



MAX PLANCK INSTITUTE  
FOR PHYSICS



# FIP/LLP searches at NA62

Jan Jerhot

Max Planck Institute for Physics

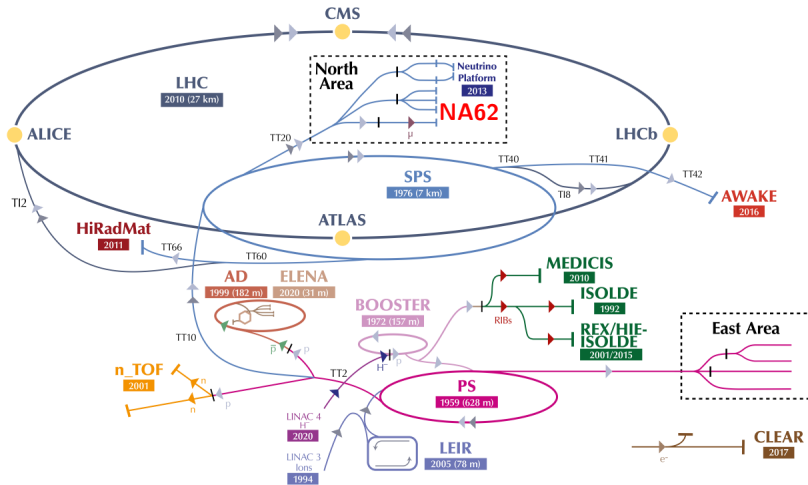
Light Dark World 2025  
September 18, 2025



European Research Council  
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# Introduction: NA62 experiment

Fixed-target experiment at CERN SPS (north area - ECN3 experimental cavern)



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- **Data-taking periods 2016-18, 2021-26:**  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  analysis of 2016-22 data published<sup>1</sup>

<sup>1</sup>Observation of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay and measurement of its branching ratio. NA62 Collaboration, *JHEP* 02(2025)191

# Introduction: Long-lived particles (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 ( $\text{dim} \leq 5$ )	PBC	decay channels ( $m \lesssim 1 \text{ GeV}$ )	
<b>dark photon</b> ( $A'_\mu$ )	vector	$-\epsilon/(2 \cos \theta_W) F'_{\mu\nu} B^{\mu\nu}$	1-2	$\ell\ell$	$2\pi, 3\pi, 4\pi, 2K, 2K\pi$
<b>dark Higgs</b> ( $S$ )	scalar	$(\mu S + \lambda S^2) H^\dagger H$	4-5	$\ell\ell$	$2\pi, 4\pi, 2K$
<b>axion/ALP</b> ( $a$ )	pseudoscalar	$(C_{VV}/\Lambda) ga V_{\mu\nu} \tilde{V}^{\mu\nu}$ $C_{ff}/(2\Lambda) \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f$	9,11 10	$\gamma\gamma, \ell\ell$	$2\pi\gamma, 3\pi, 4\pi, 2\pi\eta, 2K\pi$
<b>HNL</b> ( $N_I$ )	fermion	$F_{\alpha I} (\bar{L}_\alpha H) N_I$	6-8	$\pi\ell, K\ell, \ell_1\ell_2\nu$	

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

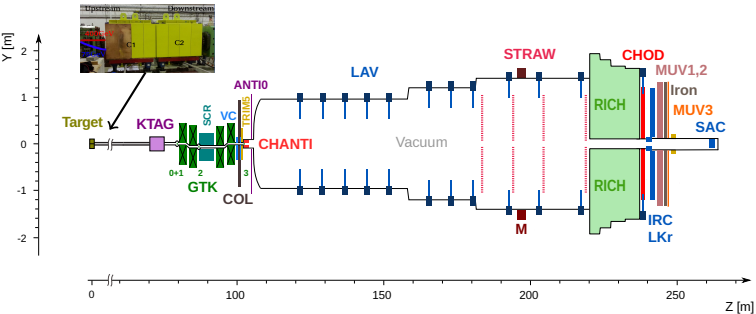
- ① NP particle production in SM particle decays - reconstruction from both initial and final state particles
- ② NP particle decay to SM particles - reconstruction of original particle from the SM final states

NA62 experiment can do both in two modes of operation - ① kaon mode<sup>2</sup> and ② **beam-dump mode**

<sup>2</sup>Following talk by E. Goudzovski.

# 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

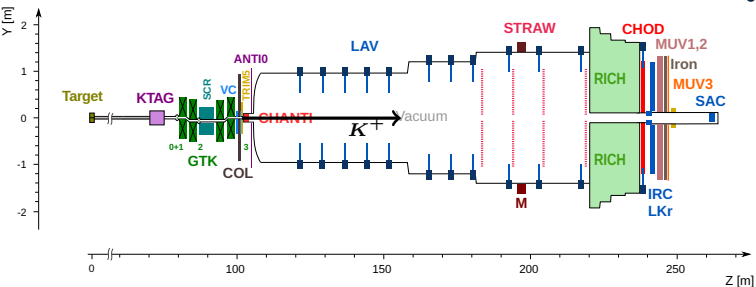


<sup>3</sup>The beam and detector of the NA62 experiment at CERN. NA62 Collaboration. 2017 *JINST* **12** P05025, [1703.08501]



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- 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)<sup>3</sup>;

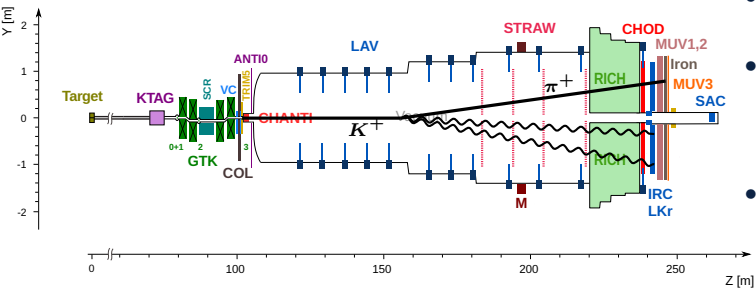


- $K^+$  tagged by **KTAG**;  $\vec{p}_K$  measured by **GTK**;

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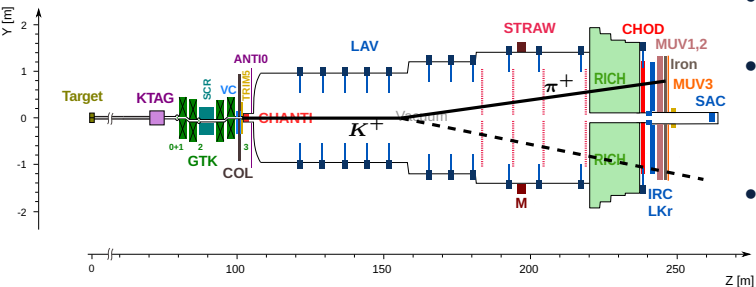
- $K^+$  tagged by **KTAG**;  
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- Decay products'  $\vec{p}$  from **STRAW**;  
time measured by **CHOD**;  
PID given by **LKr**, **MUV12**, **RICH**;  
+  $\mu$  ID provided by **MUV3**;
- Photons can be vetoed by **LKr**  
+ at large angles by 12 **LAV** stations  
→ + small angles by **SAV**(IRC/SAC);

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

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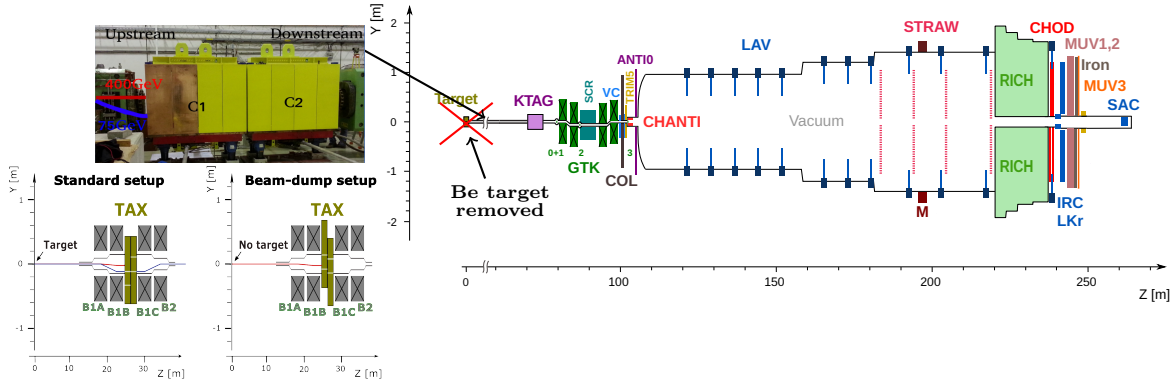
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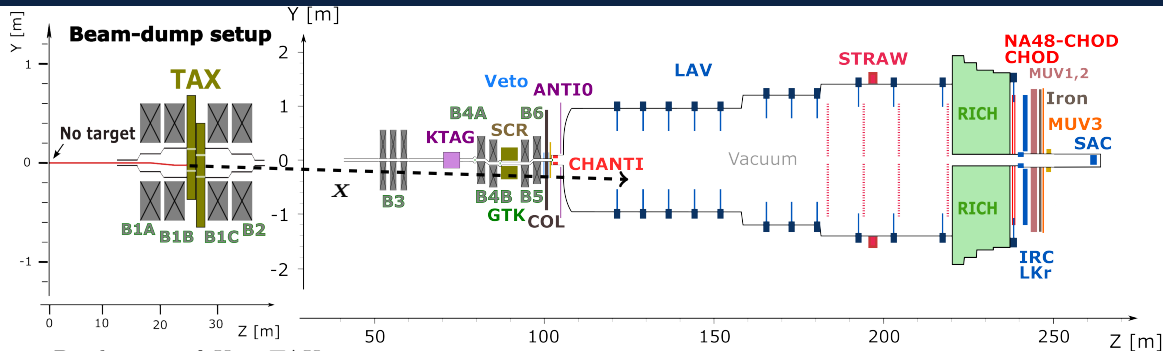
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# NA62 experiment in beam-dump mode

- Target removed and TAX closed, intensity more than twice the nominal kaon;
- Optimized sweeping from magnets between TAX and FV to reduce muon halo background;



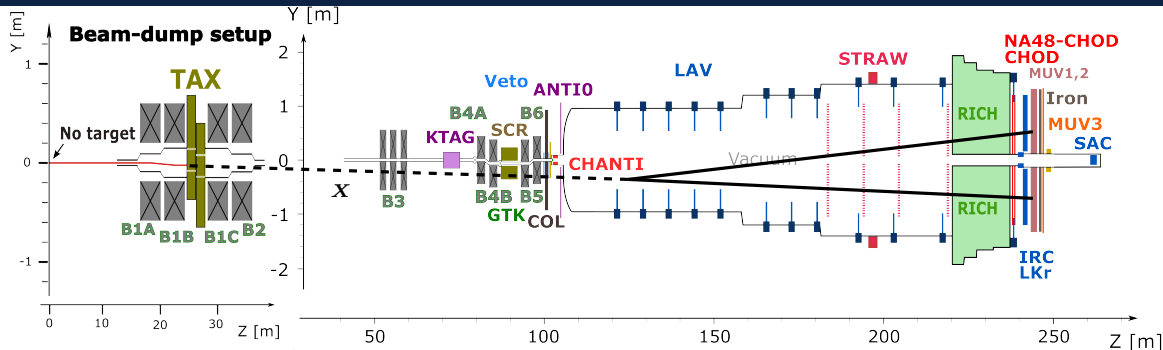
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- Production of  $X$  in TAX:

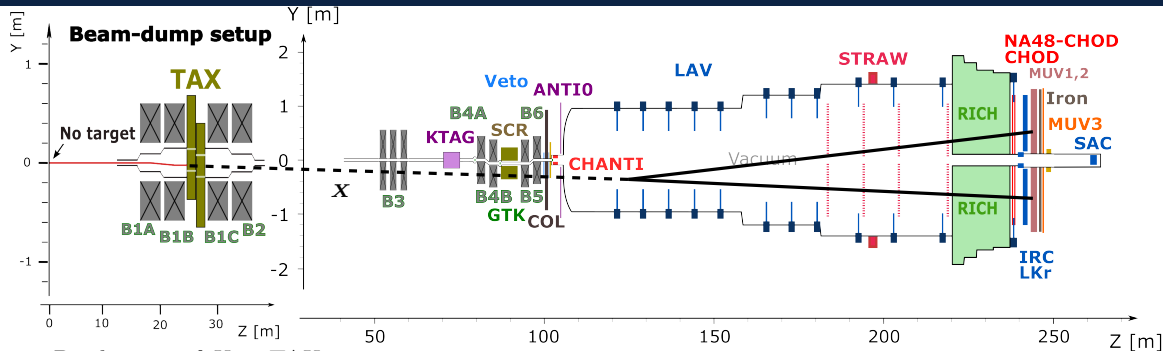
- $p$ -Bremsstrahlung  $pN \rightarrow X + ..$ ; ALP Primakoff; mixing with  $V = \{\rho, \omega, \phi\}$ ,  $P = \{\pi^0, \eta, \eta'\}$
- secondary meson decays:  $B \rightarrow KX$ ;  $P \rightarrow A'\gamma$  and  $V \rightarrow A'P$ ;  $D(B) \rightarrow K(D)(\pi)\ell X$

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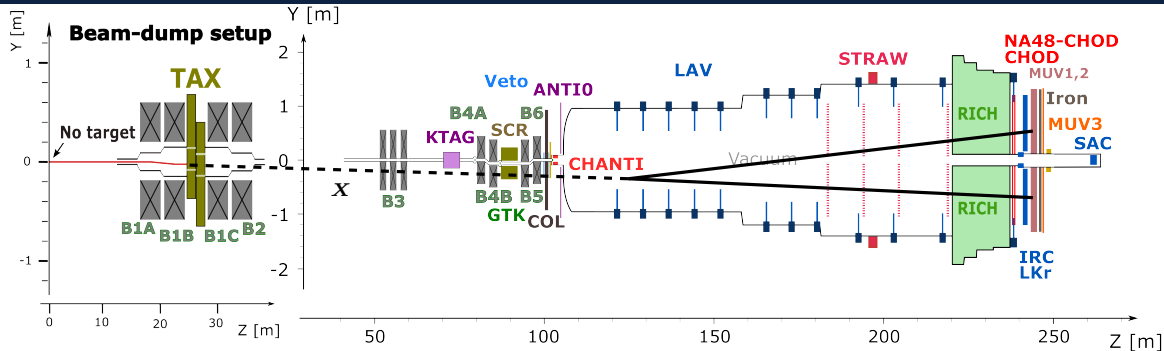
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- two trigger lines for charged particles:  $\geq 1$  hits in CHOD/20,  $> 1$  in-time hit in CHOD;  
+ neutral calorimeter-based trigger line

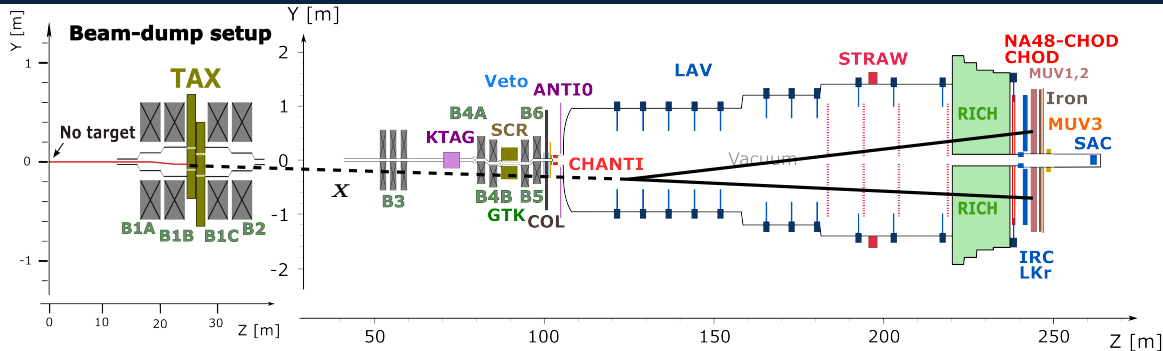
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- $N_{\text{POT}} = (1.4 \pm 0.3) \times 10^{17}$  protons on target (POT) collected in 2021; on tape:  $N_{\text{POT}} > 9 \times 10^{17}$



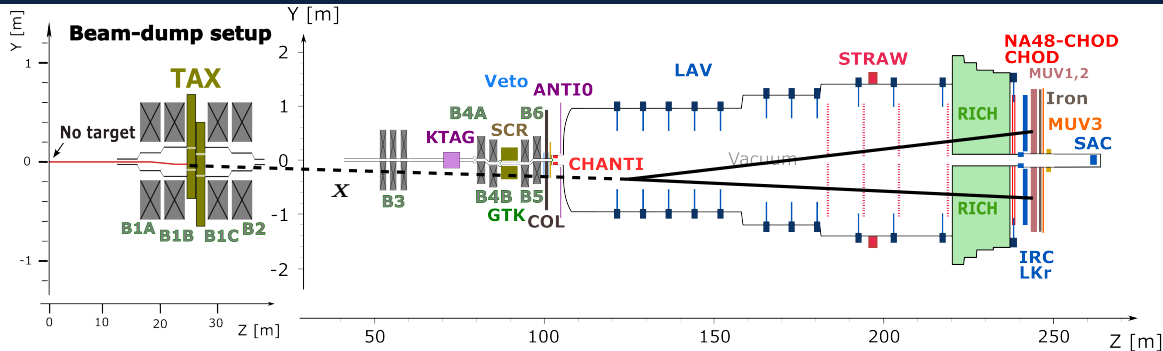
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- Di-lepton, hadronic, semi-leptonic and di-photon analyses with **full sample ongoing**.

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# Search for LLP decays in 2021 beam-dump sample (selection)

## Search strategy:

- ① selecting two oppositely charged tracks +  
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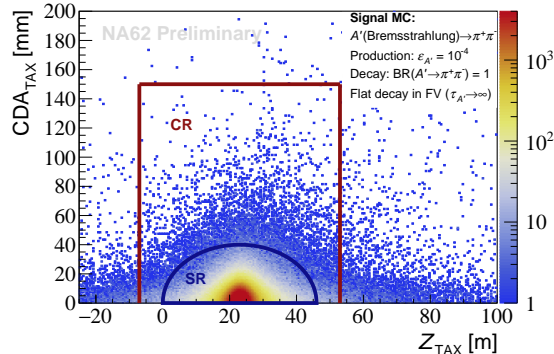
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## Signal and control regions (SR, CR):

- extrapolation of  $\vec{p}_X$  from vertex to TAX: definition of SR and CR in terms of primary vertex location
  - SR: ellipse centered at  $\{Z_{\text{TAX}}, \text{CDA}_{\text{TAX}}\} = \{23 \text{ m}, 0 \text{ mm}\}$  with semi-axes of 23 m and 40 mm
  - CR: box  $\text{CDA}_{\text{TAX}} < 150 \text{ mm}$  and  $-7 \text{ m} < Z_{\text{TAX}} < 53 \text{ m}$





# Search for LLP decays in 2021 beam-dump sample (acceptance)

In model-independent case ( $C^i = C_{\text{ref}}^i$ ,  $\text{BR}^f = 1$ ):  $N_{\text{exp}}^{if}(m_X, \Gamma_X) = N_{\text{POT}} \times \chi_{pp \rightarrow X}^i(C_{\text{ref}}^i) \times P_{\text{rd}}^i \times A_{\text{acc}}^{if}$

- $\chi_{pp \rightarrow X}(C_{\text{ref}})$ : LLP prod. probability for ref. coupling
- $P_{\text{rd}}$ : probability to reach NA62 FV and decay therein
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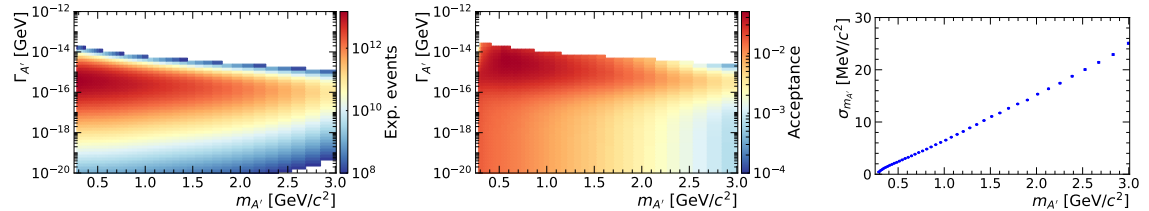


Figure: Left: expected  $A' \rightarrow \pi^+ \pi^-$  yield after full selection, assuming  $\varepsilon = 1$  and  $\text{BR} = 1$ . Center: acceptance after full selection for LLPs that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

- Distributions above obtained for all 61 combinations of production and decay channels
- All available on HepData: <https://doi.org/10.17182/hepdata.156981.v1>

# Search for LLP decays in 2021 beam-dump sample (background)

## Combinatorial:

- Background from random superposition of two uncorrelated upstream particles;

## Prompt:

- Background from secondaries of  $\mu$  interactions with the traversed material (photo-production);

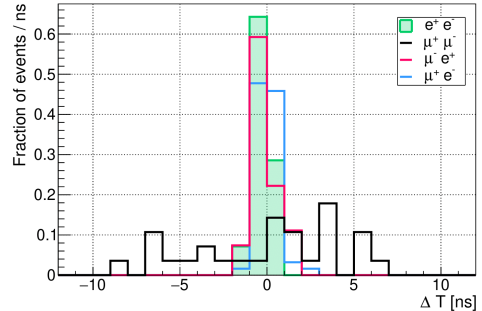


Figure:  $X \rightarrow \ell^+ \ell^-$  background before LAV veto (SR and CR masked).

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- Simulation based on data single  $\ell/\pi$  artificially overlaid to emulate a random superposition.

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- Background from secondaries of  $\mu$  interactions with the traversed material (photo-production);
- Dominating for  $e^+e^-$  ( $N_{\text{exp}}^{ee} \sim 10^{-2}$ )  
some contribution to hadrons ( $N_{\text{exp}}^{\pi\pi} < 10^{-4}$ ).
- Simulation based on backwards MC using data single  $\mu$  + unfolding in  $p$  and  $R$ .

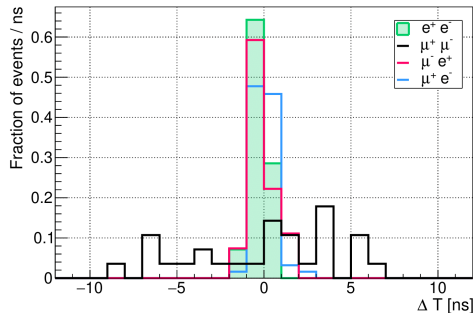


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## Kaon decays:

- Background from upstream kaons entering the FV via non-instrumented ANTI0 hole;
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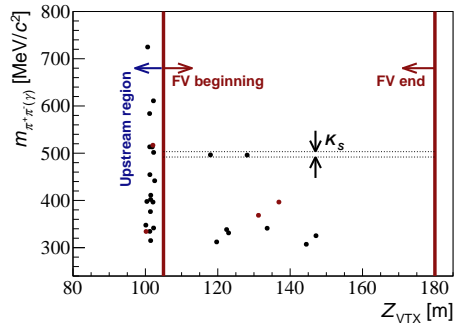


Figure:  $\pi^+\pi^-(\gamma)$  events in  $Z_{\text{VTX}}$  – invariant mass plane after inverting ANTI0 veto. Solid lines indicate the FV. Dashed lines indicate the  $K_S$   $3\sigma$  mass window.

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## Neutrino-induced background:

- Interactions of  $\nu_\mu$  from TAX in detector material;
- CC and NC interactions in passive material simulated while enhancing the interaction cross section;
- Negligible contribution found for all final states.

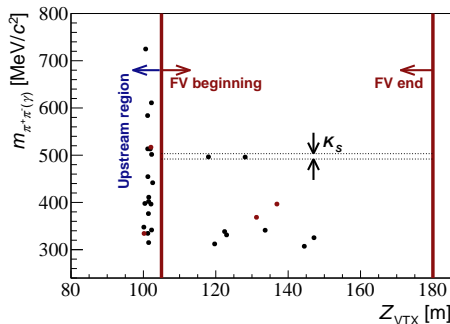


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# Search for LLP decays in 2021 beam-dump sample (background)

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

Channel	$N_{\text{exp,CR}} \pm \delta N_{\text{exp,CR}}$	$N_{\text{exp,SR}} \pm \delta N_{\text{exp,SR}}$
$\pi^+\pi^-$	$0.013 \pm 0.007$	$0.007 \pm 0.005$
$\pi^+\pi^-\gamma$	$0.031 \pm 0.016$	$0.007 \pm 0.004$
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$
$K^+K^-$	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$
$\mu^+\mu^-$	$0.17 \pm 0.02$	$0.016 \pm 0.002$
$e^+e^-$	$0.0097^{+0.049}_{-0.009}$	$0.0094^{+0.049}_{-0.009}$

Background-free hypothesis **not only** at  $N_{\text{POT}} = 1.4 \times 10^{17}$  but also for  $N_{\text{POT}} = 10^{18}$  and beyond

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- Model-dependent interpretation:<sup>5</sup>

$$N_{\text{exp}}(m_X, C_X) = \sum_{if} \text{BR}^f(m_X, C_X) \times (C^i/C_{\text{ref}}^i)^2 \times N_{\text{exp}}^{if}(m_X, \Gamma_X = \Gamma_X(m_X, C_X))$$

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

# Search for LLP decays in 2021 beam-dump sample (result)

- 0 events observed in all CRs;
- 1 event observed in  $\mu^+\mu^-$  SR ( $2.4\sigma$  global significance); 0 events observed in  $e^+e^-$  and hadronic SRs;
- Model-dependent interpretation:<sup>5</sup>  

$$N_{\text{exp}}(m_X, C_X) = \sum_{if} \text{BR}^f(m_X, C_X) \times (C^i/C_{\text{ref}}^i)^2 \times N_{\text{exp}}^{if}(m_X, \Gamma_X = \Gamma_X(m_X, C_X))$$
- Observed 90% CL contours for different models obtained using the  $\text{CL}_s$  method, combining the result for **hadronic** and **di-lepton** final states.

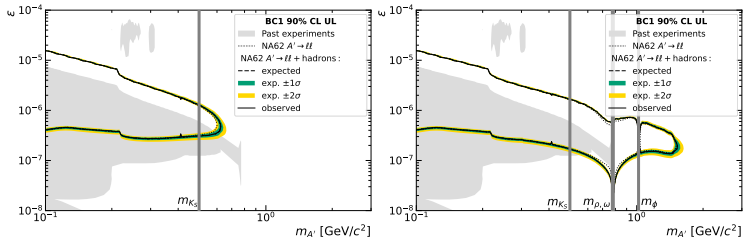


Figure: The observed 90% CL exclusion contours in BC1 (dark photon) benchmark together with the expected  $\pm 1\sigma$  and  $\pm 2\sigma$  bands (theory uncertainty not included). Left: Bremsstrahlung production without resonant enhancement. Right: Bremsstrahlung production with resonant enhancement.

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# Search for LLP decays in 2021 beam-dump sample (result)

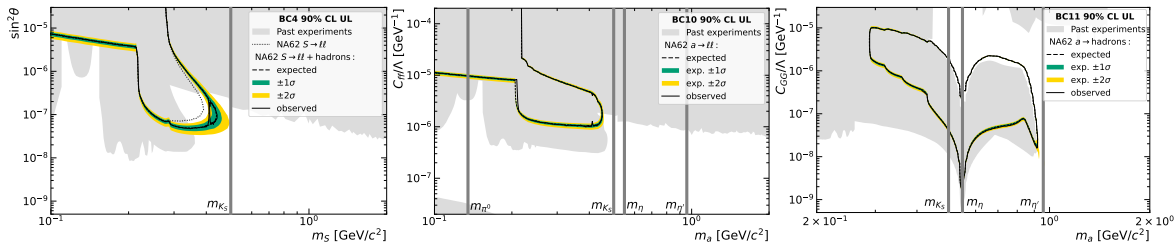


Figure: The observed 90% CL exclusion contours in BC4 (left), BC10 (center) and BC11 (right) benchmarks together with the expected  $\pm 1\sigma$  and  $\pm 2\sigma$  bands (theory uncertainty not included).

# NA62 projected sensitivity for the full BD sample

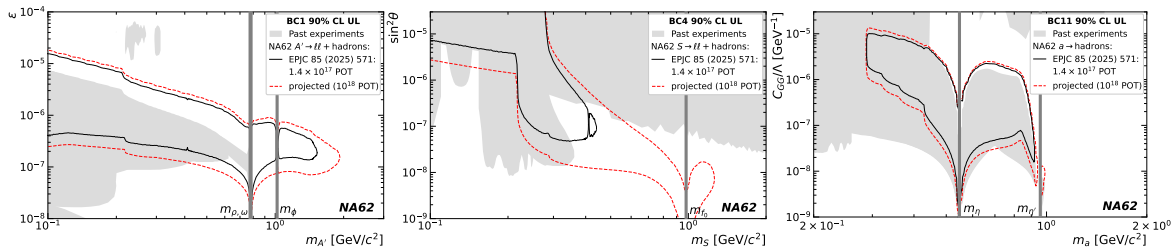


Figure: The observed 90% CL exclusion contours in BC4 (left), BC10 (center) and BC11 (right) benchmarks with 2021 data set together with the expected sensitivity for the full data sample.

# Summary

- NA62 is a multipurpose experiment allowing search for LLPs;
- Blind analyses searching for LLP decays  $X \rightarrow \ell^+ \ell^-$  and  $X \rightarrow \text{hadrons}$  have been performed on the beam-dump data collected in 2021;
- New regions of LLP parametric spaces were probed with no NP signal observed;
- Much more data in beam-dump already collected ( $> 9 \times 10^{17}$  POT);
- Data analysis of the larger sample in progress with no background limitation foreseen for all final states;
- New searches for LLP decay channels including semi-leptonic or di-gamma final states.
- Many more LLP searches in the kaon mode (**next talk**)

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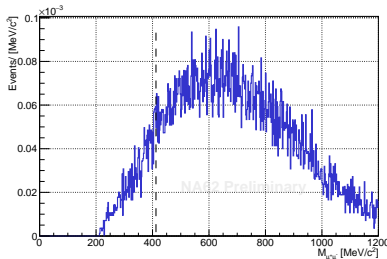
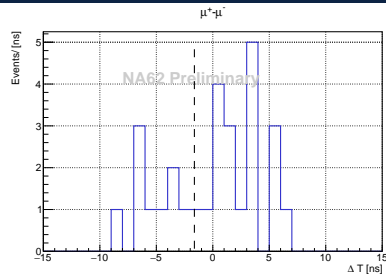
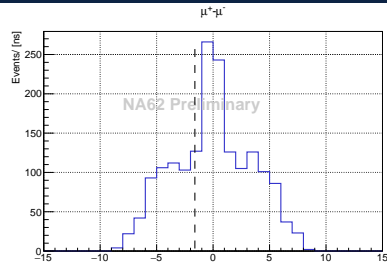
Thank you for your attention!

# Backup slides



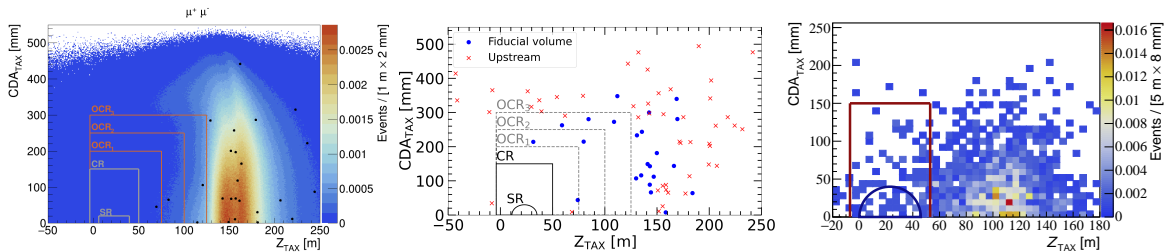
# Search for $A' \rightarrow \mu\mu$ - details on observed event

- 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
- $z_{FV} = 157.8$  m
- $CDA_{FV} = 382$  mm
- $z_{TAX} = 17$  mm
- $E/p(\mu^+) = 0.008$
- $E/p(\mu^-) = 0.018$



# Search for LLP decays in beam-dump mode (background)

Distributions of the simulated background events in the  $(Z_{\text{VTX}}, \text{CDA}_{\text{VTX}})$  plane for  $\mu^+\mu^-$ ,  $e^+e^-$  and  $\pi^+\pi^-(\gamma)$  final states:



# Search for LLP decays in beam-dump mode (PID)

- $\mu^\pm$ :  $E_{\text{LKr}}/p \sim 0 + \text{MUV3}$ ;
- $e^\pm$ :  $E_{\text{LKr}}/p \sim 1 + \text{!MUV3}$ ;
- $h^\pm$  ( $\pi^\pm$  and  $K^\pm$ ):
  - LKR+MUV12 BDT classifier  $p_\pi > 80\% + \text{!MUV3}$ ;
  - $K^\pm$ :  $h^\pm$  with  $K^+$  selected by RICH (else  $\pi^\pm$ );
  - search neutral LKr clusters and reconstruction of  $\gamma$ ,  $\pi^0$ ,  $\eta$  based on opening angle wrt decay vertex;