Precision measurements with kaon and pion decays at CERN

Andrea Bizzeti

University of Modena and Reggio Emilia
and I.N.F.N. Sezione di Firenze, Italy

on behalf of the NA48/2 and NA62 collaborations

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Outline

The NA48/2 experiment

- $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ $(K^{00}_{\mu 4})$

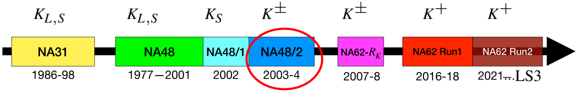
The NA62 experiment

- $\pi^0 \to e^+e^-$
- $K^+ \to \pi^+\gamma\gamma$

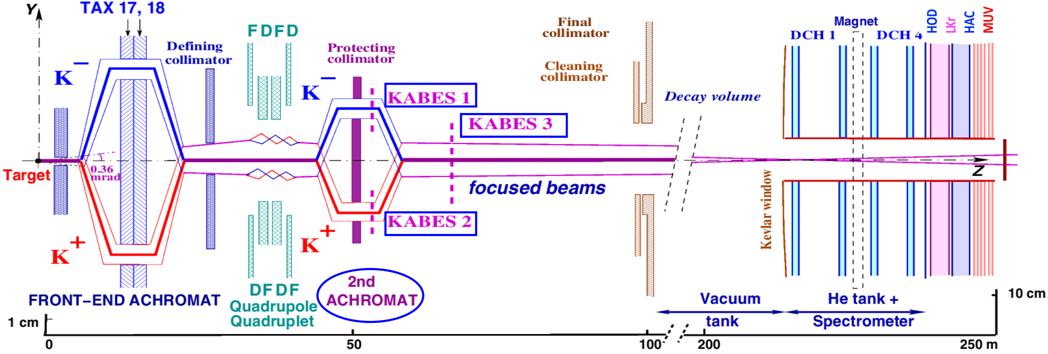
Conclusions

The NA48/2 experiment at CERN

- Fixed target experiment at CERN SPS North Area
- Experiments at CERN detecting Kaon decays-in-flight :

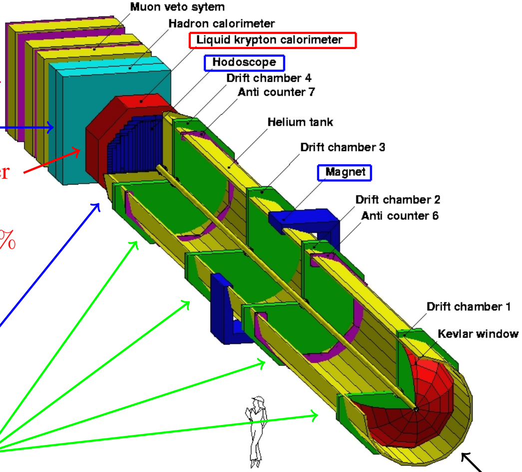


- Simultaneous 60 GeV/c K^+ and K^- beams
- Each kaon is measured with KAon BEam Spectrometer: $\sigma(X,Y) \sim 800\ \mu\text{m}$, $\sigma(P_K)/P_K \sim 1\%$, $\sigma(T) \sim 600$ ps



The NA48/2 detectors

- Muon detectors (scintillators)
- Hadron calorimeter
- Liquid Krypton (LKr) EM calorimeter
  high granularity, quasi-homogeneous
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$
  (E in GeV)
  $\sigma_x = \sigma_y \sim 1.5\,\text{mm}$ at 10 GeV
- Scintillator hodoscope (2 planes)
  fast trigger, $\sigma_t = 150\,\text{ps}$
- Magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy $\Rightarrow$ efficiency
  $\sigma_p/p = 1.02\% \oplus 0.044\%\, p$ (p in GeV/c)
- Photon vetos



Decay region $\sim$ 114 m long
Detector region $\sim$ 50 m long

Beam

$$K^{\pm} \rightarrow \pi^0 \pi^0 \mu^{\pm} \nu \;\; (K^{00}_{\mu 4})$$

[NA48/2 Collab., JHEP 03 (2024) 137]

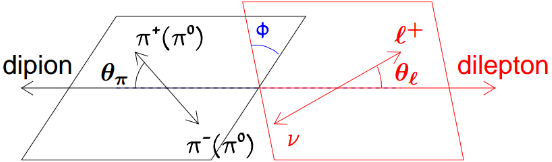
$K^{\pm} \to \pi\pi\, l^{\pm}\nu$ (K_{l4}) – current status

Theory

Five kinematic variables
(Cabibbo-Maksymowicz 1965):

$S_\pi = M^2_{\pi\pi}$, $S_e = M^2_{l\nu}$,
$\cos\theta_\pi$, $\cos\theta_l$, ϕ

K^+(at rest) $\to$ $\pi\,\pi$ $l^+\nu$ $(l = e, \mu)$



- The $K^{\pm} \to \pi\pi\, l^{\pm}\nu$ amplitudes depend on $F,\ G,\ H,\ R$ form factors.
- $\pi^0\pi^0$ in s-wave $\Rightarrow$ no dependence on $\cos\theta_\pi,\ \phi$; only F and R contribute.
- Negligible R contribution to K_{e4} due to the small electron mass.

Measurements

K_{l4} mode	BR $[10^{-6}]$	$N_{\text{candidates}}$	Experiment
K^{+-}_{e4}	42.6 ± 0.4	1 108 941	NA48/2 (2012)
K^{00}_{e4}	25.5 ± 0.4	65 210	NA48/2 (2014)
$K^{+-}_{\mu4}$	$14 \quad \pm 9$	7	Bisi et al. (1967)
$K^{00}_{\mu4}$	?		

$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ ($K^{00}_{\mu4}$) at NA48/2

Goals:

- first observation
- ChPT test
- check of R presence

Analisys challenge:

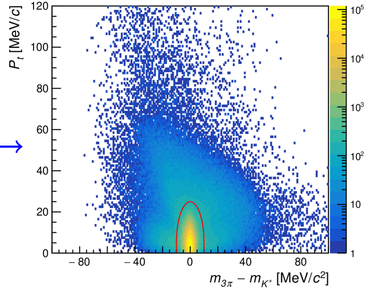
suppression of huge background from $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ $(\pi^{\pm} \to \mu^{+}\nu)$

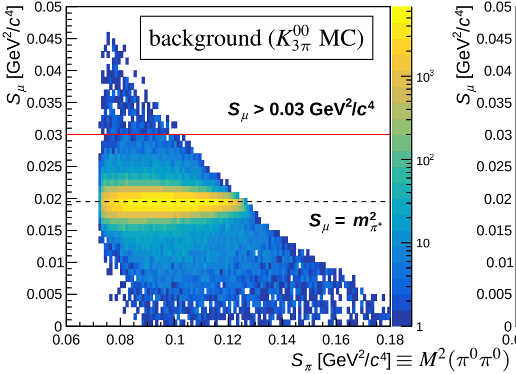
Form factors:

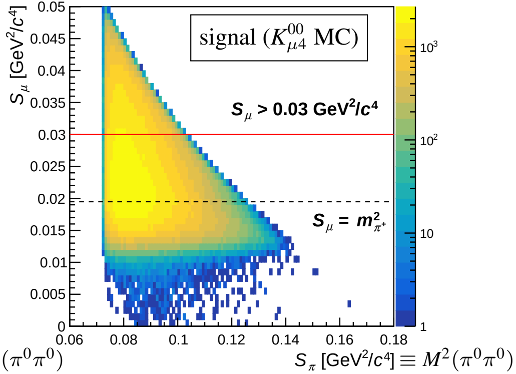
- Use the experimental $F(S_\pi, S_l)$ parameterization from K^{00}_{e4}, according to lepton universality [NA48/2, JHEP 08 (2014) 159]
- For $R(S_\pi, S_l)$ use ChPT 1–loop calculation [J.Bijnens, G.Colangelo, J.Gasser, Nucl. Phys. B 427 (1994) 427]

$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ event selection

- Use $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ ($K^{00}_{3\pi}$) as normalization channel
- First set of common cuts for signal and normalization: select one charged particle and 2 π^0s from a common origin
- Normalization events selected using 3π invariant mass and p_T →
- Dedicated kinematical cuts to select signal events
- Reject $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ events with $\pi^{\pm} \to \mu^{\pm}\nu$ decay in flight by imposing $\cos\theta_{\mu} < 0.6$ and $S_{\mu} \equiv M^2(\mu^{\pm}\nu) > 0.03\,\text{GeV}^2/\text{c}^4$



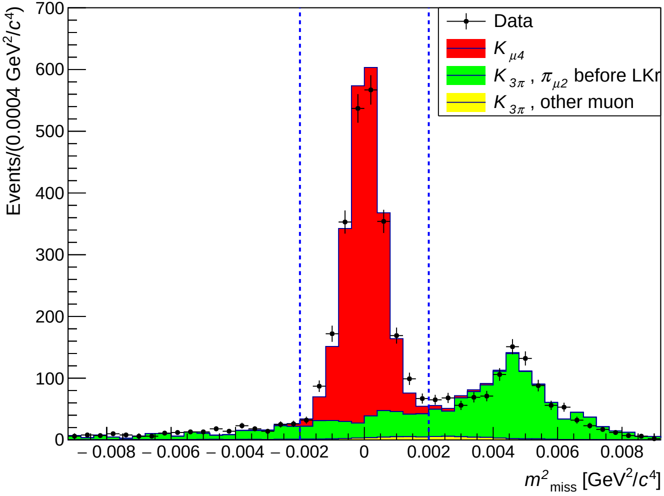




$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ Residual background

Discriminating variable: missing mass squared (= neutrino mass squared):

$$m^2_{\rm miss}c^4 = (E_K - E_{\pi^0_1} - E_{\pi^0_2} - E_\mu)^2 - |\vec{p}_K + \vec{p}_{\pi^0_1} + \vec{p}_{\pi^0_2} - \vec{p}_\mu|^2c^2$$



- 2437 events in the signal region $|m^2_{\rm miss}| < 0.002$ GeV^2/c^4
- Control regions $|m^2_{\rm miss}| > 0.002$ GeV^2/c^4 used for background evaluation
- $354 \pm 33_{\rm stat} \pm 62_{\rm syst}$ expected bkg events in signal region
- Signal acceptance: $A_S = (3.453 \pm 0.007_{\rm stat})\%$ for $S_\mu > 0.03$ GeV^2/c^4
- Normalization sample: 7.3×10^7 $K^{00}_{3\pi}$ events, $A_N = (4.477 \pm 0.002_{\rm stat})\%$

$K^\pm \to \pi^0\pi^0\mu^\pm\nu$ Branching Ratio

[JHEP 03 (2024) 137]

$$\mathcal{B}(K^\pm \to \pi^0\pi^0\mu^\pm\nu) = \frac{N_S}{N_N} \cdot \frac{A_N}{A_S} \cdot K_{\text{trig}} \cdot \mathcal{B}(K^\pm \to \pi^+\pi^0\pi^0)$$

K_{trig}: (0.999 ± 0.002) $\quad$ $\mathcal{B}(K^\pm \to \pi^+\pi^0\pi^0)$: $(1.760 \pm 0.023)\%$ [PDG 2022]

- For the restricted phase space:

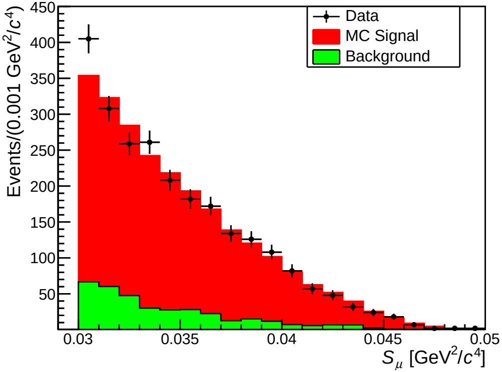
$$\mathcal{B}(K^\pm \to \pi^0\pi^0\mu^\pm\nu,\ S_l > 0.03\ \frac{\text{GeV}^2}{\text{c}^4}) = (0.65 \pm 0.02_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.01_{\text{ext}}) \times 10^{-6}$$
$$= (0.65 \pm 0.03) \times 10^{-6}$$

- For the full phase space (using $R_{\text{1-loop}}$ and $F(K^{00}_{e4})$ form factors):

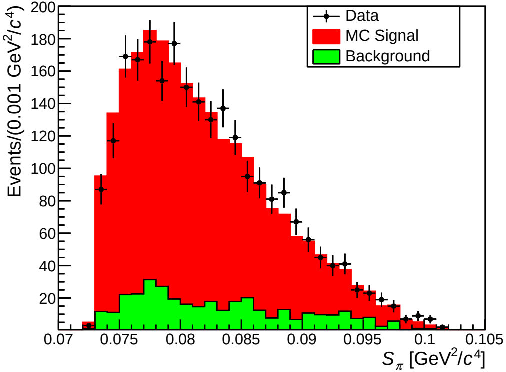
$$\mathcal{B}(K^\pm \to \pi^0\pi^0\mu^\pm\nu) = (3.45 \pm 0.10_{\text{stat}} \pm 0.11_{\text{syst}} \pm 0.05_{\text{ext}}) \times 10^{-6}$$
$$= (3.45 \pm 0.16) \times 10^{-6}$$

$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ – Quality check of simulation

Good agreement of Data with simulated Signal + Background distributions



$S_\mu = M^2(\mu\nu)$

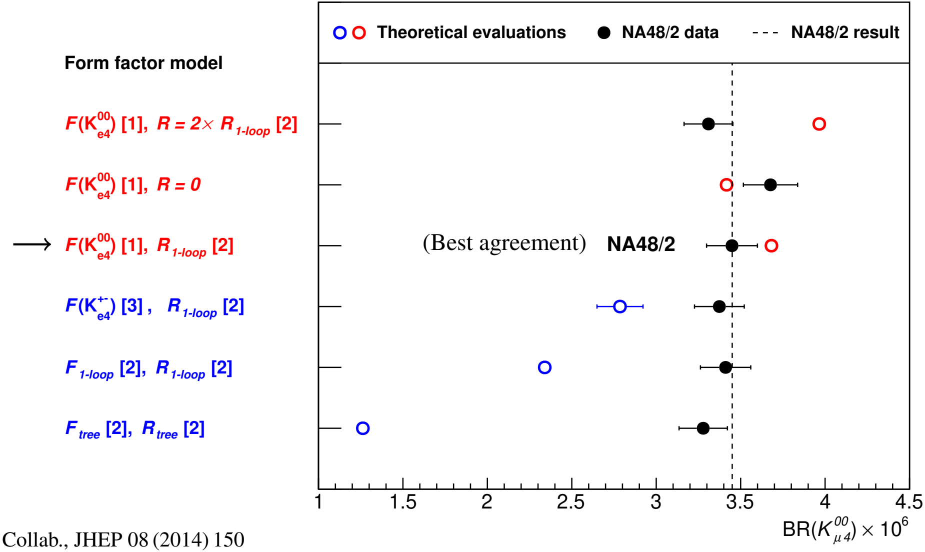


$S_\pi = M^2(\pi^0\pi^0)$

The limited kinematic space accessible does not allow a measurement of the R form factor

$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ – Comparison with theory

[JHEP 03 (2024) 137]

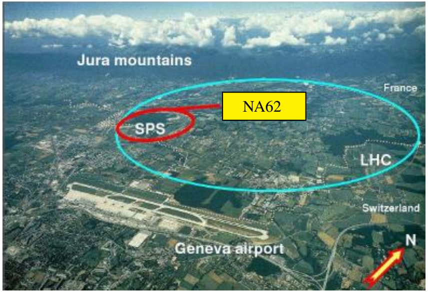


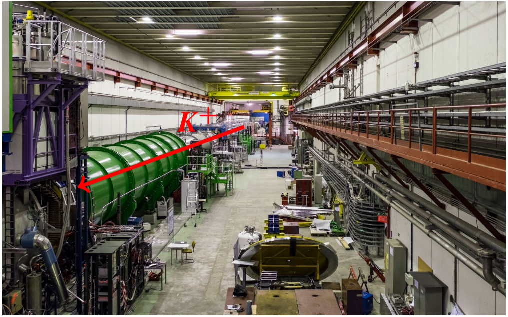
[1] NA48/2 Collab., JHEP 08 (2014) 150

[2] J. Bijnens, G. Colangelo and J. Gasser, Nucl. Phys. B 427 (1994) 427

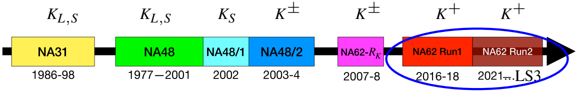
[3] L. Rosselec et al., Phys. Rev. D 15 (1977) 574

The NA62 experiment at CERN





- Fixed target experiment at CERN SPS North Area
- Experiments at CERN detecting Kaon decays-in-flight :



- Main goal: measure $BR(K^+ \to \pi^+ \nu\bar{\nu})$ at 10% accuracy
  - SM prediction: $BR_{SM} = (8.4 \pm 1.0) \times 10^{-11}$
  - Measured values:

    [E949/E787, PRL 101 (2008) 191802] $BR = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$

    [NA62, JHEP 06 (2021) 093] $BR = (10.6^{+4.0}_{-3.4}{}_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-11}$
  - Data taking resumed in 2021, data analysis ongoing

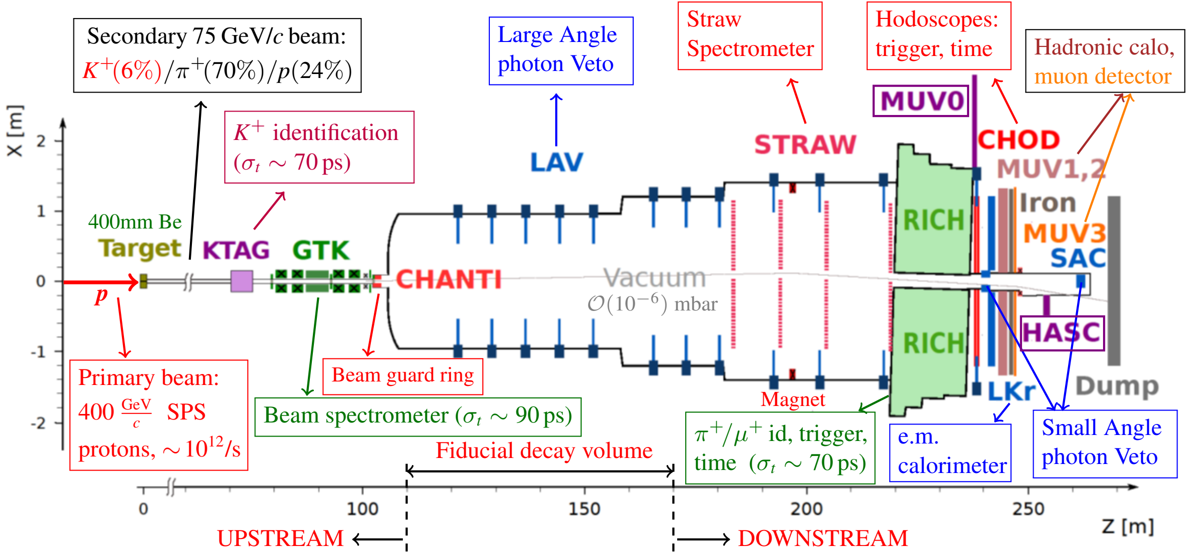
Broad physics programme: LFV/LNV searches, exotic particle searches, precision measurents (this talk)

- $\pi^0 \to e^+e^-$ (NEW preliminary)
- $K^+ \to \pi^+\gamma\gamma$ [PLB 850 (2024) 138513]
- $K^+ \to \pi^+\mu^+\mu^-$ [JHEP 11 (2022) 011, 06 (2023) 040]
- $K^+ \to \pi^0 e^+\nu\gamma$ [JHEP 2023-09,040]

The NA62 beam and detector

[JINST 12 (2017) P05025]

Designed and optimized for $K^+ \to \pi^+ \nu \bar{\nu}$



Veto on additional charged particles: MUV0 + HASC

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

NA62 new, preliminary result

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

- Experimentally observable: $\mathcal{B}(\pi^0 \to e^+e^-(\gamma)),\ x = \frac{m_{ee}^2}{m_{\pi^0}^2} > x_{\rm cut})$
  - Dalitz decay $\pi^0 \to \gamma\, e^+e^-$ dominant in low-x region
  - For $x > 0.95$, Dalitz decay $\simeq 3.3\%$ of $\mathcal{B}(\pi^0 \to e^+e^-(\gamma))$
- Previous best measurement [KTeV, PRD 75 (2007) 012004] :
  $\mathcal{B}(\pi^0 \to e^+e^-(\gamma),\ x > 0.95) = (6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$
- Using latest radiative corrections
  [JHEP 10 (2011) 122], [Eur.Phys.J.C 74 (2014) 3010]
  the result can be extrapolated and compared to theory:

	$\mathcal{B}(\pi^0 \to e^+e^-,\ \text{no-rad}) \times 10^8$
KTeV, PRD 75 (2007)	(6.84 ± 0.35)
Knecht et al., PRL 83 (1999)	6.2 ± 0.3
Dorokhov and Ivanov, PRD 75 (2007)	6.23 ± 0.09
Husek and Leupold, EPJC 75 (2015)	6.12 ± 0.06
Hoferichter et al., PRL 128 (2022)	6.25 ± 0.03

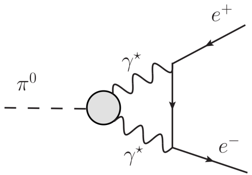


Diagram considered in theoretical predictions leading to $\mathcal{B}(\pi^0 \to e^+e^-,\ \text{no-rad})$ for various $\pi^0 \to \gamma^*\gamma^*$ transition form factors

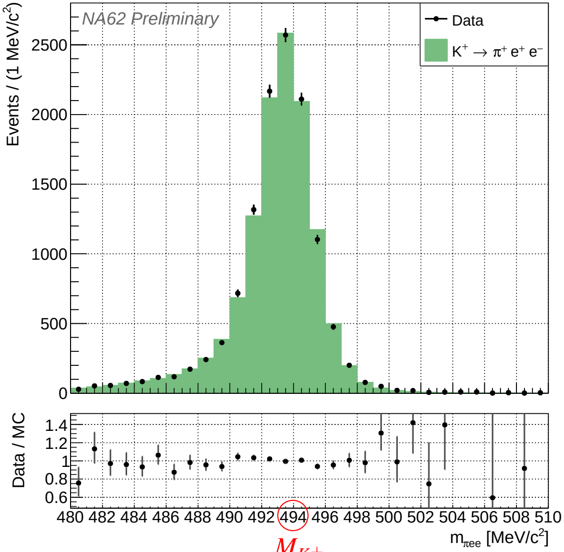
$\pi^0 \to e^+e^-$ at NA62: Data sample and Trigger

- Data sample collected by NA62 in 2017 and 2018
- Signal decay mode: $K^+ \to \pi^+\pi^0,\ \pi^0 \to e^+e^-\ (K^+ \to \pi^+\pi^0_{ee})$
  - Latest radiative corrections included in the simulation
- Normalization decay mode: $K^+ \to \pi^+e^+e^-$ $[\ \mathcal{B} = (3.00 \pm 0.09) \times 10^{-7}\ ]$
  - Identical final state as signal, same selection criteria $\to$ cancellation of systematics
  - Selected in the almost background-free region $m_{ee} > 140$ MeV/c^2
- Multi-track electron trigger used to collect both signal and normalization samples
  - Level-0: RICH, CHOD, LKr (downscaling factor $D_{\mathrm{eMT}} = 8$)
  - Level-1: KTAG, STRAW
  - Total trigger efficiency $> 90\%$ for both $K^+ \to \pi^+\pi^0_{ee}$ and $K^+ \to \pi^+e^+e^-$
- Backgrounds for the signal decay mode
  - $K^+ \to \pi^+e^+e^-$: irreducible, flat in the signal region close to the π^0 mass
  - $K^+ \to \pi^+\pi^0,\ \pi^0 \to \gamma\, e^+e^-\ (K^+ \to \pi^+\pi^0_{\mathrm{D}})$, Dalitz decay
    - large-x Dalitz decay
    - photon conversion in STRAW + selection of a $e^\pm$ from conversion
  - $K^+ \to \pi^+\pi^0,\ \pi^0 \to e^+e^-e^+e^-\ (K^+ \to \pi^+\pi^0_{\mathrm{DD}})$ with two undetected $e^\pm$

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

- Three-track vertex topology (STRAW)
- Timing cuts (KTAG, CHOD)
- Kinematic constraints on total and transverse momenta of the vertex
- Particle ID using LKr + STRAW and decay kinematics (invariant masses)
  - $\pi^+ \ : \ E/p < 0.9$
  - $e^\pm \ : \ 0.9 < E/p < 1.1$
  - $480\,\mathrm{MeV/c^2} < m_{\pi ee} < 510\,\mathrm{MeV/c^2}$
  - $m_{ee} > 130\,\mathrm{MeV/c^2}$
- background suppression:
  - Use STRAW hit information to reject $e^\pm$ tracks from γ conversion
  - Reject events with an extra track segment reconstructed in STRAW 1 and 2 compatible with the vertex

$\pi^+e^+e^-$ invariant mass



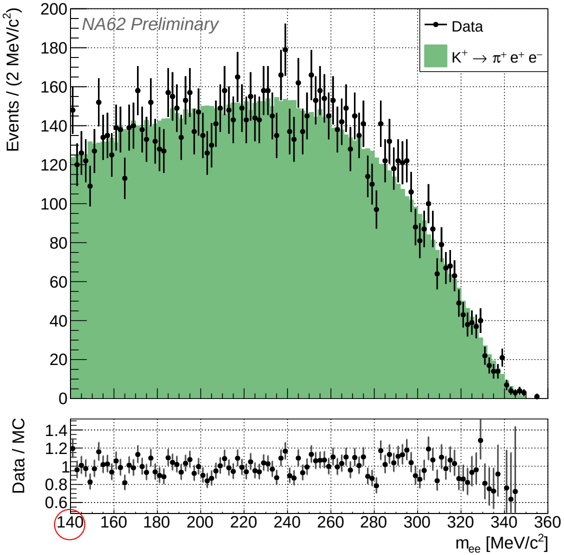
M_{K^+}

$K^+ \to \pi^+ e^+ e^-$ normalization sample

- Common selection applied
- Normalization region:
  $140\ \mathrm{MeV/c^2} < m_{ee} < 360\ \mathrm{MeV/c^2}$
- 12160 observed events
- Normalization acceptance
  $(4,70 \pm 0.01_{\mathrm{stat}})\%$
- Sample purity $> 99\%$
- Effective number of kaon decays
  $N_K = (8.62 \pm 0.08_{\mathrm{stat}} \pm 0.26_{\mathrm{ext}}) \times 10^{11}$,
  external uncertainty from

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

e^+e^- invariant mass (control region)



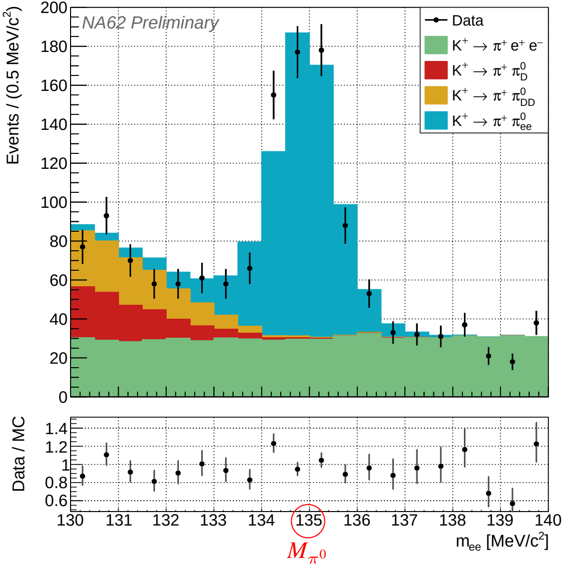
$K^+ \to \pi^+\pi^0_{ee}$ signal sample

- Common selection applied
- Fit region for signal extraction:
  $130\,\mathrm{MeV/c^2} < m_{ee} < 140\,\mathrm{MeV/c^2}$
- Signal acceptance $(x_{\text{true}} > 0.95)$
  $A(K^+ \to \pi^+\pi^0_{ee}) = (5.72 \pm 0.02_{\text{stat}})\%$
- $\pi^0 \to e^+e^-$ branching fraction obtained by performing a maximum likelihood fit of simulated samples to data

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

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

e^+e^- invariant mass (signal region)



$\pi^0 \to e^+e^-$ Preliminary result and uncertainties

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

	$\delta\mathcal{B} \times 10^8$	$\delta\mathcal{B}/\mathcal{B}$
Statistical uncertainty	0.30	5.1%
Total external uncertainty	0.19	3.2%
Total systematic uncertainty	0.11	1.9%
Contributions to the total systematic uncertainty:		
• 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%

$\pi^0 \to e^+e^-$ Summary and outlook

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

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

- Lower central value than in KTeV measurement, but results are compatible:
  $\mathcal{B}_{\mathrm{KTeV}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.33) \times 10^{-8}$
- Results agree with theoretical expectations when extrapolated using radiative corrections:
  $\mathcal{B}_{\mathrm{NA62}}(\pi^0 \to e^+e^-(\gamma), \text{no rad.}) = (6.22 \pm 0.39) \times 10^{-8}$
  $\mathcal{B}_{\mathrm{theory(2022)}}(\pi^0 \to e^+e^-(\gamma), \text{no rad.}) = (6.25 \pm 0.03) \times 10^{-8}$
- External uncertainty dominated by $\mathcal{B}(K^+ \to \pi^+e^+e^-)$ measured by NA48/2 and E865
  - New measurement of $\mathcal{B}(K^+ \to \pi^+e^+e^-)$ 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

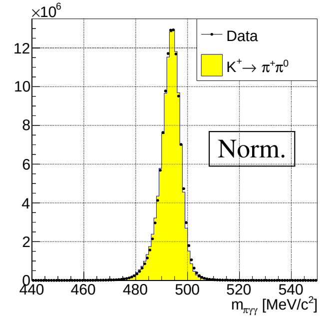
$$K^+ \to \pi^+\gamma\gamma$$

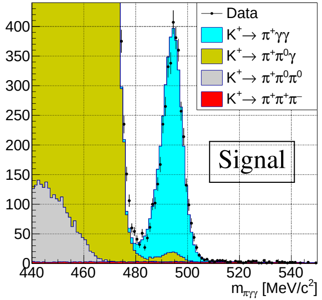
[NA62 Collab., PLB 850 (2024) 138513]

$K^+ \to \pi^+\gamma\gamma$ at NA62

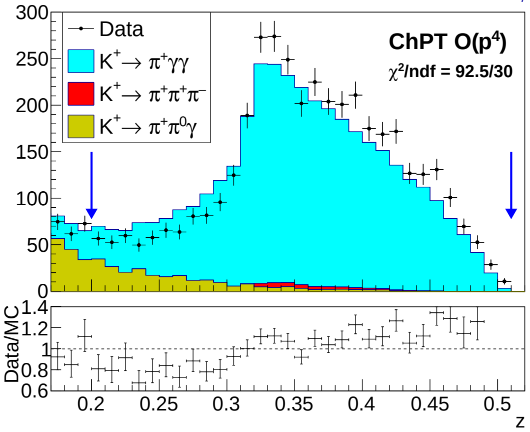
[NA62 Collab., PLB 850 (2024) 138513]

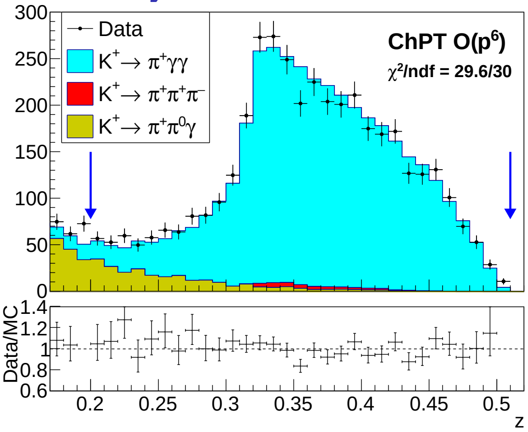
- Crucial test of ChiralPerturbation theory (ChPT)
- Main kinematic variable: $z = \frac{(P_K - P_\pi)^2}{M_K^2} = (m_{\gamma\gamma}/M_K)^2$
- Differential decay width $\mathrm{d}\Gamma/\mathrm{d}z\ (K^+ \to \pi^+\gamma\gamma)$:
  - parametrized by an unknown real parameter $\hat{c}$
  - depend on external parameters [PLB 835 (2022) 137594] extracted from $K \to 3\pi$ measurements
- Signal selection: single positive track in STRAW identified as π^+ matched with a K^+ beam track; two energy clusters in LKr; $0.20 < z < 0.51$; kinematic constraints on $m_{\pi^+\gamma\gamma}$ and $\vec{p}_{\pi^+\gamma\gamma}$
- Normalization channel $(K^+ \to \pi^+\pi^0,\ \pi^0 \to \gamma\gamma)$: minimal difference in event selection to reduce systematic effects; $0.04 < z < 0.12$
- Main background: γ energy cluster merging in LKr in $K^+ \to \pi^+\pi^0\gamma\ /\ \pi^+\pi^0\pi^0$





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

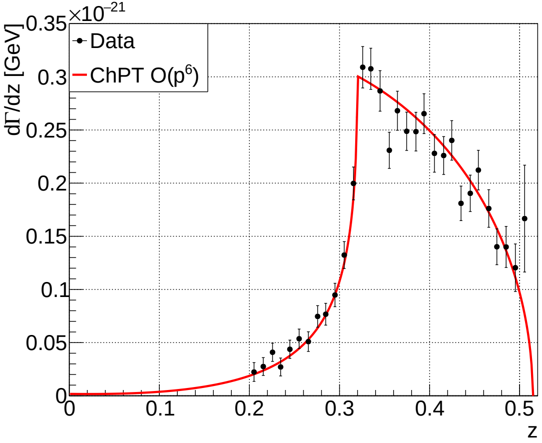


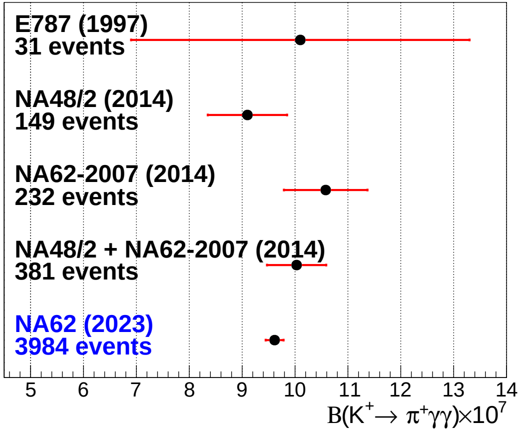


- 4039 observed events, with 291 ± 14 expected background
- The $\hat{c}$ parameter is measured in the ChPT $\mathcal{O}(p^4)$ and $\mathcal{O}(p^6)$ descriptions by performing a minimum χ^2 fit of simulated data samples to data
- ChPT $\mathcal{O}(p^4)$ p-value: 2.7×10^{-8} $\rightarrow$ not sufficient to describe $\gamma\gamma$ mass spectrum
- ChPT $\mathcal{O}(p^6)$ p-value: 0.49

$$\hat{c}_{\text{ChPT}\ \mathcal{O}(p^6)} = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$$

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



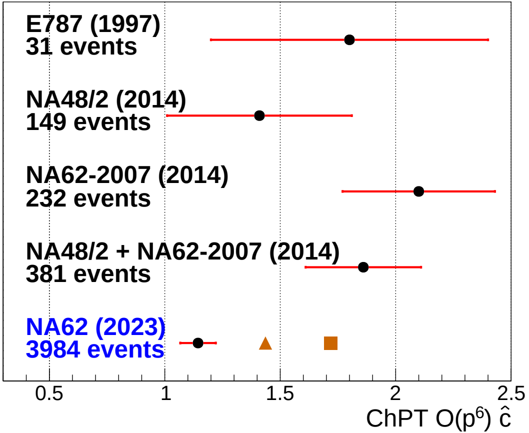


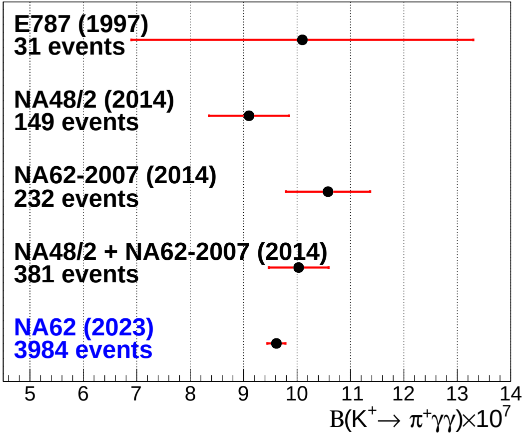
$$\hat{c}_{\text{ChPT}\,\mathcal{O}(p^6)} = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$$

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

$$\text{Model-independent BR}(K^+ \to \pi^+\gamma\gamma,\ z > 0.20) = (9.46 \pm 0.19_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$$

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





$$\hat{c}_6 = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$$

$$\text{BR}(K^+ \to \pi^+\gamma\gamma) = (9.61 \pm 0.15_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$$

▲ (■) : $\hat{c}$ obtained with external parameters used by E787 (NA48/2 and NA62-2007)

Conclusions

New NA48/2 precision measurement (2003–2004 data):

- $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ ($K^{00}_{\mu4}$) [JHEP 03 (2024) 137]
  - First observation of this decay mode
  - Measured branching fraction in good agreement with ChPT predictions

New NA62 precision measurements (2016–2018 data):

- $\pi^0 \to e^+e^-$ (new, preliminary)
  - Precision comparable with previous measurements, statistically dominated
  - Full agreement with latest theoretical calculations
- $K^+ \to \pi^+\gamma\gamma$ [Phys. Lett. B 850 (2024) 138513]
  - Results consistent with earlier measurements
  - Precision improved by a factor > 3, statistically dominated

Other recent results on precision measurements from NA62 (2016–2018 data):

- $K^+ \to \pi^0 e^+\nu\gamma$ ($K_{e3\gamma}$) [JHEP 09 (2023) 040]
- $K^+ \to \pi^+\mu^+\mu^-$ [JHEP 11 (2022) 011, JHEP 06 (2023) 040]

New NA62 physics run 2021–LS3, data analysis ongoing