Les Rencontres de Physique de la Vallée d'Aoste

Searching for DM and ALPs with NA62 in beam-dump mode

Alina Kleimenova

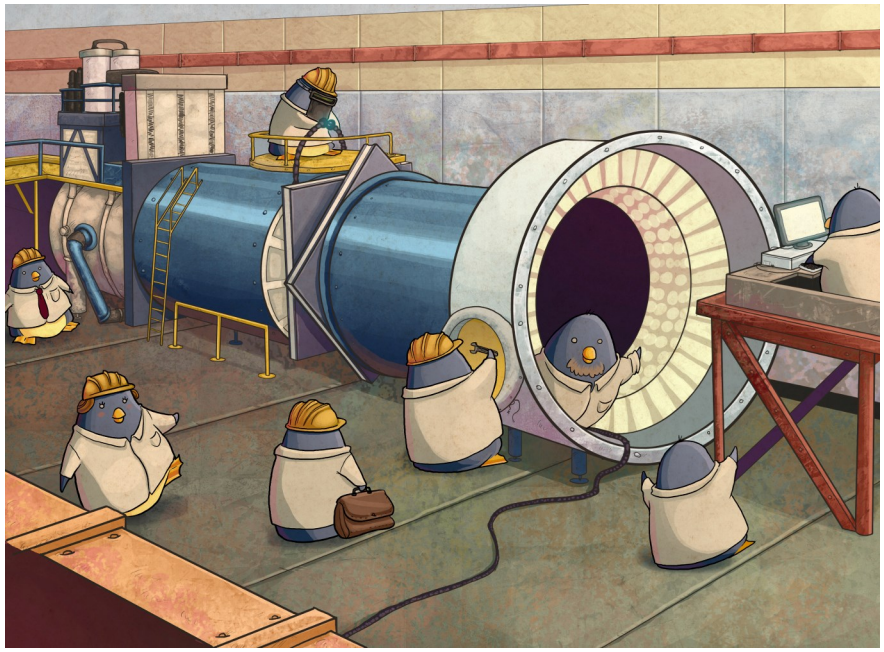
(EPFL, Lausanne)

on behalf of NA62 Collaboration

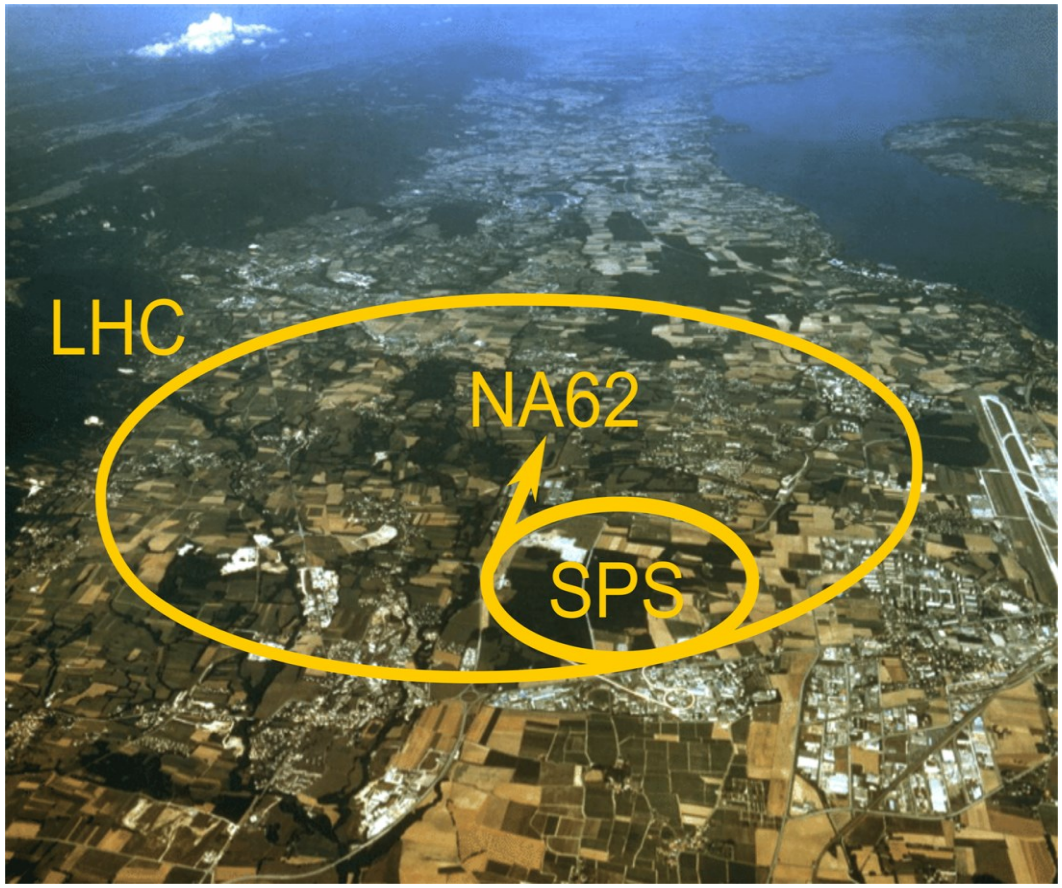
La Thuile 2023, 10th March

Outline

- Overview of the NA62 experiment
- Dark Photon (A') searches in NA62
- Results for $A' \to l^+l^-$ searches
- Summary



The NA62 experiment



~30 institutes, ~200 participants from: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Lausanne, Liverpool, Louvain, Marseille, Mainz, Moscow, Munich, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, 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)]

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$

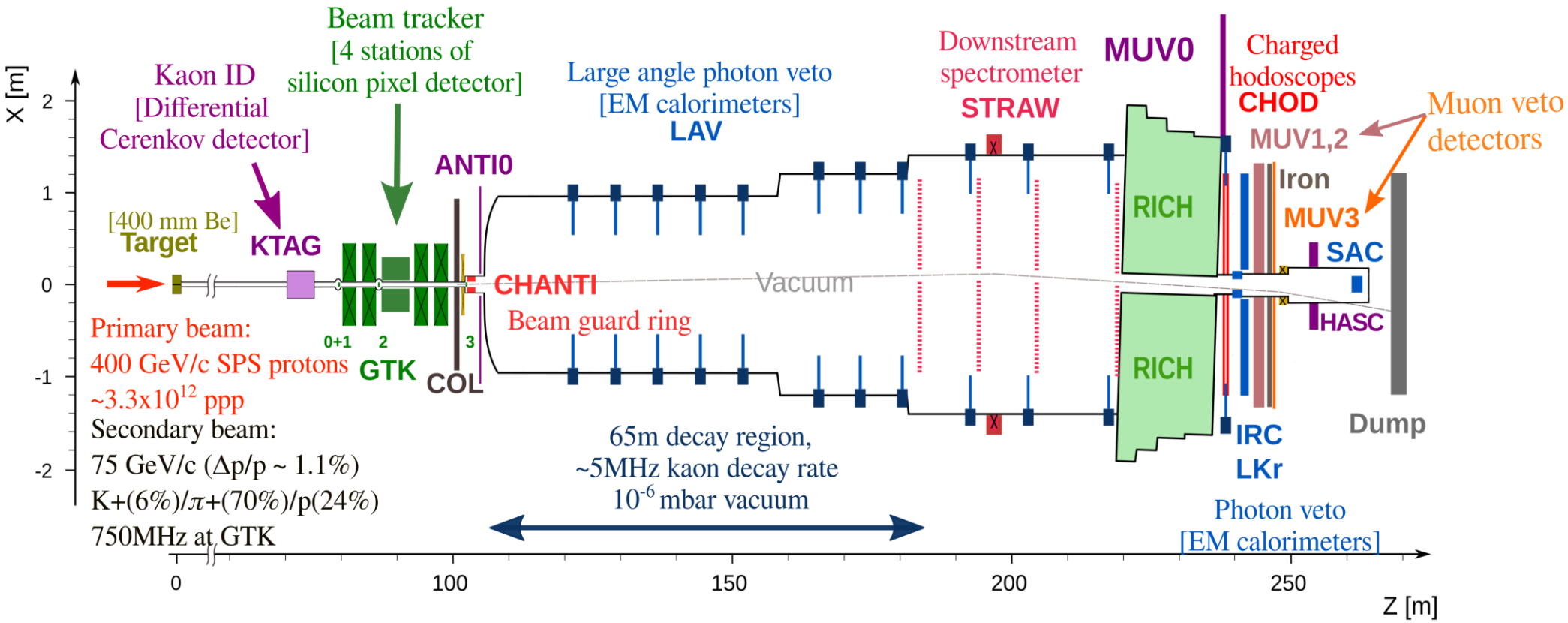
$= \left(10.6^{+4.0}_{3.4\ stat} \pm 0.9_{syst}\right) \times 10^{-11}$

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

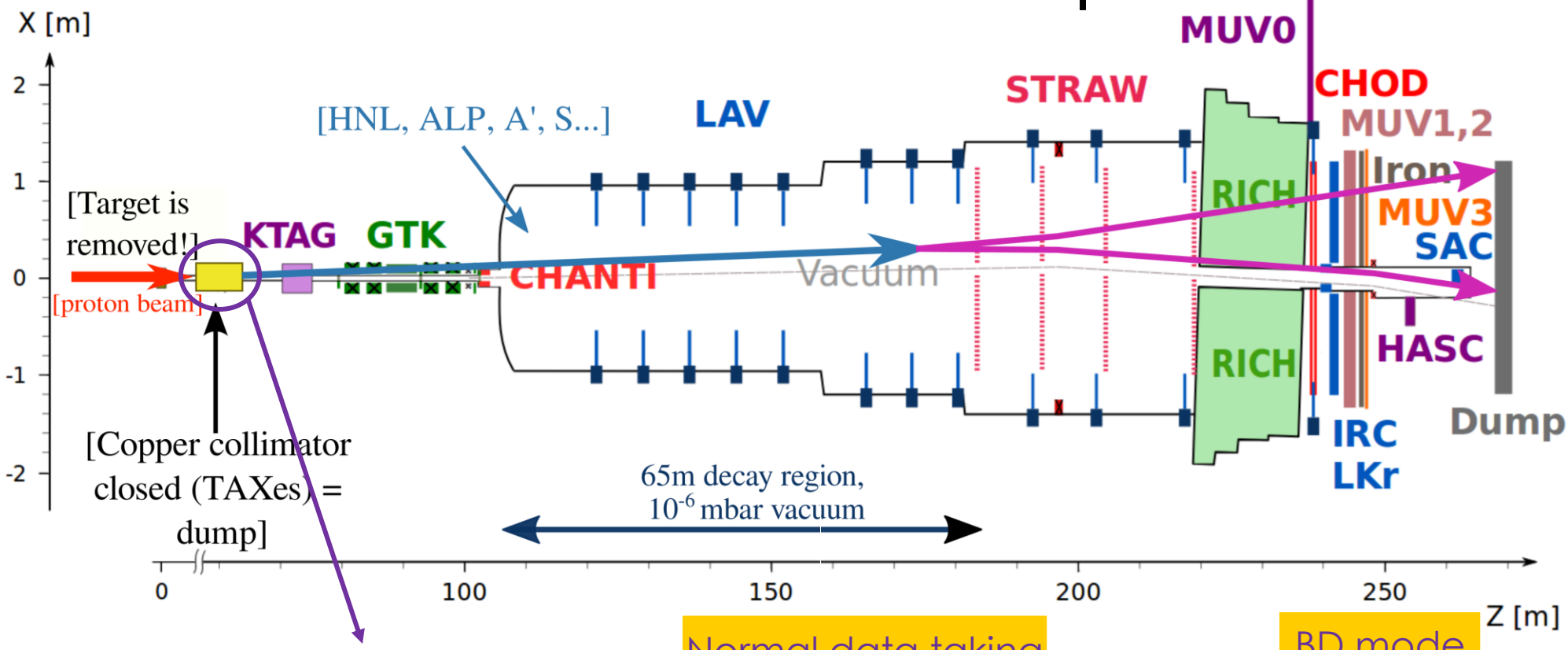


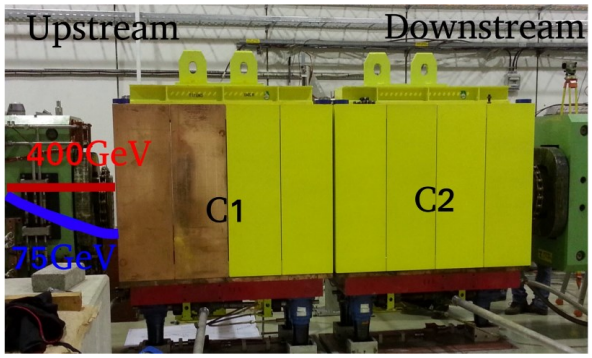
Performances:

- 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(π^+)< 35 GeV
- $\mathcal{O}(10^8)$ π^0 rejection of for E(π^0)> 40 GeV

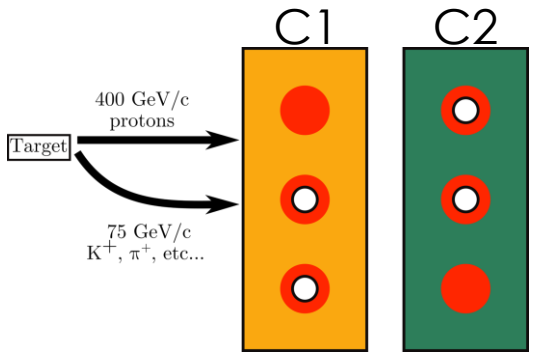
[NA62 Detector Paper, JINST 12 (2017), P05025]

NA62 in beam dump mode

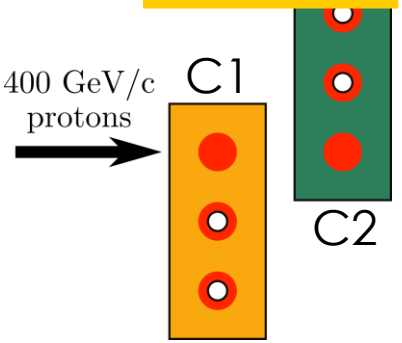




Normal data taking

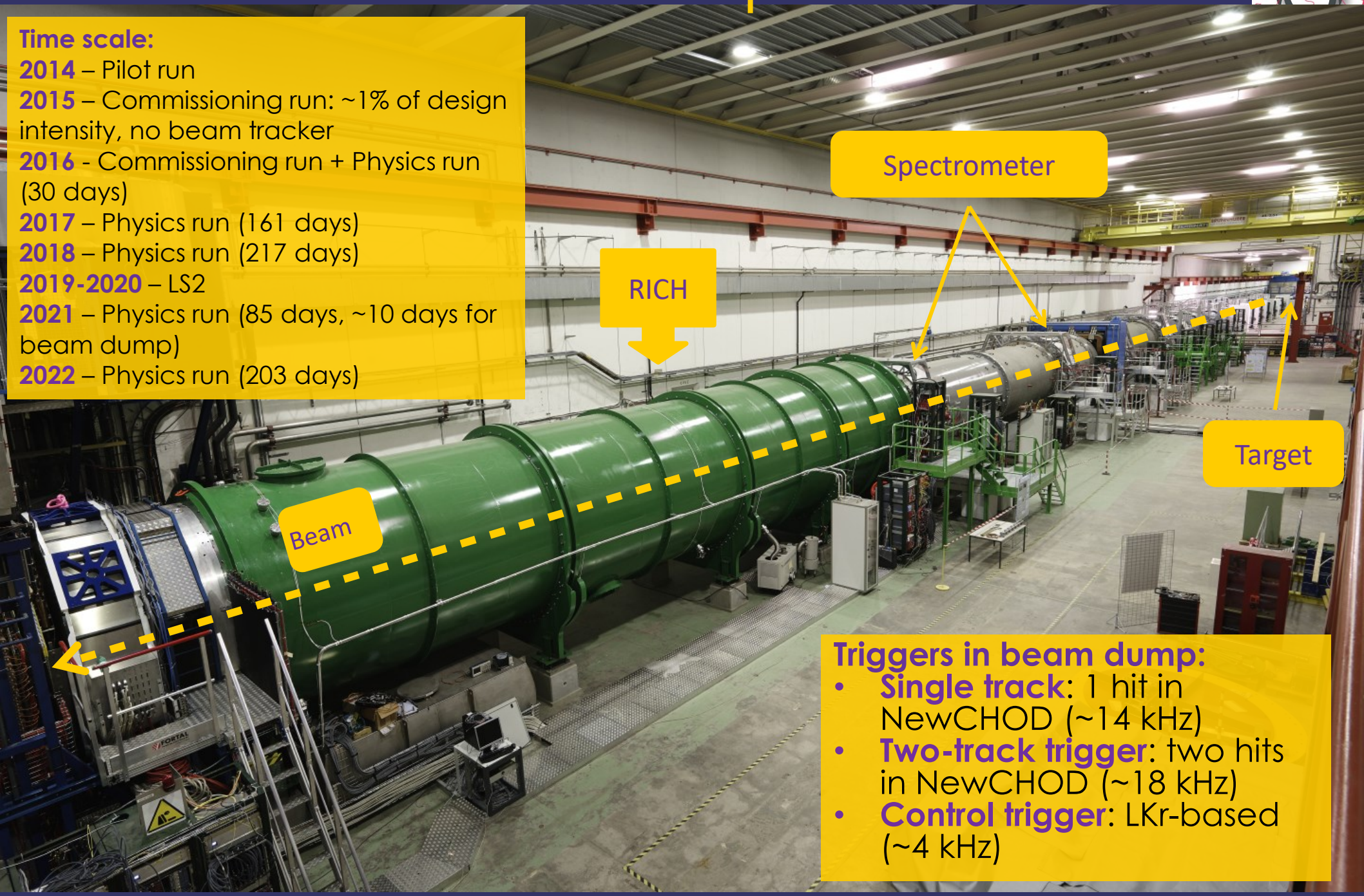


BD mode



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 – Physics run (203 days)



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:

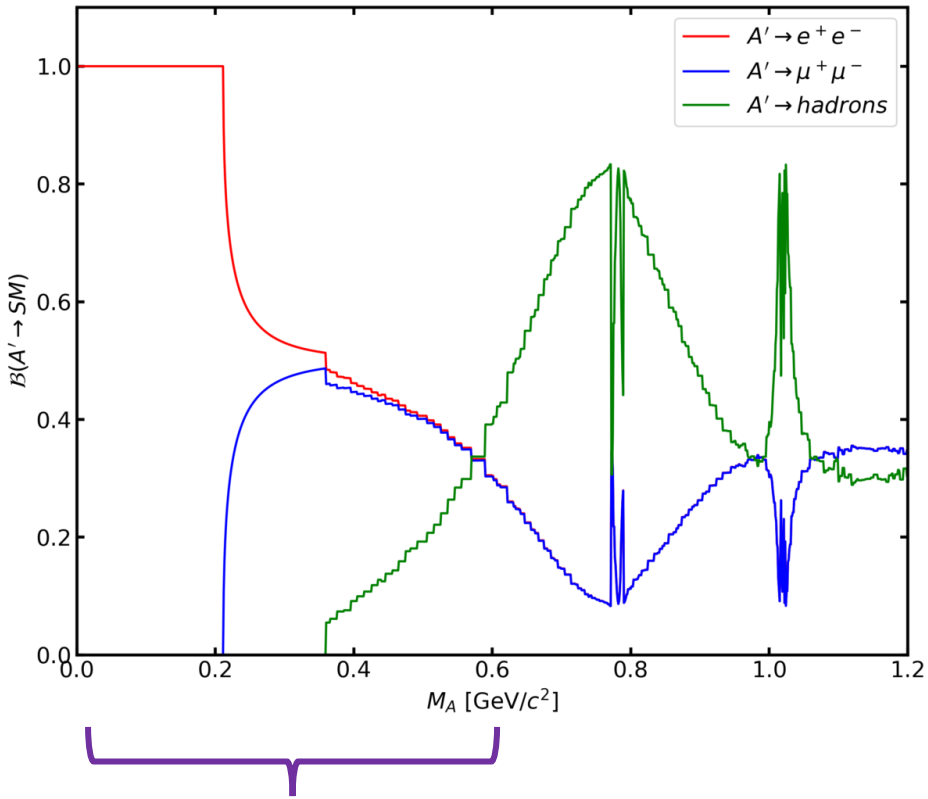
- Vector portal -> Dark Photon
- Scalar Portal -> Dark Scalar
- Neutrino portal -> HNL
- Axion portal -> ALP

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 $B_{\mu\nu}$:

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

Mass of DP and coupling are free parameters.



In the mass range <700 MeV, DP decay width is dominated by lepton-antilepton final states

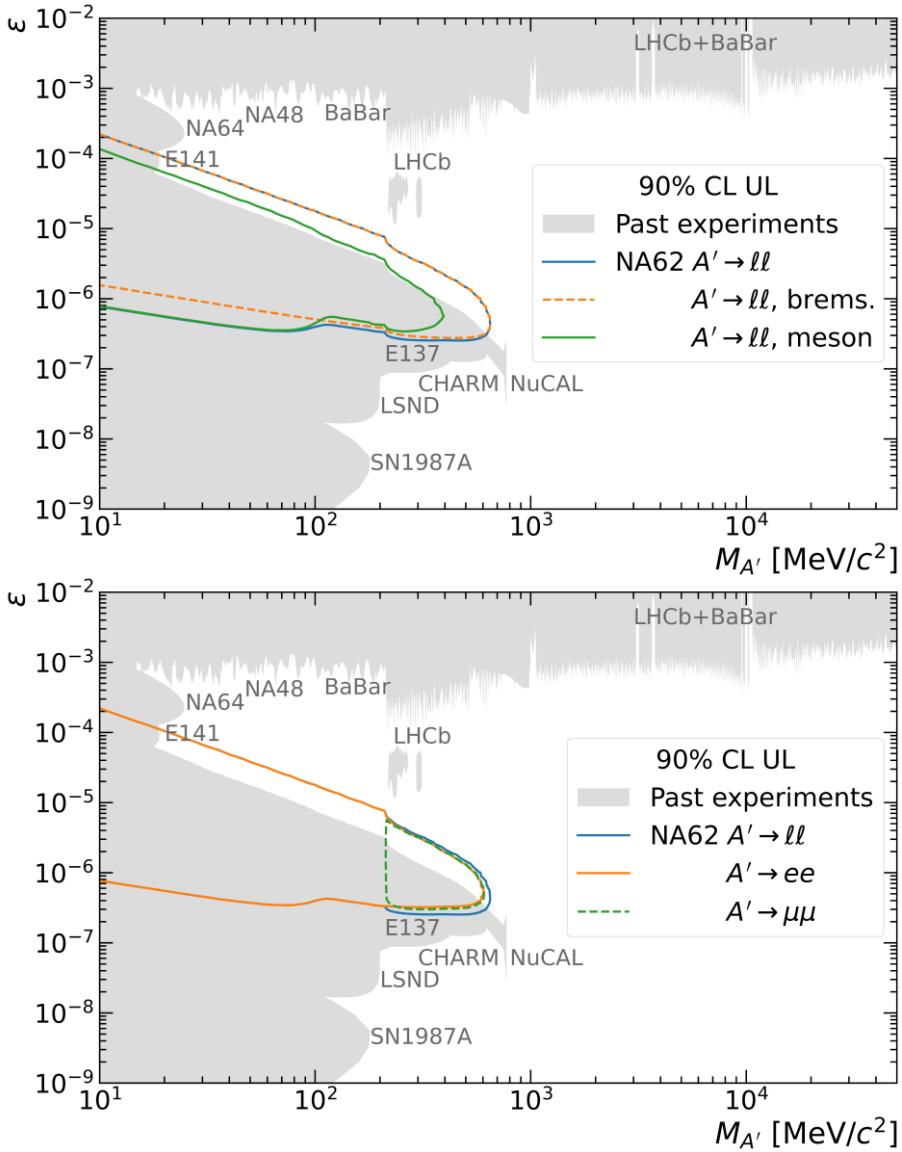
Sensitivity of NA62 to the DP

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

- Bremsstrahlung production in $pN \to XA'$
- Production in meson decay 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 for $A' \to \mu^+\mu^-$ search

The signal signature:

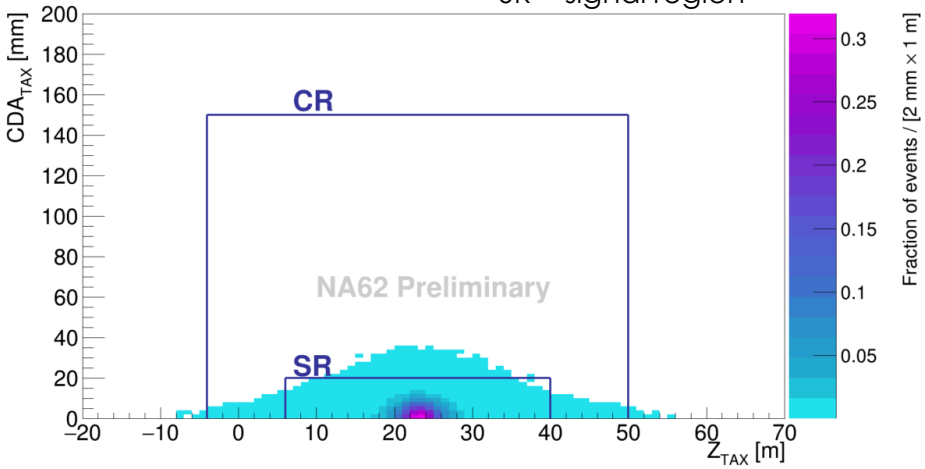
- Lepton-antilepton vertex reconstructed within the NA62 decay region and pointing back to the proton beam interaction point at the TAXes.

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 and SR kept blind up to the analysis approval

CR = control region
SR = signal region



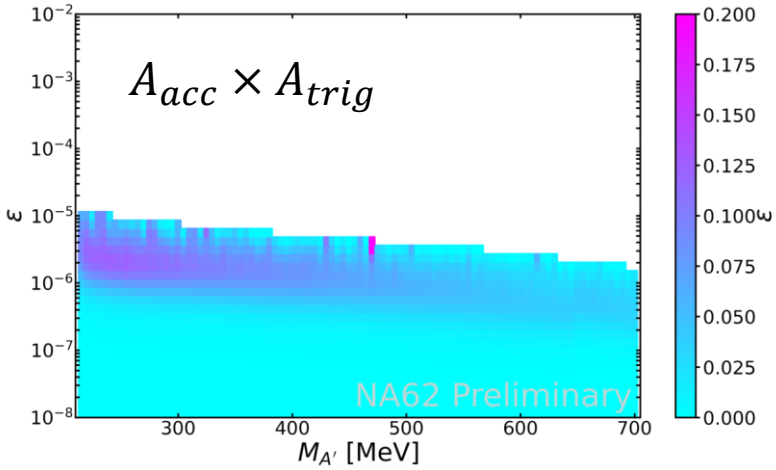
CDA_{TAX} – closest distance of approach between the beam direction at the TAX entrance and $\mu^+\mu^-$ pair direction σ_{CDA} = ~7 mm

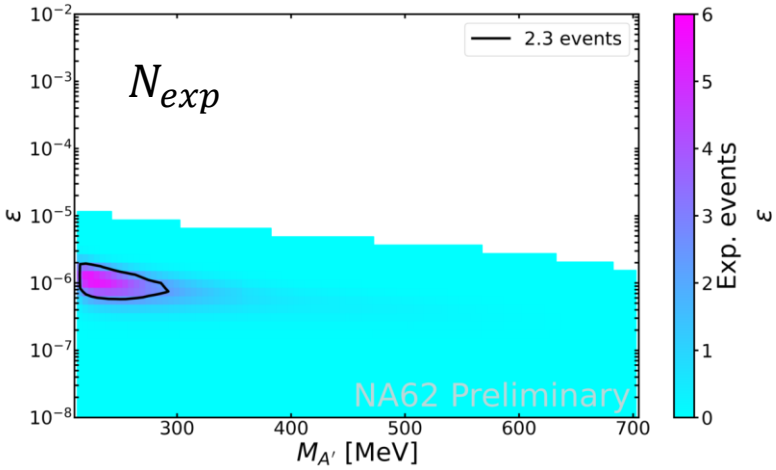
Z_{TAX} – longitudinal position, σ_Z = ~5.5 m

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

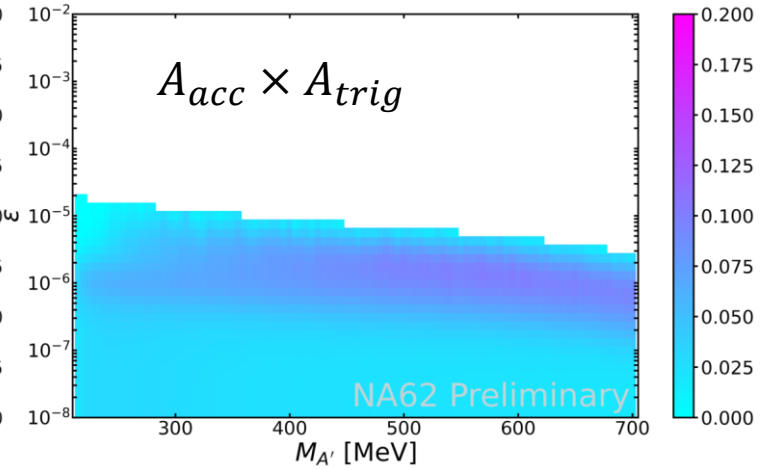
Signal efficiency and expected DP yield

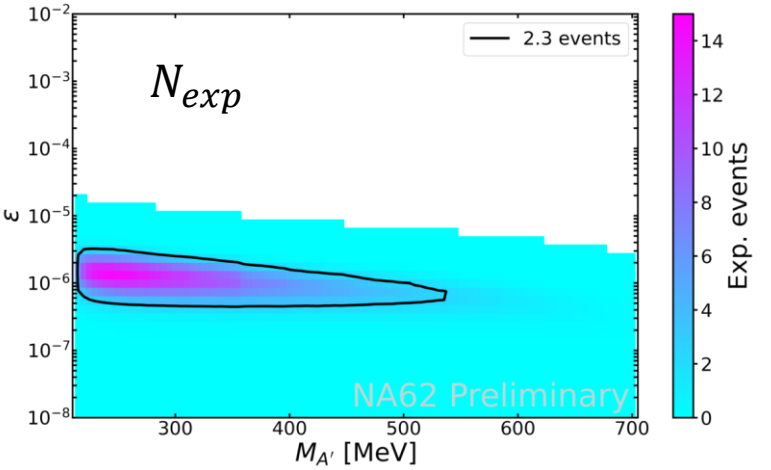
$A' \to \mu\mu$, meson production





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





$$N_{exp} = \text{POT} \times \chi(pp \to A') \times \mathcal{B}(A' \to \mu\mu) \times P_{rd}(\epsilon) \times A_{acc} \times A_{trig}$$

POT = $(1.40 \pm 0.28) \times 10^{17}$

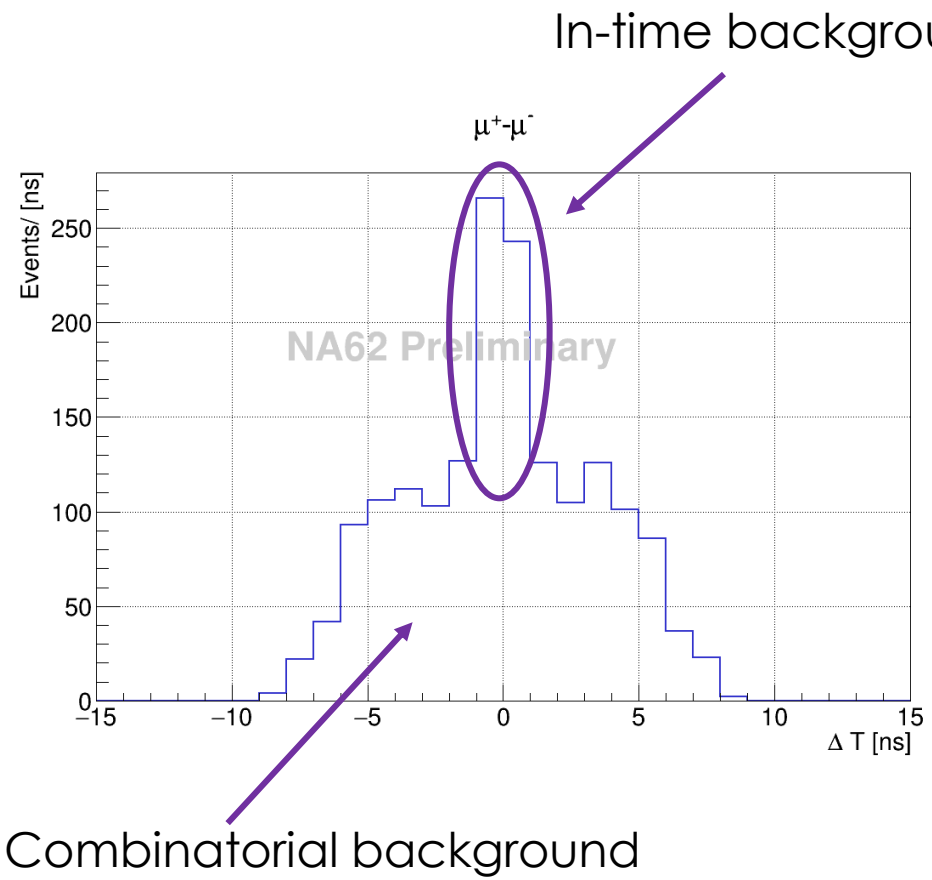
$\chi(pp \to A')$ - DP production probability

$\mathcal{B}(A' \to \mu\mu)$ - branching fraction

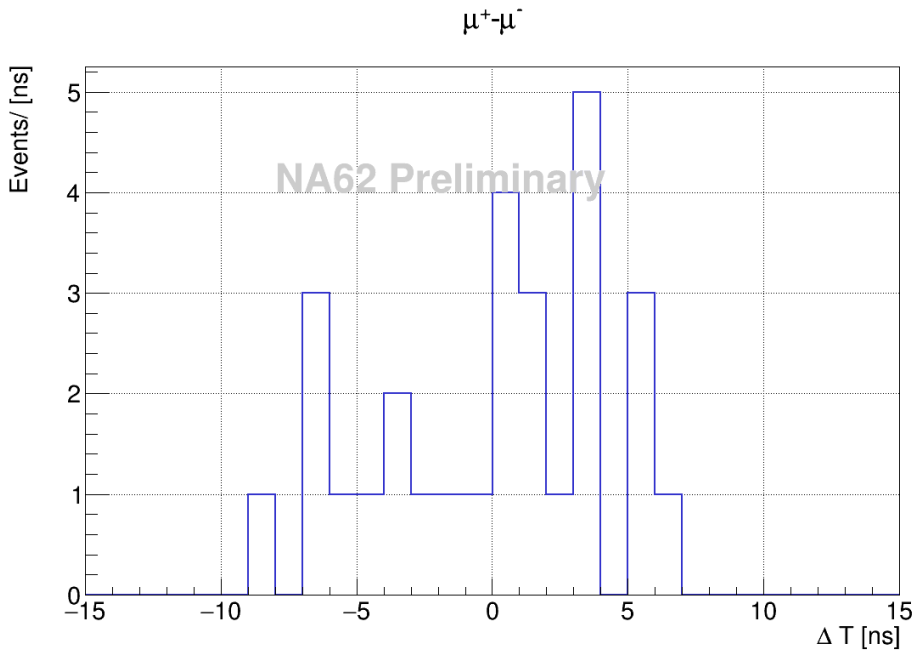
$P_{rd}(\epsilon)$ - probability to reach NA62 decay region and decay therein

$A_{acc} \times A_{trig}$ - signal selection and trigger efficiencies

Distribution of track time difference



Before LAV veto is applied
(CR&SR blinded)



Final events selected
(CR&SR blinded)

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

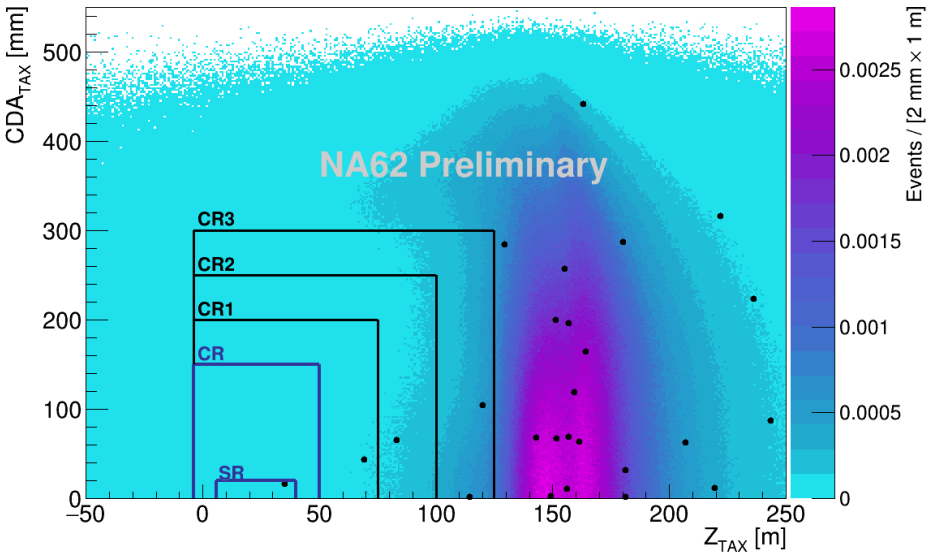
Background from secondaries of a muon interaction with the traversed material

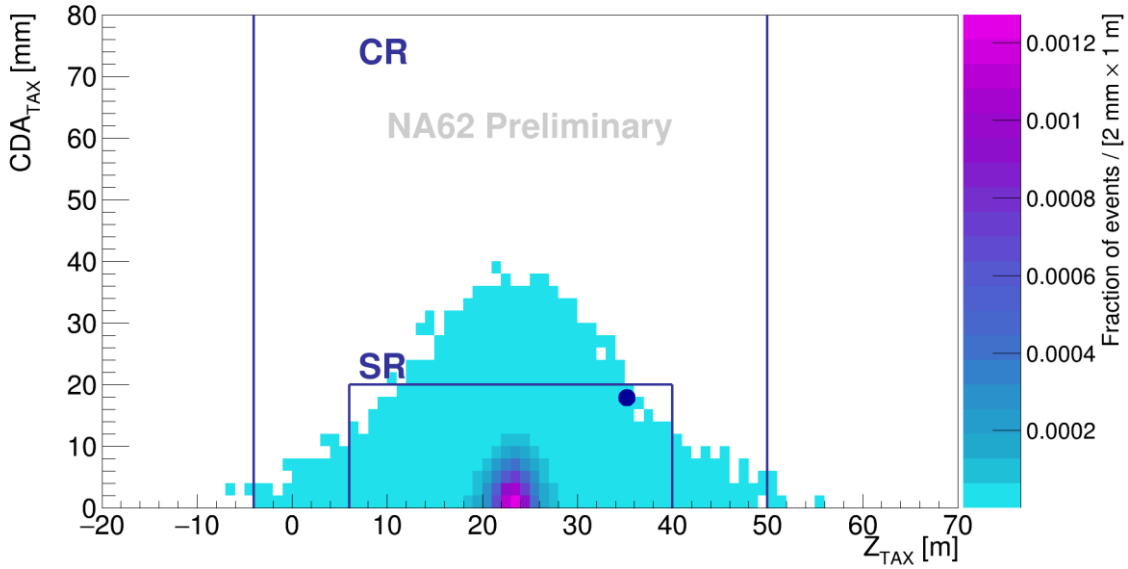
- Muon kinematic distributions extracted from selected single muons in data (backward MC)
- To correct the spread induced by the backward-forward process (straggling, multiple scattering) an unfolding technique is applied to better reproduce the data distributions.
- Relative uncertainty of MC expectation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

	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

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

Data-MC comparison: signal sample, SR open

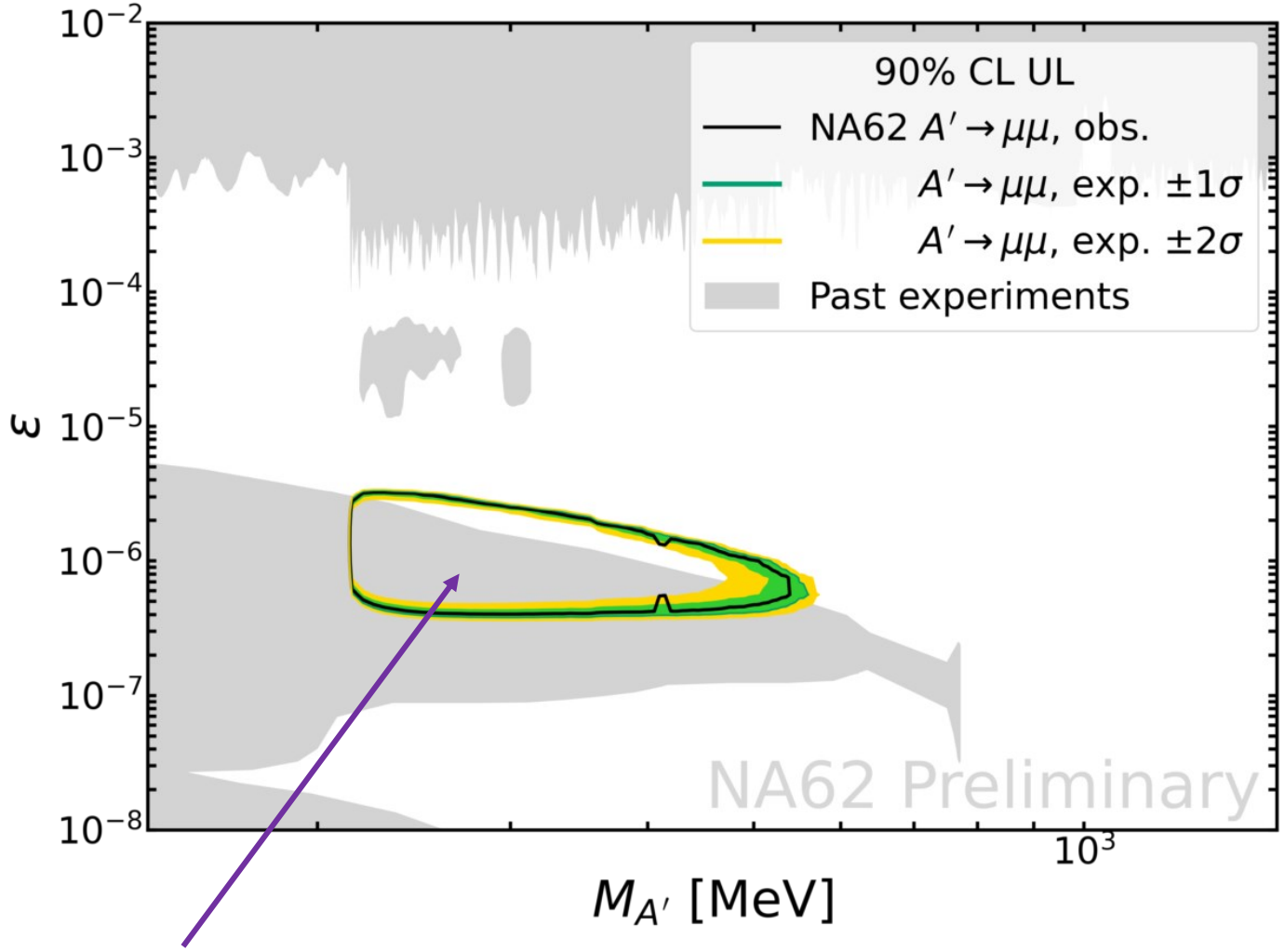




1 event observed
Counting experiment with 2.4σ global significance

Signal shape was not taken into account for the significance

Final result for $A' \to \mu^+\mu^-$

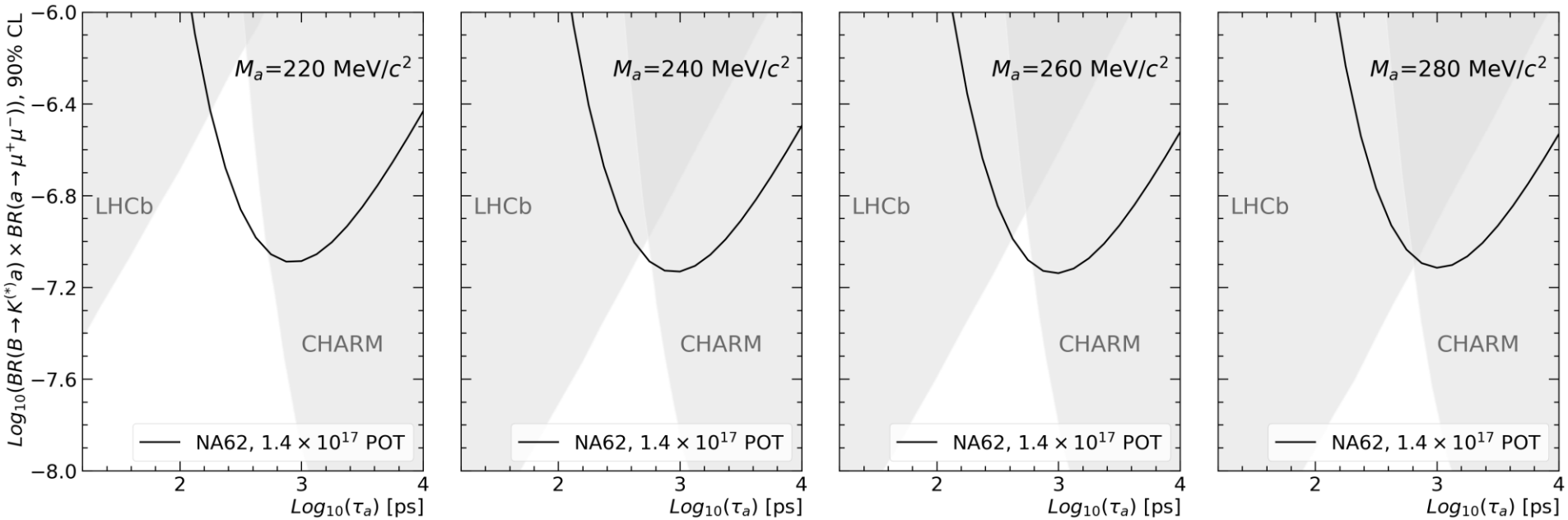


Excluded region

Model-independent limits on $a \to \mu^+\mu^-$ process

- Assume that a is a pseudoscalar(scalar) particle [Phys. Lett. B 790 (2019) 537]
- Assume mass M_a, lifetime τ_a and coupling to be independent parameters

→ Set limits in $BR\left(B \to K^{(*)}a\right) \times BR(a \to \mu^+\mu^-)$ vs τ_a parameter space for each mass separately



NEW

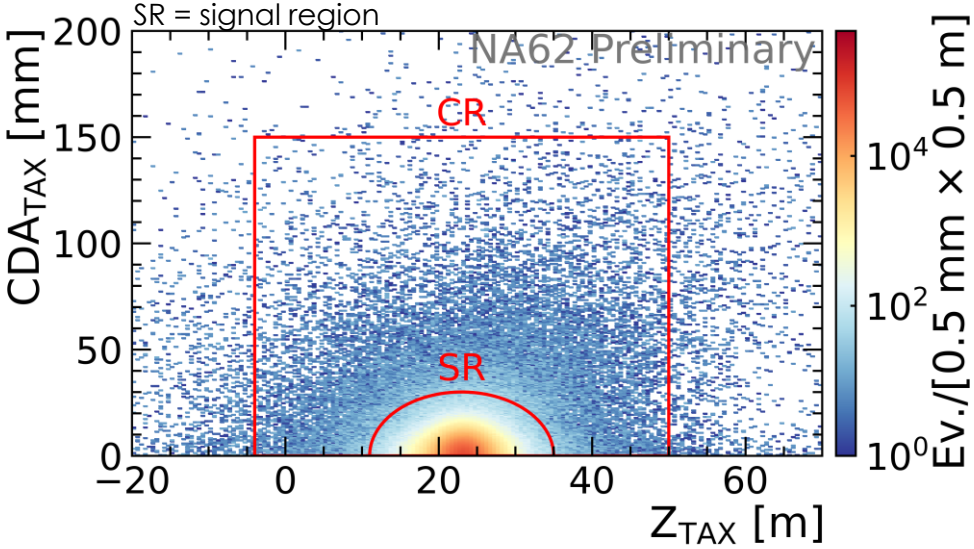
Analysis strategy for $A' \rightarrow e^+e^-$ search

Event selection:

- reconstructed track quality
- track timing coincidence with the trigger
- decay region & PID optimisation
- no in-time activity in muon veto detector MUV3
- no in-time activity at large angle veto detectors (LAV) and ANTI0 to reduce possible selection of vertices derived by interaction of incoming muons with the material in the LAVs.
- Signal region (SR) selection -> new signal region definition

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 e^+e^- pair direction σ_{CDA} = ~7 mm

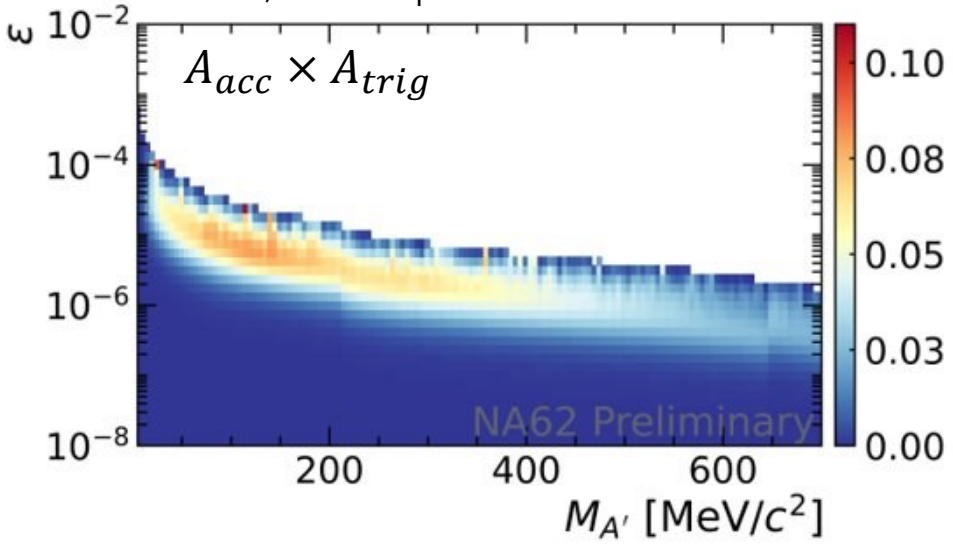
Z_{TAX} – longitudinal position, σ_Z = ~5.5 m

Signal region:
Ellipse centered around Z_{TAX} = 23 m and CDA_{TAX} = 0 mm

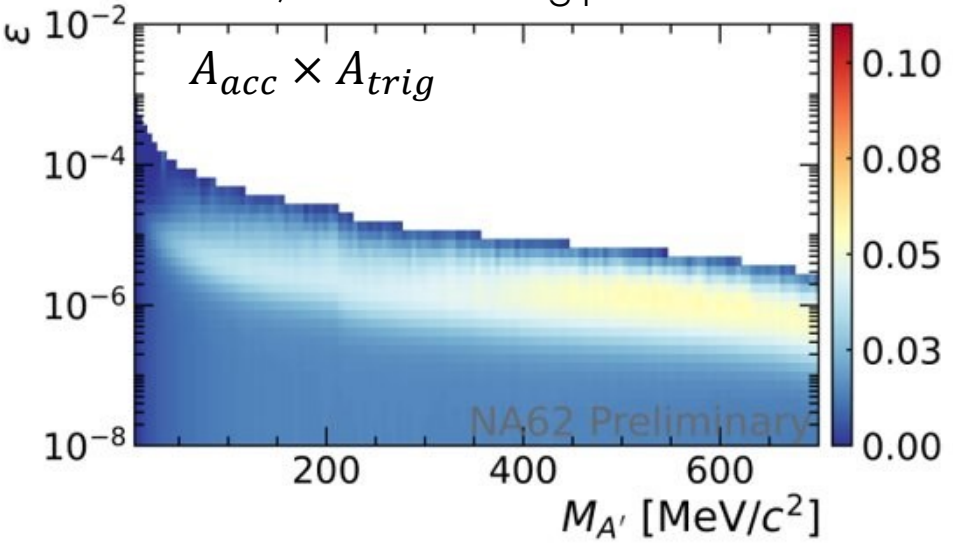
NEW

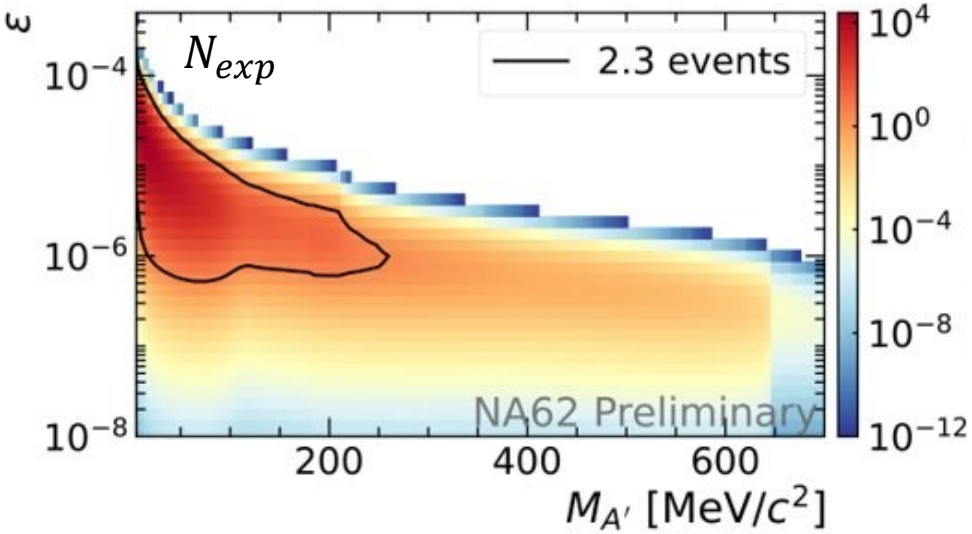
Signal efficiency and expected DP yield

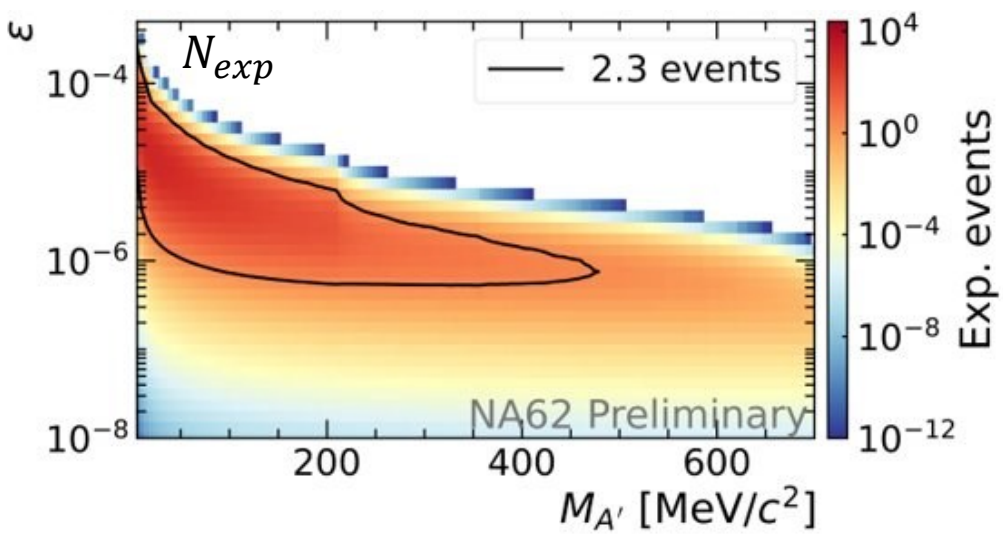
$A' \to ee$, meson production



$A' \to ee$, bremsstrahlung production







$$N_{exp} = \text{POT} \times \chi(pp \to A') \times \mathcal{B}(A' \to ee) \times P_{rd}(\epsilon) \times A_{acc} \times A_{trig}$$

NEW

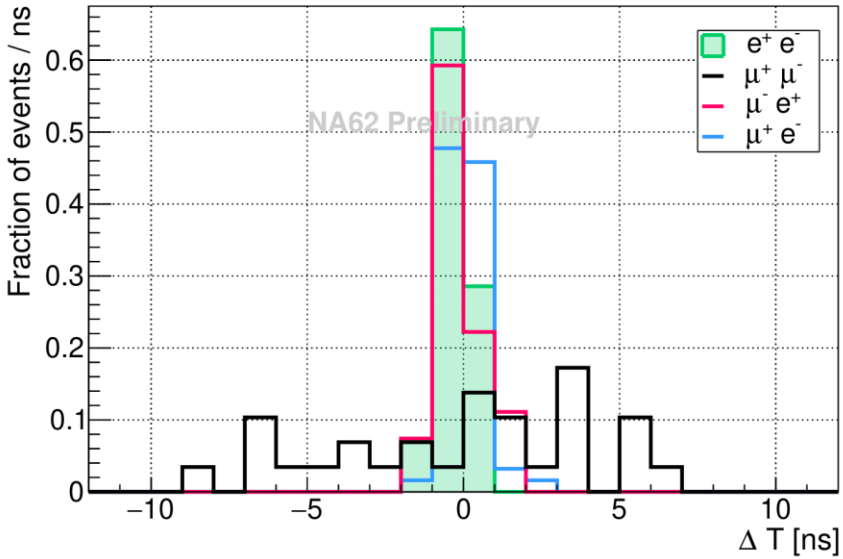
Background studies

- **Combinatorial** component estimated using the same technique as in the $\mu\mu$ analysis, now applying electron PID:

$$N_{exp} < 9 \times 10^{-4}$$

- **Prompt background** is the dominant component in this analysis → use dedicated MC developed for the $\mu\mu$ analysis. Expected number of events estimated using rejection factors η of LAV, ANTI0, SR and CR cuts obtained from MC.

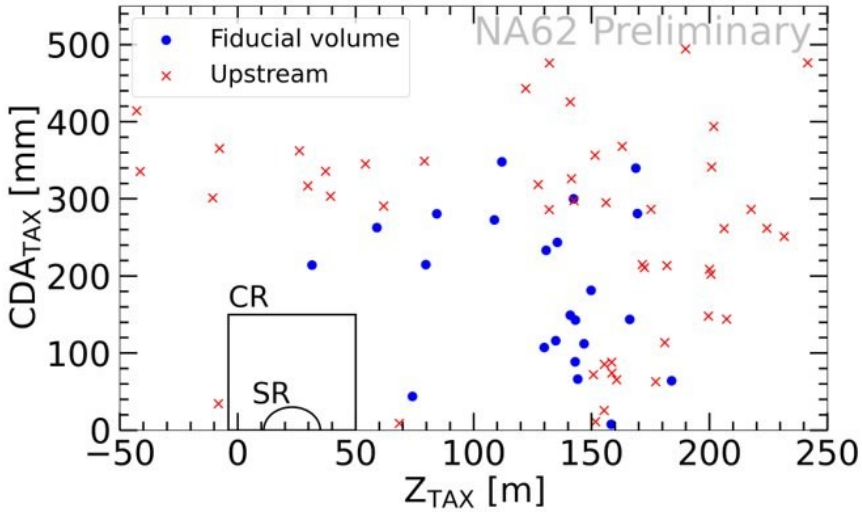
Data, SR and CR masked



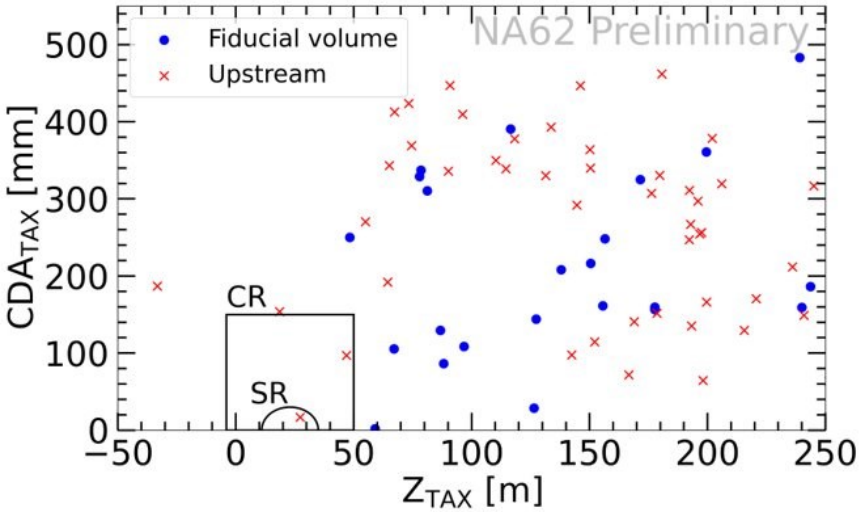
NEW

Evaluation of expected background

Data, no LAV/ANTI0 cuts, SR&CR masked



MC, no LAV/ANTI0 cuts



Fraction of events in CR/SR ~ 0.01

Condition	$N_{exp} \pm \delta N_{exp}$	$1-\eta$
e^+e^- PID	59.9 ± 6.7	–
e^+e^- PID, LAV-ANTI0	0.72 ± 0.72	$0.012^{+0.020}_{-0.008}$
e^+e^- PID, CR	0.51 ± 0.51	$0.009^{+0.018}_{-0.006}$
e^+e^- PID, SR	0.47 ± 0.47	$0.008^{+0.018}_{-0.006}$

$$N_{bkg}^{CR(SR)} = N_{bkg}^{FV}\Big|_{CR\&SR\ masked} \times \times \frac{1}{\eta_{CR}+\eta_{SR}-1} \times \times (1-\eta_{LAV-ANTI0}) \times \times \left(1-\eta_{CR(SR)}\right)$$

Expected events in CR and SR:

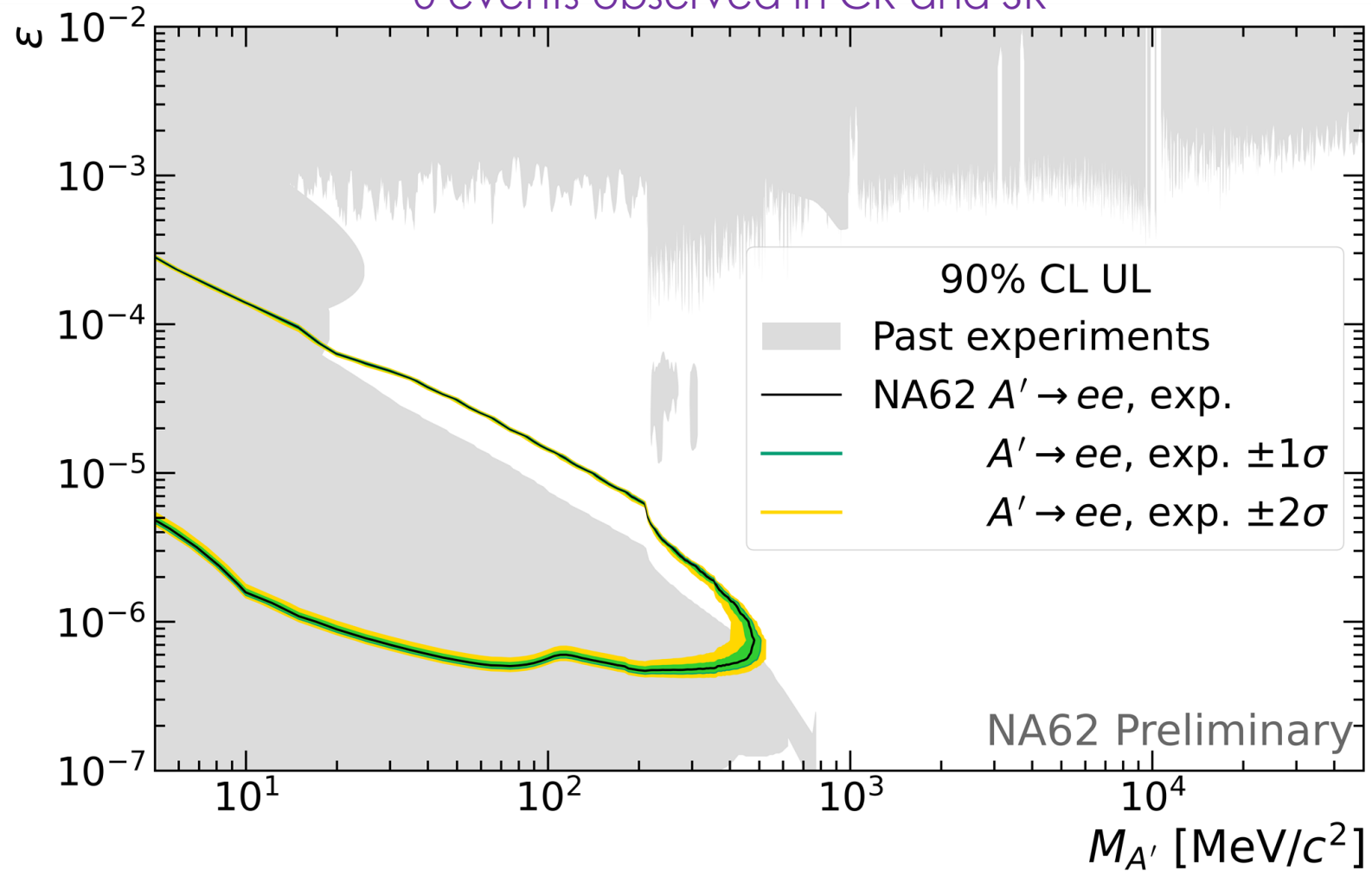
$$N_{bkg}^{CR} = 0.0097^{+0.049}_{-0.009}\ @\ 90\%\ CL$$

$$N_{bkg}^{SR} = 0.0094^{+0.049}_{-0.009}\ @\ 90\%\ CL$$

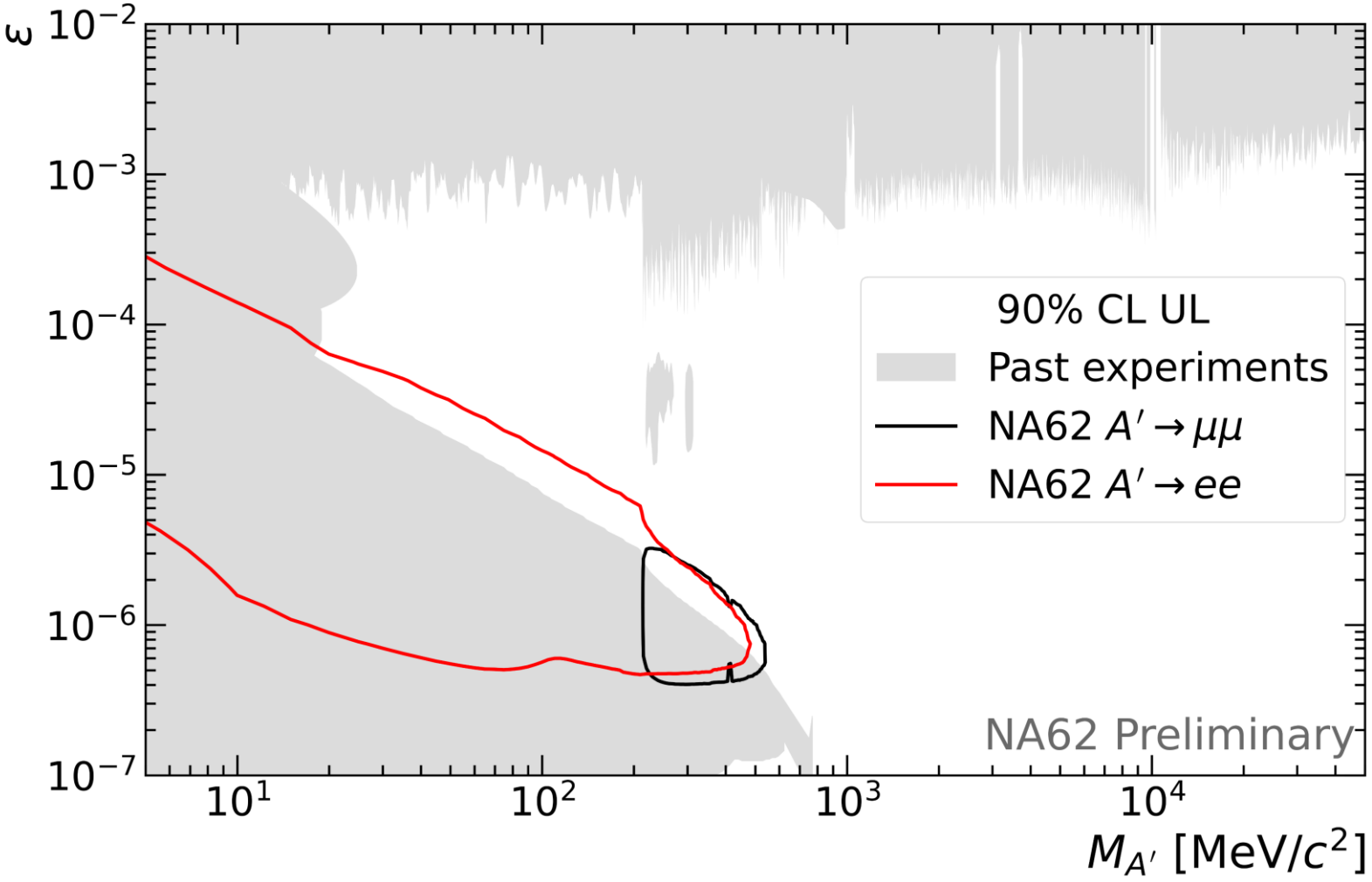
NEW

Final result for $A' \to e^+e^-$

0 events observed in CR and SR



Results for $A' \to l^+ l^-$

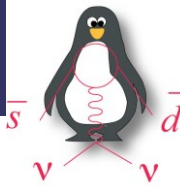


To be continued…

Summary

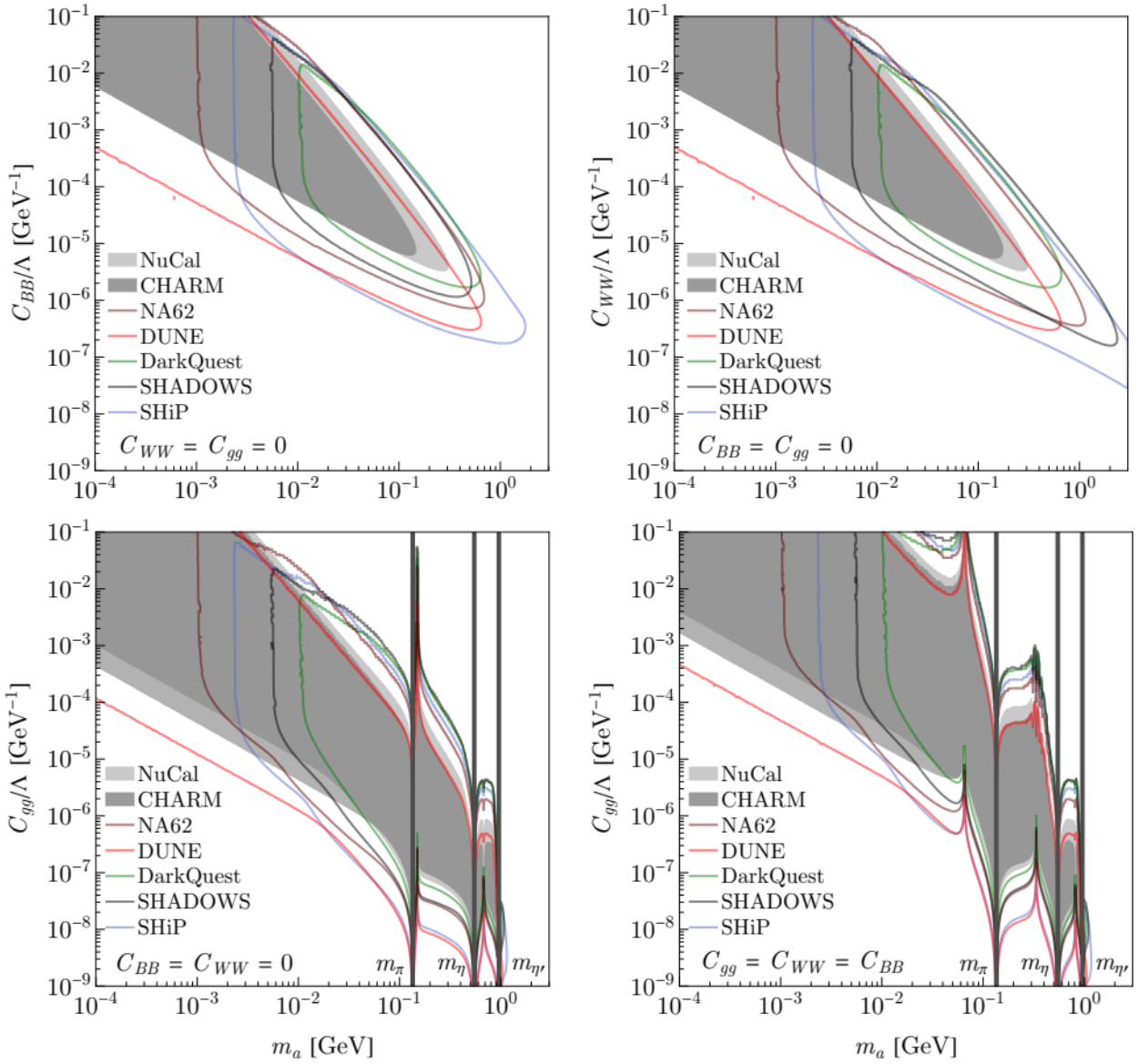
- The preliminary result on search for production and decay of an exotic particle from data collected by the NA62 experiment in beam-dump mode has been presented
- A cut-based counting experiment blind analysis to search for $A' \rightarrow l^+l^-$ has been performed on the data collected in 2021.
- With $(1.4 \pm 0.28) \times 10^{17}$ POT a 90% CL upper limits have been set, exploring new regions of the parameter space.
- Searches for decays of exotic particles to $\gamma\gamma, \pi^+\pi^-\gamma$ 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

ALPs in beam dump (projections)



[JHEP07(2022)094]

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

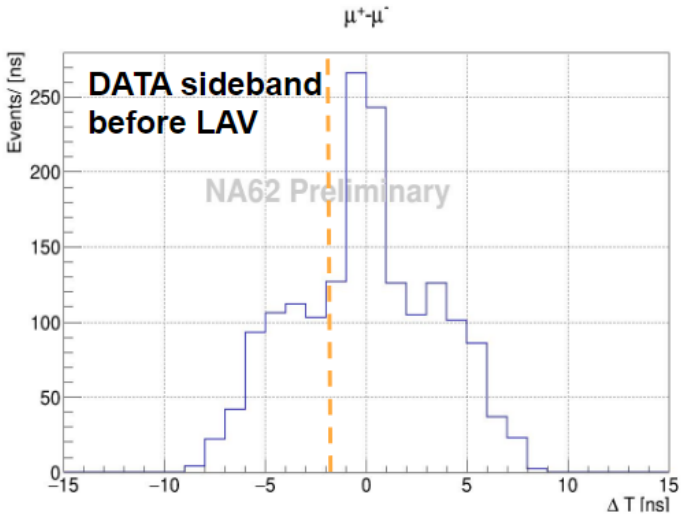
CDA_{FV} = 382 mm

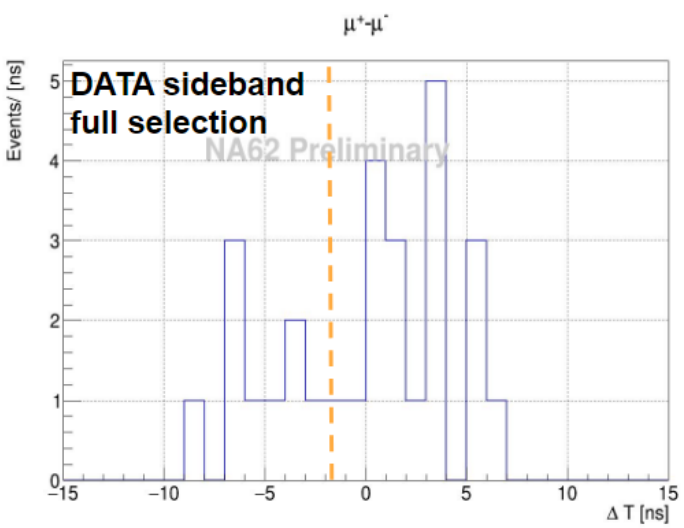
Z_{TAX} = 35.3 m

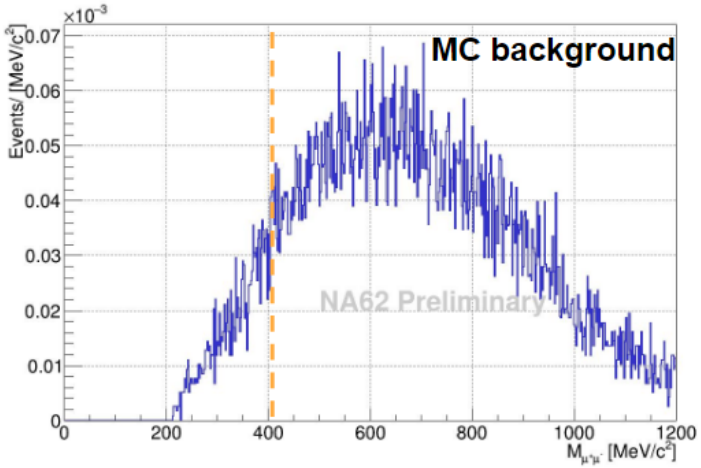
CDA_{TAX} = 17 mm

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

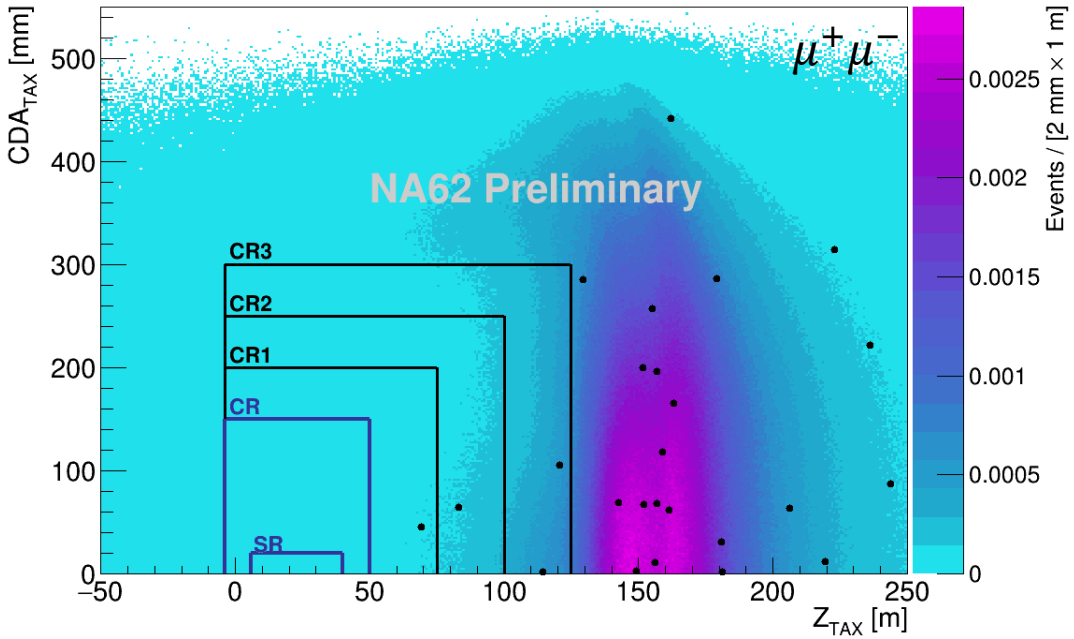
$E/P(\mu^-)$ = 0.018







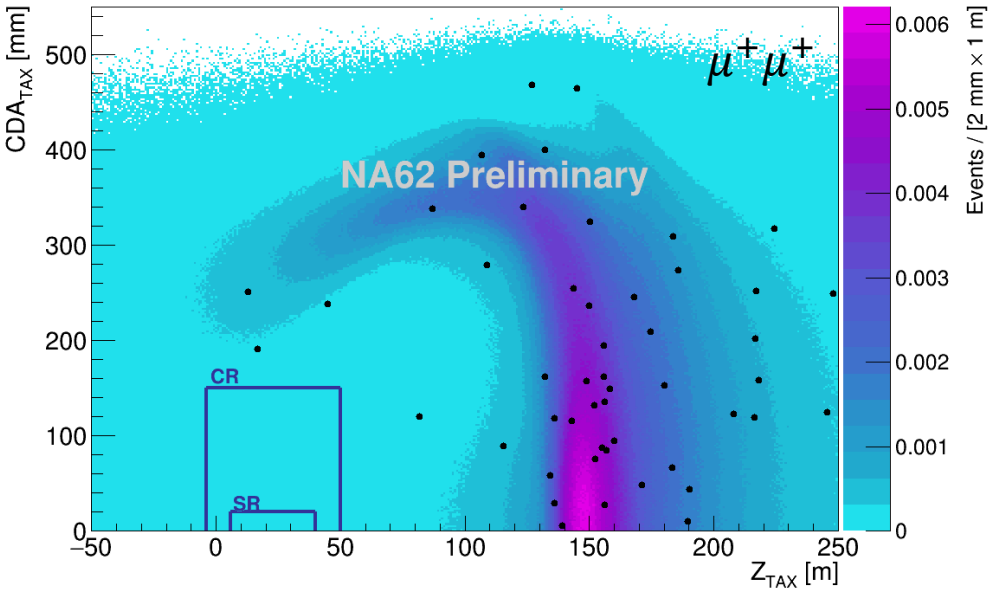
Data-MC comparison: signal sample, CRs open

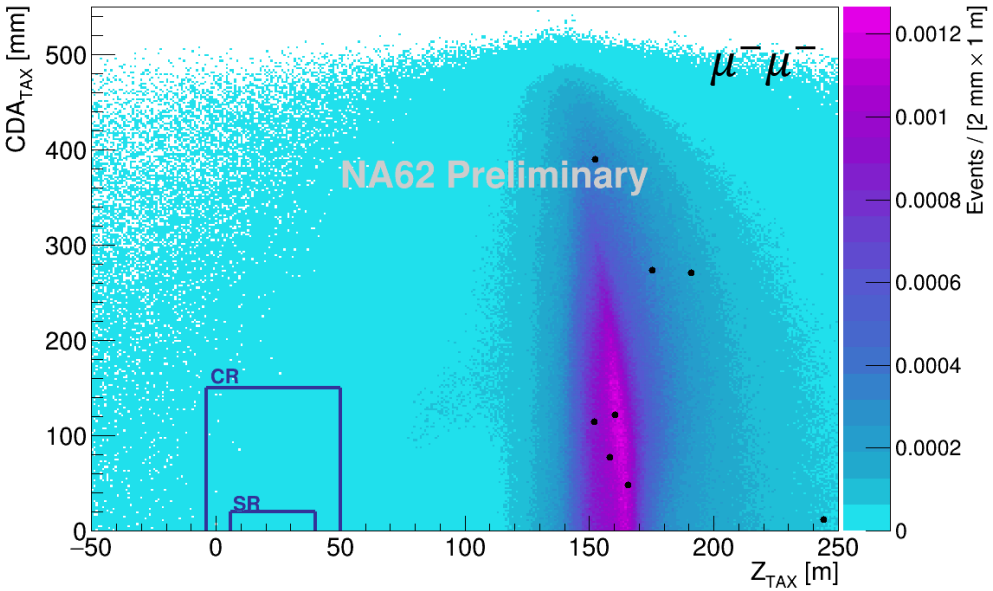


Probability to observe 1 or more events in the SR is 1.59%

	$N_{exp} \pm \delta N_{exp}$	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: control samples

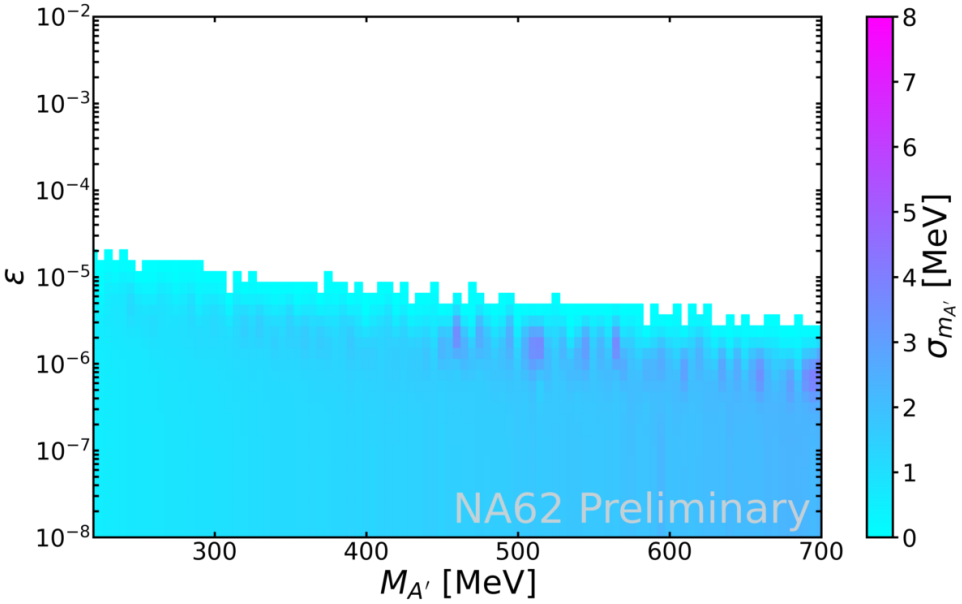




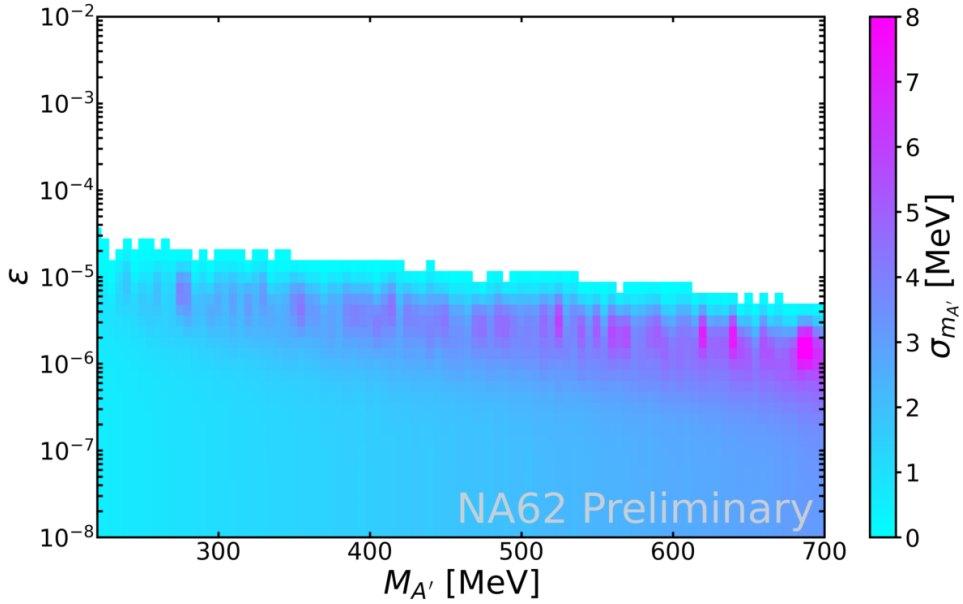
	$N_{exp} \pm \delta N_{exp}$	N_{obs}	$p(N \geq N_{obs})$	$p(L \leq L_{obs})$
Outside CR	62.5 ± 9.4	53	0.79	0.46
CR	0.46 ± 0.07	0	1.0	1.0
SR	0.040 ± 0.006	0	1.0	1.0

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

Invariant mass resolution $M_{\mu\mu}$

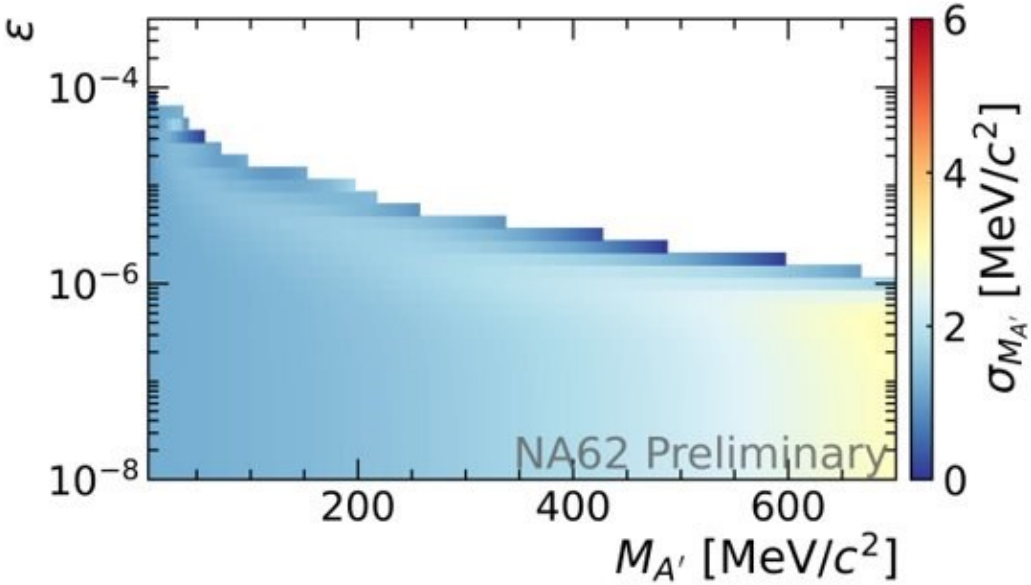


Meson production

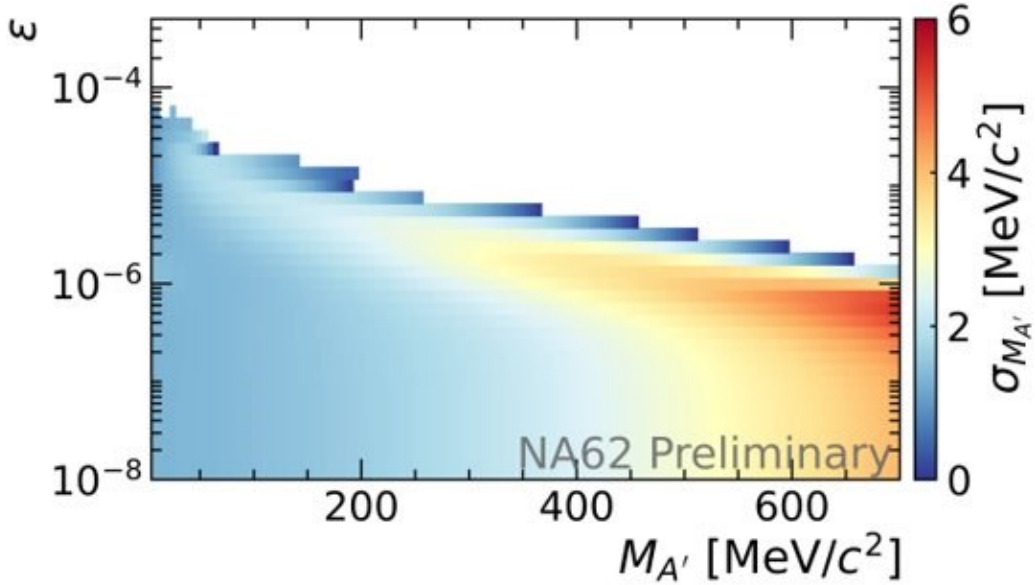


Bremsstrahlung production

Invariant mass resolution M_{ee}



Meson production



Bremsstrahlung production