The XXXI International Workshop on Deep Inelastic Scattering and Related Subjects (DIS2024)

Latest results for searches of exotic decays with NA62 in beam-dump mode

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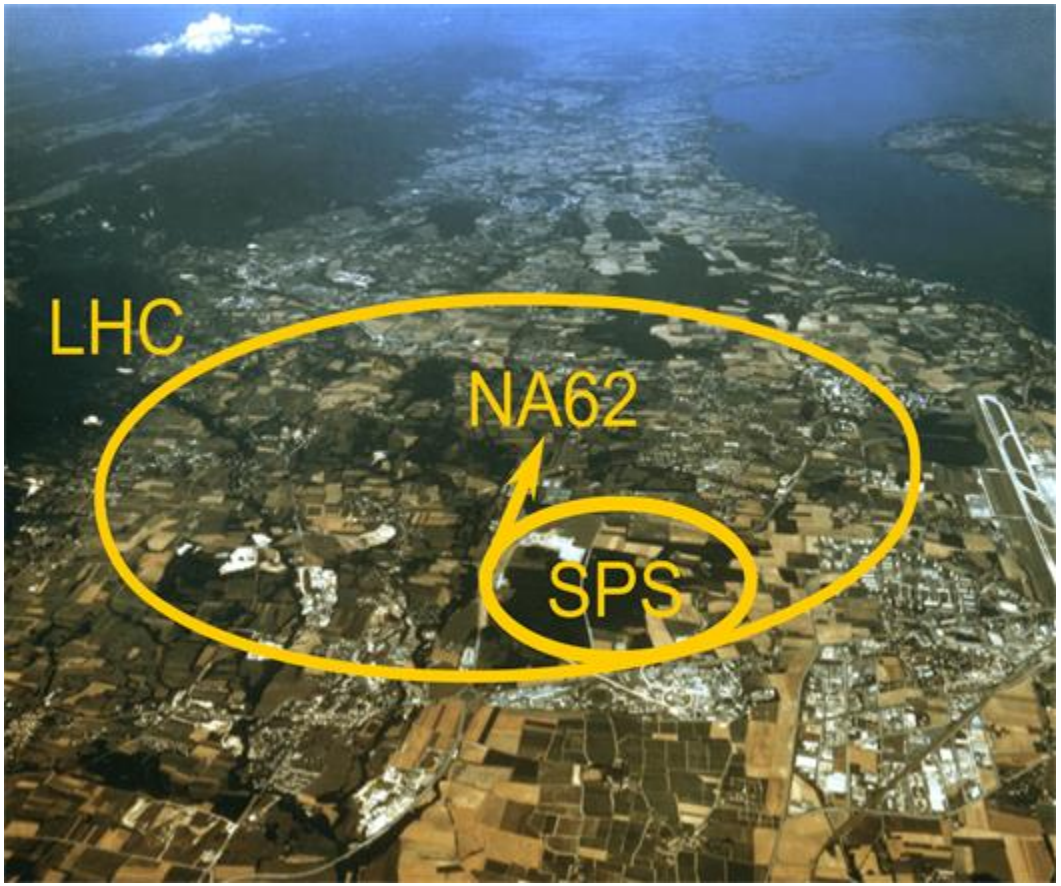
on behalf of NA62 Collaboration

European Research Council
Established by the European Commission

Grenoble 2024, 10th April

The NA62 experiment



~30 institutes, ~200 participants

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 SM prediction:

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$

[arXiv:2109.11032]

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)]

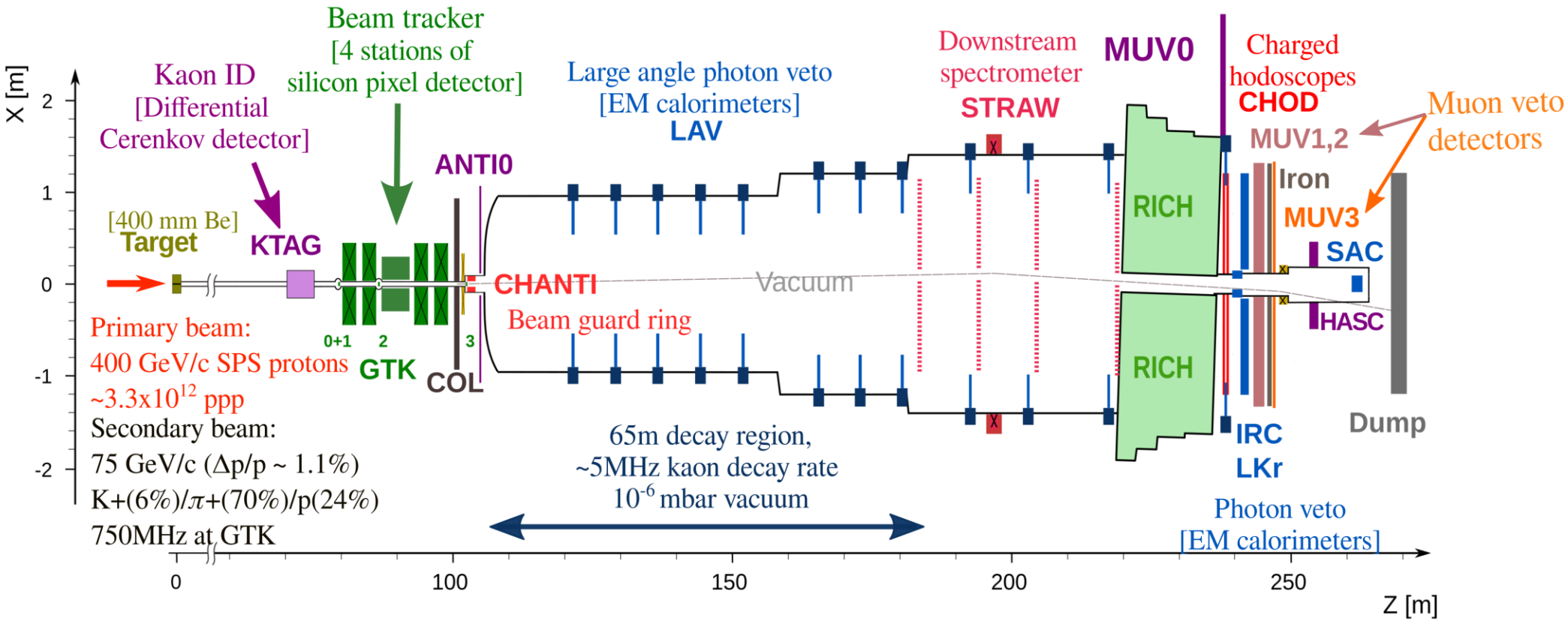
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(10.6^{+4.0}_{3.4\ stat} \pm 0.9_{syst}\right) \times 10^{-11}$$

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

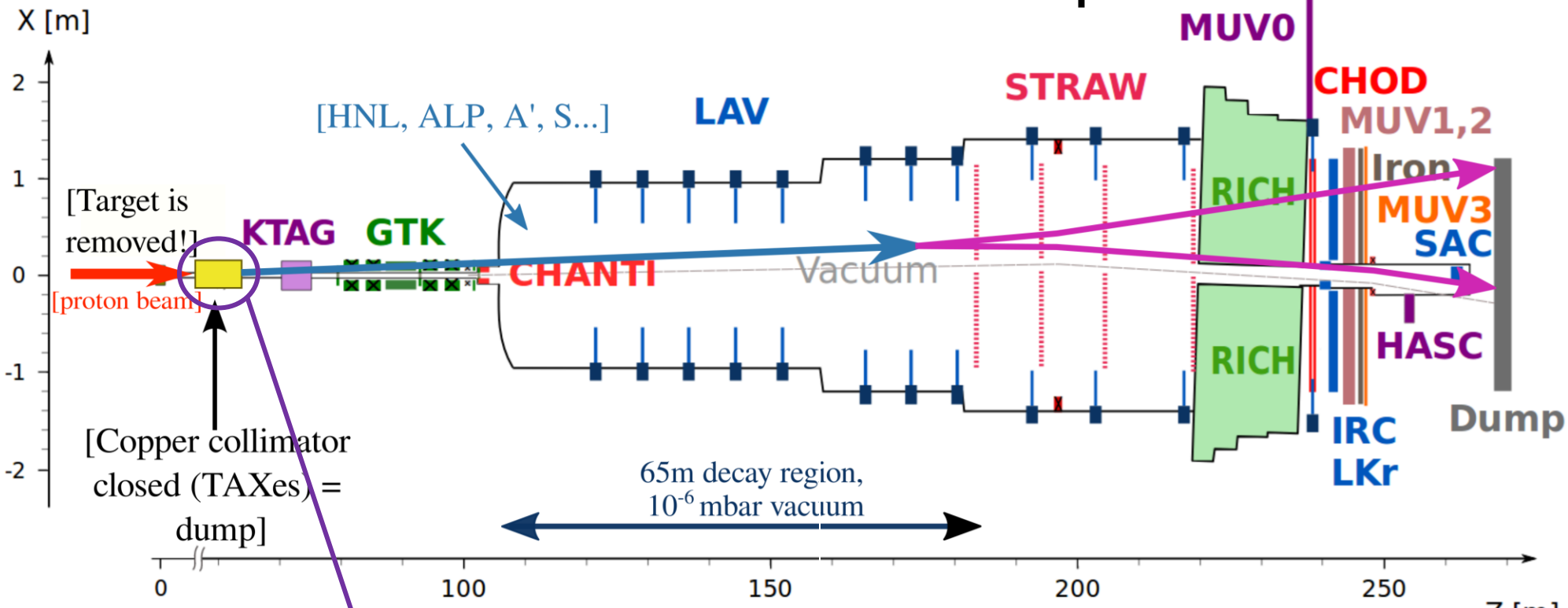


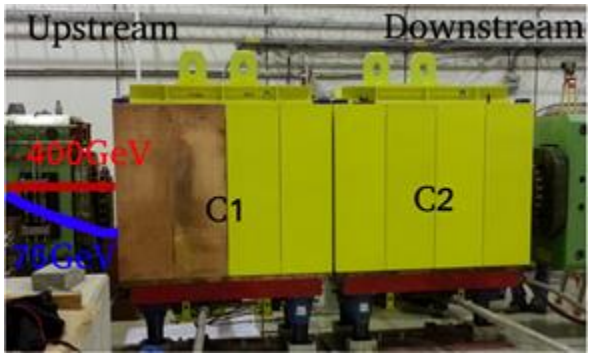
Performances:

- 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

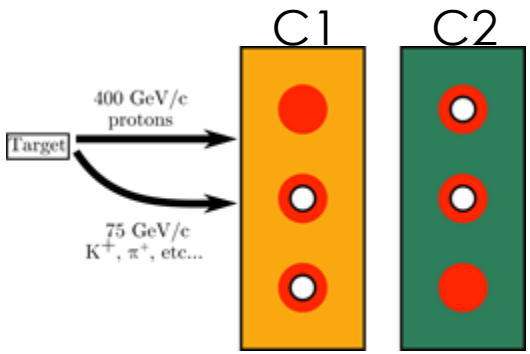
[NA62 Detector Paper, JINST 12 (2017), P05025]

NA62 in beam dump mode

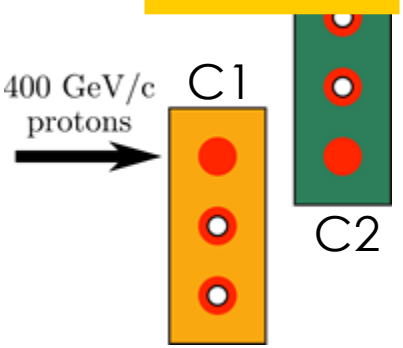




Normal data taking



BD mode



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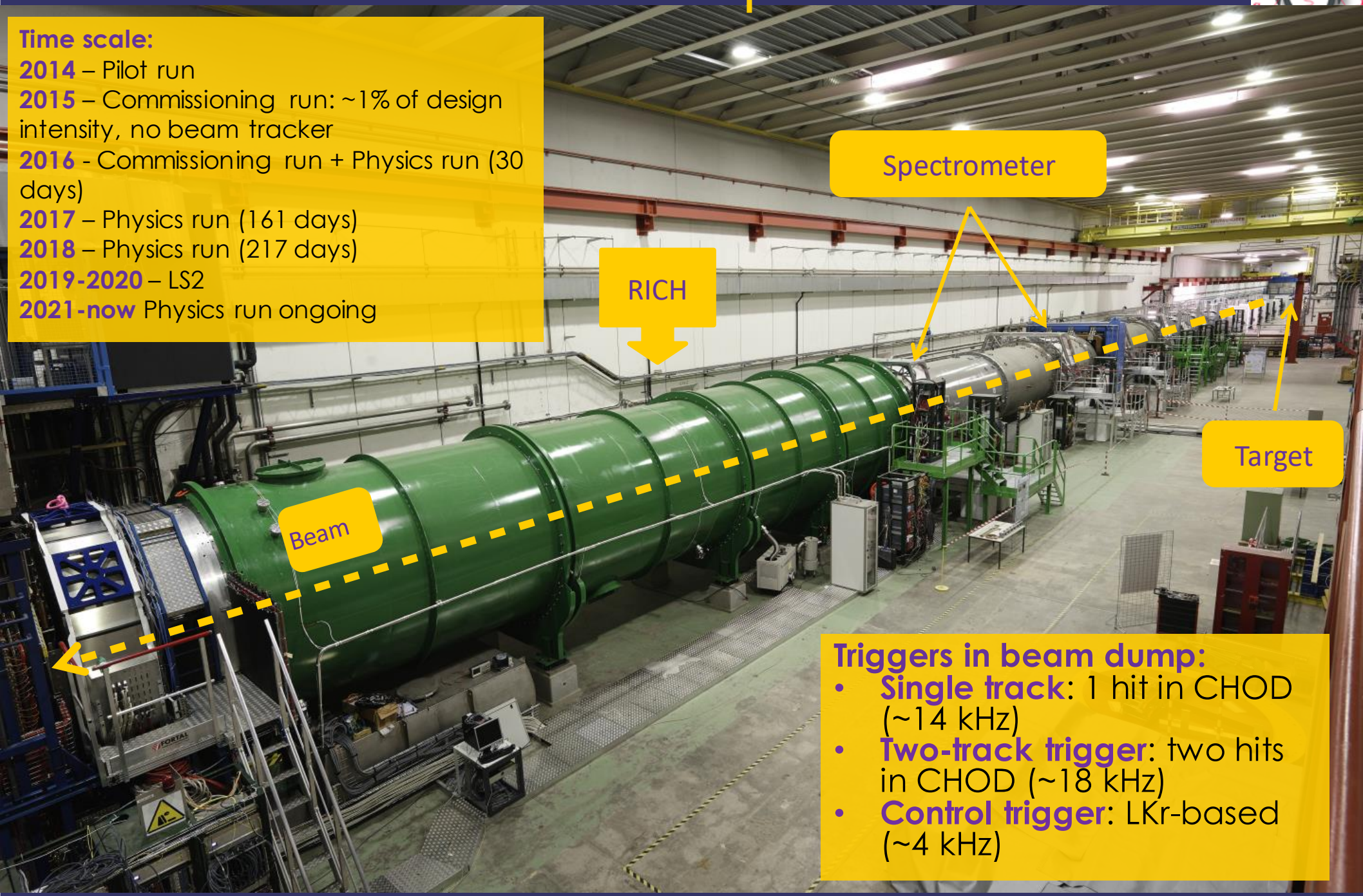

Time scale:
2014 – Pilot run
2015 – Commissioning run: ~1% of design intensity, no beam tracker
2016 - Commissioning run + Physics run (30 days)
2017 – Physics run (161 days)
2018 – Physics run (217 days)
2019-2020 – LS2
2021-now Physics run ongoing

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

Search motivation

- Searches for New Physics with fixed-target experiments are complementary to energy frontier (LHC) and indirect searches
- Smaller masses (MeV-GeV) and lower couplings are accessible

Several New Physics models proposed for study:

	type	SM portal	PBC	Decay channels
Dark photon (A')	vector	$-(\varepsilon/2cos\theta_W)F'_{\mu\nu}B^{\mu\nu}$	BC1-2	$l^+l^-, 2\pi, 3\pi, 4\pi, 2K, 2K\pi$
Dark Higgs (S)	scalar	$(\mu S + \lambda S^2)H^\dagger H$	BC4-5	$l^+l^-, 2\pi, 4\pi, 2K$
Axion/ALP(a)	pseudoscalar	$(C_{VV}/\Lambda)aV_{\mu\nu}\tilde{V}^{\mu\nu}$ $(C_{ff}/\Lambda)\partial_\mu a\bar{f}\gamma^\mu\gamma^5 f$	BC9,11 BC10	$\gamma\gamma, l^+l^-, 2\pi\gamma, 3\pi, 4\pi, 2\pi\eta, 2K\pi$
HNL (N_I)	fermion	$F_{\alpha I}(\overline{L_\alpha}H)N_I$	BC6-8	$\pi l, Kl, l_1 l_2 \nu$

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HNL (N_I)	fermion	$F_{\alpha I}(\overline{L_\alpha}H)N_I$	BC6-8	$\pi l, Kl, l_1 l_2 \nu$

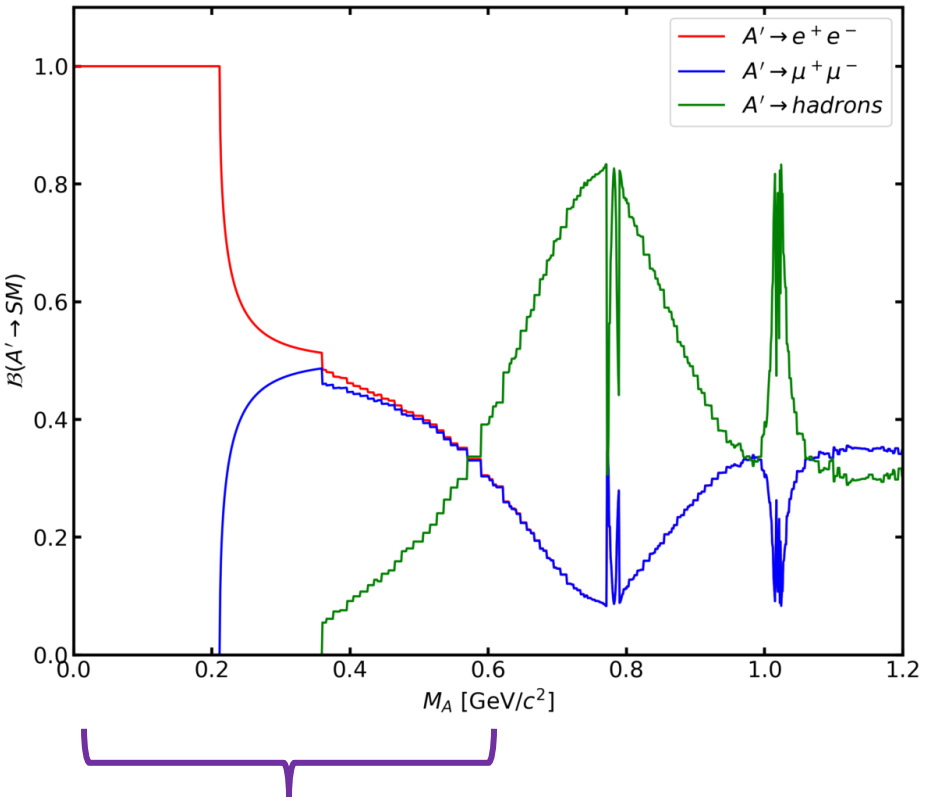
This talk

New physics searches at NA62

- Numerous decay channels and production mechanisms:
  - A': Bremsstrahlung, $P \to A'\gamma$, $V \to A'P$, where $P = \{\pi^0, \eta, \eta'\}$, $V = \{\rho, \omega, \phi\}$
  - S: $B^{\pm,0} \to K^{\pm,0,(*)}S$
  - a: Primakoff (on-, off-shell), mixing with $P = \{\pi^0, \eta, \eta'\}$, $B^{\pm,0} \to K^{\pm,0,(*)}a$

New physics searches in leptonic decays

- Numerous decay channels and production mechanisms:
  - A': Bremsstrahlung, $P \to A'\gamma$, $V \to A'P$, where $P = \{\pi^0, \eta, \eta'\}$, $V = \{\rho, \omega, \phi\}$
  - S: $B^{\pm,0} \to K^{\pm,0,(*)}S$
  - a: Primakoff (on-, off-shell), mixing with $P = \{\pi^0, \eta, \eta'\}$, $B^{\pm,0} \to K^{\pm,0,(*)}a$



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

JHEP 09, 035 (2023)
arXiv:2312.12055

Dark photon search in $A' \to l^+l^-$

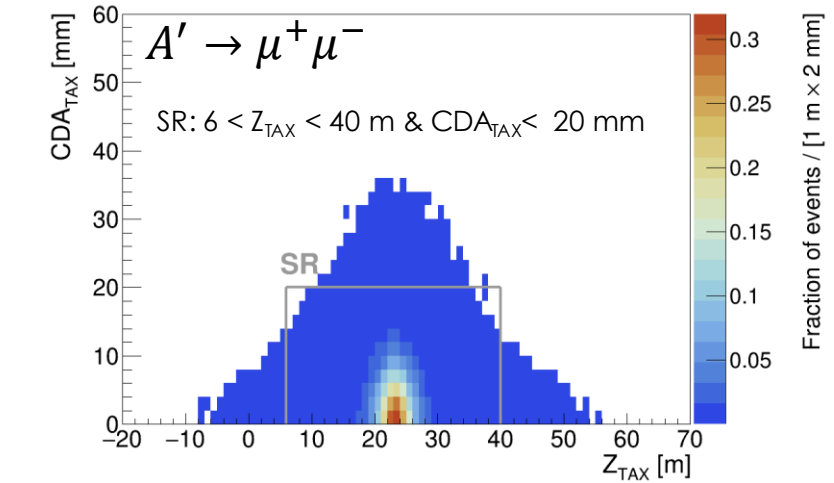
The signal signature:

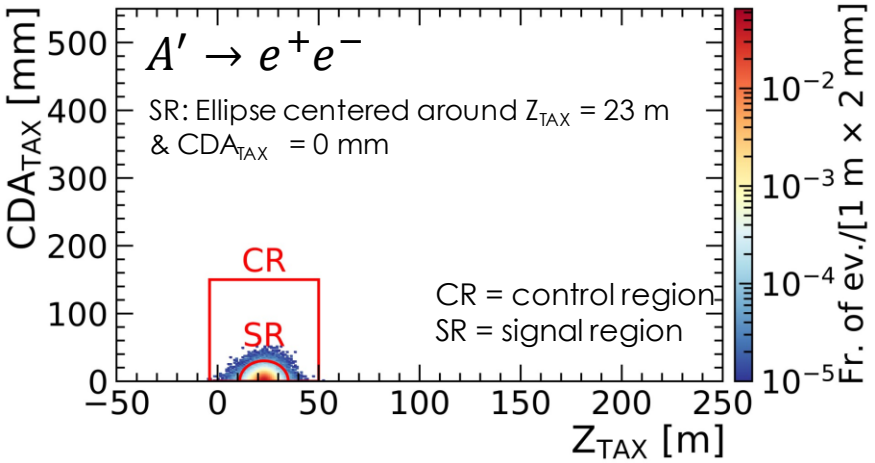
- Lepton-antilepton vertex in the NA62 decay region and pointing back to the proton beam interaction point at the TAX.

Event selection:

- Reconstructed track quality
- Track timing coincidence with the trigger
- Muon/electron identification with calorimeter and muon detector
- In ee analysis: decay region & PID optimization and no in-time activity in muon veto detector MUV3
- No in-time activity at large angle veto detectors (LAV) and ANTI0 in ee analysis to reduce possible selection of vertices derived by interaction of incoming muons with the material in the LAVs.
- Signal region (SR) selection (new SR definition in ee analysis)

CR and SR kept masked until the analysis strategy is frozen





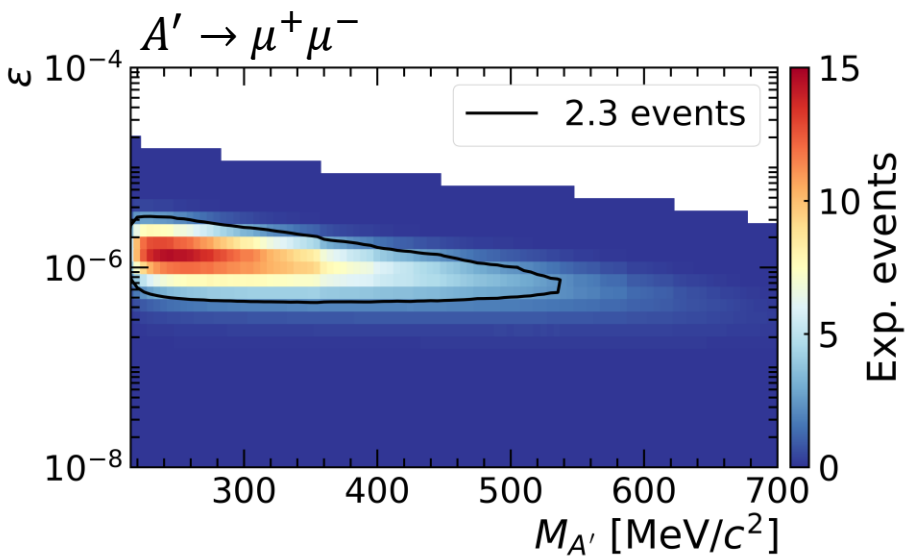
CDA_{TAX} – closest distance of approach between the beam direction at the TAX entrance and $\mu^+\mu^-$ pair direction σ_{CDA} = ~7 mm

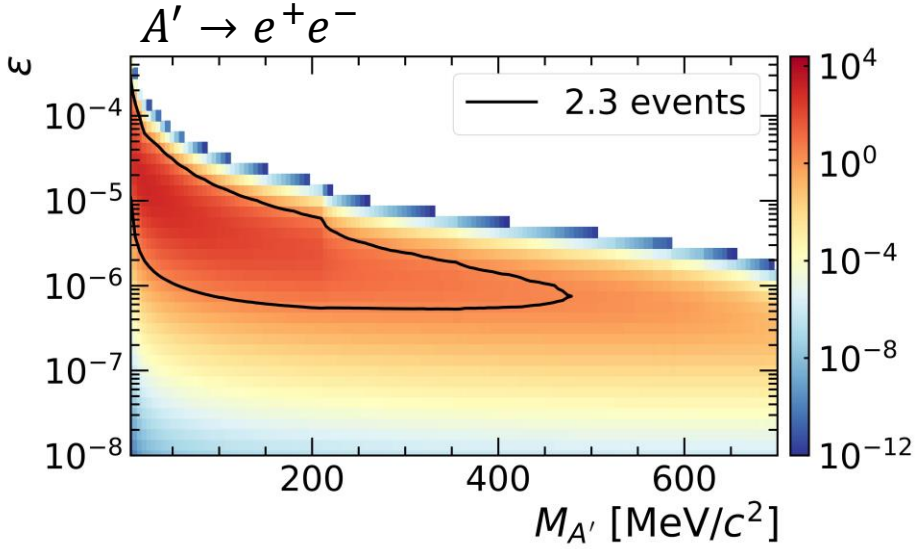
Z_{TAX} – longitudinal position, σ_Z = ~5.5 m

Expected yield

N_{exp} = POT × $\chi(pp \to A')$ × $\mathcal{B}(A' \to \mu\mu)$ × $P_{rd}(\varepsilon)$ × A_{acc} × 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
- $P_{rd}(\varepsilon)$ - probability to reach NA62 decay region and decay therein
- $A_{acc} \times A_{trig}$ - signal selection and trigger efficiencies

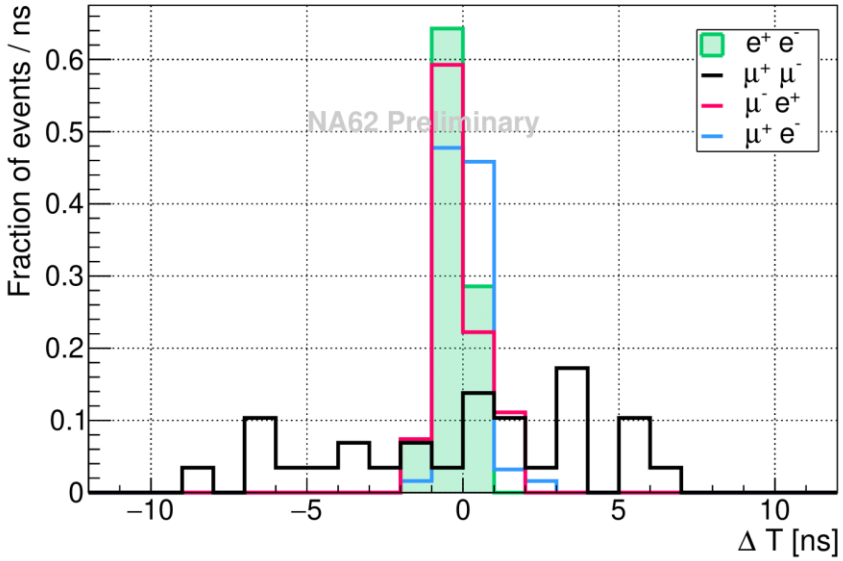




*only bremsstrahlung is shown

Background studies

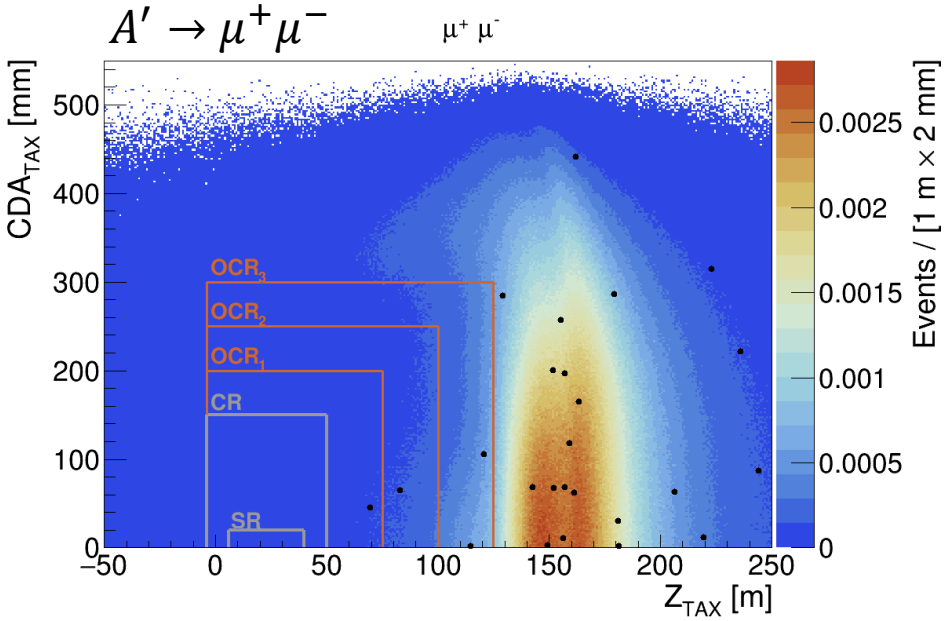
- Combinatorial background:
  - Random superposition of two uncorrelated "halo" muons
  - Dominant for $A' \to \mu^+\mu^-$
- Prompt background:
  - Secondaries of a muon interaction with traversed material
  - Dominant for for $A' \to e^+e^-$



Background studies

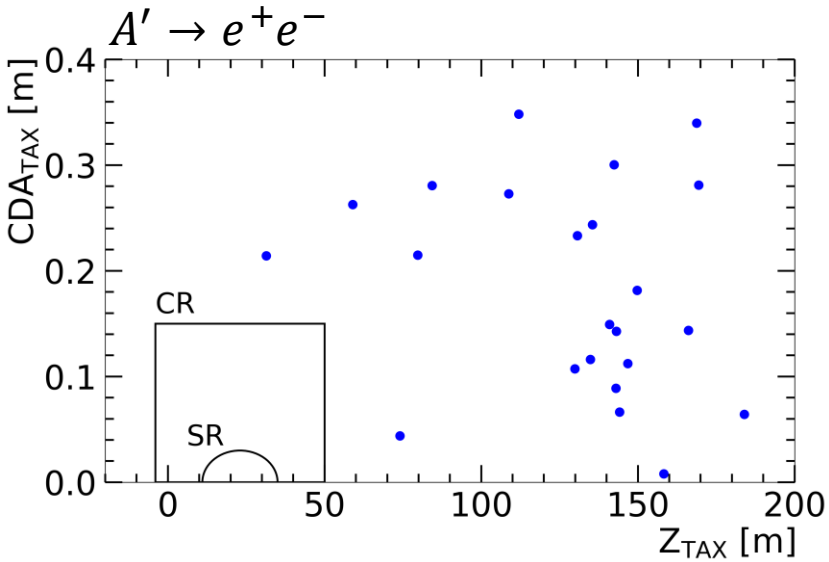
Expected events in CR and SR:

	Combinatorial	Prompt@90% CL	Upstream prompt@ 90%CL
CR	0.17 ± 0.02	< 0.004	< 0.069
SR	0.016 ± 0.002	< 0.0004	< 0.007

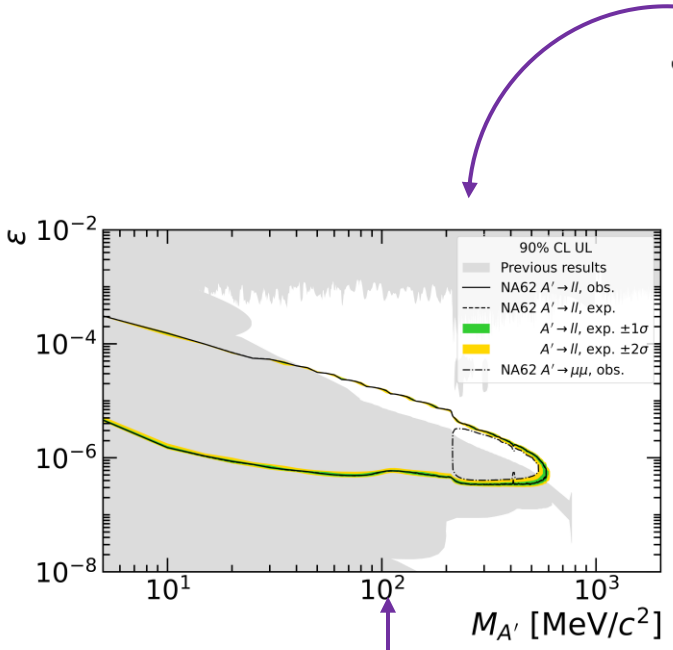


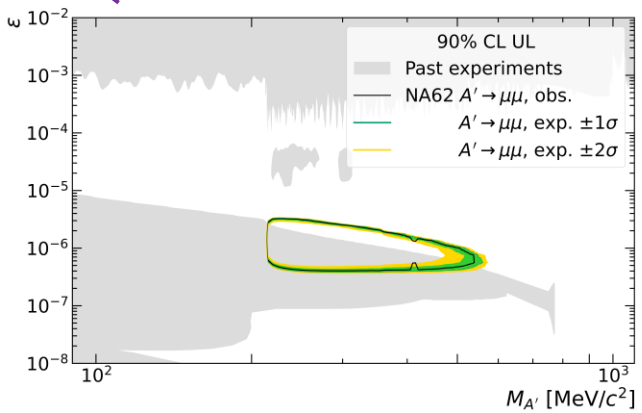
Expected events in CR and SR:

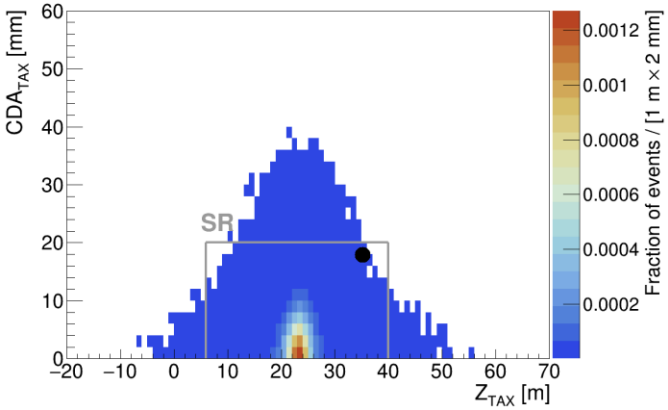
$$N_{bkg}^{CR} = 0.0097^{+0.049}_{-0.009} \text{ @ } 90\%\ CL$$
$$N_{bkg}^{SR} = 0.0094^{+0.049}_{-0.009} \text{ @ } 90\%\ CL$$

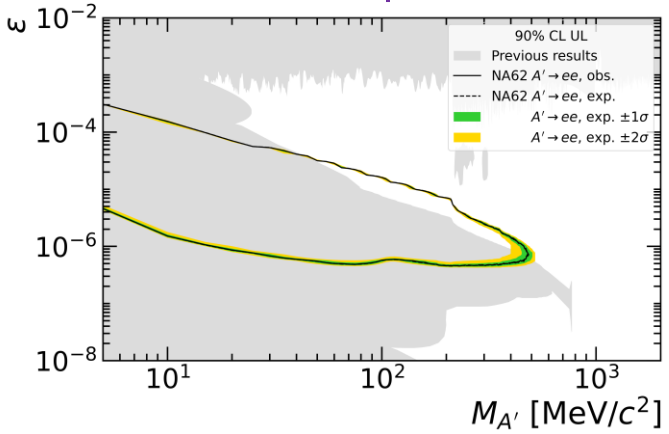


Results on the DP searches in $A' \to l^+l^-$









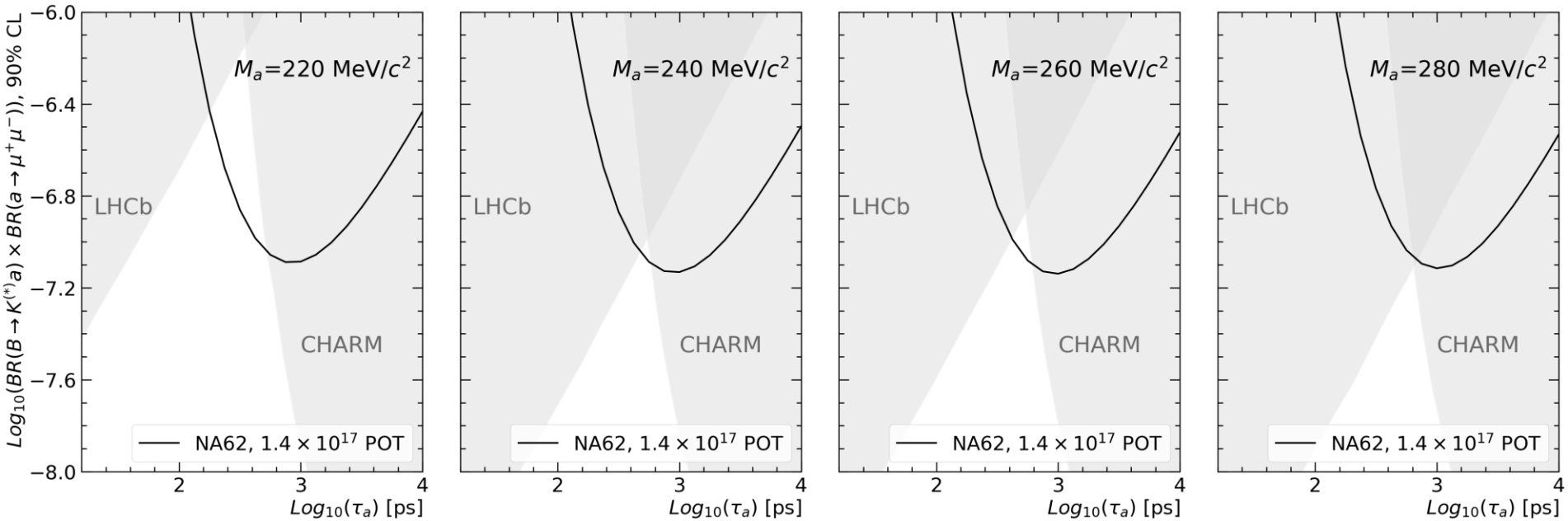
- $A' \to \mu^+\mu^-$: $N_{obs} = 1$ (2.6 σ significance)
- $A' \to e^+e^-$: $N_{obs} = 0$

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

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



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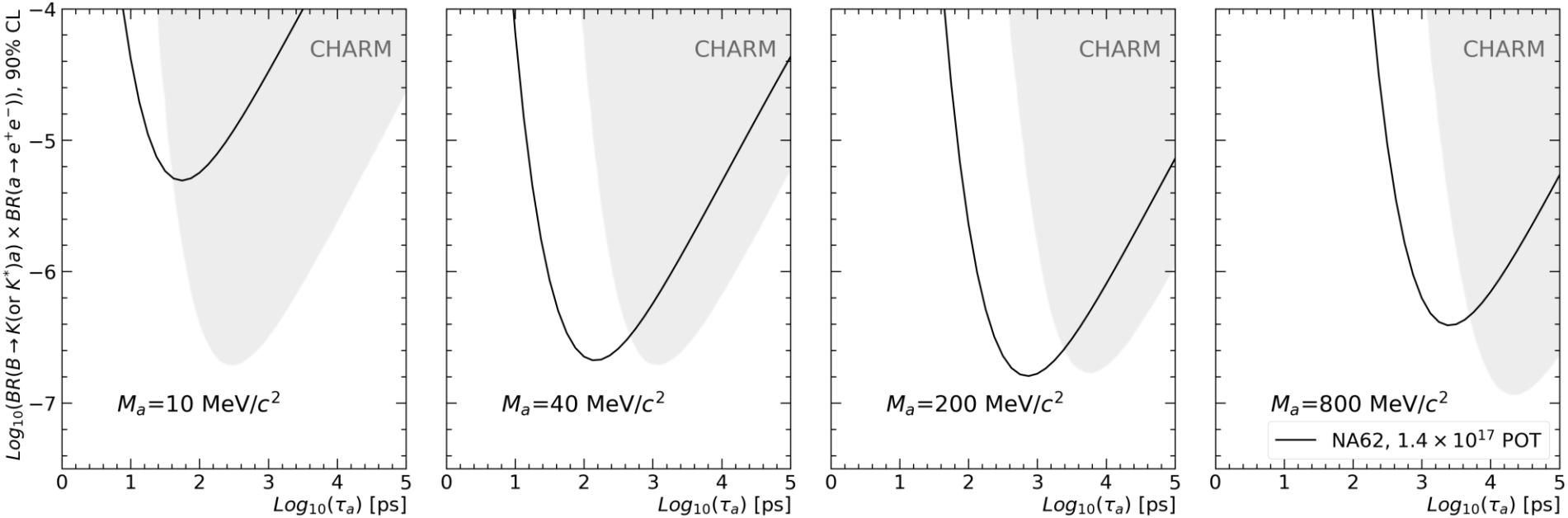


NEW

New Physics searches in hadronic decays

- Numerous decay channels and production mechanisms:
  - A': Bremsstrahlung, $P \to A'\gamma$, $V \to A'P$, where $P = \{\pi^0, \eta, \eta'\}$, $V = \{\rho, \omega, \phi\}$
  - S: $B^{\pm,0} \to K^{\pm,0,(*)}S$
  - a: Primakoff (on-, off-shell), mixing with $P = \{\pi^0, \eta, \eta'\}$, $B^{\pm,0} \to K^{\pm,0,(*)}a$
- All 36 combinations of production and decay channels studied

A'	S	a
$\pi^+\pi^-$	$\pi^+\pi^-$	$\pi^+\pi^-\gamma$
$\pi^+\pi^-\pi^0$		$\pi^+\pi^-\pi^0$
$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$
		$\pi^+\pi^-\eta$
K^+K^-	K^+K^-	
$K^+K^-\pi^0$		$K^+K^-\pi^0$

NEW

Analysis strategy

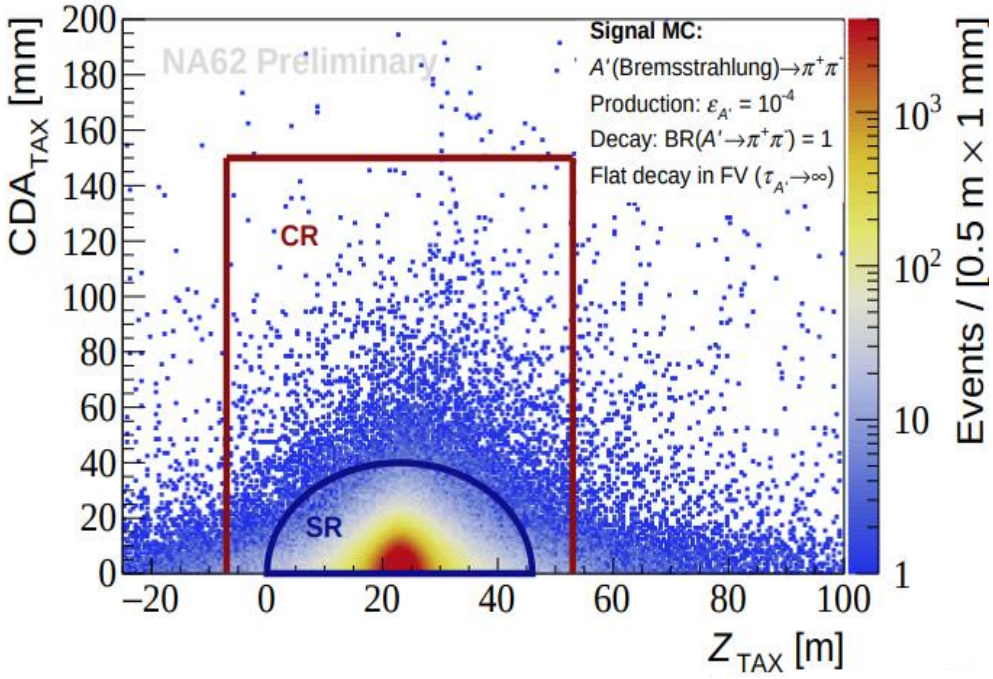
2 hadronic track selection:

- 2 good quality tracks in coincidence with each other and the trigger
- BDT particle ID selecting hadrons (calorimeters+MUV3), RICH used for kaon ID
- No in-time activity in LAV, SAV and ANTI0

Search strategy:

- Search neutral clusters in LKr and reconstruct γ, π^0, η based on time and opening angle
- Vertex reconstructed from final states is in the NA62 decay region and pointing back to the proton beam interaction point at the TAX.

CR and SR kept masked until the analysis strategy is frozen



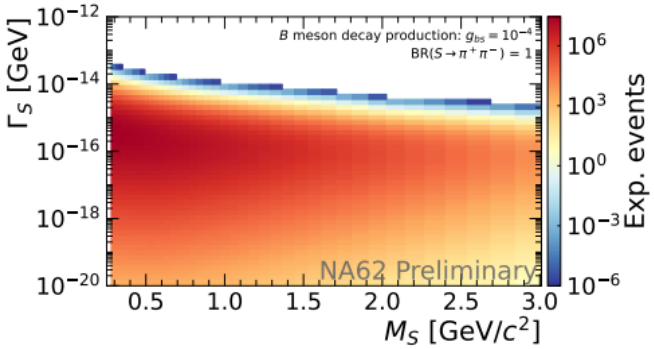
NEW

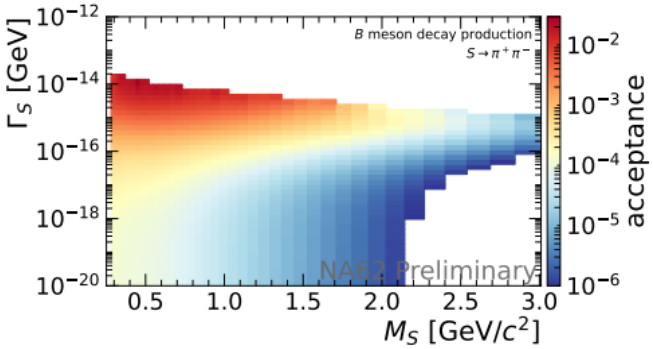
Signal efficiency and expected yield

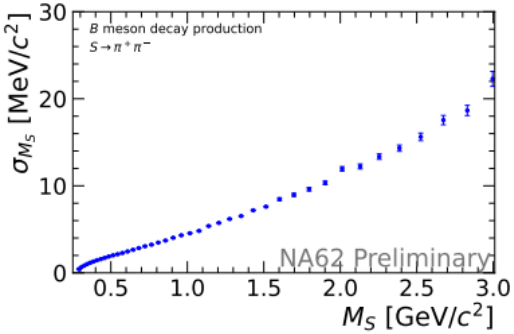
In model-independent case $X \to \pi^+\pi^-$ ($BR_{X\to\pi^+\pi^-} = 1$):

$$N_{exp}(\mathrm{M_X}, \Gamma_X) = \mathrm{POT} \times \chi\left(pp \to X(C_{ref})\right) \times P_{rd} \times A_{acc} \times A_{trig}$$

where $\chi\left(pp \to X(C_{ref})\right)$ is X production probability for reference coupling







Same distributions were obtained for all 36 combinations of production and decay channels.

NEW

Background studies

Background estimations made with MC:

- combinatorial and neutrino-induced backgrounds: negligible contributions

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- prompt background: inelastic interaction of halo muons can produce hadrons

Estimation using data-driven backward MC with measured μ halo + unfolding for correct kinematics

MC size equivalent of POT = 1.53×10^{17} (exceeding the data)

$\pi\pi$ outside CR (in ANTI0 acceptance + no vetoes applied):

- $N_{exp} = 1.8 \pm 1.4$ vs $N_{obs} = 1$ (Upstream region)
- $N_{exp} = 0.20 \pm 0.15$ vs $N_{obs} = 1$ (FV)

After applying full selection the prompt background expectations in CR and SR are below 10^{-4} in all channels

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

NEW

Background studies

Background estimations made with MC:

- combinatorial and neutrino-induced backgrounds: negligible contributions
- prompt background: inelastic interaction of halo muons can produce hadrons
- upstream background: formed by particles that are collected by the GTK achromat

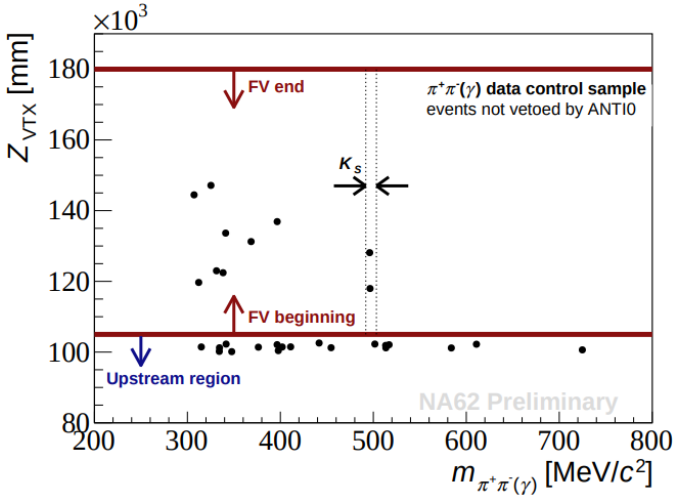
3 upstream background subcomponents observed in the control sample in the $Z_{VTX} - m_{\pi\pi}$ plane:

- 19 interactions in the region upstream the FV
- 2 $K_S \to \pi^+\pi^-$ candidates
- 8 $K^+ \to \pi^+\pi^+\pi^-$ candidates, 6 of which identified as $\pi^+\pi^-$ and 2 as $\pi^+\pi^-\gamma$

upstream interactions vetoed by ANTI0 acceptance and vertex location

for K_S 3σ window (± 5.7 MeV/c^2) around m_{K_S} kept masked

K^+-induced background simulated using selected single track K^+ forced to decay as $K^+ \to \pi^+\pi^+\pi^-$ in the FV



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

NEW

Total background estimation

Number of background events estimated at 68% CL

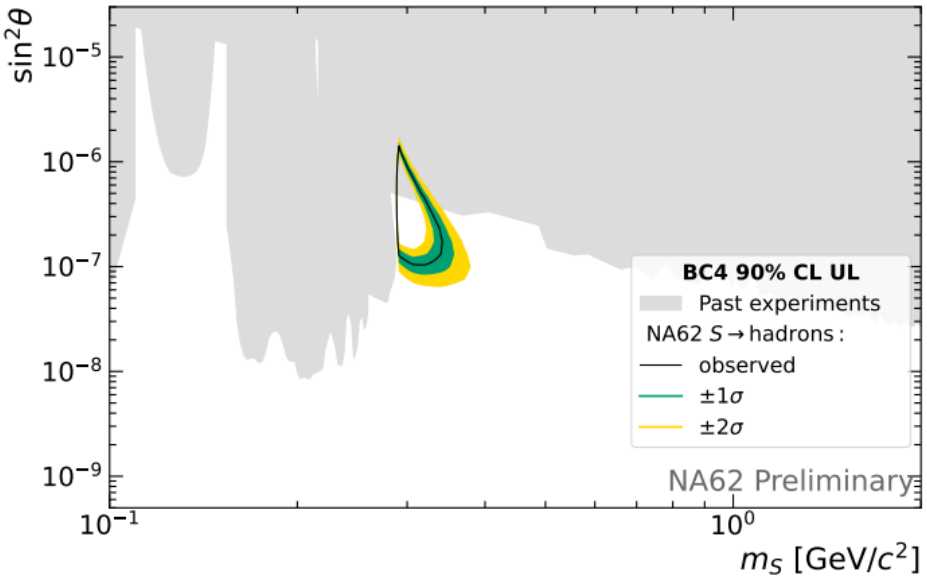
Channel	$N_{\mathrm{exp,CR}} \pm \delta N_{\mathrm{exp,CR}}$	$N_{\mathrm{exp,SR}} \pm \delta N_{\mathrm{exp,SR}}$	$N^{p>5\sigma}_{\mathrm{obs,SR}}$	$N^{p>5\sigma}_{\mathrm{obs,SR+CR}}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$	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

Background free hypothesis not only at POT= 1.4×10^{17} but also in the future full Run2 dataset of POT= 10^{18}

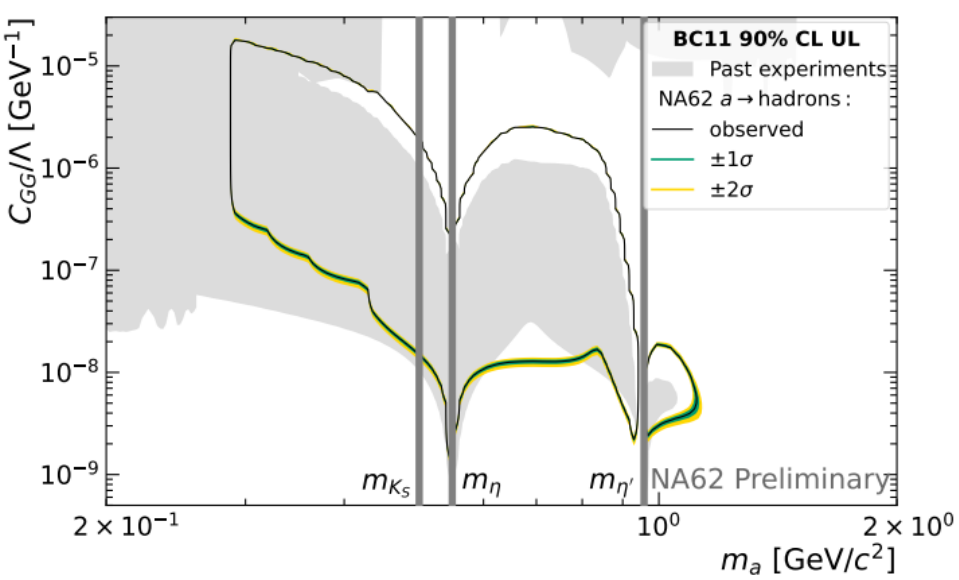
NEW

Results and interpretation

Dark scalar



ALP



0 events observed in all control and signal regions
Combination of individual production and decay channels were made with ALPINIST [JHEP 07 (2022) 094]

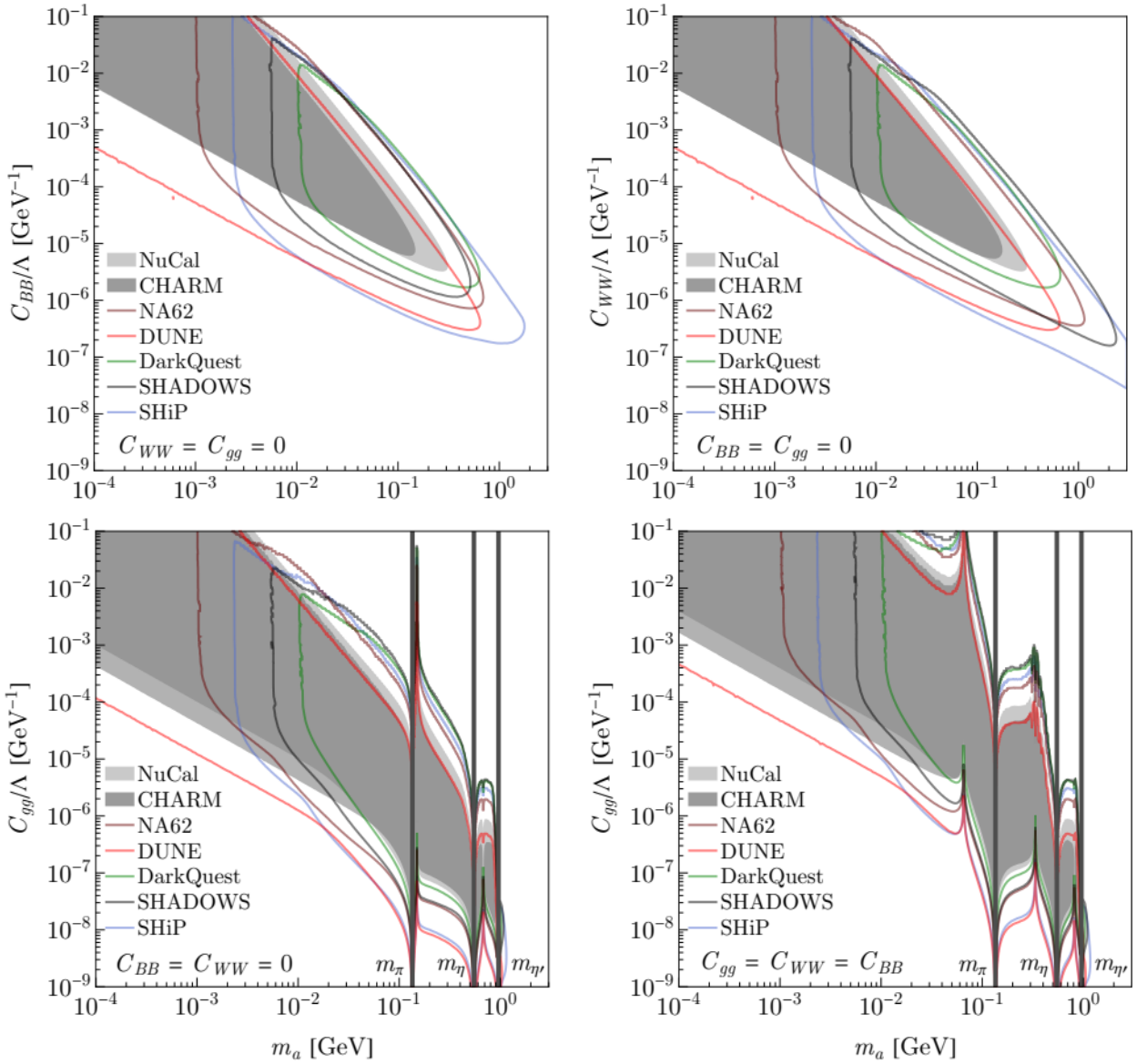
Summary

- 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 $A' \rightarrow l^+l^-$ and $X \rightarrow$ hadrons have 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 $\gamma\gamma$ and semileptonic 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!

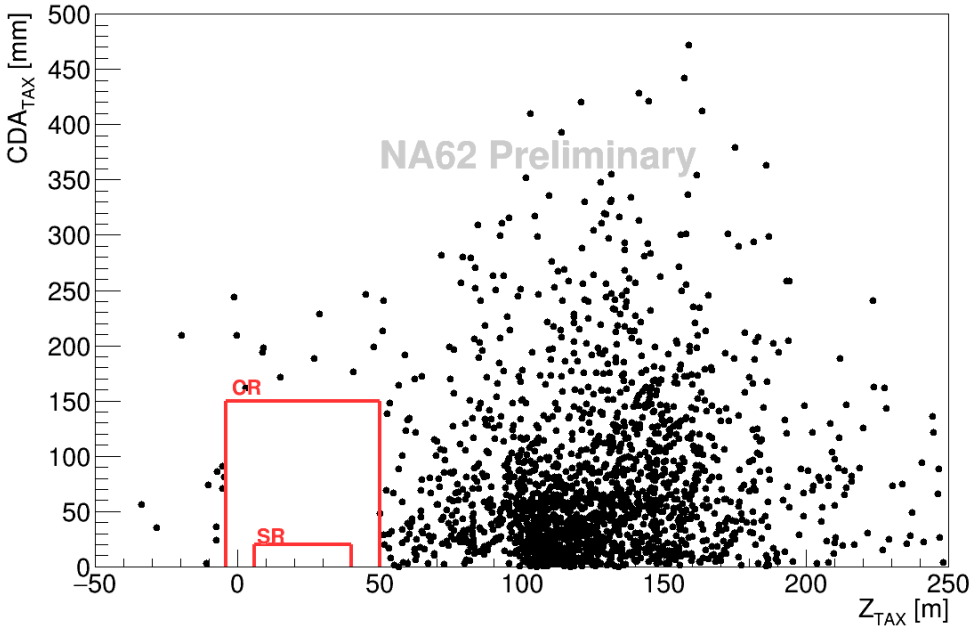
Backup slides

$a \to \gamma\gamma$ in beam dump (projections)

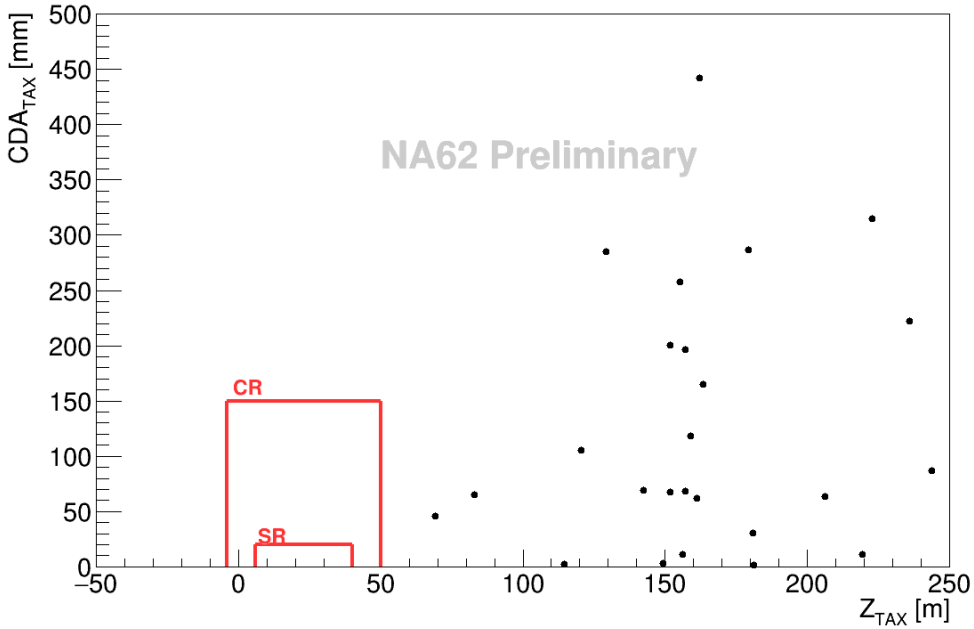


[JHEP07(2022)094]

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

Invariant mass resolution M_{ll}