Latest results and precision measurement with NA62

LLWI 2023, February 19th–25th, Lake Louise, Canada

Speaker: Radoslav Marchevski

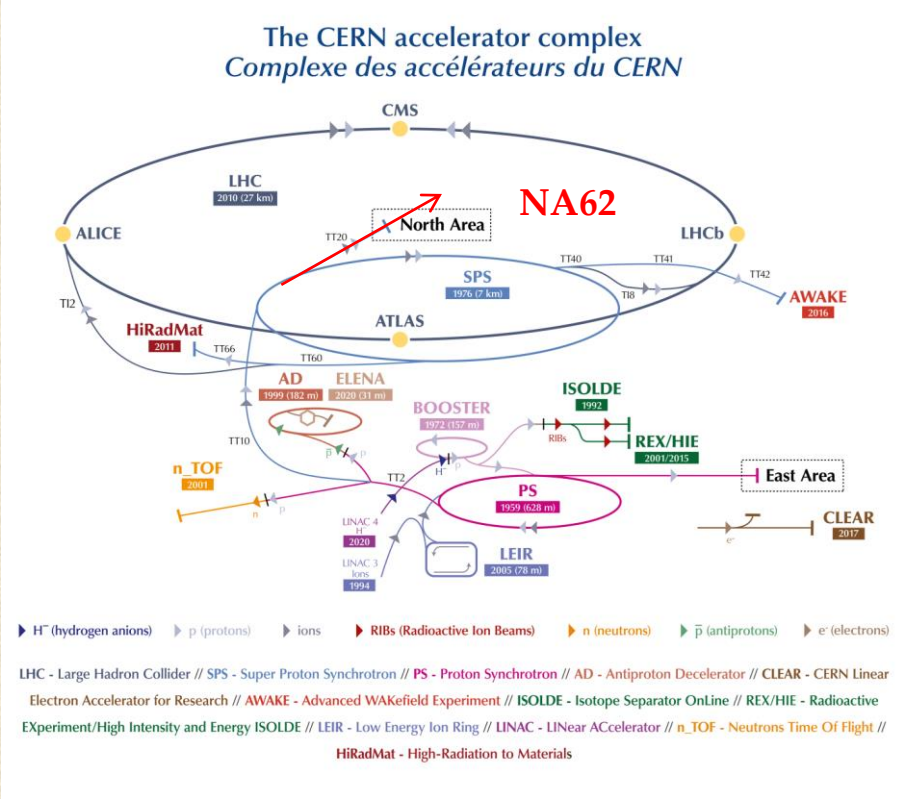
On behalf of the NA62 Collaboration

EPFL

Outline

- Measurement of the ultra rare $K^+ \to \pi^+ \nu\bar{\nu}$ process [JHEP 06 (2021) 093]
- Precision measurements of rare decays:
  - $K^+ \to \pi^+ \mu^+ \mu^-$ [JHEP 11 (2022) 011] , $K^+ \to \pi^+ \gamma\gamma$ [preliminary result]
- Searches for LFV/LNV processes: [PLB 797 (2019) 134794] , [PRL 127 (2021) 13, 131802], [PLB 830 (2022) 137172], [preliminary result]
- Dark photon searches (2021 data): $A' \to \mu^+ \mu^-$ [preliminary result]

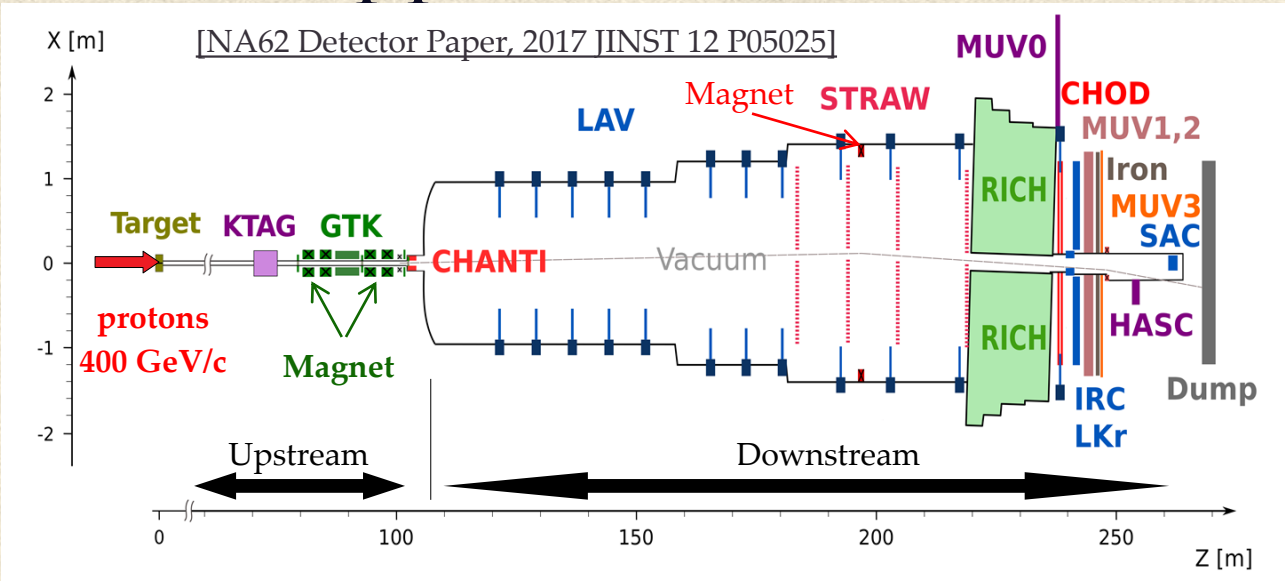
The NA62 experiment @ CERN



- Fixed-target experiment at the CERN SPS
- *NA62 Run 1 (2016-18) data-taking completed*
- NA62 Run 2 (2021+) ongoing
- Main target: $\boldsymbol{K^+ \to \pi^+ \nu\bar{\nu}}$ **decay measurement**
- <u>Broad physics program:</u>
  - Other rare charged kaon decays
  - Precision measurements
  - LFV/LNV searches
  - Exotic searches (FIPs, Dark photon, etc…)

The NA62 experimental apparatus

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



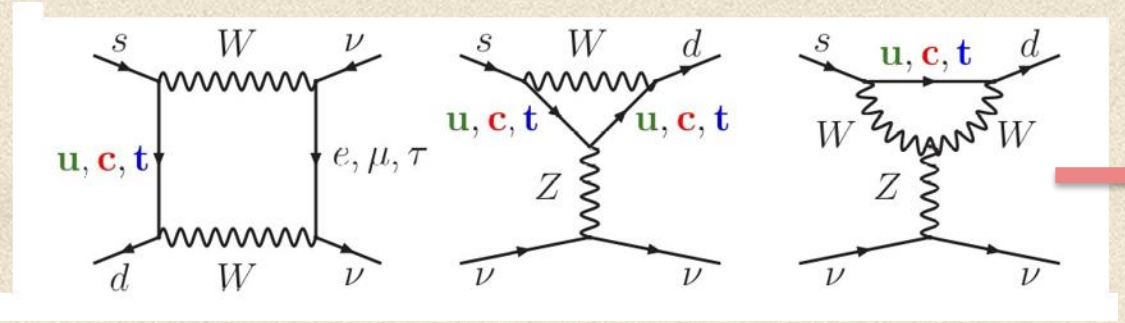
- Upstream detectors (K^+)
  - KTAG: Differential Cherenkov counter for K^+ ID
  - GTK: Silicon pixel beam tracker
  - CHANTI: Anti-counter against inelastic beam-GTK3 interactions

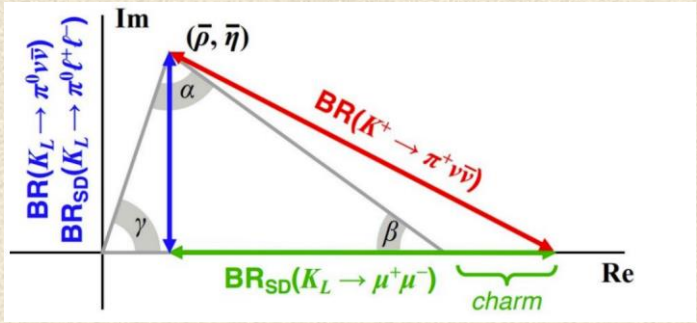
- Downstream detectors (π^+)
  - STRAW: track momentum spectrometer
  - CHOD: scintillator hodoscopes
  - LKr/MUV1/MUV2: calorimetric system
  - RICH: Cherenkov counter for $\pi/\mu/e$ ID
  - LAV/IRC/SAC: Photon veto detectors
  - MUV3: Muon veto

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

[JHEP 06 (2021) 093]

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

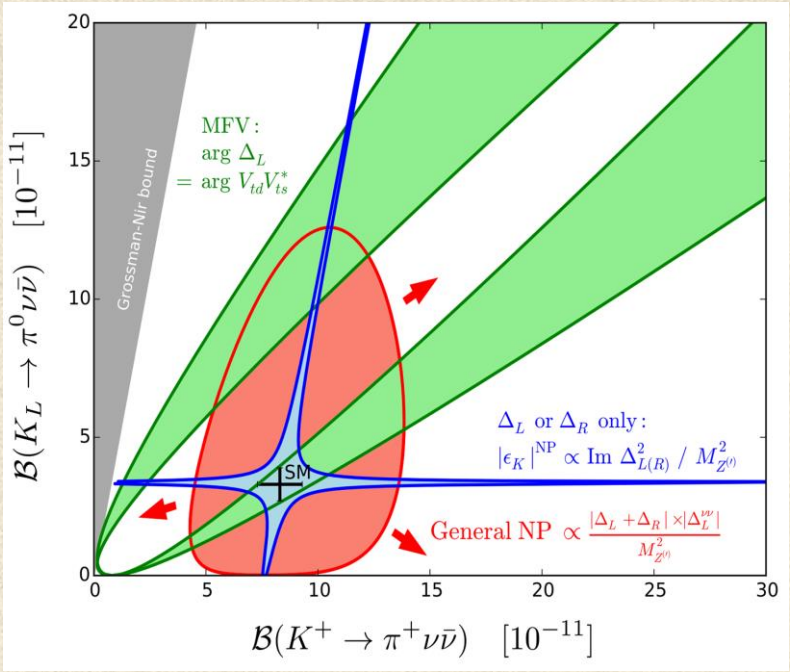




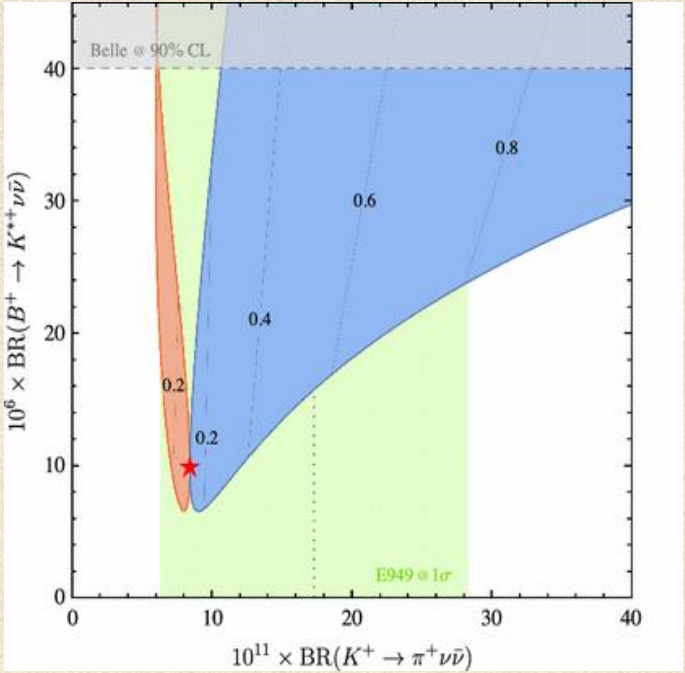
- $s \to d$ transition sensitive to the CKM structure of the SM: *tree-level FCNCs forbidden → loop + CKM suppression*
- Theoretically clean process: *dominated by short-distance physics*
- $K^+ - \pi^+$ Form Factor (FF) extracted from $K^\pm \to \pi^0 l^\pm \nu_l$: *sub-% precision*
- Sensitive to new physics in the lepton sector as well: *involves* $\nu_e, \nu_\mu,$ *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]
  - $\boldsymbol{BR_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (7.92 \pm 0.28_{theory}) \times 10^{-11} \times \left[\frac{|V_{cb}|}{41.0 \times 10^{-3}}\right]^{2.8} \times \left[\frac{\sin\gamma}{\sin 67°}\right]^{1.39}}$ [arXiv:2109.11032]

Impact in the context of BSM models

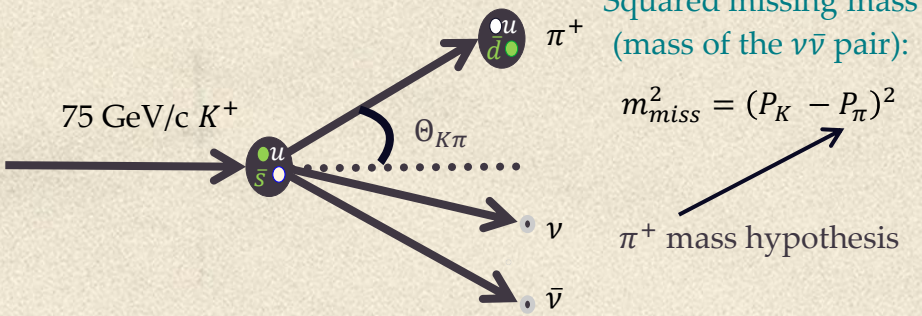
Simplified models
[Buras et. al JHEP 1511 (2015) 166]



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



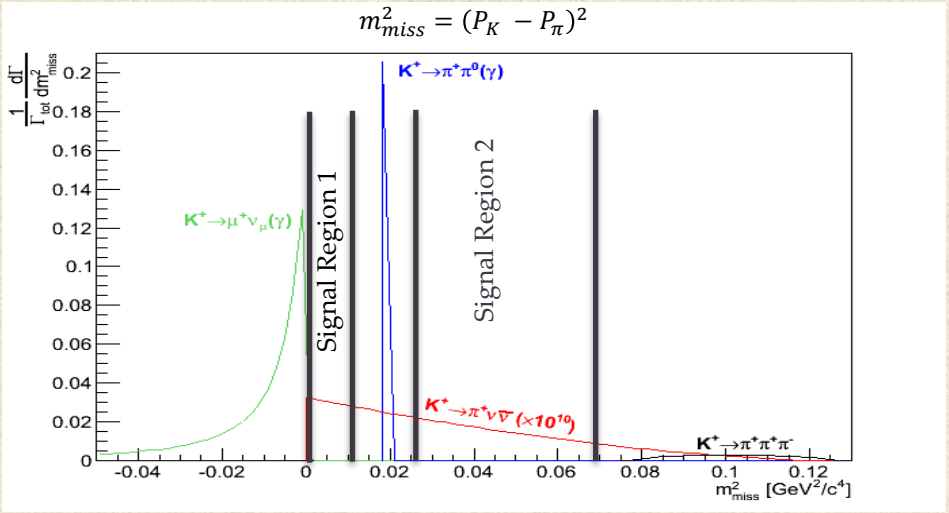
Analysis strategy



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

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

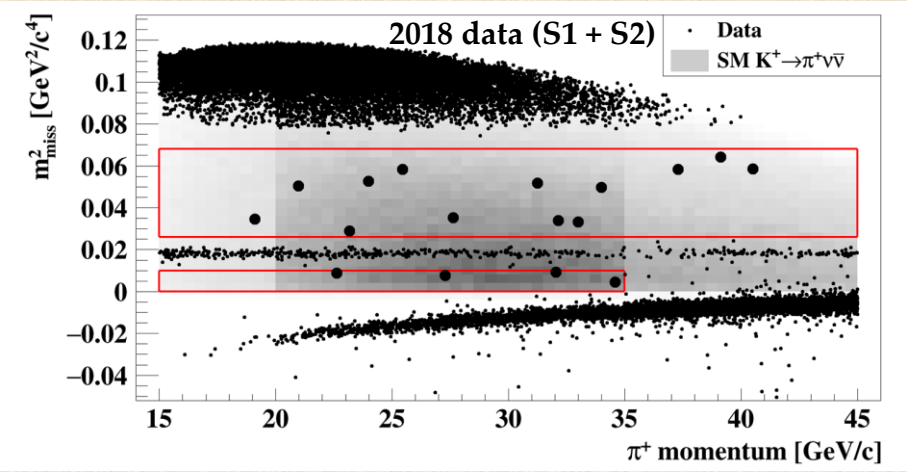
π^+ mass hypothesis

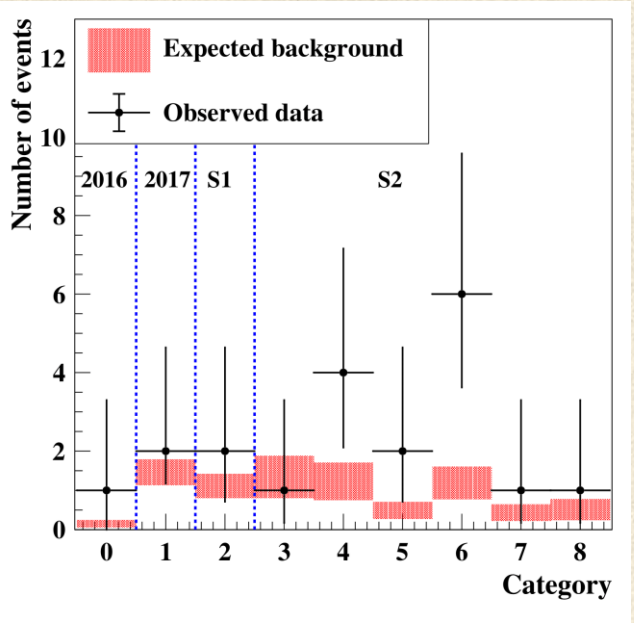


- Highly boosted decay: (75 ± 1) GeV/c K^+ ($\gamma \sim 150$)
- Large undetectable missing energy carried away by the neutrinos
- All energy from visible particles must be detected
- π^+ momentum range $15 - 45$ GeV/c ($E_{miss} > 30$ GeV)
- Hermetic detector coverage and O(100%) detector efficiency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

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

Results NA62 Run 1 (2016-18)





- Combining the complete Run 1 data set (2016-18)
  - $N_{\pi\nu\bar{\nu}}^{exp} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
  - $N_{bg}^{exp} = 7.03^{+1.05}_{-0.82}$
  - $SES = \left(0.839 \pm 0.053_{syst}\right) \times 10^{-11}$
- 20 events observed in signal region in NA62 Run 1 data
- $\boldsymbol{BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}}$ **[JHEP 06 (2021) 093]**

3.4σ significance

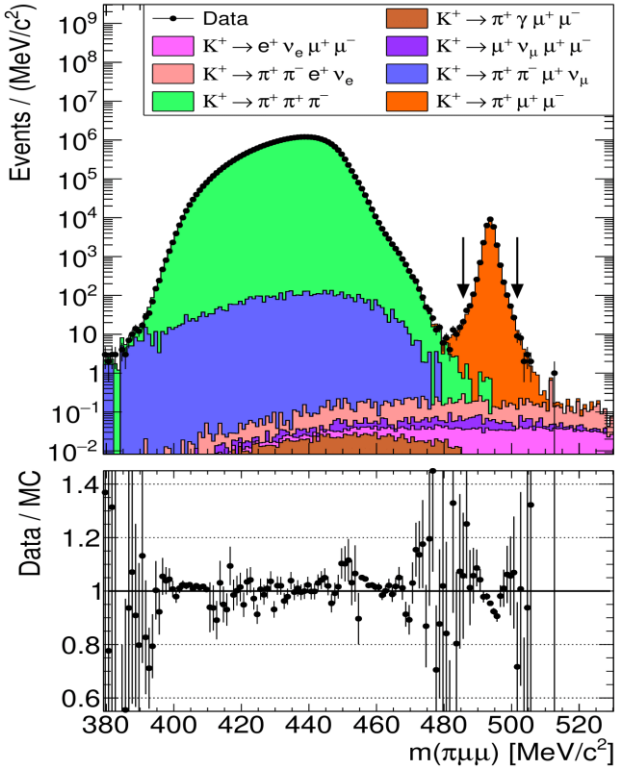
Precision measurement of the rare $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^+\gamma\gamma$ processes

[JHEP 11 (2022) 011], [preliminary result]

$K^+ \to \pi^+\mu^+\mu^-$ ($K_{\pi\mu\mu}$) 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 $O(p^6)$:
  - $\boldsymbol{W(z) = G_F m_K^2 (a_+ + b_+ z) + W^{\pi\pi}(z)}$

- <u>Main goals of the $K^+ \to \pi^+\mu^+\mu^-$ measurement with NA62:</u>
  - 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



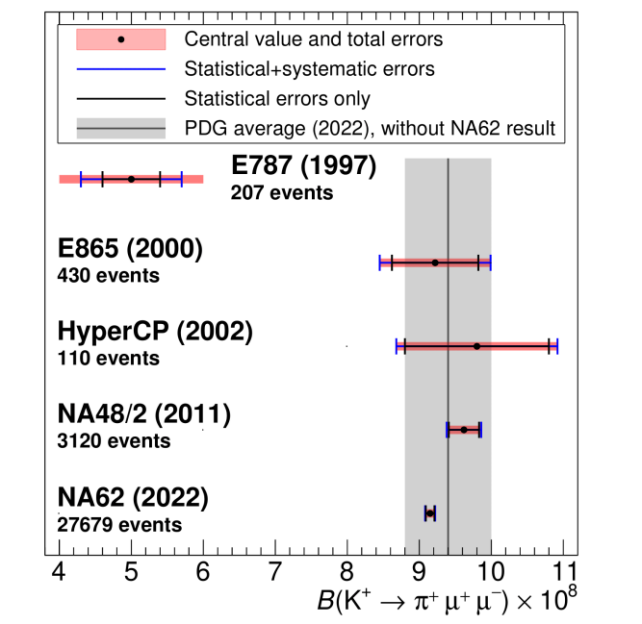
After signal selection:

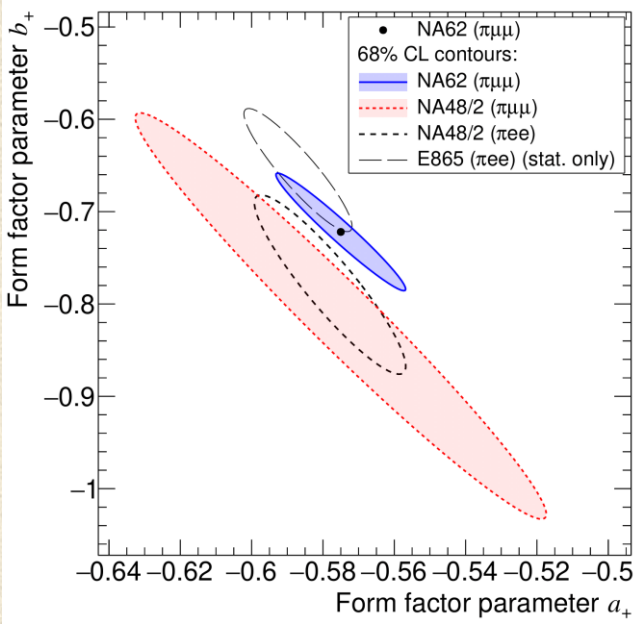
N_{obs} = 27 679 events

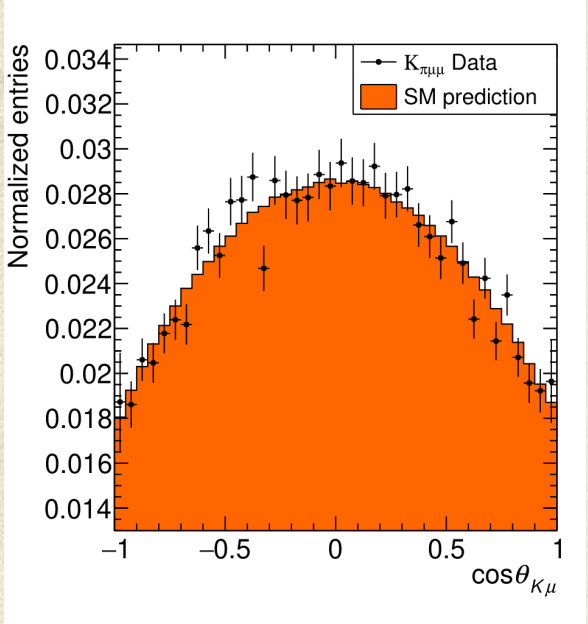
N_{bg}^{exp} = 8 events

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

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







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

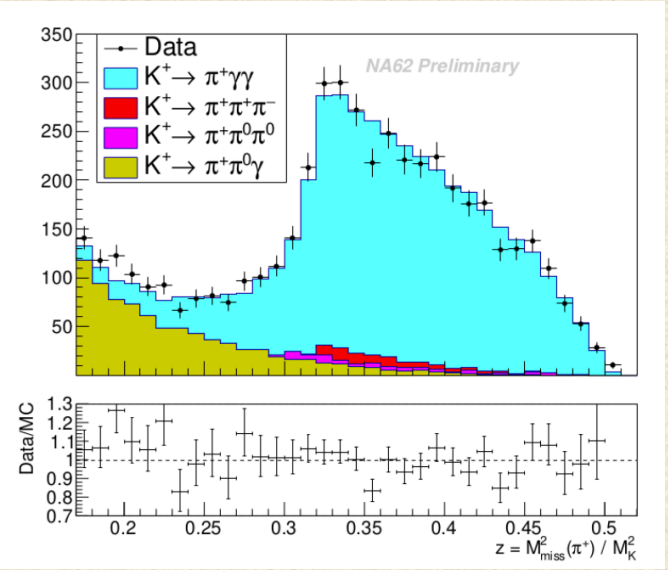
$$a_+ = -0.575 \pm 0.012_{stat}$$
$$b_+ = -0.722 \pm 0.040_{stat}$$

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

JHEP 11 (2022) 011

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

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



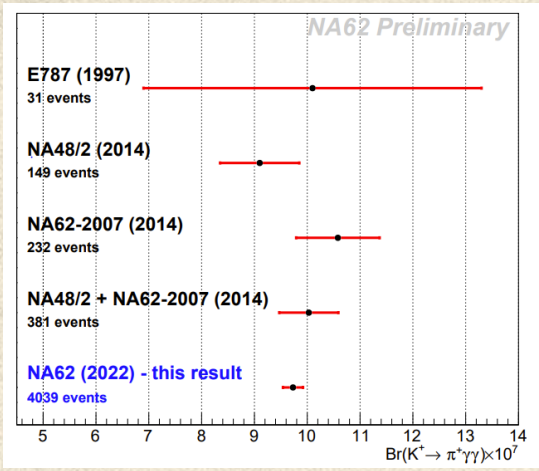
After signal selection:

$N_{obs} = 4039$ events

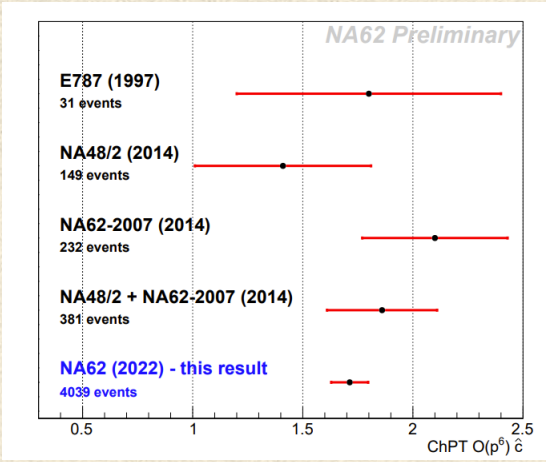
$N_{bg}^{exp} = 393 \pm 20$ events

Main background:

Cluster merging in the EM calorimeter



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



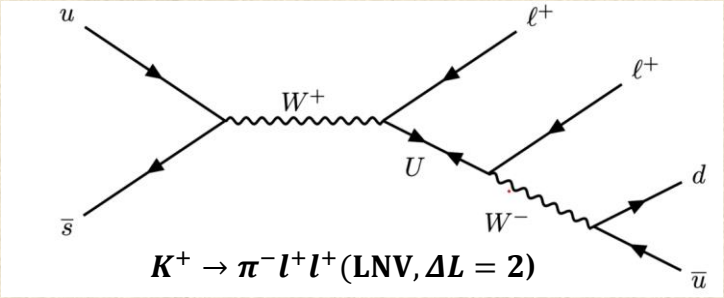
$\hat{c} = 1.713 \pm 0.075_{stat} \pm 0.037_{syst}$

Searches for Lepton Flavour and Lepton Number Violating processes with NA62

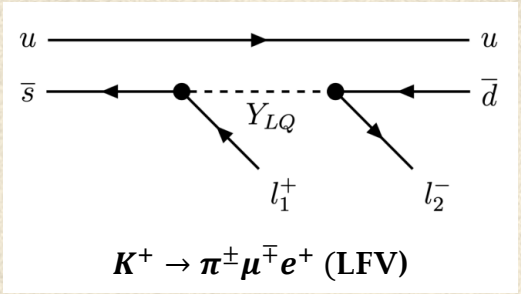
[PLB 797 (2019) 134794], [PRL 127 (2021) 13, 131802], [PLB 830 (2022) 137172], [preliminary]

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



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



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

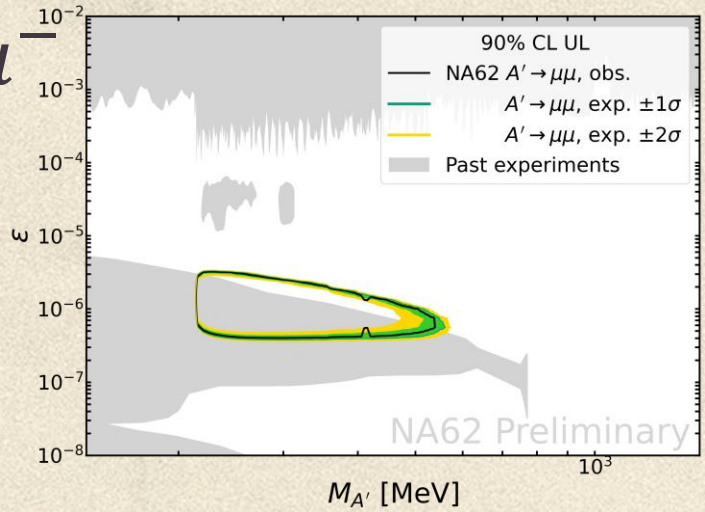
Decay channel	Previous UL	NA62 UL @ 90% CL	
$K^+ \to \pi^- \mu^+ e^+$	BR < 5.0×10^{-10}	BR < 4.2×10^{-11}	PRL 127 (2021) 131802
$K^+ \to \pi^+ \mu^- e^+$	BR < 5.2×10^{-10}	BR < 6.6×10^{-11}	PRL 127 (2021) 131802
$\pi^0 \to \mu^- e^+$	BR < 3.4×10^{-9}	BR < 3.2×10^{-10}	PRL 127 (2021) 131802
$K^+ \to \pi^- \mu^+ \mu^+$	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}	preliminary

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

[preliminary]

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

- 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

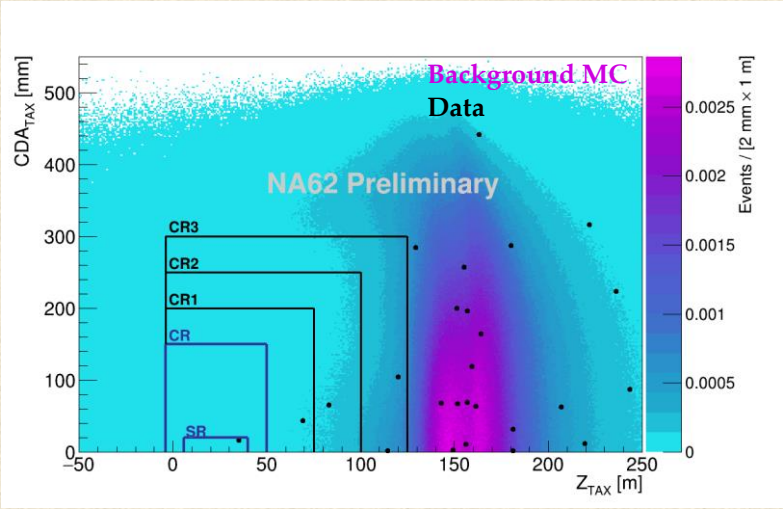


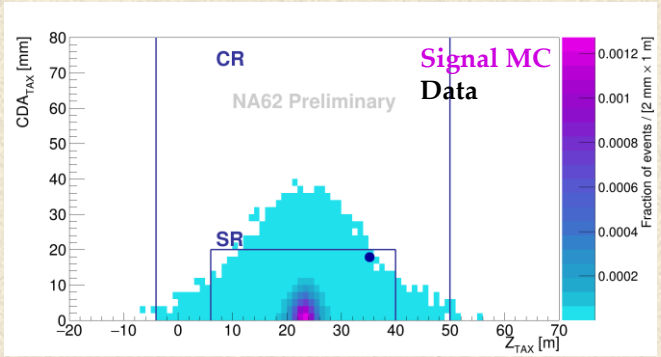
After signal selection:

$N_{obs} = 1$ event

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

2.4 σ significance (counting experiment)





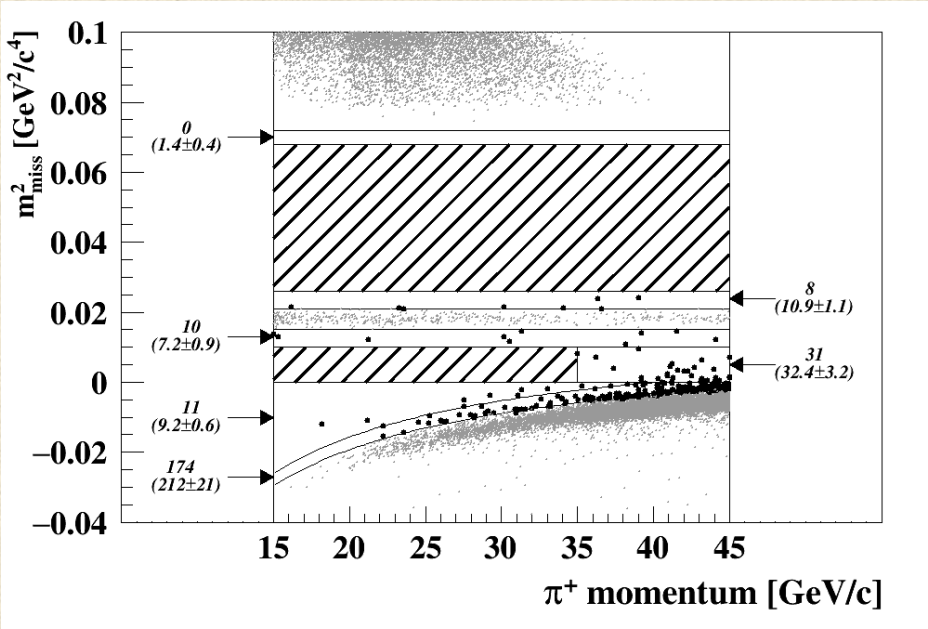
Summary

Decay channel	Data set	
$K^+ \to \pi^+ \nu\bar{\nu}$	NA62 Run 1	JHEP 06 (2021) 093
$K^+ \to \pi^+ \mu^+ \mu^-$	NA62 Run 1	JHEP 11 (2022) 011
$K^+ \to \pi^+ \gamma\gamma$	NA62 Run 1	preliminary
$K^+ \to \pi^- \mu^+ e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^+ \mu^- e^+$	NA62 Run 1	PRL 127 (2021) 131802
$\pi^0 \to \mu^- e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^- \mu^+ \mu^+$	NA62 Run 1	PLB 797 (2019) 134794
$K^+ \to \pi^- e^+ e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \pi^- \pi^0 e^+ e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \mu^- \nu e^+ e^+$	NA62 Run 1	preliminary
$A' \to \mu^+ \mu^-$	NA62 2021 data	preliminary

- Many results with the NA62 Run 1
- First results from NA62 Run 2
- NA62 will be collecting data until LS3
- **Stay tuned for more results!**

Backup

Expected signal and background contribution

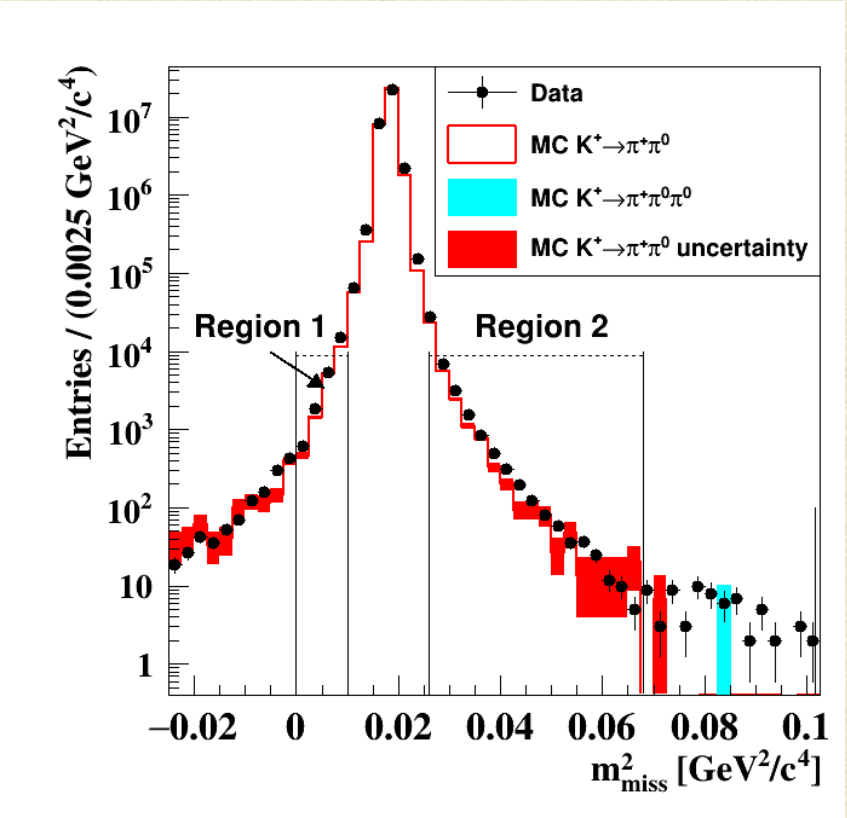


	2018 data
Expected SM signal	$7.58(40)_{syst}(75)_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$	0.75(4)
$K^+ \to \mu^+\nu(\gamma)$	0.49(5)
$K^+ \to \pi^+\pi^-e^+\nu$	0.50(11)
$K^+ \to \pi^+\pi^+\pi^-$	0.24(8)
$K^+ \to \pi^+\gamma\gamma$	< 0.01
$K^+ \to \pi^0 l^+\nu$	< 0.001
Upstream	$3.30^{+0.98}_{-0.73}$
Total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

- Combining the complete Run 1 data set (2016-18)
  - $N_{\pi\nu\bar{\nu}}^{exp} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
  - $N_{bg}^{exp} = 7.03^{+1.05}_{-0.82}$
  - $SES = \left(0.839 \pm 0.053_{syst}\right) \times 10^{-11}$

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

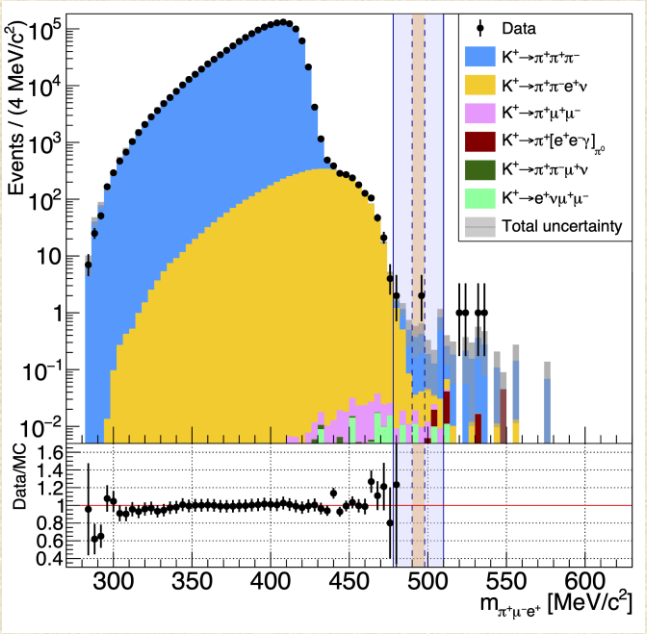
- Control $K^+ \to \pi^+\pi^0$ data selected only with calorimeters (background – free)
- The same procedure used for $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+\pi^+\pi^-$ background estimation

Systematic uncertainties, Error budget

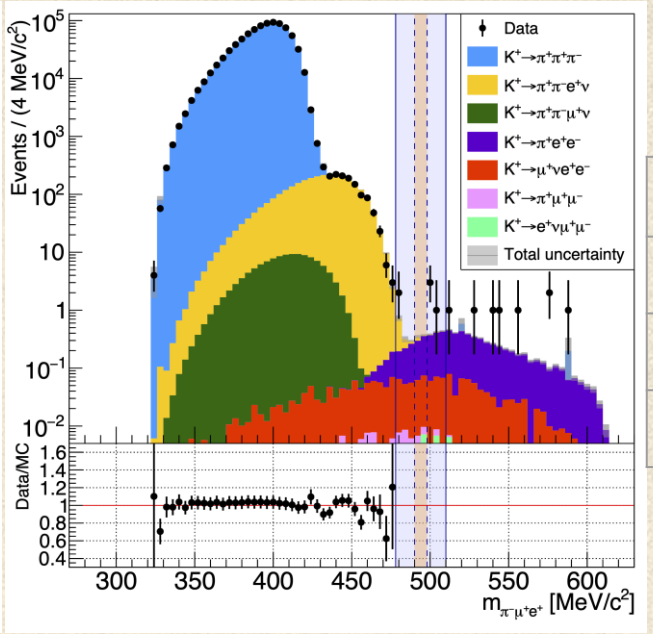
	δa_+	δb_+	$\delta\mathcal{B} \times 10^8$	$\delta A_{\rm FB} \times 10^2$
Statistical uncertainty	0.012	0.040	0.06	0.7
Trigger efficiency	0.002	0.008	0.02	0.1
Reconstruction and particle identification	0.002	0.007	0.02	0.1
Size of the simulated sample	0.002	0.007	0.01	0.1
Beam and accidental activity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

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

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



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



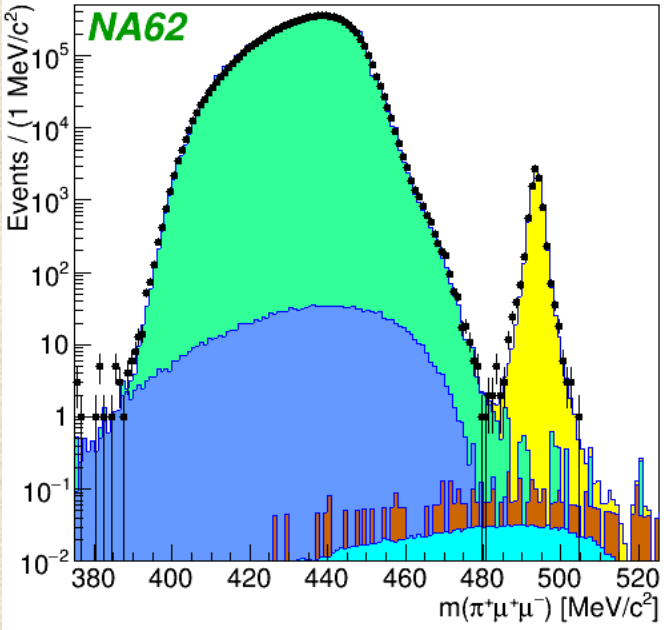
[PRL 127 (2021) 131802]

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

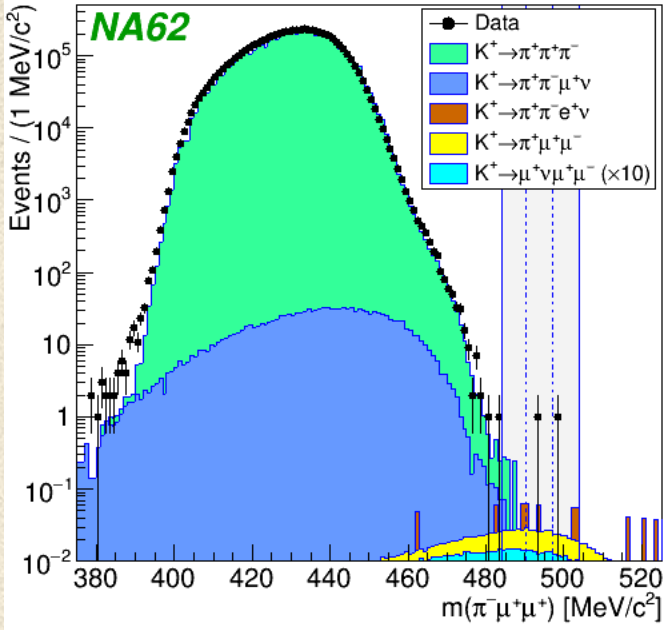
- Acceptances: ~ 5% for all modes
- SES: $1 - 2 \times 10^{-11} (K^+ \to \pi^\pm \mu^\mp e^+)$, $(1.44 \pm 0.09) \times 10^{-10}$ $(\pi^0 \to \mu^- e^+)$
- Backgrounds: 0.2 − 1.1 events (mode-dependent)

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

$K^+ \to \pi^+\mu^+\mu^-$ (normalization)



$K^+ \to \pi^-\mu^+\mu^+$ (signal)



$N^{obs}_{\pi\mu\mu} = 8357$

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

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

$\mathbf{N^{exp}_{bg} = 0.91 \pm 0.41}$

$\mathbf{N^{obs}_{SR} = 1}$

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