
Latest results and precision measurement with NA62

PSI 2022, September 16th–21th, Paul Scherrer Institute, Villingen, Switzerland

Speaker: Radoslav Marchevski

On behalf of the NA62 Collaboration

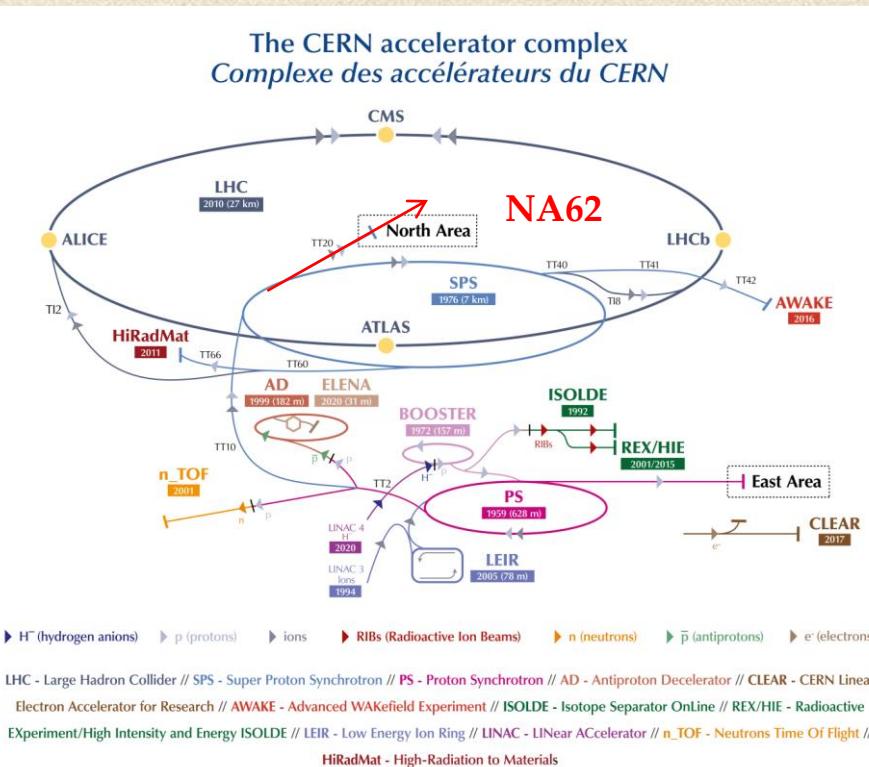
EPFL



Outline

- Measurement of the ultra rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ process [JHEP 06 (2021) 093]
- Precision measurement of the rare $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ process
[arXiv:2209.05076] (Accepted in JHEP)
- Searches for LFV/LNV processes [PLB 797 (2019) 134794], [PLB 830 (2022) 137172],
[PRL 127 (2021) 13, 131802], [Paper in preparation]

The NA62 experiment @ CERN



- Fixed-target experiment at the CERN SPS
- *NA62 Run 1 (2016-18) data-taking completed*
- NA62 Run 2 (2021+) ongoing
- 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...)

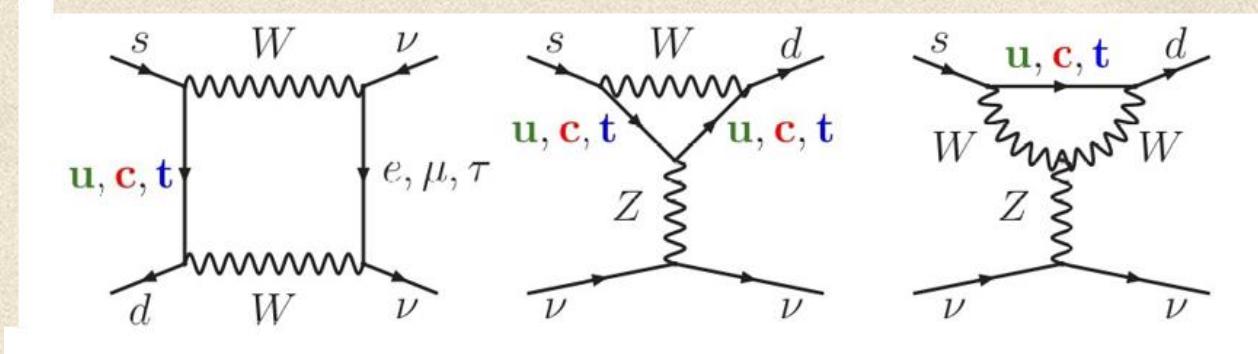


Measurement of the ultra rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ process

[JHEP 06 (2021) 093]

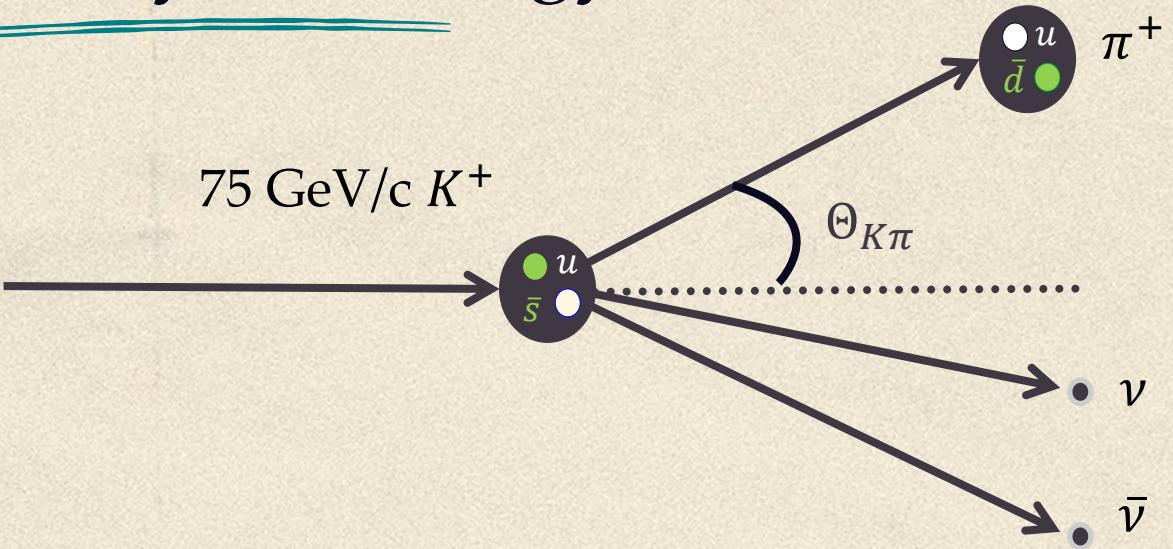


The $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay in the SM



- $s \rightarrow d$ quark transition: *loop + CKM suppression, very rare in the SM*
- Decay amplitude dominated by short-distance (SD) physics: *theoretically clean*
- Hadronic matrix element measured with $K^\pm \rightarrow \pi^0 l^\pm \nu_l$ decays: *sub-% precision*
- Latest SM predictions [[arXiv:2105.02868](https://arxiv.org/abs/2105.02868)]:
 - $BR_{SM}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (7.73 \pm 0.16_{SD} \pm 0.25_{LD} \pm 0.54_{param.}) \times 10^{-11}$
 - $BR_{SM}(K_L \rightarrow \pi^0 \nu\bar{\nu}) = (2.59 \pm 0.06_{SD} \pm 0.02_{LD} \pm 0.28_{param.}) \times 10^{-11}$

Analysis strategy



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

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

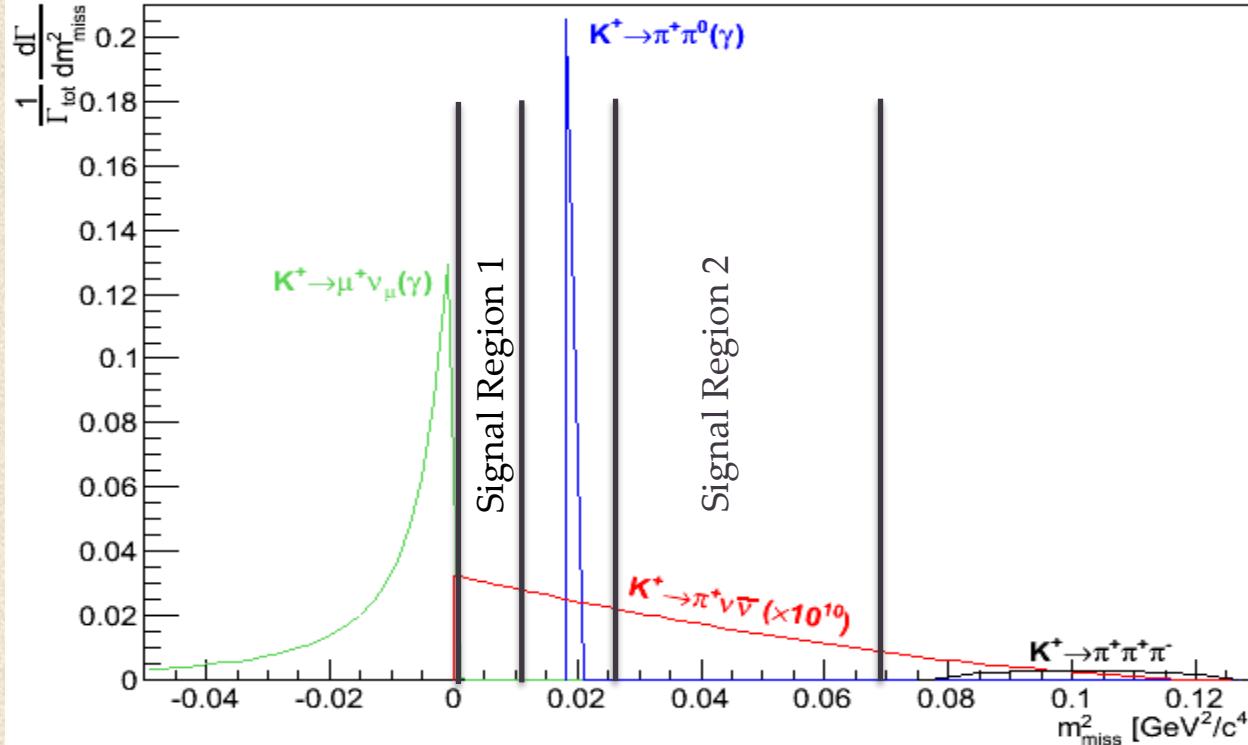
→

π^+ mass hypothesis

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

Analysis strategy

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



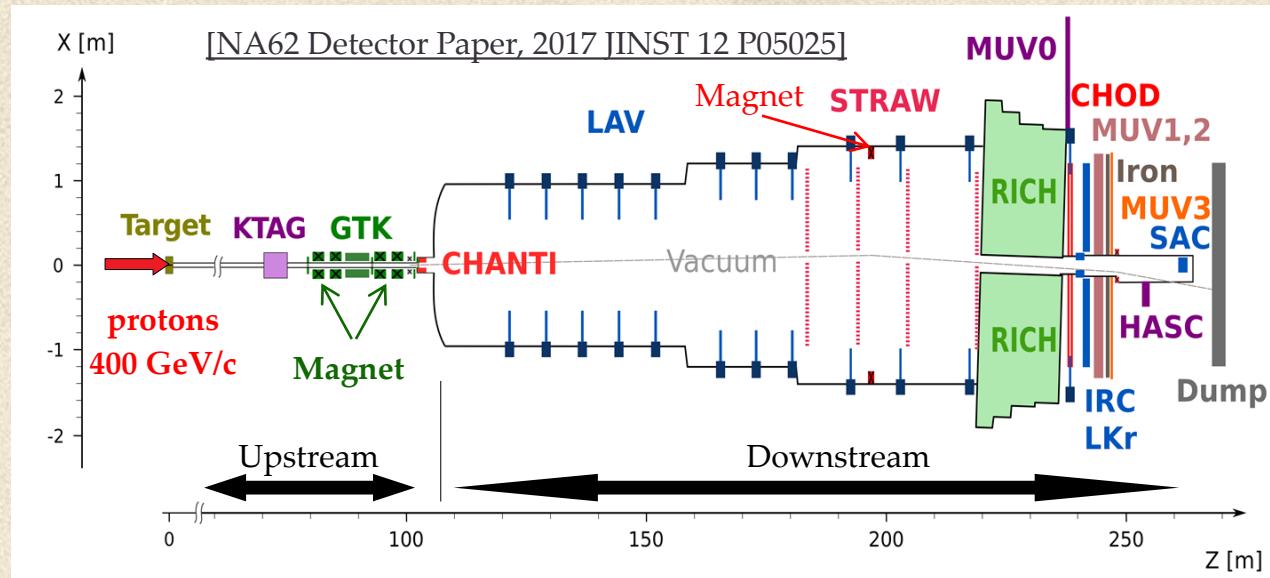
- A background suppression of $O(10^{11})$ is needed for the main K^+ decay modes

Experimental requirements

- Timing between sub-detectors $\sim \mathcal{O}(100 \text{ ps})$
 - *Fast K^+ and π^+ tagging*
- Excellent kinematic suppression $\sim \mathcal{O}(10^4)$
 - *Precise K^+ and π^+ track reconstruction and $K - \pi$ matching*
- Muon suppression (e. g. $K^+ \rightarrow \mu^+ \nu_\mu$) $\sim \mathcal{O}(10^7)$
- π^0 suppression $\sim \mathcal{O}(10^7)$
- Suppression of events with multiple charged particles (e. g. $K^+ \rightarrow \pi^+ \pi^+ \pi^-$) $\sim \mathcal{O}(10^7)$

The NA62 detector

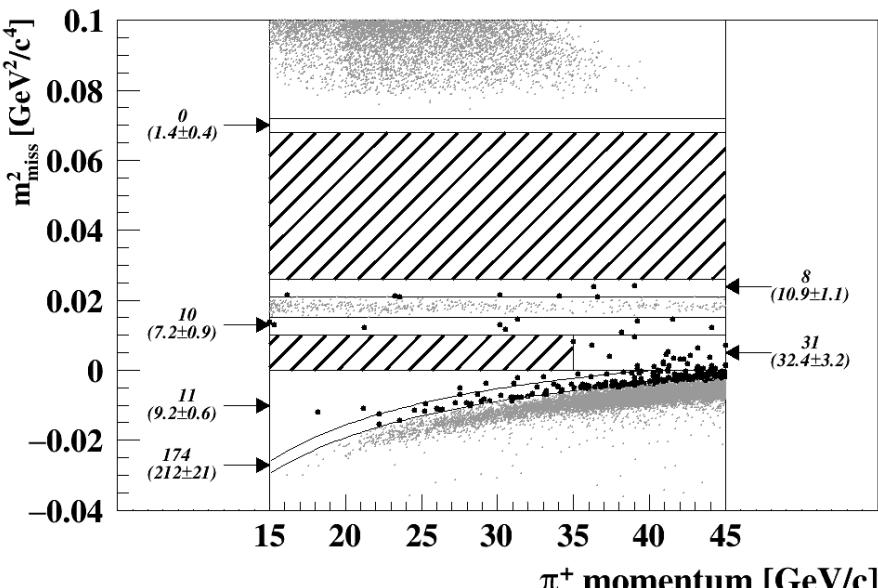
- Secondary beam
 - 75 ± 1 GeV/c momentum
 - 6% K^+ component
 - 60 m long fiducial volume
 - ~ 3 MHz K^+ decay rate



- 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

Expected signal and background contribution

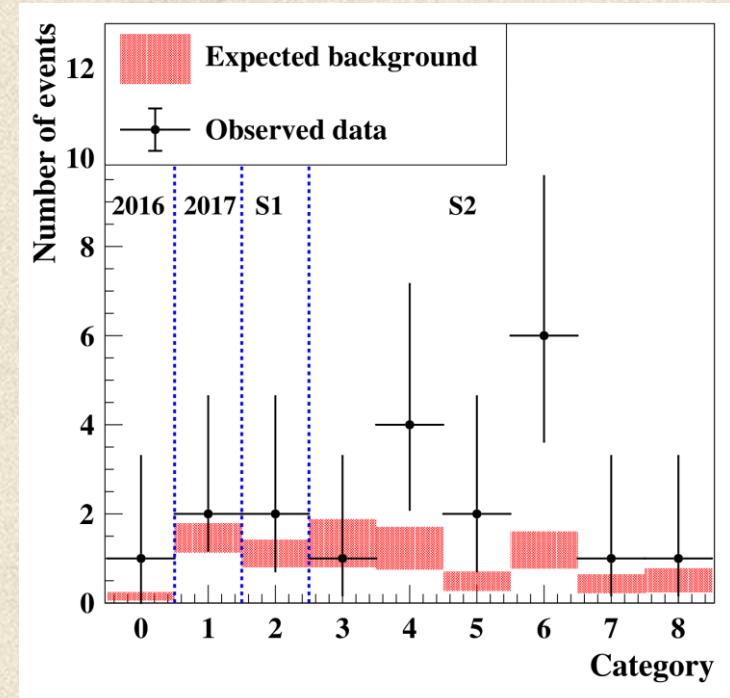
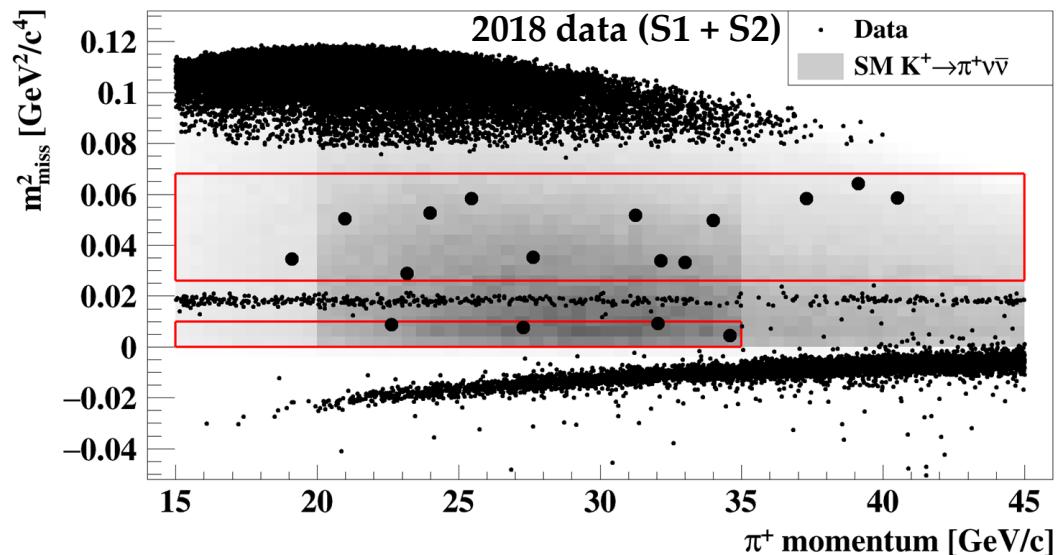


	2018 data
Expected SM signal	7.58(40) _{syst} (75) _{ext}
$K^+ \rightarrow \pi^+ \pi^0 (\gamma)$	0.75(4)
$K^+ \rightarrow \mu^+ \nu (\gamma)$	0.49(5)
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	0.50(11)
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	0.24(8)
$K^+ \rightarrow \pi^+ \gamma \gamma$	< 0.01
$K^+ \rightarrow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

- Combining the complete Run 1 data set (2016-18)

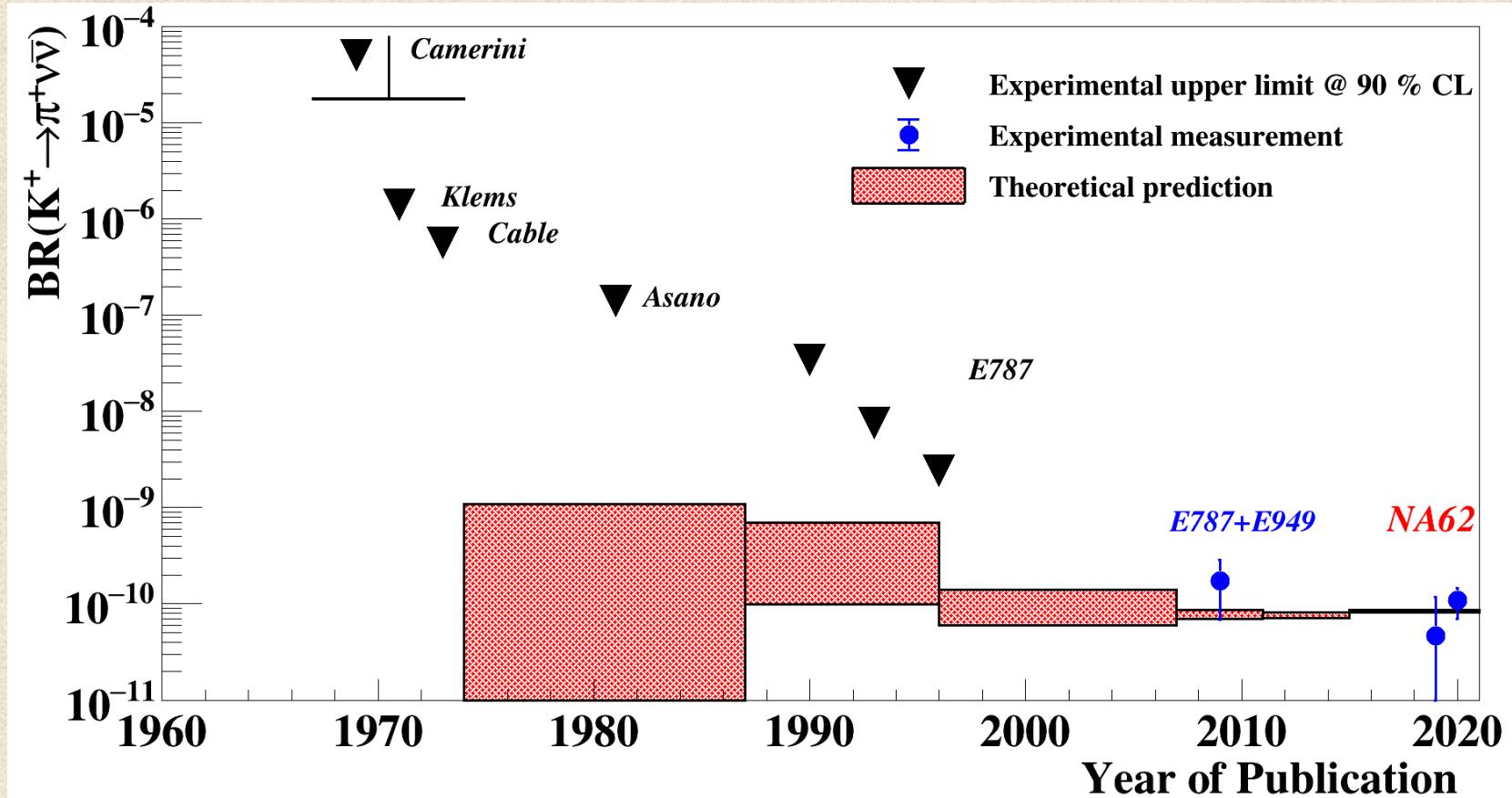
- $N_{\pi\nu\nu}^{exp} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- $N_{bg}^{exp} = 7.03^{+1.05}_{-0.82}$
- $SES = (0.839 \pm 0.053_{syst}) \times 10^{-11}$

Results NA62 Run 1 (2016-18)



- 20 events observed in signal region in NA62 Run 1 data
- $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\text{stat}} \pm 0.9|_{\text{syst}}) \times 10^{-11}$ [JHEP 06 (2021) 093]
3.4 σ significance

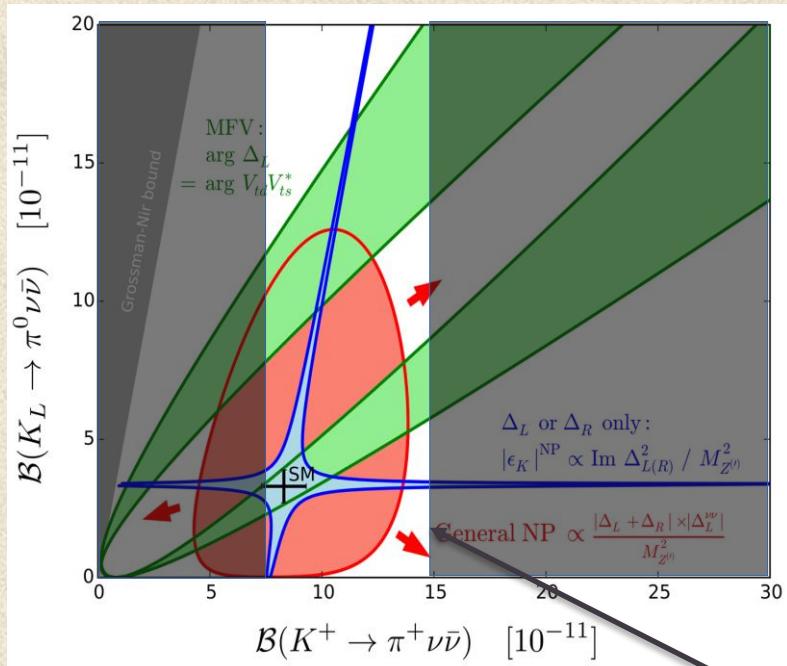
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: Historical context



Impact in the context of BSM models

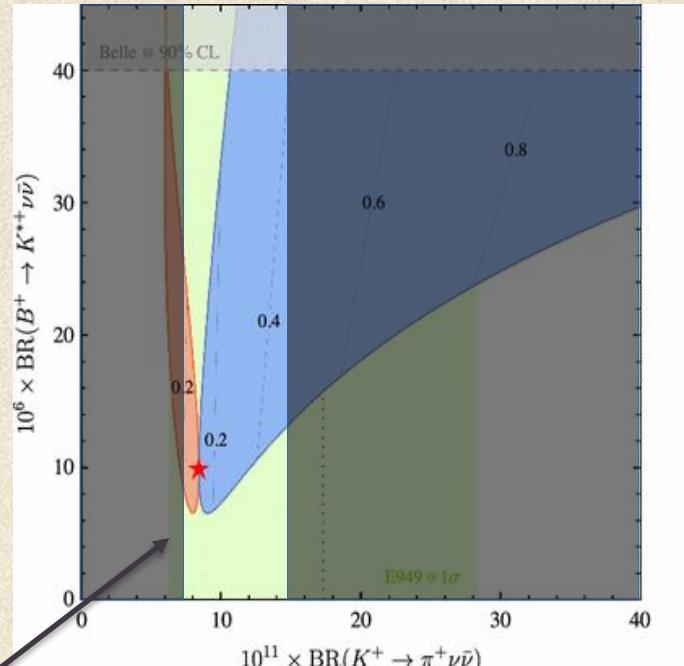
Simplified models

[Buras et. al JHEP 1511 (2015) 166]



LFU violation

[Isidori et. al Eur. Phys. J. C (2017) 77: 618]



Precision measurement of the rare $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ process

[arXiv:2209.05076] (Accepted in JHEP)

$K^+ \rightarrow \pi^+ l^+ l^-$ ($l = e, \mu$) decays

- $s \rightarrow dl^+l^-$ quark transition: **Heavily suppressed Flavour-changing neutral-current**
- Main kinematic variable: $\mathbf{z} = \frac{\mathbf{m}^2(l^+l^-)}{\mathbf{m}_K^2}$
- Form Factor (FF) of the $K^\pm \rightarrow \pi^\pm \gamma^*$ transition: $\mathbf{W(z)}$
- Chiral Perturbation Theory parametrization of $W(z)$ at $O(p^6)$:
 - $W(z) = G_F m_K^2 (\mathbf{a}_+ + \mathbf{b}_+ z) + W^{\pi\pi}(z)$

a_+, b_+ : real parameters
 $W^{\pi\pi}(z)$: complex function, two-pion loop

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

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

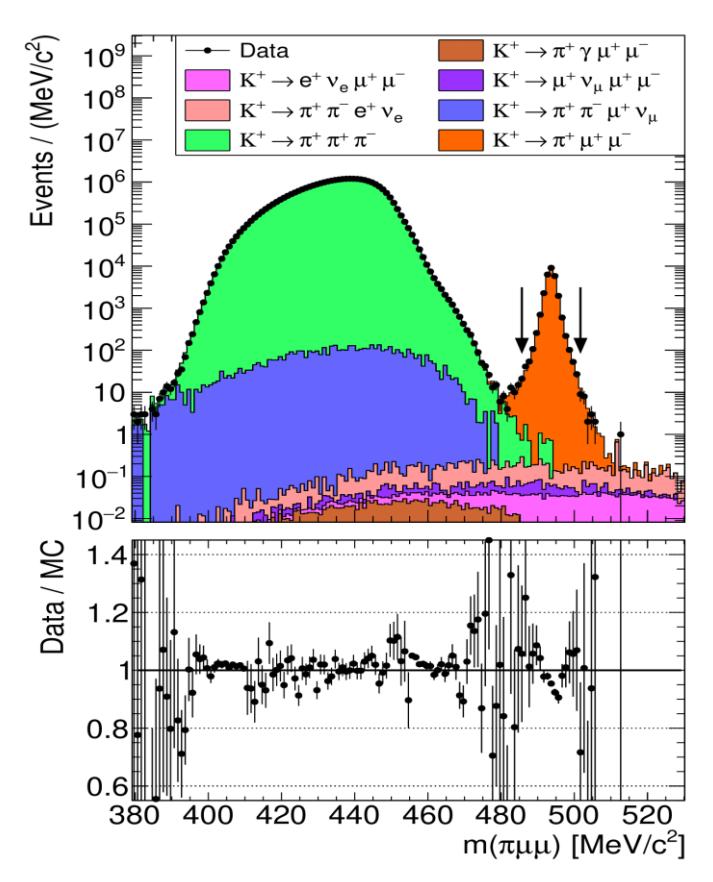
- Signal selection

- Three-track vertex topology
- π^+/μ^+ particle identification
- Kinematic cuts against $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ ($K_{3\pi}$)
- Acceptance: $A_{\pi\mu\mu} \approx 8.7\%$

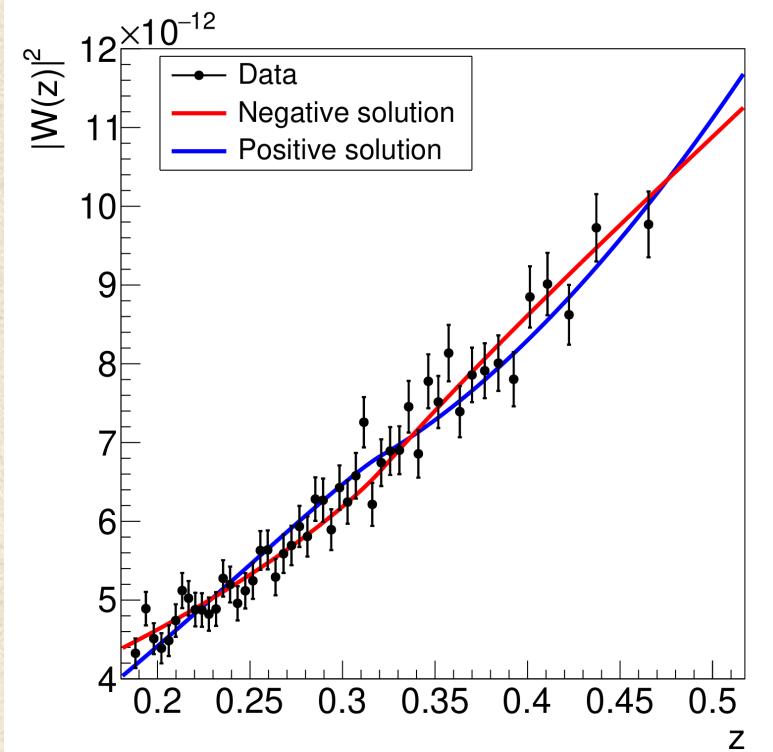
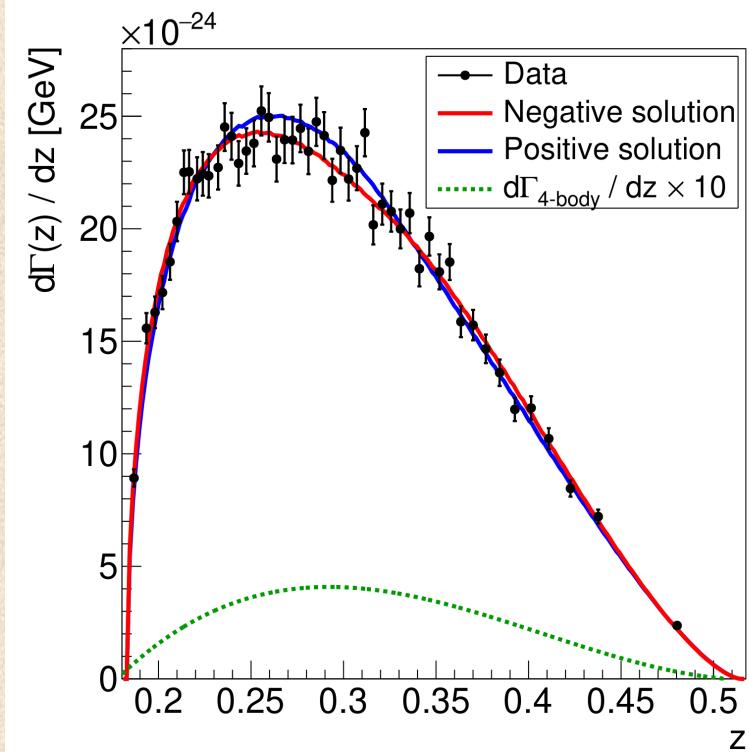
- Normalization done using $K_{3\pi}$ decays

- Kaon flux: $N_K \approx 3.5 \times 10^{12}$
- 27679 events observed ($N_{bg}^{exp} \approx 8$ events)

- Improved treatment of radiative corrections [Eur. Phys. J C70 (2010) 219]



Measurement results



Branching fraction: $BR(K^+ \rightarrow \pi^+ \mu^+ \mu^-) = (9.15 \pm 0.06_{\text{stat}}) \times 10^{-8}$

[arXiv:2209.05076] (Accepted in JHEP)

Measurement of Form Factor parameters

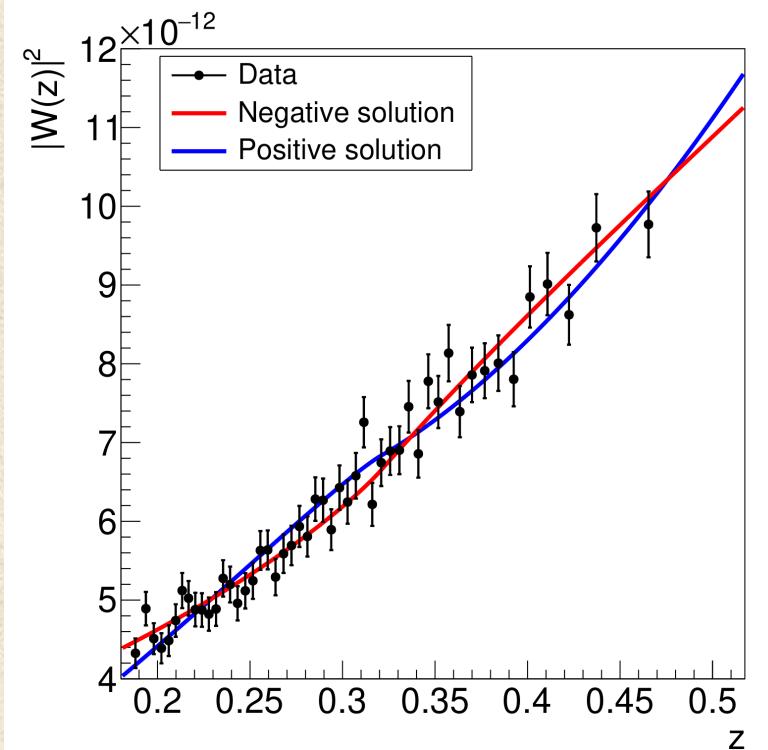
- Two possible solutions
 - a_+, b_+ both *negative* or *positive* values
- Negative solution preferred
 - $\chi^2/\text{ndf} = 45.1/48$ (p-value = 0.59)

$$a_+ = -0.575 \pm 0.012_{\text{stat}}$$

$$b_+ = -0.722 \pm 0.040_{\text{stat}}$$

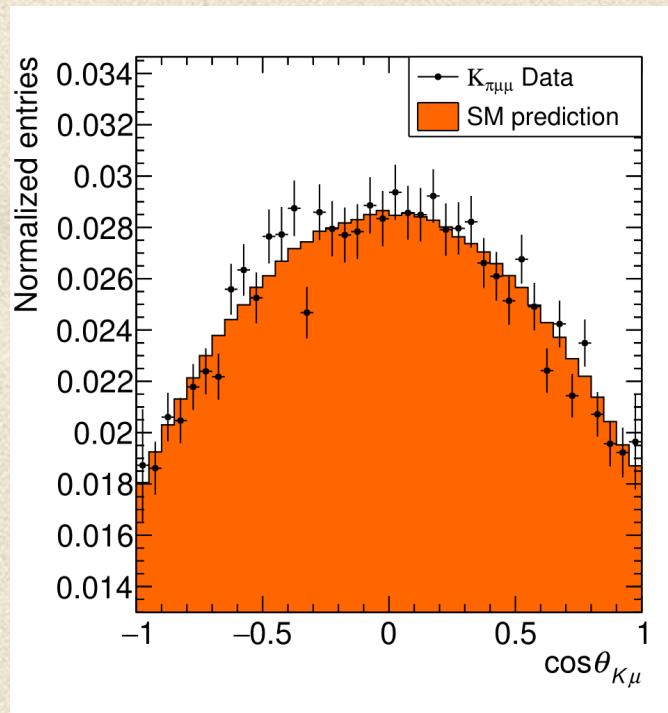
$$\text{Correlation } \rho(a_+, b_+) = -0.972$$

- Positive solution
 - $\chi^2/\text{ndf} = 56.4/48$ (p-value = 0.19)
 - $a_+ = +0.373 \pm 0.012_{\text{stat}}$
 - $b_+ = +2.017 \pm 0.040_{\text{stat}}$
 - Correlation $\rho(a_+, b_+) = -0.973$



[arXiv:2209.05076] (Accepted in JHEP)

$K^+ \rightarrow \pi^+ \mu^+ \mu^-$ asymmetry measurement result

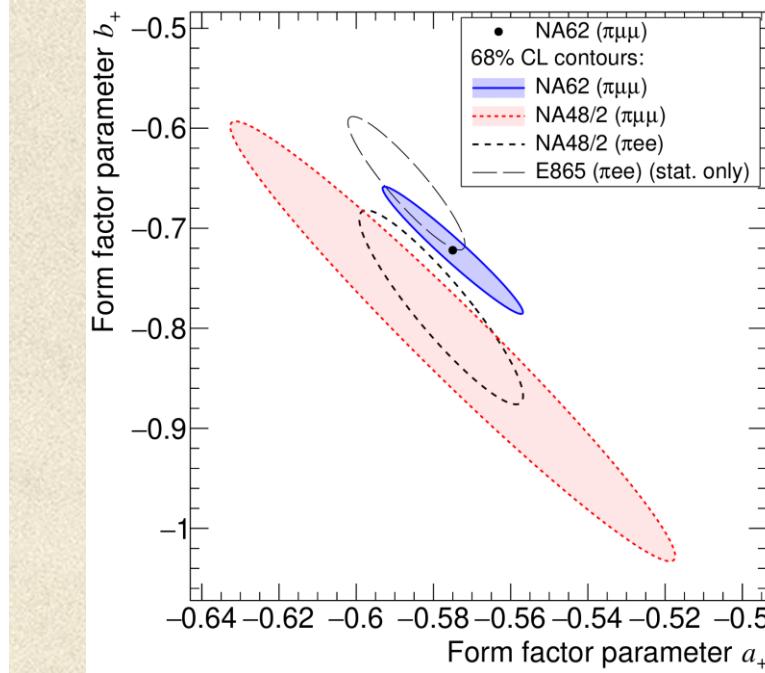
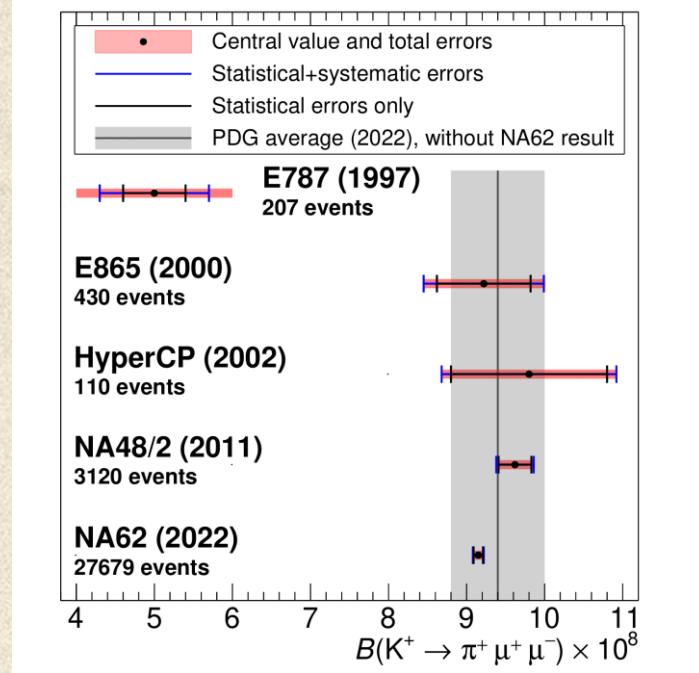


- Forward-backward asymmetry for $K_{\pi\mu\mu}$
- $A_{FB} = \frac{N(\cos\theta_{K\mu} > 0) - N(\cos\theta_{K\mu} < 0)}{N(\cos\theta_{K\mu} > 0) + N(\cos\theta_{K\mu} < 0)}$
- $\theta_{K\pi}$ – angle between K^+ and μ^- in $\mu^+\mu^-$ rest frame

Measured value: $A_{FB} = (0.0 \pm 0.7_{stat}) \times 10^{-2}$
[arXiv:2209.05076] (Accepted in JHEP)

- Statistical precision reaching upper limit from theory
 - [PRD 67 (2003) 074029], [PRD 69 (2004) 094030]

Comparison with previous measurements



- Factor ~ 3 improvement over previous $BR_{\pi\mu\mu}$ measurements
- Main differences: NA62 uses 1) new radiative corrections, 2) new α_+, β_+ values
- Agreement between the measurements: $a_+, b_+, BR_{\pi\mu\mu}, BR_{\pi\text{ee}} \rightarrow$ LFU conservation



Searches for Lepton Flavour and Lepton Number Violating processes with NA62

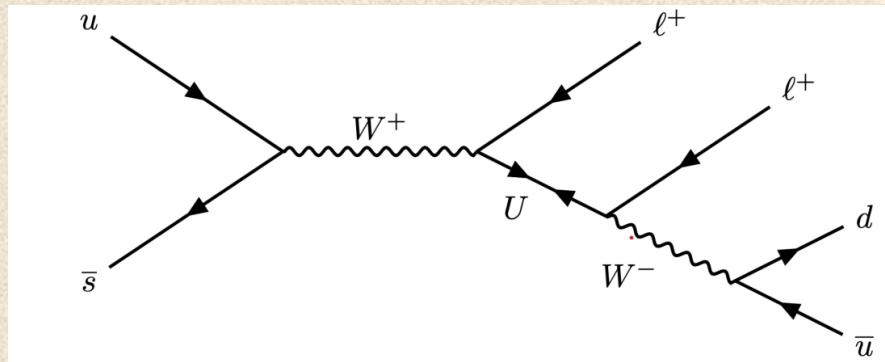
[PLB 797 (2019) 134794], [PLB 830 (2022) 137172], [PRL 127 (2021) 13, 131802], [Paper in preparation]



Motivation

- Lepton Number (L) \rightarrow 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

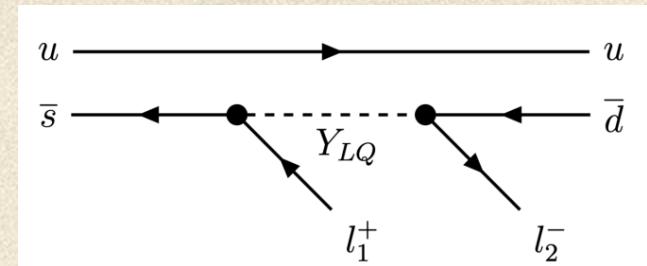
$$K^+ \rightarrow \pi^- l^+ l^+ (\Delta L = 2)$$



Mediated by a Majorana neutrino (U) [JHEP 05 (2009) 030]

$$K^+ \rightarrow \pi^+ l_1^+ l_2^- (\text{LFV})$$

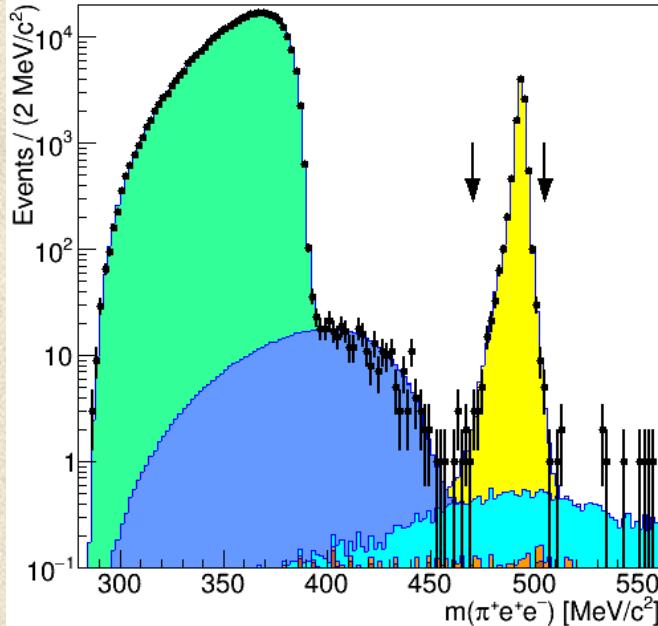
(e.g. $K^+ \rightarrow \pi^+ \mu^- e^+$: $\Delta L_e = 1, \Delta L_\mu = 1$)



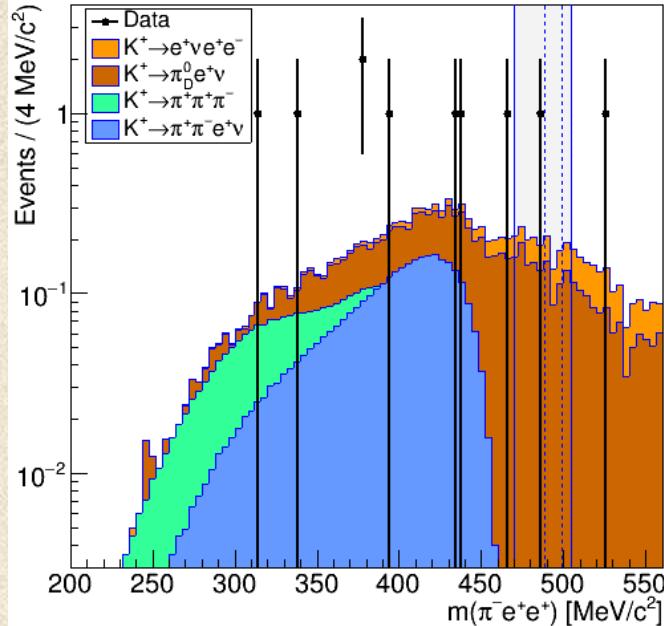
Mediated by a leptoquark (Y_{LQ}) [JHEP 12 (2019) 089]

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

$K^+ \rightarrow \pi^+ e^+ e^-$ (normalization)



$K^+ \rightarrow \pi^- e^+ e^+$ (signal)



$$N_{\pi ee}^{obs} = 11041$$

$$A_{\pi ee} = (3.62 \pm 0.02) \%$$

$$SES_{\pi ee} = (2.28 \pm 0.07) \times 10^{-11}$$

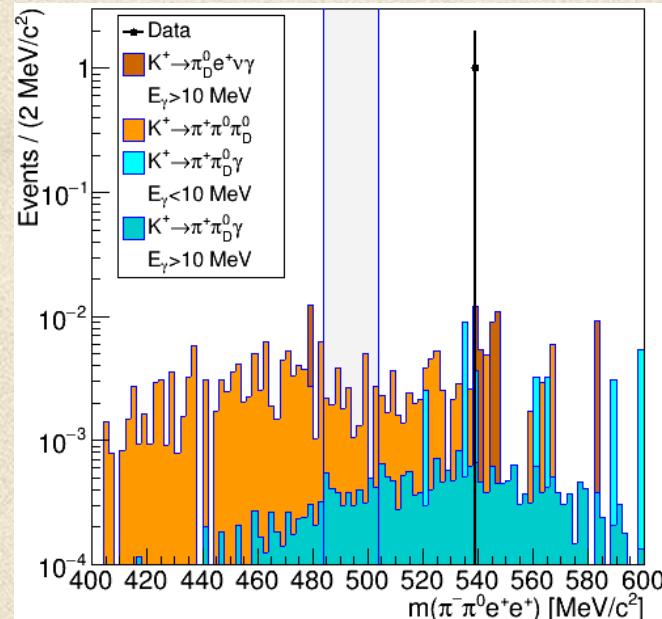
$$N_{bg}^{exp} = 0.43 \pm 0.09$$

$$N_{SR}^{obs} = 0$$

- $BR(K^+ \rightarrow \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ @ 90% CL [PLB 830 (2022) 137172]

$K^+ \rightarrow \pi^- \pi^0 e^+ e^-$ decays

$K^+ \rightarrow \pi^- \pi^0 e^+ e^-$ (signal)



- Additional selection wrt $K^+ \rightarrow \pi^- e^+ e^+$:
 - $\pi^0 \rightarrow \gamma\gamma$ reconstructed in the LKr (well-isolated)
 - Compatibility between the neutral and charged vertex

$$A_{\pi ee} = (0.271 \pm 0.003) \%$$

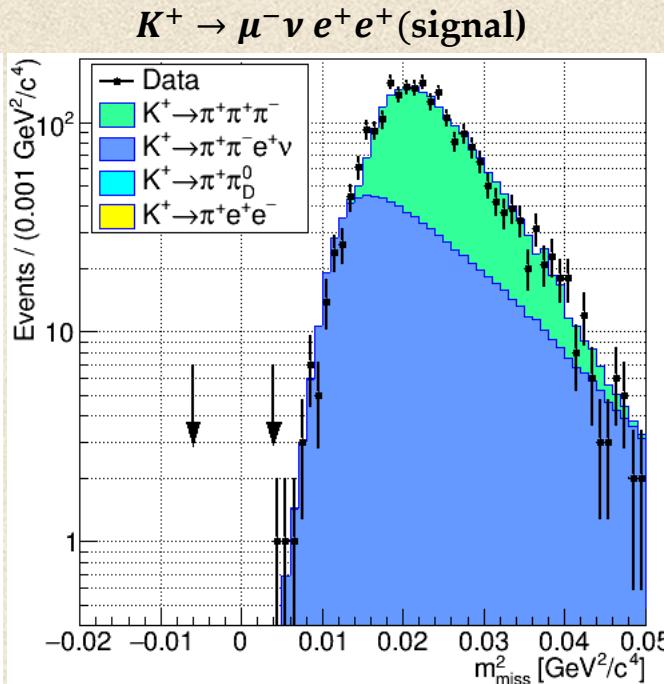
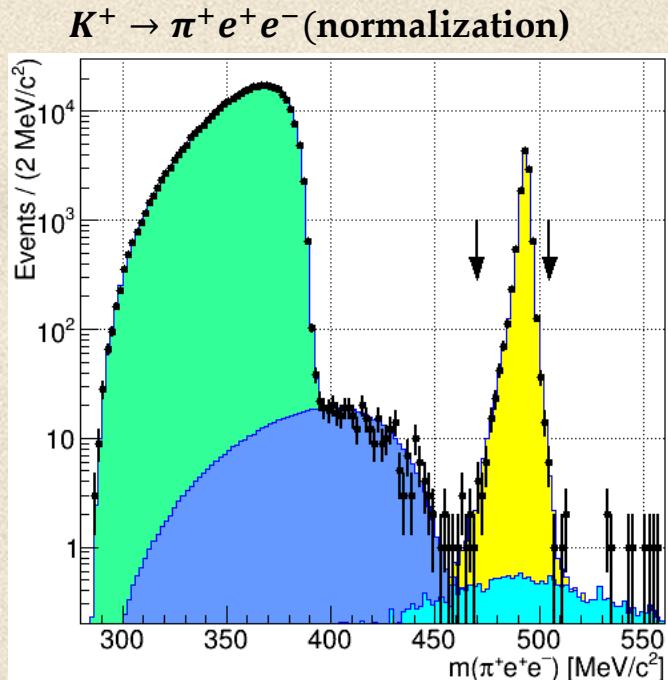
$$SES_{\pi\pi ee} = (3.68 \pm 0.12) \times 10^{-10}$$

$$N_{bg}^{exp} = \mathbf{0.044 \pm 0.020}$$

$$N_{SR}^{obs} = \mathbf{0}$$

- $BR(K^+ \rightarrow \pi^- \pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ @ 90% CL [PLB 830 (2022) 137172]

$K^+ \rightarrow \mu^- \nu e^+ e^-$ decay



$N_{\pi ee}^{obs} = 10975$
 $A_{\mu vee} = 1.44\%$
 $SES_{\mu vee} = (3.53 \pm 0.12) \times 10^{-11}$
 $N_{bg}^{exp} = 0.26 \pm 0.04$
 $N_{SR}^{obs} = 0$

- $BR(K^+ \rightarrow \mu^- \nu e^+ e^+) < 4.2 \times 10^{-11}$ @ 90% CL [Paper in preparation]

LFV/LNV searches summary

Decay channel	Previous \mathcal{B} UL (PDG)	NA62 \mathcal{B} UL	statistics	improvement
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11} , ref ¹	25% of Run 1	~ factor 2
$K^+ \rightarrow \pi^- e^+ e^+$	6.4×10^{-10}	5.3×10^{-11} , ref ²	full Run 1	~ factor 12
$K^+ \rightarrow \pi^- \pi^0 e^+ e^+$	–	8.5×10^{-11} , ref ²	full Run 1	–
$K^+ \rightarrow \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11} , ref ³	2017-18	~ factor 12
$K^+ \rightarrow \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11} , ref ³	2017-18	~ factor 8
$\pi^0 \rightarrow \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10} , ref ³	2017-18	~ factor 10
$K^+ \rightarrow \mu^- \nu e^+ e^+$	2.1×10^{-8}	8.1×10^{-11} , ref ⁴	full Run 1	~ factor 250

[1] *Phys. Lett. B* **797** (2019) 134794 [arXiv: 1905.07770]

[2] *Phys. Lett. B* **830** (2022) 137172 [arXiv: 2202.00331]

[3] *Phys. Rev. Lett.* **127** (2021) 131802 [arXiv: 2105.06759]

[4] Paper in preparation

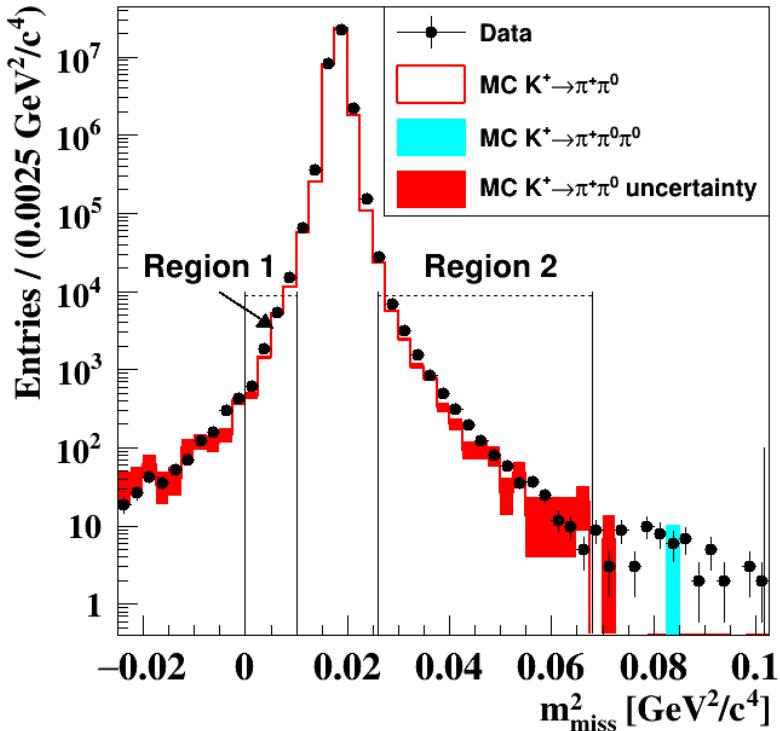
Summary and conclusions

- The most precise measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ processes
 - $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4} |_{stat} \pm 0.9 |_{syst}) \times 10^{-11}$ [JHEP 06 (2021) 093]
 - $BR(K^+ \rightarrow \pi^+ \mu^+ \mu^-) = (9.15 \pm 0.06_{stat}) \times 10^{-8}$ [arXiv:2209.05076] (Accepted in JHEP)
 - $K_{\pi\mu\mu}$ Form Factors: $a_+ = -0.575 \pm 0.013$, $b_+ = -0.722 \pm 0.043$ (compatible with LFU)
 - Forward-Backward assymmetry: $A_{FB} = (0.0 \pm 0.7) \times 10^{-2}$
- NA62 can probe a wide range of forbidden LFV/LNV K and π decays
 - Limits at the $O(10^{-10} - 10^{-11})$ range with Run 1 data
- NA62 Run 2 ongoing since last year: broad physics program to be explored
- Plans for longer term high-intensity kaon experiments (HIKE) under preparation

Backup

Results NA62 Run 1 (2016-18)

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



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

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

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

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

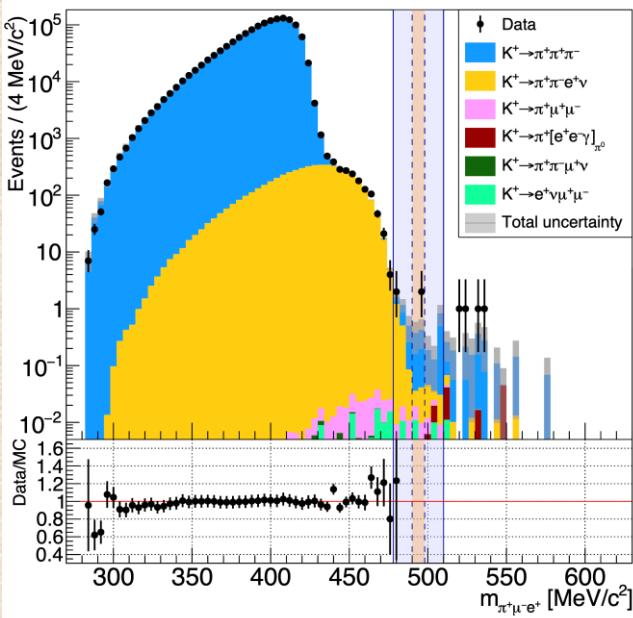
- Control $K^+ \rightarrow \pi^+\pi^0$ data selected only with calorimeters (background – free)
- The same procedure used for $K^+ \rightarrow \mu^+\nu_\mu$ and $K^+ \rightarrow \pi^+\pi^+\pi^-$ background estimation

Systematic uncertainties, Error budget

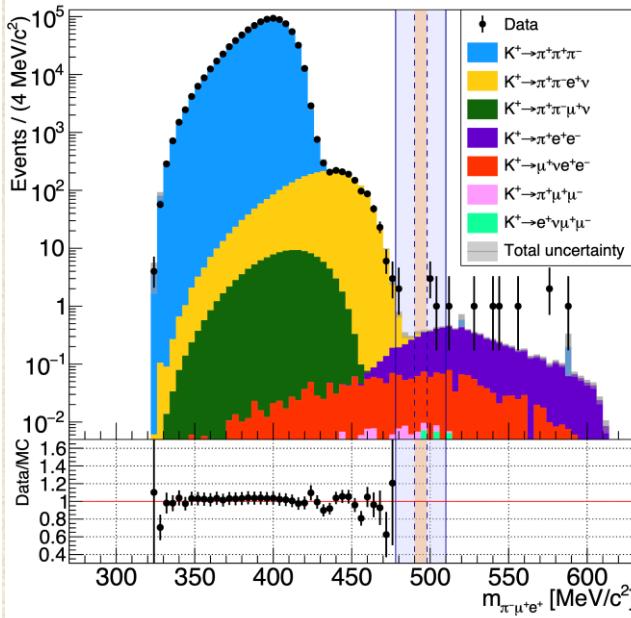
	δa_+	δb_+	$\delta \mathcal{B} \times 10^8$	$\delta A_{\text{FB}} \times 10^2$
Statistical uncertainty	0.012	0.040	0.06	0.7
Trigger efficiency	0.002	0.008	0.02	0.1
Reconstruction and particle identification	0.002	0.007	0.02	0.1
Size of the simulated sample	0.002	0.007	0.01	0.1
Beam and accidental activity 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

$K^+ \rightarrow \pi^\pm \mu^\mp e^\pm$ and $\pi^0 \rightarrow \mu^- e^+$ decays

$K^+ \rightarrow \pi^+ \mu^- e^+$ (signal)



$K^+ \rightarrow \pi^- \mu^+ e^+$ (signal)

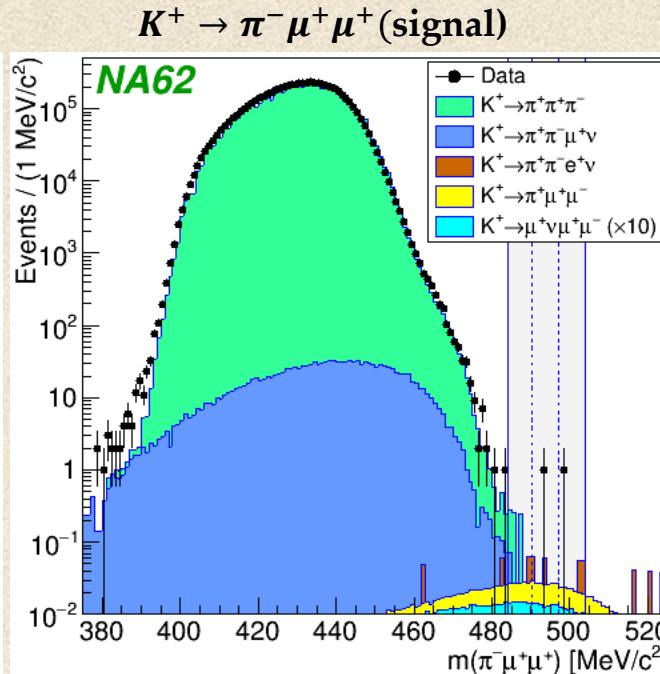
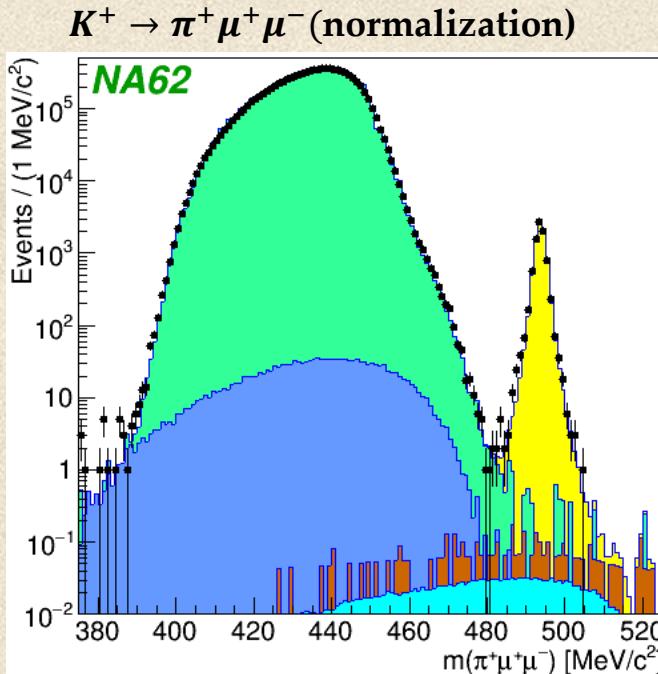


[PRL 127 (2021) 131802]

Channel	N_{SR}^{obs}	$BR[10^{-11}]$
$\pi^- \mu^+ e^+$	0	4.2
$\pi^+ \mu^- e^+$	2	6.6
$\pi^0 \rightarrow \mu^- e^+$	0	32

- Acceptances: $\sim 5\%$ for all modes
- SES: $1 - 2 \times 10^{-11} (K^+ \rightarrow \pi^\pm \mu^\mp e^\pm)$, $(1.44 \pm 0.09) \times 10^{-10} (\pi^0 \rightarrow \mu^- e^+)$
- Backgrounds: 0.2 – 1.1 events (mode-dependent)

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



$N_{\pi\mu\mu}^{obs} = 8357$

$A_{\pi\mu\mu} = 10.93\%$

$SES_{\pi\mu\mu} = (1.28 \pm 0.04) \times 10^{-11}$

$N_{bg}^{exp} = 0.91 \pm 0.41$

$N_{SR}^{obs} = 1$

- $BR(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ @ 90% CL [PLB 797 (2019) 134794]