Precision measurements of K^+ and π^0 decays at the NA62 experiment at CERN

Tomáš Husek
Charles University, Prague and *University of Birmingham*

Cairns, Australia
August 19, 2024

FACULTY OF MATHEMATICS AND PHYSICS Charles University
UNIVERSITY OF BIRMINGHAM
Co-funded by the European Union
MINISTRY OF EDUCATION, YOUTH AND SPORTS

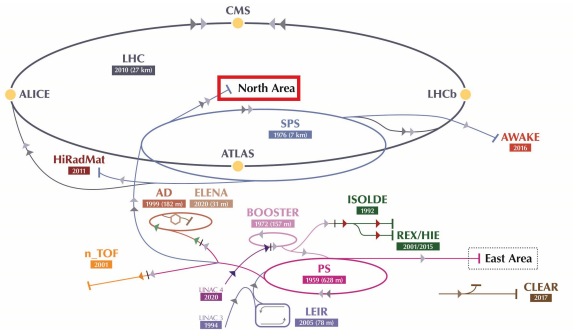
The NA62 experiment at CERN: the *charged-kaon factory*

- Main goal: measurement of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$
- Full detector installation completed in 2016
- Physics runs in 2016, 2017 and 2018 (Run 1)
- Result from full Run 1

$$\mathcal{B}^{\mathrm{NA62}}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.06^{+0.40}_{-0.34\,\mathrm{stat}} \pm 0.09_{\mathrm{syst}}) \times 10^{-10}$$

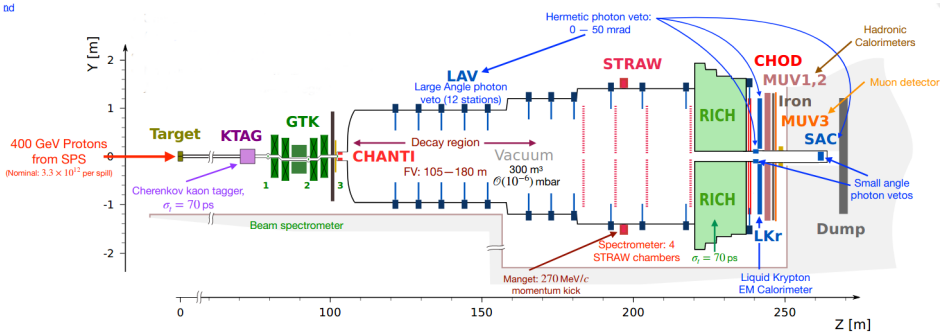
  ↪ 3.4σ significance
  ↪ JHEP 06 (2021) 093

- Data taking resumed in 2021 (after CERN LS2)
  ↪ approved until CERN LS3
  ↪ data analysis ongoing



NA62 is located in the CERN North Area, exploiting a 400 GeV proton beam extracted from the SPS accelerator

NA62 Beamline, Detector, and Datasets



- Detector designed for $K^+ \to \pi^+ \nu\overline{\nu}$ study
- K^+ decay-in-flight technique: unseparated hadron beam (70% π^+, 23% p, 6% K^+)
  $\hookrightarrow$ nominal intensity 750 MHz, K^+ momentum 75 GeV, 75 m long vacuum decay region
- **Tracking:** beam particles (GTK), decay products (STRAW)
- **Trigger and timing:** hodoscopes (CHOD)
- **PID:** K^+ (KTAG), π^+ (RICH), μ^+ (MUV3), calorimeters (LKr, MUV1, MUV2)
- **Veto systems:** beam interactions (CHANTI), γ (LAV, LKr, IRC, SAC)
- Data taking: **2016–2018** (Physics Run I, $\approx 6 \times 10^{12}$ useful K^+ decays), 2021–LS3 (Physics Run II, ongoing)

NA62

Outline

Precision measurements of K^+ and π^0 decays with NA62 Run 1 data (2016–2018)

- $K^+ \to \pi^+\mu^+\mu^-$
  ↪ JHEP 11 (2022) 011, JHEP 06 (2023) 040
- $K^+ \to \pi^+\gamma\gamma$
  ↪ Phys. Lett. B 850 (2024) 138513
- $K^+ \to \pi^0 e^+ \nu\gamma$
  ↪ JHEP 09 (2023) 040
- $\pi^0 \to e^+e^-$
  ↪ preliminary results

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

Overview

- Mediated by flavor-changing neutral-current (FCNC) weak transition $K^+ \to \pi^+\gamma^*$
  ↪ [Nucl. Phys. B291 (1987) 692–719], [Phys. Part. Nucl. Lett. 5 (2008) 76–84]
- Differential decay width: $\mathrm{d}\Gamma(z)/\mathrm{d}z \sim |W(z)|^2, \quad z = m(\mu^+\mu^-)^2/m_K^2$
- Parametrization of form factor (FF) $W(z)$ in NLO ChPT [JHEP 08 (1998) 004]

$$\boxed{W(z) = G_F M_K^2(a_+ + b_+ z) + W_{\pi\pi}(z)}$$

a_+, b_+: FF parameters, $W_{\pi\pi}(z)$: $K_{3\pi}$ pion loop term

Measurement motivation

- Together with $K_{\pi ee}$ allows for tests of LFU [J. Phys. Conf. Ser. 800 (2017) 1, 012014]
- Asymmetries in angular distributions could point to New Physics contributions
  ↪ [Phys. Rev. D 67 (2003) 074029], [Phys. Rev. D 69 (2004) 094030]

Data sample

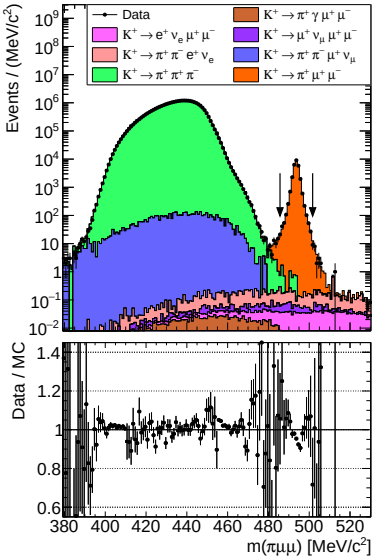
- Effective $N_K \simeq 3.48 \times 10^{12}$ kaon decays
- Normalisation channel: $K^+ \to \pi^+\pi^+\pi^-$ ($K_{3\pi}$)

Signal event selection

- Three-track vertex topology
- π^+ PID: no signal in MUV3, $E/p < 0.9$
- $\mu^\pm$ PID: signal in MUV3, $E/p < 0.2$
- Kinematic cuts to suppress $K_{3\pi}$ background

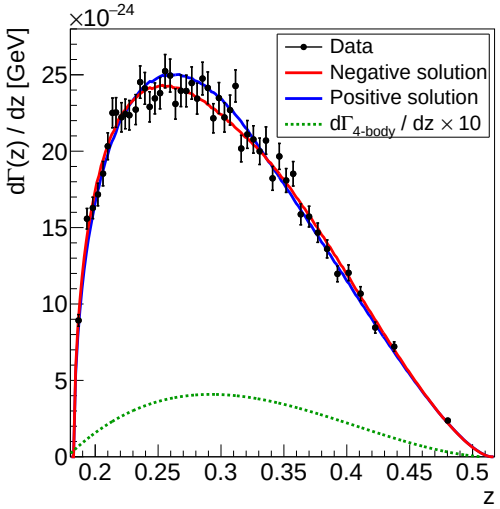
Signal sample

- $|m(\pi\mu\mu) - m_K| < 8\,\text{MeV}$
- Signal region contains **27679** events
  - ↪ $\sim 9 \times$ more than NA48/2
    - ↪ Phys. Lett. B 697 (2011) 107-115
  - ↪ negligible background: 7.8 ± 5.6 events



Model-independent $\mathcal{B}(K_{\pi\mu\mu})$ measurement

- Reconstruct $\mathrm{d}\Gamma/\mathrm{d}z$ from measured z spectrum
- Integrate to get $\mathcal{B}(K_{\pi\mu\mu}) = (9.15 \pm 0.08) \times 10^{-8}$



Model-independent $\mathcal{B}(K_{\pi\mu\mu})$ measurement

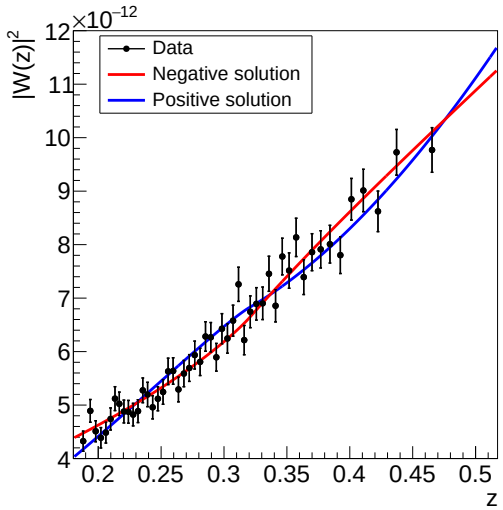
- Reconstruct $\mathrm{d}\Gamma/\mathrm{d}z$ from measured z spectrum
- Integrate to get $\mathcal{B}(K_{\pi\mu\mu}) = (9.15 \pm 0.08) \times 10^{-8}$

Form factor measurement

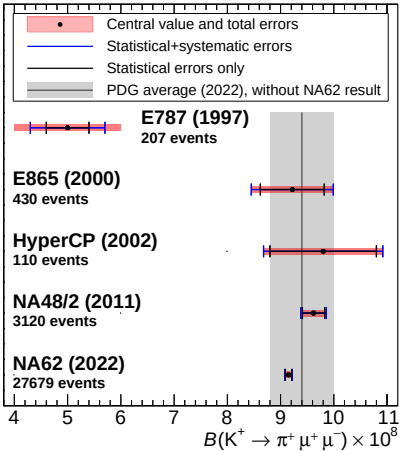
- Extract $|W(z)|^2$ from $\mathrm{d}\Gamma/\mathrm{d}z$
- Find optimal a_+, b_+ by minimising $\chi^2(a_+, b_+)$
- Results ($\chi^2/\mathrm{ndf} = 45.1/48$, p-value $= 0.59$)

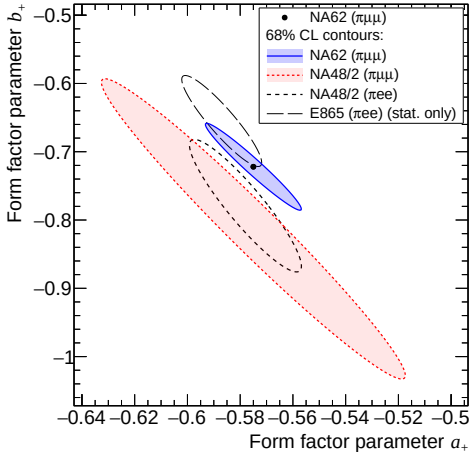
$$a_+ = -0.575 \pm 0.013$$
$$b_+ = -0.722 \pm 0.043$$

$\hookrightarrow$ correlation: $\rho(a_+, b_+) = -0.972$



- NA62 $K_{\pi\mu\mu}$ result consistent w/ previous $K_{\pi ee}$ FF measurements $\longrightarrow$ 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]

Definitions

- $\theta_{K\mu} \Leftrightarrow$ angle between the K^+ and μ^- three-momenta in the $\mu^+\mu^-$ rest frame
- Forward–backward asymmetry

$$A_{\mathrm{FB}} = \frac{\mathcal{N}(\cos\theta_{K\mu} > 0) - \mathcal{N}(\cos\theta_{K\mu} < 0)}{\mathcal{N}(\cos\theta_{K\mu} > 0) + \mathcal{N}(\cos\theta_{K\mu} < 0)}$$

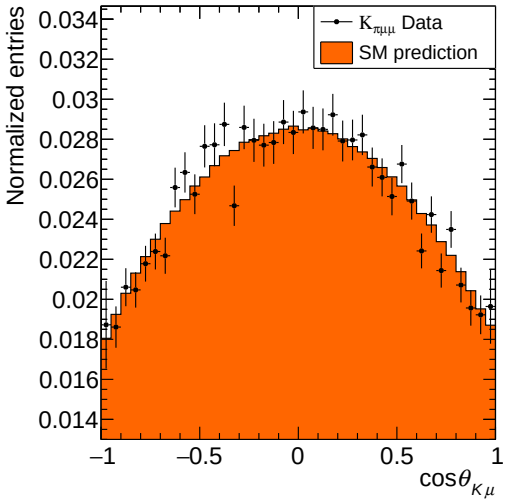
Results

- 68% CL measurement

$$A_{\mathrm{FB}} = (0.0 \pm 0.7) \times 10^{-2}$$

- 90% CL upper limit

$$|A_{\mathrm{FB}}| < 0.9 \times 10^{-2}$$

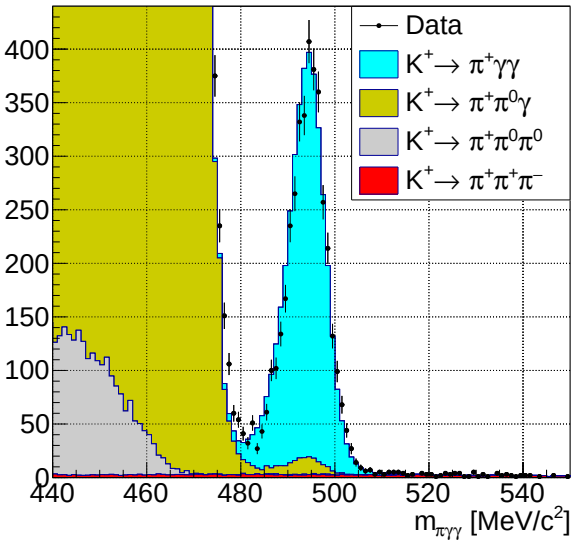


$K^+ \to \pi^+\gamma\gamma$

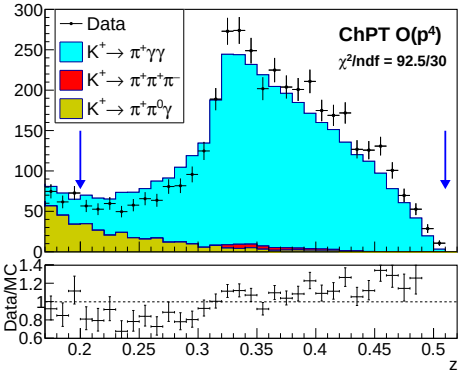
- Crucial test of Chiral Perturbation Theory (ChPT)
- Main kinematic variable: $z = \dfrac{(P_K - P_\pi)^2}{m_K^2} = \dfrac{m_{\gamma\gamma}^2}{m_K^2}$
- Branching fraction $\mathcal{B}(K^+ \to \pi^+\gamma\gamma)$ within ChPT depends on an unknown real parameter $\hat{c}$
  ↪ at higher order, several other external parameters
  ↪ PLB 835 (2022) 137594
- Signal selection: single positive track identified as π^+ matched with a K^+ track, two γ clusters in LKr, kinematic constraints on total invariant mass $m_{\pi\gamma\gamma}$ and total momentum $p_{\pi\gamma\gamma}$

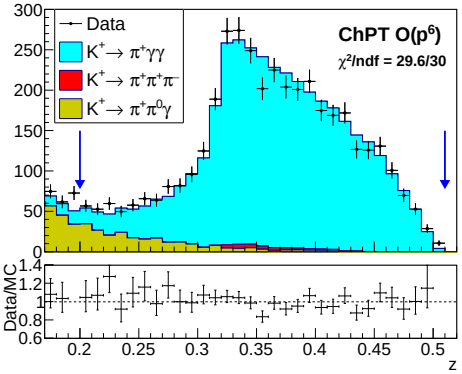
  Signal region: $0.20 < z < 0.51$
- Normalization channel to measure N_K decays: $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$. Minimal differences in event selections to reduce systematic effects

  Normalization region: $0.04 < z < 0.12$
- Main background source: cluster merging in calorimeter in $K^+ \to \pi^+\pi^0\gamma$, $\pi^0 \to \gamma\gamma$ decays



$N^{\text{obs}} = 3894,\ N^{\text{exp}}_{\text{bkg}} = 291 \pm 14$

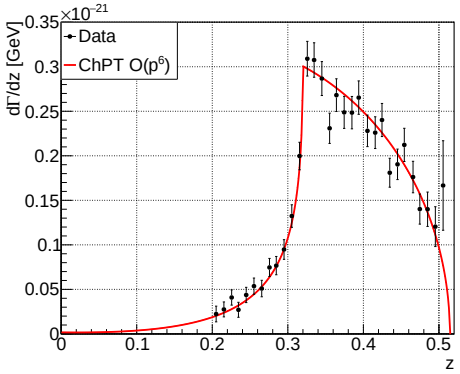


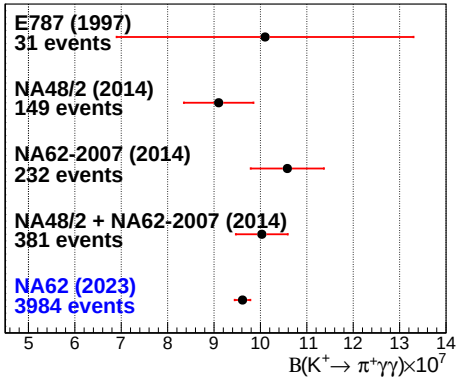


↪ $\hat{c}$ is measured in the ChPT $\mathcal{O}(p^4)$ and $\mathcal{O}(p^6)$ descriptions
- ↪ by reweighting of $K^+ \to \pi^+\gamma\gamma$ MC and performing a minimum-χ^2 fit
- ↪ ChPT $\mathcal{O}(p^4)$ p-value: 2.7×10^{-8} → not sufficient to describe the di-photon mass spectrum
- ↪ ChPT $\mathcal{O}(p^6)$ p-value: 0.49

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

$N^{\text{obs}} = 3894,\ N^{\text{exp}}_{\text{bkg}} = 291 \pm 14$





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

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

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

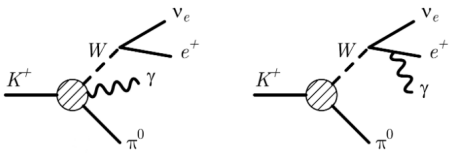
$K^+ \to \pi^0 e^+ \nu\gamma$

- Decay described in ChPT as direct emission, inner bremsstrahlung and their interference
- $\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma)$
  ↪ strongly depends on E_γ and $\theta_{e\gamma}$ cuts in K^+ rest frame
- Three kinematic ranges considered
  ↪ defined by E_γ and $\theta_{e\gamma}$ (table below)
- Measure normalized $\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma)$
  ↪ in ranges $j = \{1, 2, 3\}$:

$$R_j = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \mid E_\gamma^j, \theta_{e\gamma}^j)}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma))}$$

- Test of T-conservation
  ↪ T-odd observable ξ and its asymmetry:

$$\xi = \frac{\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\pi)}{M_K^3}, \quad A_\xi = \frac{N_{\xi>0} - N_{\xi<0}}{N_{\xi>0} + N_{\xi<0}}$$



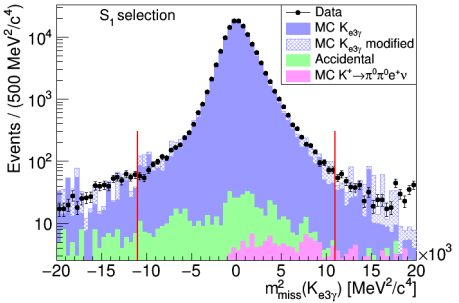
Signal selection:

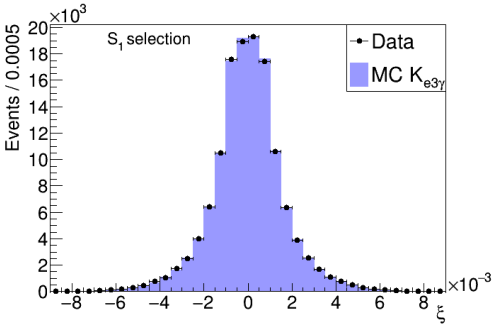
- Reconstruct and match K^+ and e^+ tracks
- Reconstruct $\pi^0 \to \gamma\gamma$ as two LKr clusters
- Radiative γ identified as isolated LKr cluster
- Kinematic constratint with the observable: $m^2_{\text{miss}} = (P_K - P_e - P_{\pi^0} - P_\gamma)^2$
- Minimal differences in signal and normalization selections, only related to the radiative photon ⇒ reduced systematic effects

State of the art:

	E_γ^j, $\theta_{e\gamma}^j$	$\mathcal{O}(p^6)$ ChPT [EPJ C 50 (2007) 557]	ISTRA+ [PAN 70 (2007) 702]	OKA [EPJ C 81 (2021) 161]
$R_1 \times 10^2$	$E_\gamma > 10$ 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	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

$N^{\text{obs}} = 1.3 \times 10^5$ with relative bkg contamination $< 1\%$





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

$\hookrightarrow$ NA62 measurements of R_j smaller than $\mathcal{O}(p^6)$ ChPT by 5% relative (3σ disagreement)

$\hookrightarrow$ sub-percent relative precision in R_j, with an improvement by a factor > 2 wrt previous measurements

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

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

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

- Latest radiative corrections
  ↪ JHEP 10 (2011) 122, EPJ C 74 (2014) 3010, PRD 110 (2024) 033004
  ↪ 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)

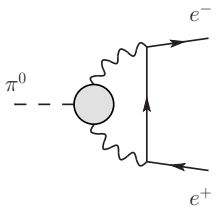


Diagram considered in theoretical predictions of $\mathcal{B}\,(\pi^0 \to e^+e^-,\ \text{no-rad})$
↪ various $\pi^0 \to \gamma^\star\gamma^\star$ transition form factors

- Fit region for signal extraction

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

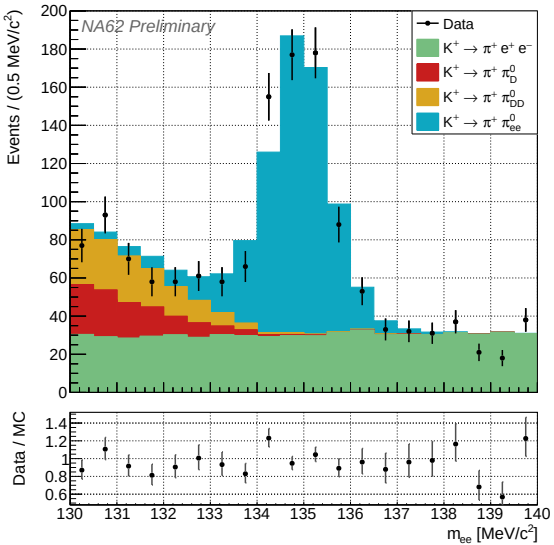
- Signal acceptance ($x_{\text{true}} > 0.95$)

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

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

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

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



- 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

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

$$\mathcal{B}^{\text{theory[2022]}}\left(\pi^0 \to e^+e^-,\, \text{no-rad}\right) = (6.25 \pm 0.03) \times 10^{-8}$$ [Phys. Rev. Lett. 128 (2022) 172004]

- 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

NA62 Physics Run I (2016–2018) results presented:

- $K^+ \to \pi^+\mu^+\mu^-$
  ↪ JHEP 11 (2022) 011, JHEP 06 (2023) 040
- $K^+ \to \pi^+\gamma\gamma$
  ↪ Phys. Lett. B 850 (2024) 138513
- $K^+ \to \pi^0 e^+ \nu\gamma$
  ↪ JHEP 09 (2023) 040
- $\pi^0 \to e^+e^-$
  ↪ Preliminary results

NA62 Physics Run II ongoing $\implies$ stay tuned

↪ experiment is approved until LS3 (2025 or 2026)
↪ plan to take as much data as possible
↪ analyses done on Run I data will be repeated on the full data set
↪ $K^+ \to \pi^+\nu\overline{\nu}$ results from 2021–2022 data samples coming soon

Thank you for listening!