Physics Beyond the Standard Model with the NA62 experiment at CERN

Lubos Bician
Charles University in Prague

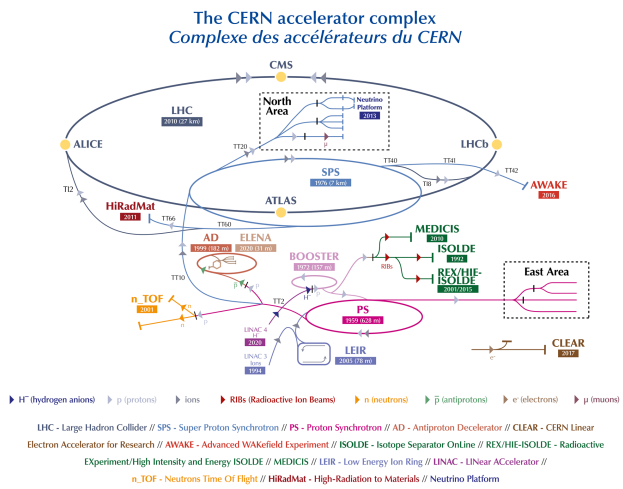
On behalf of the NA62 Collaboration

July 10, 2024

Co-funded by the European Union

MINISTRY OF EDUCATION, YOUTH AND SPORTS

Kaon Experiments at the CERN SPS



NA62: ~ 200 participants, ~ 30 institutes

- **NA31**: 1980s, *beam:* K_L/K_S
  - *First evidence of direct CPV*
- **NA48**: 1997–2001, *beam:* K_L/K_S
  - *Discovery of direct CPV*
- **NA48/1**: 2002, *beam:* K_S/hyperons
  - *Rare decay studies*
- **NA48/2**: 2003–2004, *beam:* K^+/K^-
  - *Precision measurements*
- **NA62-R_K**: 2007–2008, *beam:* K^+/K^-
  - $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$
- **NA62**: since 2015, *beam:* K^+
  2015: commissioning run
  2016-2018: NA62 Physics Run 1
  2021-ongoing: NA62 Physics Run 2

Main goal of the NA62 experiment:

- Measurement of the branching fraction of very rare ($\mathcal{B}_{\pi\nu\nu} \approx 10^{-10}$) decay $K^+ \to \pi^+\nu\bar{\nu}$
  - Result from 2016-2018 data set published in **[JHEP06 (2021) 093]**, 2021-2022 analysis ongoing

Outline of the Talk

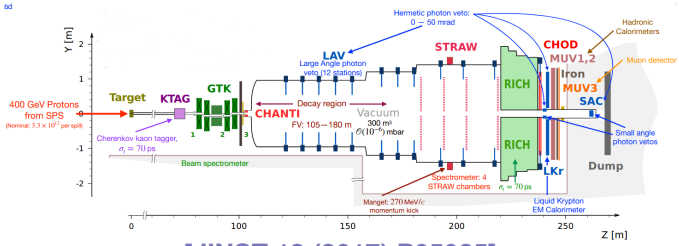
Searches for BSM physics in data from kaon runs:

- Search for $K^+ \to \mu^- \nu e^+ e^+$ **[Phys. Lett. B 838 (2023) 137679]**
  - Forbidden within the SM by either Lepton Number (LN) or Lepton Flavour (LF) conservation, depending on the neutrino flavour
  - Majorana neutrinos (ALPs or Z' particles) could mediate LNV (LFV) processes
- Searches for $K^+ \to \pi^0 \pi \mu e$ **[New, to be published]**
  - Forbidden within the SM by either LN or LF conservation, depending on the charge of the pion
- Search for $K^+ \to \pi^+ e^+ e^- e^+ e^-$ **[Phys.Lett.B 846 (2023) 138193]**
  - As 5-body decay: SM predicted branching fraction $\mathcal{B}(K_{\pi 4e}) = (7.2 \pm 0.8) \times 10^{-11}$
  - Short-lived QCD axion: $K^+ \to \pi^+ a a$, $a \to e^+ e^-$
    - Potential explanation of the "17 MeV anomaly" in de-excitations of ^{8}Be, ^{4}He, and ^{12}C nuclei
  - Cascade process involving scalar S and dark photon A': $K^+ \to \pi^+ S$, $S \to A' A'$, $A' \to e^+ e^-$
    - Allowed only if $m_S \geq 2 m_{A'}$

Searches for BSM physics in data from beam-dump runs:

- Searches for $A' \to l^+ l^-$ **[JHEP 09 (2023) 035]**, **[2312.12055]**
- Searches for Dark Scalars and ALPs **[Talk at Moriond EW 2024]**

NA62: Beam and Detector in Kaon Runs



[JINST 12 (2017) P05025]

Beam parameters:

- **Beam momentum:** 75 GeV/c ($\pm 1\%$)
- **Nominal rate:** 750 MHz
- **Positive beam:** $\sim 6\%$ K^+

Main subdetectors:

- **Beam tracker:** GTK
- **Kaon tagger:** KTAG ($\sigma_t \sim 70$ ps)
- **Downstream tracker:** ($\pi/\mu/e$): Straw
  $\sigma_p/p = 0.3\% \bigoplus 0.005\% \cdot p$[GeV/$c$]
- **Photon veto detectors:** LAV, IRC, SAC
- **Cherenkov counter:** RICH
- **Trigger and timing:**
  CHOD ($\sigma_t \sim 1$ ns), NA48-CHOD ($\sigma_t \sim 200$ ps)
- **Electromagnetic calorimeter:** LKr
  $\sigma_E/E = 4.8\%/\sqrt{E} \bigoplus 11\%/E \bigoplus 0.9\%$, $[E] =$ GeV
- **Hadronic calorimeters:** MUV1,2
- **Muon detector:** MUV3 ($\sigma_t \sim 500$ ps)

Search for $K^+ \to \mu^- \nu e^+ e^+$

Data sample:

- Full NA62 Run 1 (2016 - 2018)
- Normalisation decay channel: $K^+ \to \pi^+ e^+ e^-$
- Employed blind analysis technique

Common selection criteria:

- Three-track vertices of Straw tracks with $p \in [6, 44]$ GeV$/c$
- Particle identification using LKr energy E, Straw track momentum p, and muon detector MUV3:
  - π: $E/p < 0.85$, no in-time signal in MUV3
  - μ: $E/p < 0.2$, in-time signal in MUV3
  - e: $E/p \in [0.9, 1.1]$

$K_{\pi ee}$ selection criteria:

- $|p_{\text{vertex}} - p_{\text{beam}}| < 2$ GeV$/c$
- $m(ee) > 140$ MeV$/c^2$
- $m(\pi ee) \in [470, 505]$ MeV$/c^2$

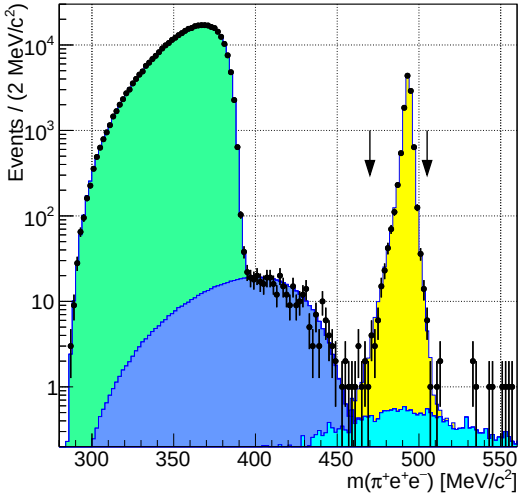
$K_{\mu \nu ee}$ selection criteria:

- $p_{\text{beam}} - p_{\text{vertex}} > 10$ GeV$/c$
- $m^2_{\text{miss}} = (P_K - P_\mu - P_{e1} - P_{e2})^2 \in [-0.006, 0.004]$ GeV$^2/c^4$

Search for $K^+ \to \mu^- \nu e^+ e^+$

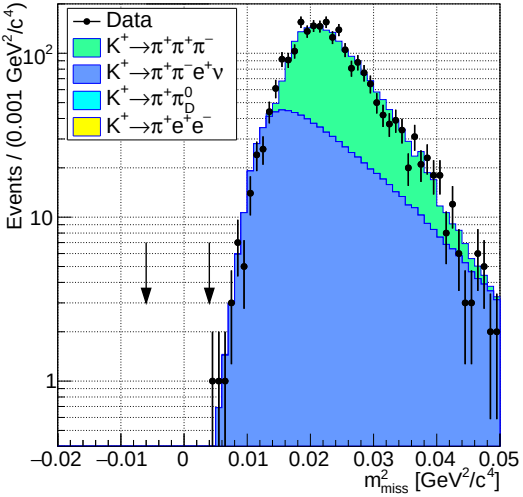
Normalisation selection

$\mathbf{N_{\pi ee} = 21401,\ N_K = 1.97(2)_{stat}(2)_{syst}(6)_{ext} \times 10^{12}}$



Signal selection ($\mathbf{N_B = 0.26 \pm 0.04}$)

No candidate observed in the signal region



$$\mathcal{B}(\mathbf{K^+ \to \mu^- \nu e^+ e^+}) < \mathbf{8.1 \times 10^{-11}}\ \textbf{@ 90\% CL}$$

Searches for $K^+ \to \pi^0\pi\mu e$

Data sample:

- Full NA62 Run 1 (2016 - 2018)
- Normalisation decay channel: $K^+ \to \pi^+ e^+ e^-$
  - Identical as in the $K^+ \to \mu^- \nu e^+ e^+$ analysis
- Employed blind analysis technique

Common selection criteria:

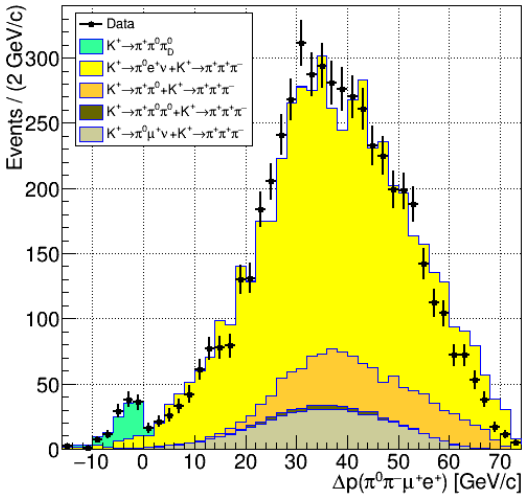
- Three-track vertices of Straw tracks with $p \in [6, 65]$ GeV$/c$
- Particle identification using LKr energy E, Straw track momentum p, and muon detector MUV3:
  - π: $E/p < 0.85$, no in-time signal in MUV3
  - μ: $E/p < 0.2$, in-time signal in MUV3
  - e: $E/p \in [0.9, 1.1]$

$K_{\pi\pi\mu e}$ ***selection criteria:***

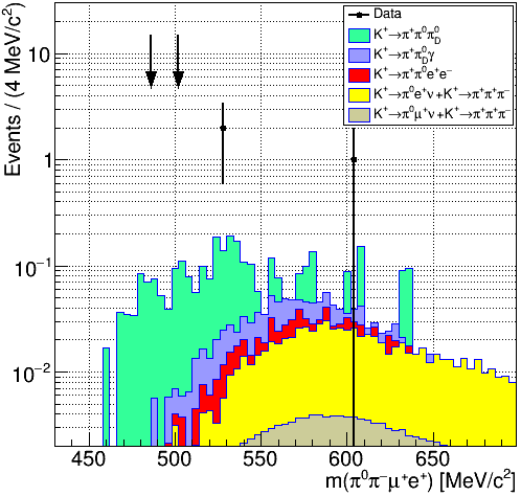
- The three vertex tracks are π, μ, e
- One in-time π^0 is reconstructed from a pair of photons in LKr
- Neutral vertex is reconstructed assuming the photons come from a π^0 decay
- The charged and neutral vertices are compatible within 8 m in Z
- Reconstructed mass $m(\pi^0\pi\mu e) \in [486, 502]$ MeV$/c^2$

Search for $K^+ \to \pi^0\pi^-\mu^+e^+$

Control selection
For background normalisation and validation
No Δp, p_T, LAV veto, and $m(\pi\pi\mu e)$ cut inverted



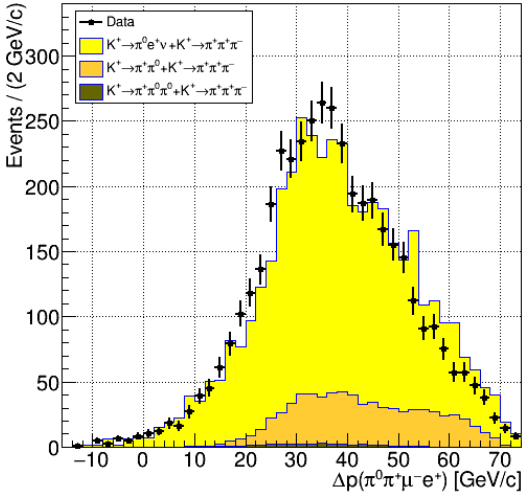
Signal selection ($N_B = 0.33 \pm 0.07$)
No candidate observed in the signal region



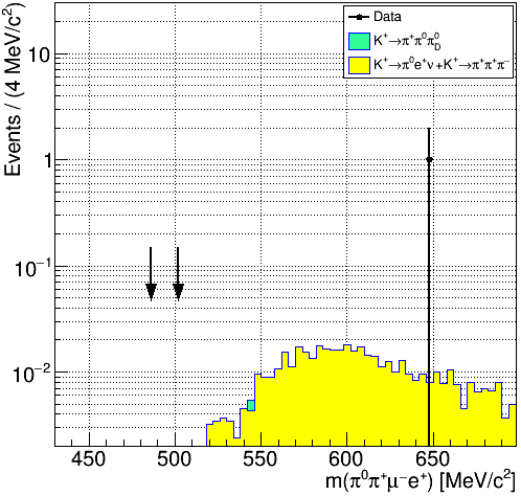
$$\mathcal{B}(K^+ \to \pi^0\pi^-\mu^+e^+) < 2.9 \times 10^{-10} \text{ @ 90\% CL}$$

Search for $K^+ \to \pi^0\pi^+\mu^-e^+$

Control selection
For background normalisation and validation
No Δp, p_T, LAV veto, and $m(\pi\pi\mu e)$ cut inverted



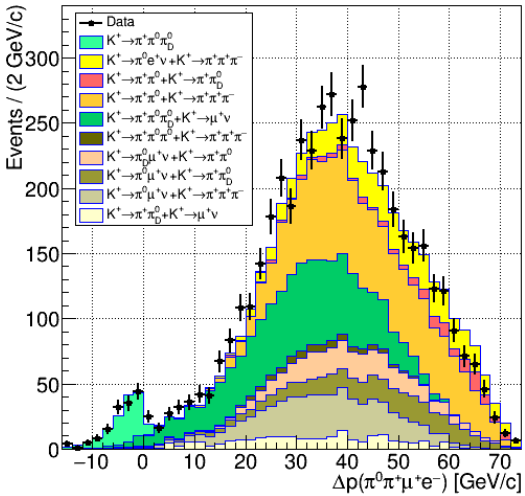
Signal selection ($N_B = 0.004 \pm 0.003$)
No candidate observed in the signal region



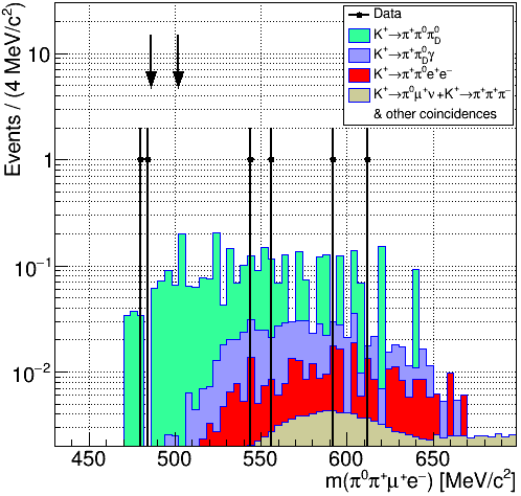
$$\mathcal{B}(K^+ \to \pi^0\pi^+\mu^-e^+) < 3.1 \times 10^{-10} \text{ @ 90\% CL}$$

Search for $K^+ \to \pi^0\pi^+\mu^+e^-$

Control selection
For background normalisation and validation
No $\Delta p, p_T$, LAV veto, and $m(\pi\pi\mu e)$ cut inverted



Signal selection ($N_B = 0.29 \pm 0.07$)
No candidate observed in the signal region



$$\mathcal{B}(K^+ \to \pi^0\pi^+\mu^+e^-) < 5.0 \times 10^{-10} \text{ @ 90\% CL}$$

Search for $K^+ \to \pi^+ e^+ e^- e^+ e^-$

Data sample:

- NA62 Run 1 (2017 - 2018)
- Normalisation decay channel: $K^+ \to \pi^+ \pi^0_{\mathrm{DD}}$ (identical final state to signal candidates)
- Employed blind analysis technique

Common selection criteria:

- Five-track vertices of Straw tracks, $p \in [5, 45]$ GeV/c
- Particle identification is based on event kinematics:
  - Three options for π^+ mass assignment are tested
  - The one giving minimal $|m_{\pi 4e} - m_K|$ is chosen

$K_{2\pi DD}$ selection criteria:

- $|m(4e) - m_{\pi^0}| < 10$ MeV/c^2

$K_{\pi 4e}$ selection criteria:

- $|m(4e) - m_{\pi^0}| > 10$ MeV/c^2
- $m^2_{\mathrm{miss}} = (P_K - P_\pi)^2 > 0$
- $|m_{\mathrm{miss}} - m_{\pi^0}| > 40$ MeV/c^2
- $p_\pi > 10$ GeV/c

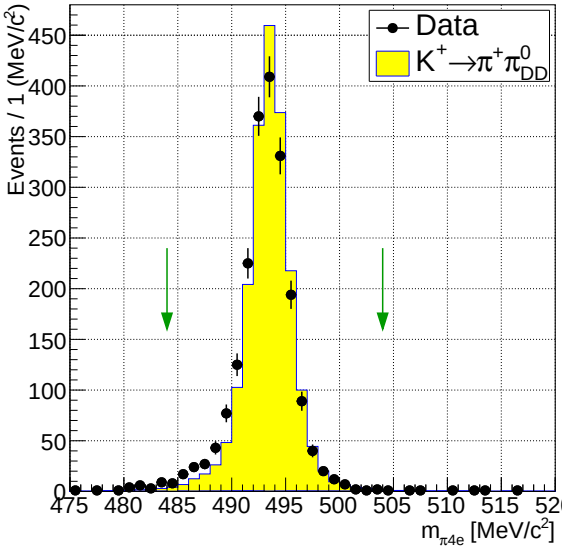
Resonant $K_{\pi 4e}$ selection criteria:

- Both $X \to e^+ e^-$ hypotheses are tested, and the one with smaller discriminant D is chosen, $D = (m_{ee1} - m_{ee2})^2 / \sigma^2_{\Delta m_{ee}}$
- For each mass hypothesis m_X, require $|m_{ee} - m_X| < 0.02 m_X$, where $m_{ee} = (m_{ee1} + m_{ee2})/2$

Search for $K^+ \to \pi^+ e^+ e^- e^+ e^-$

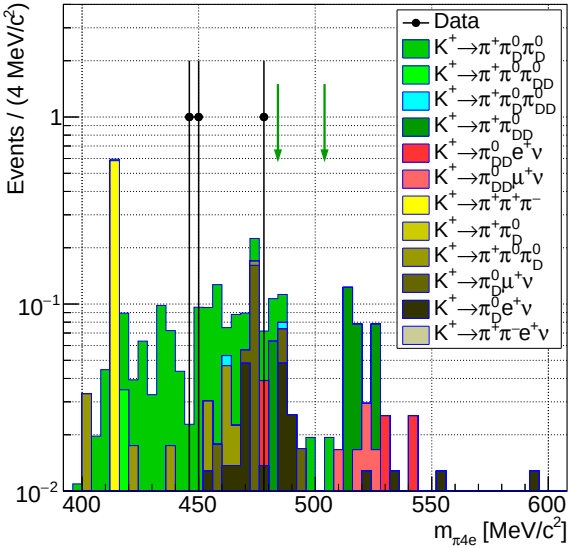
Normalisation selection

$\mathbf{N_{DD} = 2023,\ N_K \simeq 8.6(2)_{stat}(1)_{MC}(4)_{ext} \times 10^{11}}$

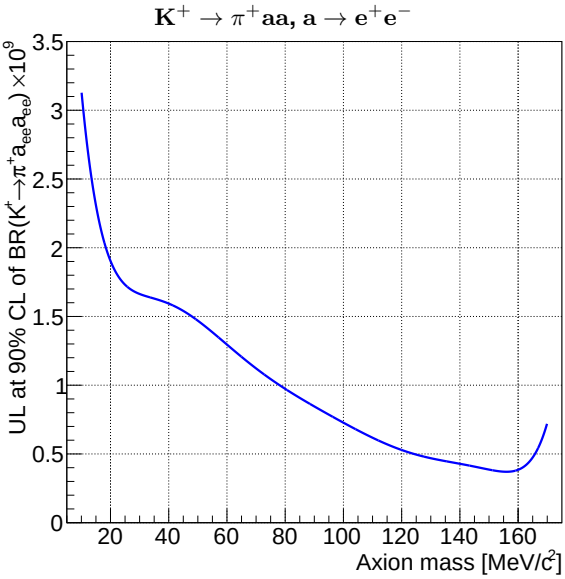


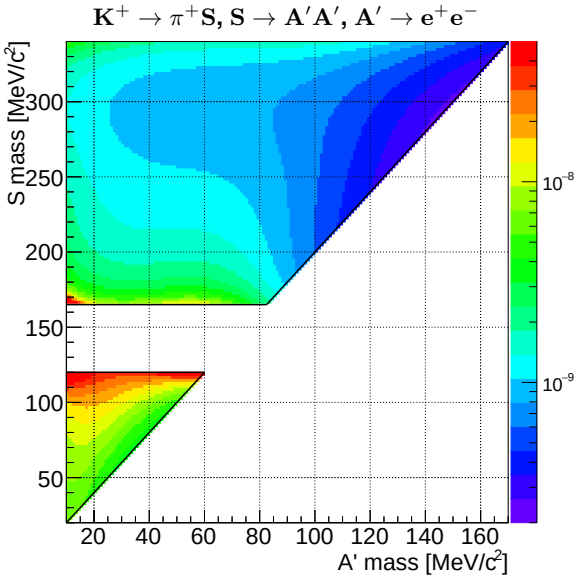
$K_{\pi 4e}$ selection ($N_B = 0.18 \pm 0.14$)

No candidate observed in the signal region



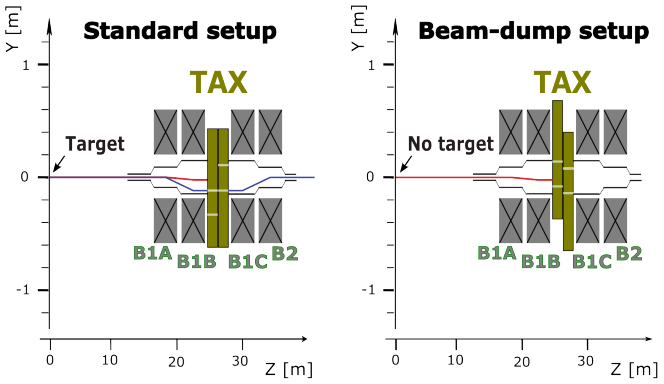
Search for $K^+ \to \pi^+ e^+ e^- e^+ e^-$





$\mathcal{B}(\mathbf{K_{\pi 4e}}) < 1.4 \times 10^{-8}$ **@ 90% CL; ULs @ 90% CL on resonant** $\mathbf{K_{\pi 4e}}$ **processes**

NA62: Beam and Detector in Beam Dump Runs



NA62 beam-dump mode:

- The Be target is lifted; the protons hit directly the 3.2 m Cu-Fe dump
- Primary proton beam operating at $1.7\times$ nominal intensity
- Upstream detectors KTAG, GTK, CHANTI are not used

Data sample:

- Beam dump data from 2021
- Collected $(1.4 \pm 0.28) \times 10^{17}$ POT

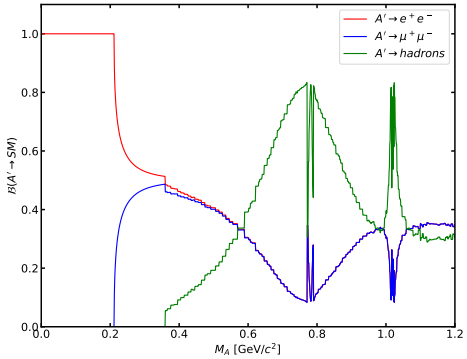
Main subdetectors:

- **Downstream tracker:** $(\pi/\mu/e)$: Straw
  $\sigma_p/p = 0.3\% \bigoplus 0.005\% \cdot p$[GeV/$c$]
- **Photon veto detectors:** LAV, IRC, SAC
- **Cherenkov counter:** RICH
- **Trigger and timing:**
  CHOD ($\sigma_t \sim 1$ ns), NA48-CHOD ($\sigma_t \sim 200$ ps)
- **Electromagnetic calorimeter:** LKr
  $\sigma_E/E = 4.8\%/\sqrt{E} \bigoplus 11\%/E \bigoplus 0.9\%$, $[E] =$ GeV
- **Muon detector:** MUV3 ($\sigma_t \sim 500$ ps)

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

Dark Photon A' model:

- New vector field $F'_{\mu\nu}$ feebly interacting with SM fields
- Free parameters: mass $m_{A'}$, coupling ε
- For $m_A < 600$ MeV/c^2, $A' \to l^+l^-$ decays dominate



Signal selection:

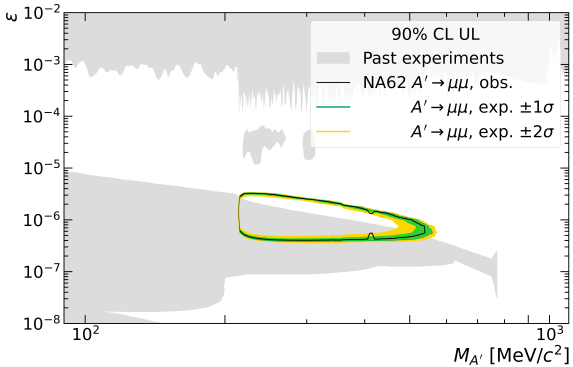
- Employed blind analysis technique (CRs and SR)
- l^+l^- vertex within NA62 fiducial volume
- $l^\pm$ PID using LKr and MUV3
- No in-time activity in LAVs or ANTI0
- Primary vertex close to p^+ beam impact point

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

$A' \to \mu^+\mu^-$

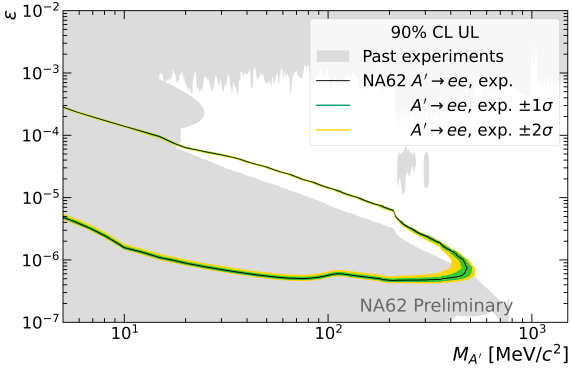
1 event observed in the SR

Corresponding to 2.4σ global significance



$A' \to e^+e^-$

0 events observed in the SR



Excluded new regions in the $\mathbf{m_{A'}}, \varepsilon$ parameter space

Searches for Dark Scalar or ALP via Hadronic Decay Modes

BSM physics models:

- New scalar S or pseudoscalar a coupled with SM fields
- Free parameters: masses and coupling constants

Signal selection:

- Employed blind analysis technique (CRs and SR)
- h^+h^- vertex within NA62 fiducial volume
- $h^\pm$ PID using calorimeters, RICH, and MUV3
- Neutral particles (γ, η, π^0) reconstructed in LKr
- No in-time activity in LAVs, SAV, or ANTI0
- Primary vertex close to p^+ beam impact point

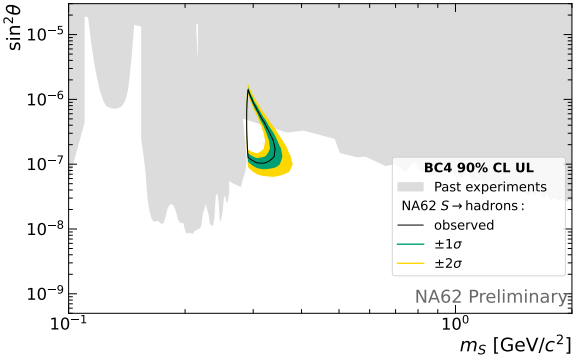
Studied modes:

DS	ALP
$\pi^+\pi^-$	$\pi^+\pi^-\gamma$
	$\pi^+\pi^-\pi^0$
$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$
	$\pi^+\pi^-\eta$
K^+K^-	
	$K^+K^-\pi^0$

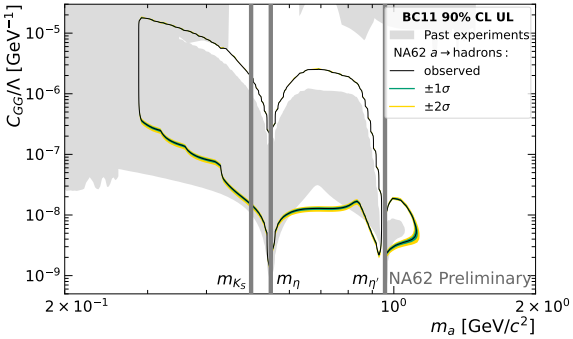
- DS: Dark Scalar S
- ALP: Axion-Like Particle a

Searches for Dark Scalar or ALP via Hadronic Decay Modes

Dark Scalar
0 events observed in the SR



Axion-Like Particle
0 events observed in the SR



Excluded new regions in the mass–coupling parameter space

Summary

Searches for BSM physics in kaon mode:

- Presented ULs on $K^+ \to \mu^- \nu e^+ e^+$, $K^+ \to \pi^0 \pi \mu e$, and $K^+ \to \pi^+ e^+ e^- e^+ e^-$ processes
- The result of $K_{\mu\nu ee}$ search improves the previous UL by a factor of 250
- NA62 performed the first search for the $K^+ \to \pi^0 \pi \mu e$ and $K^+ \to \pi^+ e^+ e^- e^+ e^-$ decays
- Other searches for rare and forbidden processes are ongoing

Searches for BSM physics in beam-dump mode:

- Presented results obtained from data collected in 2021
- Extended 90% CL exclusion regions in the mass–coupling parameter space

NA62 is approved to take data until the CERN Long Shutdown 3 (LS3)

Stay tuned for new results!

Acknowledgement

The project „MSCA Fellowships CZ – UK2“
(reg. n. CZ.02.01.01/00/22_010/0008115) is supported by the Programme Johannes Amos Comenius.

Co-funded by
the European Union