Workshop on status and perspectives of physics at high intensity

# Dark sector searches at NA62


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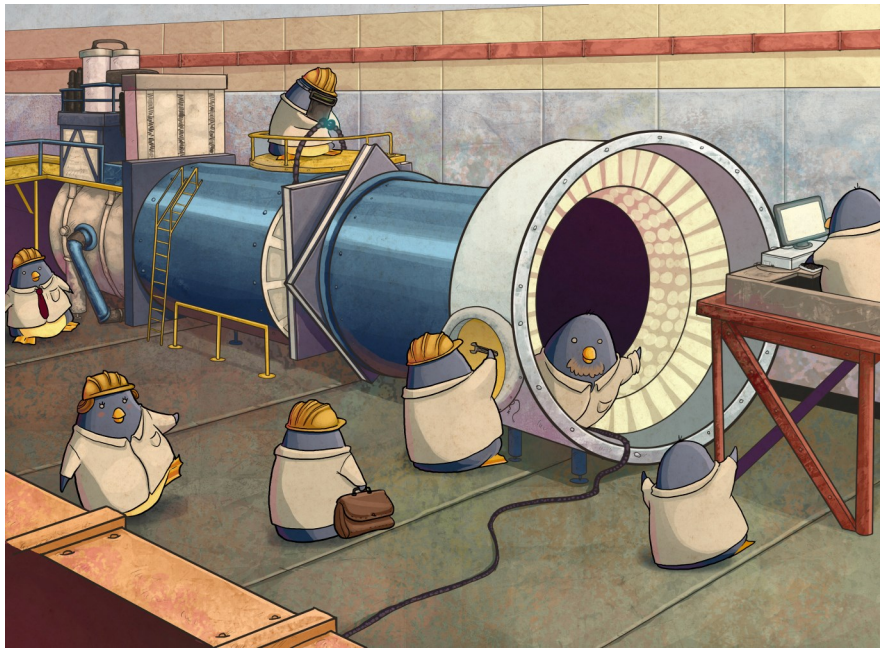
on behalf of NA62 Collaboration


European Research Council
Established by the European Commission

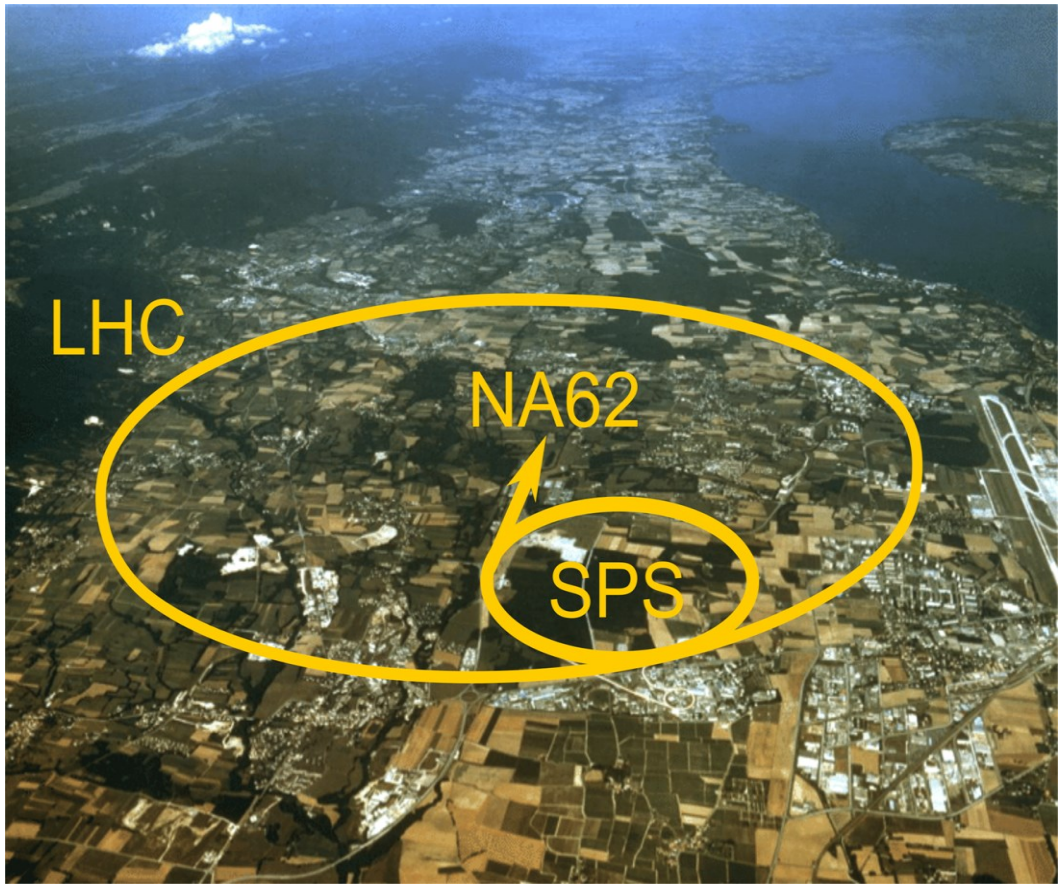
Frascati, 11th November

# Outline

- Overview of the NA62 experiment
- Searches for Heavy Neutral Leptons, Dark Scalars, Dark Photons (new results) and Axion-like Particles @NA62
- Summary



# The NA62 experiment




**~30 institutes, ~200 participants from:**
Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

**NA62** is a fixed-target experiment at CERN SPS

**Main goal**: measure $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ with 10% precision using novel kaon-in-flight technique

**Current theoretical prediction**:

$$\mathcal{B}(K^+ \to \pi\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

[Buras et al., JHEP11(2015)033]

**Experimental values**:

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$$

E949/E787[Phys. Rev D 79, 092004 (2009)]

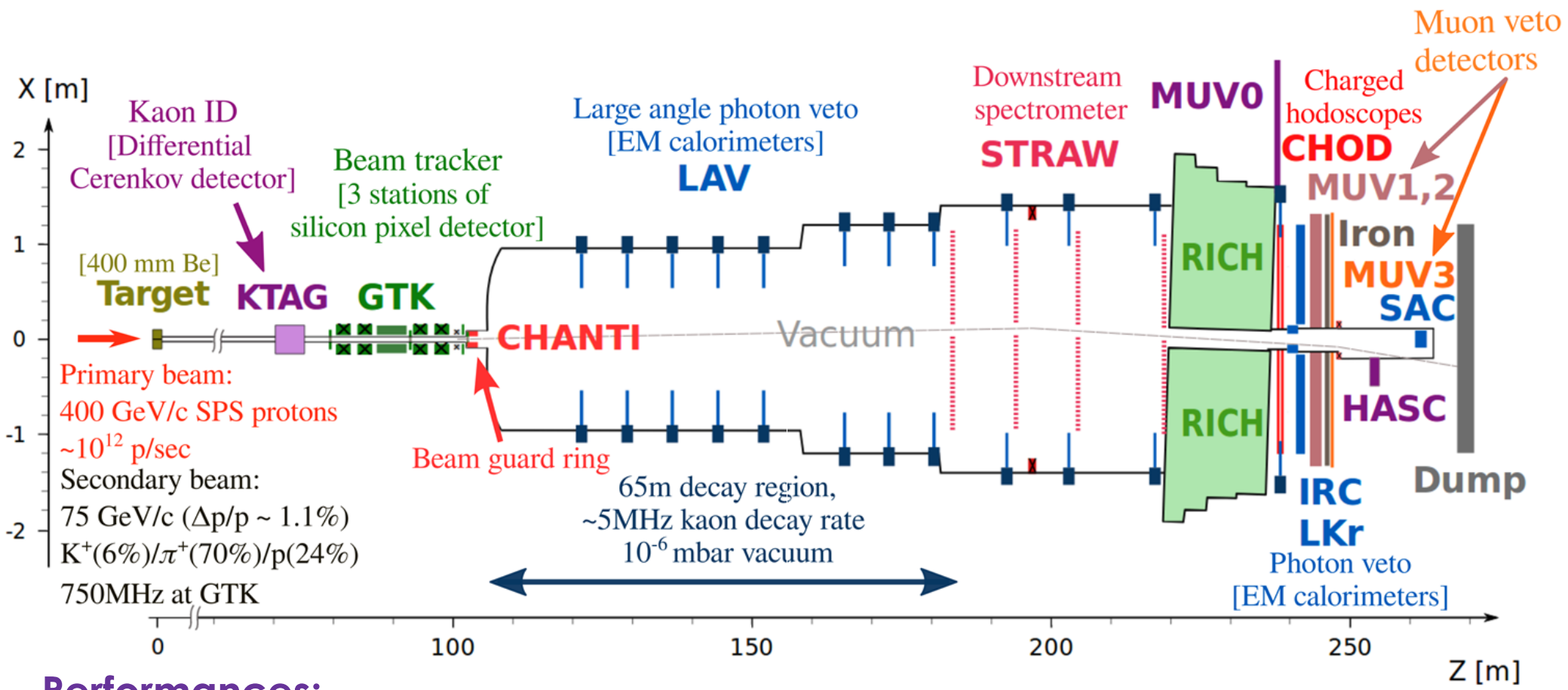
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(10.6^{+4.0}_{3.4\ stat} \pm 0.9_{syst}\right) \times 10^{-11}$$

NA62[JHEP06 (2021) 093]

**Broader physics programme:**

- **Rare/forbidden** kaon decays
- Searches for **exotic particles** in kaon decays and in **beam dump** mode

# Detector overview

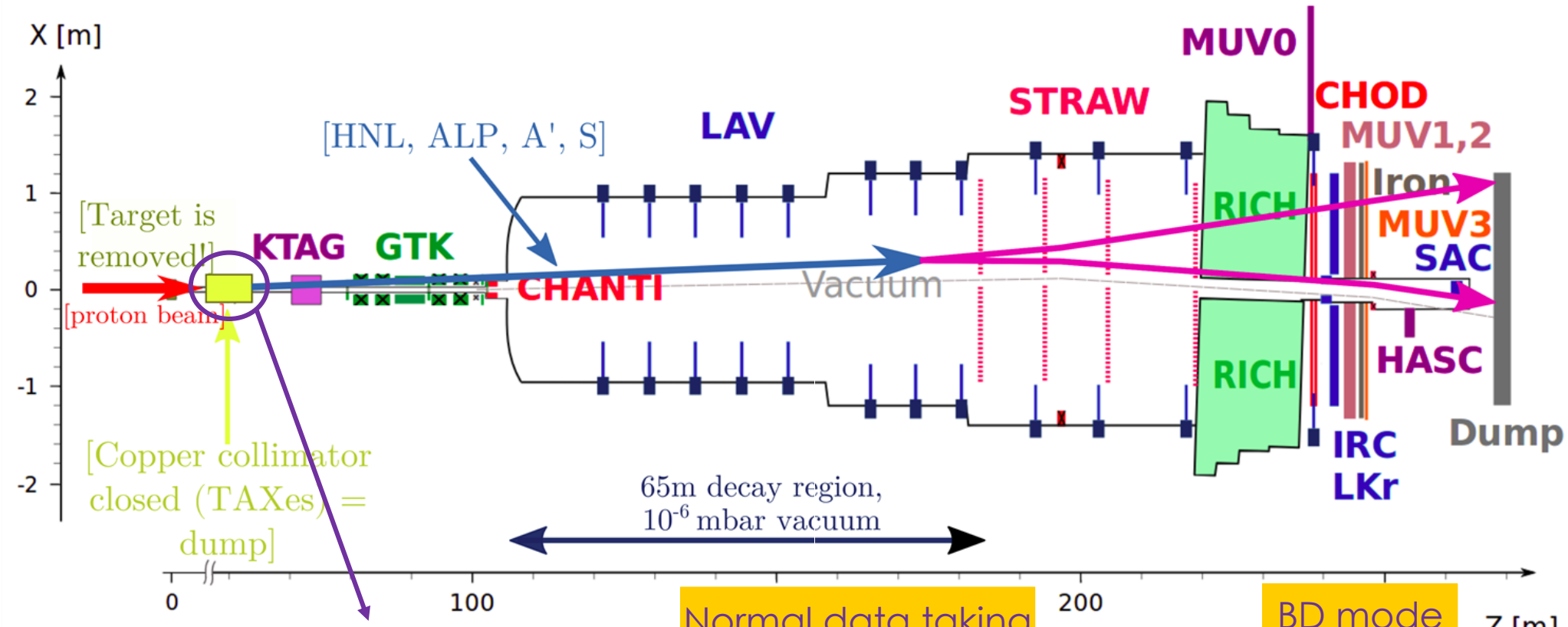


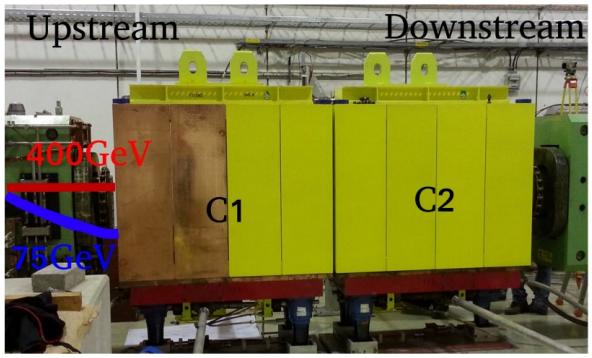

**Performances:**

- GTK-KTAG-RICH time resolution: $\mathcal{O}(100$ ps)
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $\mathcal{O}(10^7)$ muon rejection for 15 <p($\pi^+$)< 35 GeV
- $\mathcal{O}(10^8)$ $\pi^0$ rejection of for E($\pi^0$)> 40 GeV

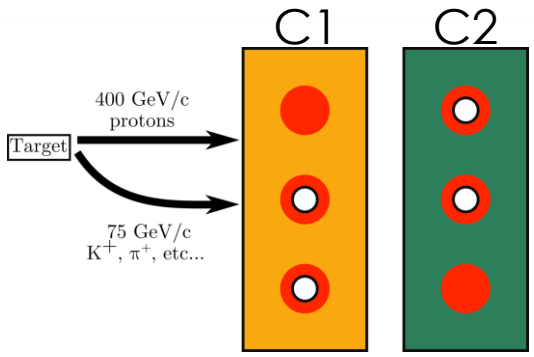
[JINST 12 (2017), P05025]

# NA62 in beam dump mode

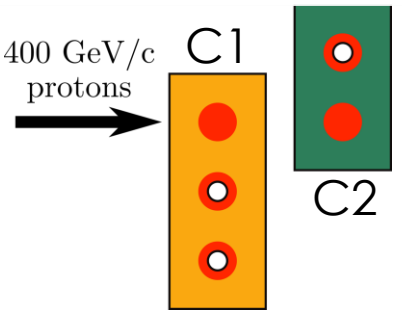


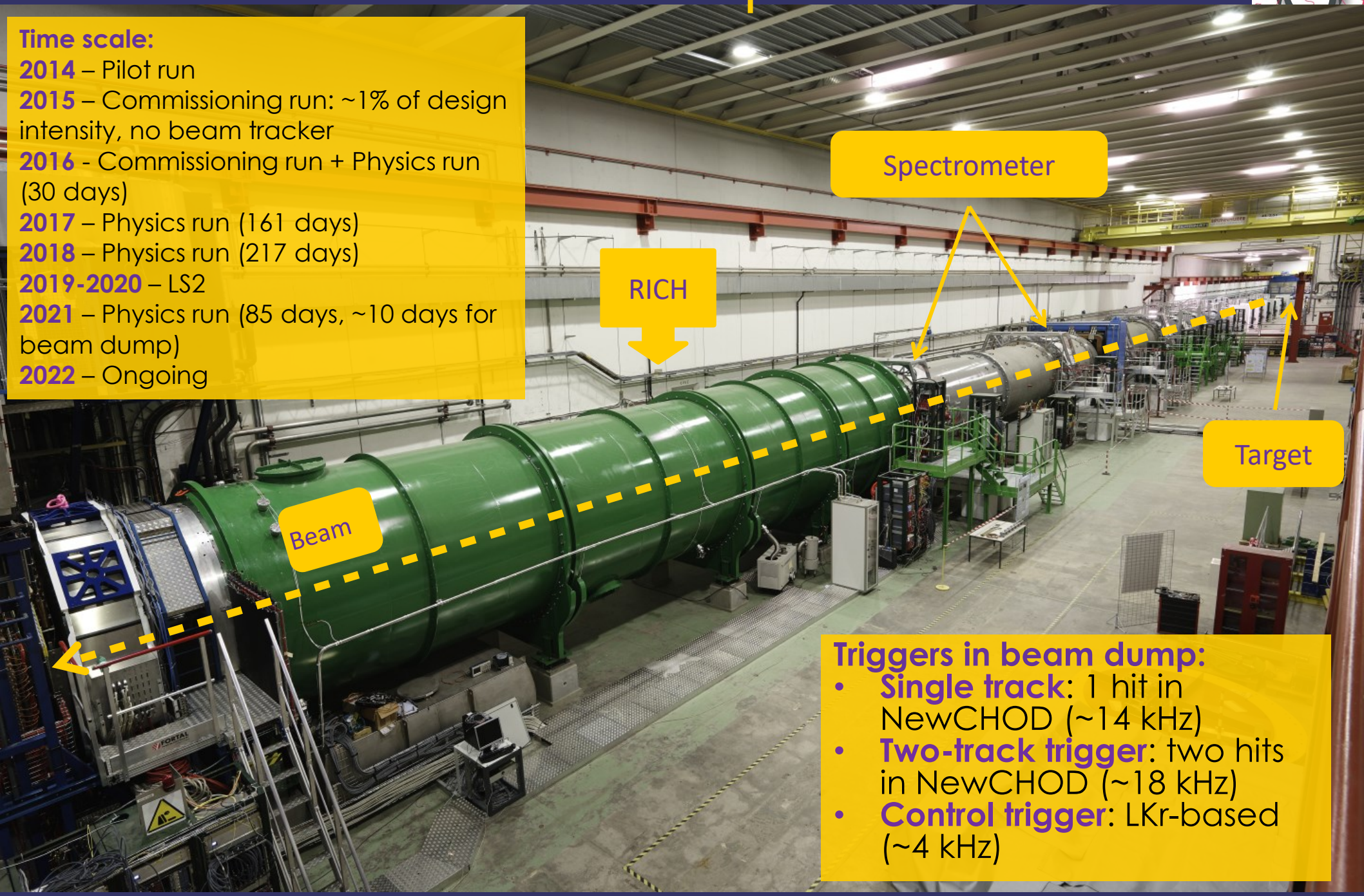

Normal data taking




BD mode



# The NA62 experiment




**Time scale:**
**2014** – Pilot run
**2015** – Commissioning run: ~1% of design intensity, no beam tracker
**2016** - Commissioning run + Physics run (30 days)
**2017** – Physics run (161 days)
**2018** – Physics run (217 days)
**2019-2020** – LS2
**2021** – Physics run (85 days, ~10 days for beam dump)
**2022** – Ongoing

**Triggers in beam dump:**
- **Single track**: 1 hit in NewCHOD (~14 kHz)
- **Two-track trigger**: two hits in NewCHOD (~18 kHz)
- **Control trigger**: LKr-based (~4 kHz)

# FIPs Searches: benchmark scenarios

- Neutrino portal → HNL:

$$\mathcal{L} \subset F_{\alpha I}\left(\overline{L}_{\alpha} H\right) N_I$$

- Scalar Portal → Dark Scalar:

$$\mathcal{L} \subset (\mu S + \lambda S^2) H^{\dagger} H$$

- Axion portal → ALP:

$$\mathcal{L} \subset \frac{C_{aX}}{\Lambda} a X_{\mu\nu} \tilde{X}^{\mu\nu}, \frac{C_{af}}{\Lambda} \partial_{\mu} a \overline{f} \gamma^{\mu} \gamma^{5} f, X = \{B, W, G\}, f = \{q, l\}$$

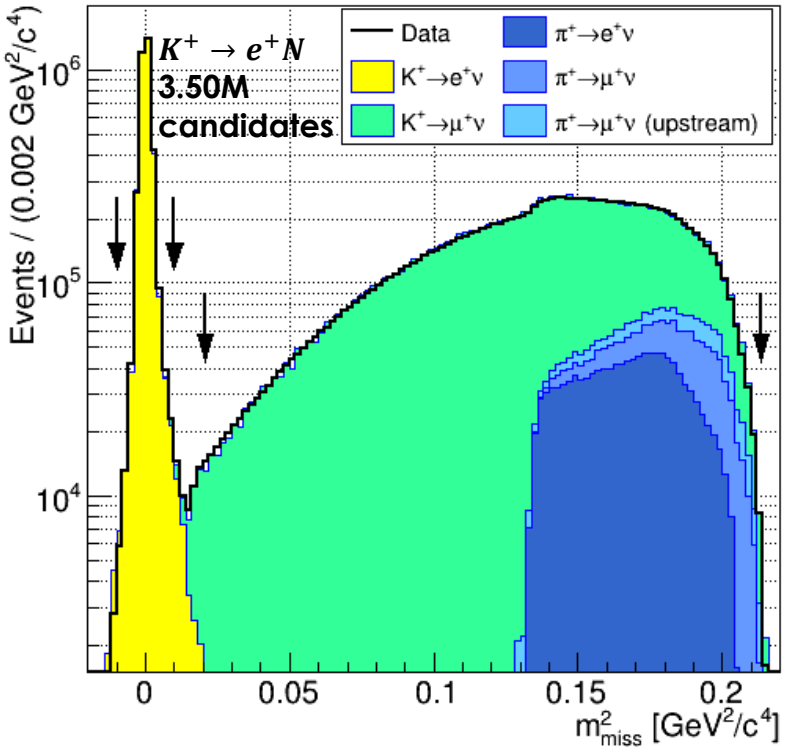
- Vector portal → Dark Photon:

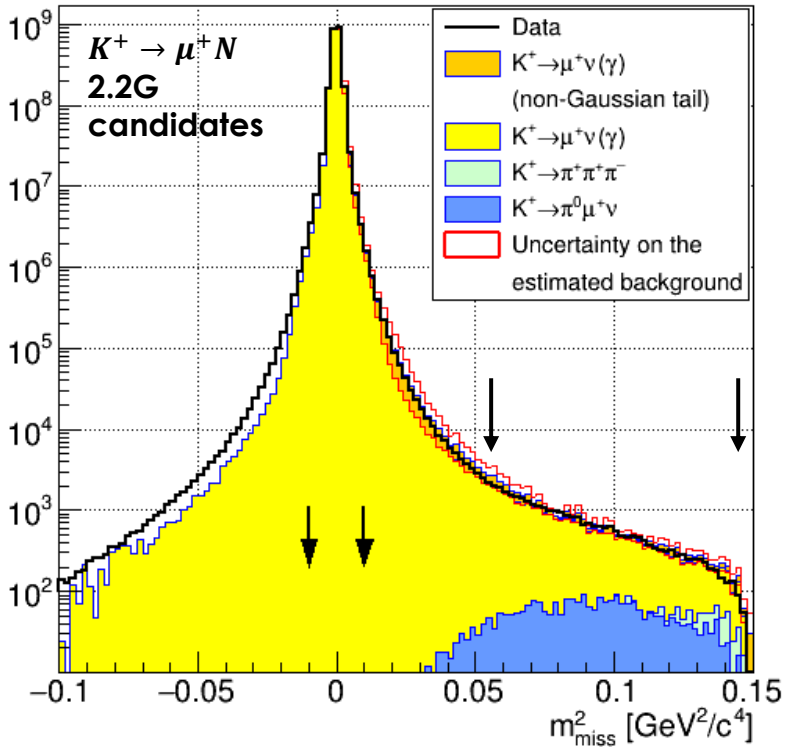
$$\mathcal{L} \subset -\epsilon \frac{1}{2 cos\theta_W} F'_{\mu\nu} B_{\mu\nu}$$

[arXiv:1901.09966]

# HNL searches in kaon decays

- Searches for HNL production in $K^+ \to l^+ N, l = \{e, \mu\}$ decays.
- N is assumed to be long-lived ($\tau_N > 50$ ns)
- Peak searches in the squared missing mass $m^2_{miss} = (P_K - P_l)^2$:
  - Scan in mass steps $\mathcal{O}(1\ \text{MeV}/c^2)$ in mass range: 144-462 MeV/$c^2$ $K^+ \to e^+ N$ and 200-384 MeV/$c^2$ for $K^+ \to \mu^+ N$



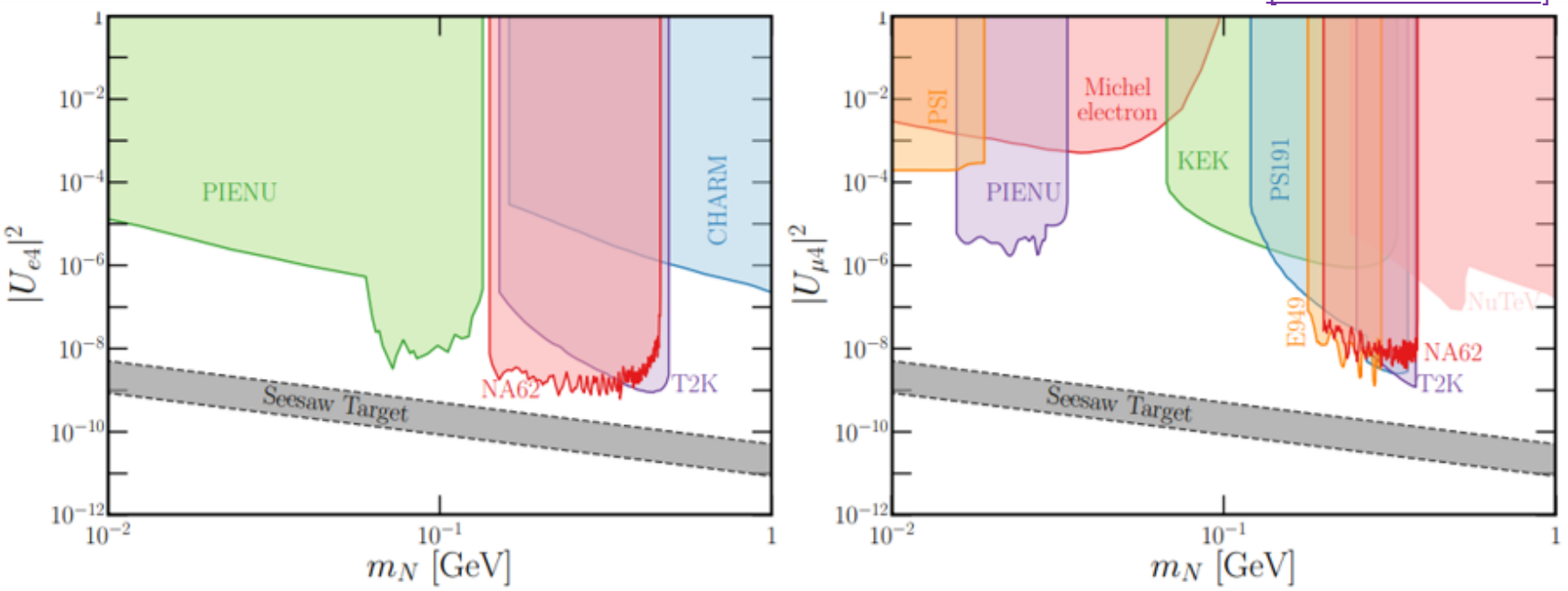




Full Run1 dataset

[PLB 807 (2020) 135599 ]
[PLB 816 (2021) 136259]

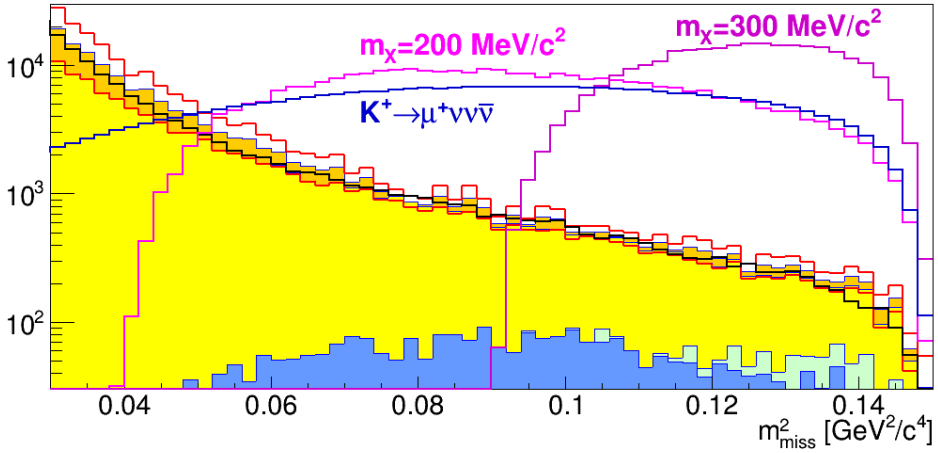
# HNL searches in kaon decays

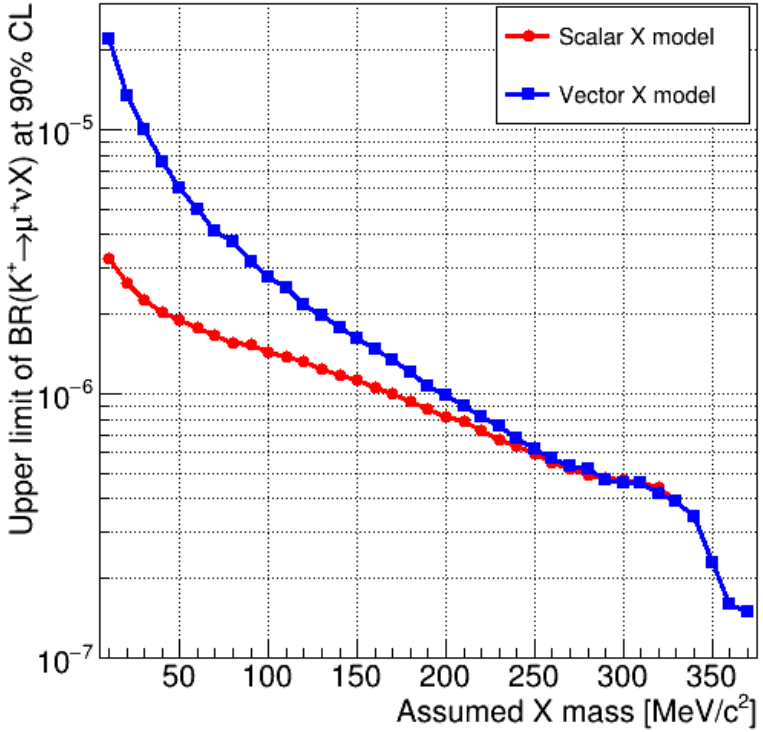
[arXiv:2201.07805]




- No signal observed
- 90% CL UL were set complementing HNL production searches from PIENU, E949 and HNL decay searches from T2K
- Close related study: $K^+ \to l^+ \nu\nu\nu$ and $K^+ \to l^+ \nu X$, $X$ is invisible: predict background from MC simulation

# $K^+ \to \mu^+\nu\nu\nu$ and $K^+ \to \mu^+\nu X$



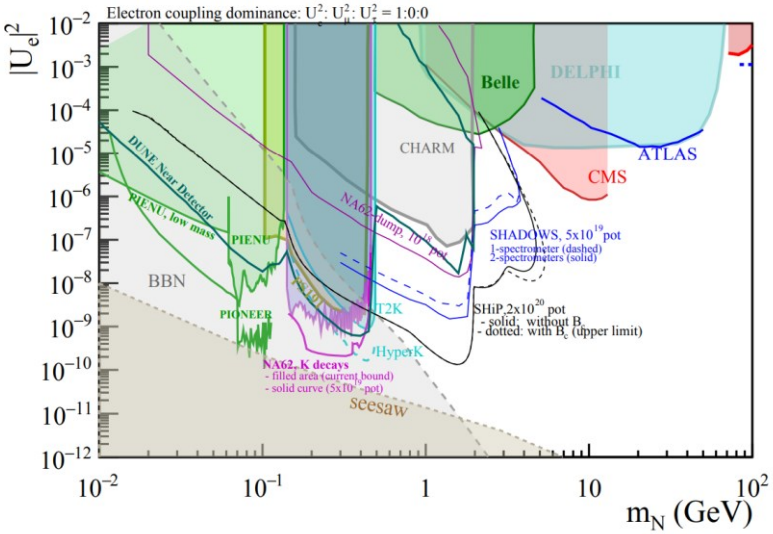

$K^+ \to \mu^+\nu\nu\nu$:

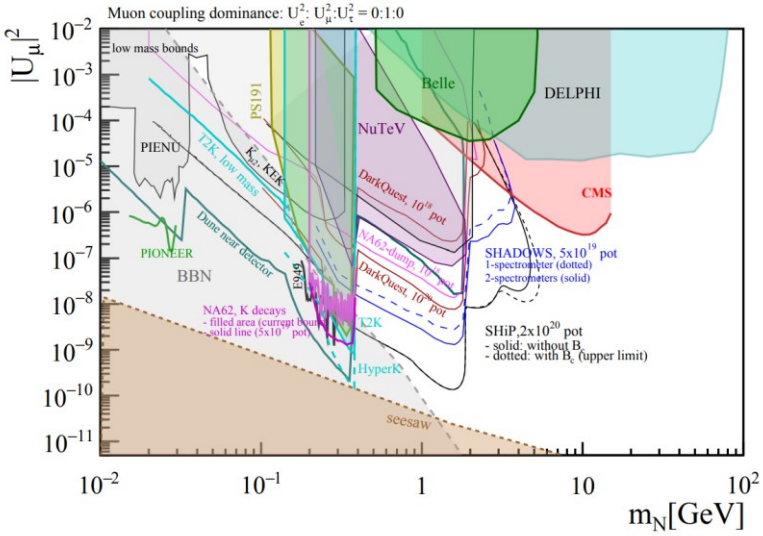
- Very rare in the SM: $\mathcal{B}(K^+ \to \mu^+\nu\nu\nu) = 1.6 \times 10^{-16}$ [JHEP1610 (2016) 039]
- The current limit: $< 2.4 \times 10^{-6}$ [E949, PRD94 (2016) 032012]
- Search region $m^2_{miss} > 0.1\ GeV^2/c^4$ (optimized to extract strongest limit)
- No signal observed
- Set upper limit: $1.0 \times 10^{-6}$ at 90%CL in the SM framework

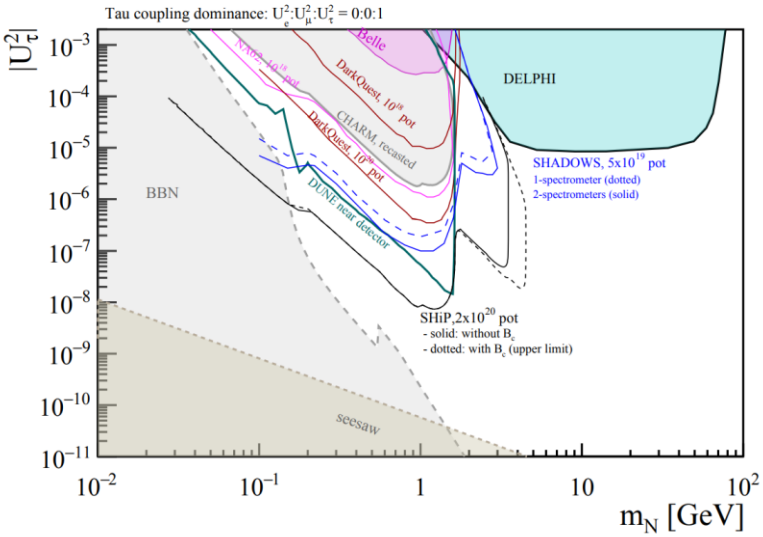
$K^+ \to \mu^+\nu X$, $X$ is scalar or vector

- [PRL124 (2020) 041802]
- Mass range $10 - 370\ MeV/c^2$
- No signal observed
- The limits obtained in the scalar model are stronger than those in the vector model due to larger mean $m^2_{miss}$ value.

# HNL searches in beam dump mode



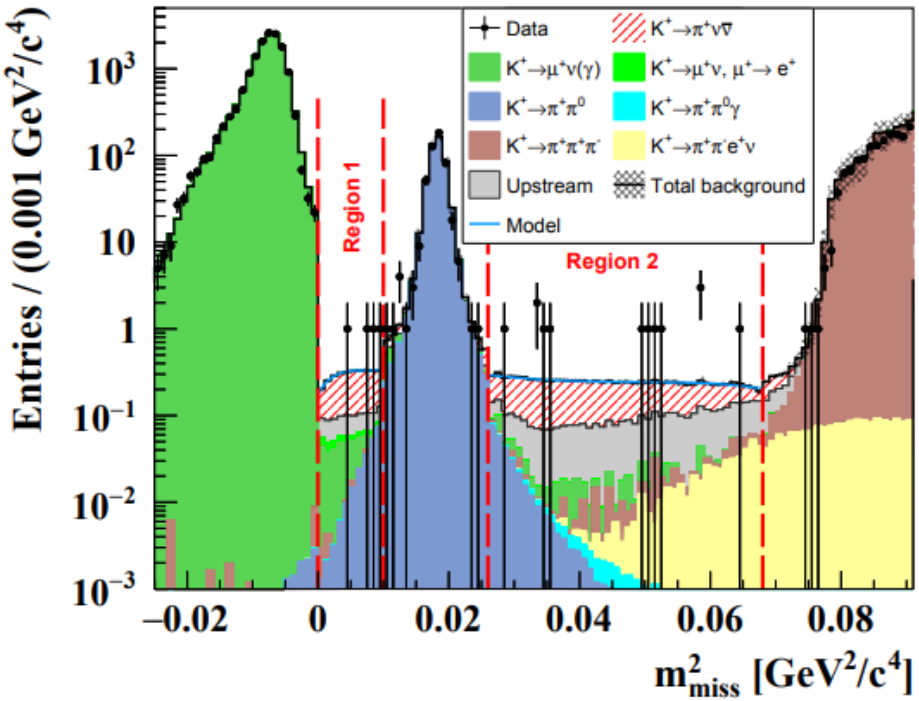

Sensitivity of NA62 to searches for HNL decays into visible 2-track final states assuming $10^{18}$ protons on dump and 0 background events.

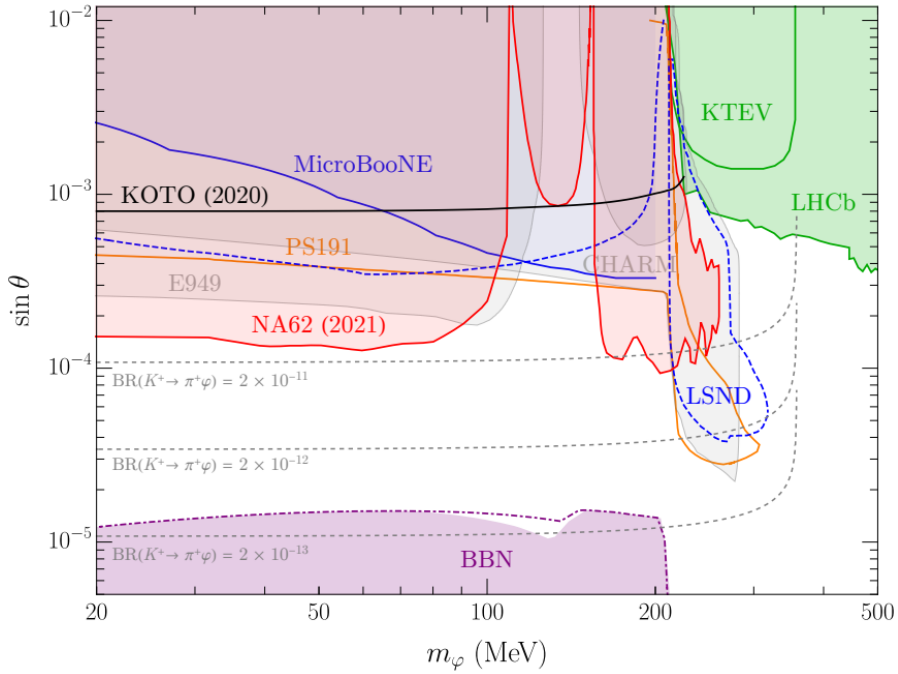
HNLs are produced in decays of B- and D-mesons

[arXiv:2203.08039]

# Dark Scalar searches in kaon decays

[arXiv:2201.07805]



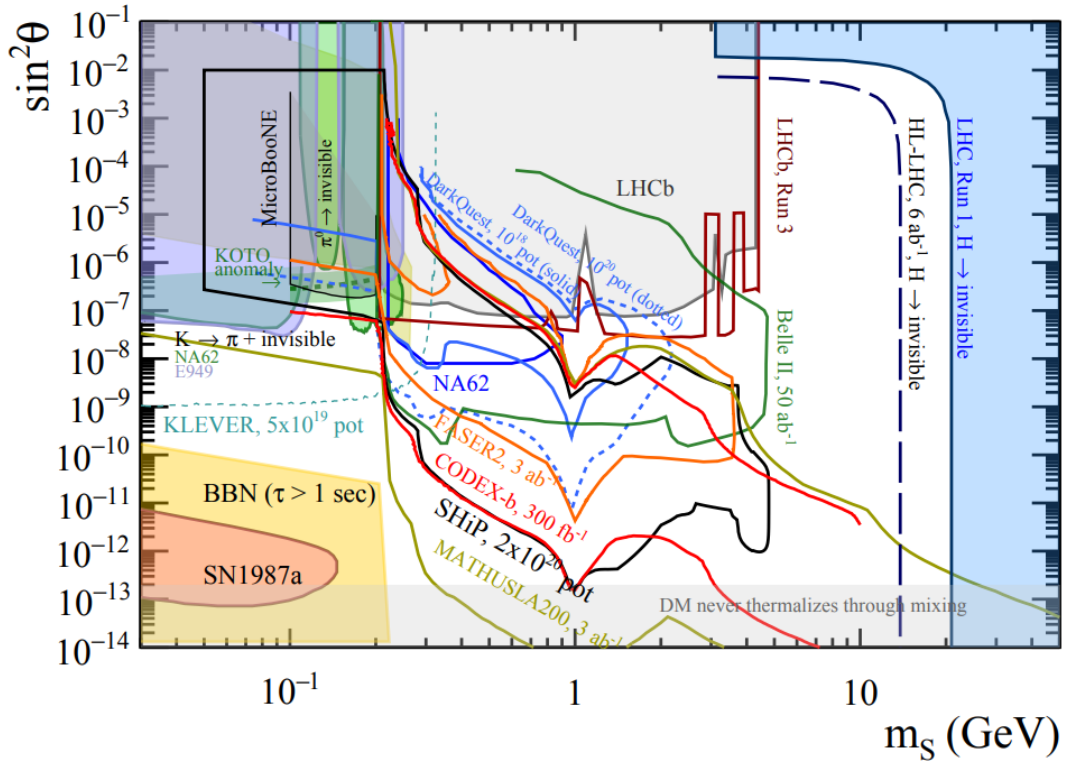

Searches for $K^+ \to \pi^+ X$ in 3 mass regions:

- $0 \le m_X \le 110$ MeV/$c^2$ (R1) and $154 \le m_X \le 260$ MeV/$c^2$ (R2) with $K^+ \to \pi^+ \nu\,\overline{\nu}$ as the main background
- $110 < m_X < 154$ MeV/$c^2$ with $K^+ \to \pi^+\pi^0$ as the main background

Results can be interpreted in different models: DS, ALP, QCD axion, axiflavon…

[JHEP03(2021)058]
[JHEP 2021, 201 (2021)]

# Dark Scalar searches in beam dump mode

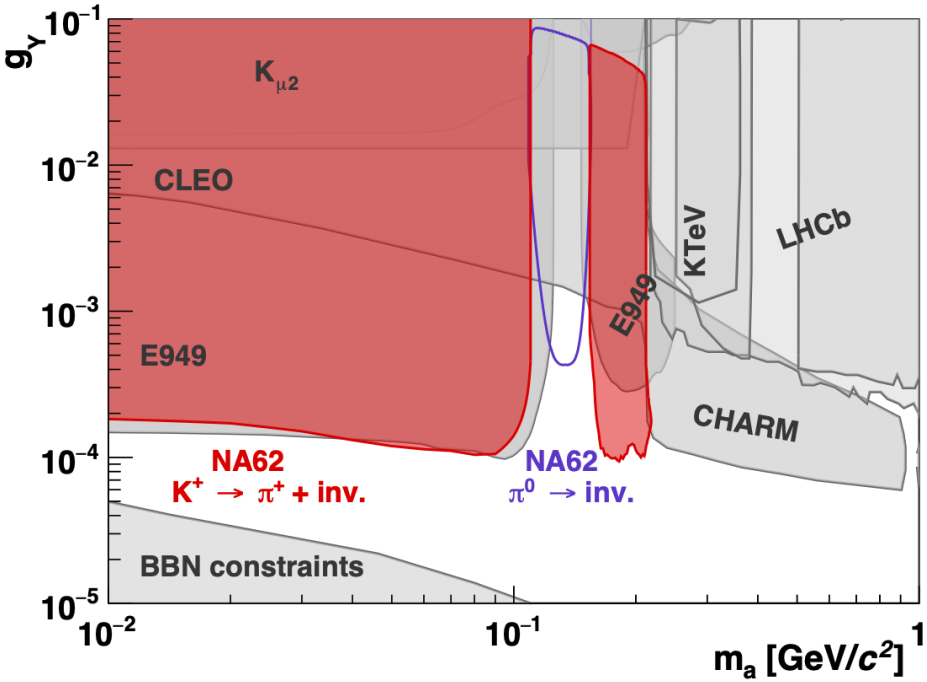



Higher masses can be probed with beam dump mode of NA62:

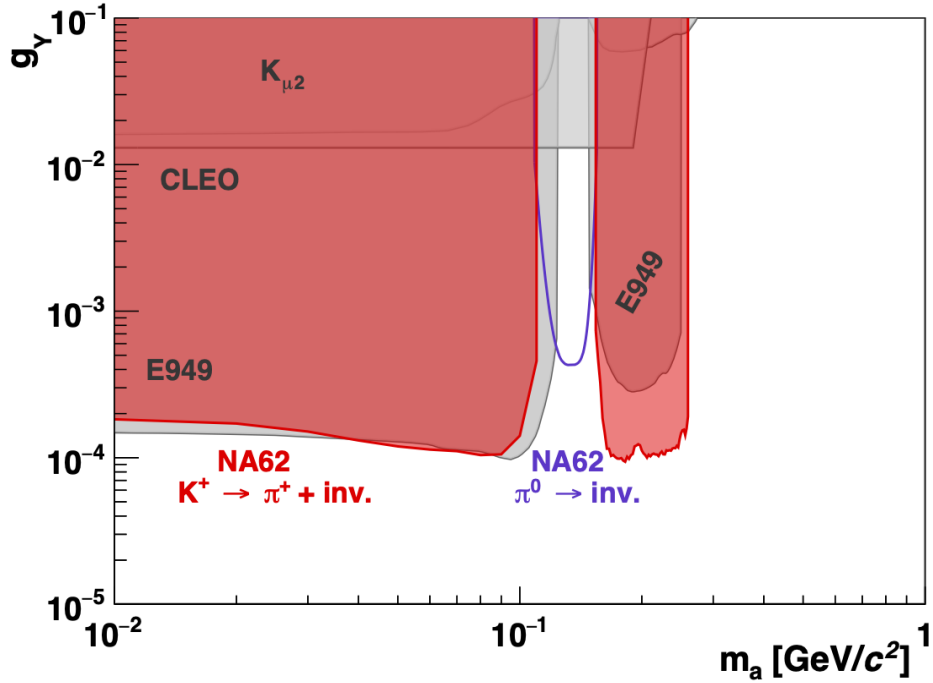
- 2-charged track final states
- $10^{18}$ protons on dump
- Production from B-meson decays

[arXiv:2102.12143]

# ALP searches in kaon decays




ALP decays to visible SM particles



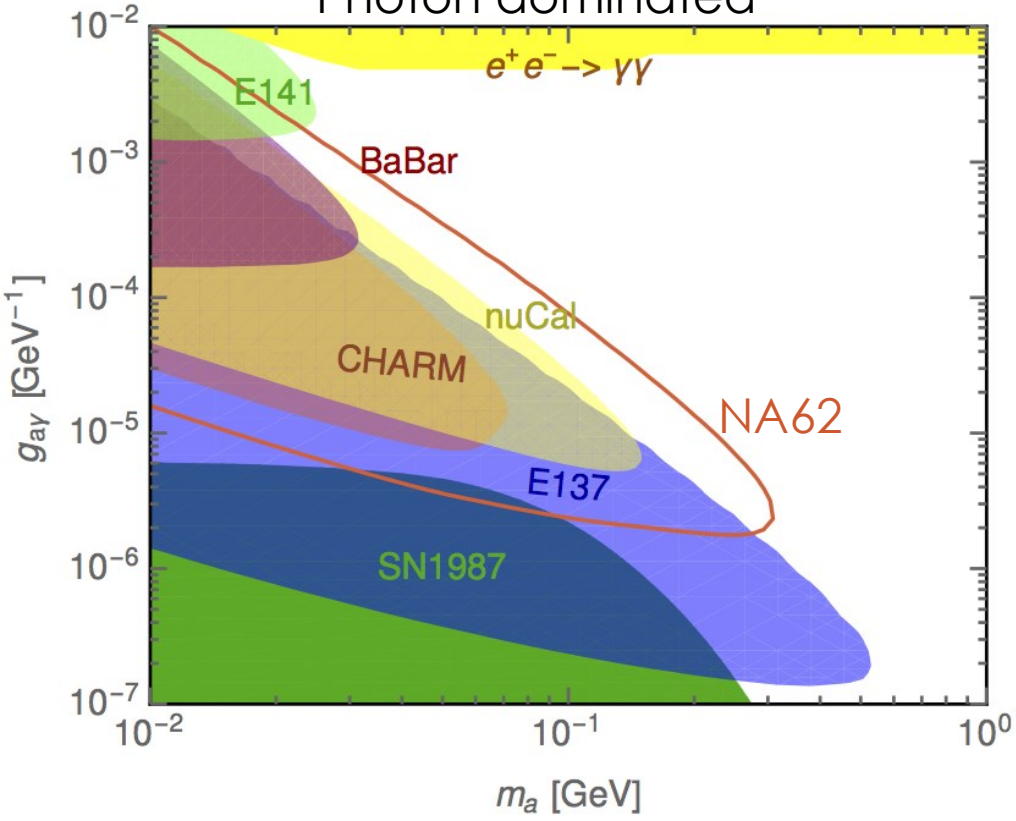

ALP decays to invisible particles
or it is long-lived

Searches for $K^+ \to \pi^+ X$ with $g_Y$ being universal ALP coupling to quark and lepton.
More interpretations of the result are in [arXiv:2201.07805]
Searches for $K^+ \to \pi^+ X, X \to l^+ l^-$ are also possible

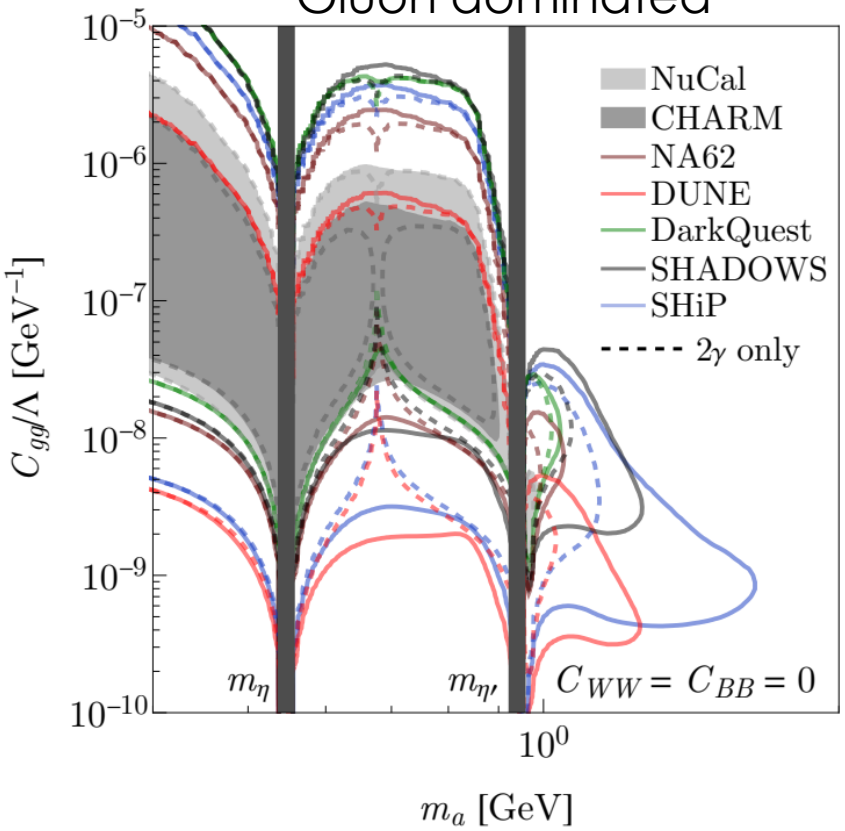
[JHEP03(2021)058]
[JHEP 2021, 201 (2021)]

# ALP searches in beam dump mode

Photon dominated




Gluon dominated




ALP masses up to 1 GeV/$c^2$ can be probed with help of NA62 beam dump data

- Neutral or charged final states
- $10^{18}$ protons on dump
- Production from Primakoff process and rare meson decays

[JHEP05(2019)213]
[JHEP07(2022)094]

# Sensitivity of NA62 to the DP

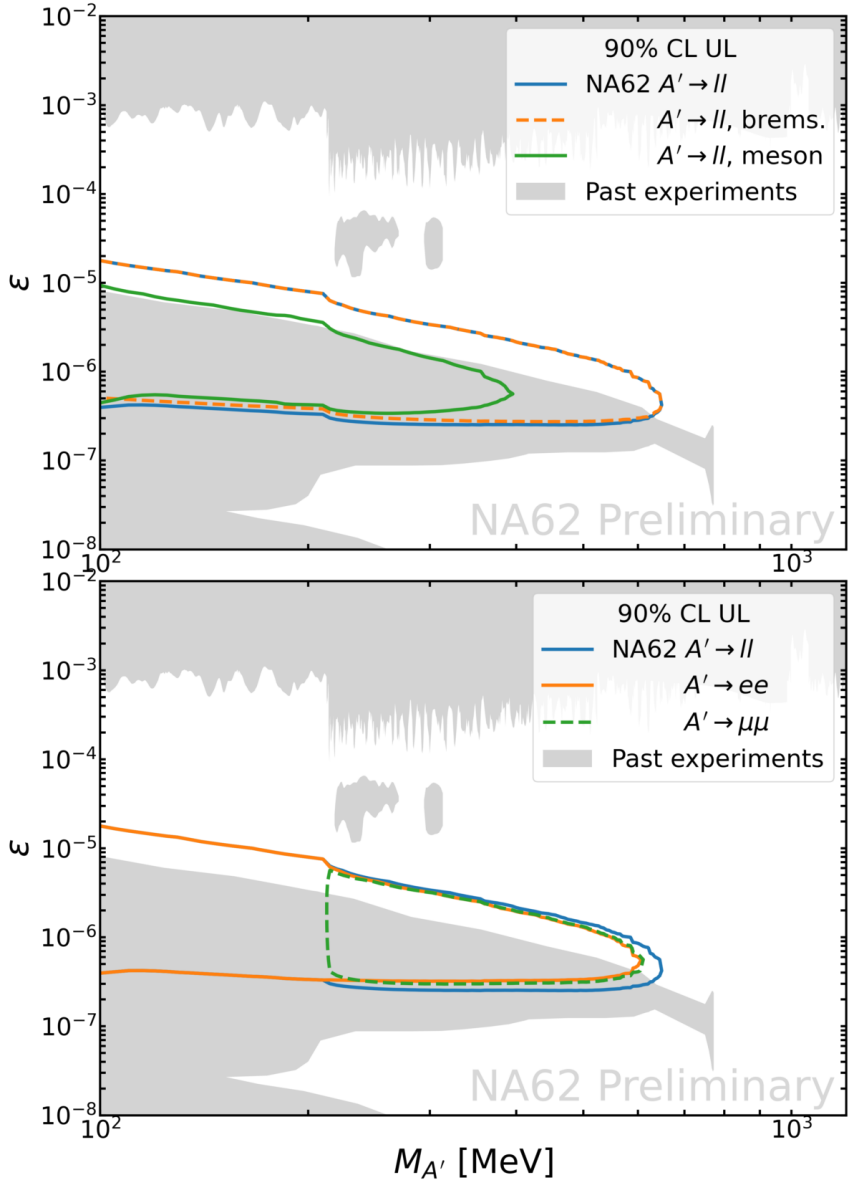
In the mass range <700 MeV/$c^2$, DP decay width is dominated by lepton-antilepton final states

Two production mechanisms are in action in proton-nucleus interaction scenario:

- Bremsstrahlung production in $pN \to XA'$
- Meson mediated production as $pN \to XM, M \to A'\gamma(\pi^0)$, where $M = \pi^0, \omega, \rho$ etc.

In 2021, NA62 collected $(1.40 \pm 0.28) \times 10^{17}$ POT.

Assuming mass and coupling to be free parameters, lepton decay mode of DP, geometrical acceptance of NA62 and 0 events observed, evaluate expected 90%CL upper limits




*The grey underlying exclusion is the one adapted by the PBC and taken from DarkCast [JHEP06(2018)004]
Several limits may differ from PBC and are taken by DarkCast team from [Phys. Rev. Lett. 126, no.18, 181801 (2021)]

# Analysis strategy

**The signal signature**:

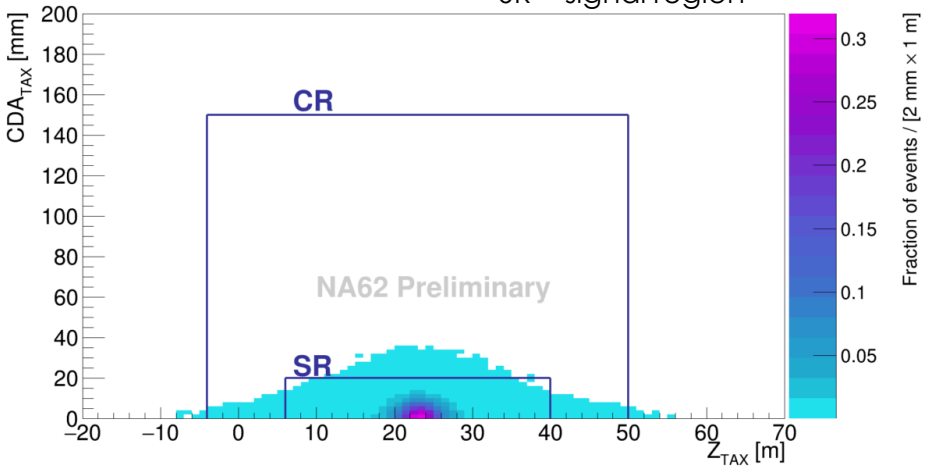
- $\mu^+\mu^-$ vertex reconstructed within the NA62 fiducial volume and pointing back to the proton beam interaction point at the TAXes.

**Event selection**:

- reconstructed track quality
- track timing coincidence with the trigger (10 ns)
- muon identification with calorimeter and muon detector
- no in-time activity at large angle veto detectors (LAV) to reduce possible selection of vertices derived by interaction of incoming muons with the material in the LAVs.
- Signal region (SR) selection

CR and SR kept blind up to the analysis approval

CR = control region
SR = signal region




$CDA_{TAX}$ – closest distance of approach between the beam direction at the TAX entrance and the lepton-antilepton pair direction $\sigma_{CDA} =$ ~7 mm

$Z_{TAX}$ – longitudinal position, $\sigma_Z =$ ~5.5 m

Signal region:
$6 < Z_{TAX} < 40$ m & $CDA_{TAX} < 20$ mm

# Background studies

## 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
- Apply same event selection criteria as in the analysis
- Each track pair has a weight to account for the 10 ns time window → independent on the rate

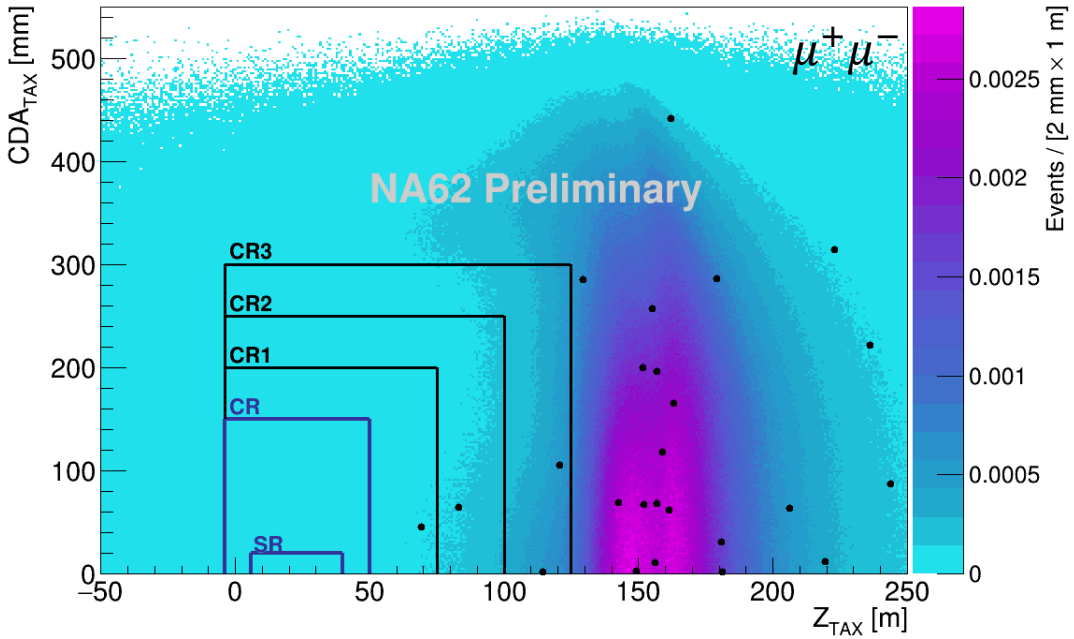
## Prompt background

Background from secondaries of a muon interaction with the traversed material

- Muon kinematic distributions extracted from selected single muons in data (backward MC)
- To correct the spread induced by the backward-forward process (straggling, multiple scattering) an unfolding technique is applied to better reproduce the data distributions.
- Relative uncertainty of MC expectation ~ 100%

Prompt background negligible with respect to combinatorial (UL @ 90%CL is 30% of combinatorial)

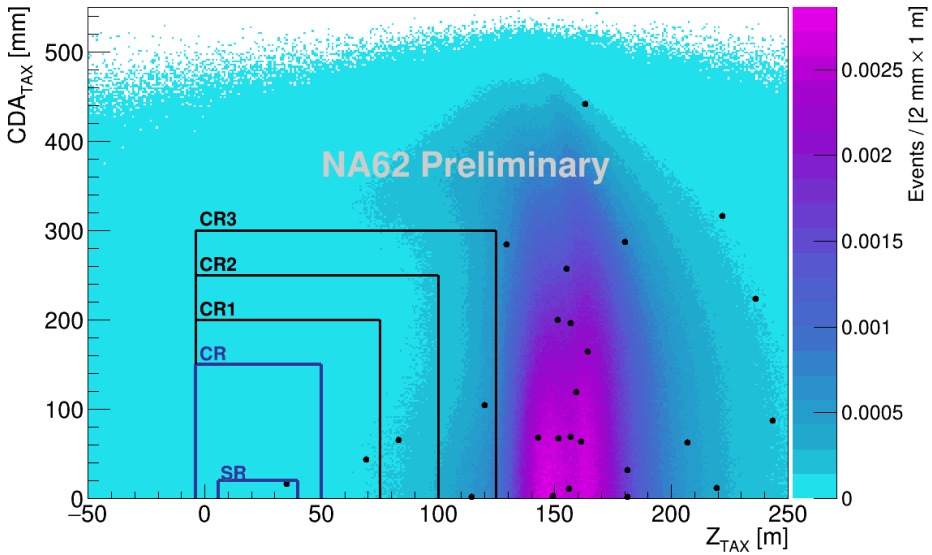
# Data-MC comparison: signal sample, CRs open

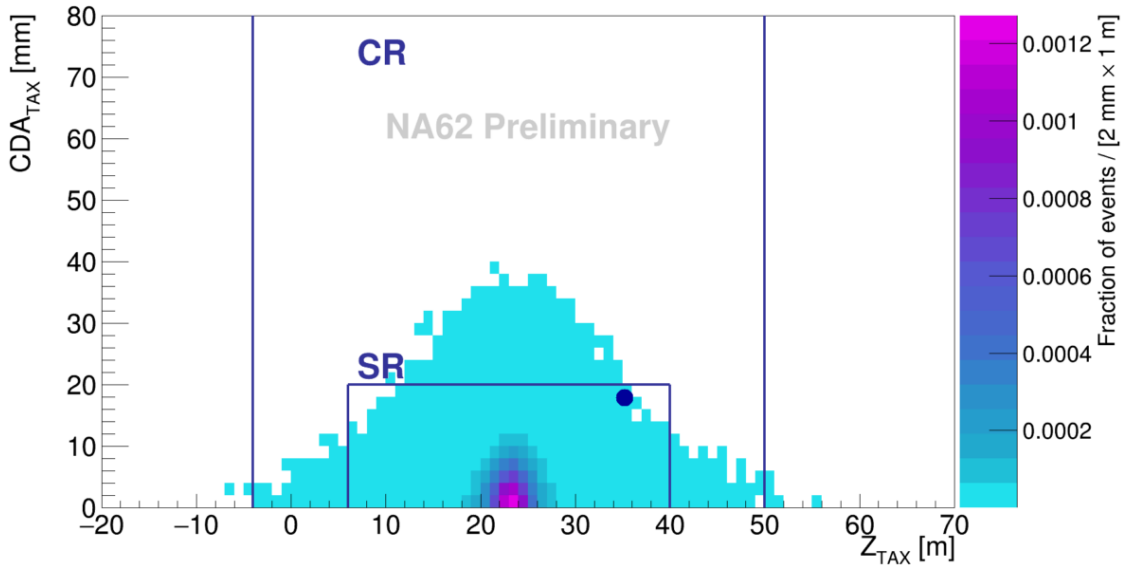



Probability to observe 1 or more events in the SR is 1.59%

| | $N_{exp} \pm \delta N_{exp}$ | $N_{obs}$ | $p(N \geq N_{obs})$ | $p(L \leq L_{obs})$ |
|---|---|---|---|---|
| Outside CR | $26.3 \pm 3.4$ | 28 | 0.47 | 0.74 |
| CR1 | $0.29 \pm 0.04$ | 1 | 0.25 | 0.25 |
| CR2 | $0.58 \pm 0.07$ | 1 | 0.44 | 0.44 |
| CR3 | $1.70 \pm 0.22$ | 2 | 0.50 | 0.68 |
| CR1+2+3 | $2.57 \pm 0.33$ | 4 | 0.26 | 0.24 |
| CR | $0.17 \pm 0.02$ | 0 | 1.0 | 1.0 |
| SR | $0.016 \pm 0.02$ | - | - | - |

# Data-MC comparison: signal sample, SR open

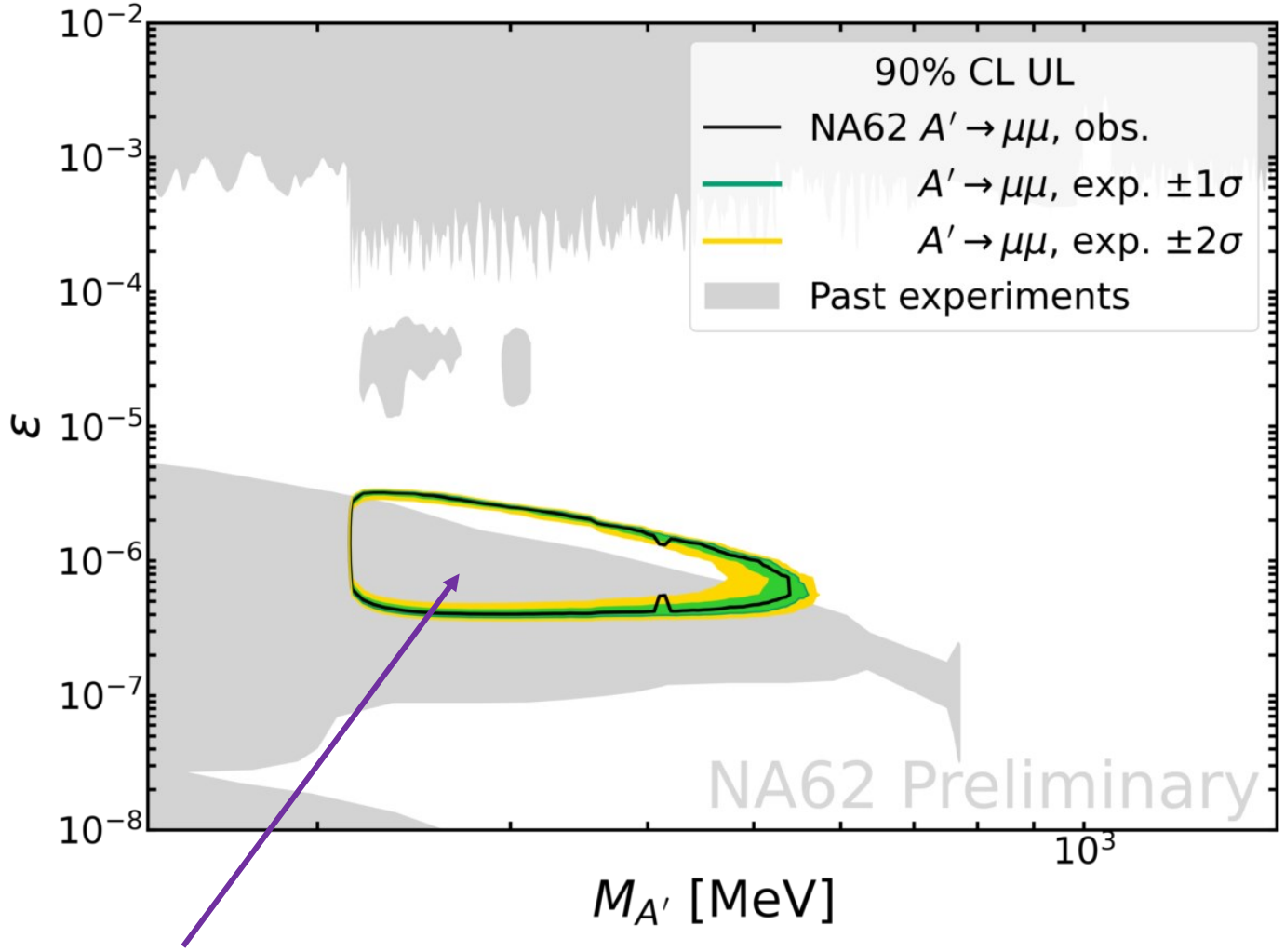



1 event observed
Counting experiment with $2.4\sigma$ global significance

Signal shape was not taken into account for the significance

# Final result




Excluded region

# Summary

- The NA62 experiment is a powerful laboratory to search for exotic particles/processes
- With NA62 Run 1 data produced results for Dark Scalars, ALP, HNL production searches
- With $(1.4 \pm 0.28) \times 10^{17}$ POT collected in 2021a 90% CL upper limit on $A' \to \mu^+\mu^-$ decay has been set, exploring a new region of the parameter space.
- Searches for decays of exotic particles to $e^+e^-, \gamma\gamma, \pi^+\pi^-\gamma$ final states, using the data collected in 2021, are ongoing.
- NA62 intends to take $10^{18}$ POT in beam dump in 2022-2025 with interesting perspectives on Dark Photons, ALPs, Dark Scalars and HNLs

**HIKE, High Intensity Kaon Experiments at the CERN SPS**

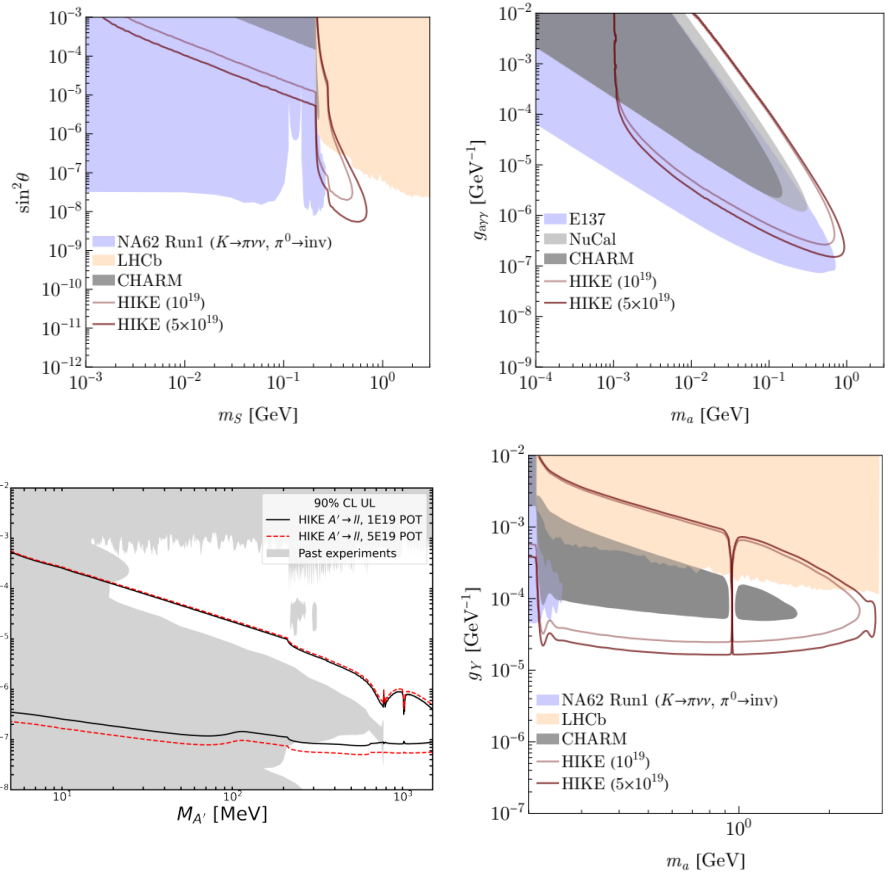
**Letter of Intent**

The HIKE Collaboration

CERN-SPSC-2022-031 / SPSC-I-257
07/11/2022

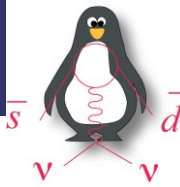
**Abstract**

A timely and long-term programme of kaon decay measurements at a new level of precision is presented, leveraging the capabilities of the CERN Super Proton Synchrotron (SPS). The proposed programme is firmly anchored on the experience built up studying kaon decays at the SPS over the past four decades, and includes rare processes, CP violation, dark sectors, symmetry tests and other tests of the Standard Model. The experimental programme is based on a staged approach involving experiments with charged and neutral kaon beams, as well as operation in beam-dump mode. The various phases will rely on a common infrastructure and set of detectors.




Submitted this week: [CERN-SPSC-2022-031]


Thank you!




# Backup slides

# Observed event

$M_{\mu\mu}$ = 411 MeV/$c^2$

$\Delta T$ = -1.69 ns

$P(\mu^+)$ = 99.5 GeV/c

$P(\mu^-)$ = 39.5 GeV/c

$Z_{FV}$ = 157.8 m

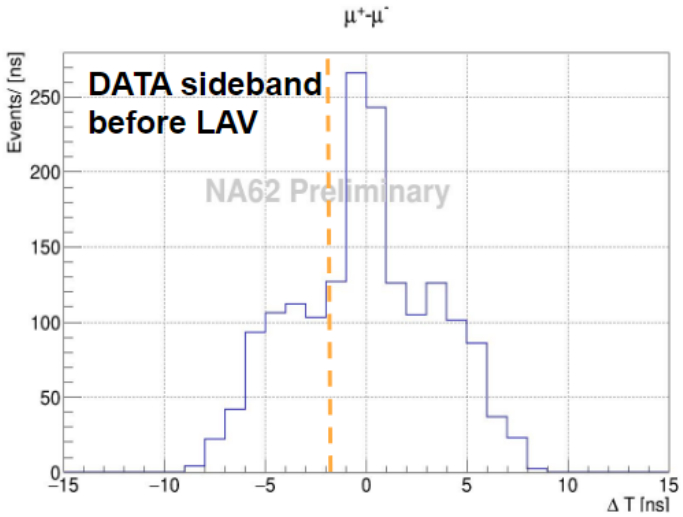
$CDA_{FV}$ = 382 mm

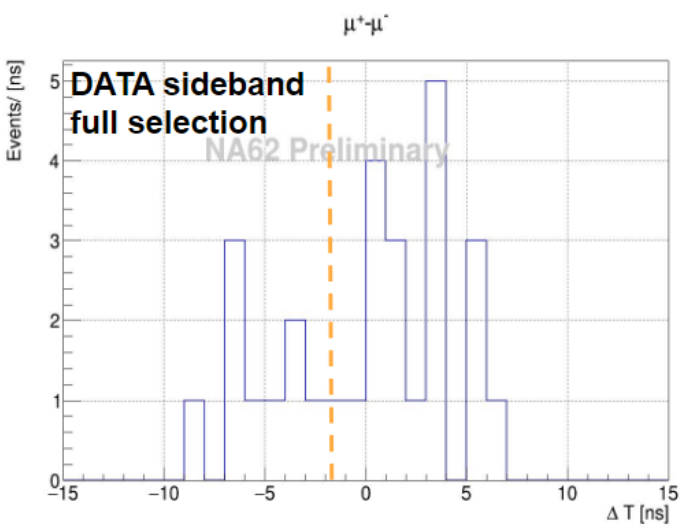
$Z_{TAX}$ = 35.3 m

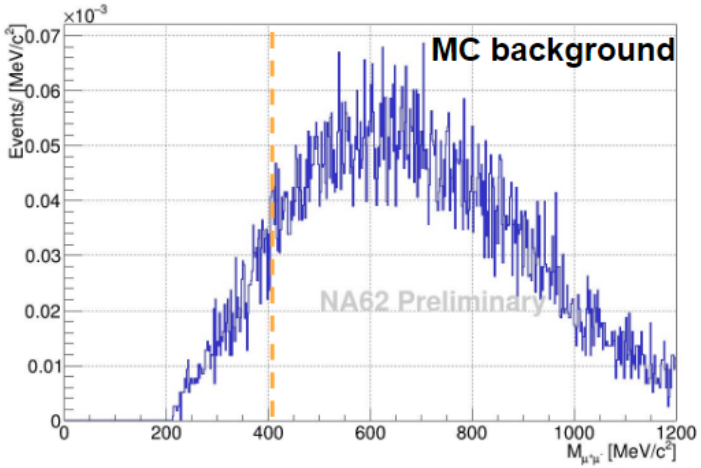
$CDA_{TAX}$ = 17 mm

$E/P(\mu^+)$ = 0.008

$E/P(\mu^-)$ = 0.018



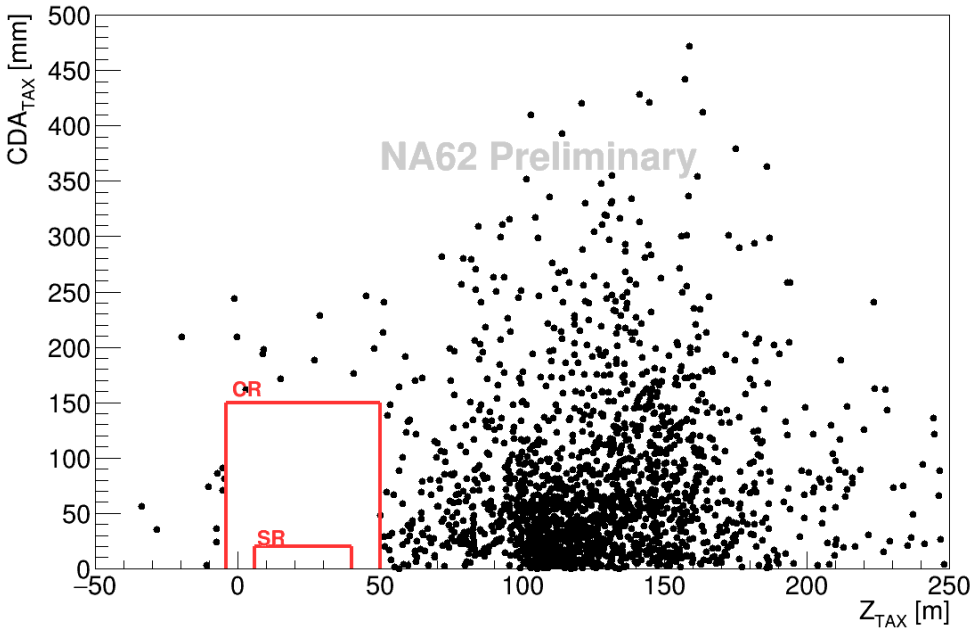



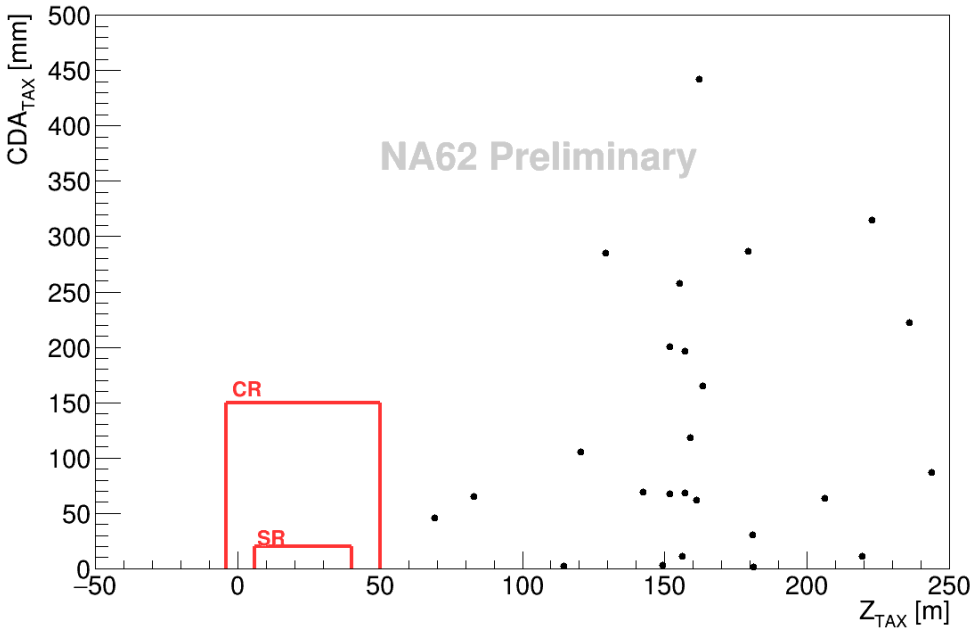
# Background summary for $A' \rightarrow \mu^+\mu^-$ analysis

| | Combinatorial | Prompt@90% CL | Upstream prompt@ 90%CL |
|---|---|---|---|
| CR | $0.17 \pm 0.02$ | $< 0.033$ | $< 0.052$ |
| SR | $0.016 \pm 0.002$ | $< 0.003$ | $< 0.005$ |

# Improvement compared 2018 data taking conditions




2018 data: $2.6 \times 10^{16}$ POT




2021 data: $1.4 \times 10^{17}$ POT

O(200) background reduction, despite higher intensity thanks to the beam line optimization