Precision measurements with Kaons at CERN

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WIN2023

International Workshops on Weak Interactions and Neutrinos

Sun Yat-sen University (SYSU) in Zhuhai, China

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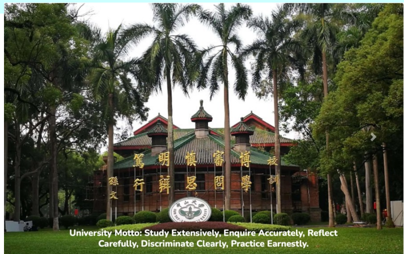
* On behalf of the NA62 Collaborations



Outline

Physics program with charged kaons successfully pursued at CERN SPS by NA62 and NA48/2

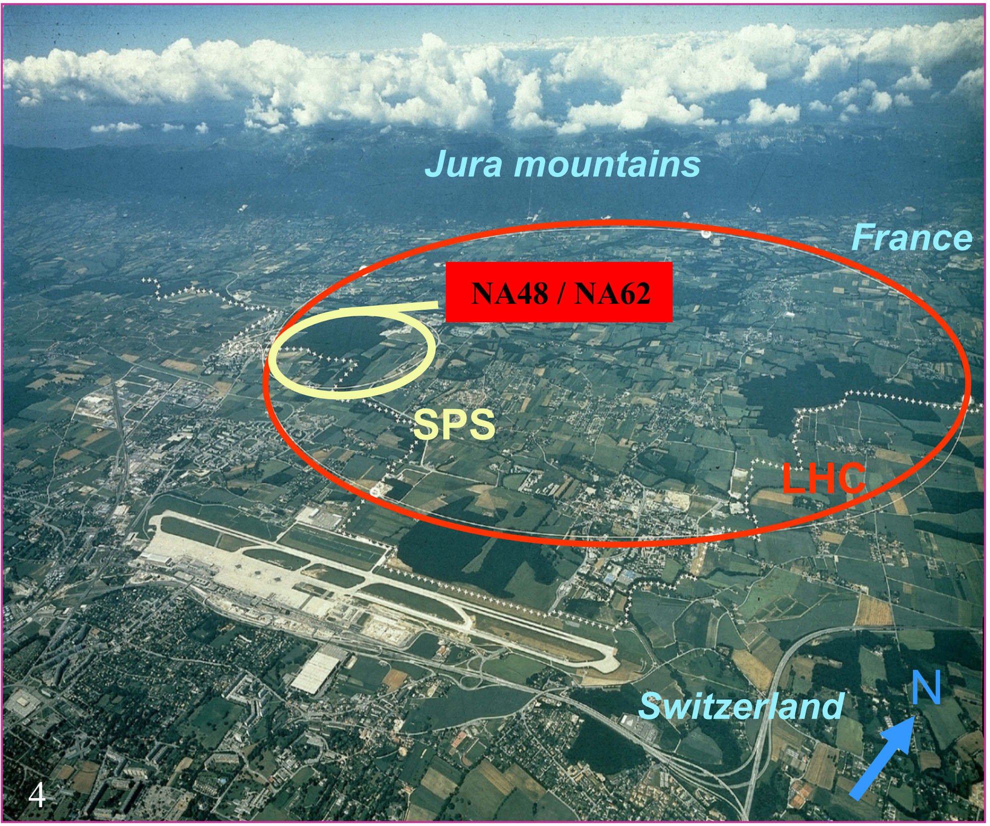
- ★ Measurement of the ultra rare process $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ — *JHEP 06 (2021) 093*
- ★ Recent results on χPT studies
  Precision measurements of the rare decays:
  - $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ — *JHEP 11(2022) 011*
  - $K^+ \rightarrow \pi^+ \gamma \gamma$ — *preliminary result*
  - $K^+ \rightarrow \pi^0 e^+ \nu \gamma$ — *arXiv: 2304.12271*
- ★ Searches for LFV/LNV processes — *PLB 797 (2019) 134794*, *PRL 127 (2021) 13 131802*, *PLB 830 (2022) 137172*, *PLB 838 (2023) 137679*
- ★ (K00μ4) first observation and BR by the NA48/2 experiment

Future of physics with kaons at CERN SPS

★ The NA62 experiment at the CERN kaon beam facility

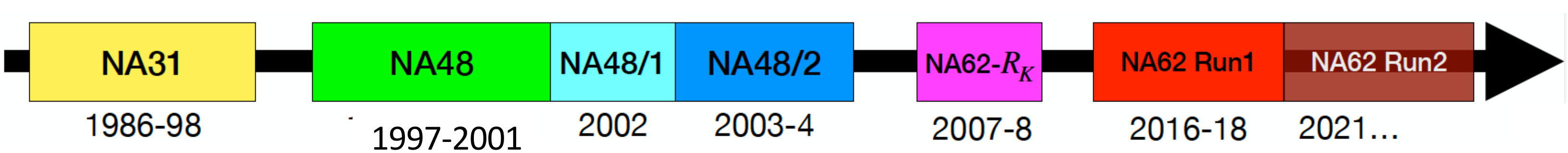
The NA62 experiment at CERN

A fixed target experiment at the CERN SPS dedicated to the study of rare decays in the kaon sector.

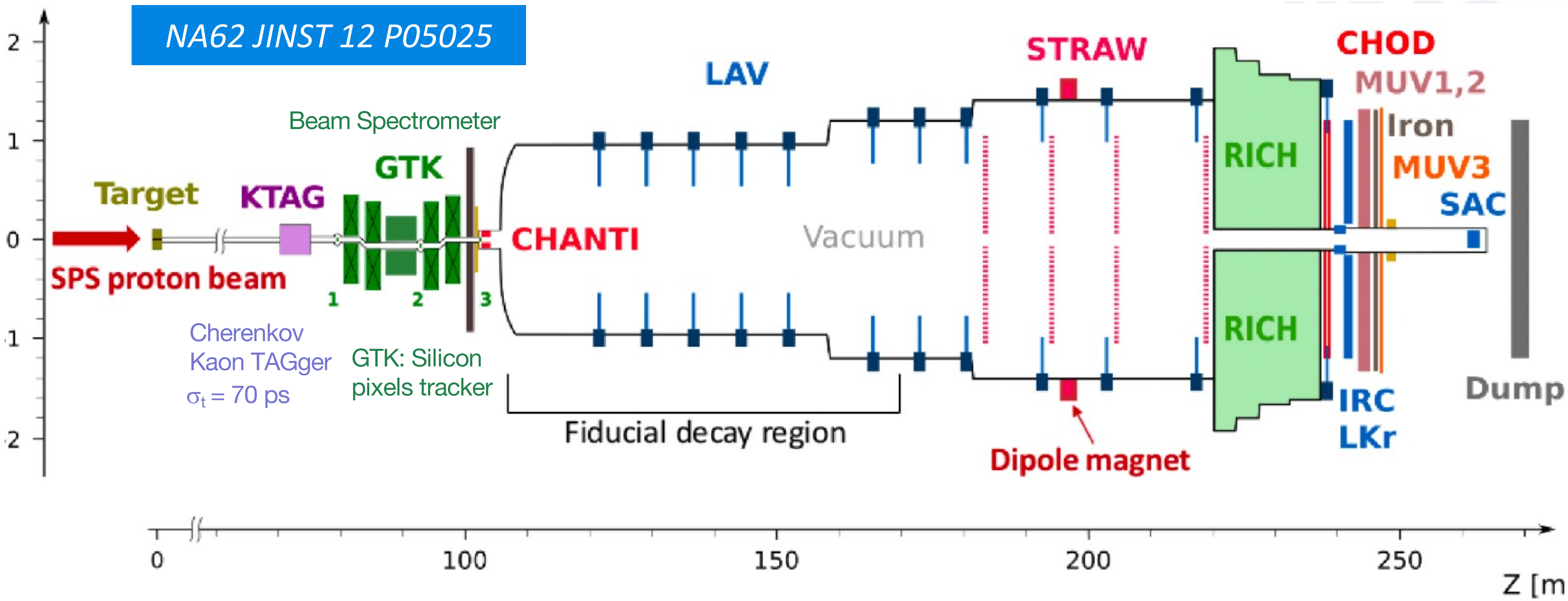


- Detector installation completed in 2016
- Physics runs in 2016, 2017 and 2018
- Data taking resumed in July 2021, approved up to CERN Long-Shutdown-3…
- Main goal: BR($K^+ \to \pi^+ \nu\bar{\nu}$) measurement
- Broad physics program thanks to unprecedented statistics for many decay modes

~300 physicists from 31 institutes in 11 countries



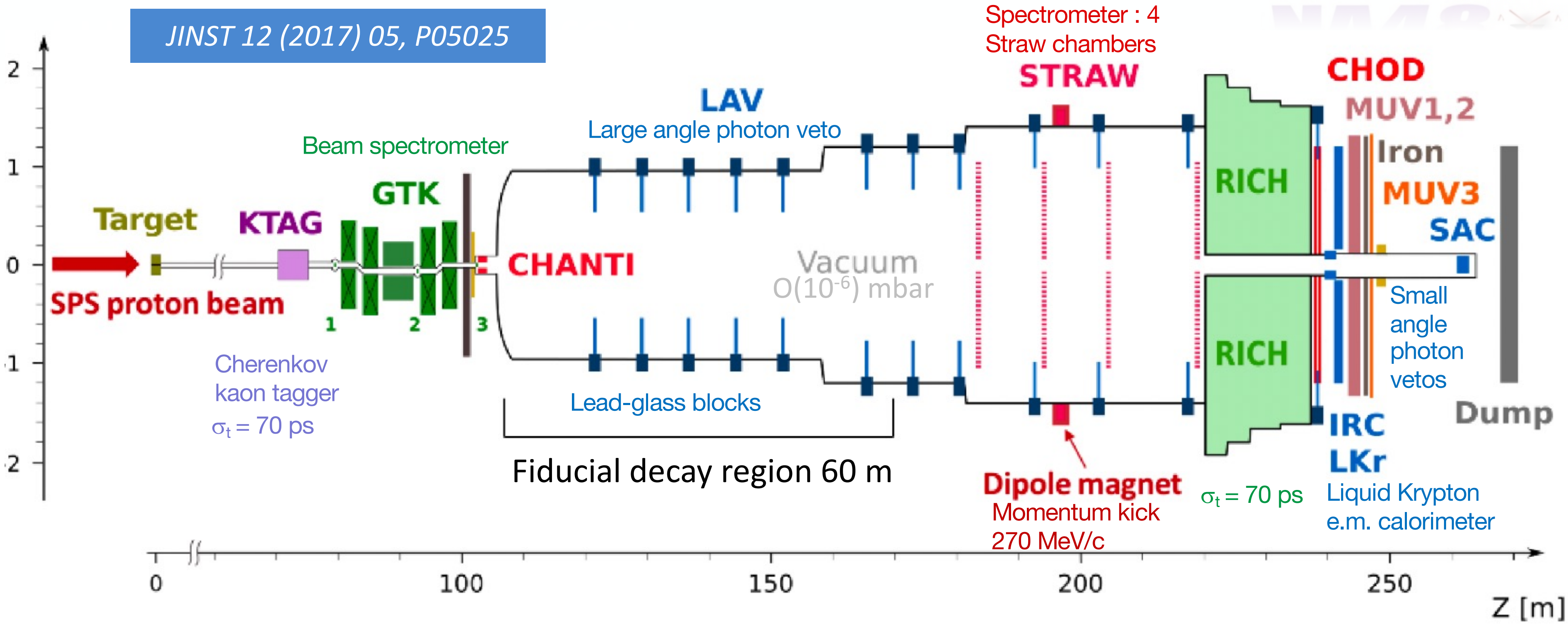
The NA62 kaon beam



- SPS beam: 400 GeV/c proton on beryllium target
- 75 ± 1 GeV/c unseparated secondary hadron beam (70% pions, 24% protons, 6% kaons)
- **Decay in-flight technique**: the high energy kaons decay in a ~60 m fiducial region

- Nominal beam particle rate (at GTK3): 750 MHz, O(10^{12}) pot per spill, ~3.5 s effective spill
- Average beam particle rate during 2018 data-taking: 500-750 MHz
- K^+ decay rate ~ 5 MHz

The NA62 detector



- Beam Si pixel spectrometer (**GTK**)
- Decay products magnetic spectrometer (**STRAW**)
- Particle identification system (**KTAG, RICH, MUVs**)
- **LKr**: electromagnetic calorimeter
- Veto system (**LAV, iRC, SAC, CHANTI, MUV, HASC**)
- CHOD: scintillator hodoscopes
- Multi level (**L0, L1, L**2) trigger

★ Measurement of the ultra rare process $K^+ \longrightarrow \pi^+ \nu \bar{\nu}$

JHEP 06 (2021) 093

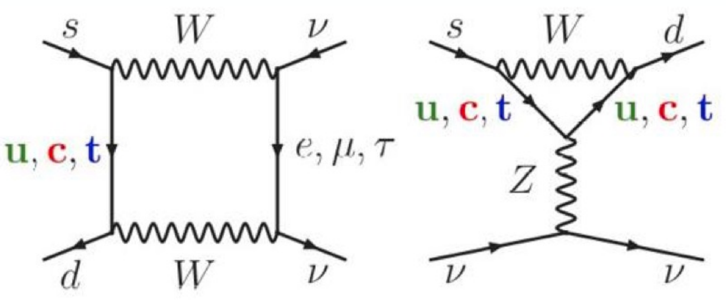
E787 and E949 experiments at BNL:

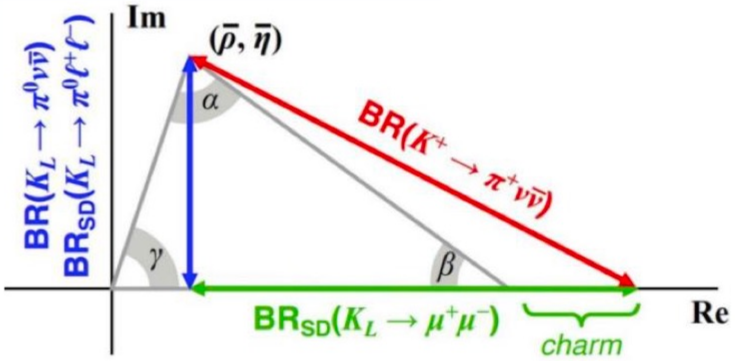
$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (17.3\ ^{+11.5}_{-10.5}) \times 10^{-11}$

Phys.Rev. D 77.052003 (2008), Phys.Rev. D 79.092004 (2009)

$K^+ \to \pi^+ \nu \bar{\nu}$: a Golden Decay Mode

SM: Box and Z-penguin diagrams





- Ultra rare FCNC: s → d transition, loop + hard GIM suppression
- Theoretically clean dominated by short-distance physics
- Negligible hadronic uncertainties
- K^+ - π^+ Form Factor (FF) extracted from $K^\pm \to \pi^0 l^\pm \nu_l$: sub % precision
- Sensitive to new physics in the lepton sector as well: involves ν_e ν_μ and ν_τ

Extremely rare process in the SM:

arXiv:2105.02868

$$BR_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = 7.73 \pm 0.16_{SD} \pm 0.25_{LD} \pm 0.54_{param.} \times 10^{-11}$$

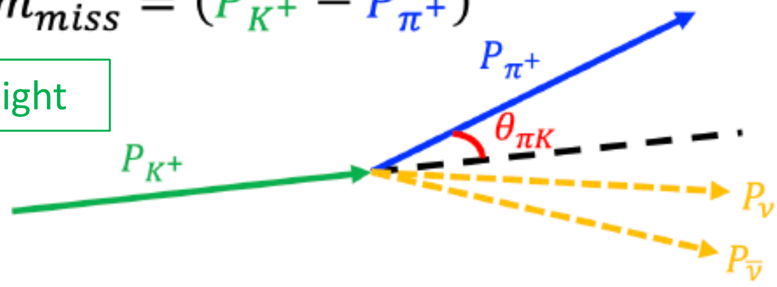
arXiv:2109.11032

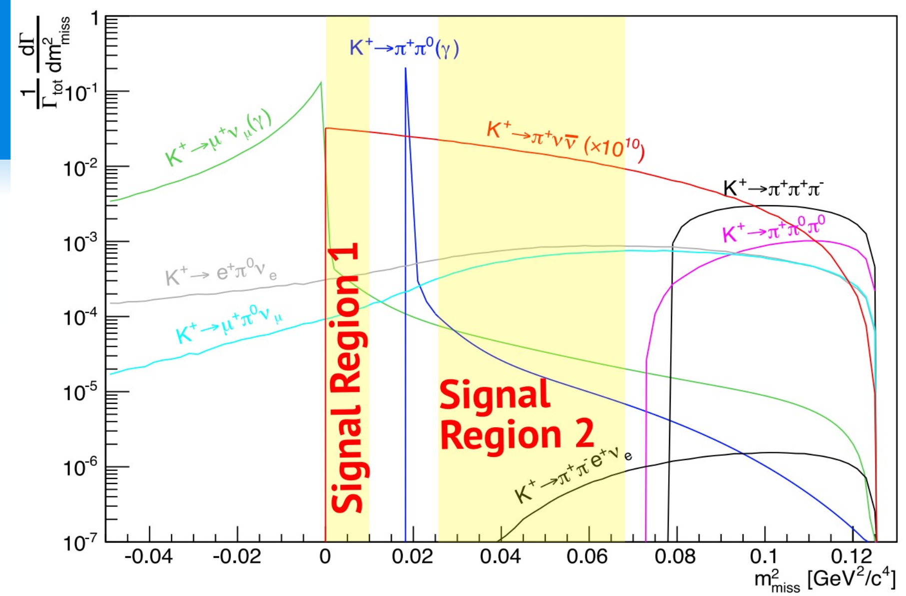
$$BR_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (7.92 \pm 0.28_{theory}) \times 10^{-11} \times [|V_{cb}|/41.0 \times 10^{-3}]^{2.8} \times [\sin\gamma/\sin 67°]^{1.39}$$

Measurements strategy

$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$

Decay in-flight



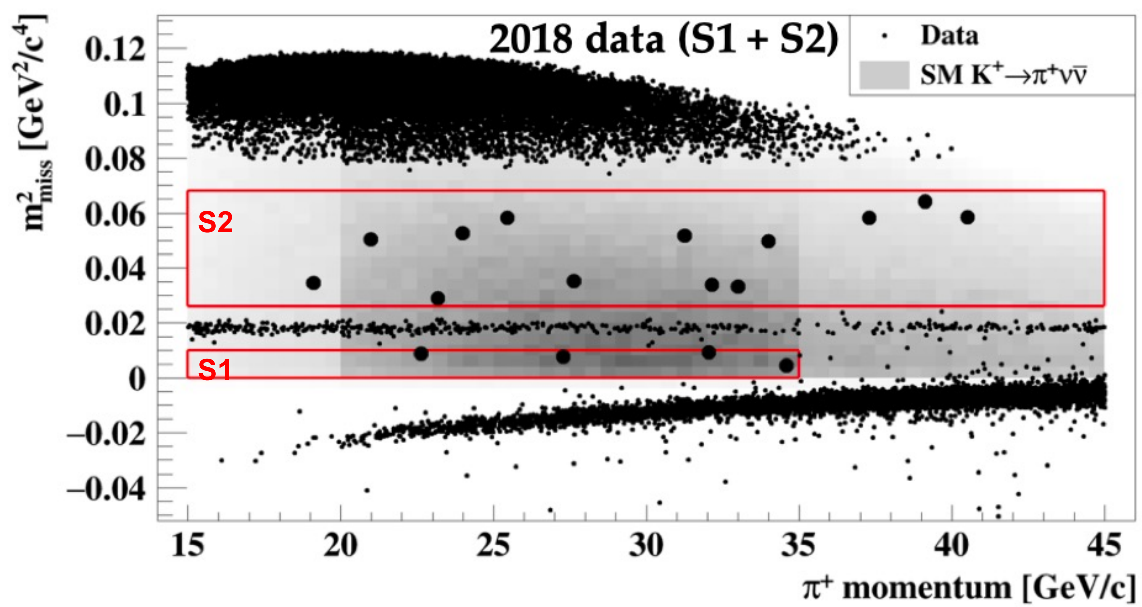


- ✓ Highly boosted decay: **K^+@(75 ± 1) GeV/c (γ 150)**
- ✓ Large undetectable missing energy carried away by the neutrinos
- ✓ All energy from visible particles must be detected + Particle ID (calorimeters, Cherenkov, muon-ID, photon veto)
- ✓ **π^+ momentum range 15-45 GeV/c (E_{miss} > 30 GeV)**
- ✓ **Hermetic detector coverage and O(100%) detector efficiency needed**
- ✓ **Blind analysis using control regions**

Requirements on background rejection:

- O(10^4) suppression from kinematic conditions
- O(10^7) from μ+ rejection
- O(10^7) from π^0 rejection
- O(100 ps) timing between sub-detectors

NA62 results from Run 1 (2016-2018)



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)	$5.42^{+1.00}_{-0.75}$

- **20 events observed in the signal region - full Run1 data sample**
- Combining the complete Run 1 data set and assuming **$BR_{SM}(8.4 \pm 1.0)\ 10^{-11}$:**

$N^{exp}_{\pi\nu\nu} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

$N^{exp}_{background} = 7.03^{+1.05}_{-0.82}$

$SES = (0.839 \pm 0.053_{syst}) \times 10^{-11}$

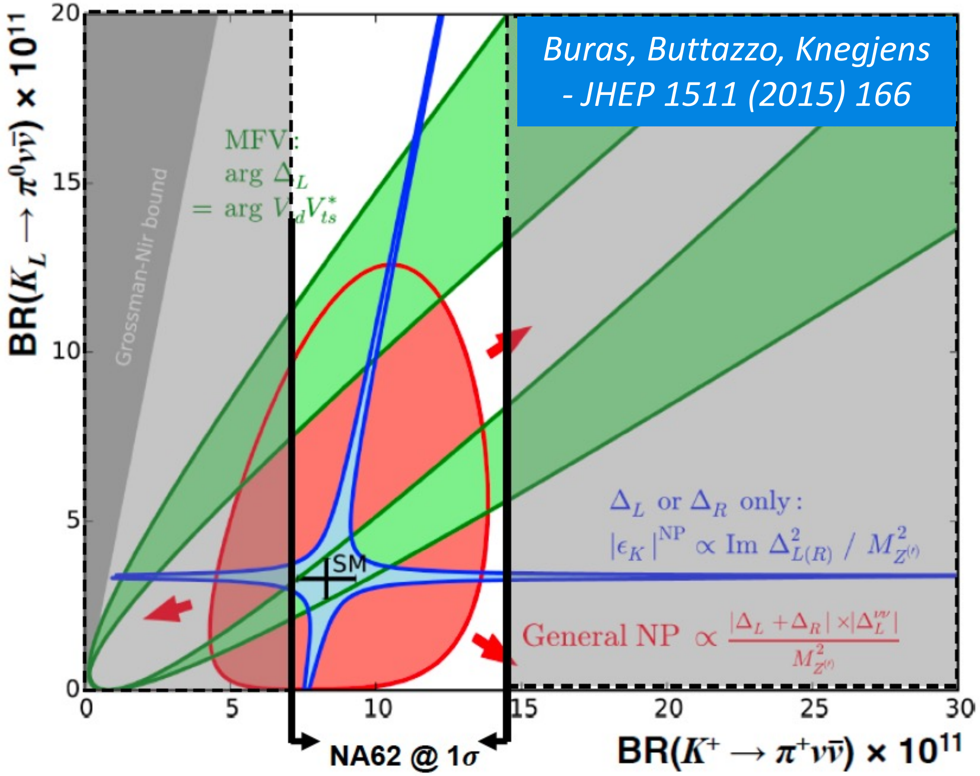
JHEP 06 (2021) 093

$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$ 3.4σ significance

Impact in the context of BSM models

NA62: BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) = ($10.6\ ^{+4.0}_{-3.4}\ |_{stat} \pm 0.9_{syst}$) x 10^{-11}

Not-SUSY models



arXiv:2006.01138

★ Recent results on χPT studies

Precision measurement of the rare processes:

$K^+ \rightarrow \pi^+ \mu^+ \mu^-$; $K^+ \rightarrow \pi^+ \gamma \gamma$; $K^+ \rightarrow \pi^0 e^+ \gamma \gamma$

JHEP 11(2022) 011

preliminary result

arXiv: 2304.12271

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

- Heavily suppressed FCNC transition: $s \to d\, l^+ l^-$
- Main kinematic variable: $z = \dfrac{m^2(l^+l^-)}{m^2_K}$
- Form Factor of the $K^\pm \to \pi^\pm \gamma^*$ transition: W(z)
- Chiral Perturbation Theory (ChPT) parametrization of W(z) at $O(p^6)$:

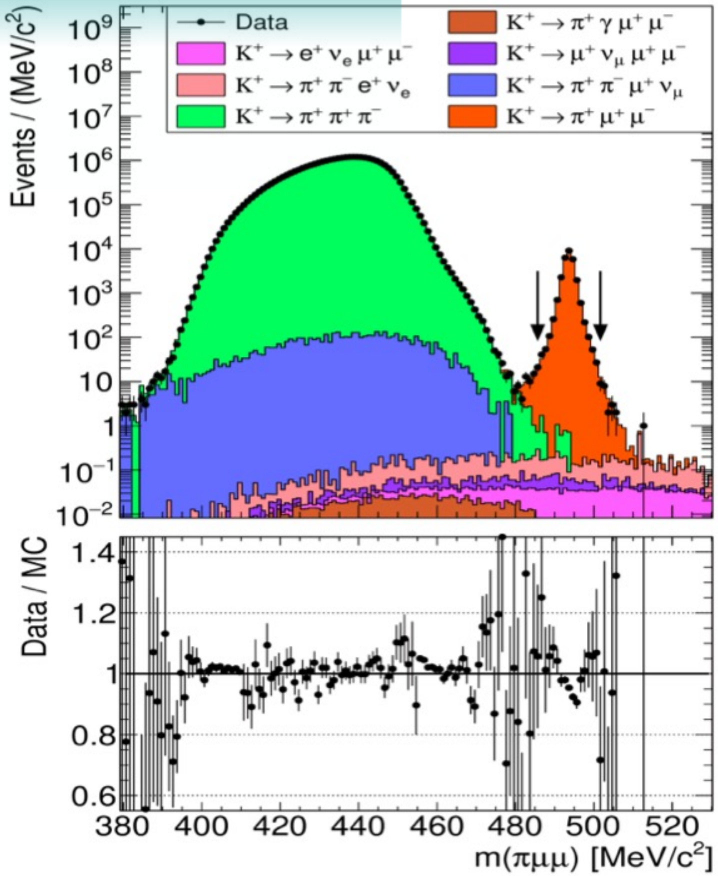
$$\mathbf{W(z) = G_F\, m^2_K\, (a_+ + b_+\, z) + W^{\pi\pi}(z)}$$

Form factors

Main goals of the measurement with NA62:

- Model independent measurement of the $B(\pi\mu\mu)$
- Measurement of the function $|W(z)|^2$
- Determine the Form Factor parameters a_+ and b_+
- Forward-backward asymmetry

Effective number of Kaons $N_K = 3.48\ 10^{12}$ (measured from K3π)



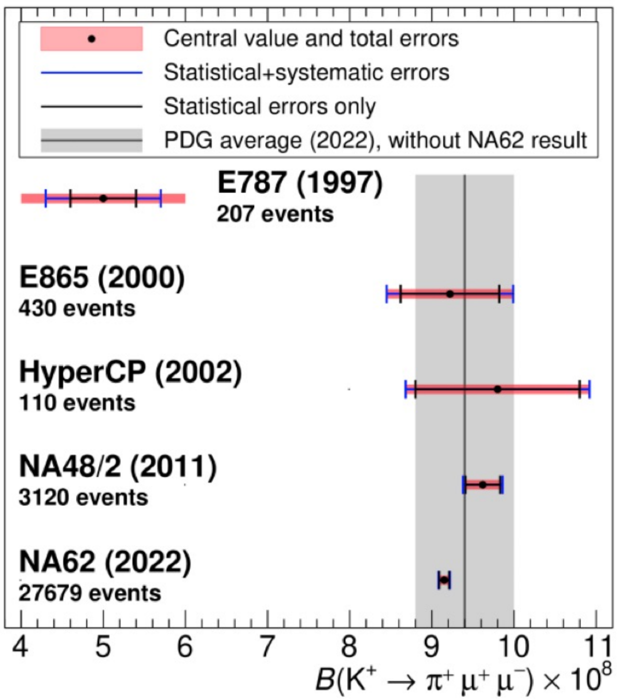
After signal selection:

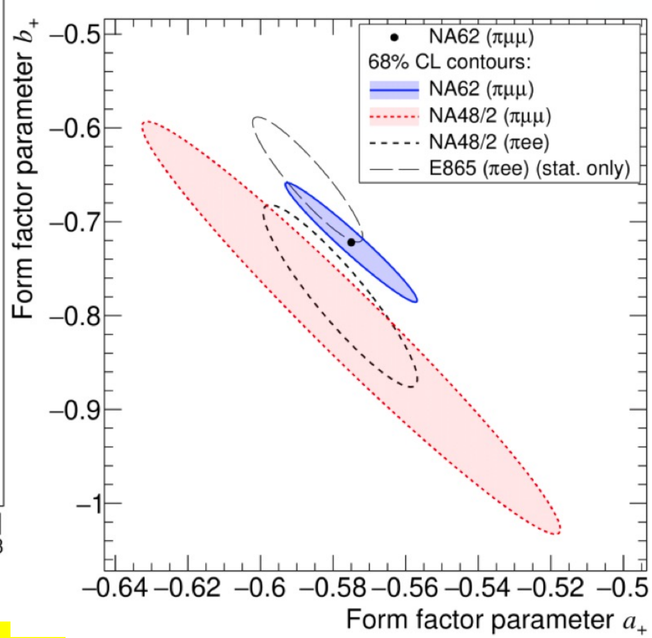
N_{obs} = 27 679 events

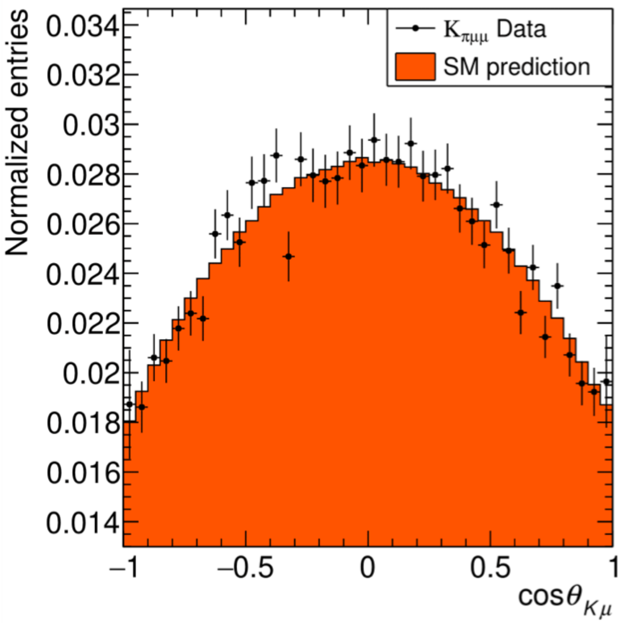
$N_{bg}^{exp} = 7.8 \pm 5.6$ events

The $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay results

JHEP 11 (2022) 011







$B_{\pi\mu\mu}$ = (9.15 ± 0.06$_{stat}$ ± 0.03$_{syst}$ ± 0.04$_{ext}$) x 10^{-8}

a_+ = - 0.575 ± 0.012$_{stat}$ ± 0.003$_{syst}$ ± 0.003$_{ext}$

b_+ = - 0.722 ± 0.040$_{stat}$ ± 0.013$_{syst}$ ± 0.011$_{sext}$

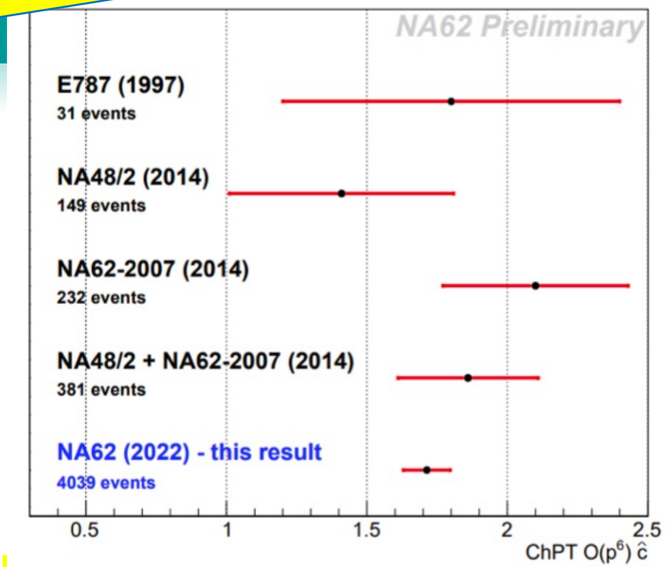
A_{FB} = (0.0 ± 0.7$_{stat}$) x 10^{-2}
68% CL measurement

| A_{FB} | < 0.9 10^{-2}
90% CL upper limit (*)
UL published as addendum
JHEP 06 (2023) 040

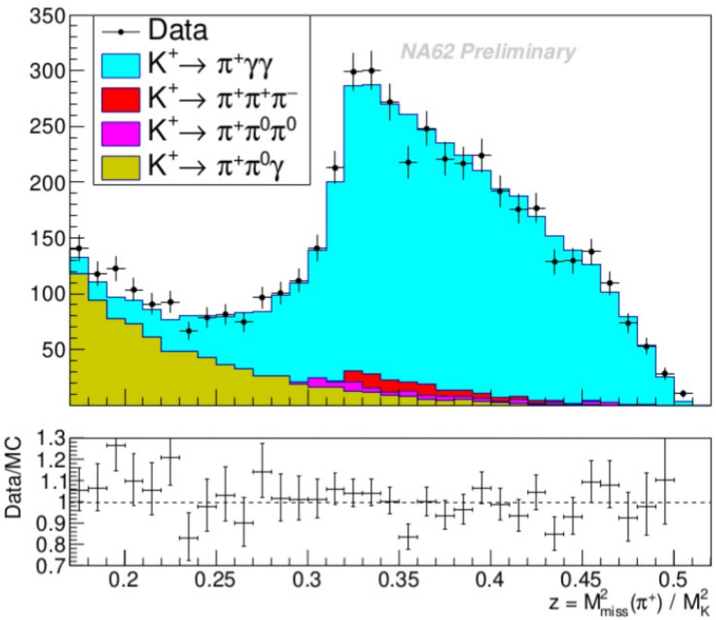
The $K^+ \to \pi^+ \gamma \gamma$ decay

preliminary

- Rare decay that allows ChPT tests at $O(p^6)$
- Main kinematic variable: $z = \frac{m^2_{\gamma\gamma}}{m^2_K}$; $y = \frac{P_K(Q_{\gamma 1}-Q_{\gamma 2})}{m^2_K}$
- $BR(K^+ \to \pi^+\gamma\gamma)$ at $O(p^6)$ parametrized by a real **parameter $\hat{c}$**



$\hat{c} = 1.713 \pm 0.075_{stat} \pm 0.037_{syst}$

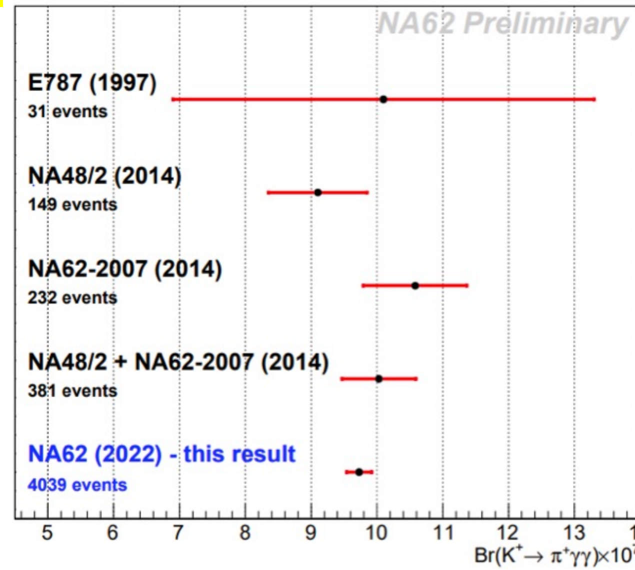


After signal selection:

N_{obs} = 4 039 events

$N_{bg}^{exp} = 393 \pm 20$ events

Main background:
Cluster merging in the e.m. calorimeter

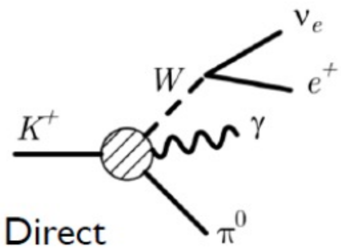


$B_{\pi\gamma\gamma} = (9.73 \pm 0.17_{stat} \pm 0.08_{syst}) \times 10^{-7}$

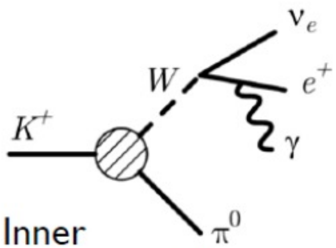
$K^+ \to \pi^0 e^+ \nu \gamma$ Precision Measurement

Theory: LD dominated (Chiral Perturbation theory)

IR and collinear divergence



Direct Emission



Inner Brehmsstrahlung

Eur. Phys. J. C 50 (2007)

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

Goal: Measurement of

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

phase space conditions

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

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

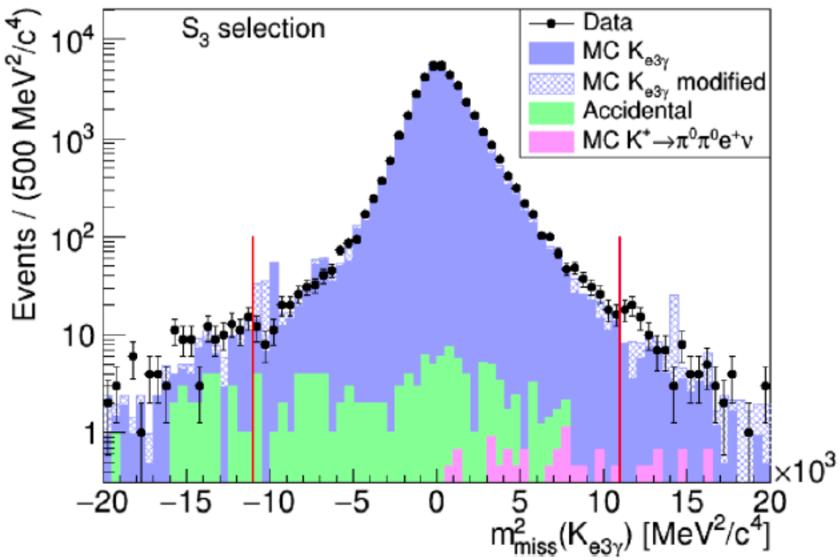
$K^+ \rightarrow \pi^0 e^+ \nu \gamma$ Precision Measurement

new result

Normalization: $K^+ \rightarrow \pi^0 e^+ \nu$
Selected as signal without γ radiative,
cut on $m^2_{miss}(K_{e3})$

$$R_j = \frac{\mathcal{B}(K_{e3\gamma^j})}{\mathcal{B}(K_{e3})} = \frac{N^{\mathrm{obs}}_{Ke3\gamma^j} - N^{\mathrm{bkg}}_{Ke3\gamma^j}}{N^{\mathrm{obs}}_{Ke3} - N^{\mathrm{bkg}}_{Ke3}} \cdot \frac{A_{Ke3}}{A_{Ke3\gamma^j}} \cdot \frac{\epsilon^{\mathrm{trig}}_{Ke3}}{\epsilon^{\mathrm{trig}}_{Ke3\gamma^j}}$$

$$A^{\mathrm{NA62}}_{\xi} = A^{\mathrm{Data}}_{\xi} - A^{\mathrm{MC}}_{\xi}$$ With $A^{MC}_{\xi} = 0$ within 10^{-4}



	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	$(1.0 \pm 1.0) \times 10^4$	$(6.0 \pm 1.8) \times 10^2$	$(3.4 \pm 1.2) \times 10^2$	$(1.2 \pm 0.6) \times 10^2$

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

	ChPT O(p^6)	ISTRA+	OKA	NA62
	Eur. Phys. J. C 50 (2007) 557 *Eur. Phys. J. C 48 (2006) 427*	*Phys.Atom. Nucl. 70 (2007) 702*	*Eur. Phys. J. C 81.2 (2021) 161* *JETP Lett. 116 (2022) 608*	*arXiv: 2304.1227i* *submitted to JHEP*
$R_1 \times 10^2$	1.804 ± 0.021	1.81 ± 0.03 ± 0.07	1.990 ± 0.017 ± 0.021	1.715 ± 0.005 ± 0.010
$R_2 \times 10^2$	0.640 ± 0.008	0.63 ± 0.02 ± 0.03	0.587 ± 0.010 ± 0.015	0.609 ± 0.003 ± 0.006
$R_3 \times 10^2$	0.559 ± 0.006	0.47 ± 0.02 ± 0.03	0.532 ± 0.010 ± 0.012	0.533 ± 0.003 ± 0.004
$A_\xi(S_1) \times 10^3$			–0.1 ± 3.9 ± 1.7	–1.2 ± 2.8 ± 1.9
$A_\xi(S_2) \times 10^3$	-0.059		7.0 ± 8.1 ± 1.5	–3.4 ± 4.3 ± 3.0
$A_\xi(S_3) \times 10^3$		0.015 ± 0.021	–4.4 ± 7.9 ± 1.9	–9.1 ± 5.1 ± 3.5

Decay rates:
- Factor > 2 more precise than previous measurements
- Relative uncertainty < 1%
- 5% smaller than ChPT prediction O(3σ)

T asymmetry:
- Compatible with no asymmetry
- Improved precision
- Uncertainty still O(10^2) larger than predictions

new result submitted to JHEP

★ Searches for Lepton Flavour and Lepton Number violation

PLB 797 (2019) 134794

PRL 127 (2021) 13 131802

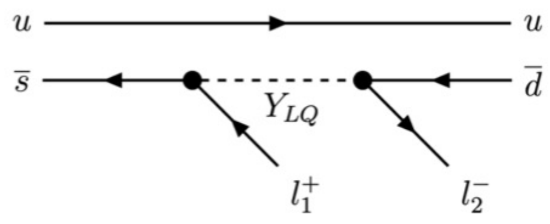
PLB 830 (2022) 137172

PLB 838 (2023) 137679

LFV/LNV searches

Lepton Flavour/Number Violation:

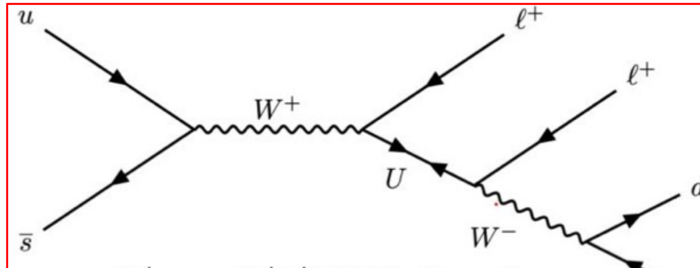
many decay modes forbidden in the SM



$K^+ \to \pi^\pm\mu^\mp e^+$ (LFV)

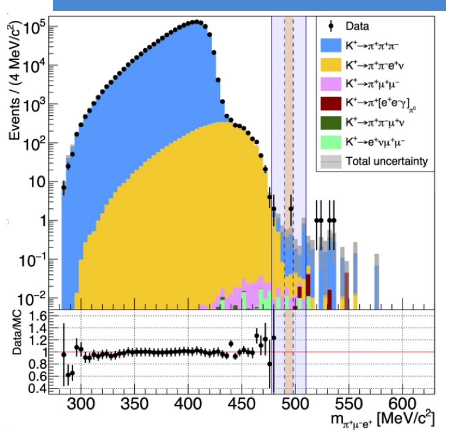
LFV - leptoquark mechanism

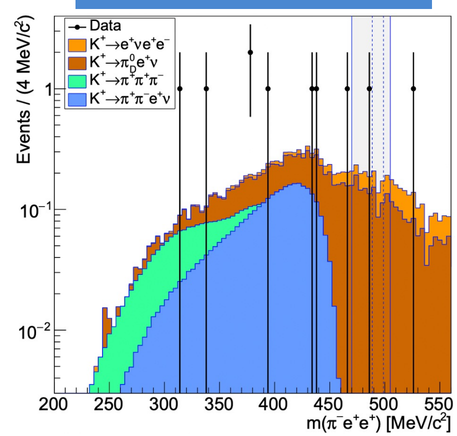
LNV - Type-I seesaw mechanism

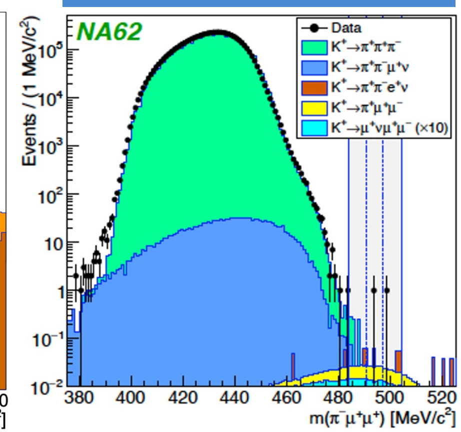


$K^+ \to \pi^- l^+ l^+ (\mathrm{LNV}, \Delta L = 2)$

$K^+ \to \pi^\mp\mu^\pm e^+$	$K^+ \to \pi^- e^+ e^+$	$K^+ \to \pi^- \mu^+ \mu^+$
PRL 127 (2021) 13, 131802	PL B 830 (2022) 137172	PLB 797 (2019) 134794







Obtained Upper Limits on BRs ~O(10^{-11})

LFV/LNV 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)

	Decay channel	Previous UL	NA62 UL @90% CL
PRL 127 (2021) 13 131802	$K^+ \to \pi^- \mu^+ e^+$	BR < 5.0 × 10^{-10}	BR < 4.2 × 10^{-11}
PRL 127 (2021) 13 131802	$K^+ \to \pi^+ \mu^- e^+$	BR < 5.2 × 10^{-10}	BR < 6.6 × 10^{-11}
PRL 127 (2021) 131802	$\pi^0 \to \mu^- e^+$	BR < 3.4 × 10^{-9}	BR < 3.2 × 10^{-10}
PLB 797 (2019) 134794	$K^+ \to \pi^- \mu^+ \mu^+$	BR < 8.6 × 10^{-11}	BR < 4.2 × 10^{-11}
PLB 830 (2022) 137172	$K^+ \to \pi^- e^+ e^+$	BR < 6.4 × 10^{-10}	BR < 5.3 × 10^{-11}
PLB 830 (2022) 137172	$K^+ \to \pi^- \pi^0 e^+ e^+$	N/A	BR < 8.5 × 10^{-10}
PLB 838 (2023) 137679	$K^+ \to \mu^- \nu e^+ e^+$	N/A	BR < 8.1 × 10^{-11}

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

Experimental results status

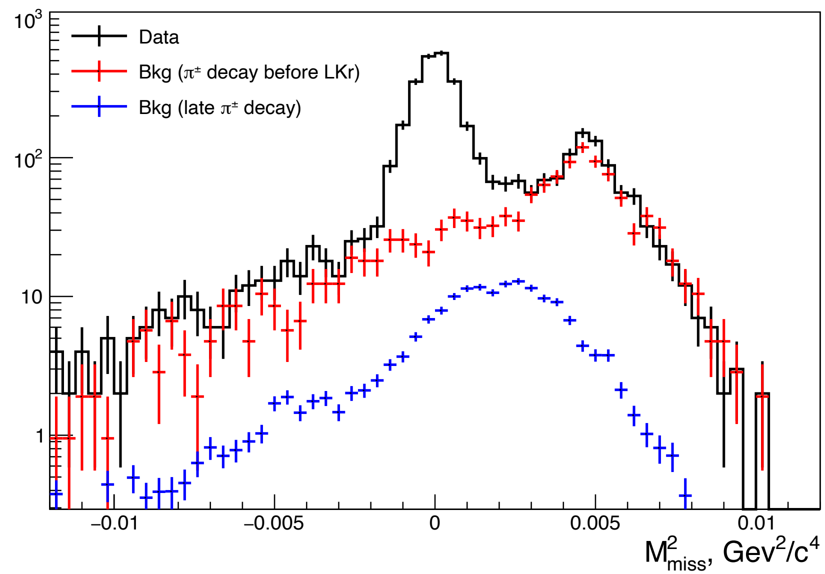
K_{l4} mode	BR $[10^{-5}]$	N_{cand}	
$K_{e4}^{\pm}$	4.26 ± 0.04	1108941	NA48/2 (2012)
K_{e4}^{00}	2.55 ± 0.04	65210	NA48/2 (2014)
$K_{\mu 4}^{\pm}$	1.4 ± 0.9	7	Bisi et al. (1967)
$K_{\mu 4}^{00}$			

- ✓ $K^{\pm} \to \pi^0 \pi^0 \pi^{\pm}$ as normalization channel
- ✓ $K^{\pm} \to \pi^0 \pi^0 (\pi^{\pm} \to \mu^{\pm} \nu)$ largest background
- ✓ $S_{\ell} = m^2(\mu^{\pm} \nu) > 0.03$ Gev²/c⁴

2 437 events observed

Background events expected = $374 \pm 0.33_{stat} \pm 62_{syst}$

Signal and predicted background events



- ✓ First Observation of muon mode with $\pi^0\pi^0$
- ✓ Test of $ChPT_{st}$

very preliminary

BR($K^{\pm} \to \pi^0 \pi^0 \mu^{\pm} \nu$, $S_{\ell} = m^2(\mu^{\pm} \nu) > 0.03$ Gev²/c⁴) $= (0.65 \pm 0.03) \times 10^{-6}$

BR($K^{\pm} \to \pi^0 \pi^0 \mu^{\pm} \nu$) $= (3.4 \pm 0.2) \times 10^{-6}$

Kaon at CERN: Plans

NA62 RUN2

•On-going: data taking foreseen at least until 2025 (included), +45-50% increase of intensity vs RUN1

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

•Hardware upgrades implemented mainly to improve on $\pi\nu\bar{\nu}$

•Trigger upgrade to study new channels (e.g. $K^+ \to \pi^+ e^+ e^-$)

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

•Continuing LNV/LFV and dark sector searches with K^+

•A new measurement of $V_{us}/\ V_{ud}$

•Direct searches of new particles below the EW scale Data taking periods in dump mode (Dark sector, Axion/Scalar ($\boldsymbol{K^+ \to \pi^+ aa}$; $\boldsymbol{K + \to \pi^+ S}$, $\boldsymbol{S \to AA}$) searches with $K^+ \to \pi^+ e^+ e^- e^+ e^-$: UL $\mathcal{O}(10^{-8})$

Future of physics with kaons at CERN SPS

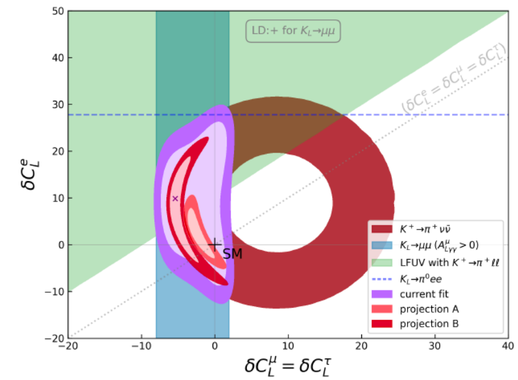
Letter of Intent: arXiv:2211.16586v1

HIKE project under discussion at CERN: K^+, K_L, dark sector searches

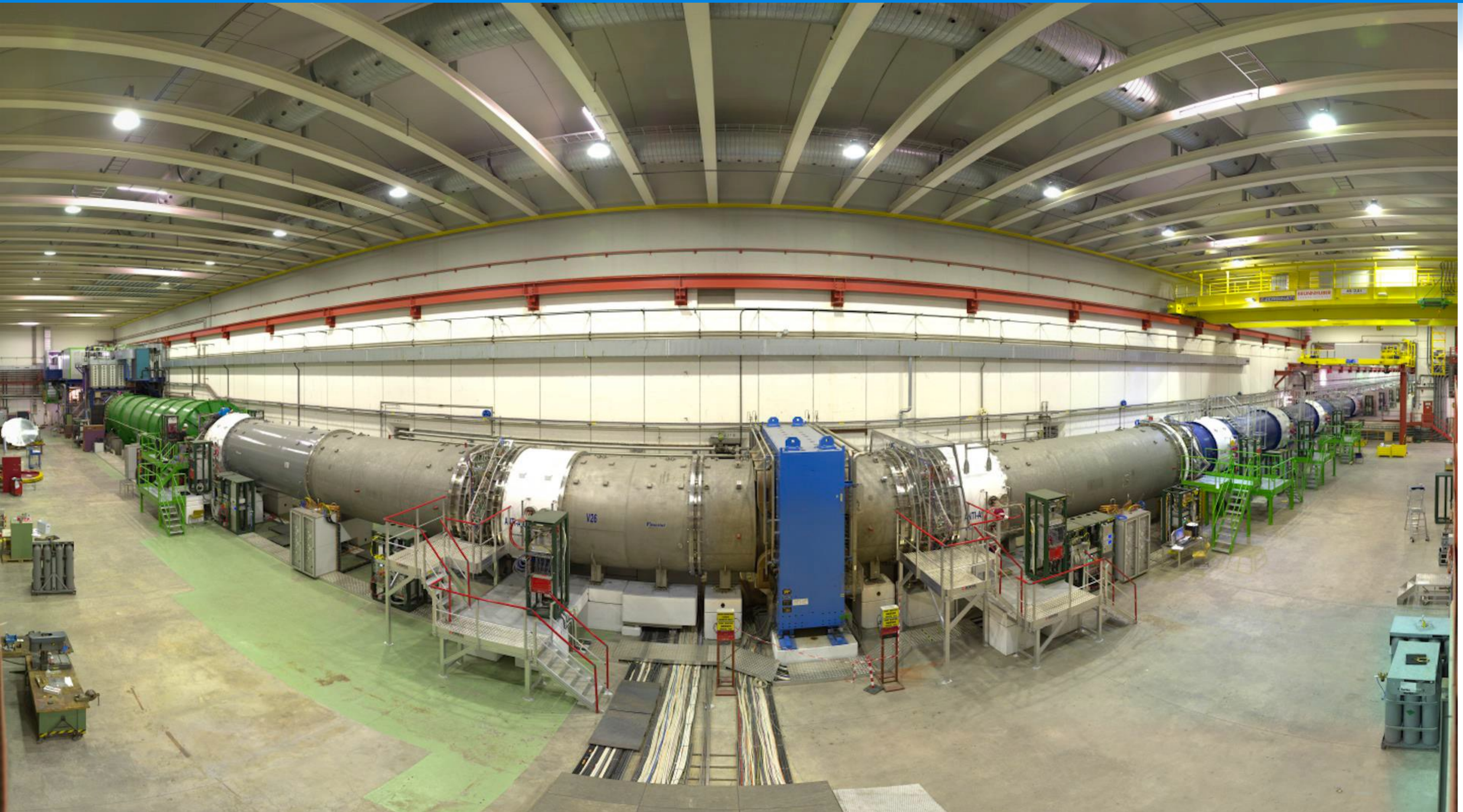
Intensity × 4-6 with respect to NA62; Detectors with $\mathcal{O}(20\ ps)$ time resolution; Similar experimental layouts

Physics program

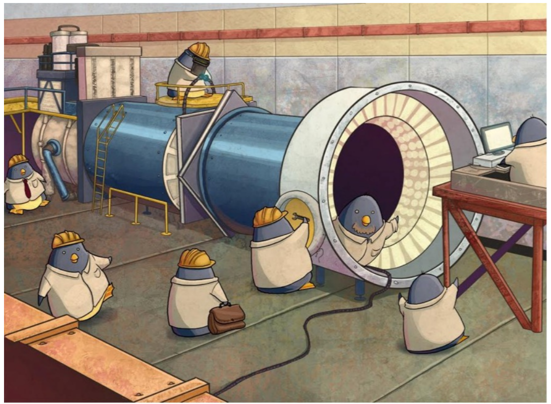
- $K^+ \to \pi^+ \nu\bar{\nu}$ approaching SM theory expectation
- $K_L \to \pi^0 l^+ l^-$ observation and measurement of the BR
- LFUV tests with precision < %
- LFV – LNV searches with $\mathcal{O}(10^{-12})$ sensitivity
- Measurement of V_{us} and main kaon decay modes
- Dump physics in synergy with Shadows experiment



Thank you for your attention



★ Backup slides



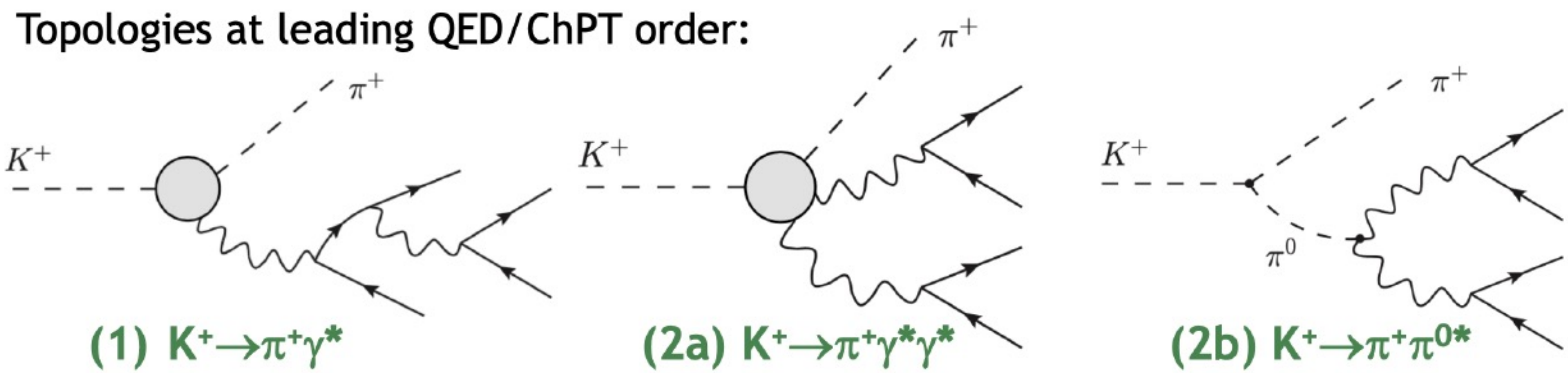
★ Exotics: Beam Dump Mode and Dark photon searches: $A' \longrightarrow \mu^+ \mu^-$

2021 data - arXiv: 2303.08666c

2021 data - preliminary result

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

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



Dark sector probe:

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

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

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

$K^+ \longrightarrow \pi^+ e^+ e^- e^+ e^-$

new result

Analysis: RUN1 Data

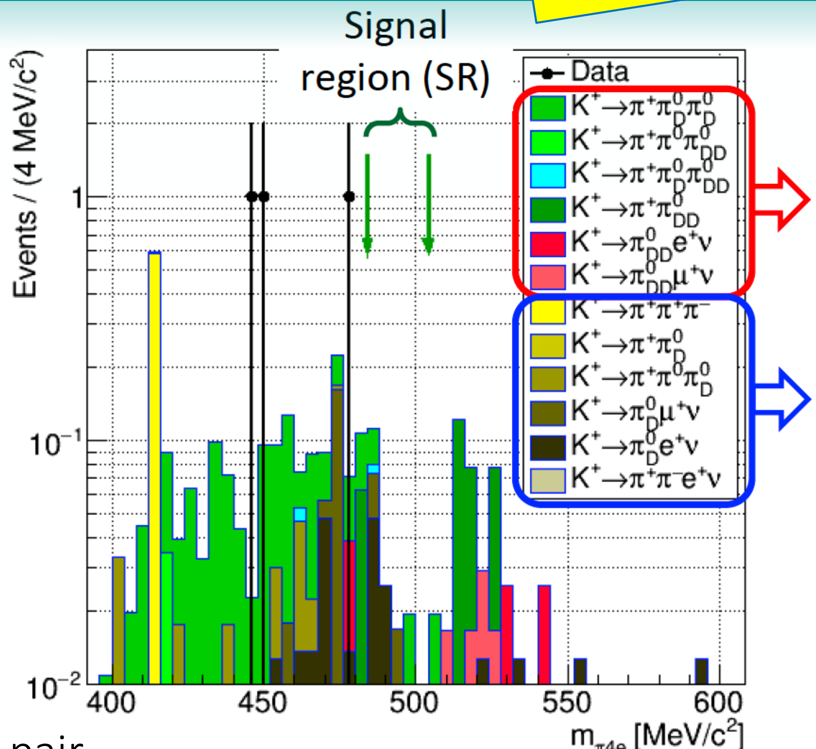
Signal ($K_{\pi 4e}$)

5 -track vertex topology

Kinematic PID of positive tracks

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

m_{4e}outside the π^0 mass region



Background:

5-track like K^+ decay

3-track K^+ decays overlapping with a $K \rightarrow 3\pi$ decay

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

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

Kinematic condition on m_{4e}

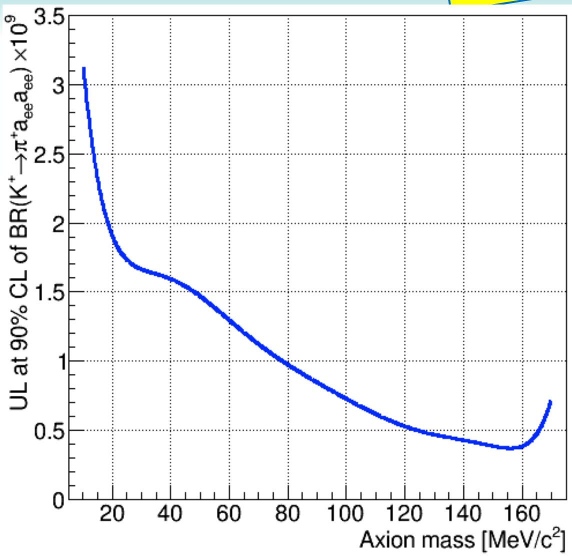
$K_{\pi 4e}$: 0.18 ± 0.06

$Dark$: 0.0004 ± 0.0004

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

new result

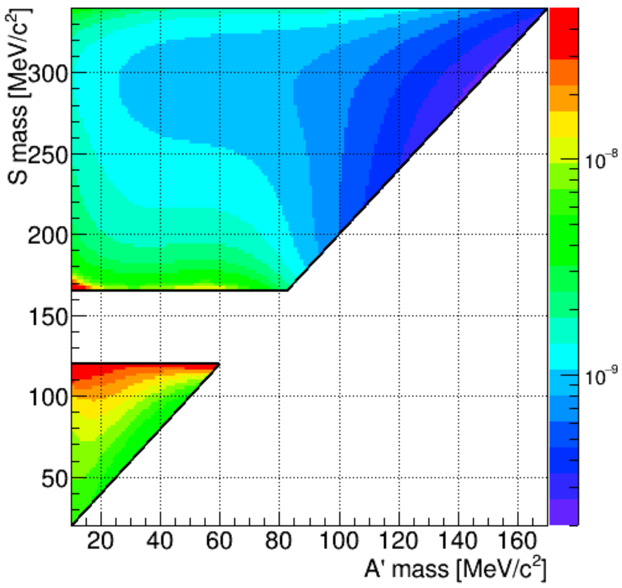
Procedure:
$K_{\pi 4e}$ SM: Acceptance from MC
Resonant amplitude negligible for selected events
No candidate observed in SR



$K^+ \rightarrow \pi^+ aa$
Uniform phase space
Mass scan 5 MeV/c^2 step

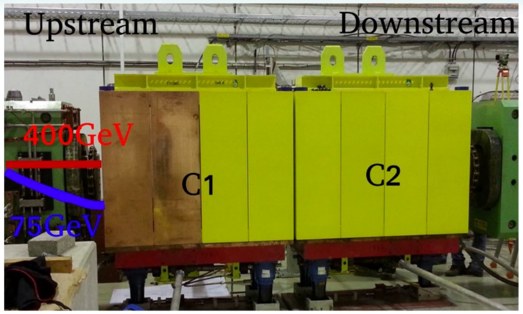
Result
$BR(K^+ \rightarrow \pi^+ e^+ e^- e^+ e^- < 1.4 \times 10^{-8}$ @90%CL

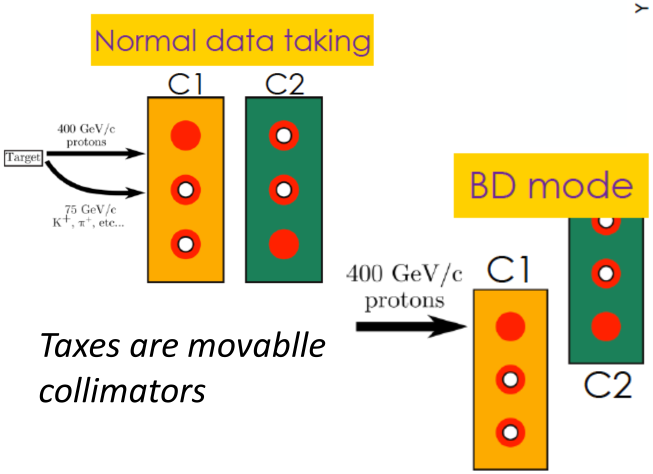
$K^+ \rightarrow \pi^+$ **S S → AA**
Di-axion AA mass scan
(mA', m_S) distribution smoothing (low MC statistics)



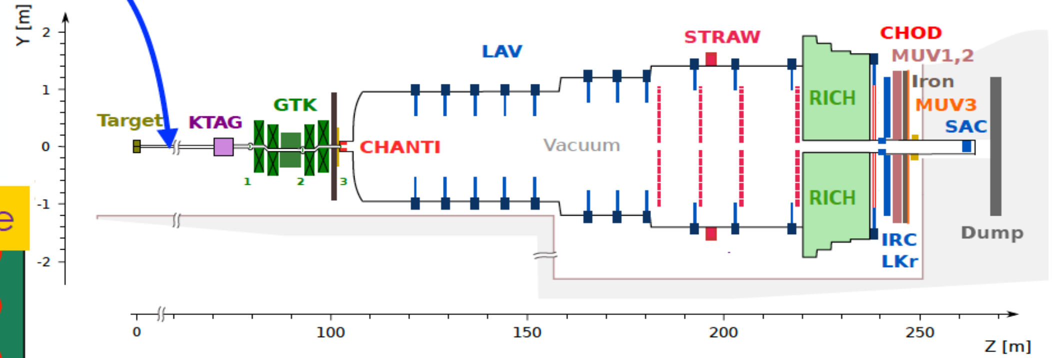
Exotics: Beam Dump Mode & $A' \to \mu^+\mu^-$

- Feebly interacting dark photon with free mass and coupling ε
- **Beam dump mode:** 3.2m Cu-Fe collimators (TAX) used as target
- Search for dark photon production in interactions with TAXs
- **(1.40 ± 0.28) x 10^{17} POT collected in ~10 days in 2021**

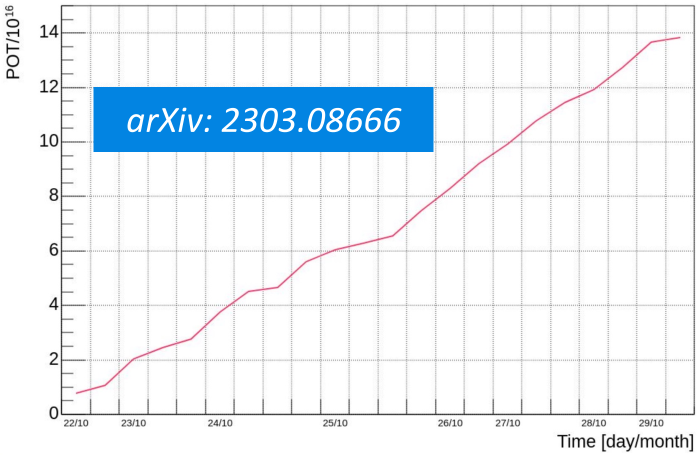




Taxes are movablle collimators

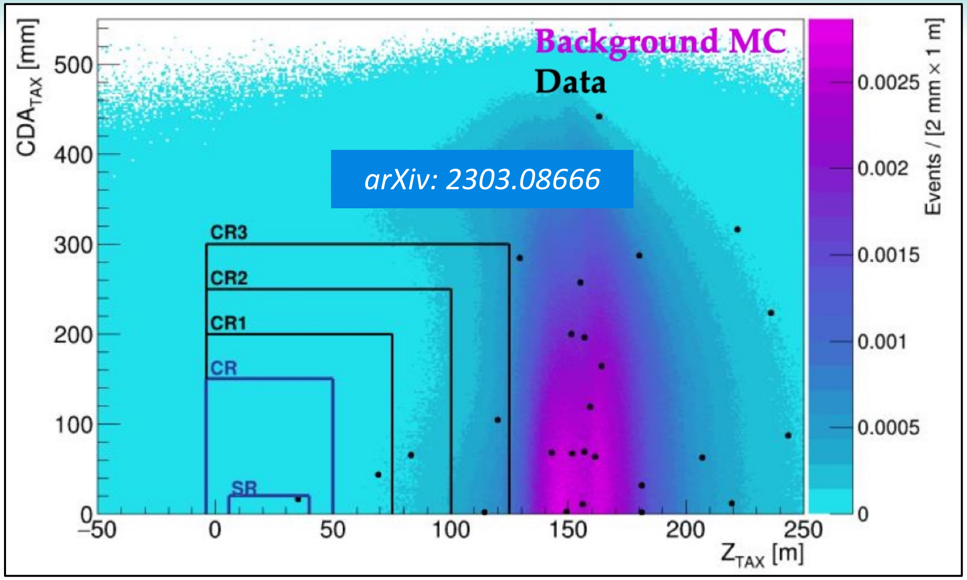


- Beam-line optimised in 2021: Improved sweeping & higher intensity
- Single & 2-track triggers.
- Search for Dark photon decays: $A' \to \mu^+\mu^-$



POT measured by beam secondary emission monitor

Dark photon searches: A’ ⟶ $\mu^+ \mu^-$



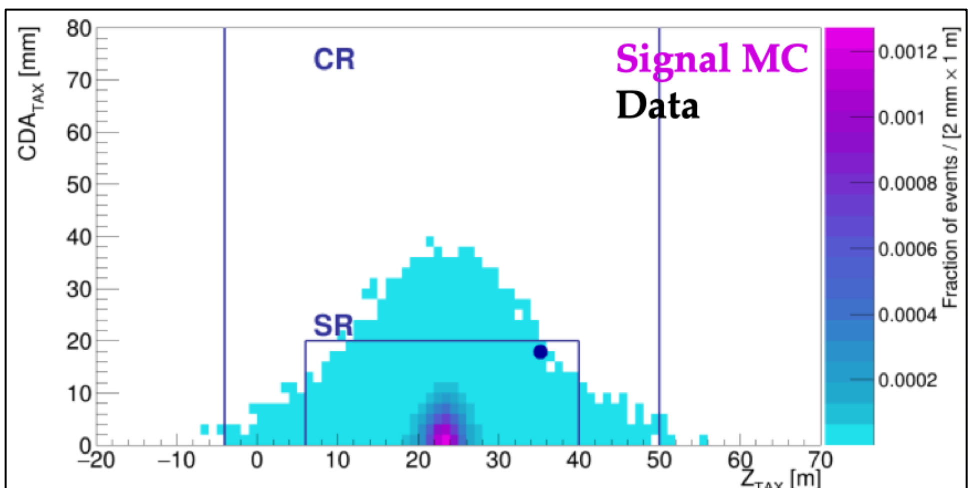
Probability to observe 1 or more events in the SR is 1.59%

After signal selection:

$N_{bg}^{expected}$ = 0.016 ± 0.002 events

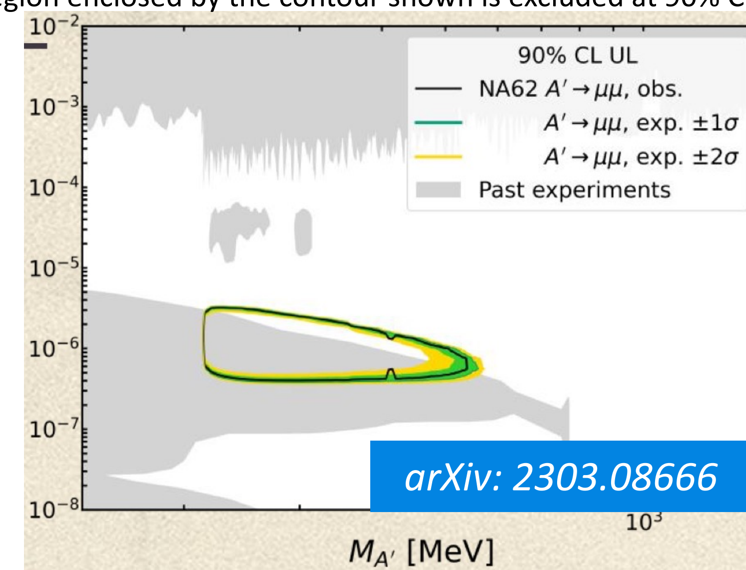
$N_{observed}$ = 1 event

2.4 σ significance (counting experiment)



Signal shape not taken into account for the significance

The region enclosed by the contour shown is excluded at 90% CL



Dark photon searches: A' → $e^+ e^-$

NEW

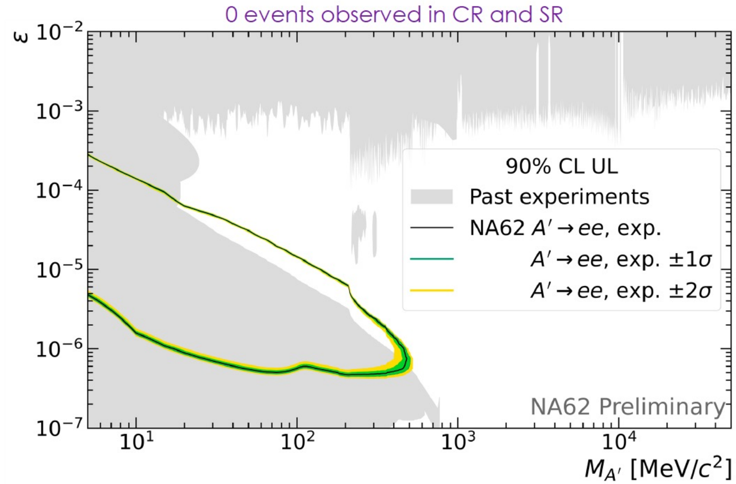
preliminary result

Expected events A' → $e^+ e^-$ in the CR and SR:

$N^{CR}_{background} = 0.0097^{+0.049}_{-0.009}$ @90% CL

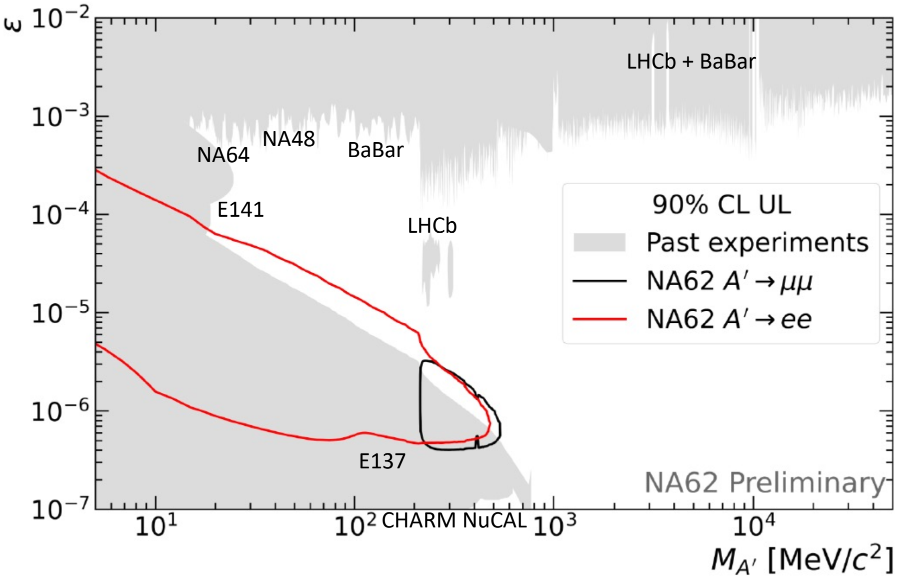
$N^{SR}_{background} = 0.0094^{+0.049}_{-0.009}$ @90% CL

A' → $e^+ e^-$



The region enclosed by the contour shown is excluded

A' → $\ell^+ \ell^-$



NA62 Goal

NA62 IS AN INTENSITY FRONTIER EXPERIMENT:

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

- **Ultra rare FCNC: s→d transition, hard GIM suppression**
- **Theoretically clean (negligible hadronic uncertainties)**

Previsione teorica*: $\mathbf{BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 8.4 \pm 1.0 \times 10^{-11}}$

Misura sperimentale: $\mathbf{BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}}$

(E787/949): (7 events)

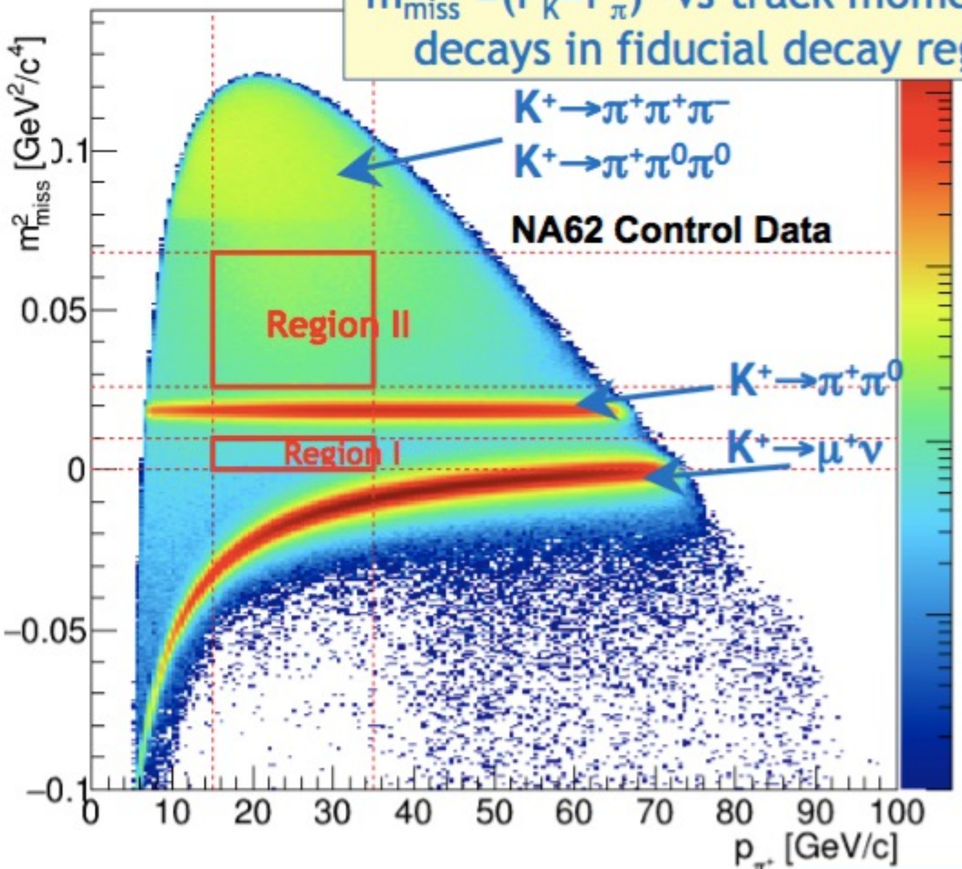
*[Buras, 1503.02693]

NA62 aims to measure to ~10%

Deviation from SM predictions would signal New Physics!

$K^+ \to \pi^+ \nu \bar{\nu}$ decay – Signal selection

$m_{miss}^2 = (P_K - P_\pi)^2$ vs track momentum;
decays in fiducial decay region



Region I (R1) and Region II (R2)

Selection criteria:
- Single track topology
- π+ Identification
- Photon rejection
- Multi-track rejection

Performances:
- $\varepsilon(\mu+) = 1\times10^{-8}$ (64% π+ efficiency)
- $\varepsilon(\pi^0) = 3 \times 10^{-8}$
- $\sigma(m_{miss}) = 1\times 10^{-3}$ GeV²/c⁴
- σ(t) ~ O(100 ps)

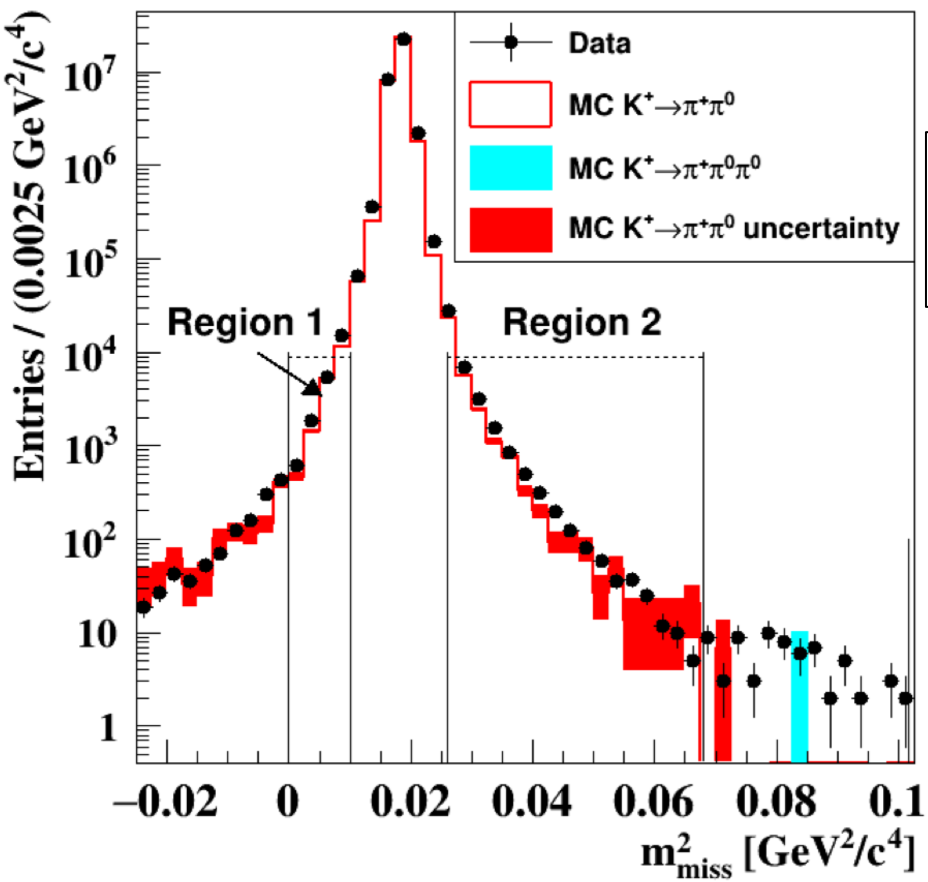
Signal and control regions are kept masked throughout the analysis

8

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay – Results Run 1 (2016-2018)

Control $K^+ \rightarrow \pi^+ \pi^0$ data used to study the tails of the m^2_{miss} distribution

Data in $\pi^+ \pi^0$ region after the $\pi\nu\nu$ selection (including π^0 rejection)



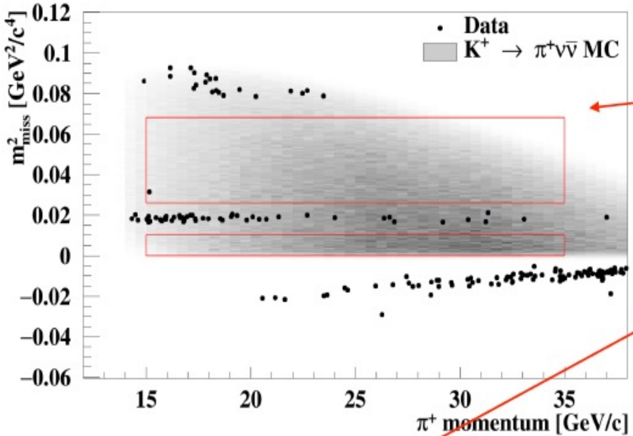
$$N^{exp}_{\pi\pi}(\text{region}) = N(\pi^+\pi^0) \cdot f_{kin}(\text{region})$$

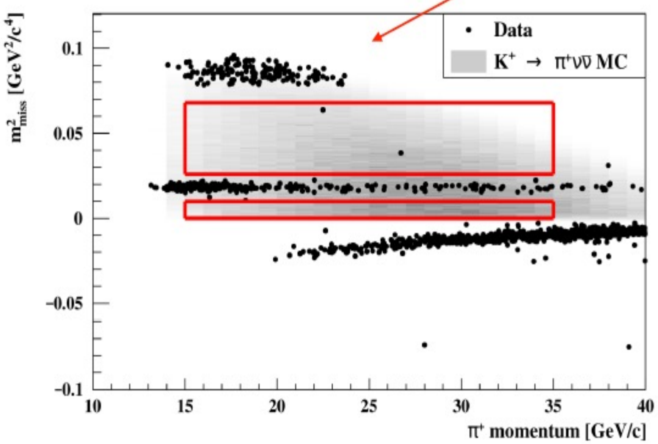
Expected $\pi^+\pi^0$ in signal region after the $\pi\nu\nu$ selection

Fraction of $\pi^+\pi^0$ in signal region measured on control data

- Control $K^+ \rightarrow \pi^+\pi^0$ data selected using only the calorimeters (background free)
- The same procedure used for $K^+ \rightarrow \mu^+ \nu_\mu$ and $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ background estimation

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay – Run 1 data





2016 data [PLB 791 (2019) 156]

$$n_{bg} = 0.152^{+0.093}_{-0.035}, n^{SM}_{\pi\nu\bar{\nu}} = 0.267 \pm 0.038$$

$$n_{obs} = 1$$

2017 data [JHEP 11 (2020) 042]

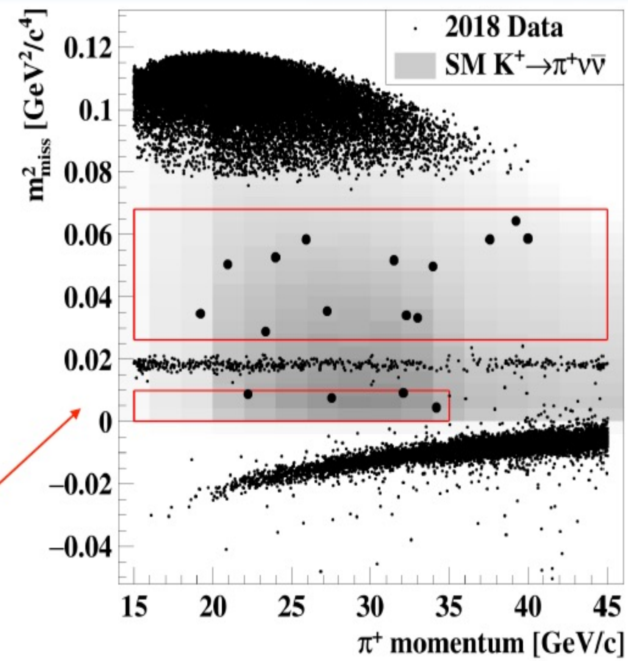
$$n_{bg} = 1.46 \pm 0.33\ ,\ n^{SM}_{\pi\nu\bar{\nu}} = 2.16 \pm 0.29$$

$$n_{obs} = 2$$

2018 data [JHEP 06 (2021) 093]

$$n_{bg} = 5.24^{+0.99}_{-0.75}\ ,\ n^{SM}_{\pi\nu\bar{\nu}} = 7.58 \pm 0.85$$

$$n_{obs} = 17$$

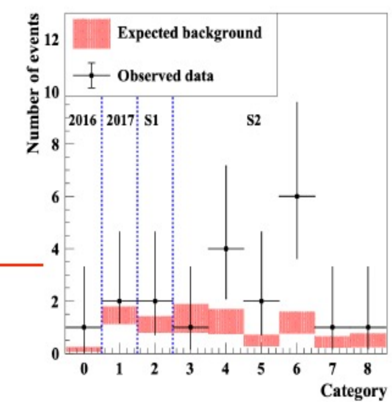


Run1 2016–18 data [JHEP 06 (2021) 093]

$$n_{bg} = 6.85^{+1.05}_{-0.82}\ ,\ n^{SM}_{\pi\nu\bar{\nu}} = 10.01 \pm 1.26\ ,\ n_{obs} = 20$$

Statistical combination:

$$\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.4}\Big|_{\text{stat}} \pm 0.09_{\text{syst}}\right) \times 10^{-11} \quad \text{at} \quad 68\,\%\ \text{CL}$$



$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay – Single Event Sensitivity (SES)

$$N^{exp}_{\pi\nu\nu} \approx N_{\pi\pi}\, \varepsilon_{RV}\, \varepsilon_{trigger} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \Longrightarrow S.E.S. = \frac{Br(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}}$$

- $N^{exp}_{\pi\nu\nu}$ $\Rightarrow$ Expected number of $\pi\nu\nu$ events
- $Br(\pi\nu\nu)$ $\Rightarrow$ SM $\pi\nu\nu$ branching ratio
- $N_{\pi\pi}$ $\Rightarrow$ $K^+ \rightarrow \pi^+\pi^0$ from control $\pi\nu\nu$-like selected without γ/multiplicity rejection
- ε_{RV} $\Rightarrow$ $\pi\nu\nu$ loss due to γ/multi-track rejection because of random activity
- $\varepsilon_{trigger}$ $\Rightarrow$ PNN trigger efficiency
- $A_{\pi\nu\nu,\pi\pi}$ $\Rightarrow$ Monte Carlo acceptances for $\pi\nu\nu$ (~3.0%*) and $\pi^+\pi^0$ (~8.5%)
- $Br(\pi\pi)$ $\Rightarrow$ PDG $K^+ \rightarrow \pi^+\pi^0$ branching ratio

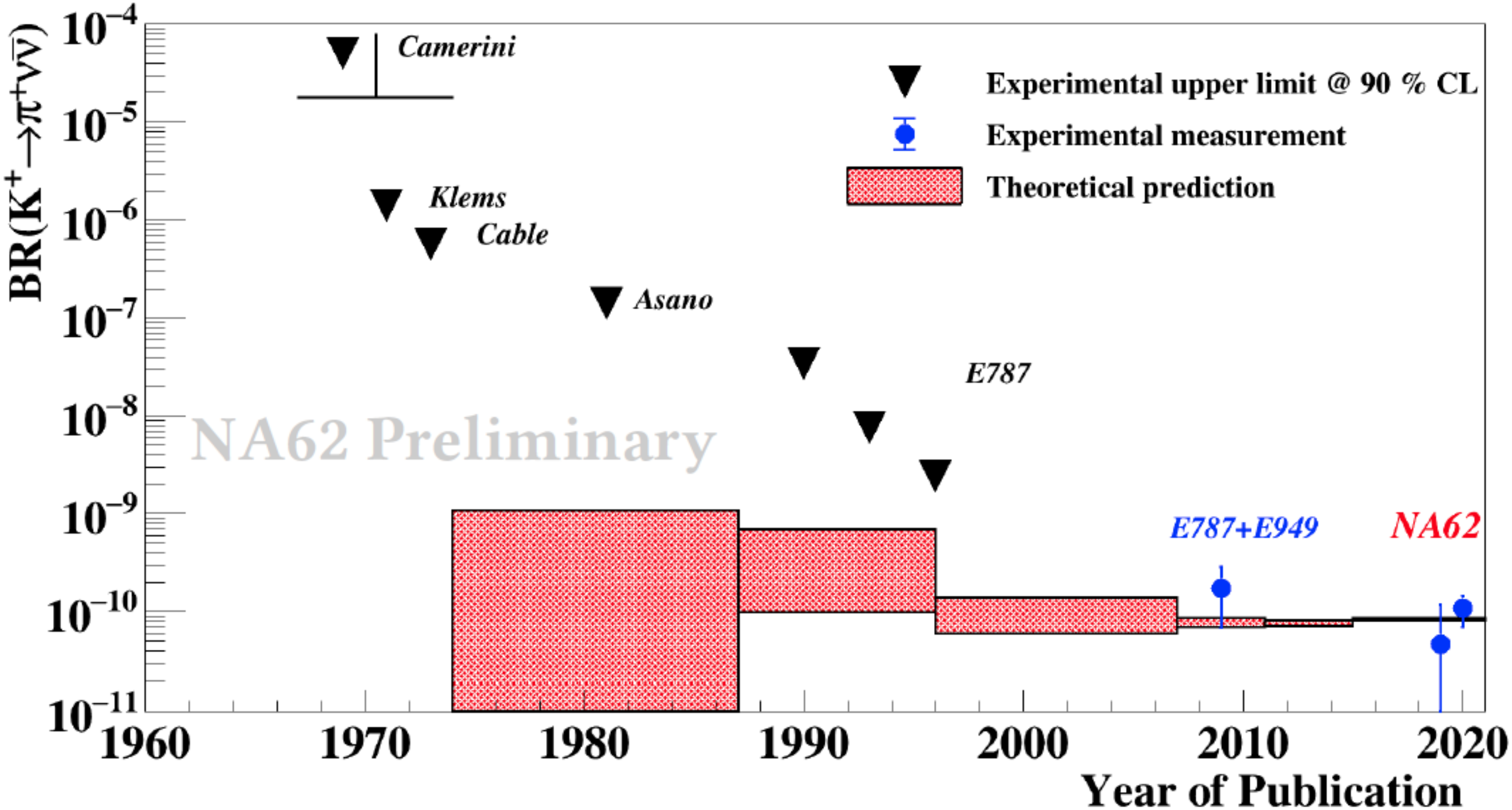
Computation in bins of pion momentum and instantaneous beam intensity

(* Vector Form Factors)

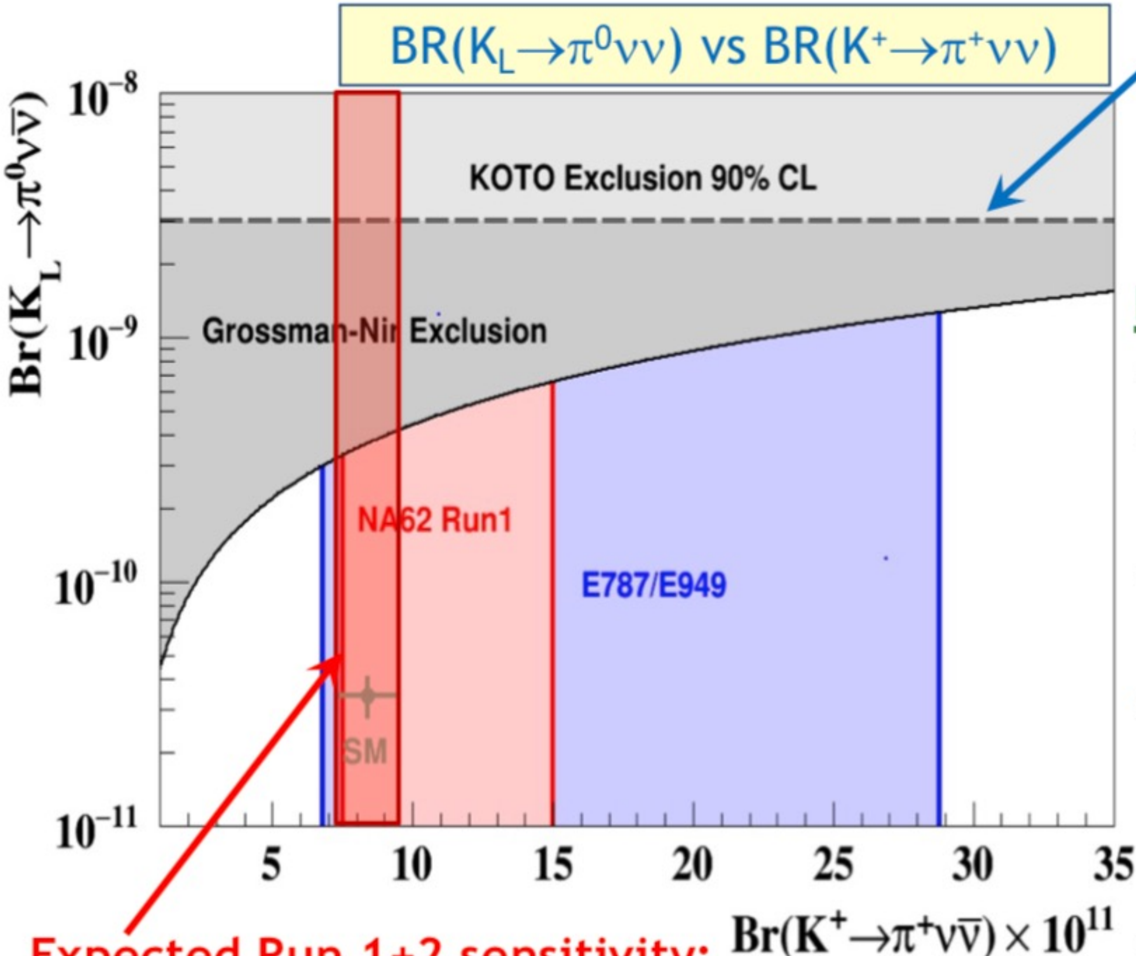
$K^+ \to \pi^+ \nu \bar{\nu}$ decay – Systematic Uncertainties and Error Budget)

	δa_+	δb_+	$\delta \mathcal{B} \times 10^8$	$\delta A_{FB} \times 10^2$
Statistical uncertainty	0.012	0.040	0.06	0.7
Trigger efficiency	0.002	0.008	0.02	0.1
Reconstruction and particle identification	0.002	0.007	0.02	0.1
Size of the simulated sample	0.002	0.007	0.01	0.1
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	0.2
branching fraction	0.001	0.003	0.04	—
radiative corrections	0.003	0.009	0.01	0.2
Parameters α_+ and β_+	0.001	0.006	—	—
Total external uncertainty	0.003	0.011	0.04	0.2
Total uncertainty	**0.013**	**0.043**	**0.08**	**0.7**

$K^+ \to \pi^+ \nu \bar{\nu}$ decay – History and time evolution



JHEP 06 (2021) 93



Expected Run 1+2 sensitivity:
$\delta BR/BR \approx 10\%$

KOTO limit (2015 data):
$BR(K_L \to \pi^0 \nu\nu) < 3.0 \times 10^{-9}$
PRL122 (2019) 021802
2016–18 data also published:
PRL126 (2021) 121801

NA62 Run 2 (up to LS3):

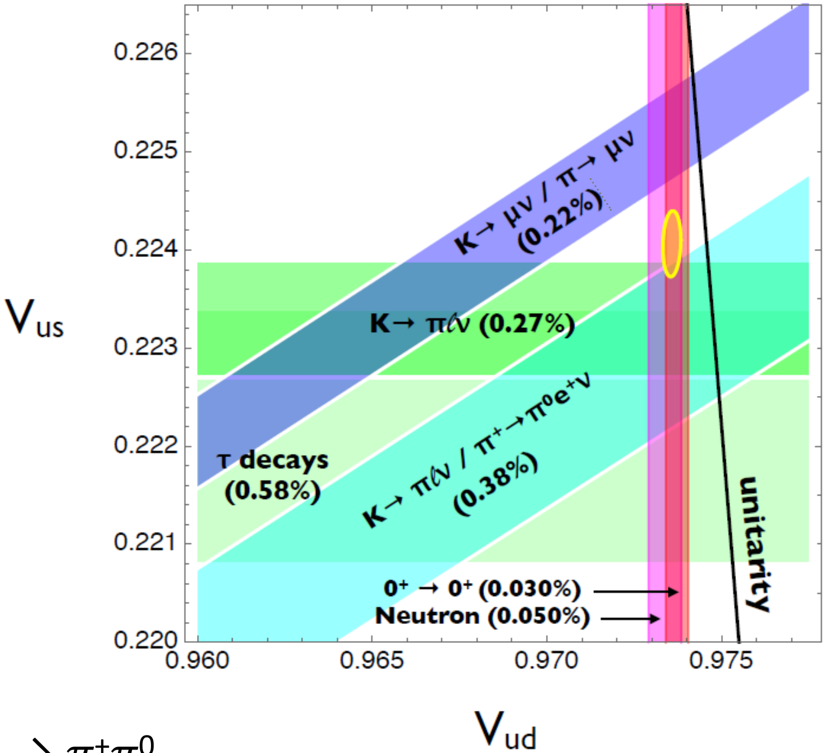
- Higher beam intensity.
- Optimised beamline, new veto detectors.
- Fourth kaon beam tracker station.
- $K^+ \to \pi^+ \nu\nu$ measurement in low-background, high-acceptance regime, at **O(10%)** precision.
- Collection of **10^{18}** POT in up to **90 days** in **beam dump mode**.

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

❖ Measurement to address the Cabibbo angle discrepancy

$$R_A^{K\mu2} = \Gamma(K_{\mu2})/\Gamma(\pi_{\mu2})$$

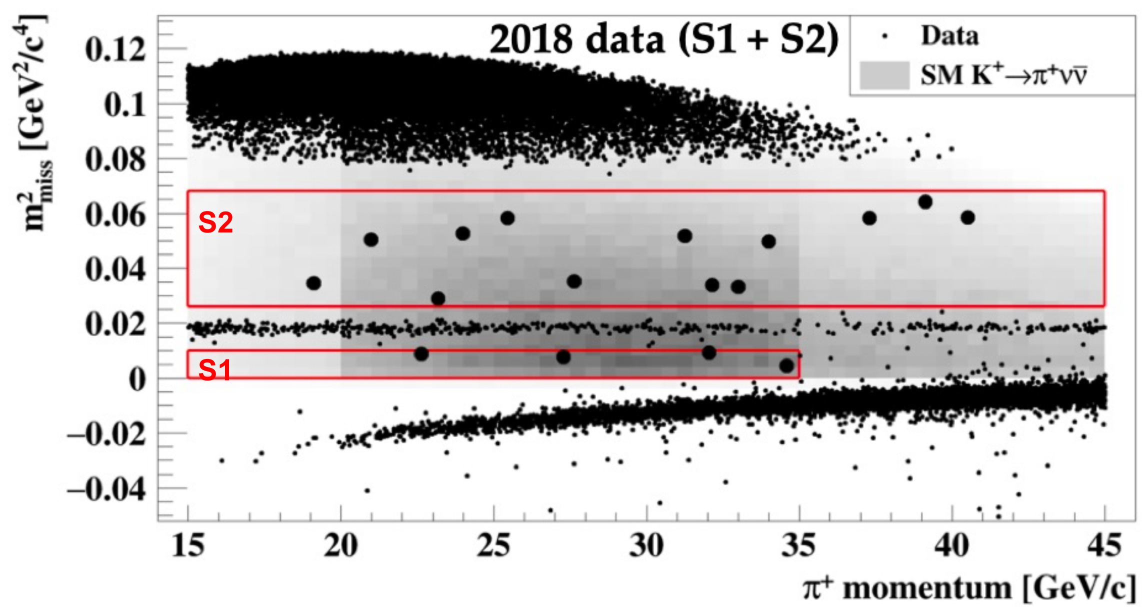
$$R_A^{K\mu3} = \Gamma(K_{\mu3})/\Gamma(\pi_{\mu3})$$

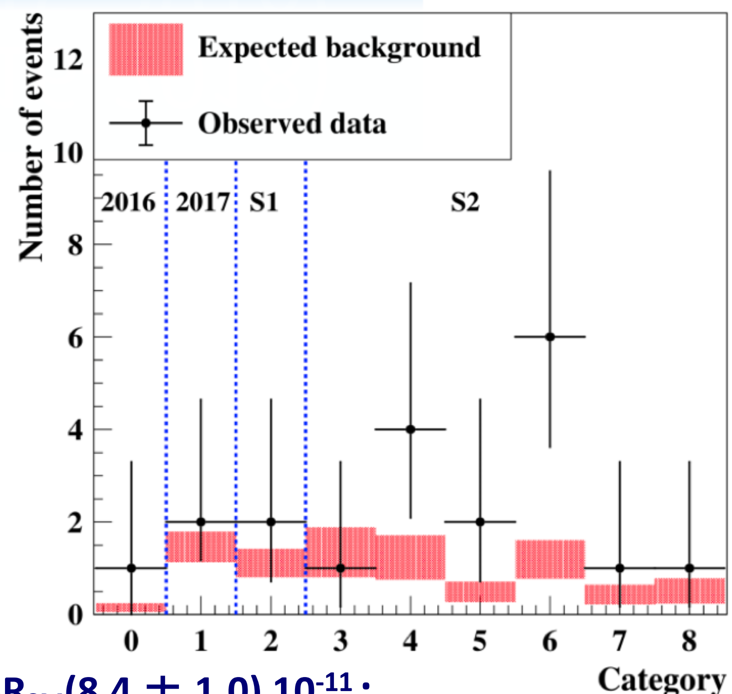


❖ Measurement strategy

- Reconstruct decay-in-flight $\pi^+ \rightarrow \mu+\nu$ from $K^+ \rightarrow \pi^+\pi^0$
- Cancellation of 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 $K^+ \rightarrow \pi^+\pi^0$

NA62 results from Run 1 (2016-2018)





- **20 events observed in the signal region**
- Combining the complete Run 1 data set and assuming $\mathbf{BR_{SM}(8.4 \pm 1.0)\ 10^{-11}}$:

$$N^{exp}_{\pi\nu\nu} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$$

$$N^{exp}_{background} = 7.03\ ^{+1.05}_{-0.82}$$

$$SES = (0.839 \pm 0.053_{syst})\ x\ 10^{-11}$$

JHEP 06 (2021) 093

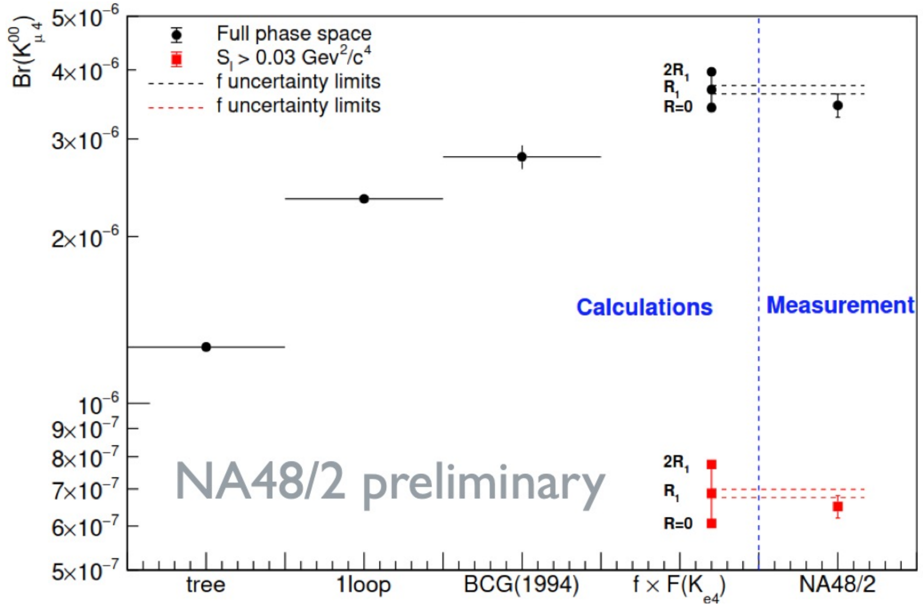
$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6\ ^{+4.0}_{-3.4}\ |_{stat} \pm 0.9_{syst})\ x\ 10^{-11}$$ **3.4σ significance**

$K^{\pm} \rightarrow \pi^0 \pi^0 \mu^{\pm} \nu$ ($K_{\mu 4}^{00}$)

Experimental results and Theory status

K_{l4} mode	BR $[10^{-5}]$	N_{cand}	
$K_{e4}^{\pm}$	4.26 ± 0.04	1108941	NA48/2 (2012)
K_{e4}^{00}	2.55 ± 0.04	65210	NA48/2 (2014)
$K_{\mu 4}^{\pm}$	1.4 ± 0.9	7	Bisi et al. (1967)
$K_{\mu 4}^{00}$			

Theory: Nucl. Phys. (1994) B 427
Phys. Rev. D 15 (1977) 574



- ✓ $K^{\pm} \rightarrow \pi^0 \pi^0 \pi^{\pm}$ as normalization channel
- ✓ $K^{\pm} \rightarrow \pi^0 \pi^0 (\pi^{\pm} \rightarrow \mu^{\pm} \nu)$ largest background
- ✓ $S_{\ell} = m^2(\mu^{\pm} \nu) > 0.03$ Gev^2/c^4

2437 events observed
Background events expected = $374 \pm 0.33_{stat} \pm 62_{syst}$

BR($K^{\pm} \rightarrow \pi^0 \pi^0 \mu^{\pm} \nu$, $S_{\ell} = m^2(\mu^{\pm} \nu) > 0.03$ Gev^2/c^4)
= $(0.65 \pm 0.03) \times 10^{-6}$

BR($K^{\pm} \rightarrow \pi^0 \pi^0 \mu^{\pm} \nu$) = $(3.4 \pm 0.2) \times 10^{-6}$

- ✓ First Observation of muon mode with $\pi^0\pi^0$
- ✓ Test of ChPT$_{st}$

preliminary