Precision measurements of kaon and pion decays at NA62

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Outline

1) The NA62 experiment at CERN
2) Measurements of K^+ and π^0 decays with NA62 Run 1 data: $K^+ \to \pi^+\mu^+\mu^-$, $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^0 e^+\nu\gamma$, $\pi^0 \to e^+e^-$.
3) Summary

BEACH 2024

Charleston, South Carolina • 6 June 2024

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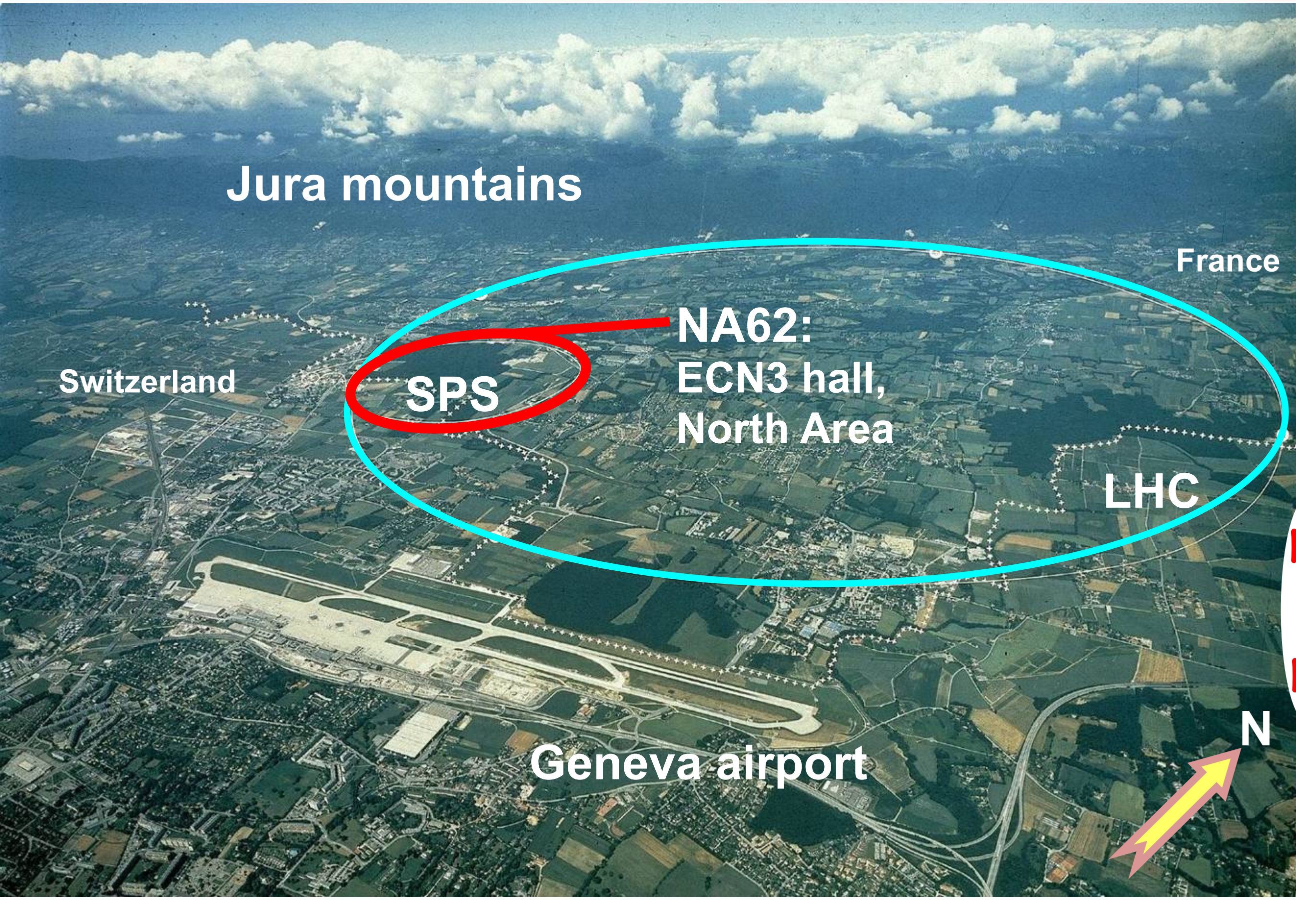
Kaon experiments at CERN



Earlier: NA31

NA48 discovery of direct CPV
- 1997: ε'/ε: K_L+K_S
- 1998: K_L+K_S
- 1999: K_L+K_S | K_S HI
- 2000: K_L only | K_S HI
- 2001: K_L+K_S | K_S HI

NA48/1
- 2002: K_S/hyperons

NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

NA62 R_K run
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ | tests

NA62
- 2015: commissioning
- 2016-18: physics run 1
- 2021-: physics run 2

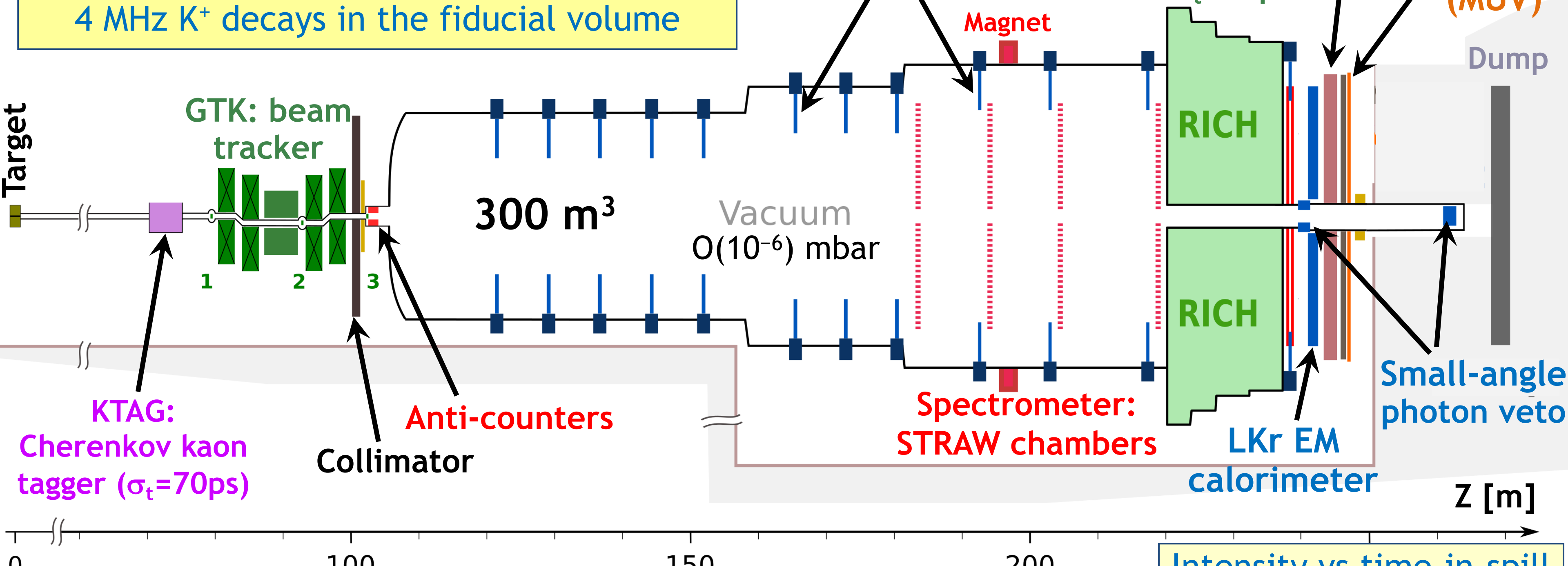
Main NA62 goal: $K^+\to\pi^+\nu\nu$ measurement to 15% precision using the decay-in-flight technique.

Currently ~300 participants from ~30 institutions.

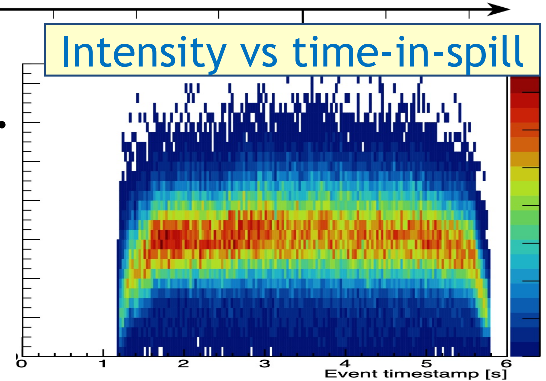
The NA62 setup

JINST 12 (2017) P05025

SPS protons: 400 GeV, 3×10^{12}/spill.
Unseparated secondary ($p/\pi^+/K^+$) beam:
75 GeV/c (±1%), divergence < 100 μrad.
Beam rate: 600 MHz; K^+ rate: 35 MHz;
4 MHz K^+ decays in the fiducial volume

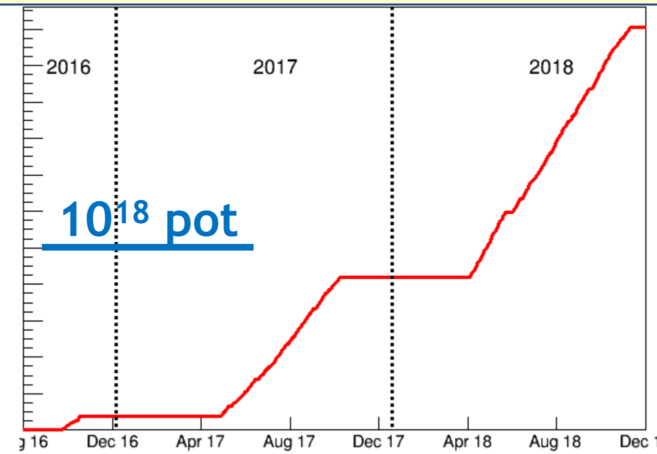


- One year ≈ **2×10^{18}** protons on target ≈ **5×10^{12} K^+** decays.
- Beam structure: ideally, uniform over a **4.8 s** long spill.
- In practice, significant variations of instantaneous beam intensity during the spill.



NA62 datasets

Run 1 integrated luminosity



Currently: ~2×10^{18} pot/year, ~5×10^{12} K^+ decays/year

Beam-dump mode: 4×10^{17} pot collected so far

- Run 1 (2016–18): N_K~10^{13} useful K^+ decays with the main trigger.
  - ✓ Sample **2016** (30 days, ~1.3×10^{12} ppp): 2×10^{11} useful K^+ decays.
  - ✓ Sample **2017** (160 days, ~1.9×10^{12} ppp): 2×10^{12} useful K^+ decays.
  - ✓ Sample **2018** (217 days, ~2.3×10^{12} ppp): 4×10^{12} useful K^+ decays.
- Run 2 (2021–): in progress (up to 3×10^{12} ppp), approved till 2025.

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

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

D'Ambrosio, Ecker, Isidori, Portoles
JHEP 08 (1998) 004

Theory 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_+

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

JHEP 11 (2022) 11

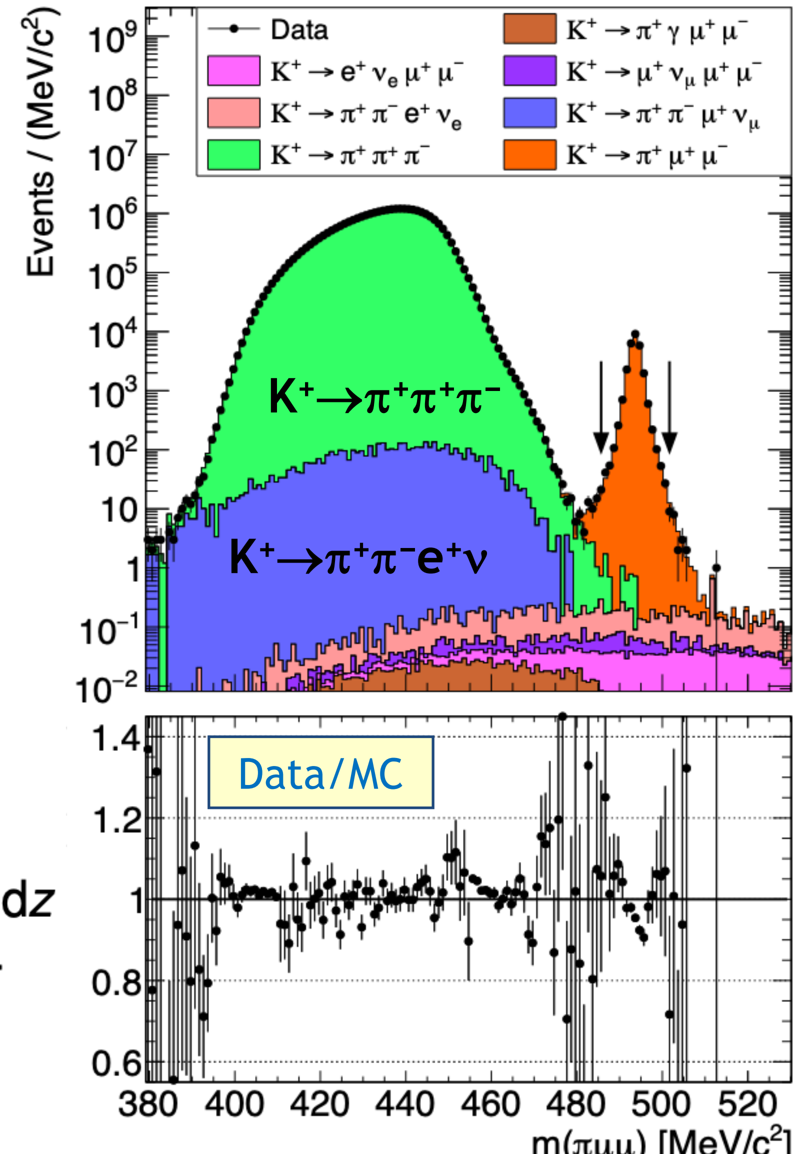
- Dedicated di-muon trigger line.
- Normalisation: $K^+ \to \pi^+\pi^+\pi^-$ decay.
- Effectively $(3.48 \pm 0.09) \times 10^{12}$ kaon decays.
- Signal candidates observed: **27679**.
- Negligible background: about **8** events.

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



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

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 $= 0.59$):

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

❖ The positive solution ($a_+>0$, $b_+>0$) cannot be excluded (p-value: 0.19).

Model-independent branching ratio
(summed over the z bins):
$BR_{MI} = (9.15\pm0.08)\times10^{-8}$

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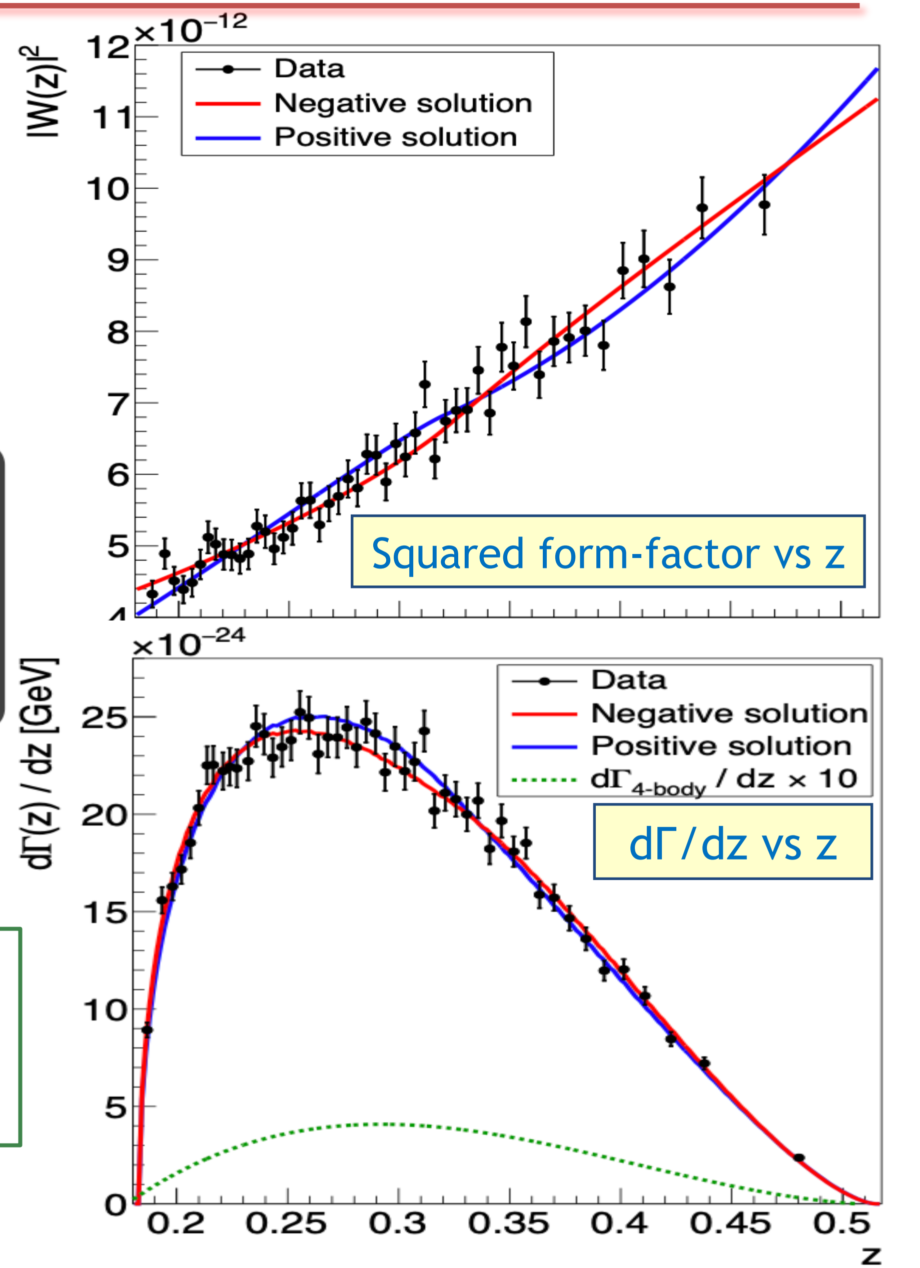

$K^+ \to \pi^+ \mu^+ \mu^-$ decay

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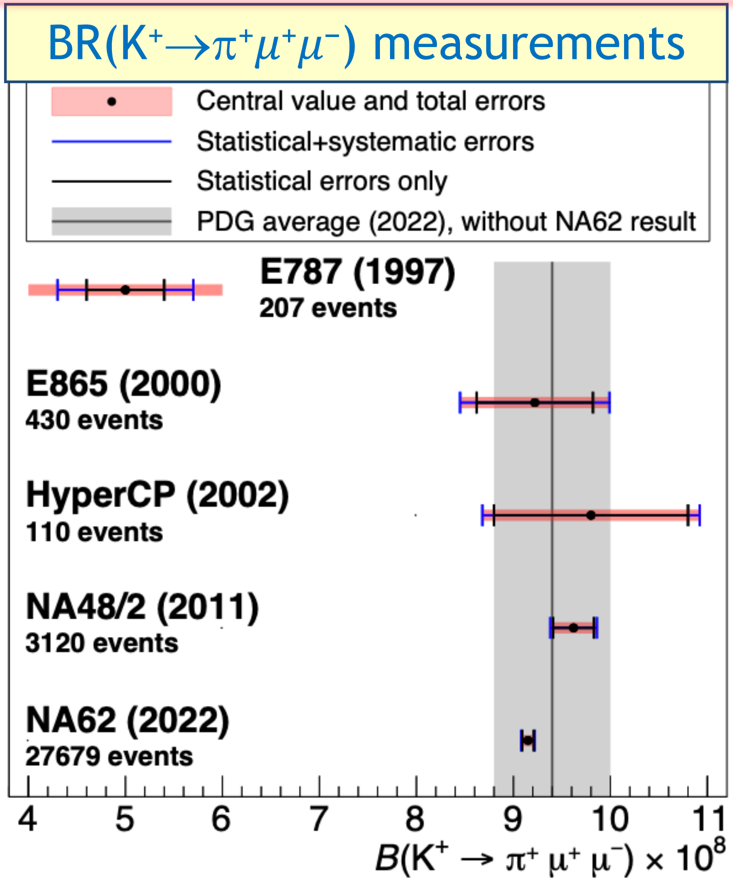
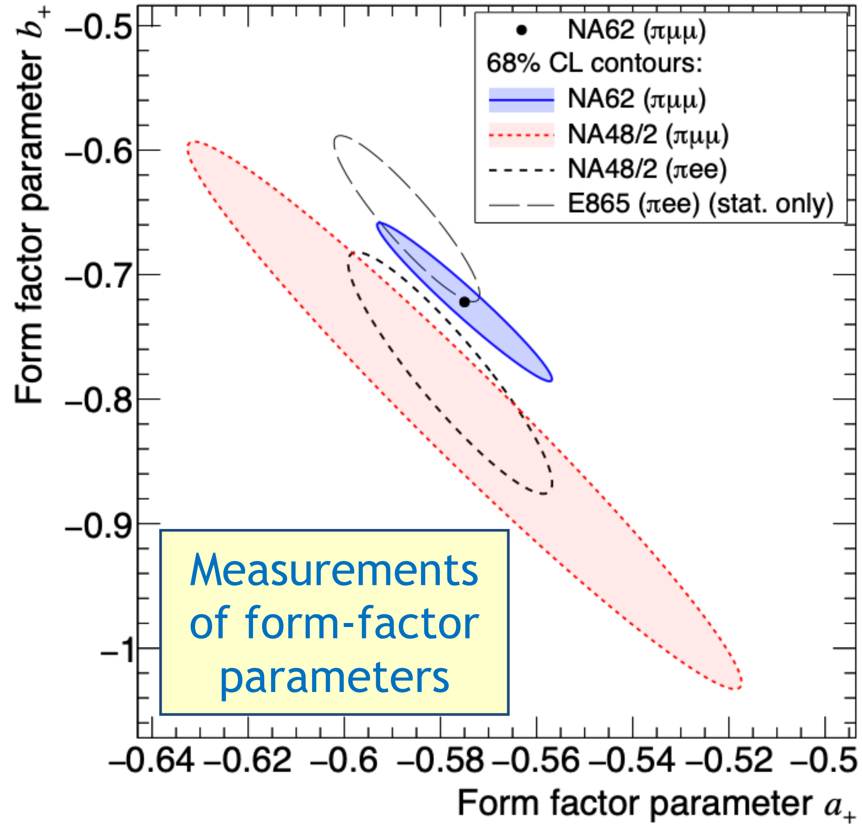




- A factor of **3** improvement on best previous **BR($K^+ \to \pi^+ \mu^+ \mu^-$)** measurement.
- Measured form-factor parameters (**a_+**,**b_+**) are compatible between **$K^+ \to \pi^+ \mu^+ \mu^-$** and **$K^+ \to \pi^+ e^+ e^-$** decays: lepton universality.
- Next step: **$K^+ \to \pi^+ \mu^+ \mu^-$** and **$K^+ \to \pi^+ e^+ e^-$** measurement with full dataset; dedicated LFU test, search for a scalar contribution

(see D'Ambrosio, Iyer, Mahmoudi, Neshatpout, arXiv:2404.03643)

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

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

Theory overview

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

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

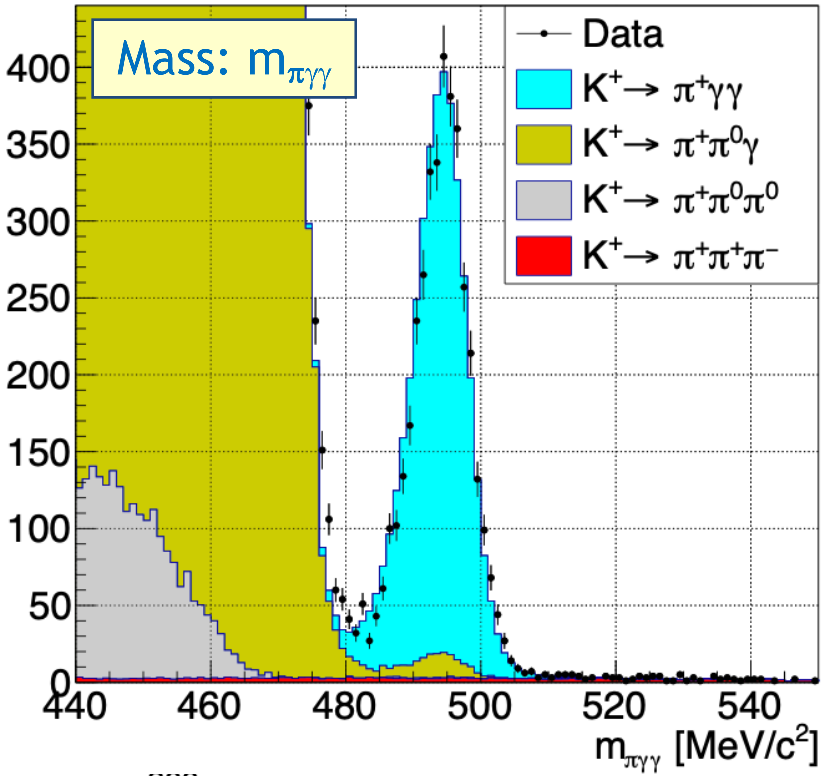
- Differential decay width *[D'Ambrosio and Portoles, PLB386 (1996) 403]*

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

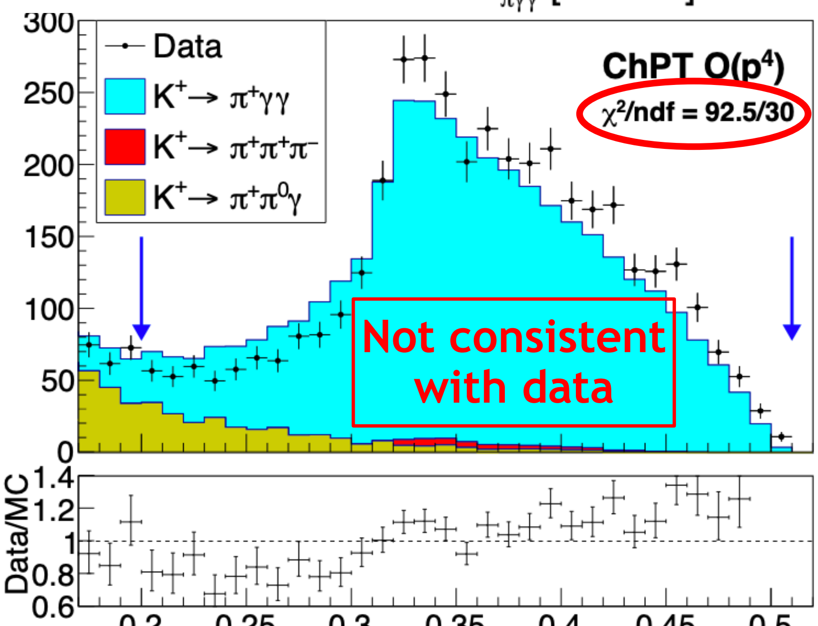
  - Decay spectrum and rate are determined by a single ChPT parameter **c**, plus external parameters extracted from **$K\to3\pi$** decays.
  - The term **B(z)**, and therefore the **y**-dependence, only appear at next-to-leading order, **$O(p^6)$**, in ChPT.
  - Goals: measurement of **c_6** and model-dependent BR.

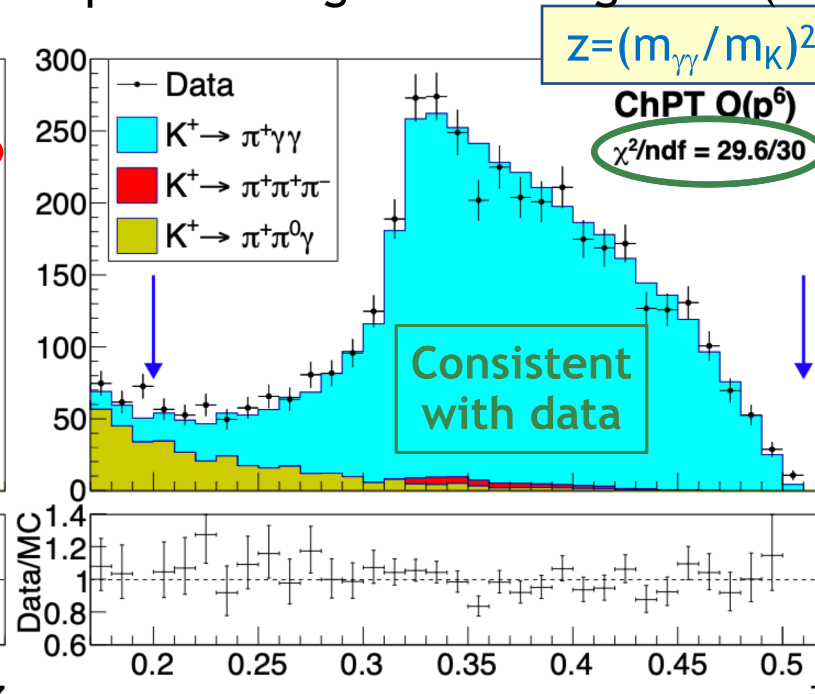
$K^+ \to \pi^+\gamma\gamma$ decay

PLB850 (2024) 138513



- Downscaled control and non-muon trigger lines.
- Normalisation: $K^+ \to \pi^+\pi^0$ decay, effectively $(5.55\pm0.03)\times10^{10}$ kaon decays.
- Candidates observed: **3984**.
- Expected background: **291±14**.
- Kinematic variable $z=(m_{\gamma\gamma}/m_K)^2$ computed using the missing mass $(K-\pi)$.

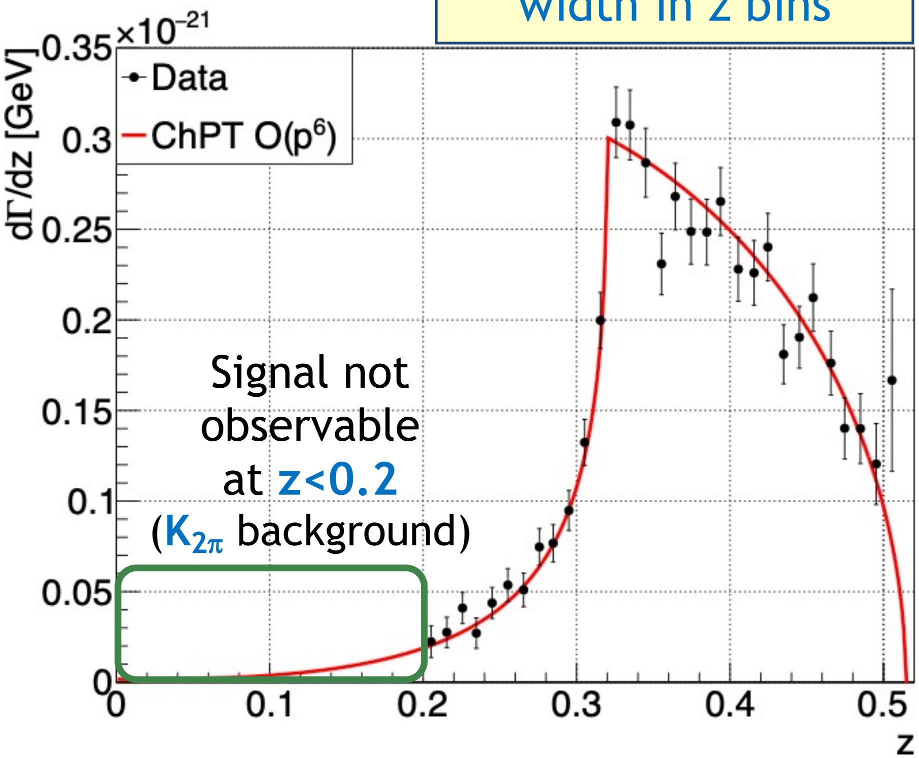




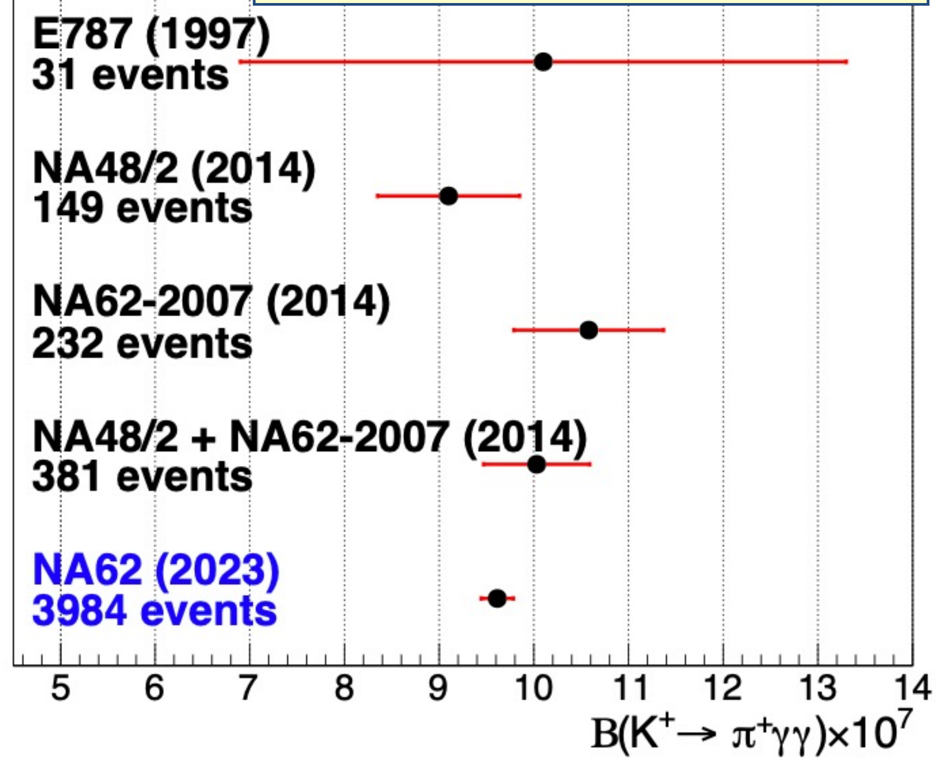
$K^+ \to \pi^+\gamma\gamma$ decay

PLB850 (2024) 138513

Differential decay width in z bins



BR($K^+ \to \pi^+\gamma\gamma$) measurements in the ChPT framework



$$\hat{c}^6 = 1.44 \pm 0.069_{\text{stat.}} \pm 0.034_{\text{syst.}}$$

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

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

ALPs in $K^+ \to \pi^+ a$, $a \to \gamma\gamma$ decay

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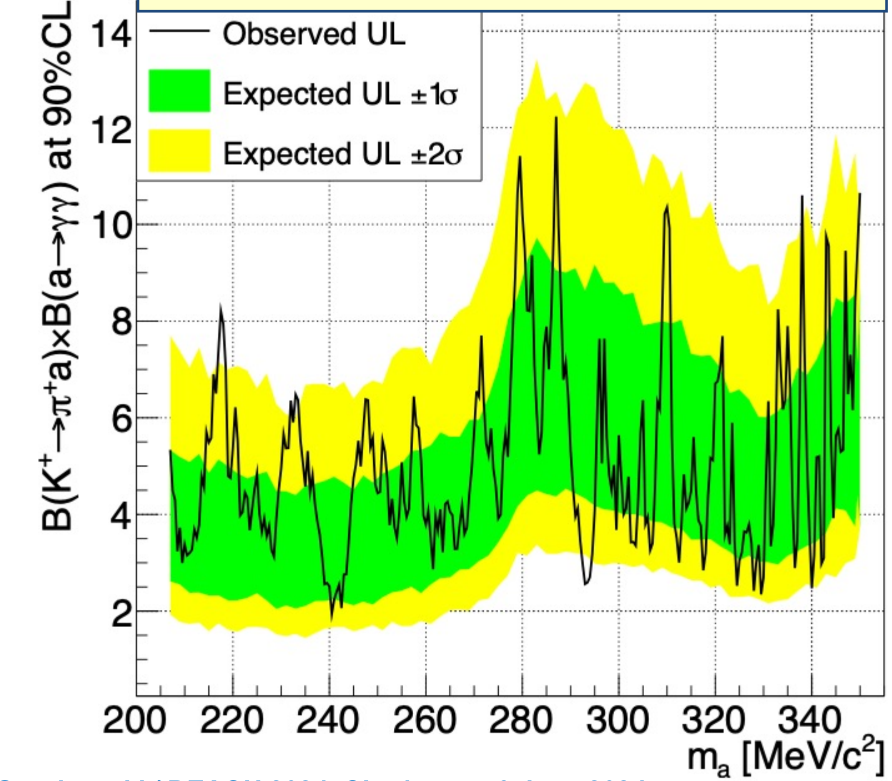
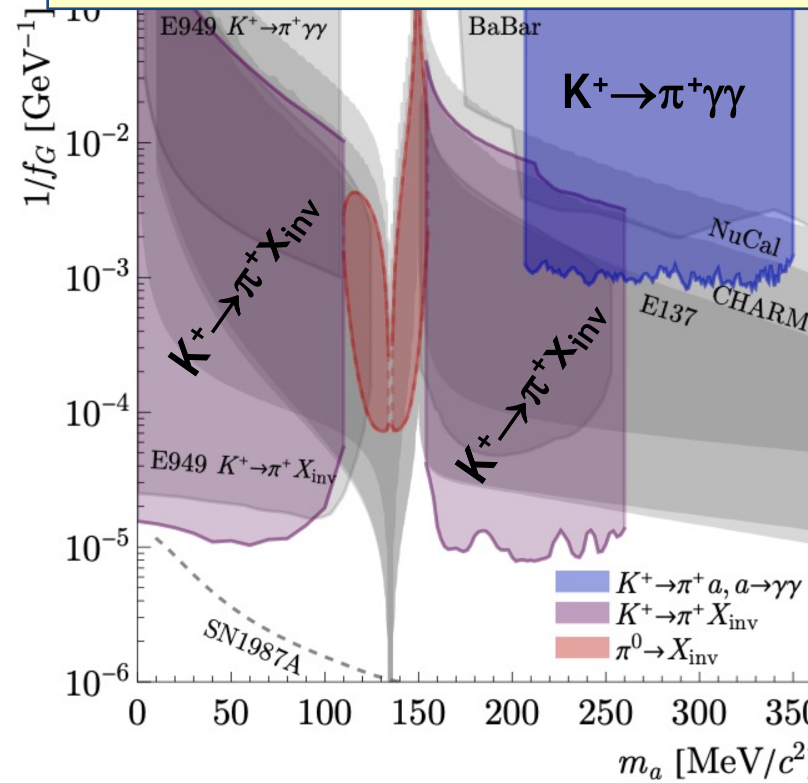
- Axion-like particle coupling to gluons: PBC scenario BC11.
- For $m_a < 3m_\pi$, the dominant decay mode is $a \to \gamma\gamma$.
- Peak search performed in the z spectrum of the $K^+ \to \pi^+\gamma\gamma$ decay.
- Sensitivity up to ALP lifetime of 3 ns (longer-lived ALP is invisible).

Limits of $BR(K^+ \to \pi^+ a) \times BR(a \to \gamma\gamma)$, prompt decay assumption



Limits on BC11 parameters $(m_a, 1/f_G)$ from this and other searches



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

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

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Theory and experiment overview

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	$\theta_{e,\gamma} > 10°$	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	$\theta_{e,\gamma} > 20°$	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): $\xi = \frac{\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\pi)}{m_K^3}$; Asymmetry: $A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$

(SM expectation ~10^{-4})

ChPT calculation: Kubis, Muller, Gasser, Schmid, EPJ50 (2007) 557

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

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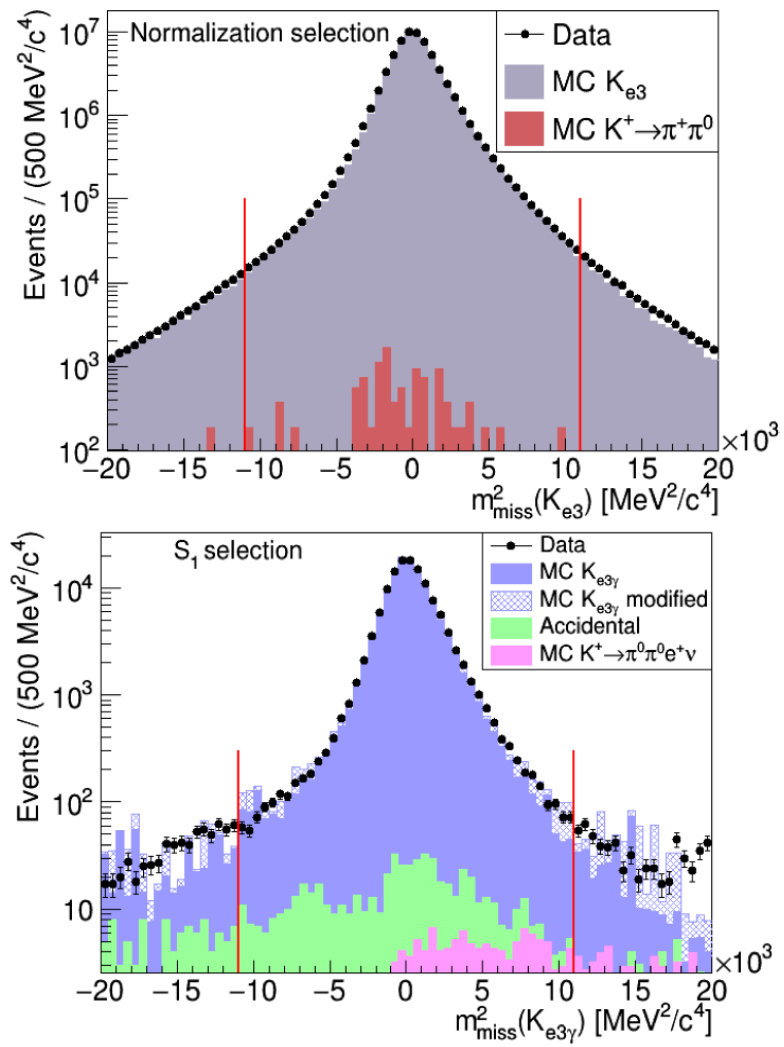
Downscaled control and non-muon trigger lines

- 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) $\approx$ **1.3×10⁵** for selection **S_1**
  - → Background: $< 1\%$
  - → Main source of bkg.: accidental activity
- Evaluation of R_j:

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

- Evaluation of asymmetry:

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



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

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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	$7.0 \pm 8.1 \pm 1.5$	$\mathbf{-9.1 \pm 5.1 \pm 3.5}$

- No T-odd asymmetry observed at the 10^{-3} level.
- Sensitivity does not reach the SM expectation.

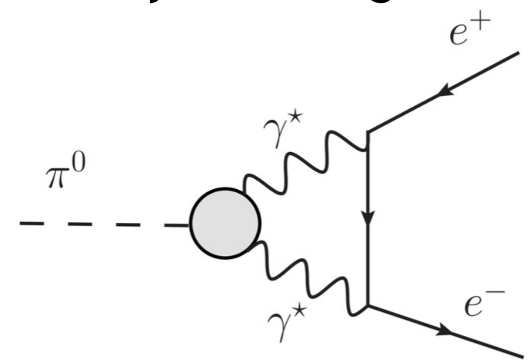
$\pi^0 \rightarrow e^+e^-$ decay

$\pi^0 \to e^+e^-$ decay

Theory overview and experimental status

(loop and helicity suppressed decay)

Leading-order Feynman diagram



- Experimentally observable:

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

  - Dalitz decay $\pi^0 \to \gamma e^+e^-$ dominant in low-x region
  - For $x > x_{\rm cut} = 0.95$, 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]

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

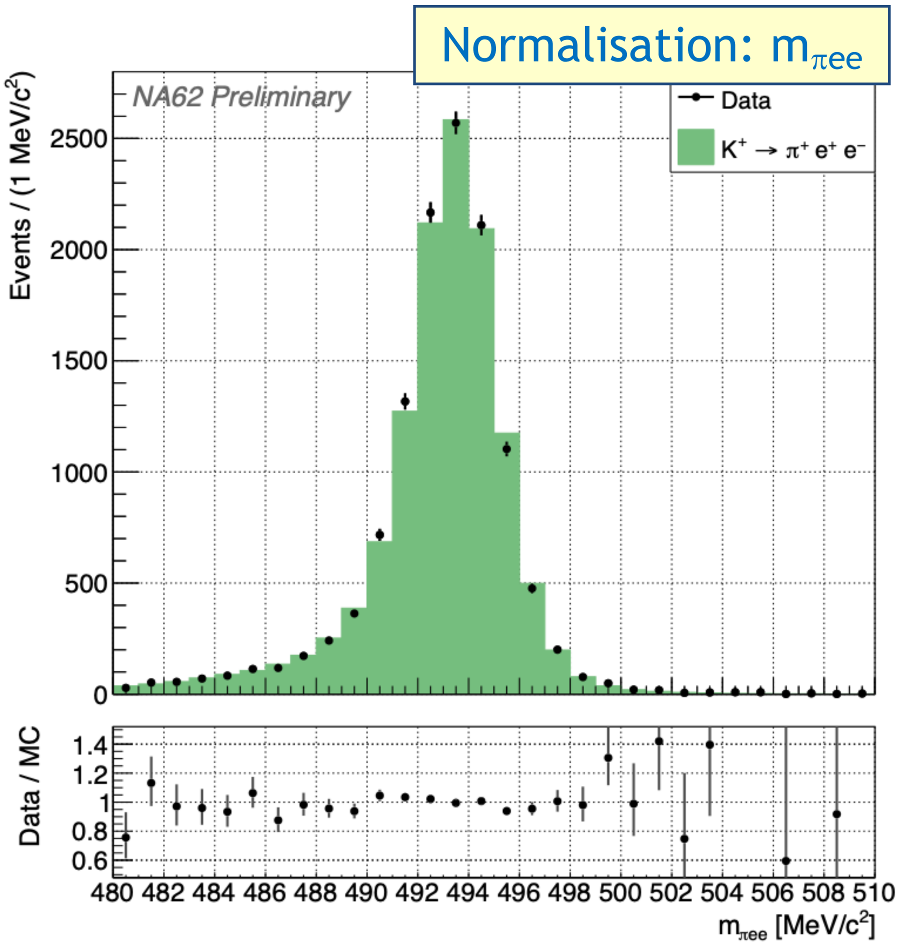
- Using latest radiative corrections in [JHEP 10 (2011) 122], [Eur.Phys.J.C 74 (2014) 8, 3010], the result can be extrapolated and compared with theory:

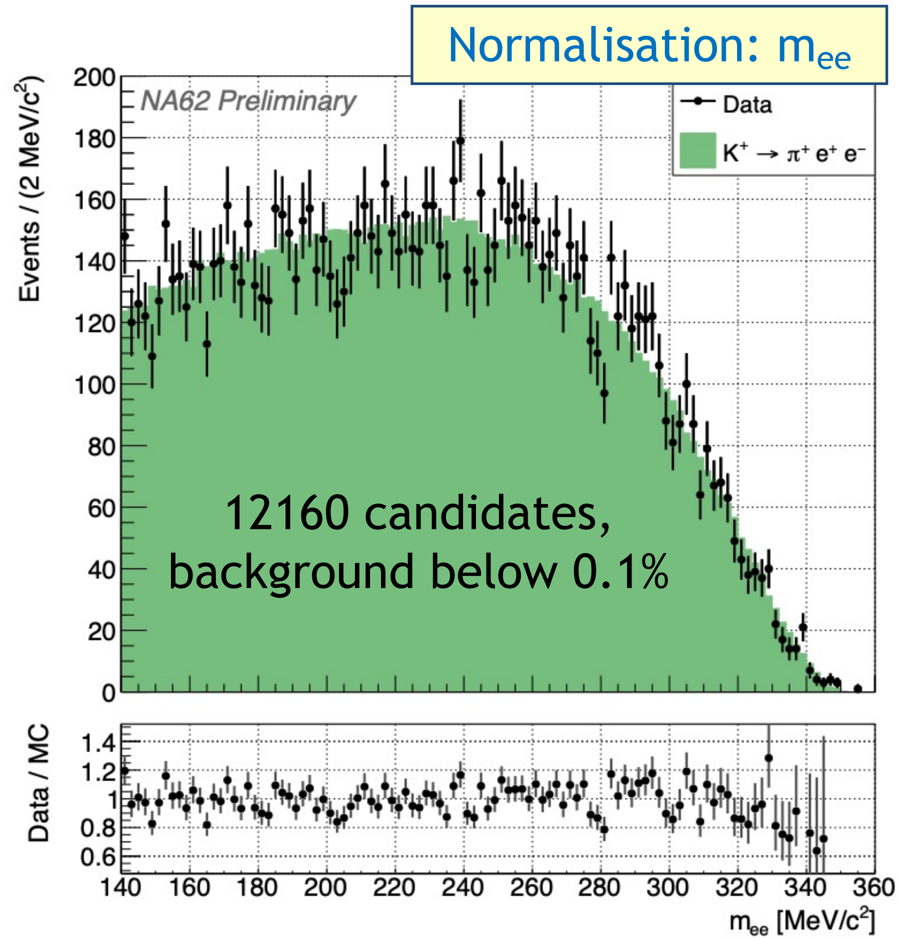
	$\mathcal{B}(\pi^0 \to e^+e^-, \text{no-rad}) \times 10^8$
KTeV, PRD 75 (2007)	6.84(35)
Knecht et al., PRL 83 (1999)	6.2(3)
Dorokhov and Ivanov, PRD 75 (2007)	6.23(9)
Husek and Leupold, EPJC 75 (2015)	6.12(6)
Hoferichter et al., PRL 128 (2022)	6.25(3)

$\pi^0 \to e^+e^-$ decay

[preliminary, to be published]

- Downscaled electron multi-track trigger line.
- Signal decay chain: $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-$.
- Normalisation: $K^+ \to \pi^+e^+e^-$ decay (selection: m_{ee}>140 MeV/c^2), effectively $(8.62\pm0.27)\times10^{11}$ kaon decays.

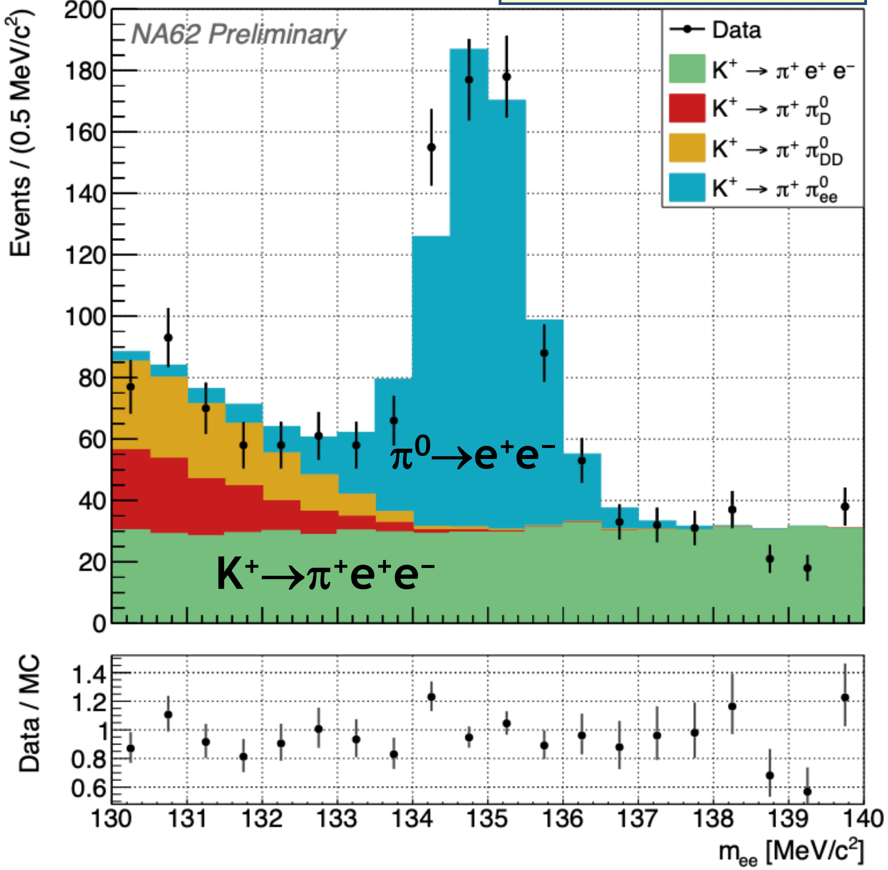




$\pi^0 \to e^+e^-$ decay

[preliminary, to be published]

Signal: m_{ee}



- Irreducible $K^+ \to \pi^+ e^+ e^-$ background.
- Other backgrounds: $K^+ \to \pi^+ \pi^0_D$, $\pi^0_D \to \gamma e^+ e^-$ with a lost or converted photon, and $K^+ \to \pi^+ \pi^0_{DD}$ with two undetected $e^\pm$.
- Signal yield: **597±29** events.
- Measurement of the signal BR:

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

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

Extrapolation using radiative corrections:

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

Good agreement with SM expectation

Summary

- NA62 Run 1 (**2016−2018**) dataset exploited for precision studies rare kaon and pion decays:
  - ✓ $K^+ \to \pi^+ \mu^+ \mu^-$ *[BR~10^{-7}; JHEP 11 (2022) 11]*
  - ✓ $K^+ \to \pi^+ \gamma\gamma$ *[BR~10^{-6}; PLB850 (2024) 138513]*
  - ✓ $K^+ \to \pi^0 e^+ \nu\gamma$ *[BR~10^{-4}; JHEP 09 (2023) 40]*
  - ✓ $\pi^0 \to e^+ e^-$ *[BR~10^{-8}; preliminary, to be published]*

- Uncertainties are generally dominated by statistical errors.

- NA62 is collecting data until **2025** (or **2026**).
  New results, including those based on the full dataset, are expected in near future.