Precision Measurements and Prospects with Kaons at CERN

Zdenko Hives

Charles University in Prague
On behalf of NA62 collaboration

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Institute of Particle and Nuclear Physics
Faculty of Mathematics and Physics
Charles University

Outline

NA62 Experiment

NA62 Recent Results

- $K^+ \to \pi^0 e^+ \nu\gamma$ $(K_{e3\gamma})$ [JHEP09(2023)040]
- $K^+ \to \pi^+ \mu^+ \mu^-$ $(K_{\pi\mu\mu})$ [JHEP11(2022)011]
- $K^+ \to \pi^+ \gamma\gamma$ $(K_{\pi\gamma\gamma})$ [arXiv:2311.01837]

NA48/2 Recent Result

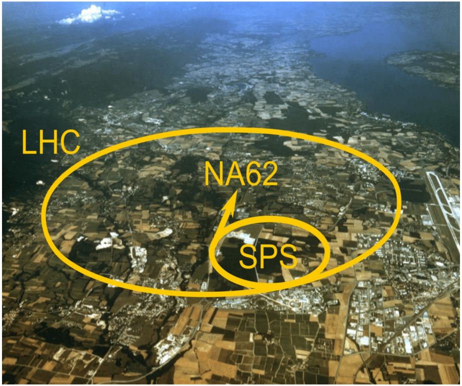
- $K^\pm \to \pi^0 \pi^0 \mu^\pm \nu$ $(K^{00}_{\mu 4})$ [arXiv.2310.20295]

NA62 Prospects for the Future (HIKE) [HIKE proposal: arXiv.2311.08231]

NA62 Experiment

- **∼200 Collaborators from ∼33 Institutes**
  Almaty, Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Florence, Glasgow, Lancaster, Lausanne, Liverpool, LNF, Louvain, Mainz, Marseille, Merced, Moscow, Munich, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosi, SLAC, Turin, TRIUMF, Vancouver UBC

NA62 Timeline	
Feb. 2007:	NA62 Approval
2009 - 2014:	Detector R&D and installation
2015:	Commissioning
2016 – 2018:	Run 1
2021 – 2025:	Run 2
Proposal for future: High Intensity Kaon Experiments	



NA62 Overview and Beam

- **NA62** is a fixed-target experiment at the North Area of CERN SPS
- **Main goal:** measure $\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu})$ with $10\,\%$ precision, using "decay-in-flight" technique
- **Primary** p^+ **beam:** $400\,\text{GeV}\,c^{-1}$, impinging on $400\,\text{mm}$ long beryllium target
- **Secondary beam:** $75\,\text{GeV}\,c^{-1}$, composition: π^+ $(70\,\%)$, p^+ $(24\,\%)$, K^+ $(6\,\%)$

- **Current theoretical prediction:** [JHEP 1511 (2015) 033]

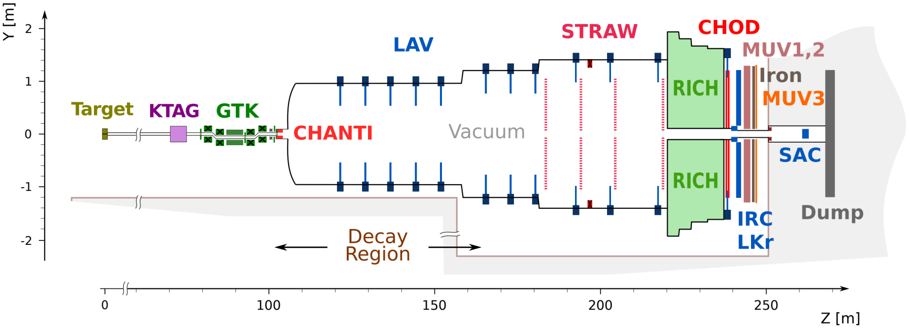
$$\mathcal{B}_{SM}(K^+ \to \pi^+ \nu\overline{\nu}) = (8.4 \pm 0.10) \times 10^{-11} \tag{1}$$

- **Latest NA62 result:** [JHEP06 (2021) 093]

$$\mathcal{B}_{NA62}(K^+ \to \pi^+ \nu\overline{\nu}) = (10.6^{+4.0}_{-3.4 stat} \pm 0.9_{syst}) \times 10^{-11} \tag{2}$$

NA62 Detector

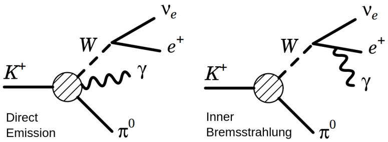
[2017 JINST 12 P05025]



- KTAG: Cherenkov threshold counter
- GTK: Si pixel beam tracker
- CHANTI: Stations of plastic scintillator slabs
- LAV: Lead glass ring calorimeter
- STRAW: Straw magnetic tracker
- RICH: Ring Imaging Cherenkov Counter
- CHOD: Multiple planes of scintillator slabs
- IRC: Inner Ring shashlik Calorimeter
- LKr: Liquid Krypton Calorimeter
- MUV1,2: Hadron calorimeters
- MUV3: Plane of scintillator slabs for muon veto
- SAC: Small angle shashlik calorimeter

$$K^+ \to \pi^0 e^+ \nu\gamma \ (K_{e3\gamma})$$

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



Diagrams for $K_{e3\gamma}$ process [Eur.Phys.J.C50:557-571,2007]

- Precision test of ChPT to level $\mathcal{O}(p^6)$
- Divergent amplitude for $E_\gamma \to 0$ and $\theta_{e,\gamma} \to 0$ due to IB contribution
- Theoretical predictions and experimental results for 3 sets of cuts (* in K^+ rest frame)

	E_γ cut *	$\theta_{e,\gamma}$ cut *	$\mathcal{O}(p^6)$ ChPT [Eur.Phys.J.C50:557-571,2007]	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	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

Measurement objectives:

- Measurement of branching fraction using K_{e3} normalisation channel

$$R_j = \frac{\mathcal{B}(K_{e3\gamma j})}{\mathcal{B}(K_{e3})} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma | E^j_\gamma \theta^j_{e,\gamma})}{\mathcal{B}(K_{e3})}$$

- Measurement of T-violation effects using T-odd variable ξ and asymmetry variable A_ξ

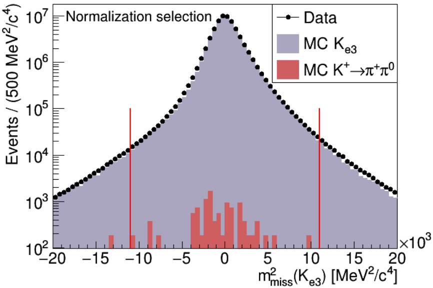
$$\xi = \frac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{M_K^3} \to A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

where $N_+(N_-)$ are numbers of events with positive(negative) ξ (in K^+ rest frame)

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

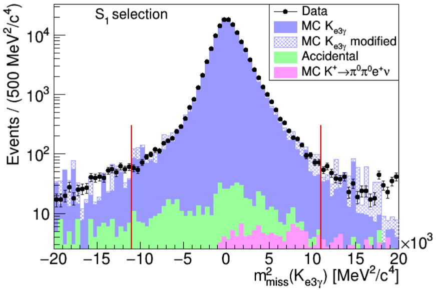
Normalisation: $K^+ \to \pi^0 e^+ \nu$ (K_{e3})

- 1 downstream track with e^+ PID
- Vertex with K^+ upstream track
- 2γ clusters in LKr with $m_{\gamma\gamma}$ compatible with π^0
- No additional photons in LAV / SAC
- Cut $m^2_{miss}(K_{e3}) = (P_K - P_{\pi^0} - P_e)^2$



Signal: $K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$)

- 1 downstream track with e^+ PID
- Vertex with K^+ upstream track
- 2γ clusters in LKr with $m_{\gamma\gamma}$ compatible with π^0 + 1 radiative γ
- No additional photons in LAV / SAC
- Cut $m^2_{miss}(K_{e3\gamma}) = (P_K - P_{\pi^0} - P_e - P_\gamma)^2$ and $m^2_{miss}(K_{e3})$



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

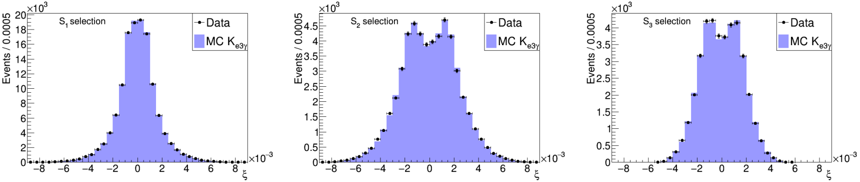
Evaluation of R_j:

$$R_j = \frac{N^{obs}_{Ke3\gamma j} - N^{bkg}_{Ke3\gamma j}}{N^{obs}_{Ke3} - N^{bkg}_{Ke3}} \cdot \frac{A_{Ke3}}{A_{Ke3\gamma j}} \cdot \frac{\epsilon^{trig}_{Ke3}}{\epsilon^{trig}_{Ke3\gamma j}}$$

- Main source of bkg.: accidental activity in LKr from misidentified e^+ or undetected γ
- Acceptances evaluated by MC
- Trigger efficiencies measured with Data

	Normalization	S_1	S_2	S_3
Selected candidates	6.6420×10^7	1.2966×10^5	0.5359×10^5	0.3909×10^5
Acceptance	$(3.842 \pm 0.002)\%$	$(0.444 \pm 0.001)\%$	$(0.514 \pm 0.002)\%$	$(0.432 \pm 0.002)\%$
Accidental background	—	$(4.9 \pm 0.2 \pm 1.3) \times 10^2$	$(2.3 \pm 0.2 \pm 0.3) \times 10^2$	$(1.1 \pm 0.1 \pm 0.5) \times 10^2$
$K^+ \to \pi^0\pi^0 e^+\nu$	$< 10^2$	$(1.1 \pm 1.1) \times 10^2$	$(1.1 \pm 1.1) \times 10^2$	$(0.1 \pm 0.1) \times 10^2$
$K^+ \to \pi^+\pi^0\pi^0$	$< 10^2$	< 20	< 20	< 20
$K^+ \to \pi^+\pi^0$	$(1.0 \pm 1.0) \times 10^4$	—	—	—
Total background	$(1.0 \pm 1.0) \times 10^4$	$(6.0 \pm 1.8) \times 10^2$	$(3.4 \pm 1.2) \times 10^2$	$(1.2 \pm 0.6) \times 10^2$
Fractional background	1.6×10^{-4}	0.46×10^{-2}	0.64×10^{-2}	0.29×10^{-2}

Evaluation of A_ξ: $A_\xi = A_\xi^{Data} - A_\xi^{MC}$



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

	$\mathcal{O}(p^6)$ ChPT [Eur.Phys.J.C50:557-571,2007]	ISTRA+	OKA	**NA62** [JHEP 09 (2023) 040]
$R_1(\times 10^2)$	1.804 ± 0.021	1.81 ± 0.03 ± 0.07	1.990 ± 0.017 ± 0.021	$\mathbf{1.684 \pm 0.005 \pm 0.010}$
$R_2(\times 10^2)$	0.640 ± 0.008	0.63 ± 0.02 ± 0.03	0.587 ± 0.010 ± 0.015	$\mathbf{0.599 \pm 0.003 \pm 0.005}$
$R_3(\times 10^2)$	0.559 ± 0.006	0.47 ± 0.02 ± 0.03	0.532 ± 0.010 ± 0.012	$\mathbf{0.523 \pm 0.003 \pm 0.003}$
$A_\xi(S_1)(\times 10^3)$			-0.1 ± 3.9 ± 1.7	$\mathbf{-1.2 \pm 2.8 \pm 1.9}$
$A_\xi(S_2)(\times 10^3)$			-4.4 ± 7.9 ± 1.9	$\mathbf{-3.4 \pm 4.3 \pm 3.0}$
$A_\xi(S_3)(\times 10^3)$		15 ± 21	7.0 ± 8.1 ± 1.5	$\mathbf{-9.1 \pm 5.1 \pm 3.5}$

R_j ratio measurement:

- Precision improved by factor > 2 from previous experiments
- Relative uncertainty $< 1\,\%$
- $\sim 5\,\%$ smaller value than ChPT prediction

A_ξ asymmetry measurement:

- Compatible with no asymmetry
- Improved precision from OKA experiment
- Uncertainties still larger than theory predictions

$$K^+ \to \pi^+\mu^+\mu^- \ (K_{\pi\mu\mu})$$

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

- FCNC process with dominant contributions via virtual photon exchange $K^\pm \to \pi^\pm\gamma^* \to \pi^\pm\ell^+\ell^-$ $(\ell = e, \mu)$ [Nucl. Phys. B291 (1987) 692-719], [JHEP 02 (2019) 049]
- Form Factor of the $K^\pm \to \pi^\pm\gamma^*$ transition: $W(z)$
- Parametrized by Chiral Perturbation Theory to order $\mathcal{O}(p^6)$ [JHEP08(1998)004]

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

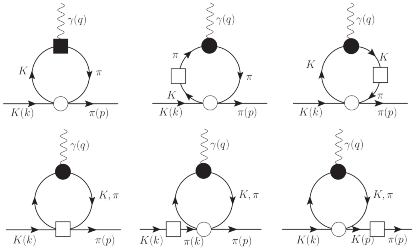
kinematic variable $z = m^2(\mu^+\mu^-)/m_K^2$

a_+, b_+: real parameters

$W^{\pi\pi}(z)$: (known) complex function describing the two-pion loop term

Measurement objectives:

- Measure model independent branching fraction $\mathcal{B}_{\pi\mu\mu}$
- Extract $|W(z)|^2$ function $\to$ determine a_+, b_+ form factor parameters
- Forward-backward asymmetry



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

Normalisation:

$(K^+ \to \pi^+\pi^+\pi^-)$

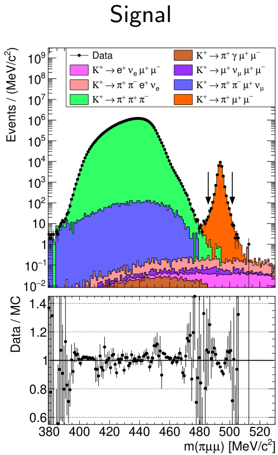
- High branching fraction $\sim 5.6\,\%$
- Kinematically similar $\to$ cancellation of systematic errors

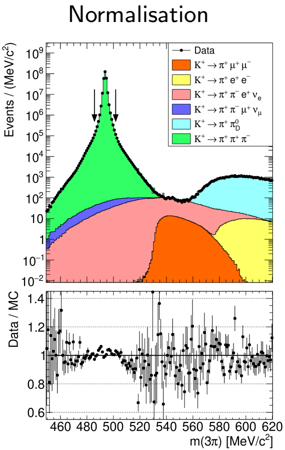
Signal:

- 3-track vertex topology
- In-time KTAG kaon signal
- π^+ calorimetric PID + !MUV3
- $\mu^\pm$ calorimetric PID + MUV3
- $m(\pi\mu\mu)$, $m(3\pi)$ requirements

Data:

- N(K^+ decays) $\approx 3.5 \times 10^{12}$
- **27 679** events observed
- $\sim$**8** bkg. events expected





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

Data divided in 50 equipopulated bins in z:

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

Model-independent $\mathcal{B}_{\pi\mu\mu}$

- From integration of measured $d\Gamma/dz$

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

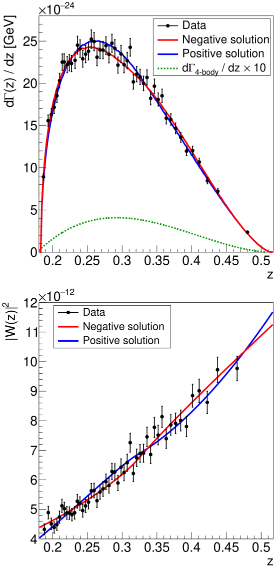
$\chi^2(a_+, b_+)$ fit evaluation

- Extract $|W(z)|^2$ from $d\Gamma(z)/dz$
- a_+, b_+: both negative or positive values (2 solutions)

  preferred negative solution: $\chi^2/ndf = 45.1/48$

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

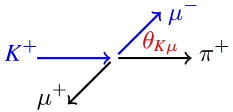
[JHEP 11 (2022) 011]

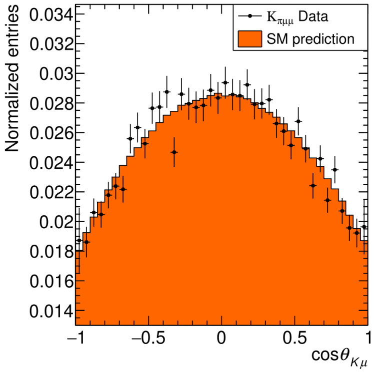


$K^+ \to \pi^+\mu^+\mu^-$: Forward-Backward Asymmetry

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

- $\theta_{K\mu}$: angle between K^+ and μ^- 3-momenta in $\mu^+\mu^-$ rest frame

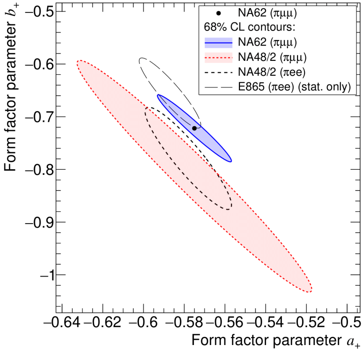


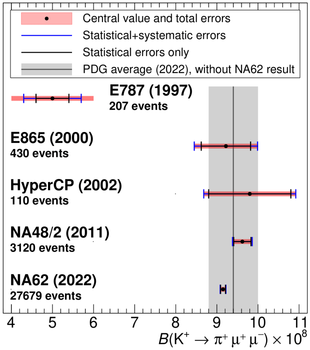


$A_{FB} = (0.0 \pm 0.7_{stat} \pm 0.2_{syst} \pm 0.2_{ext}) \times 10^{-2}$ at 68 % CL

$|A_{FB}| < 0.9 \times 10^{-2}$ at 90 % CL

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





- Sample size 9 times larger than NA48/2
- At least factor of 3 improvement wrt previous $K_{\pi\mu\mu}$ measurements
- No evidence of Lepton Flavour Universality violation
  $\to$ Agreement in a_+, b_+ between $K_{\pi\mu\mu}$ and $K_{\pi ee}$

$$K^+ \to \pi^+\gamma\gamma \ (K_{\pi\gamma\gamma})$$

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

- Long distance dominated radiative decay
  $\to$ crucial test of ChPT
- Kinematic variables:

$$z = \frac{(q_1 + q_2)^2}{M_K^2} = \frac{m_{\gamma\gamma}^2}{M_K^2}, \qquad y = \frac{p \cdot (q_1 - q_2)}{M_K^2}$$

p $= K^+$ 4-momentum

$q_{1,2} =$ photons 4-momenta

$m_K = K^+$ mass

$m_{\gamma\gamma} =$ di-photon inv. mass

$(m_{\gamma\gamma} = m_{\pi^0} => z = 0.075)$

- Differential decay width: [Phys. Lett. B 386 (1996) 403]

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

  - Spectrum and decay rate depends on one parameter: $\hat{c}$
  - $B(z) \neq 0$ from ChPT $\mathcal{O}(p^6)$; A and B depend on external parameters (extracted from $K_{3\pi}$)
- Measurement objectives:
  - Measure $c_6 = \hat{c}$ in ChPT $\mathcal{O}(p^6)$
  - Extrapolate model-dependent branching fraction
  - Obtain model-independent branching fraction

$K^+ \to \pi^+\gamma\gamma$: Selection and Analysis

Selection:

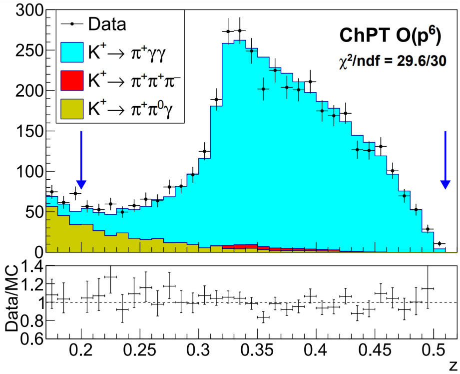
- K^+,π^+matching tracks; 2 γ's in LKr
- $z = (P_K - P_\pi)^2/M_K^2 > 0.2$
- **3984** events observed

Normalisation and Background:

- Normalisation: $K^+ \to \pi^+\pi^0$
- Background:
  - $K^+ \to \pi^+\pi^0\gamma, \pi^+\pi^0\pi^0$ (γ merging in LKr)
  - $K^+ \to \pi^+\pi^+\pi^-$ (out-of-acceptance tracks)
  - **291** $\pm$ **14** bkg. events expected

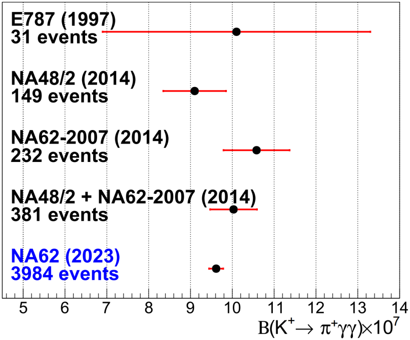
Fit:

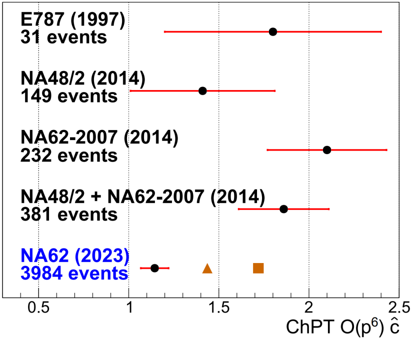
- MC reweighted for different $\hat{c}_6$ values
- Scan of $\hat{c}_6$ to find minimum χ^2



Leading order $\mathcal{O}(p^4)$ is not sufficient for di-photon mass spectrum description.

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





NA62 result uses external parameters from: [Phys. Lett. B 835 (2022) 137594]

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

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

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

▲ Result using external parameters for E787 measurement

■ Result using external parameters for NA48/2 measurement

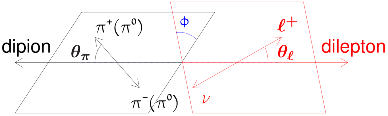
$$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu \ (K^{00}_{\mu 4})$$

at NA48/2 experiment

$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$: Overview

General:

- $K^{\pm} \to \pi\pi\ell^{\pm}\nu$ ($K_{\ell 4}$) decays depend on 4 Form Factors described by 5 kinematic (Cabibbo-Maksymowicz) variables [Nucl.Phys.B427:427-454,1994]
- For $K^{00}_{\mu 4}$: dependence only on F and R (because of no dependence on $\cos\theta_\pi, \phi$ in $\pi^0\pi^0$ s-wave)
- For K^{00}_{e4}: dependence only on F (because of e small mass)



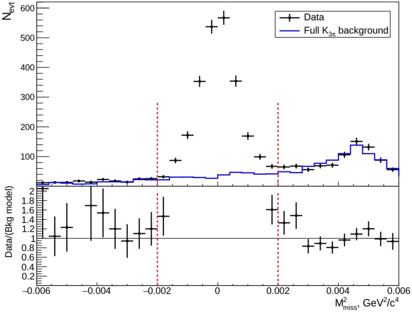
- S_π: dipion mass squared
- S_ℓ: dilepton mass squared
- θ_π: in dipion frame
- θ_ℓ: in dilepton frame
- ϕ: angle between dipion and dilepton frame

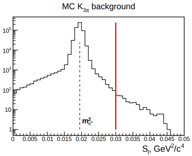
Previous Results:

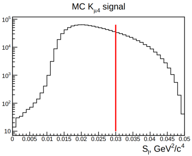
$K_{\ell 4}$ mode	$\mathcal{B}(K_{\ell 4})[\times 10^{-5}]$	N_{cand}	published
$K^{\pm}_{e4}$	4.26 ± 0.04	1 108 941	[NA48/2 (2012)]
K^{00}_{e4}	2.55 ± 0.04	65 210	[NA48/2 (2014)]
$K^{\pm}_{\mu 4}$	1.4 ± 0.9	7	[Bisi et al. (1967)]
$K^{00}_{\mu 4}$	?		

$K^{00}_{\mu 4}$: first observation
check for presence of R contrib.
test of ChPT
potential study of $\pi\pi$ rescattering

$K^\pm \to \pi^0\pi^0\mu^\pm\nu$: Selection and Analysis







Selection:

- 4 photons consistent with $2\pi^0$ in time-spatial matching with the track
- $M^2_{miss} = (P_K - P(\pi^0_1) - P(\pi^0_2) - P(\mu^\pm))^2$
- **2437** events observed

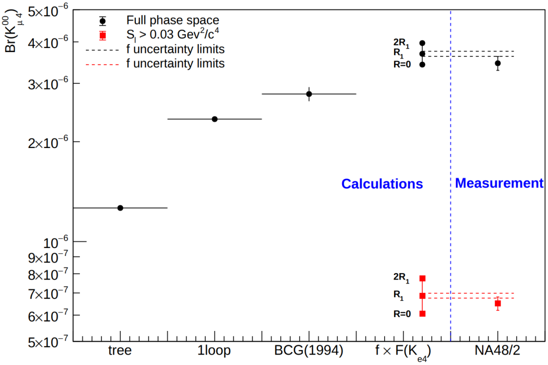
Normalisation and Background:

- $K^\pm \to \pi^\pm\pi^0\pi^0$ $(K_{3\pi})$
- Huge background from $K^\pm \to \pi^0\pi^0(\pi^\pm \to \mu^\pm\nu)$
- Restricted phase-space: $S_\ell > 0.03\,\mathrm{GeV}^2/c^4$
- $\mathbf{354} \pm \mathbf{33}_{stat} \pm \mathbf{62}_{syst}$ bkg. expected

Analysis:

$$\mathcal{B}(K^{00}_{\mu4}) = \frac{N_S}{N_N} \cdot \frac{A_N}{A_S} \cdot K_{trig.} \cdot \mathcal{B}(K^{00}_{3\pi})$$

$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$: Results



Theory:

- J.Bijnens, G.Colangelo, J.Gasser: $K_{\ell 4}$ - Decays beyond one loop

  [Nucl. Phys. B, 427(1994) 427]

  - tree approximation
  - 1-loop
  - BCG(1994): Beyond 1-loop with F calc. from

  [Rosselet etc. Phys. Rev. D15 (1977) 574]

- Re-calculated now:
  - $F(K_{e4})$ from NA48/2
  - $R_1 = R(1\ loop)$

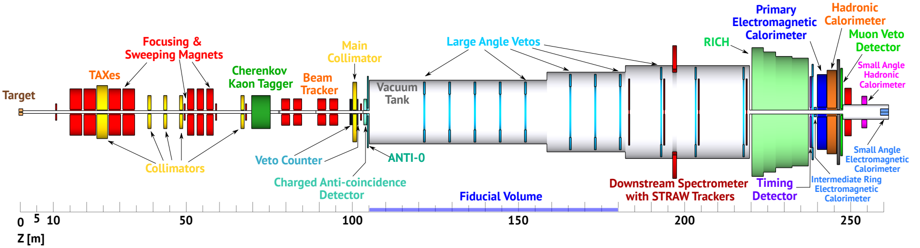
$$\mathcal{B}(K^{00}_{\mu 4}, S_\ell > 0.03) = (0.65 \pm 0.019_{stat} \pm 0.024_{syst}) \times 10^{-6} = (0.65 \pm 0.03) \times 10^{-6}$$

$$\mathcal{B}(K^{00}_{\mu 4}) = (3.4 \pm 0.10_{stat} \pm 0.13_{syst}) \times 10^{-6} = (3.4 \pm 0.2) \times 10^{-6}$$

High Intensity Kaon Experiments (HIKE) at the CERN SPS

- Hike proposal to SPSC submitted in November 2023 [HIKE proposal]
- Beam intensity: 4 × NA62
- 2 Phases:
  - K^+ Phase-1
  - K_L Phase-2
- Proposed start after LS3

HIKE: Phase1 ($K^+ \to \pi^+ \nu \bar{\nu}$)

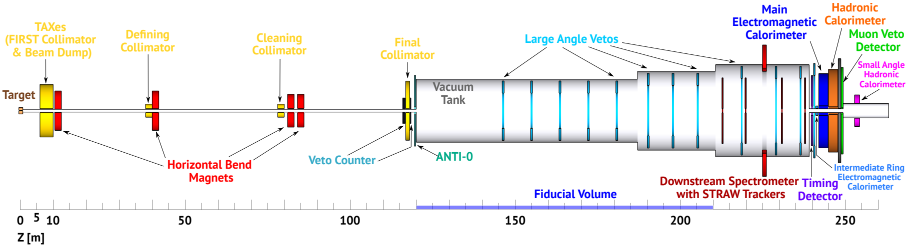


- NA62-like design of experiment
- **Improved timing:** to withstand the increased beam intensity
- **Equal or better key performances at high rate:** to keep background under control and further suppress dominant background from upstream K^+ decays [e.g. kinematic rejection, photon rejection, particle identification]
- **Increase in signal acceptance:** up to $\times 2$, thanks to new more granular/performant detectors and fully-software trigger

Overall: HIKE-Phase1 statistics $\sim \times 8$ wrt NA62

Main Objective: $\mathcal{O}(5\,\%)$ precision expected for $K^+ \to \pi^+ \nu \bar{\nu}$

HIKE: Phase2 ($K_L \to \pi^0 \ell^+ \ell^-$)



- A multi-purpose K_L decay experiment
- Reconfiguration of Phase1 setup:
  - Kaon tagger, beam spectrometer, RICH and small-angle calorimeter removed
  - Straw Spectrometer shortened and chambers realigned
- 120 m long neutral beamline
  - Secondary beam opening angle $= 0.4$ mrad; 2.4 mrad production angle
  - Mean momentum of decaying K_L mesons $= 46$ GeV c^{-1}

Main Objective: First observation @ $> 5\sigma$ of $K_L \to \pi^0 \ell^+ \ell^- [\ell = e, \mu]$
and measurement of both ultra-rare decay modes

Summary

NA62 approved to run until end of 2025 (start of LS3)

Recent NA62 precision measurement results of:

- $K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$) [JHEP09(2023)040]
- $K^+ \to \pi^+ \mu^+ \mu^-$ ($K_{\pi\mu\mu}$) [JHEP11(2022)011]
- $K^+ \to \pi^+ \gamma\gamma$ ($K_{\pi\gamma\gamma}$) [arXiv:2311.01837]

Recent NA48/2 result:

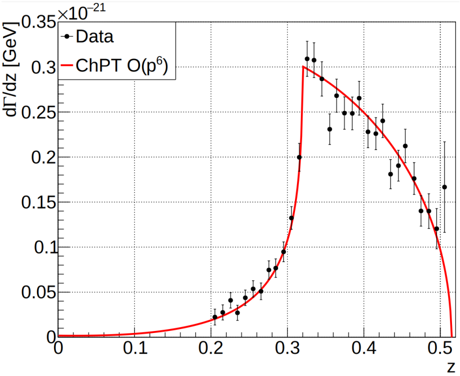
- $K^\pm \to \pi^0 \pi^0 \mu^\pm \nu$ ($K^{00}_{\mu 4}$) [arXiv.2310.20295]

Future prospects:

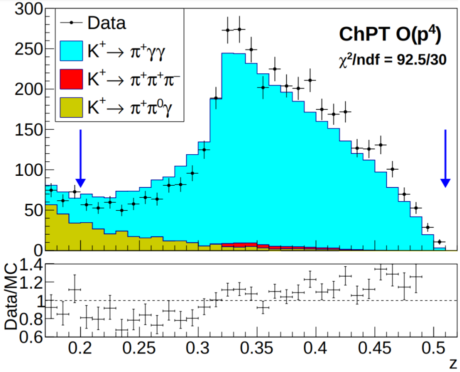
- NA62 expects many new results from Run2 analysis (2021-2025)
- Long-term plan after LS3: proposal of HIKE [arXiv.2311.08231]

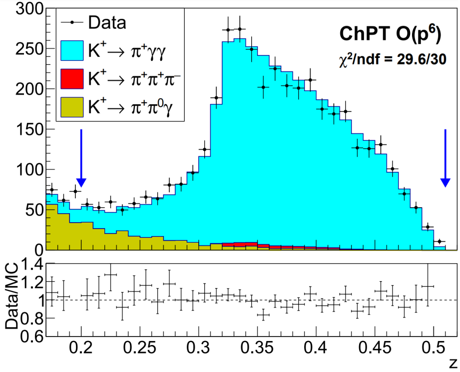
Backup Slides

$K^+ \to \pi^+\gamma\gamma$: Model Independent Branching Fraction



$K^+ \to \pi^+\gamma\gamma$: ChPT $\mathcal{O}(p^6)$ necessity





- In order to describe the observed di-photon mass spectrum, the next-to-leading order contribution in chiral perturbation theory was found to be necessary