Institute of Particle and Nuclear Physics
Faculty of Mathematics and Physics
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Precision measurements of kaon decays at NA62 experiment

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on behalf of NA62 collaboration

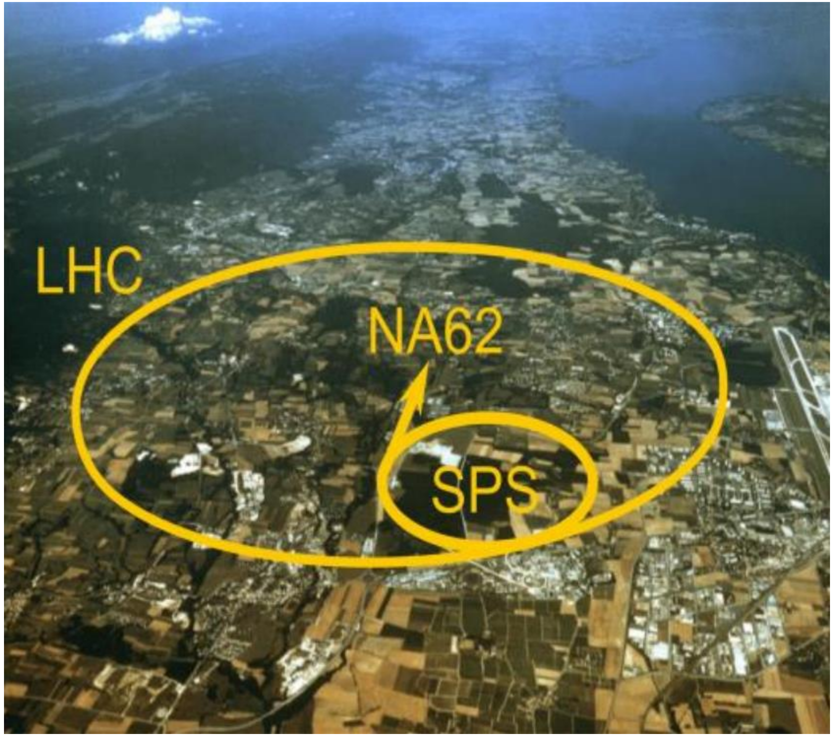
Outline

- Overview of NA62

- Precision measurements of rare decays:
  - $K^+ \rightarrow \pi^0 e^+ \nu\gamma \; (K_{e3g})$
  - $K^+ \rightarrow \pi^+ \mu^+ \mu^- (K_{\pi\mu\mu})$
  - $K^+ \rightarrow \pi^+ \gamma\gamma \; (K_{\pi\gamma\gamma})$
  - $K^+ \rightarrow \pi^+ \pi^- \pi^+ \gamma \; (K_{3\pi\gamma})$

- Summary

NA62 Experiment



~200 participants, ~30 institutes from:

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

NA62 Timeline	
Feb. 2007:	NA62 Approval
2009 - 2014:	Detector R&D and installation
2015:	Commissioning
2016 – 2018:	Run 1
2021 – 2025:	Run 2
Proposal for future: High Intensity Kaon Experiments	

NA62 Experiment

- **NA62** is a fixed-target experiment at the North Area of CERN SPS
- **Primary p^+ beam:** 400 GeV/c, impinging on 400mm long beryllium target
- **Secondary beam:** 75 GeV/c, composition: π^+(70%), p^+(24%), K^+(6%)
- **Main goal:** measure $B(K\to\pi^+\nu\bar{\nu})$ with 10% precision, using "decay-in-flight" technique
- Requires ~10^{13} kaon decays
- **Current theoretical prediction:**

$$Br_{SM}(K\to\pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \cdot 10^{-11}$$

[Buras et al., JHEP11(2015)033]

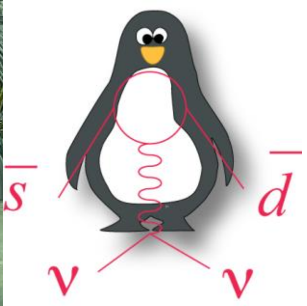
- **Latest experimental results:**

$$Br_{E949}(K\to\pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}{}_{stat}) \cdot 10^{-11}$$

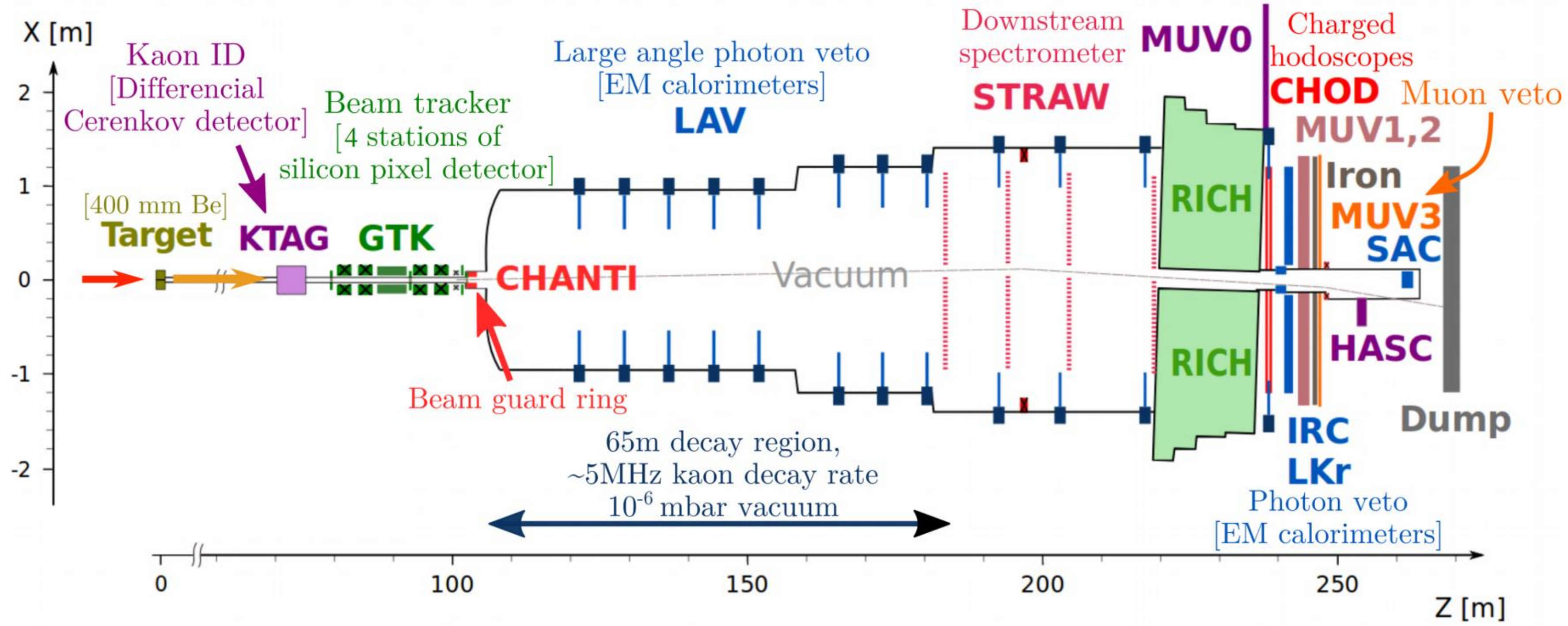
[E949/E787[Phys. Rev D 79, 092004 (2009)]]

$$Br_{NA62}(K\to\pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}{}_{stat} \pm 0.9_{syst}) \cdot 10^{-11}$$

[NA62[JHEP06(2021)093]]



NA62 Detector System Overview



[JINST 12 (2017) P05025]

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

- Long distance decay described by Chiral Perturbation Theory
- Measurement goals:
  - $R_j = \frac{\mathcal{B}(K_{e3\gamma}{}^j)}{\mathcal{B}(K_{e3})} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \,|\, E_\gamma^j, \theta_{e\gamma}^j)}{\mathcal{B}(K_{e3})}$

Phase space conditions

[Eur. Phys. J. C 50 (2007)]

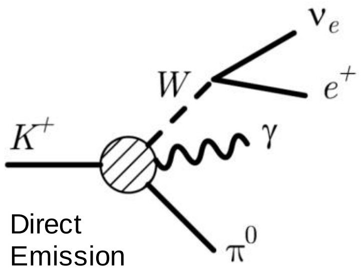
	$E_\gamma^j,\ \theta_{e\gamma}^j$	ChPT
$R_1 \times 10^2$	$E_\gamma > 10$ MeV, $\theta_{e\gamma} > 10°$	1.804 ± 0.021
$R_2 \times 10^2$	$E_\gamma > 30$ MeV, $\theta_{e\gamma} > 20°$	0.640 ± 0.008
$R_3 \times 10^2$	$E_\gamma > 10$ MeV, $0.6 < \cos\theta_{e\gamma} < 0.9$	0.559 ± 0.006

  - T-violation effects:

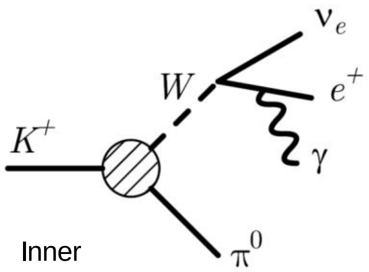
$$\xi = \frac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{M_K^3} \longrightarrow A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

where ξ is the T-odd observable (in kaon rest frame), A_ξ is the asymmetry variable with $N_+(N_-)$ being the numbers of events with positive (negative) ξ.

$A_\xi \in (-10^{-4}, -10^{-5})$ [SM and beyond]



Direct Emission



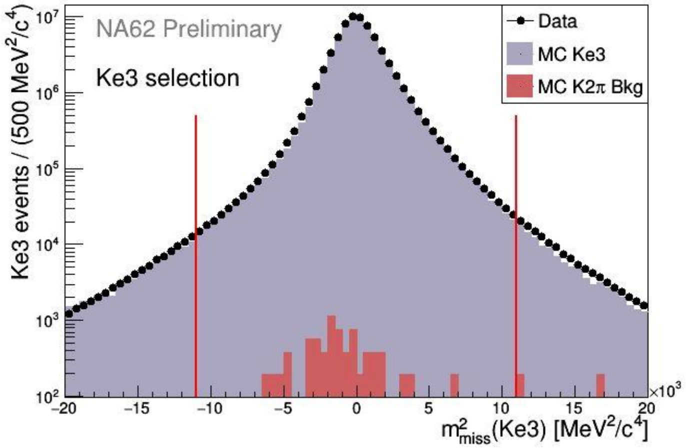
Inner Bremsstrahlung

[Eur. Phys. J. C 50 (2007)]

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

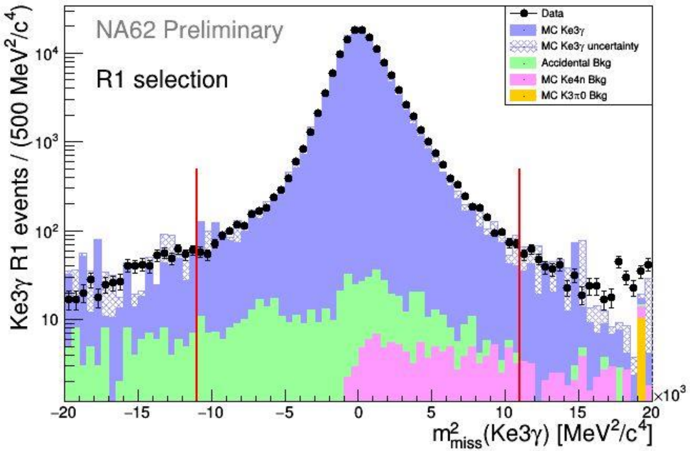
Normalisation: $K^+ \to \pi^0 e^+ \nu$ (K_{e3})

- 1 downstream track with e^+ PID
- Vertex with K^+ upstream track
- 2γ clusters in LKr with $m_{\gamma\gamma}$ compatible with π^0
- No additional photons in LAV / SAC
- Cut on $m^2_{miss}(K_{e3}) = (P_K - P_{\pi^0} - P_e)^2$



Signal: $K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$)

- 1 downstream track with e^+ PID
- Vertex with K^+ upstream track
- 2γ clusters in LKr with $m_{\gamma\gamma}$ compatible with π^0 + 1 radiative γ
- No additional photons in LAV / SAC
- Cut on $m^2_{\gamma\gamma}(K_{e3\gamma}) = (P_K - P_{\pi^0} - P_e - P_\gamma)^2$ and $m^2_{miss}(K_{e3})$



[arXiv:2304.12271]

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

Procedure for R_j:

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

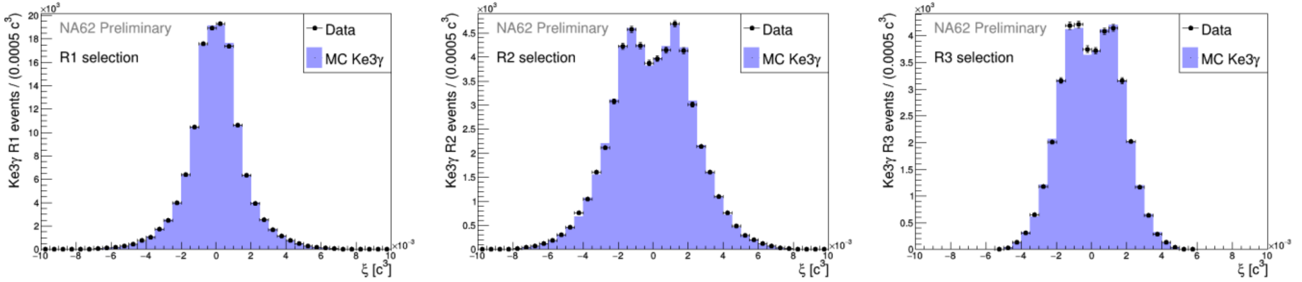
- Bkg from accidental activity in LKr (data driven estimation), from misidentified e+ or undetected γ (MC driven estimate)
- Acceptances evaluated by MC
- Trigger efficiencies measured with data

	Normalization	S_1	S_2	S_3
Selected candidates	6.6420×10^7	1.2966×10^5	0.5359×10^5	0.3909×10^5
Acceptance	$(3.842 \pm 0.002)\%$	$(0.444 \pm 0.001)\%$	$(0.514 \pm 0.002)\%$	$(0.432 \pm 0.002)\%$
Accidental	—	$(4.9 \pm 0.2 \pm 1.3) \times 10^2$	$(2.3 \pm 0.2 \pm 0.3) \times 10^2$	$(1.1 \pm 0.1 \pm 0.5) \times 10^2$
$K^+ \to \pi^0\pi^0 e^+\nu$	—	$(1.1 \pm 1.1) \times 10^2$	$(1.1 \pm 1.1) \times 10^2$	$(0.1 \pm 0.1) \times 10^2$
$K^+ \to \pi^+\pi^0\pi^0$	—	< 20	< 20	< 20
$K^+ \to \pi^+\pi^0$	$(1.0 \pm 1.0) \times 10^4$	—	—	—
Total background	$(1.0 \pm 1.0) \times 10^4$	$(6.0 \pm 1.8) \times 10^2$	$(3.4 \pm 1.2) \times 10^2$	$(1.2 \pm 0.6) \times 10^2$
Fractional background	1.6×10^{-4}	0.46×10^{-2}	0.64×10^{-2}	0.29×10^{-2}

[arXiv:2304.12271]

Procedure for A_ξ:

$$A_\xi = A_\xi^{Data} - A_\xi^{MC}$$



$K^+ \to \pi^0 e^+ \nu\gamma$: Results and Comparison with the World

	ChPT $O(p^6)$ [Eur. Phys. J. C 50 (2007)]	ISTRA+ [Phys. Atom. Nucl. 70 (2007)]	OKA [JETP Lett. 116 (2022)] [Eur. Phys. J. C 81.2 (2021)]	NA62 [arXiv:2304.12271]
$R_1 \times 10^2$	1.804 ± 0.021	1.81 ± 0.03 ± 0.07	1.990 ± 0.017 ± 0.021	1.715 ± 0.005 ± 0.010
$R_2 \times 10^2$	0.640 ± 0.008	0.63 ± 0.02 ± 0.03	0.587 ± 0.010 ± 0.015	0.609 ± 0.003 ± 0.006
$R_3 \times 10^2$	0.559 ± 0.006	0.47 ± 0.02 ± 0.03	0.532 ± 0.010 ± 0.012	0.533 ± 0.003 ± 0.004
$A_\xi(S_1) \times 10^3$	/	/	–0.1 ± 3.9 ± 1.7	–1.2 ± 2.8 ± 1.9
$A_\xi(S_2) \times 10^3$			7.0 ± 8.1 ± 1.5	–3.4 ± 4.3 ± 3.0
$A_\xi(S_3) \times 10^3$			–4.4 ± 7.9 ± 1.9	–9.1 ± 5.1 ± 3.5

Decay Rate:
- factor > 2 more precise than previous experiments
- Relative uncertainty < 1%
- 5% smaller than ChPT prediction

T-asymmetry
- Compatible with no asymmetry
- Improved precision from OKA experiment
- Uncertainty still $O(10^2)$ larger than prediction

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

- FCNC decay described by the means of Chiral Perturbation Theory (ChPT), mediated by one photon exchange $K^+ \to \pi^+\gamma^*$
  [Nucl. Phys. B291 (1987) 692–719] , [Phys. Part. Nucl. Lett. 5 (2008) 76–84]

- Differential decay width:

$$\frac{d\Gamma(z)}{dz} \sim |W(z)|^2, \qquad z = \frac{m(\mu^+\mu^-)^2}{m_K^2}$$

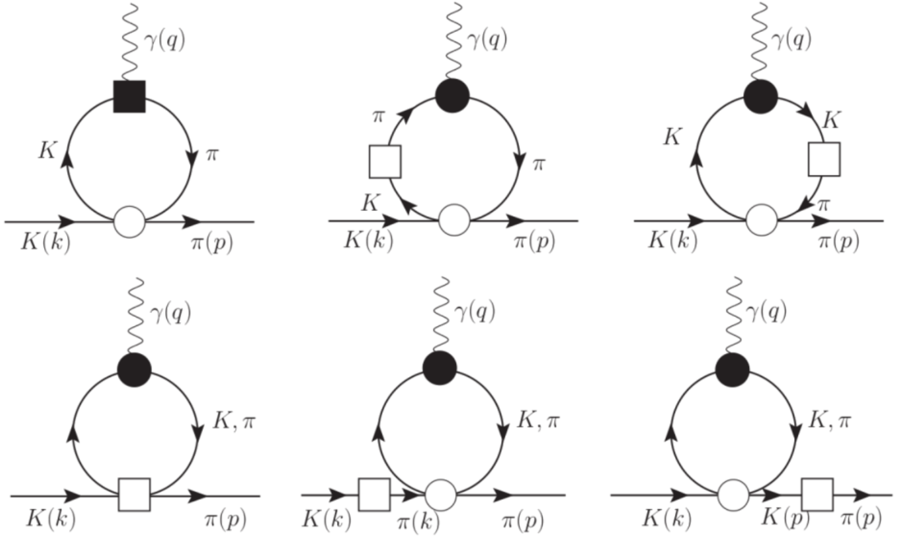
- Parametrization of Form Factor at $O(p^6)$:

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

  a_+, b_+: Form Factor parameters,
  $W^{\pi\pi}(z)$: $K_{3\pi}$ pion loop term

  [JHEP 08 (1998) 004]

- Measurements:
  - FF parameters: a_+, b_+
  - Model independent branching fraction $\mathcal{B}(K_{\pi\mu\mu})$
  - Forward-backward asymmetry



$K^+ \rightarrow \pi^+\mu^+\mu^-$: Selection

Normalisation: $K^+ \rightarrow \pi^+\pi^+\pi^-(K_{3\pi})$

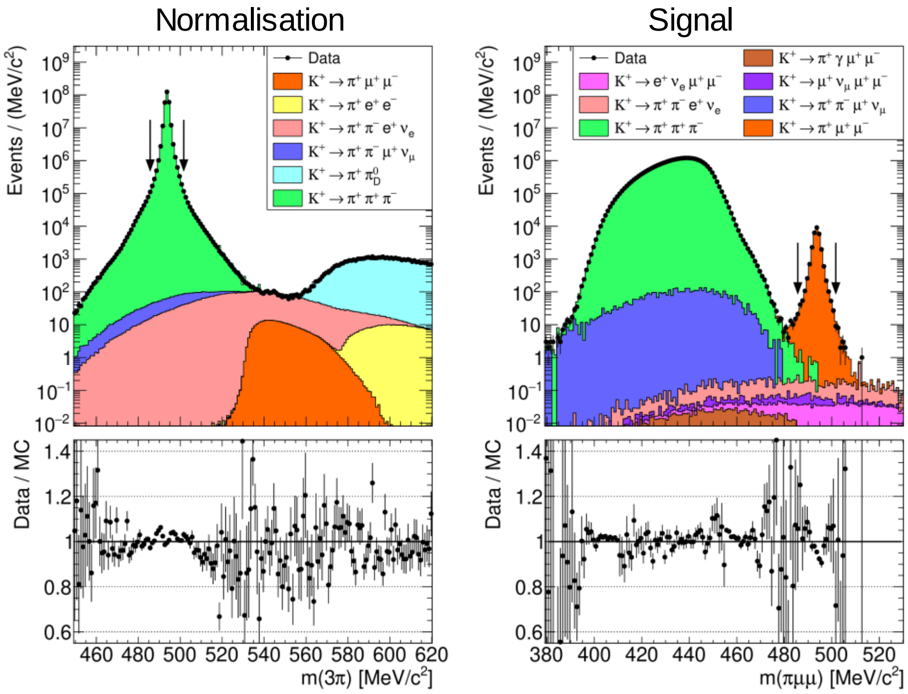
- High BR ~ 5.6%
- Kinematically similar
- Cancellation of systematic errors

Signal Selection:

- 3-track vertex
- Event in time with KTAG
- π^+ PID: no signal in MUV3
- $\mu^\pm$ PID: signal in MUV3
- Kinematic cuts to suppress $K_{3\pi}$ events
- $|m_{\pi\mu\mu} - m_K| < 8\ MeV/c^2$

Data Sample:

- Effective kaon decays $N_K \approx 3.48\times10^{12}$
- Events selected: 27679
- Background expected: ~8



$K^+ \to \pi^+\mu^+\mu^-$: Branching Fraction and Form Factors

Model-independent $\mathcal{B}(K_{\pi\mu\mu})$ measurement:

- Reconstruct $d\Gamma(z)/dz$ from measured z spectrum (data divided into 50 equipopulated bins)

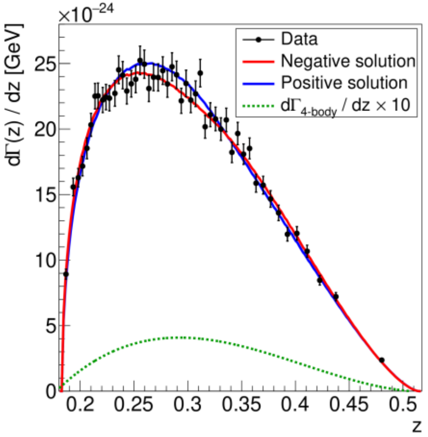
$$\left(\frac{d\Gamma(z)}{dz}\right) = \frac{N_{\pi\mu\mu,i}}{A_{\pi\mu\mu,i}} \frac{1}{\Delta z_i} \frac{1}{N_K} \frac{\hbar}{\tau_K}$$

where Δz_i - bin width, $N_{\pi\mu\mu,i}$ - number of signal events, $A_{\pi\mu\mu,i}$ - signal acceptance, N_K - effective number of kaon decays, $\hbar$ – reduced Planck's constant, τ_K - mean $K^\pm$ lifetime

- Integrate over z to get:

$$\mathcal{B}(K_{\pi\mu\mu}) = (9.18 \pm 0.08) \times 10^{-8}$$

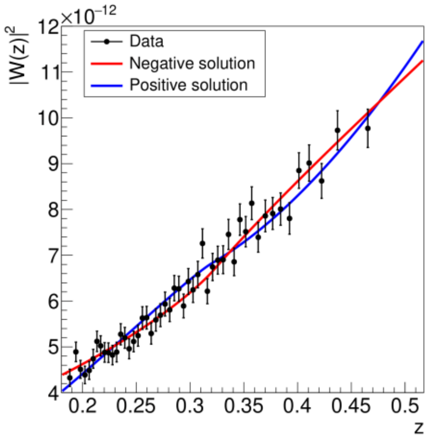
[JHEP 11 (2022) 011]



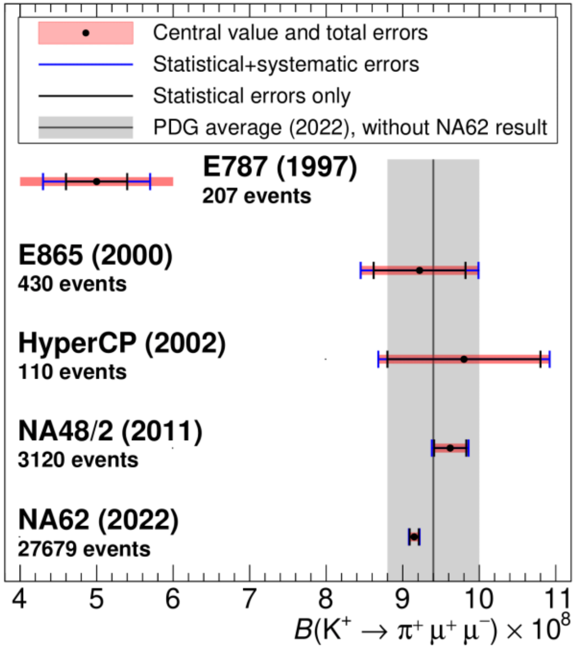
Form factor measurement:

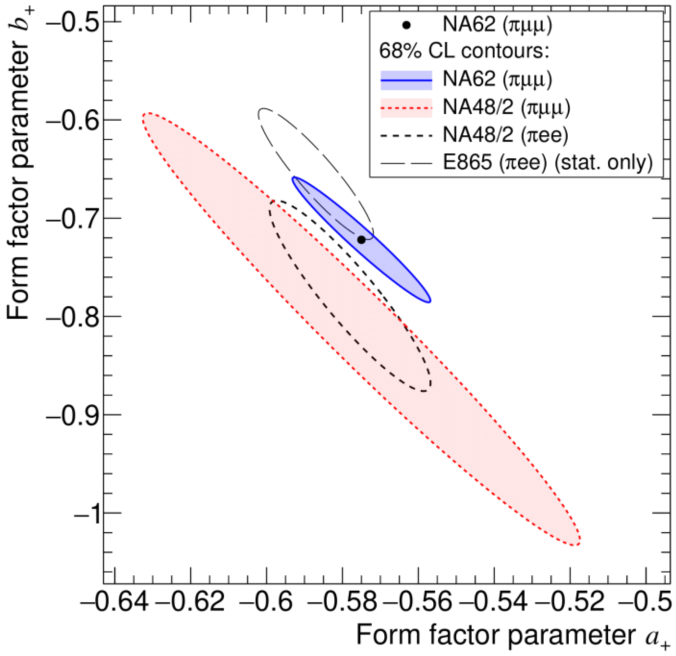
- Extract $|W(z)|^2$ from $d\Gamma(z)/dz$
- Find optimal a_+, b_+ by minimizing $\chi^2(a_+, b_+)$
- Results - preferred negative ($\chi^2/ndf = 45.1/48$, p-value = 0.59):
  - $a_+ = -0.575 \pm 0.013$
  - $b_+ = -0.722 \pm 0.043$
  - Correlation: $\rho(a_+, b_+) = -0.972$

[JHEP 11 (2022) 011]



$K^+ \to \pi^+\mu^+\mu^-$: Comparison with the World





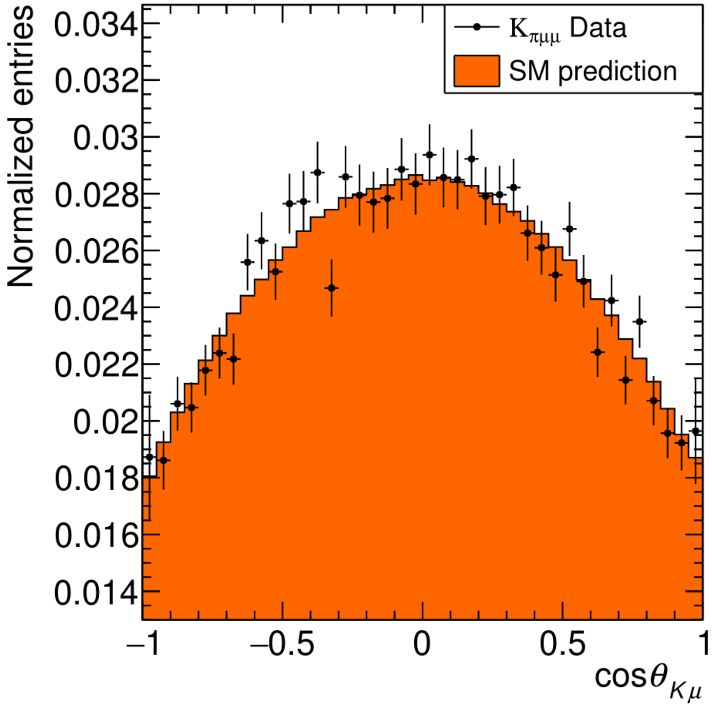
- Much improved precision
- Sample size ~9x larger than NA48/2
- No evidence for LFU

$K^+ \rightarrow \pi^+\mu^+\mu^-$: Forward-Backward Asymmetry

Definition:

- $\theta_{K\mu}$ is angle between the K^+ and μ^- 3-momenta in the $\mu^+\mu^-$ rest frame
- Forward-backward asymmetry:

$$A_{FB} = \frac{\mathcal{N}(\cos\theta_{K\mu} > 0) - \mathcal{N}(\cos\theta_{K\mu} < 0)}{\mathcal{N}(\cos\theta_{K\mu} > 0) + \mathcal{N}(\cos\theta_{K\mu} < 0)}$$



Results:

- $A_{FB} = (0.0 \pm 0.7_{stat} \pm 0.2_{syst} \pm 0.2_{ext}) \times 10^{-2}$ @ 68% CL
- $|A_{FB}| < 0.9 \times 10^{-2}$ @ 90% CL

[JHEP 11 (2022) 011]

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

- Radiative non-leptonic decay described by chiral perturbation theory (leading order at $\mathcal{O}(p^4)$ with contributions from $\mathcal{O}(p^6)$) [Phys. Lett. B 386 (1996) 403]
- Main kinematic variable:

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

where p is K^+ 4-momentum, $q_{1,2}$ are photons 4-momenta, m_K is mass of K^+ and $m_{\gamma\gamma}$ is di-photon invariant mass

- Decay width:

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

non-zero $\mathcal{O}(p^6)$ contributions

- Measurements:
  - Measure $\hat{c}$
  - Extrapolate model dependent branching franction

$K^+ \to \pi^+\gamma\gamma$: Signal Selection

Data sample:

- Full NA62 Run1 dataset
- Normalization channel: $K^+ \to \pi^+\pi^0$

Signal selection:

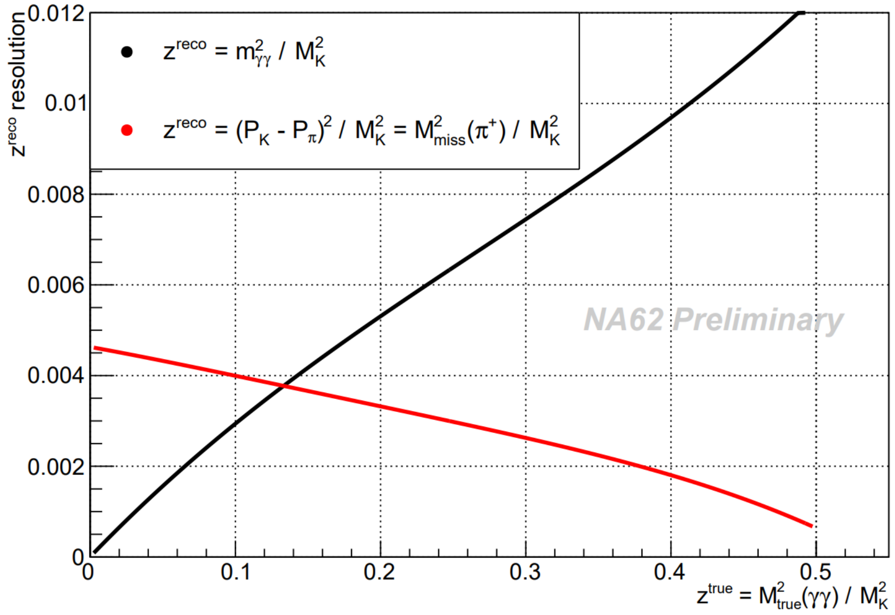
- 1 good track in STRAW
- 2 good clusters in LKr
- K^+ - π^+ matching tracks (vertex reconstructed)
- Kinematic cuts for daughter particles (total E, total p_T, $m_{\pi\gamma\gamma}$)

Additional sample cut:

- Redefinition of z as

$$z = \frac{(P_K - P_\pi)^2}{m_K^2}$$

- Signal region: $z > 0.25$



$K^+ \to \pi^+\gamma\gamma$: Signal and Background

Signal events ($z > 0.25$):

- 4039 events found
  → ~10x more than NA48/2 and NA62-2007

Background:

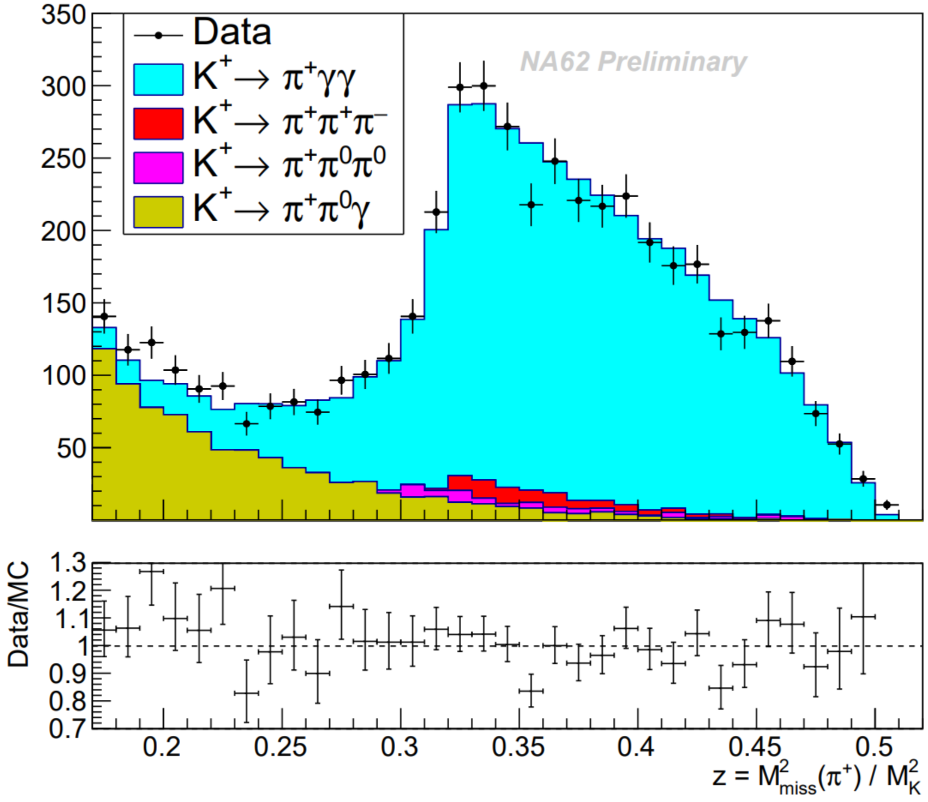
- Cluster merging in LKr:
  - $K^+ \to \pi^+\pi^0\gamma$, $\pi^0 \to \gamma\gamma$
  - $K^+ \to \pi^+\pi^0\pi^0$, $\pi^0 \to \gamma\gamma$
- Missing tracks in STRAW:
  - $K^+ \to \pi^+\pi^+\pi^-$
- Background contamination: 393 ± 20 events

Fitting procedure:

- MC reweighted for different values of $\hat{c}$
- Scan of $\hat{c}$ to find maximum log-likelihood

$$ln\mathcal{L} = \sum_i (k_i ln\lambda_i(\hat{c}) - \lambda_i(\hat{c}) - \ln(k_i!)),$$

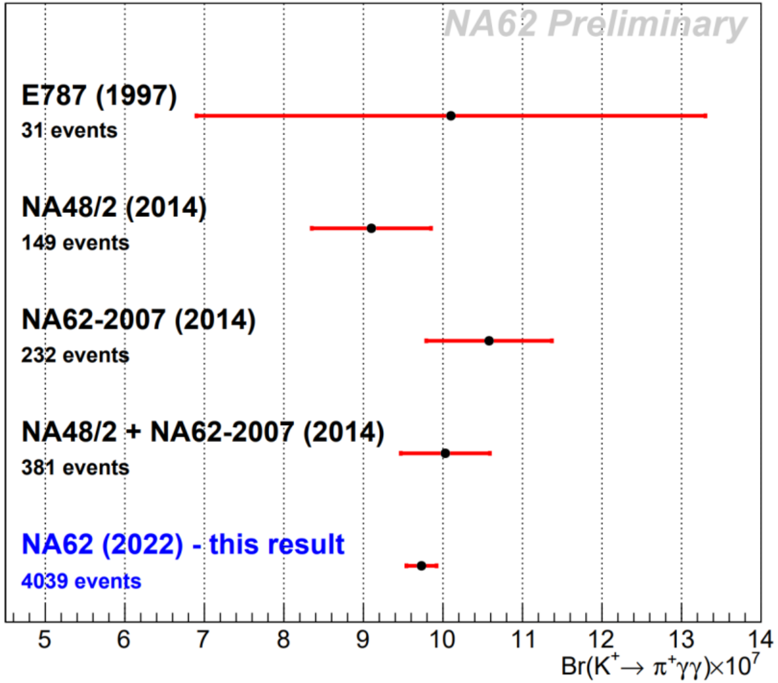
$$\lambda_i(\hat{c}) = \lambda_i^S(\hat{c}) + \lambda_i^B$$

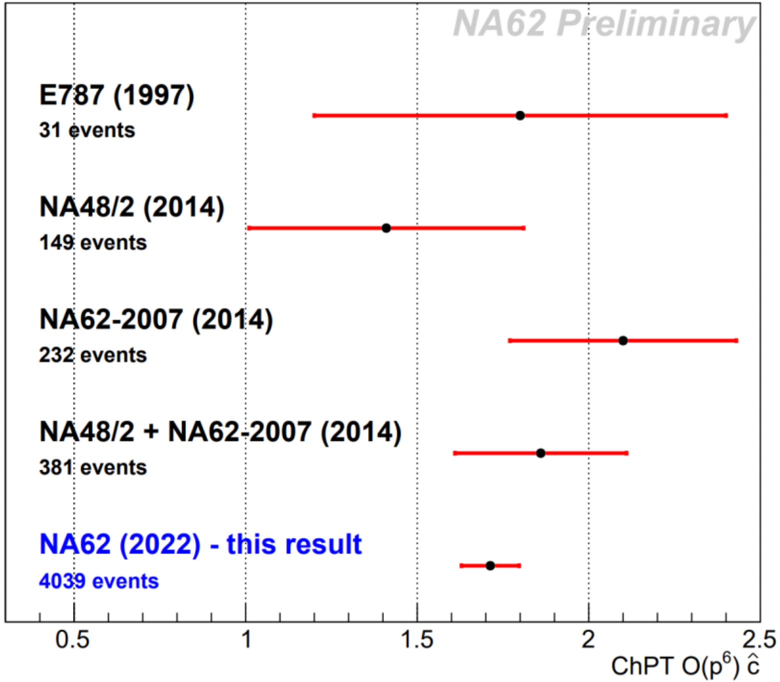


$K^+ \to \pi^+\gamma\gamma$: Results and comparison with World

$$\mathcal{B}r(K^+ \to \pi^+\gamma\gamma) = (9.73 \pm 0.17_{stat.} \pm 0.08_{syst.}) \times 10^{-7}$$

$$\hat{c}_6 = 1.713 \pm 0.075_{stat.} \pm 0.037_{syst.}$$





$K^+ \to \pi^+\pi^-\pi^+\gamma$: Introduction

- Theoretical: G. D'Ambrosio, G. Ecker, G.Isidori, H. Neufeld (1997)
  - $K^+ \to \pi^+\pi^-\pi^+\gamma$ described by chiral perturbation theory to order $\mathcal{O}(p^4)$
  - Integrated for $E_\gamma > 5$ MeV $\mathcal{B}r(K^+ \to \pi^+\pi^-\pi^+\gamma)_{theor.}$ **= (1.26 ± 0.01) · 10⁻⁴** [doi: 10.1007/s002880050554]

E_γ	Γ_{GB}	$\frac{\Gamma_{GB} - \Gamma_{Low}}{\Gamma}$	$\frac{\Gamma_E - \Gamma_{GB}}{\Gamma}$	Γ_M	BR
10–20	$(2.32 \pm 0.02) \cdot 10^{-18}$	$-1.7 \cdot 10^{-3}$	$-4.2 \cdot 10^{-4}$	$1.3 \cdot 10^{-24}$	$(4.36 \pm 0.04) \cdot 10^{-5}$
20–30	$(7.63 \pm 0.07) \cdot 10^{-19}$	$-4.8 \cdot 10^{-3}$	$-1.2 \cdot 10^{-3}$	$3.2 \cdot 10^{-24}$	$(1.43 \pm 0.01) \cdot 10^{-5}$
30–40	$(2.62 \pm 0.03) \cdot 10^{-19}$	$-9.2 \cdot 10^{-3}$	$-2.4 \cdot 10^{-3}$	$4.1 \cdot 10^{-24}$	$(4.93 \pm 0.05) \cdot 10^{-6}$
40–50	$(7.66 \pm 0.08) \cdot 10^{-20}$	$-1.5 \cdot 10^{-2}$	$-4.1 \cdot 10^{-3}$	$3.2 \cdot 10^{-24}$	$(1.44 \pm 0.01) \cdot 10^{-6}$
50–60	$(1.43 \pm 0.02) \cdot 10^{-20}$	$-2.1 \cdot 10^{-2}$	$-6.2 \cdot 10^{-3}$	$1.3 \cdot 10^{-24}$	$(2.69 \pm 0.03) \cdot 10^{-7}$
60–70	$(7.23 \pm 0.09) \cdot 10^{-22}$	$-2.8 \cdot 10^{-2}$	$-8.5 \cdot 10^{-3}$	$1.2 \cdot 10^{-25}$	$(1.36 \pm 0.02) \cdot 10^{-8}$
10–70	$(3.44 \pm 0.03) \cdot 10^{-18}$	$-3.4 \cdot 10^{-3}$	$-8.5 \cdot 10^{-4}$	$1.3 \cdot 10^{-23}$	$(6.46 \pm 0.06) \cdot 10^{-5}$

[MeV]

- Experimental:
  - M. M. Shapkin et al. (OKA collaboration), 2018
    - Collected **~450 events** with E(γ) > 30 MeV
    - Measured **$Br(K^+ \to \pi^+\pi^-\pi^+\gamma) = (0.71 \pm 0.05)\times10^{-5}$** [arXiv:1808.09176]
  - **NA62** has capabilities to increase the number of observed decays by multiple orders of magnitude and validate the predictions on whole range of photon energy spectrum

Summary

- Analysis of $K^+ \to \pi^0 e^+ \nu\gamma$ finished and published in [arXiv:2304.12271]
  - Sample size is ~130k events in R_1, ~54k in R_2 and ~39k in R_3
  - R_j for individual regions: $R_1 = (1.715 \pm 0.005_{stat} \pm 0.010_{syst}) \times 10^2$
    $R_2 = (0.609 \pm 0.003_{stat} \pm 0.006_{syst}) \times 10^2$
    $R_3 = (0.533 \pm 0.003_{stat} \pm 0.004_{syst}) \times 10^2$
  - T-asymmetry: $A_\xi(S_1) = (-1.2 \pm 2.8_{stat} \pm 1.9_{syst}) \times 10^3$
    $A_\xi(S_2) = (-3.4 \pm 4.3_{stat} \pm 3.0_{syst}) \times 10^3$
    $A_\xi(S_3) = (-9.1 \pm 5.1_{stat} \pm 3.5_{syst}) \times 10^3$

- Analysis of $K^+ \to \pi^+ \mu^+ \mu^-$ finished and published in [JHEP 11 (2022) 011]
  - Sample size is 27679 events collected in 2017 and 2018 with negligible background
  - Model independent branching fraction: $\mathcal{B}(K_{\pi\mu\mu}) = (9.18 \pm 0.08) \times 10^{-8}$
  - Form Factors extracted: $a_+ = -0.575 \pm 0.013$, $b_+ = -0.722 \pm 0.043$
  - Forward-Backward asymmetry: $A_{FB} = (0.0 \pm 0.7_{stat} \pm 0.2_{syst} \pm 0.2_{ext}) \times 10^{-2}$ @ 68% CL
    $|A_{FB}| < 0.9 \times 10^{-2}$ @ 90% CL

- Analysis of $K^+ \to \pi^+ \gamma\gamma$ (preliminary results)
  - Sample size is 4039 events collected in Run1 with ~10% background contamination
  - Branching fraction: $\mathcal{B}r(K^+ \to \pi^+ \gamma\gamma) = (9.73 \pm 0.17_{stat.} \pm 0.08_{syst.}) \times 10^{-7}$
  - Form Factor parameter: $\hat{c}_6 = 1.713 \pm 0.075_{stat.} \pm 0.037_{syst.}$

- Analysis of $K^+ \to \pi^+ \pi^- \pi^+ \gamma$ is in progress. Currently the background processes are being evaluated.

Backup Slides