

Physics with kaons at NA62

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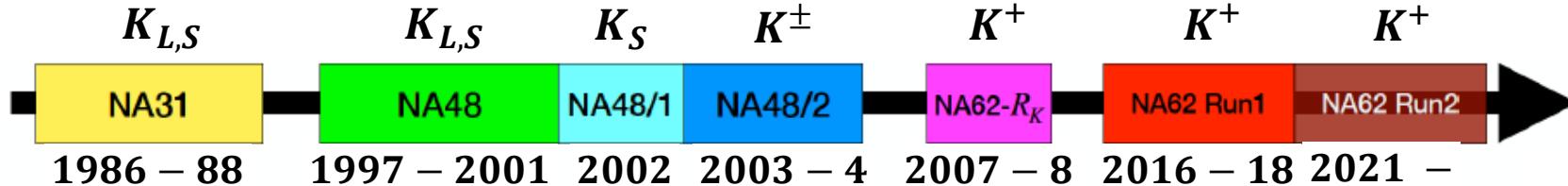
Outline

Physics program with charged kaons successfully pursued at CERN SPS by NA62

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- Recent results on χPT studies
- LFUV, LNV, LFV studies
- New result on dark sector studies with kaon decays

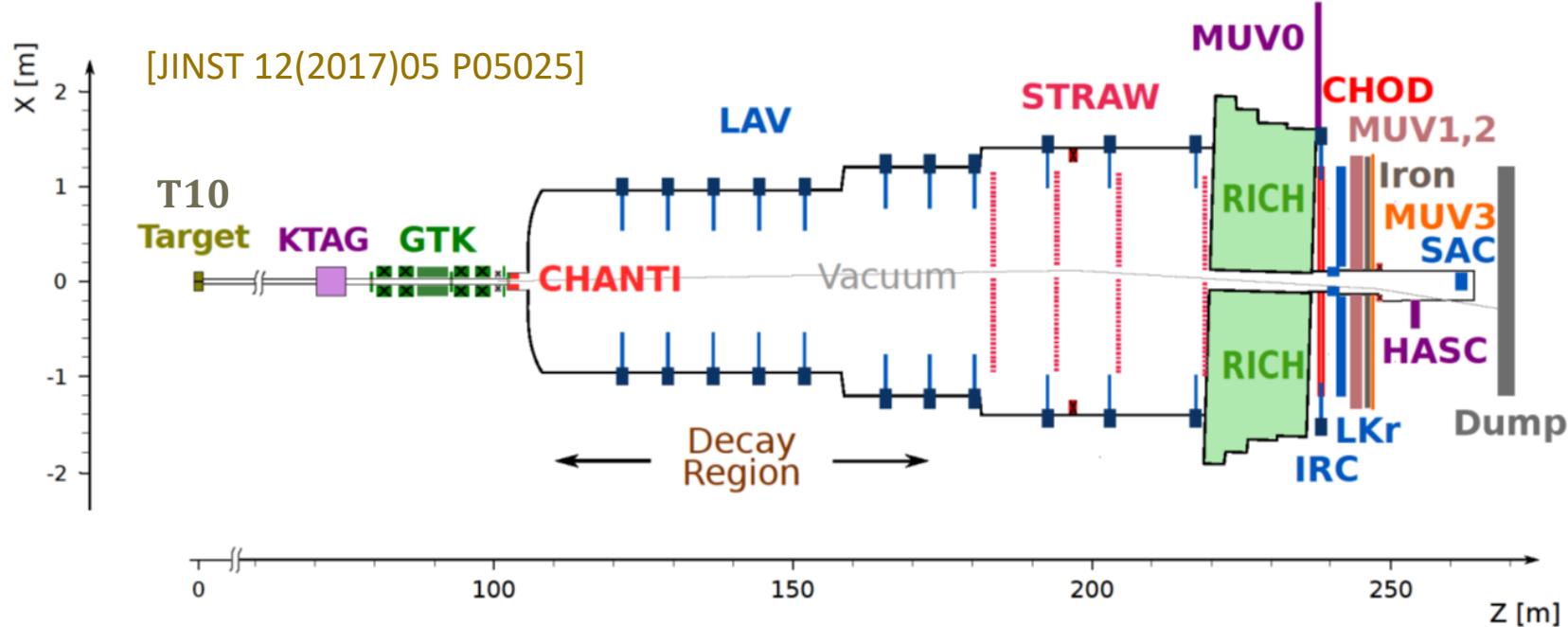
Future of physics with kaons at CERN SPS

^{P326}**NA62** at CERN SPS



~ 300 physicists from 31 institutions

The NA62 Experiment



Nominal Intensity

33×10^{11} ppp on T10

Incoming K^+ , 75 GeV/c, 1% rms

Timing by KTAG ($\sigma_t \sim 70$ ps); measured by GTK; rate at GTK ~ 600 MHz

Outgoing π^+

Timing by RICH ($\sigma_t \sim 70$ ps); measured by STRAW; rate at Straw ~ 5 MHz

γ /multitrack veto (LAV, LKr, IRC, SAC, HASC)

$\pi^0 \rightarrow \gamma\gamma$ suppression

Particle ID (RICH, LKr, MUV1,2,3)

μ^+ suppression

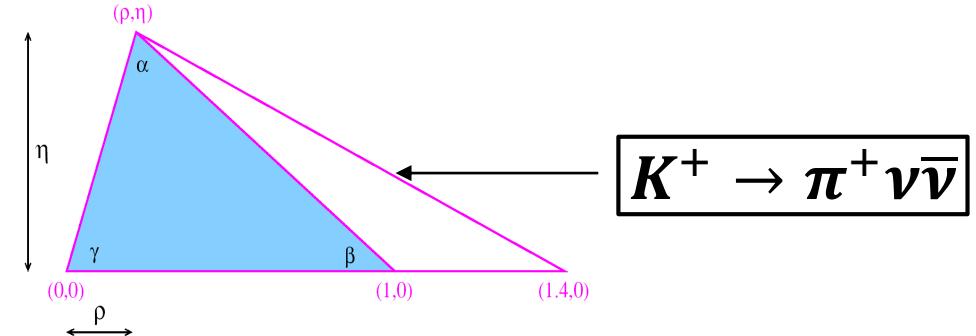
The NA62 Physics Program

Flavour Physics

- Indirect search for NP at high mass scale
- Direct and indirect search for NP through LFV/LNV processes

Hidden Sector Physics

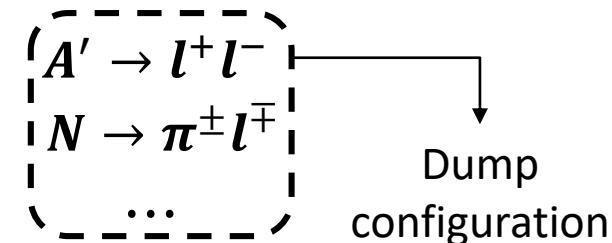
- Test of low-energy hadronic theories (e.g. χPT)
- Direct searches of new particles below the EW scale



$$\begin{array}{ll} K^+ \rightarrow \pi^+ l^+ l^- & K^+ \rightarrow \mu^- \nu e^+ e^+ \\ K^+ \rightarrow \pi^\pm \mu^\mp e^+ & K^+ \rightarrow \pi^- \pi^0 e^+ e^+ \\ K^+ \rightarrow \pi^- l^+ l^+ & \dots \end{array}$$

$$K^+ \rightarrow \pi^+ \gamma\gamma \quad K^+ \rightarrow \pi^0 e^+ \nu e^- \quad \dots$$

$$\begin{array}{l} K^+ \rightarrow \pi^+ X \\ K^+ \rightarrow l^+ N \\ K^+ \rightarrow \pi^+ a a, a \rightarrow e^+ e^- \end{array}$$



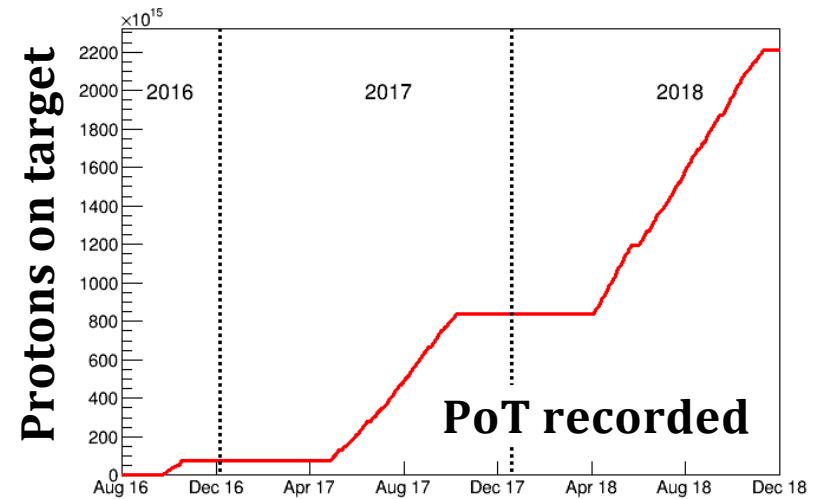
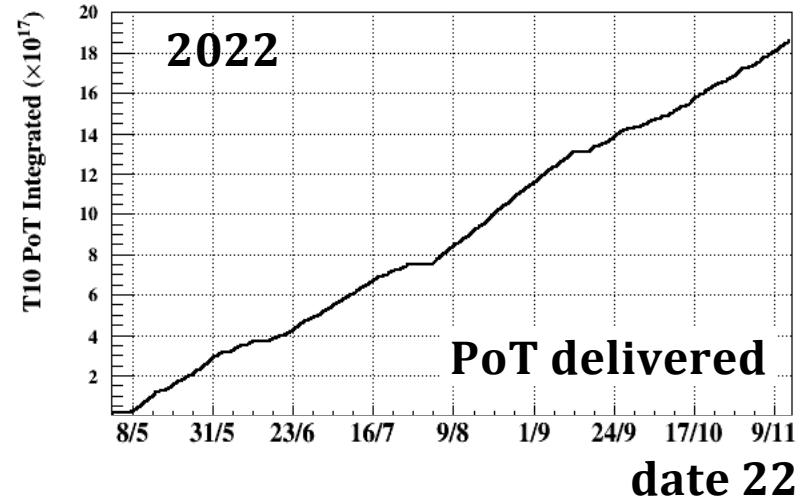
NA62 Data Taking Periods

	Beam intensity	Spills ($\times 10^3$)
“RUN2”	2025	approved
	2024	approved
	2023	on - going
	2022	nominal
	2021	~ nominal

Long Shutdown 2

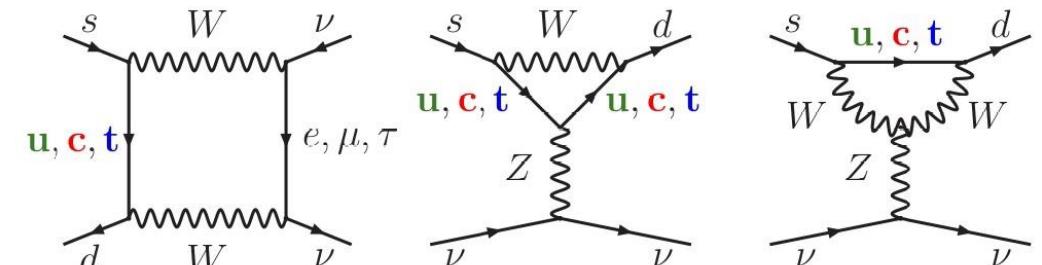
“RUN1”	2018	0(65)% nominal	500
	2017	0(55)% nominal	300
	2016	0(40)% nominal	80 Commissioning

* 33×10^{11} protons per spill on target



$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

- FCNC loop processes: $s \rightarrow d$ coupling and highest CKM suppression
- Very clean theoretically: SD dominated. Hadronic matrix element $\propto \text{BR}(K_{l3})$ (precisely measured)



- SM predictions $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left(\frac{|V_{cb}|}{0.0407} \right)^{2.8} \left(\frac{\gamma}{73.2^\circ} \right)^{0.74}$ [Buras et al. JHEP 11 (2015) 33]
 Parameters from full CKM fit $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \cdot 10^{-11}$ (uncertainty mainly from CKM parameters)
 Appropriate combination of CKM matrix elements $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.60 \pm 0.42) \cdot 10^{-11}$ [Buras et al. arXiv:2205.01118v1]
- Very high sensitivity to new physics:
 Unique probe in flavour physics to reach a model independent $\mathcal{O}(100)$ TeV mass scale
 $\mathcal{O}(50\%)$ BR variations in many different models (Z' , Little Higgs, Randall-Sundrum, non-MVF MSSM, LFUV leptoquark...)

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: RUN1 analysis

Kinematic selection based on $m_{\text{miss}}^2 = (P_{K^+} - P_{\pi^+})^2$

$15 < P_{\pi^+} < (35)45 \text{ GeV}/c$

$\mathcal{O}(100 \text{ ps})$ Timing between sub-detectors

$\geq 10^3$ Kinematic background suppression

$\geq 10^8$ Muon suppression

$\geq 10^8$ π^0 (from $K^+ \rightarrow \pi^+ \pi^0$) suppression

MVA techniques for PID and accidental background suppression

Normalization from $K^+ \rightarrow \pi^+ \pi^0$

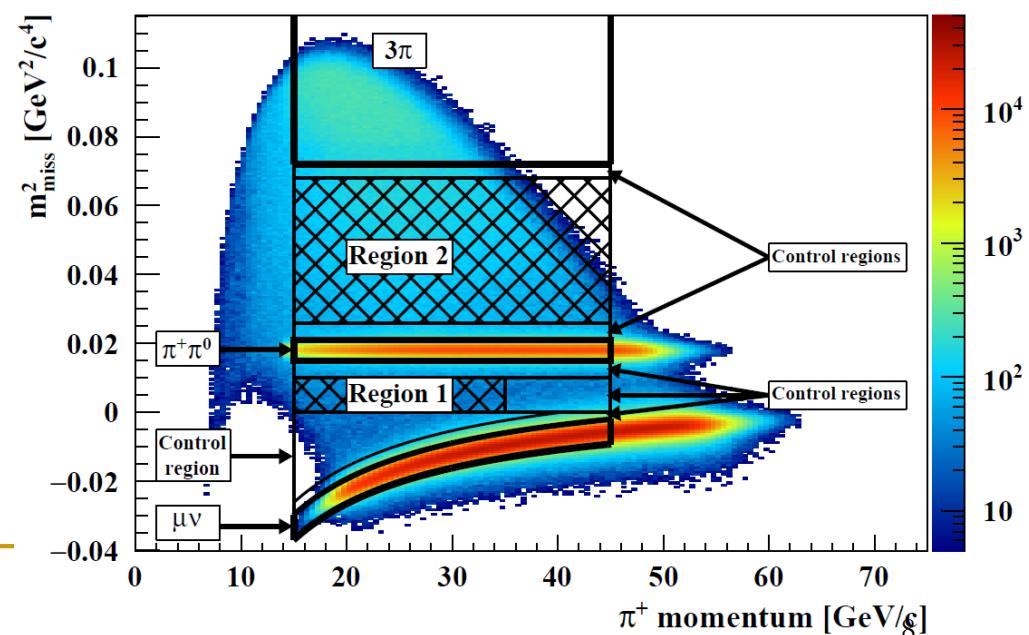
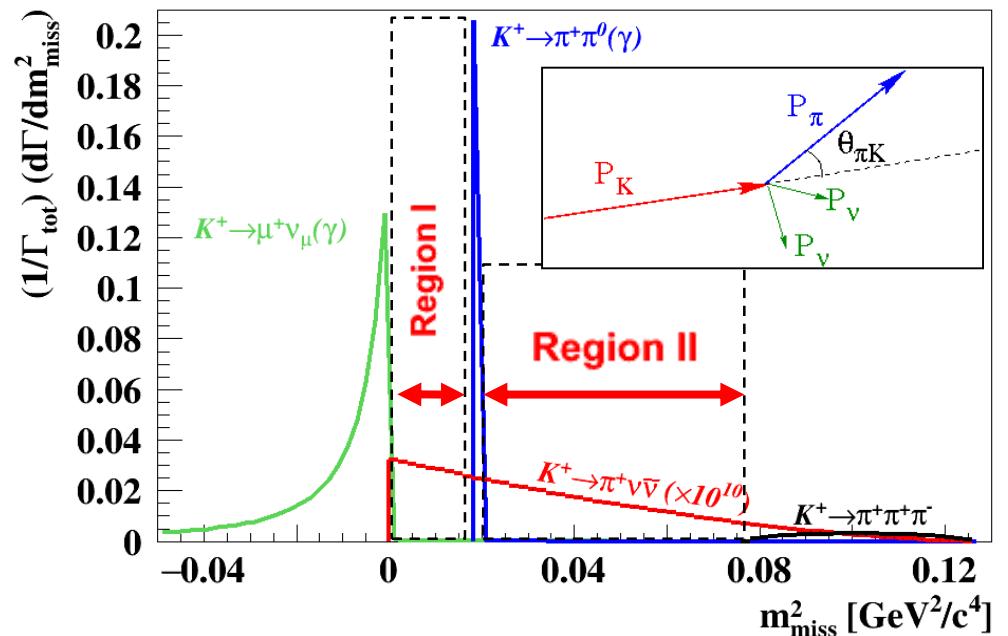
Signal loss from random activity measured on data ("Random Veto")

Analysis optimized in bins of π^+ momentum

Background from K^+ decays and accidentals

Data – driven background estimate

2 Signal regions in m_{miss}^2 , blind analysis



$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: RUN1 result

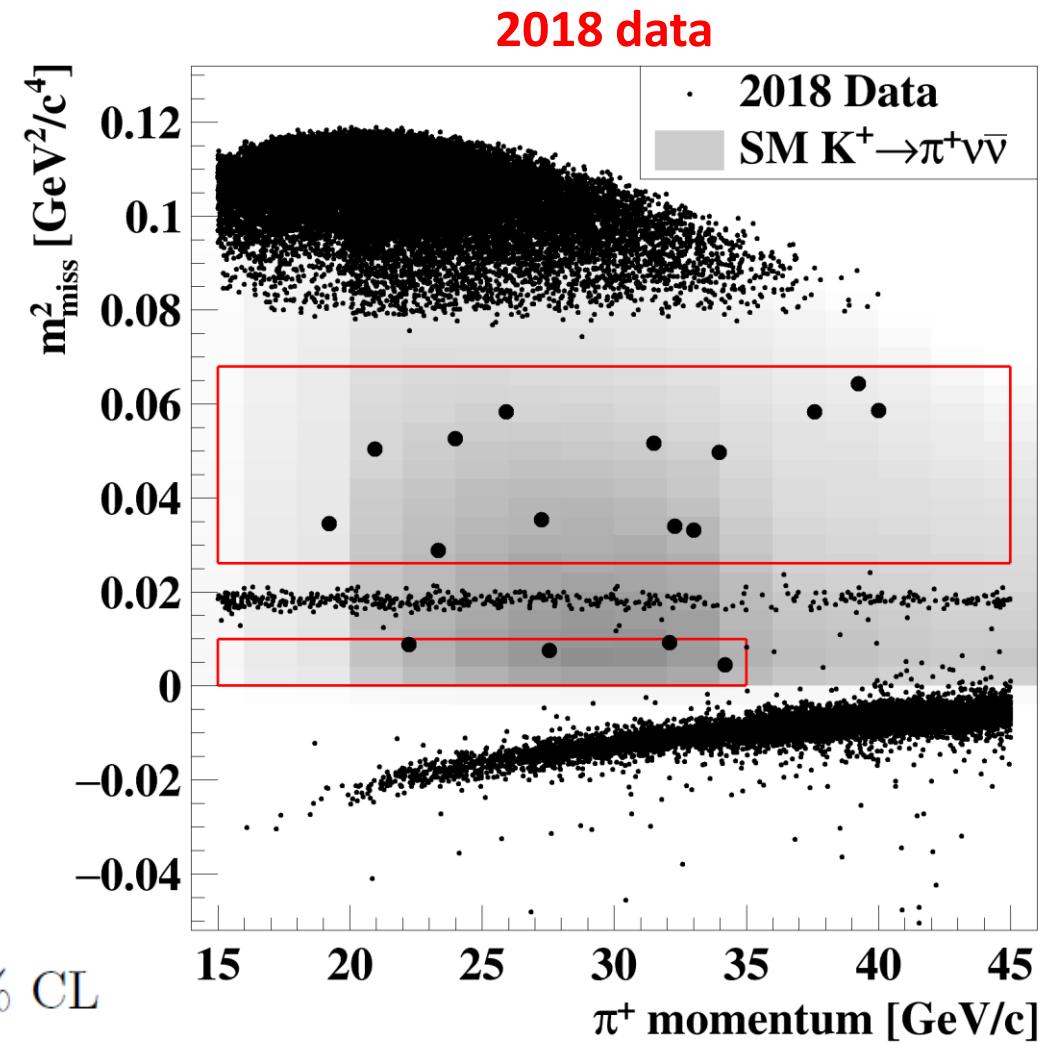
$$N_{\pi\nu\bar{\nu}}^{\text{exp}} = 10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}}, \quad N_{\text{background}}^{\text{exp}} = 7.03^{+1.05}_{-0.82}.$$

Channel	Background (2018)
$\pi^+ \pi^0$	0.75 ± 0.05
$\mu^+ \nu$	0.64 ± 0.08
$\pi^+ \pi^- e^+ \nu$	0.51 ± 0.10
$\pi^+ \pi^+ \pi^-$	0.22 ± 0.10
$\pi^+ \gamma \gamma$	< 0.01
$\pi^0 l^+ \nu$	< 0.001
Upstream	$3.30^{+1.00}_{-0.75}$
Total (2018)	$5.42^{+1.00}_{-0.75}$

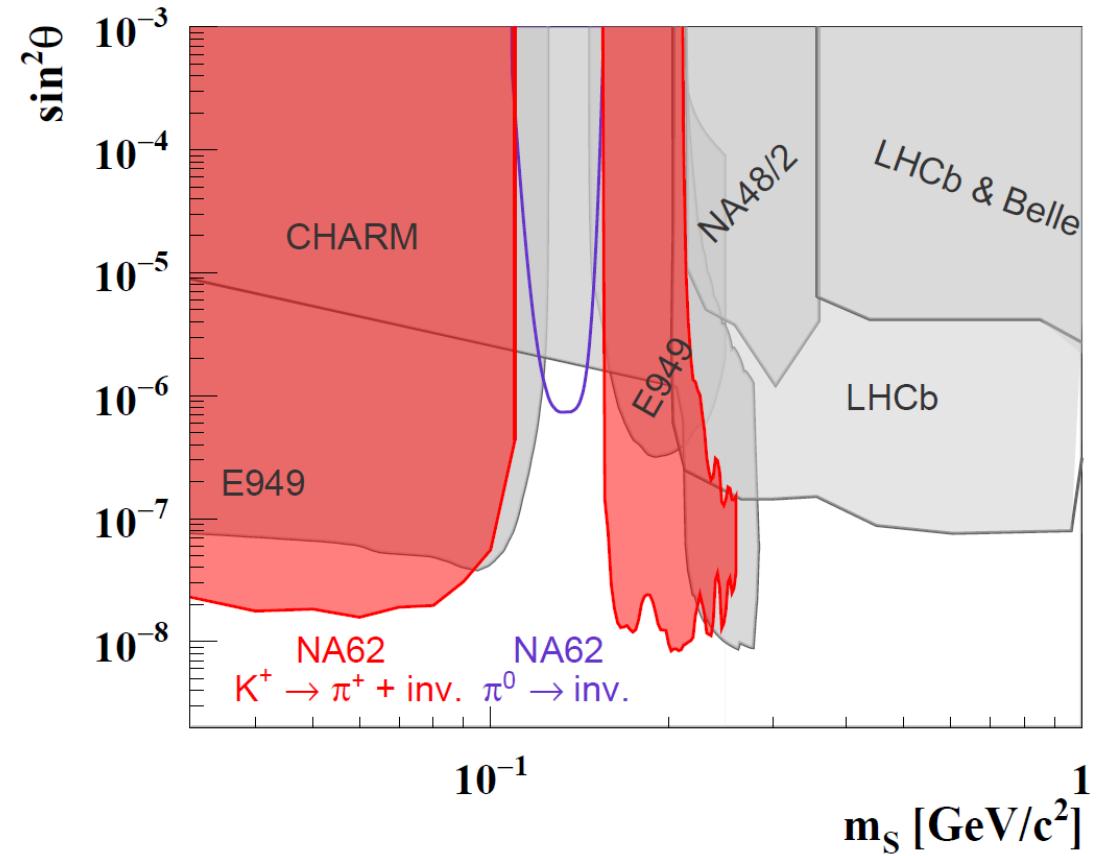
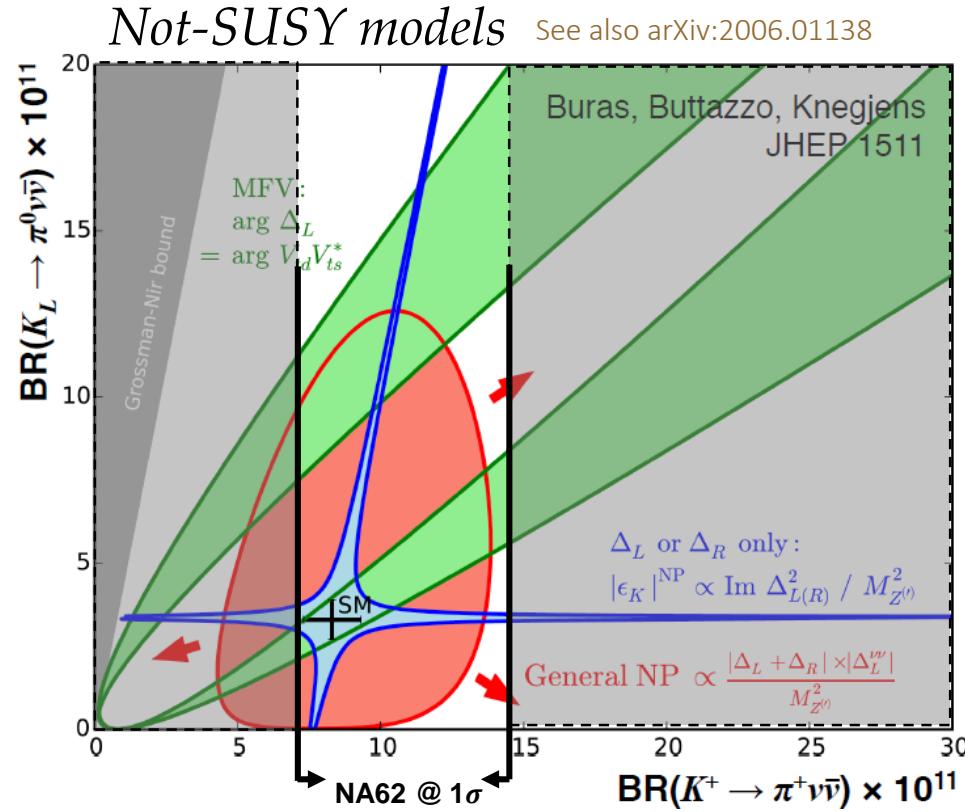
$N_{\text{obs}} = 20$ 3.4σ evidence for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4} |_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-11}$ at 68% CL

[JHEP 06(2021) 093]



$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: RUN1 result



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

Theory: LD dominated (Chiral Perturbation Theory) D'Ambrosio, Portoles PLB 386 403 (1996)

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

↓
depend on external parameters

Kinematic variables

$$z = m_{\gamma\gamma}^2 / M_K^2$$
$$y = \frac{P_K(P_{\gamma 1} - P_{\gamma 2})}{M_K^2}$$

Goal: Measurement of $BR(K^+ \rightarrow \pi^+ \gamma\gamma)$ and \hat{c}

Analysis: RUN 1 data

Signal selection: π^+ track matching K^+ track; EM calorimeter γ pair; $z = (P_K - P_\pi)^2 / M_K^2$

Signal: $\sim 4 \times 10^3$ events, $\sim 10\%$ background

$\begin{cases} \text{Cluster merging: } K^+ \rightarrow \pi^+ \pi^0 \gamma, K^+ \rightarrow \pi^+ \pi^0 \pi^0 \\ \text{Multi-track with tracks missing: } K^+ \rightarrow \pi^+ \pi^+ \pi^- \end{cases}$

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

Procedure

- \hat{c} from fit of z assuming $\mathcal{O}(p^6)$

$$\ln \mathcal{L} = \sum_i_{\text{bins}} [k_i \ln \lambda_i(\hat{c}) - \lambda_i(\hat{c}) - \ln(k_i!)]$$

observed events
 ↑
 expected S+B: $\lambda_i^S(\hat{c}) + \lambda_i^B$
 $z > 0.25$

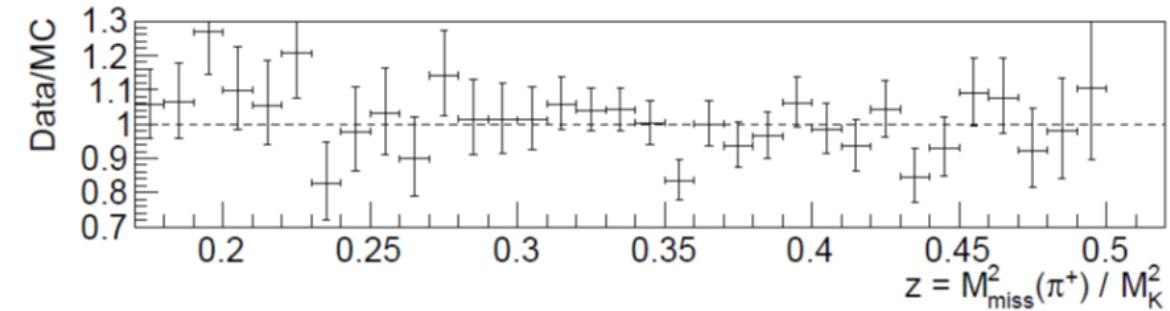
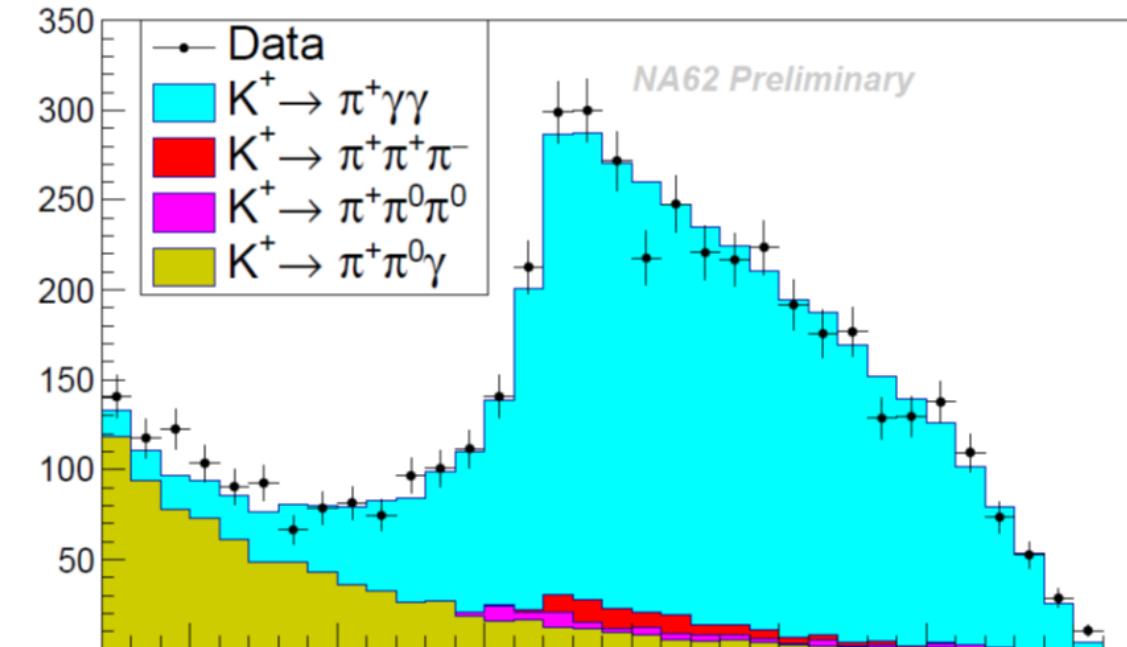
External parameters fixed

Rev Mod Phys 84 399 (2012), Science 368 (2020), Nucl. Phys. B648 (2003)

Final result will use D'Ambrosio, Knech, Neshatpour, arXiv:2209.02143

- Model independent $BR(K^+ \rightarrow \pi^+ \gamma\gamma)$

normalization: $K^+ \rightarrow \pi^+ \pi^0$



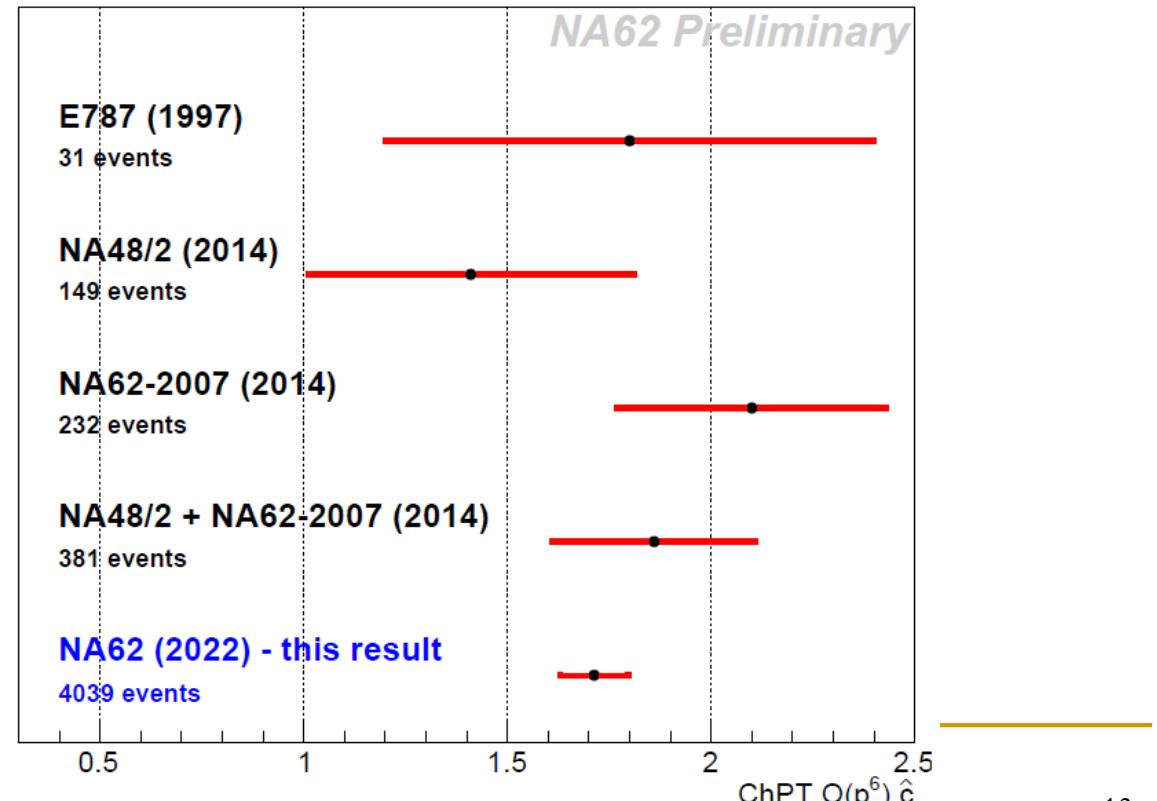
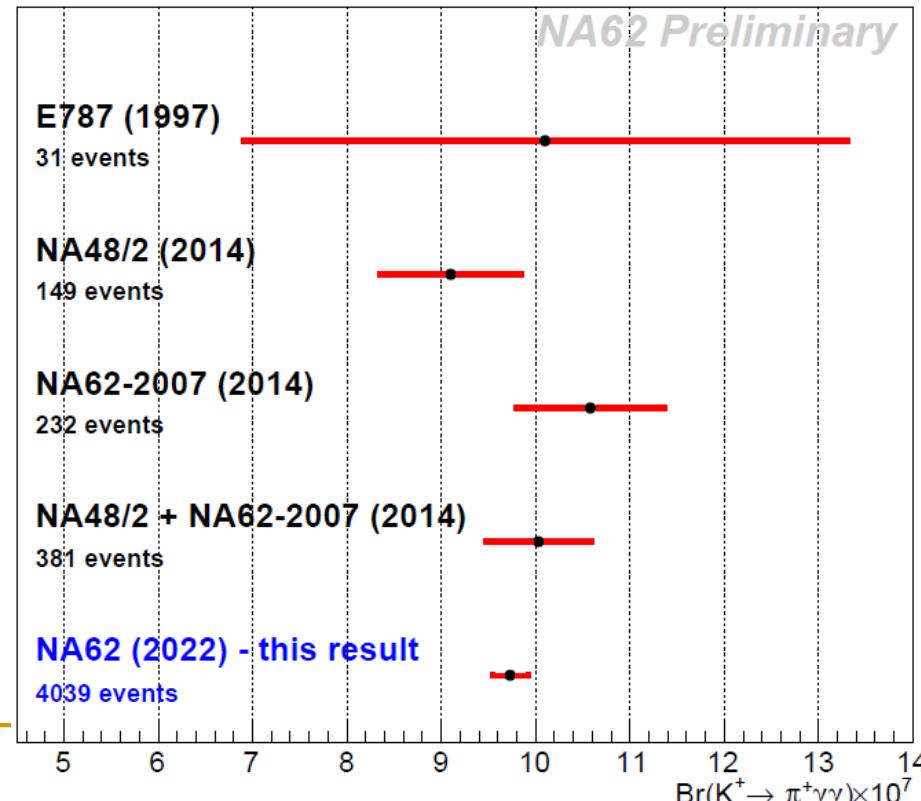
$K^+ \rightarrow \pi^+ \gamma\gamma$ Precision measurement

Result (Preliminary)

$$N_{obs} = 4039 \quad N_{bkg} = 393 \pm 20$$

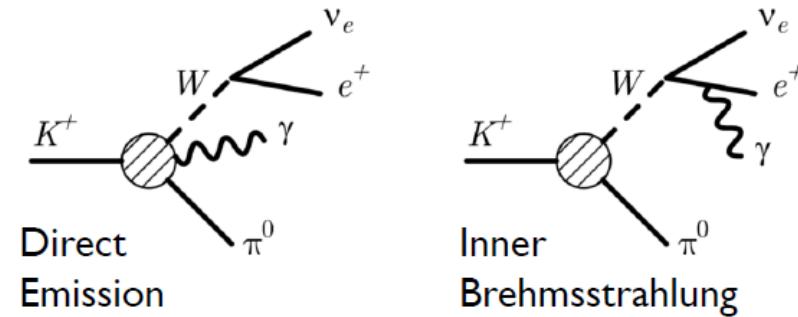
$$\hat{c} = 1.713 \pm 0.075_{stat} \pm 0.037_{syst} \text{ } O(p^6)$$

$$BR(K^+ \rightarrow \pi^+ \gamma\gamma) = (9.73 \pm 0.17_{stat} \pm 0.08_{syst}) \times 10^{-7}$$



$K^+ \rightarrow \pi^0 e^+ \nu \gamma$ Precision measurement

Theory: LD dominated (Chiral Perturbation Theory)
IR and collinear divergence



Goal: Measurement of

$$R_j = \frac{\mathcal{B}(K_{e3\gamma^j})}{\mathcal{B}(K_{e3})} = \frac{\mathcal{B}(K^+ \rightarrow \pi^0 e^+ \nu \gamma | E_\gamma^j, \theta_{e\gamma}^j)}{\mathcal{B}(K^+ \rightarrow \pi^0 e^+ \nu(\gamma))}$$

phase space
conditions

Eur. Phys. J. C 50 (2007)

	$E_\gamma^j, \theta_{e\gamma}^j$	ChPT
$R_1 \times 10^2$	$E_\gamma > 10 \text{ MeV}, \theta_{e\gamma} > 10^\circ$	1.804 ± 0.021
$R_2 \times 10^2$	$E_\gamma > 30 \text{ MeV}, \theta_{e\gamma} > 20^\circ$	0.640 ± 0.008
$R_3 \times 10^2$	$E_\gamma > 10 \text{ MeV}, 0.6 < \cos \theta_{e\gamma} < 0.9$	0.559 ± 0.006

$$A_\xi = \frac{N_+ - N_-}{N_+ + N_-} \quad \text{with } N_\pm = N(\xi \gtrless 0) \text{ and } \xi = \frac{\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\pi)}{(M_K \cdot c)^3}$$

$A_\xi \in (-10^{-4}, -10^{-5})$ [SM and beyond]

$K^+ \rightarrow \pi^0 e^+ \nu \gamma$ Precision measurement

Analysis: RUN1 Data

Signal: e^+ track matching K^+ track; e^+ PID;

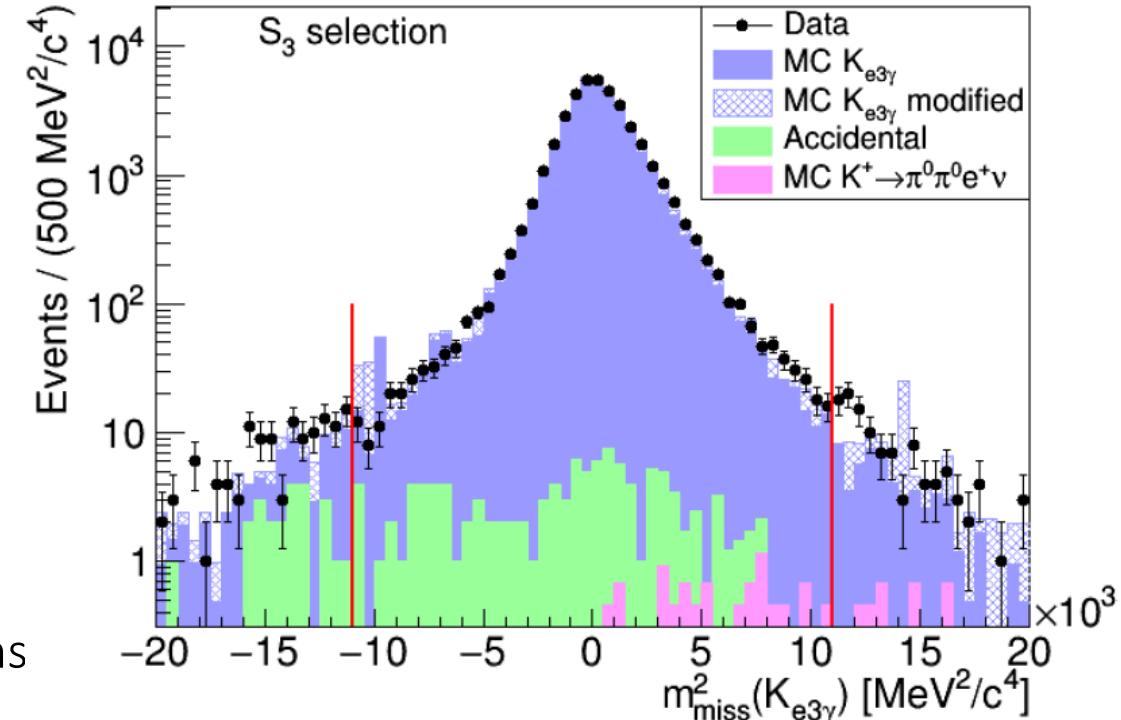
2 EM calorimeter γ from π^0 , 1 radiative;

Veto of additional photons

Conditions on $m_{miss}^2(K_{e3\gamma}) = (P_K - P_e - P_{\pi^0} - P_\gamma)^2$

Normalization: $K^+ \rightarrow \pi^0 e^+ \nu$

Selected as signal without γ radiative, different kin. conditions



	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	—	$(4.9 \pm 0.2 \pm 1.3) \times 10^2$	$(2.3 \pm 0.2 \pm 0.3) \times 10^2$	$(1.1 \pm 0.1 \pm 0.5) \times 10^2$
$K^+ \rightarrow \pi^0 \pi^0 e^+ \nu$	—	$(1.1 \pm 1.1) \times 10^2$	$(1.1 \pm 1.1) \times 10^2$	$(0.1 \pm 0.1) \times 10^2$
$K^+ \rightarrow \pi^+ \pi^0 \pi^0$	—	< 20	< 20	< 20
$K^+ \rightarrow \pi^+ \pi^0$	$(1.0 \pm 1.0) \times 10^4$	—	—	—
Total background	$(1.0 \pm 1.0) \times 10^4$	$(6.0 \pm 1.8) \times 10^2$	$(3.4 \pm 1.2) \times 10^2$	$(1.2 \pm 0.6) \times 10^2$

$K^+ \rightarrow \pi^0 e^+ \nu \gamma$ Precision measurement

Procedure:

$$R_j = \frac{\mathcal{B}(K_{e3\gamma^j})}{\mathcal{B}(K_{e3})} = \frac{N_{Ke3\gamma^j}^{\text{obs}} - N_{Ke3\gamma^j}^{\text{bkg}}}{N_{Ke3}^{\text{obs}} - N_{Ke3}^{\text{bkg}}} \cdot \frac{A_{Ke3}}{A_{Ke3\gamma^j}} \cdot \frac{\epsilon_{Ke3}^{\text{trig}}}{\epsilon_{Ke3\gamma^j}^{\text{trig}}}$$

EM calorimeter response correction
Acceptance correction for multiple radiative γ

$$A_\xi^{\text{NA62}} = A_\xi^{\text{Data}} - A_\xi^{\text{MC}} \quad \text{With } A_\xi^{\text{MC}} = 0 \text{ within } 10^{-4}$$

Results: [arXiv:2304.12271]

$$R_1 \times 10^2 = 1.715 \pm 0.005_{\text{stat}} \pm 0.010_{\text{syst}} = 1.715 \pm 0.011$$

$$R_2 \times 10^2 = 0.609 \pm 0.003_{\text{stat}} \pm 0.006_{\text{syst}} = 0.609 \pm 0.006$$

$$R_3 \times 10^2 = 0.533 \pm 0.003_{\text{stat}} \pm 0.004_{\text{syst}} = 0.533 \pm 0.004$$

Systematics: EM calorimeter response modelling, acceptance correction, theoretical model, MC statistics

$$A_\xi(S_1) \times 10^3 = -1.2 \pm 2.8_{\text{stat}} \pm 1.9_{\text{syst}}$$

$$A_\xi(S_2) \times 10^3 = -3.4 \pm 4.3_{\text{stat}} \pm 3.0_{\text{syst}}$$

$$A_\xi(S_3) \times 10^3 = -9.1 \pm 5.1_{\text{stat}} \pm 3.5_{\text{syst}}$$

Systematics: MC statistics

$K^+ \rightarrow \pi^0 e^+ \nu \gamma$ Precision measurement

Result comparison:

	NA62	ChPT	ISTRA+	OKA
$R_1 \times 10^2$	1.715 ± 0.011	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
$R_2 \times 10^2$	0.609 ± 0.006	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$
$R_3 \times 10^2$	0.533 ± 0.004	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$
$A_\xi(S_1) \times 10^3$	$-1.2 \pm 2.8 \pm 1.9$			$-0.1 \pm 3.9 \pm 1.7$
$A_\xi(S_2) \times 10^3$	$-3.4 \pm 4.3 \pm 3.0$			$+7.0 \pm 8.1 \pm 1.5$
$A_\xi(S_3) \times 10^3$	$-9.1 \pm 5.1 \pm 3.5$			$-4.4 \pm 7.9 \pm 1.9$

$K^+ \rightarrow \pi^+ l^+ l^-$ Precision measurement

Theory

FCNC LD dominated*, mediated by $K^+ \rightarrow \pi^+ \gamma^*$; kinematic variable $z = m(l\bar{l})^2/M_K^2$

$$\frac{d\Gamma}{dz} = \frac{d\Gamma_{3\text{-body}}}{dz} + \frac{d\Gamma_{4\text{-body}}}{dz} \quad \text{with} \quad \frac{d\Gamma_{3\text{-body}}}{dz} \propto |W(z)|^2 \quad \text{and} \quad W(z) = G_F M_K^2 (\color{red}a_+ + b_+ z) + W^{\pi\pi}(z)$$

$K_{3\pi}$ loop term
↓
 $\color{red}a_+$ $\color{red}b_+$ Form factors

Lepton universality (LU) predicts same a, b for $l = e, \mu$

Asymmetries in angular distribution could point to NP contributions

Goal

$K^+ \rightarrow \pi^+ \mu^+ \mu^-$ form factors measurement

Model independent measurement of $BR(K^+ \rightarrow \pi^+ \mu^+ \mu^-)$

$K^+ \rightarrow \pi^+ \mu^+ \mu^-$ forward – backward asymmetry measurement

$K^+ \rightarrow \pi^+ l^+ l^-$ Precision measurement

Analysis: RUN1 Data

Signal: 3 - track vertex topology

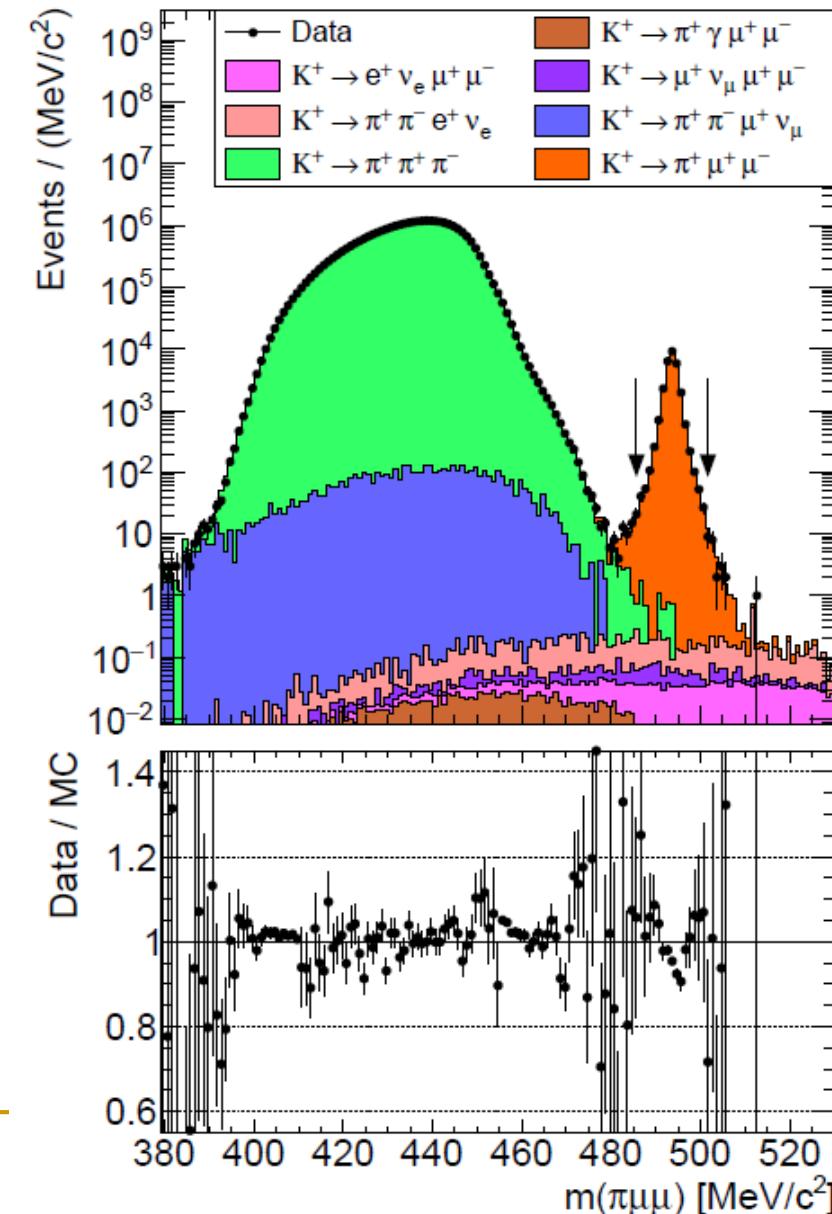
π^\pm and μ PID with calorimeters

Kinematic conditions on $m(\pi\mu\mu)$

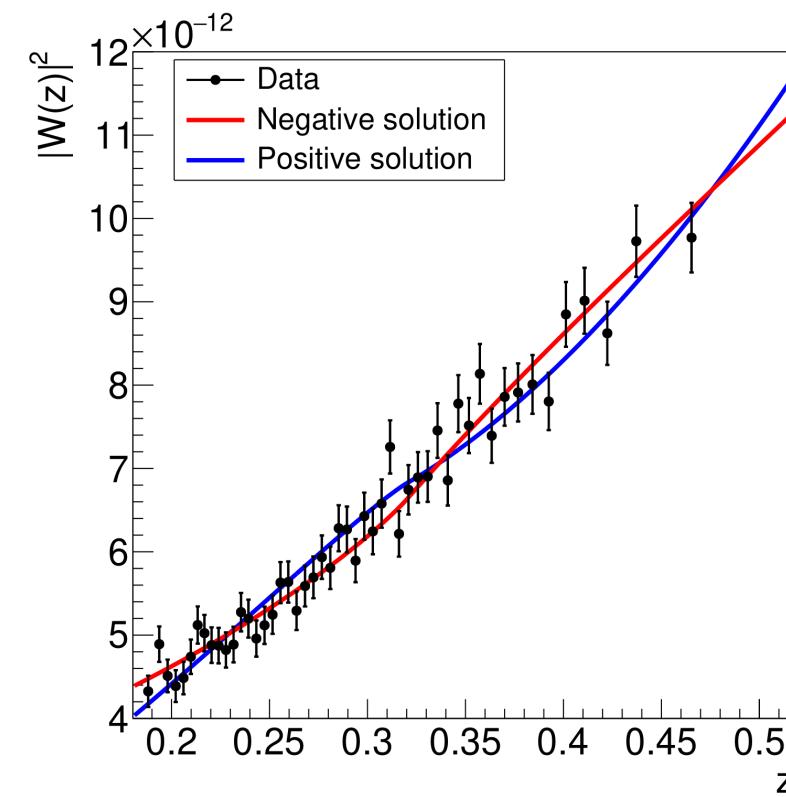
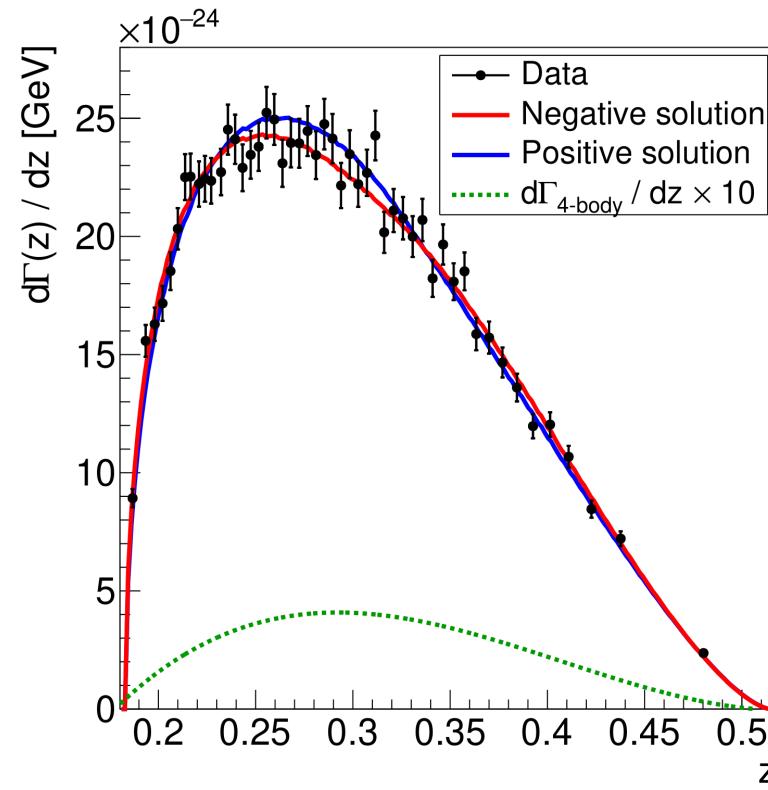
Normalization: $K^+ \rightarrow \pi^+ \pi^+ \pi^-$

Same 3 – track signal selection, π PID, specific kin. conditions

K^+ decays	$\sim 3.5 \times 10^{12}$
Signal	27679
Estimated Background	7.8 ± 5.6



$K^+ \rightarrow \pi^+ l^+ l^-$ Precision measurement



Procedure:

- Model independent $BR(K^+ \rightarrow \pi^+ \mu^+ \mu^-)$: $\left(\frac{d\Gamma(z)}{dz} \right)_i = \frac{N_{\pi\mu\mu,i}}{A_{\pi\mu\mu,i}} \cdot \frac{1}{\Delta z_i} \cdot \frac{1}{N_K} \cdot \frac{\hbar}{\tau_K}$ (Equi-populated bins)
- Form factors: Extract $|W(z)|^2$ from $d\Gamma/dz$, $\chi^2(a_+, b_+)$ minimization

$K^+ \rightarrow \pi^+ l^+ l^-$ Precision measurement

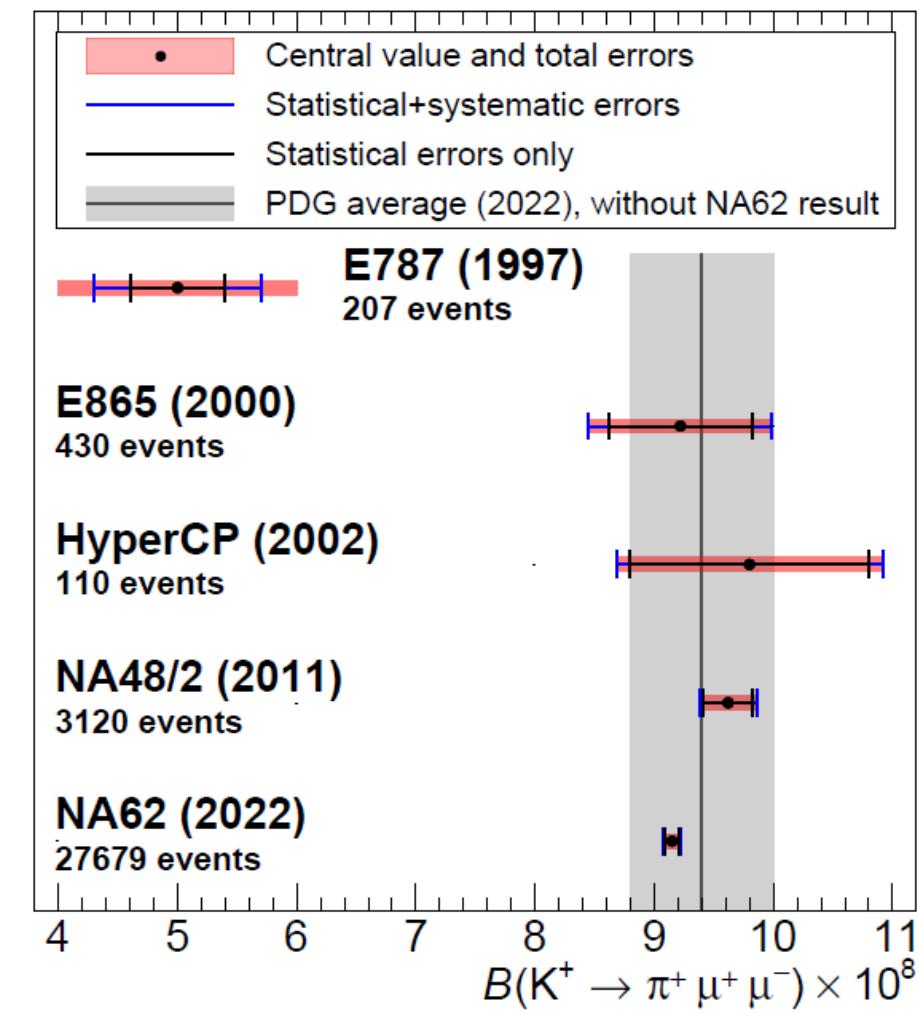
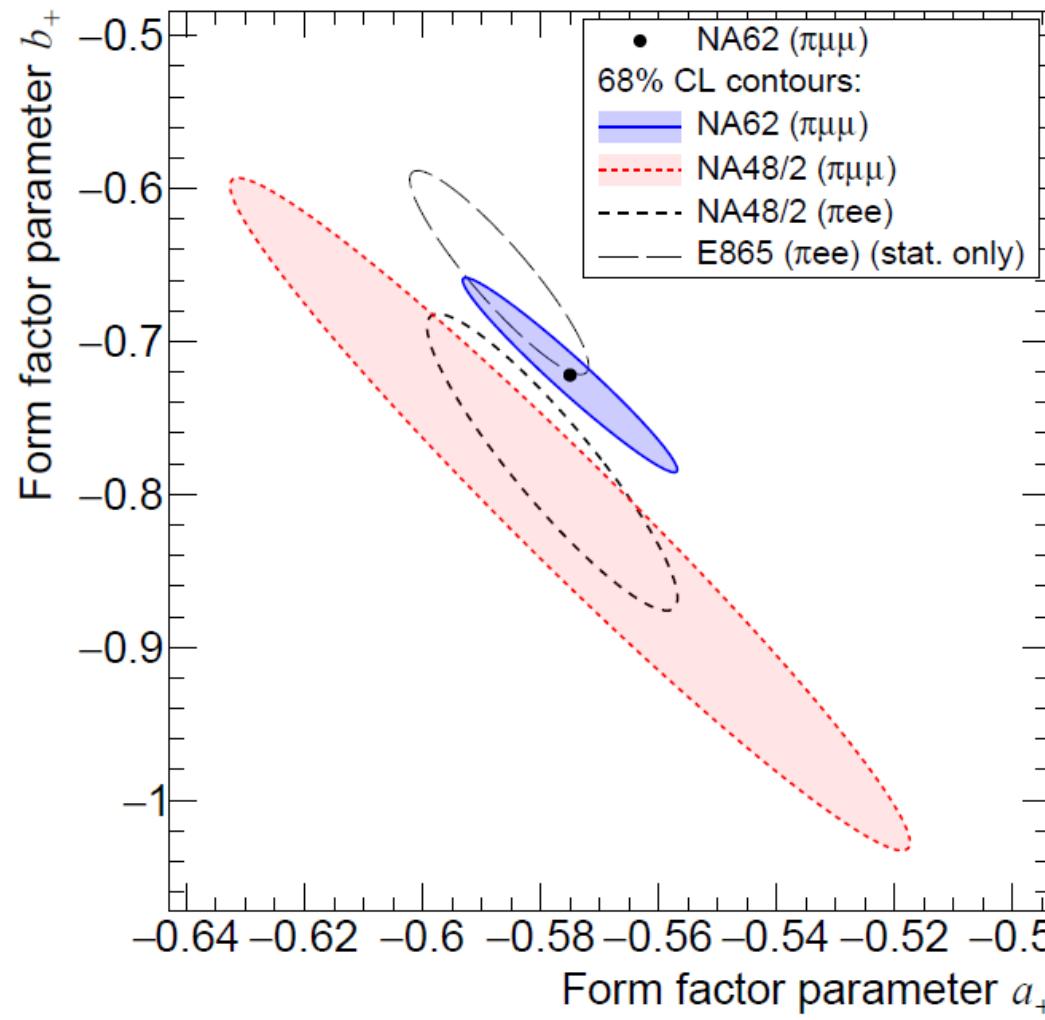
Results:

[JHEP 11(2022) 011]

$a_+ = -0.575 \pm 0.013$	$\chi^2/\text{ndf} = 45.1/48$
$b_+ = -0.722 \pm 0.043$	
$BR(K^+ \rightarrow \pi^+ \mu^+ \mu^-) = (9.15 \pm 0.08) \times 10^{-8}$	

	δa_+	δb_+	$\delta \mathcal{B}_{\pi\mu\mu} \times 10^8$
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 α_+ and β_+	0.001	0.006	—
Total external uncertainty	0.003	0.011	0.04

$K^+ \rightarrow \pi^+ l^+ l^-$ Precision measurement



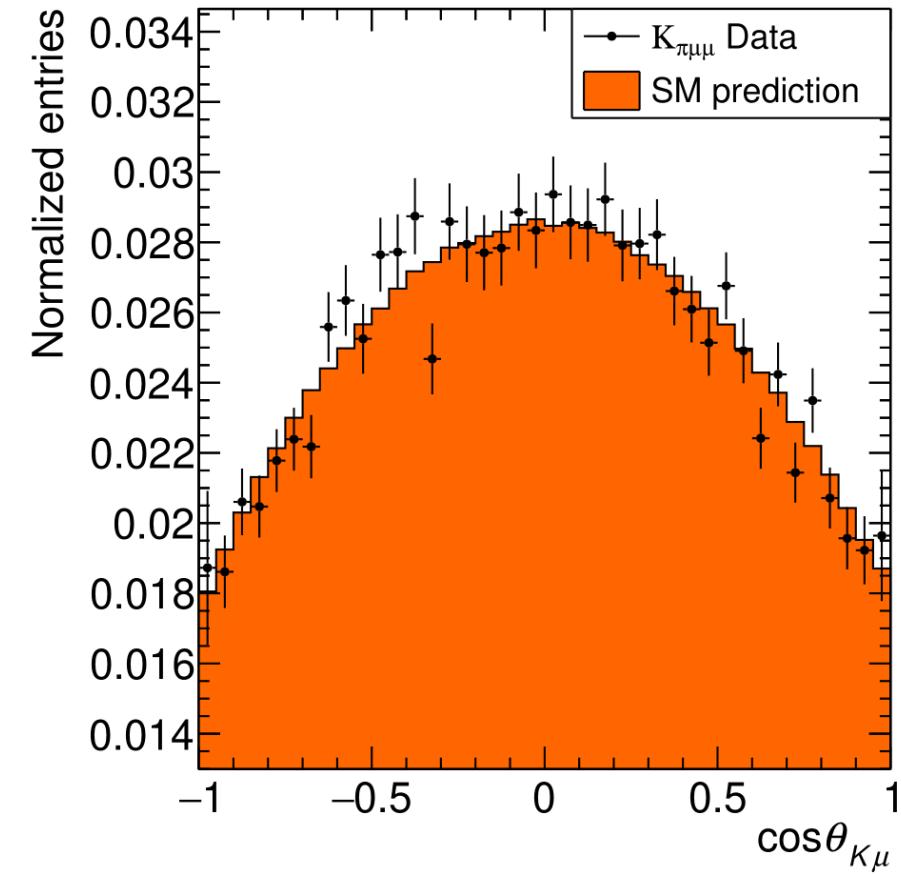
$K^+ \rightarrow \pi^+ l^+ l^-$ Precision measurement

- Forward backward asymmetry: $A_{FB} = \frac{\mathcal{N}(\cos \theta_{K\mu} > 0) - \mathcal{N}(\cos \theta_{K\mu} < 0)}{\mathcal{N}(\cos \theta_{K\mu} > 0) + \mathcal{N}(\cos \theta_{K\mu} < 0)}$ $\theta_{K\mu}$: $K\mu^-$ angle in $\mu\mu$ rest frame

Result:

$$A_{FB} = (0.0 \pm 0.7) \times 10^{-2} \text{ @ 68% CL}$$

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



LNV – LFV Searches

Theory: decays forbidden by SM; Direct search of NP: Majorana neutrino (LNV), Leptoquark (LFV)

NA62: Several channels studied with RUN1 data

Analysis: key points → tracking resolution and particle identification

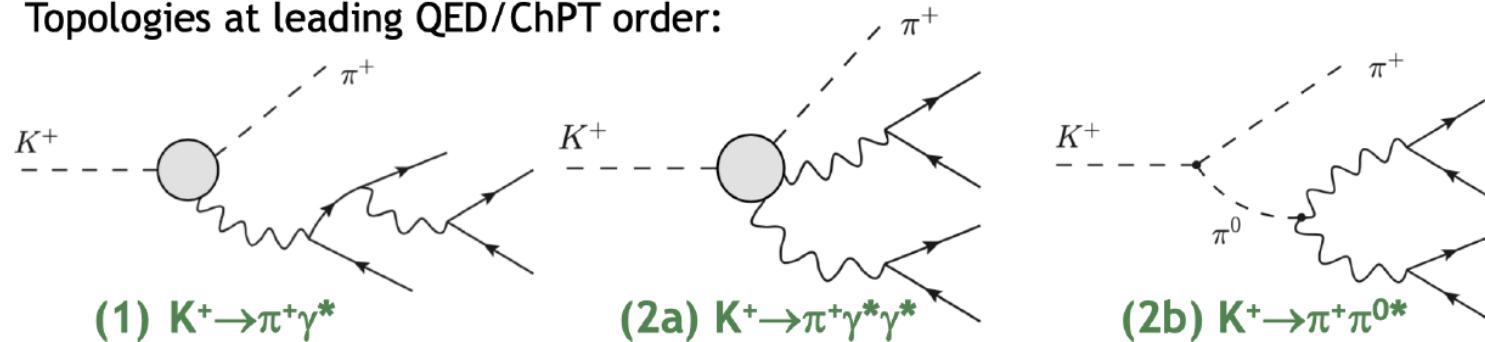
Result: no signal observed → 90% CL Upper Limit (UL) on Branching Ratios (BR)

	BR UL PDG 2019	BR UL NA62	Expected background	Observed	
$K^+ \rightarrow \pi^- \mu^+ e^+$	50×10^{-11}	4.2×10^{-11}	1.07 ± 0.20	0	PRL 127 (2021) 131802
$K^+ \rightarrow \pi^+ \mu^- e^+$	52×10^{-11}	6.6×10^{-11}	0.92 ± 0.34	2	PRL 127 (2021) 131802
$\pi^0 \rightarrow \mu^- e^+$	34×10^{-10}	3.2×10^{-10}	0.23 ± 0.15	0	PRL 127 (2021) 131802
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	0.91 ± 0.41	1	PLB 797 (2019) 134794
$K^+ \rightarrow \pi^- e^+ e^+$	64×10^{-11}	5.3×10^{-11}	0.43 ± 0.09	0	PLB 830 (2022) 137172
$K^+ \rightarrow \pi^- \pi^0 e^+ e^+$	N/A	8.5×10^{-10}	0.044 ± 0.020	0	PLB 830 (2022) 137172
$K^+ \rightarrow \mu^- \nu e^+ e^+$	N/A	8.1×10^{-11}	0.26 ± 0.04	0	PLB 838 (2022) 137679

$$K^+ \rightarrow \pi^+ e^+ e^- e^+ e^- \quad (\text{New result})$$

Theory: SM allowed $BR = (7.2 \pm 0.7) \times 10^{-11}$ (outside π^0 pole) arXiv:2207.02234

Topologies at leading QED/ChPT order:



Dark sector probe:

$K^+ \rightarrow \pi^+ aa$ with $a \rightarrow e^+ e^-$ QCD axion, e.g. $m_a = 17$ MeV $BR = 1.7 \times 10^{-5}$ arXiv:2012.02142

$K^+ \rightarrow \pi^+ S$ with $S \rightarrow A'A'$ dark scalar and $A' \rightarrow e^+ e^-$ dark photon ($m_S > 2m_{A'}$) arXiv:2012.02142

Goal: Search for: 1) SM process ($K_{\pi 4e}$) 2) QCD di-axion 3) Dark cascade

$$K^+ \rightarrow \pi^+ e^+ e^- e^+ e^- \quad (\text{New result})$$

Analysis: RUN1 Data

Signal ($K_{\pi 4e}$)

5 - track vertex topology

Kinematic PID of positive tracks

Conditions on $m_{\pi 4e}$, m_{miss}^2 (1)

m_{4e} outside the π^0 mass region

Signal ($K^+ \rightarrow \pi^+ aa$ "Dark")

Same selection as $K_{\pi 4e}$

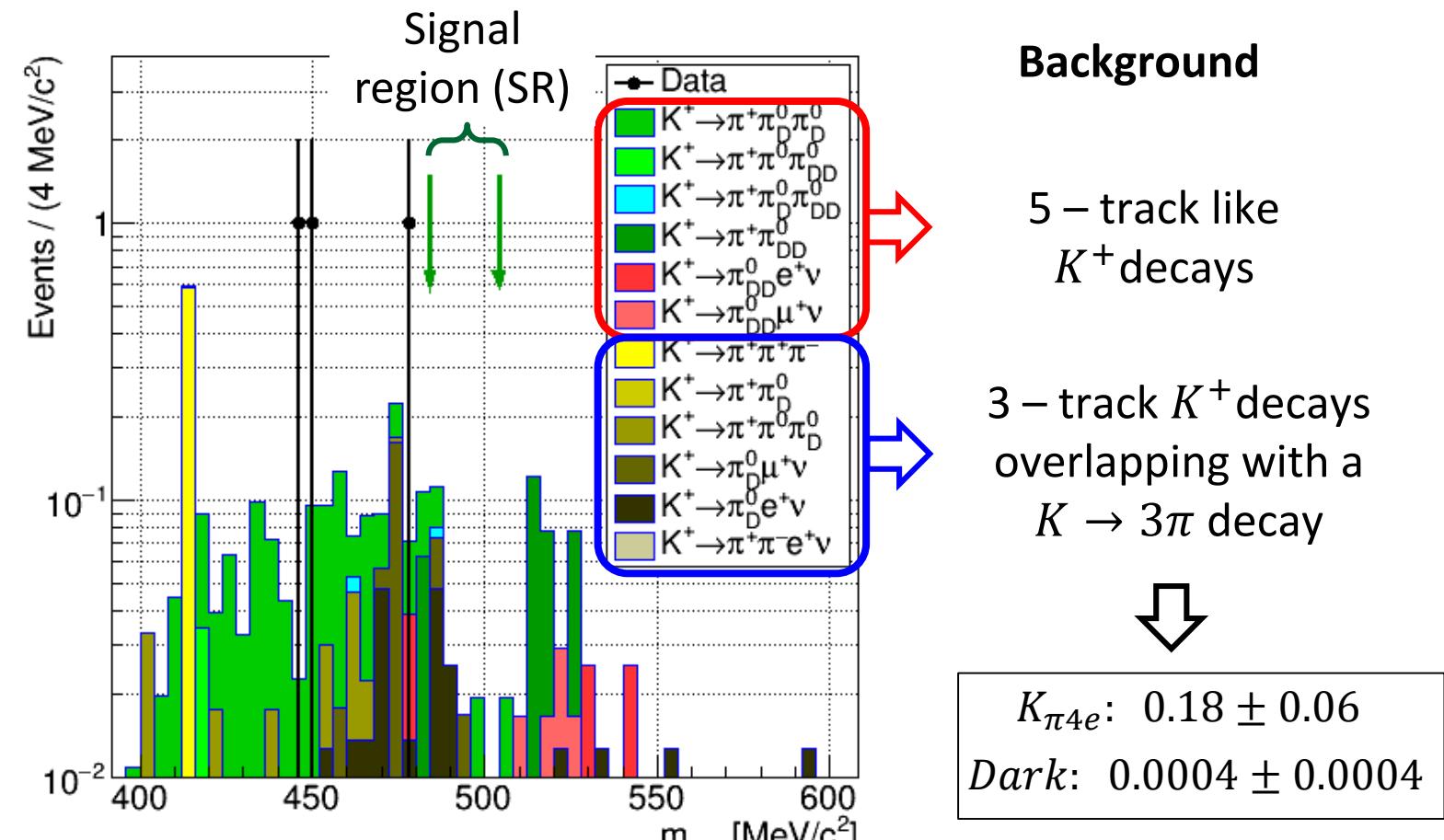
Choice of the optimal $e^+ e^-$ mass pair

Condition on m_{ee}

Normalization: $K^+ \rightarrow \pi^+ \pi_{DD}^0$ (2)

5 - track topology and PID as for $K_{\pi 4e}$

Kinematic condition on m_{4e}



$$(1) m_{miss}^2 = (P_K - P_\pi)^2$$

$$(2) \pi^0 \rightarrow e^+ e^- e^+ e^-$$

$$K^+ \rightarrow \pi^+ e^+ e^- e^+ e^- \quad (\text{New result})$$

Procedure:

$K_{\pi 4e}$ SM: Acceptance from MC

Resonant amplitude negligible for selected events

No candidate observed in SR

$$K^+ \rightarrow \pi^+ aa$$

Uniform phase-space

Mass scan 5 MeV/ c^2 step

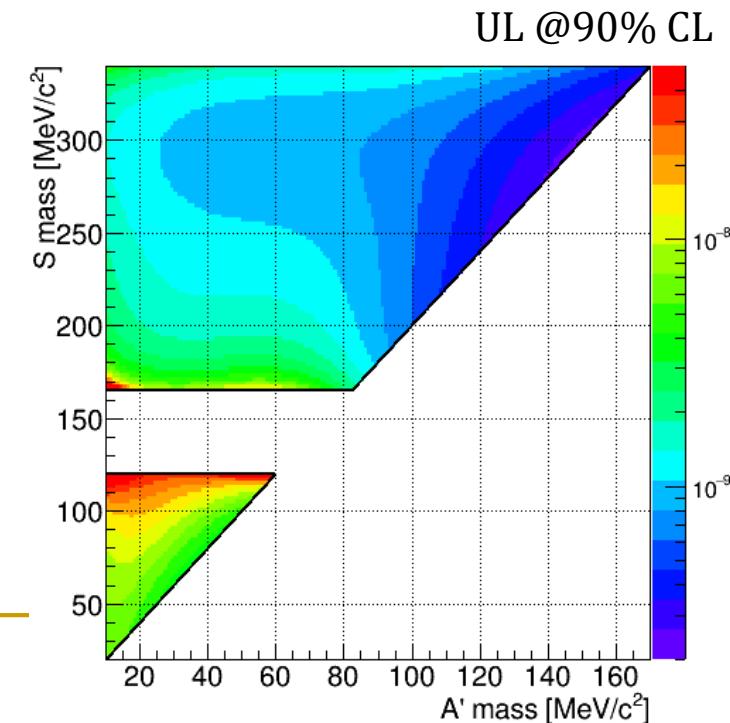
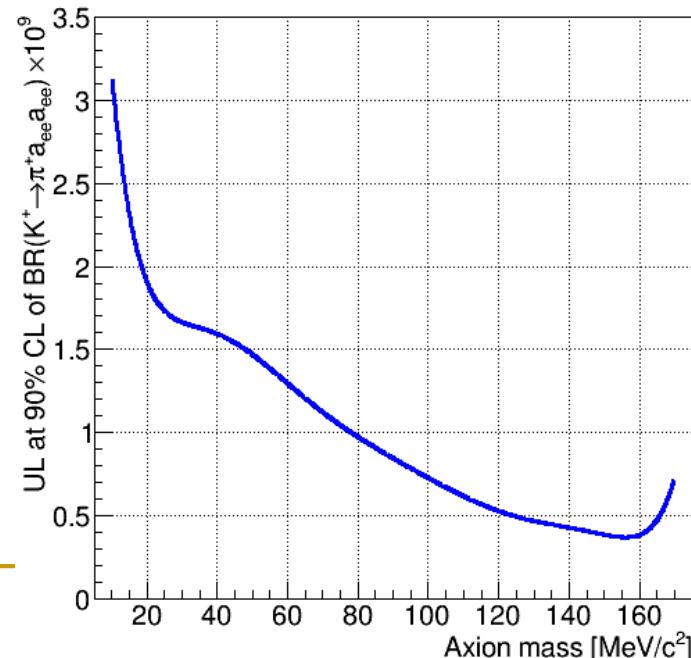
$$K^+ \rightarrow \pi^+ S, S \rightarrow AA$$

Di-axion aa mass scan

($m_{A'}$, m_S) distribution smoothing (low MC statistics)

Result

$$BR(K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-) < 1.4 \times 10^{-8} \quad @90\% \text{ CL}$$



Kaon at CERN: Plans

NA62 RUN2

- On-going: data taking foreseen at least until 2025 (included), +45-50% increase of intensity vs RUN1
- Hardware upgrades implemented mainly to improve on $\pi\nu\nu$
- Single Event Sensitivity to SM $K^+ \rightarrow \pi^+\nu\bar{\nu}$ with 2022 data $\lesssim 10^{-11}$
- Average selected $\pi\nu\nu$ yield per spill: $\gtrsim 2.5 \times 10^{-5}$ / spill
- Mitigation of intensity – related effects
- Analysis optimization in progress to further increase performance
- Trigger upgrade to study new channels (e.g. $K^+ \rightarrow \pi^+ e^+ e^-$)
- Continuing LNV/LFV and dark sector searches with K^+
- A new measurement of V_{us}
- Data taking periods in dump [see J. Jerhot talk in parallel session]



$\mathcal{O}(15)\%$ final precision
expected on $\text{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu})$



$\mathcal{O}(\%)$ LFUV test
 $\times 2$ lower UL (10^{-11} sensitivity)

Plans for V_{us}/V_{ud} Measurements

Potential measurements to address the Cabibbo angle anomaly:

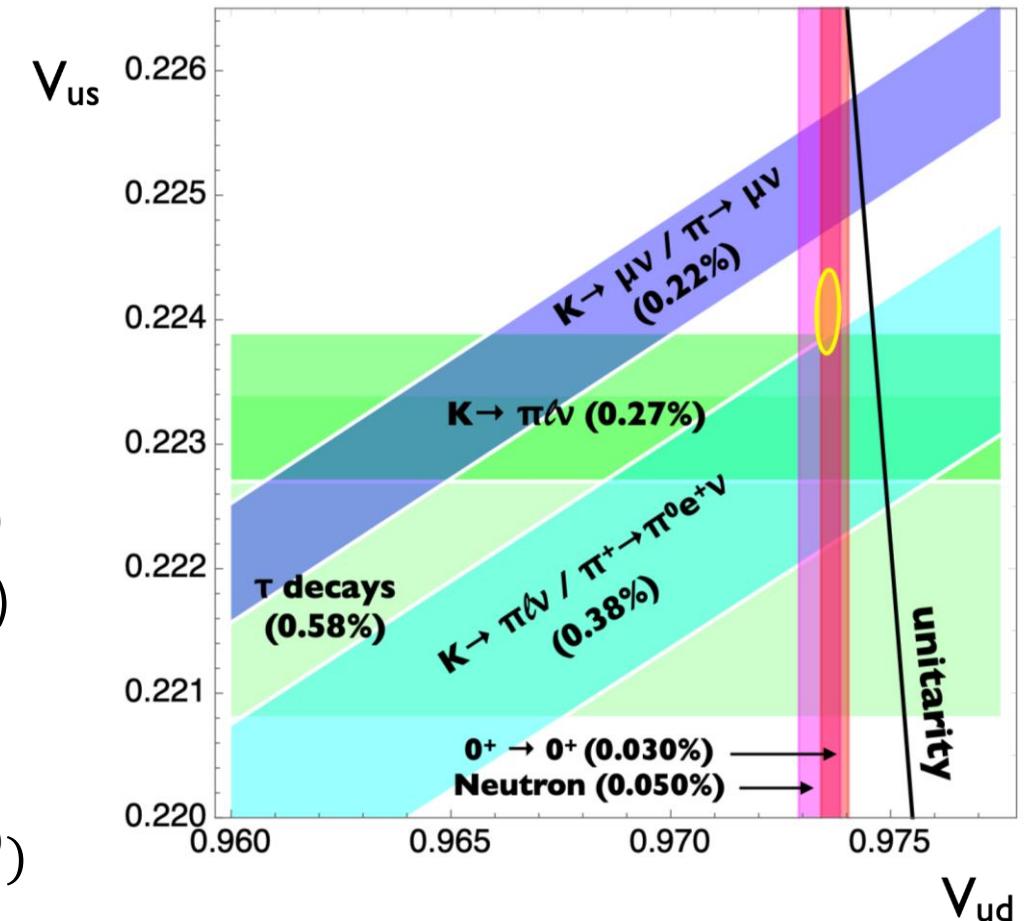
$$R_A^{K\mu_2} = \frac{\Gamma(K\mu_2)}{\Gamma(\pi\mu_2)}$$

$$R_A^{K\mu_3} = \frac{\Gamma(K\mu_3)}{\Gamma(\pi\mu_2)}$$

Strategy:

- Reconstructing decay-in-flight $\pi^+ \rightarrow \mu^+\nu$ from $K^+ \rightarrow \pi^+\pi^0$
- Cancellation of several systematic uncertainties (e.g. μ PID)
- Analysis ongoing on RUN1 data
- Expected statistical uncertainty < 1%
- Target systematic uncertainty $O(0.1\%)$
- External uncertainty from the knowledge of $\mathcal{B}(K^+ \rightarrow \pi^+\pi^0)$

arXiv:2111.05338



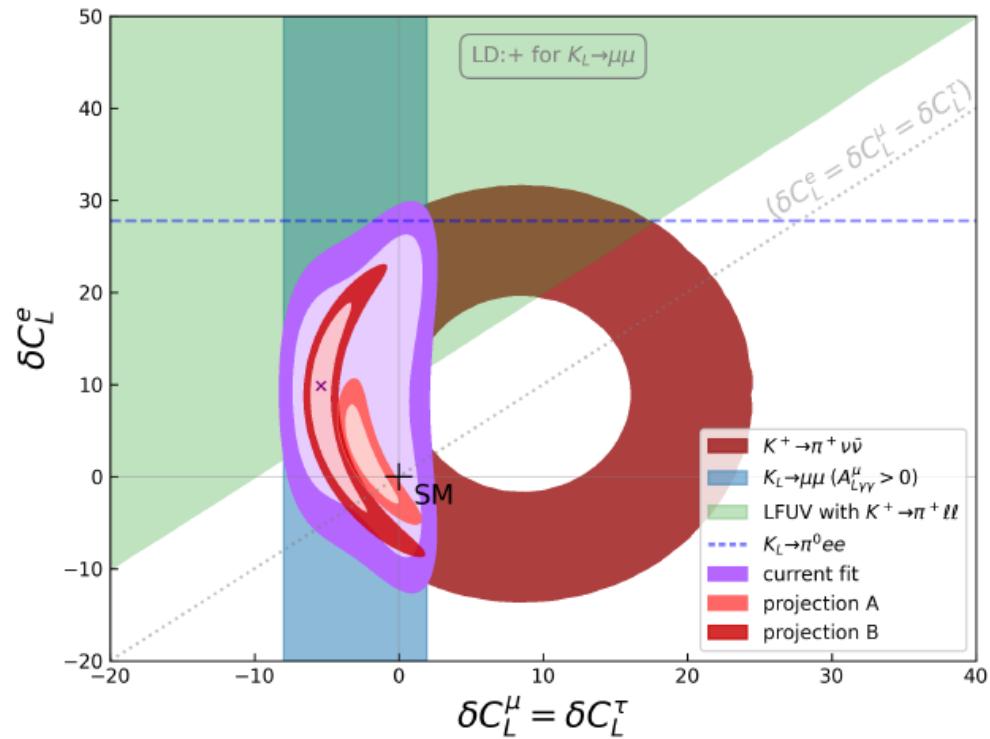
Kaon at CERN: Prospects - HIKE



(LoI - arXiv:2211.16586v1) [proposal to SPSC under preparation]

- K^+ and K_L physics program at CERN SPS after LS3
 - Intensity $\times 4 - \times 6$ with respect to NA62
 - Detectors with $\mathcal{O}(20\text{ ps})$ time resolution
 - Similar experimental layouts for charged and neutral phase
-
- **Physics program**
 - $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ approaching SM theory expectation
 - $K_L \rightarrow \pi^0 l^+ l^-$ observation and measurement of the BR
 - LFUV tests with precision < %
 - LFV – LNV searches with $\mathcal{O}(10^{-12})$ sensitivity
 - Measurement of V_{us} and main kaon decay modes
 - Dump physics in synergy with Shadows experiment

[arXiv:2206.14748v1]



Conclusions

Physics program with charged kaons successfully pursued at CERN SPS by NA62 (until LS3)

[JHEP06(2021)093]

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

$$BR = (10.6_{-3.4}^{+4.0} \pm 0.9) \times 10^{-11} \text{ (from data of 2016-17-18)}$$

Recent results on χPT studies

$$K^+ \rightarrow \pi^+ \gamma\gamma: \mathcal{O}(\%) \text{ precision}$$

$$K^+ \rightarrow \pi^0 e^+ \nu \gamma: \mathcal{O}(< \%) \text{ precision}$$

[arXiv:2304.12271]

$$K^+ \rightarrow \pi^+ \mu^+ \mu^-: \mathcal{O}(\%) \text{ precision}$$

[JHEP11(2022)011]

$$\mathcal{O}(10^{-11}) \text{ UL @ 90% CL}$$

LFUV, LNV, LFV studies

New result on dark sector studies with kaon decays

$$\text{Axion/scalar searches with } K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-: \mathcal{O}(10^{-8}) \text{ UL}$$

Future of physics with kaons at CERN SPS

HIKE project under discussion at CERN

$$K^+, K_L, \text{dark sector searches}$$

[arXiv:2211.16586v1]