FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University

Precision measurements of kaon and pion decays at NA62

Lubos Bician
lubos.bician@cern.ch

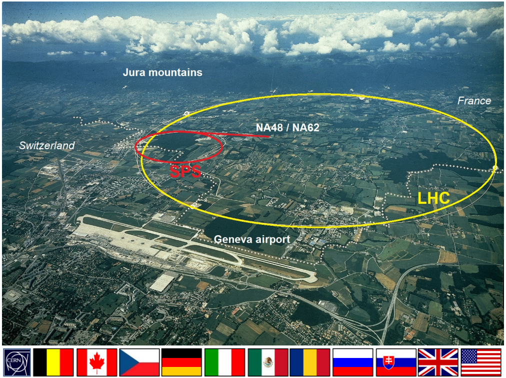
Charles University in Prague
on behalf of the NA62 Collaboration

Second International Conference on the Physics of the Two Infinities
November 19, 2025

Co-funded by
the European Union

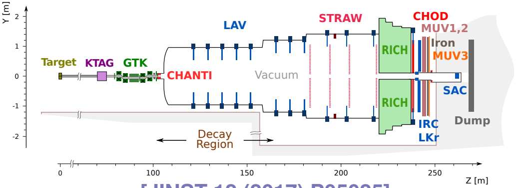
MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Kaon Experiments at CERN



NA62: ~ 200 participants, ~ 30 institutes

- **NA31**: 1980s, *beam:* K_L/K_S
  - *First evidence of direct CPV*
- **NA48**: 1997–2001, *beam:* K_L/K_S
  - *Discovery of direct CPV*
- **NA48/1**: 2002, *beam:* K_S/hyperons
  - *Rare decay studies*
- **NA48/2**: 2003–2004, *beam:* K^+/K^-
  - *Precision measurements*
- **NA62-R_K**: 2007–2008, *beam:* K^+/K^-
  - $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$
- **NA62**: since 2015, *beam:* K^+
  2015: commissioning run
  2016-2018: NA62 Physics Run 1
  2021-ongoing: NA62 Physics Run 2



[JINST 12 (2017) P05025]

Beam parameters in K^+ mode:

- **Beam momentum:** 75 GeV/c ($\pm 1\%$)
- **Nominal rate:** 750 MHz
- **Positive beam:** $\sim 6\%$ K$^+$

Main subdetectors:

- **Beam tracker:** GTK ($\sigma_p = 0.15$ GeV$/c$)
- **Kaon tagger:** KTAG ($\sigma_t = 70$ ps)
- **Downstream tracker:** $(\pi/\mu/e)$: Straw $\sigma_p/p = 0.3\% \bigoplus 0.005\% \cdot p$[GeV$/c$]
- **Photon veto detectors:** LAV, IRC, SAC
- **Cherenkov counter:** RICH
- **Trigger and timing:** CHOD ($\sigma_t = 1$ ns), NA48-CHOD ($\sigma_t = 200$ ps)
- **Electromagnetic calorimeter:** LKr $\sigma_E/E = 4.8\%/\sqrt{E} \bigoplus 11\%/E \bigoplus 0.9\%$, $[E] =$ GeV
- **Hadronic calorimeters:** MUV1,2
- **Muon detector:** MUV3 ($\sigma_t = 500$ ps)

- Measurement of the branching fraction of very rare ($\mathcal{B}_{\pi\nu\nu} \approx 10^{-10}$) decay $K^+ \to \pi^+\nu\bar{\nu}$
  - Main goal of the experiment with the first observation published in **[JHEP02 (2025) 191]**
  - See Zuzana's talk for details on the measurement
- **Precision measurements**:
  - Up to $\mathcal{O}(0.1\%)$ level tests of ChPT and SM
  - Precision measurements of ChPT parameters

Decay	Dataset	Status	Reference
$K^+ \to \pi^+\mu^+\mu^-$ ($K_{\pi\mu\mu}$)	NA62 Run 1 (2017-2018)	Published	**[JHEP11 (2022) 011]**
$K^+ \to \pi^0 e^+\nu\gamma$ ($K_{\pi e\nu\gamma}$)	NA62 Run 1 (2017-2018)	Published	**[JHEP 09 (2023) 040]**
$K^+ \to \pi^+\gamma\gamma$ ($K_{\pi\gamma\gamma}$)	NA62 Run 1 (2016-2018)	Published	**[PLB 850 (2024) 138513]**
$\pi^0 \to e^+e^-$ (π^0_{ee})	NA62 Run 1 (2017-2018)	Preliminary	**[La Thuile 2024]**
$K^+ \to \pi^+\pi^+\pi^-\gamma$ ($K_{3\pi\gamma}$)	NA62 Run 1 (2017-2018)	Preliminary	**[KAON25]**
$K^+ \to e^+\nu_e\gamma$ ($K_{e2\gamma}$)	NA62 Run 1 (2017-2018)	Preliminary	**[KAON25]**
$K^+ \to \mu^+\nu\mu^+\mu^-$ ($K_{\mu\nu\mu\mu}$)	NA62 Run 1+2 (2017-2024)	Preliminary	**[KAON25]**

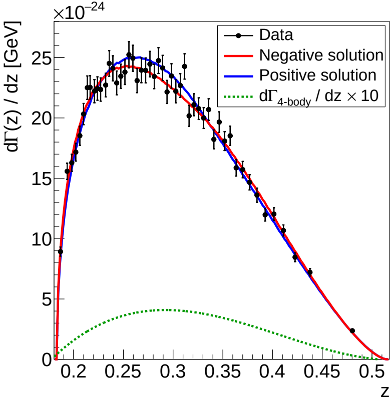
- Searches for rare and forbidden (e.g. LNV or LFV) K^+ decays
- Searches for exotic particles: dark photon, axions, HNLs,...

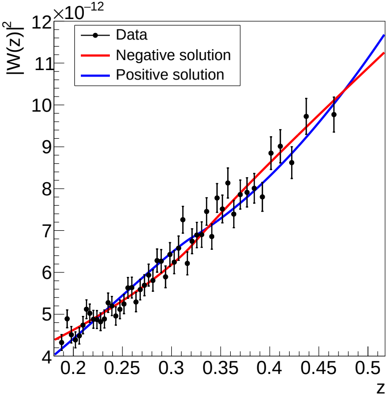
Selection:

- 2μ multi-track (2μMT) trigger line used
- Normalisation on $K_{3\pi}$ (MT) events
- Signal selection: reconstruct 3-track ($\pi\mu\mu$)-compatible vertex
- Kinematic cuts to suppress $K_{3\pi}$ background

Analysis strategy:

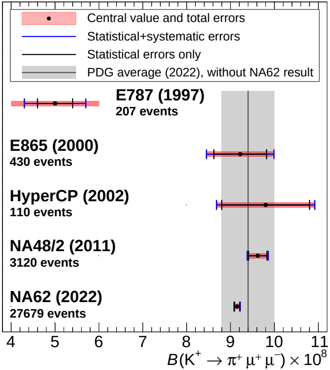
- Reconstruct dΓ/dz from measured $z = m^2(\mu^+\mu^-)/m_K^2$ spectrum
- Integrate to get model-independent $\mathcal{B}(K_{\pi\mu\mu})$
- Extract form factor (FF) $|W(z)|^2$ from dΓ/dz
- Fit FF parameters a_+, b_+ by min. $\chi^2(a_+, b_+)$

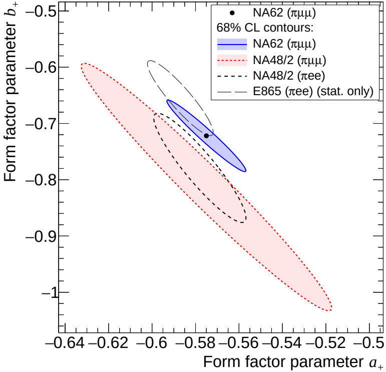




$K^+ \to \pi^+\mu^+\mu^-$: Results

- NA62 $K_{\pi\mu\mu}$ result consistent previous $K_{\pi ee}$ FF measurements $\to$ no tension in LFU observed





- E865, $K_{\pi ee}$: [Phys. Rev. Lett. 83 (1999) 4482-4485]
- HyperCP, $K_{\pi\mu\mu}$: [Phys. Rev. Lett. 88 (2002) 111801]
- NA48/2, $K_{\pi ee}$: [Phys. Lett. B 677 (2009) 246-254]
- NA48/2, $K_{\pi\mu\mu}$: [Phys. Lett. B 697 (2011) 107-115]

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

$$\boldsymbol{\mathcal{B}_{\text{MI}}(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.06_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.04_{\text{ext}}) \times 10^{-8}}$$

Goals:

- Measure **normalised** $\boldsymbol{\mathcal{B}(K^+ \to \pi^0 e^+ \nu \gamma)}$ in various $(E_\gamma, \theta_{e\gamma})$ ranges; $j \in \{1, 2, 3\}$:

$$\mathcal{R}_j = \frac{N^{obs}_{Ke3\gamma,j} - N^{bkg}_{Ke3\gamma,j}}{N^{obs}_{Ke3} - N^{bkg}_{Ke3}} \cdot \frac{A_{Ke3}}{A_{Ke3\gamma,j}} \cdot \frac{\varepsilon^{trig}_{Ke3}}{\varepsilon^{trig}_{Ke3\gamma,j}}$$

- Study T-odd variable ξ via **asymmetry**:

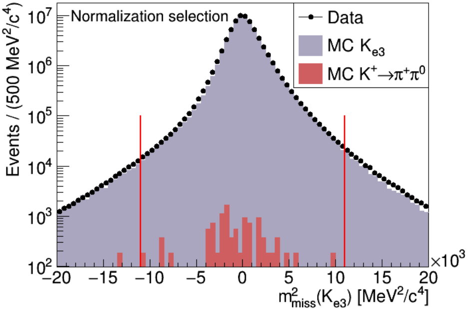
$$A_\xi^{\text{NA62}} = A_\xi^{\text{DATA}} - A_\xi^{\text{MC}}, \quad \xi = \frac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{(m_K \cdot c^3)}$$

Signal selection:

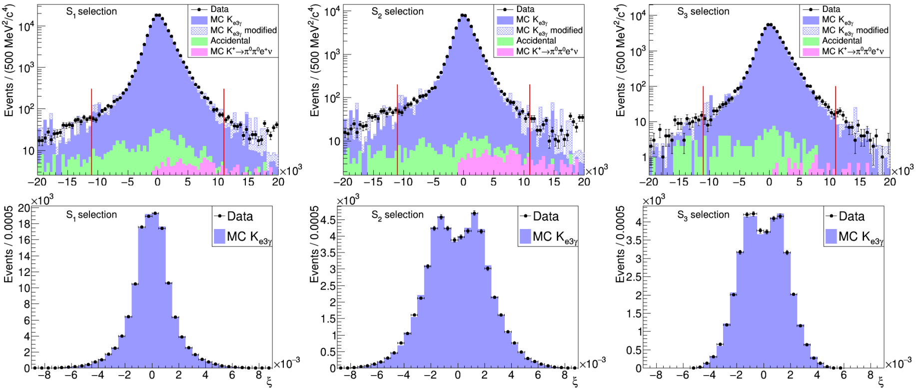
- Min-bias and non-muon trigger lines
- Normalisation: $K^+ \to \pi^0 e^+ \nu(\gamma)$
- Reconstruct K^+ (GTK) and e^+ (Straw)
- π^0 identification with 2 γ in LKr
- Radiative γ identified as isolated cluster
- Minimal differences in signal and normalisation selections $\Rightarrow$ **reduced systematic effects**

Analysis strategy:

- Background $< 1\%$, mainly accidental
- Signal decay described in MC by ChPT at $\mathcal{O}(p^6)$
- Normalisation selection acceptance is defined wrt full phase space
- Evaluation of $\boldsymbol{\mathcal{R}_j}$
- Evaluation of asymmetry $\mathbf{A_\xi^{NA62}}$



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



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

$\mathcal{R}$ measurement:

- **Precision improved by a factor > 2**
- Results smaller by 5% than ChPT prediction

Asymmetry measurement:

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

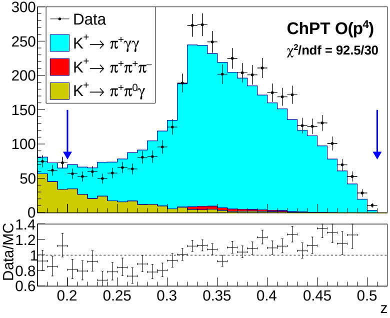
$K^+ \to \pi^+\gamma\gamma$: Introduction

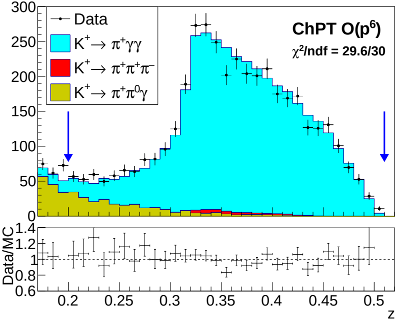
Selection:

- Min-bias and non-muon trigger lines
- Normalisation: $K^+ \to \pi^+\pi^0$
- Single positive track + two γ clusters
- $K^+ - \pi^+$ matching, reconstruct vertex
- π^+ identification & μ^+ rejection
- **Signal region: $0.2 < z < 0.51$**

Analysis strategy:

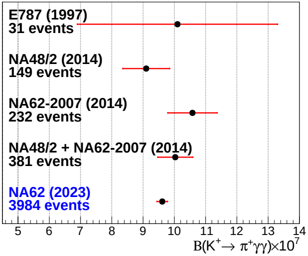
- Main background:
  - cluster merging in calorimeter
  - multi-track events, tracks out of acceptance
- Data distributed in 31 equal bins
- $\hat{c}$ obtained from $z = m^2_{\gamma\gamma}/m^2_K$ spectrum
- Model independent $\mathcal{B}$ obtained by summing z-spectrum in all bins in signal range

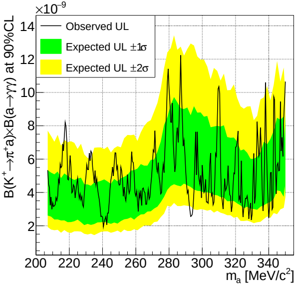


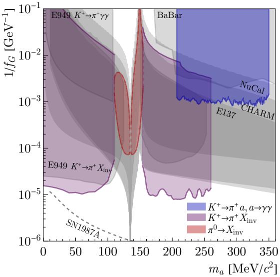


Fit with ChPT at $O(p^4)$ is disfavoured with respect to ChPT at $O(p^6)$

- Form factor parameter and branching fraction measurements
- First search for production and prompt decay of an axion-like particle with gluon coupling in the process $K^+ \to \pi^+ a$, $a \to \gamma\gamma$







$$N_{\text{bcg}}^{\text{exp}} = 291 \pm 14, \quad N^{\text{obs}} = 3984$$

$$\hat{c} = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$$

$$\mathcal{B}_{\text{ChPT @ }\mathcal{O}(p^6)}(K^+ \to \pi^+\gamma\gamma) = (9.61 \pm 0.15_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$$

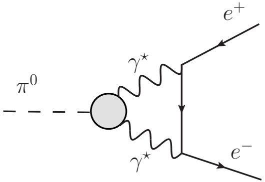
$$\mathcal{B}_{\text{MI}}(K^+ \to \pi^+\gamma\gamma | z > 0.2) = (9.46 \pm 0.19_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$$

Goal:

- Measurement of $\boldsymbol{\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > 0.95)}$

Overview:

- Experimentally accessible: $\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > x_{\text{cut}})$, $x = m_{ee}^2/m_{\pi^0}^2$
  - Low x region dominated by Dalitz decay $\pi^0 \to e^+e^-\gamma$
  - For $x > x_{cut} = 0.95$, Dalitz contribution only 3.3%
- Previously measured by KTeV: $\mathcal{B}_{\text{KTeV}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$ **[Phys. Rev. D 75.012004]**



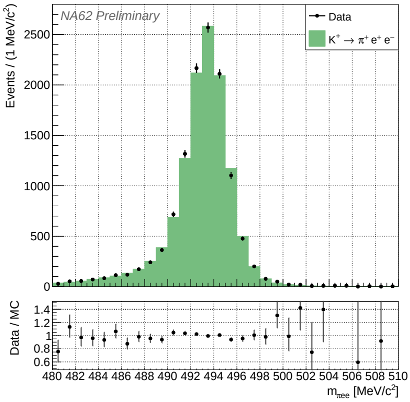
Signal selection:

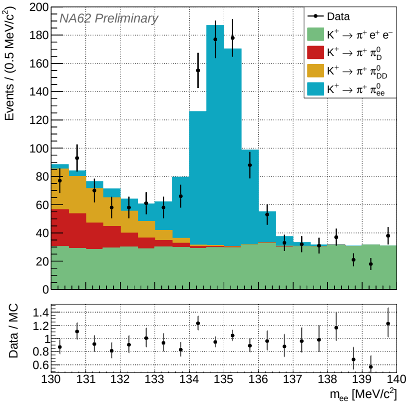
- Multi-track electron trigger line
- Normalisation: $K^+ \to \pi^+e^+e^-$, computed in a background-free region $140\ \text{MeV}/c^2 < m_{ee} < 360\ \text{MeV}/c^2$
- Minimal differences in signal and normalisation event selections ⇒ **reduced systematic effects**
- 3-track vertex topology
- **Signal measured in region $\boldsymbol{130\ \text{MeV}/c^2 < m_{ee} < 140\ \text{MeV}/c^2}$**

Analysis strategy:

- Background:
  - Irreducible $K^+ \to \pi^+e^+e^-$
  - Multiple Dalitz decays with undetected particles (γ, e)
- $\boldsymbol{\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > 0.95)}$ obtained by performing **maximum likelihood fit** of simulated samples to data
- Using latest radiative corrections the **result can be extrapolated to obtain $\boldsymbol{\mathcal{B}(\pi^0 \to e^+e^-, \text{no rad})}$**

$\pi^0 \to e^+e^-$: Preliminary Results





$$N_K = (8.62 \pm 0.27) \times 10^{11}$$

Signal yield ≈ 600 events

$$\boldsymbol{\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.37) \times 10^{-8}}$$

$$\boldsymbol{\mathcal{B}(\pi^0 \to e^+e^-, \text{no rad}) = (6.22 \pm 0.39) \times 10^{-8}}$$

Preliminary result in agreement with SM expectation

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

Common features:

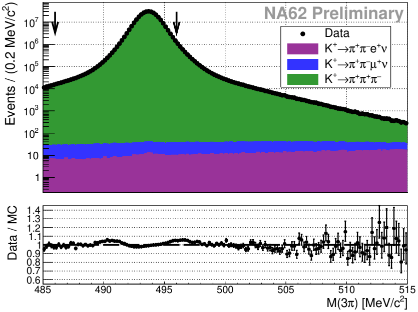
- Data from NA62 Run 1 (2017-2018)
- Multi-track trigger line used
- Require 3-track $(\pi\pi\pi)$-compatible vertex
- Associate GTK track to 3π vertex

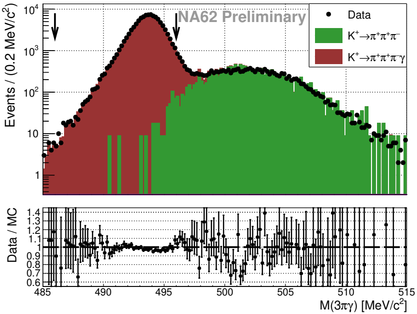
Normalisation ($K_{3\pi}$) selection:

- $N_K = (7.400 \pm 0.001_{\text{stat}} \pm 0.032_{\text{ext}}) \times 10^{10}$

Signal selection:

- Reconstruct γ in the LKr
- Kinematic cuts against $K_{3\pi}$ background





- Kinematic fit and unfolding techniques performed on selected events

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

- $K_{3\pi\gamma}$ branching fraction measured with respect to E^*_γ (photon energy in kaon rest frame):

$\mathbf{E}^*_\gamma$ **[MeV]**	$\mathcal{B}_{\mathbf{NA62}}(\mathbf{E}^*_\gamma)$ Preliminary	$\mathcal{B}_{\mathbf{Theory}}(\mathbf{E}^*_\gamma)$ [ZPhysC 76 (1997) 301]	$\mathcal{B}_{\mathbf{OKA}}(\mathbf{E}^*_\gamma)$ [EPJC 79 (2019) 1]
10–20	$(4.22 \pm 0.05) \cdot 10^{-5}$	$(4.36 \pm 0.04) \cdot 10^{-5}$	
20–30	$(1.42 \pm 0.02) \cdot 10^{-5}$	$(1.43 \pm 0.01) \cdot 10^{-5}$	
30–40	$(4.86 \pm 0.09) \cdot 10^{-6}$	$(4.93 \pm 0.05) \cdot 10^{-6}$	$(5.17 \pm 0.34) \cdot 10^{-6}$
40–50	$(1.53 \pm 0.05) \cdot 10^{-6}$	$(1.44 \pm 0.01) \cdot 10^{-6}$	$(1.55 \pm 0.12) \cdot 10^{-6}$
50–60	$(2.80 \pm 0.31) \cdot 10^{-7}$	$(2.69 \pm 0.03) \cdot 10^{-7}$	$(3.5 \pm 0.5) \cdot 10^{-7}$
60–70		$(1.36 \pm 0.02) \cdot 10^{-8}$	$(1.1 \pm 0.6) \cdot 10^{-8}$
10–60	$(6.30 \pm 0.06) \cdot 10^{-5}$	$(6.45 \pm 0.06) \cdot 10^{-5}$	
30–60	$(6.66 \pm 0.10) \cdot 10^{-6}$	$(6.64 \pm 0.05) \cdot 10^{-6}$	
30–70		$(6.65 \pm 0.05) \cdot 10^{-6}$	$(7.1 \pm 0.4_{\text{stat}} \pm 0.3_{\text{syst}}) \cdot 10^{-6}$

Good agreement with theoretical predictions and measurements by the OKA experiment

$K^+ \to \mu^+\nu\mu^+\mu^-$: Branching Fraction Measurement (Preliminary)

Common features:

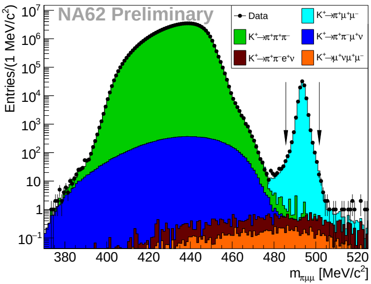
- Full available NA62 statistics (Run 1+2)
- 2μ multi-track (2μMT) trigger line

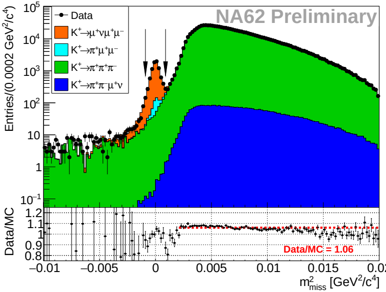
Normalisation ($K_{\pi\mu\mu}$) selection:

- Require 3-track ($\pi\mu\mu$)-compatible vertex
- Kinematic cuts against $K_{3\pi}$ background
- Observed 94112 $K_{\pi\mu\mu}$ candidates
- $N_K = (1.475 \pm 0.005_{\text{stat}}) \times 10^{13}$

Signal selection:

- Require 3-track ($\mu\mu\mu$)-compatible vertex
- Kinematic cuts against $K_{3\pi}$ background
- Observed 8227 $K_{\mu\nu\mu\mu}$ candidates
- Expected bckg.: $892 \pm 11_{\text{stat}} \pm 54_{\text{syst}}$





$$\mathcal{B}(K^+ \to \mu^+\nu\mu^+\mu^-) = (1.301 \pm 0.017_{\text{stat}} \pm 0.012_{\text{syst}} \pm 0.012_{\text{ext}}) \times 10^{-8}$$

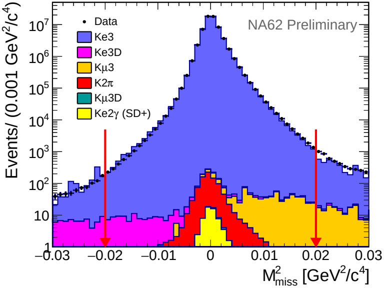
First observation of the $K_{\mu\nu\mu\mu}$ decay

Common features:

- Data from NA62 Run 1 (2017-2018)
- Non-muon trigger used
- Require single good e^+ track
- Match a GTK kaon to the e^+ track

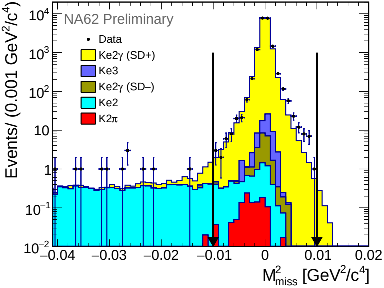
Normalisation (K_{e3}) selection:

- π^0 reconstructed from two γ clusters in LKr
- Kinematic $K^+ \to \pi^+\pi^0$ suppression
- $N_K \sim 2.9 \times 10^{10}$



Signal selection:

- Reconstruct the radiative γ in the LKr
- Kinematic cuts against $K_{e2}, K_{e3}, K_{2\pi}$ backgrounds



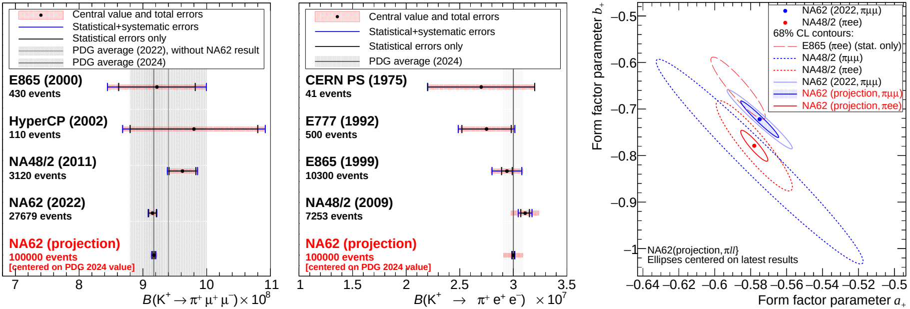
$$\mathcal{B}(K_{e2\gamma}, \mathrm{SD}^+) = (0.466 \pm 0.003_{\mathrm{stat}} \pm 0.003_{\mathrm{syst}} \pm 0.004_{\mathrm{ext}}) \times 10^{-5}$$

Most precise measurement of SD$^+$ amplitudes in kaon decays to date

$K^{\pm} \to \pi^{\pm}\ell^{+}\ell^{-}$: NA62 Full Dataset Prospects

Final 2016–2026 projections:

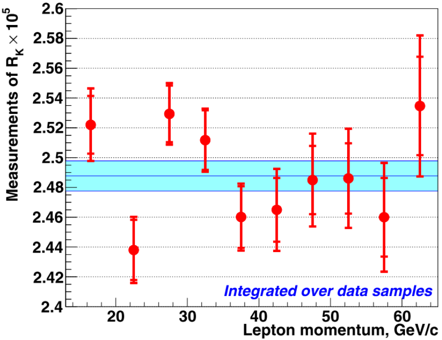
- $K^+ \to \pi^+\mu^+\mu^-$: > 100k candidates with negligible background
- $K^+ \to \pi^+e^+e^-$: > 100k candidates with negligible background
- Plots below assume 0.3% systematic uncertainties on $\mathcal{B}(K_{\pi\ell\ell})$ (same as $K_{\pi\mu\mu}$ Run 1)
- LFU tests by comparing a_+^{ℓ} and b_+^{ℓ} parameters from the two modes
- Total (a_+^{μ}, b_+^{μ}) errors expected to improve by factor ~ 1.5 with respect to current best results
- Total (a_+^{e}, b_+^{e}) errors expected to improve by factor ~ 3 with respect to current best results



$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$: NA62 Full Dataset Prospects

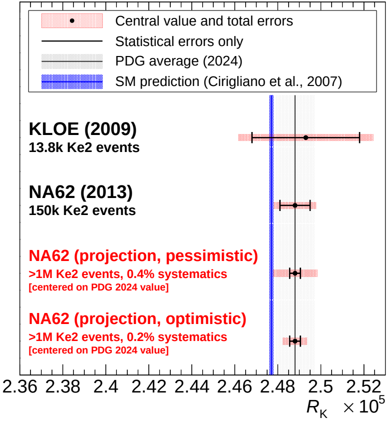
NA62 (2007 run) **[PLB719(2013)326]**:

- Dedicated run with NA48/2 detector
- 150k K_{e2} event candidates
- Systematic uncertainty 0.3%
- Main systematics:
  - $K_{\mu 2}$ contamination in K_{e2} sample
  - $K_{e3}, K_{2\pi}$ contamination in K_{e2} sample



Novel technique:

- Select $K_{\mu 2}$ with μ decays inside RICH
- Both $K_{\ell 2}$ from the main (PNN) trigger line
- Analysis well-advanced
- **Statistics:** ~ 1M K_{e2} in 2017-2018 only
- **Systematic uncertainty:** work in progress



Precision Measurements at NA62: Summary

Measurements performed so far:

- Analysis of the $K^+ \to \pi^+\mu^+\mu^-$ decay (final results)
  - Sample of 27679 $K_{\pi\mu\mu}$ events collected in 2017-2018 with negligible background
  - Model-independent branching fraction: $\mathcal{B}(K_{\pi\mu\mu}) = (9.15 \pm 0.08) \times 10^{-8}$
  - Form-factor measurement: $|W(z)|^2$ extracted; $a_+ = -0.575 \pm 0.013$, $b_+ = -0.722 \pm 0.043$
  - Forward-backward asymmetry: $A_{\mathrm{FB}} = (0.0 \pm 0.7) \times 10^{-2}$; $|A_{\mathrm{FB}}| < 0.9 \times 10^{-2}$ @ 90% CL
- Analysis of the $K^+ \to \pi^0 e^+\nu\gamma$ decay (final results)
  - Sample of 1.3×10^5 $K_{\pi e\nu\gamma}$ events collected with $< 1\%$ background
  - Normalised branching fraction and possibly T-violating asymmetry are measured
- Analysis of the $K^+ \to \pi^+\gamma\gamma$ decay (final results)
  - Sample of 3984 $K_{\pi\gamma\gamma}$ events collected with $< 10\%$ background
  - Branching fraction: $\mathcal{B}(K_{\pi\gamma\gamma}) = (9.61 \pm 0.17) \times 10^{-7}$
  - Form-factor parameter $\hat{c} = 1.444 \pm 0.077$
  - Search for production and prompt decay of an axion-like particle with gluon coupling in the process $K^+ \to \pi^+ a$, $a \to \gamma\gamma$
- Preliminary results on the following measurements were presented:
  - $\pi^0 \to e^+e^-$ decay branching fraction
  - $K^+ \to \pi^+\pi^+\pi^-\gamma$ decay branching fraction in bins of E^*_γ
  - First observation and branching fraction measurement of $K^+ \to \mu^+\nu\mu^+\mu^-$ decay
  - $K^+ \to e^+\nu_e\gamma$ (SD$^+$) branching fraction, most precise kaon decay SD$^+$ amplitude measurement
- Other precision analyses at NA62 are ongoing

Full NA62 dataset projections:

- $K^+ \to \pi^+\ell^+\ell^-$ decays measurement – branching fractions and LFU tests
- $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$ measurement

Stay tuned for more results from NA62!

Acknowledgement

The project „MSCA Fellowships CZ – UK2“
(reg. n. CZ.02.01.01/00/22_010/0008115) is supported by the Programme Johannes Amos Comenius.

Co-funded by the European Union

MINISTRY OF EDUCATION, YOUTH AND SPORTS