Latest results from the NA62 Experiment @CERN

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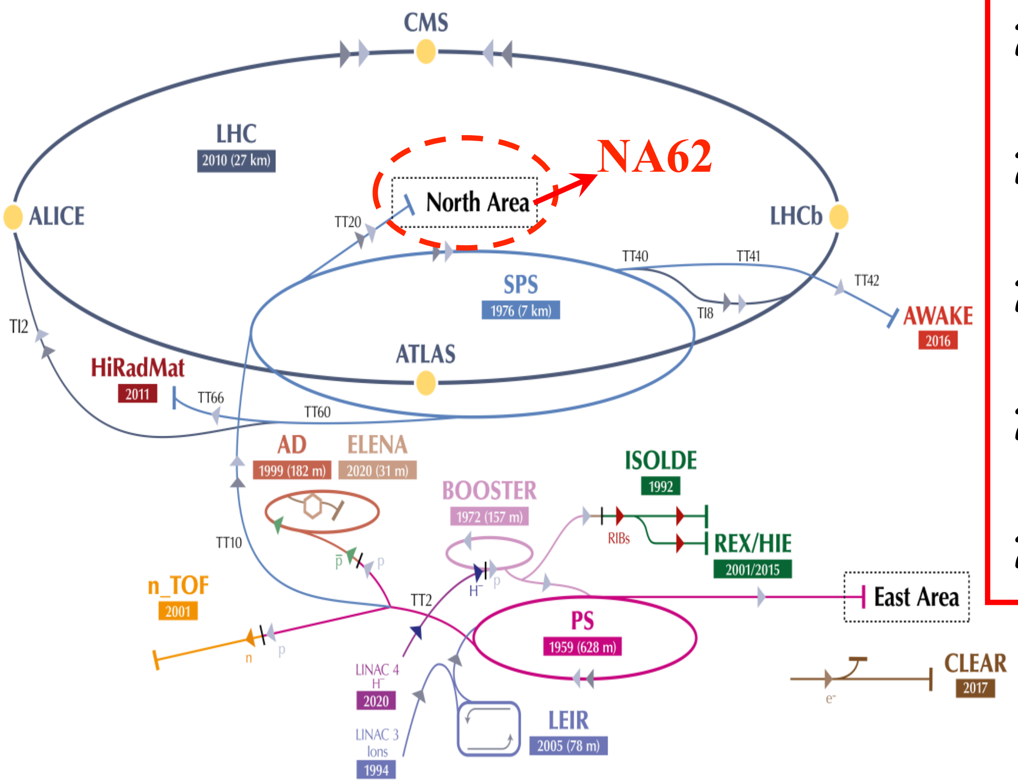
on behalf of NA62 Collaboration

BLOIS 2024

35th Rencontres de Blois on Particle Physics and Cosmology

Blois 20th – 25th October 2024

NA62 Experiment



2009-2014 Detector R&D
Installation
2015 Pilot run and commissioning

2016–2018 NA62 Physics Run 1

2019-2020 CERN Long Shutdown 2 (LS2)

2021-LS3 NA62 Physics Run 2

Data taking is currently ongoing

Currently ~300 participants from ~30 institutions

- Multi purpose high-intensity Kaon experiment
- Broad physics programme in kaon and pion sectors
- **Primary goal**: precision measurement of $\mathbf{BR}(K^+ \to \pi^+ \nu\bar{\nu})$

This talk

!!! New Results
F. Brizioli talk at Plenary Flavor session !!!

NA62 Broad Physics Programme

Kaon Beam Mode

400 GeV/c SPS proton beam on target

Dump Beam Mode

400 GeV/c SPS proton beam on dump module

Flavor Physics

- Low energy **QCD tests**
- Precise tests of **lepton flavor universality, lepton number and flavor violation**
- First row **CKM unitarity**
- **New Physics** searches at the EW scale with sizeable coupling to SM particles **via indirect effects in loops**

Hidden Sector

- **New Physics** searches below the EW scales (MeV-GeV range) feebly-coupled to SM particles **via direct detection of long-lived particles**
- Dark Photon (DP), Axion Like Particle (ALP), Dark Scalar (S), Heavy Neutral Lepton (N)

Outline

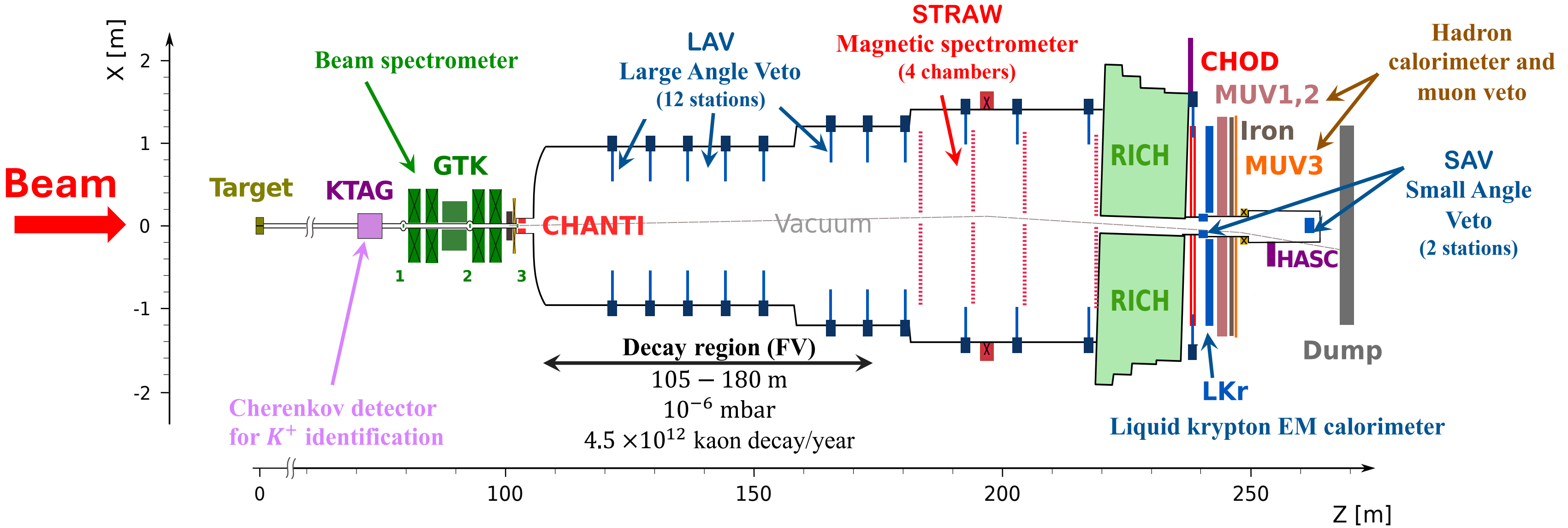
- Experiment apparatus
- Precision measurements with kaon and pion
  - $K^+ \to \pi^+\gamma\gamma$, $\pi^o \to e^+e^-$
- Lepton Number and Flavor Violation searches
  - $K^+ \to \pi\pi^o\mu e$
- Hidden Sector searches with kaons and in dump mode
  - $K^+ \to \pi^+X\ (X \to \gamma\gamma),\ A' \to \ell^+\ell^-$ and $X \to hadrons$
- Conclusions

NA62 Detector Layout

[NA62 Detector Paper, 2017 JINST 12 P05025]

Detector layout optmized for the main measurement $K^+ \to \pi^+ \nu \bar{\nu}$

TOP view



NA62 Performance Keystones:

- High-precision time measurements $\mathcal{O}(100)$ps timing between detectors
- High-efficiency and high-precision tracking $\mathcal{O}(10^4)$ background suppression from kinematics
- High-performance particle identification system $> 10^7$ muon rejection
- Hermetic photon-veto system $> 10^8$ rejection of π^0 from $K^+ \to \pi^+ \pi^0$ decays

NA62 Detector Layout

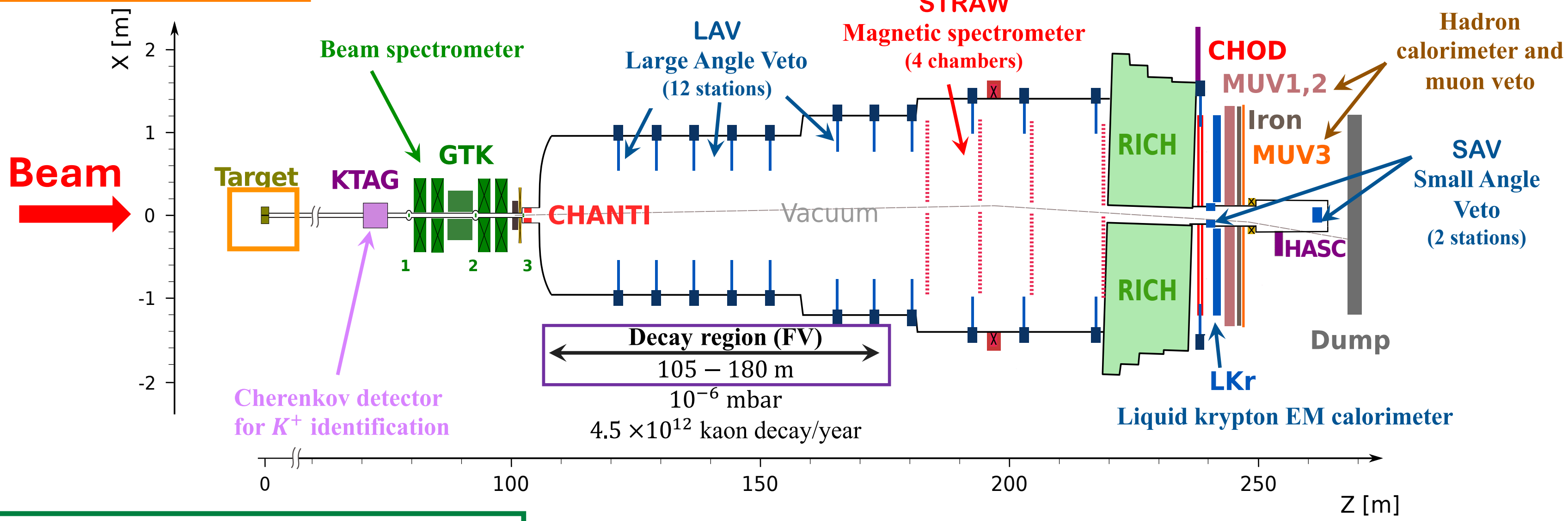
Primary beam from SPS:
- ✧ 400 GeV/c protons

Secondary hadronic beam:
- ✧ $K^+(6\%)/p(23\%)/\pi^+(70\%)$
- ✧ 75 GeV/c ($\pm$ 1%)

[NA62 Detector Paper, 2017 JINST 12 P05025]

Upstream detectors for K^+ identification, momentum and directions
Fiducial volume 105–165 m from target 4.5×10^{12} kaon decays/year
Downstream detectors for K^+ decay products

TOP view



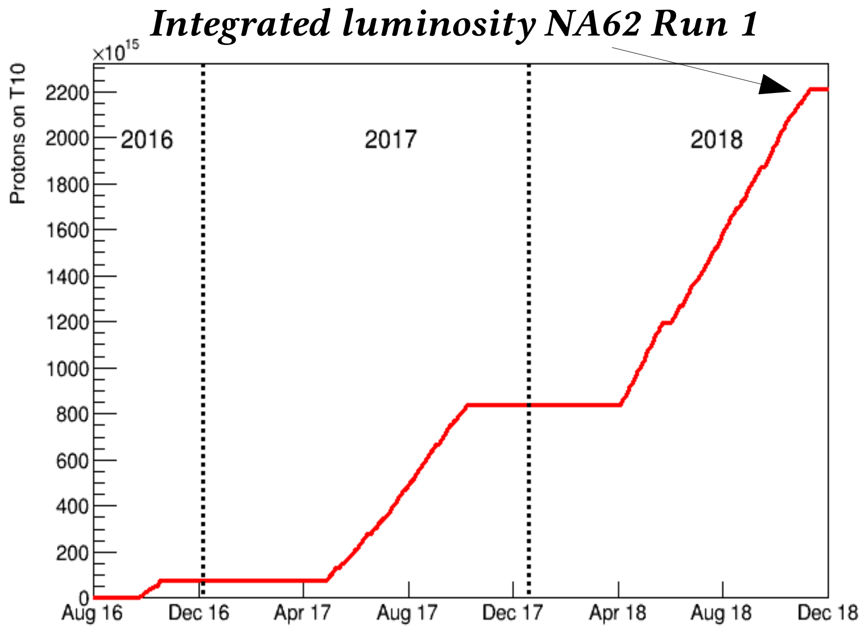
- ✧Kaon tagger KTAG
  Cherenkov detector 70ps time resolution
- ✧Beam spectrometer GTK
  Si-pixel stations for momentum and position
- ✧Anticounter CHANTI
  veto detector

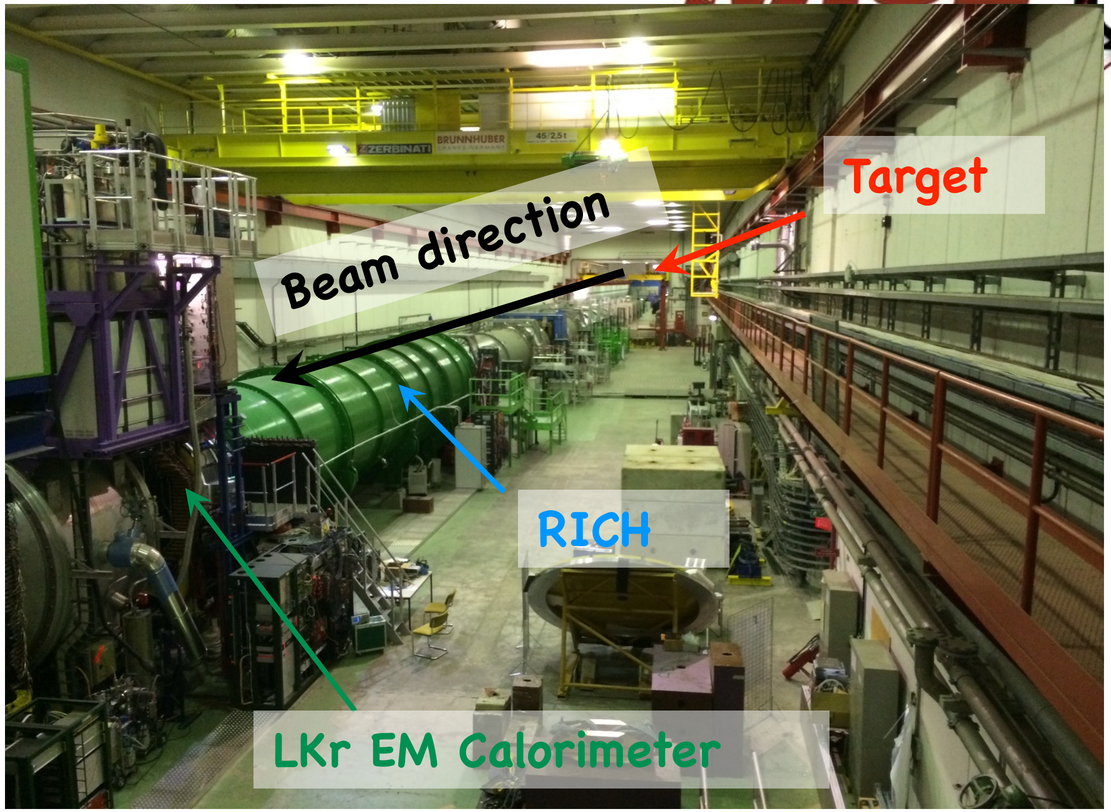
- ✧Tracking STRAW Spectrometer 4 chambers + 1 dipole magnet
- ✧Timing and trigger hodoscopes (CHODs)
- ✧Particle ID: RICH + Calorimeters (EM + hadron) + Muon Veto
- ✧Photon Veto system (LKr, LAV, SAV) hermetic veto 0-50mrad

NA62 Data Taking

- **Run1** 2016 (45 days), 2017 (160 days) and 2018 (217 days)
  $\sim 2.2 \times 10^{18}$ Proton On Target (POT) collected in Run1
  $6 \times 10^{12}\ K^{+}$ decays

- **Run2** 2021 (85 days), 2022 (215 days), 2023 (150 days), 2024 ongoing and until LS3
  Larger K^{+} sample expected
  1.4×10^{17} POT collected in beam dump (10 days in 2021)
  One additional week in beam dump both in 2023&2024





- Dedicate trigger streams to collect both single-track and multi-track final state events, based on hardware L0 and software L1 trigger

[Performance of the NA62 Trigger System, JHEP03 (2023) 122]

PRECISION MEASUREMENTS

Additional analyses on precision not covered here:

$K^+ \to \pi^+\mu^+\mu^-$ [JHEP11 (2022) 011]

$K^+ \to \pi^o e^+\nu\gamma$ [JHEP09 (2023) 040]

$K^+ \to \pi^+\gamma\gamma$

Published results in
Phys. Lett. B850 (2024) 138513

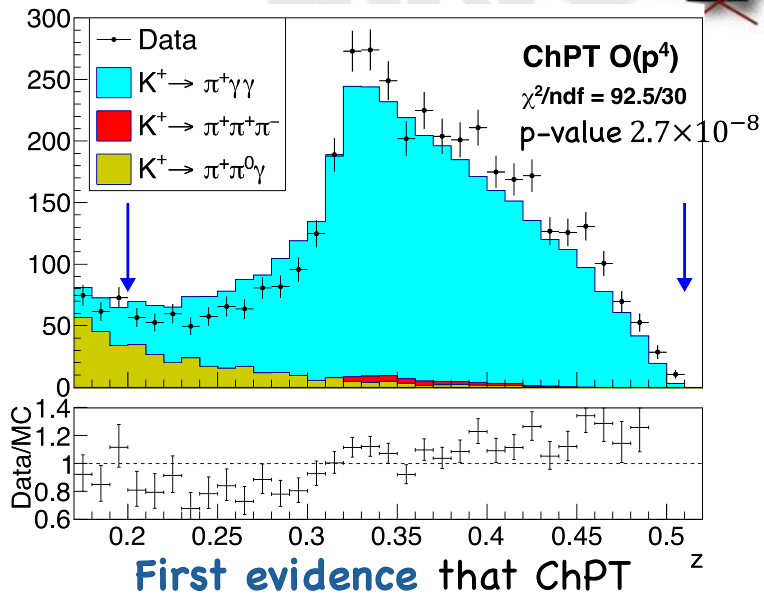
NA62

- Crucial test of Chiral Perturbation Theory (ChPT)
- **All** results so far consistent with leading order $\mathcal{O}(p^4)$ ChPT description
- Decay rate and spectrum determined by a **single**, a priori unknown, $\mathcal{O}(1)$ **parameter** $\hat{c}$ [Phys. Lett. B386 (1996) 403]
- Decay described kinematic variable $z = \frac{m^2_{\gamma\gamma}}{m^2_K}$

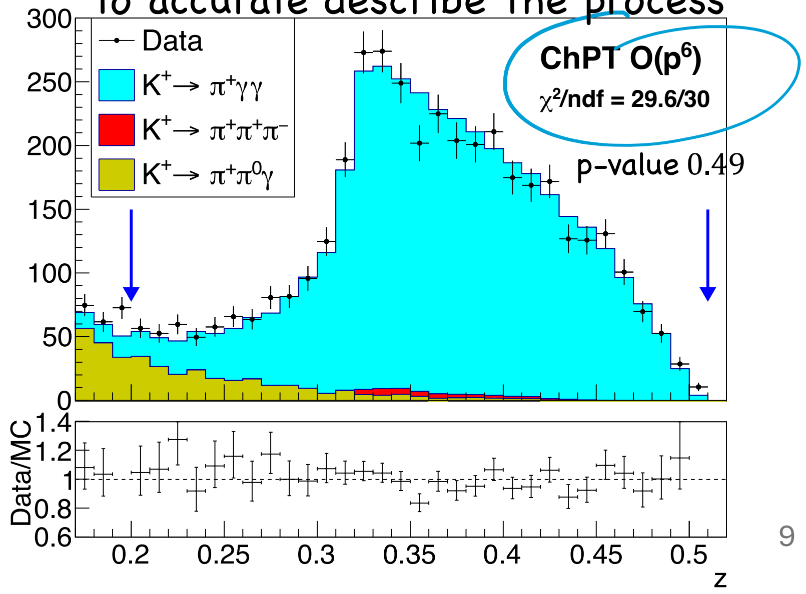
Fit to data point of z distribution to extract $\hat{c}$ parameter

NA62 analysis details:

- Full Run1 data sets
- External parameters from [Rev. Mod. Phys. 84 (2012)][Phys. Lett. B835 (2022)]
- Normalize to $K^+ \to \pi^+\pi^o, \pi^o \to \gamma\gamma$ events $N_K \sim 5.6 \times 10^{10}$
- Analysis performed in $z = \frac{(P_{K^+} - P_{\pi^+})^2}{m^2_{K^+}} > 0.2$ **signal region**
- $N^{obs}_{K_{\pi\gamma\gamma}} = 3984$, $N^{\exp}_{\rm bkg} = 291 \pm 14$
- Backgrounds (validate in control regions with enhanced background and check Data/MC agreement)
  - Multi-γ with merged clusters (e.g. $K^+ \to \pi^+\pi^o\gamma$)
  - $K^+ \to \pi^+\pi^+\pi^-$ with 2 non reconstructed tracks



First evidence that ChPT description at **NLO $\mathcal{O}(p^6)$** is needed to accurate describe the process



$K^+ \to \pi^+\gamma\gamma$

Published results in
Phys. Lett. B850 (2024) 138513

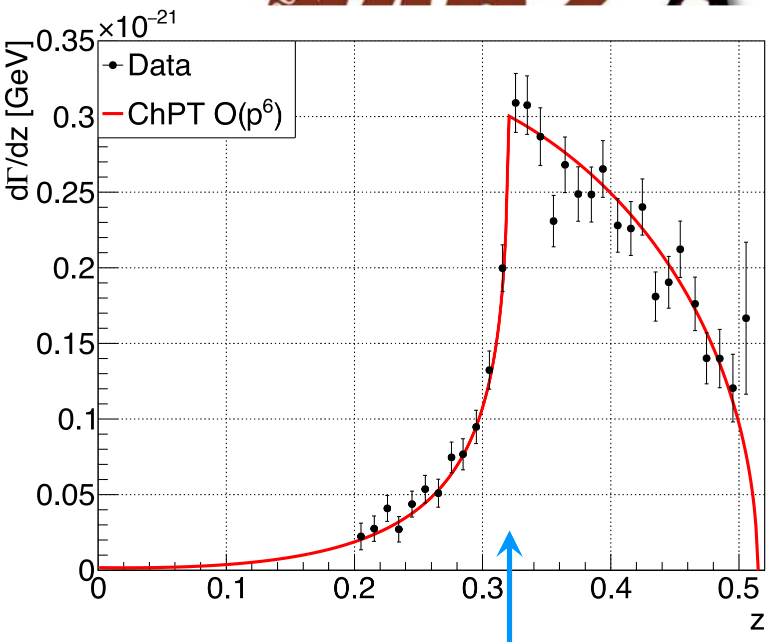
Results in the ChPT $\mathcal{O}(p^6)$ description:

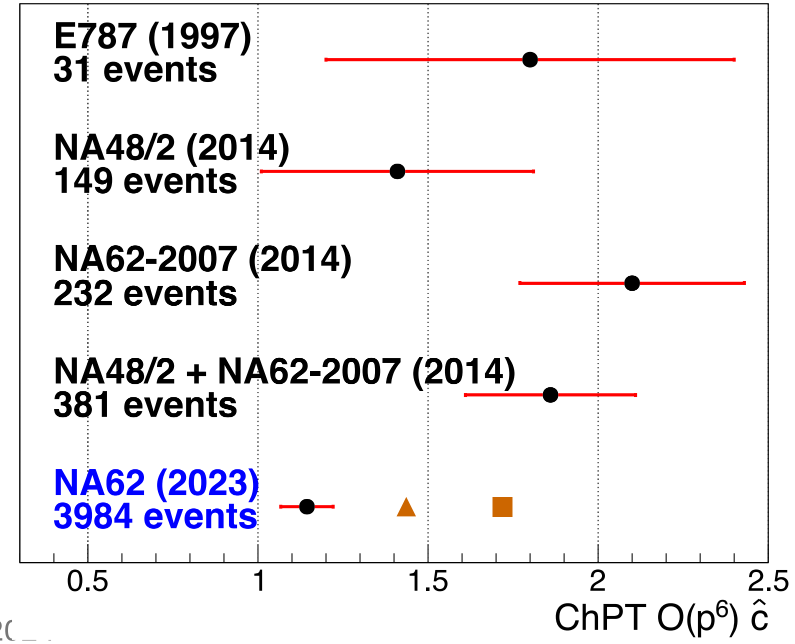
$$\hat{c}_6 = 1.144 \pm 0.077$$

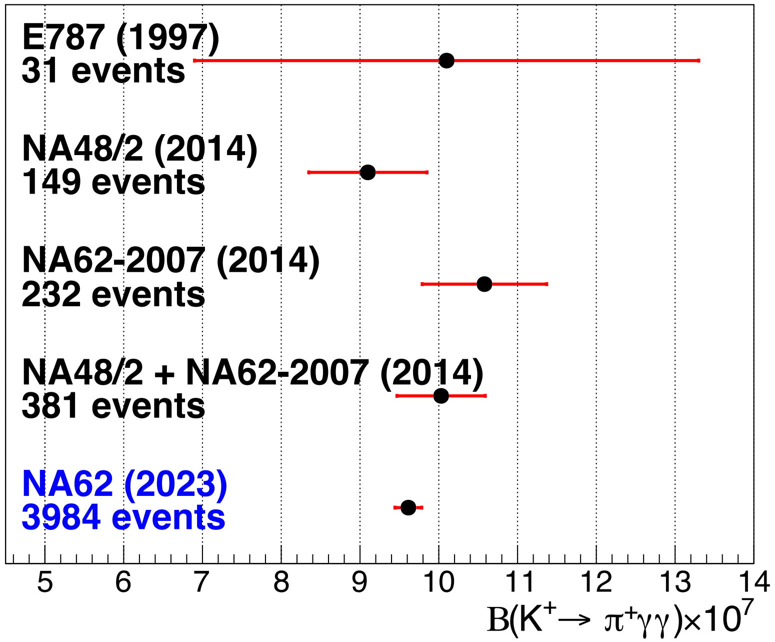
$$\mathrm{BR}_{\mathrm{ChPT}\mathcal{O}(p^6)}(K^+ \to \pi^+\gamma\gamma) = (9.61 \pm 0.17) \times 10^{-7}$$

Model independent branching ratio summing over z bins

$$\mathrm{BR}_{\mathrm{MI}}(K^+ \to \pi^+\gamma\gamma |\, z > 0.2) = (9.46 \pm 0.20) \times 10^{-7}$$







Good agreement between model-independent BR and ChPT description

$\pi^o \rightarrow e^+e^-$

PRELIMINARY RESULTS

$$BR(\pi^o \rightarrow \gamma\gamma) \approx 98.82\%$$
$$BR(\pi^o_D \rightarrow \gamma e^+e^-) \approx 1.17\%$$

- Measurement of a very rare decay of π^o
- Measurement experimentally challenging due to presence of radiative photon in final state
- Important role of radiative corrections
- Observable accessible by the experimets **BR inclusive of final-state radiation**

$$\mathbf{BR(\pi^o \rightarrow e^+e^-(\gamma)\,|\,x > x_{cut})} \qquad x = \frac{m_{ee}^2}{m_{\pi^o}^2}$$

  - Dalitz decay $\pi^o_D \rightarrow \gamma e^+e^-$ dominant in low-x region
  - For $x > 0.95$ only $\approx 3.3\%$ of π^o_D enter the $\pi^o \rightarrow e^+e^-(\gamma)$ signal region

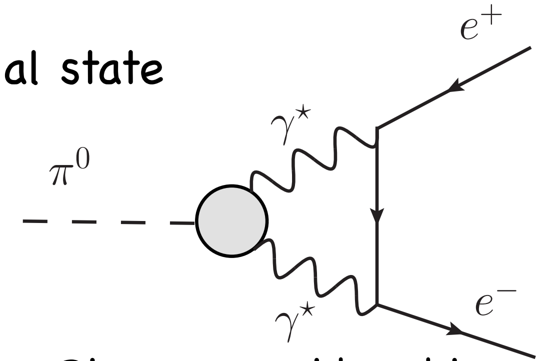


Diagram considered in theoretical predictions leading to $BR(\pi^o \rightarrow e^+e^-)$. Various $\pi^o \rightarrow \gamma^*\gamma^*$ transition form factors are considered

- State of the art so far (latest radiative corrections [JHEP10 (2011) 122] [Eur. Phys. J. 74 (2014) 8, 3010])

Experimental KTeV $\quad BR(\pi^o \rightarrow e^+e^-) = (6.84 \pm 0.35) \times 10^{-8}$
Phys. Rev. D 75 (2014) 012004

Theory $\quad BR(\pi^o \rightarrow e^+e^-) = (6.25 \pm 0.03) \times 10^{-8}$
Phys. Rev. Lett. 128 (2022) 112002

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

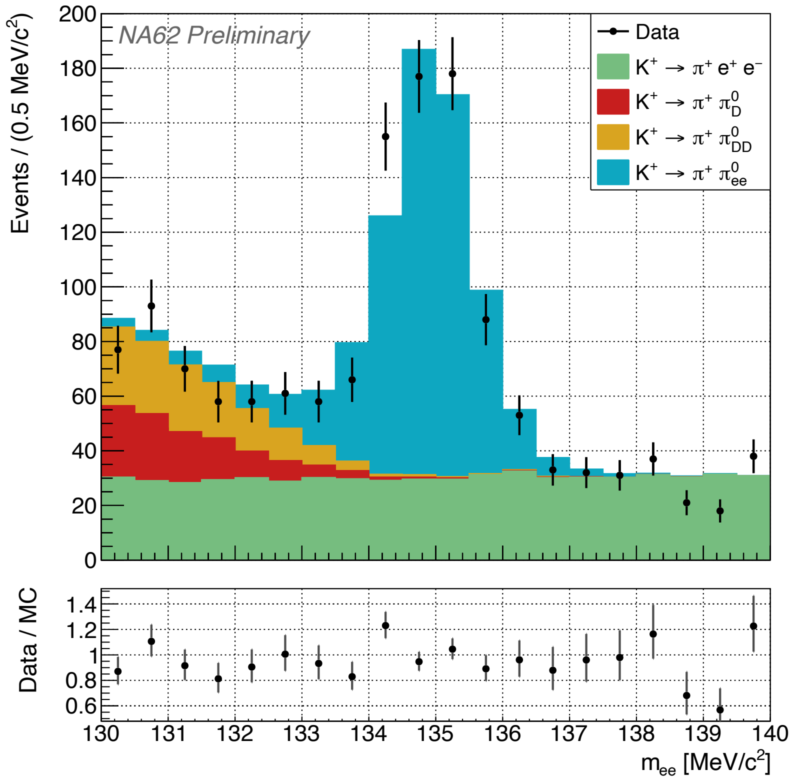
PRELIMINARY RESULTS

- Large sample of π^o available in NA62 via $K^+ \to \pi^+\pi^o$ decay
- Dedicate **multi-track electron** trigger line
- Normalization $K^+ \to \pi^+e^+e^-$ (same final state and trigger)

  $$N_K \sim 8.6 \times 10^{11}$$

  - 3-track final state with vertex in FV
  - m_{ee} $130 - 140\ \mathrm{MeV}/c^2$ for signal
  - m_{ee} $140 - 360\ \mathrm{MeV}/c^2$ for normalization
- Main backgrounds:
  - $K^+ \to \pi^+e^+e^-$ irreducible and flat in signal region
  - $K^+ \to \pi^+\pi^o_D$ $(\pi^o \to e^+e^-\gamma)$ irreducible at high x tail, or γ conversion in STRAW Spectrometer
  - $K^+ \to \pi^+\pi^o_D\pi^o_D$ with two undetected $e^\pm$

$$\mathbf{BR_{Preliminary}(\pi^o \to e^+e^-) = (6.22 \pm 0.39)\times 10^{-8}}$$



- 1402 observed candidates
- Acceptance $\sim 5.7\%$
- **Maximum likelihood fit of simulated samples to data to extract BR**
- Signal yield 597 ± 29
- $\chi^2/ndf = 25.3/19$ p-value$= 0.152$

Lepton Number and Lepton Flavor Violation Searches

Additional analyses on precision not covered here:

$K^+ \to \pi^-\mu^+\mu^+$ [Phys. Lett. B797 (2019) 134794]

$K^+ \to \pi^-(\pi^o)e^+e^+$[Phys. Lett. B830 (2022) 137172]

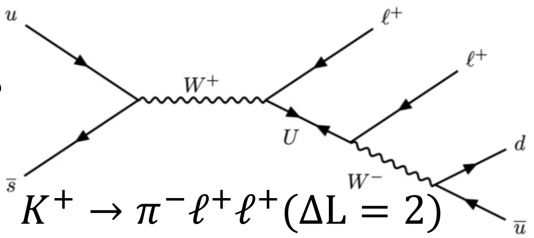
$K^+ \to \pi^\mp\mu^\pm e^+, \pi^o \to \mu^- e^+$ [Phys. Rev. Lett. 127 (2021) 131802]

$K^+ \to \mu^-\nu e^+e^+$ NA62Coll., Phys. Lett. B838 (2023) 137679]

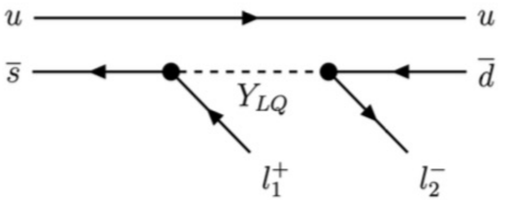
$K^+ \to \pi\pi^o\mu e$

Published results in
arXiv:2409.12981
Submitted to Phys. Lett. B

- Lepton Number (LN) and Lepton Flavor (LF) conserved in SM
- Observations of LN and LF violation clear signs of New Physics
- Several scenario for generating LNV/LFV in charged processes



$K^+ \to \pi^-\ell^+\ell^+(\Delta L = 2)$
LNV process mediated by Majorana neutrino (U)
[JHEP 05 (2009) 030]



$K^+ \to \pi^+\ell_1^+\ell_2^-$ LFV process mediated by a leptoquark (Y_{LQ})
[JHEP 12 (2019) 089]

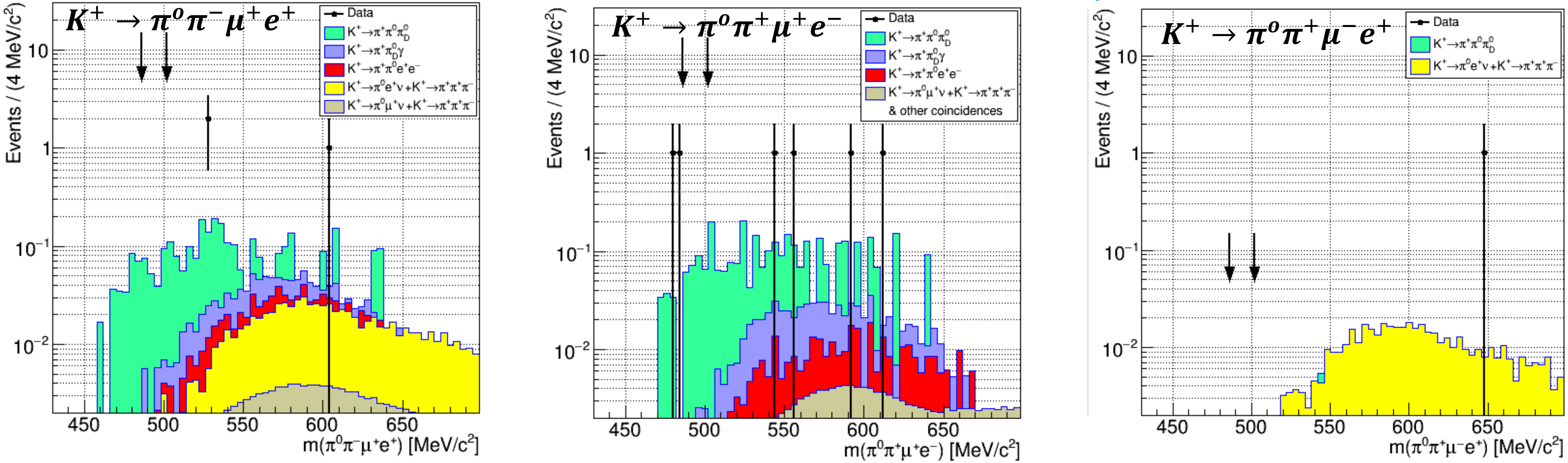
- Rich programme @NA62 in search for LN and LF violation
- Dedicate multi-track trigger streams with electron and/or muon in final states
- Analysis carried on with blind principle
- World's leading sensitivity in many channels with **UL** $\mathcal{O}(10^{-10})/\mathcal{O}(10^{-11})$

$$K^+ \to \pi^-\mu^+\mu^+, \quad K^+ \to \pi^-(\pi^o)e^+e^+, \quad K^+ \to \pi^\mp\mu^\pm e^+, \quad \pi^o \to \mu^- e^+, \quad K^+ \to \mu^-\nu e^+ e^+$$

- First search for LNV decay $K^+ \to \pi^o\pi^-\mu^+e^+$ and LFV decays $K^+ \to \pi^o\pi^+\mu^\pm e^\mp$
  - Normalization channel $K^+ \to \pi^+e^+e^-$ (BR~3×10^{-7}) 10975 candidates selected ⟶ $N_K \approx 2\times10^{12}$
  - Full reconstruction of signal final state $\pi^o \to \gamma\gamma$ in EM calo, 3 charged tracks with PID $\pi\mu e$
  - Background from single or coincidence of two K^+ decays, with mis-PID and/or π decay-in-flight (evaluated with simulation validated in control samples)

$K^+ \to \pi\pi^o\mu e$

Published results in
arXiv:2409.12981
Submitted to Phys. Lett. B



0 signal observed in the signal region $486 < m_{\pi^o\pi\mu e} < 502\ \mathrm{MeV}/c^2$ for all 3 investigated

Channel	Expected Background	Mechanism	UL on BR @ 90% CL
$K^+ \to \pi^o\pi^-\mu^+e^+$	0.33 ± 0.07	$K^+ \to \pi^+\pi^o\pi^o_D$ with soft γ undetected, $\pi^+ \to \mu^+\nu$ DIF and $e \to \pi$ mis-ID	2.9×10^{-10}
$K^+ \to \pi^o\pi^+\mu^+e^-$	0.29 ± 0.07		5.0×10^{-10}
$K^+ \to \pi^o\pi^+\mu^-e^+$	0.004 ± 0.003	$K^+ \to \pi^o e^+\nu + K^+ \to \pi^+\pi^+\pi^-$ with $\pi^- \to \mu^-\nu$ DIF and 1 π^+ undetected	3.1×10^{-10}

Hidden Sector Searches

Additional analyses on hidden sector not covered here:

$K^+ \to \pi^+ XX (X \to e^+e^-, X \to e^+e^-)$ [Phys. Lett. B846 (2023) 138193]

$K^+ \to e^+ N$ [Phys. Lett. B 807 (2020) 135599]

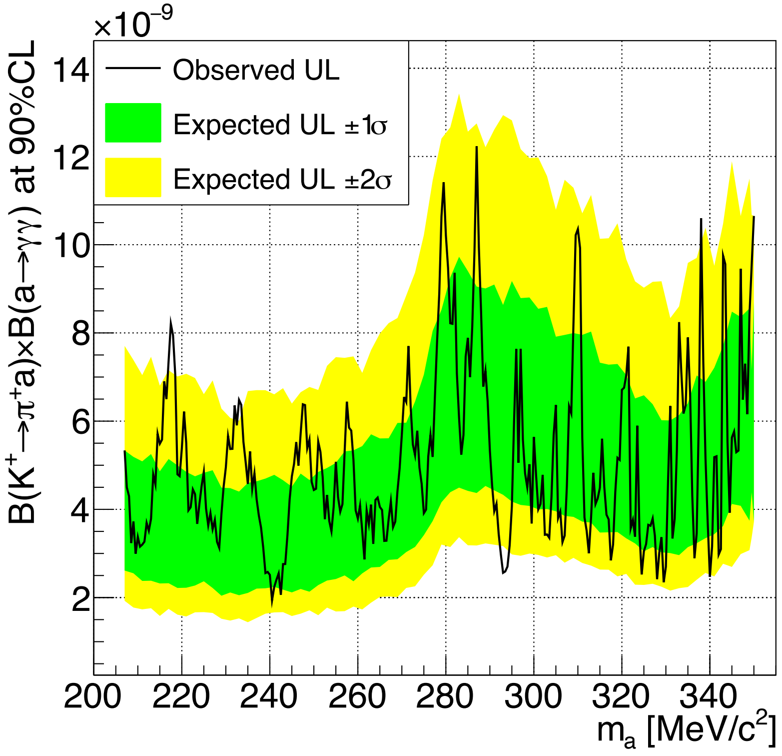
$K^+ \to \mu^+ N$ [Phys. Lett. B 816 (2021) 136259]

$K^+ \to \mu^+ \nu X$, $K^+ \to \mu^+ \nu \bar{\nu} \nu$ [Phys. Lett. B 816 (2021) 136259]

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

Published results in
Phys. Lett. B850 (2024) 138513

- Axion-like particle (ALP) search in $a \to \gamma\gamma$ channel (dominant final state for $m_a < 3m_\pi$)
- **Direct by product of $K^+ \to \pi^+\gamma\gamma$ analysis**



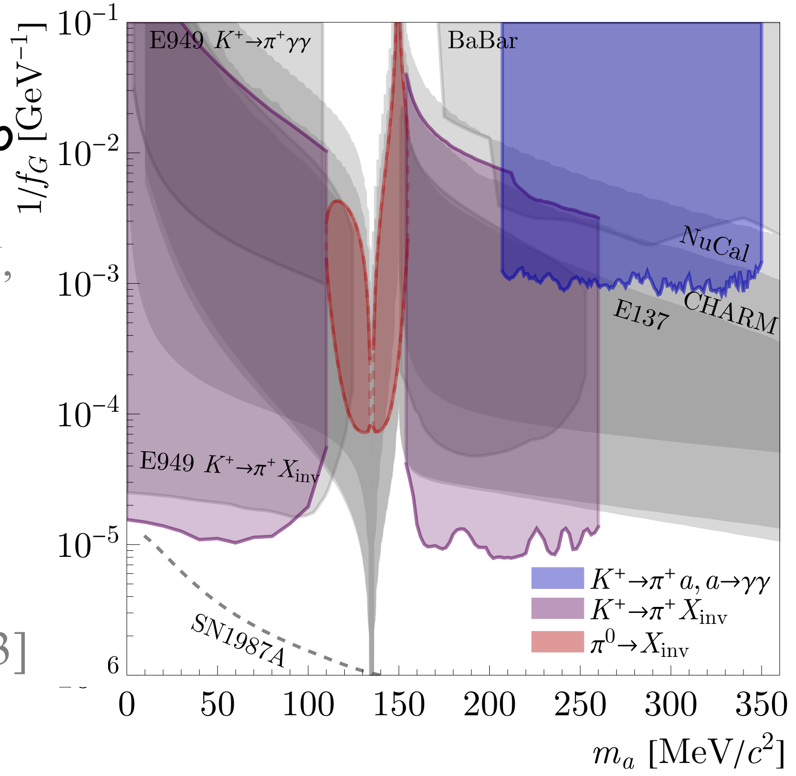
- Peak search over $m_a = \sqrt{(P_K - P_\pi)^2}$ in the range **$207 - 350$ MeV/c^2** in step of 0.5 MeV/c^2
- In each mass hyp. background estimation with simulations
- ***UL*** on $\mathrm{BR}(K^+ \to \pi^+ a)$ assuming **prompt** $a \to \gamma\gamma$ ($\tau_a = 0$)
- Sensitivity limited by $K^+ \to \pi^+\gamma\gamma$ background

Results interpreted in the **BC11** scenario
ALP with dominant gluon coupling

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

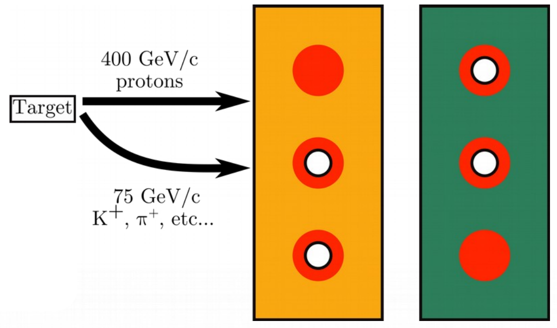
Exclusion limits in the parameter space coupling *vs* mass together with NA62 results for invisible a decays

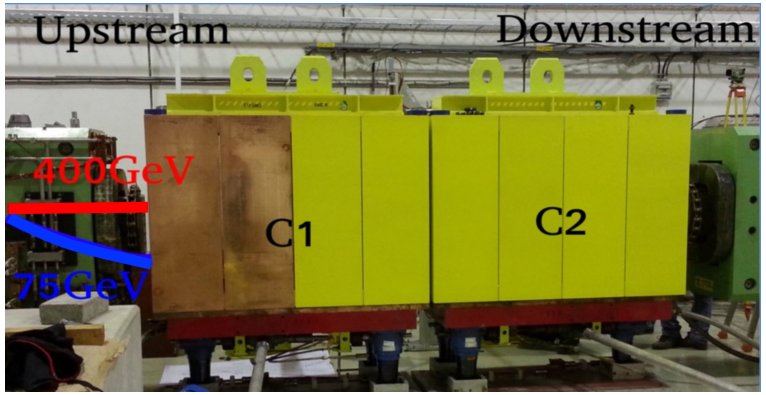
[JHEP02 (2021) 201][JHEP06 (2021) 93]



NA62 in Beam Dump Configuration

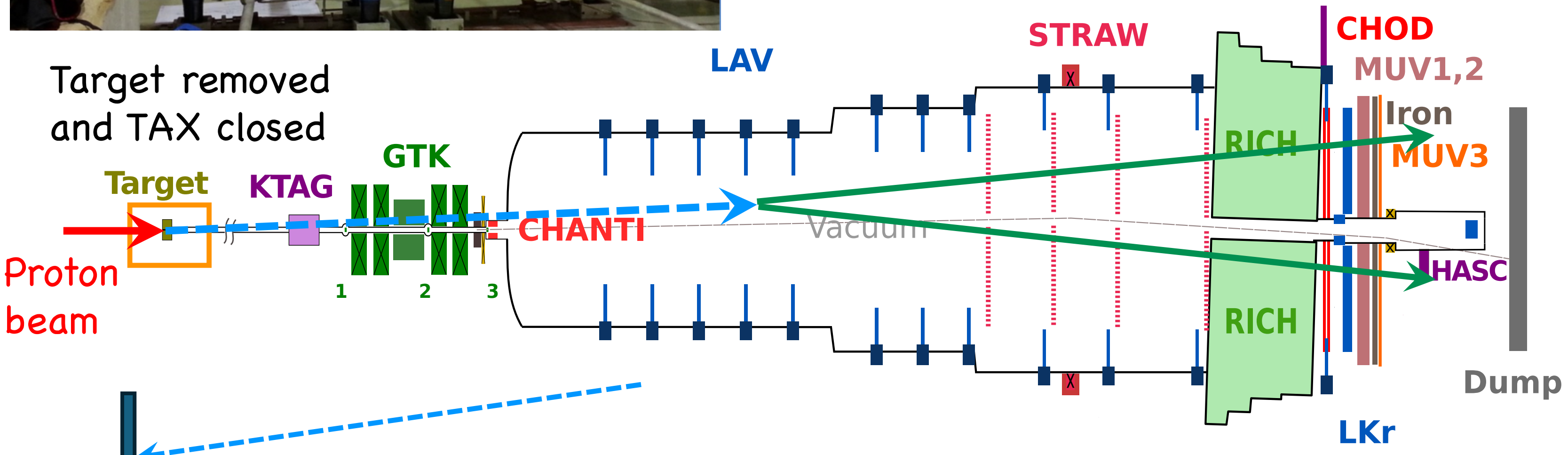
Normal data taking with Be target in place



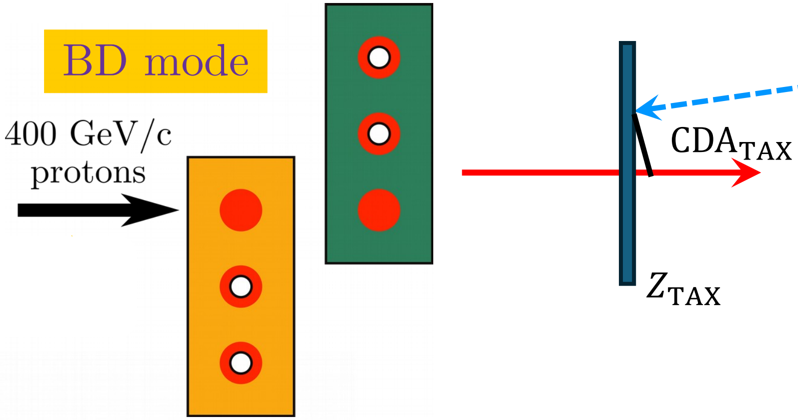


- 3.2m long Cu-Fe collimator (TAX)
- 19.6 interaction length
- $\times 1.5$ nominal proton intensity wrt kaon mode
- 1.4×10^{17} POT collected and analyzed in 2021
- additional data collected in 2023-2024
- aim at 10^{18} **POT** before end of Run2

Target removed and TAX closed



Beam Dump mode
Be target lifted and Tax collimator closed



- Signal region of the search define in the plane
  - Z_{TAX} longitudinal position primary vertex
  - CDA_{TAX} closest distance of approach between beam direction (at TAX entrance) and track pair direction

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

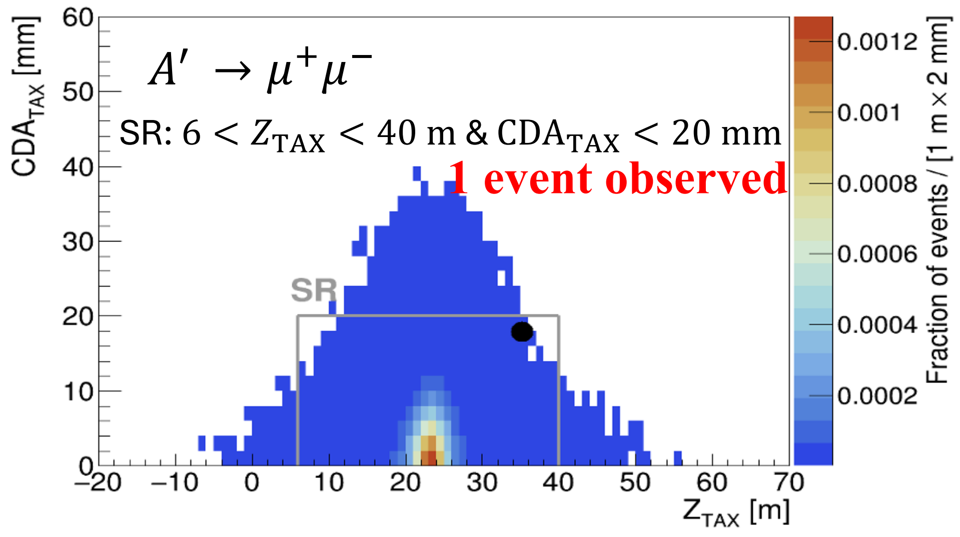
Published results in
Phys. Rev. Lett. 133 (2024) 111802
JHEP 09 (2023)

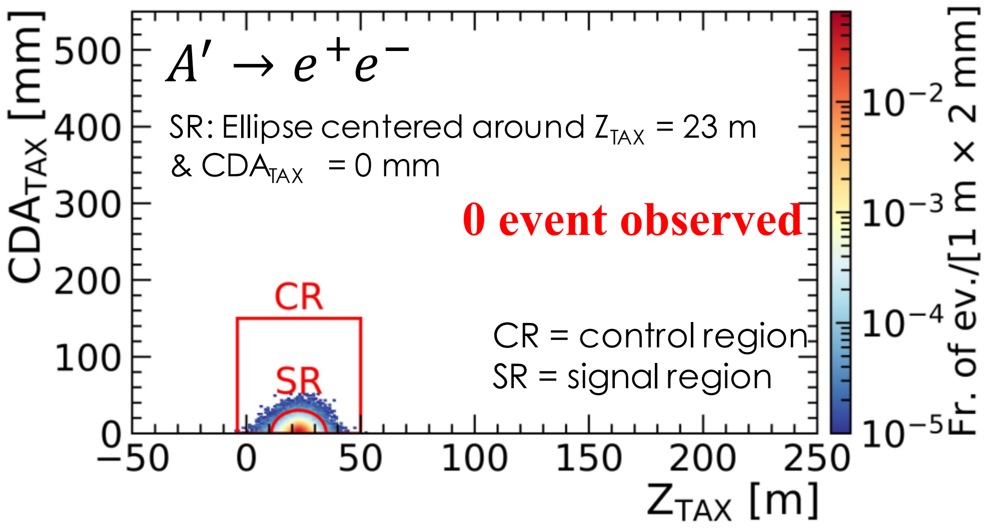
- SM extension via vector portal Dark Photon A'
- New vector field feebly interacting with SM particles
- **Free parameters of the model $m_{A'}$ and kinetic coupling ε**

- Production mechanism
  - Bremsstrahlung: $\gamma^* p \to A' p'$
    virtual photon exchange between proton and nucleus
  - Meson decay:
    $P \to \gamma A', V \to PA'$ with $V = \{\rho, \omega, \phi\}$ and , $P = \{\pi^o, \eta, \eta'\}$

- **Dominant decay in** $\ell\bar{\ell}$ pair for $m_{A'} < 700\ \mathrm{MeV/c^2}$
  e^+e^- and $\mu^+\mu^-$ channels investigated

- Blind technique
- Backgrounds data-driven and simulation
  - Combinatorial dominant for μ channel
    random superposition of 2 uncorrelated halo μ
  - Prompt dominant for e channel
    secondary particles from μ-halo interaction with material upstream or inside decay volume





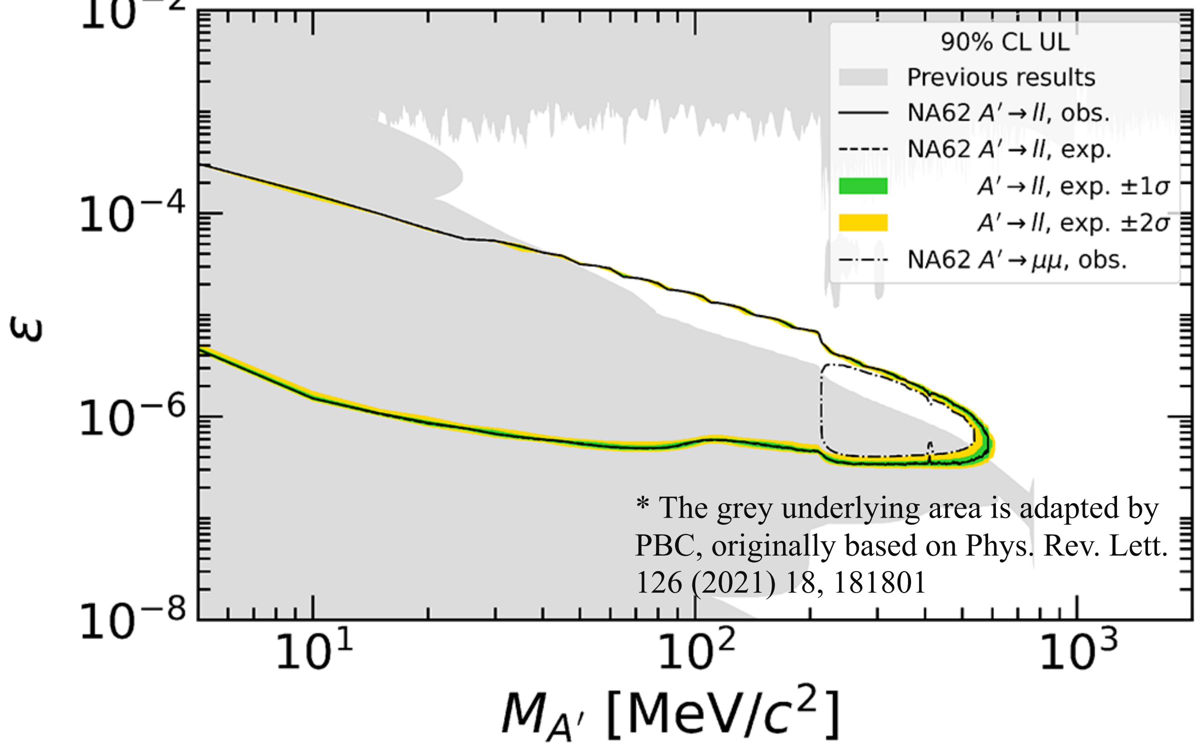
$A' \rightarrow \ell^+\ell^-$

Published results in
Phys. Rev. Lett. 133 (2024) 111802
JHEP 09 (2023)

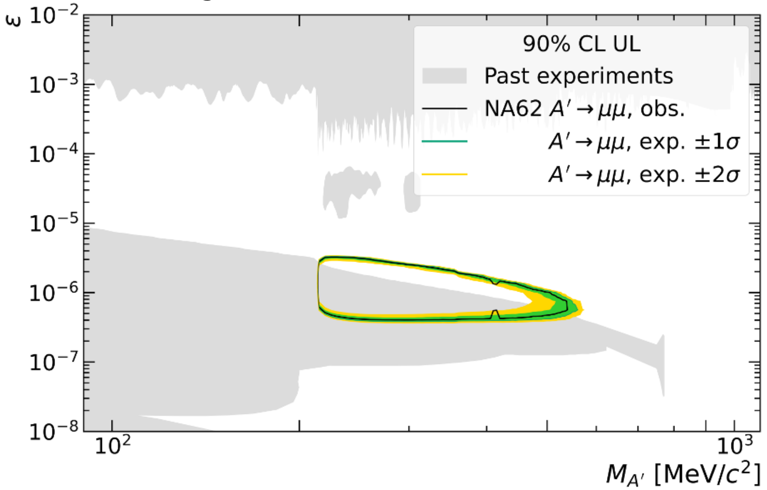
- Exclusion limit at 90% CL in the parameter space coupling ε *vs* $m_{A'}$
- Region enclosed by the contour is excluded
- Mass region $\mathbf{50 < m_{A'} < 600\ MeV/c^2}$

(In published papers also ALP scenario is presented)

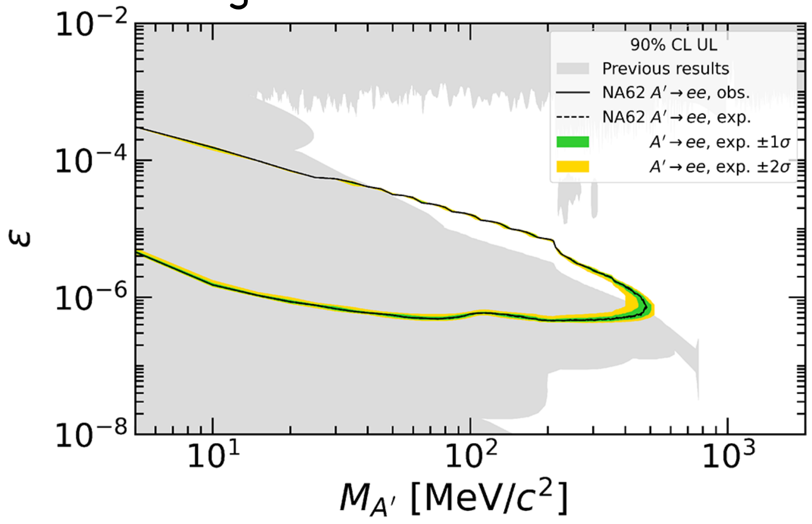
Combine results $A' \rightarrow \ell^+\ell^-$ search



Single contribution μ channel



Single contribution e channel



$X \to hadrons$

PRELIMINARY RESULTS

NA62

- **New Physics search with hadron final state**

- Dark Photon
  - Bremsstrahlung: $\gamma^* p \to A' p'$
    virtual photon exchange between proton and nucleus
  - Meson decays:
    $P \to \gamma A', V \to PA'$ with $V = \{\rho, \omega, \phi\}$ and , $P = \{\pi^o, \eta, \eta'\}$

- Dark Scalar
  - B meson decays: $B^{\pm,0} \to K^{\pm,0,(*)} S$

- ALP
  - Primakoff (on-/off-shell)
  - Mixing with pseudoscalar mesons $P = \{\pi^o, \eta, \eta'\}$
  - B meson decays: $B^{\pm,0} \to K^{\pm,0,(*)} a$

Proven that searches are **background free** not only at $N_{POT} = 1.4 \times 10^{17}$ but also in the future **full Run2** beam dump dataset of $N_{POT} = 10^{18}$

Particle	Final State
Dark Photon A'	$\pi^+\pi^-, \pi^+\pi^-\pi^o, \pi^+\pi^-\pi^o\pi^o,$ $K^+K^-, K^+K^-\pi^o$
Dark Scalar S	$\pi^+\pi^-, \pi^+\pi^-\pi^o\pi^o,$ K^+K^-
ALP a	$\pi^+\pi^-\gamma, \pi^+\pi^-\pi^o,$ $\pi^+\pi^-\pi^o\pi^o, \pi^+\pi^-\eta,$ $K^+K^-\pi^o$

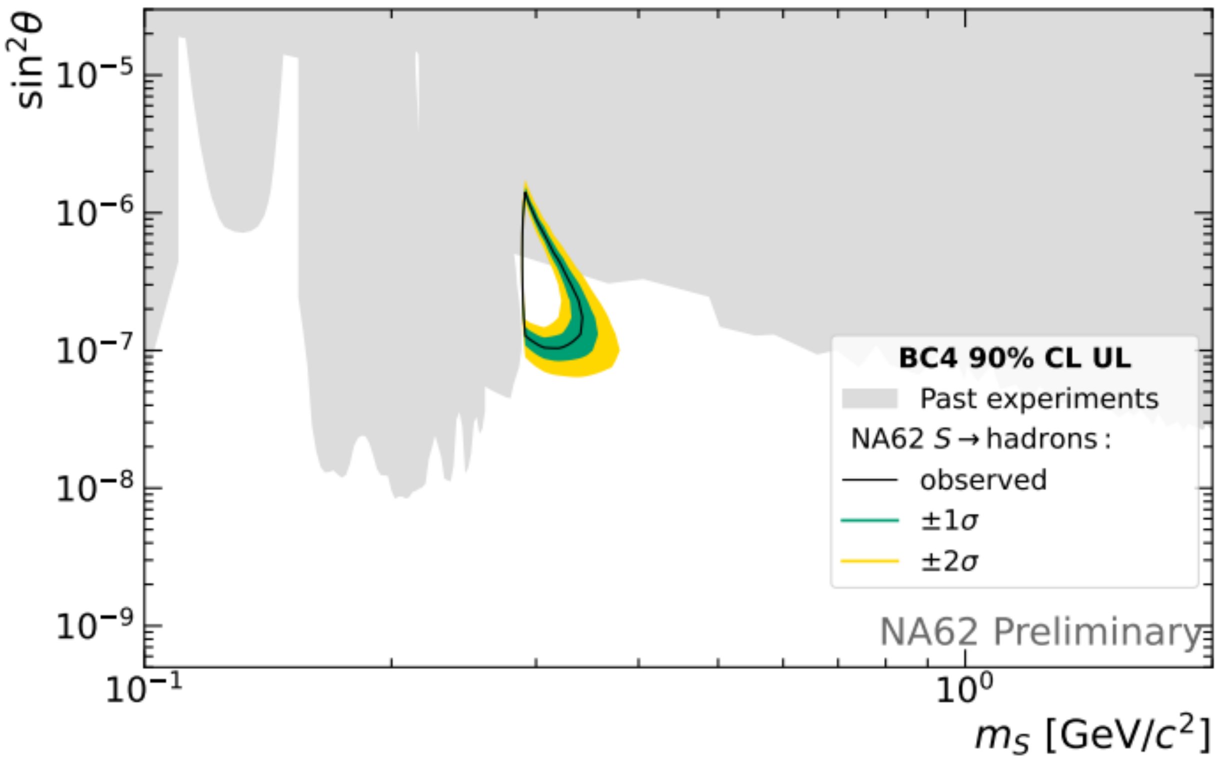
Altogether 36 combinations of production and decay channels studied

- 2 charged hadrons in the final state
- full PID (calorimeter and RICH)
- neutral cluster in EM calorimeter to reconstruct γ, π^o and η
- Vertex in FV and pointing back to TAX

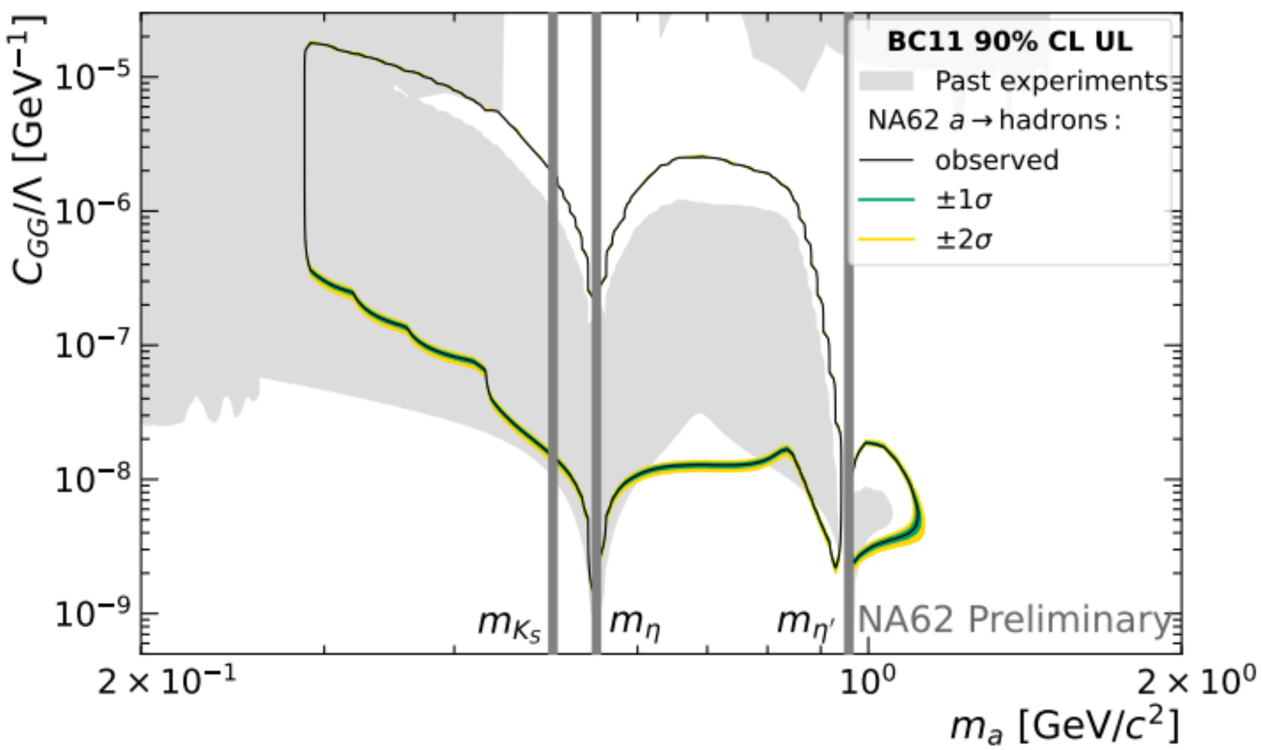
$X \rightarrow hadrons$

PRELIMINARY RESULTS

Dark Scalar exclusion limit



ALP exclusion limit



- **0** events observed in all control and signal regions
- Exclusion limit at 90% CL set on the parameter space coupling *vs* mass

Combination of all 36 productions/decay modes made through ALPINIST

[Axion-Like Particles In Numerous Interactions Simulated and Tabulated, JHEP07 (2022) 094]

CONCLUSIONS

- **NA62 successfully completed Run1 (2016-2018)**

- Run2 data taking currently ongoing (from 2021 until LS3 at CERN)

- **Rich physics programme to test the Standard Model and search for New Physics**
  - Precision measurement in kaon and pion decays

    $$K^+ \to \pi^+\gamma\gamma \text{ and } \pi^0 \to e^+e^-$$

  - Lepton Number and Flavor Violation decays

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

  - Hidden Sector with kaons

    $$K^+ \to \pi^+X\ (X \to \gamma\gamma)$$

  - Hidden Sector in dump mode

    $$A' \to \ell^+\ell^-, a \to \ell^+\ell^- \text{and } X \to hadrons\ (X = A', S, a)$$

Many other analyses ongoing…

…and many new data are ready to be analyzed…

… and to be collected until LS3!

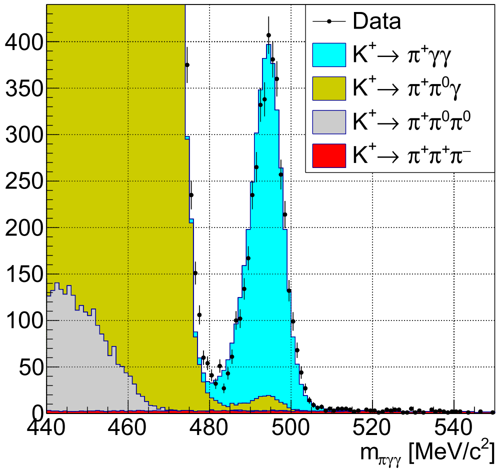
THANK YOU FOR YOUR ATTENTION!

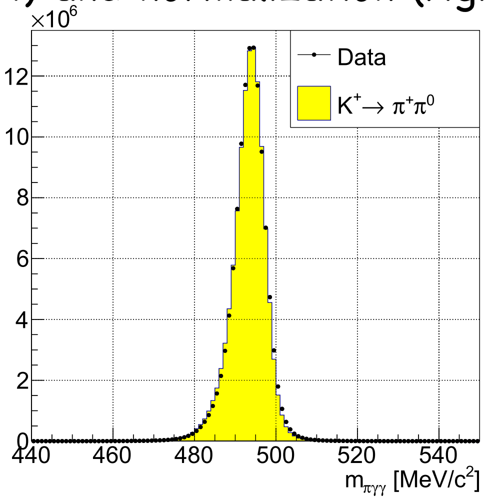
Backup Slides

$K^+ \to \pi^+\gamma\gamma$

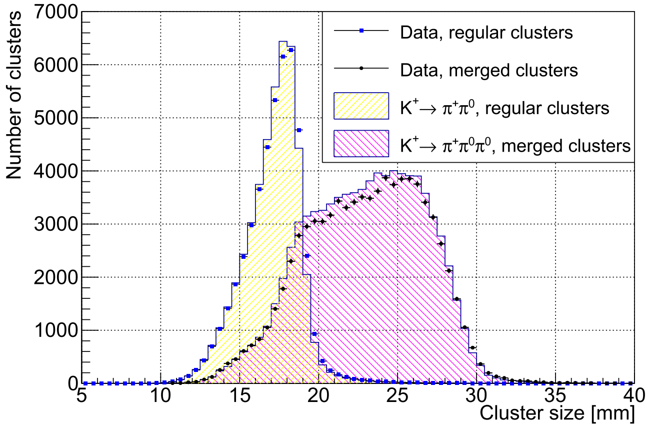
Published results in
Phys. Lett. B850 (2024) 138513

$m_{\pi\gamma\gamma}$ spectra for signal (left) and normalization (right)





- Background contamination in normalization $< 10^{-5}$
- Select event in $440 < m_{\pi\gamma\gamma} < 550$ MeV/c^2
- Normalization $z \in [0.04\,, 0.12]$
- Signal $z \in [0.20\,, 0.51]$



Cluster size cut against multi-photon background with merged clusters in EM calorimeter

$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_K}{2^9\pi^3}\left[z^2\left(\left|A(\hat{c},z,y^2) + B(z)\right|^2 + |C(z)|^2\right) + \left(y^2 - \frac{1}{4}\lambda(1, r_\pi^2, z)\right)^2 |B(z)|^2 \right]$$

Decay rate parametrization in ChPT framework from
[G. D'Amborsio, J. Portolés, Phys. Lett. B386 (1996) 403]

Parameter	E787 [4]	NA48/2, NA62 [5,6]	This measurement
$G_8 m_K^2 \times 10^6$	2.24	2.202	2.202
$\alpha_1 \times 10^8$	91.71	93.16	92.80
$\alpha_3 \times 10^8$	−7.36	−7.62	−7.45
$\beta_1 \times 10^8$	−25.68	−27.06	−26.46
$\beta_3 \times 10^8$	−2.43	−2.22	−2.50
$\gamma_3 \times 10^8$	2.26	2.95	2.78
$\zeta_1 \times 10^8$	−0.47	−0.40	−0.11
$\xi_1 \times 10^8$	−1.51	−1.83	−1.20
η_i $(i = 1, 2, 3)$	0	0	0

External parameters used in this analysis and in previous analysis

[4] [Phys. Rev. Lett. 79 (1997) 4079]
[5] [Phys. Lett. B730 (2014) 141]
[6] [Phys. Lett. B732 (2014) 65]

Estimated background contributions in the $K_{\pi\gamma\gamma}$ sample.

Source	Estimated background
$K^+ \to \pi^+\pi^0\gamma$	$240 \pm 8_{stat} \pm 12_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$35 \pm 1_{stat} \pm 1_{syst}$
$K^+ \to \pi^+\pi^0\pi^0$	$9 \pm 2_{stat}$
$K^+ \to \pi^0 e^+\nu(\gamma)$	$7 \pm 1_{stat}$
Total	$291 \pm 8_{stat} \pm 12_{syst}$

Background contributions

Systematics sources

Systematic uncertainties for $\hat{c}$, $\mathcal{B}$ and $\mathcal{B}_{MI}(z > 0.2)$ measurements.

Source	$\delta\hat{c}$	$\delta\mathcal{B} \times 10^7$	$\delta\mathcal{B}_{MI}(z > 0.2) \times 10^7$
Number of kaon decays	0.026	0.056	0.064
Simulation of multi-photon backgrounds	0.016	0.034	0.026
Simulation of $K_{3\pi}$ background	0.001	0.002	0.003
Limited size of simulated samples	0.014	0.030	0.018
Total	0.034	0.072	0.072

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

PRELIMINARY RESULTS

Previous best measurement by KTeV

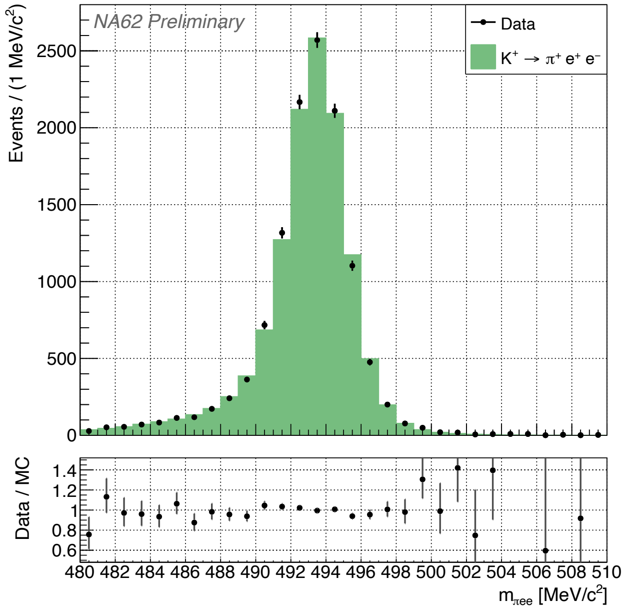
$$BR_{\mathrm{KTeV}}(\pi^o \to e^+e^-(\gamma)\,|\,x > 0.95) = (6.44 \pm 0.25\ 0.22) \times 10^{-8}$$

794 signal candidates with 52.7 ± 11.2 background events

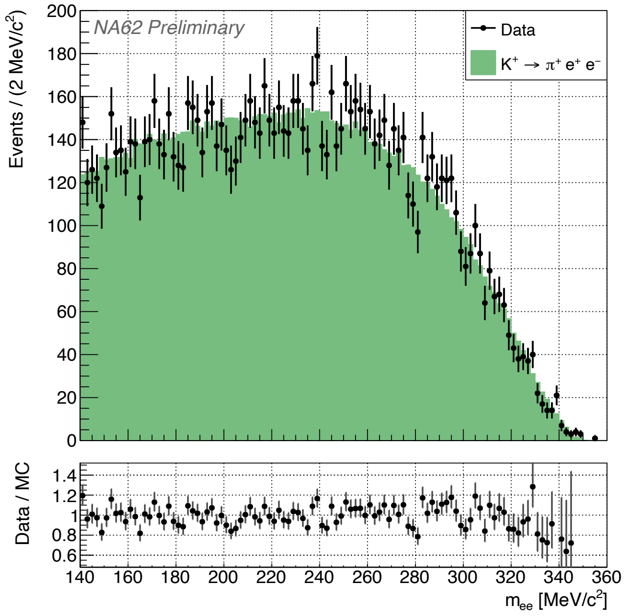
[Phys. Rev. D75 (2007) 012004]

	$BR(\pi^o \to e^+e^-)$
KTeV, PRD 75 (2007) 012004	$(6.84 \pm 0.35)\times 10^8$
Knecht et al., PRL 83 (1999)	$(6.2 \pm 0.3) \times 10^8$
Dorokhov and Ivanov, PRD 75 (2007)	$(6.23 \pm 0.09) \times 10^8$
Husek and Leupold, EPJ C 75 (2015)	$(6.12 \pm 0.06) \times 10^8$
Hoferichter et al., PRL 128 (2022)	$(6.25 \pm 0.03)\times 10^8$

$m_{\pi ee}$ spectra



m_{ee} spectra for normalization



$$BR(\pi^o \to e^+e^-\,|\,x > 0.95) = (5.86 \pm 0.30_{stat.} \pm 0.11_{syst.} \pm 0.19_{ext.})\times 10^{-8}$$
$$= (5.86 \pm 0.37) \times 10^{-8}$$

$$BR(\pi^o \to e^+e^-) = (6.22 \pm 0.39)\times 10^{-8}$$

12160 candidates for normalization

Acceptance ~4.7%

Background < 1%

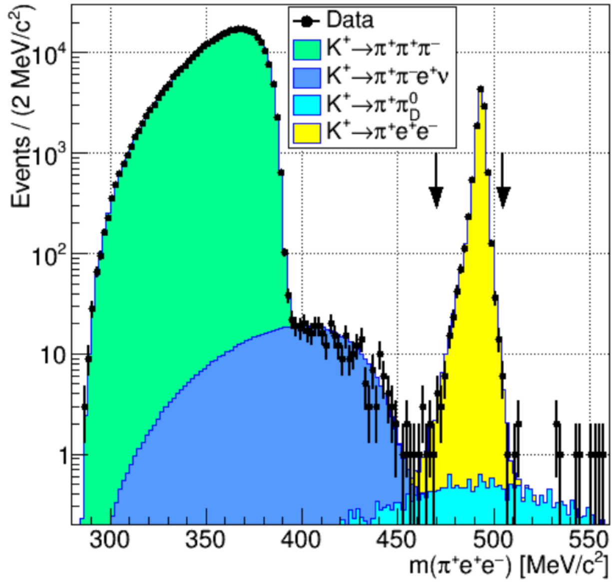
N_K dominat by external uncertainty from BR

NA62 preliminary result: ncertainty contributions

	$\delta\mathcal{B}$ [10^{-8}]	$\delta\mathcal{B}/\mathcal{B}$ [%]
Statistical uncertainty	0.30	5.1
Total external uncertainty	0.19	3.2
Total systematic uncertainty	0.11	1.9
Trigger efficiency	0.07	1.2
Radiative corrections for $\pi^0 \to e^+e^-$	0.05	0.9
Background	0.04	0.7
Reconstruction and particle identification	0.04	0.7
Beam simulation	0.03	0.5

$K^+ \to \pi\pi^o\mu e$

Published results in
arXiv:2409.12981
Submitted to Phys. Lett. B



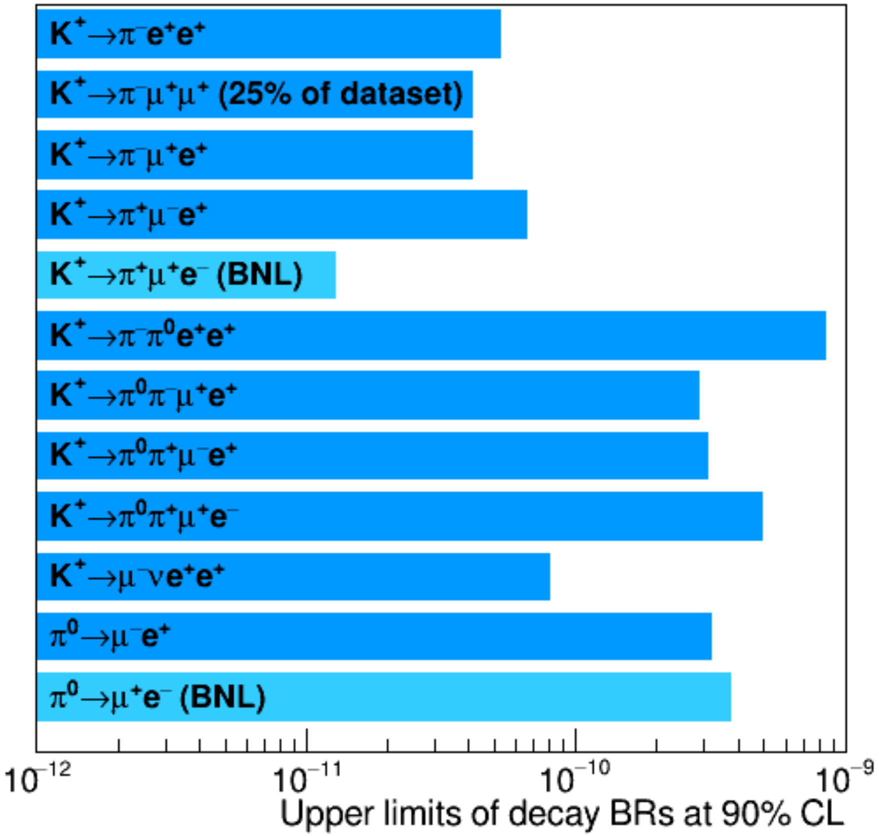
- Normalization channel $K^+ \to \pi^+e^+e^-$
- Similar final state (3 tracks with one pion and pne electron)
- Same trigger stream
- Close decay
- $470 < m_{\pi ee} < 505\ \mathrm{MeV}/c^2$
- 10975 candidate observed
- Background contamination $\mathcal{O}(10^{-3})$

Background mechanism considered
DIF = decay-in-flight
Direct = no mis-PID involved

Background source	$\mathcal{B}$	$\pi^0\pi^-\mu^+e^+$	$\pi^0\pi^+\mu^-e^+$	$\pi^0\pi^+\mu^+e^-$
$K^+\to\pi^+\pi^0\pi^0_D$	4.1×10^{-4}	$e^-\to\pi^-$	$e^-\to\mu^-$	$e^+\to\pi^+$ or $e^+\to\mu^+$
$K^+\to\pi^+\pi^0_D\gamma$ ($E^*_\gamma>10$ MeV)	7.8×10^{-6}	$e^-\to\pi^-$	$e^-\to\mu^-$	$e^+\to\pi^+$ or $e^+\to\mu^+$
$K^+\to\pi^+\pi^0e^+e^-$	4.2×10^{-6}	$e^-\to\pi^-$	$e^-\to\mu^-$	$e^+\to\pi^+$ or $e^+\to\mu^+$
$K^+\to\pi^0_D\mu^+\nu\gamma$ ($E^*_\gamma>10$ MeV)	7.4×10^{-7}	$e^-\to\pi^-$	–	$e^+\to\pi^+$
$K^+\to\pi^0\pi^0_D\mu^+\nu$	7.9×10^{-8}	$e^-\to\pi^-$	–	$e^+\to\pi^+$
$K^+\to\pi^+\pi^0\pi^0$, $\pi^0\to e^+e^-$	2.6×10^{-9}	$e^-\to\pi^-$	$e^-\to\mu^-$	$e^+\to\pi^+$ or $e^+\to\mu^+$
$K^+\to\pi^+\pi^0+K^+\to\pi^+\pi^+\pi^-$	1.1×10^{-2}	$\pi^+\to e^+$	$\pi^+\to e^+$	$\pi^-\to e^-$
$K^+\to\pi^+\pi^0\pi^0+K^+\to\pi^+\pi^+\pi^-$	1.0×10^{-3}	$\pi^+\to e^+$	$\pi^+\to e^+$	$\pi^-\to e^-$
$K^+\to\pi^0e^+\nu+K^+\to\pi^+\pi^+\pi^-$	2.8×10^{-3}	π^+ DIF	π^- DIF	$\pi^-\to e^-$
$K^+\to\pi^0\mu^+\nu+K^+\to\pi^+\pi^+\pi^-$	1.8×10^{-3}	$\pi^+\to e^+$	$\pi^+\to e^+$	$\pi^-\to e^-$
$K^+\to\pi^+\pi^0_D+K^+\to\mu^+\nu$	1.5×10^{-3}	–	–	$e^+\to\gamma$
$K^+\to\pi^+\pi^0_D+K^+\to\pi^+\pi^0$	5.0×10^{-4}	$e^-\to\pi^-$	$e^-\to\mu^-$	π^+ DIF
$K^+\to\pi^+\pi^0\pi^0_D+K^+\to\mu^+\nu$	2.6×10^{-4}	$e^-\to\pi^-$	$e^-\to\mu^-$	direct
$K^+\to\pi^+\pi^0\pi^0_D+K^+\to\pi^+\pi^0$	8.3×10^{-5}	$e^-\to\pi^-$	$e^-\to\mu^-$	π^+ DIF
$K^+\to\pi^0\mu^+\nu+K^+\to\pi^+\pi^0_D$	8.0×10^{-5}	$e^-\to\pi^-$	$e^-\to\mu^-$	direct
$K^+\to\pi^0_D\mu^+\nu+K^+\to\pi^+\pi^0$	8.0×10^{-5}	$e^-\to\pi^-$	$e^-\to\mu^-$	direct
$K^+\to\pi^+\pi^0\pi^0+K^+\to\pi^+\pi^0_D$	4.2×10^{-5}	$e^-\to\pi^-$	$e^-\to\mu^-$	π^+ DIF
$K^+\to\pi^0_De^+\nu+K^+\to\pi^0\mu^+\nu$	2.0×10^{-5}	$e^-\to\pi^-$	–	$e^+\to\pi^+$
$K^+\to\pi^0e^+\nu+K^+\to\pi^0_D\mu^+\nu$	2.0×10^{-5}	$e^-\to\pi^-$	–	$e^+\to\pi^+$
$K^+\to\pi^0\mu^+\nu+K^+\to\pi^+\pi^0\pi^0_D$	1.4×10^{-5}	$e^-\to\pi^-$	$e^-\to\mu^-$	direct
$K^+\to\pi^0\mu^+\nu+K^+\to\pi^0_D\mu^+\nu$	1.3×10^{-5}	$e^-\to\pi^-$	–	$e^+\to\pi^+$
$K^+\to\pi^0_D\mu^+\nu+K^+\to\pi^+\pi^0\pi^0$	6.8×10^{-6}	$e^-\to\pi^-$	$e^-\to\mu^-$	direct
$K^+\to\pi^+\pi^-e^+\nu+K^+\to\pi^0\mu^+\nu$	1.4×10^{-6}	direct	π^- DIF	$\pi^-\to e^-$
$K^+\to\pi^0\pi^0e^+\nu+K^+\to\pi^+\pi^+\pi^-$	1.4×10^{-6}	π^+ DIF	π^- DIF	$\pi^-\to e^-$

LNV&LFV State-of-the-Art

NA62 searches with Run1 data



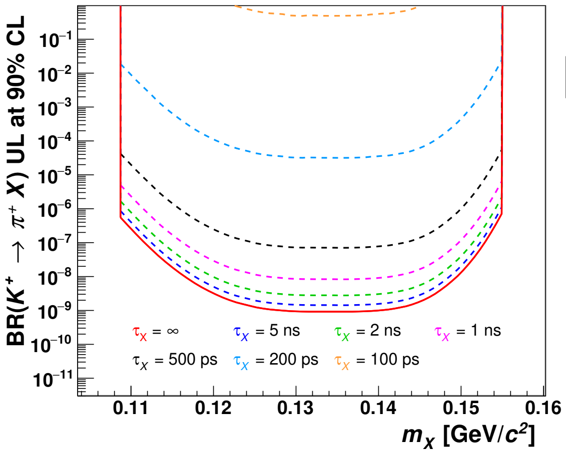
Channel	NA62 UL @ 90% CL		Improvement
$K^+ \to \pi^- e^+ e^+$	5.3×10^{-11}	Phys. Lett. B 830 (2022) 137172	factor ~12
$K^+ \to \pi^- \mu^+ \mu^+$	4.2×10^{-11}	Phys. Lett. B 797 (2019) 134794	factor ~2
$K^+ \to \pi^- \mu^+ e^+$	4.2×10^{-11}	Phys. Rev. Lett. 127 (2021) 12, 131802	factor ~12
$K^+ \to \pi^+ \mu^- e^+$	6.6×10^{-11}		factor ~8
$K^+ \to \pi^- \pi^o e^+ e^+$	8.5×10^{-11}	Phys. Lett. B 830 (2022) 137172	first search
$K^+ \to \pi^o \pi^- \mu^+ e^+$	2.9×10^{-10}	arXiv:2409.12981 Submitted to Phys. Lett. B	first search
$K^+ \to \pi^o \pi^+ \mu^- e^+$	3.1×10^{-10}		first search
$K^+ \to \pi^o \pi^+ \mu^+ e^-$	5.0×10^{-10}		first search
$K^+ \to \mu^- \nu e^+ e^+$	2.1×10^{-8}	Phys. Lett. B838 (2023) 137679	factor ~250
$\pi^o \to \mu^- e^+$	3.4×10^{-9}	Phys. Rev. Lett. 127 (2021) 12, 131802	factor ~10

Plusblished results

$K^+ \rightarrow \pi^+ X_{inv}$

Published results in
JHEP02 (2021) 201
JHEP 06 (2021) 93

- Search as a direct by product of $\pi^o \rightarrow invisible$ analysis
- Signal in $110 \leq m_X \leq 155$ MeV$/c^2$
- Main background $\pi^o \rightarrow \gamma\gamma$ rejection $\varepsilon = \left(2.8^{+5.9}_{-2.1}\right) \times 10^{-9}$



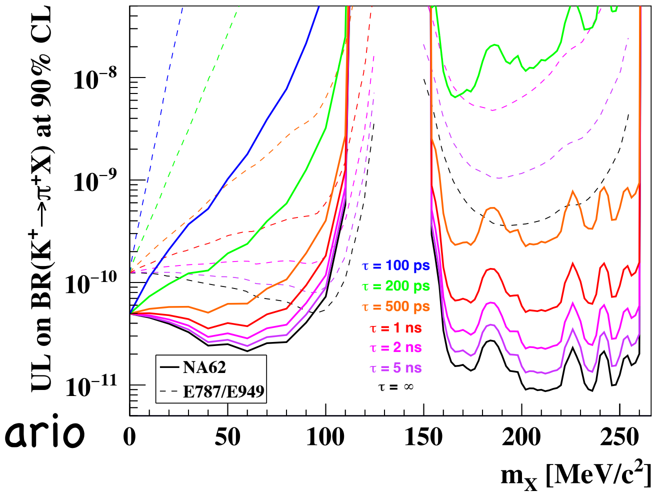
[JHEP02 (2021) 201]

$\mathbf{BR(\pi^o \rightarrow inv) < 4.4 \times 10^{-9}}$
@ 90% CL

- Search as a direct by product of main $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ analysis
- Signal in $0 \leq m_X \leq 110$ MeV$/c^2$ and $154 \leq m_X \leq 260$ MeV$/c^2$
- Main background is $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

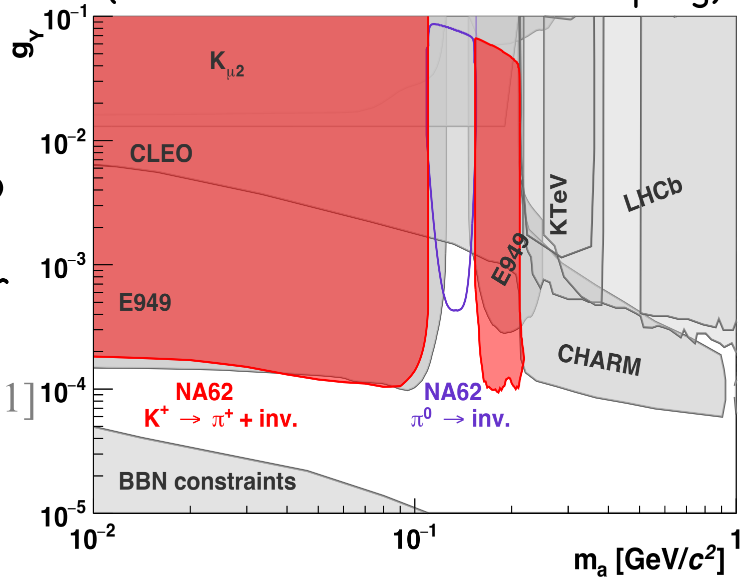
[JHEP06 (2021) 93]

NA62 Run1 results vs m_X
for different X lifetime

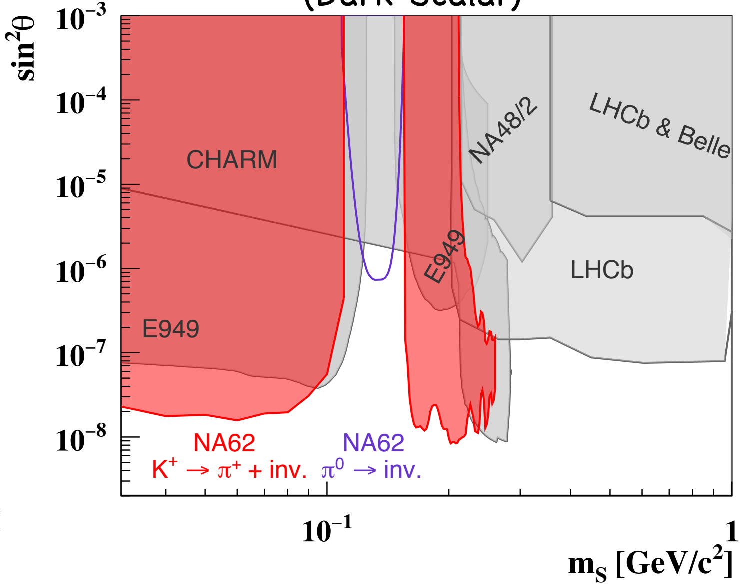


Hidden Sector scenario
from
Physics Beyond Collider
project at CERN
[J. Phys. G47 (2020) 010501]

Limits on BC10 scenario
(ALP with dominat fermion coupling)



Limits on BC4 scenario
(Dark Scalar)

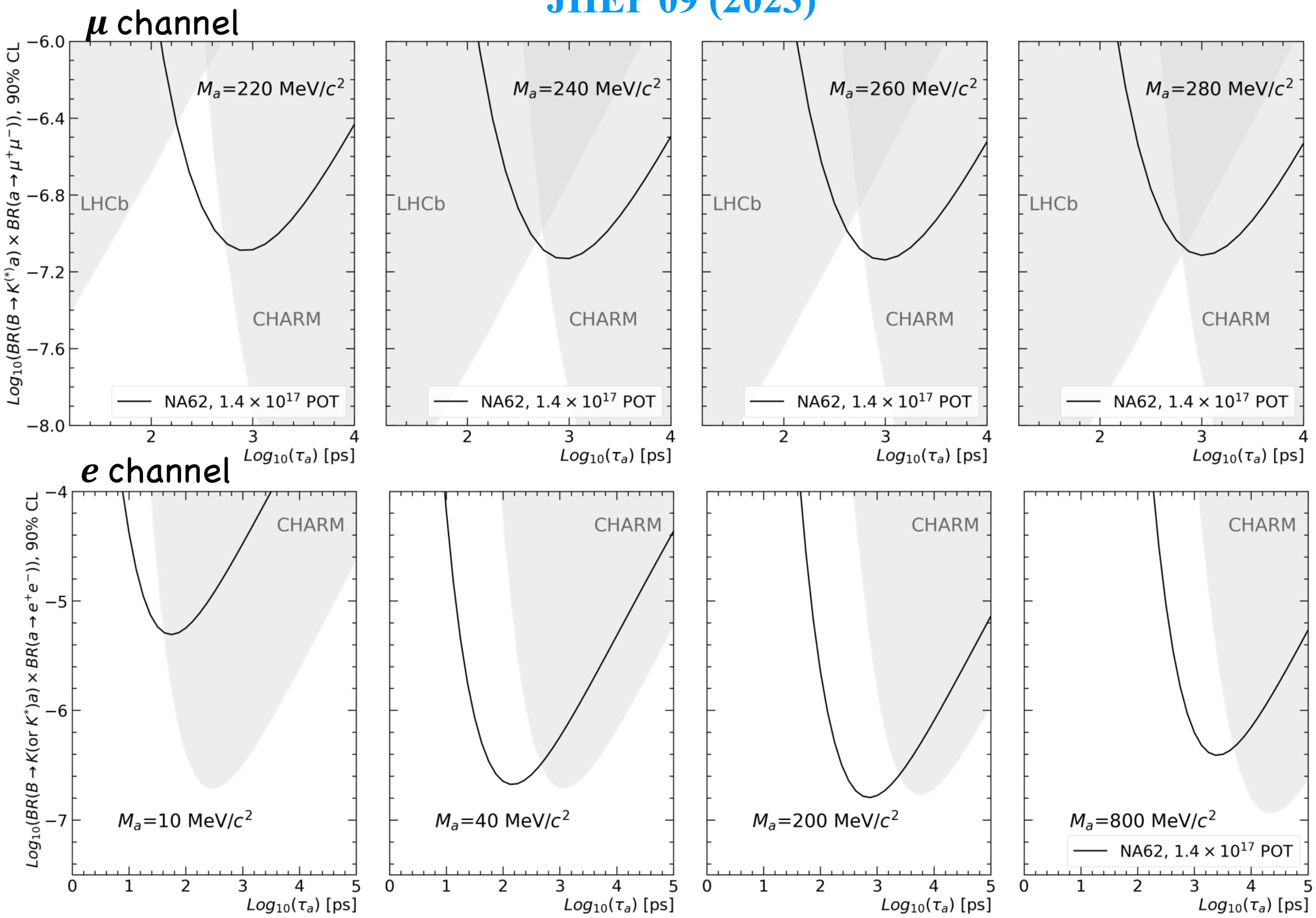


$a \to \ell^+\ell^-$

Published results in
Phys. Rev. Lett. 133 (2024) 111802
JHEP 09 (2023)

ALP search

- Production mechanism:
  B meson decay: $B \to K^{(*)}a$
- **Model independent approach**: assume mass m_a, lifetime τ_a and coupling to be independent parameters
- $\mathrm{BR}(B \to Ka)\times\mathrm{BR}(a \to \ell\ell)$ vs τ_a for each mass separately



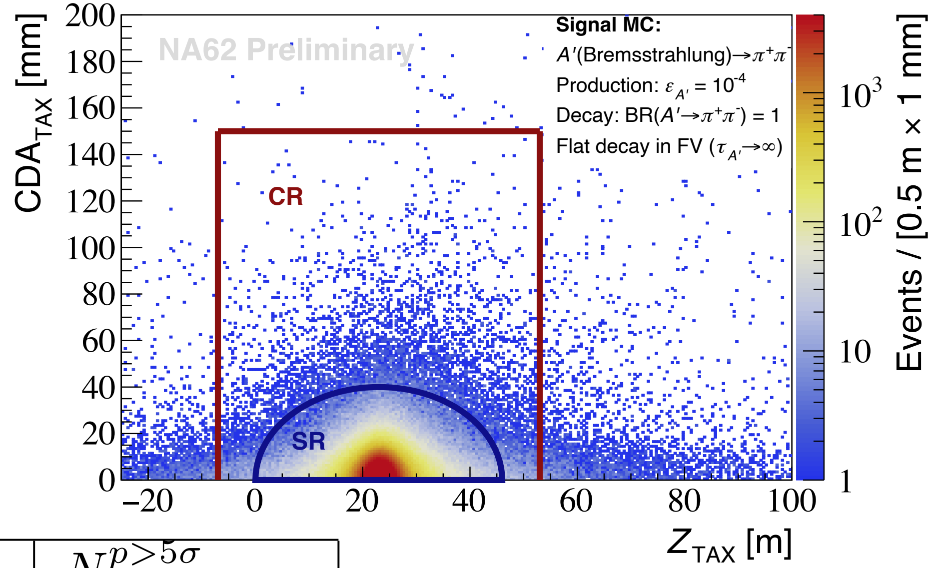
PRELIMINARY RESULTS

$X \to$ hadrons

Background sources

- Combinatorial data-driven event overlay (negligible)
- Neutrino-induced: GENIE+PYTHIA+GEANT4 (negligible)
- Prompt: data-driven+GEANT4, inelastic interaction of halo μ ($< 10^{-4}$ in all channels)
- Upstream: data-driven+GEANT4, particles selected by the GTK achromat:
  - Upstream interactions (veto by ANTI0 and vertex)
  - K_S candidates (3σ window around m_{K_S} kept masked)
  - K^+-induced background (simulated using selected single K^+ tracks forced to decay in $K^+ \to \pi^+\pi^+\pi^-$ in FV)

Example signal region for $A' \to \pi^+\pi^-$
SR: ellipse center $\{Z_{\mathrm{TAX}}, \mathrm{CDA}_{\mathrm{TAX}}\} = \{23\mathrm{m}, 0\mathrm{mm}\}$, semi-axes of $23\mathrm{m}$ and $40\mathrm{mm}$
CR: $\mathrm{CDA}_{\mathrm{TAX}} < 150\mathrm{mm}$ and $-7\mathrm{m} < Z_{\mathrm{TAX}} < 53\mathrm{m}$



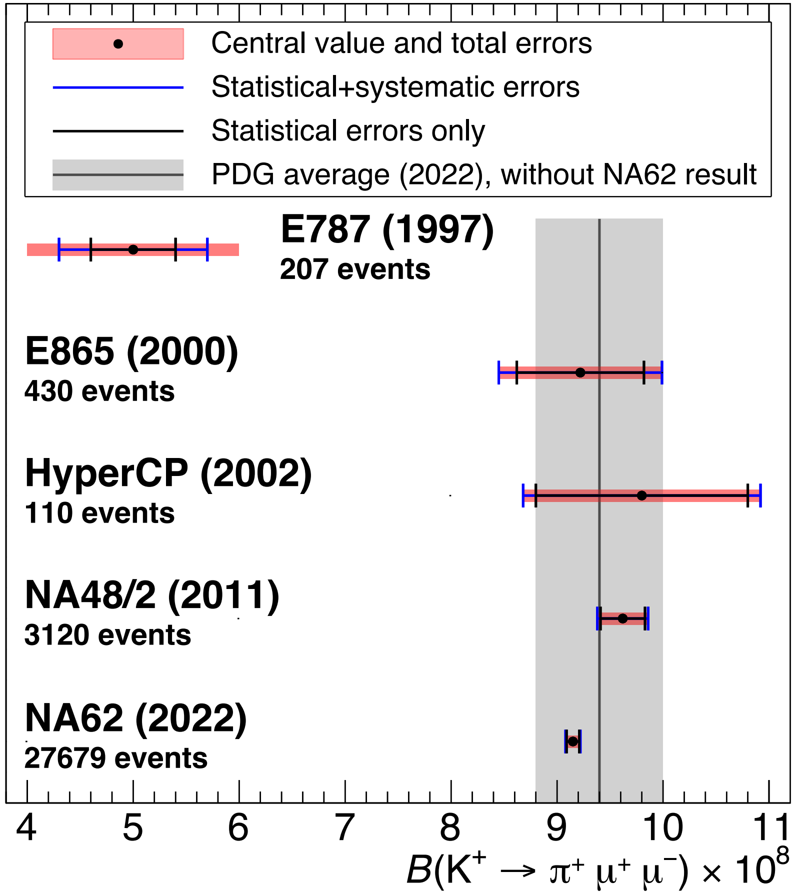
Channel	$N_{\mathrm{exp,CR}} \pm \delta N_{\mathrm{exp,CR}}$	$N_{\mathrm{exp,SR}} \pm \delta N_{\mathrm{exp,SR}}$	$N^{p>5\sigma}_{\mathrm{obs,SR}}$	$N^{p>5\sigma}_{\mathrm{obs,SR+CR}}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0})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

Summary of background expectation (68% CL) for each final state and minimum number of observed events for a background-only p-value above 5σ

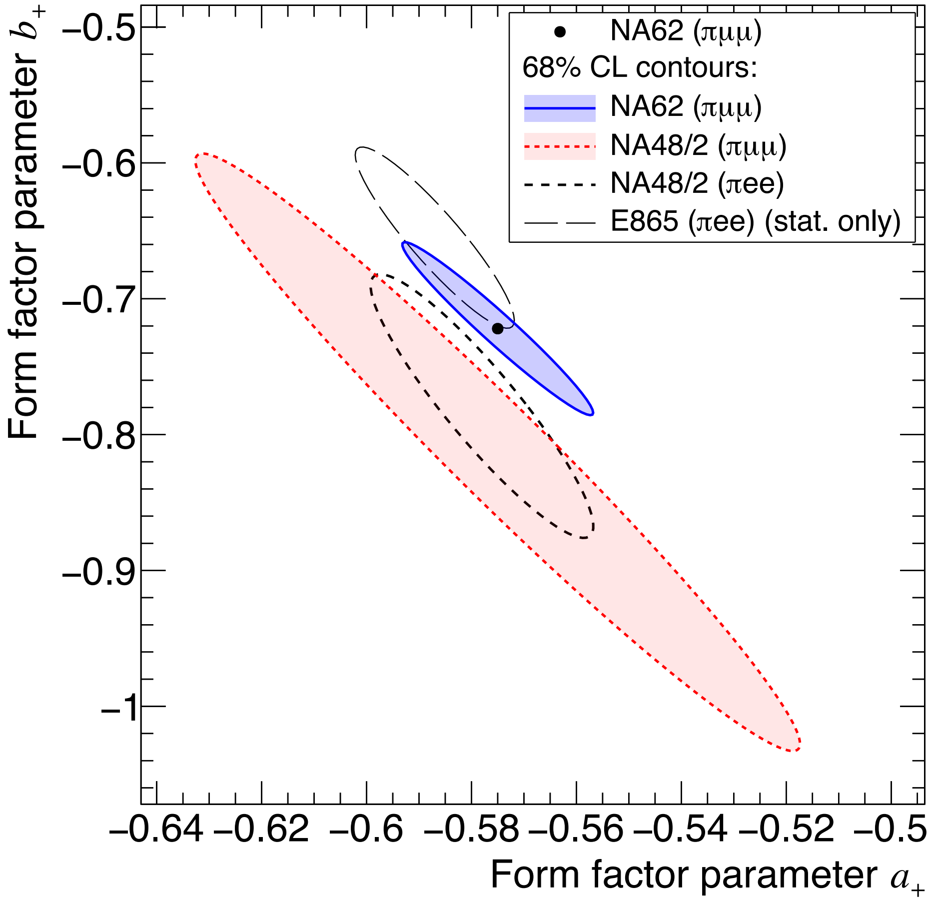
$K^+ \to \pi^+\mu^+\mu^-$

Published results in
JHEP11 (2022) 011

- Model-independent BR
  - $\mathbf{BR(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \times 10^{-8}}$
  - **Improvement by a factor ≥ 3**
  - Consistent with previous measurements



- ChPT form factor parameter
  - $a_+ = -0.575 \pm 0.013,\ b_+ = -0.722 \pm 0.043$
  - **Compatible with previous measurements (as expected by LFU) in $\mu\mu$ and ee channel**

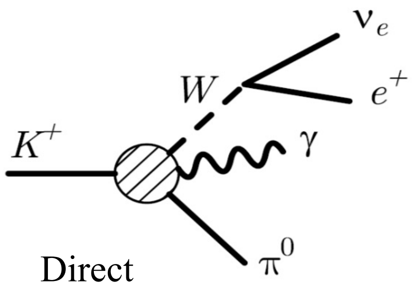


$K^+ \to \pi^o e^+ \nu\gamma$

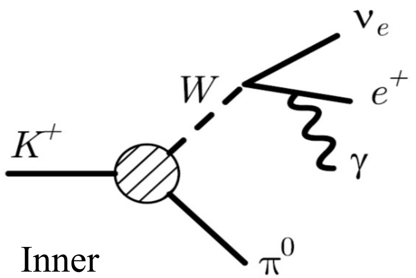
Published results in
JHEP09 (2023) 040

- Decay described in ChPT as direct emission, inner bremsstrahlung and their interference
- BR strongly **depends on E_γ and $\theta_{e\gamma}$** cuts in K^+ rest frame
- **Three kinematic regions** considered

$$R_j = \frac{\mathrm{BR}(K^+ \to \pi^o e^+ \nu\gamma \mid E_\gamma^j, \theta_{e,\gamma}^j)}{\mathrm{BR}(K^+ \to \pi^o e^+ \nu)}$$



Direct Emission



Inner Bremsstrahlung

- Test of **T-conservation** via T-odd variable

$$\xi = \frac{\vec{p_\gamma}\cdot(\vec{p_e}\times\vec{p_\pi})}{m_K^3}, \; A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

State of the art:

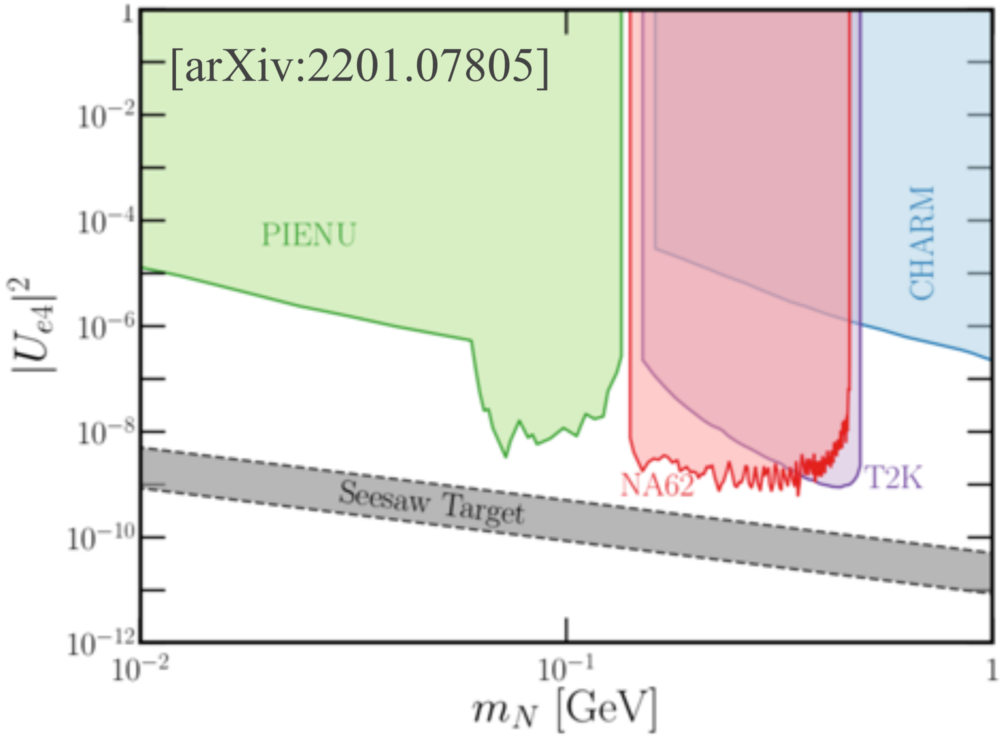
	E_γ^j, $\theta_{e\gamma}^j$	$\mathcal{O}(p^6)$ ChPT [EPJ C 50 (2007)]	ISTRA+ [PAN 70 (2007)]	OKA [EPJ C 81 (2021)]
$R_1 \times 10^2$	$E_\gamma > 10$ MeV, $\theta_{e\gamma} > 10°$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
$R_2 \times 10^2$	$E_\gamma > 30$ MeV, $\theta_{e\gamma} > 20°$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$
$R_3 \times 10^2$	$E_\gamma > 10$ MeV, $0.6 < \cos\theta_{e\gamma} < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

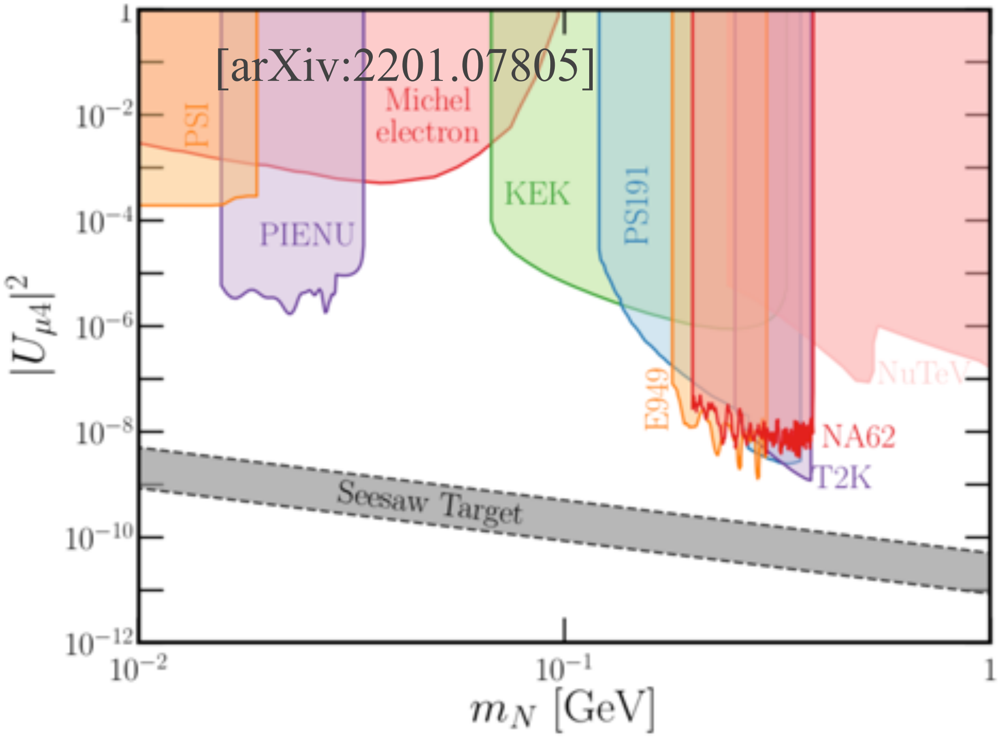
NA62 measurements of R_j smaller than $\mathcal{O}(p^6)$ ChPT by 5% relative (disagreemenr: 3 standard deviations)
Improvement on experimental precision of R_j measurements by a factor > 2

	range 1	range 2	range 3
$R \times 10^2$	$1.715 \pm 0.005_{\mathrm{stat}} \pm 0.010_{\mathrm{syst}}$	$0.609 \pm 0.003_{\mathrm{stat}} \pm 0.006_{\mathrm{syst}}$	$0.533 \pm 0.003_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}}$
$A_\xi \times 10^2$	$-0.1 \pm 0.3_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}}$	$-0.3 \pm 0.4_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}}$	$-0.9 \pm 0.5_{\mathrm{stat}} \pm 0.4_{\mathrm{syst}}$

$K^+ \to \ell^+ N$

NA62 Coll., Phys. Lett. B 807 (2020) 135599 (e channel)
NA62 Coll., Phys. Lett. B 816 (2021) 136259 (μ channel)





NA62 results:

- $|U_{e4}|^2$ **UL** $\mathcal{O}(10^{-9})$ complimentary to search for $\pi^+ \to e^+ N$
- $|U_{\mu 4}|^2$ **UL** $\mathcal{O}(10^{-8})$ complimentary to search for $\pi^+ \to \mu^+ N$
- Muon channel extension:
  - $\mathbf{K^+ \to \mu^+ \nu X}$ scalar or vector with $m_X \in 10 - 310$ MeV/c^2 **UL** $\mathcal{O}(10^{-5} - 10^{-7})$
  - $\mathbf{BR(K^+ \to \mu^+ \nu \nu \bar{\nu}) < 1.0 \times 10^{-6}}$ @ 90% CL

NA62 Coll., Phys. Lett. B816 (2021) 136259