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Update and outlook of rare K decays at NA62

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on behalf of the NA62 Collaboration

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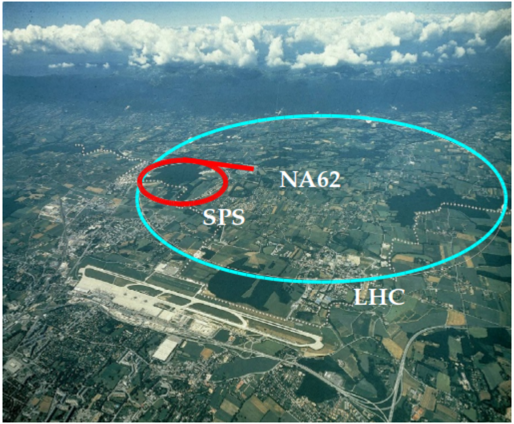
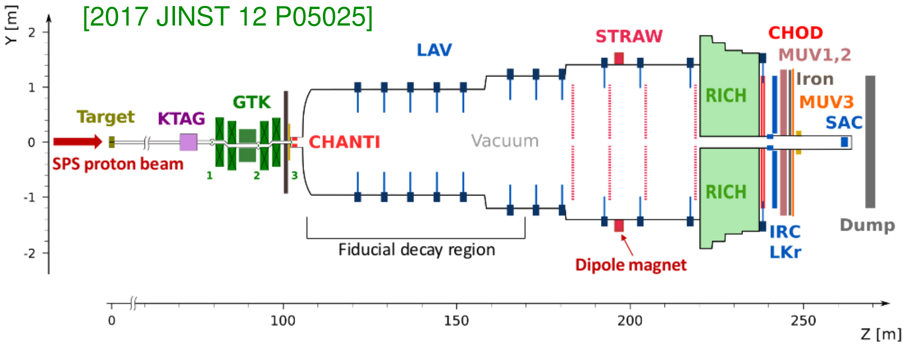
NA62 Experiment at CERN

- Detector installation completed in 2016
- Physics runs in 2016 – 2018 (Run 1)
- Data taking resumed in 2021,
  approved up to CERN LS3 (Run 2)
- Main goal: $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ measurement
  $\to$ See plenary talk by Karim Massri
- NA62 program: K^+ physics and more
  $\to$ **This talk:** focus on other rare K^+ decays



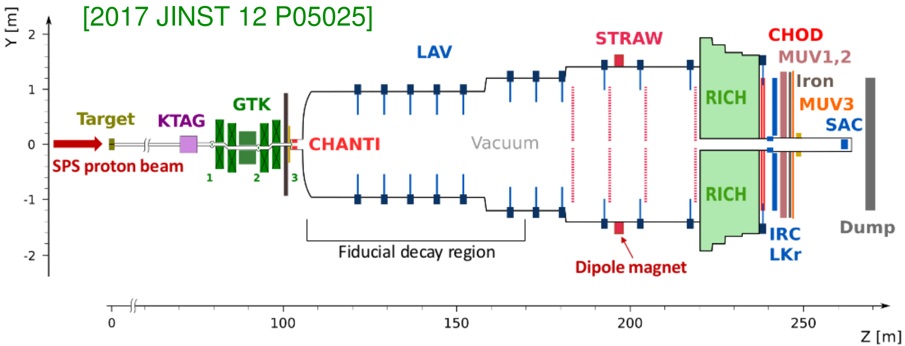
NA62: located at CERN in the *North Area*
$\to$ fixed-target experiment
$\to$ using 400 GeV/c SPS proton beam

NA62 Beam



- SPS beam: 400 GeV/c proton on beryllium target
- Secondary hadron 75 GeV/c beam
- 70% pions, 24% protons, 6% **kaons**
- Nominal beam particle rate (at GTK3): 750 *MHz*
- Average beam particle rate during 2018 data-taking: 450 – 500 *MHz*

NA62 Detector



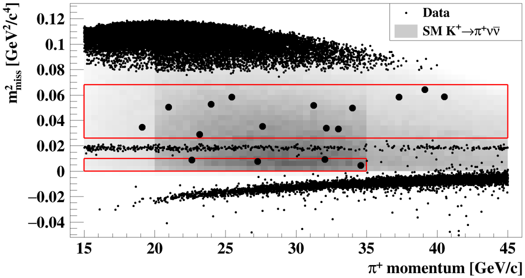
- **KTAG**: differential Cherenkov counter
- GTK: Si pixel beam tracker
- CHANTI: stations of plastic scintillator bars
- LAV: lead glass ring calorimeters
- **STRAW**: straw magnetic spectrometer
- **RICH**: Ring Imaging Cherenkov counter
- **CHOD**: planes of scintillator tiles and slabs
- IRC: inner ring shashlik calorimeter
- **LKr**: liquid krypton electromagnetic calorimeter
- MUV1,2: hadron calorimeter
- **MUV3**: plane of scintillator tiles for muon ID
- SAC: small angle shashlik calorimeter

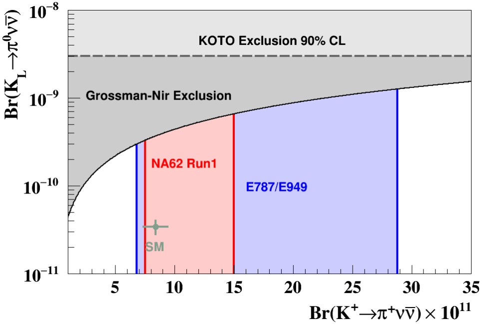
NA62 $K^+ \to \pi^+ \nu \bar{\nu}$ Result from Run 1

- SM prediction: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{SM}} = (8.4 \pm 1.0) \times 10^{-11}$ [JHEP 11 (2015) 033]
- NA62 Run 1 = 2016 – 2018 data:
  20 signal candidates, expected background: 7.0 events [JHEP 06 (2021) 093]

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{NA62}} = (10.6^{+4.0}_{-3.4}|_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-11}$$

17 events observed in 2018 data:





NA62 Physics

Broad physics program at NA62:

- Main goal: $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ measurement
- Precision measurements of rare kaon decays,
  Following analyses of 2017–2018 data presented in **this talk:**

→	$K^+ \to \pi^+ \mu^+ \mu^-$ decay	[JHEP 11 (2022) 011]
→	$K^+ \to \pi^0 e^+ \nu \gamma$ decay	[JHEP 09 (2023) 040]
→	$K^+ \to \pi^+ \gamma \gamma$ decay	(preliminary results)

- Searches for lepton number and lepton flavour violating decays
  → e.g. $K^+ \to \pi^- (\pi^0) e^+ e^+$ [PLB 830 (2022) 137172]
- Searches for very rare decays
  → e.g. $K^+ \to \pi^+ e^+ e^+ e^- e^-$ [arXiv:2307.04579, accepted by PLB]
- Searches for feebly interacting particles
  a) Kaon mode: search for FIP production and/or decay [PLB 807 (2020) 135599]
  e.g. heavy neutral lepton search in $K^+ \to \ell^+ \nu_H$ [PLB 816 (2021) 136259]
  b) Beam dump mode: e.g. dark photon search $A' \to \mu^+ \mu^-$ [JHEP 09 (2023) 035]

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

$K^\pm \to \pi^\pm \ell^+ \ell^-$ decays ($\ell = e, \mu$)

- Flavour-changing neutral-current processes
- Kinematic variable $z = m^2(\ell^+\ell^-)/m_K^2$
- Dominant contribution via virtual photon exchange $K^\pm \to \pi^\pm \gamma^* \to \pi^\pm \ell^+ \ell^-$
- Form factor of the $K^\pm \to \pi^\pm \gamma^*$ transition: $W(z)$
- Chiral Perturbation Theory parameterization of $W(z)$ at $\mathcal{O}(p^6)$:

$$W(z) = G_F m_K^2 (a_+ + b_+ z) + W^{\pi\pi}(z)$$

a_+, b_+: real parameters
$W^{\pi\pi}(z)$: complex function, two-pion loop

Main goals of the NA62 $K^+ \to \pi^+\mu^+\mu^-$ measurement:

- Measure model-independent branching fraction $\mathcal{B}_{\pi\mu\mu}$
- Measure function $|W(z)|^2$
- Determine FF parameters a_+ and b_+

$K^+ \to \pi^+\mu^+\mu^-$: Sample and Analysis

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

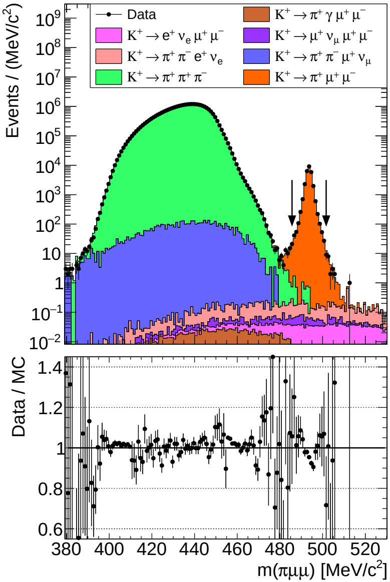
- Data: **27679 events observed**
- Normalization using $K^+ \to \pi^+\pi^+\pi^-$: $N(K^+\text{decays}) \approx 3.5 \times 10^{12}$
- Expected background: ≈ 8 events

Analysis:

- Data divided in 50 equipopulated bins in z:

$$\left(\frac{d\Gamma(z)}{dz}\right)_i = \frac{N_{\pi\mu\mu,i}}{A_{\pi\mu\mu,i}} \cdot \frac{1}{\Delta z_i} \cdot \frac{1}{N_K} \cdot \frac{\hbar}{\tau_K}$$

- Integrating $d\Gamma(z)/dz \to$ model-independent $\mathcal{B}$
- $|W(z)|^2$ function values extracted from $d\Gamma(z)/dz$
- Fit of $|W(z)|^2$ data points $\to$ ChPT form factor parameter measurement

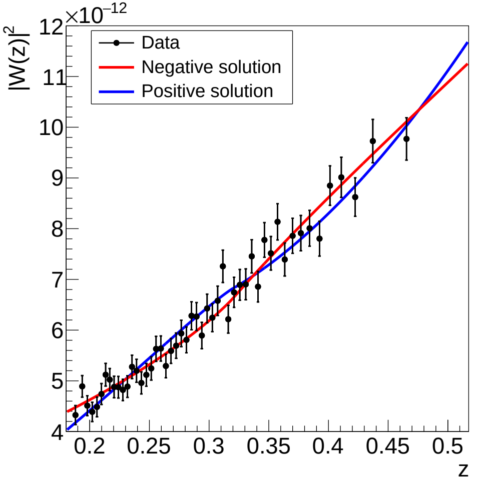


$K^+ \to \pi^+\mu^+\mu^-$: Measurement Results

Form factor parameters:

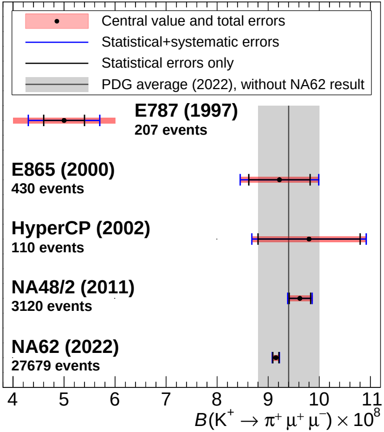
- Two possible solutions:
  a_+, b_+: both *negative* or *positive* values
- Preferred negative solution
  $\chi^2/\text{ndf} = 45.1/48$ (p-value $= 0.59$):

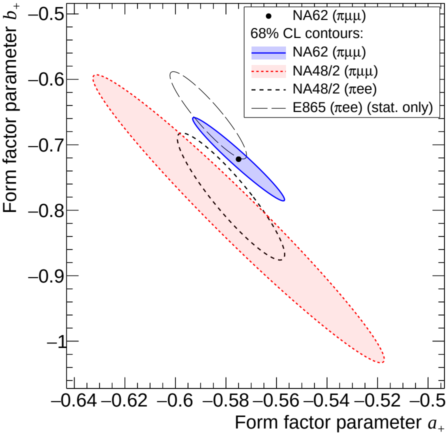
$$a_+ = -0.575 \pm 0.013$$
$$b_+ = -0.722 \pm 0.043$$
$$\text{correlation } \rho(a_+, b_+) = -0.972$$



Branching fraction: $\mathcal{B}_{\pi\mu\mu} = (9.15 \pm 0.08) \times 10^{-8}$

$K^+ \to \pi^+\mu^+\mu^-$: Comparison with Previous Measurements



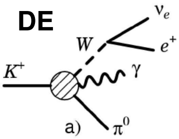


- At least **factor of 3** improvement wrt previous $K_{\pi\mu\mu}$ measurements
- Measurements are compatible

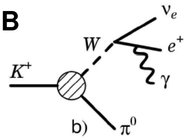
  $\to$ Agreement in a_+, b_+ from $K_{\pi\mu\mu}$ and $K_{\pi ee}$ $\to$ lepton flavour universality ✓

$K^+ \to \pi^0 e^+ \nu\gamma$: Overview

DE



IB



Inner Bremsstrahlung (IB) decay amplitude:
→ divergent for $E_\gamma \to 0$ and $\theta_{e,\gamma} \to 0$

Theoretical predictions and experimental measurements for **3 sets** of cuts:
minimal E_γ and $\theta_{e,\gamma}$ (in K^+ rest frame)

$$R_j = \frac{\mathcal{B}(Ke3\gamma^j)}{\mathcal{B}(Ke3)} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \mid E_\gamma^j,\ \theta_{e,\gamma}^j)}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma))}$$

	E_γ cut	$\theta_{e,\gamma}$ cut	$O(p^6)$ *ChPT* [EPJ C 50, 557]	ISTRA+	OKA
R_1 $(\times 10^2)$	$E_\gamma > 10\ MeV$	$\theta_{e,\gamma} > 10^\circ$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
R_2 $(\times 10^2)$	$E_\gamma > 30\ MeV$	$\theta_{e,\gamma} > 20^\circ$	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	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

T-odd observable ξ (K^+ rest frame): $\xi = \dfrac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{m_K^3}$; Asymmetry: $A_\xi = \dfrac{N_+ - N_-}{N_+ + N_-}$

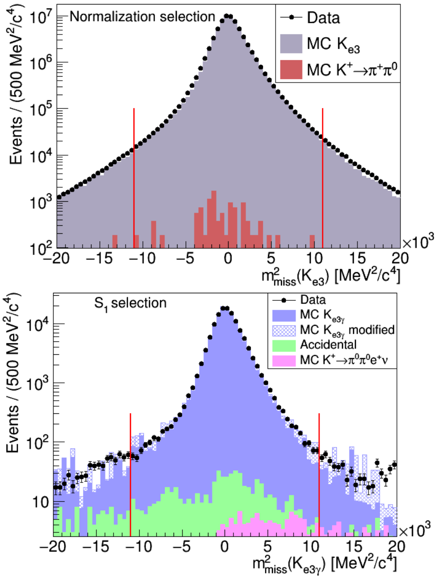
$K^+ \to \pi^0 e^+ \nu\gamma$: Samples and Analysis

- Normalization: $K^+ \to \pi^0 e^+ \nu$
  N(events) $\approx 6.6 \times 10^7$, 10^{-4} background
- $K^+ \to \pi^0 e^+ \nu\gamma$ signal samples, 3 regions S_i:
  - → N(events) $\approx 1 \times 10^5$
  - → Background: $< 1\%$
  - → Main source of bkg.: accidental activity
- Evaluation of R_j:

$$R_j = \frac{\mathcal{B}(K_{e3\gamma^j})}{\mathcal{B}(K_{e3})} = \frac{N^{\rm obs}_{Ke3\gamma^j} - N^{\rm bkg}_{Ke3\gamma^j}}{N^{\rm obs}_{Ke3} - N^{\rm bkg}_{Ke3}} \cdot \frac{A_{Ke3}}{A_{Ke3\gamma^j}} \cdot \frac{\epsilon^{\rm trig}_{Ke3}}{\epsilon^{\rm trig}_{Ke3\gamma^j}}.$$

- Evaluation of asymmetry:

$$A^{\rm NA62}_{\xi} = A^{\rm Data}_{\xi} - A^{\rm MC}_{\xi}$$



$K^+ \to \pi^0 e^+ \nu\gamma$: Results

Ratio measurement:

	$O(p^6)$ *ChPT*	ISTRA+	OKA	**NA62**
R_1 $(\times 10^2)$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$\mathbf{1.715 \pm 0.005 \pm 0.010}$
R_2 $(\times 10^2)$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$\mathbf{0.609 \pm 0.003 \pm 0.006}$
R_3 $(\times 10^2)$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$\mathbf{0.533 \pm 0.003 \pm 0.004}$

- Precision improved by a factor > 2
- About 5% smaller value than ChPT prediction

Asymmetry measurement:

	ISTRA+	OKA	**NA62**
$A_\xi(S_1)$ $(\times 10^3)$		$-0.1 \pm 3.9 \pm 1.7$	$\mathbf{-1.2 \pm 2.8 \pm 1.9}$
$A_\xi(S_2)$ $(\times 10^3)$		$-4.4 \pm 7.9 \pm 1.9$	$\mathbf{-3.4 \pm 4.3 \pm 3.0}$
$A_\xi(S_3)$ $(\times 10^3)$	15 ± 21	$7.0 \pm 8.1 \pm 1.5$	$\mathbf{-9.1 \pm 5.1 \pm 3.5}$

- Compatible with no asymmetry
- Uncertainties still larger than theory expectations

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

- Long-distance dominated radiative decay
- Crucial test of Chiral Perturbation Theory
- Kinematic variables (q_i: photon momenta, p: kaon momentum)

$$z = \frac{(q_1 + q_2)^2}{m_K^2} = \frac{m_{\gamma\gamma}^2}{m_K^2}, \qquad y = \frac{p \cdot (q_1 - q_2)}{m_K^2}$$

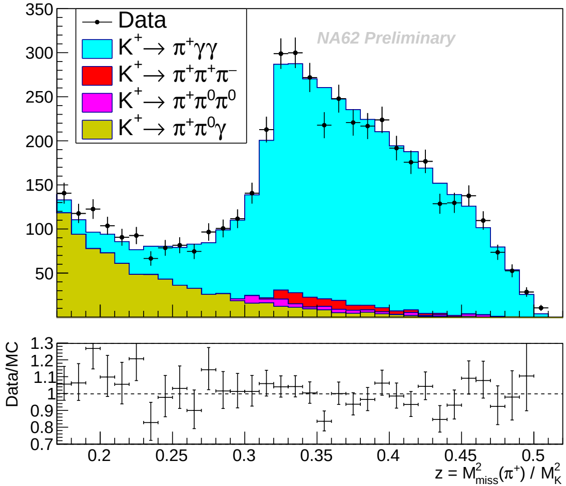
- Differential decay width [PLB 386 (1996) 403]:

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

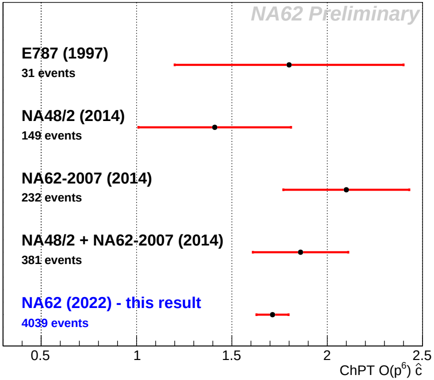
→ The spectrum and rate depend on one parameter $\hat{c}$
→ $B(z)$ appears at ChPT $\mathcal{O}(p^6)$
→ Goal: measure $\hat{c}_6$ and the corresponding branching fraction

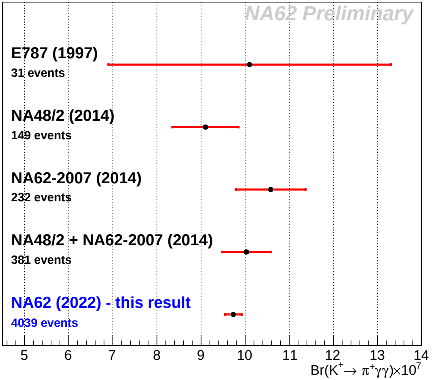
$K^+ \to \pi^+\gamma\gamma$: Sample and Analysis

- Normalization: $K^+ \to \pi^+\pi^0$
- $K^+ \to \pi^+\gamma\gamma$ signal sample, $z > 0.25$:
  - → 4039 events observed
  - → Expected background: 393 ± 20 events
  - → Main source of bkg.: $K^+ \to \pi^+\pi^0\gamma$
- Fit procedure:
  - → MC reweighted for different values of $\hat{c}_6$
  - → Maximum likelihood fit



$K^+ \to \pi^+\gamma\gamma$: Preliminary Results





$$\hat{c}_6 = (1.713 \pm 0.084), \qquad \mathcal{B}(K^+ \to \pi^+\gamma\gamma) = (9.73 \pm 0.19) \times 10^{-7}$$

Outlook for Rare Kaon Decays from NA62

NA62 Run 1: 2016 – 2018

- Multiple analyses ongoing, stay tuned for new results soon

NA62 Run 2: 2021 – CERN LS3

- Increase in beam intensity
- Beamline and detector improvements for $K^+ \to \pi^+ \nu\bar{\nu}$ measurement
  $\to$ Target relative precision for $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$: 15%
- Trigger improvements, reduced downscaling factor for events with e^+e^- final state
  $\to$ Large sample of di-electron decays (including $K^+ \to \pi^+ e^+ e^-$) will be collected

Long-term Outlook: HIKE

- Letter of Intent: arXiv:2211.16586, proposal to SPSC in preparation
- K^+ (Phase-1) and K_L (Phase-2) physics program after LS3
- Beam intensity: $4\times$ NA62
- Large improvement in precision for $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ and other kaon decays
- Observation and first measurement of decays $K_L \to \pi^0 \ell^+ \ell^-$

$\rightarrow$ See plenary talk by K. Massri

Rare Kaon Decays at NA62: Summary

Run 1 (2016 – 2018):

- Golden mode: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-11}$ [JHEP 06 (2021) 093]
- Recent precision measurements of:
  - → $K^+ \to \pi^+\mu^+\mu^-$ decay [JHEP 11 (2022) 011]
  - → $K^+ \to \pi^0 e^+\nu\gamma$ decay [JHEP 09 (2023) 040]
  - → $K^+ \to \pi^+\gamma\gamma$ decay (preliminary, final results in preparation)
- Measurement uncertainties dominated by statistical errors

Outlook:

- NA62 continues to take data in Run 2 (2021 – LS3): expect many new results
- Long-term plan (after LS3): proposal for High Intensity Kaon Experiments (HIKE)