Kaon physics: present and future

Congrès Général de la Société Française de Physique, 2023, July 3rd–7th, Paris

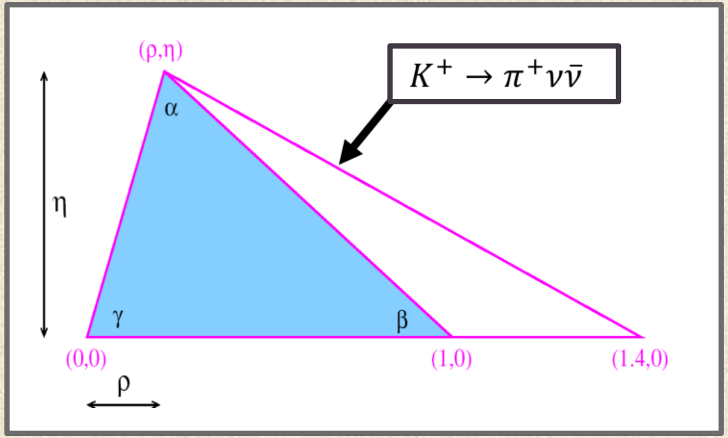
Speaker: Radoslav Marchevski
On behalf of the NA62 Collaboration

Outline

- Key kaon physics observables
- Status of the KOTO experiment
- Physics program with charged kaons successfully pursued at CERN SPS by NA62
    - Measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ process
    - Recent results on χ_{PT} studies
    - LFUV, LFV, LNV studies
    - New results on dark sector studies with kaon decays
- Future of kaon physics at the CERN SPS

Key kaon physics observables

The NA62 physics program



Flavour physics

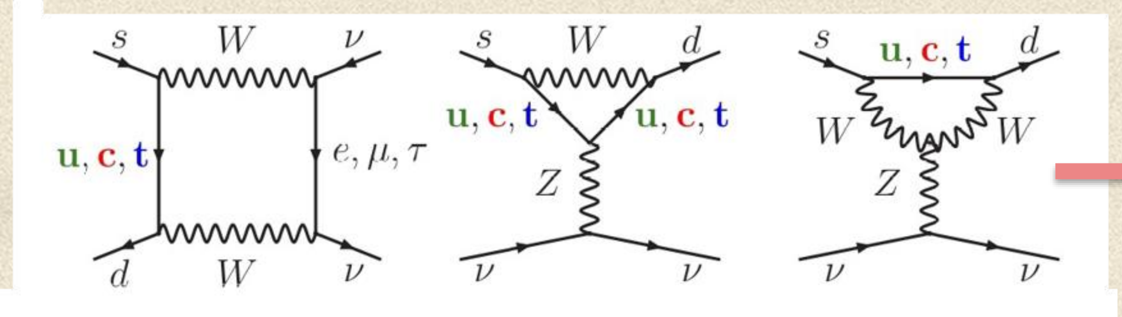
- Indirect searches for NP at high mass scale
- Direct and indirect searches for NP through LFV/LNV processes
  - $K^+ \to \pi^+ l^+ l^-$, $K^+ \to \mu^- \nu e^+ e^+$, $K^+ \to \pi^\pm \mu^\mp e^+$
  - $K^+ \to \pi^- \pi^0 e^+ e^+$, $K^+ \to \pi^- l^+ l^+$, …
- Test of low-energy hadronic theories (e.g. χ_{PT})
  - $K^+ \to \pi^+ \gamma\gamma$, $K^+ \to \pi^0 e^+ \nu \gamma$, …

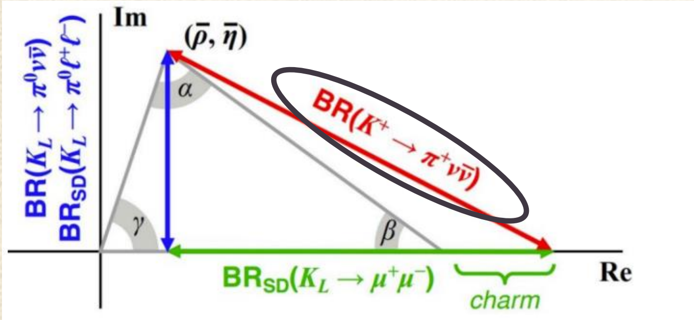
Hidden sector physics

- Direct searches for new particles below the EW scale
  - $K^+ \to \pi^+ X$, $K^+ \to l^+ N$,
  - $K^+ \to \pi^+ a a$, $a \to e^+ e^-$

$A' \to l^+ l^-$
$N \to \pi^\pm \mu^\mp$
…

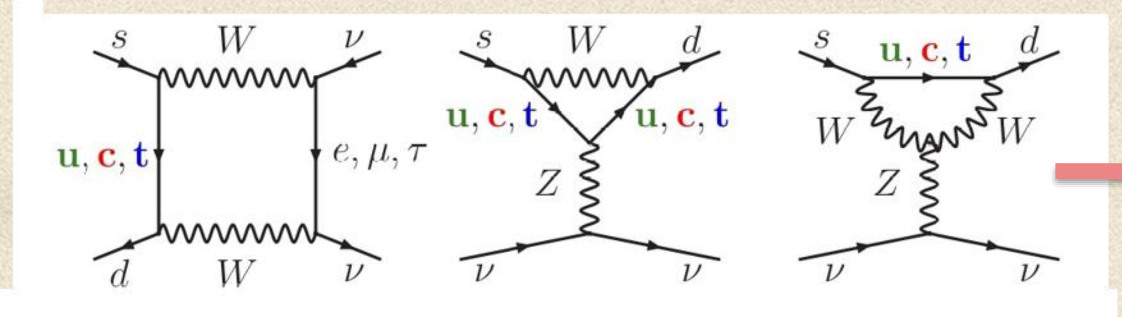
$K^+ \to \pi^+ \nu\bar{\nu}$: a **golden** decay mode

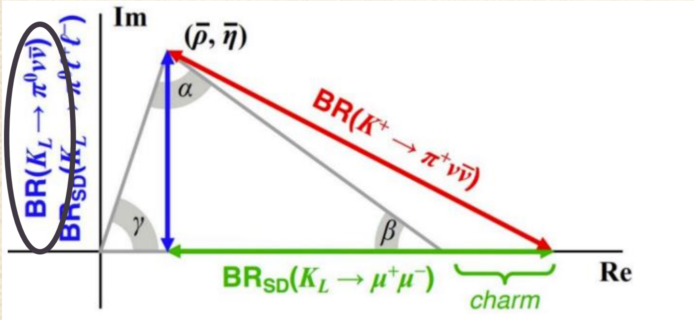




- $s \to d$ transition sensitive to the CKM structure of the SM: *tree-level FCNCs forbidden → loop + CKM suppression*
- Theoretically clean process: *dominated by short-distance physics*
- $K - \pi$ Form Factor (FF) extracted from $K \to \pi l \nu_l$: *sub-% precision*
- Sensitive to new physics in the lepton sector as well: *involves ν_e, ν_μ, and ν_τ*
- Extremely rare process in the SM:
  - $\boldsymbol{BR_{SM}(K^+ \to \pi^+\nu\bar{\nu}) = (7.73 \pm 0.16_{SD} \pm 0.25_{LD} \pm 0.54_{param.}) \times 10^{-11}}$ [arXiv:2105.02868]
  - $\boldsymbol{BR_{SM}(K^+ \to \pi^+\nu\bar{\nu}) = (7.92 \pm 0.28_{theory}) \times 10^{-11} \times \left[\frac{|V_{cb}|}{41.0\times10^{-3}}\right]^{2.8} \times \left[\frac{\sin\gamma}{\sin 67^\circ}\right]^{1.39}}$ [arXiv:2109.11032]

$K_L \to \pi^0 \nu\bar{\nu}$: another golden decay mode





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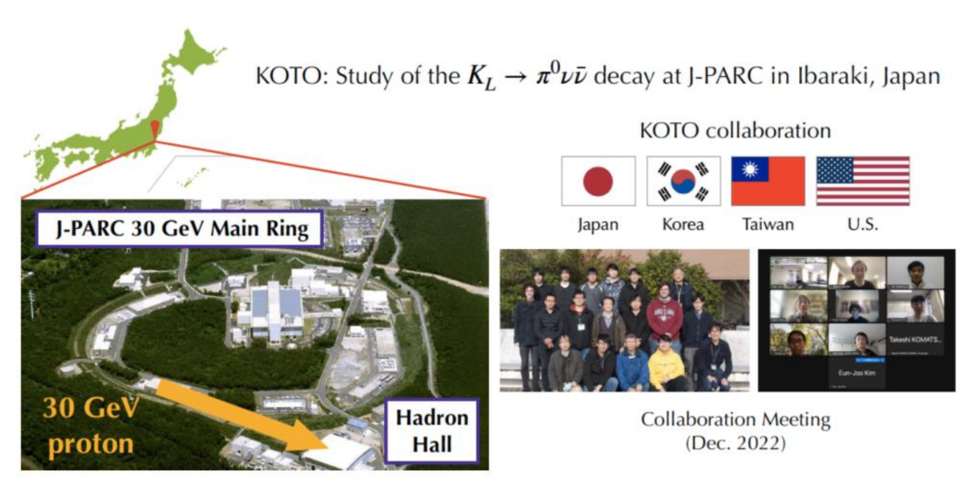
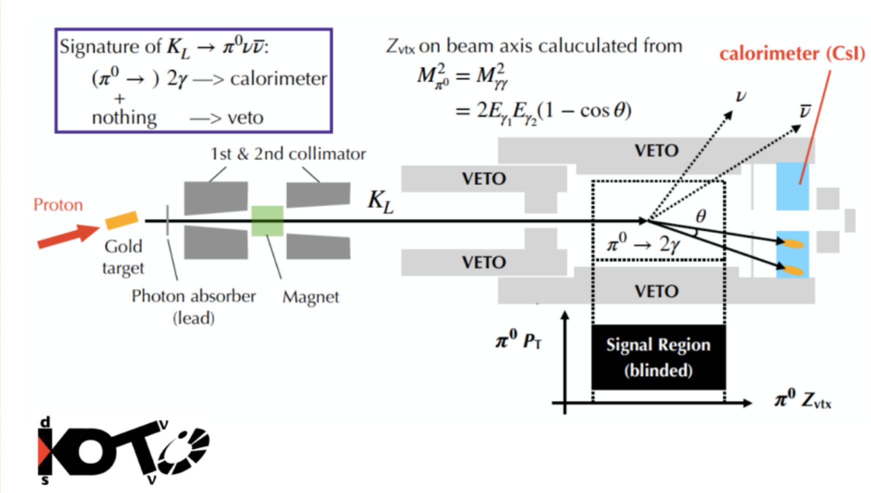
- Sensitive to new physics in the lepton sector as well: *involves* ν_e, ν_μ, *and* ν_τ
- Extremely rare process in the SM:
  - $\boldsymbol{BR_{SM}(K_L \to \pi^0\nu\bar{\nu}) = (2.59 \pm 0.06_{SD} \pm 0.02_{LD} \pm 0.28_{param.}) \times 10^{-11}}$ [arXiv:2105.02868]
  - $\boldsymbol{BR_{SM}(K_L \to \pi^0\nu\bar{\nu}) = (2.61 \pm 0.04_{theory}) \times 10^{-11} \times \left[\frac{|V_{cb}|}{41.0\times10^{-3}}\right]^4 \times \left[\frac{\sin\gamma}{\sin 67°}\right]^2 \times \left[\frac{\sin\beta}{\sin 22.2°}\right]^2}$ [arXiv:2109.11032]

Status of the KOTO experiment

The KOTO experiment @ JPARC

More info to be found in the talk of Bob Hsiung @ FPCP 2023





- Extremely challenging measurement
    - Nothing → two photons + missing transverse momentum
    - Relies on high efficiency hermetic particle veto
- Lowest direct limit: $BR(K_L \to \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{-9}$ [PRL 122 (2019) 2, 021802]

The KOTO experiment @ JPARC

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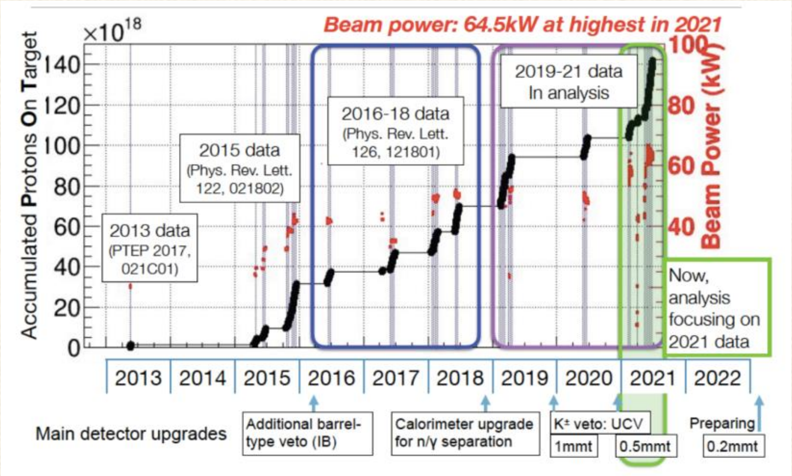
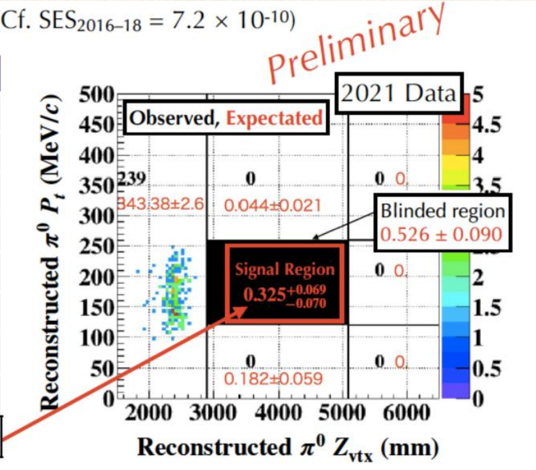


Single Event Sensitivity (SES) = 7.9 × 10^{-10} (Cf. SES$_{2016–18}$ = 7.2 × 10^{-10})

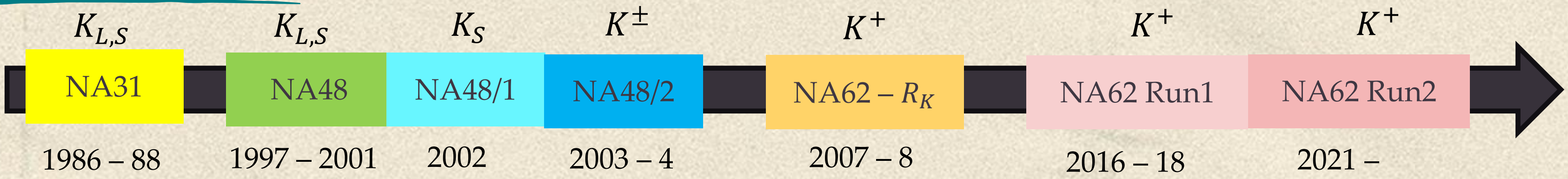
Source	#BG in Signal Region
$K_L \to 2\pi^0$	0.141 ± 0.059
$K^\pm$	0.043 +0.016/-0.022
Hadron cluster	0.042 ± 0.007
Halo $K_L \to 2\gamma$	0.013 ± 0.006
Scattered $K_L \to 2\gamma$	0.025 ± 0.005
η production at CV	0.023 ± 0.010
Upstream π^0	0.02 ± 0.02
$K_L \to 3\pi^0$	0.019 ± 0.019
Total	**0.325 +0.069/-0.070**

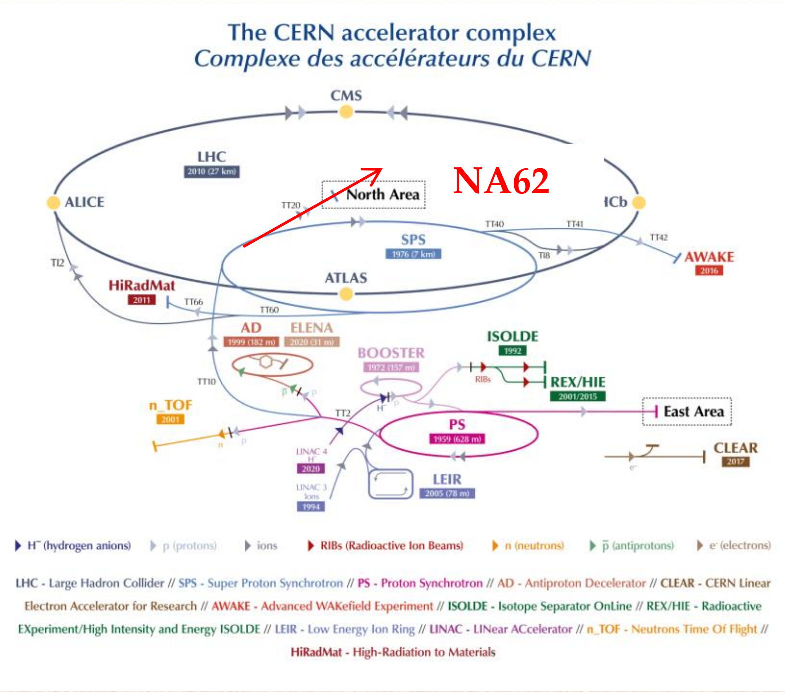


- Analysis significantly improved
  - Charged kaon background identified (charge-exchange in the beam collimators)
  - Larger background from $K_L \to 2\pi^0$ decays →wrong modelling of photonuclear interactions in GEANT
- Unblinding of the newest KOTO 2021 data set coming soon

Measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ process at NA62

The NA62 experiment @ CERN



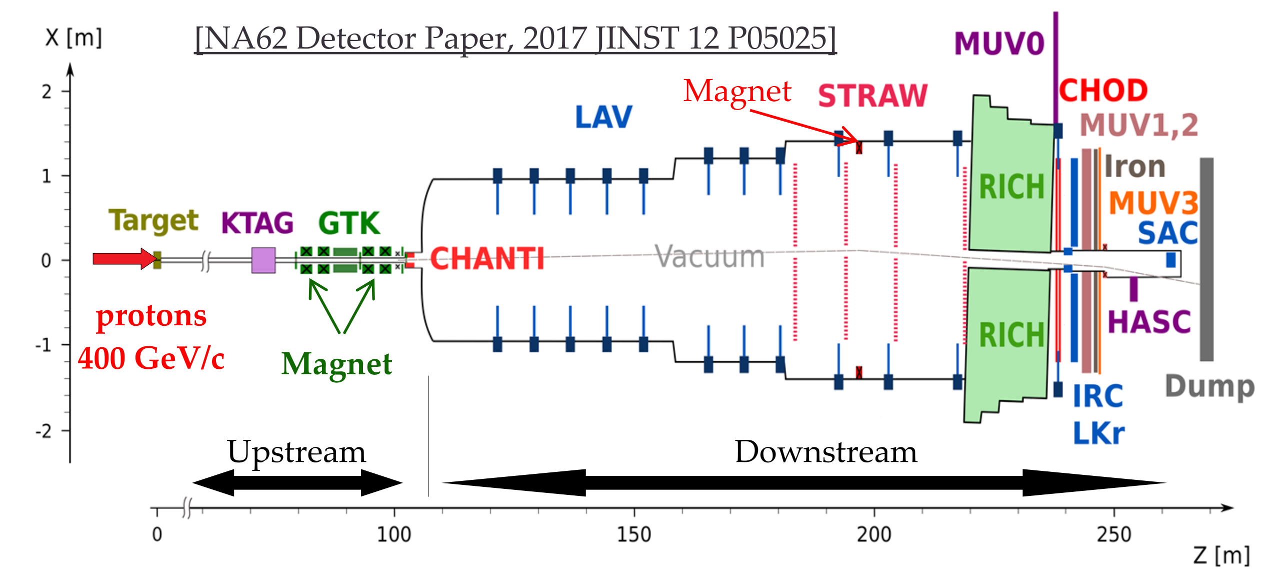


- Long tradition of kaon experiments at CERN
- NA62 main target: $\boldsymbol{K^+ \to \pi^+ \nu\bar{\nu}}$ **decay measurement**
- <u>Broad physics program:</u>
  - Other rare charged kaon decays
  - Precision measurements
  - LFV/LNV searches
  - Exotic searches (FIPs, Dark photon, etc…)

NA62 collaboration ~ 300 physicists from 31 institutions

The NA62 experimental apparatus

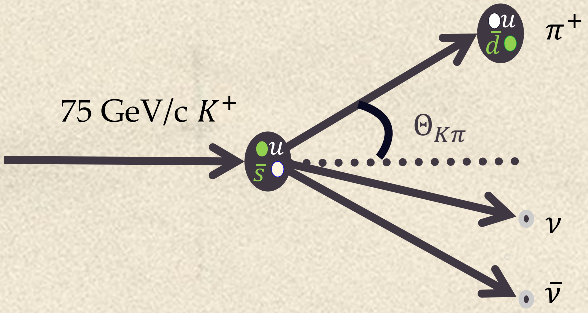
- Secondary beam
  - 75 ± 1 GeV/c momentum
  - 6% K^+ component
  - 60 m long fiducial volume
  - ~ 3 MHz K^+ decay rate



- Upstream detectors (K^+)
  - KTAG: Differential Cherenkov counter for K^+ ID
  - GTK: Silicon pixel beam tracker
  - CHANTI: Anti-counter against inelastic beam-GTK3 interactions

- Downstream detectors (π^+)
  - STRAW: track momentum spectrometer
  - CHOD: scintillator hodoscopes
  - LKr/MUV1/MUV2: calorimetric system
  - RICH: Cherenkov counter for $\pi/\mu/e$ ID
  - LAV/IRC/SAC: Photon veto detectors
  - MUV3: Muon veto

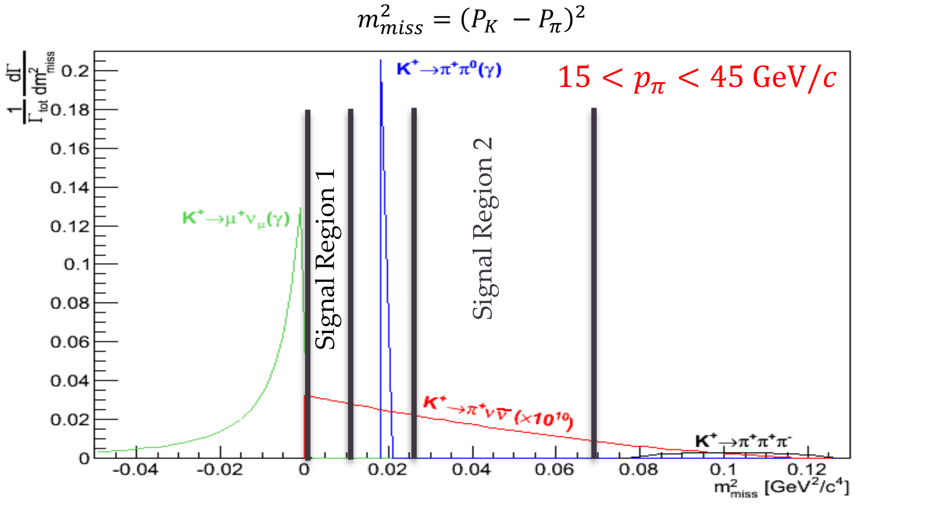
Analysis strategy



Squared missing mass (mass of the $\nu\bar{\nu}$ pair):

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

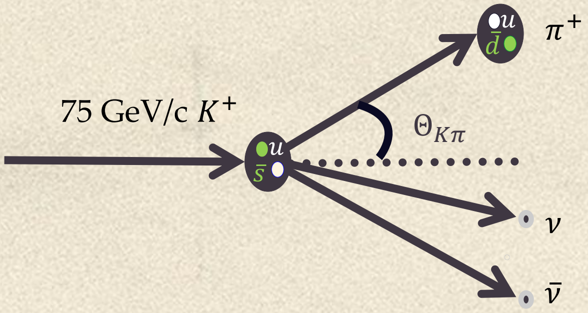
π^+ mass hypothesis



- Highly boosted decay: (75 ± 1) GeV/c K^+ ($\gamma \sim 150$)
- Large undetectable missing energy carried away by the neutrinos
- All energy from visible particles must be detected
- π^+ momentum range $15 - 45$ GeV/c ($E_{miss} > 30$ GeV)
- Hermetic detector coverage and O(100%) detector efficiency needed

- **Requirements:**
  - Kinematic suppression – $O(10^4)$
  - μ^+ rejection – $O(10^7)$
  - π^0 rejection – $O(10^7)$
  - Time resolution – $O(100\text{ ps})$

Analysis strategy



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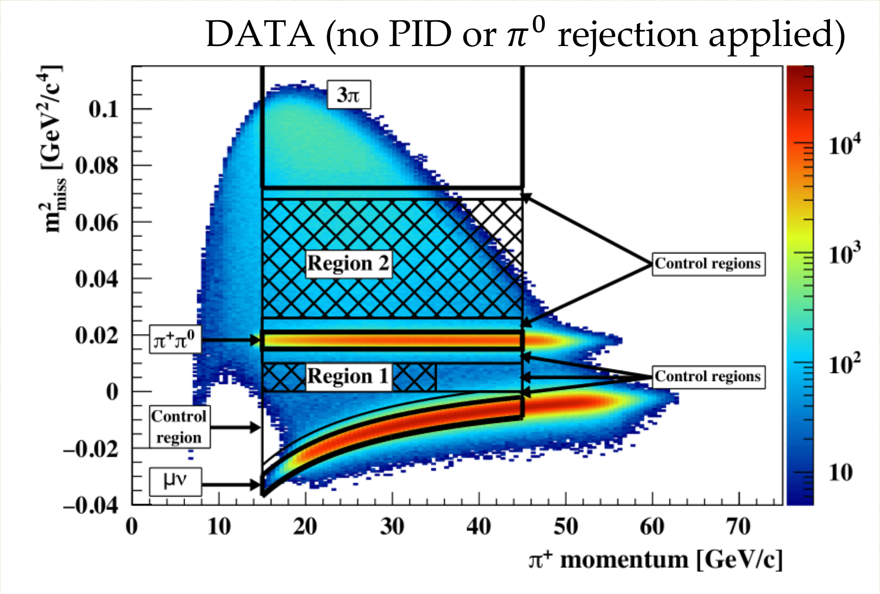

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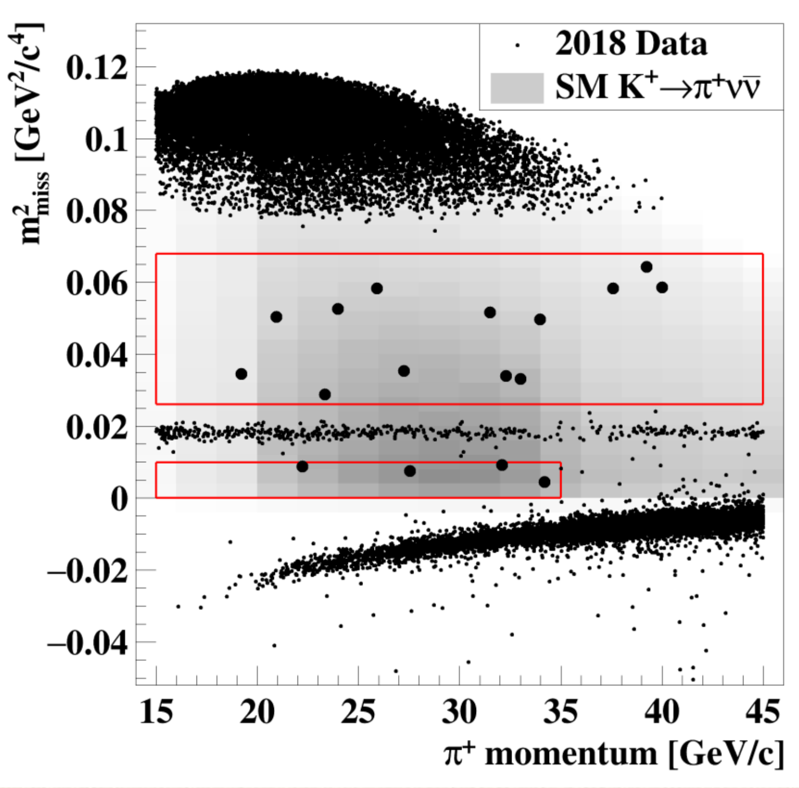
Results NA62 Run 1 (2016-18)

	Background (2018)
Expected SM signal	$7.58(40)_{syst}(75)_{ext}$
$K^+ \rightarrow \pi^+\pi^0(\gamma)$	0.75(4)
$K^+ \rightarrow \mu^+\nu(\gamma)$	0.49(5)
$K^+ \rightarrow \pi^+\pi^- e^+\nu$	0.50(11)
$K^+ \rightarrow \pi^+\pi^+\pi^-$	0.24(8)
$K^+ \rightarrow \pi^+\gamma\gamma$	< 0.01
$K^+ \rightarrow \pi^0 l^+\nu$	< 0.001
Upstream	$3.30^{+0.98}_{-0.73}$
Total background	$5.28^{+0.99}_{-0.74}$

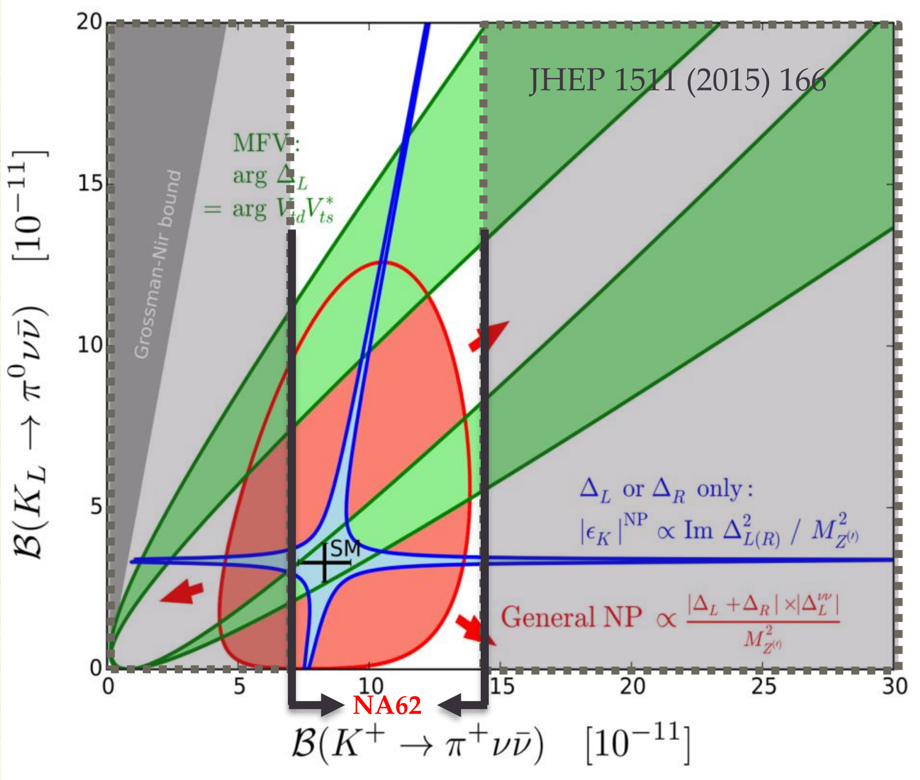


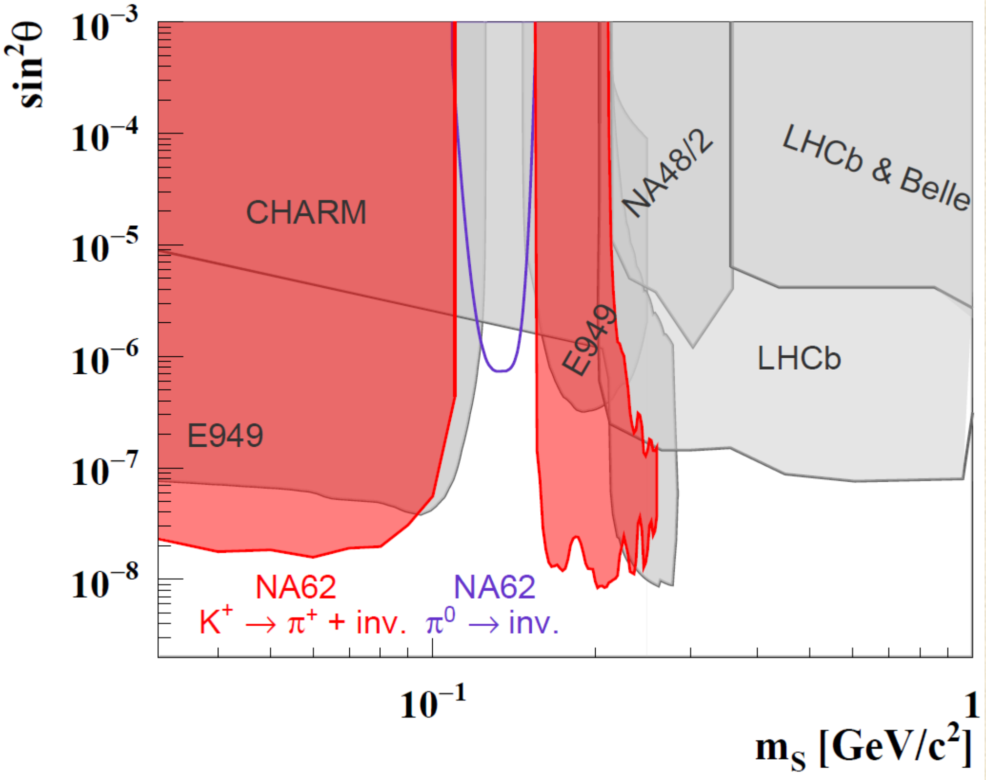
- $N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- $N^{exp}_{bg} = 7.03^{+1.05}_{-0.82}$
- $SES = (0.839 \pm 0.053_{syst}) \times 10^{-11}$
- $\boldsymbol{BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}}$ **[JHEP 06 (2021) 093]**

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

Impact in the context of BSM models

Non-SUSY models [See also arXiv:2006.01138]



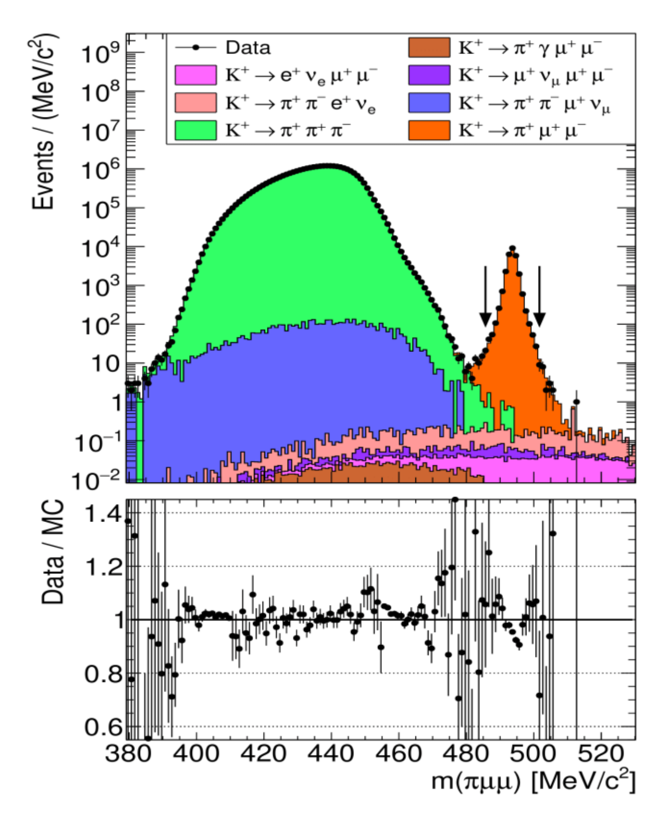


Precision measurement of the rare $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^+\gamma\gamma$ processes

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

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

- Main goals of the $K^+ \to \pi^+\mu^+\mu^-$ measurement with NA62:
  - Model-independent measurement of the $B_{\pi\mu\mu}$branching fraction
  - Measure the function $|W(z)|^2$
  - Determine the Form Factor parameters a_+ and b_+
  - Forward – backward asymmetry



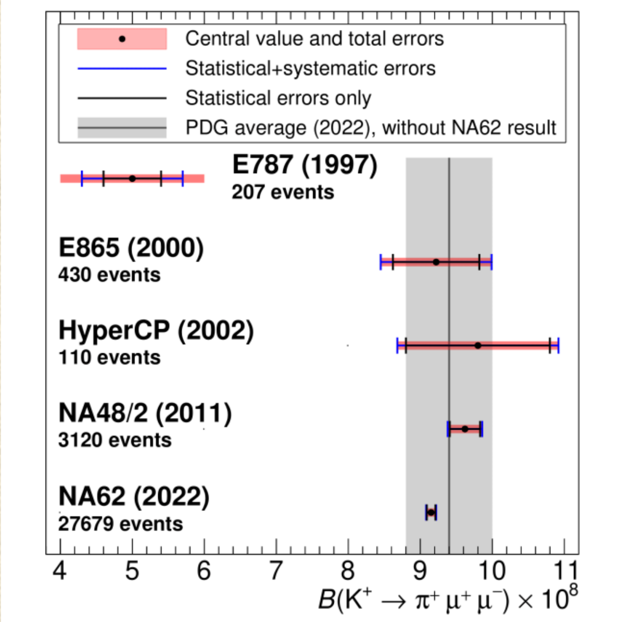
After signal selection:

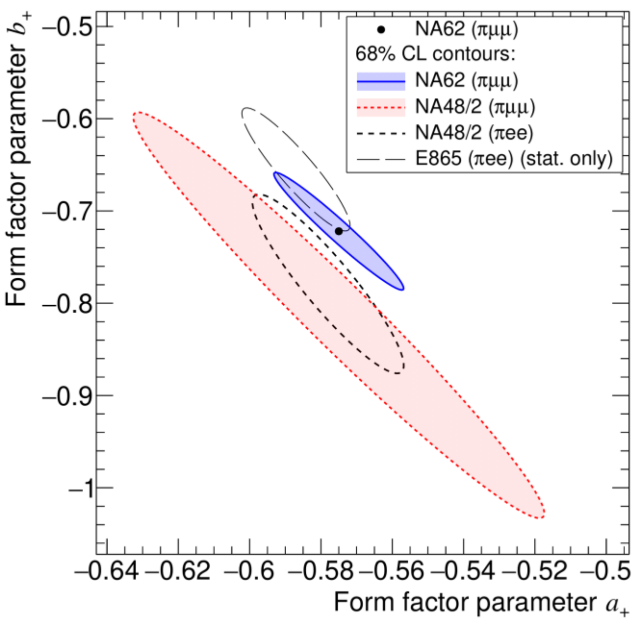
$N_{obs} = 27\,679$ events

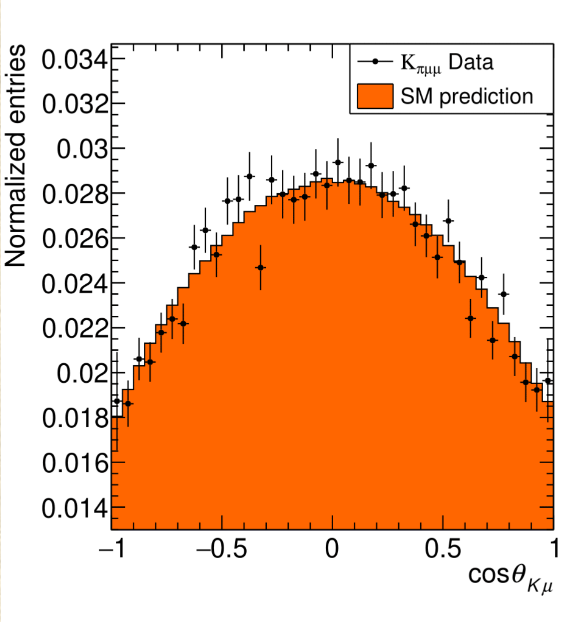
$N_{bg}^{exp} = 7.8 \pm 5.6$ events

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

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







$B_{\pi\mu\mu} = (9.15 \pm 0.06_{stat}) \times 10^{-8}$

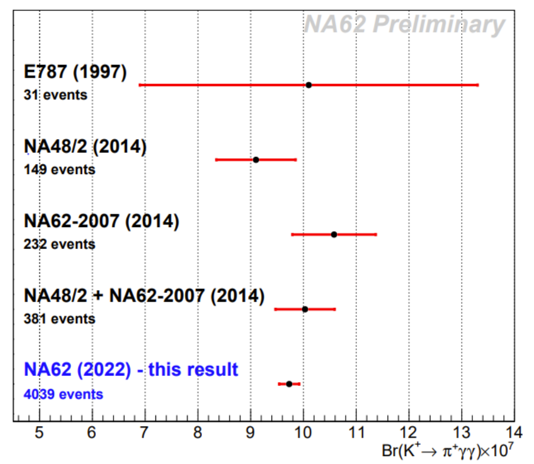
$a_+ = -0.575 \pm 0.012_{stat} \pm 0.003_{syst} \pm 0.003_{ext}$
$b_+ = -0.722 \pm 0.040_{stat} \pm 0.013_{syst} \pm 0.011_{ext}$

$A_{\mathrm{FB}} = (0.0 \pm 0.7_{stat}) \times 10^{-2}$

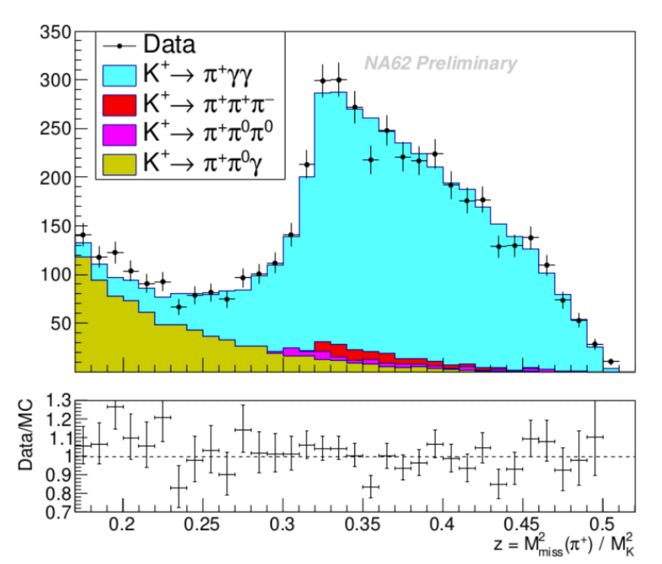
JHEP 11 (2022) 011

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

- Rare decay that allows χ_{PT} tests at $O(p^6)$
- Main kinematic variables: $\boldsymbol{z} = \frac{m^2(\gamma\gamma)}{m_K^2}$, $\mathbf{y} = \frac{P_K(Q_{\gamma_1} - Q_{\gamma_2})}{m_K^2}$
- BR($K^+ \to \pi^+\gamma\gamma$) at $O(p^6)$ parametrized by a real parameter $\hat{c}$



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



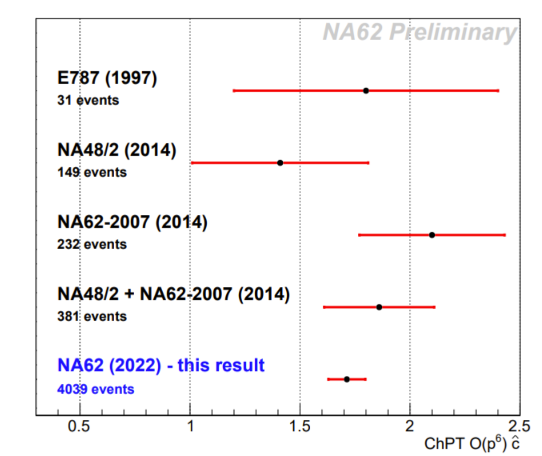
After signal selection:

$N_{obs} = 4039$ events

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

Main background:

Cluster merging in the EM calorimeter

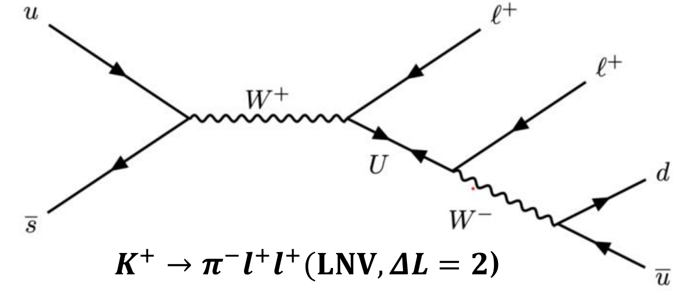


$$\hat{c} = 1.713 \pm 0.075_{stat} \pm 0.037_{syst}$$

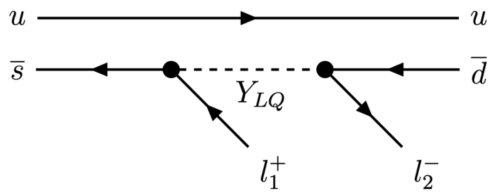
Searches for Lepton Flavour and Lepton Number Violating processes with NA62

LFV/LNV searches

- Lepton Number (**L**) → accidental $U(1)$ symmetry of the SM
  - Conserved for each flavour L_e, L_μ, L_τ in the SM
- Notable example of LF violation: *neutrino oscillation*
- Several scenarios of generating LFV/LNV in charged processes
- Key analysis points: tracking resolution and particle identification



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



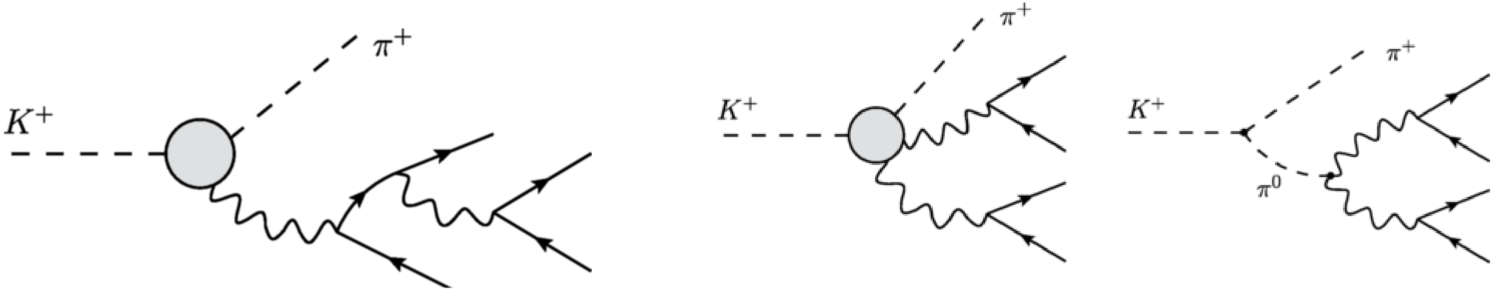
$\boldsymbol{K^+ \to \pi^\pm \mu^\mp e^+}$ **(LFV)**

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

$K^+ \to \pi^+ e^+ e^- e^+ e^-$ decays **(New result)**

- Heavily suppressed SM process with $BR = (7.2 \pm 0.7) \times 10^{-11}$ (outside π^0 pole) [PRD 106, L071301]

Topologies at leading QED/ChPT order:



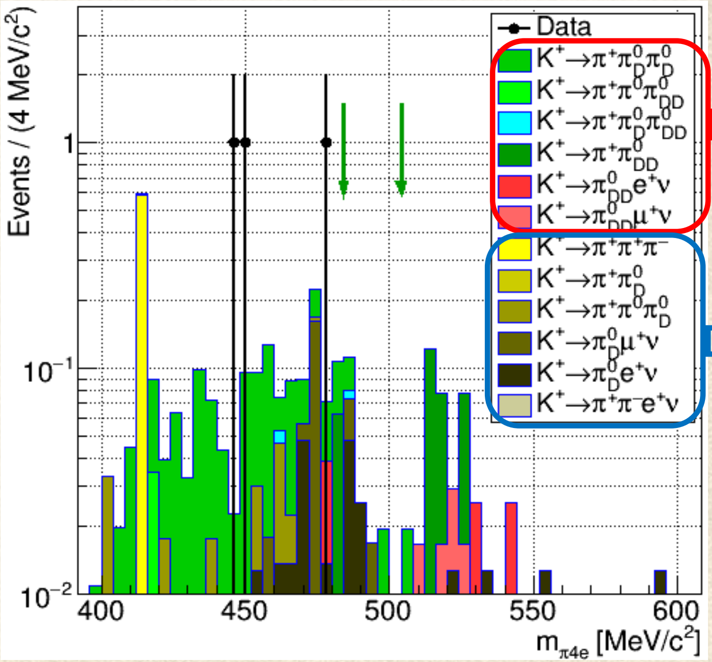
(1) $K^+ \to \pi^+ \gamma^*$ (2a) $K^+ \to \pi^+ \gamma^* \gamma^*$ (2b) $K^+ \to \pi^+ \pi^{0*}$

- 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 ($m_S > 2m_{A'}$) [arXiv:2012.02142]

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

$K^+ \to \pi^+ e^+ e^- e^+ e^-$ decays **(New result)**

- Complete RUN1 data set analyzed
- Signal ($K_{\pi 4e}$)
  - Kinematic PID of positive tracks
  - Conditions on $m_{\pi 4e}, m^2_{miss}$ (1)
  - m_{4e} outside the π^0 mass region
- Signal ($K^+ \to \pi^+ aa$ "Dark")
  - Same selection as $K_{\pi 4e}$
  - Choice of the optimal e^+e^- mass pair
- Normalization: $K^+ \to \pi^+ \pi^0_{DD}$ (2)
  - 5 – track topology and PID as for $K_{\pi 4e}$
  - Kinematic condition on m_{4e}



Background

5 – track like K^+ decays

3 – track K^+ decays overlapping with a $K^+ \to 3\pi$ decay

After signal selection:

$N_{obs} = 0$ events

$N^{exp}_{bg} = 0.18 \pm 0.06$ events

$K^+ \to \pi^+ e^+ e^- e^+ e^-$ decays **(New result)**

$K_{\pi 4e}$ SM

- Acceptance from MC
- Resonant amplitude negligible for selected events

$K^+ \to \pi^+ aa$

- Uniform phase space
- Mass scan with 5 MeV/c^2 step

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

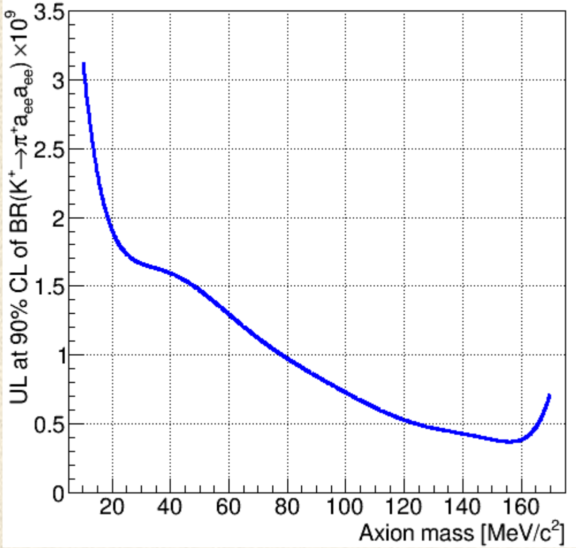
- Di-axion aa mass scan
- $(m_{A'}, m_S)$ distribution smoothing (low MC statistics)

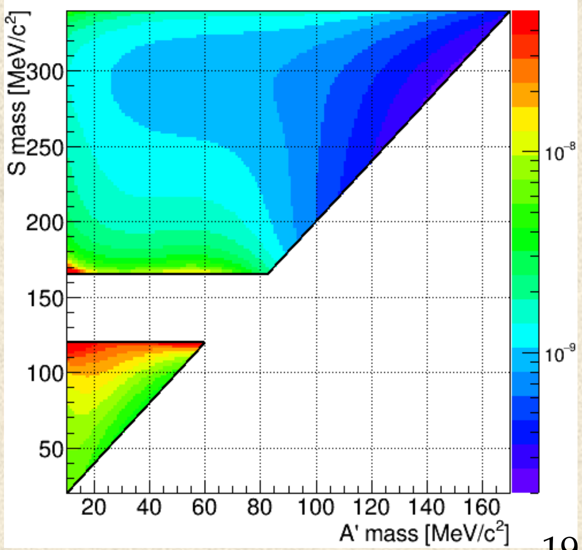
No candidate observed in SR

⇩

$$\boldsymbol{BR(K^+ \to \pi^+ e^+ e^- e^+ e^-) < 1.4 \times 10^{-8}}$$

@90% CL





Future of kaon physics at the CERN SPS

Future of kaons at CERN

- NA62 RUN2 ongoing:
  - data taking foreseen until at least 2025 (included)
  - +45-50% larger intensity than Run1
  - Hardware upgrades implemented to enhance $K^+ \to \pi^+ \nu\bar{\nu}$ sensitivity

- Single Event Sensitivity to SM $K^+ \to \pi^+ \nu\bar{\nu}$ with 2022 data $< 10^{-11}$
- Average sensitivity per spill $\geq 2.5 \times 10^{-5}$
- Mitigation of intensity-related efects
- Analysis optimizations ongoing to further increase performance

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

- Trigger upgrades to study other channels (e.g. $K^+ \to \pi^+ e^+ e^-$)
- Continuing LNV/LFV and dark sector searches with K^+
- A new measurement of V_{us}

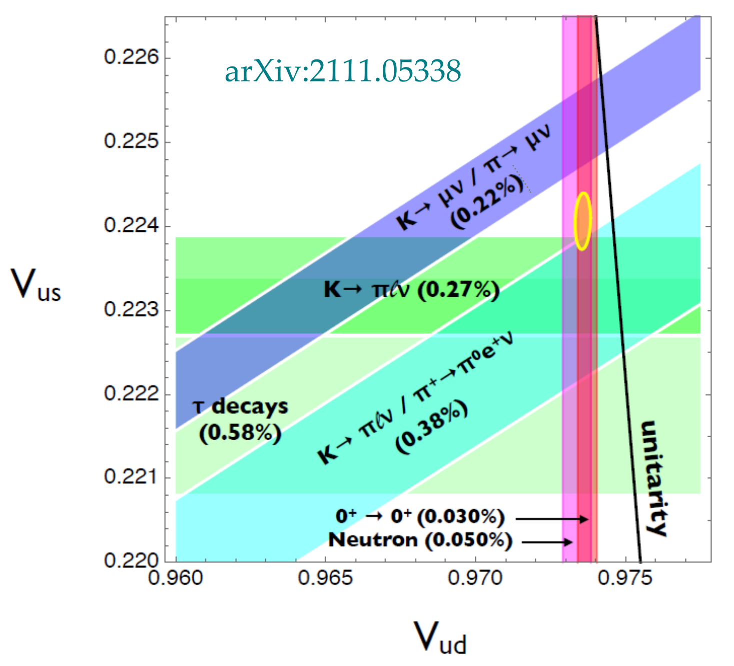
⇒ $O(\%)$ LFUV tests
$\times$ 2 lower ULs (10^{-11} sensitivity)

- Data-taking periods in dump to search for hidden sector particles

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

- Measurement to address the Cabibbo angle discrepancy

$$R_A^{K_{\mu 2}} = \frac{\Gamma(K_{\mu 2})}{\Gamma(\pi_{\mu 2})} \qquad R_A^{K_{\mu 3}} = \frac{\Gamma(K_{\mu 3})}{\Gamma(\pi_{\mu 2})}$$



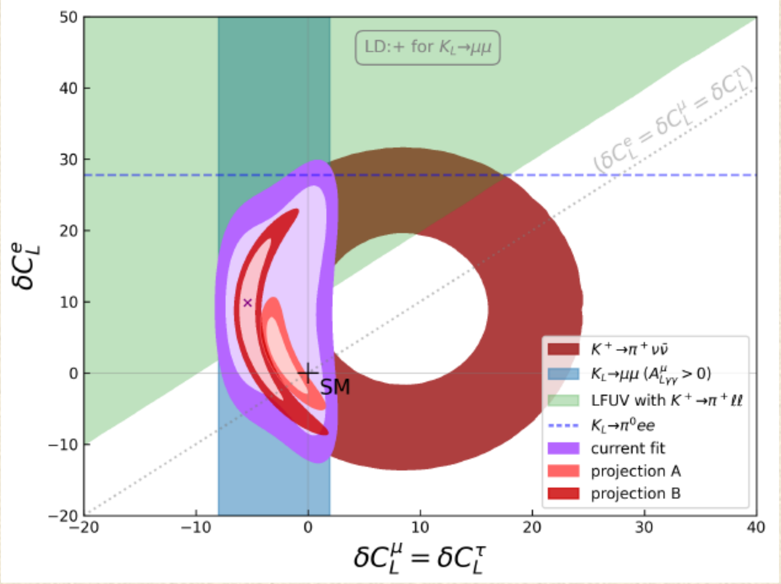
- Measurement strategy
  - Reconstruct decay-in-flight $\pi^+ \to \mu^+ \nu$ from $K^+ \to \pi^+ \pi^0$
  - Cancellation of systematic uncertainties (e.g. μ PID)
  - Analysis ongoing on RUN1 data
  - Expected statistical uncertainty < 1%
  - Target systematic uncertainty $O(0.1\%)$
  - External uncertainty from the knowledge of $K^+ \to \pi^+ \pi^0$

Kaon at CERN: prospects - HIKE

High Intensity Kaon Experiments

- Letter of Intent: arXiv:2211.16586v1 [proposal to the SPSC under preparation]
  - K^+ and K_L physics program at CERN SPS after LS3
  - Intensity $\times 4 - \times 6$ larger than NA62
  - Detectors with $O(20\text{ps})$ time reslution
  - Similar experimental layouts for charged and nautral phase

arXiv:2206.14748v1



- Physics program
  - $K^+ \to \pi^+ \nu\bar{\nu}$ approaching SM theory precision
  - $K_L \to \pi^0 l^+ l^-$ observation + branching fraction measurement
  - LFUV tests with precision < 1%
  - LFV/LNV searches with $O(10^{-12})$ sensitivity
  - Measurement of V_{us} and main kaon decay modes
  - Dump physics in synergy with Shadows experiment

Conclusions

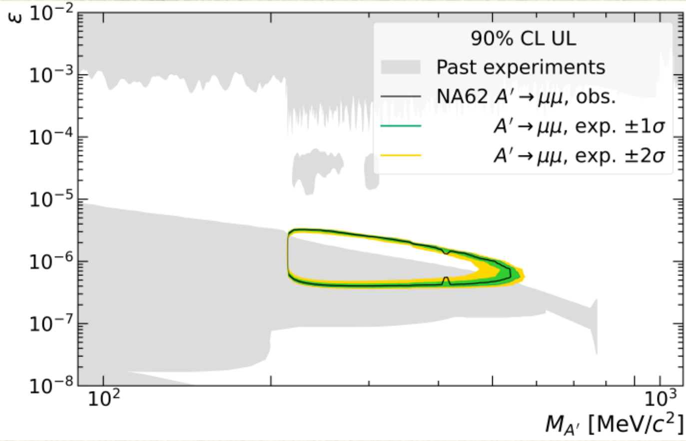
- Kaon physics experiments are in full steam
- The KOTO experiment is pushing the boundary down towards the $K_L \to \pi^0 \nu\bar{\nu}$ decay
- Charged kaon physics successfully pursued at CERN SPS by NA62
  - **$K^+ \to \pi^+ \nu\bar{\nu}$ RUN1 (2016-18):** $\mathrm{BR} = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$ [JHEP06(2021)093]
  - **Precision χ_{PT} studies:** $K^+ \to \pi^+\gamma\gamma$ to $O(\%)$ precision [paper in preparation]
  - **LFUV, LFV, and LNV studies:** $K^+ \to \pi^+\mu^+\mu^-$ to $O(\%)$ precision [JHEP11(2022)011]
  - **New dark sector studies with kaon decays:** axion/scalar searches with $K^+ \to \pi^+e^+e^-e^+e^-$ – $O(10^{-8})$UL
- Exciting prospects for the future of kaon physics at CERN SPS
  - **HIKE project under discussion at CERN:** rich K^+, K_L program, dark sector searches
  - **Plenty of opportunities for newcommers to contribute (hardware, analysis, new ideas)**

Backup

Dark photon searches (2021 data): $A' \to \mu^+\mu^-$

Dark photon searches: $A' \to \mu^+\mu^-$

[arXiv:2303.08666v1]



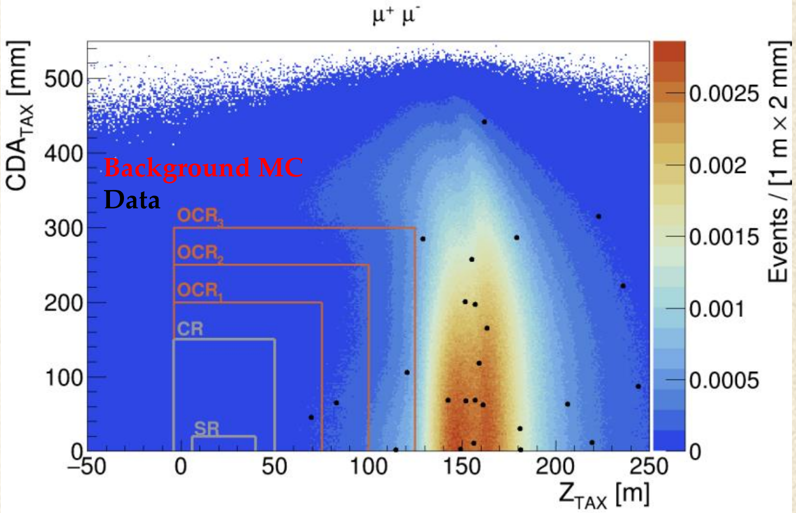
- Feebly interacting dark photon with free mass and coupling ϵ
- Beam dump mode: 3.2 m Cu-Fe collimators (TAX) used as a target
- Search for dark photon production in interaction with TAXs
- $(1.40 \pm 0.28) \times 10^{17}$ POT collected in ~ 10 days in 2021

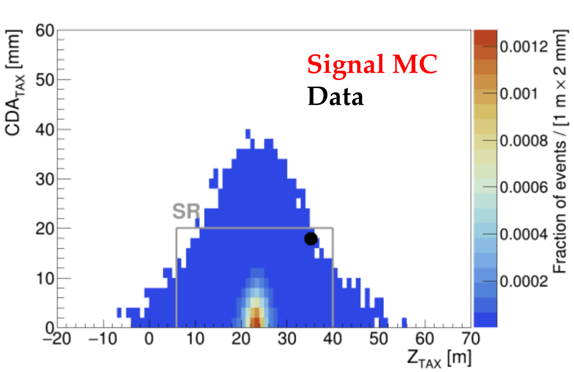
After signal selection:

$N_{obs} = 1$ event

$N_{bg}^{exp} = 0.016 \pm 0.002$ events

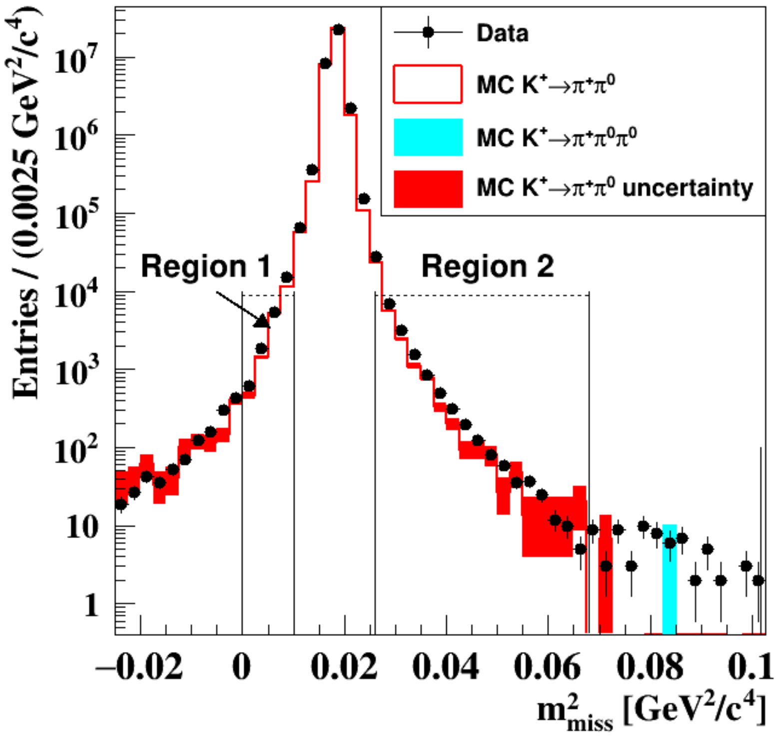
2.4 σ global significance (counting experiment)





Results NA62 Run 1 (2016-18)

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



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

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

Expected $K^+ \to \pi^+\pi^0$ in signal regions after the $\pi\nu\bar{\nu}$ selection

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

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

Systematic uncertainties, Error budget

	δa_+	δb_+	$\delta \mathcal{B} \times 10^8$	$\delta A_{\mathrm{FB}} \times 10^2$
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**