JOHANNES GUTENBERG UNIVERSITÄT MAINZ

# New Results on rare Kaon and Pion Decays @NA62


Atakan Tuğberk Akmete | JGU Mainz

(atakan.tugberk.akmete@cern.ch)

On behalf of the NA62 collaboration


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Federal Ministry of Education and Research

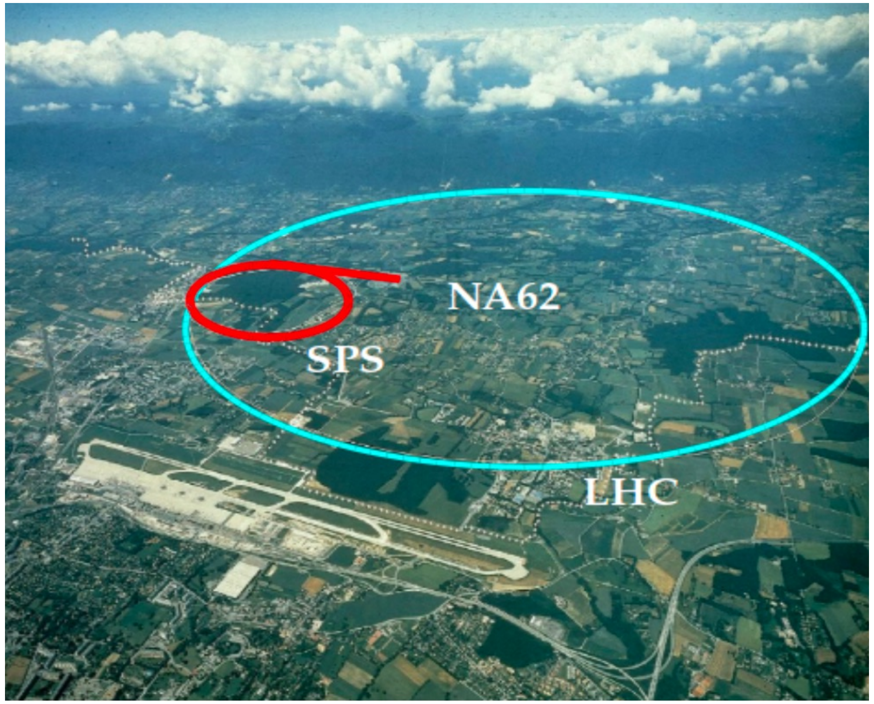
PRISMA+

# The NA62 Experiment at CERN: The K$^+$ factory

- Fixed-target experiment with 400 GeV/c protons from SPS
- Physics runs:
  - 2016, 2017 and 2018 (Run 1): $N_{K^+} \approx 6\,x\,10^{12}$
  - Run 2 started in 2021 and approved until CERN LS3
- Broad physics program:
  - Measurement of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$
  - Forbidden kaon decays (LFV/LNV)
  - Exotic particles searches
  - Precision measurements of rare decays (**this talk**):
    - $\pi^0 \to e^+e^-$ (**NEW preliminary**)
    - $K^+ \to \pi^+\gamma\gamma$ **[PLB 850 (2024) 138513]**

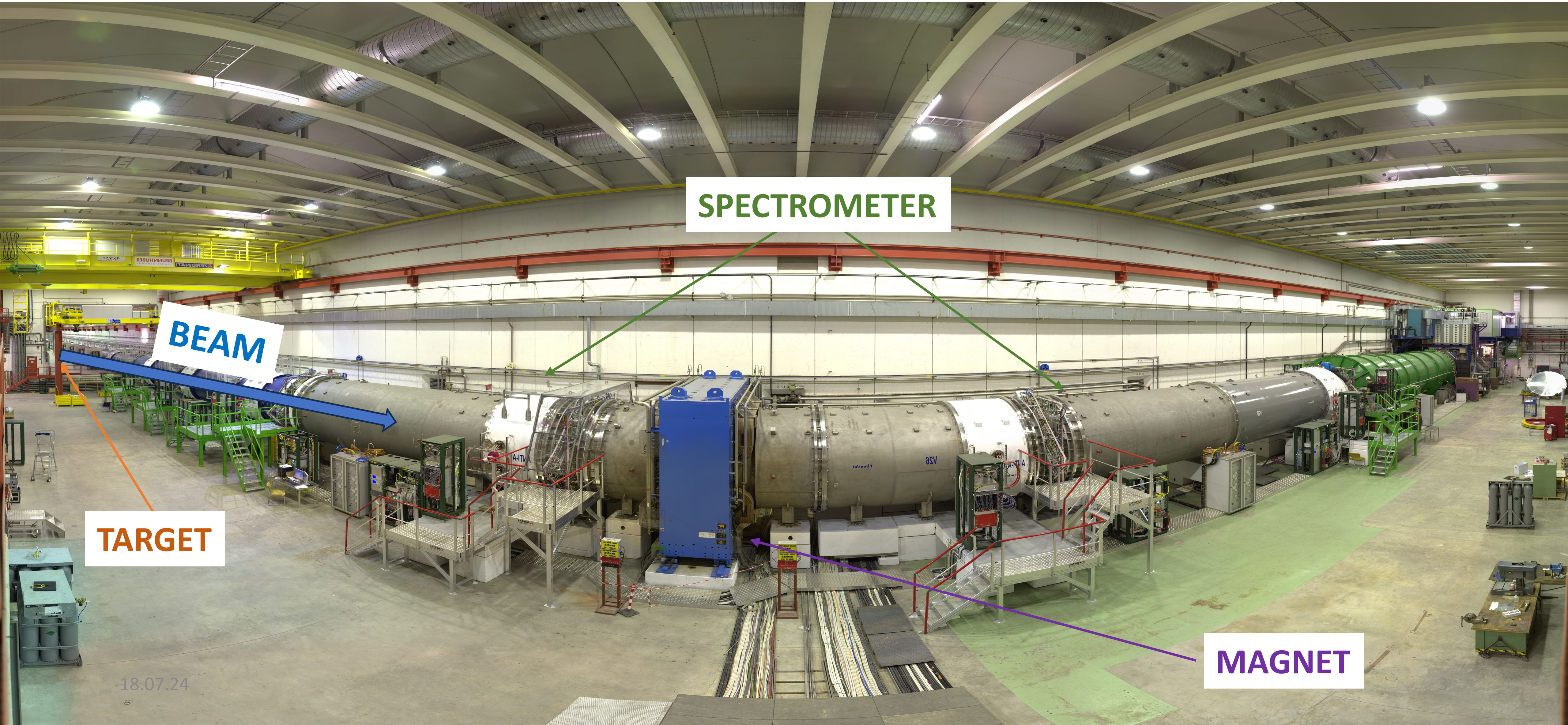
Previous talk by R. Fiorenza (refers to the first two items)

**From the NA62 data collected in 2017-2018** (refers to the last two items)



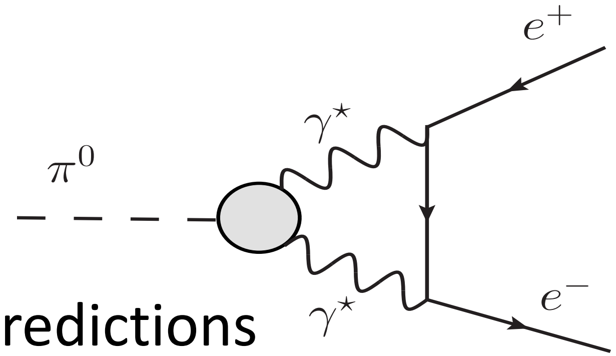

~300 collaborators from ~30 institutes

# The NA62 Beamline and Detector



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

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




- Radiative corrections play an important role for comparison with SM predictions
  - Lowest-order via a two-photon intermediate state

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

$$\boldsymbol{\mathcal{B}_{KTeV}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.25 \pm 0.22)\times 10^{-8}} \text{ with } x = m_{ee}^2/m_{\pi^0}^2$$

  - For $x > 0.95$, Dalitz decays are ~**3.3%** of $\boldsymbol{\mathcal{B}(\pi^0 \to e^+e^-(\gamma))}$

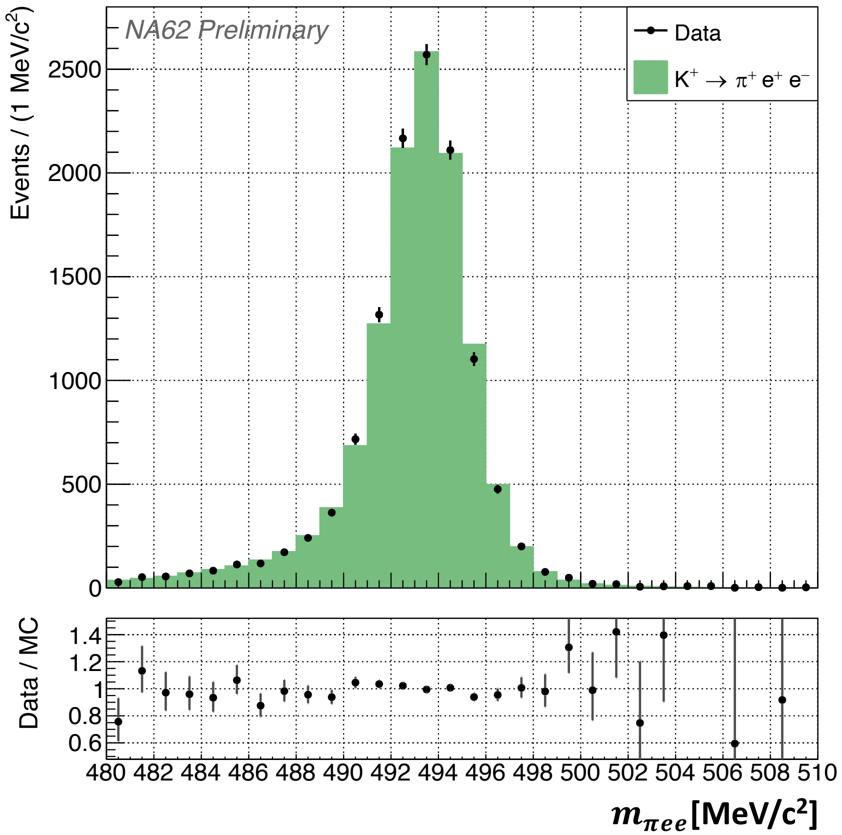
- Predictions [JHEP 10 (2011) 122] and [Eur.Phys.J.C 74 (2014) 8, 3010]:

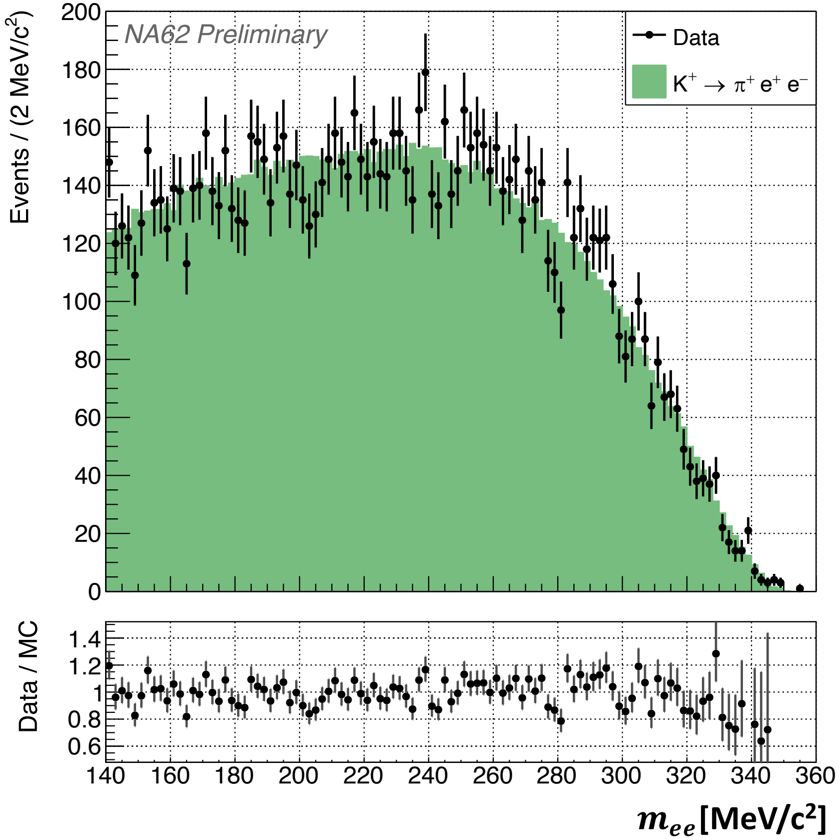
| | $\mathcal{B}(\pi^0 \to e^+e^-$, no-rad$) \times 10^8$ |
|---|---|
| KTeV, PRD 75 (2007) | 6.84(35) |
| Knecht et al., PRL 83 (1999) | 6.2(3) |
| Dorokhov and Ivanov, PRD 75 (2007) | 6.23(9) |
| Husek and Leupold, EPJC 75 (2015) | 6.12(6) |
| Hoferichter et al., PRL 128 (2022) | 6.25(3) |

➢ NA62 has a great opportunity to tag $O(10^{10})$ $\pi^0$ decays via $K^+ \to \pi^+\pi^0$ and both $K^+$ and $\pi^+$ reconstructed

# Data sample and trigger

- **Signal** $K^+ \rightarrow \pi^+\pi^0; \pi^0 \rightarrow e^+e^- \equiv K^+ \rightarrow \pi^+\pi^0_{ee}$ and **normalization** $K^+ \rightarrow \pi^+e^+e^-$
- Same decay topology → <u>systematics cancel</u>
- Background-free region for normalization: $m_{ee} \in (140, 360)$ **MeV/c²**
- $N^{obs} = 12160$ and $N_{K^+} = (8.62 \pm 0.08_{stat} \pm 0.26_{ext})\times 10^{11}$



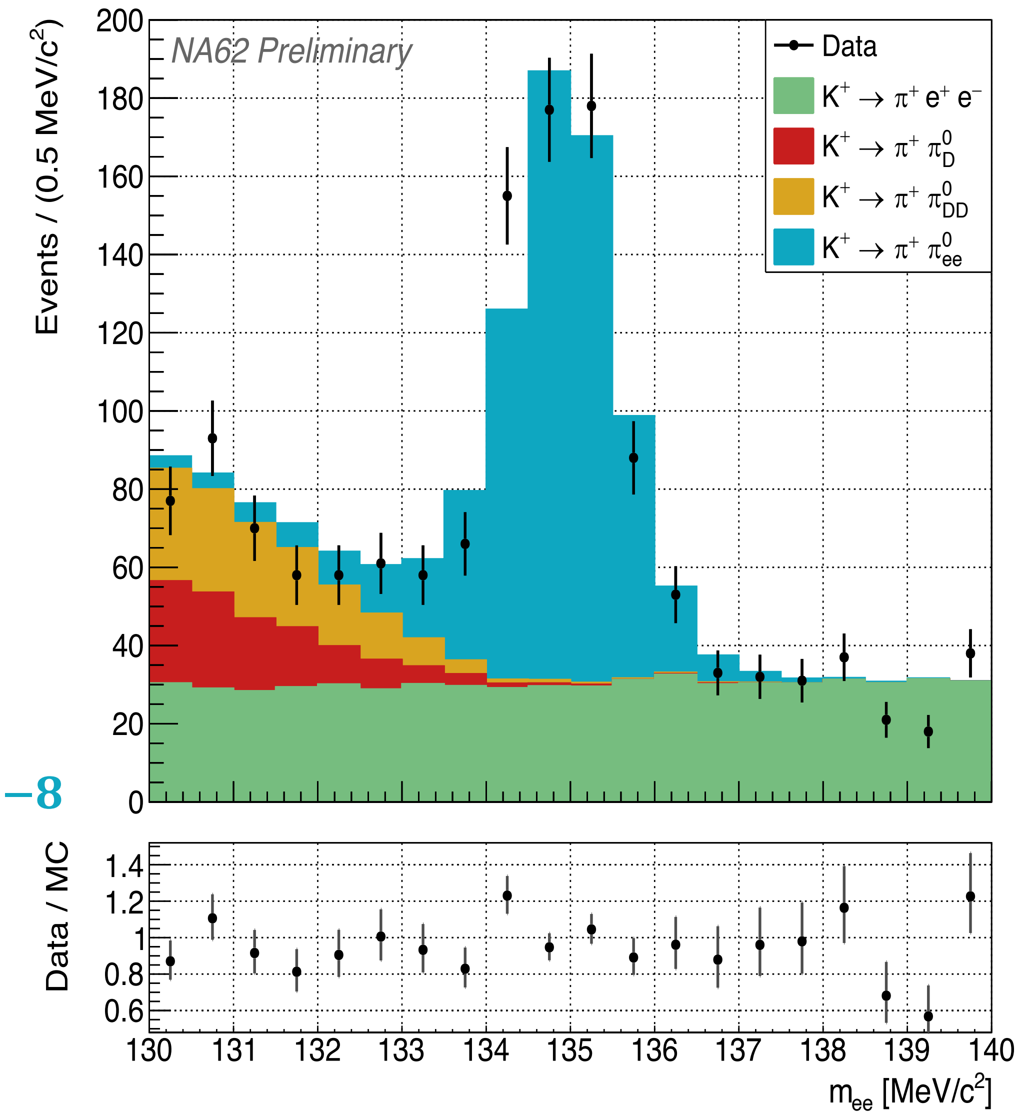
# Signal $K^+ \to \pi^+\pi^0_{ee}$

- Fit region for signal extraction:

  $$m_{ee} \in (130, 140)\ MeV/c^2$$

- Backgrounds sources:
  - $K^+ \to \pi^+e^+e^-$: irreducible, flat in signal region
  - $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma e^+e^- \equiv K^+ \to \pi^+\pi^0_D$
  - $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-e^+e^- \equiv K^+ \to \pi^+\pi^0_{DD}$
- Maximum likelihood fit of the $m_{ee}$ signal:
  - **Fit result: 597 ± 29 signal events**
  - $\chi^2/ndf = 25.3/19$, p-value: 0.152

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



# Preliminary Results and Uncertainties

- The results are compatible with the previous measurement and the theoretical predictions:

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

$$\boldsymbol{= (5.86 \pm 0.37)\times 10^{-8}}$$

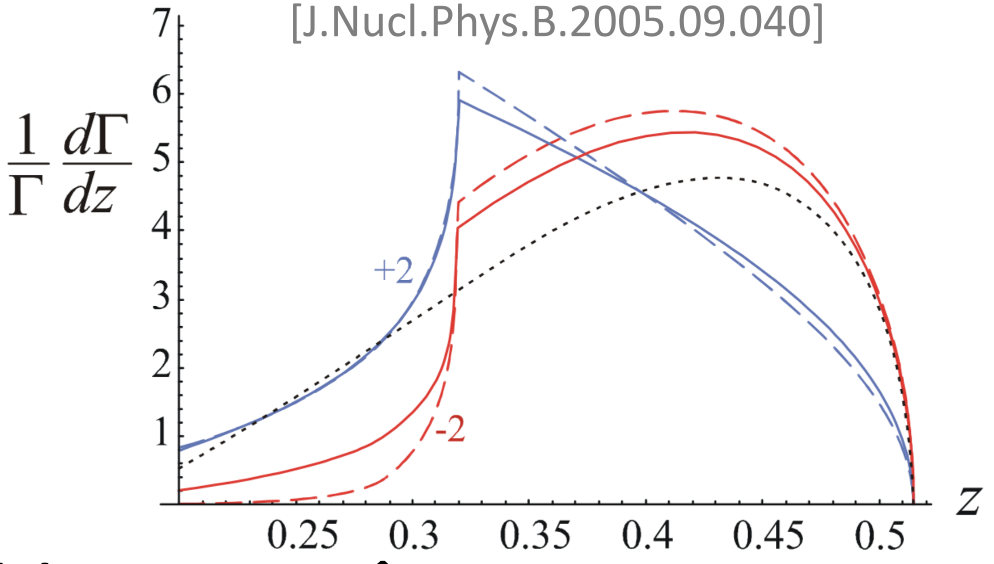
| | $\delta\mathcal{B}[10^{-8}]$ | $\delta\mathcal{B}/\mathcal{B}[\%]$ |
|---|---|---|
| **Statistical uncertainty** | 0.30 | 5.1 |
| Trigger efficiency | 0.07 | 1.2 |
| Radiative corrections for $\pi^0 \to e^+e^-$ | 0.05 | 0.9 |
| Background | 0.04 | 0.7 |
| Reconstruction and particle-ID | 0.04 | 0.7 |
| Beam simulation | 0.03 | 0.5 |
| **Total systematic uncertainty** | 0.11 | 1.9 |
| **Total external uncertainty** | 0.19 | 3.2 |

$$K^+ \rightarrow \pi^+\gamma\gamma$$

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

- Crucial test of Chiral Perturbation Theory (ChPT) describing low-energy QCD processes
  - ChPT at the leading order $\boldsymbol{O(p^4)}$ including next-to-leading order $\boldsymbol{O(p^6)}$ contributions necessary for observed di-photon mass spectrum

- **Main kinematic variable:** $\boldsymbol{z = \frac{(P_K - P_\pi)^2}{m_K^2} = \frac{m_{\gamma\gamma}^2}{m_K^2}}$




- $\mathcal{B}(K^+ \to \pi^+\gamma\gamma)$ parameterized in ChPT by **unknown O(1) parameter $\hat{c}$**

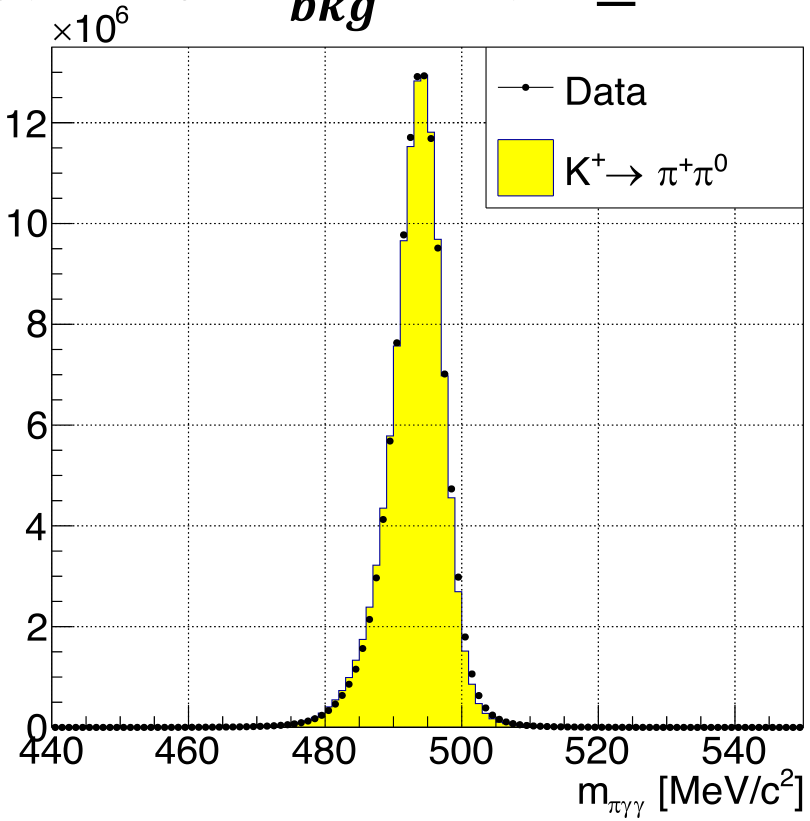
$$\frac{\partial \Gamma}{\partial y \partial z}(\hat{c}, y, z) = \frac{m_K}{2^9\pi^3}\left[z^2\left(|A(\hat{c}, z, y^2) + B(z)|^2 + |C(z)|^2\right) + \left(y^2 - \frac{1}{4}\lambda(1, r_\pi^2, z)\right)^2 |B(z)|^2\right].$$

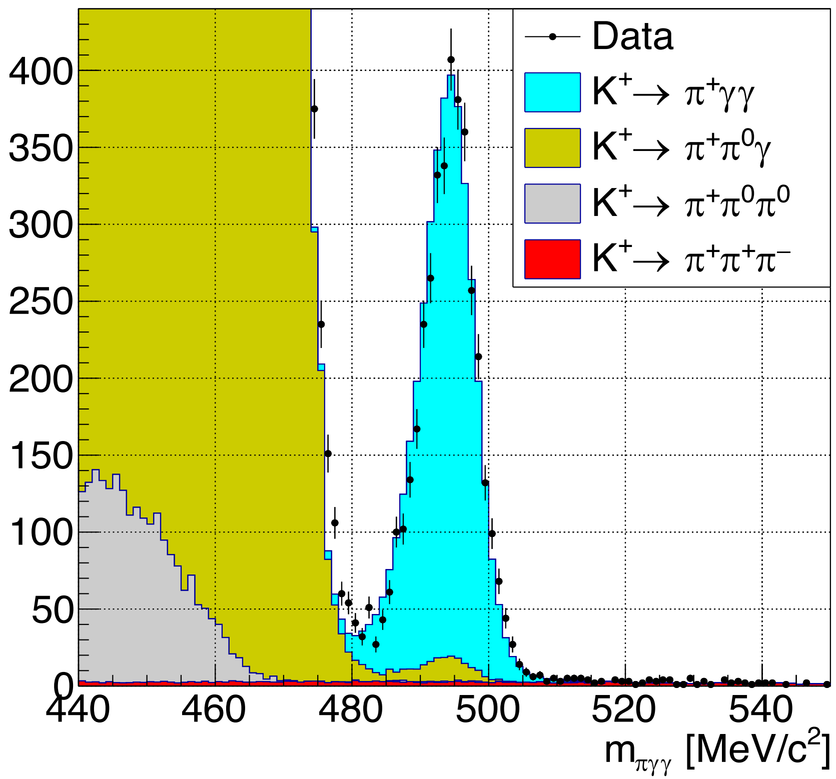
[Phys. Lett. B386 (1996) 403]

appears at O(p⁶)

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

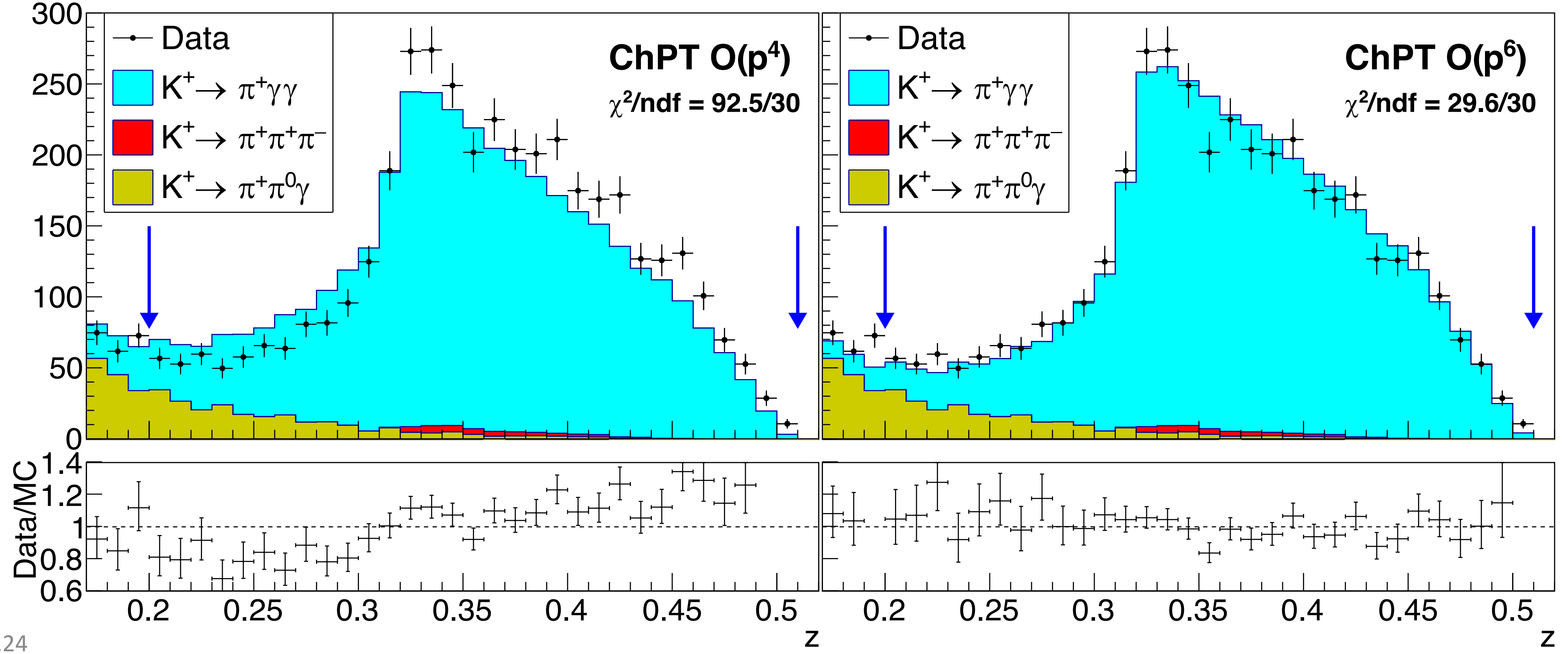
- **Signal $K^+ \to \pi^+\gamma\gamma$** in $z \in (0.20, 0.51)$ and **normalization $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma\gamma$** in $z \in (0.04, 0.12)$
- Same decay topology → systematics cancel
- Main bkg source $K^+ \to \pi^+\pi^0; \pi^0 \to \gamma\gamma$ with cluster merging in calorimeter
- $N^{obs} = 3894$ with $N^{exp}_{bkg} = 291 \pm 14$



# ChPT $\hat{c}$ Fit Results

- $\hat{c}$ **measured** in $O(p^4)$ and $O(p^6)$ by $\chi^2$ **minimization** of simulated samples to data
- ChPT $O(p^4)$ is not sufficient to describe the data
- $\hat{c}_{ChPT\ O(p^6)} = \mathbf{1.144 \pm 0.069_{stat} \pm 0.034_{syst}}$



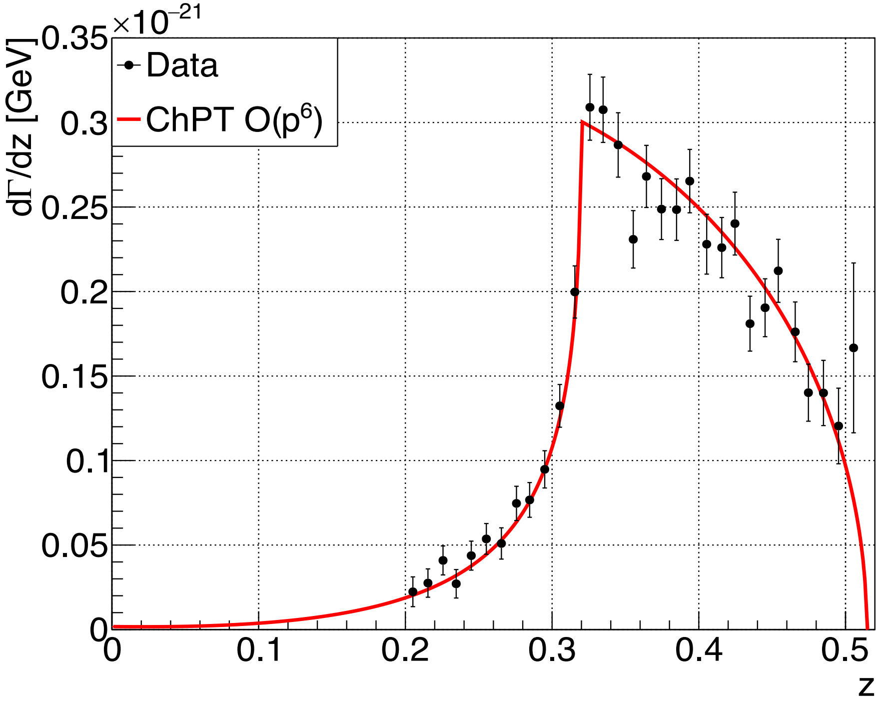
# $\mathcal{B}(K^+ \rightarrow \pi^+\gamma\gamma)$

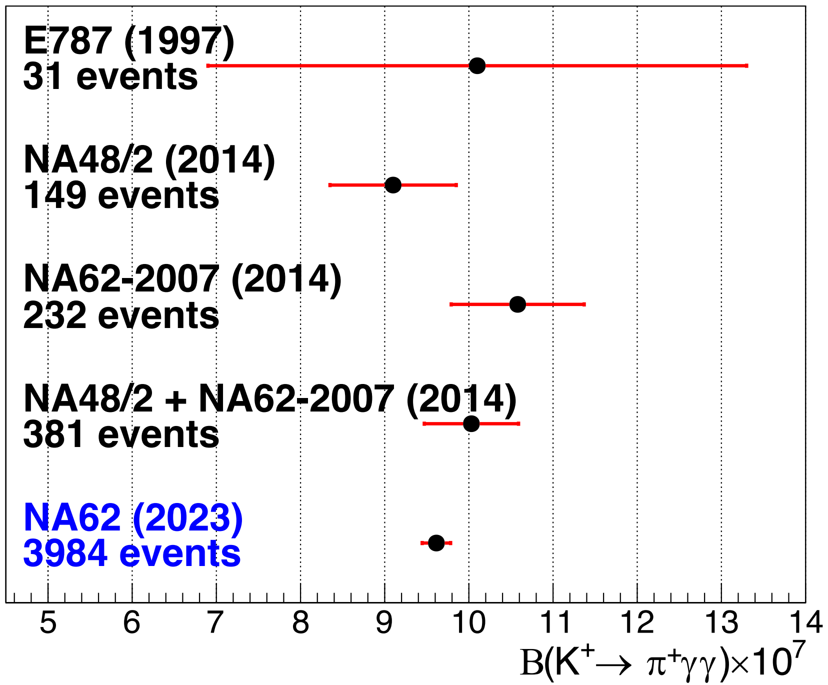
- Differential decay-width in O(p⁶) with $\hat{c}$ summed over the full z-range:

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

- Model independent measurement (markers) summed over z bins > 0.20:

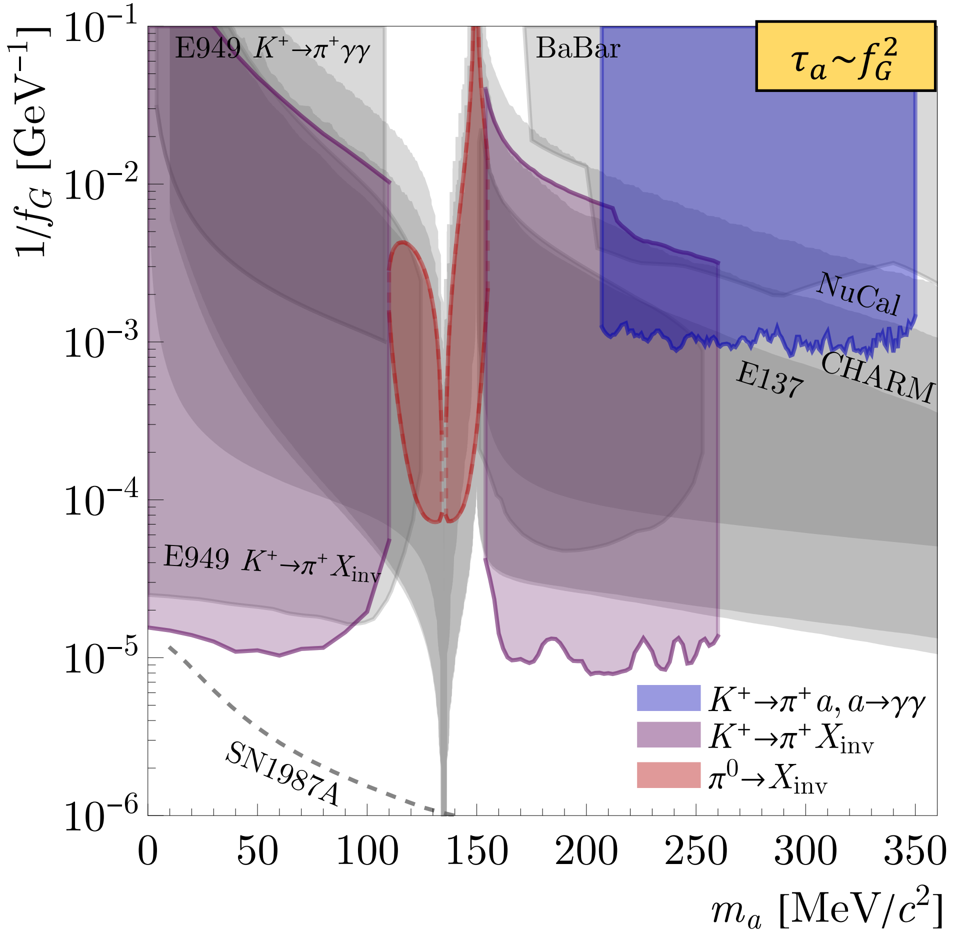
$$\mathcal{B}_{M.I.}(K^+ \rightarrow \pi^+\gamma\gamma | z > 0.20) = (9.46 \pm 0.19_{stat} \pm 0.07_{syst})\times 10^{-7}$$



# First Search for ALPs in $K^+ \to \pi^+ a,\ a \to \gamma\gamma$

- Peak search over $m_{\gamma\gamma} = \sqrt{(\boldsymbol{P}_K - \boldsymbol{P}_\pi)^2}$ in range **207-350 MeV/c²** with 0.5 MeV/c² bins
- Exclusion regions at 90% CL on ALP coupling in the BC11 scenario; limits are from the **present search** and the **earlier NA62 results**



# Conclusions

- NA62 physics **Run 2** started in 2021 and ongoing until CERN LS3

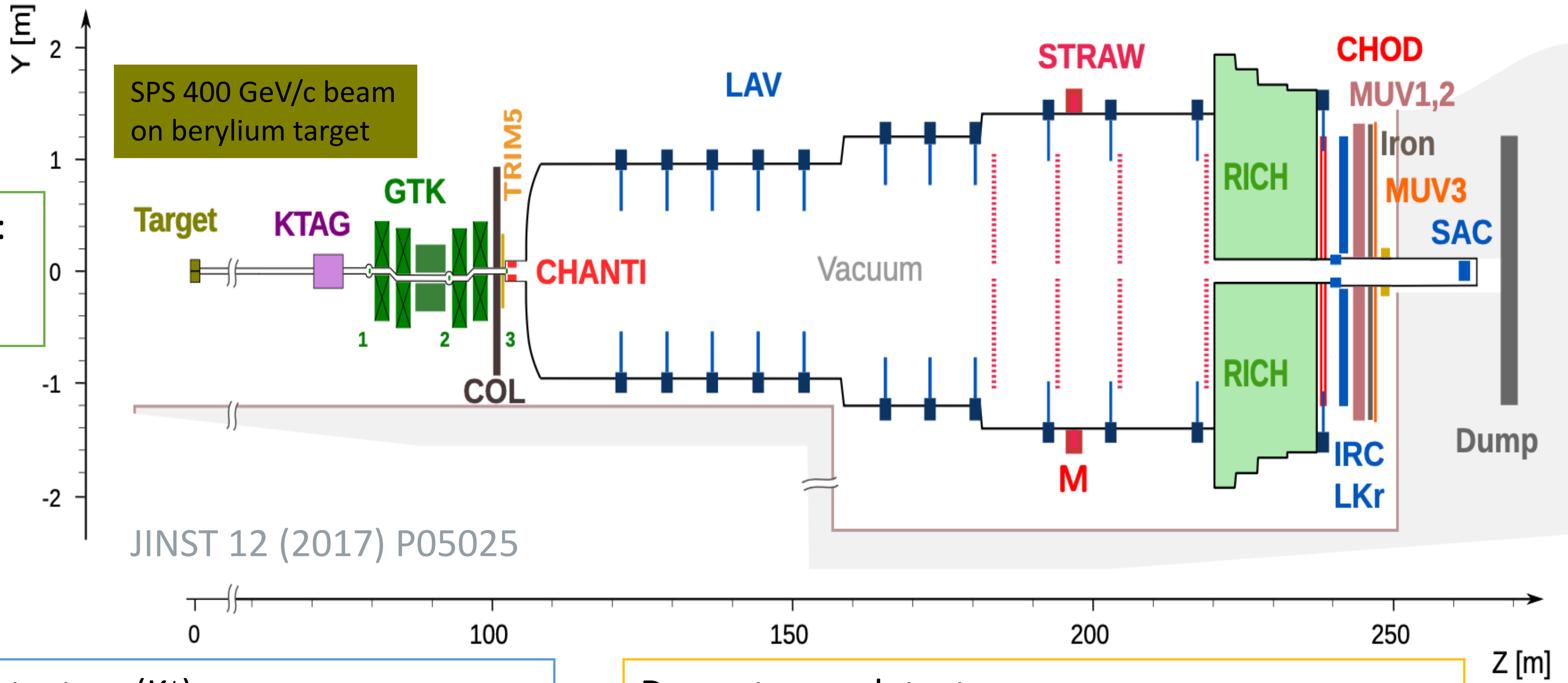
- $\boldsymbol{\pi^0 \to e^+e^-}$ (**new preliminary result**):
  - Precision comparable with the previous measurement, statistically dominated
  - Full agreement with the latest theoretical predictions

- $\boldsymbol{K^+ \to \pi^+\gamma\gamma}$ (**PLB 850 (2024) 138513**):
  - Improved precision by **a factor of > 3**, statistically dominated
  - ChPT O($p^4$) is not sufficient to describe the data
  - First search for ALP with gluon coupling in $\boldsymbol{K^+ \to \pi^+ a, a \to \gamma\gamma}$ decays

# BACKUP SLIDES

# The NA62 Detector

Secondary hadron 75 GeV/c beam:
- 70% $\pi^+$, 24% $p^+$, 6% $K^+$
- Beam particle rate: ~750 MHz




Upstream detectors ($K^+$):
- KTAG: differential Cherenkov counter for $K^+$ ID
- GTK: Si pixel beam tracker for $K^+$ momentum
- CHANTI: Anti-counter for upstream particles

Downstream detectors:
- STRAW: track momentum spectrometer
- LKr/MUV1/MUV2: Calorimeters for $\pi/\mu$ separation
- RICH: Cherenkov counter for $\pi/\mu/e$ ID
- LAV/SAC/IRC: Photon veto detectors
- MUV3: Muon veto detector

# $\pi^0 \to e^+e^-$: Summary and Outlook

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

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

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

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

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

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

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

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

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

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

- Test of T-conservation by T-odd observable $\xi$ and its T-asymmetry $A_\xi$:

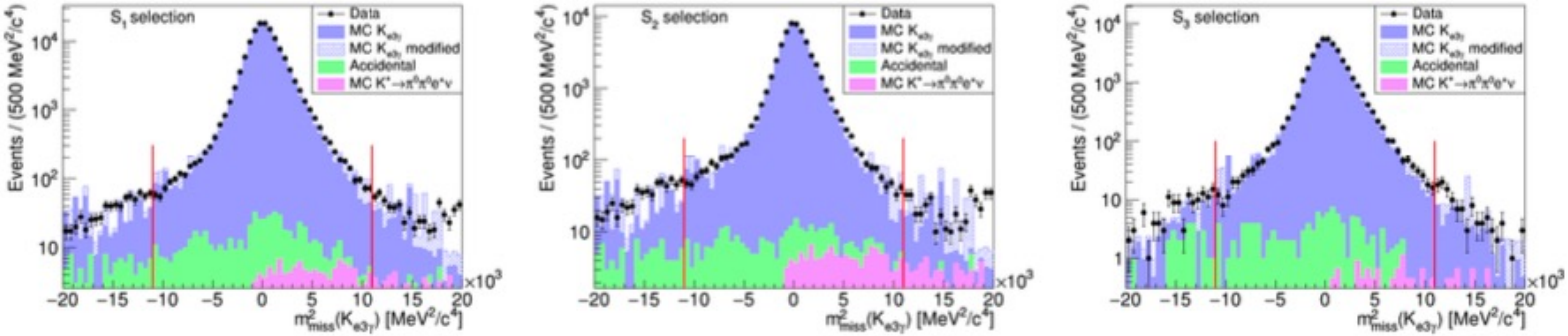
$$\xi = \frac{\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\pi)}{(M_K \cdot c)^3}; \; A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

| | $E_\gamma^j, \theta_{e\gamma}^j$ | ChPT | ISTRA+ | OKA |
|---|---|---|---|---|
| $R_1 \times 10^2$ | $E_\gamma > 10 MeV, \; \theta_{e\gamma} > 10°$ | $1.804 \pm 0.021$ | $1.81 \pm 0.03 \pm 0.07$ | $1.990 \pm 0.017 \pm 0.021$ |
| $R_2 \times 10^2$ | $E_\gamma > 30 MeV, \; \theta_{e\gamma} > 20°$ | $0.640 \pm 0.008$ | $0.63 \pm 0.02 \pm 0.03$ | $0.587 \pm 0.010 \pm 0.015$ |
| $R_3 \times 10^2$ | $E_\gamma > 10 MeV, 0.6 < cos\theta_{e\gamma} < 0.9$ | $0.559 \pm 0.006$ | $0.47 \pm 0.02 \pm 0.03$ | $0.532 \pm 0.010 \pm 0.012$ |

# $K^+ \rightarrow \pi^0 e^+ \nu\gamma$: Signal selection

- $K^+$ and $e^+$ tracks reconstructed and matched
- $\pi^0 \rightarrow \gamma\gamma$ reconstructed as two LKr clusters
- One isolated LKr cluster is identified as radiative $\gamma$
- Kinematic constraint: $m^2_{miss}(K_{e3\gamma}) = (\boldsymbol{P}_K - \boldsymbol{P}_e - \boldsymbol{P}_{\pi^0} - \boldsymbol{P}_\gamma)^2$
- Minimal differences in signal and normalization selections; only related to the radiative photon → reduced systematics

# $K^+ \to \pi^0 e^+ \nu \gamma$: 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 $3\sigma$)

Improvement on experimental precision of $R_j$ measurements by a factor $> 2$

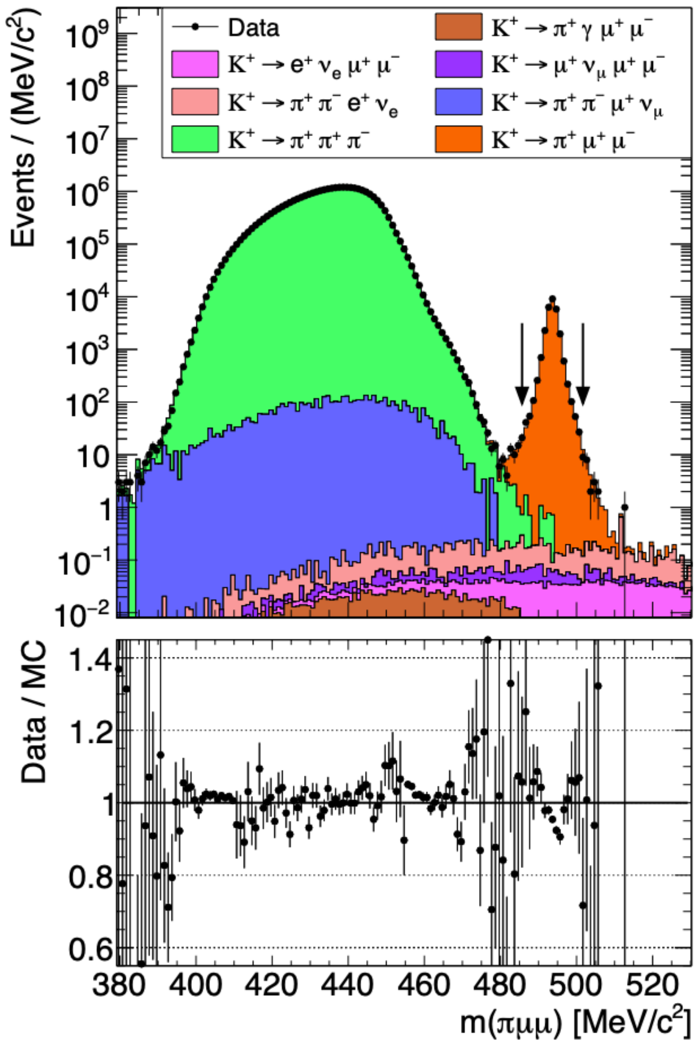
# $K^+ \to \pi^0 e^+ \nu \gamma$: Error budget

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% |

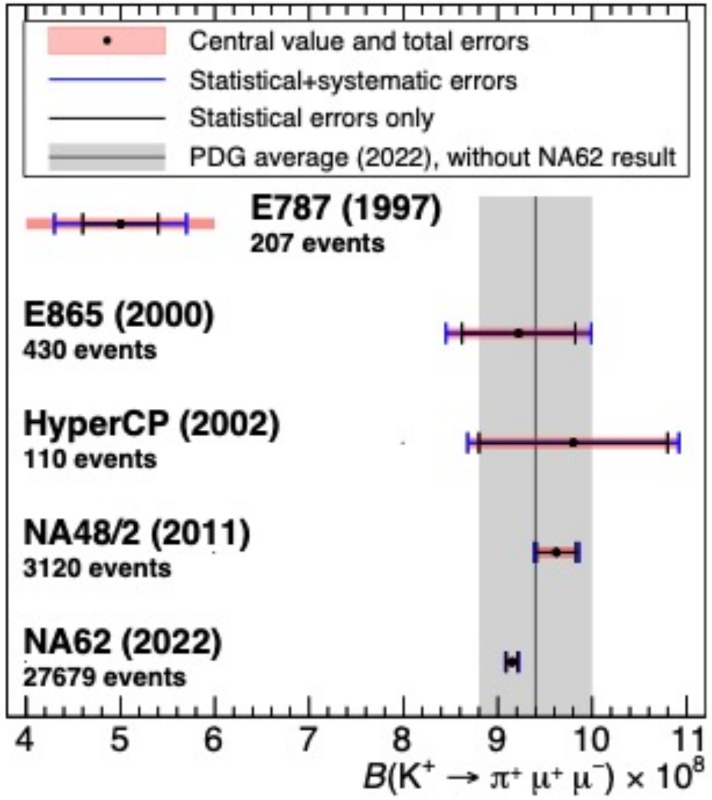
# $K^+ \rightarrow \pi^+\mu^+\mu^-$: Overview

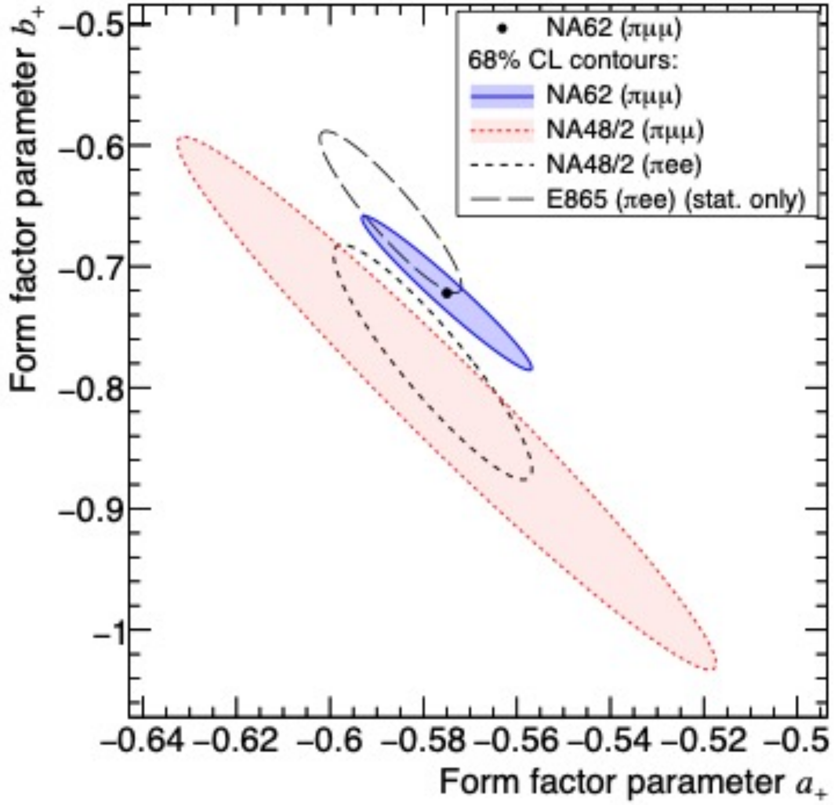
- Flavor changing neutral current decay $K^+ \rightarrow \pi^+ l^+ l^-$ where $l = e, \mu$
- Contribution to the decays are mediated by virtual photon exchange: $K^\pm \rightarrow \pi^\pm \gamma^* \rightarrow \pi^\pm l^+ l^-$
- Main kinematic variable: $z = m_{ll}^2 / m_K^2$
- $W(z) = (a_+ + z \,.\, b_+) G_F m_K^2 + W^{\pi\pi}(z)$ is the form factor of $K^\pm \rightarrow \pi^\pm \gamma^*$ parameterized in ChPT $O(\mathrm{p}^6)$ with real parameters $a_+$, $b_+$
- Test of lepton flavor universality
- Measurements:
  - $\mathcal{B}(K^+ \rightarrow \pi^+\mu^+\mu^-)$; function $|W(z)|^2$ from $d\Gamma/dz$; form factor parameters $a_+$, $b_+$
- Signal selection:
  - Three tracks identified as $\pi^+\mu^+\mu^-$
  - Kinematic cuts to suppressing $K^\pm \rightarrow \pi^+\pi^+\pi^-$ events
- Normalization sample $K^\pm \rightarrow \pi^+\pi^+\pi^-$:
  - For measuring the number of kaon decays
  - Minimal differences in the event selection to reduce systematics



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

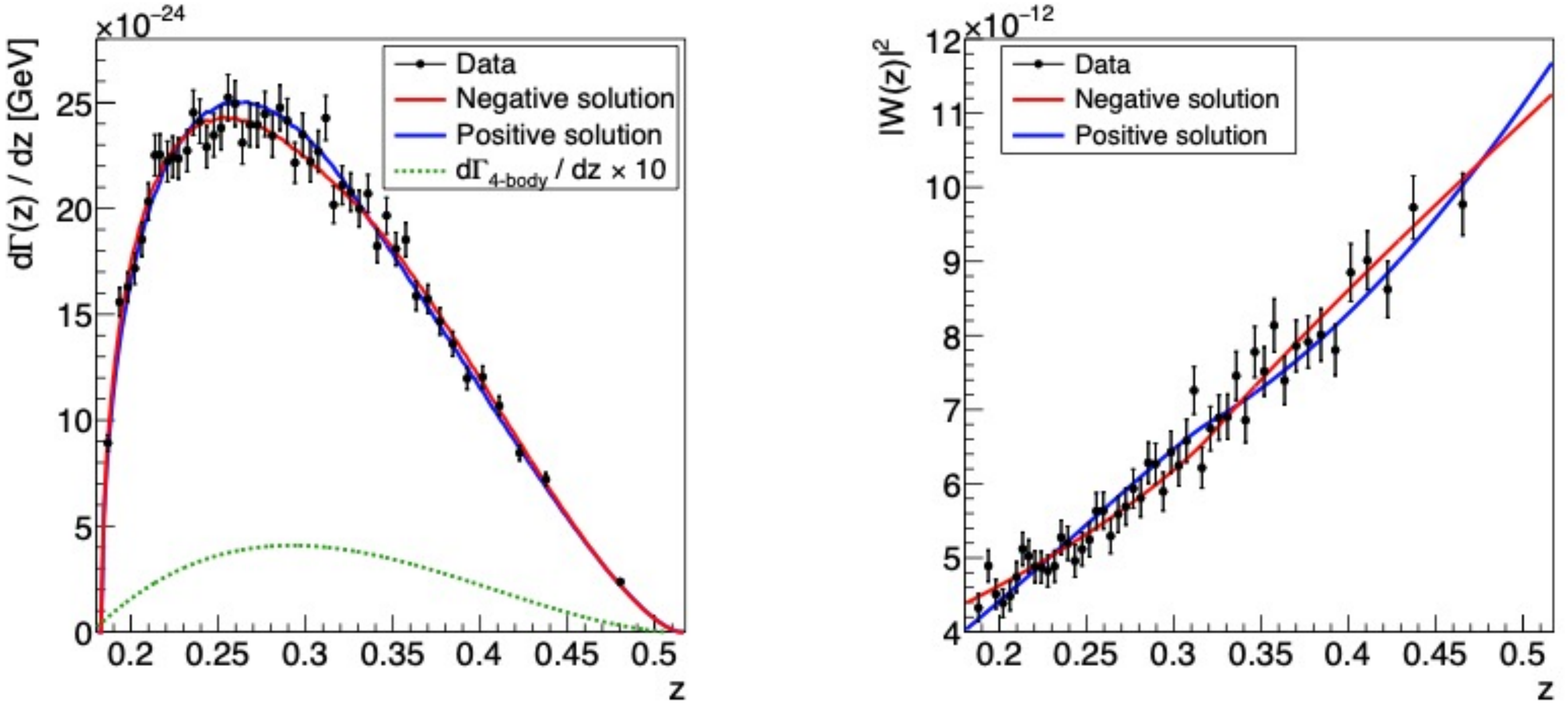
27679 observed events with negligible background




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

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

| | $\delta a_+$ | $\delta b_+$ | $\delta \mathcal{B}_{\pi\mu\mu} \times 10^8$ |
|---|---|---|---|
| **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 $\alpha_+$ and $\beta_+$ | 0.001 | 0.006 | — |
| **Total external uncertainty** | 0.003 | 0.011 | 0.04 |
| **Total uncertainty** | **0.013** | **0.043** | **0.08** |