Precision measurements at the NA62 experiment

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On behalf of the NA62 Collaboration

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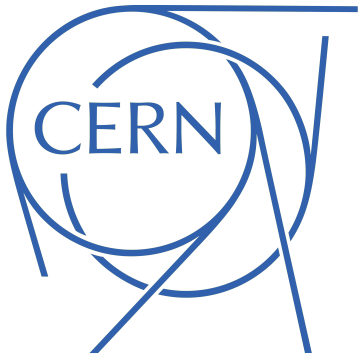
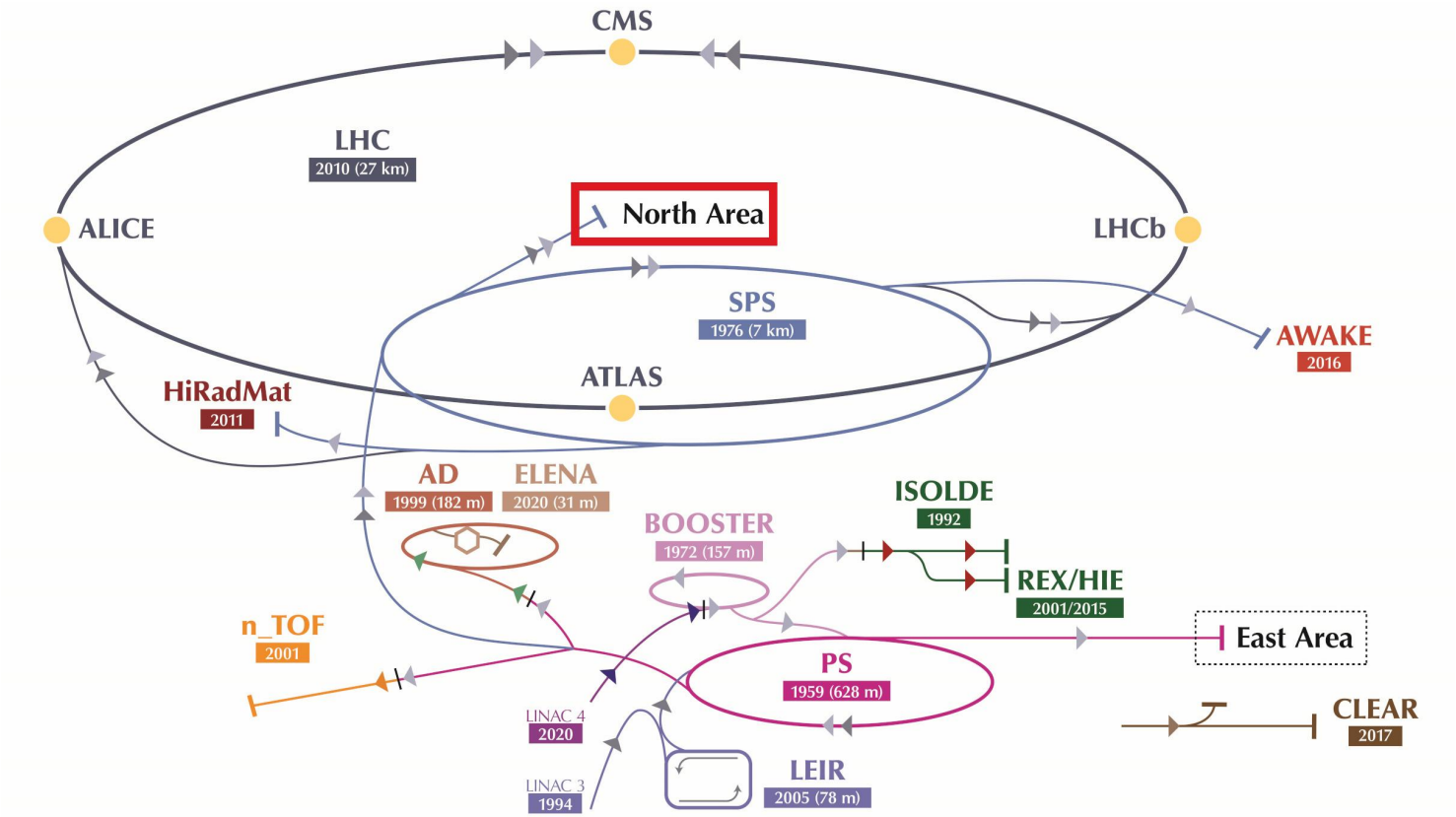
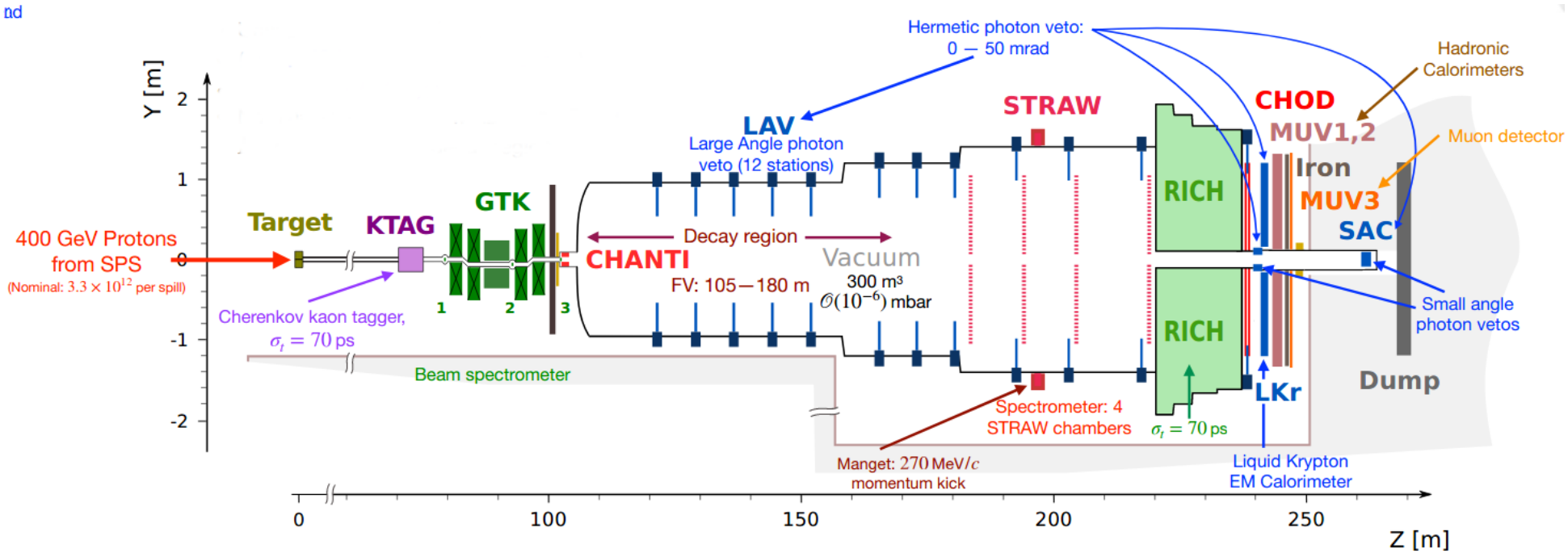


Precision measurements with kaon and pion decays with NA62 Run 1 data (2016-2018):

- $K^+ \to \pi^+\mu^+\mu^-$ [JHEP11(2022)011] [JHEP06(2023)040]
- $K^+ \to \pi^+\gamma\gamma$ [Phys.Lett.B 850 (2024) 138513]
- $K^+ \to \pi^0 e^+ \nu\gamma$ [JHEP09(2023)040]
- $\pi^0 \to e^+e^-$ [Preliminary results]



NA62 Beamline, Detector and Datasets



- Detector designed for $K^+ \to \pi^+ \nu\bar{\nu}$ study
- **K^+ decay-in-flight technique**: unseparated hadron beam (70% π^+, 23% p, 6% K^+), nominal intensity 750 MHz, K^+ momentum 75 GeV/c, 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, $\sim 6 \times 10^{12}$ useful K^+ decays)**, 2021–LS3 (Physics Run II, ongoing)

[JINST 12(2017) P05025]

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

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

$K^\pm \to \pi^\pm l^+ l^-$ decays ($l = e, \mu$)

- **Flavour changing neutral current processes**
- Ideal for **test of lepton flavour universality**
- Dominant contribution via virtual photon exchange: $K^\pm \to \pi^\pm \gamma^* \to \pi^\pm l^+ l^-$
- Kinematic variable $\mathbf{z = m^2_{l^+l^-}/m^2_K}$
- **Form factor** of $K^\pm \to \pi^\pm \gamma^*$ transition $\mathbf{W(z)}$ parametrized in ChPT at $\mathcal{O}(p^6)$ as

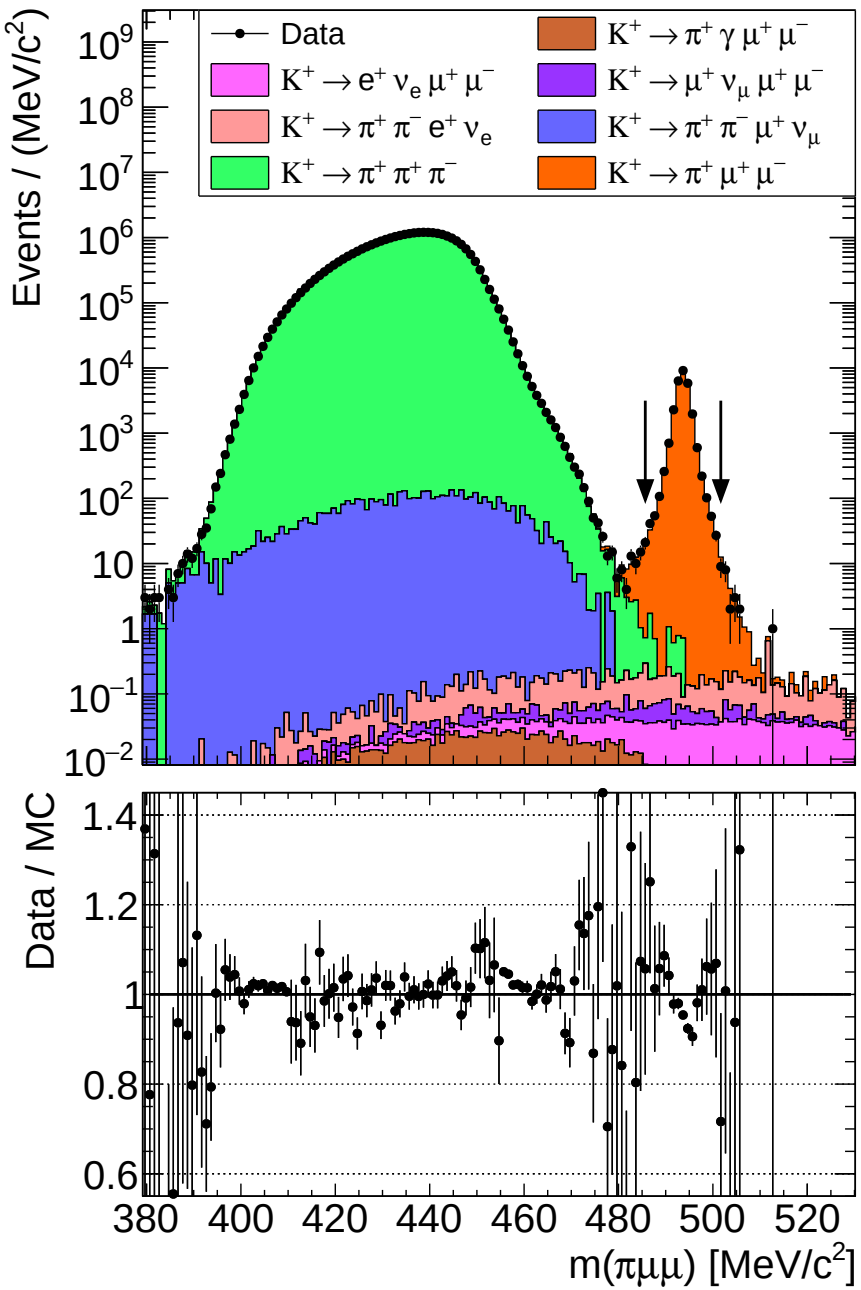
$$W(z) = (a_+ + z b_+) G_F m_K^2 + W^{\pi\pi}(z)$$

with **real parameters $\mathbf{a_+, b_+}$** and (known) complex function $W^{\pi\pi}(z)$

Goals:

- Measure **model independent** $\mathcal{B}(K^+ \to \pi^+\mu^+\mu^-)$
- Measure $|\mathbf{W(z)}|^2$
- Determine form factor parameters $\mathbf{a_+, b_+}$

[JHEP11(2022)011]



Selection:

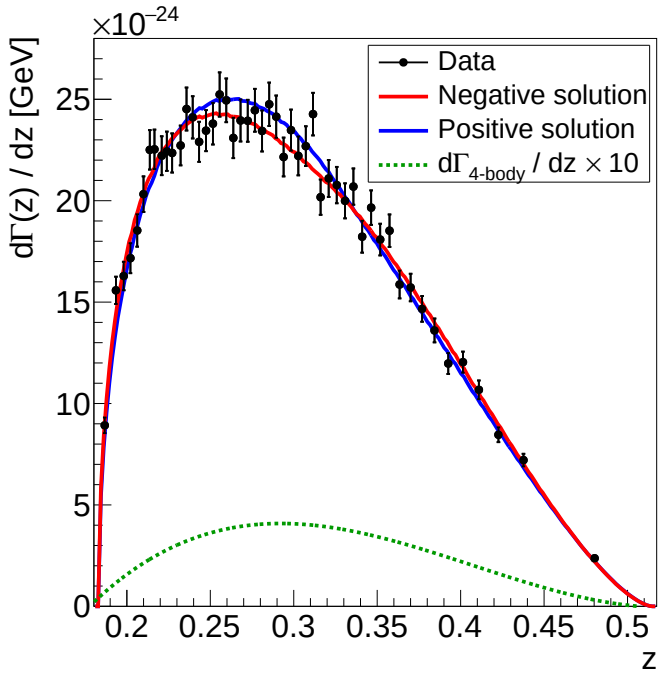
- 2μ multi-track trigger line used for signal selection
- Normalization: $K^+ \to \pi^+\pi^+\pi^-$ from multi-track triggered data $\to N_K$ decays
- Generic 3-track selection cuts
- Tracks identified as $\pi^+\mu^+\mu^-$
- Kinematic cuts suppressing $K_{3\pi}$ events
- Minimal differences in signal and normalization event selections $\Rightarrow$ **reduced systematic effects**

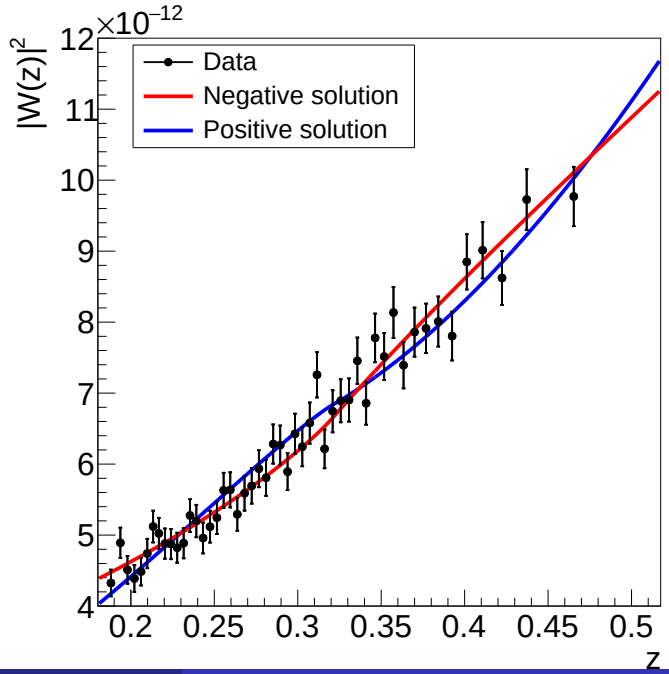
Analysis strategy:

- Data distributed in 50 equipopulated z bins
- Differential decay width is given by

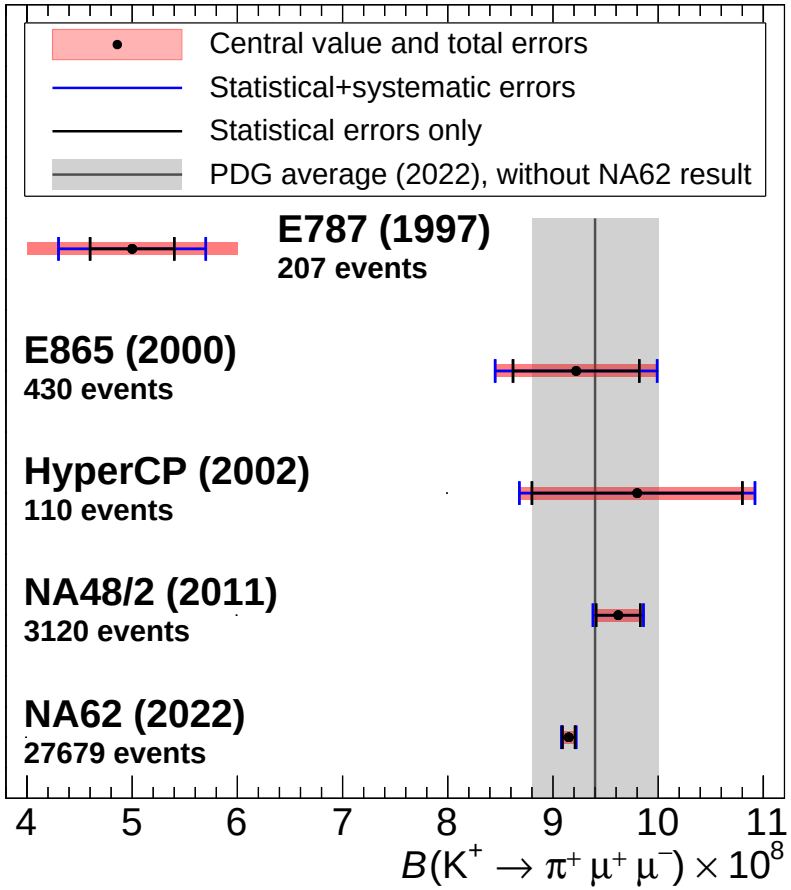
$$\left(\frac{d\Gamma(z)}{dz}\right)_i = \frac{N_{\pi\mu\mu,i}}{A_{\pi\mu\mu,i}} \frac{1}{\Delta z_i} \frac{1}{N_K} \frac{\hbar}{\tau_K}$$

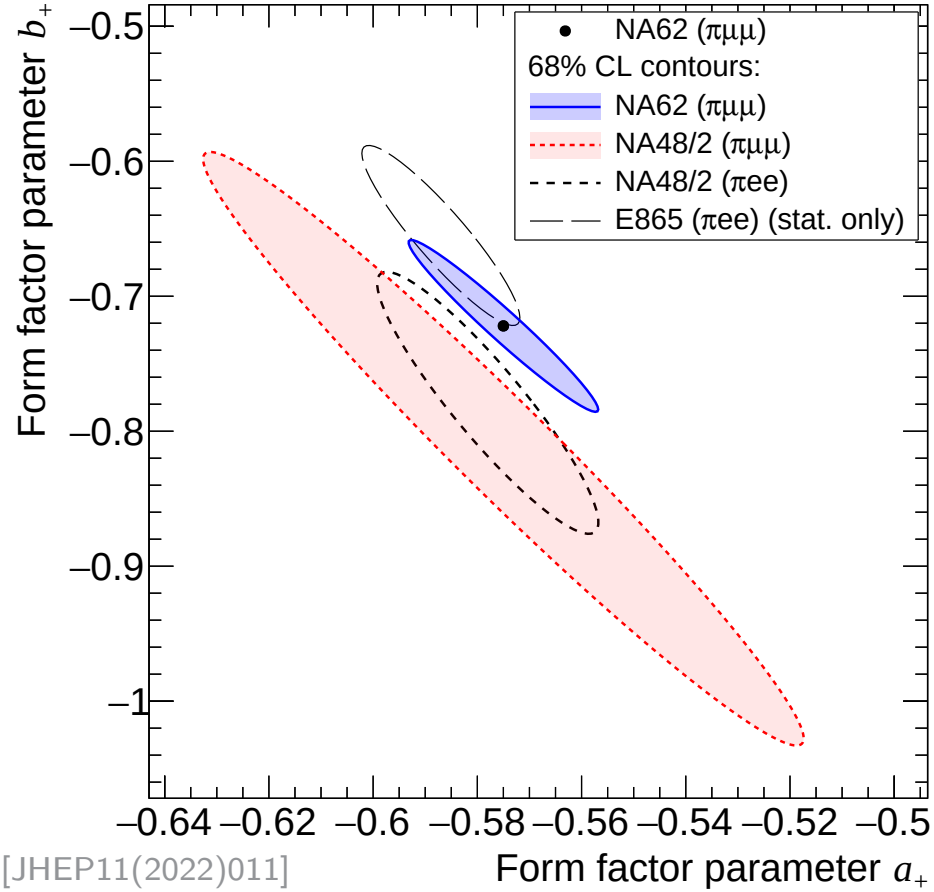
- Model independent $\mathcal{B}$ obtained by summing $\frac{d\Gamma}{dz}$ in all 50 bins
- $|\mathbf{W(z)}|^2$ function values extracted from $\frac{d\Gamma}{dz}$
- ChPT form factor parameters $\mathbf{a}_+$, $\mathbf{b}_+$ extracted from the fit of $|W(z)|^2$ data points





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





[JHEP11(2022)011]

$$N^{obs} = 27679$$
$$a_+ = -0.575 \pm 0.013$$
$$b_+ = -0.722 \pm 0.043$$
$$\rho(a_+, b_+) = -0.972$$

$$\mathcal{B}(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \times 10^{-8} \text{ at } 68\% CL$$

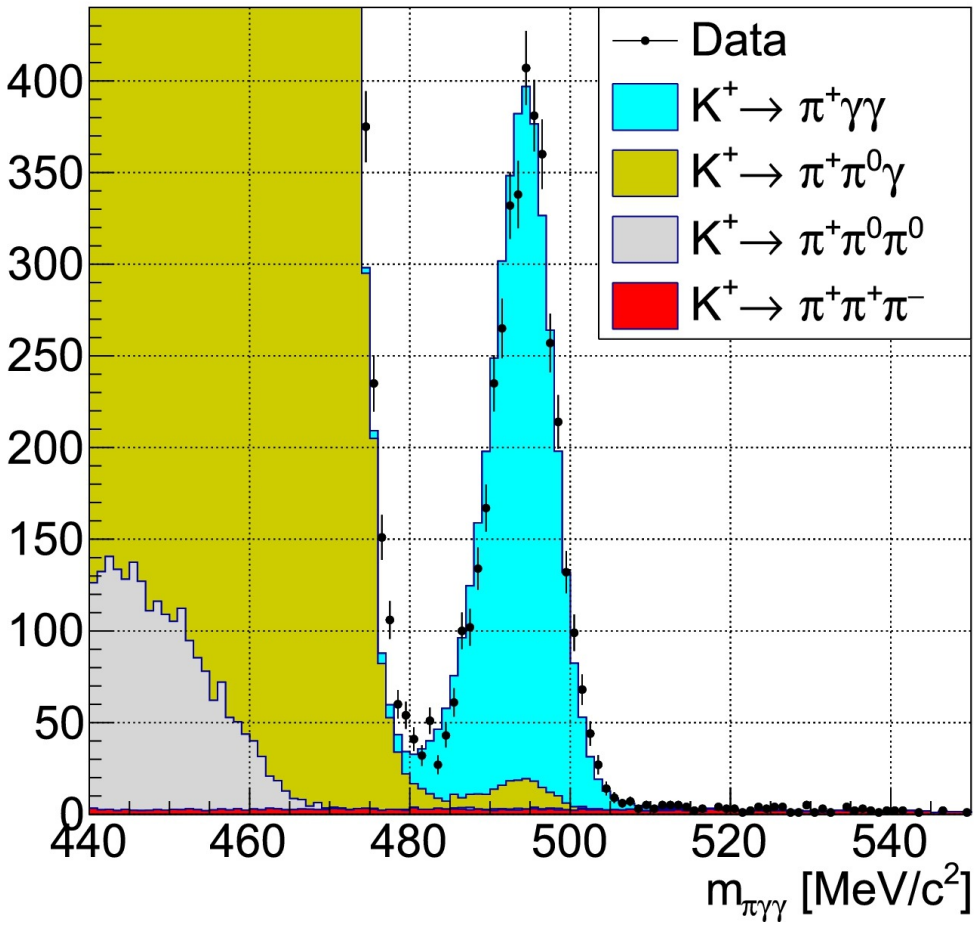
$$K^+ \to \pi^+ \gamma\gamma$$

- Long-distance dominated radiative decay
- Crucial **test of Chiral Perturbation Theory**
- Kinematic variables

$$z = \frac{(P_K - P_\pi)^2}{m_K^2} \equiv \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2$$

$$y = \frac{P_K(Q_{\gamma_1} - Q_{\gamma_2})}{m_K^2}$$

- **z** computed using K^+ and π^+ reconstructed 4-momenta
- **Branching fraction $\mathcal{B}(K^+ \to \pi^+\gamma\gamma)$** parametrized in ChPT by an unknown **real parameter $\hat{c}$**
- $B(z)$ appears at ChPT $\mathcal{O}(p^6)$



Goals:

- Determine $\hat{c}$
- Measure **model independent** $\mathcal{B}(K^+ \to \pi^+\gamma\gamma)$

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

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

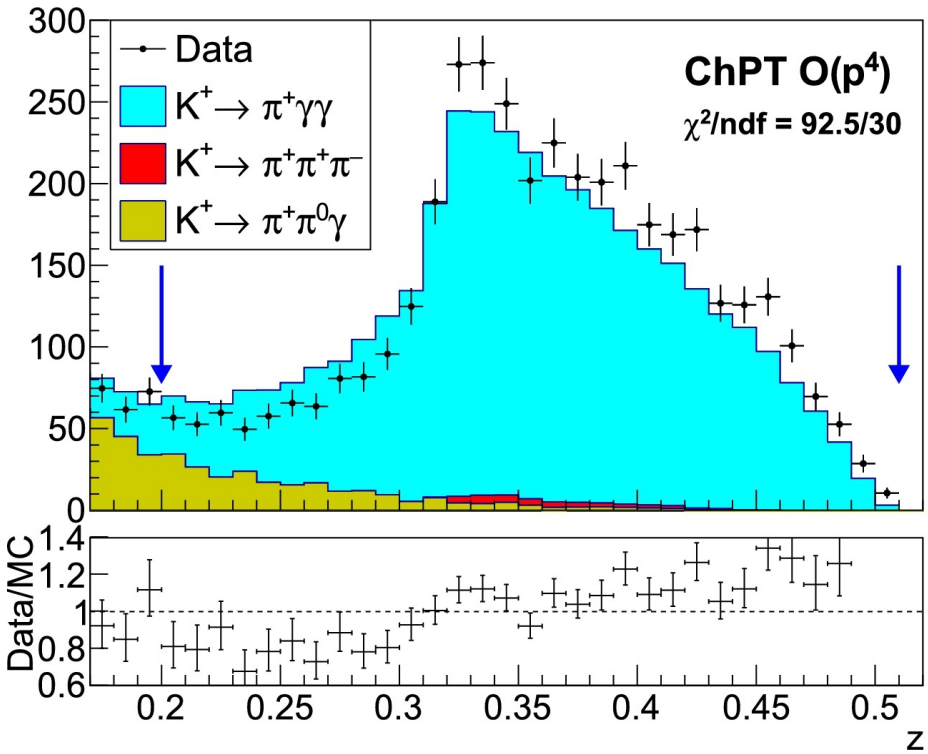
Selection:

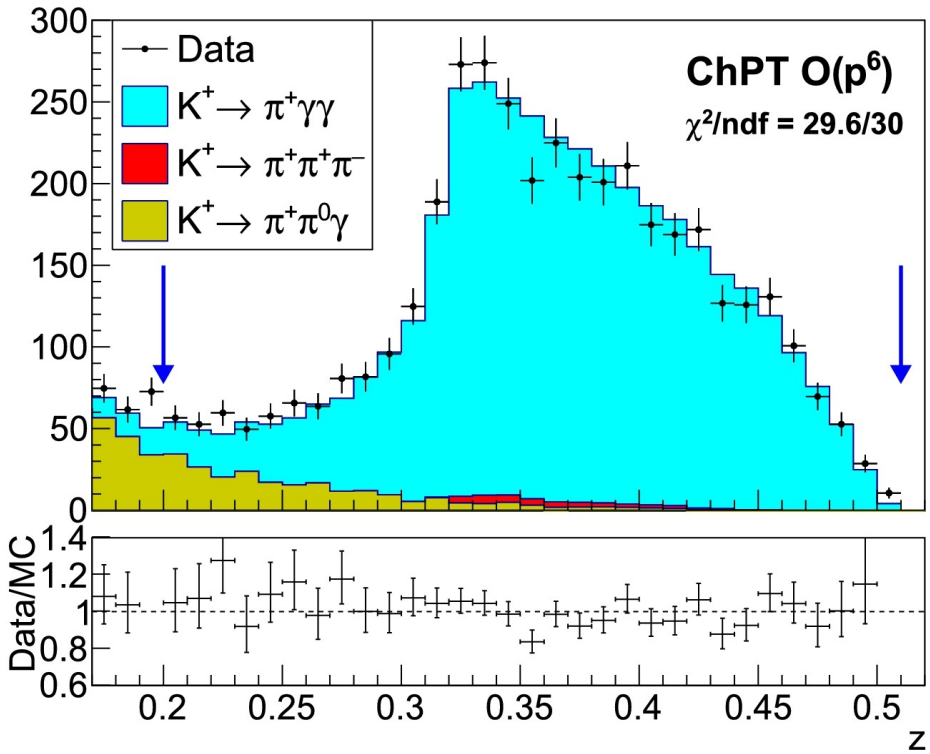
- Min-bias and non-muon trigger lines
- Normalization: $K^+ \to \pi^+\pi^0$
- Single positive track
- $K^+ - \pi^+$ matching, reconstruct vertex
- Two γ clusters
- π^+ identification & μ^+ rejection
- **Signal region: $0.2 < z < 0.51$**

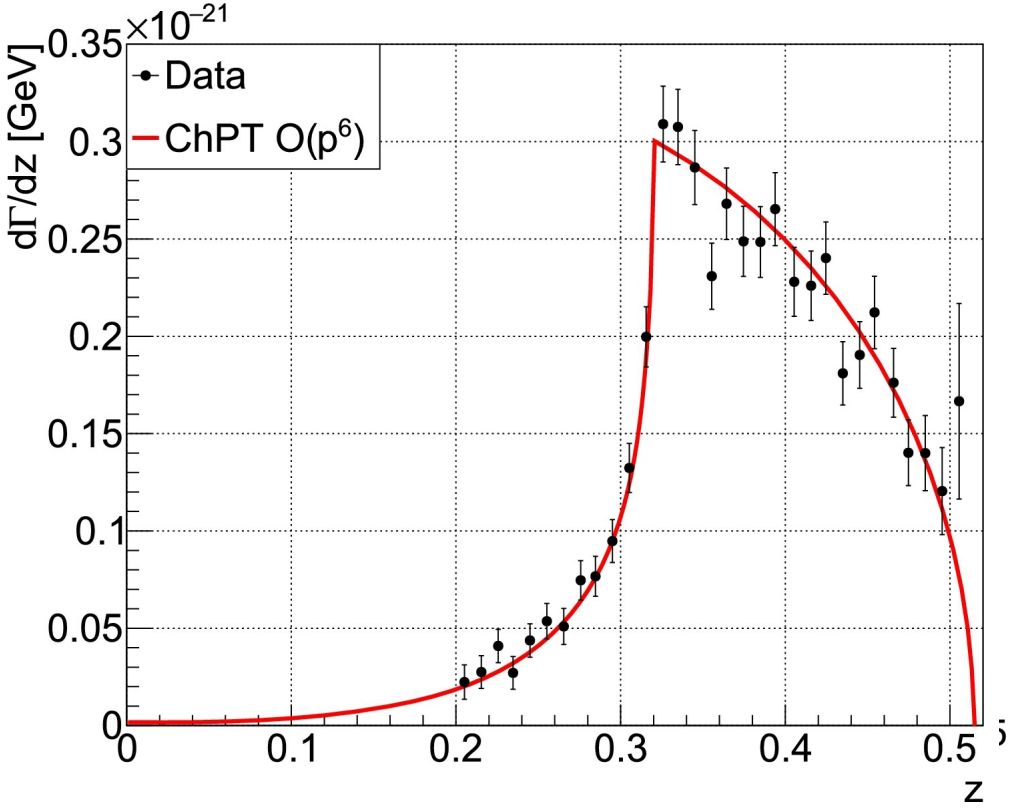
Analysis strategy:

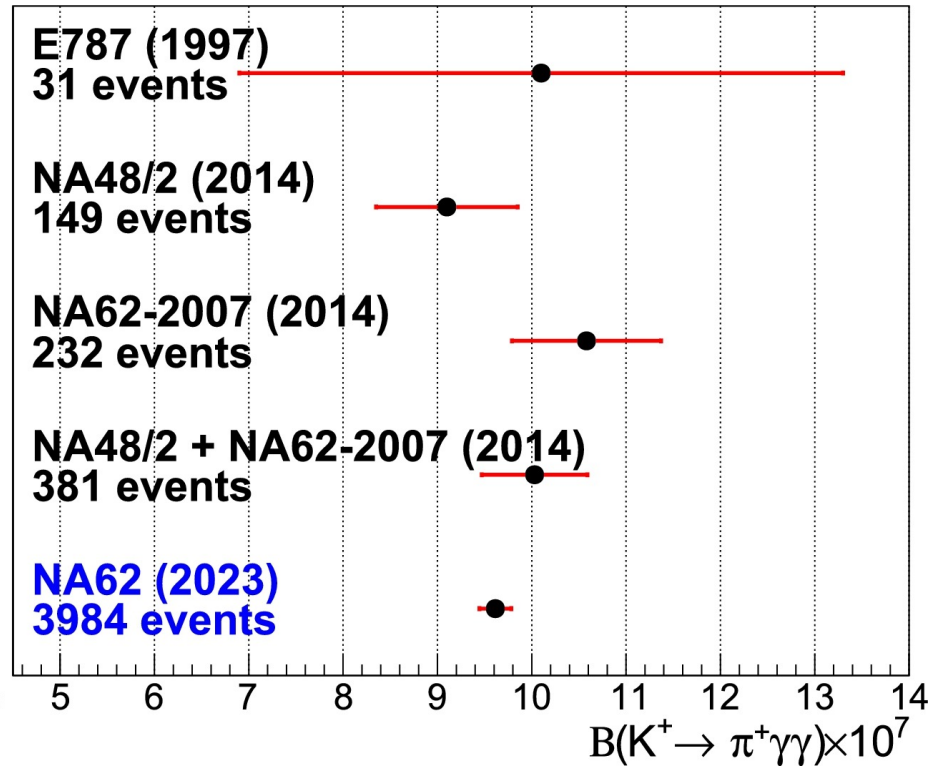
- Main background:
  - cluster merging in calorimeter ($K^+ \to \pi^+\pi^0\gamma$, $\pi^0 \to \gamma\gamma$ or $K^+ \to \pi^+\pi^0\pi^0$, $\pi^0 \to \gamma\gamma$)
  - multi-track events, tracks out of acceptance
- Data distributed in 31 equal bins
- $\hat{c}$ obtained by χ^2 fit of z-spectrum
- Model independent $\mathcal{B}$ obtained by summing z-spectrum in all bins in signal range

[Phys.Lett.B 850 (2024) 138513]









$N_{bcg}^{exp} = 291 \pm 14$

$N^{obs} = 3984$

$\hat{c} = 1.44 \pm 0.069_{stat} \pm 0.034_{syst}$

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

$$\mathcal{B}_{MI}(K^+ \to \pi^+\gamma\gamma | z > 0.2) = (9.46 \pm 0.19_{stat} \pm 0.07_{syst}) \times 10^{-7}$$

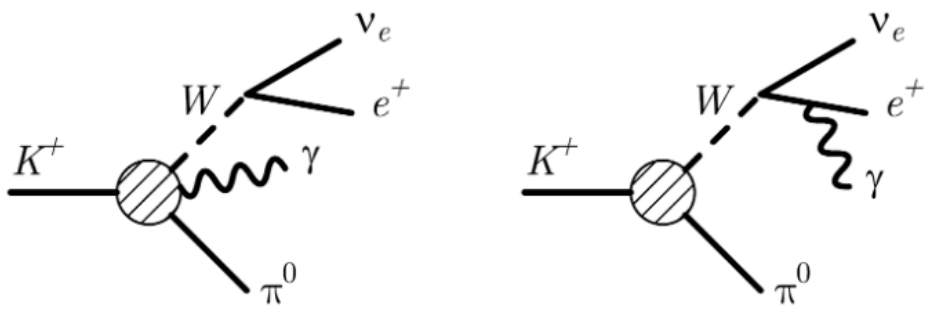
[Phys.Lett.B 850 (2024) 138513]

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

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

- 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 cut-off
  - $\theta_{e,\gamma}$ cut-off in K^+ rest frame
- **Three kinematic ranges** considered (defined by E_γ and $\theta_{e,\gamma}$ $\to$ table below)
- **Normalized branching fraction** defined as:

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



- **Test of T-conservation** thanks to T-odd observable ξ

$$\xi = \frac{\vec{p}_\gamma(\vec{p}_e \times \vec{p}_\pi)}{M_K^3}$$

$$\mathbf{A}_\xi = \frac{\mathbf{N}_{\xi>0} - \mathbf{N}_{\xi<0}}{\mathbf{N}_{\xi>0} + \mathbf{N}_{\xi<0}}$$

Current (theory) expectations and results:

- $A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$

[Eur.Phys.J.C50(2007)] [Phys.Atom.Nuclei 70(2007)] [Eur.Phys.J.C81(2021)]

	S1	S2	S3
A_ξ^{OKA} $\times 10^3$	$-0.1 \pm 3.9_{stat} \pm 1.7_{syst}$	$-4.4 \pm 7.9_{stat} \pm 1.9_{syst}$	$7.0 \pm 8.1_{stat} \pm 1.5_{syst}$

	E_γ^j	$\theta_{e,\gamma}^j$	$O(p^6)$ ChPT	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	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

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

Goals:

- Measure **normalized** $\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma)$ in ranges $j = \{1, 2, 3\}$:

$$\mathcal{R}_j = \frac{N^{obs}_{Ke3\gamma,j} - N^{bkg}_{Ke3\gamma,j}}{N^{obs}_{Ke3} - N^{bkg}_{Ke3}} \cdot \frac{A_{Ke3}}{A_{Ke3\gamma,j}} \cdot \frac{\varepsilon^{trig}_{Ke3}}{\varepsilon^{trig}_{Ke3\gamma,j}}$$

- Evaluate **asymmetry**:

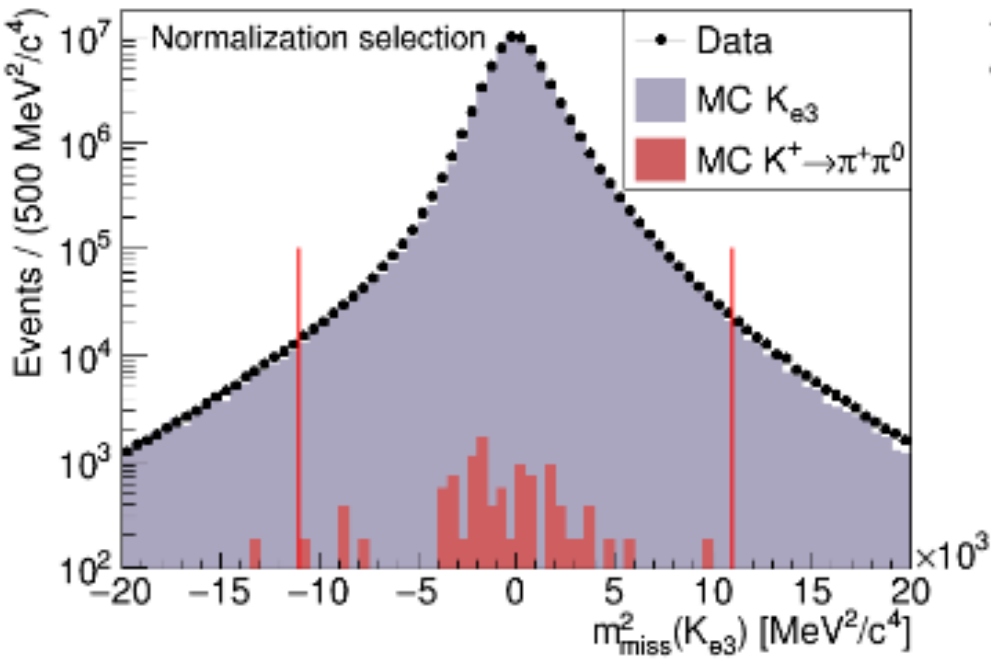
$$A^{NA62}_{\xi} = A^{DATA}_{\xi} - A^{MC}_{\xi}$$

Signal selection:

- Min-bias and non-muon trigger lines
- Normalization: $K^+ \to \pi^0 e^+ \nu$
- Reconstruct K^+ and e^+
- π^0 identification with 2 γ
- Radiative γ identified as isolated cluster
- Minimal differences in signal and normalization selections $\Rightarrow$ **reduced systematic effects**

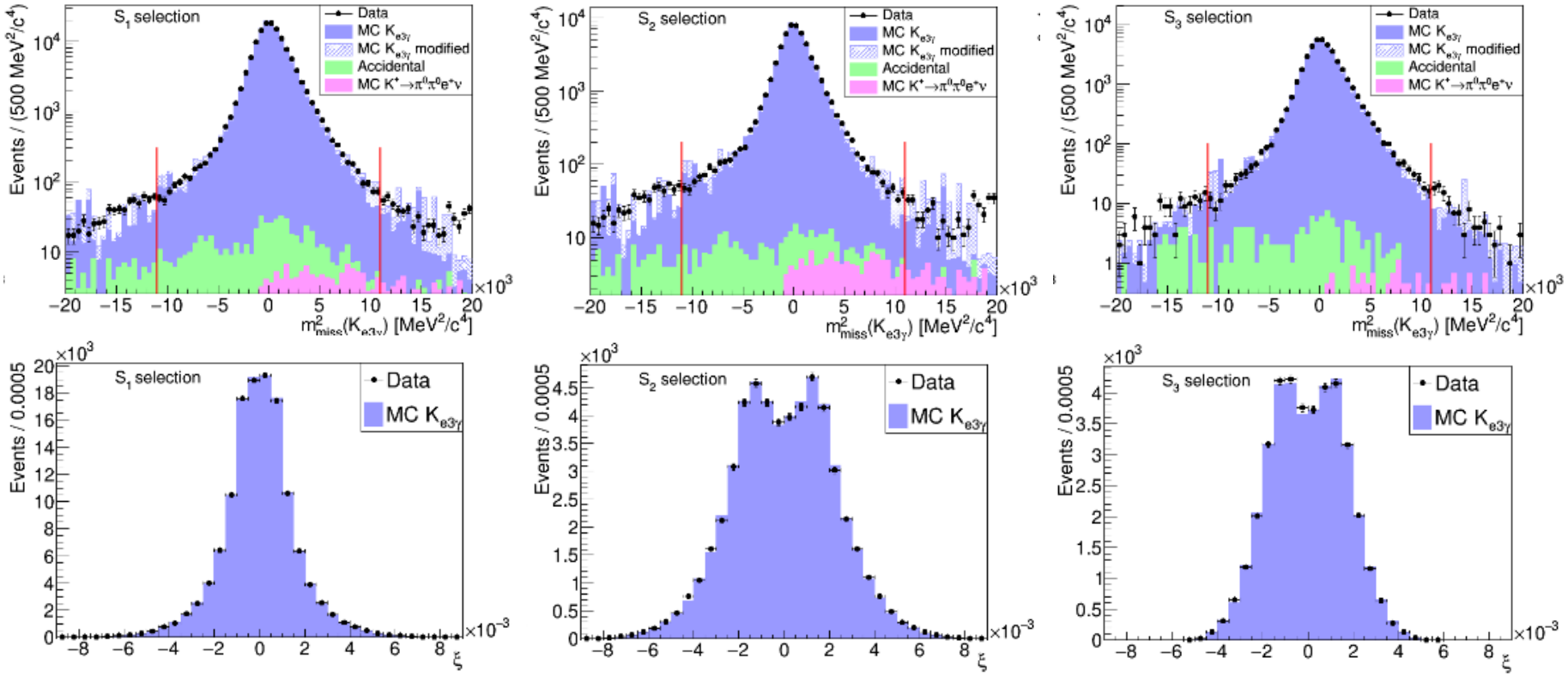
Analysis strategy:

- Background $< 1\%$, mainly accidental
- Signal decay described in MC by ChPT at $\mathcal{O}(p^6)$
- Normalization selection acceptance is defined wrt full phase space
- Evaluation of $\mathcal{R}_j$
- Evaluation of asymmetry $\mathbf{A^{NA62}_{\xi}}$



[JHEP09(2023)040]

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



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

$\mathcal{R}$ measurement:

- **Precision improved by a factor > 2**
- Results smaller by 5% than ChPT prediction

Asymmetry measurement:

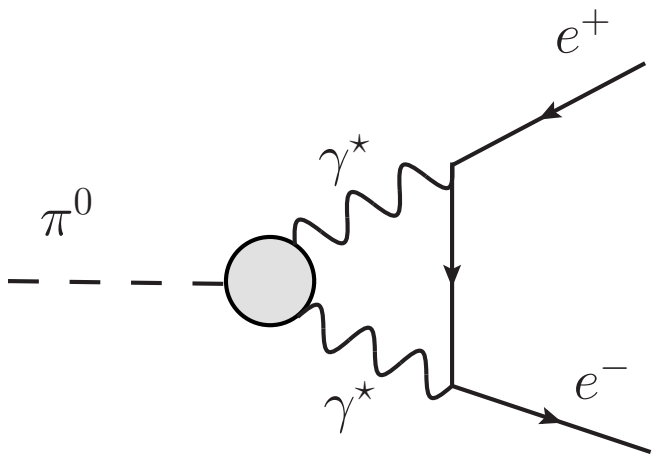
- **Compatible with no asymmetry**
- Uncertainties larger than theory expectations

[JHEP09(2023)040]

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

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

- Experimentally accessible:
  $\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > x_{\text{cut}})$,
  $x = m_{ee}^2/m_{\pi^0}^2$
  - Low x region dominated by Dalitz decay $\pi^0 \to e^+e^-\gamma$
  - For $x > x_{cut} = 0.95$, Dalitz contribution only 3.3%
- Previously measured by KTeV:
  $\mathcal{B}_{\text{KTeV}}(\pi^+e^+e^-, x > 0.95) =$
  $(6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$
  [PhysRevD.75.012004]



Goals:

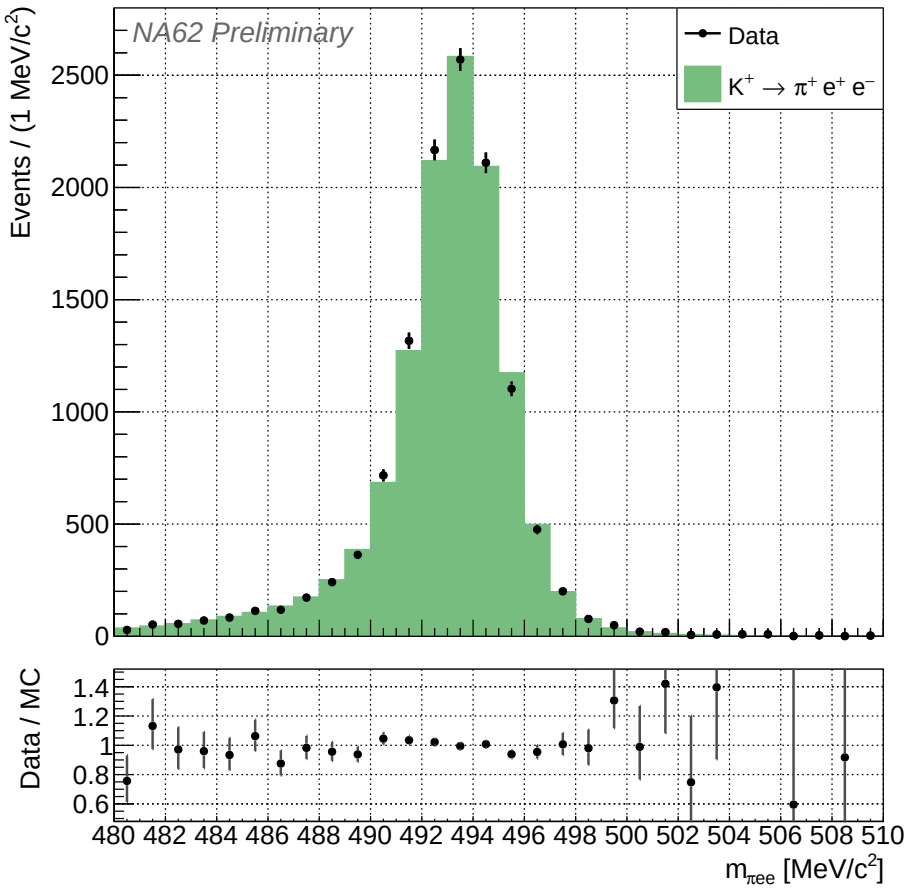
- Measurement of
  $\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > 0.95)$

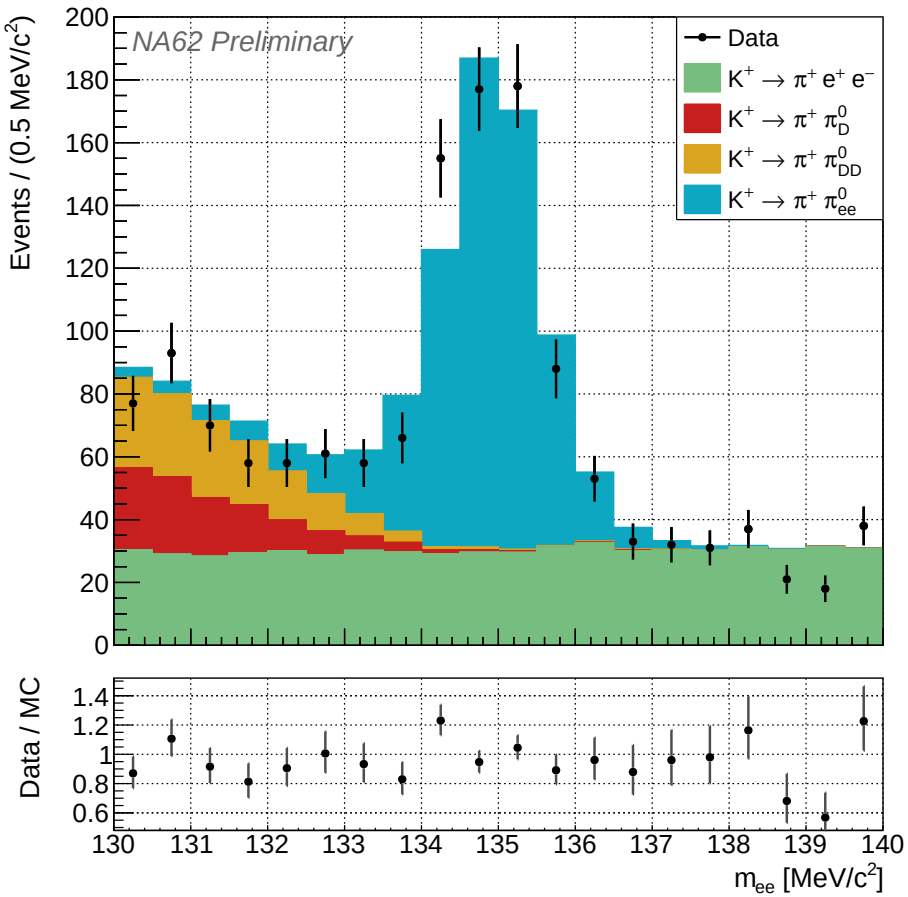
Signal selection:

- Multi-track electron trigger line
- Normalization: $K^+ \to \pi^+e^+e^-$, computed in a background-free region
  $140 MeV/c^2 < m_{ee} < 360 MeV/c^2$
- Minimal differences in signal and normalization event selections $\Rightarrow$ **reduced systematic effects**
- 3-track vertex topology
- **Signal measured in region**
  $\mathbf{130 MeV/c^2 < m_{ee} < 140 MeV/c^2}$

Analysis strategy:

- Background:
  - Irreducible $K^+ \to \pi^+e^+e^-$
  - Multiple Dalitz decays with undetected particles (γ, e)
- $\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > 0.95)$ obtained by performing **maximum likelihood fit** of simulated samples to data
- Using latest radiative corrections the **result can be extrapolated to obtain**
  $\mathcal{B}(\pi^0 \to e^+e^-, \text{no rad})$





$$N_K = (8.62 \pm 0.27) \times 10^{11}$$

Signal yield ≈ 600

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

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

Result in agreement with SM expectation.

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

- $K^+ \to \pi^+\mu^+\mu^-$ [JHEP11(2022)011] [JHEP06(2023)040]
- $K^+ \to \pi^+\gamma\gamma$ [Phys.Lett.B 850 (2024) 138513]
- $K^+ \to \pi^0 e^+ \nu\gamma$ [JHEP09(2023)040]
- $\pi^0 \to e^+e^-$ [Preliminary results]

NA62 Physics Run II ongoing, 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
- $K^+ \to \pi^+\nu\bar{\nu}$ results from 2021-2022 data samples coming soon