Recent results from precision measurements at the NA62 experiment

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New Trends in High-Energy and Low-x Physics

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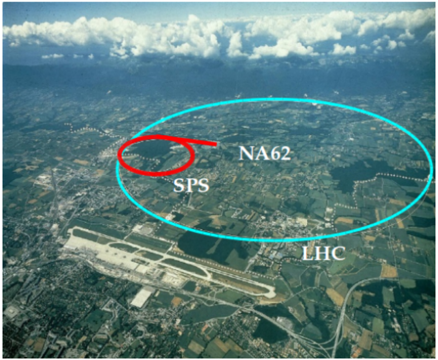
NA62 Experiment

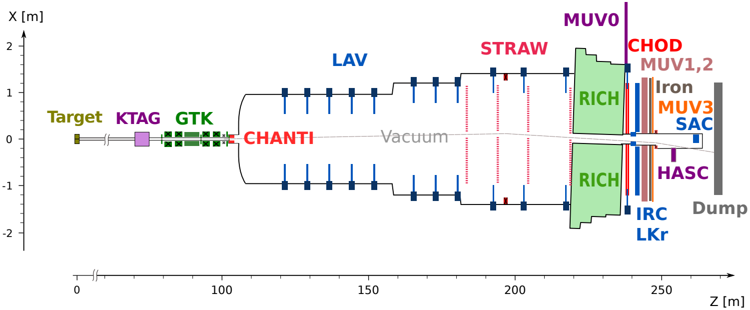


Precision measurements at NA62

- $K^+ \to \pi^+\mu^+\mu^-$ [JHEP 11 (2022) 011]
- $K^+ \to \pi^0 e^+\nu\gamma$ [JHEP 09 (2023) 040]
- $K^+ \to \pi^+\gamma\gamma$ [PLB 850 (2024) 138513]
- $\pi^0 \to e^+e^-$ (new preliminary result)

- Fixed target experiment at CERN SPS (North Area)
- Decay-in-flight technique
- Measure the ultra-rare Kaon decay $K^+ \to \pi\nu\bar{\nu}$ with 10% precision
- SM Prediction:
  $\mathcal{B}(K^+ \to \pi\nu\bar{\nu}) = (8.4 \pm 1.0) \cdot 10^{-11}$
  [Buras et al., JHEP 1511 (2015) 033]
- Experimental value:
  $\mathcal{B}(K^+ \to \pi\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5\text{stat.}} \pm 0.9_{\text{sys.}}) \cdot 10^{-11}$
  [E949/E787, Phys. Rev D 79, 092004 (2009)]
  $\mathcal{B}(K^+ \to \pi\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4\text{stat.}} \pm 0.9_{\text{sys.}}) \cdot 10^{-11}$
  [NA62, JHEP06 (2021) 093]
- Data taking resumed in 2021, after LS2, approved until LS3; data analysis ongoing

NA62 Beam and detector

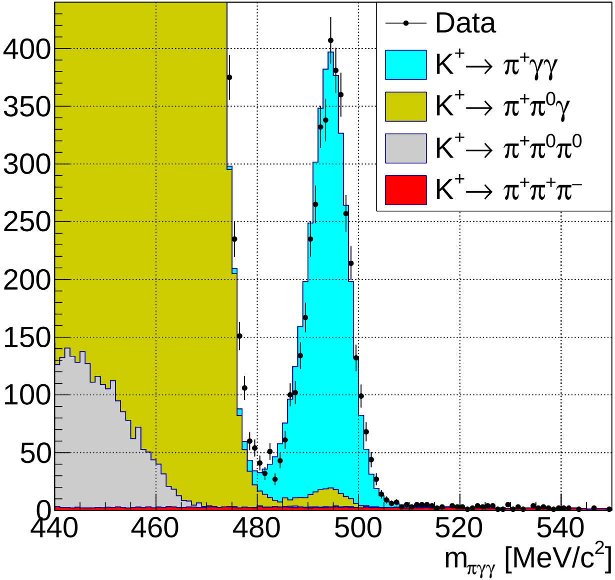


- 400 GeV/c primary beam from SPS on beryllium target
- Secondary 75 GeV/c hadron beam: 70% pions, 24% protons, 6% kaons
- 750MHz nominal beam particle rate
- 450-500MHz average beam particle rate

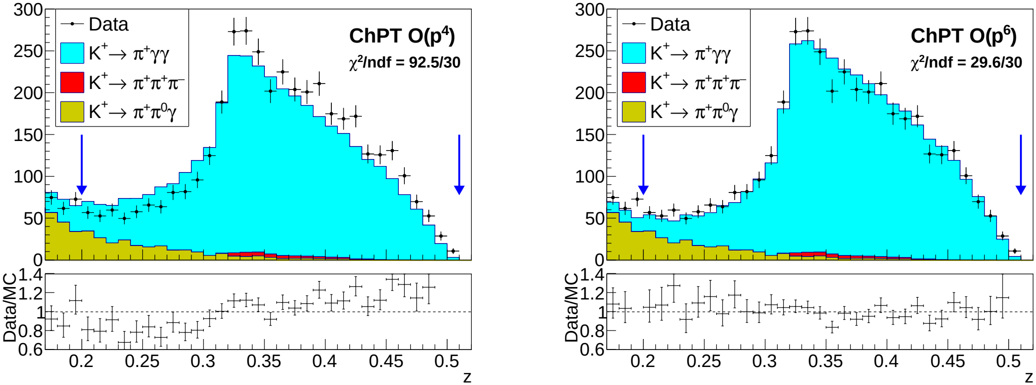
- Timing between subdetectors: $\mathcal{O}(100\text{ps})$
- KTAG, GTK - Kaon ID and beam tracker
- STRAW, RICH, LKr, HASC, MUVs - PID and direction; μ^+ rejection at $\mathcal{O}(10^7)$
- LAV, LKr, IRC, SAV - photon veto; $\pi^0 \to \gamma\gamma$ rejection at $\mathcal{O}(10^7)$

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

- Crucial test of ChPT
- Main kinematic variable : $z = (q_1 + q_2)^2/M_K^2 = m_{\gamma\gamma}^2/M_K^2$
- $\mathcal{B}(K^+ \to \pi^+\gamma\gamma)$ parameterized in ChPT by an unknown real parameter $\hat{c}$
- Signal selection
  - Single positive track identified as π^+ matched with a K^+ track
  - Two γ clusters in LKr
  - Kinematic constraints on $m_{\pi\gamma\gamma}$ and $p_{\pi\gamma\gamma}$
  - $z \in (0.20, 0.51)$
- Normalization selection: done using $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma\gamma$ with $z \in (0.04, 0.12)$
- Main background is due to $K^+ \to \pi^+\pi^0\gamma, \pi^0 \to \gamma\gamma$ decay; cluster merging in calorimeter

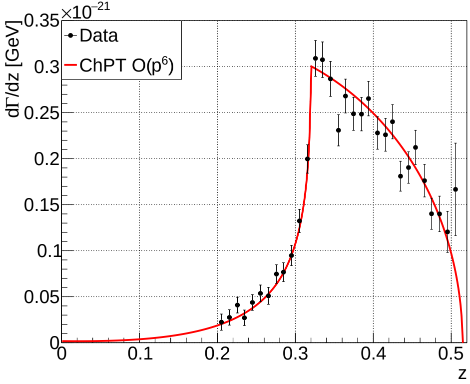


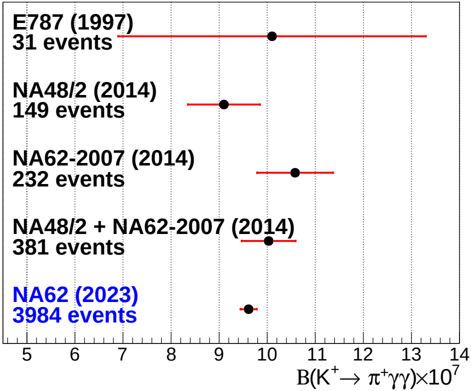
$K^+ \to \pi^+\gamma\gamma$ results



- 3984 observed events; 291 $\pm$ 14 events - expected background
- $\hat{c}$ parameter measured in ChPT $\mathcal{O}(p^4)$ and $\mathcal{O}(p^6)$ using χ^2 minimization
- ChPT $\mathcal{O}(p^4)$ p-value: $2.7 \cdot 10^{-8}$: not sufficient to describe the di-photon mass spectrum
- ChPT $\mathcal{O}(p^6)$ p-value: 0.49

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





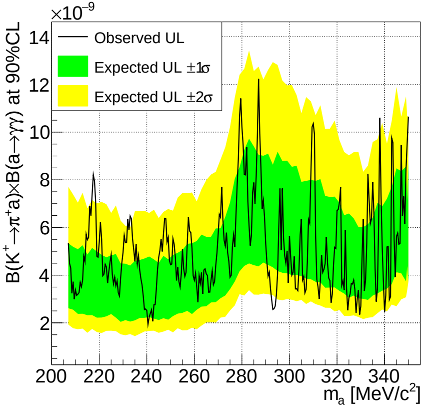
$$\hat{c}^6 = 1.144 \pm 0.069_{\text{stat.}} \pm 0.034_{\text{syst.}}$$

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

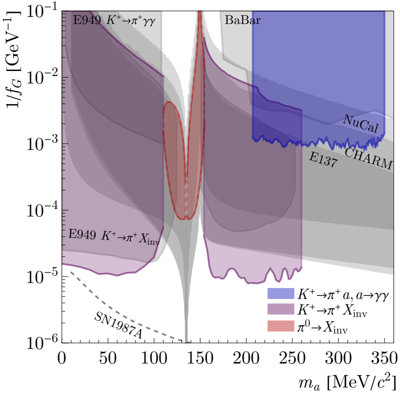
$$\mathcal{B}_{\text{MI}}(K^+ \to \pi^+\gamma\gamma | z > 0.20) = (9.46 \pm 0.19_{\text{stat.}} \pm 0.07_{\text{syst.}}) \cdot 10^{-7}$$

First search for ALP in $K^+ \to \pi^+ A$, $A \to \gamma\gamma$ decays

- Peak search over $m_a = \sqrt{(P_K - P_\pi)^2}$ in the range 207 - 350 MeV/c^2 in steps of 0.5 MeV/c^2
- m_a resolution: from 2.0 MeV/c^2 to 0.2 MeV/c^2 across the search range
- In each m_a hypothesis, background estimated from simulations and UL on number of signal events using CLs method



Prompt $a \to \gamma\gamma$ decay



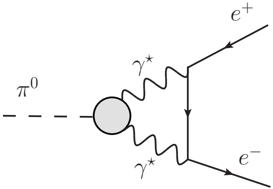
$\tau_a \sim f_G^2$

$\pi^0 \to e^+e^-$: Overview

- Experimentally observable:

$$\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > x_{\text{cut}}), \quad x = m_{ee}^2/m_{\pi^0}^2$$

  - Dalitz decay $\pi^0 \to \gamma\, e^+e^-$ dominant in low-x region
  - For $x > x_{\text{cut}} = 0.95$, Dalitz decay $\approx 3.3\%$ of $\mathcal{B}(\pi^0 \to e^+e^-(\gamma))$



- Previous best measurement by KTeV [Phys.Rev.D 75 (2007) 012004]

$$\mathcal{B}_{\text{KTeV}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$$

- Using latest radiative corrections in [JHEP 10 (2011) 122], [Eur.Phys.J.C 74 (2014) 8, 3010], the result can be extrapolated and compared with theory:

- Diagram considered in theoretical predictions leading to $\mathcal{B}(\pi^0 \to e^+e^-, \text{no-rad})$ for various $\pi^0 \to \gamma^\star\gamma^\star$ transition form factors.

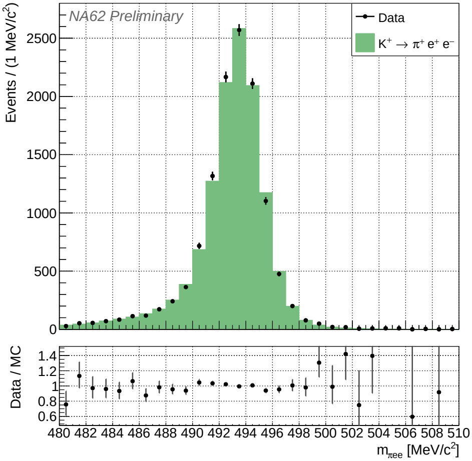
	$\mathcal{B}(\pi^0 \to e^+e^-, \text{no-rad}) \times 10^8$
KTeV, PRD 75 (2007)	6.84(35)
Knecht et al., PRL 83 (1999)	6.2(3)
Dorokhov and Ivanov, PRD 75 (2007)	6.23(9)
Husek and Leupold, EPJC 75 (2015)	6.12(6)
Hoferichter et al., PRL 128 (2022)	6.25(3)

Data Sample and Trigger

- Data sample collected by NA62 in 2017 and 2018
- Signal decay mode: $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^- \equiv K^+ \to \pi^+\pi^0_{ee}$
  - Latest radiative corrections included in the simulation
- Normalization decay mode: $K^+ \to \pi^+e^+e^-$
  - Identical final state as the signal, common selection criteria $\to$ cancellation of systematics
  - Selecting almost background-free region $m_{ee} > 140\,\text{MeV}$
- *Multi-track electron* trigger line used to collect both $K^+ \to \pi^+\pi^0_{ee}$ and $K^+ \to \pi^+e^+e^-$
  - Downscaling factor $D_{eMT} = 8$
  - Level-0: RICH, CHOD, LKr
  - Level-1: KTAG, Straw
  - Total trigger efficiency $\approx$ 90% for both signal and normalization
- Backgrounds for the signal decay mode:
  - $K^+ \to \pi^+e^+e^-$: irreducible, flat in the signal region close to the π^0 mass
  - $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\, e^+e^- \equiv K^+ \to \pi^+\pi^0_D$
    a) Large-x tail of the π^0 Dalitz decay distribution
    b) Photon conversion in STRAW + selection of a $e^\pm$ track from the conversion
  - $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-e^+e^- \equiv K^+ \to \pi^+\pi^0_{DD}$, π^0 double Dalitz decay with two undetected $e^\pm$

Common Selection Criteria for $K^+ \to \pi^+\pi^0_{ee}$ and $K^+ \to \pi^+e^+e^-$

- Three track vertex topology (STRAW)
- Timing cuts (CHOD, KTAG)
- Kinematic constraints on total and transverse momenta of the vertex
- Particle ID using LKr + STRAW and decay kinematics
  - π^+: $E/p < 0.9$
  - $e^\pm$: $E/p \in (0.9, 1.1)$
  - Total invariant mass: $m_{\pi ee} \in 480\,\text{MeV}$ to $510\,\text{MeV}$
  - Di-electron invariant mass: $m_{ee} > 130\,\text{MeV}$
- Background suppression:
  - Using STRAW hit information to reject $e^\pm$ tracks from γ conversions
  - Reject events with a track segment reconstructed in the first two STRAW chambers compatible with the vertex



$K^+ \to \pi^+ e^+ e^-$ Normalization Sample

- Common selection applied
- Normalization region:

$$m_{ee} \in 140\,\text{MeV to } 360\,\text{MeV}$$

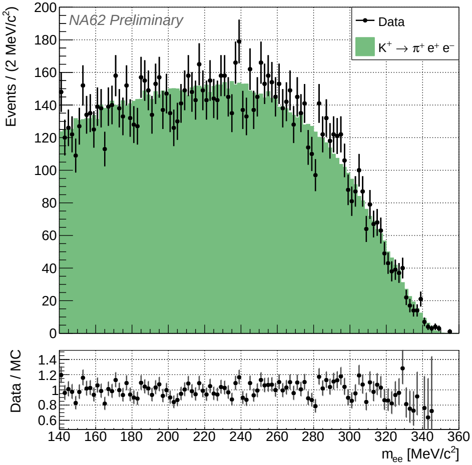
- Number of observed events: 12160
- Acceptance:

$$A(K^+ \to \pi^+ e^+ e^-) = (4.70 \pm 0.01_{\text{stat}})\%$$

- Sample purity $> 99.9\%$
- Effective number of kaon decays:

$$N_K = (8.62 \pm 0.08_{\text{stat}} \pm 0.26_{\text{ext}}) \times 10^{11}$$

  - External uncertainty from $\mathcal{B}_{\text{PDG}}(K^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^{-7}$



$K^+ \to \pi^+\pi^0_{ee}$ Signal Sample

- Common selection applied
- Fit region:

$$m_{ee} \in 130\,\text{MeV to } 140\,\text{MeV}$$

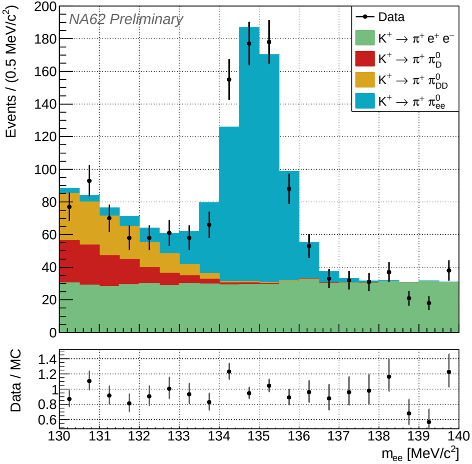
- Signal acceptance ($x_{\text{true}} > 0.95$):

$$A(K^+ \to \pi^+\pi^0_{ee}) = (5.72 \pm 0.02_{\text{stat}})\%$$

- Branching fraction of $\pi^0 \to e^+e^-$ obtained by performing maximum likelihood fit of simulated samples to data

$$\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.30_{\text{stat}}) \times 10^{-8}$$

  - Branching fractions of other decays: external input from PDG 2023
  - Fitted signal event yield: 597 ± 29
  - Chi-squared test: $\chi^2/\text{ndf} = 25.3/19$, p-value: 0.152



Preliminary Result and Uncertainties

$$\mathcal{B}_{\mathrm{NA62}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.30_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}} \pm 0.19_{\mathrm{ext}}) \times 10^{-8} = (5.86 \pm 0.37) \times 10^{-8}$$

	$\delta\mathcal{B}$ $[10^{-8}]$	$\delta\mathcal{B}/\mathcal{B}$ [%]
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

$K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-$ - Summary and Outlook

- New preliminary result based on data collected by NA62 in 2017 – 2018:

  $\mathcal{B}_{\text{NA62}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.30_{\text{stat}} \pm 0.11_{\text{syst}} \pm 0.19_{\text{ext}}) \times 10^{-8} = (5.86 \pm 0.37) \times 10^{-8}$

- Lower central value than in KTeV measurement, but results are compatible:

$$\mathcal{B}_{\text{KTeV}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.33) \times 10^{-8}$$

- Result in agreement with theoretical expectations when extrapolated using radiative corrections:

$$\mathcal{B}_{\text{NA62}}\left(\pi^0 \to e^+e^-, \text{no-rad}\right) = (6.22 \pm 0.39) \times 10^{-8}$$

$$\mathcal{B}_{\text{theory (2022)}}\left(\pi^0 \to e^+e^-, \text{no-rad}\right) = (6.25 \pm 0.03) \times 10^{-8}$$

- External uncertainty dominated by $\mathcal{B}(K^+ \to \pi^+e^+e^-)$, measured by NA48/2 and E865
  - New analysis of $K^+ \to \pi^+e^+e^-$ is planned at NA62
- Ongoing NA62 data taking (2021 – LS3)
  - Optimized multi-track electron trigger line with reduced downscaling
  - Collecting large samples of decays with di-electron final states

Conclusions

- $\pi^0 \to e^+e^-$ (new preliminary result):
  - Precision comparable with previous measurement, dominated by statistics
  - Full agreement with latest theoretical predictions
- $K^+ \to \pi^+\gamma\gamma$ [PLB 850 (2024) 138513]:
  - Results consistent with previous measurements
  - Improved precision, by a factor of > 3, dominated by statistics
  - First search for ALP with gluon coupling in $K^+ \to \pi^+ a$, $a \to \gamma\gamma$ decays
- Other recent results on precision measurements from NA62 Run 1 data:
  - $K^+ \to \pi^0 e^+ \nu\gamma$: [JHEP 09 (2023) 040]
  - $K^+ \to \pi^+\mu^+\mu^-$: [JHEP 11 (2022) 011]
- NA62 physics Run 2 started in 2021 and ongoing until CERN LS3, data analysis ongoing

Back-up slides

$K^+ \to \pi^0 e^+ \nu\gamma$ overview

- Decay described by inner bremsstrahlung and structure dependent processes and their interference
- $\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma)$ depends on E_γ and $\theta_{e\gamma}$
- $R_j = \dfrac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma | E_\gamma^j, \theta_{e\gamma}^j)}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma)}$ with $j = 1, 2, 3$
  ranges where normalized branching ratio is measured
- Amplitude of the decay is senzitive to T-violating contributions
  T-odd observable ξ and the corresponding T-asymmetry A_ξ: $\xi = \dfrac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{(M_K \cdot c)^3}$; $A_\xi = \dfrac{N_+ - N_-}{N_+ + N_-}$

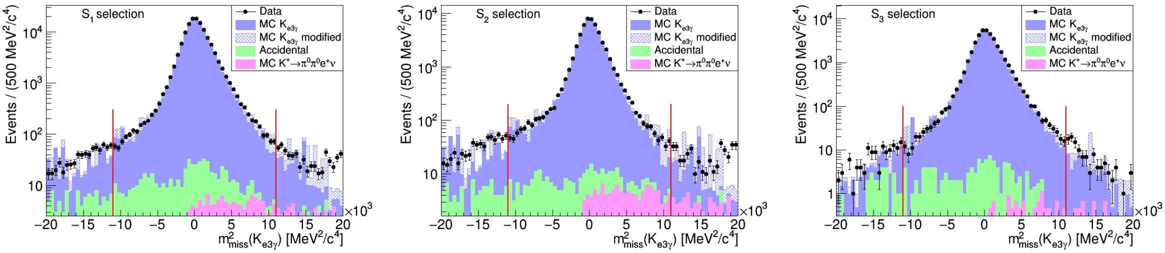
State of the art:

	$E_\gamma^j, \theta_{e\gamma}^j$	ChPT	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	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

$K^+ \to \pi^0 e^+ \nu\gamma$ signal selection

- K^+ and e^+ tracks reconstructed and matched
- $\pi^0 \to \gamma\gamma$ reconstructed as two LKr clusters
- One isolated LKr clusted is identified as radiative γ
- $m^2_{\text{miss}}(K_{e3\gamma}) = (P_K - P_e - P_{\pi^0} - P_\gamma)^2$ used as kinematic constraint
- Signal and normalization selection differences are related only to radiative photon to reduce systematic effects

$K^+ \to \pi^0 e^+ \nu \gamma$ results



	Range 1	Range 2	Range 3
$R \cdot 10^2$	$1.715 \pm 0.005_{\text{stat.}} \pm 0.010_{\text{syst.}}$	$0.609 \pm 0.003_{\text{stat.}} \pm 0.006_{\text{syst.}}$	$0.533 \pm 0.003_{\text{stat.}} \pm 0.004_{\text{syst.}}$
$A_\xi \cdot 10^3$	$-1.2 \pm 2.8_{\text{stat.}} \pm 1.9_{\text{syst.}}$	$-3.4 \pm 4.3_{\text{stat.}} \pm 3.0_{\text{syst.}}$	$-9.1 \pm 5.1_{\text{stat.}} \pm 3.5_{\text{syst.}}$

- $1.3 \cdot 10^5$ observed events; $< 1\%$ relative background contamination
- NA62 measurement of R_j smaller than $\mathcal{O}(p^6)$ ChPT by 5% relative (disagreement 3σ)
- Improvement on experimental precision of R_j measurements by a factor > 2

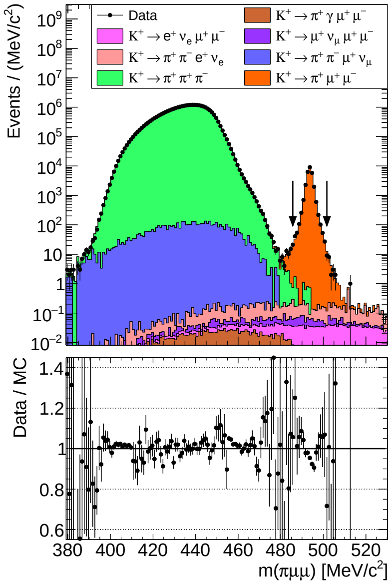
$K^+ \to \pi^0 e^+ \nu\gamma$ analysis: error budged

Relative uncertainties in the R_j measurements.

	$\delta R_1/R_1$	$\delta R_2/R_2$	$\delta R_3/R_3$
Statistical	0.3%	0.4%	0.5%
Limited MC sample size	0.2%	0.4%	0.4%
Background estimation	0.1%	0.2%	0.1%
LKr response modelling	0.4%	0.5%	0.4%
Photon veto correction	0.3%	0.4%	0.3%
Theoretical model	0.1%	0.5%	0.1%
Total systematic	0.6%	0.9%	0.7%
Total	0.7%	1.0%	0.8%

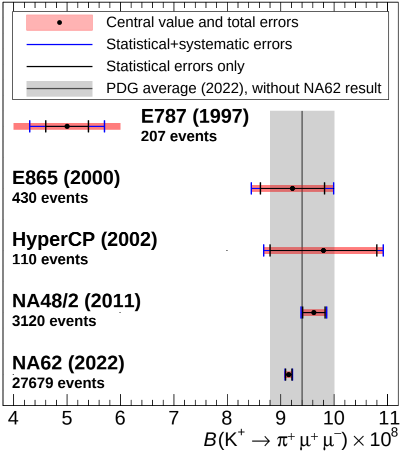
$K^+ \to \pi^+\mu^+\mu^-$ overview

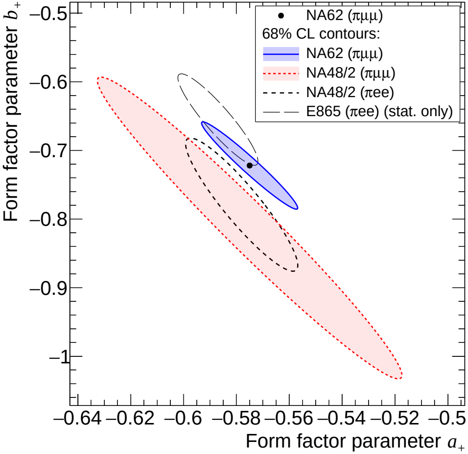
- Flavour changing neutral current decay
- Contribution to the decays are mediated by virtual photon exchange: $K^\pm \to \pi^\pm\gamma^* \to \pi^\pm l^+ l^-$
- Main kinematic variable $z = m^2_{l^+l^-}/m^2_K$
- $W(z) = (a_+ + z \cdot b_+)G_F m_K^2 + W^{\pi\pi}(z)$ is the form factor of $K^\pm \to \pi^\pm\gamma^*$ parameterized in ChPT $\mathcal{O}(p^6)$; a_+, b_+ - real parameters
- Contributes to experimental test of lepton flavour universality
- Goals:
  - Measure $\mathcal{B}(K^+ \to \pi^+\mu^+\mu^-)$
  - Measure function $|W(z)|^2$ (from $d\Gamma/dz$)
  - Measure form factor parameters a^+, b^+
- Signal selection: three tracks identified as π^+, μ^+, μ^-; kinematic cuts to supress $K_{3\pi}$
- Normalization channel: $K^+ \to \pi^+\pi^+\pi^-$



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

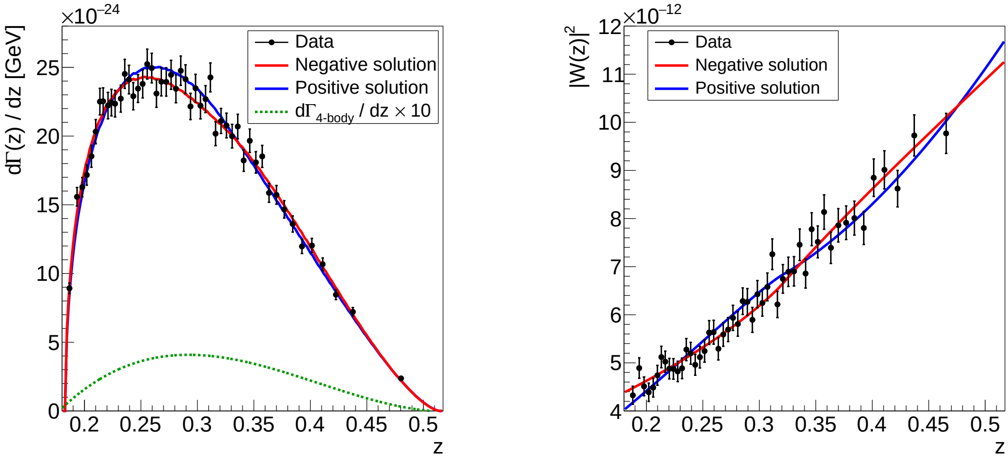
27679 observed events with negligible background





$$a_+ = -0.575 \pm 0.013;\ b_+ = -0.722 \pm 0.043$$
$$\mathcal{B}(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \cdot 10^{-8} \text{ at 68\% CL}$$

$K^+ \to \pi^+\mu^+\mu^-$ decay width and form factor



$$\frac{d\Gamma(z)}{dz} = \frac{d\Gamma_{\text{3-body}}(z)}{dz} + \frac{d\Gamma_{\text{4-body}}(z)}{dz} = g(z)\cdot|W(z)|^2 + \frac{d\Gamma_{\text{4-body}}(z)}{dz}$$

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

	δa_+	δb_+	$\delta \mathcal{B}_{\pi\mu\mu} \times 10^8$
Statistical uncertainty	0.012	0.040	0.06
Trigger efficiency	0.002	0.008	0.02
Reconstruction and particle identification	0.002	0.007	0.02
Size of the simulated $K_{\pi\mu\mu}$ sample	0.002	0.007	0.01
Beam and accidental activity simulation	0.001	0.002	0.01
Background	0.001	0.001	—
Total systematic uncertainty	0.003	0.013	0.03
$K_{3\pi}$ branching fraction	0.001	0.003	0.04
$K_{\pi\mu\mu}$ radiative corrections	0.003	0.009	0.01
Parameters α_+ and β_+	0.001	0.006	—
Total external uncertainty	0.003	0.011	0.04
Total uncertainty	**0.013**	**0.043**	**0.08**