Recent Results from NA62 Experiment

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TRIUMF
on behalf of the NA62 Collaboration

Lake Louise Winter Institute 2024
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Chateau Lake Louise

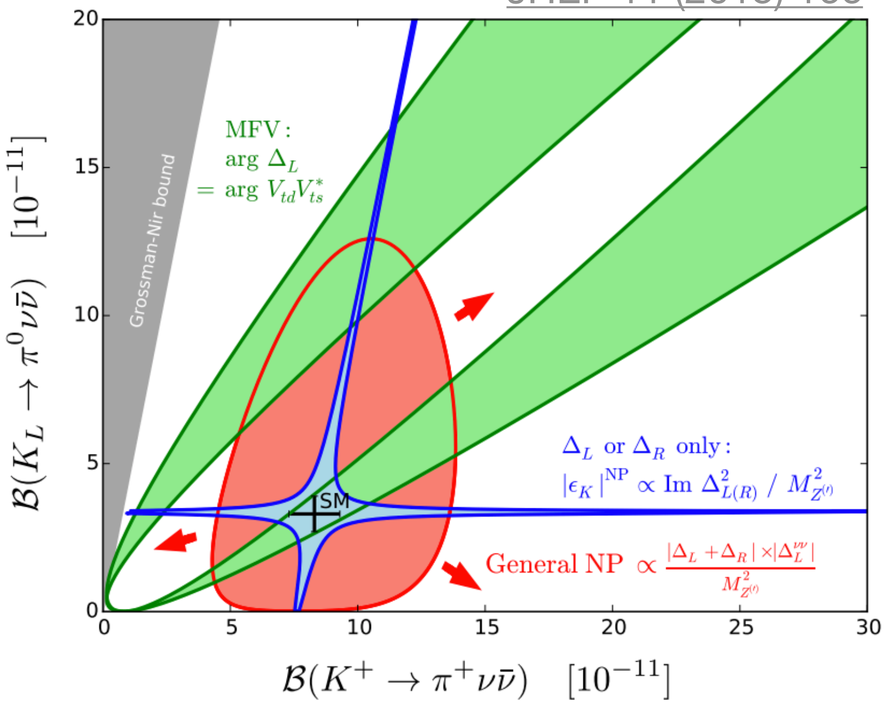
TRIUMF is located on the traditional, ancestral, and unceded territory of thexʷməθkʷəy̓əm (Musqueam) people, who for millennia have passed on their culture, history, and traditions from one generation to the next on this site.

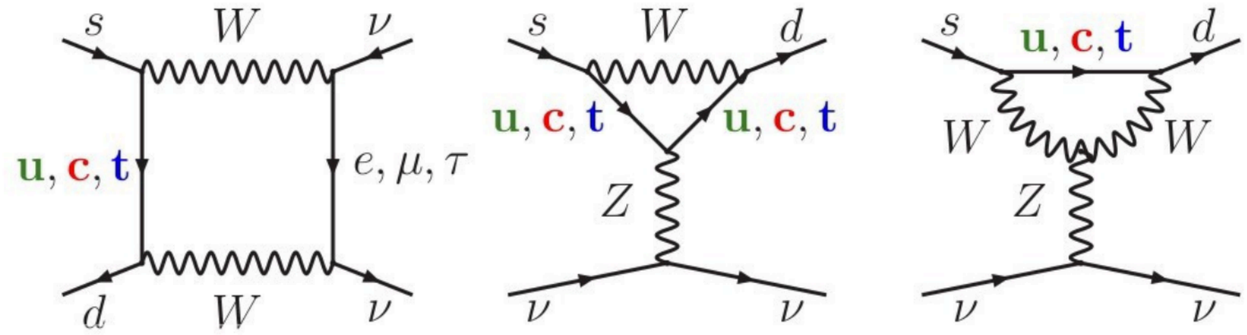
$K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

- FCNC loop process:
  - $s \to d$ coupling and highest CKM suppression
- Theoretically clean:
  - Minimal hadronic uncertainties
  - Hadronic matrix element extracted from the well-known $K^+ \to \pi^0 e^+ \nu$
- Possibly sensitive to new physics at O(100 TeV): Leptoquark, Z', Little Higgs w/ T-parity, Supersymmetry…

arXiv:1802.00786 JHEP 02 (2018) 101 JHEP 12 (2020) 097 JHEP 11 (2015) 166 EPJC 76 (2016) 182 PTEP 12 (2016) 123B02

JHEP 11 (2015) 166





arXiv:2205.01118

Decay mode	$\mathcal{B}_{\rm SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\bar{\nu}$	8.60 ± 0.42
$K_L \to \pi^0 \nu\bar{\nu}$	2.94 ± 0.15

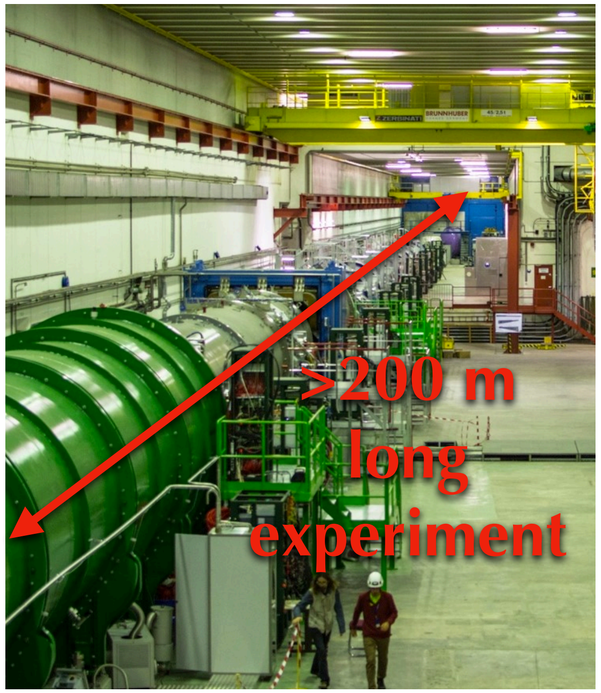
NA62: Kaon Experiment @ CERN SPS

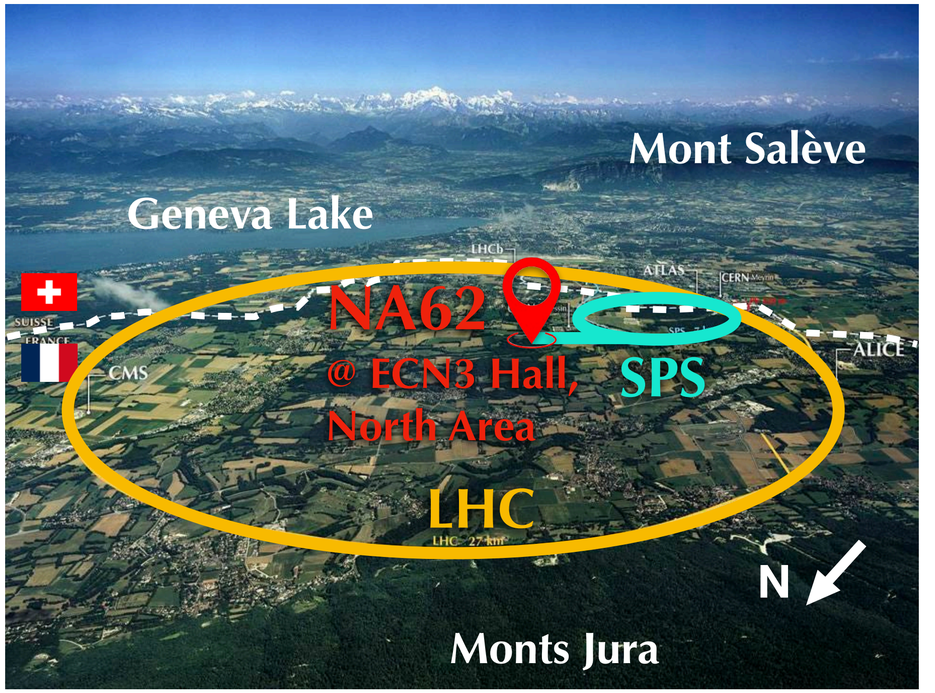
The CERN K^+ factory:

- **Fixed target** experiment at **CERN SPS North Area**
- Kaon **decay-in-flight** technique

Main goal:

- measure $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ with $\mathcal{O}(15\%)$ **precision**





Theoretical prediction: arXiv:2205.01118

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

Latest NA62 result: JHEP06 (2021) 093

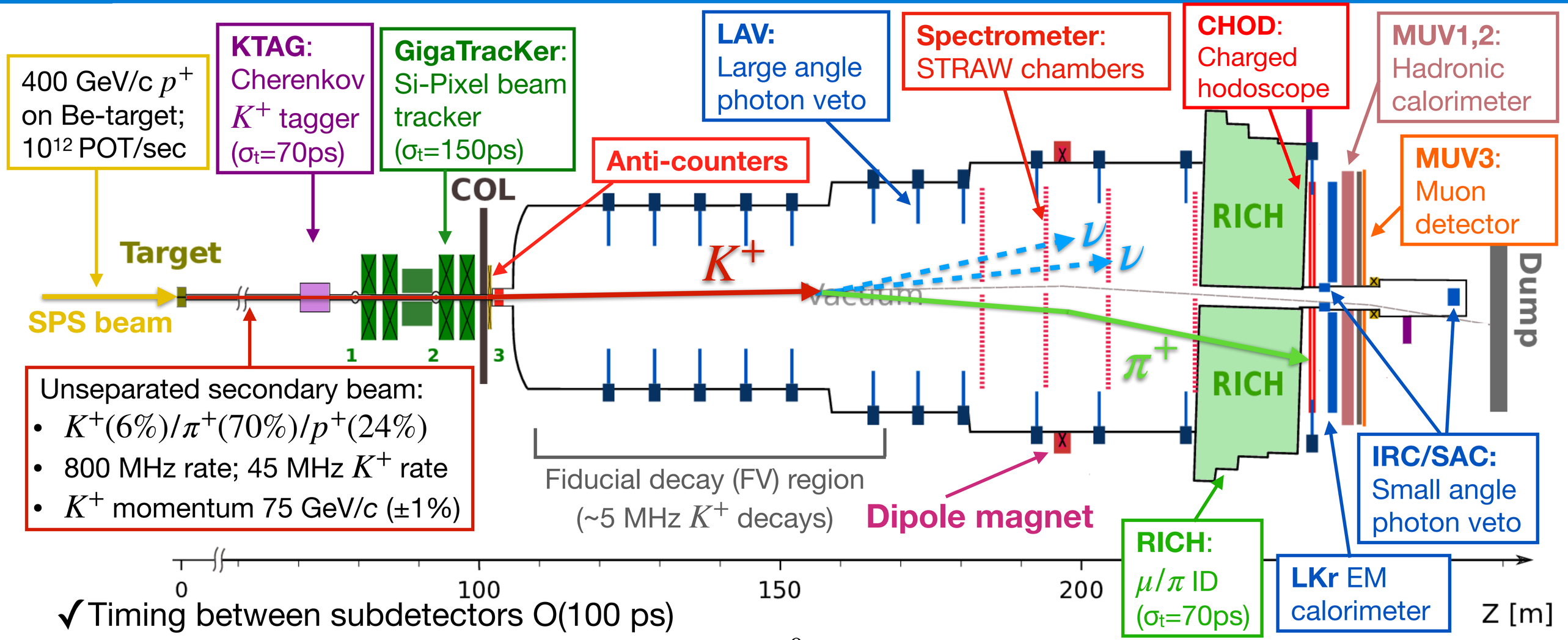
$$\mathcal{B}_{\mathrm{meas}}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4\,\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$$

at 68% CL (3.4σ significance)

Earlier CERN Kaon experiments	NA62 R_K phase	NA62 Run 1	NA62 Run 2
since 1986	2007-08	2016-18	2021- Present

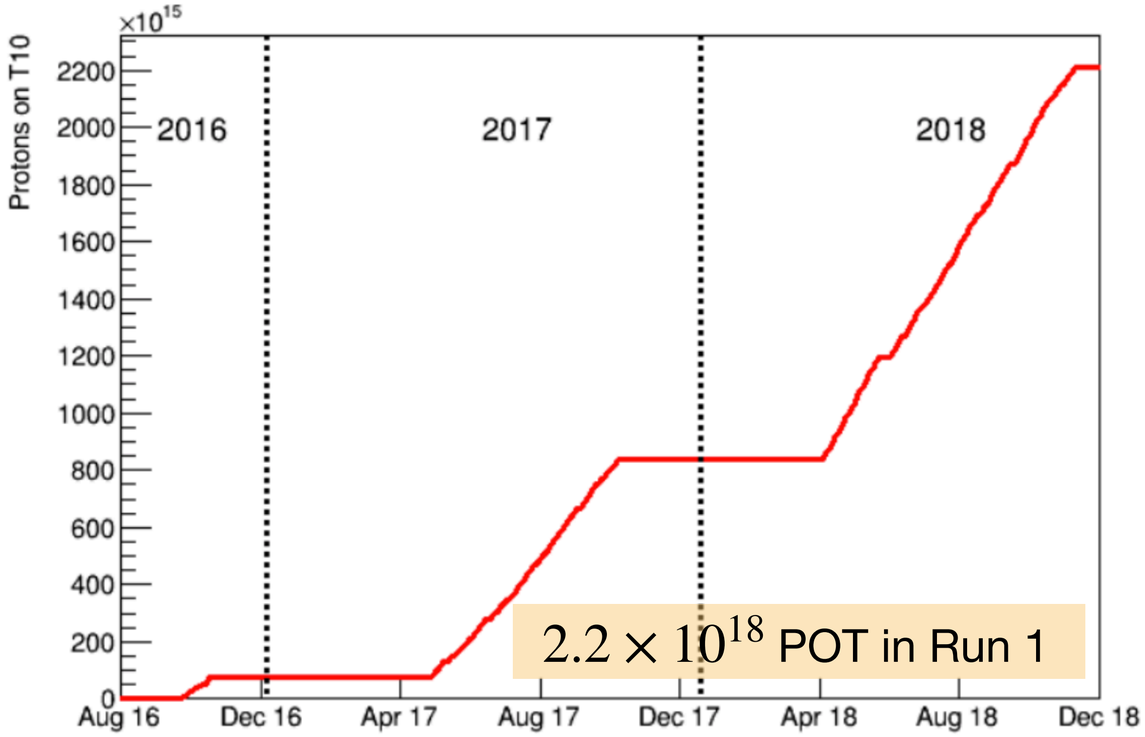
The NA62 Beam and Detector

JINST 12 (2017) P05025



- ✓ Timing between subdetectors O(100 ps)
- ✓ Kinematic rejection factor O(10^4) for $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$
- ✓ Hermetic photon veto (LAV+LKr+IRC+SAC): $\pi^0 \to \gamma\gamma$ suppression factor O(10^8) from $K^+ \to \pi^+\pi^0$
- ✓ Particle ID (RICH+LKr+HAC+MUV): muon suppression factor O(10^7) from $K^+ \to \mu^+\nu$

NA62 Data Taking



Run 1 physics data taking:

Physics run	Days of data taking	Nominal intensity	Useful kaon decays
2016	30	40%	2×10^{11}
2017	161	60%	2×10^{12}
2018	217	60%	4×10^{12}

Run 2 physics data taking:

2021: ~100 days of physics run (100% nom. intensity)
w/ 10 days of beam dump mode

2022: ~200 days of physics run (100% nom. intensity)

2023: ~150 days of physics run (70-100%% nom. intensity)
w/ 14 days of beam dump mode

Data-taking ongoing for NA62 Run 2
(two more years until Long Shutdown 3)

Broad Physics Programme @ NA62

NA62 Run 1& Run 2 Physics Results

Precision Measurements

★ $K^+ \to \pi^+\gamma\gamma$ **This talk**
Phys. Lett. B 850 (2024) 138513

★ $K^+ \to \pi^0 e^+ \nu\gamma$
JHEP 09 (2023) 040

• $K^+ \to \pi^+\mu^+\mu^-$
JHEP 11 (2022) 011

• $K^+ \to \pi^+\nu\bar{\nu}$
JHEP 06 (2021) 093

Rare decay process & Lepton Number/Flavour Violation Searches

★ $K^+ \to \pi^+ e^+ e^- e^+ e^-$ **This talk**
Phys. Lett. B 846 (2023) 138193

★ $K^+ \to \mu^- \nu e^+ e^+$
Phys. Lett. B 838 (2023) 137679

• $K^+ \to \pi^-(\pi^0) e^+ e^+$
Phys. Lett. B 830 (2022) 137172

• $K^+ \to \pi^-\mu^+e^+, K^+ \to \pi^+\mu^-e^+,$ $\pi^0 \to \mu^- e^+$
Phys. Rev. Lett. 127 (2021) 131802

• $K^+ \to \pi^-\mu^+\mu^+$
Phys. Lett. B 797 (2019) 134794

Hidden Sector Searches

★ $A' \to e^+e^-$
arXiv: 2312.12055

★ $A' \to \mu^+\mu^-$
JHEP 09 (2023) 035

} **This talk**

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

• $K^+ \to \pi^+ X$
JHEP 03 (2021) 058
JHEP 02 (2021) 201

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

• $\pi^0 \to A'\gamma$
JHEP 05 (2019) 182

- Recent results published in 2023-24 are marked by ★)

Measurement of $K^+ \to \pi^+\gamma\gamma$ decay

Phys. Lett. B 850 (2024) 138513

- A crucial precision test of chiral perturbation theory (ChPT) in rare Kaon decays
- Both decay spectrum and rate strongly depend on **an unknown real parameter** $\hat{c}$
- Decay width of $K^+ \to \pi^+\gamma\gamma$ in ChPT $\mathcal{O}(p^6)$ [Phys. Lett. B 386 (1996) 403] :

$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_K}{(8\pi)^3}\left[z^2\left(\left|A(\hat{c},z,y^2)+B(z)\right|^2+\left|C(z)\right|^2\right)+\left(y^2-\frac{1}{4}\lambda\left(1,r_\pi^2,z\right)\right)^2\left|B(z)\right|^2\right]$$

$$y = \frac{P_K\left(P_{\gamma 1}-P_{\gamma 2}\right)}{m_K^2} \qquad z = \frac{m_{\gamma\gamma}^2}{m_K^2} \qquad r_\pi = \frac{m_\pi}{m_K}$$

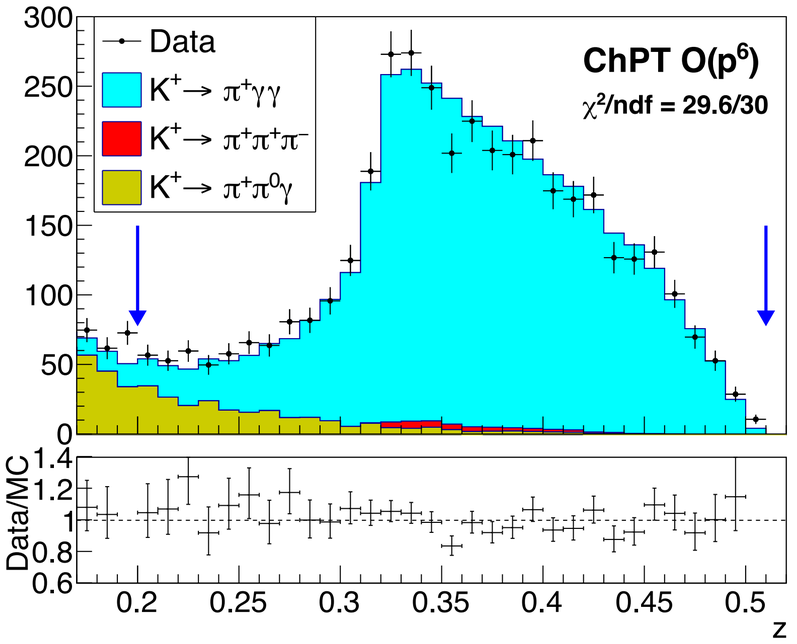
$A(\hat{c},z,y^2)$ and $B(z)$ are loop diagram contributions

$C(z)$ is the pole contribution, which is at a few percent to the total decay rate

- Analyzed with Run 1 data (2017-18)
- Normalization channel: $K^+ \to \pi^+\pi^0$ $(0.04 < z < 0.12)$
- Number of K^+ decays in FV $= (5.55 \pm 0.03) \times 10^{10}$

- SR: (i) $K^+ - \pi^+$ matching tracks, (ii) 2 γ's in the LKr Calorimeter, (iii) $0.2 < z < 0.51$
- Expected bkg events in SR $= (291 \pm 14)$
- A total of **3984** $K^+ \to \pi^+\gamma\gamma$ **candidates** observed in data

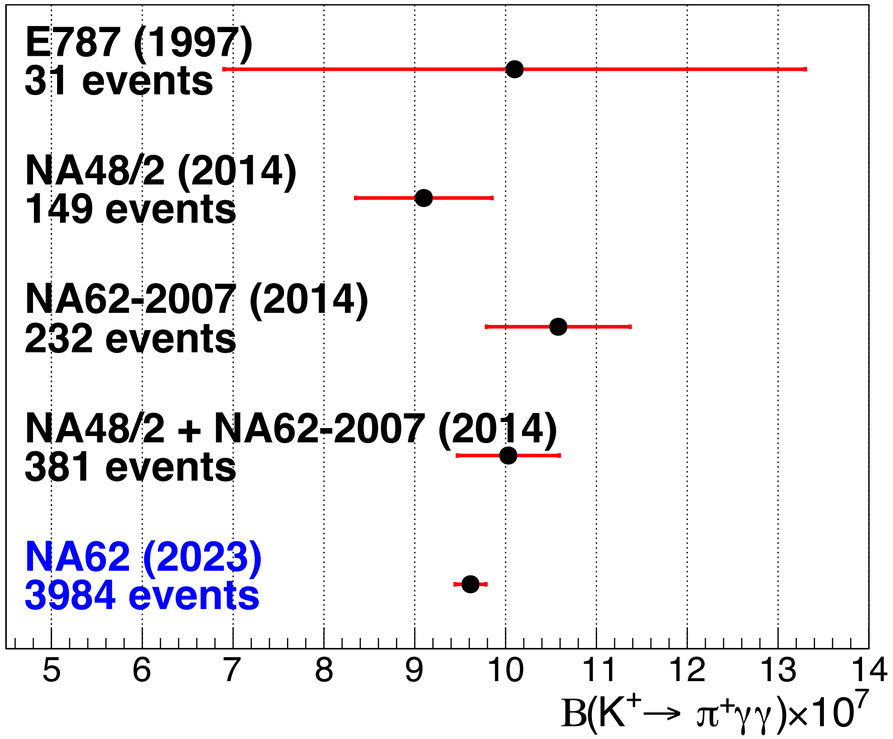
Model-independent measurement performed by reweighing MC spectrum for different values of $\hat{c}$ and extracting the best-fit $\hat{c}$ value.

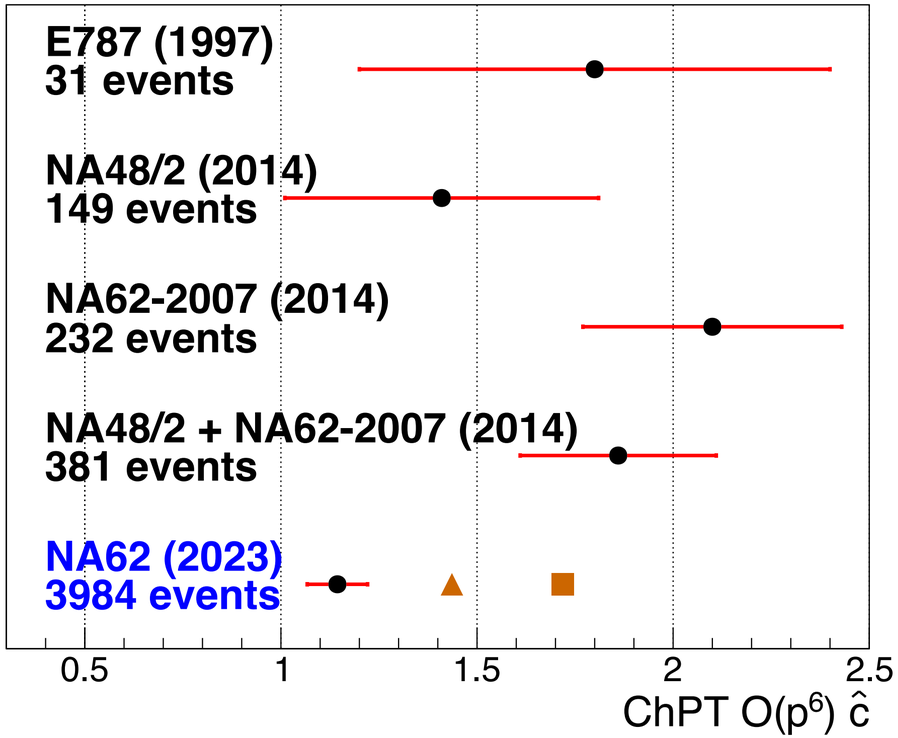


Measurement of $K^+ \to \pi^+\gamma\gamma$ decay

Phys. Lett. B 850 (2024) 138513

- Results:





▲ Result using external parameters for E787 measurement

■ Result using external parameters for NA48/2 and NA62-2007 measurements

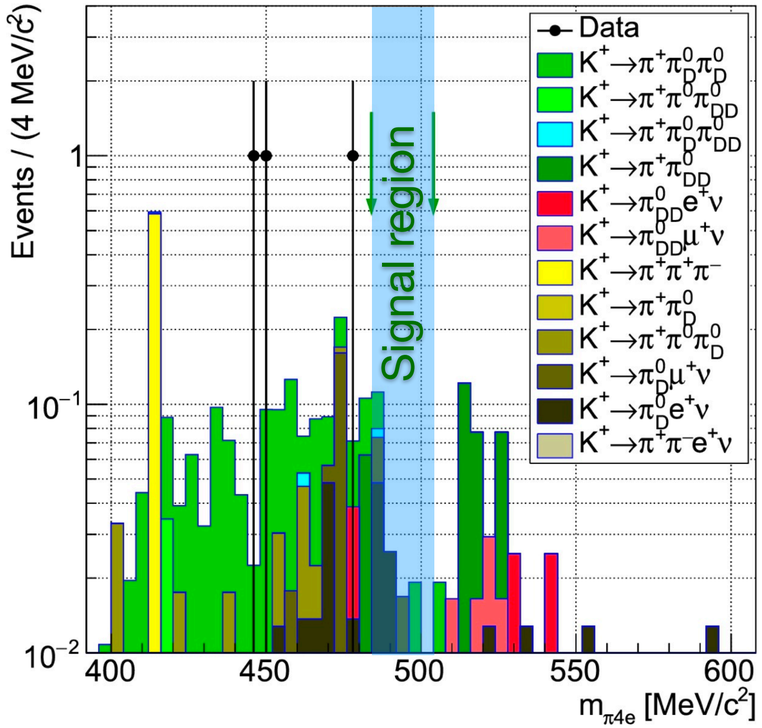
- $\hat{c} = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$
- $\mathcal{B}(K^+ \to \pi^+\gamma\gamma) = (9.61 \pm 0.15_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$
- **A factor of three improvement** in precision over previous measurements

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

Phys. Lett. B 846 (2023) 138193

- $K^+ \to \pi^+ e^+ e^- e^+ e^-$ ($K_{\pi 4e}$) is a heavily suppressed process (outside the π^0 pole) in SM
  - $\mathcal{B}(K_{\pi 4e}, \text{non res.}) = (7.2 \pm 0.7) \times 10^{-11}$ [Phys. Rev. D106 (2022) L071301]
- Excellent probe for various dark-sector mediators [Phys. Rev. D105 (2022) 015017]
  - prompt cascade decay process involving a **dark scalar** S decaying into **dark photon pair** A'
    $K^+ \to \pi^+ S,\ S \to A'A', A' \to e^+e^-$
  - **short-lived QCD axions** a via the $K^+ \to \pi^+ aa,\ a \to e^+e^-$ process
    - If $m_a = 17\,\text{MeV}$, $\mathcal{B}(K^+ \to \pi^+ aa) > 2 \times 10^{-8}$ is predicted

Potential explanation to the 17 MeV Anomaly in Beryllium Nuclear Decays
[Phys. Rev. D103 (2021) 055018]



- Analyzed with Run 1 data (2017-18)
- Normalization channel: $K^+ \to \pi^+ \pi^0, \pi^0 \to e^+e^-e^+e^-$ $\left(K_{2\pi DD}\right)$
- Number of K^+ decays in fiducial volume
  $= (8.58 \pm 0.19_{\text{stat}} \pm 0.07_{\text{MC}} \pm 0.41_{\text{ext}}) \times 10^{11}$

- SR: Box cut on invariant mass $m_{\pi 4e}$ around K^+ mass while excluding π^0 mass peak in $m^2_{\text{miss}} \equiv \left(P_{K^+} - P_{\pi^+}\right)^2$ to reject $K_{2\pi DD}$ events.
- Expected bkg events in SR $= 0.18 \pm 0.14$
- **Zero $K_{\pi 4e}$ candidates observed**
- $\mathcal{B}(K_{\pi 4e}, \text{non res.}) < 1.4 \times 10^{-8}$ @ 90% CL

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

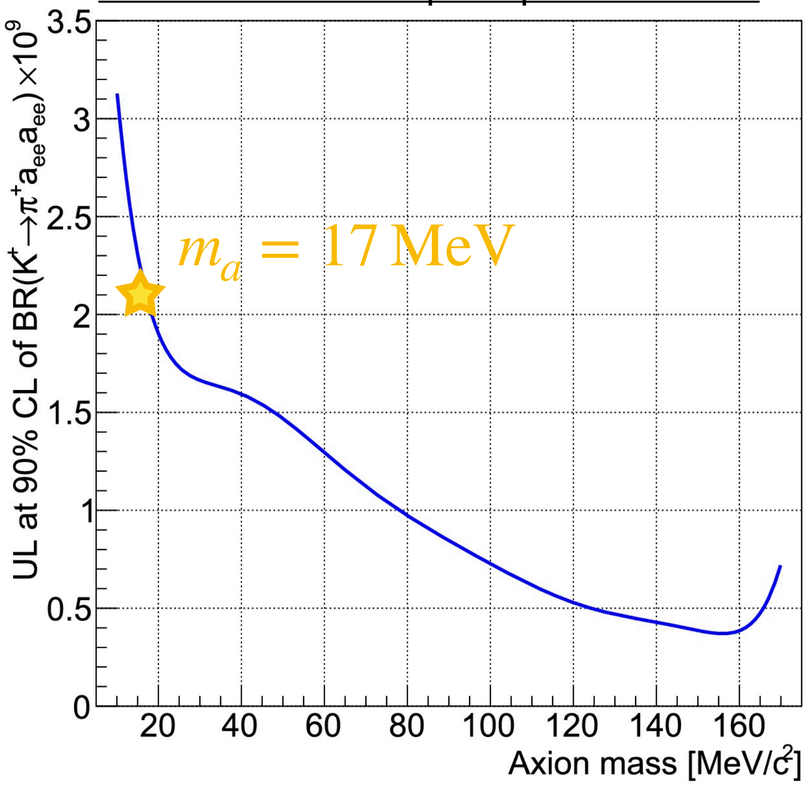
Phys. Lett. B 846 (2023) 138193

- In addition to $K_{\pi 4e}$ selection, require consistency between the masses of two e^+e^- pairs
  - Expected bkg events in SR $= (0.0004 \pm 0.0004)$
  - Zero candidates observed in SR

- $\mathcal{B}(K^+ \to \pi^+ aa) \times \left[\mathcal{B}(a \to e^+e^-)\right]^2 < 2.1 \times 10^{-9}$ at 90% CL for $m_a = 17\,\mathrm{MeV}$
- **Excludes the QCD axion as possible explanation of the 17 MeV Be anomaly (requires $\mathcal{B}(K^+ \to \pi^+ aa) > 2 \times 10^{-8}$)**

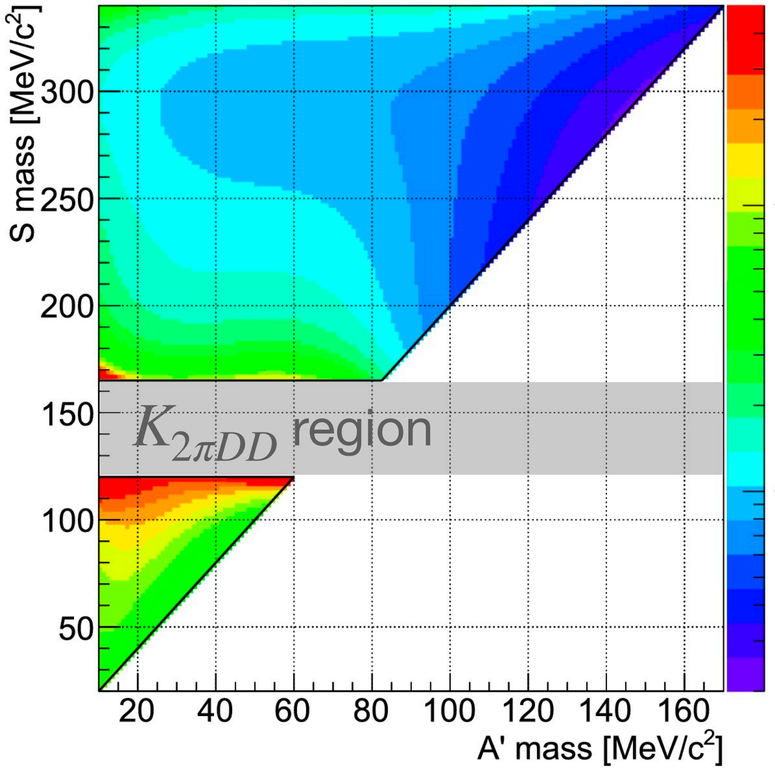
Short-lived QCD axion

$K^+ \to \pi^+ aa$ with prompt $a \to e^+e^-$



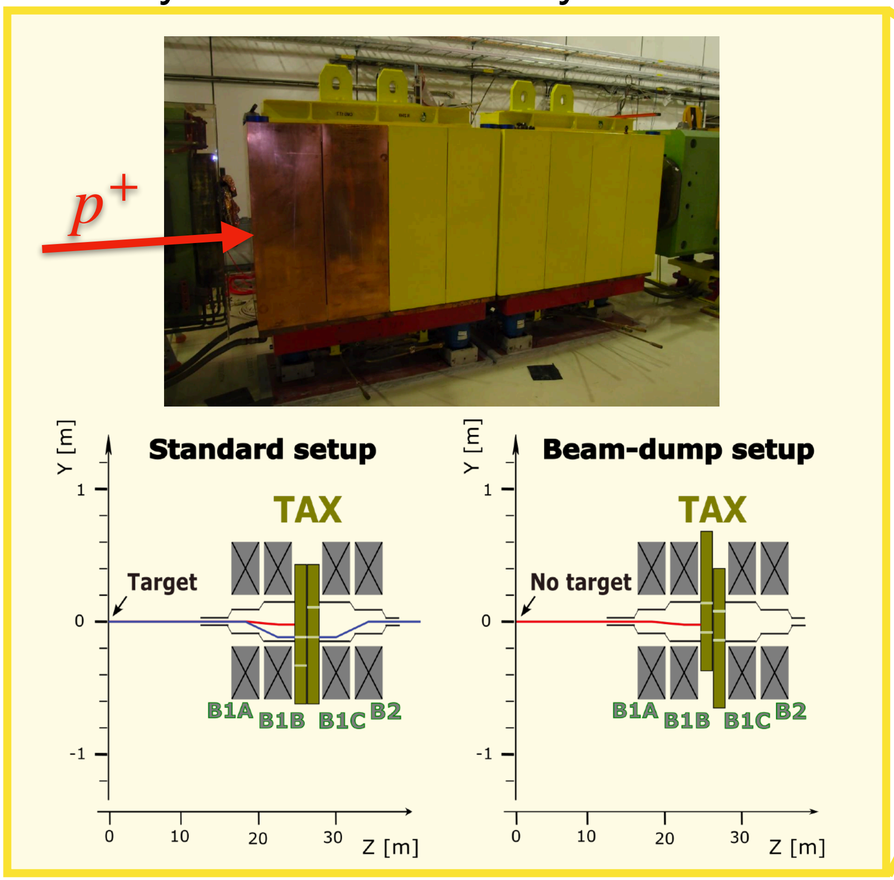
Prompt dark cascade decay

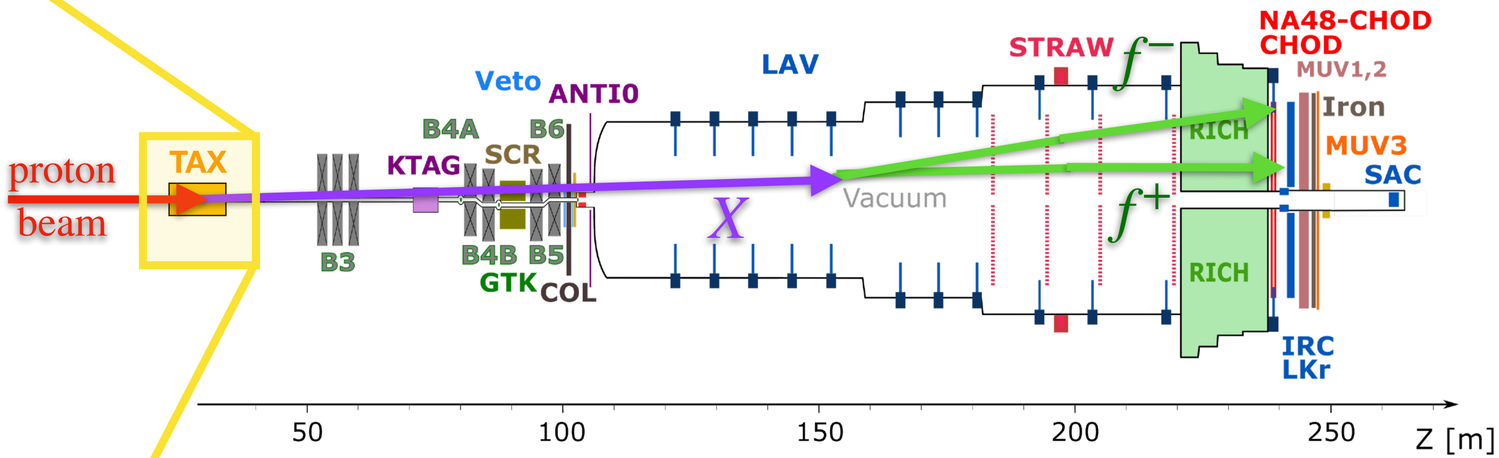
$K^+ \to \pi^+ SS, S \to A'A', A' \to e^+e^-$



Beam dump mode of NA62

- The bump-dump physics programme was introduced in 2021 for hidden sector searches
  - K12 beamline Be target (T10) is moved away from the beam
  - **3.2 m Cu-Fe collimators (TAX)** with misaligned apertures act as the **beam-dump target**
  - **TAX magnets** and additional upstream magnets are used to **eliminate halo muons**
  - Primary 400 GeV proton beam from the SPS (170% nominal intensity) impinges directly on the TAX, leaving only neutrinos and any neutral exotic particles propagating into the fiducial volume





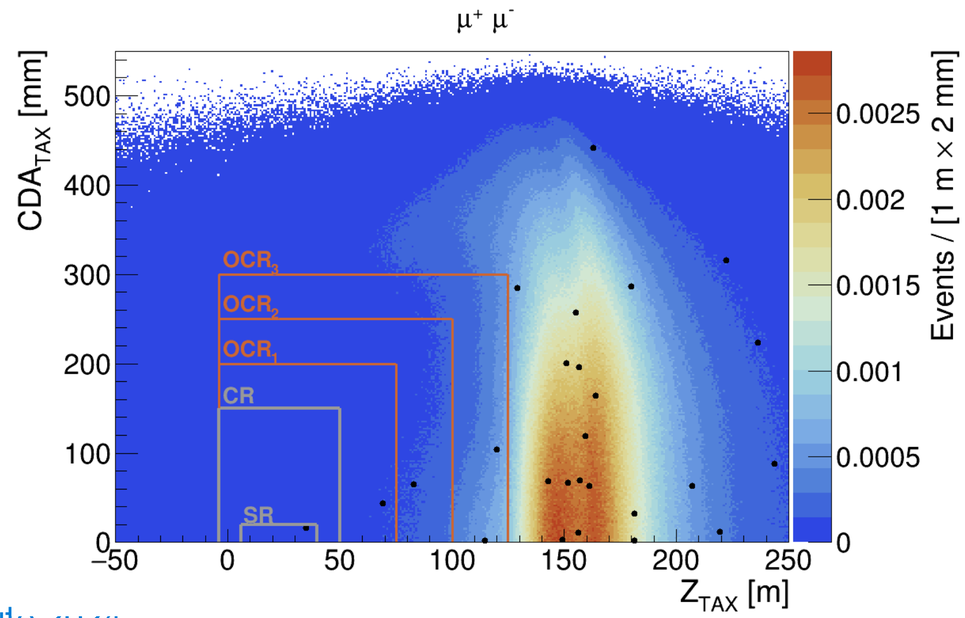
Configuration can be switched between nominal physics run and beam dump mode **within $\mathcal{O}$(min)**

Search for dark photon $A' \to \ell^+\ell^-, \ell = e/\mu$

arXiv: 2312.12055
JHEP09(2023)035

- Search for feebly interacting dark photon A' decaying to SM fermions with coupling ϵ
  - NA62 beam dump mode could detect direct dark photon production, where ϵ is in the range of $[10^{-7},\ 10^{-5}]$ and $M_{A'}$ is in the range of MeV/c^2 to GeV/c^2
  - **For $M_{A'} < 700\,\mathrm{MeV}/c^2$, the dominant decay channels of dark photon are di-lepton modes**
- Analyzed with $(1.40 \pm 0.28) \times 10^{17}$ POT collected in 10 days of beam dump runs in 2021
- Dominant background sources:
  - Combinatorial background (for μ-channel): **accidental pairing of unrelated μ or e** from different primary proton interactions
  - Prompt background (for e-channel): **lepton pairs ($\mu\mu/ee/\mu e$) from secondary interactions** of incident muons in traversed material

- Selections:
  - 2 in-time lepton tracks ($\mu\mu/ee$)
  - Good decay vertex reconstruction between the 2 tracks and the primary beam nominal path
- SR and CR defined with **two key variables**:
  - $\mathrm{CDA_{TAX}} \equiv$ **distance of closest approach between the output tracks and the beam path**
  - $Z_{\mathrm{TAX}} \equiv$ **longitudinal position of the decay vertex**

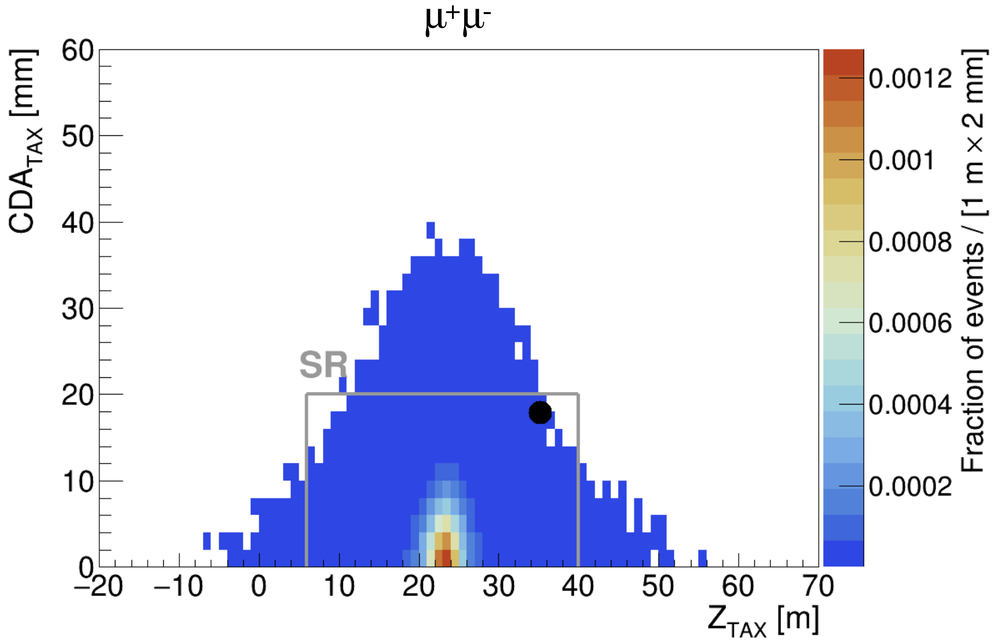


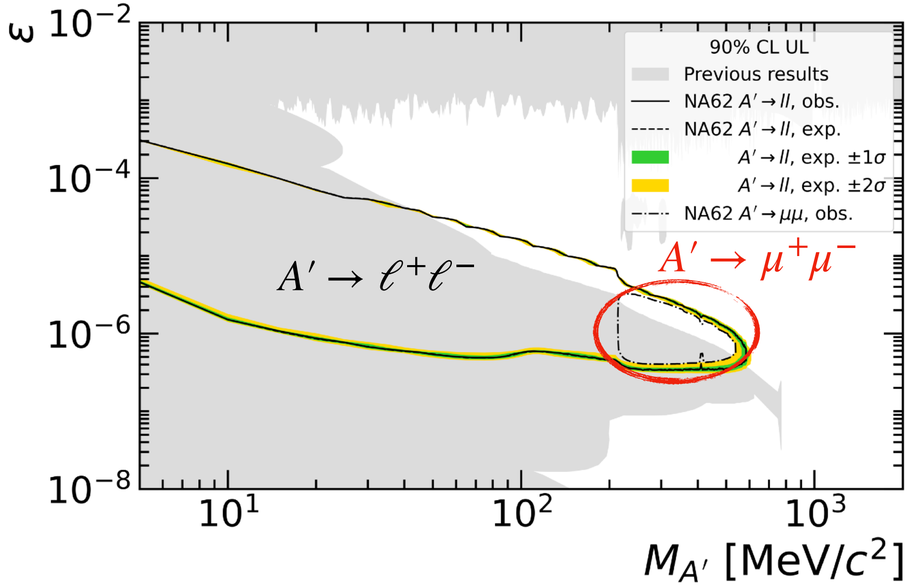
Search for dark photon $A' \to \ell^+\ell^-, \ell = e/\mu$

arXiv: 2312.12055
JHEP09(2023)035

- Results:

- Expected bkg events in μ-SR $= 0.016 \pm 0.002$
- Expected bkg events in e-SR $= 0.0094^{+0.0206}_{-0.0072}$
- Zero candidates observed in the both neighbouring μ-/e-CR
- **Zero candidates observed in the e-SR**
- **One candidate observed in the μ-SR**, with invariant mass of $411\,\mathrm{MeV}/c^2$ (2.4σ global significance)
  - $\Delta t(\mu^+, \mu^-) = 1.69\,\mathrm{ns}$, which is at 2σ from the mean
  - Located near the edge of the SR





- **Exclusion limits at 90% CL are interpreted in the $(M_{A'}, \epsilon)$-plane**
  - Extended the limits of previous experiments in the mass range $215 - 550\,\mathrm{MeV}/c^2$ for $\epsilon \sim \mathcal{O}(10^{-6})$
- **Exclusion limits** are also placed on **axion-like particle model**, where the result is found to improve on previous limits for masses of $< 280\,\mathrm{MeV}/c^2$ ($10 - 800\,\mathrm{MeV}/c^2$) in the e- (μ-) channel

Summary & Outlook

Measurement of $K^+ \to \pi^+\gamma\gamma$ decay

- A factor of three improvement in precision over previous measurements
- Interpretation of the results for axion-like particle search is also reported

Search for BSM $K_{\pi 4e}$

- First search for $K_{\pi 4e}$ → Exclusion limit of $\mathcal{B}(K_{\pi 4e}, \text{non res.})$ is a factor of 200 higher than the SM prediction
- Improved constraint on QCD axion and (dark scalar + dark photon) models
- Potential QCD axion explanation of the Be “17 MeV” anomaly is excluded by the search

Search for dark photon $A' \to \ell^+\ell^-, \ell = e/\mu$ in beam dump mode

- Improved constraint to dark photon $A' \to \ell^+\ell^-, \ell = e/\mu$
- More analyses going with current beam dump dataset

New result on $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ with early Run 2 data expected this year
NA62 will take data until 2025. Stay tuned for more results!

Proposal for the **High Intensity Kaon Experiments (HIKE)** at CERN SPS has been submitted [HIKE Proposal]

- **Multi-phase physics program (Phase 1 w/ K^+ and Phase 2 w/ K_L)**
- Main goal is to measure $K^+ \to \pi^+\nu\bar{\nu}$ with 5% precision level
- Plus a broad physics program with precision measurements, searches for LFV/LNV
- and rare decays, as well as dump-mode searches

HIKE
High Intensity Kaon Experiments

TRIUMF