FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University

New $\pi^0 \to e^+e^-$ result from NA62

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on behalf of the NA62 Collaboration

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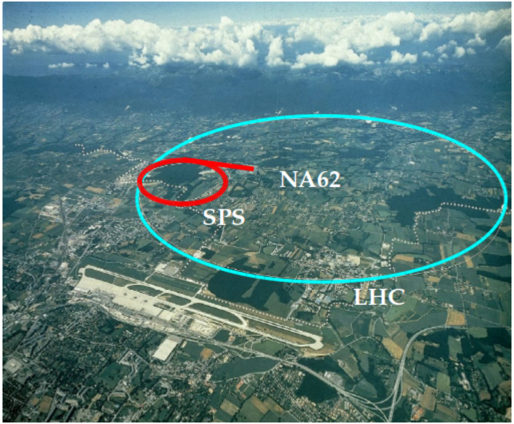
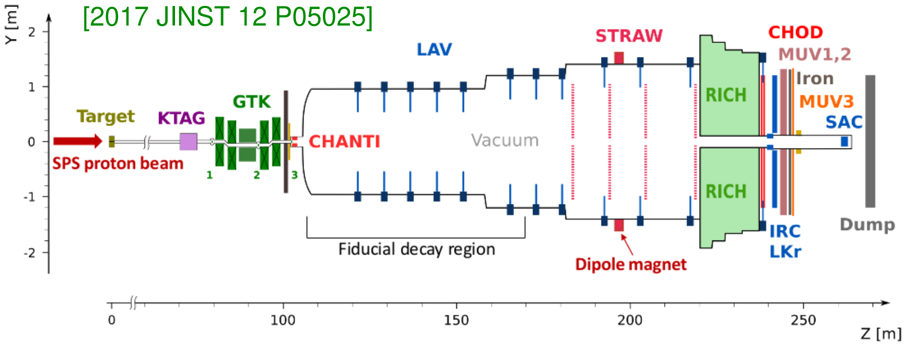
NA62 Experiment at CERN

- Detector installation completed in 2016
- Physics runs in 2016 – 2018 (Run 1)
- Data taking resumed in 2021,
  approved up to CERN LS3 (Run 2)
- Main goal: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ measurement
  $\to$ Run 1 result: [JHEP 06 (2021) 093]
- NA62 program: K^+ physics and more



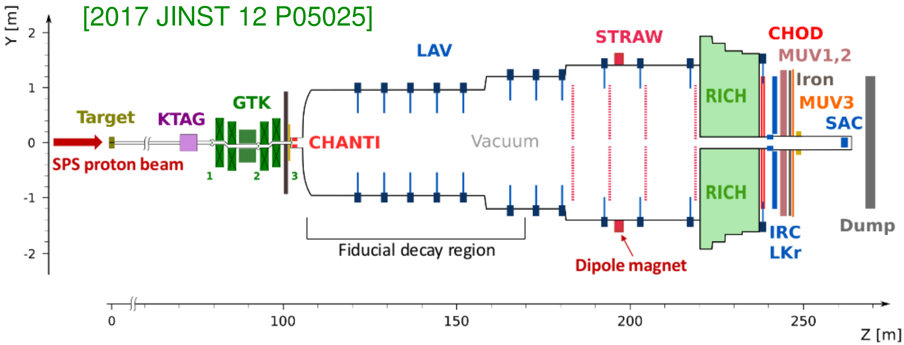
NA62: located at CERN in the *North Area*
$\to$ fixed-target experiment
$\to$ using 400 GeV/c SPS proton beam

NA62 Beam



- SPS beam: 400 GeV/c proton on beryllium target
- Secondary hadron 75 GeV/c beam
- 70% pions, 24% protons, 6% **kaons**
- Nominal beam particle rate (at GTK3): 750 *MHz*
- Average beam particle rate during 2018 data-taking: 450 – 500 *MHz*

NA62 Detector



- **KTAG**: differential Cherenkov counter
- GTK: Si pixel beam tracker
- CHANTI: stations of plastic scintillator bars
- LAV: lead glass ring calorimeters
- **STRAW**: straw magnetic spectrometer
- **RICH**: Ring Imaging Cherenkov counter
- **CHOD**: planes of scintillator tiles and slabs
- IRC: inner ring shashlik calorimeter
- **LKr**: liquid krypton electromagnetic calorimeter
- MUV1,2: hadron calorimeter
- MUV3: plane of scintillator tiles for muon ID
- SAC: small angle shashlik calorimeter

NA62 Physics

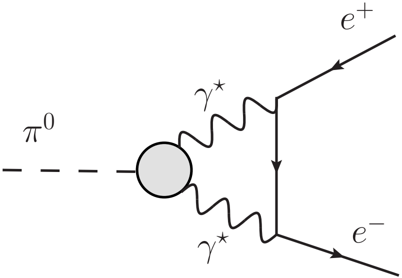
Main topic of this presentation:

→ $\pi^0 \to e^+e^-$ decay measurement (preliminary results)

Broad physics program at NA62:

- Main goal: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ measurement
- Precision measurements of rare kaon decays (spare slides):
  - → $K^+ \to \pi^+\gamma\gamma$ decay [PLB 850 (2024) 138513]
  - → $K^+ \to \pi^0 e^+\nu\gamma$ decay [JHEP 09 (2023) 040]
  - → $K^+ \to \pi^+\mu^+\mu^-$ decay [JHEP 11 (2022) 011]
- Searches for lepton number and lepton flavour violating decays
- Searches for very rare decays
- Searches for feebly interacting particles

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



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

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 $\mathcal{B}(\pi^0 \to e^+e^-(\gamma))$

$\pi^0 \to e^+e^-$: Previous Measurement

- Experimentally observable:

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

- Previous best measurement by KTeV [PRD 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], [EPJC 74 (2014) 8, 3010], [PRD 110 (2024), 033004], 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)

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

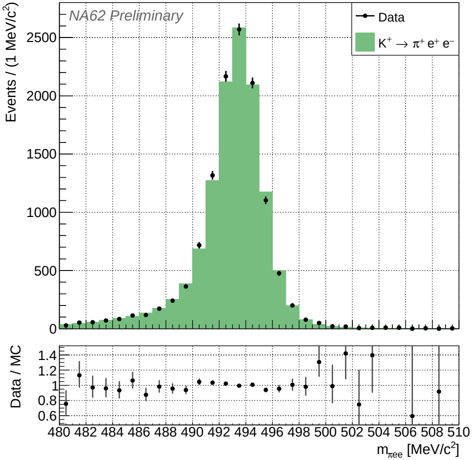
Backgrounds

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: $m_{\pi ee} \in (480, 510)\,\text{MeV}$
  - 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:

$$m_{ee} \in (140, 360)\,\mathrm{MeV}$$

- Number of observed events: 12160
- Acceptance:

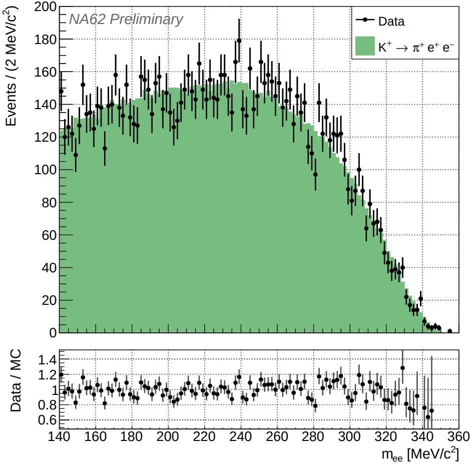
$$A(K^+ \to \pi^+ e^+ e^-) = (4.70 \pm 0.01_{\mathrm{stat}})\,\%$$

- Sample purity $> 99.9\%$
- 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

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



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

- Common selection applied
- Fit region:

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

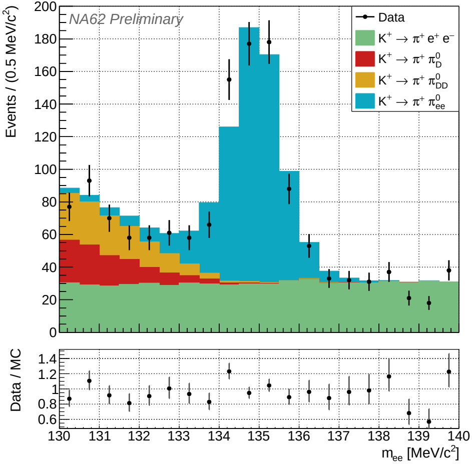
- Signal acceptance ($x_{\text{true}} > 0.95$):

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

- 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
  - χ^2 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

Summary and Outlook

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

$$\mathcal{B}_{\mathrm{NA62}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.30_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}} \pm 0.19_{\mathrm{ext}}) \times 10^{-8}$$
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- Lower central value than in KTeV measurement, but results are compatible:

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

- Result in agreement with theory when extrapolated using radiative corrections:

$$\mathcal{B}_{\mathrm{NA62}}\left(\pi^0 \to e^+e^-, \text{no-rad}\right) = (6.22 \pm 0.39) \times 10^{-8}$$
$$\mathcal{B}_{\mathrm{theory\ (2022)}}\left(\pi^0 \to e^+e^-, \text{no-rad}\right) = (6.25 \pm 0.03) \times 10^{-8}$$

- External uncertainty from $\mathcal{B}(K^+ \to \pi^+e^+e^-)$, 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

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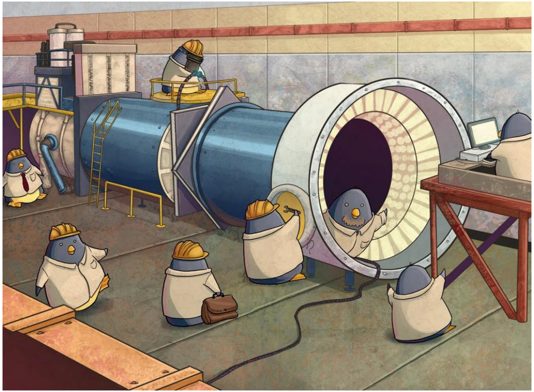
Thank you for your attention

Spare slides: Other results from NA62

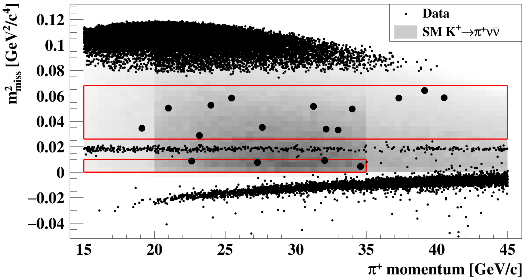


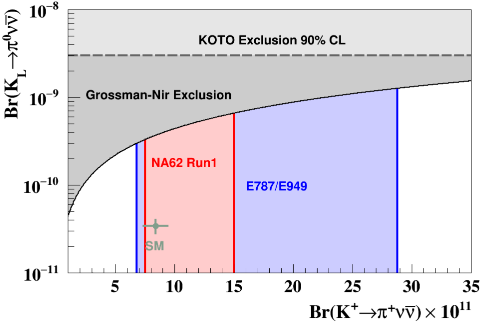
NA62 $K^+ \to \pi^+ \nu\bar{\nu}$ Result from Run 1

- SM prediction: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = (8.4 \pm 1.0) \times 10^{-11}$ [JHEP 11 (2015) 033]
- NA62 Run 1 = 2016 – 2018 data:
  20 signal candidates, expected background: 7.0 events [JHEP 06 (2021) 093]

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{NA62}} = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$$

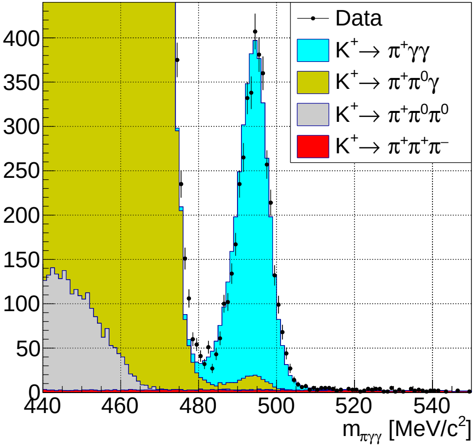
17 events observed in 2018 data:



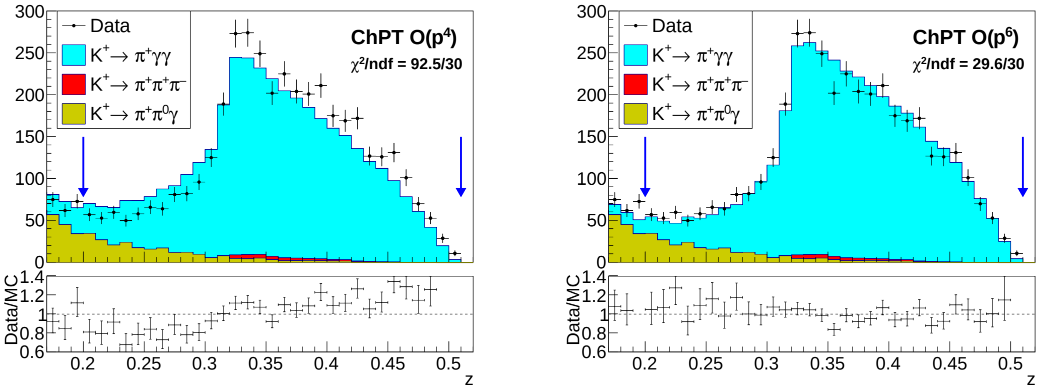


$K^+ \to \pi^+\gamma\gamma$: Overview

- 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 $m_{\pi\gamma\gamma}$, $p_{\pi\gamma\gamma}$
  - $z \in (0.20, 0.51)$
- Normalization: $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma\gamma$ with $z \in (0.04, 0.12)$
- Main background:
  $K^+ \to \pi^+\pi^0\gamma, \pi^0 \to \gamma\gamma$ decay;
  cluster merging in calorimeter

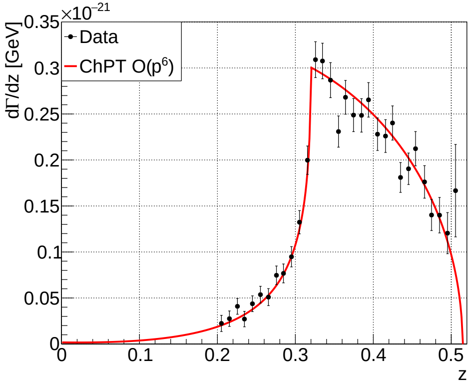


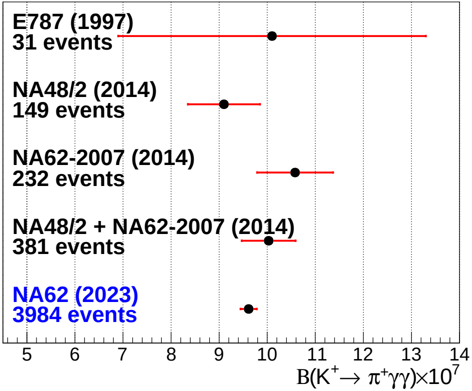
$K^+ \to \pi^+\gamma\gamma$: Results



- 3984 observed events; 291 ± 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 z spectrum
- ChPT $\mathcal{O}(p^6)$ p-value: 0.49

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





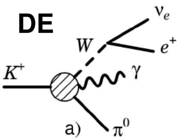
$$\hat{c}^6 = 1.144 \pm 0.069_{\text{stat.}} \pm 0.034_{\text{syst.}}$$

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

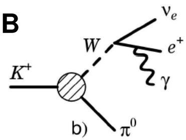
$$\mathcal{B}_{\text{MI}}(K^+ \to \pi^+\gamma\gamma | z > 0.20) = (9.46 \pm 0.19_{\text{stat.}} \pm 0.07_{\text{syst.}}) \cdot 10^{-7}$$

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

DE



IB



Inner Bremsstrahlung (IB) decay amplitude:
$\rightarrow$ 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 $(\times 10^2)$	$E_\gamma > 10\ MeV$	$\theta_{e,\gamma} > 10^\circ$	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	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

T-odd observable ξ (K^+ rest frame): $\xi = \dfrac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{m_K^3}$; Asymmetry: $A_\xi = \dfrac{N_+ - N_-}{N_+ + N_-}$

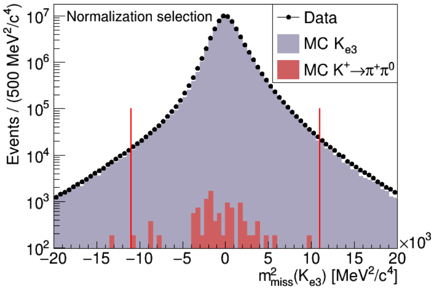
$K^+ \to \pi^0 e^+ \nu\gamma$: Samples and Analysis

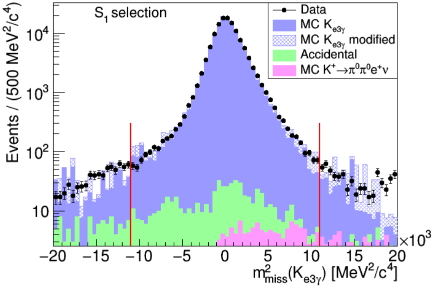
- Normalization: $K^+ \to \pi^0 e^+ \nu$
  N(events) $\approx 6.6 \times 10^7$, 10^{-4} background
- $K^+ \to \pi^0 e^+ \nu\gamma$ signal samples, 3 regions S_i:
  - $\to$ N(events) $\approx 1 \times 10^5$
  - $\to$ Background: $< 1\%$
  - $\to$ Main source of bkg.: accidental activity
- Evaluation of R_j:

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

- Evaluation of asymmetry:

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





$K^+ \to \pi^0 e^+ \nu\gamma$: 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	$7.0 \pm 8.1 \pm 1.5$	$\mathbf{-9.1 \pm 5.1 \pm 3.5}$

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

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

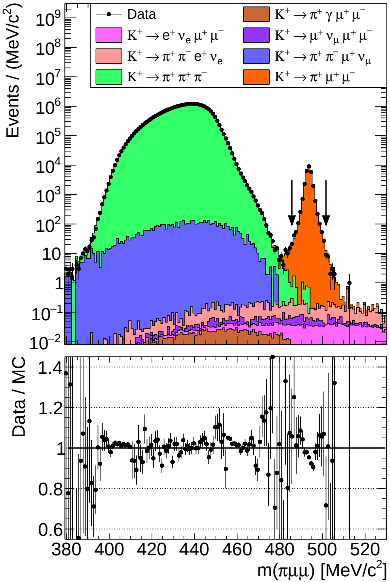
$K^+ \to \pi^+\mu^+\mu^-$: Sample and Analysis

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

- Data: **27679 events observed**
- Normalization using $K^+ \to \pi^+\pi^+\pi^-$: $N(K^+ \text{decays}) \approx 3.5 \times 10^{12}$
- Expected background: ≈ 8 events

Analysis:

- Data divided in 50 equipopulated bins in z:
$$\left(\frac{\mathrm{d}\Gamma(z)}{\mathrm{d}z}\right)_i = \frac{N_{\pi\mu\mu,i}}{A_{\pi\mu\mu,i}} \cdot \frac{1}{\Delta z_i} \cdot \frac{1}{N_K} \cdot \frac{\hbar}{\tau_K}$$
- Integrating $\mathrm{d}\Gamma(z)/\mathrm{d}z \to$ model-independent $\mathcal{B}$
- $|W(z)|^2$ function values extracted from $\mathrm{d}\Gamma(z)/\mathrm{d}z$
- Fit of $|W(z)|^2$ data points $\to$ ChPT form factor parameter measurement

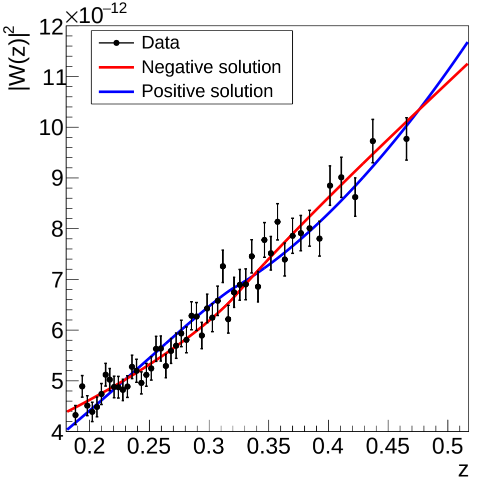


$K^+ \to \pi^+\mu^+\mu^-$: Measurement Results

Form factor parameters:

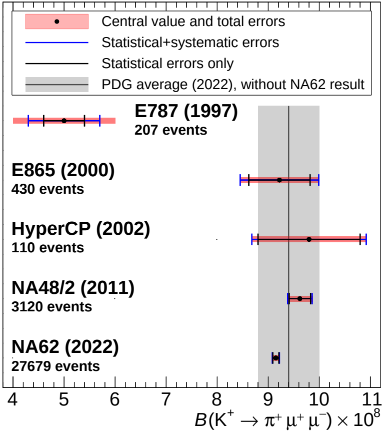
- Two possible solutions:
  a_+, b_+: both *negative* or *positive* values
- Preferred negative solution
  $\chi^2/\text{ndf} = 45.1/48$ (p-value $= 0.59$):

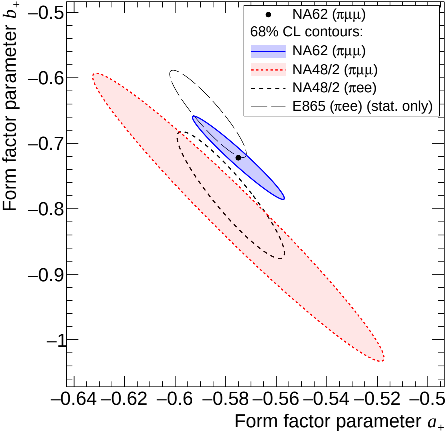
$$a_+ = -0.575 \pm 0.013$$
$$b_+ = -0.722 \pm 0.043$$
$$\text{correlation } \rho(a_+, b_+) = -0.972$$



Branching fraction: $\mathcal{B}_{\pi\mu\mu} = (9.15 \pm 0.08) \times 10^{-8}$

$K^+ \to \pi^+\mu^+\mu^-$: Comparison with Previous Measurements





- At least **factor of 3** improvement wrt previous $K_{\pi\mu\mu}$ measurements
- Measurements are compatible
  $\rightarrow$ Agreement in a_+, b_+ from $K_{\pi\mu\mu}$ and $K_{\pi ee}$ $\rightarrow$ lepton flavour universality ✓