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

19th Patras Workshop on Axions, WIMPs and WISPs

16-20 September 2024

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On Behalf of the NA62 Collaboration

# Axion/ALP Parameter Space

Mass
μeV to TeV

Excluded

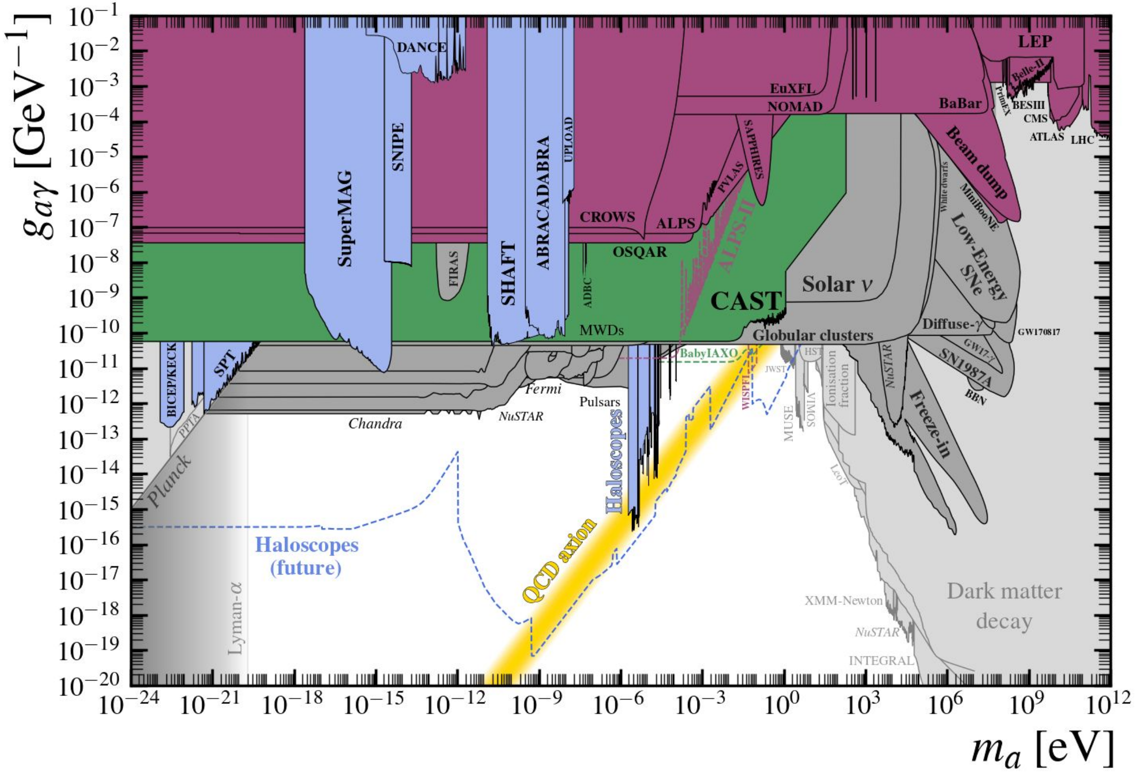
Interaction Strength

**LLPs from Weak-Scale Physics**
LHC

**LLPs from Light-Weight Physics**
Fixed-Target
B-Physics

**LLPs from Ultra-Light Physics**
RF, Laser

Ciaran O'Hare



# 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.);

➔ 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 ($m \lesssim$ 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 | $(C_{VV}/\Lambda)\, a V_{\mu\nu} \tilde{V}^{\mu\nu}$<br>$(C_{ff}/\Lambda)\, \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f$ | 9, 11<br>10 | $\gamma\gamma$, $\ell\ell$ | $2\pi\gamma$, $3\pi$, $4\pi$, $2\pi\eta$, $2K\pi$ |
| **dark Photon ($A'_\mu$)** | 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:

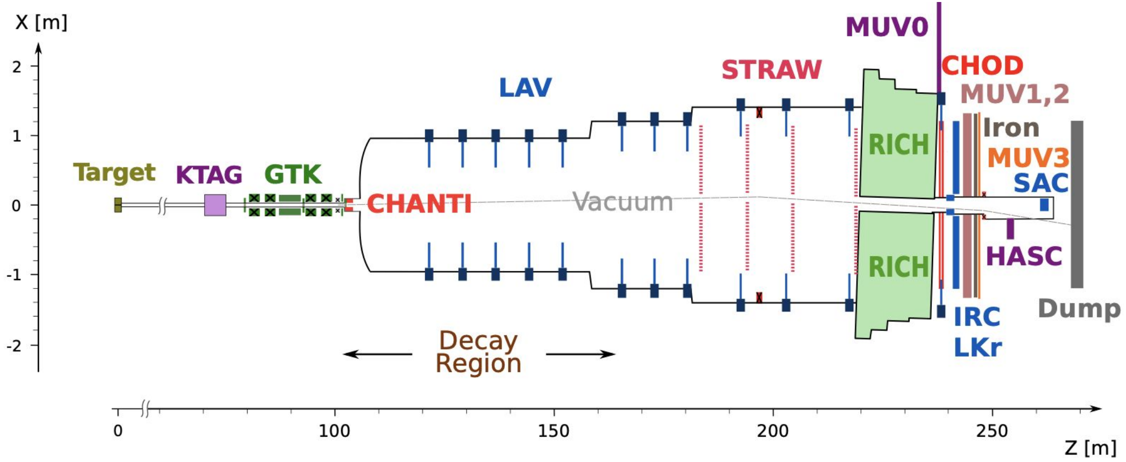
- ➔ **Beam-Dump mode**: Search NP particles into the Final States composed of SM particles;
- ➔ **K mode**: Search NP particles in SM particle decays.

# The NA62 Experiment

- Fixed-target experiment @ CERN North Area (SPS)
- Main goal is to measure ultra-rare $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ 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

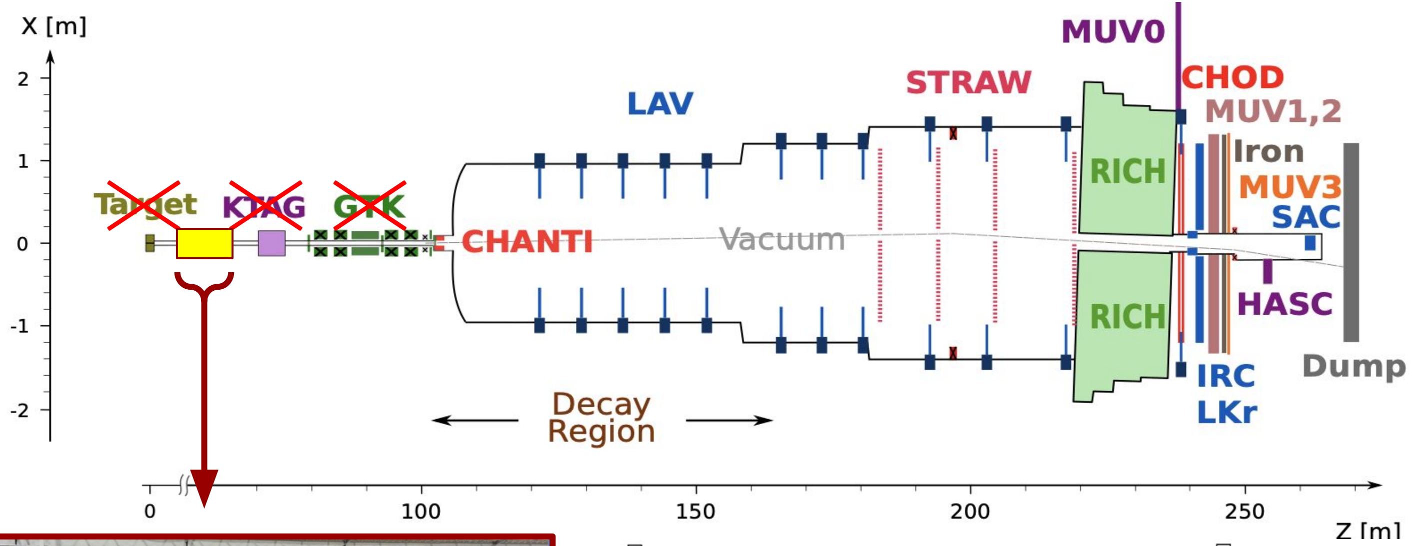
- ➔ 400 GeV/c primary $p^+$ beam collides *Be* target with ~$10^{12}$ proton/s on spill; 75 GeV/c secondary beam (~6% of $K^+$) selected using **TAX** collimators.
- ➔ $K^+$ (~5MHz) decay-in-flight in 60 m long fiducial volume (FV)[1];
- ➔ $K^+$ tagged by **KTAG** and 3 mom. determined by **GTK**;
- ➔ Decay products' 3 mom. measured by **STRAW**; time measured by **CHOD**; PID given by **LKr**, **MUV1**, **MUV2** and **RICH**; $\mu$-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;

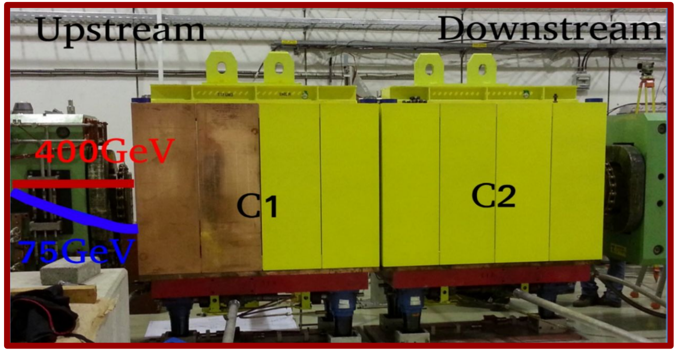


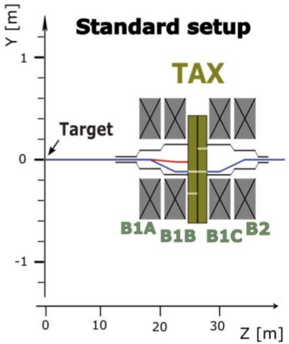

- ➔ Overall experimental time resolution reaches $\mathcal{O}$( 100) ps

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

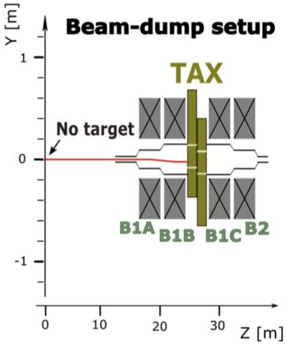
# The NA62 Experiment in beam-dump mode - I -



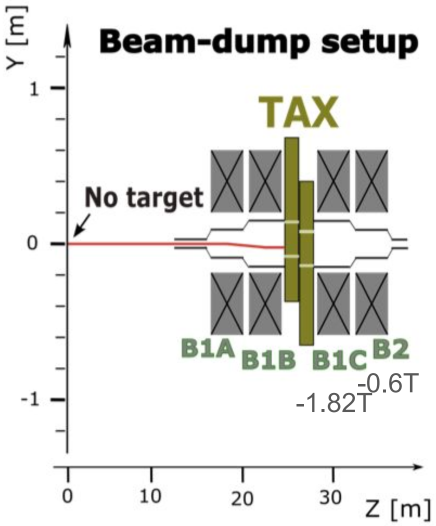



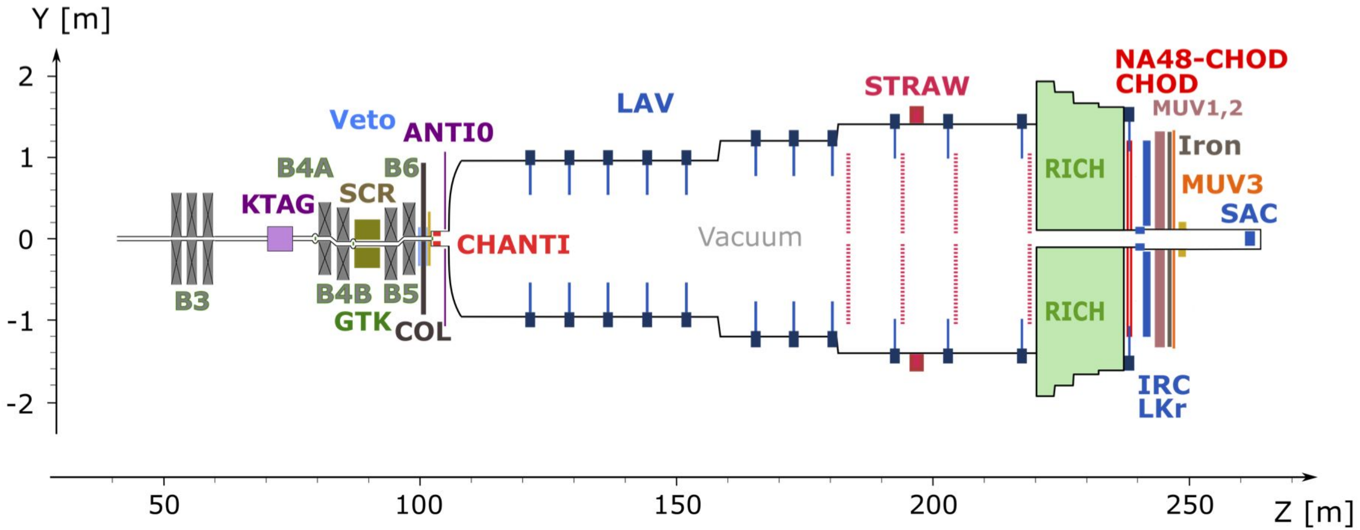

TAX closed



# The NA62 Experiment in beam-dump mode - II -

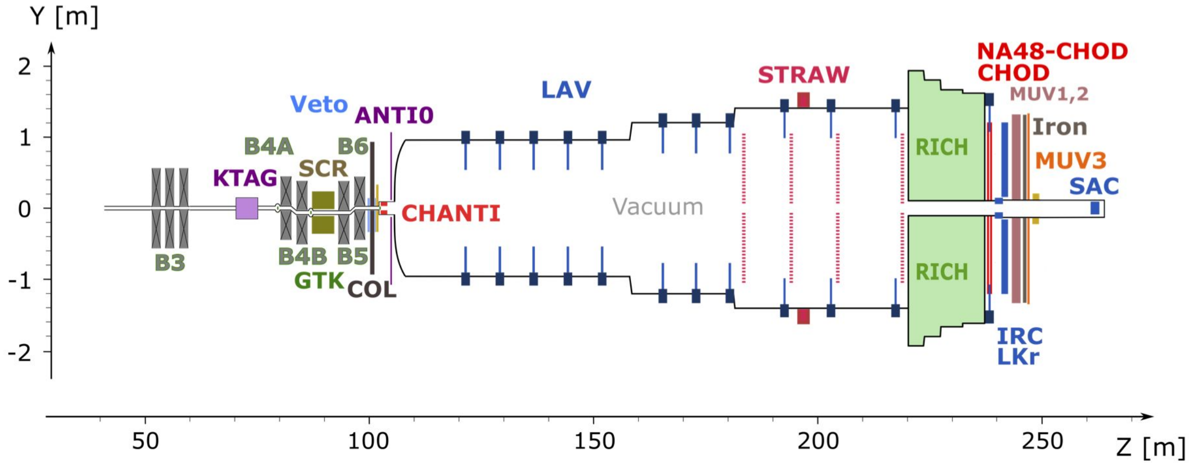
- ➔ reduced background from penetrating particles through improved sweeping from magnets downstream of the TAX;
- ➔ increase proton beam intensity ~1.5xNominal;



# 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*, *Phys. Rev. Lett.* ***133***, *111802*].

# 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, $P \to A'\gamma$, $V \to A'P$
    $V = \{\varrho, \omega, \phi\}$
  - 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<br>mixing $(\pi^0/\eta/\eta')$<br>$B$ 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's 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 $\pi^0$, $\gamma$, and $\eta$ 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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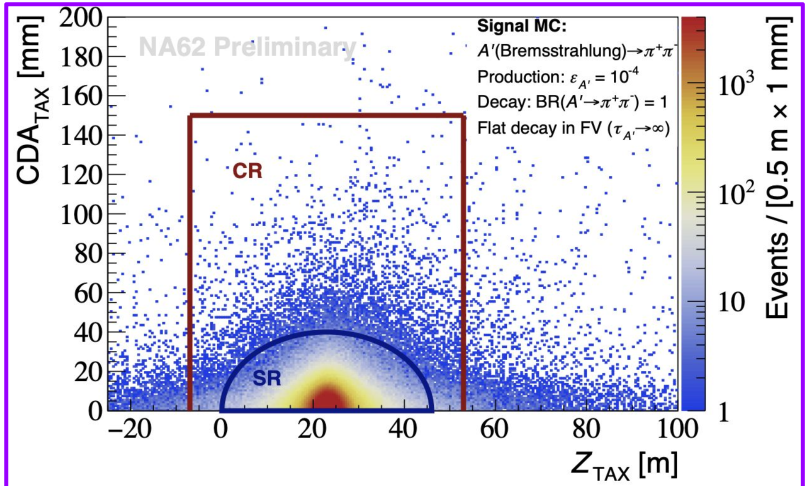


### $A' \rightarrow \pi^+\pi^-$ signal MC and definition of signal and control region

- ➔ **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:** $\mu$-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 $\mu$-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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  Prompt BKG from CR & SR
  $N_{exp} < 10^{-4}$ for all channels

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

# The Background overview - Upstream - I -

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

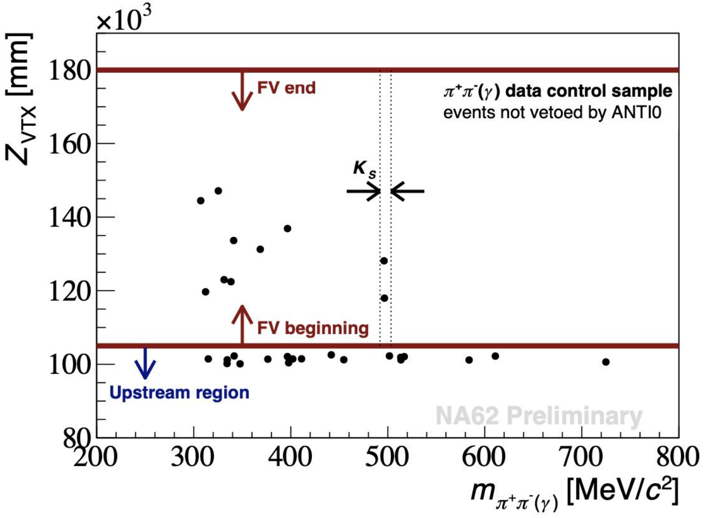


Figure: Events not in ANTI0 acceptance or not vetoed by ANTI0 in $Z_{\mathrm{VTX}}$ – invariant mass plane. Solid lines indicate the FV. Dashed lines indicate the $K_S$ $3\sigma$ mass window.

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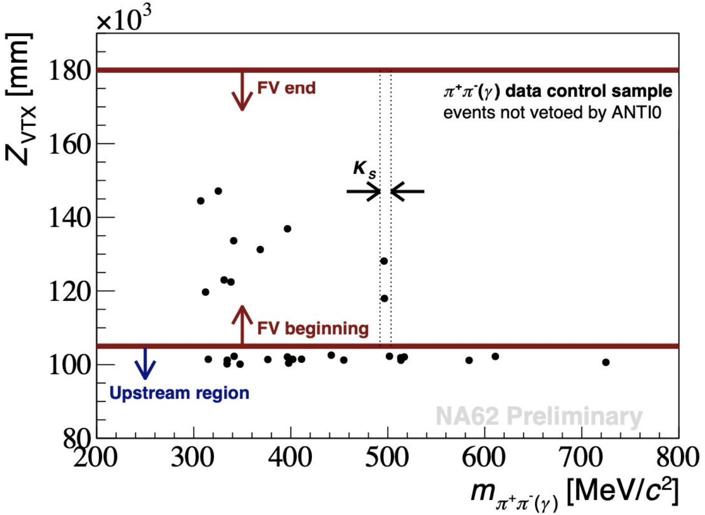
**In the control samples (no veto by ANTI0), 3 subcomponents observed in the $Z_{vtx}$ - $m_{\pi\pi}$ plane;**

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

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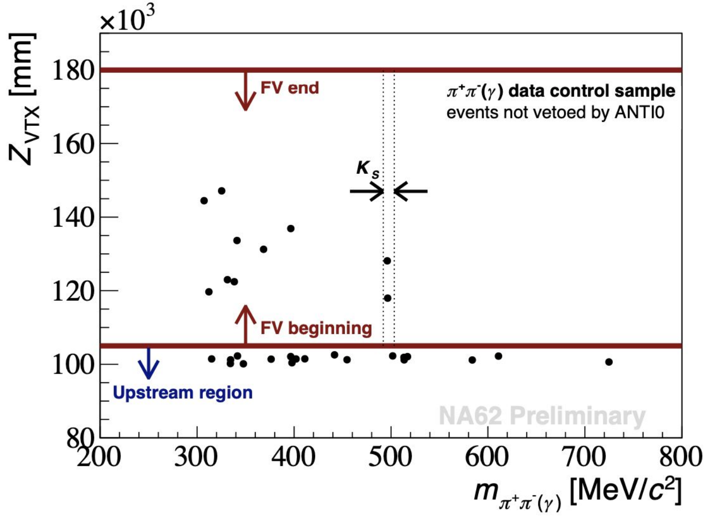
- ➔ 2 $K_S \rightarrow \pi^+\pi^-$ ;
  **$m_{K_S} \pm 3\sigma$ ( ± 5.7 MeV/c$^2$) kept masked**
- ➔ 8 $K^+ \rightarrow \pi^+\pi^+\pi^-$
  **6 identified as $\pi^+\pi^-$ and 2 $\pi^+\pi^-\gamma$**

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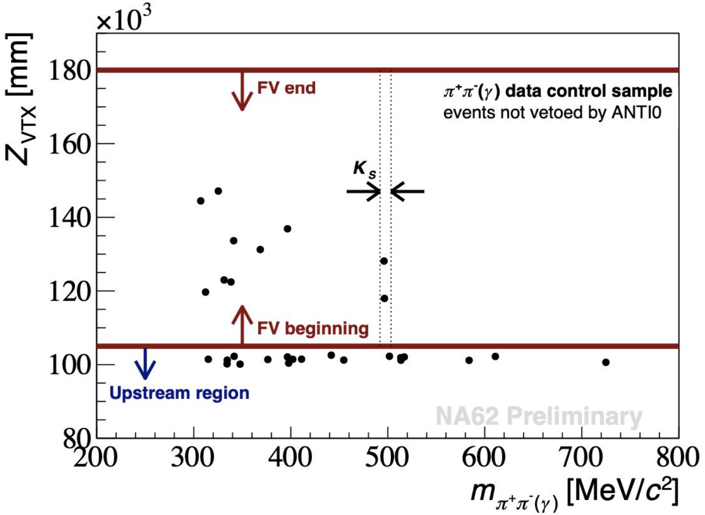
**A dedicated MC for $K^+$-induced BKG simulated using selected $K^+$ tracks which are forced to decay as $K^+ \to \pi^+\pi^+\pi^-$ in the FV**

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# The Background overview - Upstream - II -

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

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

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

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

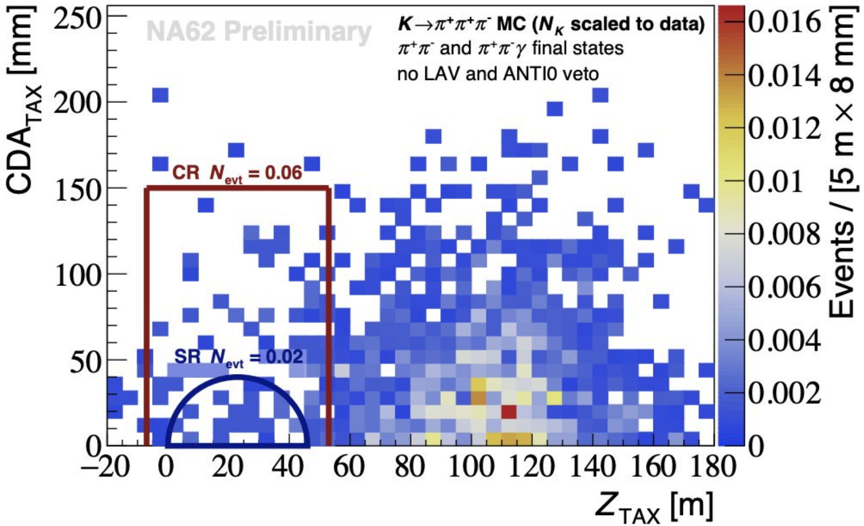



Figure: $N_{exp}$ from $K_{3\pi}$ in the primary vertex $Z$ and CDA plane before applying ANTI0 acceptance.

➔ Inside CR & SR; $N_{exp}$:

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

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

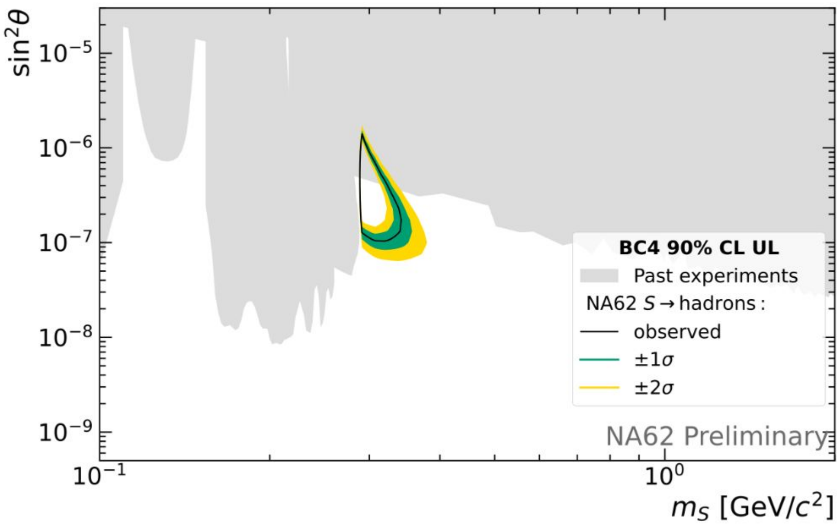
# The Background overview - Total -

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 $5\sigma$ in SR and SR+CR (global significance, flat background in $m_{\rm inv}$ assumed).

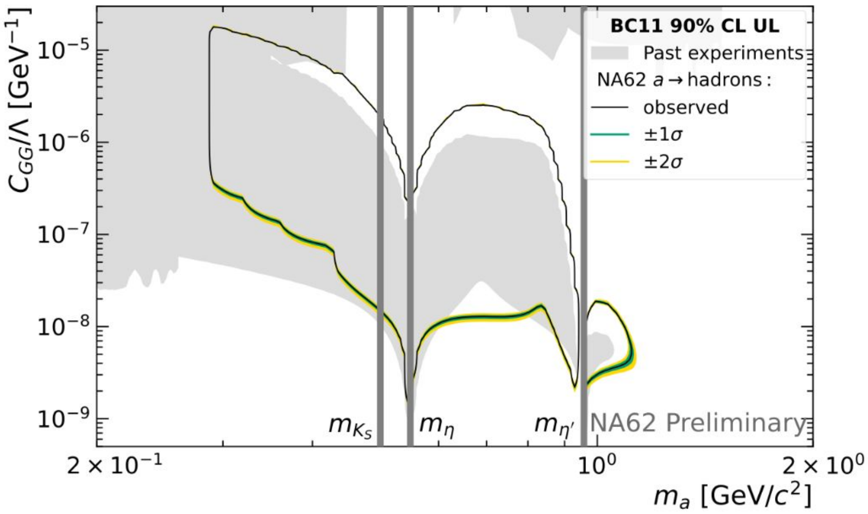
| Channel | $N_{\rm exp,CR} \pm \delta N_{\rm exp,CR}$ | $N_{\rm exp,SR} \pm \delta N_{\rm exp,SR}$ | $N^{p>5\sigma}_{\rm obs,SR}$ | $N^{p>5\sigma}_{\rm obs,SR+CR}$ |
|---|---|---|---|---|
| $\pi^+\pi^-$ | $0.013 \pm 0.007$ | $0.007 \pm 0.005$ | 3 | 4 |
| $\pi^+\pi^-\gamma$ | $0.031 \pm 0.016$ | $0.007 \pm 0.004$ | 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.
- ➔ Data-taking: new samples, ~ $4.6 \times 10^{17}$ POT, already collected in 2023&2024 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.

CERN Article: NA62 announces its first search for long-lived particles

# Σας ευχαριστώ για την προσοχή σας

# Backup

# WIMP to WIMPless

| | WIMP Miracle | WIMPless Miracle - J. Feng |
|---|---|---|
| **Mass Range** | 100 GeV – 1 TeV. | (sub-)GeV. |
| **Interaction Type** | Interacts via the weak nuclear force (Standard Model interactions). | Interacts through dark sector forces, independent of the weak force. |
| **Relic Abundance Mechanism** | Thermal freeze-out: WIMPs were in thermal equilibrium and annihilated until their interactions froze out as the universe expanded and cooled. | Thermal freeze-out within a hidden sector, where dark sector particles annihilate through hidden interactions and decouple from equilibrium as the universe expands and cools. |
| **Detection Methods** | Direct detection (e.g., XENON1T, LUX), indirect detection (e.g., gamma rays from annihilation), and collider searches (e.g., LHC). | Indirect detection targeting unique dark sector signatures (e.g., dark photons, ALPs, HNL), often requiring specialized experimental setups (e.g., NA62 at SPS; FASER, MATHUSLA, Codex-b at LHC). |
| **Theoretical Motivation** | Supported by Supersymmetry (SUSY) and other Beyond Standard Model (BSM) theories, offering a natural explanation for weak-scale dark matter. | Motivated by hidden sector models in BSM theories, light mediator, portal, providing flexibility in mass and coupling parameters. |
| **Advantages** | - Predictive power: Simple and elegant explanation for dark matter abundance.<br>- Strong theoretical motivation from SUSY and weak-scale physics. | - Flexibility in mass and coupling strength.<br>- Can evade current experimental constraints that limit the WIMP parameter space. |
| **Cosmological Implications** | WIMPs fit well within the standard cosmological model, affecting structure formation and the thermal history of the universe. | WIMPless models allow for more diverse roles in cosmology, potentially involving interactions with both visible and hidden sectors. |

# The Sensitivity

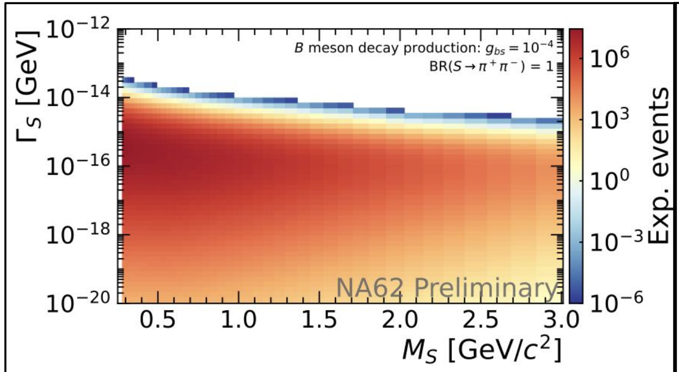
**$X \to \pi^+\pi^-$; Model-Independent approach;**

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

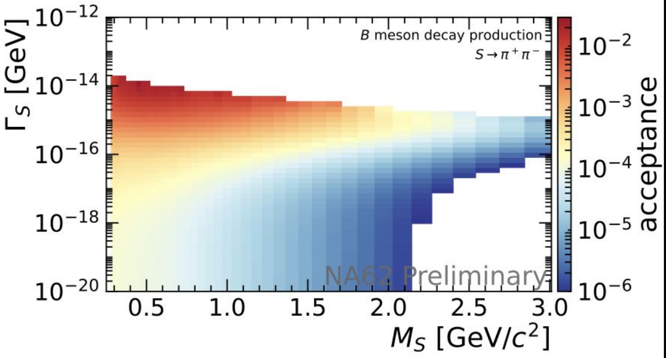
$\chi_{pp\to X}(C_{ref})$: X production probability for ref. coupling

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

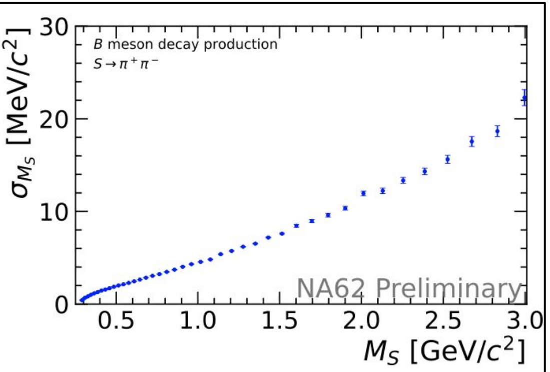
$A_{acc} \times A_{trig}$: Signal selection and trigger efficiency




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

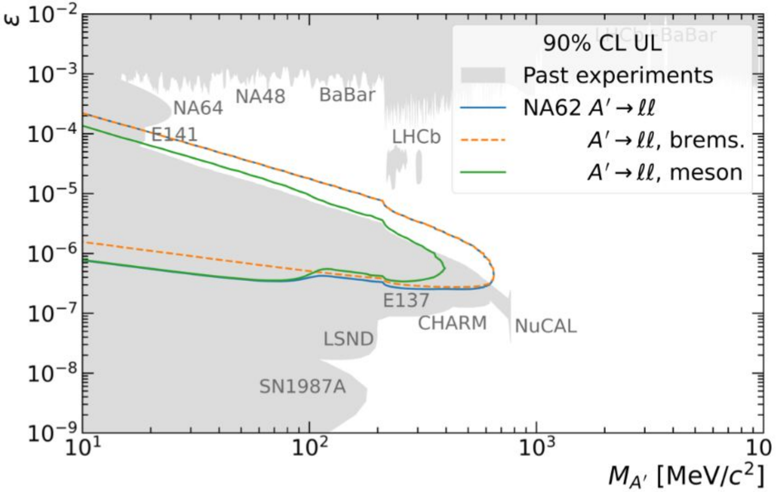



Figure: Sensitivity per production mechanism assuming 0 observed events in $1.4 \times 10^{17}$ POT.

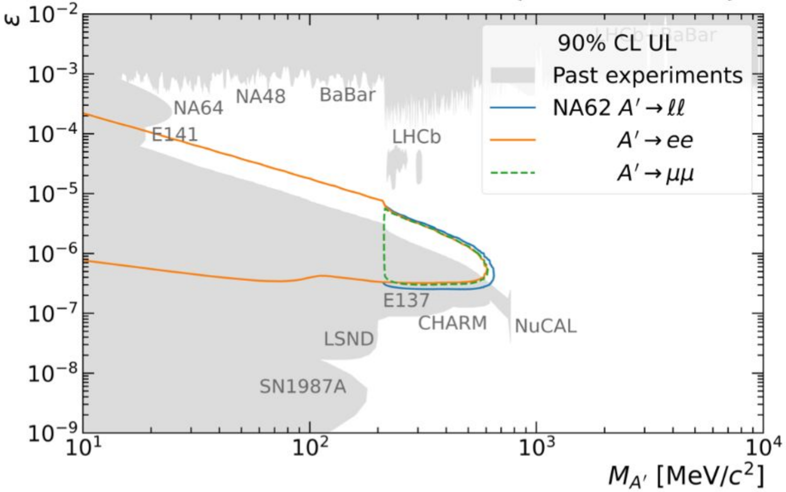



Figure: Sensitivity per decay mode assuming 0 observed events in $1.4 \times 10^{17}$ POT.

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

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

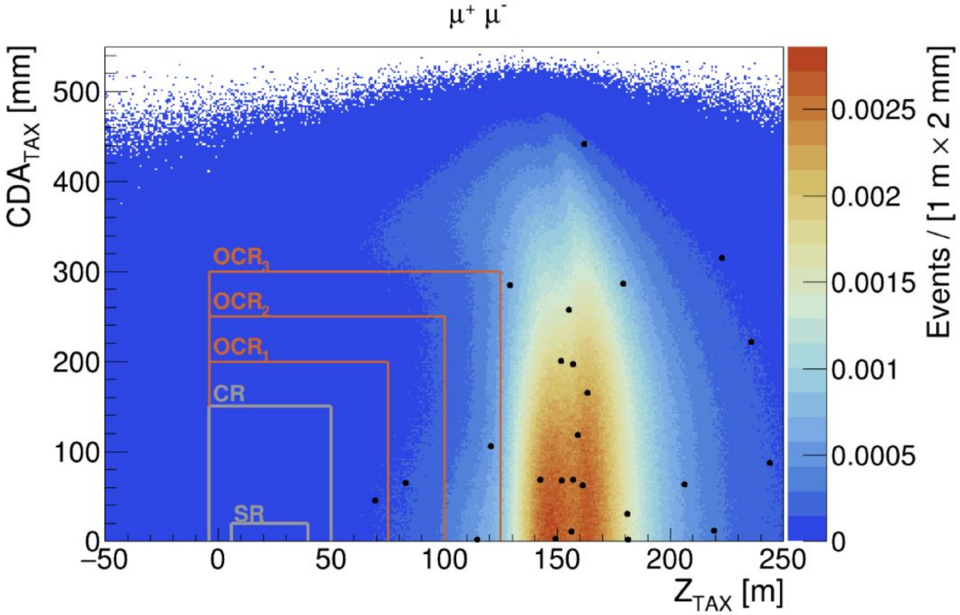



Figure: Data-MC comparison, SR closed.

| | $N_{\rm exp} \pm \delta N_{\rm exp}$ | $N_{\rm obs}$ | $p_{N \geq N_{\rm obs}}$ | $p_{L \leq L_{\rm obs}}$ |
|---|---|---|---|---|
| outside CR | $26.3 \pm 3.4$ | 28 | 0.41 | 0.74 |
| OCR3 | $1.70 \pm 0.22$ | 2 | 0.25 | 0.25 |
| OCR2 | $0.58 \pm 0.07$ | 1 | 0.44 | 0.44 |
| OCR1 | $0.29 \pm 0.04$ | 1 | 0.50 | 0.68 |
| OCR1+2+3 | $2.57 \pm 0.33$ | 4 | 0.26 | 0.24 |
| CR | $0.17 \pm 0.02$ | 0 | 1.0 | 1.0 |
| SR | $0.016 \pm 0.002$ | - | - | - |

- 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:

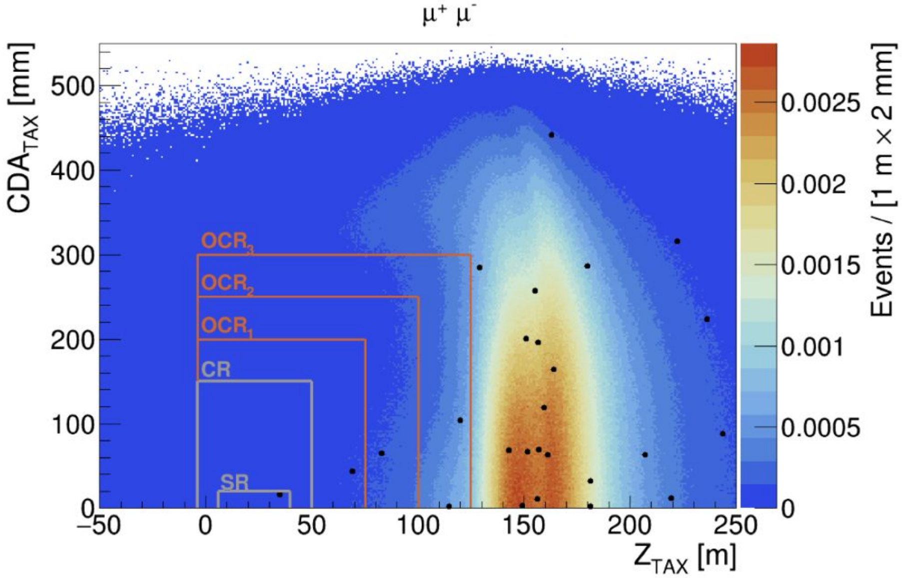



Figure: Data-MC comparison, CRs and SR open.

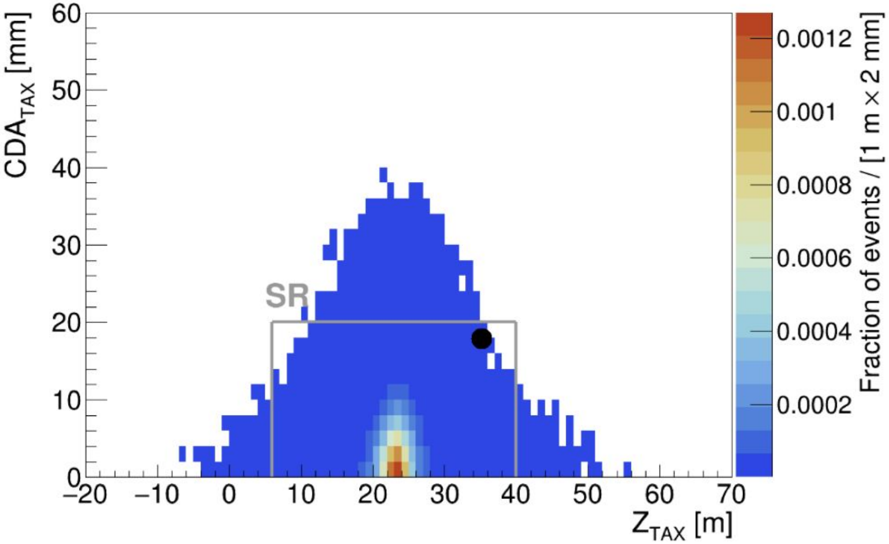



Figure: Signal MC - data: 1 event observed - counting experiment with 2.4$\sigma$ significance. Signal shape not taken into account for the significance.

# The Search for exotic (preudo)scalar

Phys. Rev. Lett. **133**, 111802

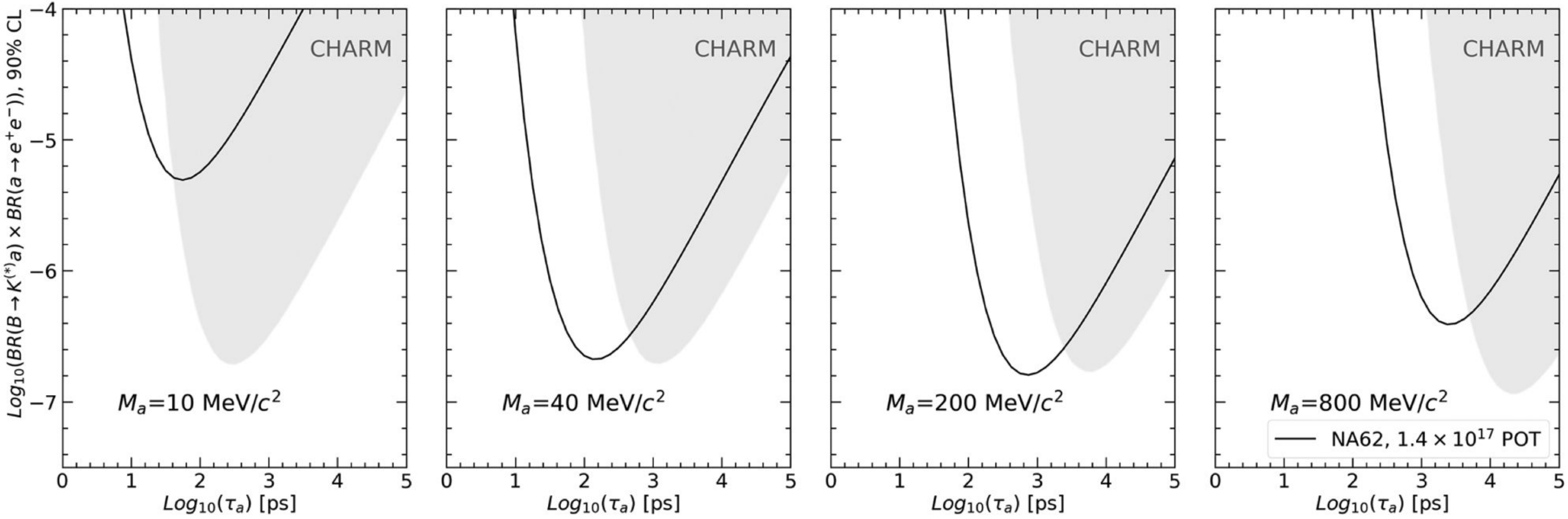



FIG. 5. Exclusion region in the plane of the ALP lifetime $(\tau_a)$ and the product of branching ratios $BR(B \to K^{(*)}a) \times BR(a \to e^+e^-)$ in the search for an axionlike particle $a$ produced in $B$ meson decays (solid curve). Four values of the ALP mass are considered. The region of the parameter space above the black line is excluded at 90% CL. The excluded regions by CHARM [34] measurements are shown as gray-filled areas.

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

Phys. Rev. Lett. **133**, 111802

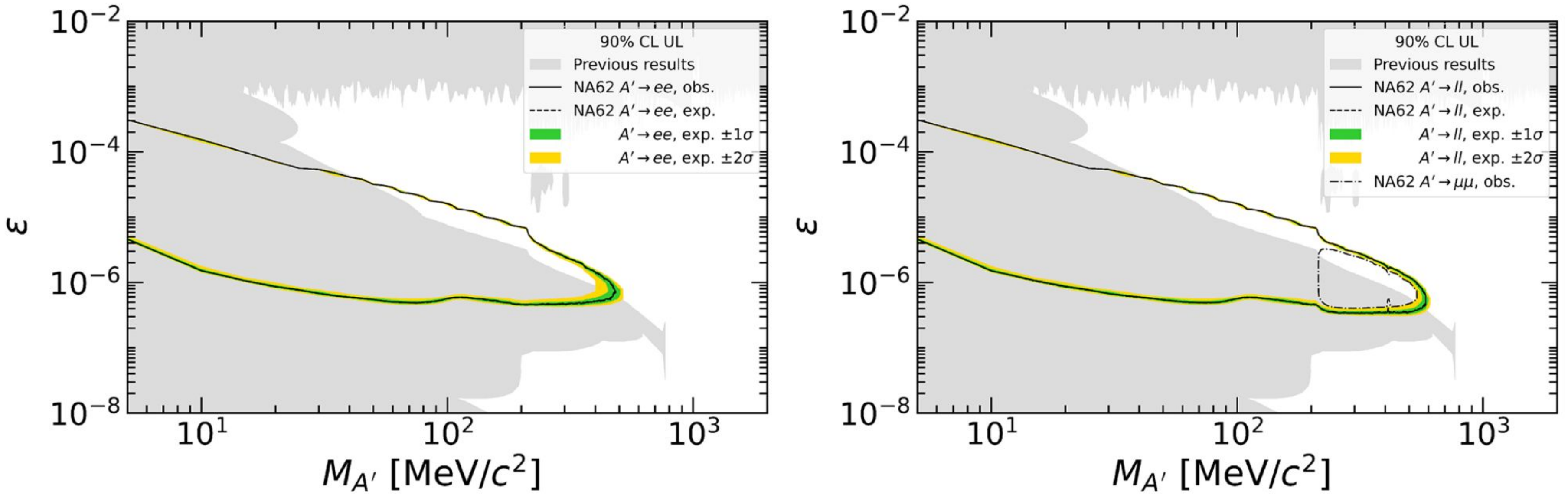



FIG. 4. Observed and expected exclusion contours, at 90% CL, in the plane $(M_{A'}, \varepsilon)$ for the $A' \to e^+e^-$ analysis (left) and the combined $A' \to e^+e^-$ and $A' \to \mu^+\mu^-$ analyses (right) together with the expected $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) bands. Previous results, including the recent FASER result [25] are shown in gray. The NA62 $A' \to \mu^+\mu^-$ result [10] is shown with a dot-dashed line in the right panel.

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

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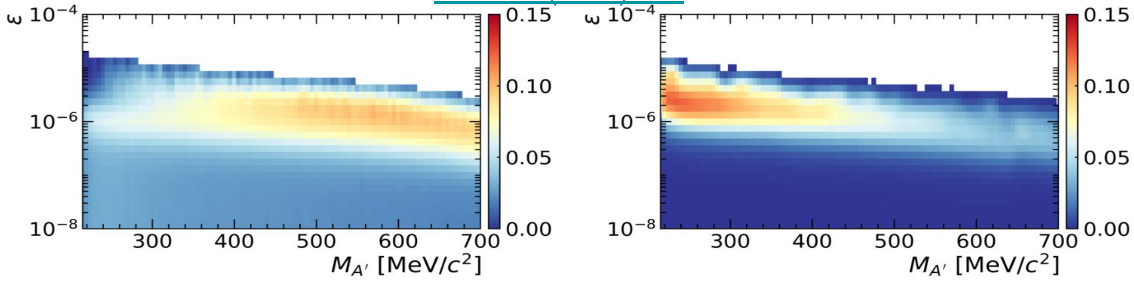


**Figure 11**. Selection and trigger efficiency for the $A' \to \mu^+\mu^-$ signal, as a function of the $A'$ mass and coupling constant. Left (right) panel refers to the bremsstrahlung (meson-decay) production mode.

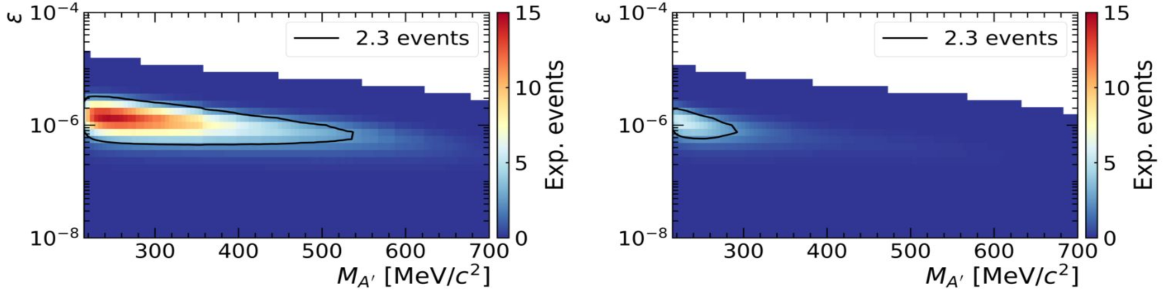


**Figure 13**. Expected number of events for the $A'$ decay to $\mu^+\mu^-$ as a function of the $A'$ mass and coupling constant. Left (right) panel refers to bremsstrahlung (meson-decay) production. The black contours correspond to 2.3 events.

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

Phys. Rev. Lett. **133**, 111802

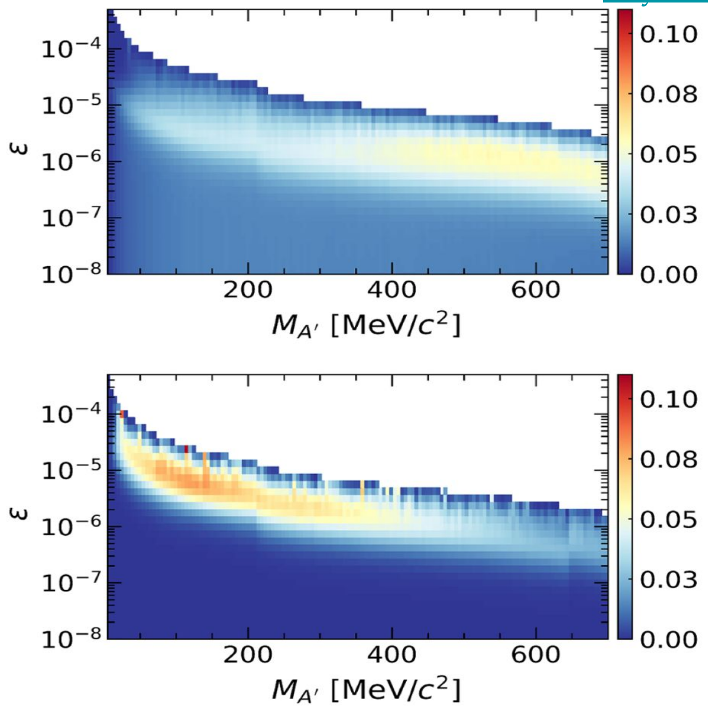


FIG. 6. Selection and trigger efficiency (color scale) for the $A' \to e^+e^-$ in the plane $(M_{A'}, \varepsilon)$. The bremsstrahlung (meson-mediated) production mode is shown in the top (bottom) panel.

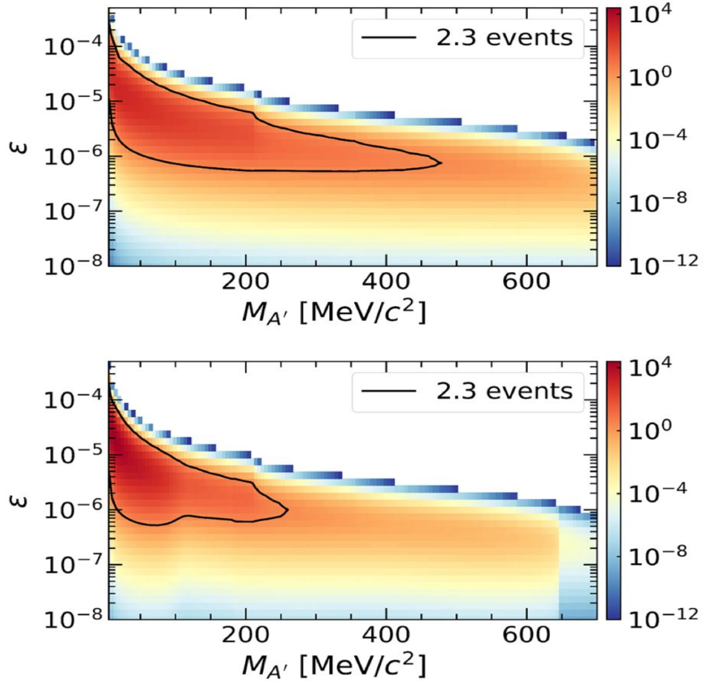


FIG. 7. Expected number of events in SR (color scale) for the $A' \to e^+e^-$ decay in the plane $(M_{A'}, \varepsilon)$. The bremsstrahlung (meson-mediated) production mode is shown in the top (bottom) panel. The black contour corresponds to 2.3 events.

# The BeamDump Magnet

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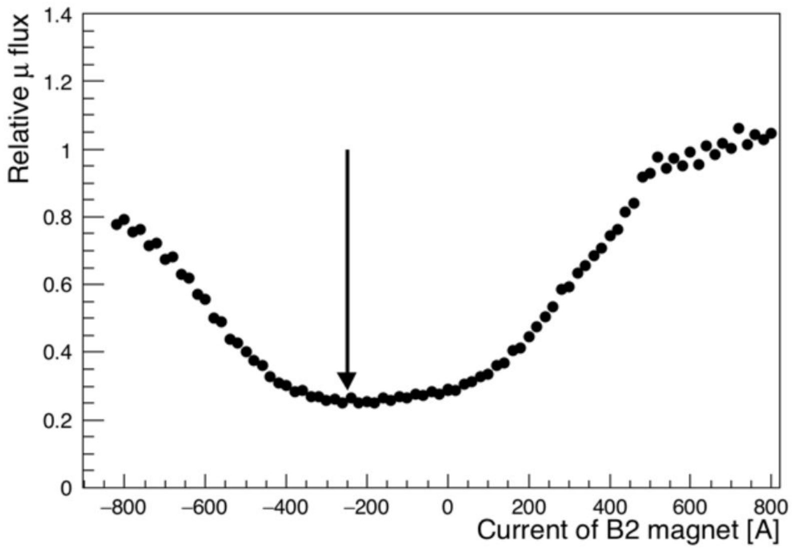


**Figure 2**. Relative muon flux measured by the MUV3 detector (section 2.1) as a function of the B2 magnet current. The reference point for the standard operation is +770 A, corresponding to a field strength of 1.8 T. The arrow indicates the working point for the beam-dump data taking, −250 A.

# The BeamDump Magnet

## DARK PHOTON, DARK HIGGS, HNLS

- This provides an organizing principle that motivates specific examples of new, weakly interacting light particles. There are just a few options:

- Spin 1 — SM - - - - $F_{\mu\nu}F_D^{\mu\nu}$ - - - - Dark Force

→ dark photon, couples to SM fermions with suppressed couplings proportional to charge: $\varepsilon q_f$. Holdom (1986)

- Spin 0 — SM - - - $h^\dagger h \phi_D^\dagger \phi_D$ - - - Dark Scalar

→ dark Higgs boson, couples to SM fermions with suppressed coupling proportional to mass: $\sin\theta\, m_f$. Patt, Wilczek (2006)

- Spin 1/2 — SM - - - - $hL\psi_D$ - - - - Dark Fermion

→ Heavy neutral leptons, mixes with SM $\nu$s with suppressed mixing $\sin\theta$.

Feng@LLP workshop

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