First NA62 search for long-lived new physics particle hadronic decays

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See S. Martellotti's talk for NA62 in Kaon Mode

Flavour Physics

Search for New Physics at the EW scale with sizeable coupling to SM particles via indirect effects in loops:

Experiment main goal:

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

Search for lepton flavour and number violation, rare and forbidden decays:

$K^+ \to \pi^\pm \mu^\mp e^+$

$K^+ \to \pi^- l^+ l^+$

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

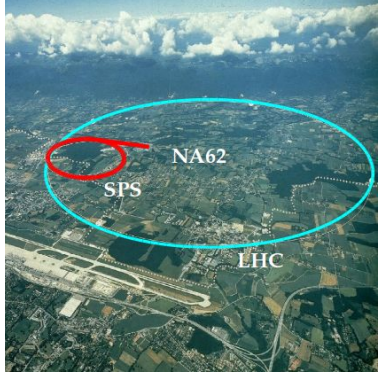
$(K^+ \to \pi^+ \pi^0)\, \pi^0 \to \text{invisible}$

Hidden sector Physics

Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles:

Dark Photon(**DP**), Axion Like Particle (**ALPs**), Dark Scalar (**S**), Heavy neutral Lepton(**N**)

$K^+ \to l^+ N$

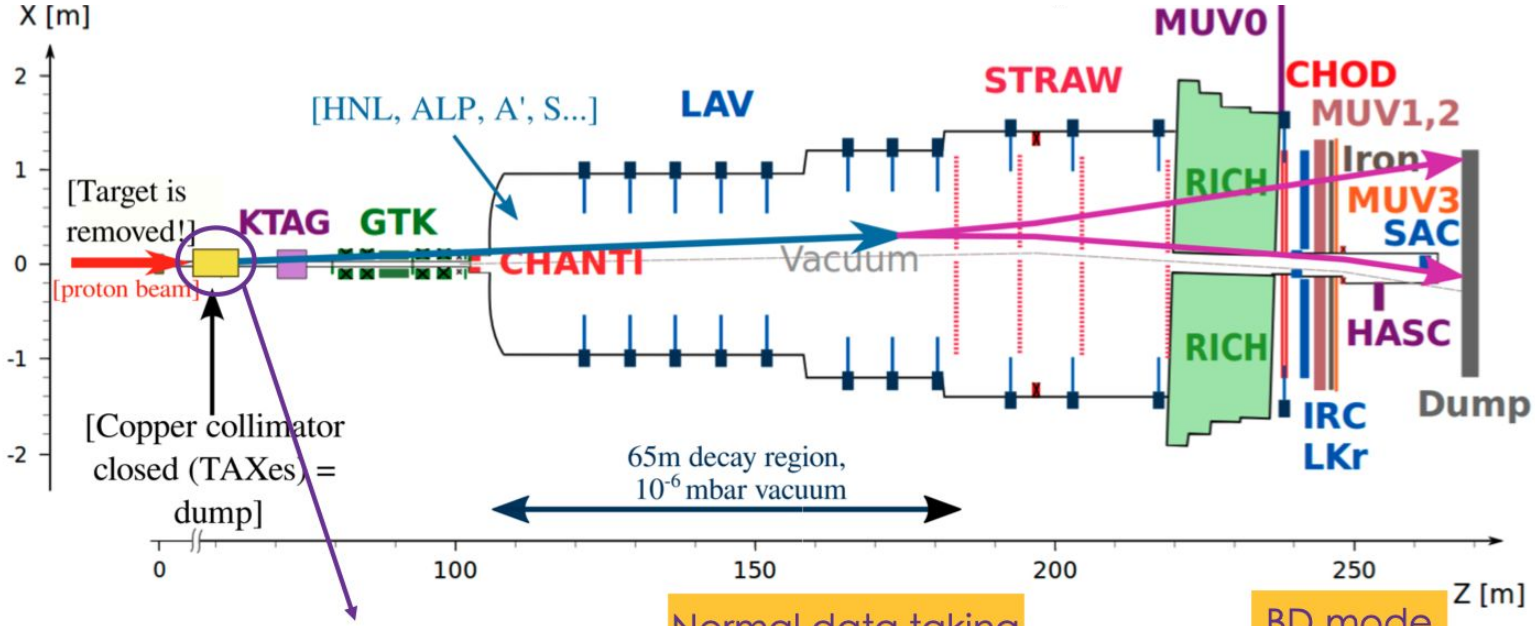


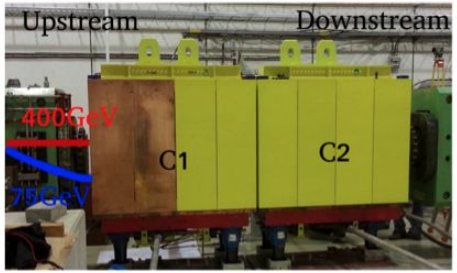
The NA62 experiment at the SPS

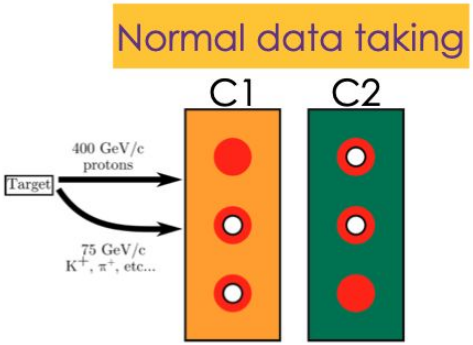
NA62 @ CERN North Area, exploits a 400 GeV/c primary proton beam from the SPS. 2-3 x 10^{12} protons/spill in K mode, 5.6-6.6 x 10^{12} protons/spill in beam dump operation (~ x1.5 wrt K mode)

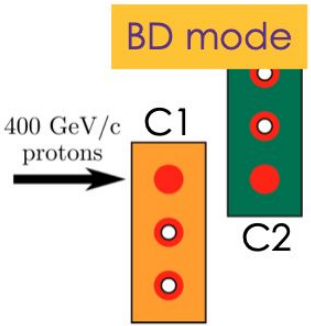
JINST 12 P05025 (2017)

NA62 in beam dump mode

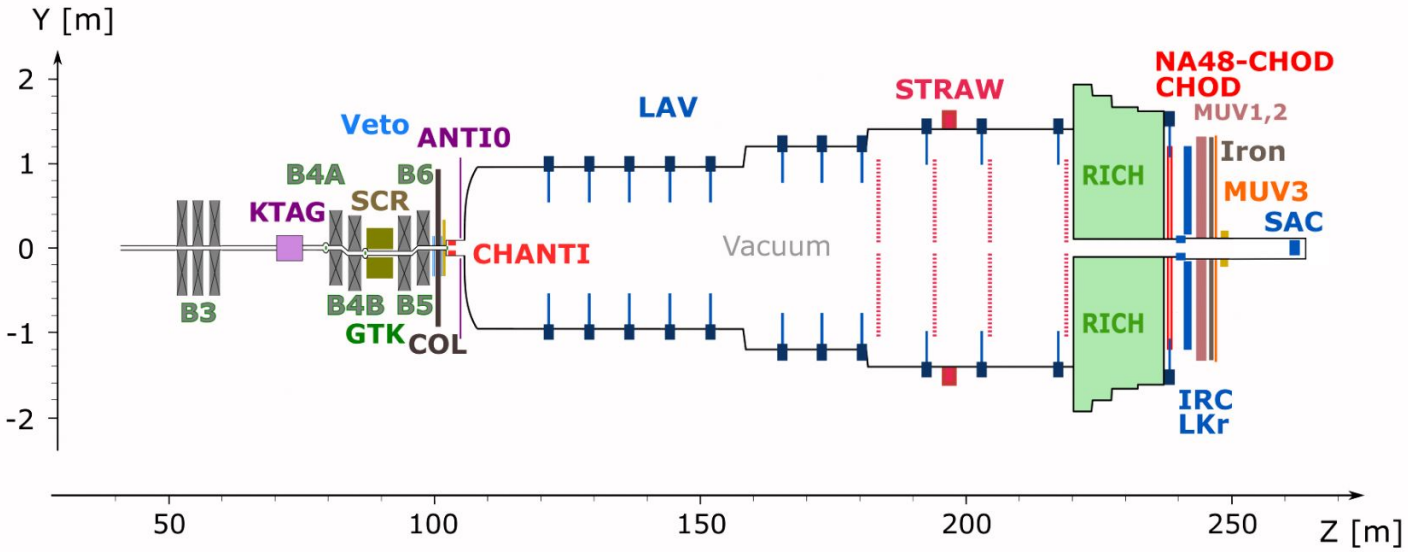








NA62 in beam dump mode



Sweeping

- **B3** a triplet of magnetization-satured dipole magnets
- **SCR** a toroidally-magnetized iron collimator
- **B5 and B6** magnets

Upstream

- **COL** cleaning collimator
- **ANTI0** scintillator hodoscope

Downstream

- **STRAW** spectrometer for momentum and direction measurements
- **LKr, LAV, IRC and SAC** photon veto system

CHOD for trigger timing

(1.43± 0.28) x 10^{17} Protons On Target (POTs) collected in 10 days in 2021

Search motivations

- Search for new physics (NP) at fixed target experiments is complementary to the energy frontier searches (LHC) and indirect searches
- Smaller masses (MeV-GeV) and lower couplings are accessible
- Dark sector portals typically probed:

NP particle	Type	SM portal	PBC	Decay channels
dark photon (A'_μ)	vector	$-(\epsilon/2\cos\theta_W)F'_{\mu\nu}B^{\mu\nu}$	BC1-2	$\ell\ell$, 2π, 3π, 4π, 2K, 2Kπ
Dark Higgs (S)	scalar	$(\mu S + \lambda S^2)H^\dagger H$	BC4-5	$\ell\ell$, 2π, 4π, 2K
axion/ALP (a)	pseudoscalar	$(C_{VV}/\Lambda)aV_{\mu\nu}\tilde{V}^{\mu\nu}$ $(C_{ff}/\Lambda)\partial_\mu a\, f\, \gamma^\mu\gamma^5 f$	BC9,11 BC10	γγ, $\ell\ell$, 2πγ, 3π, 4π, 2πη, 2Kπ

New Physics searches

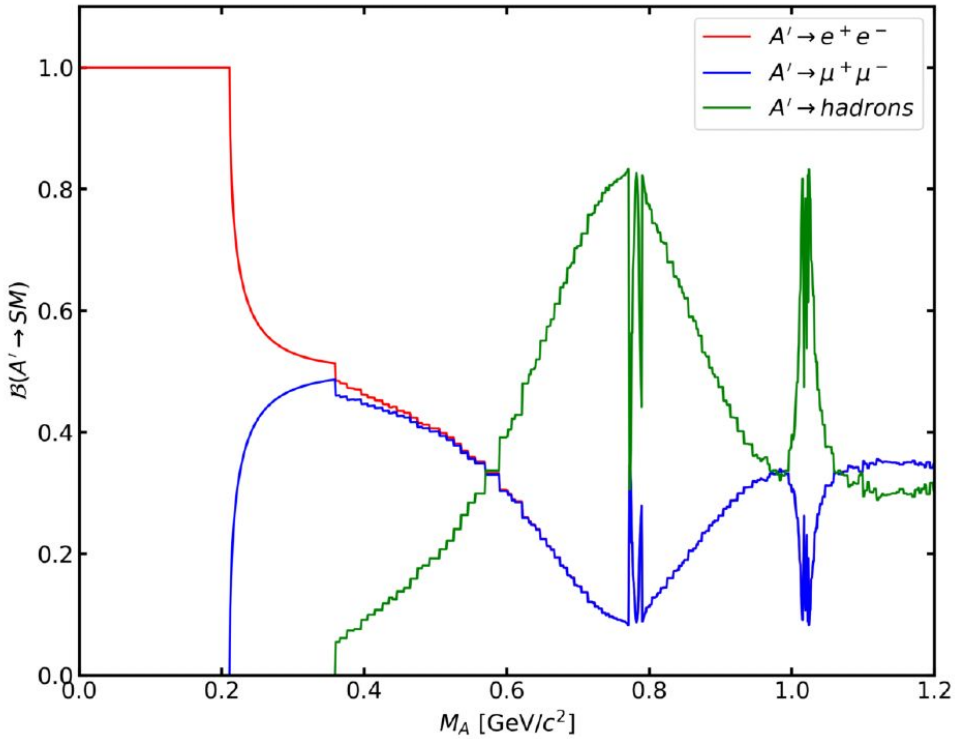
Numerous decay channels and production mechanism have been simulated:

DP Bremsstrahlung $\ell\ell$

Meson mediated

model	production channels	decay channels
DP	Bremsstrahlung	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
		K^+K^-
		$K^+K^-\pi^0$
	light meson decay	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
DS	B meson decay	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0\pi^0$
		K^+K^-
ALP	Primakoff mixing ($\pi^0/\eta/\eta'$) B meson decay	$\pi^+\pi^-\gamma$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
		$\pi^+\pi^-\eta$
		$K^+K^-\pi^0$

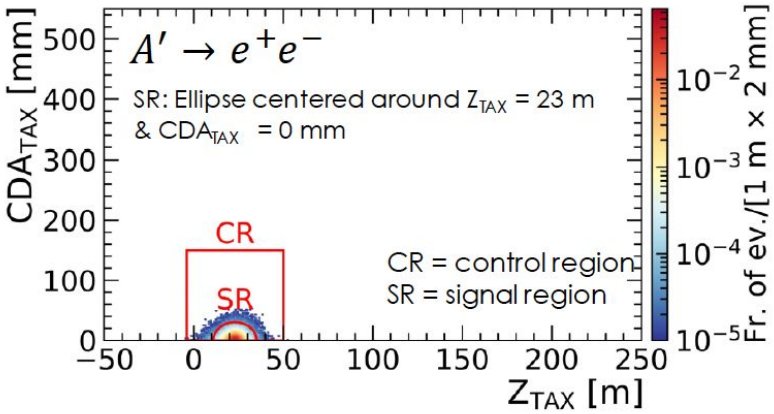
36 combinations of production and decay channels studied for hadronic analysis only



Mass range < 600 MeV dominated by di-lepton decay

Analysis strategies

- Trigger lines: single/di-tracks in CHOD (from 2 in time tiles if di-track)
- 2 good quality opposite charge tracks in coincidence wrt trigger:
  - $\ell^+\ell^-$: μ/e cut based identification with calorimeters and muon detector



- No-in time activity from LAVs (and ANTI0)
- Decay vertex within the smart FV
- Primary extrapolated production vertex close to the proton TAX interaction point

CDA – closest distance of approach between the beam direction at the TAX entrance and decay direction

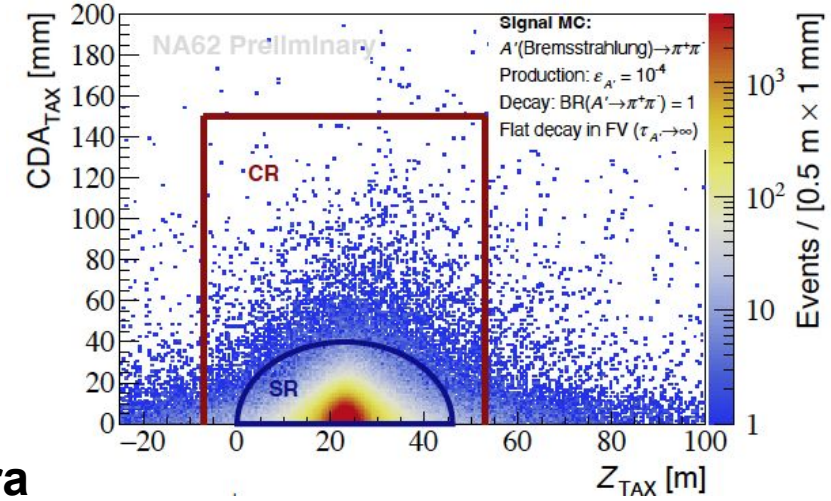
RMSCDA= ~7 mm

ZTAX – longitudinal position,

RMSZ= ~5.5 m

Analysis strategies

- Trigger lines: single/di-tracks in CHOD (from 2 in time tiles if di-track)
- 2 good quality opposite charge tracks in coincidence wrt trigger:
  - $\ell^+\ell^-$: ***μ***/e cut based identification with calorimeters and muon detector
  - **For h^+h^- BDT particle ID (calo and MUV3), RICH used for tagging K**
- **For h^+h^- analysis: reconstruction of extra γ, π^0, η based on LKr cluster time and opening angle**
- No-in time activity from LAVs and ANTI0
- Decay vertex within the smart FV
- Primary extrapolated production vertex close to the proton TAX interaction point



CDA – closest distance of approach between the beam direction at the TAX entrance and decay direction

RMS$_{CDA}$= ~7 mm

ZTAX – longitudinal position,

RMS$_Z$= ~5.5 m

Background determination

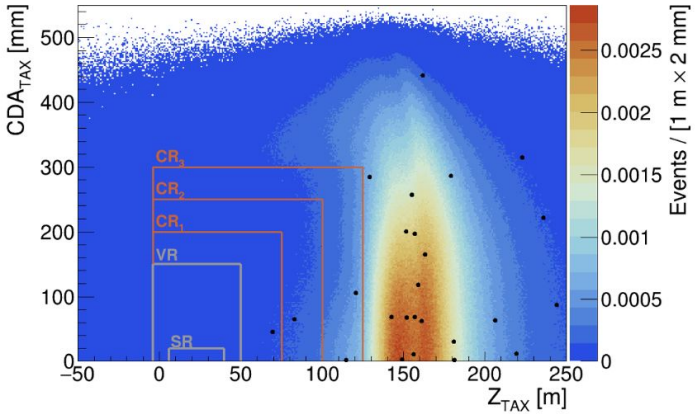
- **Combinatorial and neutrino-induced backgrounds**: negligible contributions in h^+h^- or e^+e^- , dominant for $\boldsymbol{\mu^+\mu^-}$ (halo muons)
- **Prompt background**: inelastic interaction of halo muons can produce hadrons or e^+e^-
- **Upstream background**: formed by particles that are collected by the GTK achromat

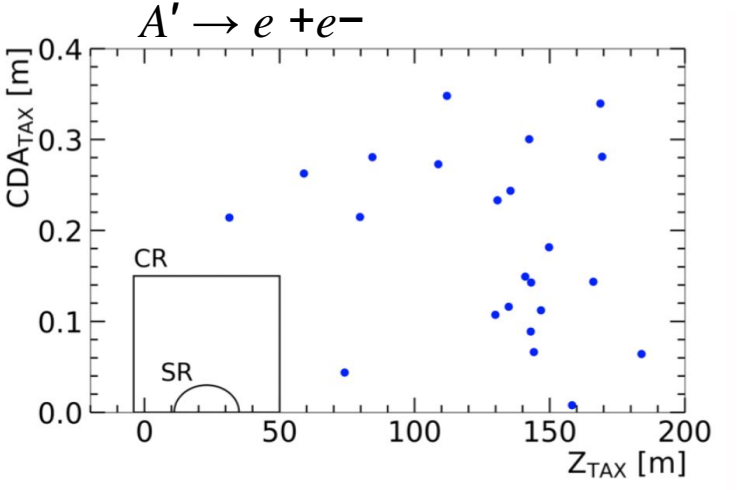
Background determination for A'→ℓℓ

- **Combinatorial and neutrino-induced backgrounds**
- **Prompt background**
- **Upstream background**

	Combinatorial	Prompt @ 90% CL	Upstream prompt@ 90% CL
N bkg SR	**0.016 ± 0.002**	<0.0004	< 0.007

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

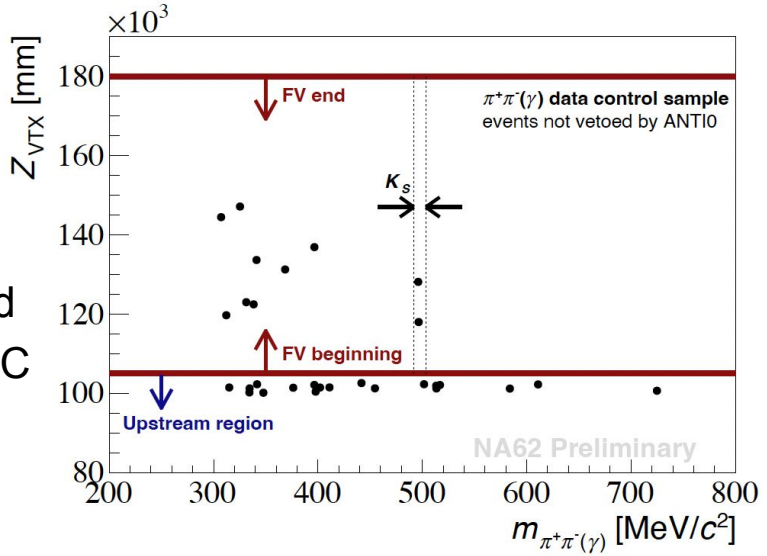




Background determination for X → hh

- **Combinatorial and neutrino-induced backgrounds**
- **Prompt background**:
- **Upstream background**

  - 3 upstream background subcomponents for hh observed in the control sample in the $Z_{VTX}-m_{\pi\pi}$ plane:
  - interactions in the region upstream the FV → vertex location and ANTI0 acceptance
  - $K_S \to \pi^+\pi^-$ candidates → m_{Ks} ± 5.7 MeV/c kept masked
  - $K^+ \to \pi^+\pi^+\pi^-$ candidates, 6 of which identified as $\pi^+\pi^-$ and 2 as $\pi^+\pi^-\gamma$ → use dedicated MC



Background determination for X → hh

- **Combinatorial and neutrino-induced backgrounds**
- **Prompt background**:
- **Upstream background**

- For the h^+h^- analysis channels at 68% CL:

Channel	$N_{\mathrm{exp,CR}} \pm \delta N_{\mathrm{exp,CR}}$	$N_{\mathrm{exp,SR}} \pm \delta N_{\mathrm{exp,SR}}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 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^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$

background-free hypothesis not only at $N_{POTs} = 1.4 \times 10^{17}$ but also in the future full **Run 2 dataset** of $N_{POTs} = 10^{18}$

Dark photon searches for A' → $\ell^+\ell^-$

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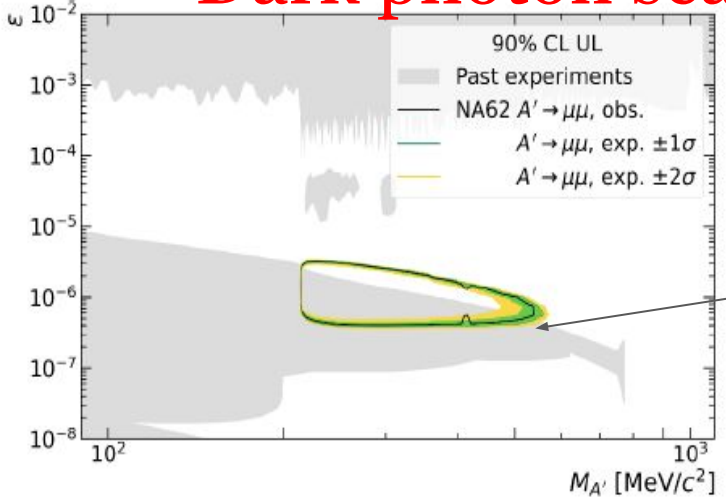
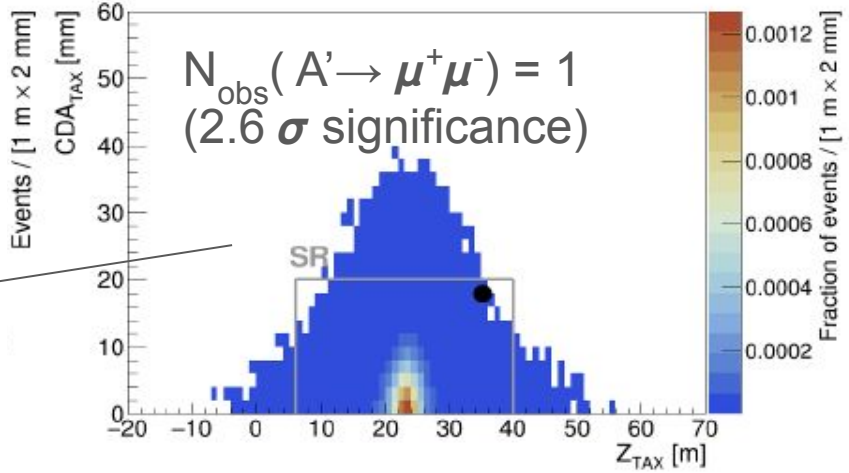
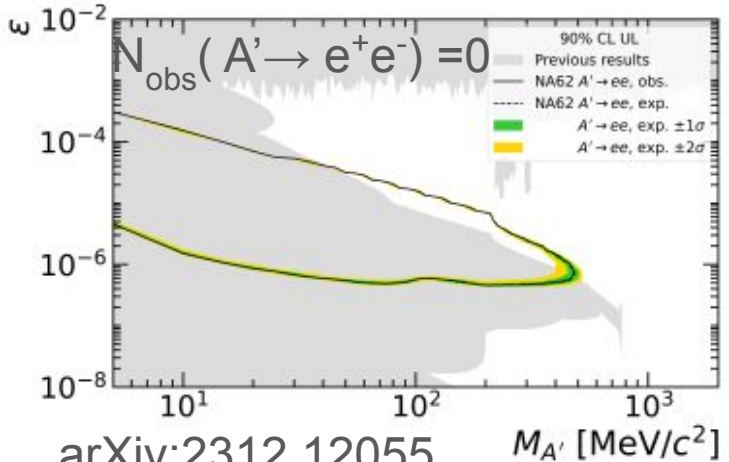
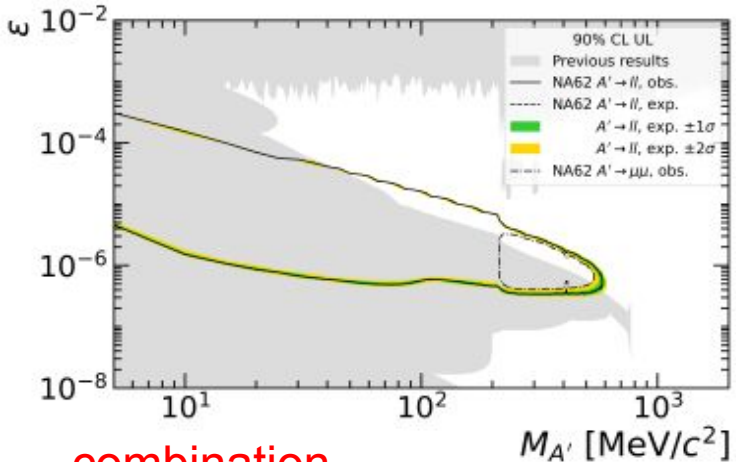






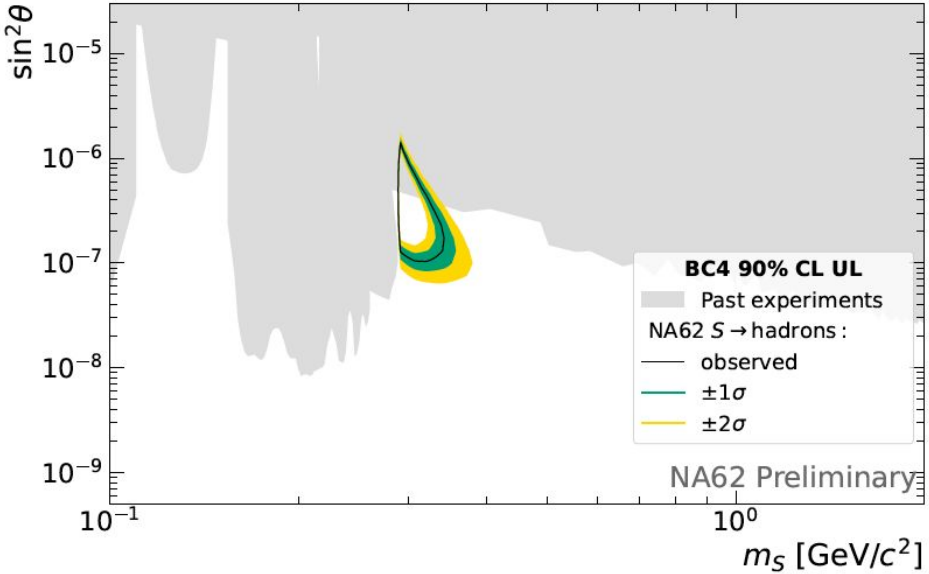
arXiv:2312.12055



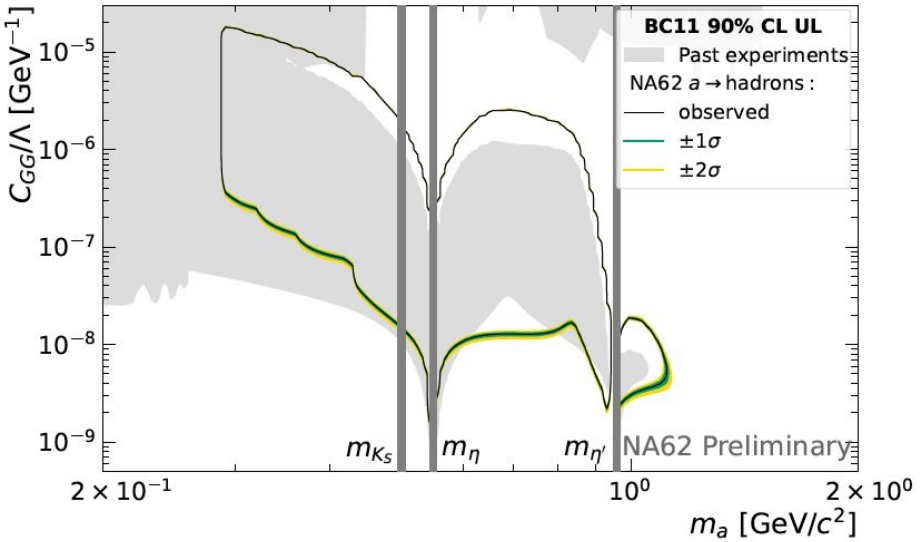
combination

Hadronic decay results and interpretation

Dark scalar



ALP



- 0 events observed in CR and SR for all channels
- No standalone 90% CL exclusion for BC1 (dark photon).
- Combination of individual production and decay channels were made with ALPINIST JHEP 07 (2022) 094

Conclusions

- Blind searches for exotic particle decaying into ee, ***μμ*** and hadrons have been performed on the data collected in 2021 exploring new regions of parameter space accessible to the NA62 experiment in beam dump mode

- With $(1.43 \pm 0.28) \times 10^{17}$ POTs 90% CL upper limits have been set, excluding new regions of the parameter space

- Searches for exotic particles decaying into semi-leptonic or di-gamma final states using data collected in 2021 are in progress

- Data-taking ongoing: a total of 10^{18} POTs in beam-dump mode expected by the LHC LS3 ($(2.4 \pm 0.5) \times 10^{17}$ POTs already collected in 2023) with interesting perspectives on dark photons, ALPs, dark scalars and HNLs.

Spare slides

Search for Dark Photons

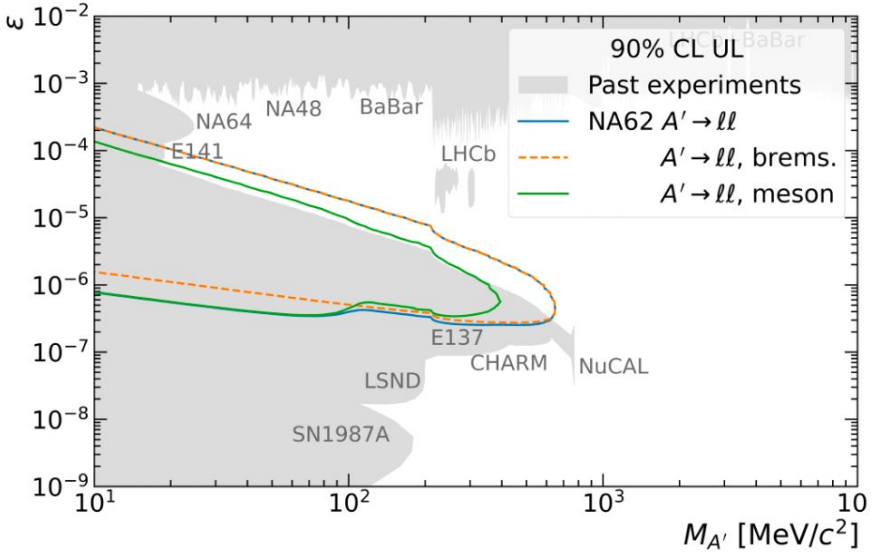


Figure: Sensitivity per production mechanism assuming 0 observed events in 1.4×10^{17} POT.

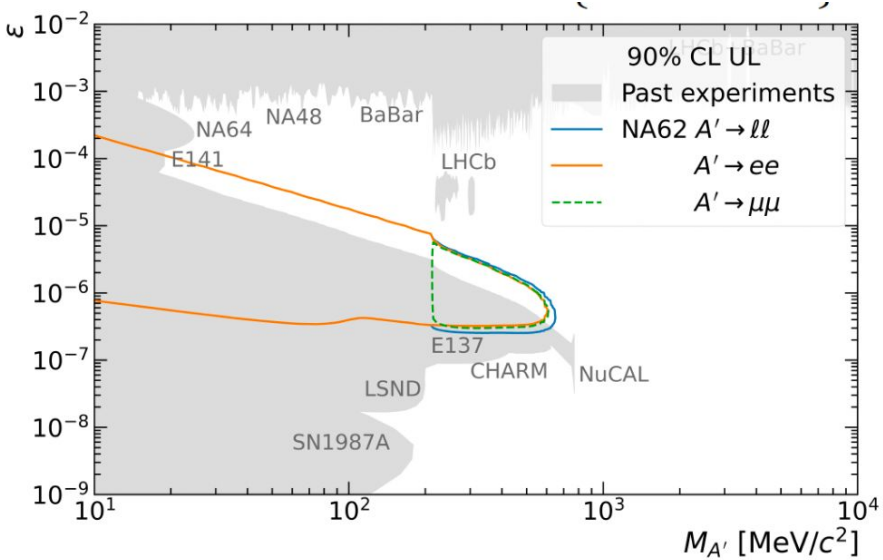
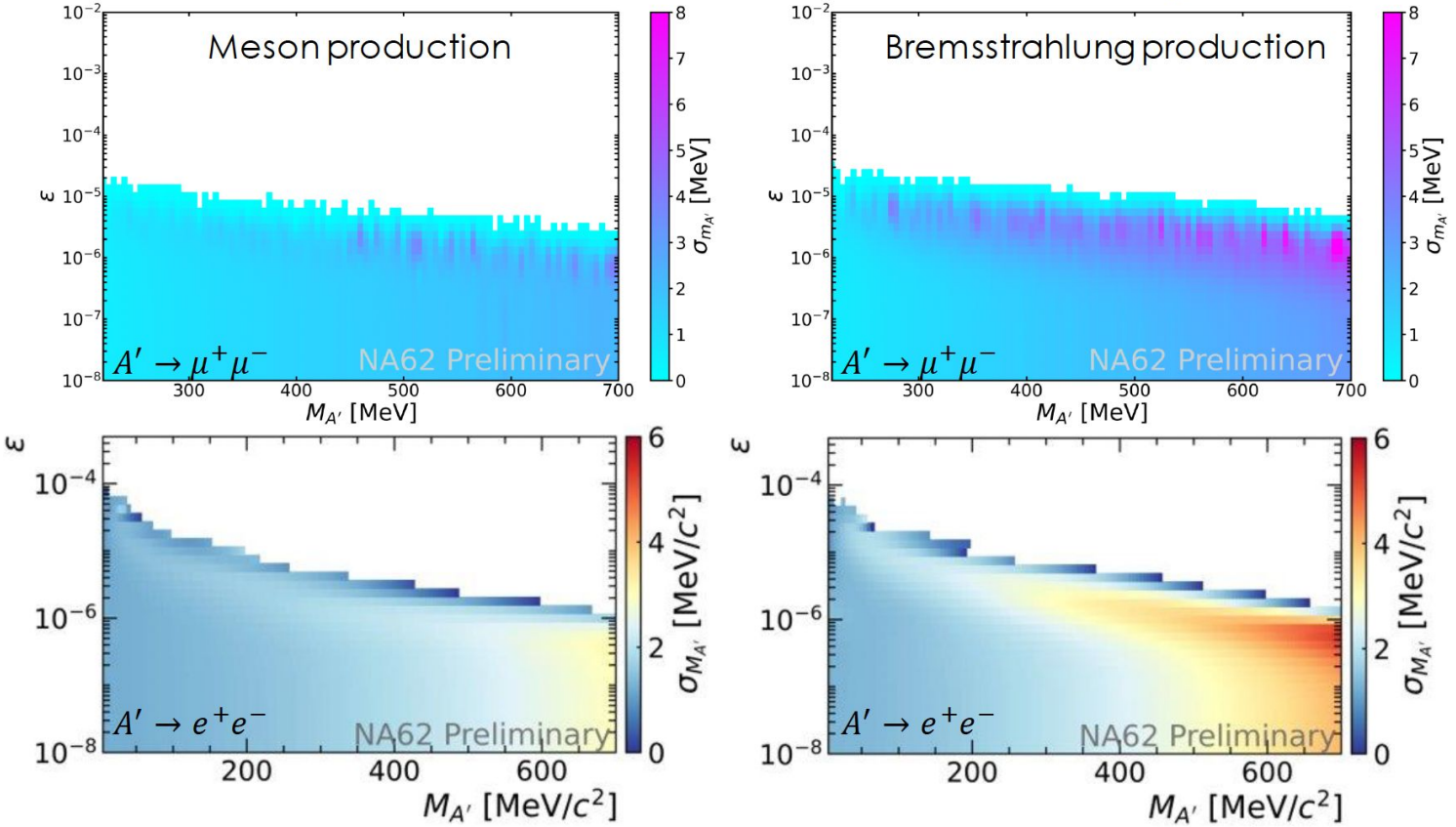
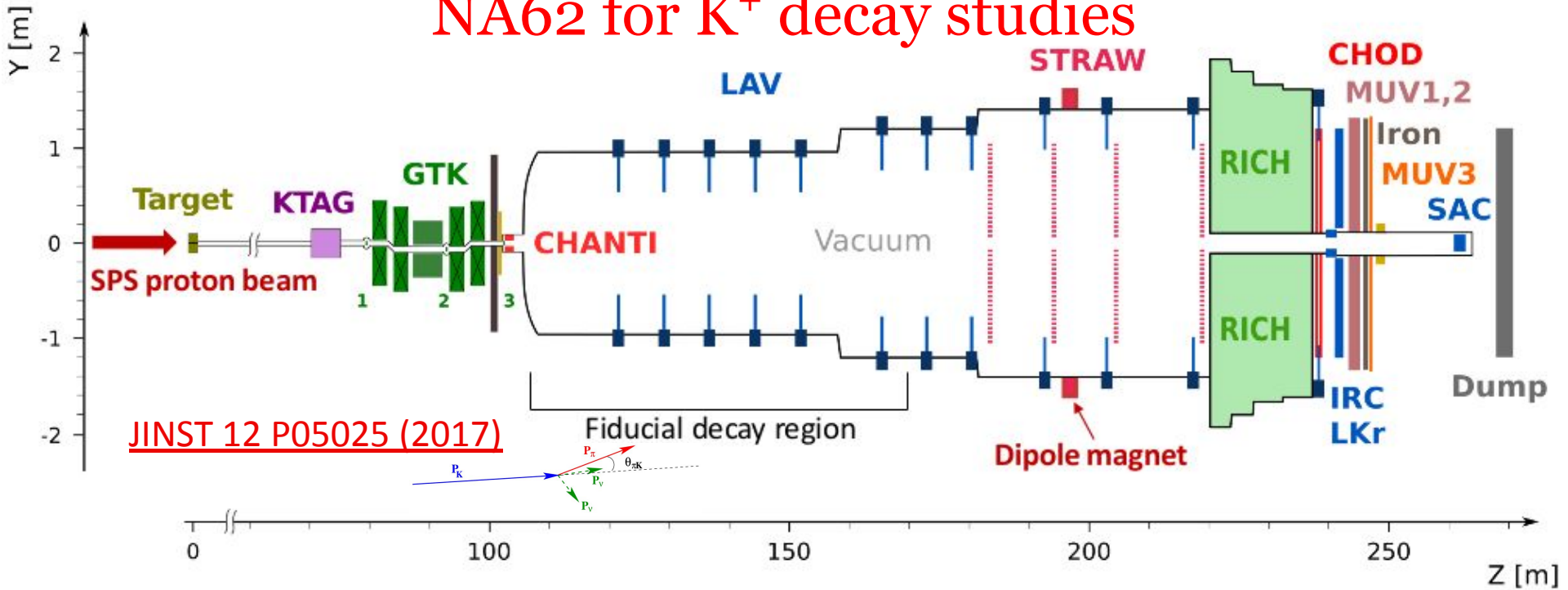


Figure: Sensitivity per decay mode assuming 0 observed events in 1.4×10^{17} POT.

Invariant mass resolution $m_{\ell\ell}$



NA62 for K^+ decay studies



Upstream particle:

KTAG: Differential Cherenkov for K^+ ID

GTK: Si pixel tracker

CHANTI: Anti-counter for inelastic interactions

Decay region detectors (π^+):

STRAW: Track momentum spectrometer

CHOD: Scintillator hodoscope

RICH: For $\pi/\mu/e$ ID

LKR/MUV1/2: Calorimetric systems

Vetos:

LAV/IRC/SAC: photons

MUV3: muons