Physics **Beyond the Standard Model**

with the

NA62 experiment at CERN

Excited QCD 2024 Benasque, January 16, 2024

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on behalf of the NA62 collaboration

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outline

the NA62 experiment – layout in standard mode

latest update on $K^+ \to \pi^+ \nu\bar{\nu}$ ⇒ implications to NP

search for **non-SM** $K^+ \to \pi^+ e^+ e^+ e^- e^-$ ⇒ axion, dark scalar, dark photon

search for **LFV/LNV** $K^+ \to \mu^- \nu e^+ e^+$

the NA62 beam-dump mode

search for dark photon through $A' \to \mu^+ \mu^-$

NA62

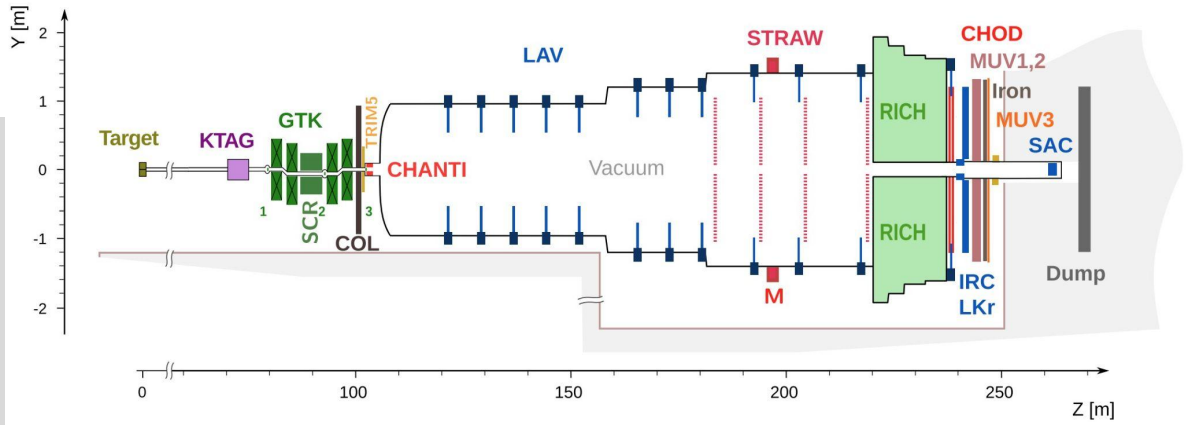
high-intensity unseparated hadron beam from CERN SPS protons (400 GeV/*c*, ~2 × 10^{12} *p*/spill) on a target ⇒ K^+ (~75 GeV/*c*) into an instrumented **decay tunnel in vacuum**

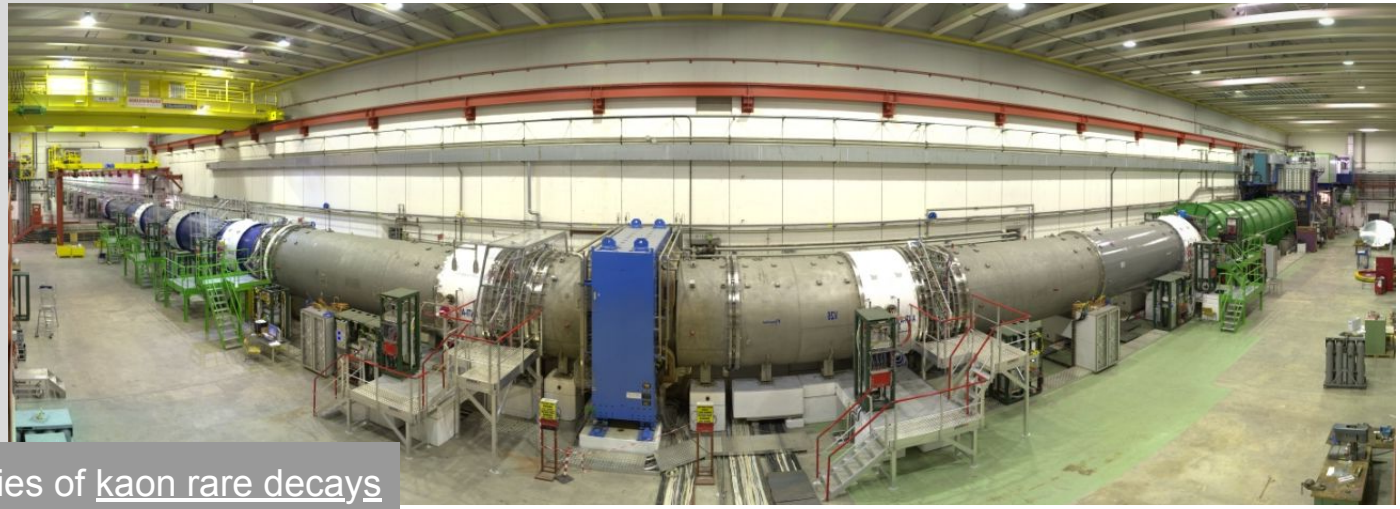
high-res timing *O*(100 ps) for upstream-downstream particle matching in a high-rate environment

powerful PID – *K*, π, μ, *e*, photons

reconstruction of the full kinematics of all charged particles and photons

efficient and hermetic **photon veto**





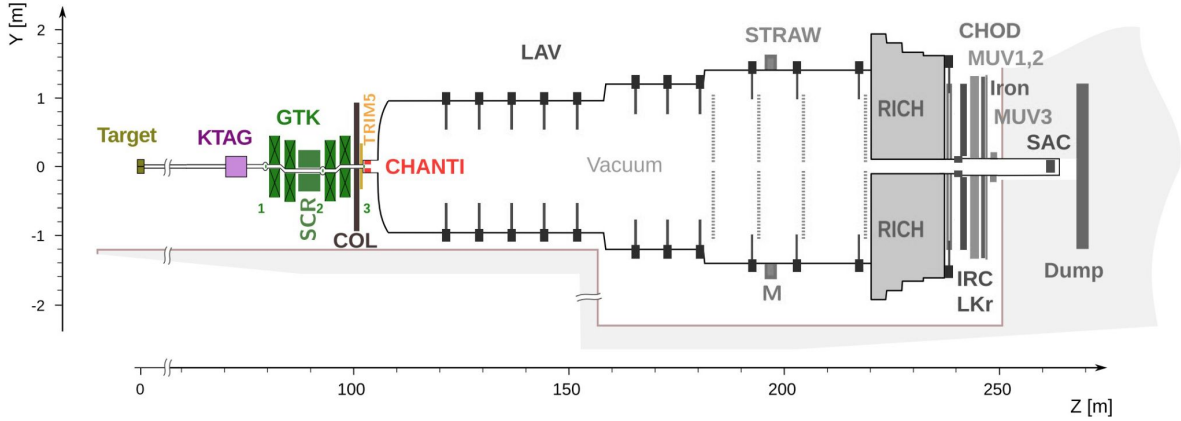
⇒ studies of kaon rare decays

NA62 **upstream stage**

KTAG

CEDAR-H for K^+ selection

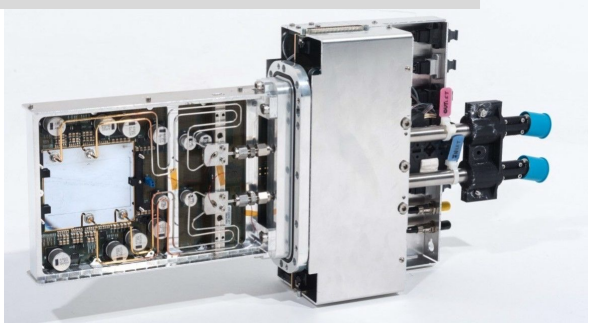
$\sigma_t \sim 70$ ps, eff > 99%

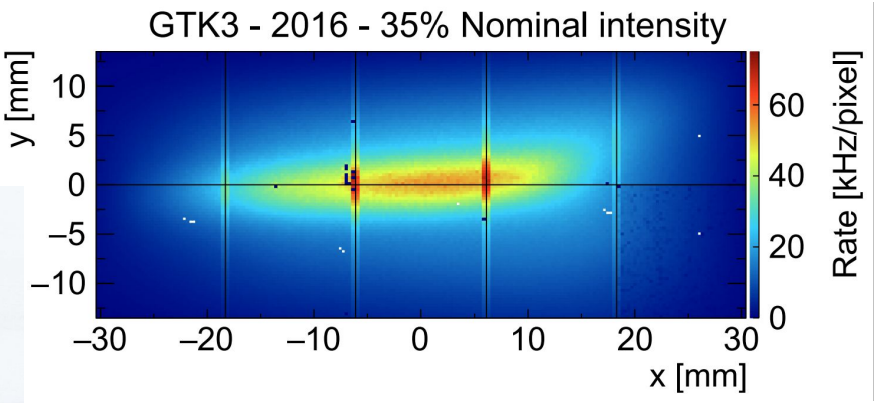


GigaTracKer

4 Si pixel detectors for tracking and high-res momentum measurement with an achromat

$\sigma_t \sim 100$ ps, $\sigma_\theta \sim 16$ μrad, $\Delta p/p \sim 0.2\%$



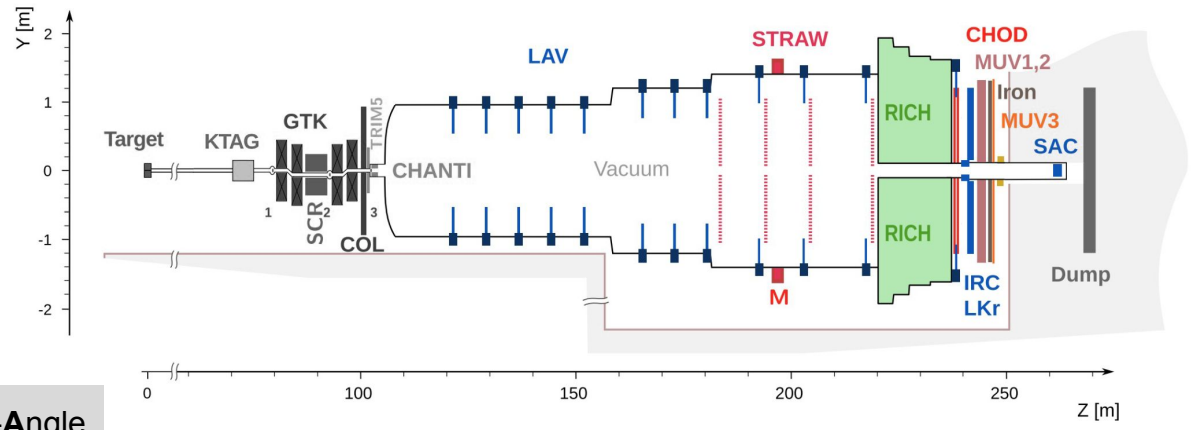


JINST 12 (2017) P05025

NA62 FV & downstream stage

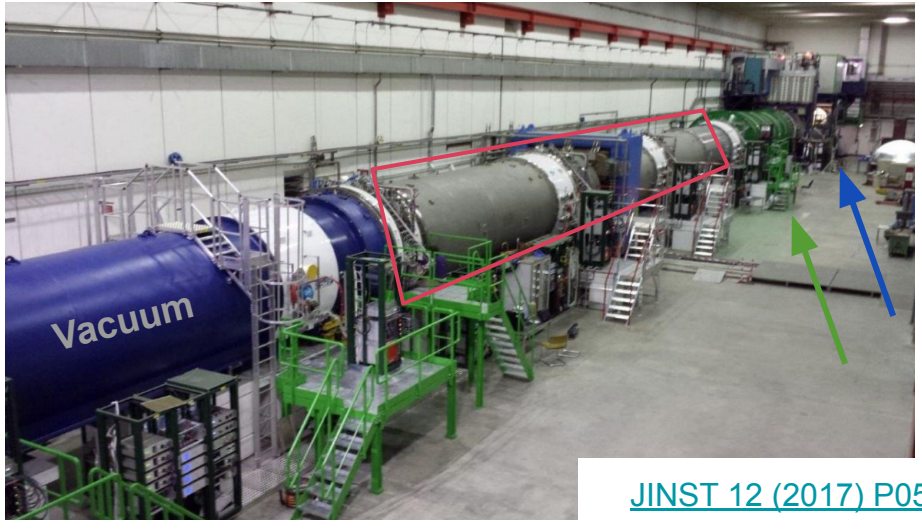
spectrometer

4 (*x*, *y*, *u*, *v*) STRAW stations around a horizontal bending magnet + downstream **C**harged-particle **HOD**oscopes
⇒ output tracking and momentum reconstruction
$\sigma_x \sim 130$ μm, $\Delta p/p \sim 0.3\% + 0.005\% p$



photon veto/calorimeters

Large-**A**ngle **V**eto (lead glass arrays) all around the fiducial volume (up to 50 mrad) + electromagnetic calorimeters at the rear end (below 8.5 mrad):
Liquid **Kr**ipton
Intermediate-**R**ing **C**alorimeter
Small-**A**ngle **C**alorimeter
10^8 π^0 suppression



RICH muon system

for output-state PID
overall ~10^7 μ suppression
in the RICH: ~10^{-2} μ/π separation, ring σ_t < 100 ps

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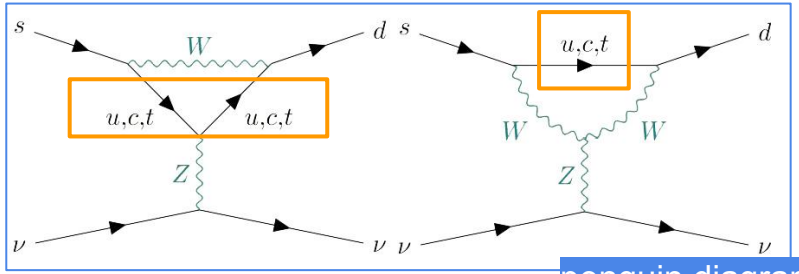
$K^+ \to \pi^+ \nu\bar{\nu}$



penguin diagrams

FCNC: forbidden at tree level ⇒ only proceeds through penguin and box diagrams, highly sensitive to the CKM structure

quadratic GIM mechanism

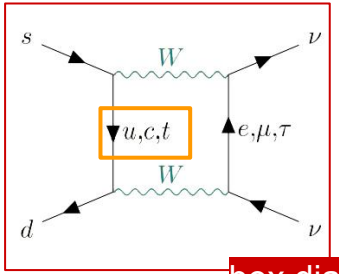
hierarchy of CKM elements

→ very rare!

heaviest contribution from the *t*, i.e. short-distance

K-π form factors determined with sub-% precision from the K_{e3} observations through SU(2) isospin symmetry

→ clean SM prediction



box diagram

highly sensitive to new flavour physics through

- clean deviations between observations and SM
- CP violation (together with the neutral counterpart $K_L \to \pi^0 \nu\bar{\nu}$)
- lepton flavour non-universality
- constraining leptoquark models
- …

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

arXiv:2109.11032

$BR_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (7.86 \pm 0.61) \times 10^{-11}$

JHEP 09 (2022) 148

$BR_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (7.73 \pm 0.61) \times 10^{-11}$

arXiv:2105.02868

$K^+ \to \pi^+ \nu\bar{\nu}$ at NA62 **strategy**

full-Run1 (2016-2018) dataset

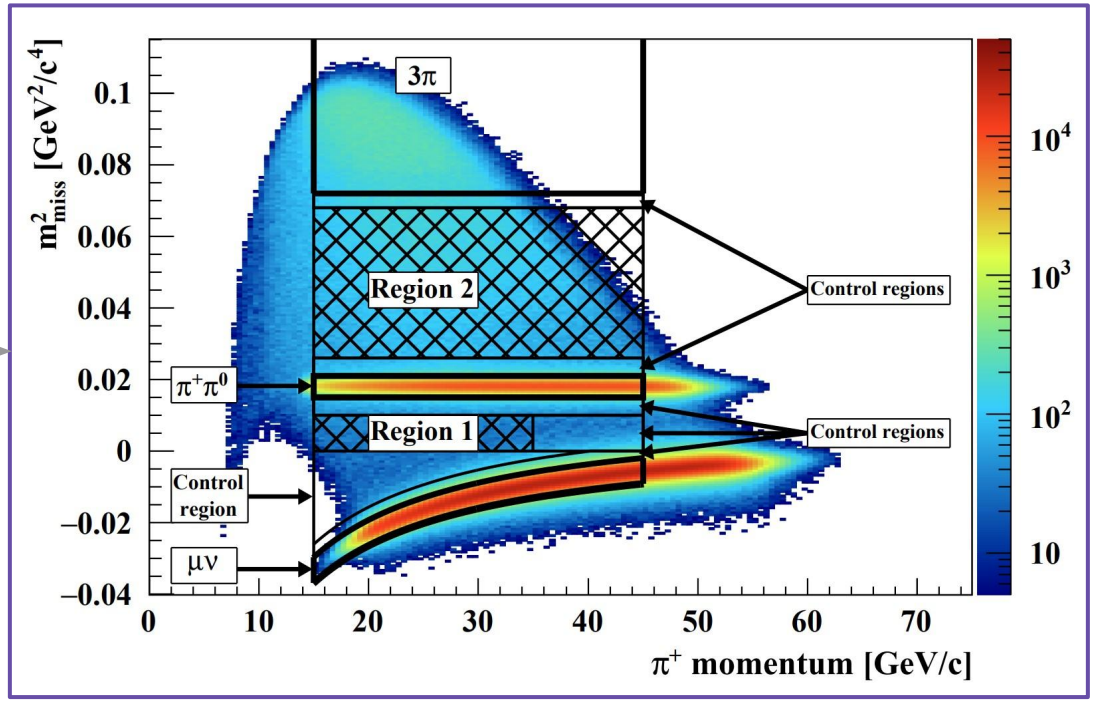
search for a single output π^+ (mass hypothesis) matching an input K^+ with vertex inside the FV, fully detected charged-particle energy and some missing momentum

selection variables:

- **pion momentum**
- missing invariant mass $m_{miss}^2 = (P_K - P_\pi)^2$

⇒ different phase-space regions for

- signal (Region 1 and Region 2)
- normalisation channel, i.e. $K^+ \to \pi^+\pi^0$ (collected with dedicated trigger mask)
- control of the main background channels



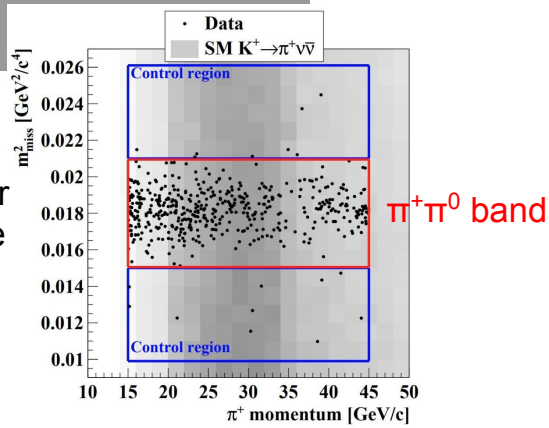
JHEP 06 (2021) 093

$K^+ \to \pi^+\nu\bar{\nu}$ at NA62 **strategy**

main background contributions:

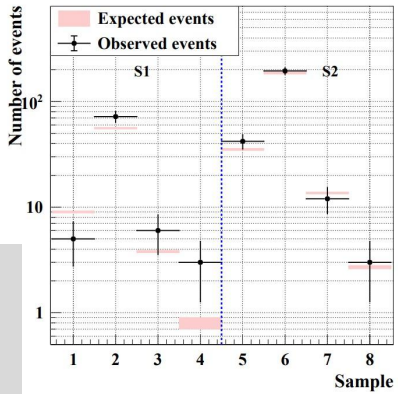
$K^+ \to \pi^+\pi^0$

evaluated from data collected with minimum-bias trigger in a dedicated phase space region ($\pi^+\pi^0$ band)



$K^+ \to \pi^+\pi^-e^+\nu$

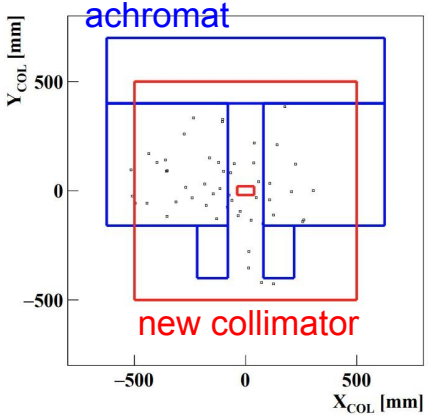
only affects Region 2; evaluated with MC only

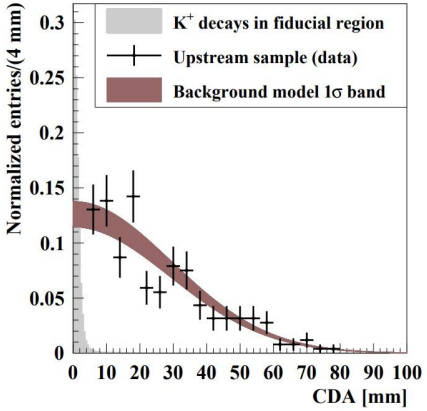


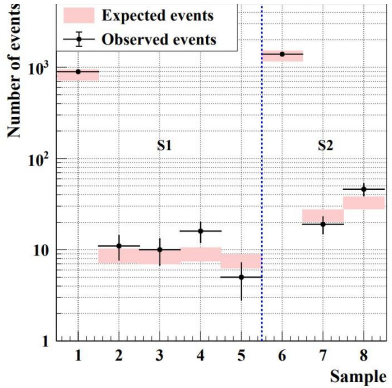
S1 (S2): before (after) upstream collimator replacement, i.e. 20% (80%) of 2018 data

upstream background

pions from interactions between GTK2 and 3 or in the beamline; evaluated from a dedicated data sample







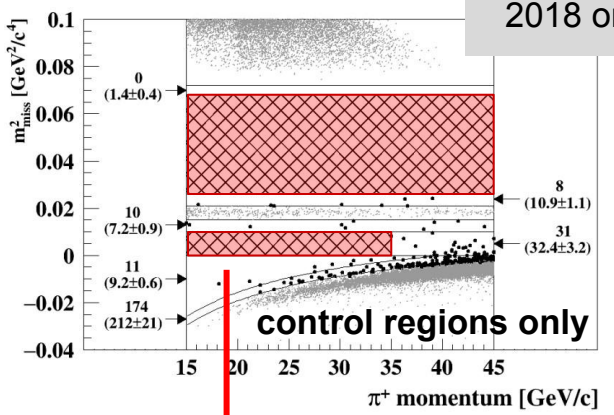
$K^+ \to \pi^+\pi^+\pi^-$

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

evaluated from data collected with minimum-bias trigger in dedicated phase space regions (3π, $\mu\nu$)

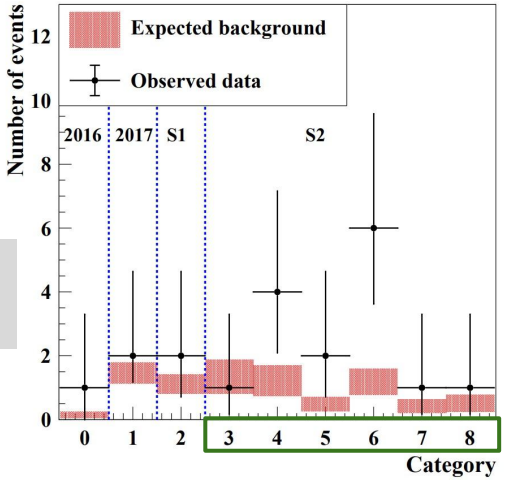
JHEP 06 (2021) 093

$K^+ \to \pi^+ \nu\bar{\nu}$ at NA62 **results**

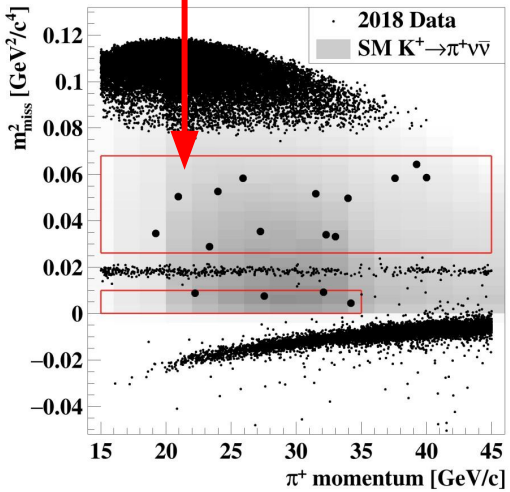


2018 only

full-Run1 (2016-2018)



different output momentum bins



N^{meas} matches N^{exp} in all the control regions

overall $\boldsymbol{N^{exp}}$ **= 10.01** ± 0.42_{syst} ± 1.19_{ext} (sig) **+ 7.03** (+1.05, –0.82) (bkg)

overall $\boldsymbol{N^{meas}}$ **= 20** (+17 in 2018 only)

- from background-only hypothesis test: **3.4 sigma** significance
- $\mathbf{BR_{meas}(K^+ \to \pi^+ \nu\bar{\nu}) = [10.6\ (+4.0, -3.4)_{stat} \pm 0.9_{syst}] \times 10^{-11}}$ at 68% CL
- most precise measurement to date!

JHEP 06 (2021) 093

$K^+ \to \pi^+ \nu\bar{\nu}$ & $K^+ \to \pi^+ X$

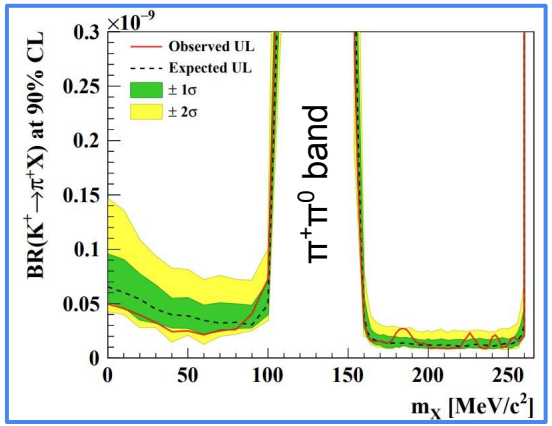
search for ***X* dark scalar/pseudo-scalar** that

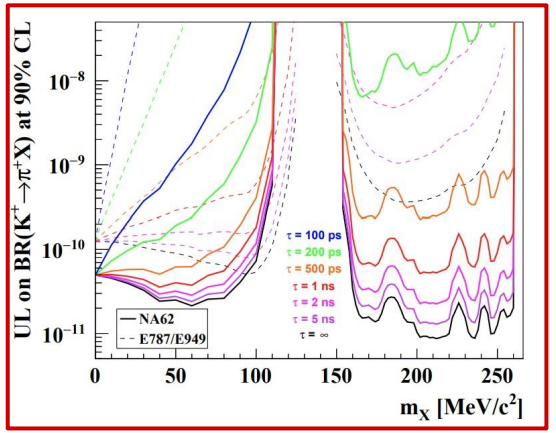
- is stable or only decays into other dark (i.e. invisible) particles
- lives long enough to decay (into SM particles) outside the detector volume

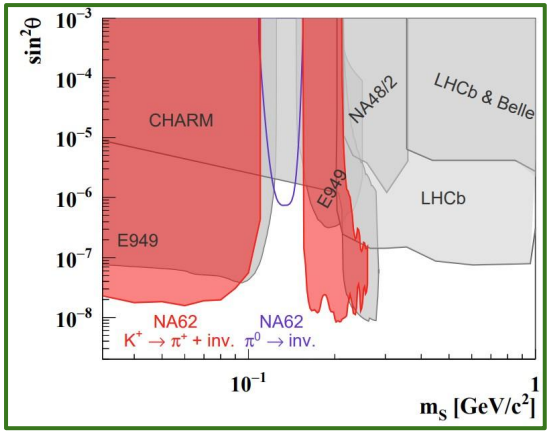
background sources: same as $K^+ \to \pi^+ \nu\bar{\nu}$, but here the latter is a (dominant) source of background as well

background-only hypothesis test ⇒ ULs

specific case of *X* = *S* dark scalar which mixes with the Higgs via $\sin^2\theta$ (inversely proportional to the scalar lifetime)







JHEP 06 (2021) 093

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

first experimental observation to date

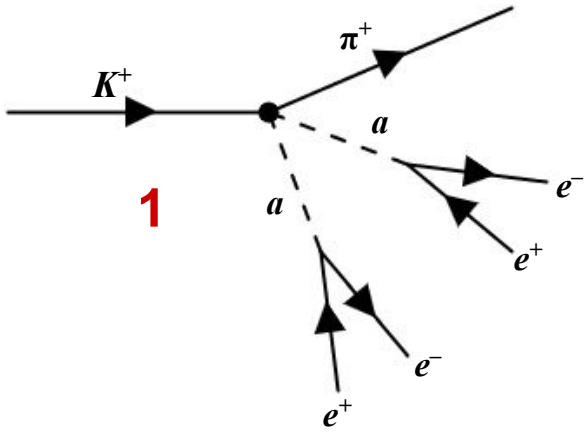
process exists in SM, both in

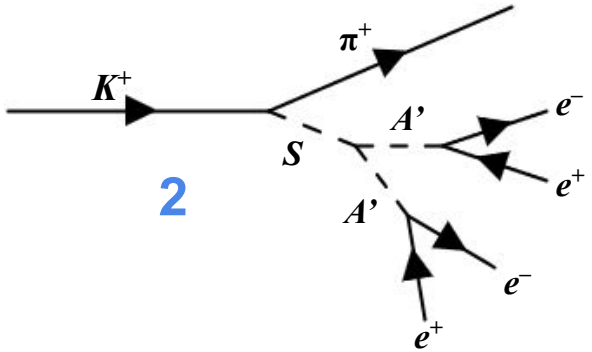
- resonant ($\mathbf{K_{2\pi DD}}$ – π^0 pole) and
- non-resonant ($\mathbf{K_{\pi 4e}}$ – through channels with photons)

mode ⇒ BSM component proceeds through production of multiple dark-sector particles off-pole

⇒ two decay chains involving

1. the emission of two *a* (dark axion) followed by $a \to e^+e^-$
2. the pair production *S* (dark scalar) → 2*A*' (dark photons) foll by $A' \to e^+e^-$





$K^+ \to \pi^+ e^+ e^+ e^- e^-$ strategy

signal: off-pole $K_{\pi 4e}$
normalisation: $K_{2\pi DD}$

high charged particles multiplicity in output stage ⇒ reconstruction based entirely on STRAW in order to maximise acceptance, no PID detectors:

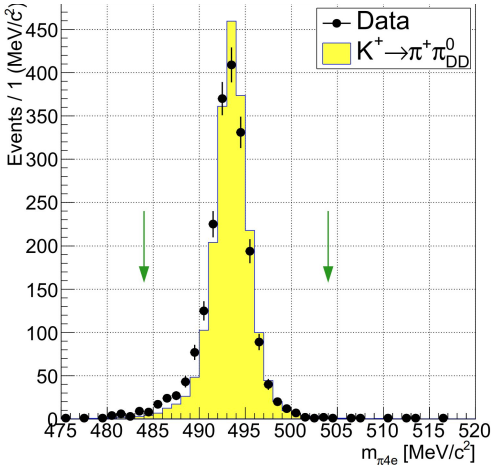
3 positive-charge tracks + 2 negative-charge tracks ⇒ assume the pion mass for the each positive-charge track and select the assumption leading to minimum $|m_{\pi 4e} - m_K|$

phase space restricted to $m_{\pi 4e}$ in (484, 504) MeV/c

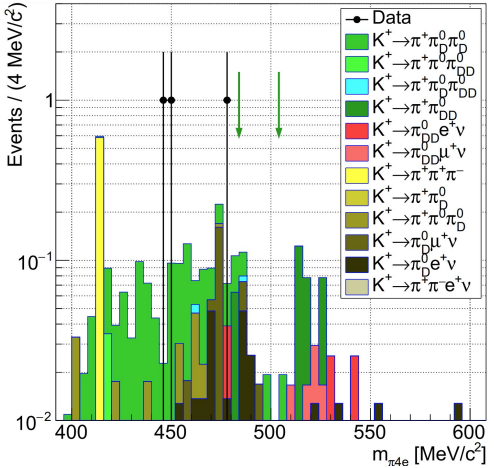
selection variables:

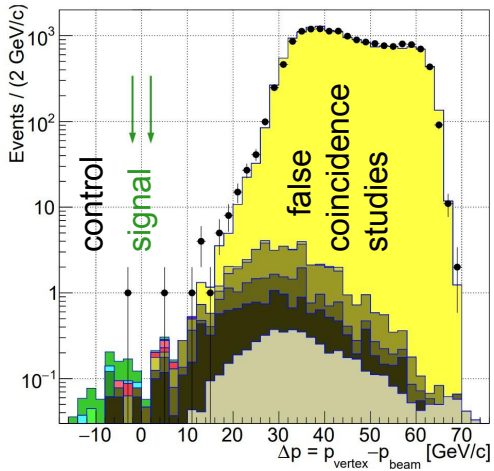
- $|m_{4e} - m_{\pi 0}| > 10$ MeV/c ⇒ to go off pole (opposite for normalisation selection)
- $m_{miss}{}^2 > 0$ and $|m_{miss} - m_{\pi 0}| > 40$ MeV/c ⇒ production of intermediate dark states
- $p_\pi > 10$ GeV/c ⇒ to suppress $K^+ \to \pi^+ \pi^0_D \pi^0_D$
- $\Delta p = p_{vertex} - p_{beam}$ ⇒ to distinguish background characterisation, signal ($|\Delta p| < 2$ MeV/c) and control regions
- minimum $D = (m_{ee1} - m_{ee2})^2/(4.9 \times 10^{-3}\, m_{ee})^2$ among all e^+e^- pairs, where $m_{ee} = (m_{ee1} + m_{ee2})/2$ ⇒ selection of exotic candidates in general

normalisation selection



signal selection

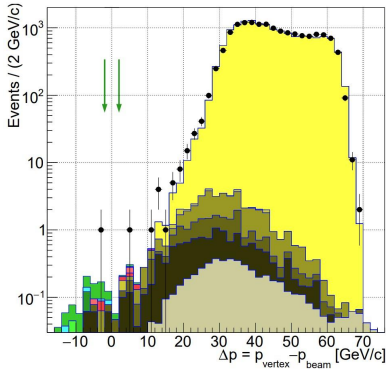




PLB 864 (2023) 138193

2017-2018 dataset

$K^+ \to \pi^+ e^+ e^+ e^- e^-$ results



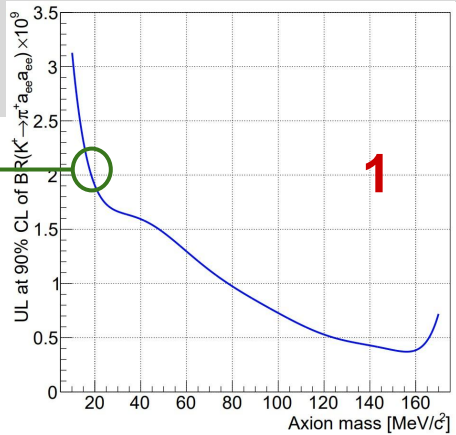
Source	Branching ratio (or their product)	Control region	Control region, loose selection	Signal region
Single decays				
$K_{2\pi DD}$	6.9×10^{-6}	0.06 ± 0.06	0.06 ± 0.06	–
$K^+ \to \pi^+ \pi^0_D \pi^0_D$	2.4×10^{-6}	0.30 ± 0.06	2.47 ± 0.16	0.04 ± 0.02
$K^+ \to \pi^0_{DD} e^+ \nu$	1.7×10^{-6}	0.10 ± 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

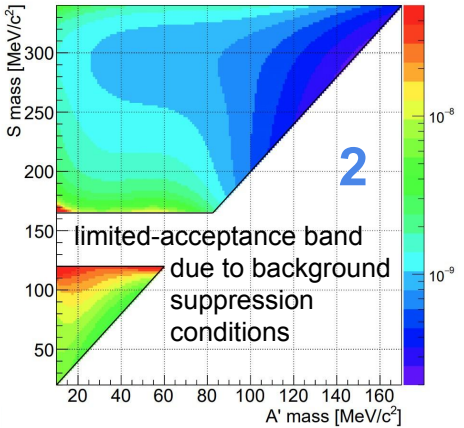
constraint on p_π lifted

specific exotic model *X*:

$|m_{ee} - m_X| < 0.02 m_X$

exclusion of the QCD axion explanation for the 17 MeV anomaly



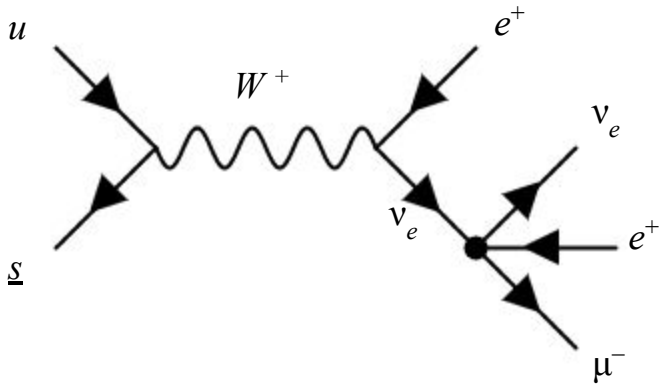


PLB 864 (2023) 138193

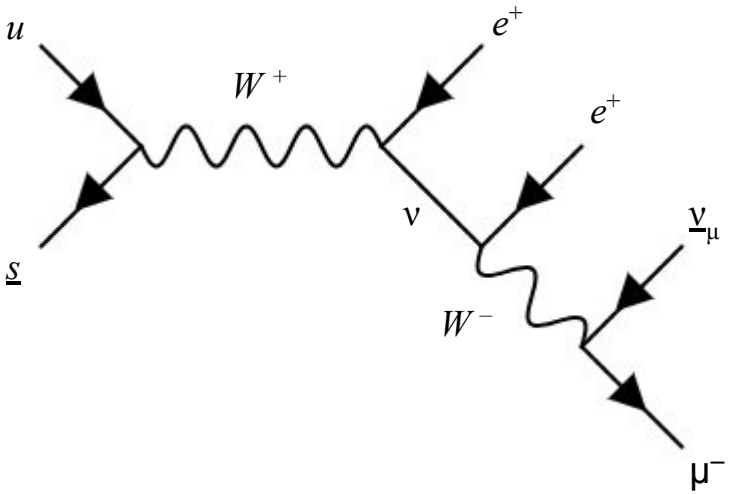
$K^+ \to \mu^- \nu e^+ e^+$

either LFV or LNV+LFV, depending on neutrino flavour and lepton number sign

e.g.: L=0, L_e=-1, L_μ=1



e.g.: L=-2, L_e=-2, L_μ=0



forbidden in the SM

most precise limit to date: 2.1×10^{-8} 90% CL
PLB 62 (1976) 485

LFV	Majorana nature of the neutrino
LNV+LFV	NP indirect search (ALP, Z')

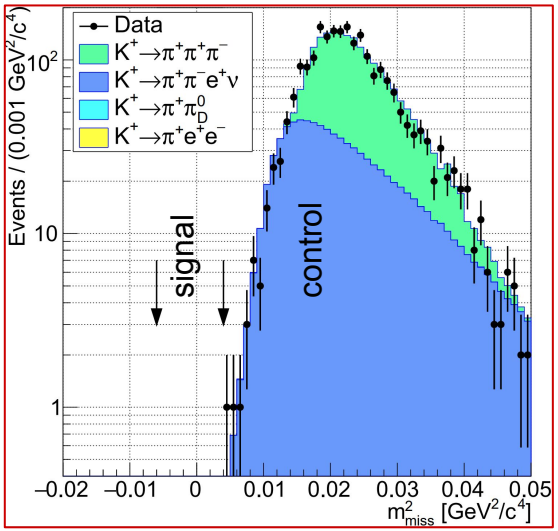
$K^+ \to \mu^- \nu e^+ e^+$ strategy

full-Run1
(2016-2018) dataset

- 3 on-time tracks in STRAW with total charge +1 and momenta in (6, 44) GeV/*c*
- PID based on ratio between *E* (from LKr) and *p* (from spectrometer)

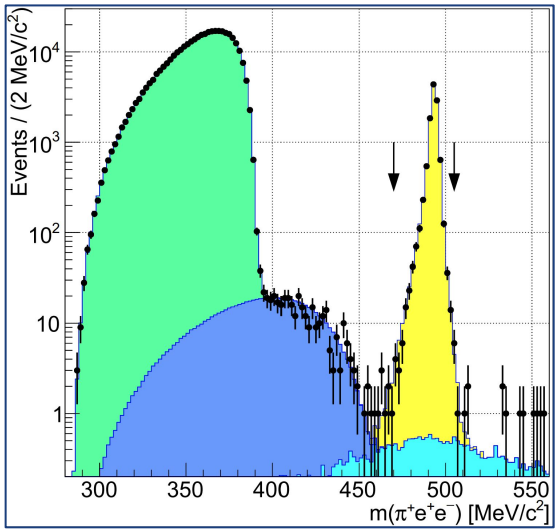
signal specific

- $\Delta p < -10$ GeV/*c*
- vertex at least 3 m into the FV
- no off-track high-energy clusters in LKr



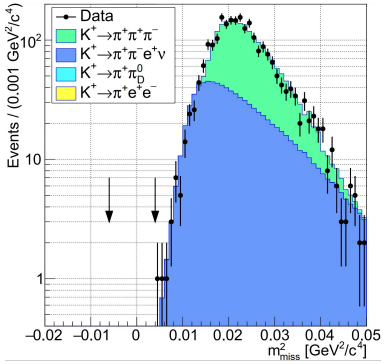
normalisation ($K^+ \to \pi^+e^+e^-$) specific

- $|\Delta p| < 2$ GeV/*c*
- total $p_T < 30$ MeV/*c*
- $m_{ee} > 140$ MeV/c^2



PLB 838 (2023) 137679

$K^+ \to \mu^- \nu e^+ e^+$ results



m^2_{miss} regions

Signal is in (-0.006, 0.004) GeV^2/c^4

Mode / Region	Lower	Signal	Upper
$K^+ \to \pi^+\pi^+\pi^-$	< 0.07	< 0.07	1412 ± 11
$K^+ \to \pi^+\pi^-e^+\nu$	0.01 ± 0.01	0.16 ± 0.02	867 ± 1
$K^+ \to \pi^+\pi^+\pi^-$ (upstream)	< 0.03	0.06 ± 0.03	1.5 ± 0.3
$K^+ \to \pi^+\pi^-e^+\nu$ (upstream)	0.01 ± 0.01	0.01 ± 0.01	0.14 ± 0.03
$K^+ \to \pi^0_D e^+\nu$	0.02 ± 0.01	0.01 ± 0.01	0.02 ± 0.01
$K^+ \to e^+\nu\mu^+\mu^-$	< 0.01	< 0.01	0.05 ± 0.02
Total expected	0.04 ± 0.02	0.26 ± 0.04	2281 ± 11
Data	0	0	2271

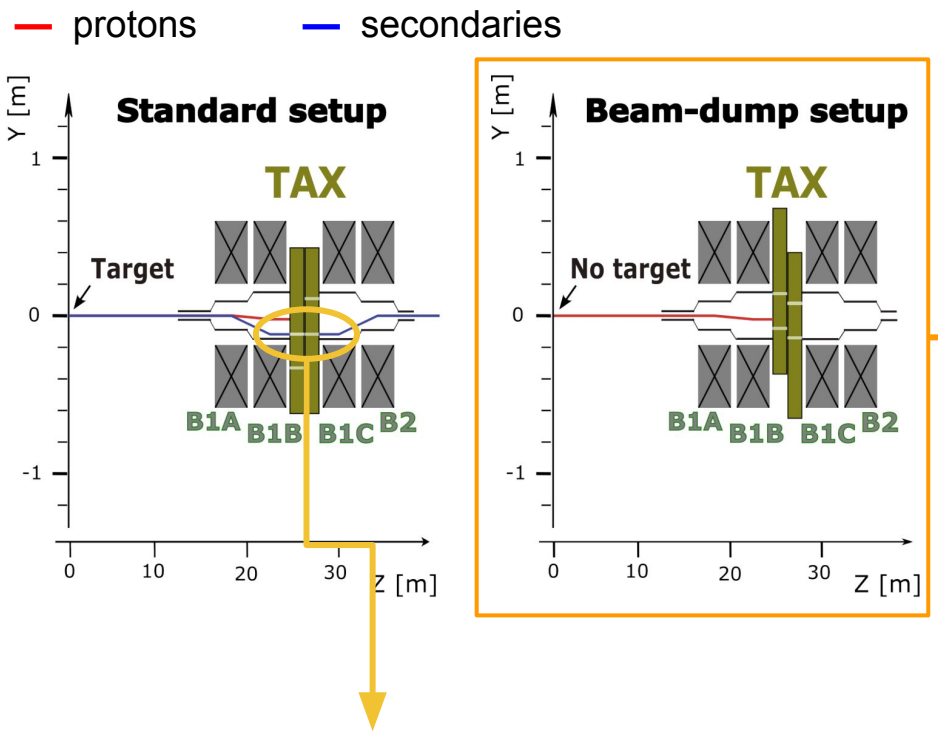
- no events observed in the signal region
- BR estimate depends on the phase space distribution in the signal region ⇒ assumed to be uniform
- $\underline{BR_{new}(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11}}$ 90% CL, i.e. 250 times better than previous result
- sensitivity is not sufficient to constrain models involving Majorana neutrinos and LFV NP

PLB 838 (2023) 137679

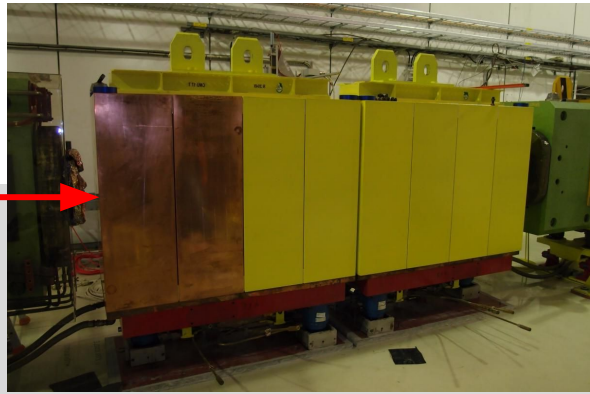
more on LFV/LNV at NA62

Channel	BR UL (90% CL)	Sample	Reference
$K^+ \to \pi^-\mu^+\mu^+$	4.2×10^{-11}	17AB	PLB 797 (2019) 134794
$K^+ \to \pi^-\mu^+e^+$	4.2×10^{-11}	Run1 (2017–2018)	PRL 127 (2021) 13, 131802
$K^+ \to \pi^+\mu^-e^+$	6.6×10^{-11}	Run1 (2017–2018)	PRL 127 (2021) 13, 131802
$\pi^0 \to \mu^-e^+$	3.2×10^{-10}	Run1 (2017–2018)	PRL 127 (2021) 13, 131802
$K^+ \to \pi^-e^+e^+$	5.3×10^{-11}	Run1	PLB 830 (2022) 137172
$K^+ \to \pi^-\pi^0e^+e^+$	8.5×10^{-10}	Run1	PLB 830 (2022) 137172

NA62 **beam-dump mode**



holes in TAXes properly aligned for 75 GeV/*c* ± 1%



K12 beamline Be target (T10) is removed

holes in TAXes are misaligned

⇒ SPS 400-GeV primary protons are dumped into 800 mm Cu + 2400 mm Fe

also, surrounding achromat (B1C, B2) set to the same polarity for muon halo elimination

⇒ only neutrinos and neutral exotic particles can propagate into the experiment

primary beam at 170% the standard mode intensity

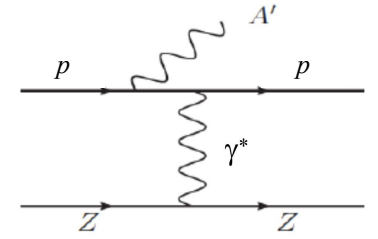
$A' \rightarrow \mu^+\mu^-$

$M_{A'}$ mass
ε ($\ll 1$) coupling constant

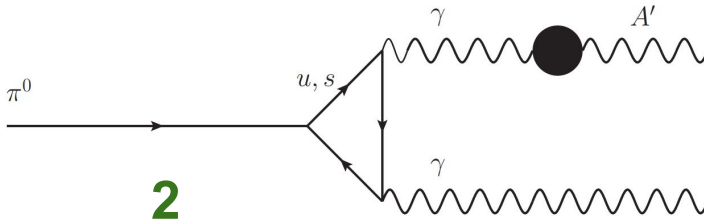
dark photons in the dump, from
1. p-bremsstrahlung
2. non-SM meson decays

for ε in (10^{-7}, 10^{-5}) and $M_{A'}$ in the MeV/c^2-to-GeV/c^2 range, the decay length when $p_{A'} > 10$ GeV/c ranges between O(10 m) and O(10 km)

if $M_{A'} \lesssim 700$ MeV/c^2 the main decay channels are those into (SM) di-lepton states $\Rightarrow \mu^+\mu^-$



1



2

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

~10 dedicated days of data taking in 2021

tracking with STRAW

PID based on LKr, MUV1-2 (hadronic calorimeters) and MUV3

RICH is not used

CHOD provides time reference

external interactions suppressed by the photon veto

signal search:

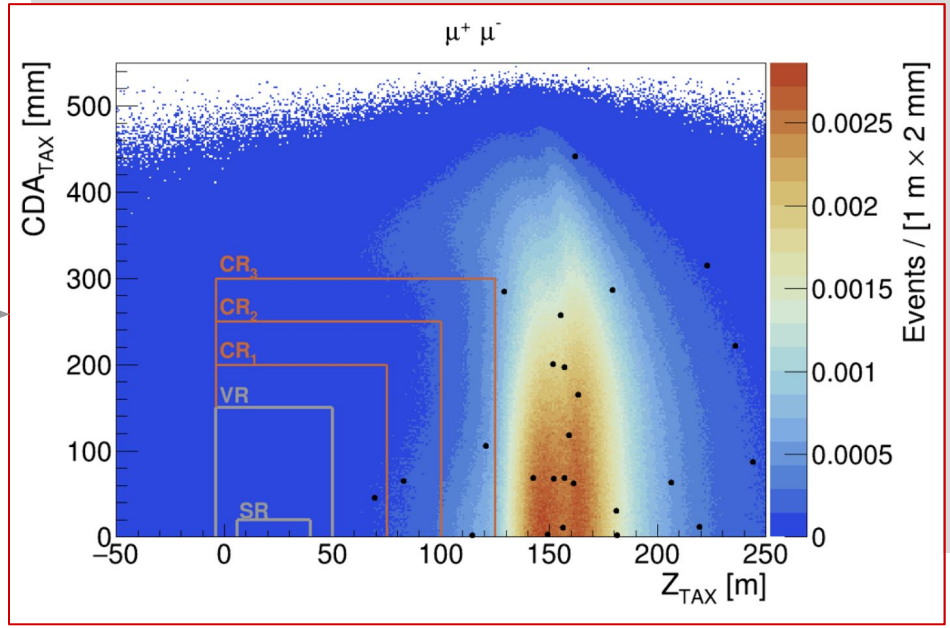
- 2 muon tracks in STRAW, with on-time signals in CHOD
- good vertex between the 2 tracks and the primary beam nominal path

selection variables:

- $\boldsymbol{Z_{TAX}}$ longitudinal position in the dump
- $\boldsymbol{CDA_{TAX}}$ distance of closest approach between the output tracks and the beam path

background:

- prompt (on-time) background: pairs of leptons ($\mu\mu$, ee, μe) from secondary interactions of muons within the traversed material ⇒ negligible!
- combinatorial background: all combinations of μ and e from different interactions



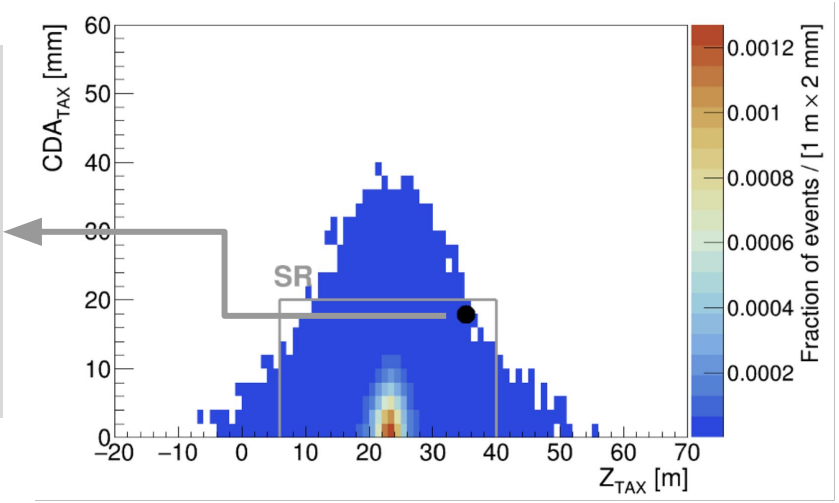
JHEP 09 (2023) 035

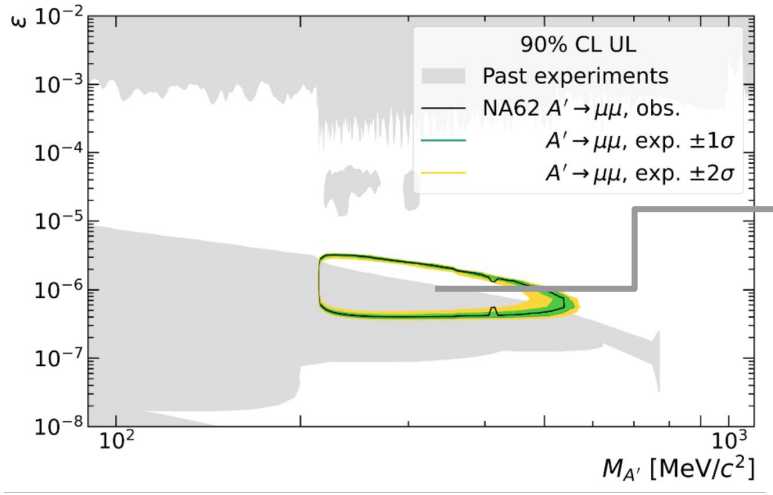
$A' \to \mu^+\mu^-$ results

0 events in the validation region (VR) surrounding the signal region (SR)

1 event in the SR with 2-track invariant mass 411 MeV/c^2

- ↘ 2.4-sigma significance
- ↘ at the edge of SR
- ↘ 2-track time difference is at 2 STDs from the mean
- ↘ might be combinatorial background





solid line: region excluded at 90% CL
+ uncertainty in absence of signal event with **1-sigma** and **2-sigma** statistical coverage

also, the ALP interpretation $a \to \mu^+\mu^-$ was considered: previous limits have been improved for $M_a < 280$ MeV/c^2

JHEP 09 (2023) 035

in conclusion

$K^+ \to \pi^+ \nu\bar{\nu}$

- ↘ best BR measurement to date
- ↘ improved constraint to $K^+ \to \pi^+ X$ (dark scalar/pseudo-scalar)
- ↘ aiming at intensity increase and detector performance improvement
  ⇒ goal: 15% precision by the end of Run2
- ↘ towards HIKE Phase 1…

non-SM **$K^+ \to \pi^+ e^+ e^+ e^- e^-$**

- ↘ first measurement ⇒ new constraints to dark axion and dark scalar + dark photon models

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

- ↘ improved upper limit

dump-mode **$A' \to \mu^+ \mu^-$**

- ↘ limits extended
- ↘ 1 event in the signal region, close to the edge
- ↘ improved constraint to the $a \to \mu^+ \mu^-$ as well

High **I**ntensity **K**aon **E**xperiments

a multi-phase, general purpose kaon experiment to extend the NA62 physics program at the CERN SPS into the HL-LHC era and beyond

Phase 1 (K^+) and Phase 2 (K_L)

$K^+ \to \pi^+ \nu\bar{\nu}$ to 5%
LFV/LNV
rare decays
precision measurements
dump-mode searches …

thank you!

any comments or questions? contact me at *mattia.soldani@lnf.infn.it*!

trigger masks

PNN (main)

L0
- 1 charged particle in RICH
- 1-to-4 hits in CHOD
- no hits in MUV3
- <2 clusters in LKr with <30 GeV

L1
- 1 kaon in KTAG
- 1+ tracks in STRAW
- <2 hits in LAV

dedicated CHOD-based **minimum bias** (downscaled by 400) for the PNN normalisation

MT (downscaled by 100)
- 3 tracks in STRAW
- RICH and CHOD conditions in L0
- KTAG conditions in L1

***e*MT** (downscaled by 8)
- MT
- 20+ GeV in LKr

μMT (downscaled by 8)
- MT
- 10+ GeV in LKr
- 1+ hit in MUV3 outer tiles

trigger masks

in dump mode

H2	2 in-time hits in CHOD
Q1	1 hit in CHOD (downscaled by 20)
Control	1 cluster in LKr

$K^+ \to \pi^+ \nu\bar{\nu}$ Single Event Sensitivity

$$SES = \frac{\mathrm{BR}(K^+ \to \pi^+\pi^0) \cdot A_{\pi\pi}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\bar{\nu}} \cdot \epsilon_{\mathrm{RV}} \cdot \epsilon_{\mathrm{trig}}^{\mathrm{PNN}}}$$

2018 only

	Subset S1	Subset S2
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^{2}$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^{2}$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon_{\mathrm{trig}}^{\mathrm{PNN}}$	0.89 ± 0.05	0.89 ± 0.05
ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
$N_{\pi\nu\bar{\nu}}^{\mathrm{exp}}$	$1.56 \pm 0.10 \pm 0.19_{\mathrm{ext}}$	$6.02 \pm 0.39 \pm 0.72_{\mathrm{ext}}$

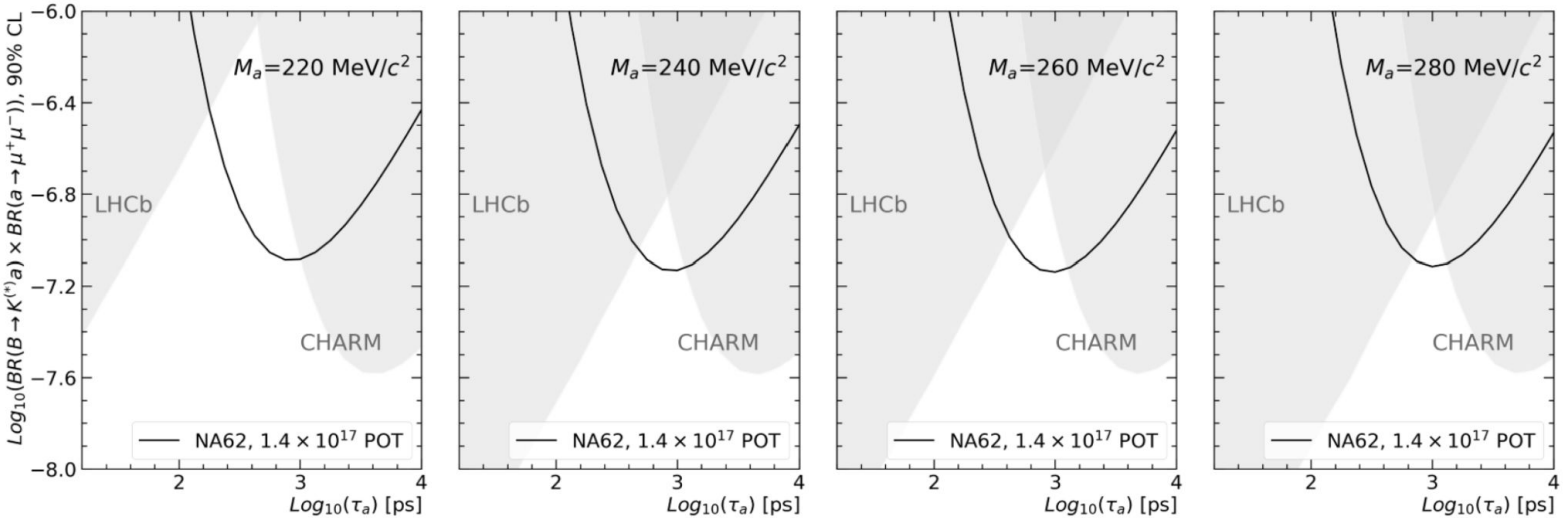
full-Run1 (2016-2018)

$$SES = (0.839 \pm 0.053_{\mathrm{syst}}) \times 10^{-11}$$

$K^+ \to \pi^+ \nu\bar{\nu}$ 2018 background estimates

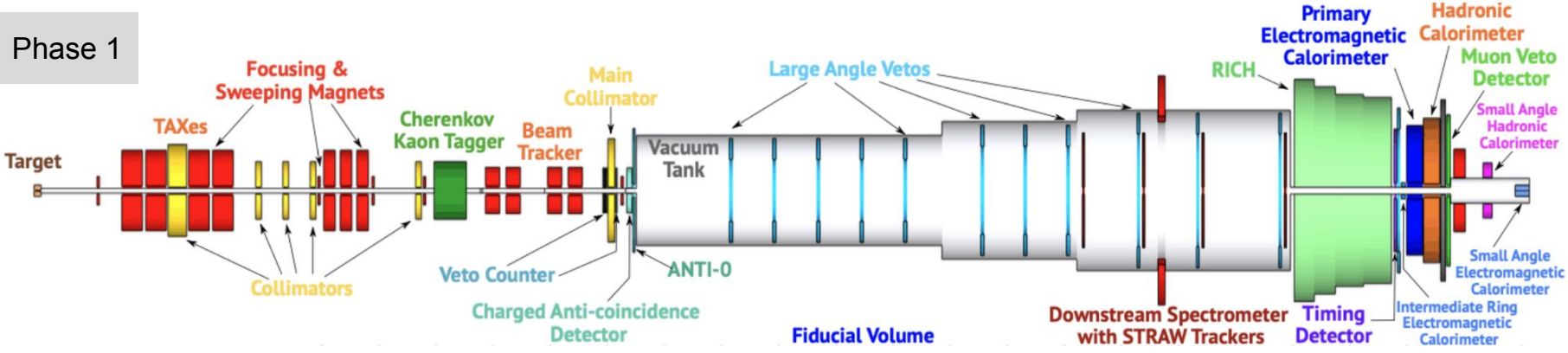
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

$a \to \mu^+\mu^-$ from dump-mode data



HIKE layout

Phase 1



Phase 2