Latest results and precision measurements from the NA62 experiment

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on behalf of the NA62 Collaboration

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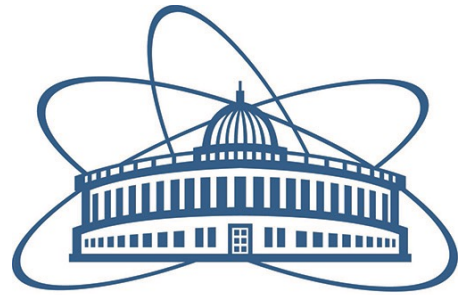
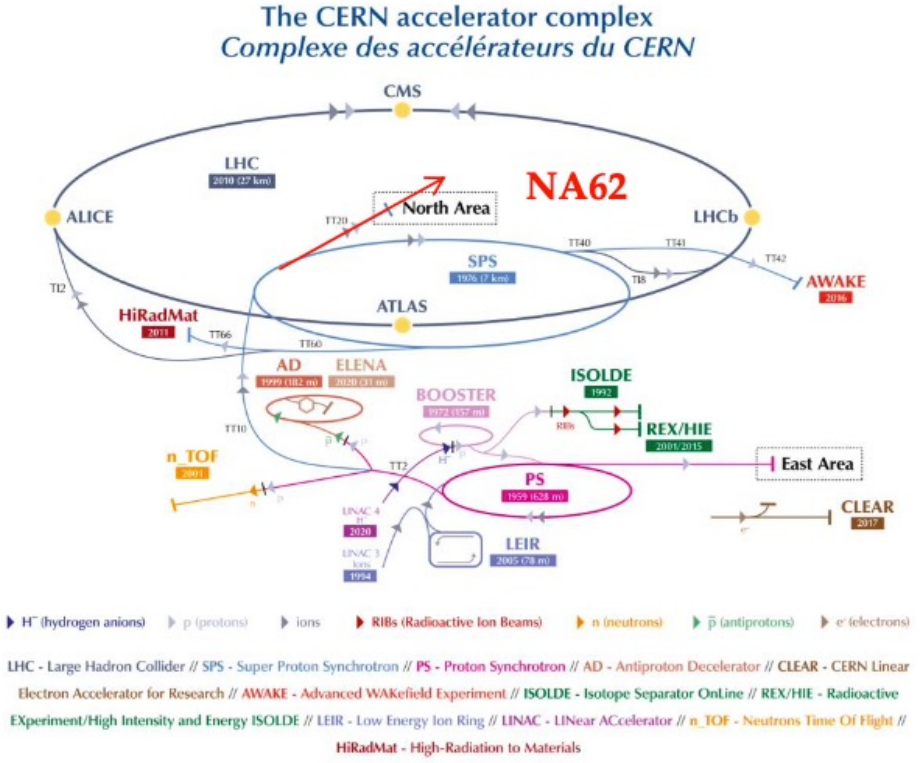


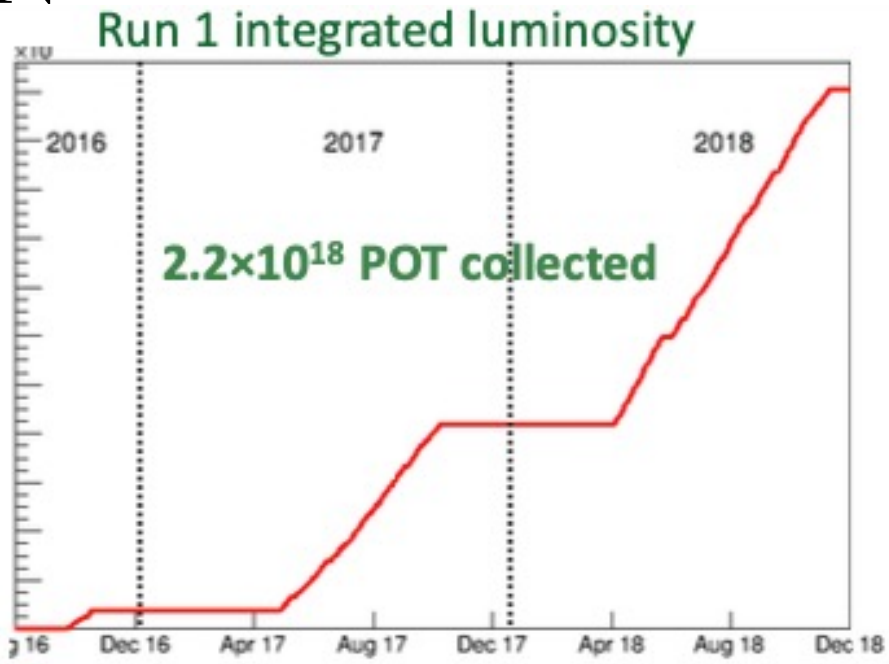
Outline

- Measurement of the ultra rare $K^+ \to \pi^+ \nu\bar{\nu}$ process [JHEP 06 (2021) 093]
- Precision measurements of the rare decays:
  - $K^+ \to \pi^+ \mu^+ \mu^-$ [JHEP 11 (2022) 011]
  - $K^+ \to \pi^+ \gamma\gamma$ [preliminary]
- Searches for *LFV/LNV* processes: [PLB 797 (2019) 134794], [PRL 127 (2021) 13, 131802], [PLB 830 (2022) 137172], [PLB838 (2023) 137679]
- Dark photon searches (2021 data): $A` \to \mu^+ \mu^-$ [preliminary]

The NA62 experiment @CERN

- High precision fixed-target Kaon experiment at the CERN SPS
- Main goal: **$K^+ \to \pi^+ \nu\bar{\nu}$ decay measurement**
- Broad physics program:
  - Other rare charged kaon decays
  - Precision measurements
  - LFV/LNV searches
  - Exotic searches (FIPs, Dark photon, etc…)



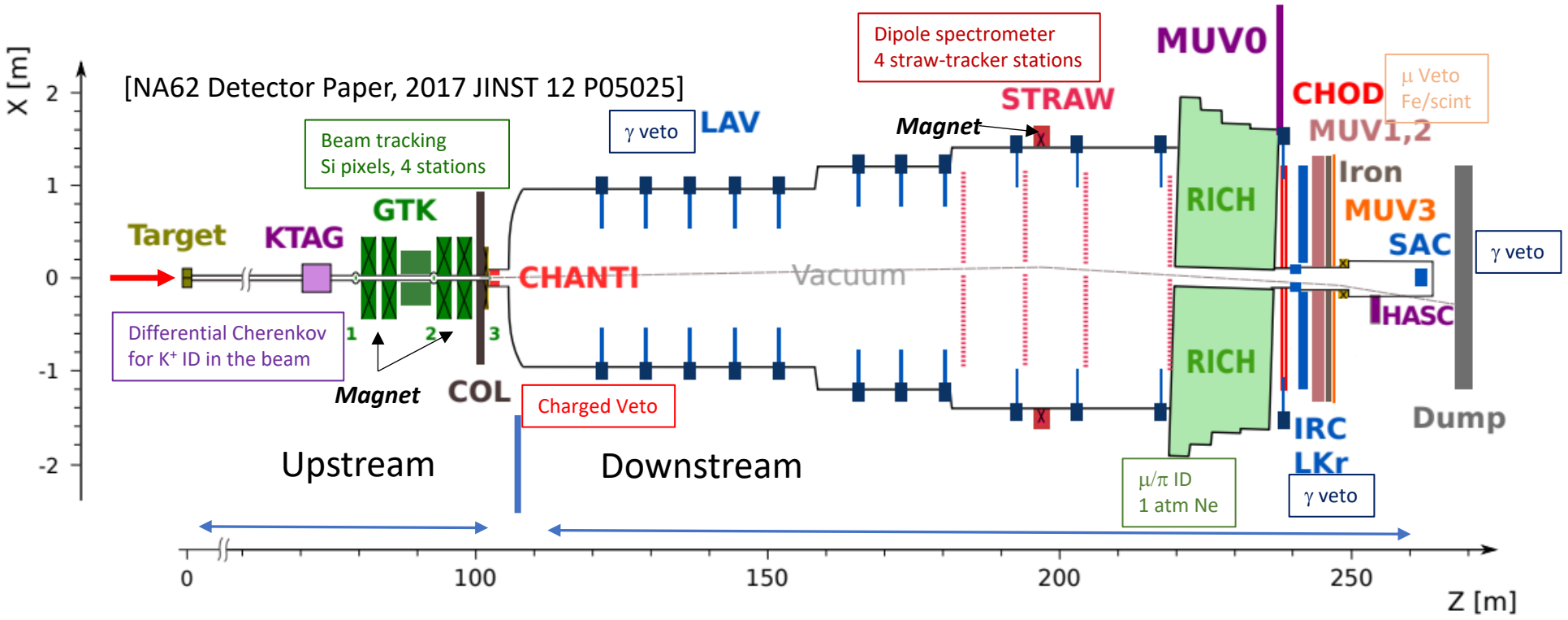


- *2008: NA62 Approval*
- *2014: NA62 Pilot Run (partial layout)*
- *2015: Commissioning run*
- *2016-18: NA62 RUN 1 data-taking completed*
- 2021+: NA62 RUN 2 ongoing

The NA62 experimental apparatus

➢**SPS beam**
400 GeV/c protons
3.5s spill

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



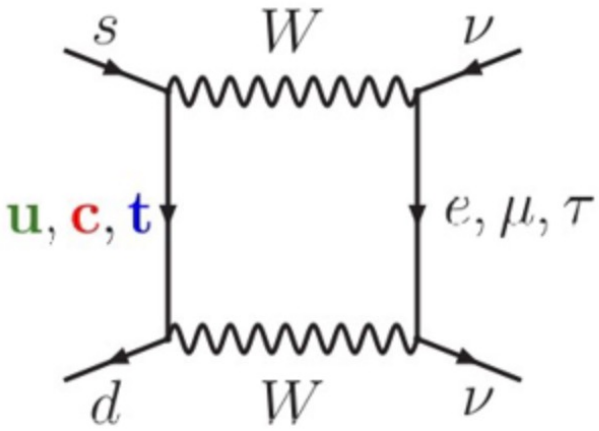
➢**Upstream detectors (K^+)**
KTAG: Differential Cherenkov counter for K^+ ID
GTK: Silicon pixel beam tracker
CHANTI: Anti-counter against inealstic beam-GTK interactions

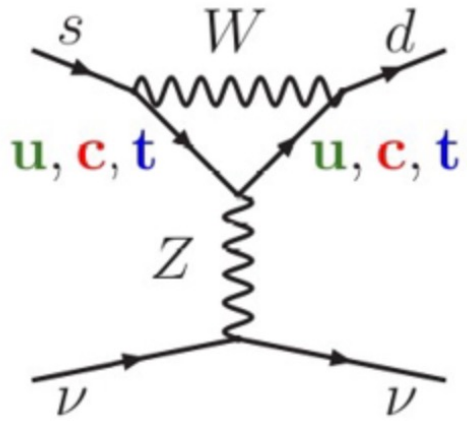
➢**Downstream detectors (π^+)**
STRAW: track momentum spectrometer
CHOD: scintilator hodoscopes
LKr/MUV1,2: calorimeter system
RICH: Cherenkov counter for π/μ/e ID

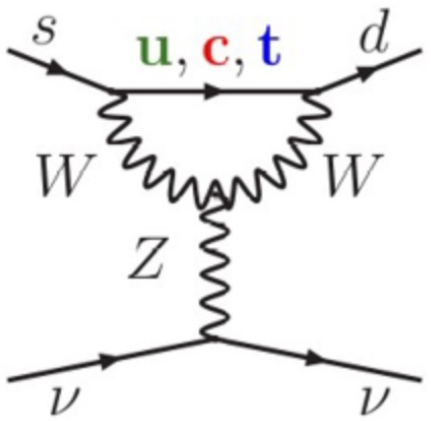
Measurement of the ultra rare $K^+ \to \pi^+ \nu\bar{\nu}$ process

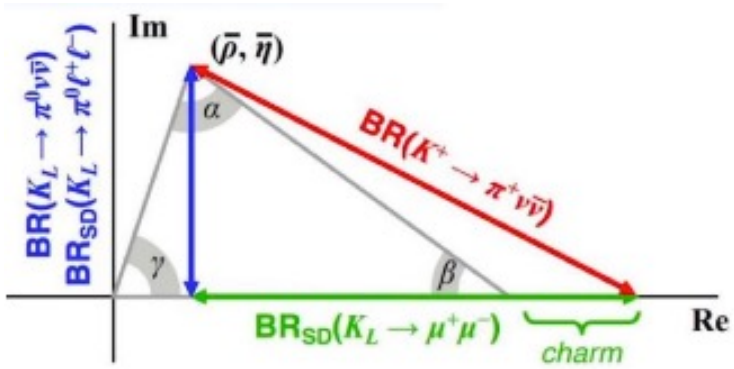
[JHEP 06 (2021) 093]

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





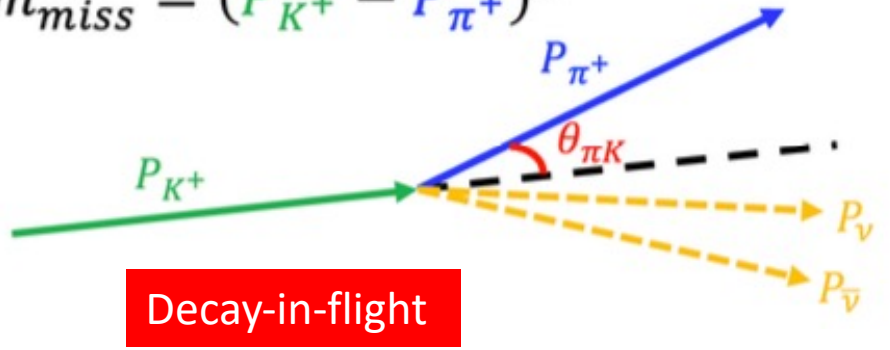




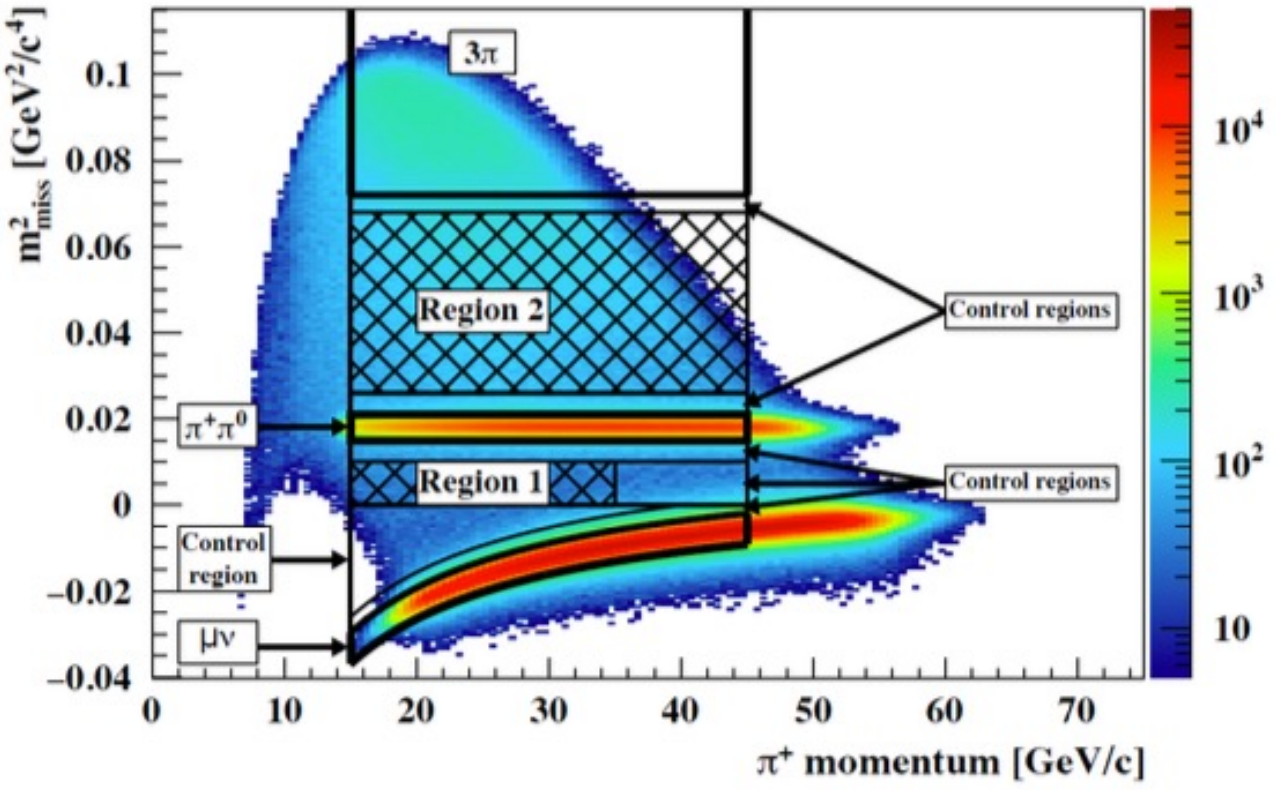
- Ultra rare FCNC: ***s → d*** transition sensitive to the CKM structure of the SM: *tree-level FCNCs forbidden ⟹ loop + CKM suppression*
- Theoretically clean process: *dominated by short-distance physics (SD)*
- K^+ - π^+ Form Factor (FF) extracted from $K^{\pm} \to \pi^0 l^{\pm} \nu_l$: *sub-% precision*
- Sensitive to new physics in the lepton sector as well: *involves ν_e, ν_μ and ν_τ*
- **Extremely rare process in the SM:**
  - $BR_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (7.73 \pm 0.16_{SD} \pm 0.25_{LD} \pm 0.54_{param.}) \times 10^{-11}$ [arXiv: 2105.02868]
  - $BR_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (7.92 \pm 0.28_{theory}) \times 10^{-11} \times \left[\frac{|V_{cb}|}{41.0 \times 10^{-3}}\right]^{2.8} \times \left[\frac{sin\gamma}{sin67°}\right]^{1.39}$ [arXiv:2109:11032]

Analysis strategy

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



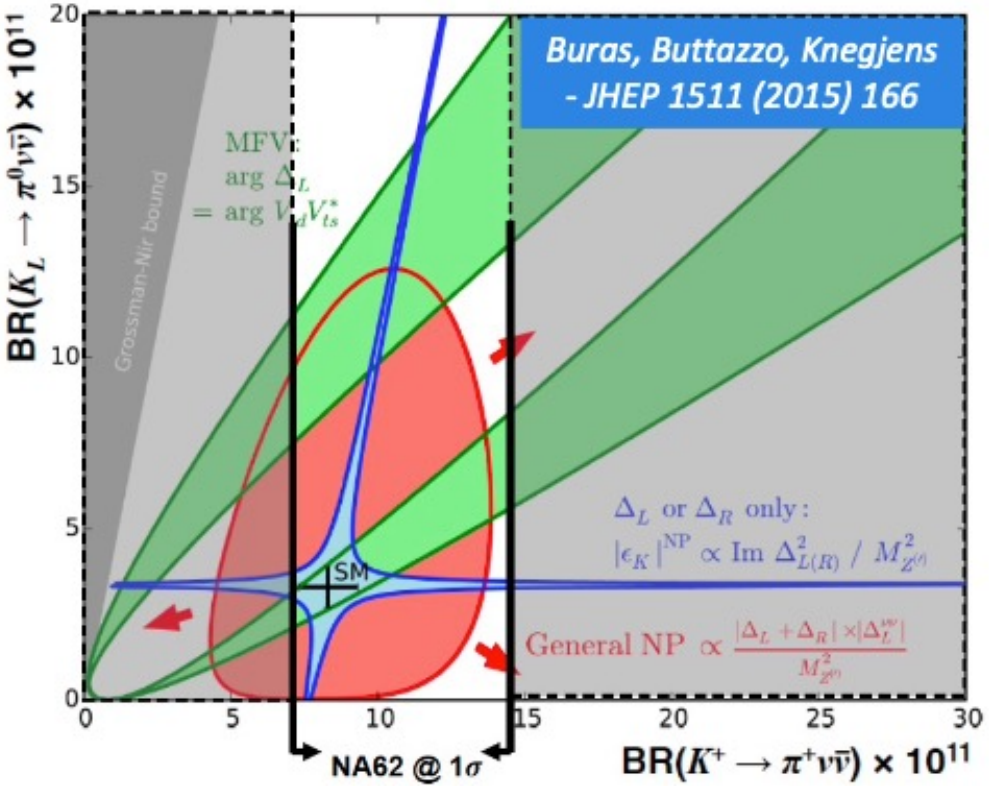
Decay-in-flight



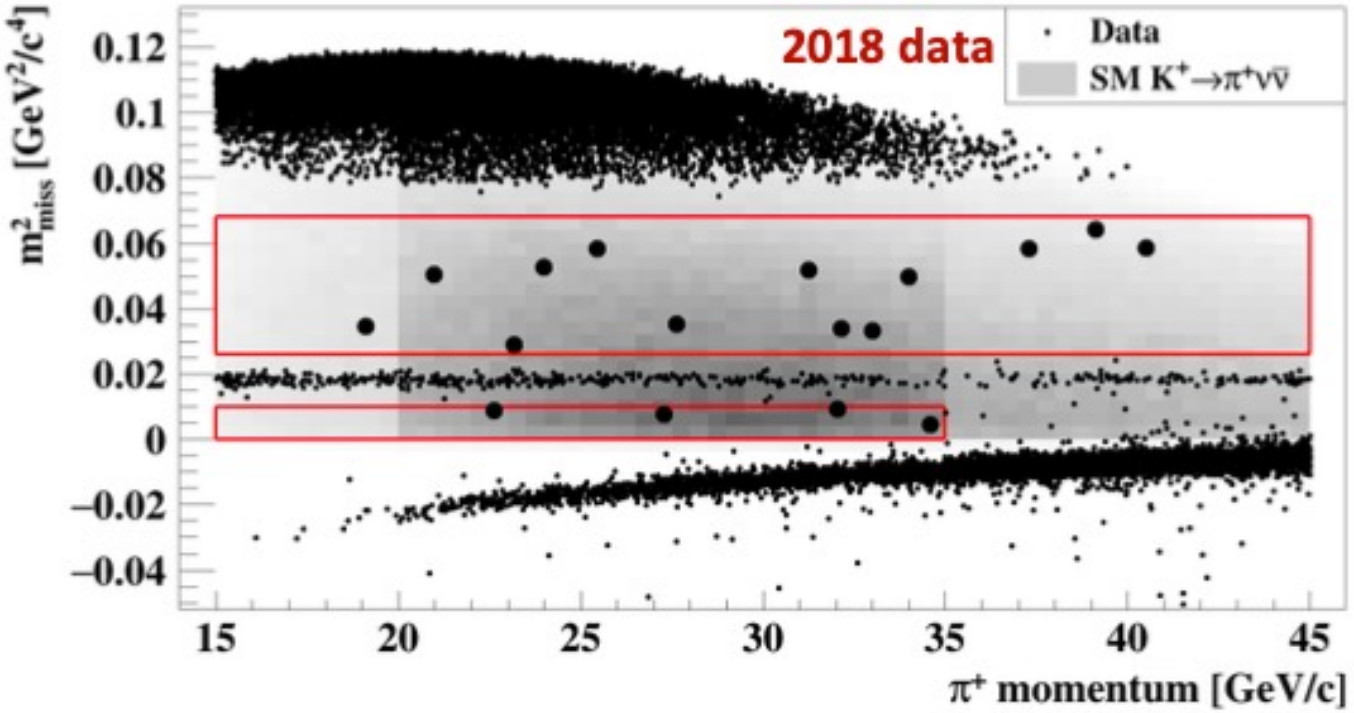
- Highly boosted decay: K^+ (75 ± 1) GeV/c
- Large undetectable missing energy carried away by the neutrinos
- All energy from visible particles must be detected
- π^+ momentum range 15 – 45 GeV/c ($E_{miss.}$ > 30 GeV)
- Hermetic detector coverage and O(100%) detector efficiency needed
- Blind analysis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

- **Requirements on background rejection:**
  - $O(10^4)$ suppresion from kinematic conditions
  - $O(10^7)$ from μ^+ rejection
  - $O(10^7)$ from π^0 rejection
  - O(100 ps) timing between sub-detectors

Results NA62 Run 1 (2016-18)



**Not-SYSY models*
[arXiv:2006.01138]



- Combining the complete RUN 1 data set (2016-18)
  - $N_{pnn}^{exp} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
  - $N_{bg}^{exp} = 7.03^{+1.05}_{-0.82}$
  - SES = $(0.839 \pm 0.053_{syst})$ x 10^{-11}
- 20 events observed in the signal region – full NA62 RUN 1 data set

BR($K^+ \to \pi^+ \nu\bar{\nu}$) = $\left(10.6^{+4.0}_{-3.4}|_{stat.} \pm 0.9_{syst.}\right) x\ 10^{-11}$ @ 68% CL [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], [JHEP 06 (2023) 040], preliminary, arXiv: 2304.12271

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

- Heavily suppressed FCNC transition: $s \to dl^+l^-$
- FCNC decay described in the scope of ChPT,
  mediated by one photon exchange $K^\pm \to \pi^\pm\gamma^*$
- Mainly kinematic variable: $z = \frac{m^2(l^+l^-)}{m_K^2}$
- Chiral Perturbation Theory (ChPT) parametrization of $W(z)$ at $O(p^6)$:

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

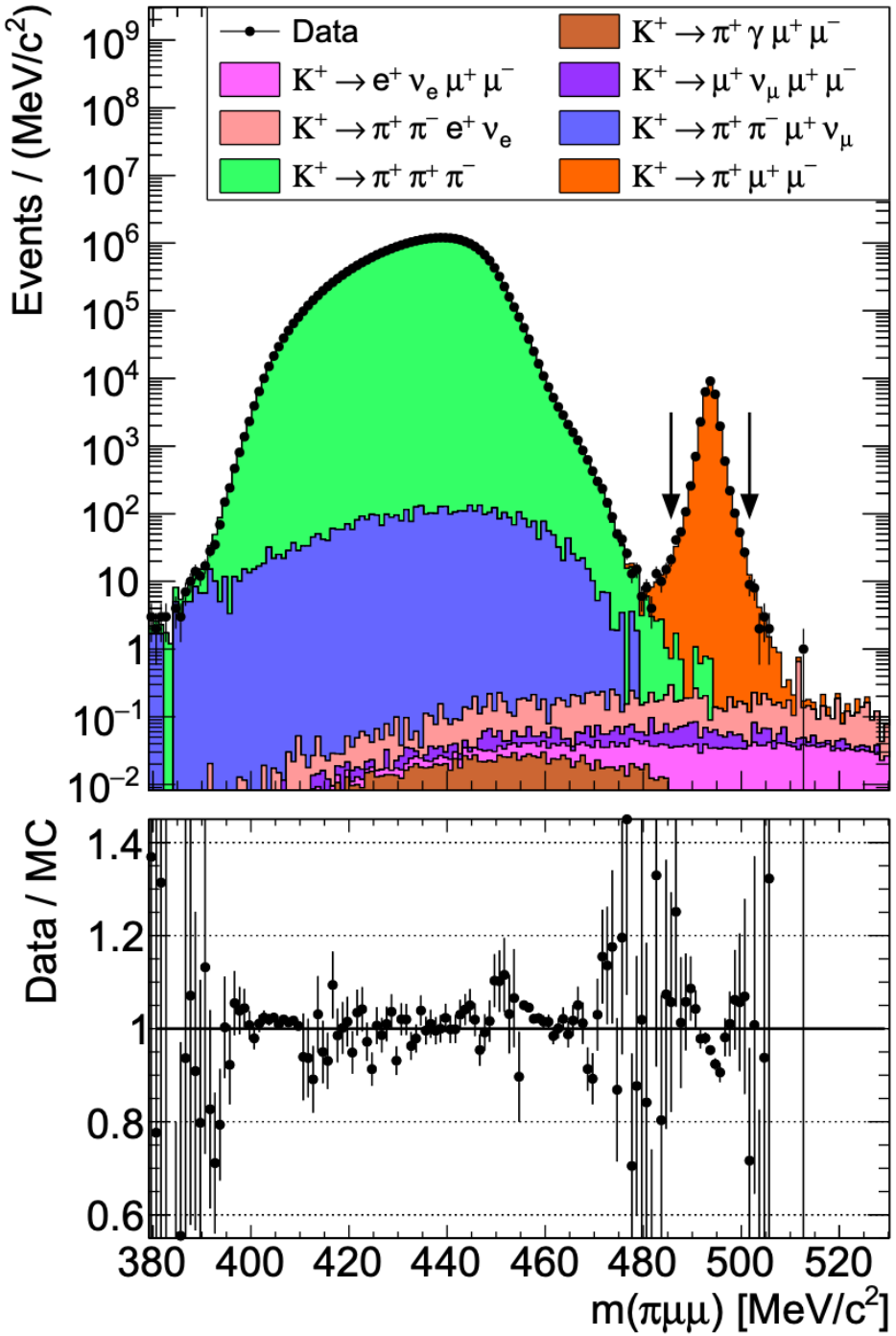
Main goals of the $K^+ \to \pi^+\mu^+\mu^-$ measurements with NA62:

- Model-independent measurement of the B(Kπμμ) branching fraction
- Measurement of the function $|W(z)|^2$
- Determine the Form Factor parameters a_+ and b_+
- Forward - backward assymetry

After signal selection:

N_{obs} = 27679 events

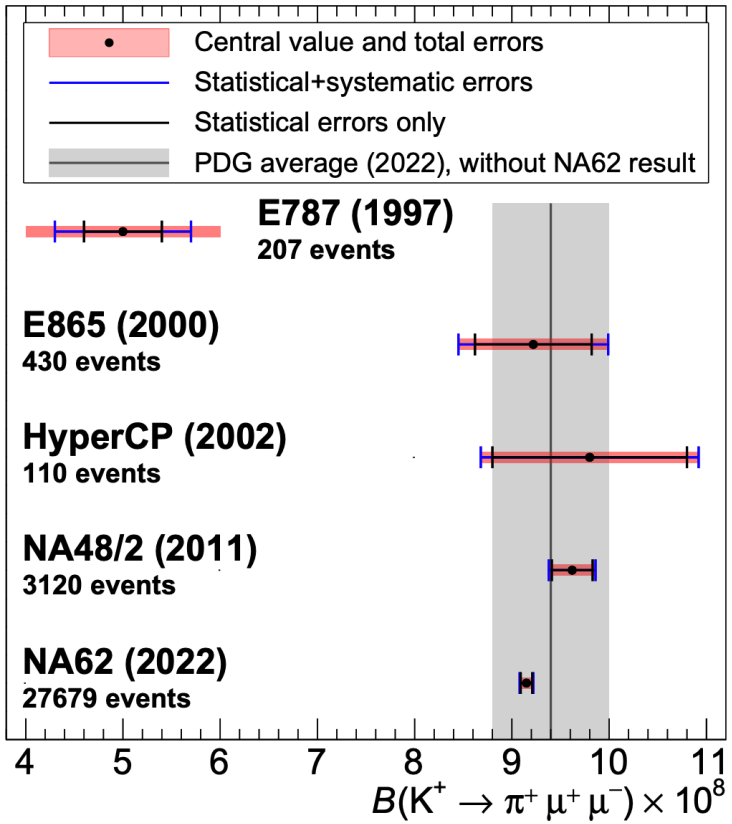
N_{bg}^{exp} = 8 events



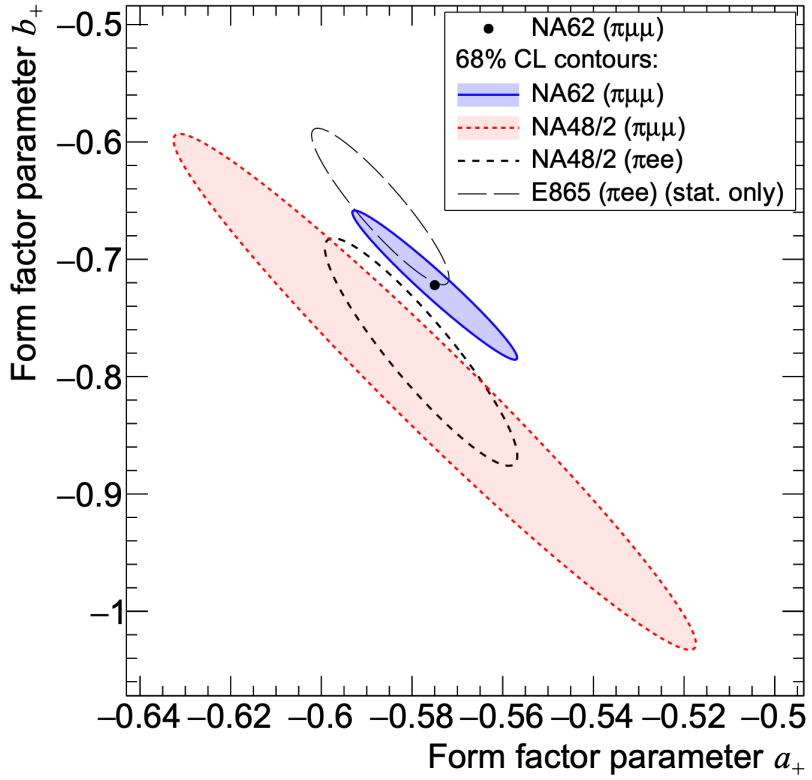
$K^+ \to \pi^+\mu^+\mu$ decays: Results

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

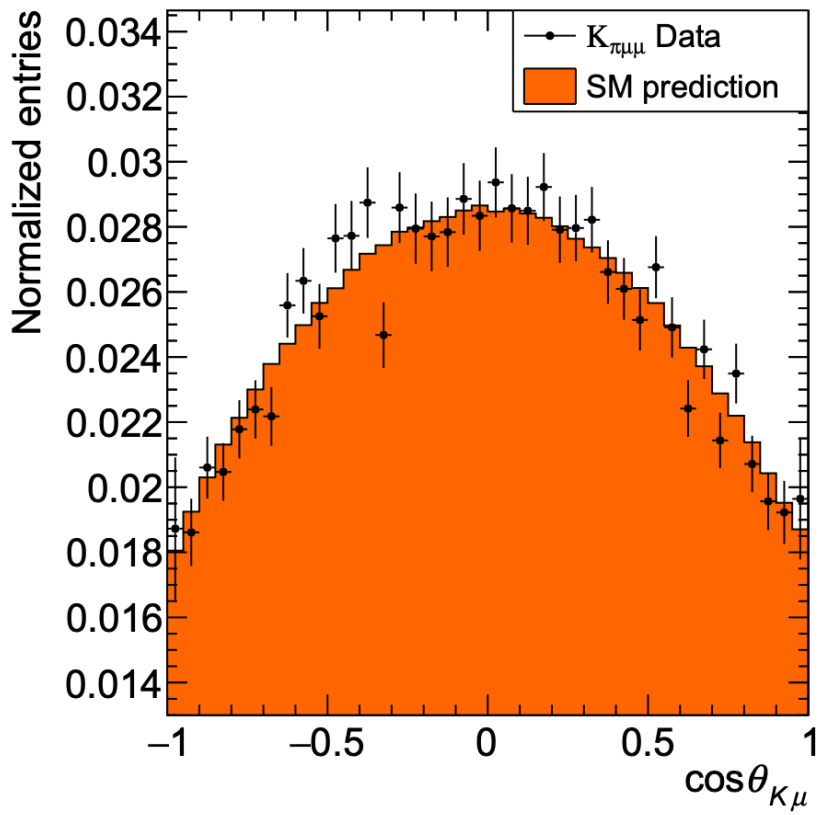
[JHEP 11 (2022) 011]



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



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

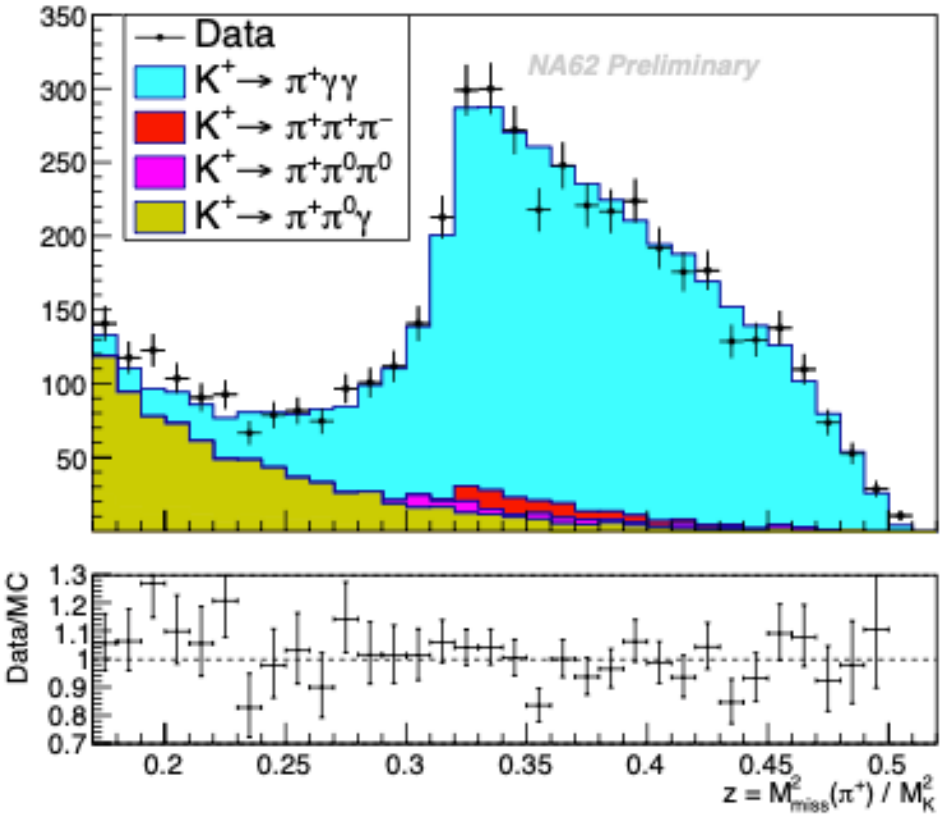


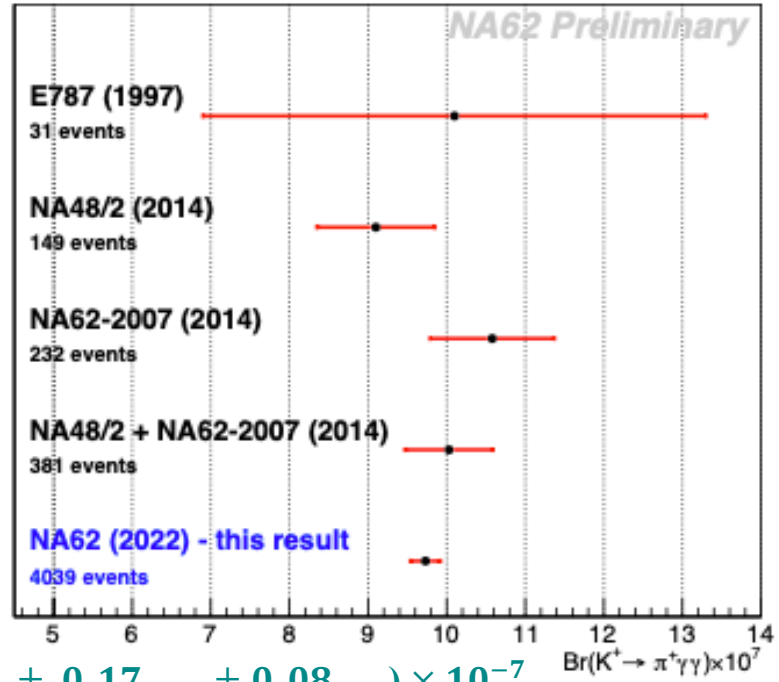
$$A_{FB} = (0.0 \pm 0.7_{stat}) \times 10^{-2} \text{ @ } 68\%\ CL$$

NEW: $|A_{FB}| < 0.9 \times 10^{-2}$
@ 90% *CL upper limit**
UL published as addendum [JHEP 06 (2023) 040]

$K^+ \to \pi^+\gamma\gamma$ decays

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

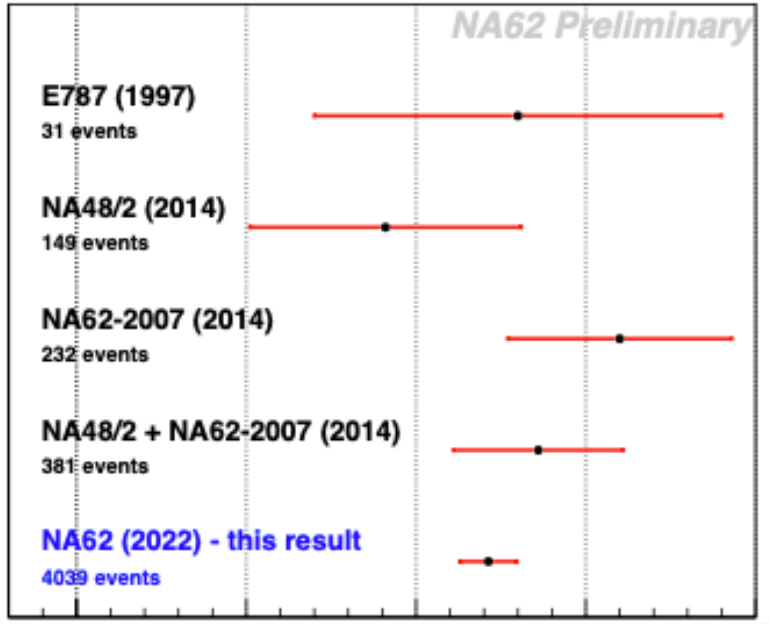




$B_{\pi\gamma\gamma} = (9.73 \pm 0.17_{stat} \pm 0.08_{syst}) \times 10^{-7}$

Main background:
Cluster merging in the EM calorimeter

After signal selection:
$N_{obs} = 4039$ events
$N_{bg}^{exp} = 393 \pm 20$ events



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

Searches for Lepton Flavor and Lepton Number Violating (LFV/LNV) processes with NA62

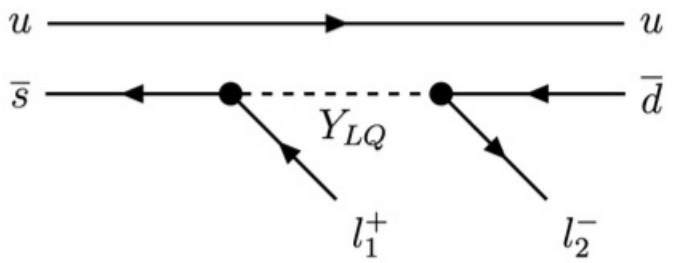
[PLB 797 (2019) 134794], [PRL 127 (2021) 13, 131802], [PLB 830 (2022) 137172], [PLB 838 (2023) 137679]

LFV/LNV searches

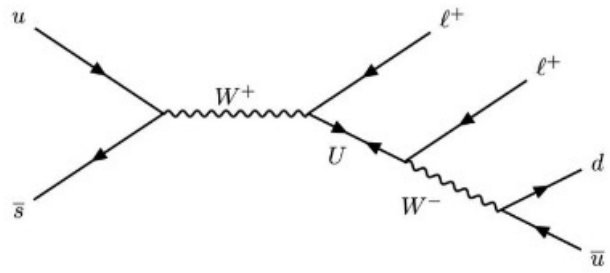
Theory: Violation of Lepton Number (LNV) and Lepton Flavor (LFV) conservation laws predicted in BSM models

(for example via Majorana neutrinos or leptoquark)

- 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)



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



$K^+ \to \pi^- \ell^+ \ell^+$ (LNV, ΔL = 2)

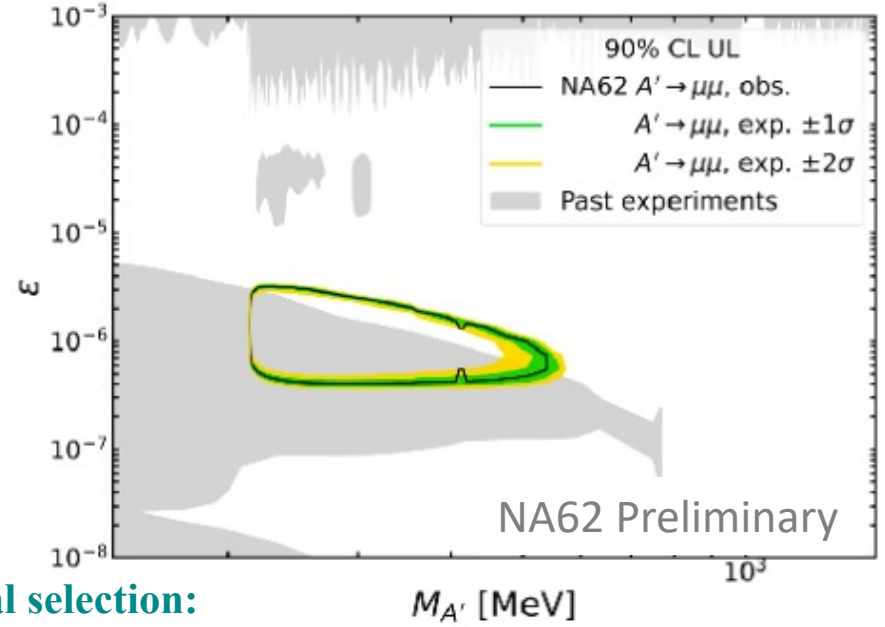
Decay channel	BR UL PDG 2019	BR UL NA62	Expected background	Observed	Improvement (by factor)
$K^+ \to \pi^- \mu^+ e^+$	50×10^{-11}	4.2×10^{-11}	1.07 ± 0.20	0	12
$K^+ \to \pi^+ \mu^- e^+$	52×10^{-11}	6.6×10^{-11}	0.92 ± 0.34	2	8
$\pi^0 \to \mu^- e^+$	34×10^{-10}	3.2×10^{-10}	0.23 ± 0.15	0	11
$K^+ \to \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	0.91 ± 0.41	1	2
$K^+ \to \pi^- e^+ e^+$	64×10^{-11}	5.3×10^{-11}	0.43 ± 0.09	0	12
$K^+ \to \pi^- \pi^0 e^+ e^+$	N/A	8.5×10^{-10}	0.044 ± 0.020	0	
$K^+ \to \mu^- \nu e^+ e^+$	N/A	8.1×10^{-11}	0.26 ± 0.04	0	

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

[preliminary]

Dark photon searches: $A` \rightarrow \mu^+\mu^-$

- 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
- (1.4 ± 0.28) x 10^{17} POT collected in ~10 days in 2021

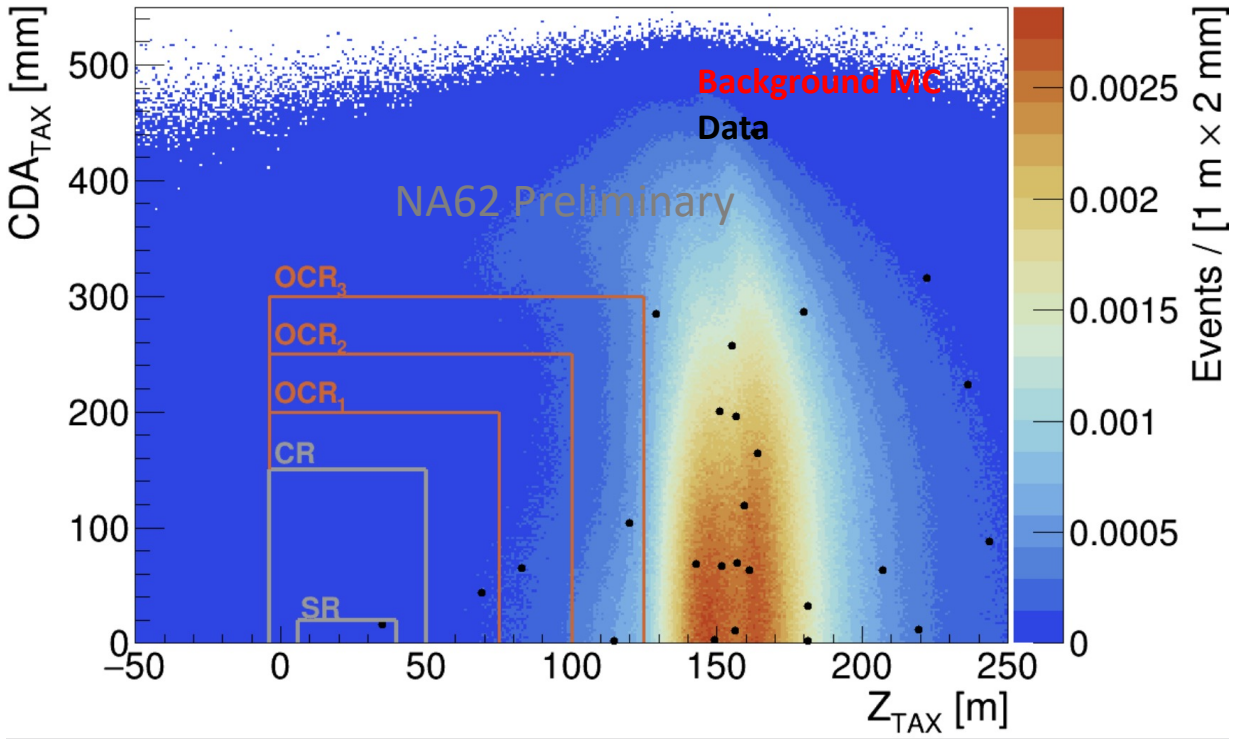


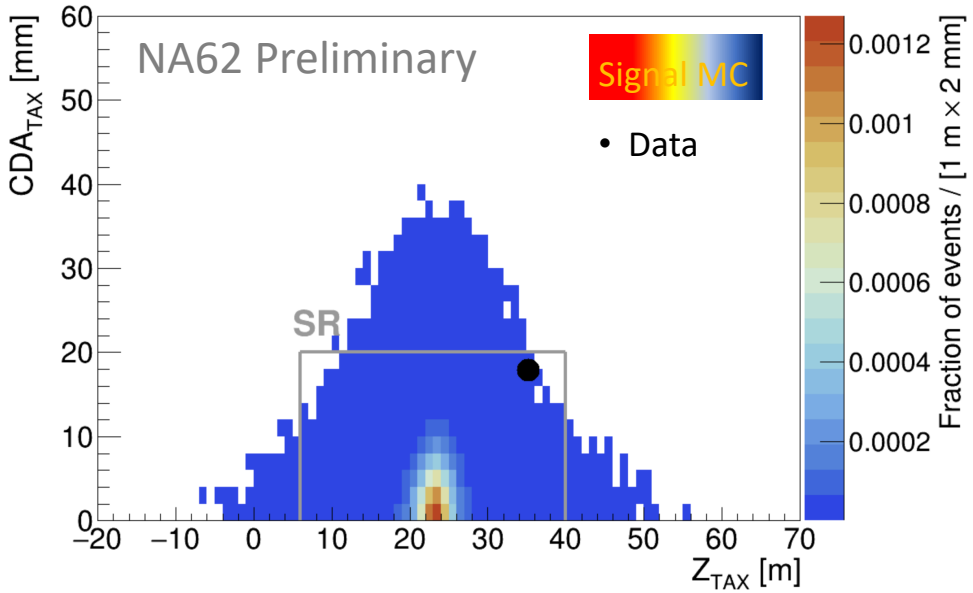
After signal selection:

N_{obs} = 1 event observed

$N_{bg}^{exp} = 0.016 \pm 0.002$ 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 JHEP 06 (2023) 040
$K^+ \to \pi^+\gamma\gamma$	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
$K^+ \to \pi^-\pi^0e^+e^+$	NA62 RUN 1	PLB 830 (2022) 137172
$K^+ \to \mu^-\nu e^+e^+$	NA62 RUN 1	PLB838 (2023) 137679
$A' \to \mu^+\mu^-$	NA62 2021 data	preliminary

Many results with the NA62 RUN 1

First result from NA62 RUN 2

Kaon at CERN: Plans

NA62 RUN 2

- On-going: data taking foreseen at least until 2025 (included), +45-50% increase of intensity vs Run 1
- Hardware upgrades implemented mainly to improve on $\pi^+\nu\bar{\nu}$
- Trigger upgrade to study new channels (e.g. $K \to \pi ee$)
- 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 searches with $K^+ \to \pi^+ e^+ e^- e^+ e^-$: UL $O(10^{-8})$)

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

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

Future of physics with kaons at CERN SPS

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

Intensity x 4-6 with respect to NA62; Detectors with 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 $O(10^{-12})$ sensitivity
- Measurement of V_{us} and main kaon decay modes
- Dump physics in synergy with Shadows experiment

Letter of Intent: arXiv:2211.16586v1

Stay tuned for more results!!!