Recent results from the NA62 experiment

LHCP, June 3rd–7th 2024, Boston, USA

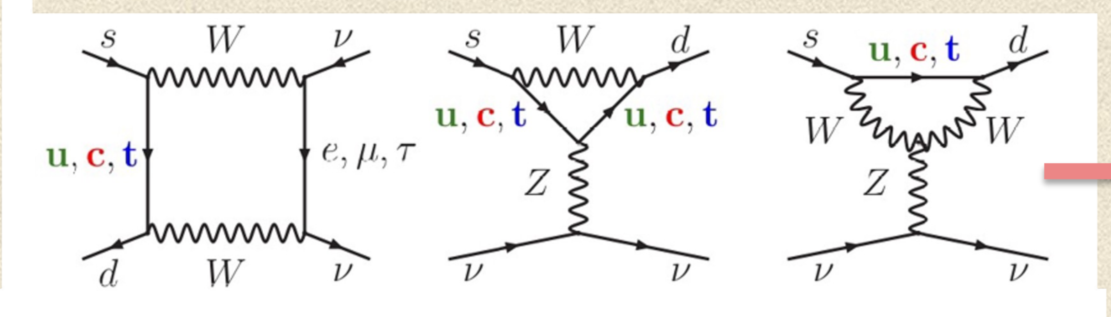
Speaker: Radoslav Marchevski

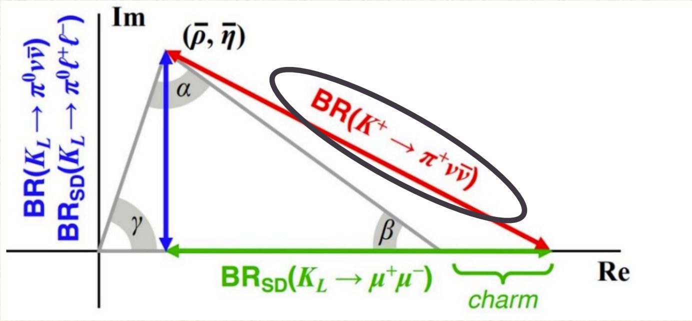
On behalf of the NA62 Collaboration

Outline

- New results and updates from the physics program with charged kaons at NA62
  - Measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ process
  - Low-energy QCD tests (Chiral Perturbation Theory, χ_{PT})
  - Searches for Lepton Flavour (LF) and Lepton Number (LN) violating decays

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





- $s \rightarrow d$ transition sensitive to the CKM structure of the SM: *loop + CKM suppression*
- Theoretically clean process: *dominated by short-distance physics*
- $K - \pi$ Form Factor (FF) extracted from $K \rightarrow \pi l \nu_l$: *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:
  - $BR_{SM}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = \left(7.73 \pm 0.16_{SD} \pm 0.25_{LD} \pm 0.54_{param.}\right) \times 10^{-11}$ [arXiv:2105.02868]
  - $BR_{SM}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = \left(7.92 \pm 0.28_{theory}\right) \times 10^{-11} \times \left[\frac{|V_{cb}|}{41.0 \times 10^{-3}}\right]^{2.8} \times \left[\frac{\sin\gamma}{\sin 67°}\right]^{1.39}$ [arXiv:2109.11032]

Testing the SM with FCNC: BSM models

Just two examples

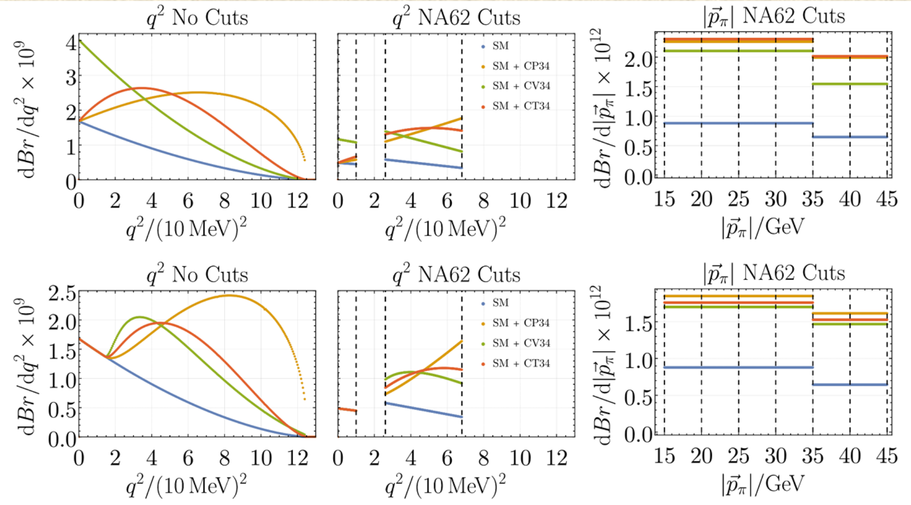
Many others exist (correlations with B and D physics)

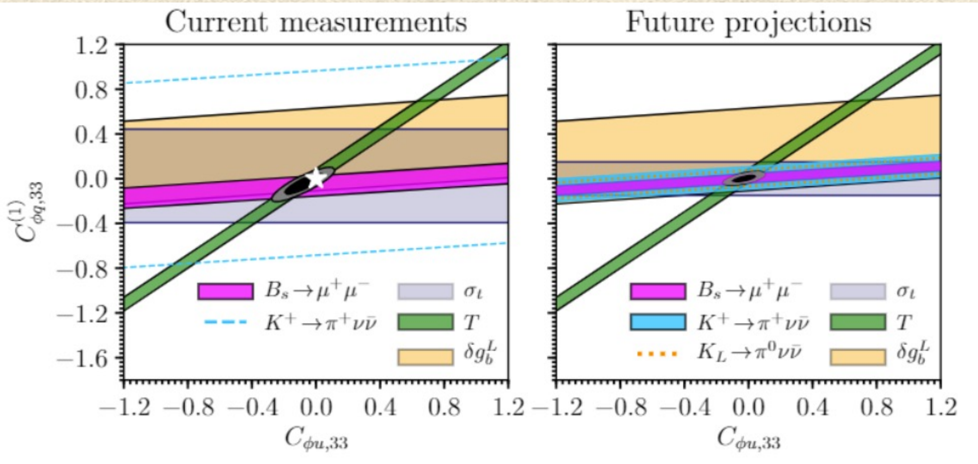
$(\bar{L}_L N_R)\epsilon(\bar{Q}_L d_R)$

[arXiv:2312.06494]

Kaons @ CERN White Paper

[arXiv:2311.02923]





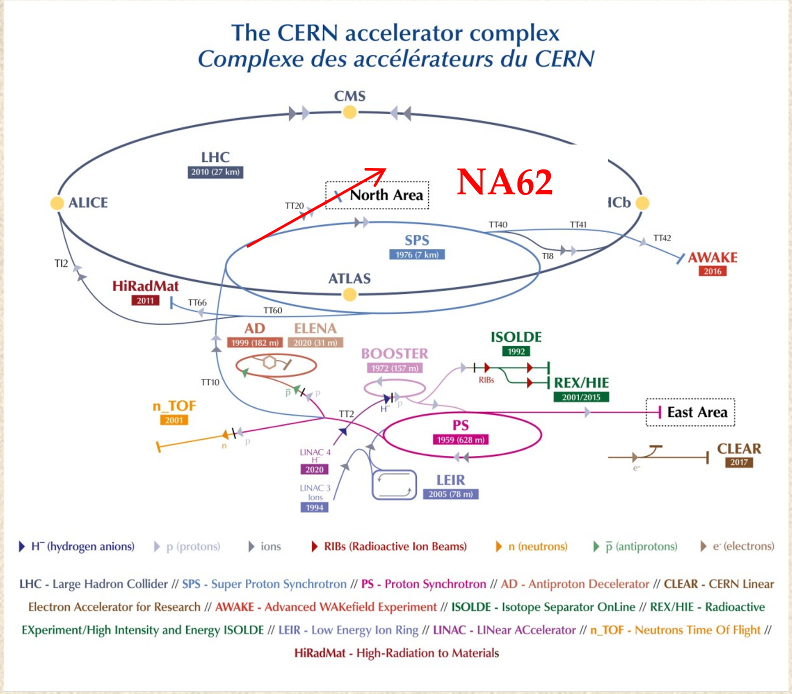
- Possibility to distinguish between NP from Majorana vs Dirac neutrinos
- Modifications of the shape of the BR as a function of q^2
- Improved measurement of $K^+ \to \pi^+\nu\bar{\nu}$ important

- Constraints on anomalous ttZ couplings
- σ_t – single-top production
- $T, \delta g_b^L$ –EW precision parameters

- Correlations: EW precision physics and flavour!

The NA62 experiment @ CERN

$K_{L,S}$	$K_{L,S}$	K_S	$K^{\pm}$	K^+	K^+	K^+
NA31	NA48	NA48/1	NA48/2	NA62 – R_K	NA62 Run1	NA62 Run2
1986 – 88	1997 – 2001	2002	2003 – 4	2007 – 8	2016 – 18	2021 –

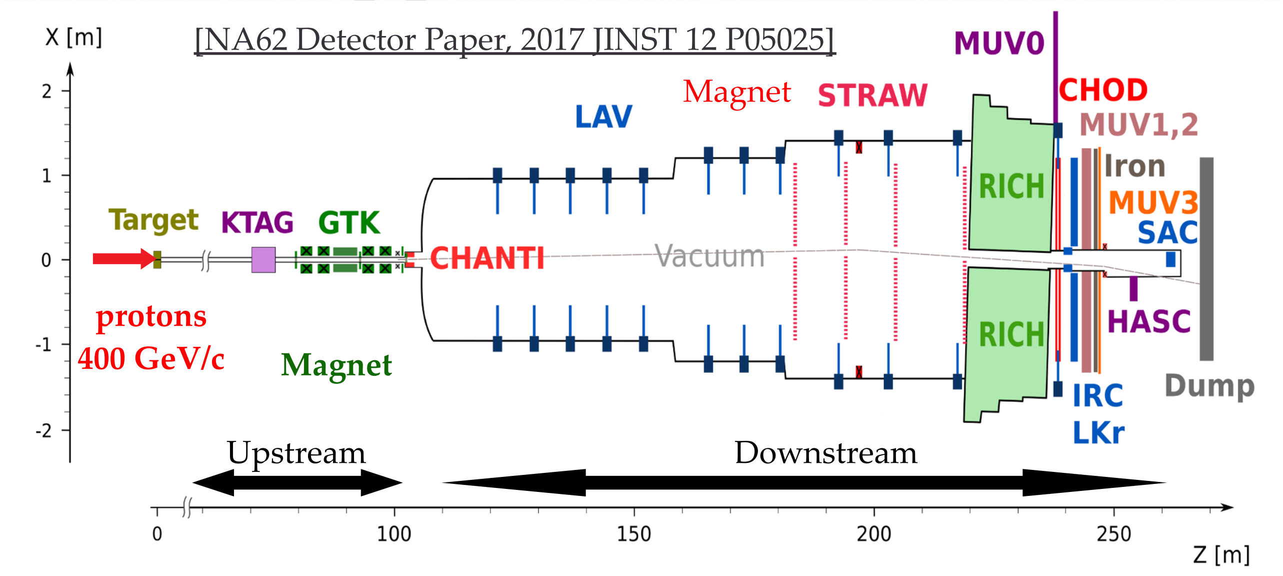


- Long tradition of kaon experiments at CERN
- NA62 main target: **$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay measurement**
- Broad physics program:
  - Other rare charged kaon decays
  - Precision measurements
  - LFV/LNV searches
  - Exotic searches (FIPs, Dark photon, etc…)

NA62 collaboration ~ 300 physicists from 31 institutions

The NA62 experimental apparatus

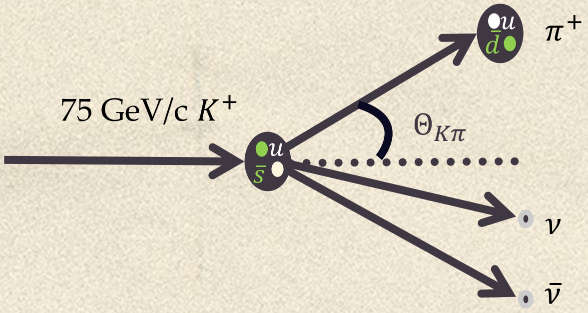
- Secondary beam
  - 75 ± 1 GeV/c momentum
  - 6% K^+ component
  - 60 m long fiducial volume
  - ~ 3 MHz K^+ decay rate



- 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

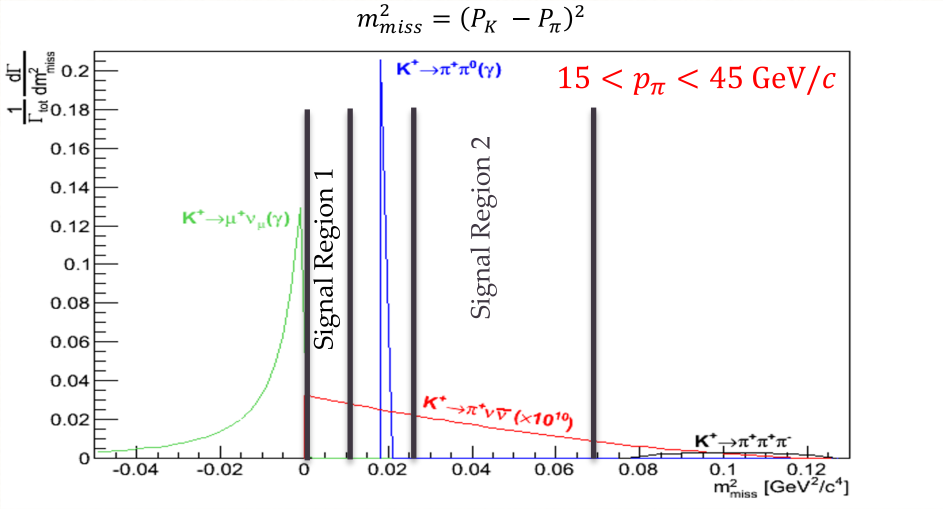
Analysis strategy



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

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

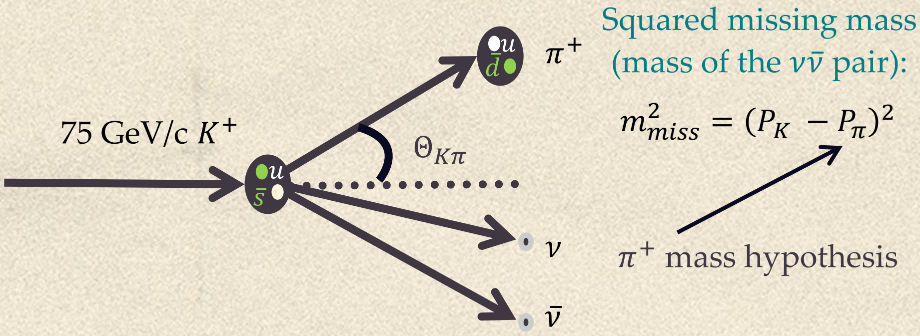
π^+ mass hypothesis

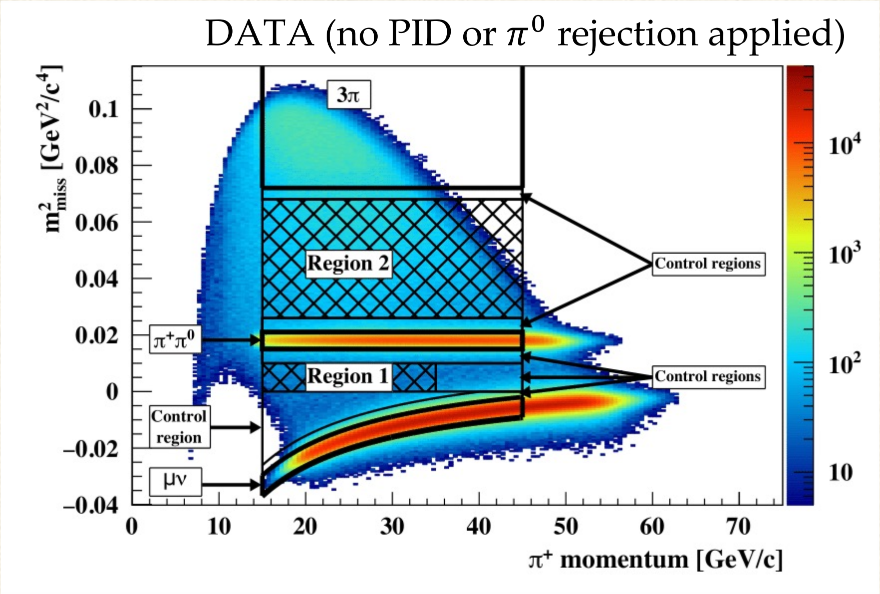


- Highly boosted decay: (75 ± 1) GeV/c K^+ $(\gamma \sim 150)$
- Large undetectable missing energy carried away by the neutrinos
- All energy from visible particles must be detected
- π^+ momentum range 15 – 45 GeV/c ($E_{miss} > 30$ GeV)
- Hermetic detector coverage and O(100%) detector efficiency needed

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

Analysis strategy





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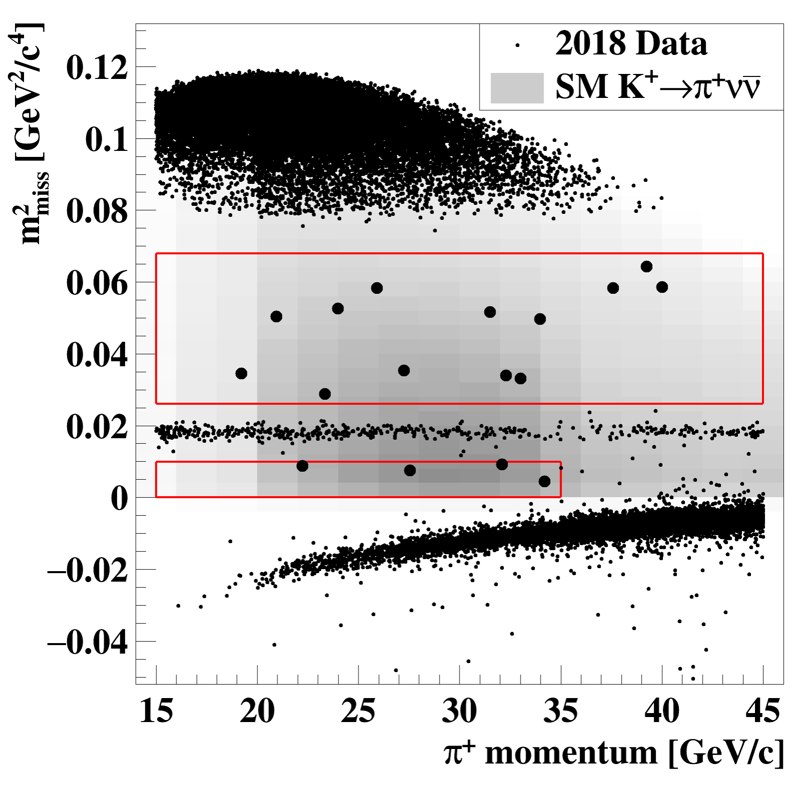
Results NA62 Run 1 (2016-18)

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



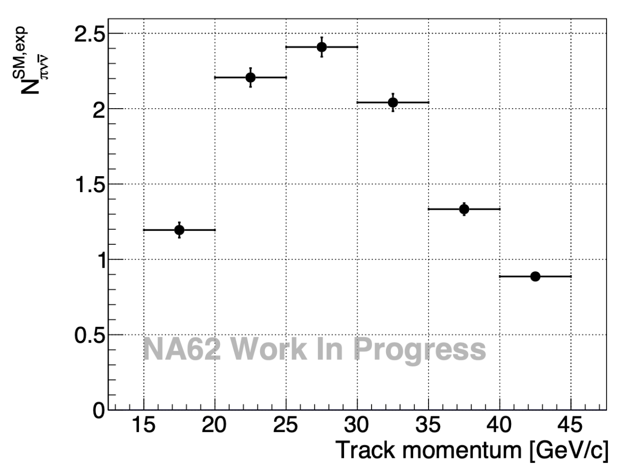
- $N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- $N^{exp}_{bg} = 7.03^{+1.05}_{-0.82}$
- $SES = (0.839 \pm 0.053_{syst}) \times 10^{-11}$
- $\boldsymbol{BR(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}}$ **[JHEP 06 (2021) 093]**

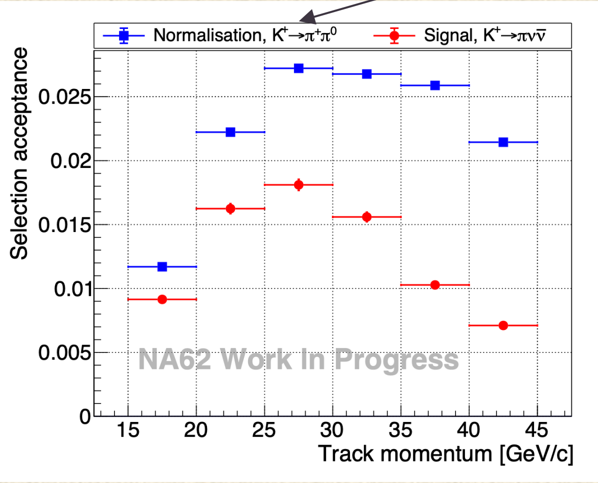
$N_{obs} = 20$ **3.4σ evidence for $K^+ \to \pi^+\nu\bar{\nu}$**

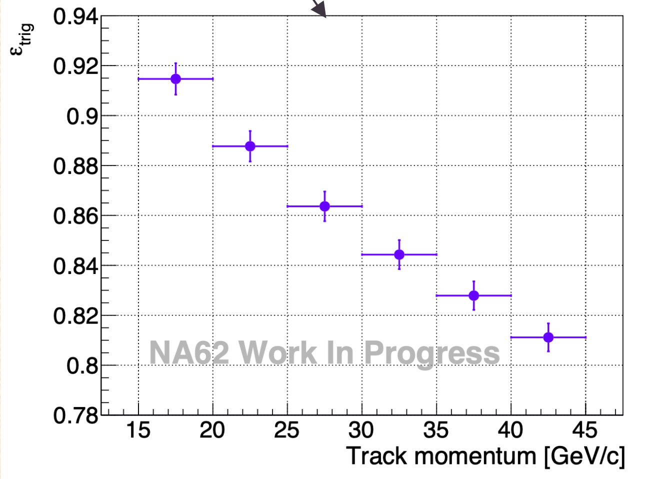
$K^+ \to \pi^+ \nu\bar{\nu}$ in Run 2 (2021+)

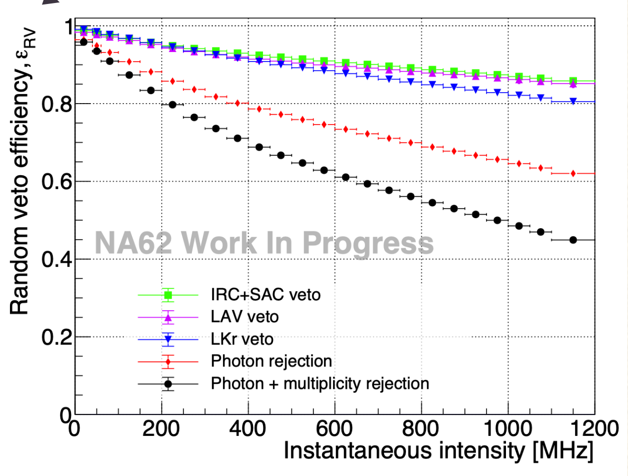
- Analysis of 2021 + 2022 data set ongoing
- $K^+ \to \pi^+\pi^0$ used as a normalization decay

$$N^{SM,exp}_{\pi\nu\bar{\nu}} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}}{A_{\pi\pi}} D_0 N_{\pi\pi} \epsilon_{trig} \epsilon_{RV}$$









$K^+ \to \pi^+ \nu\bar{\nu}$ in Run 2 (2021+)

Hardware improvements after LS2

- 4th GTK station to improve K^+ tracking
- VetoCounter in upstream region to reduce upstream background and Anti0 to reduce muon halo
- HASC calorimeter downstream to reject γ from conversions with the RICH beam pipe
- Cedar-H: Cherenkov detector for K^+-id filled with Hydrogen instead of Nitrogen

Work in progress (*)

Expected events (R1+R2)

	2018	2021+2022
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$7.58 \pm 0.40_{syst} \pm 0.75_{ext}$	10.07 ± 0.31
$K^+ \to \pi^+\pi^0(\gamma)$	0.75 ± 0.05	0.86 ± 0.06
$K^+ \to \mu^+\nu(\gamma)$	0.64 ± 0.08	0.93 ± 0.20
$K^+ \to \pi^+\pi^- e^+\nu$	0.51 ± 0.10	$0.84^{+0.35}_{-0.28}$
$K^+ \to \pi^+\pi^+\pi^-$	0.22 ± 0.10	0.11 ± 0.03
$K^+ \to \pi^+\gamma\gamma$	< 0.01	0.01 ± 0.01
$K^+ \to \pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$3.30^{+1.00}_{-0.75}$	$8.0^{+2.2}_{-1.8}$
Total background	$5.42^{+1.00}_{-0.75}$	$10.8^{+2.2}_{-1.9}$

(*) CERN-SPSC-2024-012 / SPSC-SR-345

Variable	2021 ($t > 2$ s)	2022	21+22
$(N_{\pi\pi} D_0)/400$ [$\times 10^7$]	3.713	16.374	20.087
ε_{trig}	$(83.5 \pm 1.3)\%$	$(86.3 \pm 1.5)\%$	$(85.8 \pm 1.4)\%$
ε_{RV}	$(63.0 \pm 0.5)\%$	$(63.8 \pm 0.5)\%$	$(63.6 \pm 0.5)\%$
$A_{\pi\pi}$		$13.525 \pm 0.005\%$	
$A_{\pi\nu\bar{\nu}}$		$7.7 \pm 0.2\%$	
$\mathcal{B}_{SES}[\times 10^{-11}]$	4.68 ± 0.17	1.01 ± 0.03	0.83 ± 0.03
$N^{SM,exp}_{\pi\nu\bar{\nu}}$	1.80 ± 0.06	8.28 ± 0.24	10.07 ± 0.31
$N^{SM,exp}_{\pi\nu\bar{\nu}}$ per burst	1.7×10^{-5}	2.5×10^{-5}	2.3×10^{-5}

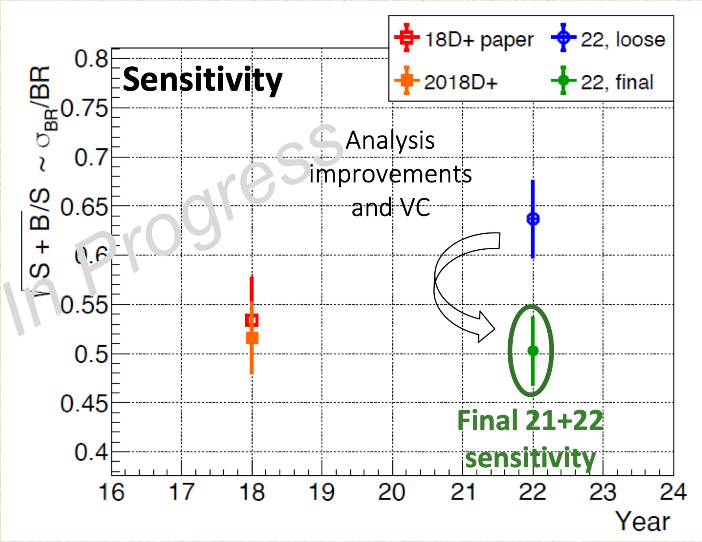
Work in progress (*)

Studies ongoing to understand background scaling between Run 1 and Run 2

$K^+ \to \pi^+\nu\bar{\nu}$ in Run 2 (2021+)

Analysis improvements after LS2

- Signal acceptance improved by 20%, maintaining background rejection at the same level, $A^{2018}_{\pi\nu\bar{\nu}} = (6.4 \pm 0.6)\%$
- Uncertainty of the Signal Event Sensitivity improved significantly in Run 2 (7% → 4%) due to more precise understanding of the trigger and random veto efficiencies
- Signal yield improved by 50% ,$N_{\pi\nu\bar{\nu}}/\text{burst}^{2018} = 1.7\times10^{-5}$



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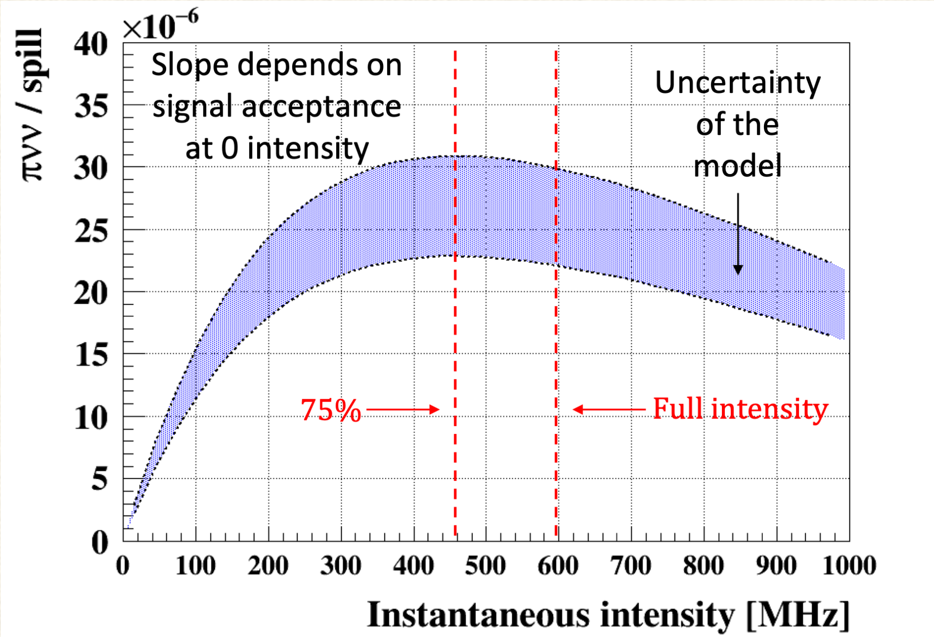
$K^+ \to \pi^+ \nu\bar{\nu}$ in Run 2 (2021+)

- Work ongoing to finalise the first results with Run 2 data (2021+22)
- Data in 2021+22 taken pushing the hardware limit of NA62
- Essential studies performed to understand optimal intensity with best sensitivity to $K^+ \to \pi^+ \nu\bar{\nu}$ decays
- Operating at intensities optimized to achieve best Single Event Sensitivity in 2023 and 2024!

Stay tuned for new results soon!



Low-energy QCD tests: $K^+ \to \pi^+\gamma\gamma$ ($K_{\pi\gamma\gamma}$)

- Radiative non-leptonic kaon decays allow tests of Chiral Perturbation Theory (χ_{PT}), describing low-energy QCD processes

- Main kinematic variables: $z = \frac{(p_{\gamma 1}+p_{\gamma 2})^2}{m_K^2} = \frac{m_{\gamma\gamma}^2}{m_K^2}$, $y = \frac{P_K(Q_{\gamma_1} - Q_{\gamma_2})}{m_K^2}$

- The differential decay rate parametrized in χ_{PT}: strong dependence on z and weak dependence on y

only free parameter

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

lowest order loop amplitude $\mathcal{O}(p^4)$

next to leading order loop amplitude $\mathcal{O}(p^6)$

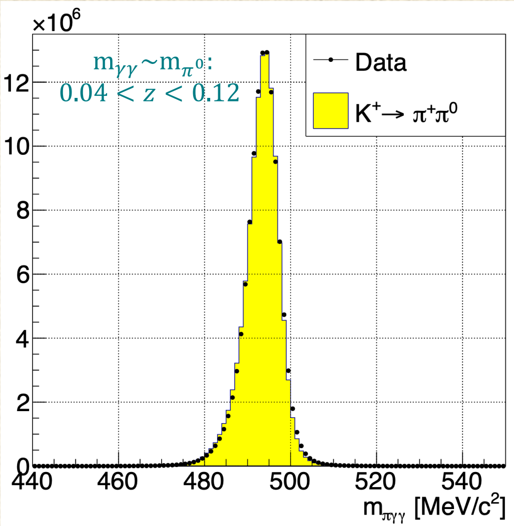
- BR($K^+ \to \pi^+\gamma\gamma$) and $\hat{c}$ depend on **8 external parameters** fixed using Phys. Lett. B 835 (2022) 137594

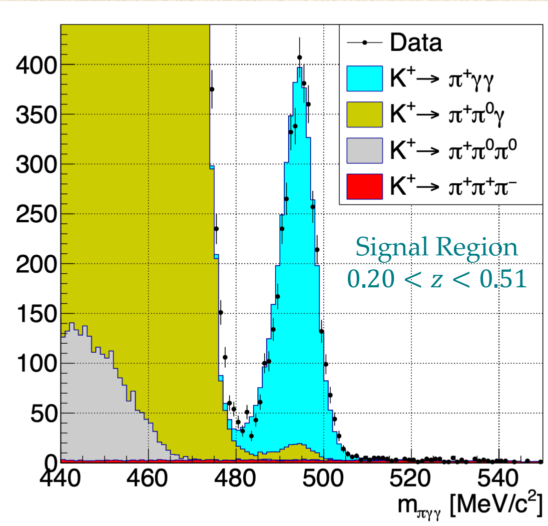
$K^+ \rightarrow \pi^+\gamma\gamma$ ($K_{\pi\gamma\gamma}$) selection

- Analysis using Run 1 data sample
- $K^+ \rightarrow \pi^+\gamma\gamma$ selection
  - one single positive π^+ track
  - $K^+ - \pi^+$ matching and vertex reconstruction
  - 2 good γ clusters in the LKr calorimeter
  - Kinematic cuts on total E, p_T and $m_{\pi\gamma\gamma}$
- Background sources
  - Cluster merging in LKr:

    $K^+ \rightarrow \pi^+\pi^0\gamma(\pi^0 \rightarrow \gamma\gamma)$

    $K^+ \rightarrow \pi^+\pi^0\pi^0(\pi^0 \rightarrow \gamma\gamma)$
  - Multi-track events with tracks missing (mainly $K \rightarrow \pi\pi\pi$)
- $K^+ \rightarrow \pi^+\pi^0$ used as a normalisation channel to measure N_K





After selection:

$N_K = (5.55 \pm 0.03) \times 10^{10}$

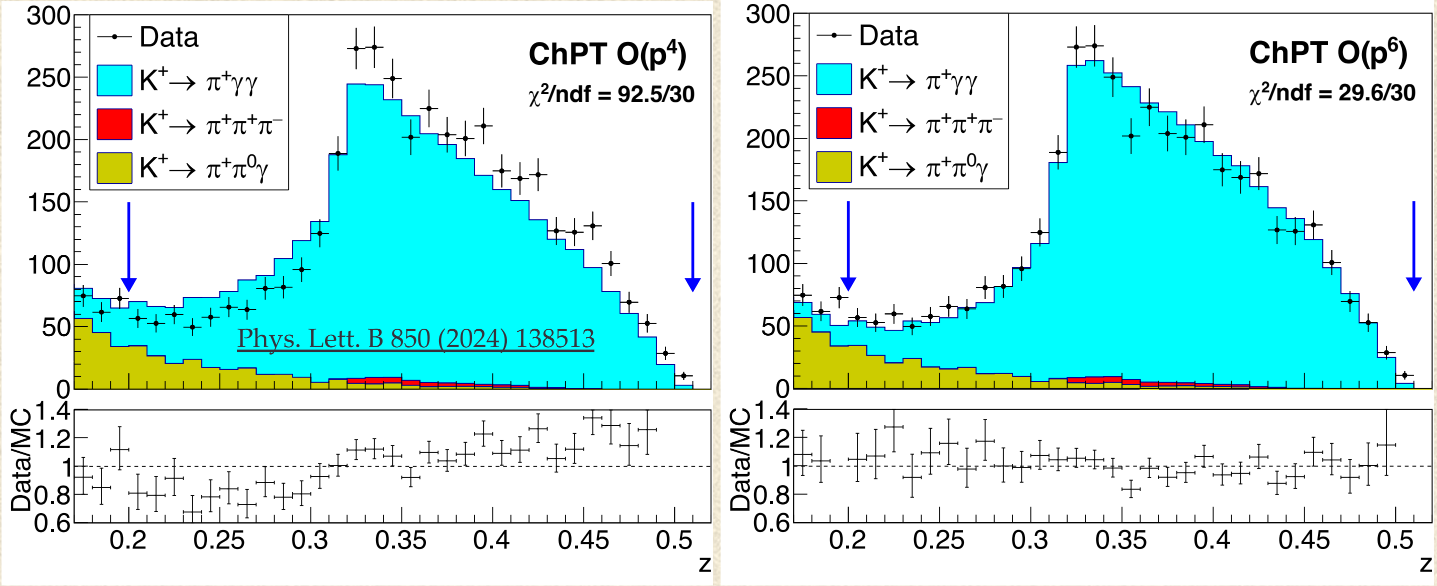
$N_{obs} = 3984$ events

$N_{bg}^{exp} = 291 \pm 14$ events

Phys. Lett. B 850 (2024) 138513

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

- Reconstructed z spectrum of the signal candidates: $\boldsymbol{z = (P_K - P_\pi)^2/M_K^2}$ (better resolution than $m_{\gamma\gamma}^2/m_K^2$)



z spectrum fitted using the theoretical parametrisation in 31 bins of $z(\delta z = 0.01)$

Model-dependent measurement: MC spectrum reweighted for different values of $\hat{c}$ and extracting the best-fit value

First evidence that the $\mathcal{O}(p^4)$ description is not compatible with the data: $\mathcal{O}(p^6)$ is required

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

- Model-independent $BR(K^+ \to \pi^+\gamma\gamma)$ measurement and the corresponding decay width are computed in ach z bin

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

$$BR(K^+ \to \pi^+\gamma\gamma)_{MI} = (9.46 \pm 0.19_{stat} \pm 0.07_{syst})\times 10^{-7}$$

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

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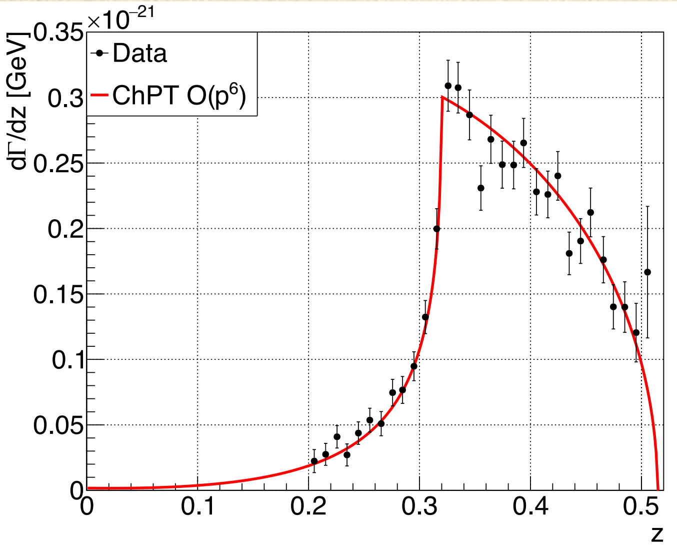
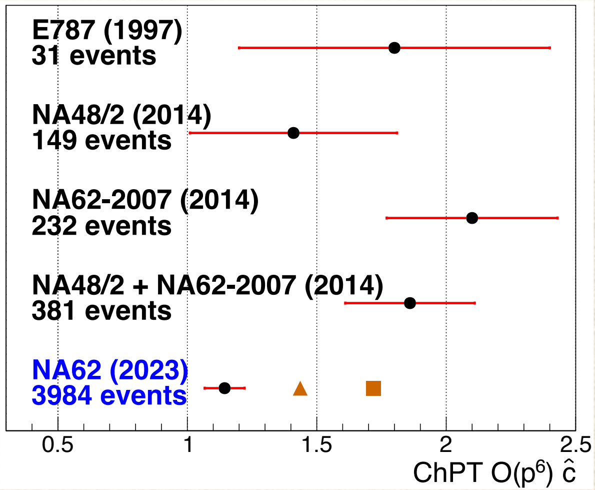
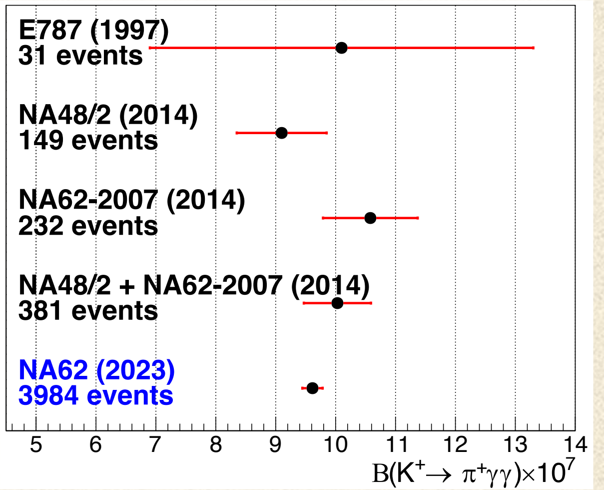
Comparison between model-independent measurement and $O(p^6)$ parametrisation in χ_{PT}



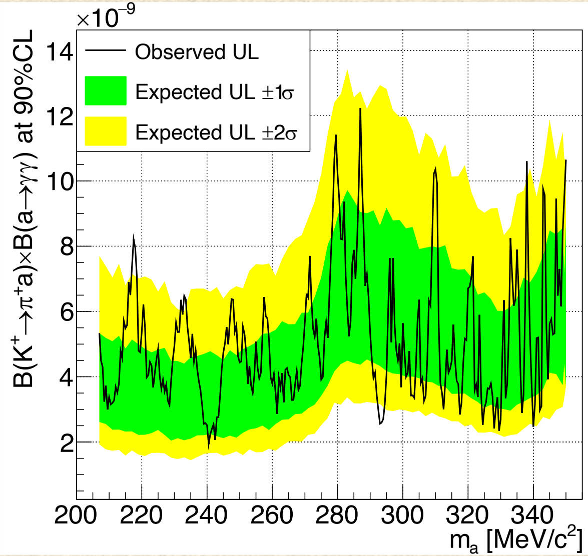


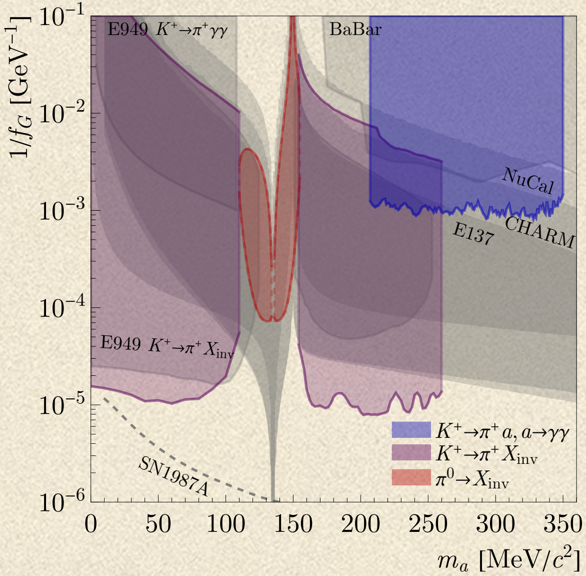


$\hat{c}$ value depends on the external parameter values. To test the consistency of the result with the old measurements $\hat{c}$ is also evaluated with the external parameter values used by E878 (triangle) and NA48/2-NA62-2007 (square)

Search for ALPs in $K^+ \to \pi^+ a, a \to \gamma\gamma$ decays

- Hidden sector scenario in which axion-like particle (ALP) couples to gluons: BC11 (if $m_a < 3m_\pi, a \to \gamma\gamma$)
- Peak search in $m_a = \sqrt{(P_K - P_\pi)^2}$: 287 hypotheses, 207-350 MeV/c^2 range, 0.5 MeV/c^2 step
- m_a resolution: 0.2 – 2.0 MeV/c^2 across the mass range
- Upper limit at 90% CL using CL_s method set to N_S (number of signal events) in each bin





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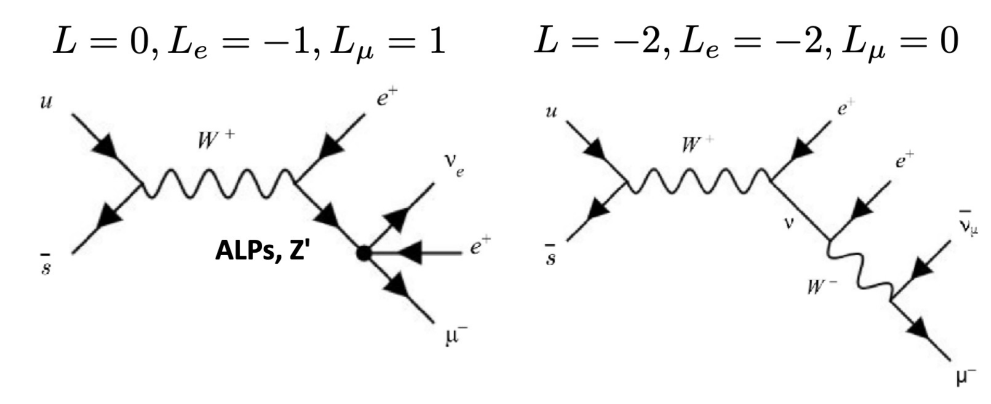
Assuming **prompt $a \to \gamma\gamma$ decay** ($\tau_a = 0$) we get an upper limit on the branching ratio

$$BR(K^+ \to \pi^+ a) = \frac{N_S}{N_K \cdot A_S}$$

If we assume $\tau_a \neq 0$ **a signal acceptance loss function** is considered increasing with τ_a due to vertex displacement ($f_G^{-1} \sim \tau_a^{-0.5}$)

LFV/LNV searches: $K^+ \to \mu^- \nu e^+ e^+$

- Lepton flavour or lepton number violating decay depending on the neutrino flavour: ν_e or ν_μ



Potential observation will provide

- Evidence for BSM models involving flavour violating ALPs and Z' (LFV)
- Evidence for Majorana neutrino (LNV)

Past upper limit

- $BR(K^+ \to \mu^- \nu e^+ e^+) < 2.1 \times 10^{-8}$

- Selection
  - Exactly three well separated downstream tracks (STRAW) forming a vertex with $Q_{vtx} = +1$
  - Particle identification of the track candidates (μ^-, e^+, e^+)
  - Photon veto downstream of the vertex (against Dalitz decays)

  $K^+ \to \pi^+ \pi^0_D, K^+ \to \pi^0_D e^+ \nu (\pi^0_D \to \gamma e^+ e^-)$

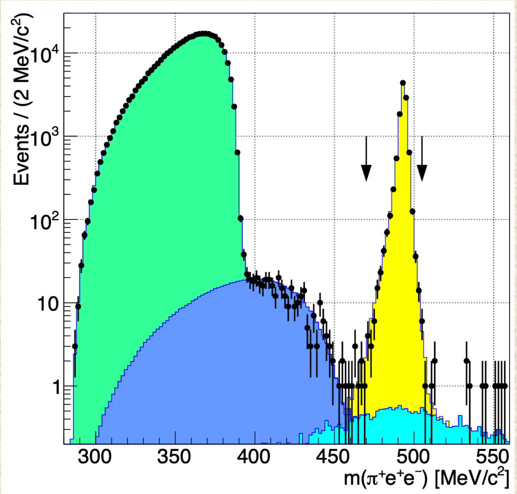
Analysis using Run 1 dataset

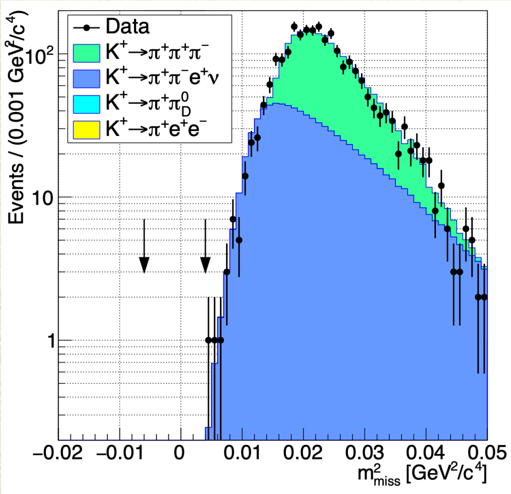
$K^+ \to \mu^- \nu e^+ e^+$ analysis and result

- $m^2_{miss} = (P_K - P_\mu - P_{e1} - P_{e2})^2 = m^2_\nu$
- Signal region: $(-6\times10^{-3} < m^2_{miss} < 4\times10^{-3})$GeV/c^2
- K^+ in the fiducial region: $1.97(2)_{stat}(2)_{syst}(6)_{ext}\ \times10^{12}$
- $K^+ \to \pi^+ e^+ e^-$ used for normalization
  - Same 3-track vertex selection + beam constraint ($|P_{beam} - P_{vtx}| < 2\text{GeV}/c$)
  - Particle identification of the track candidates (π^+, e^+, e^-)

Mode / Region	Lower	Signal	Upper
$K^+ \to \pi^+\pi^+\pi^-$	< 0.07	< 0.07	1412 ± 11
$K^+ \to \pi^+\pi^- e^+\nu$	0.01 ± 0.01	0.16 ± 0.02	867 ± 1
$K^+ \to \pi^+\pi^+\pi^-$ (upstream)	< 0.03	0.06 ± 0.03	1.5 ± 0.3
$K^+ \to \pi^+\pi^- e^+\nu$ (upstream)	0.01 ± 0.01	0.01 ± 0.01	0.14 ± 0.03
$K^+ \to \pi^0_D e^+\nu$	0.02 ± 0.01	0.01 ± 0.01	0.02 ± 0.01
$K^+ \to e^+\nu\mu^+\mu^-$	< 0.01	< 0.01	0.05 ± 0.02
Total expected	0.04 ± 0.02	0.26 ± 0.04	2281 ± 11
Data	0	0	2271

After signal selection:
$N_{obs} = 0$ events
$N^{exp}_{bg} = 0.26 \pm 0.04$ events





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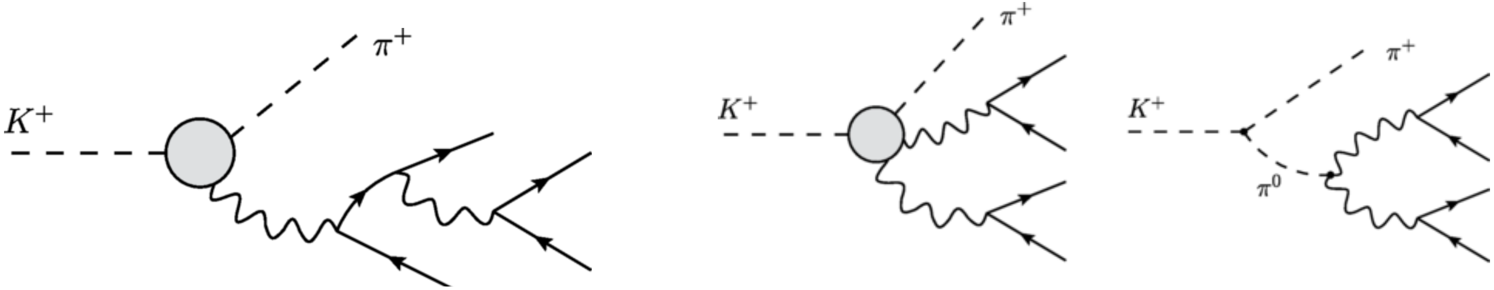
$BR(K^+ \to \mu^- \nu e^+ e^+) < 8.1\times10^{-11}$ @90% CL

- Improvement by a factor 250 over previous searches

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

- 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:



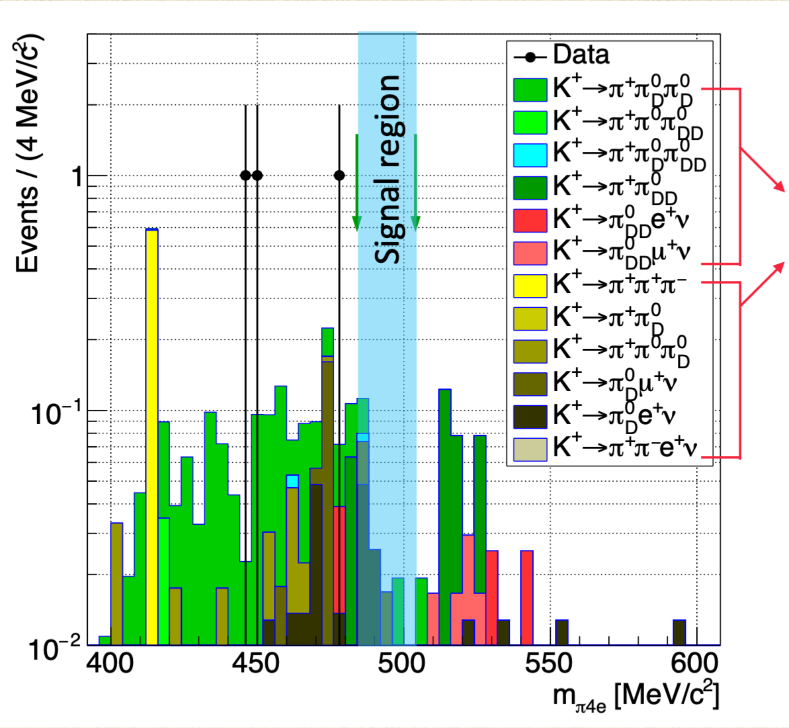
(1) $K^+ \to \pi^+ \gamma^*$ (2a) $K^+ \to \pi^+ \gamma^* \gamma^*$ (2b) $K^+ \to \pi^+ \pi^{0*}$

- 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

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

- Complete Run 1 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 ($K^+ \rightarrow \pi^+ aa$ “Dark”)
  - Same selection as $K_{\pi 4e}$
  - Choice of the optimal e^+e^- mass pair
- Normalization: $K^+ \rightarrow \pi^+ \pi^0_{DD}$(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 $K^+ \rightarrow 3\pi$ decay

After signal selection:

$N_{obs} = 0$ events

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

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

$K_{\pi 4e}$ 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

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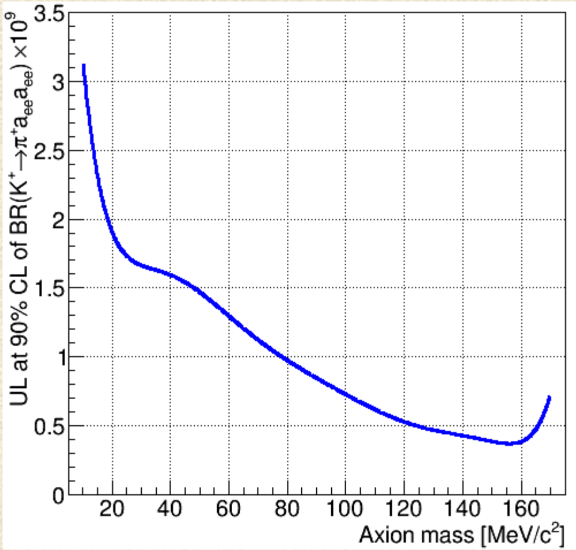

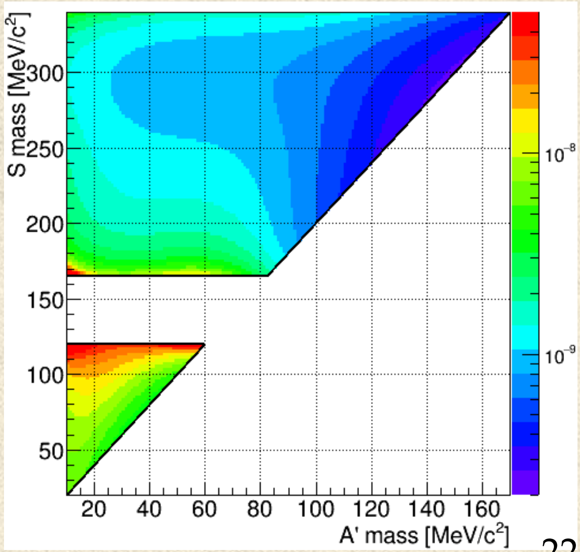

Conclusions

$K^+ \to \pi^+\gamma\gamma$	NA62 Run 1	PLB 850 (2024) 138513
$K^+ \to \pi^+e^+e^-e^+e^-$	NA62 Run 1	PLB 846 (2023) 138193
$K^+ \to \mu^-\nu e^+e^+$	NA62 Run 1	PLB 838 (2023) 137679
$K^+ \to \pi^0e^+\nu\gamma$	NA62 Run 1	JHEP 09 (2023) 040
$K^+ \to \mu^-\nu e^+e^+$	NA62 Run 1	PLB 838 (2023) 137679
$K^+ \to \pi^-(\pi^0)e^+e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \pi^+\mu^+\mu^-$	NA62 Run 1	JHEP 11 (2022) 011
$\pi^0 \to \mu^-e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^+\mu^-e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^-\mu^+e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^+\nu\bar{\nu}$	NA62 Run 1	JHEP 06 (2021) 093
....		

- The NA62 experiment is in full steam
- New results and many new analyses to come
- Work ongoing to finalise the flagship $K^+ \to \pi^+\nu\bar{\nu}$ analysis, with Run 2 data (2021+22)
  - Significantly improved sensitivity with respect to Run 1
  - **Stay tuned for results in the near future**

NA62 will take data until the end of 2025

Many new exciting measurements and searches to come with the full data set!