Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

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RECENT RESULTS ON DARK SECTOR SEARCHES AT NA62

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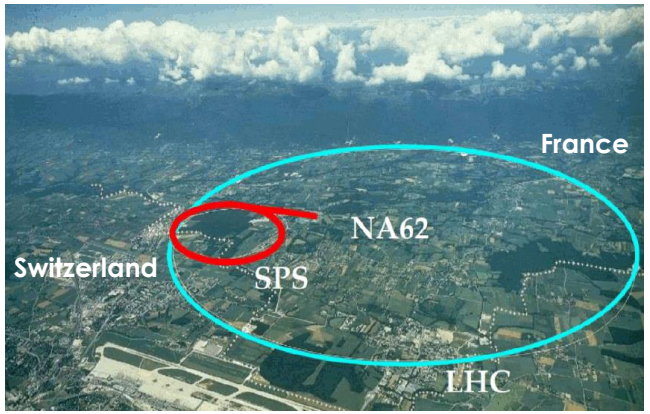
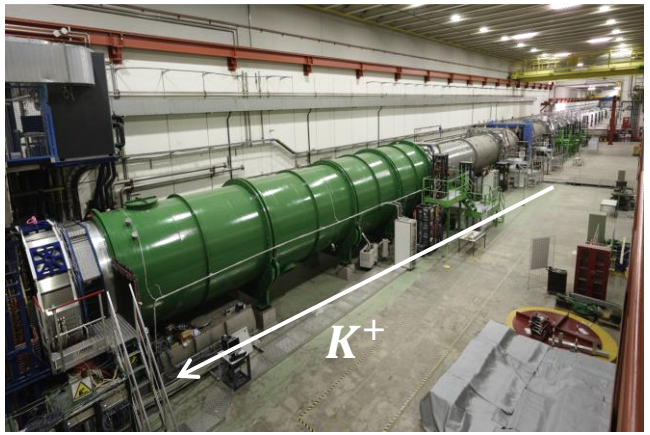
THE NA62 EXPERIMENT AT CERN





- **High-intensity fixed target** experiment at CERN SPS

2008 Approval	2009 → 2015 Detector R&D and commisioning	**Run1:** 2016 -2017-2018 physics runs	LS2	**Run2:** 2021 - today new physics rus

- **Primary goal: measurement of $BR(K^+ \to \pi^+ \nu\bar{\nu})$ at $\mathcal{O}(15\%)$**
  - $BR_{NA62\ Run1}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.4\ stat} \pm 0.9_{syst} \right) \times 10^{-11}$ at 68% CL (3.4 σ significance) [JHEP06(2021)093]
  - PRELIMINARY result from 2021+2022 data analysis → Gemma's talk!
- **Broad physics program both in flavor physiscs…**
  - Precise SM tests in K and π decays :e.g. first row CKM unitarity → Ilaria (Rosa)'s talk!
  - Searches for LFV ($K^+ \to \pi^+ l_1^+ l_2^-$) and LNV ($K^+ \to \pi^-(\pi^0) l^+ l^+$) decays
  - …
- **…and in hidden sector searches** → this talk!

THE DARK SIDE OF NA62

- **Direct searches for New Physics (NP) in K^+ decays or in a dedicated beam dump program**
- Complementary to direct searches at high energy colliders (mass scale O(1 TeV)) and indirect searches in rare and forbidden decays (mass scales up to O(100 TeV))
- **Smaller masses (MeV-GeV)** and **lower couplings to the SM** (larger dataset) are accessible

NP particle	Type	Minimal portal	Decay ($m \leq GeV$)	PBC*
Dark photon (A')	Vector	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$	$ll, 2\pi, 3\pi$	BC1-2
Dark scalar (S)	Scalar	$(\mu S + \lambda S^2) H^\dagger H$	$ll, 2\pi$	BC4-5
ALP (a)	Pseudoscalar	$\frac{C_{ff}}{\Lambda} \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f$, $\frac{C_{VV}}{\Lambda} a V_{\mu\nu} \tilde{V}^{\mu\nu}$	$\gamma\gamma, ll, 2\pi\gamma, 3\pi, 2\pi\eta$	BC10, BC9-11
HNL (N)	fermion	$F_{\alpha I} (\bar{L}_\alpha H) N_I$	$\pi l(\nu), l_1 l_2(\nu)$	BC6-8

*Physics Beyond Collider project at CERN [J. Phys. G47 (2020) 010501]

In the following:

- searches for K^+ decays to multiple dark sector mediators in the $\pi^+ e^+ e^- e^+ e^-$ final state
- searches $X' \to l^+ l^-$ in dump mode with $X = A', ALP$

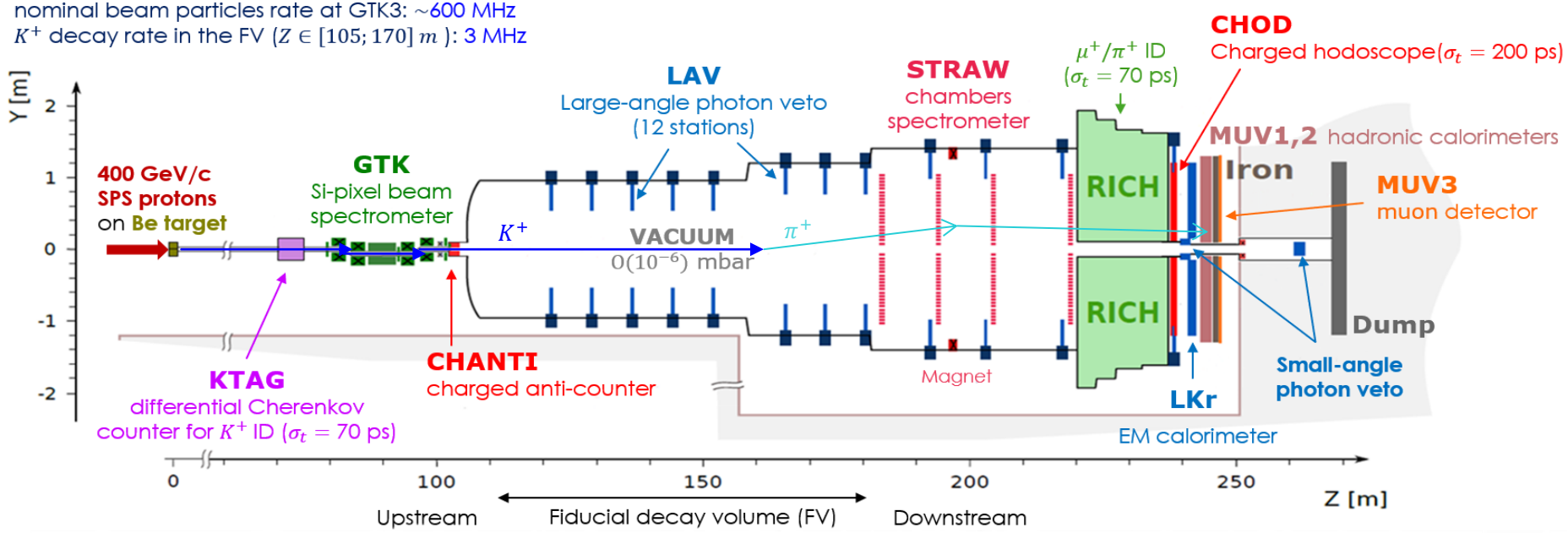
Other searches not covered here:
$K^+ \to e^+ N$ [Phys. Lett. B 807 (2020) 135599]
$K^+ \to \mu^+ N$ [Phys. Lett. B 816 (2021) 136259]
$K^+ \to \mu^+ \nu X_{inv}$ [Phys. Lett. B 816 (2021) 136259]
$K^+ \to \pi^+ X_{inv}$ [JHEP06(2021)093]
$\pi^0 \to X_{inv}$ [JHEP02(2021)201]
and much more channels under study!

NA62 SEARCHES FOR K^+ DECAYS TO MULTIPLE DARK SECTOR MEDIATORS IN THE $\pi^+ e^+ e^- e^+ e^-$ FINAL STATE

NA62 IN KAON MODE

Secondary beam:

- Unsepareted (70%)π^+, (24%)p, (6%)K^+ beam with 75 GeV/c momentum ($\Delta p/p \sim 1{,}1\%$)
- nominal beam particles rate at GTK3: ~600 MHz
- K^+ decay rate in the FV ($Z \in [105; 170]\ m$): 3 MHz



- detector layout designed and optimized for $K^+ \to \pi^+ \nu\bar{\nu}$ study, fully described in [JINST 12 (2017) P05025]
- see also Adam's talk about KTAG
- ~ 2.2 × 10^{18} Proton On Target (POT) collected during Run1 - 2016 (45 days), 2017 (160 days) and 2018 (217 days)
- ~ 6.2×10^{12} K^+ decays collected by the main trigger line + dedicated trigger streams running in parallel [JHEP03 (2023) 122]
- Run 2 (2021 -) in progress

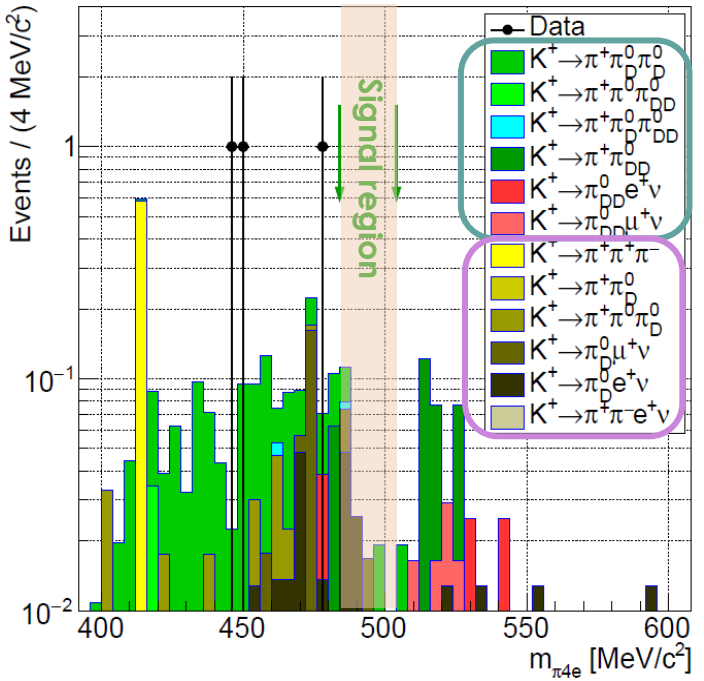
K^+ INTO π^+4e SEARCHES: MOTIVATIONS

- **K^+ decays to final states with multiple dark–sector mediators**
  - Probe **short-lived QCD axions** (a) through the $K^+ \to \pi^+ a a,\ a \to e^+e^-$ process
    - If $m_a = 17$ MeV, $BR(K^+ \to \pi^+ a a) > 2 \times 10^{-8}$ is predicted [Phys.Rev.D105(2022)015017]
    - possibility for a **conclusive test of QCD axion explanation for the "17 MeV" anomaly** [Phys.Rev.D103(2021)055018, Eur.Phys.J.C83(2023)230]
  - Investigate the **prompt dark cascade process** $K^+ \to \pi^+ S, S \to A'A',\ A' \to e^+e^-$ involving a **dark scalar** (S) **promptly decaying into dark photons** (A') [Phys.Rev.D105(2022)015017]
- $K^+ \to \pi^+e^+e^-e^+e^-$ ($K_{\pi 4e}$): heavily suppressed process (outside the π^0 pole) within the SM
  - $BR_{SM\ LO}(K^+ \to \pi^+ 4e, \text{non res.}) = (7.2 \pm 0.7) \times 10^{-11}$ [Phys. Rev. D106 (2022) L071301]
  - Resonant contribution: $K^+ \to \pi^+\pi^0$ followed by the double Dalitz decay $\pi^0_{DD} \to e^+e^-e^+e^-$ ($BR \sim 10^{-6}$)

SEARCH FOR $K^+ \to \pi^+ e^+ e^- e^+ e^-$ AT NA62

[Phys. Lett. B 846 (2023) 138193]

- NA62 Run1 data collected by the multi-electron trigger analyzed
- $K^+ \to \pi^+ \pi^0_{DD} (K_{2\pi DD})$ for normalization. Effective number of K^+decays in the FV: $(8.58 \pm 0.19_{stat} \pm 0.07_{MC} \pm 0.41_{ext}) \times 10^{11}$
- **Invariant mass $m_{\pi 4e}$** used to distinguish between signal and bkg + **blind analysis strategy**
- $K_{\pi 4e}$ signal selection: box cut on m_{4e} and $m^2_{miss} \equiv (P_K - P_{\pi^+})^2$ excluding the π^0 mass peak to reject the $K_{2\pi DD}$ decay



Backgrounds from 5-track and 7-track K^+ decays (only $BR > 10^{-8}$considered)

Backgrounds from 3-track K^+ decays in coincidence with a $K^+ \to \pi^+ \pi^+ \pi^-$ in time (only pairs of 3-track decays with products of $BRs > 10^{-6}$)

Expected bkg events in SR = (0.18 ± 0.14)
Observed events in SR = 0

First search!

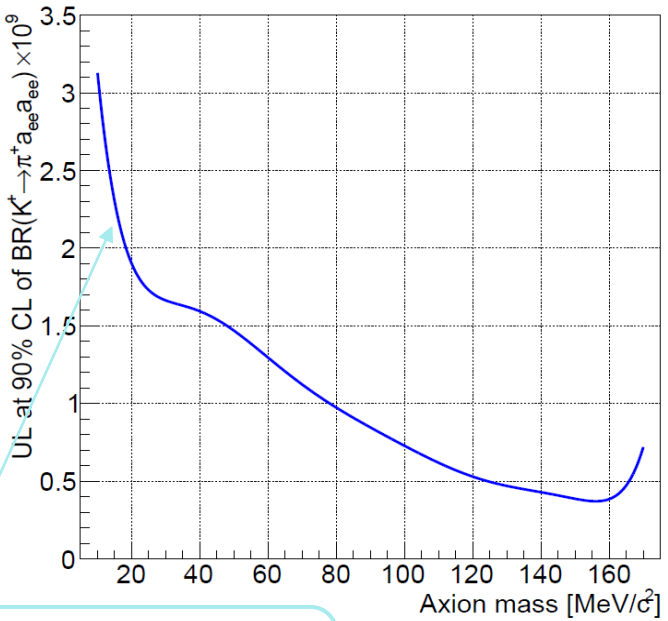
$BR(K^+ \to \pi^+ 4e, \text{non res.}) < 1.4 \times 10^{-8}$ **@ 90% CL**
→ O(200) larger w.r.t. SM expectations

HIDDEN SECTOR IN K^+ INTO π^+4e DECAY

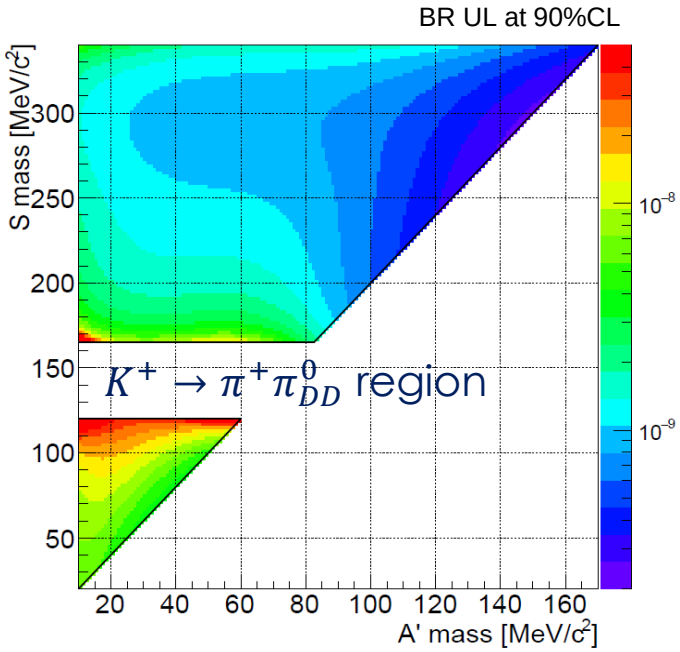
[Phys. Lett. B 846 (2023) 138193]

- NA62 Run1 data collected by the multi-electron trigger analyzed
- $K_{\pi 4e}$ selection + consistency of the masses of two e^+e^- pairs. Same SR as $K_{\pi 4e}$:
  Exp. bkg events in SR = (0.0004 ± 0.0004)
  Observed events in SR = 0
- Uniform phase space assumed for K^+ decays, isotropic decays of dark states [Phys.Rev.D105(2022)015017]

Short-lived QCD axion:
$K^+ \to \pi^+ aa$ with prompt $a \to e^+e^-$



Prompt dark cascade
$K^+ \to \pi^+ S, S \to A'A', A' \to e^+e^-$
with $S(A')$ dark scalar(photon)

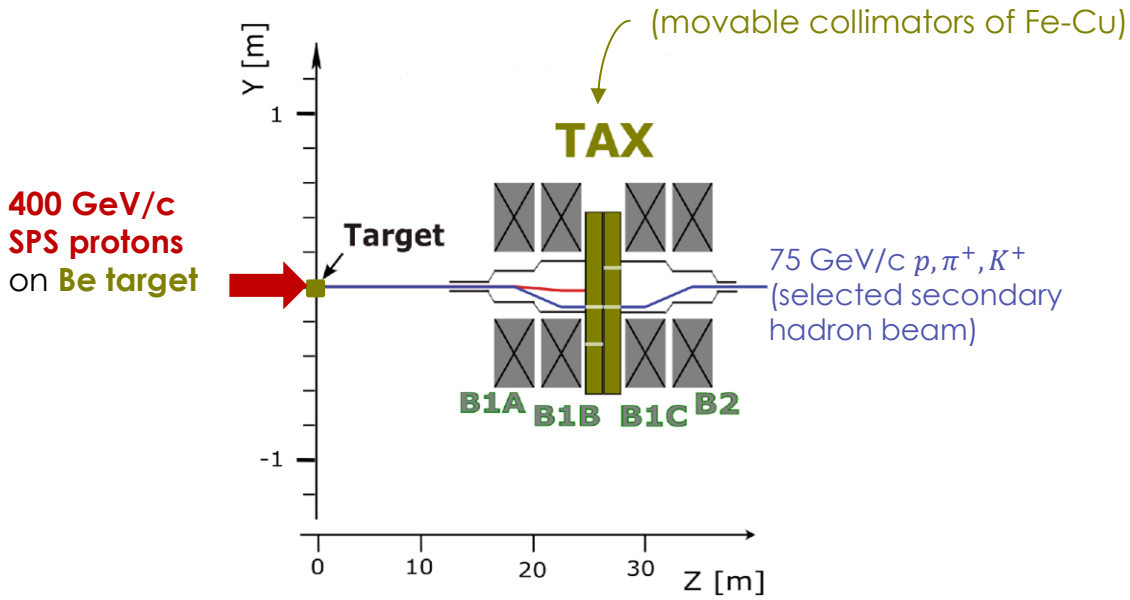


$BR(K^+ \to \pi^+ aa) BR(a \to e^+e^-)^2 < 2.1 \times 10^{-9}$ at 90% C.L. for $m_a = 17\ MeV/c^2$ **exclude** the QCD axion as possible explanation of the "17 MeV" anomaly (from theory: $BR(K^+ \to \pi^+ aa) > 2 \times 10^{-8}$)

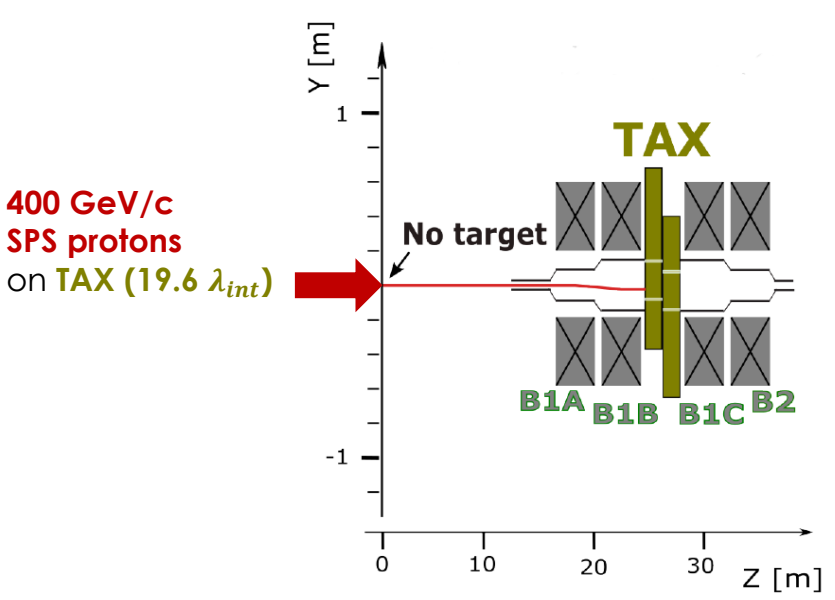
HIDDEN SECTOR SEARCHES IN DUMP MODE AT NA62

NA62 OPERATION MODES

Kaon mode



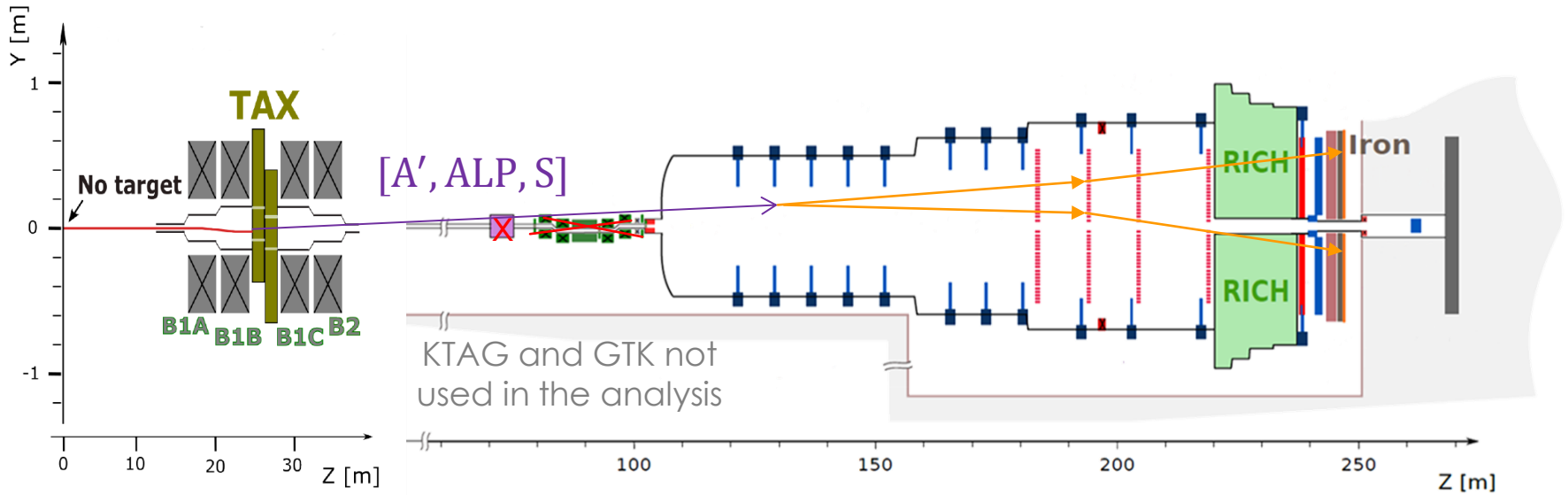
Dump mode



From Kaon mode to Dump mode (details in JHEP09(2023)035)

- **Be target removed and TAX closed** (holes in the movable sections of the collimators misaligned)
- Improved sweeping from magnets downstream to the TAX to reduce "halo" μ from pion decays within the TAX
- Intensity: $(50 - 60) \times 10^{11}$ proton per pulse ($\sim 1.5 \times$ nominal)

NA62 IN DUMP MODE



- $(1.4 \pm 0.28) \times 10^{17}$ POT collected in ~ **10 days** of data taking **in 2021;** additional data collected in 2023-2024
- Due to the feeble coupling to SM, exotic particles can punch through tens of meters of material before decaying
- **Signal region of exotic searches defined in the plane CDA_{TAX} *vs* Z_{TAX}**

CDA_{TAX}: closest distance of approach to the beam direction at the TAX entrance of the reconstructed exotic direction ($\sigma_{CDA} \sim 7\ mm$)
Z_{TAX}: longitudinal position of the interaction point ($\sigma_Z \sim 5.5\ m$)

HIDDEN SECTOR SEARCHES IN $X' \to l^+l^-$ FINAL STATE

[JHEP09(2023)035] [PHYS. REV. LETT. 133 (2024) 111802]

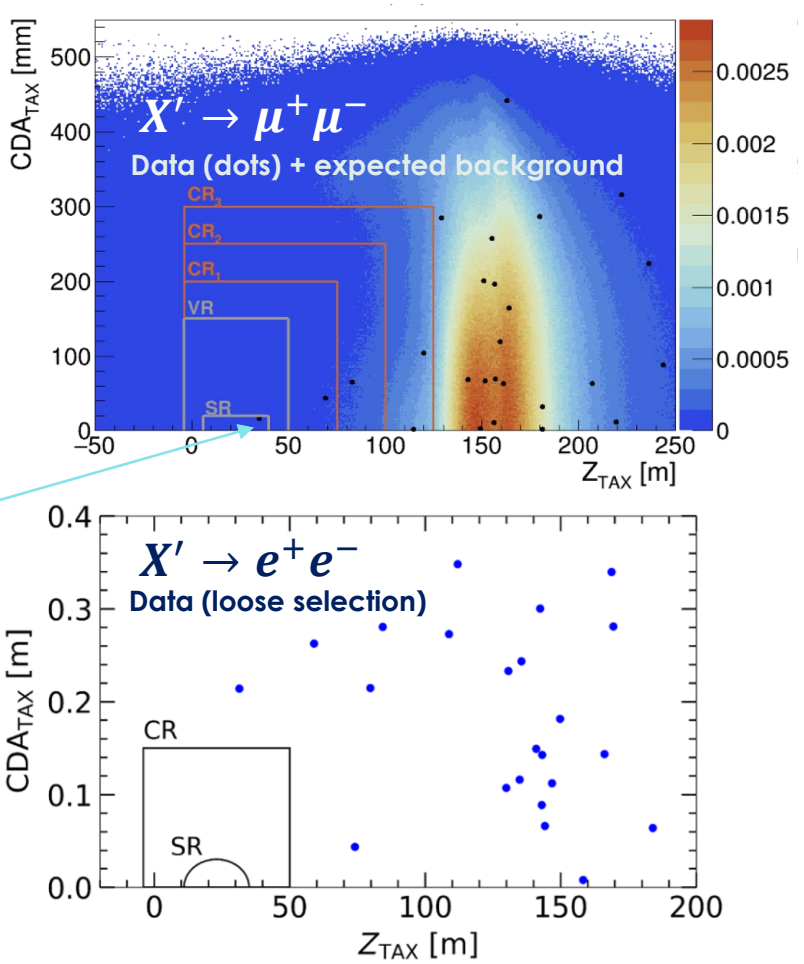
- **Experimental signature:** l^+l^- vertex reconstructed within the NA62 fiducial volume and di-lepton three-momentum pointing back to the proton beam interaction point at the TAX

- **Blind analysis strategy**: Signal and Control (Validation) Regions kept masked until the analysis strategy is frozen

- **$X' \to \mu^+\mu^-$ analysis**
  - Main bkg: combinatorial bkg due to random superposition of two uncorrelated "halo" muons. $N^{bkg}_{exp,VR} = 0.17 \pm 0.02$, $N^{bkg}_{exp,SR} = 0.016 \pm 0.002$
  - **0 event observed in the VR, 1 event observed in the SR**

Counting experiment with 2.4σ global significance

- **$X' \to e^+e^-$ analysis**
  - Main bkg: prompt bkg due to the secondary particles from the interaction of "halo" muons with the material upstream or inside the decay volume. $N^{bkg}_{exp,CR} = 9.7^{+21.3}_{-7.3} \times 10^{-3}$, $N^{bkg}_{exp,SR} = 9.4^{+20.6}_{-7.2} \times 10^{-3}$
  - **0 event observed in the CR, 0 event observed in the SR**



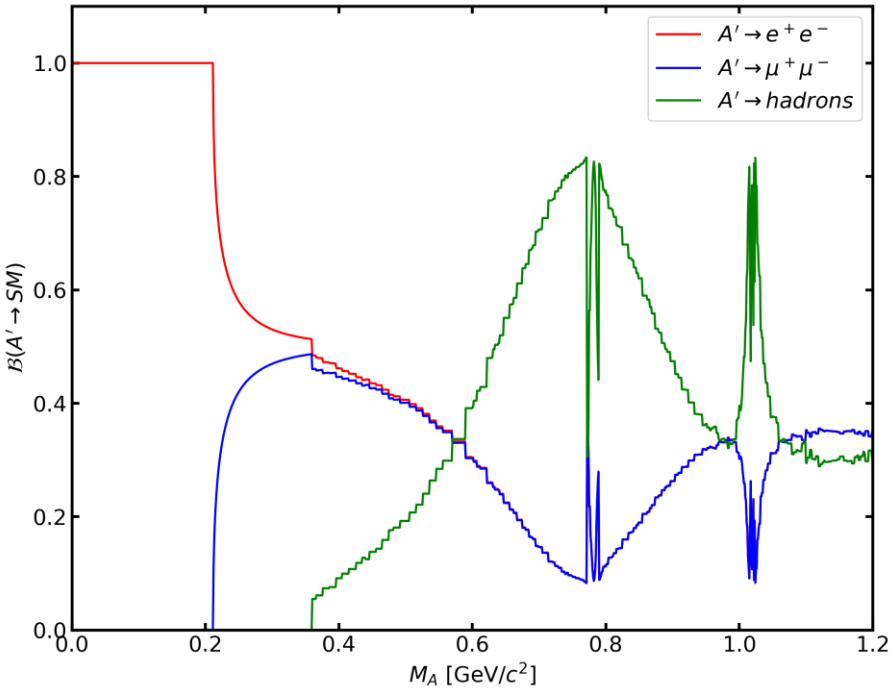
DARK PHOTON SEARCHES IN $A' \rightarrow l^+l^-$ FINAL STATE

[JHEP09(2023)035] [PHYS. REV. LETT. 133 (2024) 111802]

- Interpretation of $X \rightarrow l^+l^-$ results in the SM extension with production of a **Dark Photon** A' with kinetic mixing with the SM hypercharge: $\mathcal{L} \supset -\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$

- Two A' production mechanism in the beam-dump setup
  - Bremsstrahlung production: $\gamma^* p \rightarrow A' p'$
  - meson-mediated production : $P \rightarrow A' + \gamma$ or $V \rightarrow PA'$ with $P = \{\pi^0, \eta, \eta'\}$ and $V = \{\rho, \omega, \Phi\}$

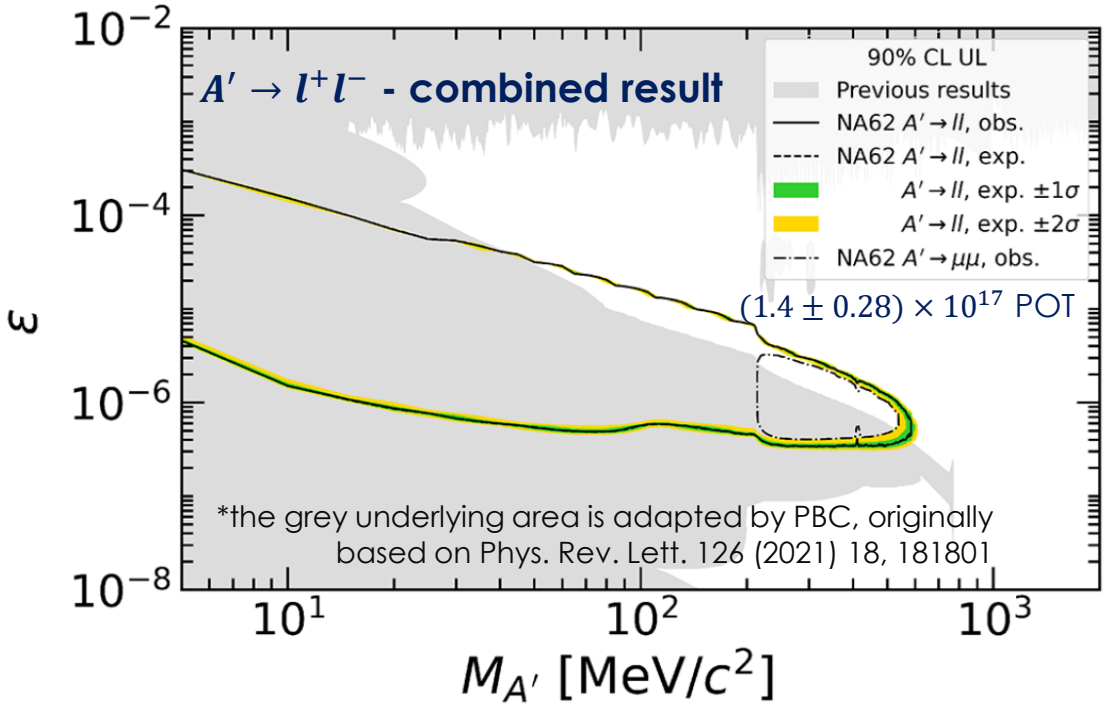
- Decay into lepton pairs dominant for $\mathrm{M}_{A'} < 700\ MeV/c^2$

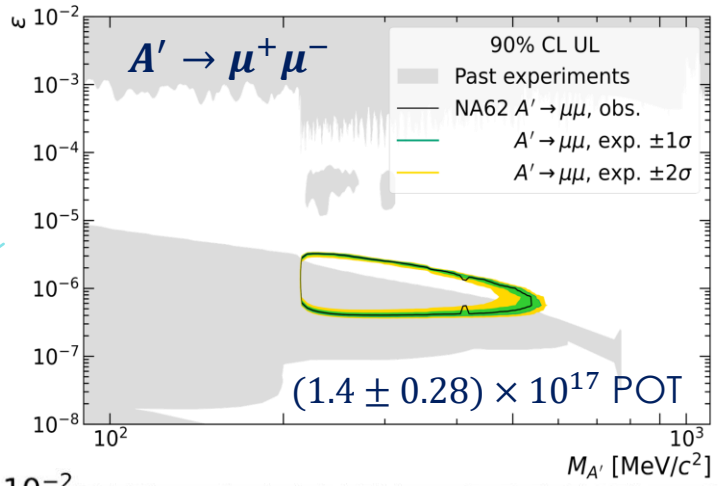


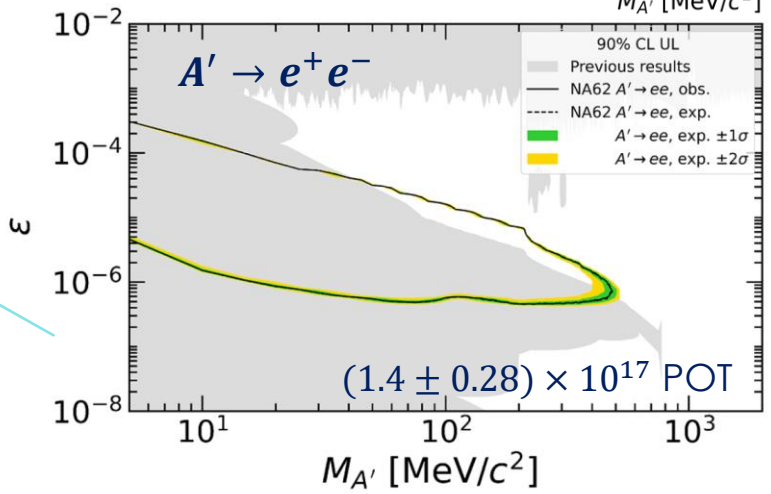
DARK PHOTON EXCLUSION LIMITS AT 90% CL

[JHEP09(2023)035] [PHYS. REV. LETT. 133 (2024) 111802]

- Free parameters of the model: $M_{A'}$ and kinetic coupling ϵ
- The region enclosed by the contour is excluded, extending the previous limits for $\mathbf{50 < M_{A'} < 600\ MeV/c^2}$ **with** $\mathbf{10^{-6} < \epsilon < 4 \times 10^{-5}}$





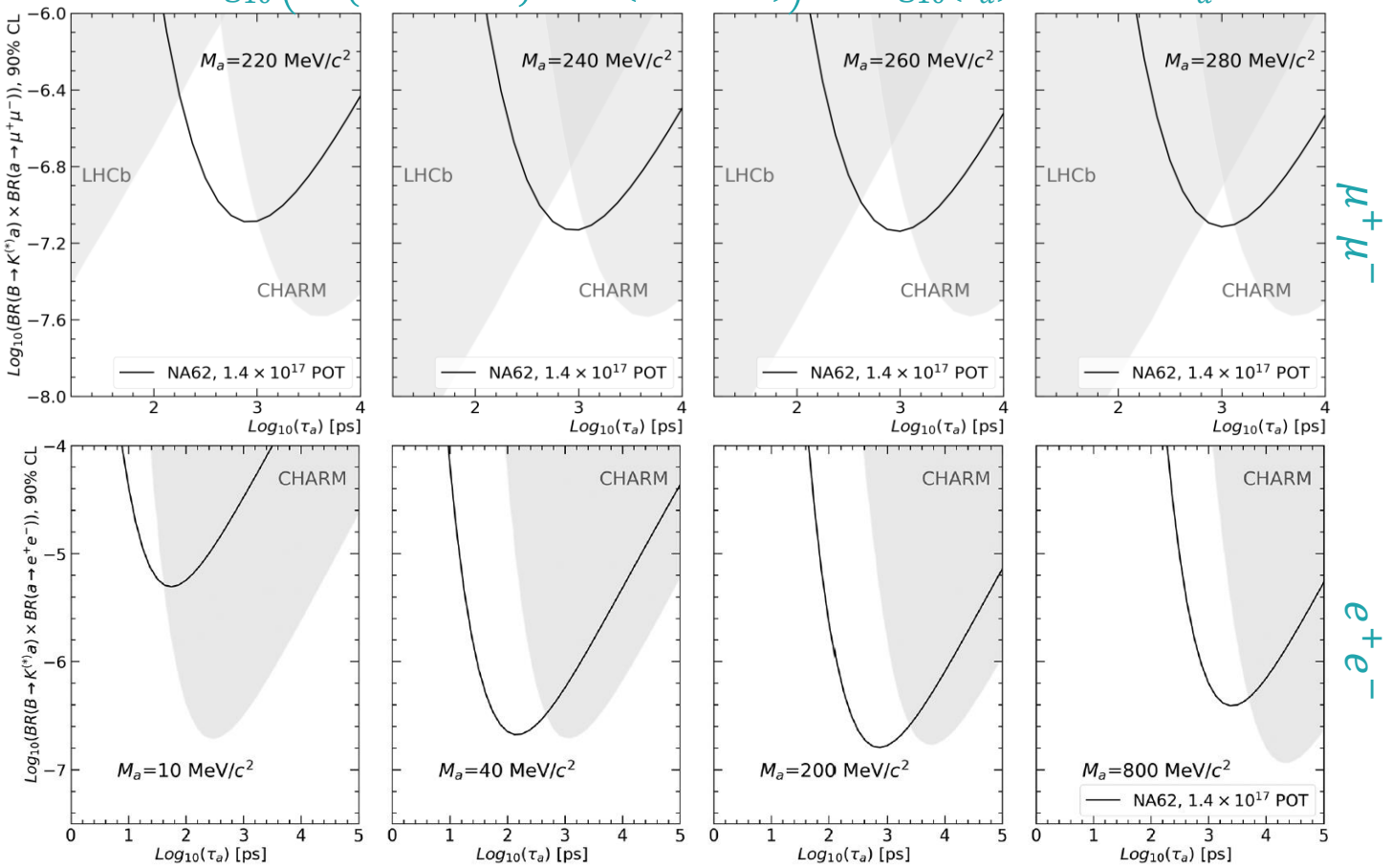


ALP EXCLUSION LIMITS AT 90% CL

[JHEP09(2023)035] [PHYS. REV. LETT. 133 (2024) 111802]

- Interpretation of $X \to l^+l^-$ results in SM extensions with the emission in $b \to s$ transitions of a **pseudoscalar particle a coupled to SM fermionic fields**
- Production mechanisms in the beam-dump setup: B mesons decay: $B^{\pm,0} \to K^{\pm,0,*}a$
- **Model-independent approach** to account for non-uniform couplings to SM fermions [Phys. Lett. B 790 (2019) 537]
  - the ALP mass M_a and lifetime τ_a, and $BR\left(B \to K^{(*)}a\right) \times BR(a \to l^+l^-)$ are free parameters
- New regions excluded in both $a \to \mu^+\mu^-$ and $a \to e^+e^-$ searches

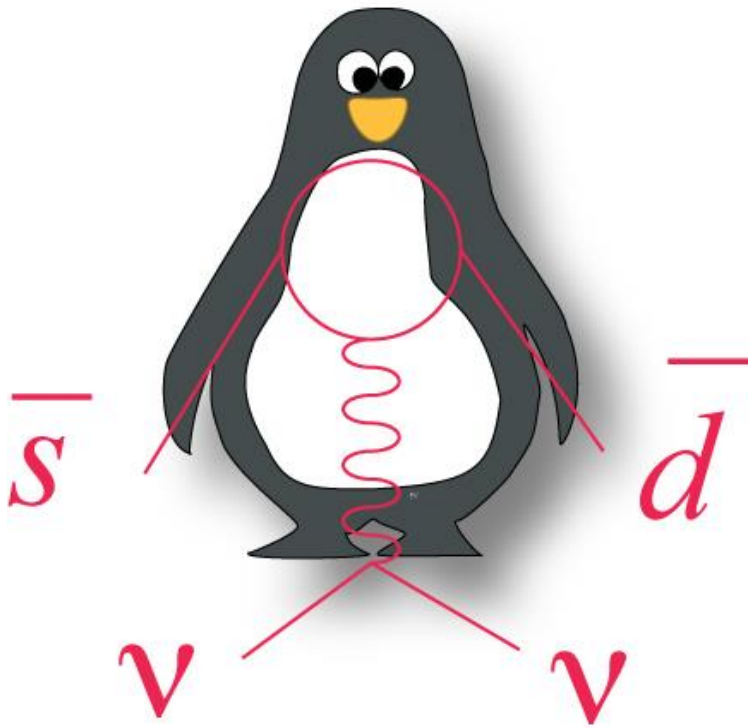
$\mathrm{Log}_{10}\left(BR\left(B \to K^{(*)}a\right) \times BR(a \to l^+l^-)\right)$ vs $\mathrm{Log}_{10}(\tau_a)$ for fixed M_a



OUTLOOK & CONCLUSIONS

CONCLUSIONS

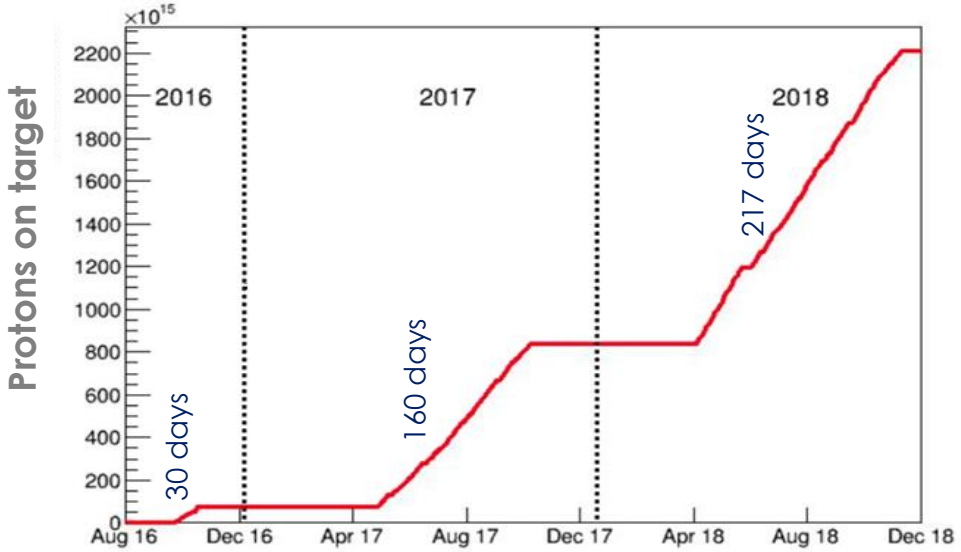
- NA62 is a multipurpose experiment exploiting an high intensity beam extracted from the CERN SPS
- Recent results concerning direct searches for NP has been presented
  - BR ULs (at 90% C.L.) of $\mathcal{O}(10^{-9})$ for $K^+ \to \pi^+ a_{ee} a_{ee}$ and $K^+ \to \pi^+ S, S \to A'A', A' \to e^+e^-$ prompt decay chains, with a QCD axion and $S(A')$ dark scalar(photon) by the analysis of Run1 data
  - By data collected in dump mode in 2021 (1.4×10^{17} POT), new exclusion limits at 90% CL has been set for models involving dark photons and ALP coupling to fermions in the $X \to l^+l^-$ final state
- Many other analyses are in progress: eg: $X \to hadrons$ $(X = a, S, A')$ or semileptonic and $\gamma\gamma$ final state
- Run2 data taking is ongoing, providing new samples to be analyzed. NA62 aims to collect 10^{18} POT in beam dump mode by the end of Run2, with interesting perspectives on dark photons, ALPs, dark scalars and HNLs



Back-Up

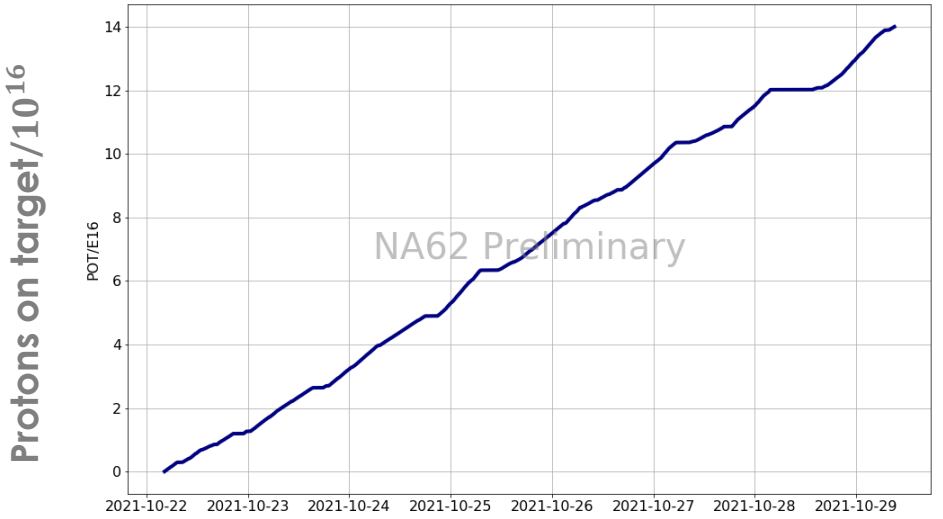
NA62 DATASETS

Kaon mode - Run1 integrated luminosity



- **Run 1 (2016-2017-2018):** $\sim 6.2 \times 10^{12}$ useful K^+ decays collected by the main trigger line + dedicated trigger streams collecting single-track or multi-track final state events [JHEP03 (2023) 122]
- Run 2 (2021 -) in progress; approved till LS3

Dump mode - 2021 integrated luminosity



- $(1.4 \pm 0.28) \times 10^{17}$ POT collected in ~ **10 days** of data taking **in 2021**
- additional data collected in 2023-2024

- aim at 10^{18} POT before end of Run2

HIDDEN SECTOR SEARCHES IN $X' \to l^+l^-$ FINAL STATE

[JHEP09(2023)035] [PHYS. REV. LETT. 133 (2024) 111802]

Experimental signature: l^+l^- vertex reconstructed within the NA62 fiducial volume and di-lepton three-momentum 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 (elliptical SR definition in ee analysis instead of box)

ΔT suggest two types of background
(from $\mu\mu$ analysis)

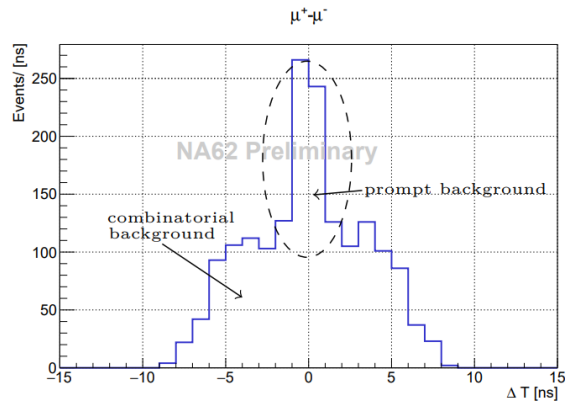


Figure: ΔT before LAV veto is applied (CR, SR masked).

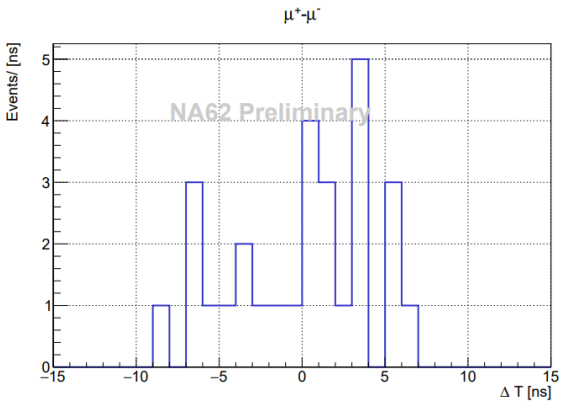
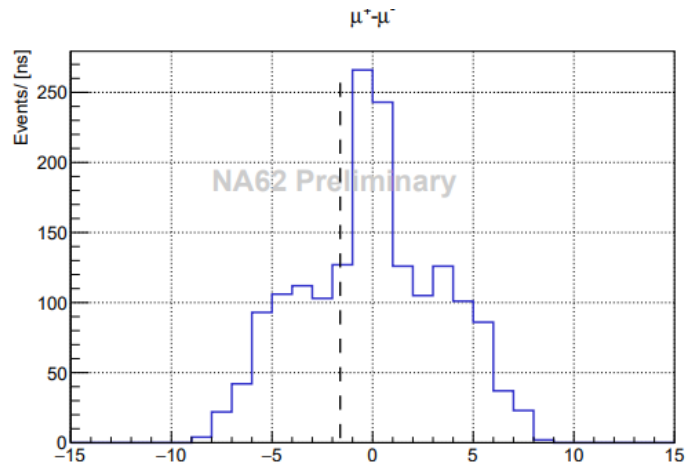
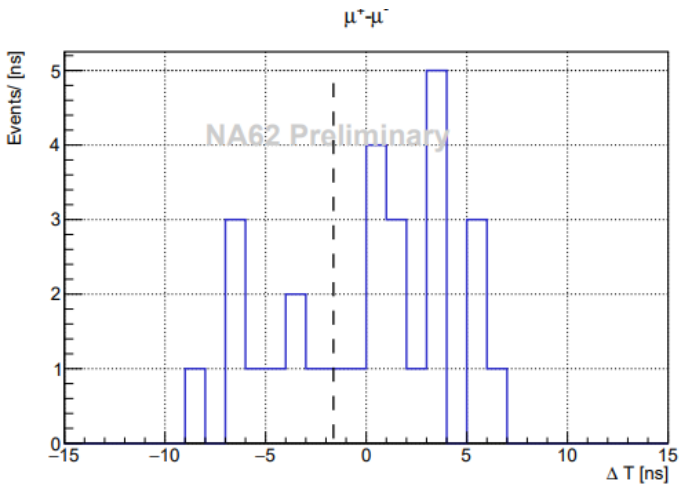


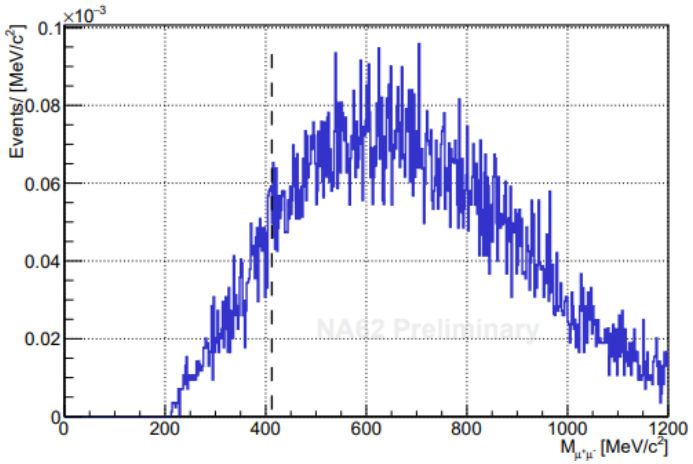
Figure: ΔT after full selection (CR, SR masked).

$X' \to \mu^+\mu^-$: DETAILS ON THE OBSERVED EVENT

[JHEP09(2023)035]





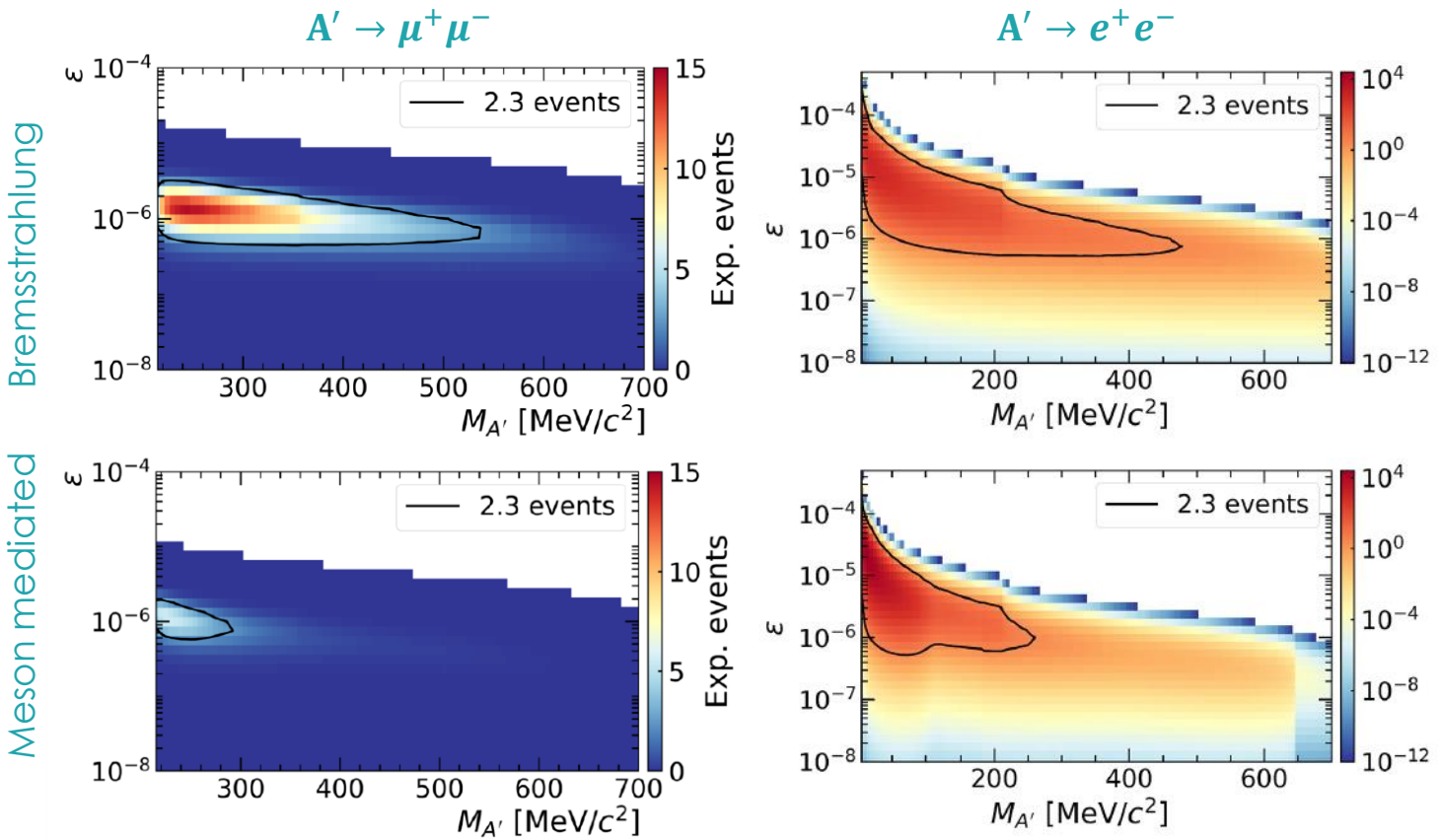


- Invariant mass: $m_{\mu\mu} = 411\ \mathrm{MeV/c^2}$
- Time difference: $\Delta T = -1.69\ ns$
- Momenta: $P(\mu^+) = 99.5\ GeV/c\ ;\ P(\mu^-) = 39.6\ GeV/c$
- $Z_{FV} = 157.8\ m$
- $Z_{TAX} = 17\ m, CDA_{TAX} = 382\ mm$
- $E/p(\mu^+) = 0.008, E/p(\mu^+) = 0.018$

$A' \rightarrow l^+l^-$ FINAL STATE: EXPECTED SIGNAL YIELD

[JHEP09(2023)035] [PHYS. REV. LETT. 133 (2024) 111802]

$$N_{exp} = N_{POT} \times \chi(pp \rightarrow A') \times BR(A' \rightarrow l^+l^-) \times P_{RD}(\epsilon) \times A_{acc} \times A_{trigger}$$



- $N_{POT} = (1.40 \pm 0.28) \times 10^{17}$
- $\chi(pp \rightarrow A')$ = DP production probability
- $BR(A' \rightarrow l^+l^-)$ = branching ratio to the l^+l^- final state
- $P_{RD}(\epsilon)$ = probability to reach the NA62 fiducial decay volume and decay therein
- $A_{acc} \times A_{trigger}$ = signal selection and trigger efficiencies

EXOTIC SEARCHES IN X → *hadrons* FINAL STATE

[PRELIMINARY]

- $X \to h^+h^-$ or $X \to h^+h^-x$ with $h = \{\pi, K\}$ and $x = \{\gamma, \pi^0, 2\pi^0, \eta\}$
- **Experimental signature:**
  - h^+h^- vertex reconstructed within the NA62 fiducial volume
  - up to four additional photons (LKr clusters) associated to the event
  - total three-momentum pointing back to the proton beam interaction point at the TAX
- **Blind analysis strategy: Signal and Control Regions defined in the CDA_{TAX} vs Z_{TAX} plane**
- **Main bkg: upstream background** due to particles that are collected by the GTK achromat. Proven that searches are **background free,** not only at 1.4×10^{17} POT but also in the future full Run2 beam dump dataset of 10^{18} POT

Numerous exotic particles production and decay channels are possibles

	Production mechanism in the beam-dump setup	Possible final states
Dark photon (A')	❖ Bremsstrahlung ❖ meson-mediated	$\pi^+\pi^-$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^0\pi^0$ K^+K^- $K^+K^-\pi^0$
Dark scalar (S)	B mesons decay: $B^{\pm,0} \to K^{\pm,0,*}S$	$\pi^+\pi^-$ $\pi^+\pi^-\pi^0\pi^0$ K^+K^-
ALP (a)	❖ B mesons decay: $B^{\pm,0} \to K^{\pm,0,*}a$ ❖ Primakoff (on-, off-shell) ❖ Mixing with $P = \{\pi^0, \eta, \eta'\}$	$\pi^+\pi^-\gamma$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^0\pi^0$ $\pi^+\pi^-\eta$ $K^+K^-\pi^0$

Altogether, **36 combinations** of production and decay channels were studied

HIDDEN SECTOR SEARCHES IN $X' \rightarrow hadron$ FINAL STATE

[PRELIMINARY]

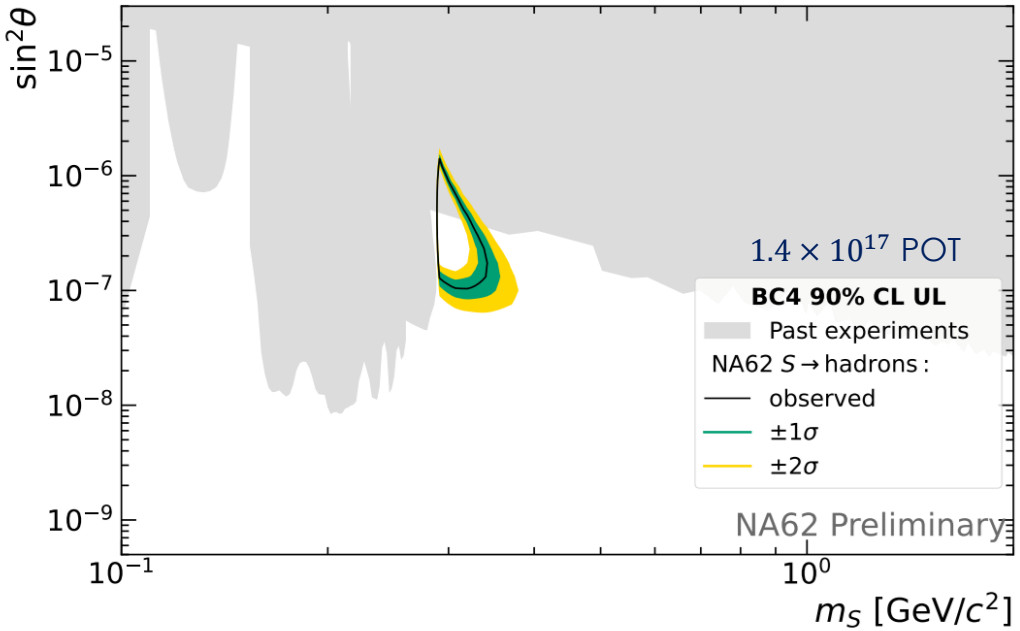
Table: Summary of total expected number of background events at 68% CL for all studied decay channels in CR and SR after full selection. Needed number of observed events N_{obs} for p-value more than 5σ from background-only hypothesis in SR and SR+CR (global significance, flat background in m_{inv} assumption).

Channel	$N_{\text{exp,CR}} \pm \delta N_{\text{exp,CR}}$	$N_{\text{exp,SR}} \pm \delta N_{\text{exp,SR}}$	$N_{\text{obs,SR}}^{p>5\sigma}$	$N_{\text{obs,SR+CR}}^{p>5\sigma}$
$\pi^+\pi^-$	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

RESULTS FROM $X \rightarrow hadrons$ SEARCHES AND INTERPRETATIONS
[PRELIMINARY]

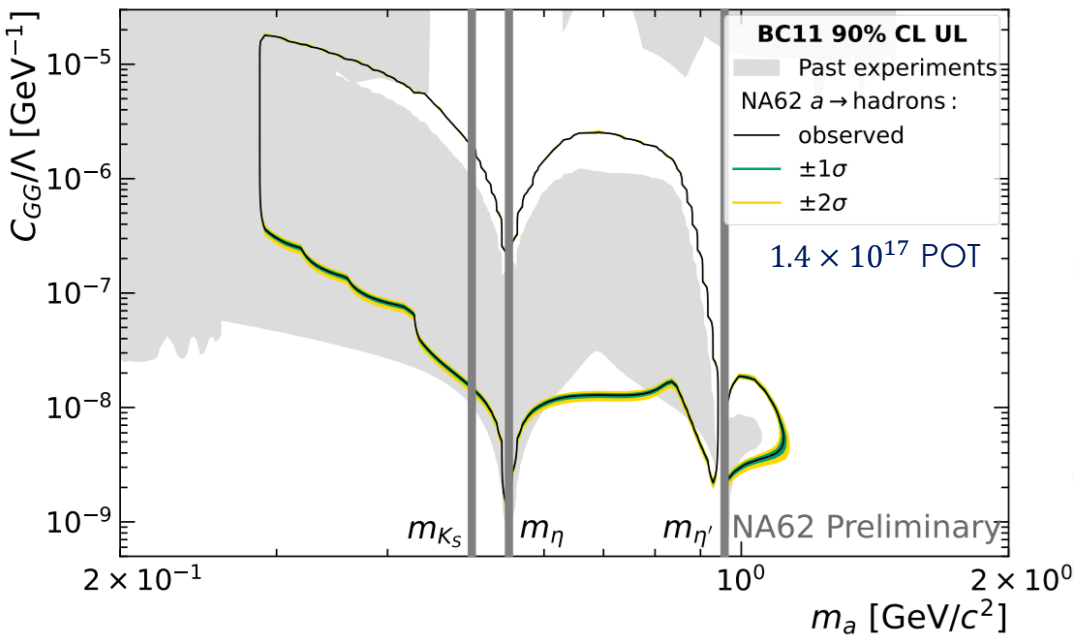
0 events observed in all control and signal regions

Dark scalar exclusion limits



Higgs mixed scalar: $\mathcal{L} \supset (\mu S + \lambda S^2) H^\dagger H$ with $\lambda = 0$;
θ = mixing angle between S and the SM Higgs field

ALP exclusion limits



ALP coupled to gluons: $\mathcal{L} \supset \frac{a}{f_G} G_{\mu\nu} \tilde{G}^{\mu\nu}$; $f_G^{-1} = 16\pi\alpha_s C_{GG}/\Lambda$

*Public tool ALPINIST [JHEP 07 (2022) 094] used to combine the results from individual production and decay channels

HNL SEARCHES IN KAON MODE

[PHYS.LETT.B 807 (2020) 135599], [PHYS.LETT.B 816 (2021) 136259]

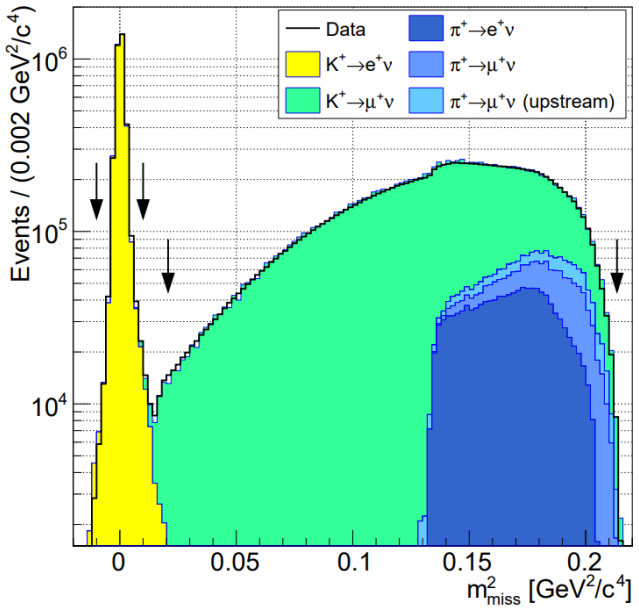
- Portal interaction (general form): $\mathcal{L} \supset F_{\alpha I}(\bar{L}_\alpha H)N_I$
- From diagonalizing mass terms for neutrinos → mixing $\nu_\alpha - N_I$, which can be parametrized by $U_{\alpha I}$
- Search for N production in K^+ decays: $BR(K^+ \to l^+ N) = BR(K^+ \to l^+ \nu) \cdot \rho_l(m_N) \cdot |U_{l4}|^2$ with $\rho_l(m_N)$ kinematic factor

Assumptions ensuring N to be stable with respect the detector volume

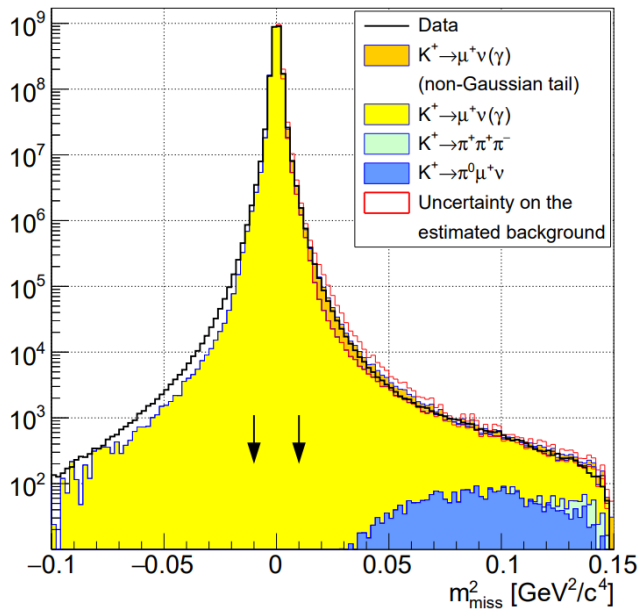
- N decays exclusively to SM particles
- lifetime of N exceeding 50 ns

Search strategy: Peak search in the continuous distribution of $\boldsymbol{m^2_{miss} = (P_K - P_l)^2}$

$\boldsymbol{m^2_{miss} = (P_K - P_e)^2}$



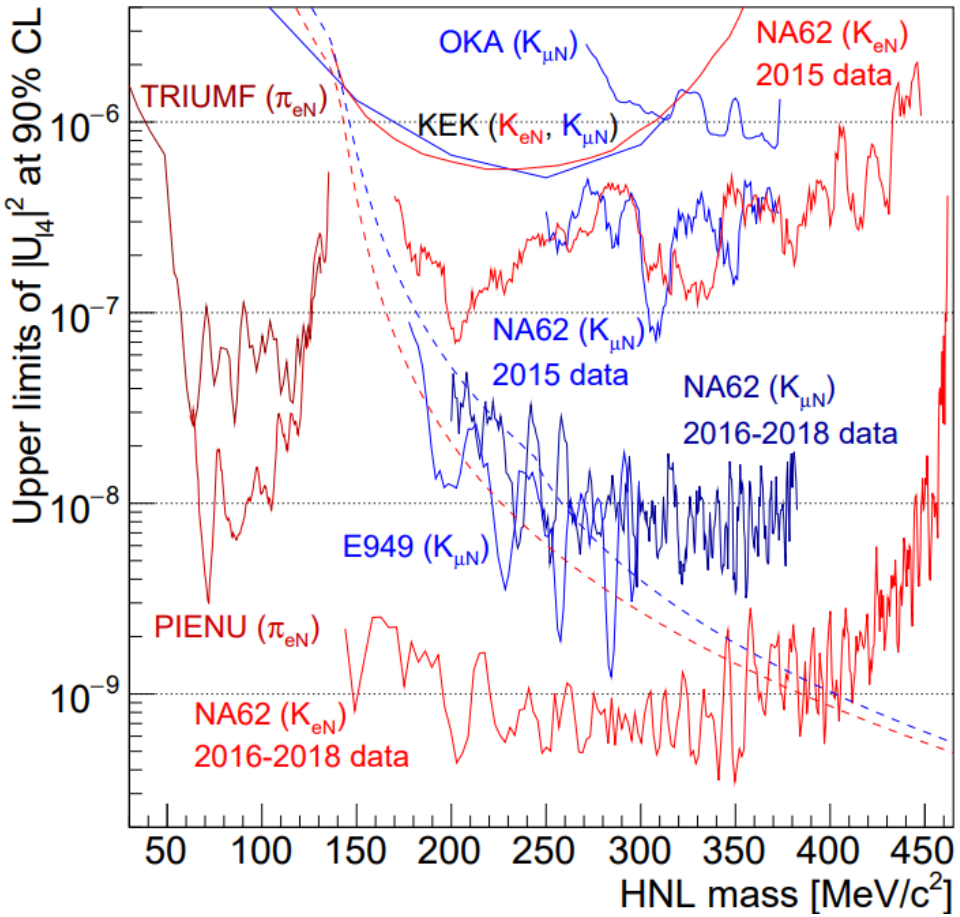
$\boldsymbol{m^2_{miss} = \left(P_K - P_\mu\right)^2}$



HNL SEARCHES IN KAON MODE

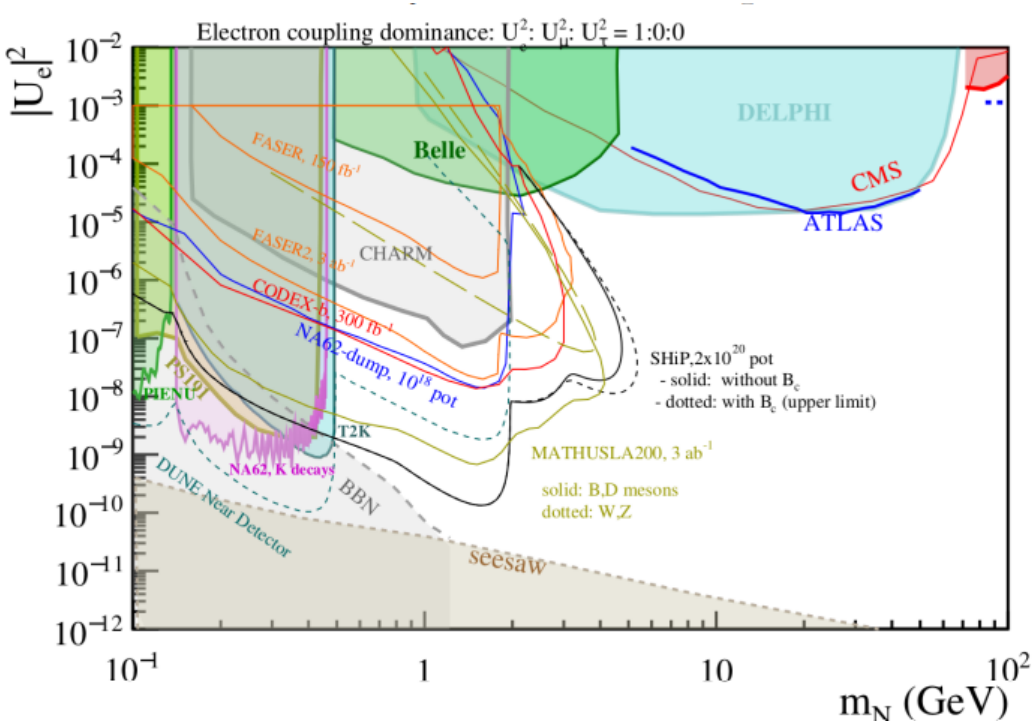
[PHYS.LETT.B 807 (2020) 135599], [PHYS.LETT.B 816 (2021) 136259]

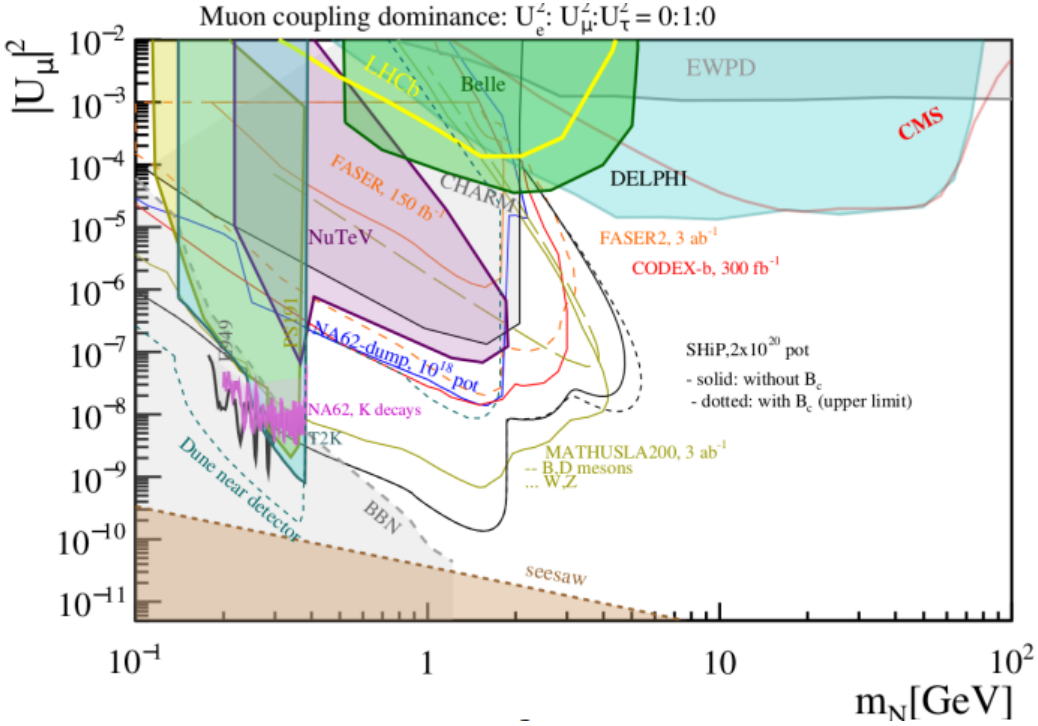
- Mass range considered:
  - $144 < m_N < 462\ MeV/c^2$ in $K^+ \to e^+ N$
  - $200 < m_N < 384\ MeV/c^2$ in $K^+ \to \mu^+ N$
- UL at 90% CL
  - At the level of $10^{-9}\ |U_{e4}|^2$
  - At the level of $10^{-8}\ |U_{\mu 4}|^2$



HNL SEARCHES IN DUMP MODE (PROJECTIONS)

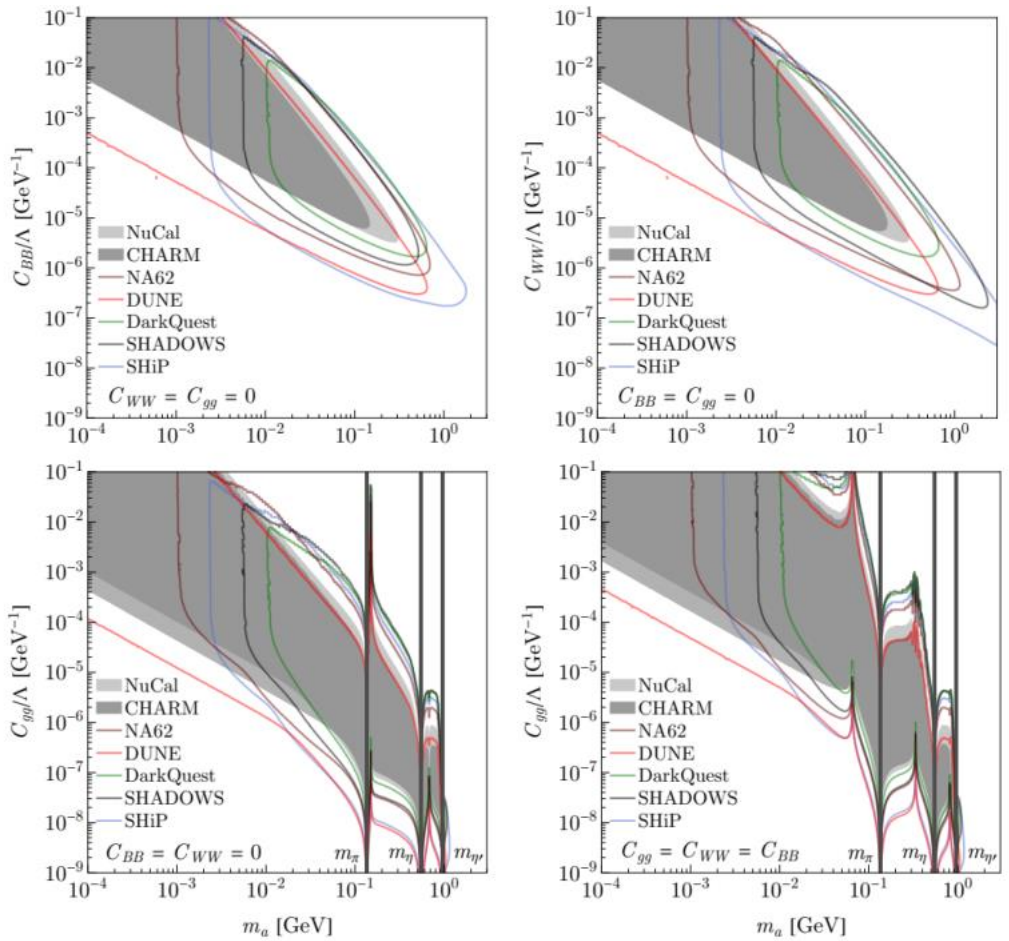
[Eur.Phys.J.C 81 (2021) 11, 1015]





$a \to \gamma\gamma$ SEARCHES IN DUMP MODE (PROJECTIONS)

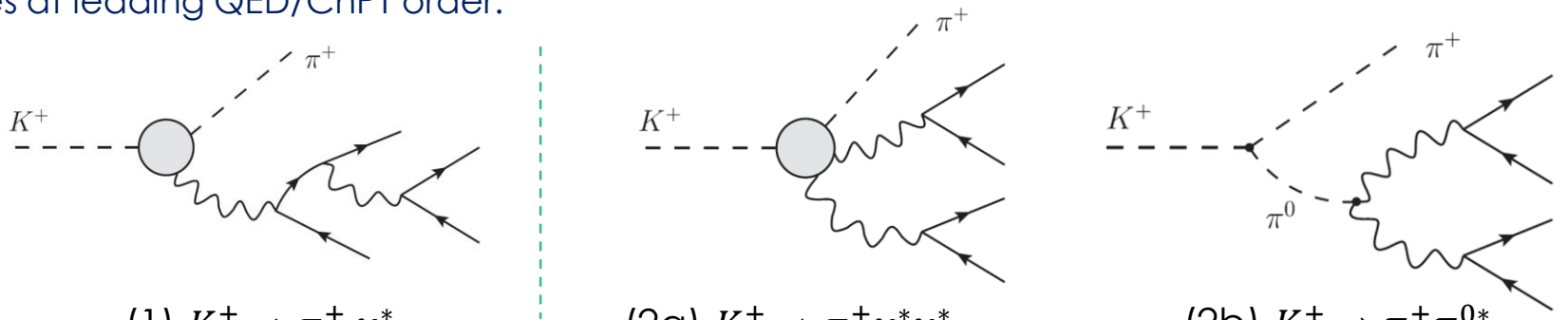
[JHEP07(2022) 094]



SM NON RES. $K^+ \to \pi^+ e^+ e^- e^+ e^-$

[Phys. Lett. B 846 (2023) 138193]

- $\boldsymbol{K^+ \to \pi^+ e^+ e^- e^+ e^-}$ $\boldsymbol{(K_{\pi 4e})}$: heavily suppressed process (outside the π^0 pole) within the SM
  - Topologies at leading QED/ChPT order:



(1) $K^+ \to \pi^+ \gamma^*$ (2a) $K^+ \to \pi^+ \gamma^* \gamma^*$ (2b) $K^+ \to \pi^+ \pi^{0*}$

  - $\boldsymbol{BR_{SM\ LO}(K^+ \to \pi^+ 4e, \text{non res.}) = (7.2 \pm 7) \times 10^{-11}}$ [Phys. Rev. D106 (2022) L071301]
  - Resonant contribution ((2b) topology with on-shell π^0)
    - $K^+ \to \pi^+ \pi^0$ followed by the double Dalitz decay $\pi^0_{DD} \to e^+ e^- e^+ e^-$
    - Measured $BR(K^+ \to \pi^+ \pi^0_{DD}) = (6.9 \pm 0.3) \times 10^{-6}$ [Prog. Theor. Exp. Phys. 2022 (2022) 083C01]

- **NA62 MC of SM $(K^+ \to \pi^+ 4e, \text{non res.})$ includes topologies (1), (2a) and their interference only**
  - Non-resonant part of contribution (2b) does not interfere with the other amplitudes, peaks at $m_{4e} \sim m_{\pi^0}$ and accounts for 3% of the total decay rate in the $|m_{4e} - m_{\pi^0}| > 10\ \text{MeV/c}^2$ used in this analysis.

SEARCH FOR K^+ INTO π^+4e AT NA62

[Phys. Lett. B 846 (2023) 138193]

- Data collected by dedicated **electron multi-track and multi-track trigger lines**
- **Fully kinematic analysis**
  - **Track selection: momentum, direction and time (STRAW)**
  - 5-track events forming a Q=+1 vertex in the FV and vertex momentum $\left(\left|\sum_{final\ state}\vec{p}_f\right|\right)$ consistent with beam (i.e. K^+) average momentum
  - **only STRAW spectometer infos for PID of final state particles**
    - **Multiple soft tracks in the final state not fully contained in the downstream detectors**
- **Expected background and selection acceptances from MC**
- **Discriminating kinematic variable and blind analysis strategy**
  - Signal region (SR) kept closed until final bkg validation in control regions

K^+ INTO $\pi^+e^+e^-e^+e^-$:FULLY KINEMATIC PID

[Phys. Lett. B 846 (2023) 138193]

- **Only STRAW spectometer infos (i.e. Q/p) for PID of final state particles**

  Possible thanks to strong kinematic constraints:

  $m_{\pi 4e} \equiv$ 5-track invariant mass
  $m_{4e} \equiv 4e$ invariant mass
  $m^2_{miss} \equiv (P_K - P_{\pi^+})^2 =$ squared missing mass $K - \pi^+$
  $m_{ee} \equiv= e^+e^-$ invariant mass → For hidden sector searches: $K^+ \to \pi^+ aa$ with prompt $a \to e^+e^-$ and prompt dark cascade $K^+ \to \pi^+ S, S \to A'A', A' \to e^+e^-$

- In the event: three positively charged tracks and two negatively charged tracks.
- Three assignments of the mass ($m_{e^+} \backslash m_{e^+} \backslash m_{\pi^+}$) to one of the positively charged tracks are possible.
- In each mass assignment: $m_{\pi 4e}$, m_{4e}, m^2_{miss} are evalueted. Optimal mass assignment (o.m.a.): **min($|m_{\pi 4e} - m_K|$)**

Normalization selection ($K^+ \to \pi^+\pi^0_{DD}$ events)

$|m_{4e} - m_{\pi^0}| < 10\ MeV/c^2$
in the o.m.a.

$K_{\pi 4e}$ selection

($A_{\pi 4e} = (1.85 \pm 0.06_{stat}) \times 10^{-4}$)

$|m_{4e} - m_{\pi^0}| < 10\ MeV/c^2$
$m^2_{miss} > 0$,
$|m_{miss} - m_{\pi^0}| > 40\ MeV/c^2$
in each mass assignment

$|\vec{p}_\pi| > 0$ in the o.m.a.

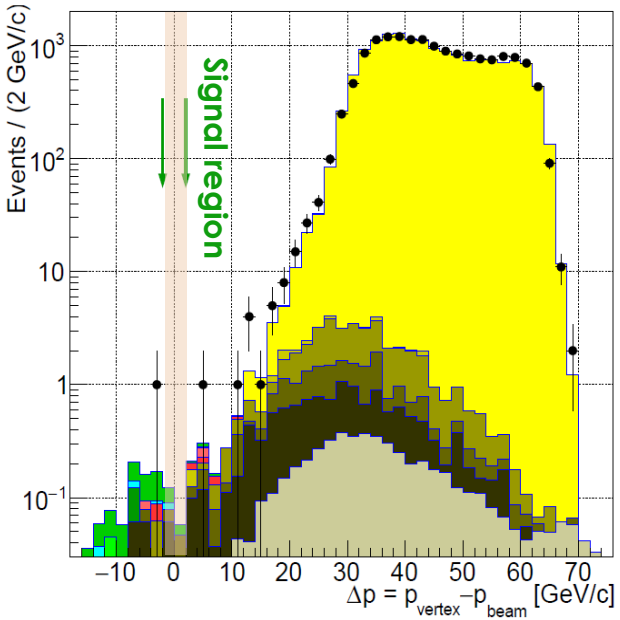
Hidden sector selection

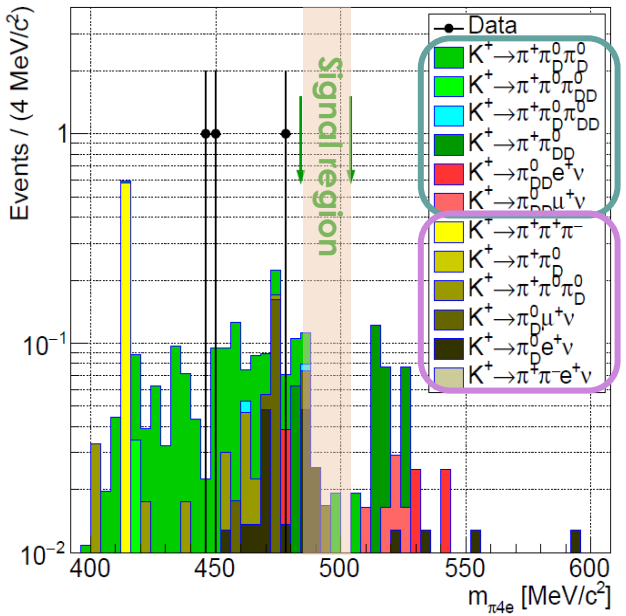
$K_{\pi 4e}$ selection + (in the o.m.a.) consistency of the two possibles di-electron mass, $m_{ee,1}$, $m_{ee,2}$, in between 3σ, with σ = mass resolution (σ estimate from MC of dark signal processes)

K^+ INTO $\pi^+e^+e^-e^+e^-$ AT NA62

[Phys. Lett. B 846 (2023) 138193]

- **To suppress $K^+ \to \pi^+\pi^0_{DD}$**: box cut on m_{4e} and m^2_{miss} excluding the π^0 mass peak in each possible mass assignment
- Expected background from MC; MC validation from momentum excess Δp





$p_{vtx} = |(\sum_{f=1}^{5} \vec{p}_{track,f})|$

p_{beam} measured central beam momentum

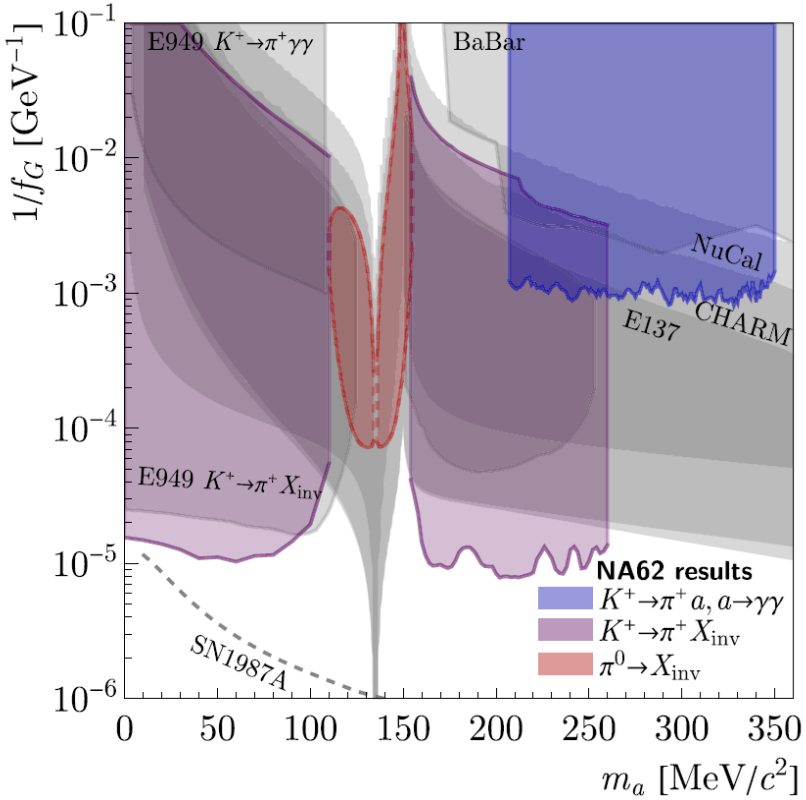
Backgrounds from 5-track and 7-track K^+ decays
(only $BR > 10^{-8}$considered)

Backgrounds from 3-track K^+ decays in coincidence with a $K^+ \to \pi^+\pi^+\pi^-$ in time
(only pairs of 3-track decays with products of $BRs > 10^{-6}$)

Source	Branching ratio (or their product)	Control region	Control region, loose selection	Signal region
Single decays				
$K_{2\pi DD}$	6.9×10^{-6}	0.06 ± 0.06	0.06 ± 0.06	–
$K^+ \to \pi^+\pi^0_D\pi^0_D$	2.4×10^{-6}	0.30 ± 0.06	2.47 ± 0.16	0.04 ± 0.02
$K^+ \to \pi^0_{DD}e^+\nu$	1.7×10^{-6}	0.10 ± 0.05	0.10 ± 0.05	–
$K^+ \to \pi^+\pi^0\pi^0_{DD}$	1.2×10^{-6}	0.03 ± 0.03	0.03 ± 0.03	–
$K^+ \to \pi^0_{DD}\mu^+\nu$	1.1×10^{-6}	0.02 ± 0.02	0.03 ± 0.02	–
$K^+ \to \pi^+\pi^0_D\pi^0_{DD}$	1.4×10^{-8}	0.05 ± 0.02	0.10 ± 0.02	0.01 ± 0.01
Coincidences with a $K^+ \to \pi^+\pi^+\pi^-$ decay				
$K^+ \to \pi^0_D e^+\nu$	3.3×10^{-5}	0.15 ± 0.07	0.15 ± 0.07	0.08 ± 0.05
$K^+ \to \pi^+\pi^0\pi^0_D$	2.3×10^{-5}	0.03 ± 0.03	0.08 ± 0.05	–
$K^+ \to \pi^0_D\mu^+\nu$	2.2×10^{-5}	0.03 ± 0.02	0.04 ± 0.02	0.05 ± 0.02
Total		0.77 ± 0.13	3.06 ± 0.21	0.18 ± 0.06
Data		1	4	0

NA62 EXCLUSION LIMITS AT 90%CL FROM K^+ DECAYS FOR ALP COUPLING TO GLUONS

- **Search for ALP coupling to gluons** (PBC scenario BC11)
  - Effective interaction: $\mathcal{L} \supset \frac{a}{f_G} G_{\mu\nu}\tilde{G}^{\mu\nu}$
- Free parameters of the model: (m_a, f_G^{-1})
- $K^+ \to \pi^+ a, a \to \gamma\gamma$ **is sensitive up to ALP lifetime** $\tau_a = 3\ ns$ $(1/f_G \sim \sqrt{\tau_a} < 1\ TeV^{-1})$
  - extension to $\tau_a \neq 0$ of the limits set for $a \to \gamma\gamma$ prompt [PLB 850 (2024) 138513]
  - search limited by the SM backgrounds
- $K^+ \to \pi^+ a_{inv}$ **is sensitive to longer lifetimes** (ALP escape the detector before decay or decays into invisible final states) JHEP06(2021)093
  - extension of the $K^+ \to \pi^+ \nu\bar{\nu}$ analysis
  - search not limited by backgrounds and profiting for larger dataset (main trigger line)
- $K^+ \to \pi^+ \pi^0(\gamma), \pi^0 \to a_{inv}$ **allows to set limits in the mass range** $110 - 155\ MeV/c^2$ [JHEP02(2021)201]



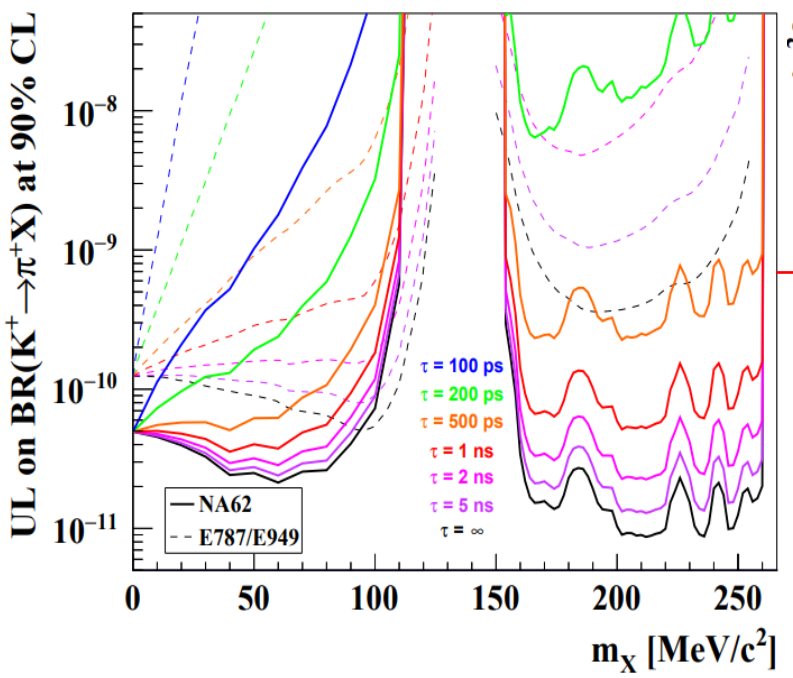
The interpretation of the results of the NA62 search for the $K^+ \to \pi^+ X_{inv}$ decay as a **Higgs mixed dark scalar long-lived** or **decaying into invisible (PBC scenario BC4)** is also reported in JHEP06(2021)093

$K^+ \to \pi^+ X$ AT NA62

[JHEP06(2021)093]

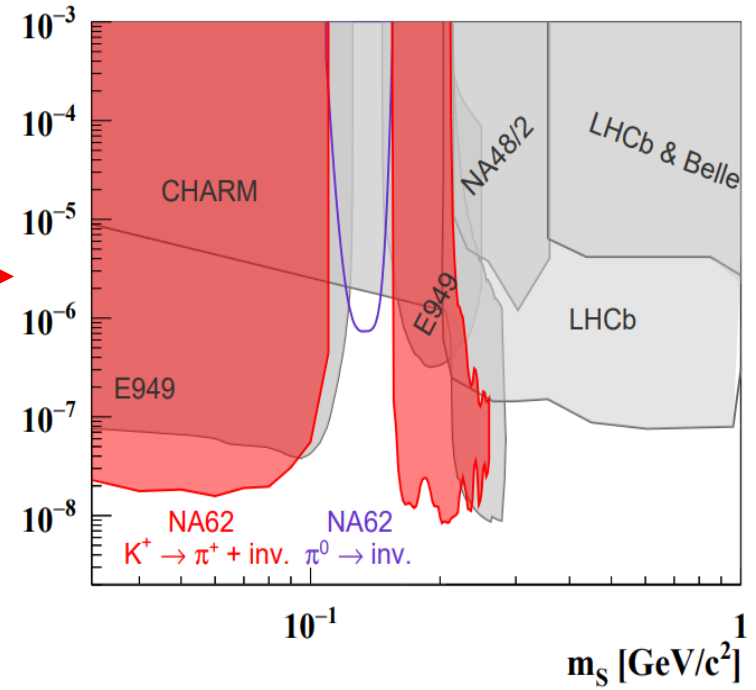
- $K^+ \to \pi^+ X$, with X = invisible new particle: dark scalar, ALP, QCD Axion … **decaying into invisible or long-lived**
- Same experimental signature as SM $K^+ \to \pi^+ \nu\bar{\nu}$
  - $K^+ \to \pi^+ X$: mainly analysis of the $K^+ \to \pi^+ \nu\bar{\nu}$ spectrum
  - Main SM bkg: $K^+ \to \pi^+ \nu\bar{\nu}$
- Whole NA62 Run1 data set analysed
- New upper limits improve on BNL-E949 [PRD79 (2009) 092004] over most of m_X accessible range

Upper Limits at 90% CL vs m_X for different lifetimes (τ)



Model-independent results for X long-lived and decaying into SM

Searches for long-lived dark scalar decaying into SM



Results interpreted in a scenario where X is a dark scalar mixing with the SM Higgs; $\sin^2\theta$ is the mixing parameter