First results for searches of exotic decays with NA62 in beam-dump mode
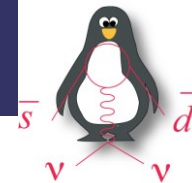
Alina Kleimenova

(Comenius University, Bratislava)

on behalf of NA62 Collaboration

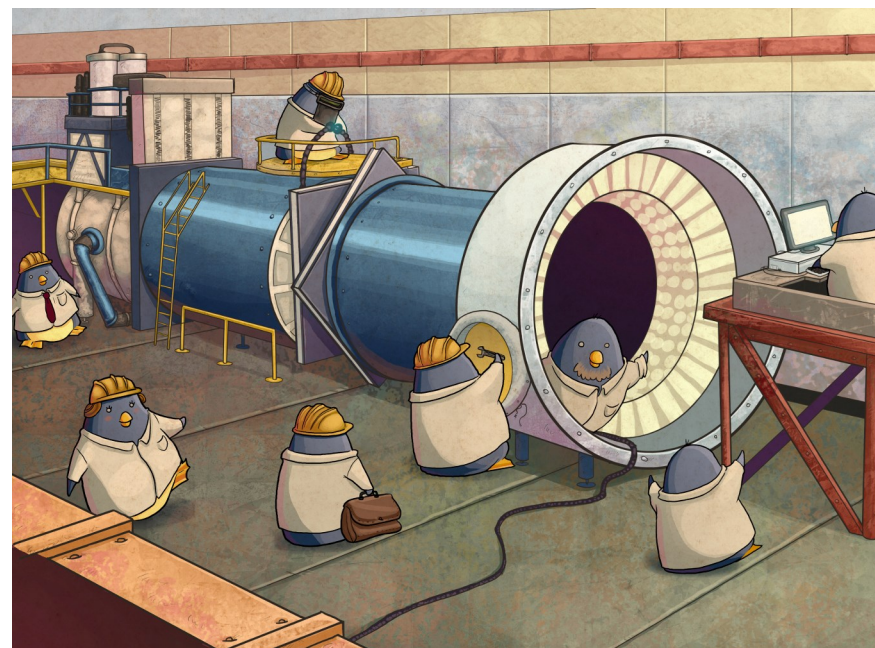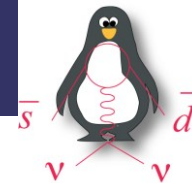European Research Council
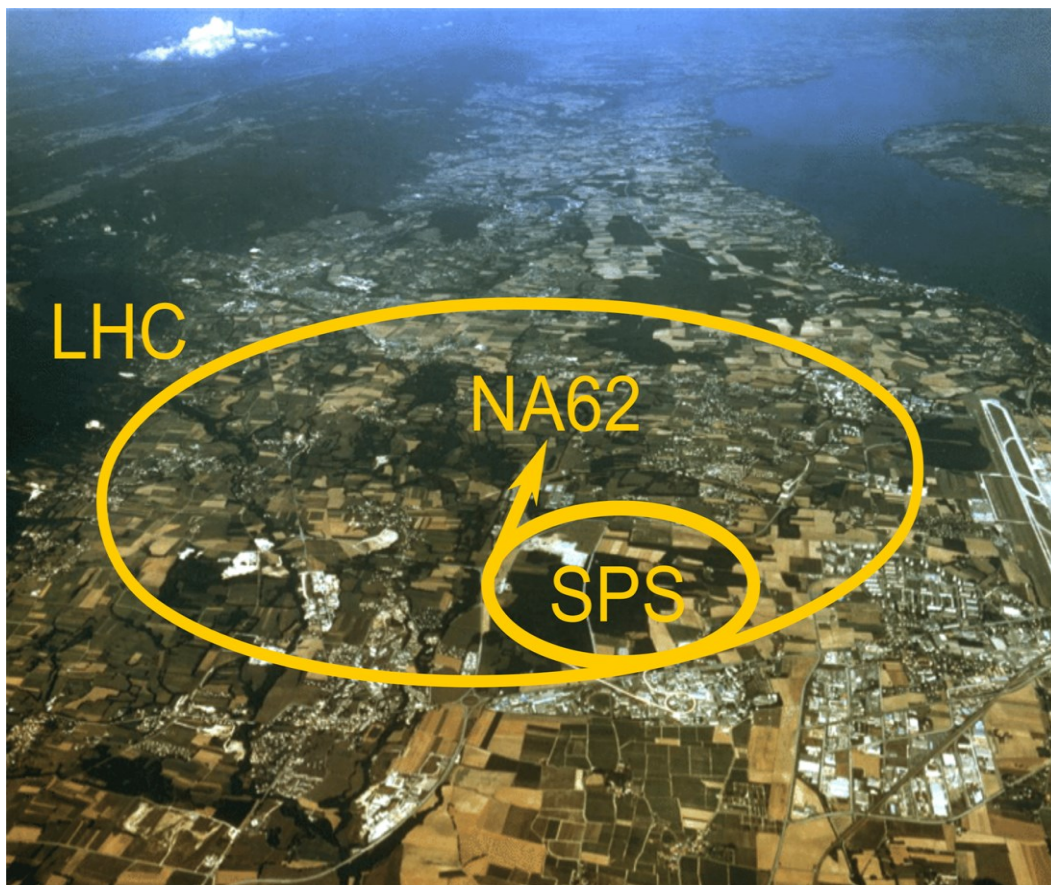Established by the European Commission

Patras 2022, 9th August

Outline

- Overview of the NA62 experiment

- Dark Photon (A') searches in NA62

- Results for $A' \rightarrow \mu^+\mu^-$ searches

- 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)]
$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$$
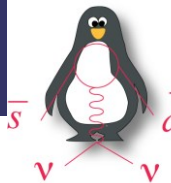$$= \left(10.6^{+4.0}_{3.4}{}_{stat} \pm 0.9_{syst}\right) \times 10^{-11}$$
NA62[JHEP06 (2021) 093]
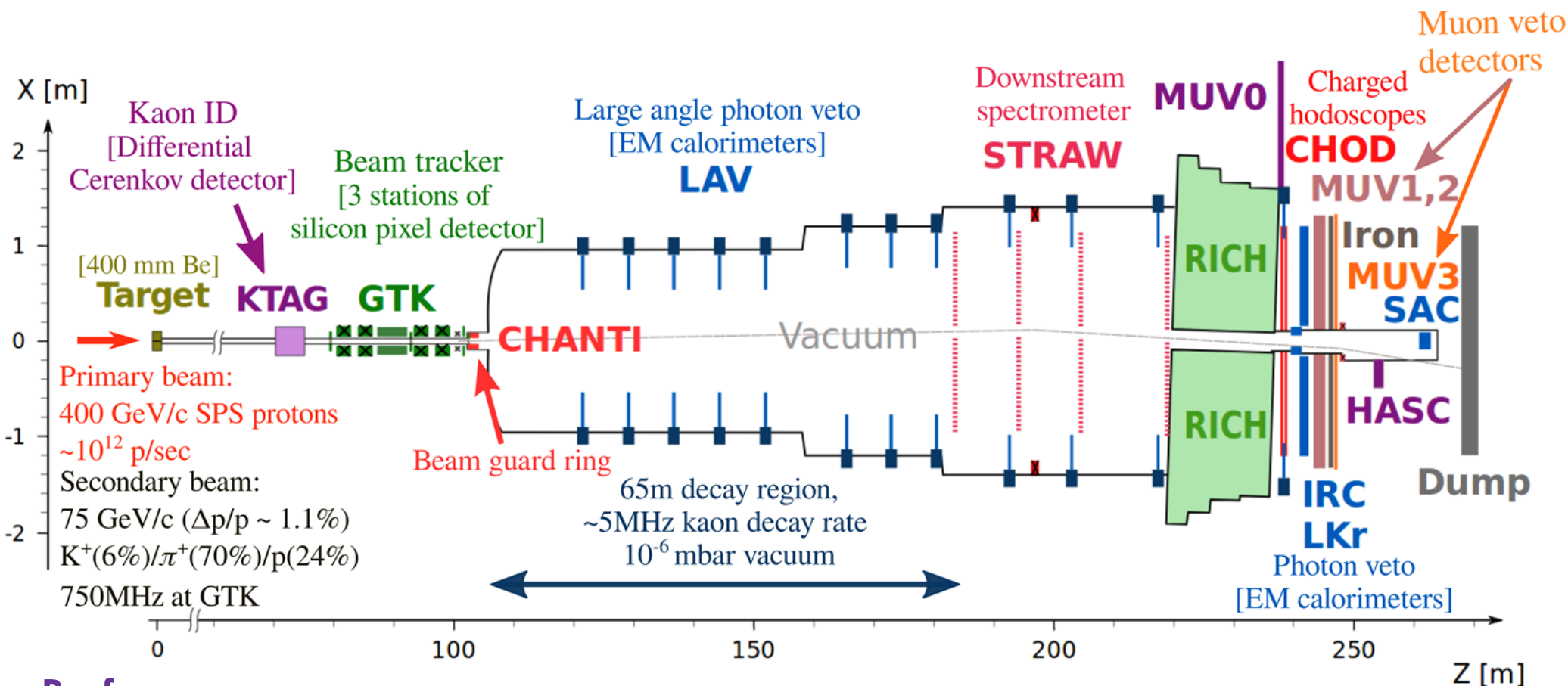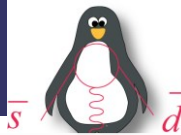
Broader physics programme:
- **Rare/forbidden** kaon decays
- Searches for **exotic particles** in kaon decays and in **beam dump** mode
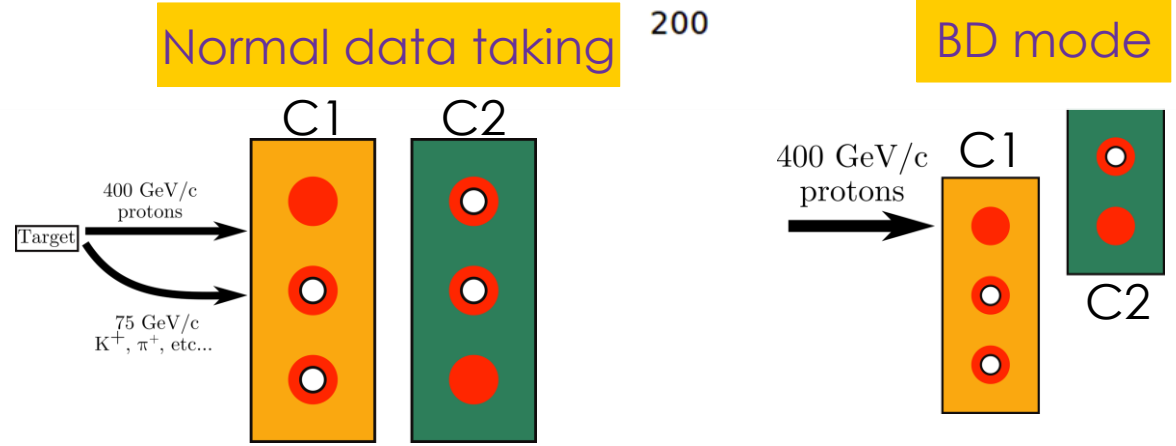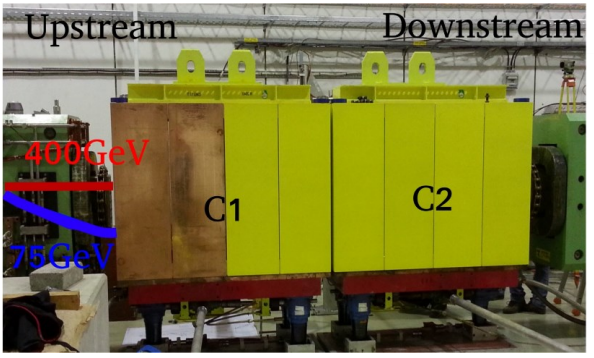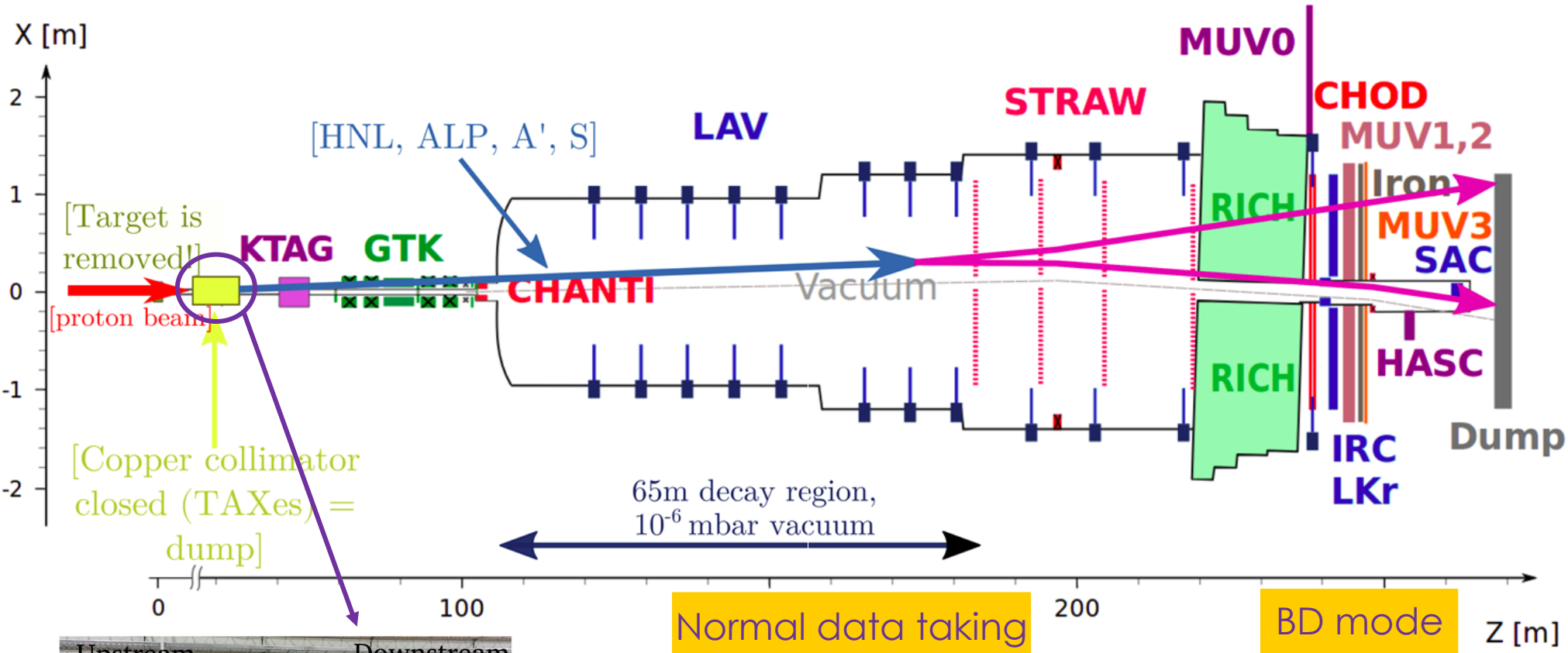
Detector overview

Performances:

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

[NA62 Detector Paper, JINST 12 (2017), P05025]

NA62 in beam dump mode

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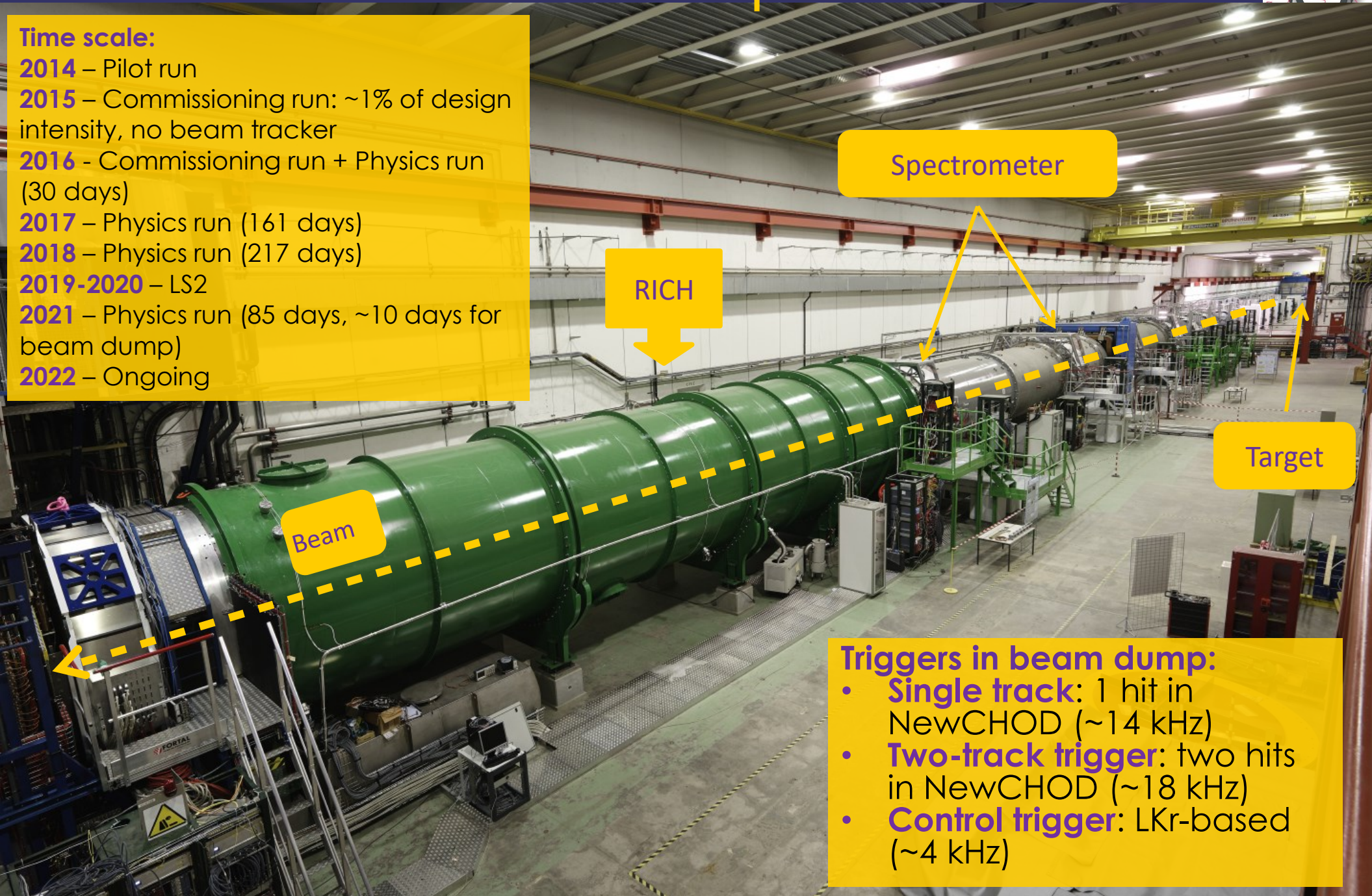**2016** - Commissioning run + Physics run (30 days)
2017 – Physics run (161 days)
2018 – Physics run (217 days)
2019-2020 – LS2
2021 – Physics run (85 days, ~10 days for beam dump)
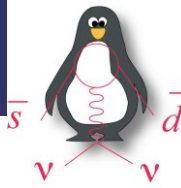**2022** – Ongoing

Spectrometer

RICH

Target

Beam

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)

Search motivation

Several New Physics models proposed for study:

•   Vector portal -> Dark Photon

•   Scalar Portal -> Dark Scalar

•   Neutrino portal -> HNL

•   Axion portal -> ALP

Dark Photon (DP) model introduces a new vector field $F'_{\mu\nu}$ symmetric under U(1) transformation which feebly interacts with the SM fields.
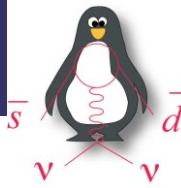
Kinetic-mixing interaction with the SM hypercharge $B_{\mu\nu}$:

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

Mass of DP and coupling are free parameters.
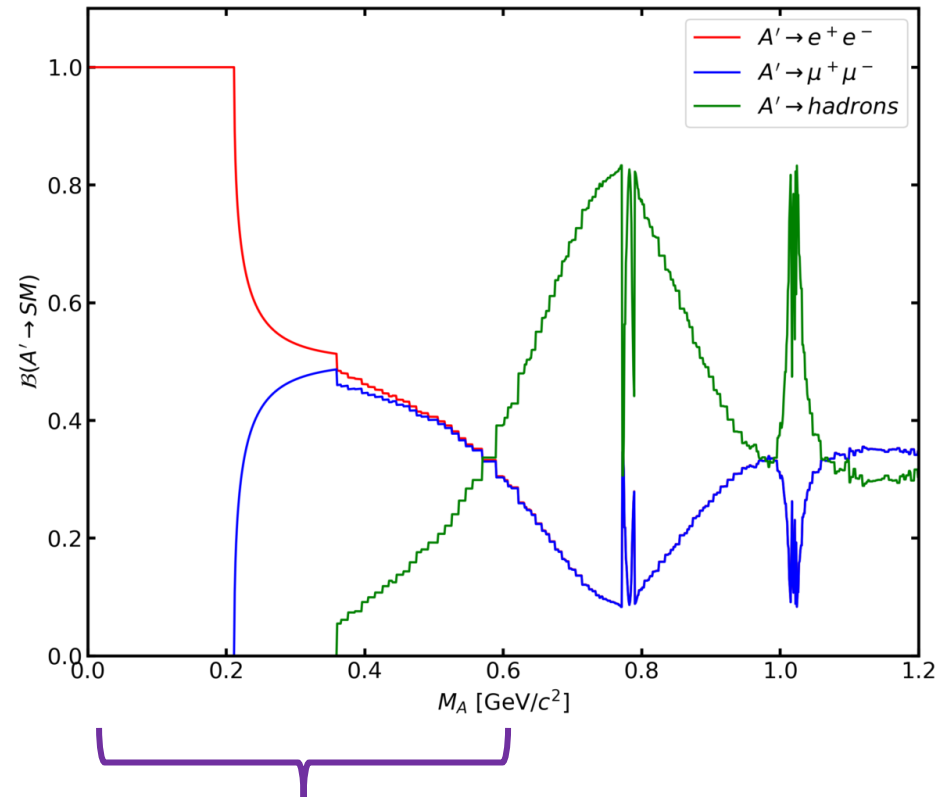
In the mass range <700 MeV, DP decay width is dominated by lepton-antilepton final states

Sensitivity of NA62 to the DP

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

This talk will focus only on muon decay mode of DP
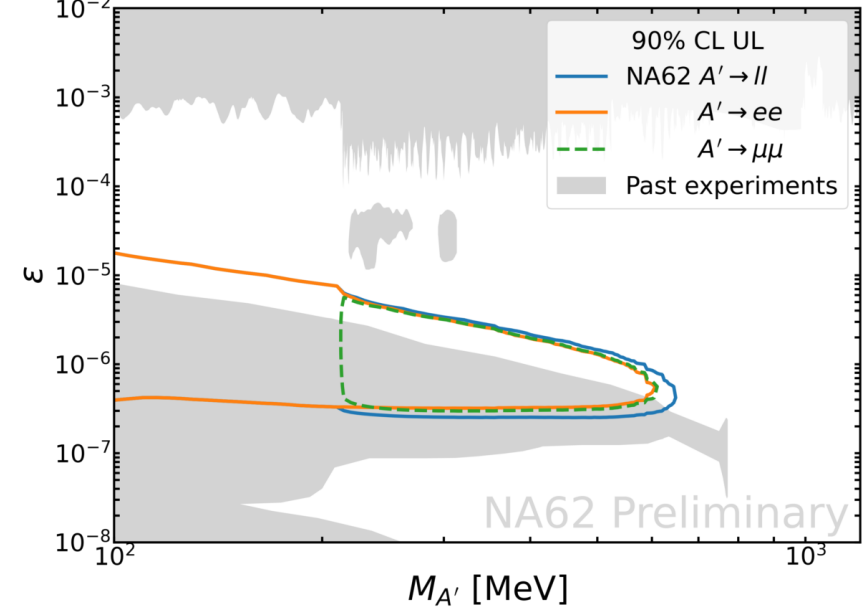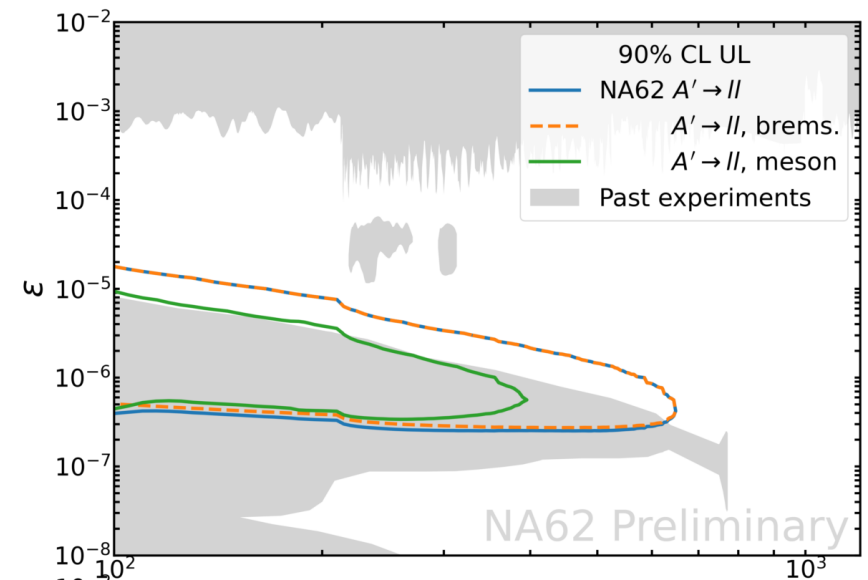
*The grey underlying exclusion is the one adapted by the PBC and taken from DarkCast [JHEP06(2018)004]
Several limits may differ from PBC and are taken by DarkCast team from [Phys. Rev. Lett. 126, no.18, 181801 (2021)]
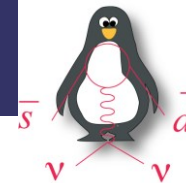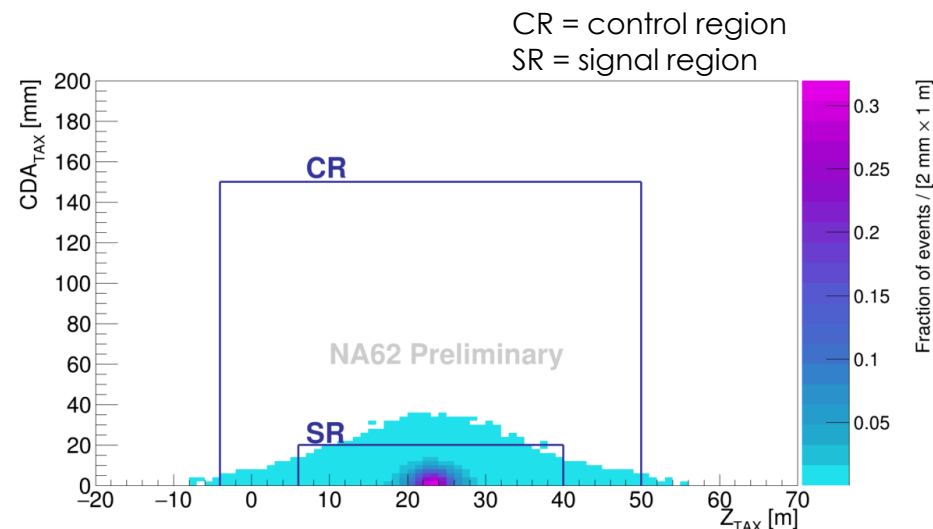
Analysis strategy

The signal signature:

- Lepton-antilepton 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
- 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.
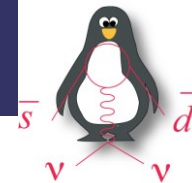- Signal region (SR) selection

CR = control region
SR = signal region

NA62 Preliminary

CDA_{TAX} – closest distance of approach between the beam direction at the TAX entrance and the lepton-antilepton pair direction $\sigma_{CDA} = $ ~7 mm
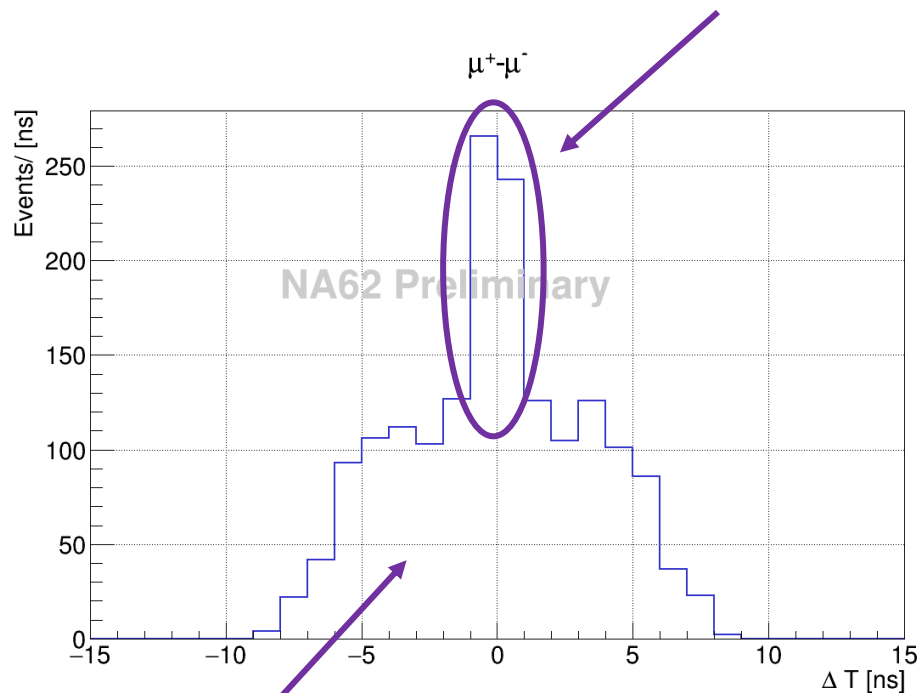
Z_{TAX} – longitudinal position, $\sigma_Z = $ ~5.5 m

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

CR and SR kept blind up to the analysis approval

Distribution of track time difference
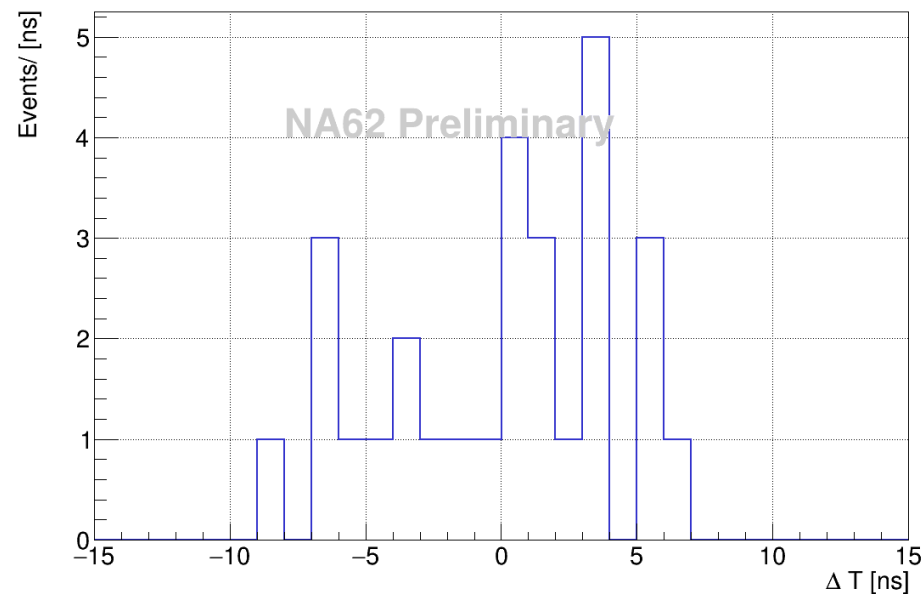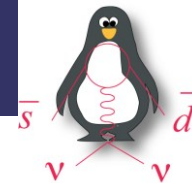

In-time background

Combinatorial background

Before LAV veto is applied
(CR&SR blinded)
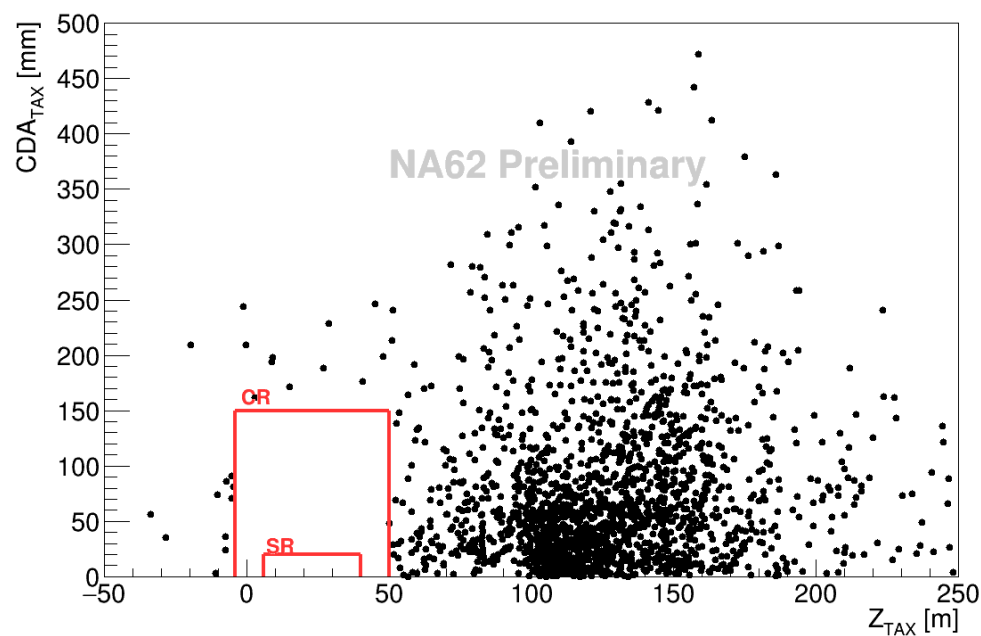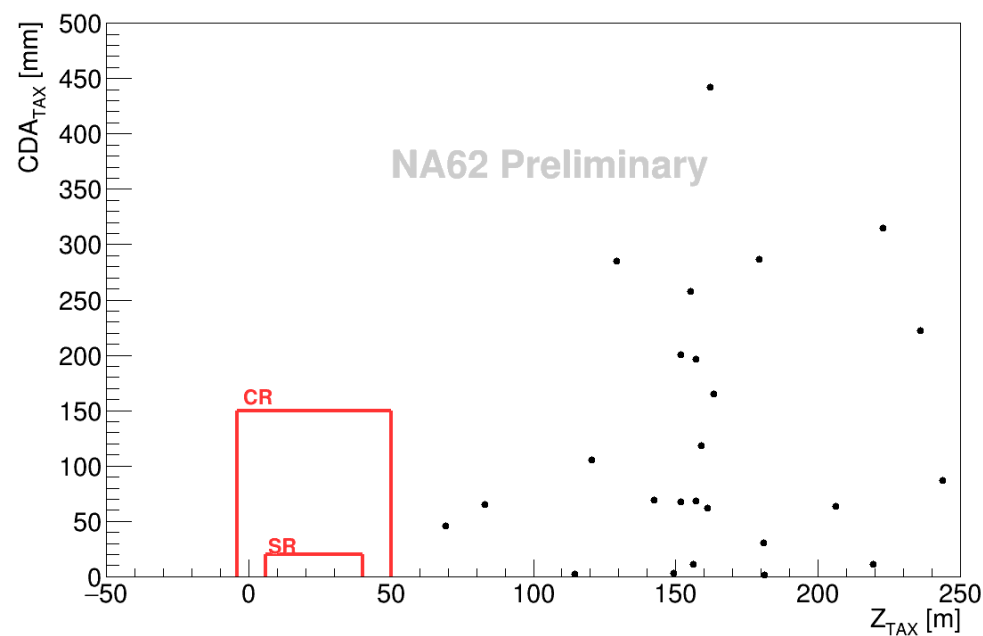
Final events selected
(CR&SR blinded)

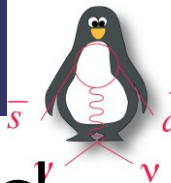# Improvement compared 2018 data taking conditions

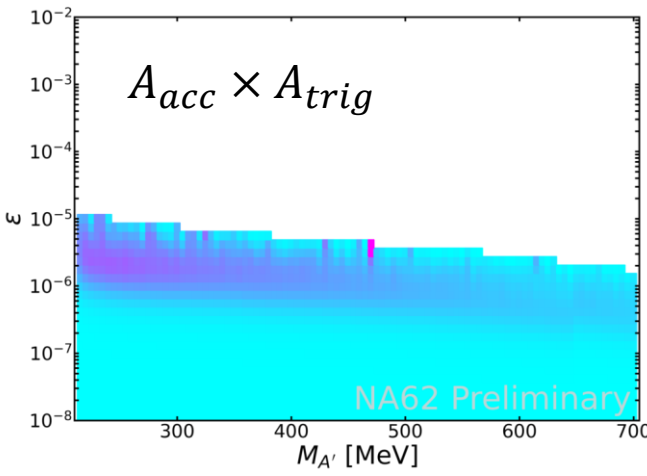2018 data: 2.6×10^{16} POT

2021 data: 1.4×10^{17} POT

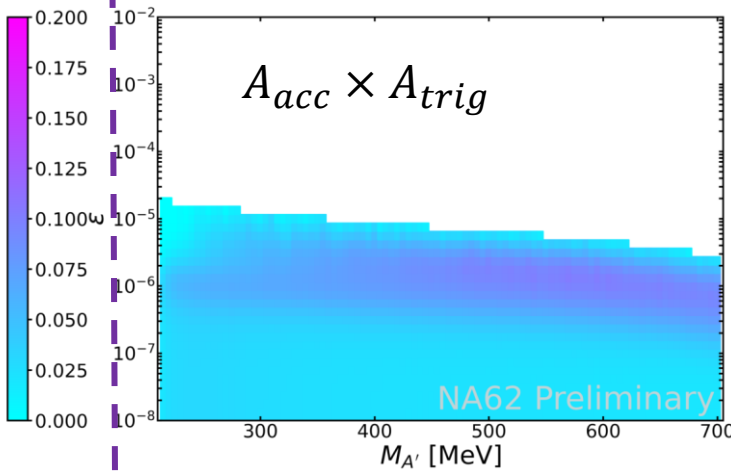O(200) background reduction, despite higher intensity thanks to the beam line optimization

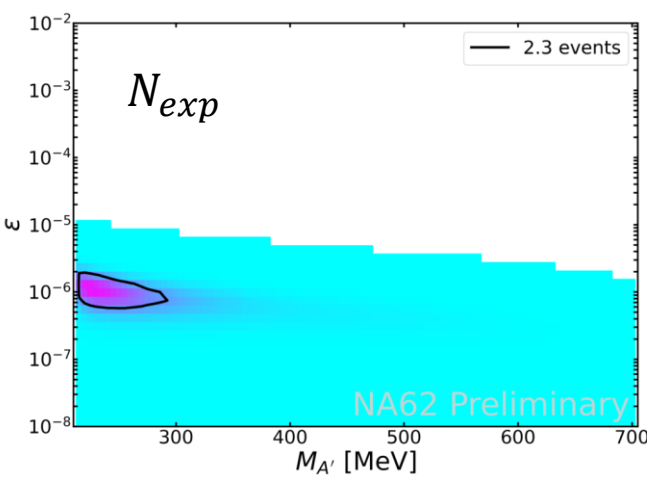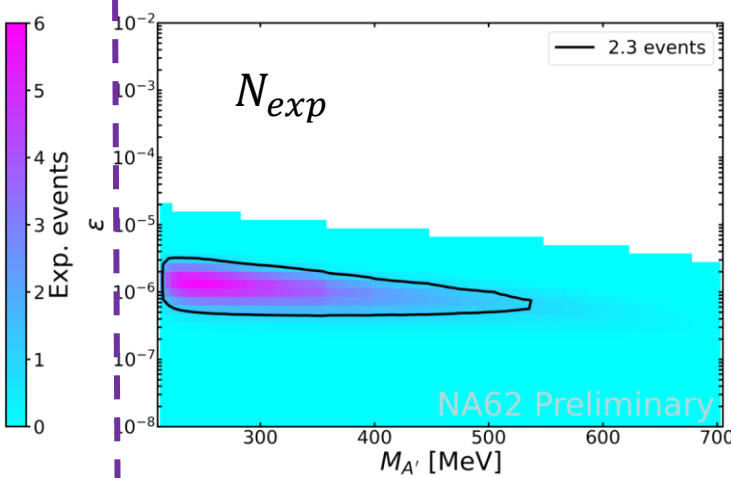# Signal efficiency and expected DP yield

$A' \to \mu\mu$, meson production

$A' \to \mu\mu$, direct production

$$N_{exp} = POT \times \chi(pp \to A')$$
$$\times \mathcal{B}(A' \to \mu\mu)$$
$$\times P_{rd}(\epsilon)$$
$$\times A_{acc} \times A_{trig}$$
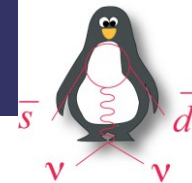
POT = $(1.40 \pm 0.28) \times 10^{17}$

$\chi(pp \to A')$ - DP production probability
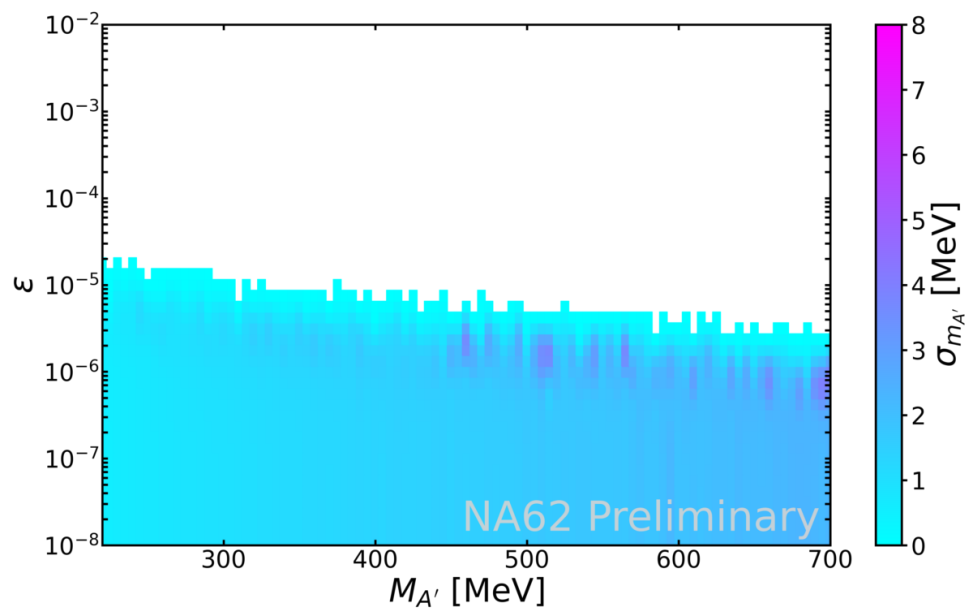
$\mathcal{B}(A' \to \mu\mu)$ - branching fraction

$P_{rd}(\epsilon)$ - probability to reach NA62 decay volume and decay therein
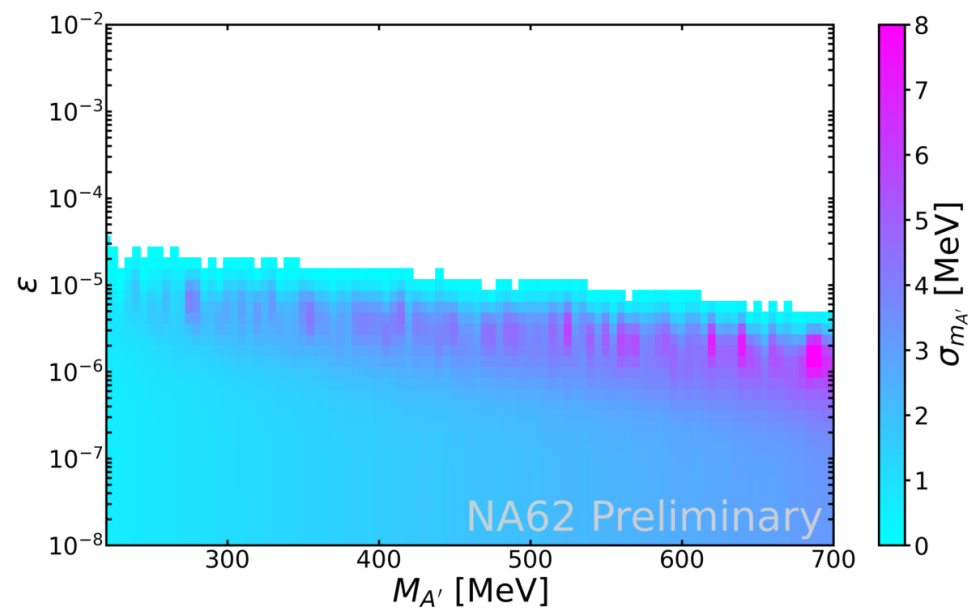
$A_{acc} \times A_{trig}$ - signal selection and trigger efficiencies
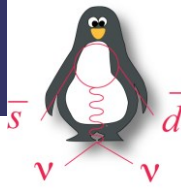
Invariant mass resolution

Meson production

Direct production

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 independent on the rate to account for the 10 ns time window

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%

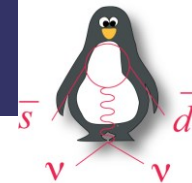Prompt background negligible with respect to combinatorial (UL @ 90%CL is 30% of combinatorial)
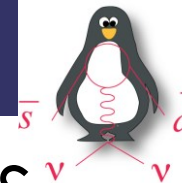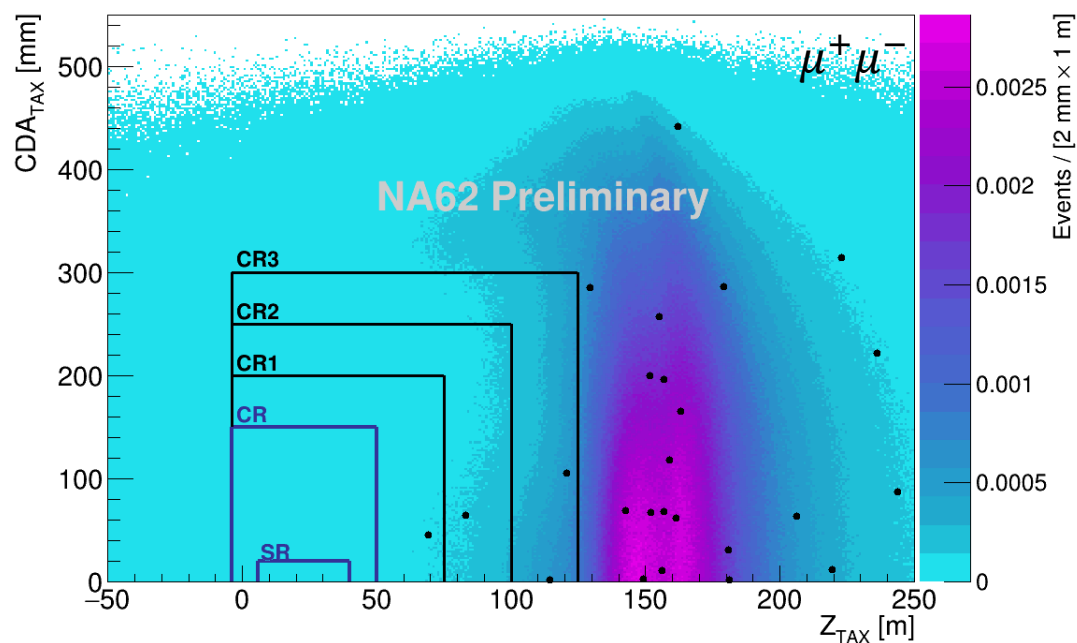
Data-MC comparison: control samples
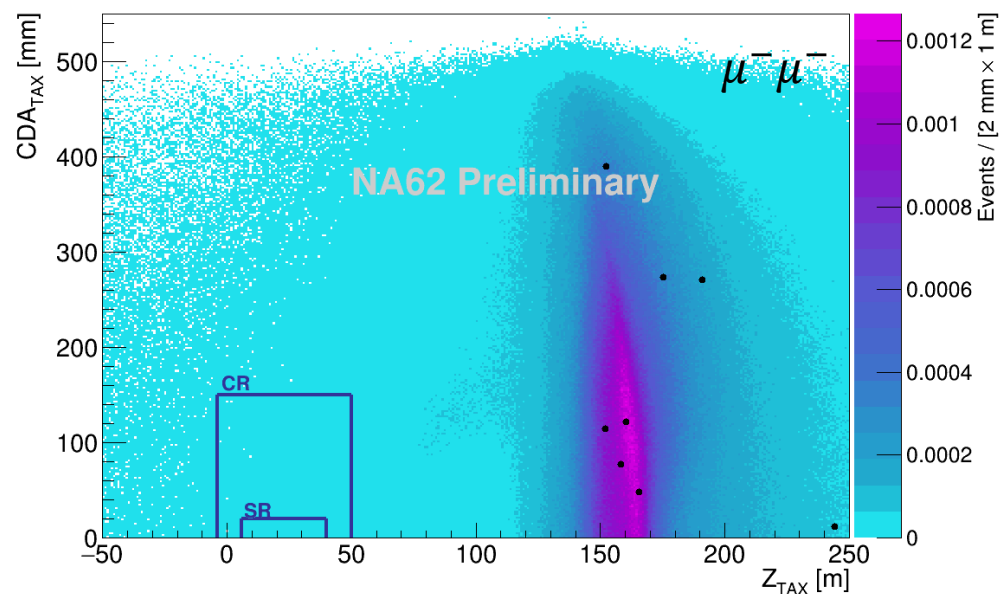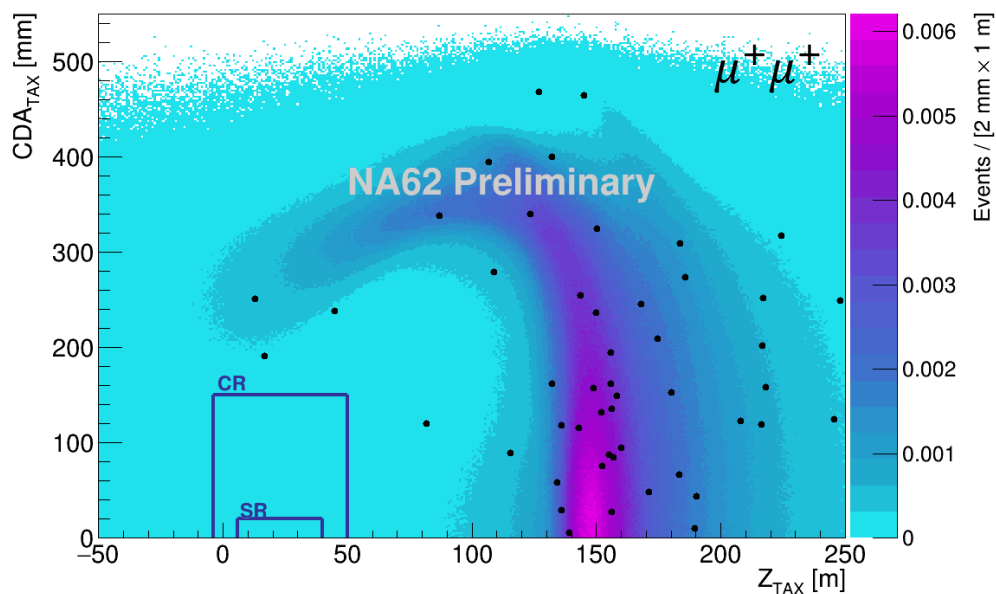
	$N_{exp} \pm \delta N_{exp}$	N_{obs}	$p(N \geq N_{obs})$	$p(L \leq L_{obs})$
Outside CR	62.5 ± 9.4	53	0.79	0.46
CR	0.46 ± 0.07	0	1.0	1.0
SR	0.040 ± 0.006	0	1.0	1.0

	$N_{exp} \pm \delta N_{exp}$	N_{obs}	$p(N \geq N_{obs})$	$p(L \leq L_{obs})$
Outside CR	9.1 ± 1.4	8	0.67	0.88
CR	0.050 ± 0.007	0	1.0	1.0
SR	0.005 ± 0.001	0	1.0	1.0

First results for searches of exotic decays with NA62 in beam-dump mode (A. Kleimenova)
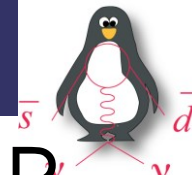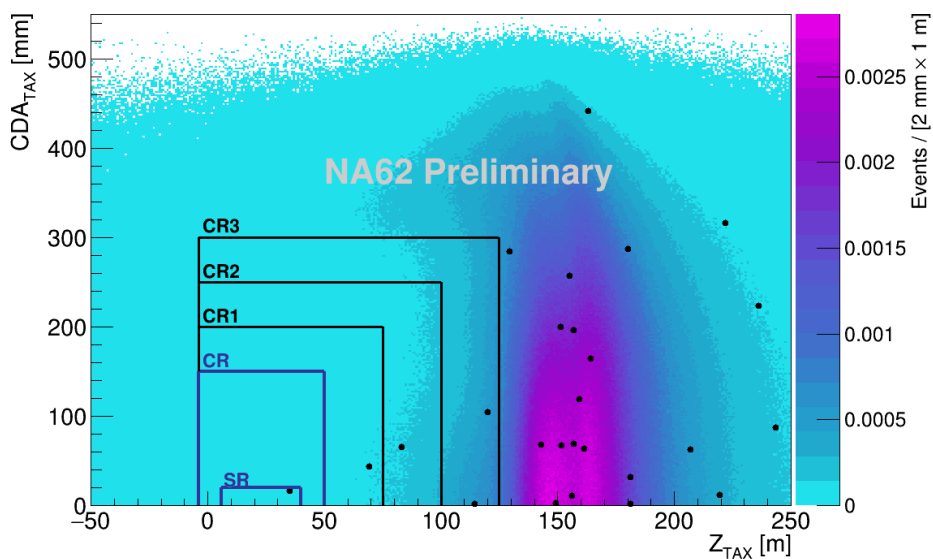
Data-MC comparison: signal sample, CRs open

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

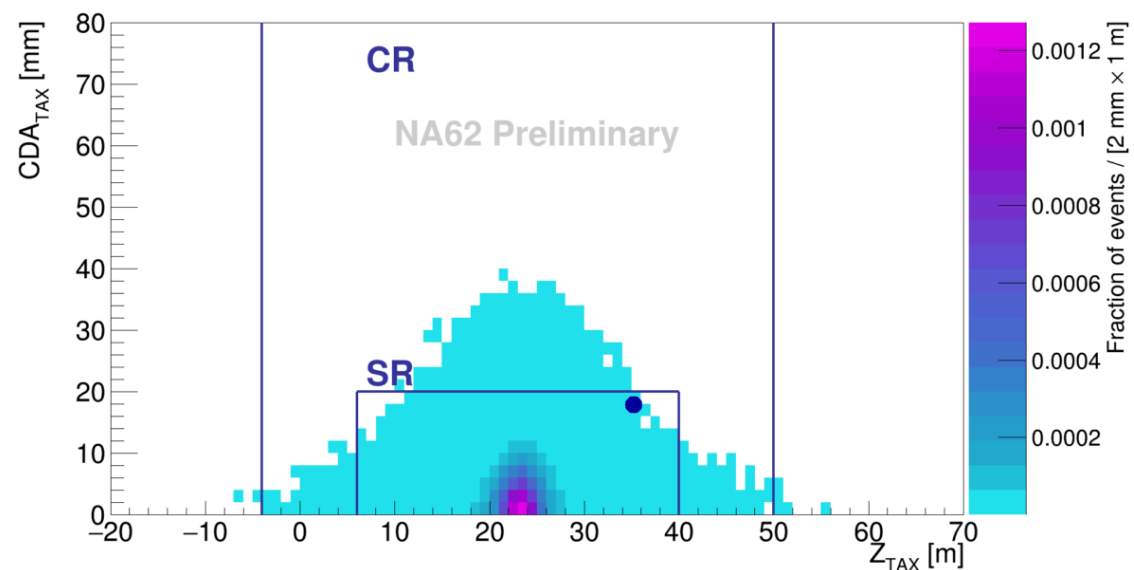|	$N_{exp} \pm \delta N_{exp}$	N_{obs}	$p(N \geq N_{obs})$	$p(L \leq L_{obs})$
Outside CR	26.3 ± 3.4	28	0.47	0.74
CR1	0.29 ± 0.04	1	0.25	0.25
CR2	0.58 ± 0.07	1	0.44	0.44
CR3	1.70 ± 0.22	2	0.50	0.68
CR1+2+3	2.57 ± 0.33	4	0.26	0.24
CR	0.17 ± 0.02	0	1.0	1.0
SR	0.016 ± 0.02	-	-	-

Data-MC comparison: signal sample, SR open

1 event observed

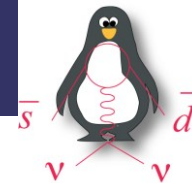Counting experiment with 2.4σ global significance

Signal shape was not taken into account for the significance

Final result

Excluded region
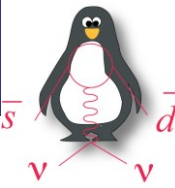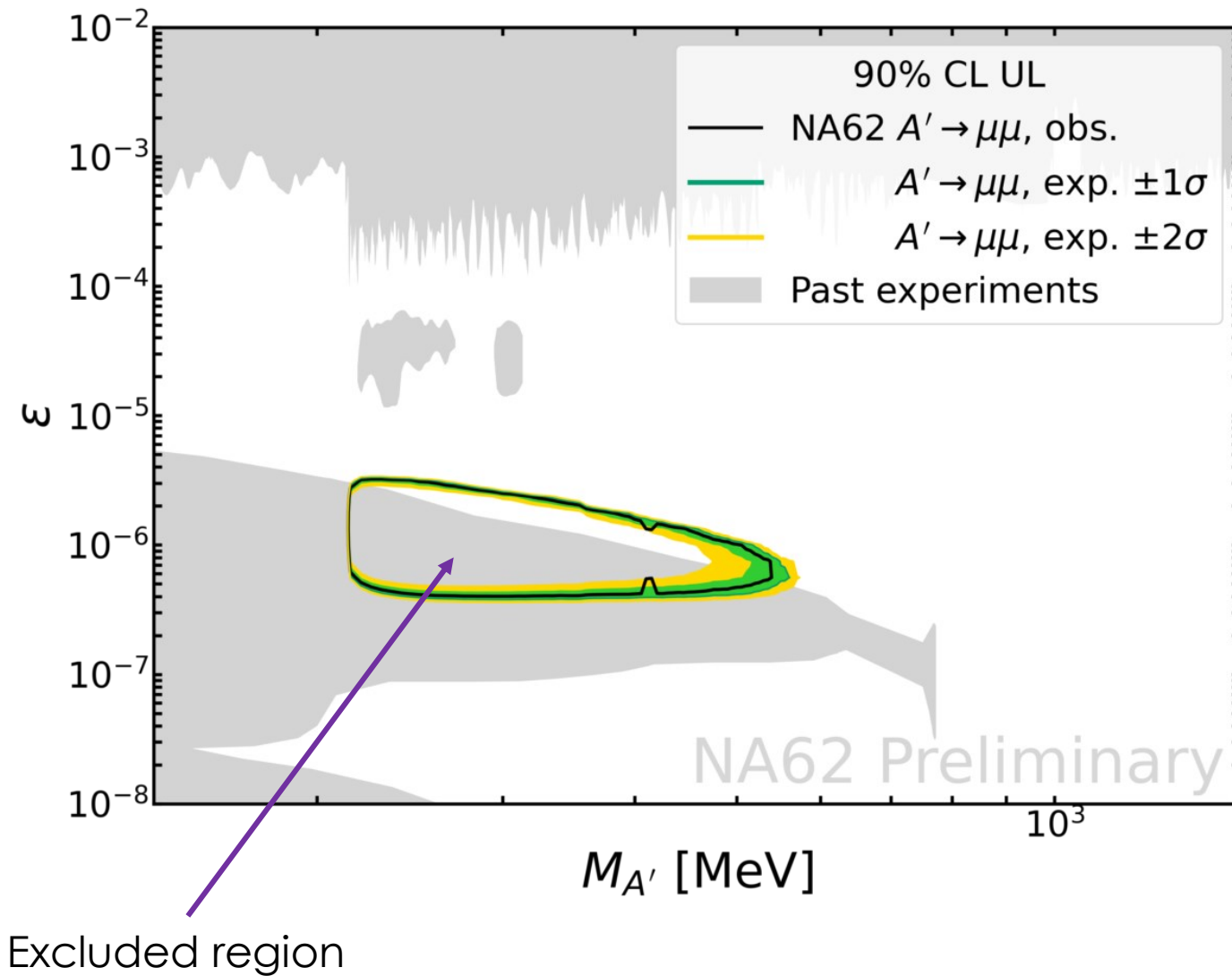
Summary

- The first preliminary result on search for production and decay of an exotic particle from data collected by the NA62 experiment in beam-dump mode has been presented

- A cut-based counting experiment blind analysis to search for $A' \rightarrow \mu^+\mu^-$ has been performed on the data collected in 2021.

- With $(1.4 \pm 0.28) \times 10^{17}$ POT a 90% CL upper limit 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
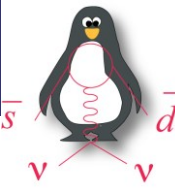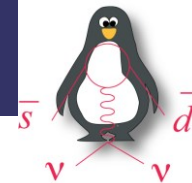
Thank you!
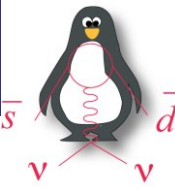
Backup slides

Observed event

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

ΔT = -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

First results for searches of exotic decays with NA62 in beam-dump mode (A. Kleimenova)
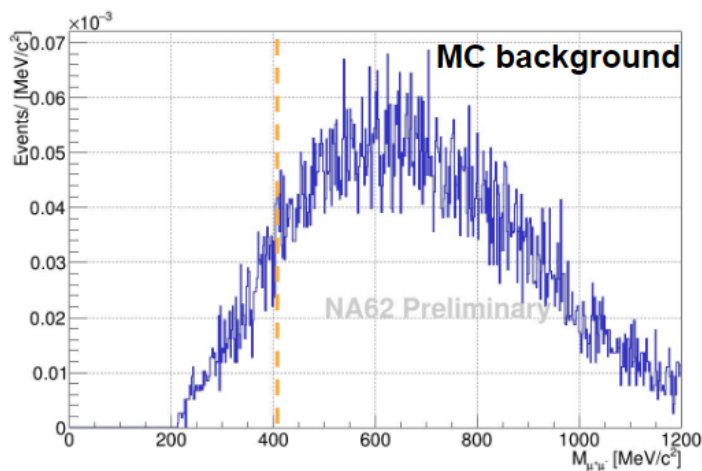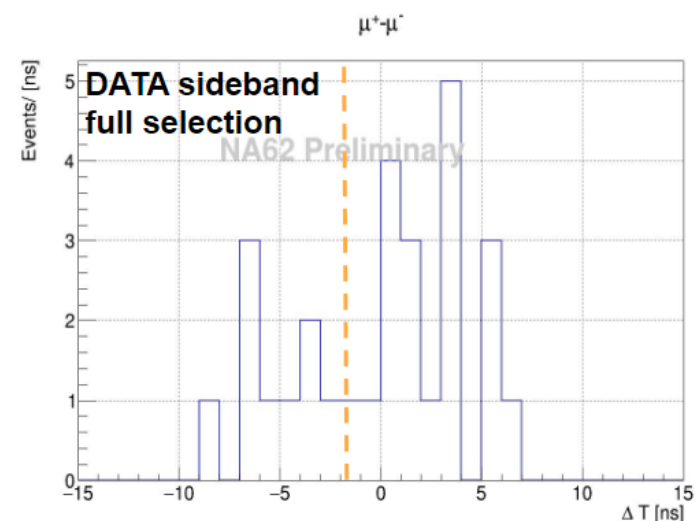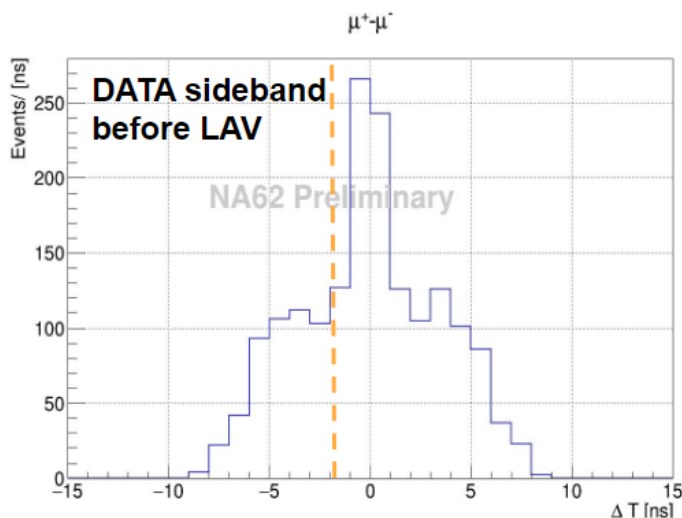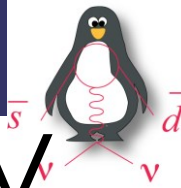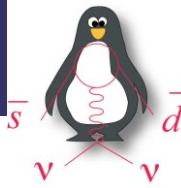
MC prompt background: no LAV veto
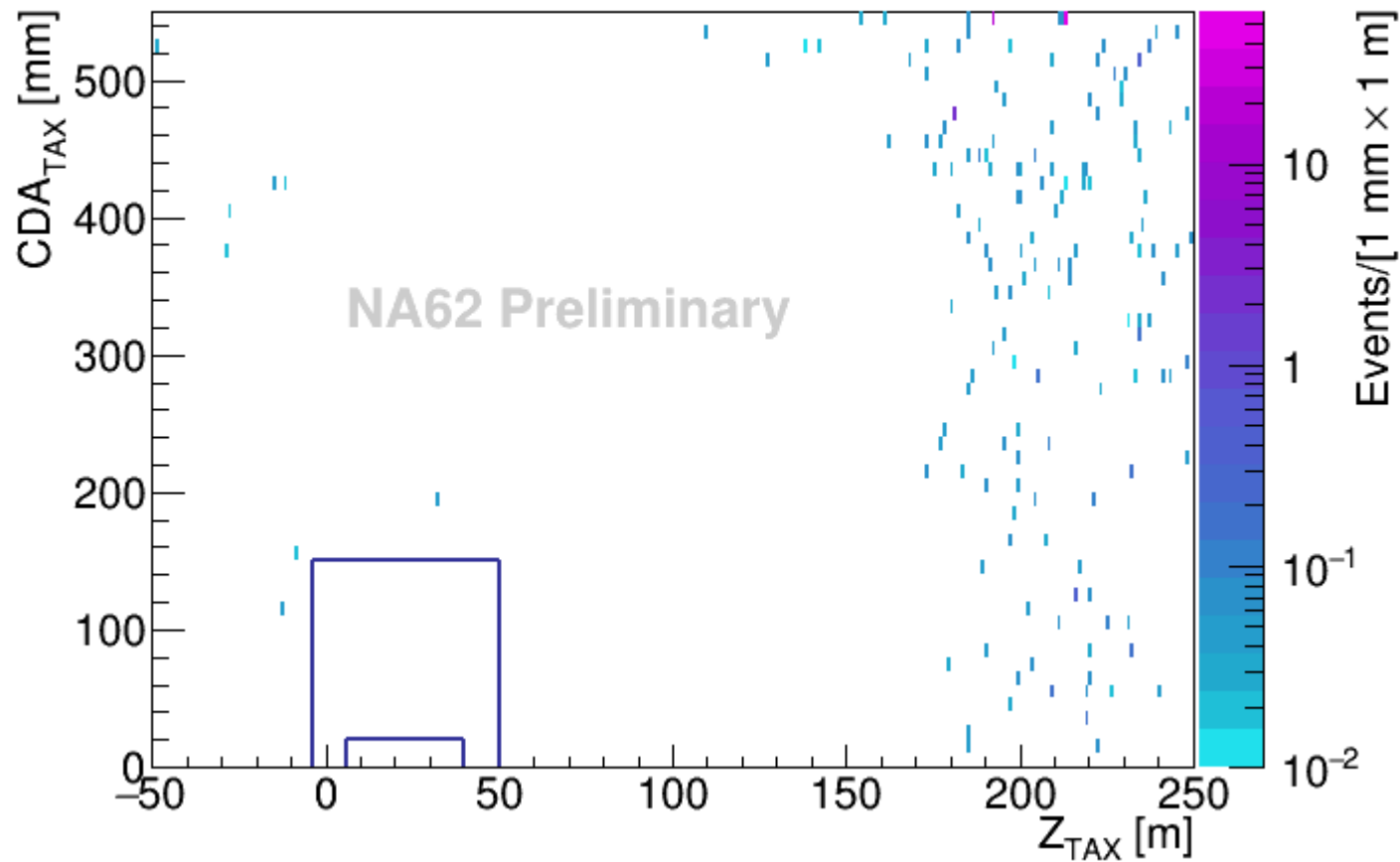
Background summary for $A' \to \mu^+\mu^-$ analysis

	Combinatorial	Prompt@90% CL	Upstream prompt@ 90%CL
CR	0.17 ± 0.02	< 0.033	< 0.052
SR	0.016 ± 0.002	< 0.003	< 0.005