Figure: Events not in ANTI0 acceptance or not vetoed by ANTI0 in Z_{VTX} – invariant mass plane. Solid lines indicate the FV. Dashed lines indicate the K_S 3σ mass window.

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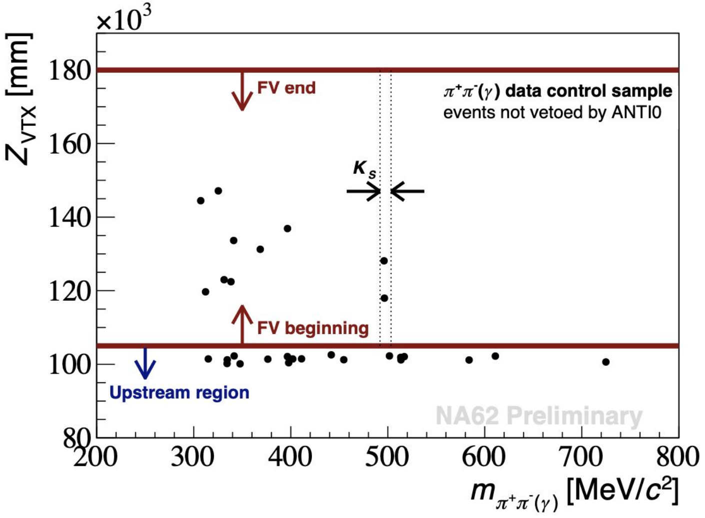
In the control samples (no veto by ANTI0), 3 subcomponents observed in the Z_{vtx} - $m_{\pi\pi}$ plane;

- ➔ 19 upstream interactions;
- ➔ 2 $K_S \to \pi^+\pi^-$;
- ➔ 8 $K^+ \to \pi^+\pi^+\pi^-$



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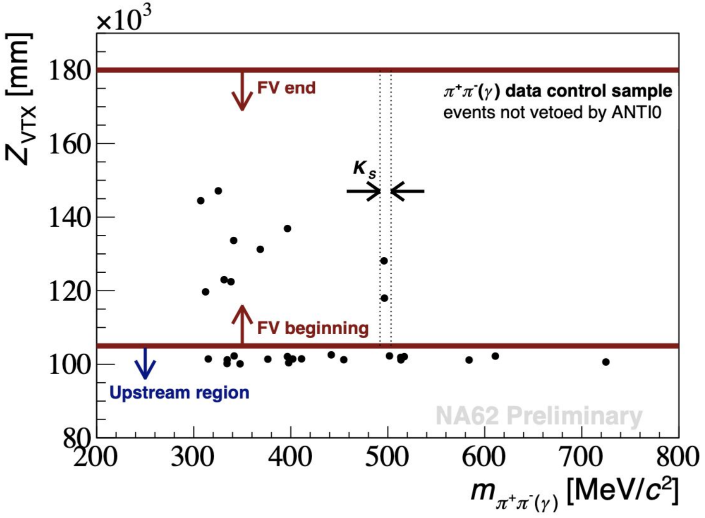
  6 identified as $\pi^+\pi^-$ and 2 $\pi^+\pi^-\gamma$



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A dedicated MC for K$^+$-induced BKG simulated using selected K$^+$ tracks which are forced to decay as $K^+ \rightarrow \pi^+\pi^+\pi^-$ in the FV

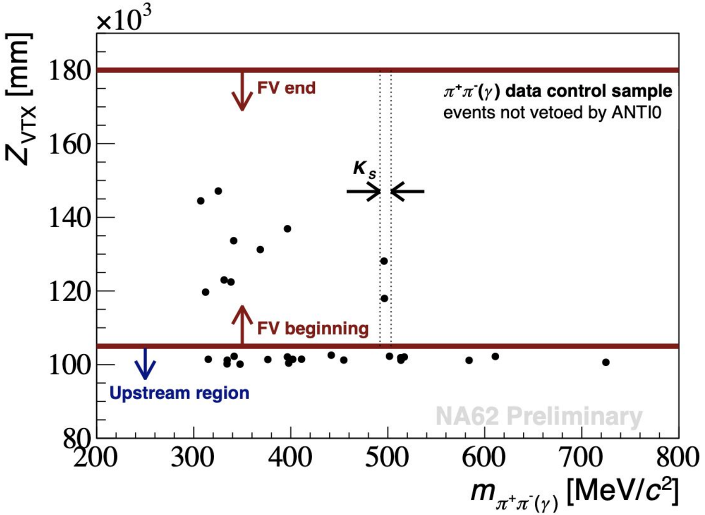


Figure: Events not in ANTI0 acceptance or not vetoed by ANTI0 in Z_{VTX} – invariant mass plane. Solid lines indicate the FV. Dashed lines indicate the K_S 3σ mass window.

The Background overview - Upstream - II -

➔ Outside CR/SR **before** ANTI0 acc.; N_{exp}:

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

➔ Outside CR/SR **after** ANTI0 acc.; N_{exp}:

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

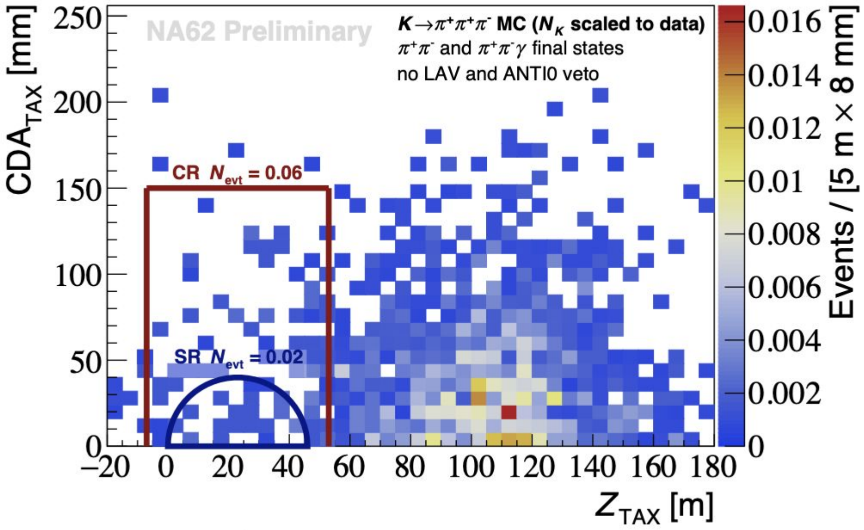


Figure: N_{exp} from $K_{3\pi}$ in the primary vertex Z and CDA plane before applying ANTI0 acceptance.

➔ Inside CR & SR; N_{exp}:

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

➔ Additionally, simulations for K_{e4} & $K_{\mu 4}$ decays performed; negligible contributions

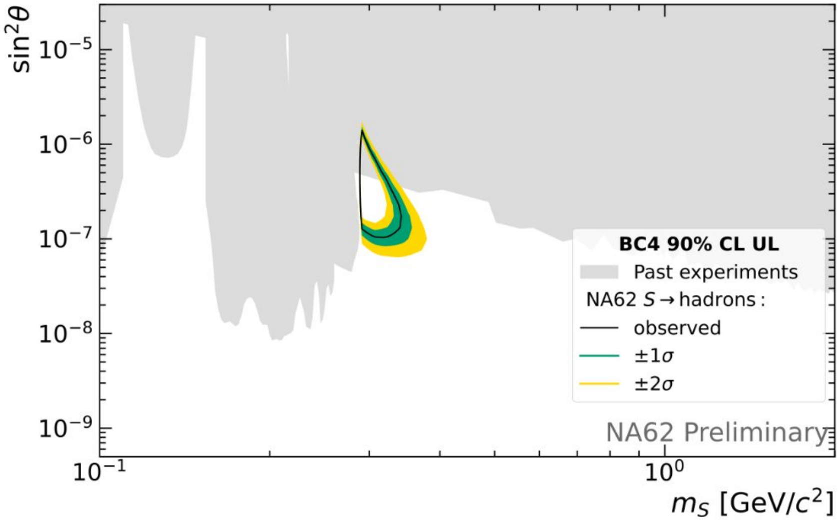
The Background overview - Total -

Table: Expected number of background events (68% CL) in CR and SR. Minimum number of observed events $N_{\rm obs}$ for a background-only p-value above 5σ in SR and SR+CR (global significance, flat background in $m_{\rm inv}$ assumed).

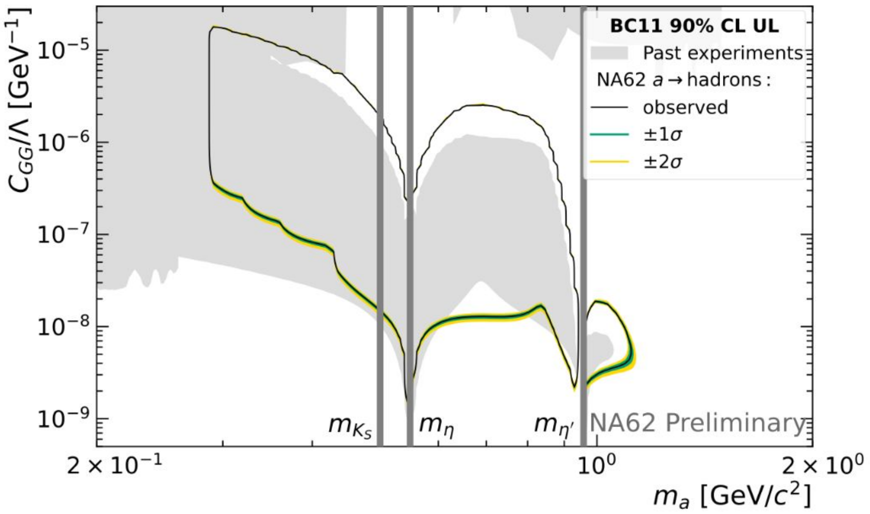
Channel	$N_{\rm exp,CR} \pm \delta N_{\rm exp,CR}$	$N_{\rm exp,SR} \pm \delta N_{\rm exp,SR}$	$N^{p>5\sigma}_{\rm obs,SR}$	$N^{p>5\sigma}_{\rm obs,SR+CR}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$	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
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$	1	1
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

The Preliminary Results

BC4: Dark Scalar



BC11: Axion-Like Particle



- ➔ 0 events observed in all signal and control regions.
- ➔ For the combination of results from individual production and decay channels, the ALPINIST[3] has been used.
- ➔ No standalone 90% CL exclusion for BC1: Dark Photon.

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

The Conclusion

- Preliminary result from the NA62 experiment in beam-dump mode on the search for an exotic particle's production and decay have been presented:
  - Conducted a blind analysis until the opening of control and signal regions.
  - **No evidence of new physics signals**
  - NA62 set 90% CL upper limit and new regions of dark scalar and axion-like particle parameter spaces have been excluded.

- Search for exotic particles decaying into semi-leptonic or di-gamma final states are in progress.
- Ongoing data-taking: new sample, ~ 2.4×10^{17} POT, already collected in 2023 and 10^{18} POT in beam-dump mode expected by the LHC LS3 with interesting perspectives on the searches of dark photons, ALPs, dark scalars and HNLs.

Thank you for your attention

Backup

The Sensitivity

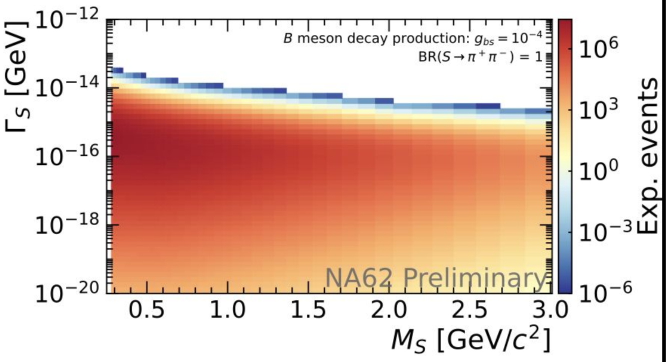
$X \to \pi^+\pi^-$; Model-Independent approach;

- ➔ $BR(X \to \pi^+\pi^-) = 1$;
- ➔ $N_{exp}(M_X, \Gamma_X) = N_{POT} \times \chi_{pp \to X}(C_{ref}) \times P_{rd} \times A_{acc} \times A_{trig}$

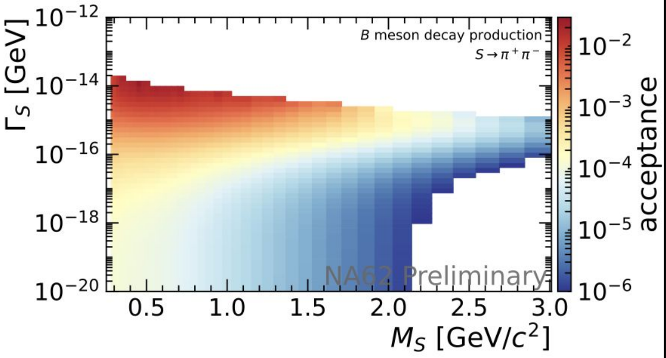
$\chi_{pp \to X}(C_{ref})$: X production probability for ref. coupling

P_{rd}: Probability to reach and decay in FV

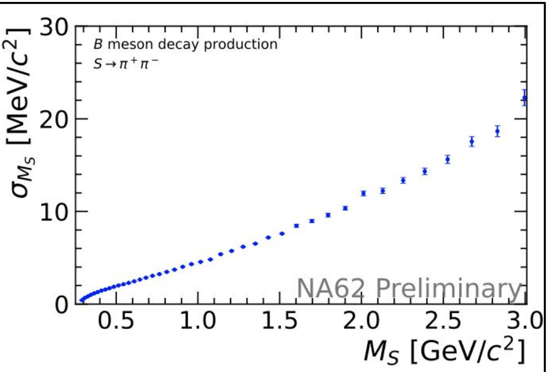
$A_{acc} \times A_{trig}$: Signal selection and trigger efficiency



Number of expected $S \to \pi^+\pi^-$ events after full selection where $g_{bs} = 10^{-4}$ and BR = 1



Acceptance of full selection for an exotic decay in the FV



Mass resolution of the reconstructed exotic

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

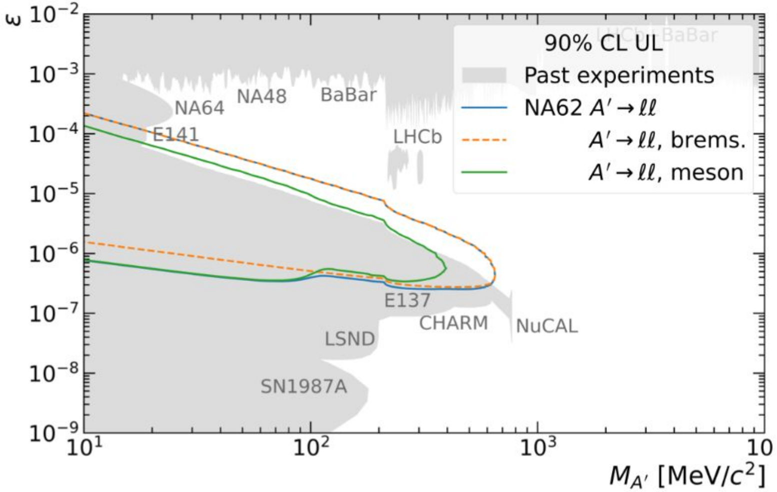


Figure: Sensitivity per production mechanism assuming 0 observed events in 1.4×10^{17} POT.

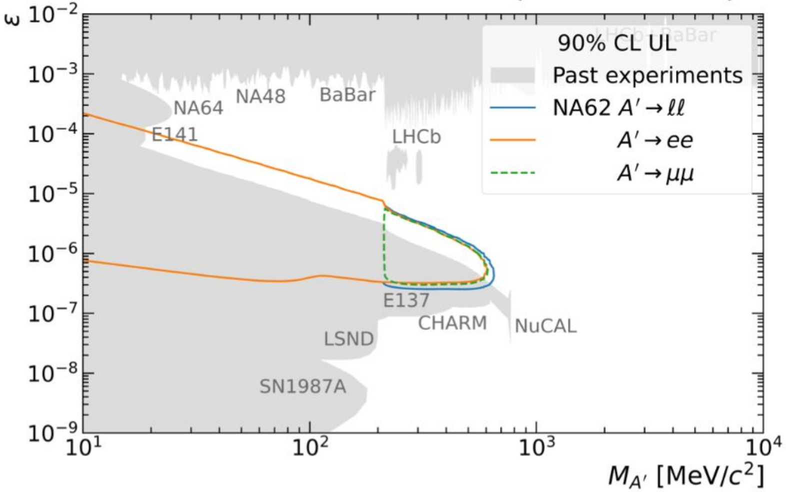


Figure: Sensitivity per decay mode assuming 0 observed events in 1.4×10^{17} POT.

The 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}

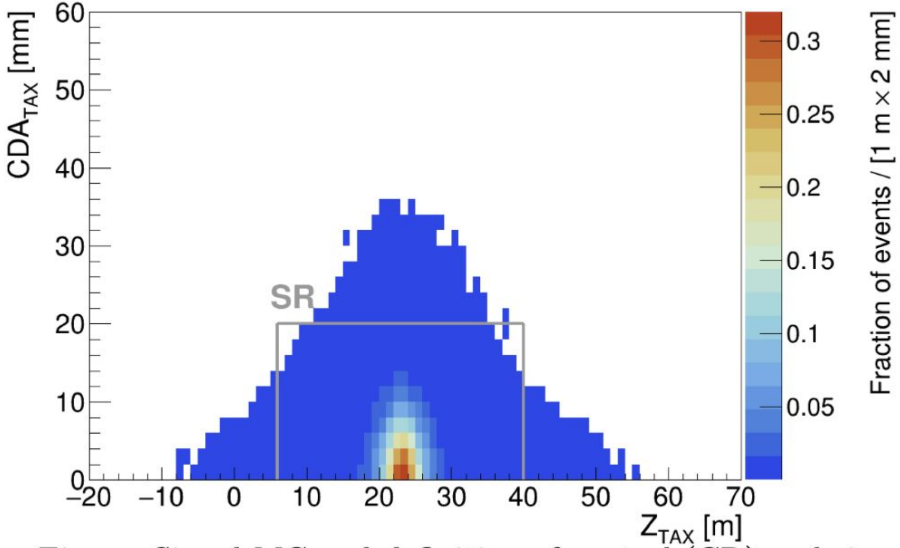


Figure: Signal MC and definition of control (CR) and signal regions (SR) for $A' \to \mu\mu$.

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

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

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

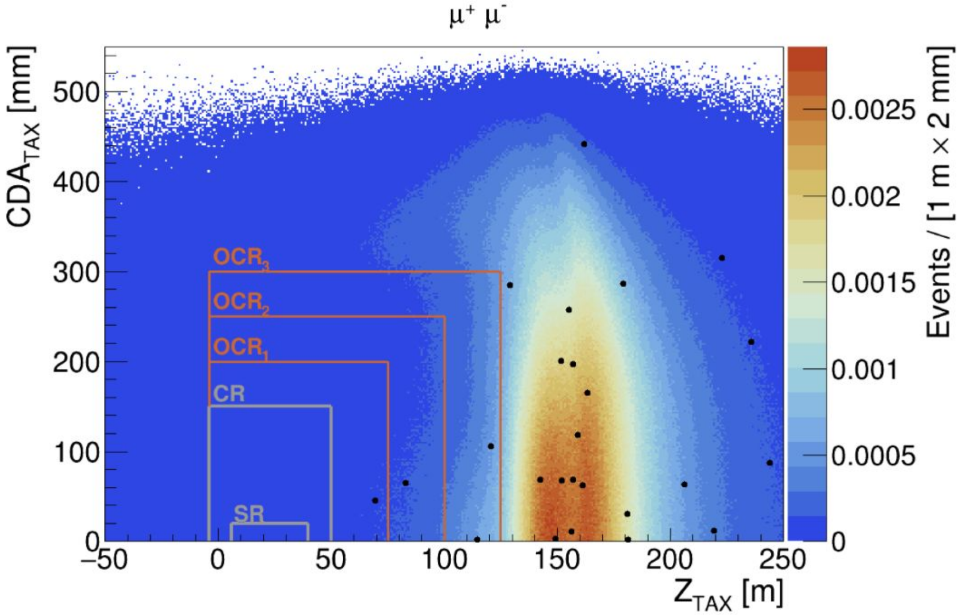


Figure: Data-MC comparison, SR closed.

	$N_{\text{exp}} \pm \delta N_{\text{exp}}$	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%

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

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

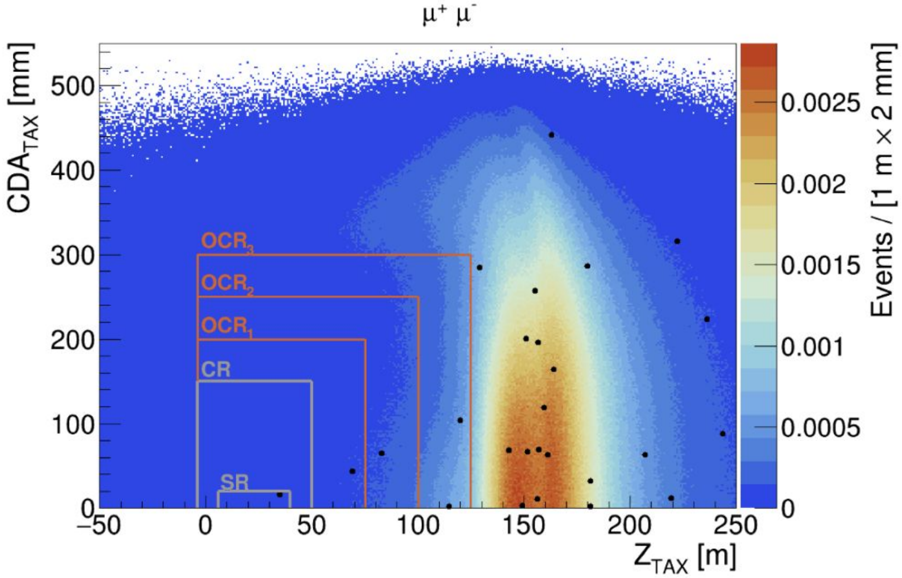


Figure: Data-MC comparison, CRs and SR open.

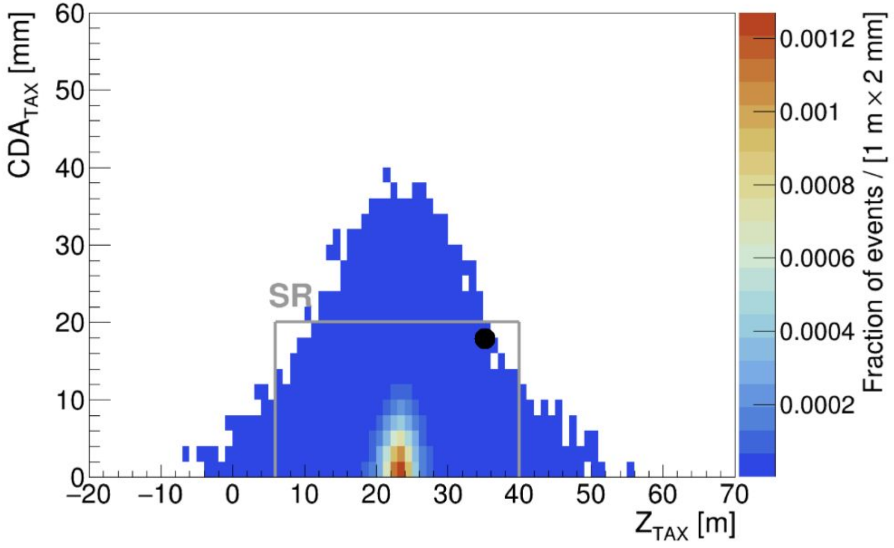


Figure: Signal MC - data: 1 event observed - counting experiment with 2.4σ significance. Signal shape not taken into account for the significance.

The Search for exotic (preudo)scalar

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

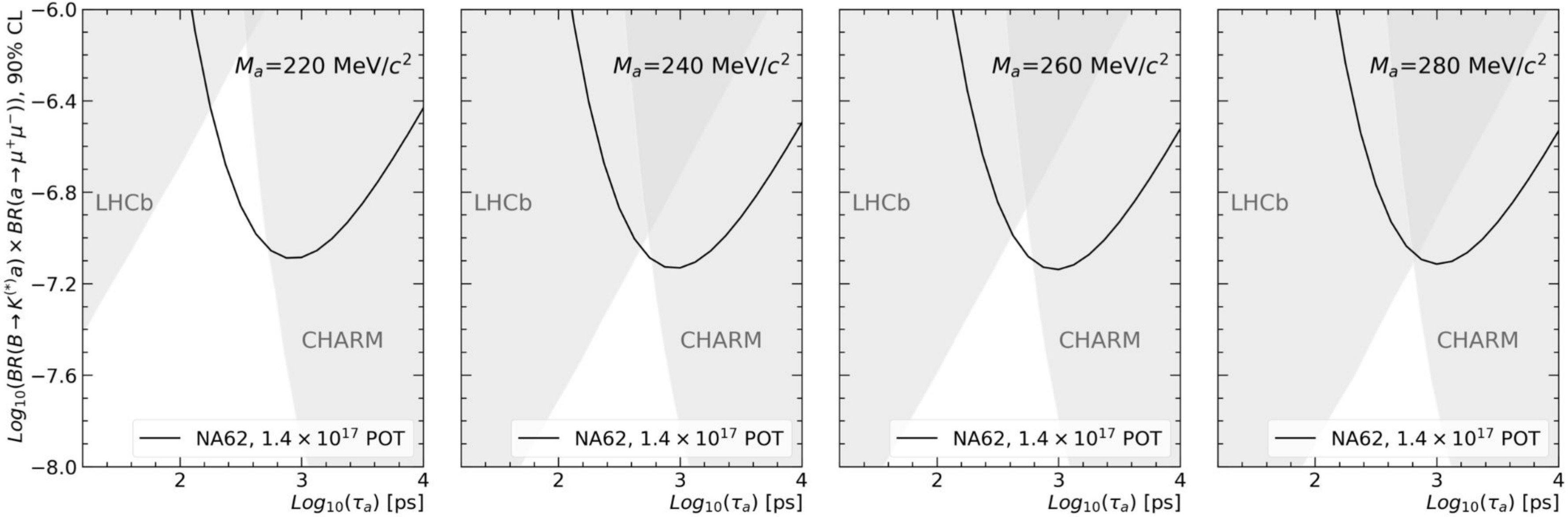


Figure: Resulting exclusion @90% CL for (pseudo)scalar a with mass M_a and lifetime τ_a.

The 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}

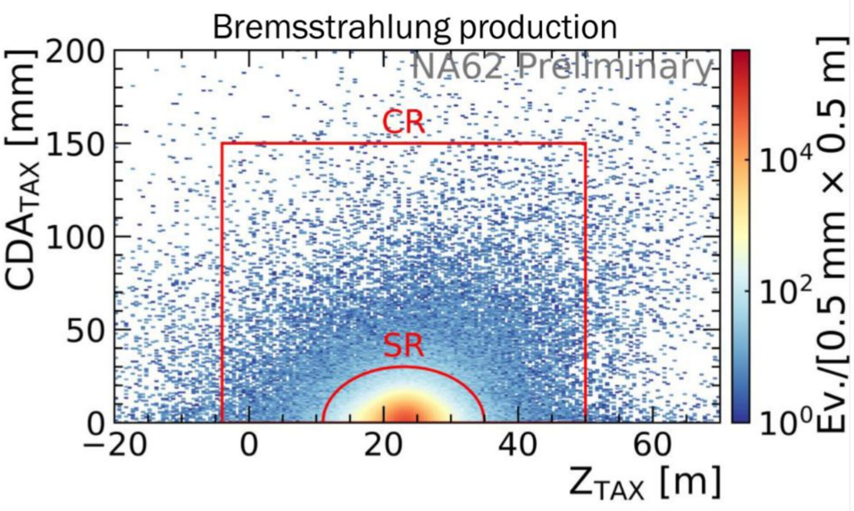


Figure: Signal MC and definition of control (CR) and signal regions (SR) for $A' \to ee$.

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

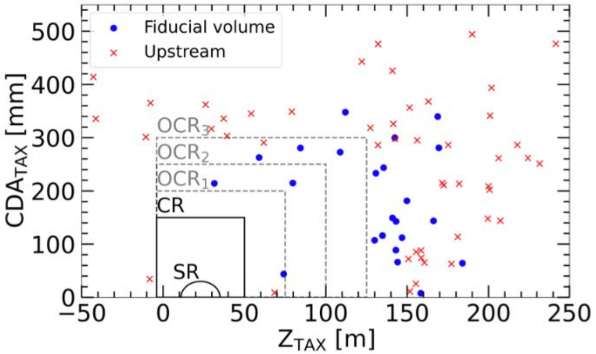


Figure: Data no LAV/ANTI0, CR/SR closed.

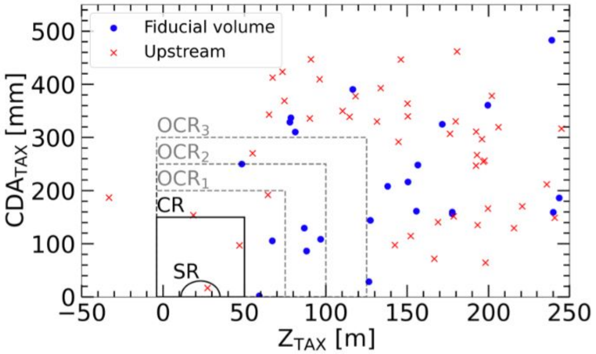


Figure: MC no LAV/ANTI0, CR/SR open.

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

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

0 events observed in CR and SR:

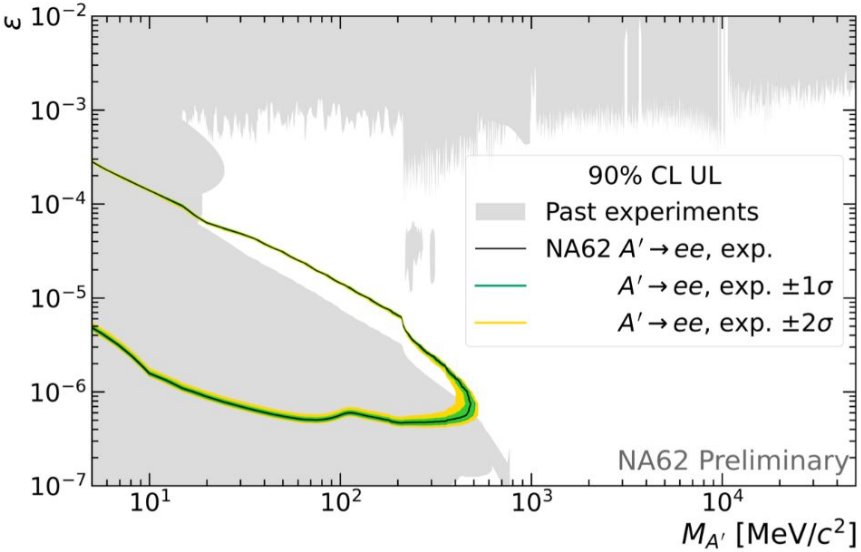


Figure: Final result with upper limit @90% CL.

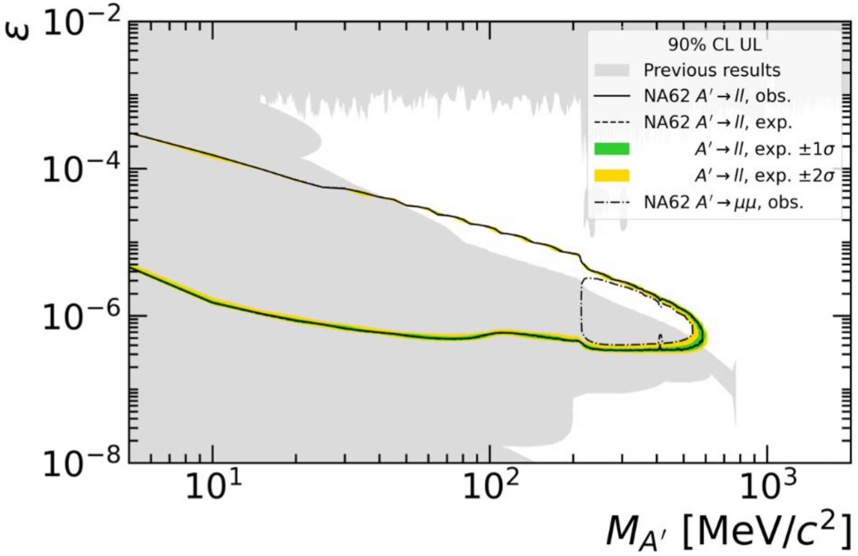


Figure: Resulting exclusion @90% CL from combined results of $\mu\mu$ and ee analyses.

The Search for dark photons ($A' \rightarrow \mu\mu$) - background -

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)

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

ΔT of the tracks suggests two types of background mechanisms

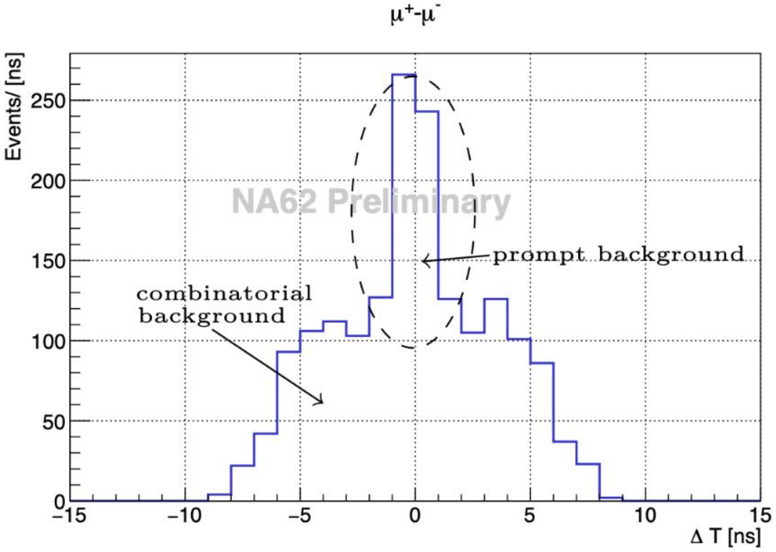


Figure: ΔT before LAV veto is applied (CR, SR masked).

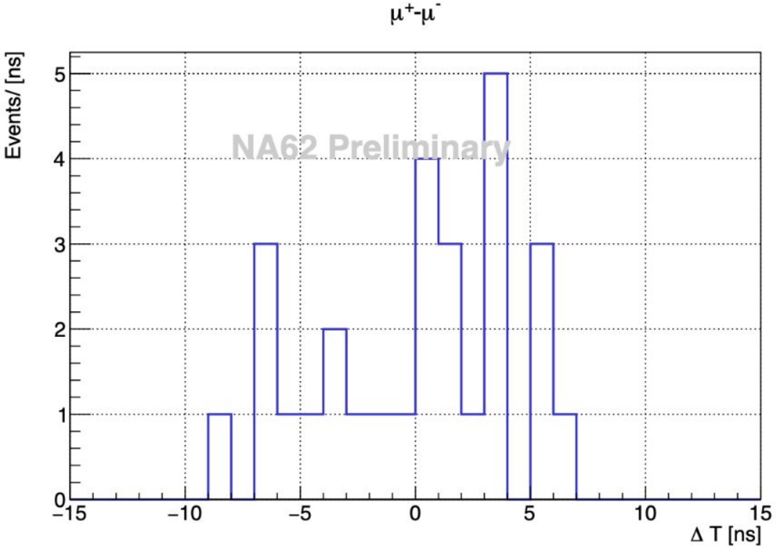
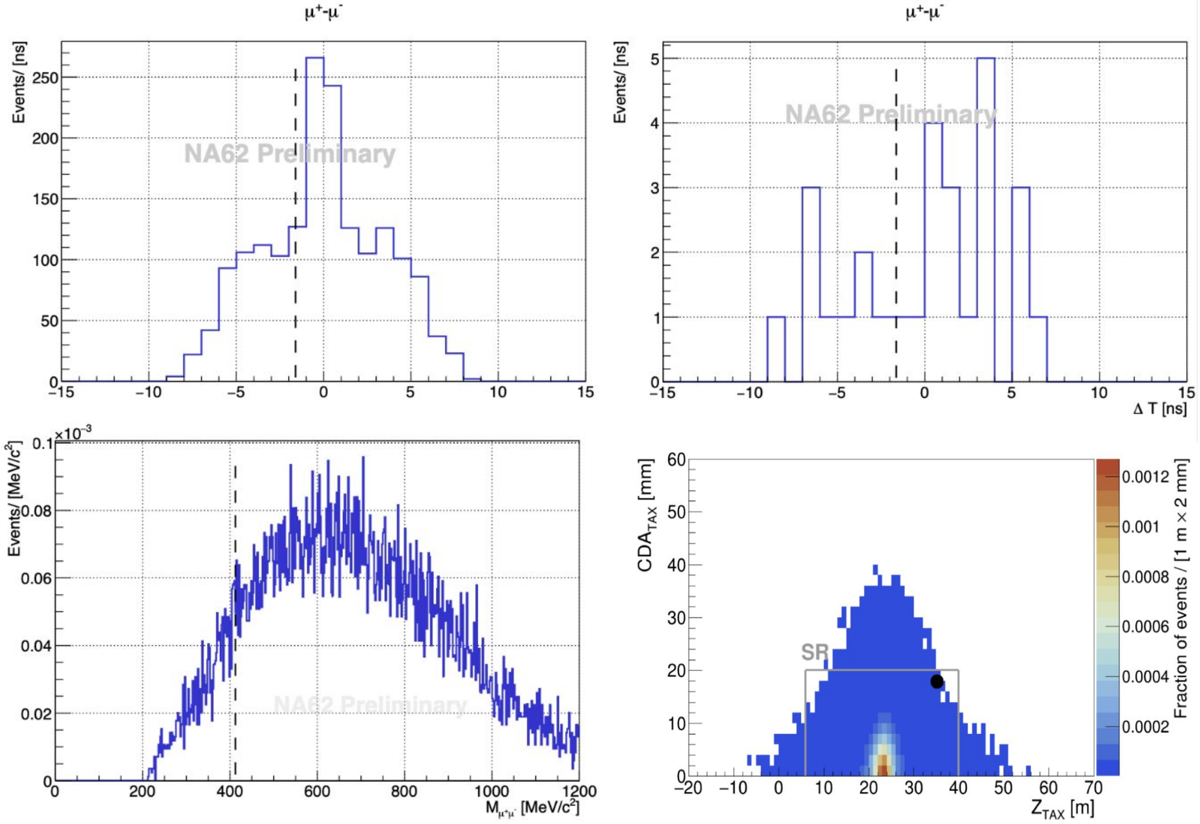


Figure: ΔT after full selection (CR, SR masked).

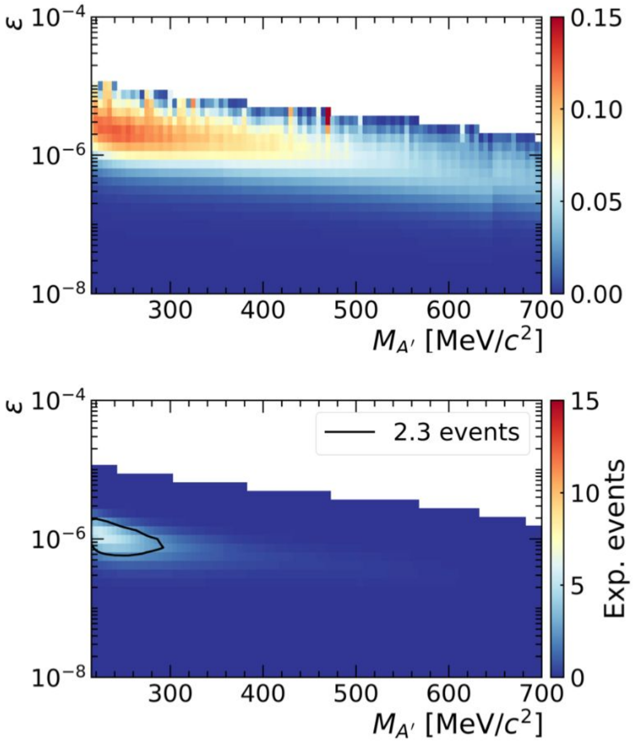
The Search for dark photons ($A' \to \mu\mu$) - observed event -

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

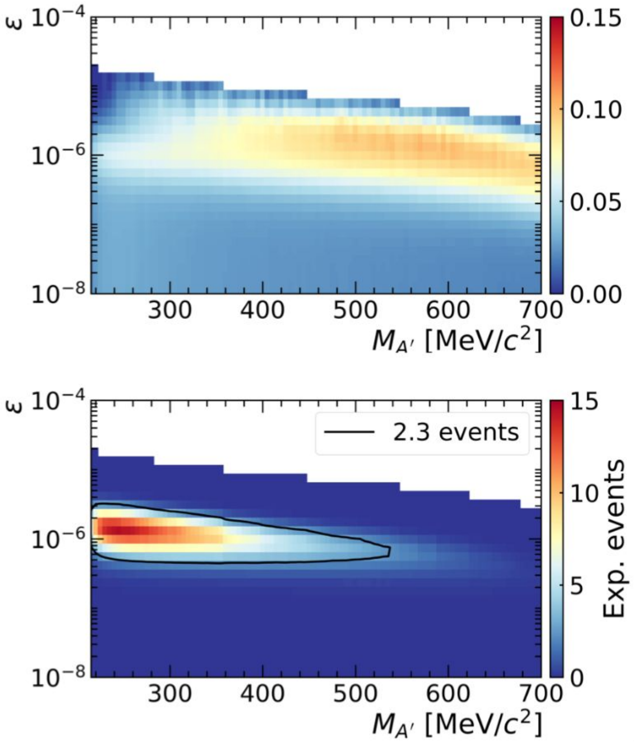


The Search for dark photons ($A' \to \mu\mu$) - selection efficiency & signal yield -

Meson-mediated production:

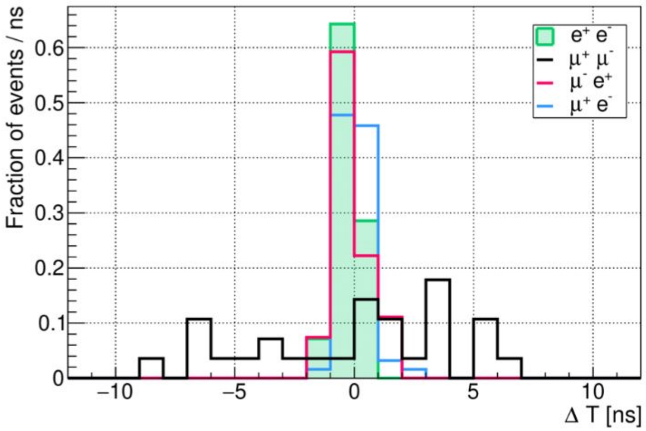


Bremsstrahlung production:



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

Background before LAV veto (SR and CR masked)



Combinatorial:

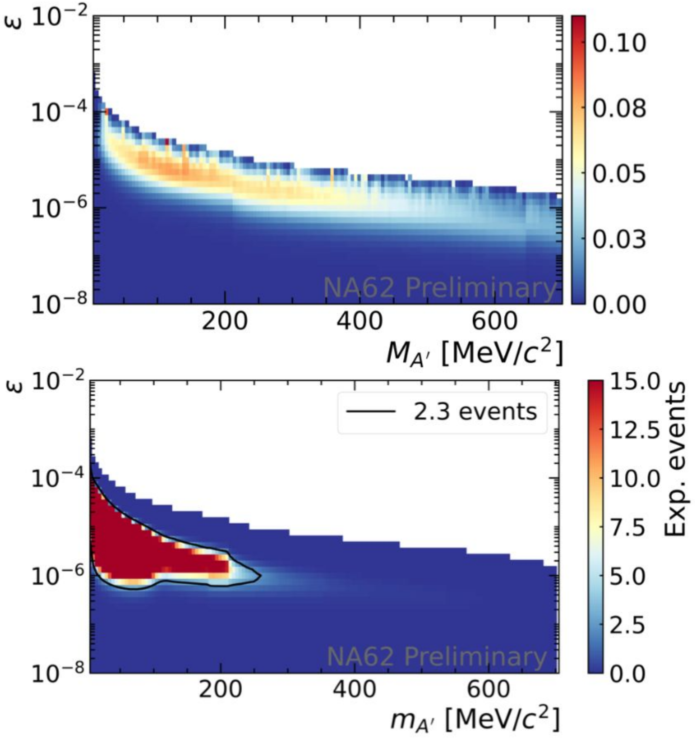
- Same technique as for $\mu\mu$ - negligible: $N_{\text{exp}} < 9 \times 10^{-4}$

Prompt:

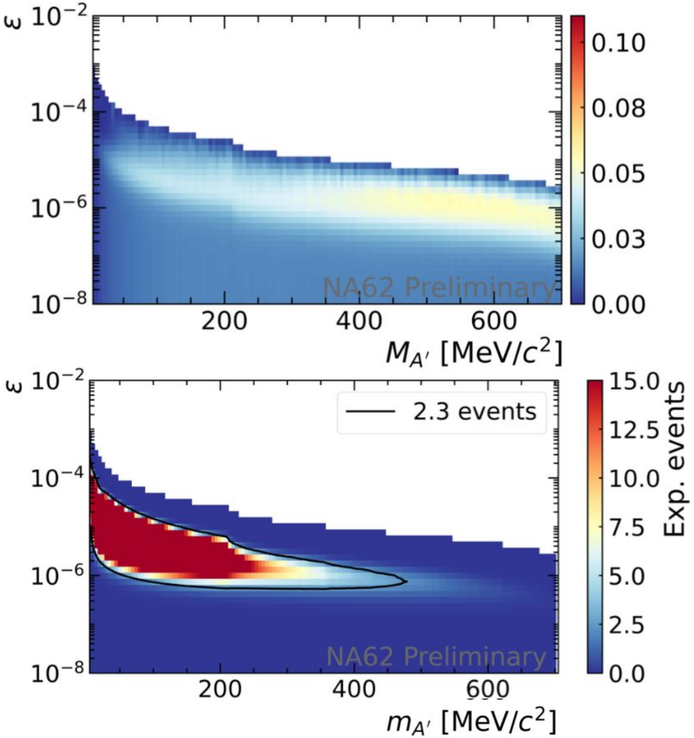
- Dominating for ee. Expected number of events estimated using rejection factors η for LAV, ANTI0, CR, SR obtained from dedicated MC.

The Search for dark photons ($A' \to ee$) - selection efficiency & signal yield -

Meson-mediated production:



Bremsstrahlung production:



The MC: DP(Brems) → $\pi^+\pi^-$

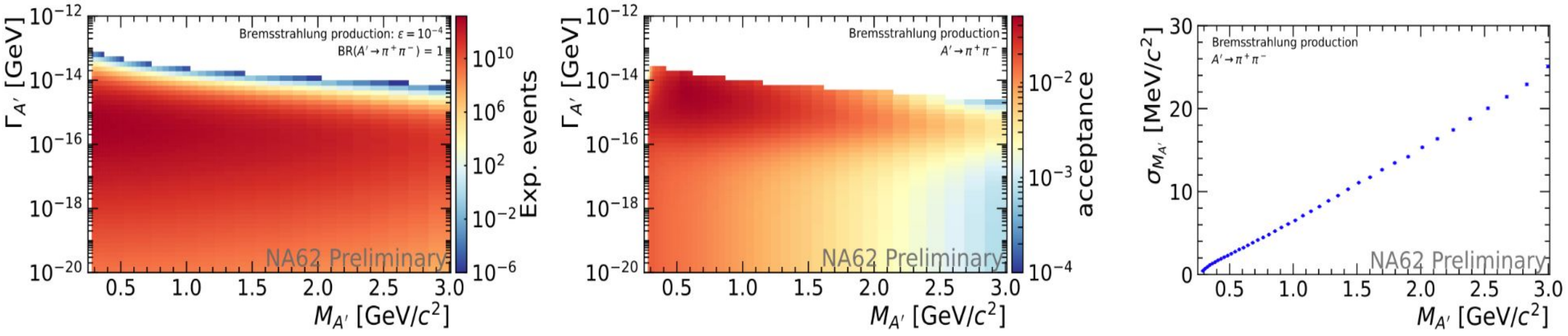


Figure: Left: expected yield after full selection, assuming $\epsilon = 10^{-4}$ and BR = 1. Center: acceptance for events that reached the FV and decayed therein. Right: Mass resolution of the reconstructed new-physics state.