Measurement of the rare $K^+ \to \pi^+ \nu\nu$ decay from the NA62 experiment at CERN

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DIS 2022 – Santiago de Compostela

May 2nd-6th, 2022

Outline

- The NA62 experiment at CERN
- Study of the $K^+ \rightarrow \pi^+ \nu\nu$ decay
- Search for $K^+ \rightarrow \pi^+ X$
- Prospects and conclusions

Kaon decays at CERN

Kaon decay in flight experiments.
NA62: ~200 participants, ~30 institutes

Earlier: NA31

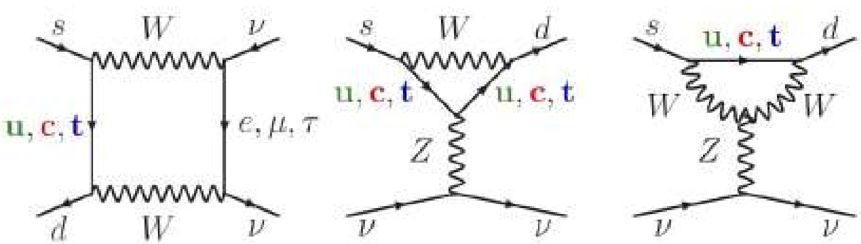
NA48 (discovery of direct CPV)	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
	2003: K^+/K^-	
NA48/2	2004: K^+/K^-	
NA62 R_K phase	2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
	2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
NA62	2014: pilot run	
	2015: commissioning run	
	2016 – 18 : $K^+ \to \pi^+ \nu\nu$ run	
	2021 – : $K^+ \to \pi^+ \nu\nu$ run	

The NA62 experiment

- Main goal
  - Measurement of BR ($K^+ \rightarrow \pi^+ \nu\nu$) with 10% accuracy

- But also a broader physics programme
  - Rare K+ decays
  - LNV/LFV in K+ decays
  - Hidden sector particles
  - Dump mode: MeV-GeV hidden sector
    - Dark photons
    - Heavy Neutral Leptons
    - Axions/Axion-like Particles
  - With parallel high-efficiency trigger masks with a minimal load to the main stream

$K^+ \to \pi^+ \nu\bar{\nu}$: clean theoretical environment



FCNC loop processes:
s->d coupling
Highest CKM suppression

Very clean theoretically
No hadronic uncertainties
Hadronic matrix element related to the precisely measured BR ($K^+ \to \pi^0 e^+ \nu$)

SM predictions [Buras et al. JHEP 1511 (2015) 33]

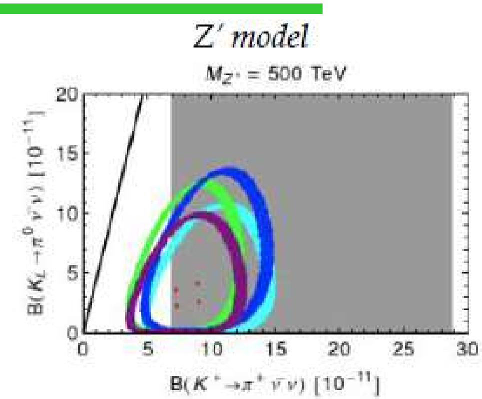
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \cdot \left(\frac{V_{cb}}{0.0407}\right)^{2.8} \cdot \left(\frac{\gamma}{73.2^0}\right)^{0.74} = (0.84 \pm 0.10) \cdot 10^{-10}$$

$$BR(K^0 \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \cdot \left(\frac{V_{ub}}{0.00388}\right)^{2} \cdot \left(\frac{V_{cb}}{0.0407}\right)^{2} \cdot \left(\frac{\sin\gamma}{\sin 73.2^0}\right)^{0.74} = (0.34 \pm 0.06) \cdot 10^{-10}$$

$K \to \pi\nu\nu$ are the most sensitive probes to NP models among B and K decays

The combined measurement of K^+ and K_L modes could shed light on the flavour structure of NP ($\Delta S=2$ / $\Delta S=1$ correlation)

$K \to \pi\nu\bar{\nu}$ NP sensitivity



Simplified Z, Z′ models

A. J. Buras, D. Buttazzo, R. Knegiens, JHEP 1511 (2015) 166

More specific NP models

Littlest Higgs with T-parity

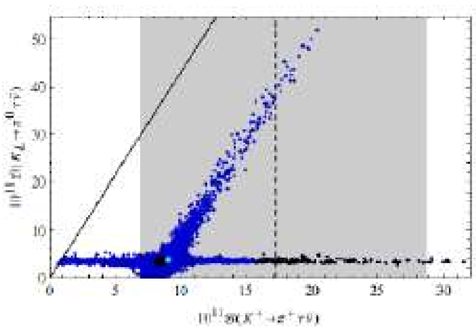
M. Blanke, A.J. Buras, S. Recksiegel, EPJ C76 (2016) 182

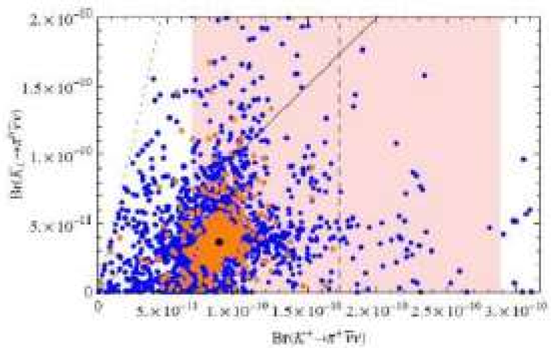
Custodial Randall-Sundrum

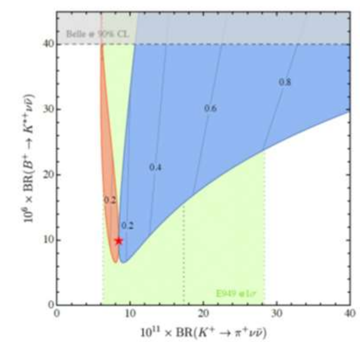
JHEP 0903 (2009) 108

LFU Violation

Isidori et al, EPJC (2017) 77



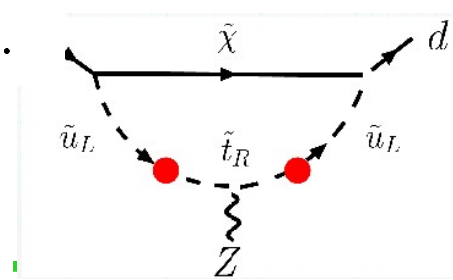




- Started to be probed at LHC, small effects in B physics.

Best probe of MSSM non-MFV [JHEP 0608 (2006) 064]

- E.g. non-MFV in up-squarks trilinear terms
- Still not excluded by the recent LHCb data.



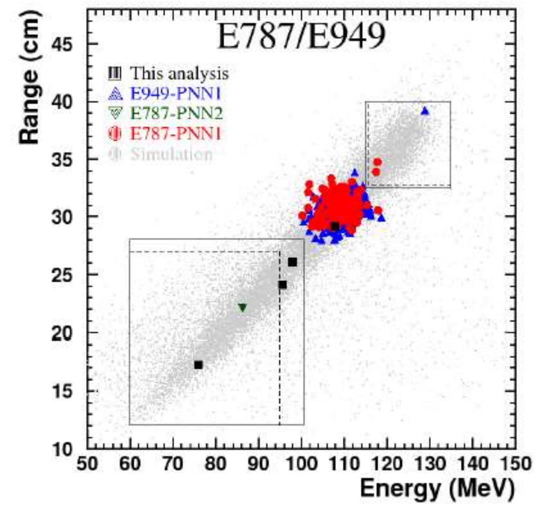
Previous status of $K^+ \to \pi^+\nu\bar{\nu}$

E787/E949 @Brookhaven: 7 candidates $K^+ \to \pi^+\nu\nu$
2 experiments, stopped kaon technique

- Separated K⁺ beam (710 MeV/c, 1.6MHz)
- PID: range (entire π+→μ+→e+ decay chain)
- Hermetic photon veto system

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05})\times 10^{-10}$$

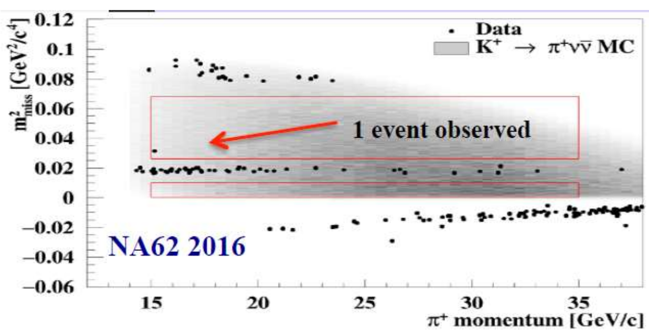
Phys. Rev. D77,052003 (2008), Phys. Rev. D79,092004 (2009)

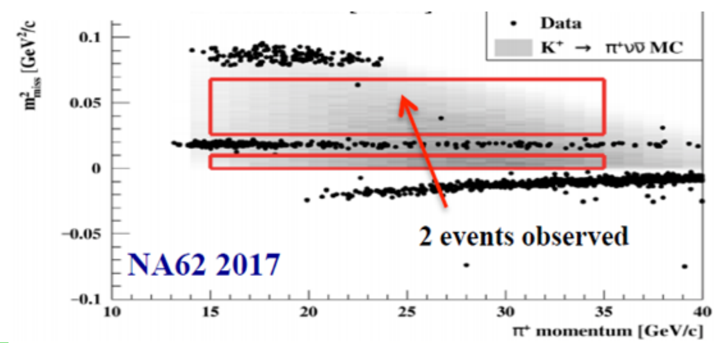


NA62, result from 2016+2017 data:

$$BR(K^+ \to \pi^+\nu\bar{\nu}) < 1.78\times 10^{-10} (90\%\ CL)$$

Phys. Lett. B 791 (2019) 156
JHEP 11 (2020) 042





NA62 goals and challenges

- Measurement of the $K^+ \rightarrow \pi^+ \nu\nu$ branching ratio
  - This requires at least 10^{13} Kaon decays
  - In-flight decay technique
  - 75 GeV/c beam helps in background rejection
    - Event selection with P_π<35 GeV/c (45 GeV/c in region 2 for 2018 data)
    - i.e. $K_{\pi 2}$ decays have around more than ~40 GeV of electromagnetic energy
    - $O(10^{12})$ rejection factor of common K decays

Good tracking devices

Accurate measurement of the kaon momentum
Accurate measurement of the pion momentum
Missing mass cut: $O(10^5)$ rejection on $K_{\mu 2}$, $O(10^4)$ on $K_{\pi 2}$

Veto detectors

Photons: to reduce the background by a factor of 10^8
Muons: add a rejection factor of $O(10^5)$

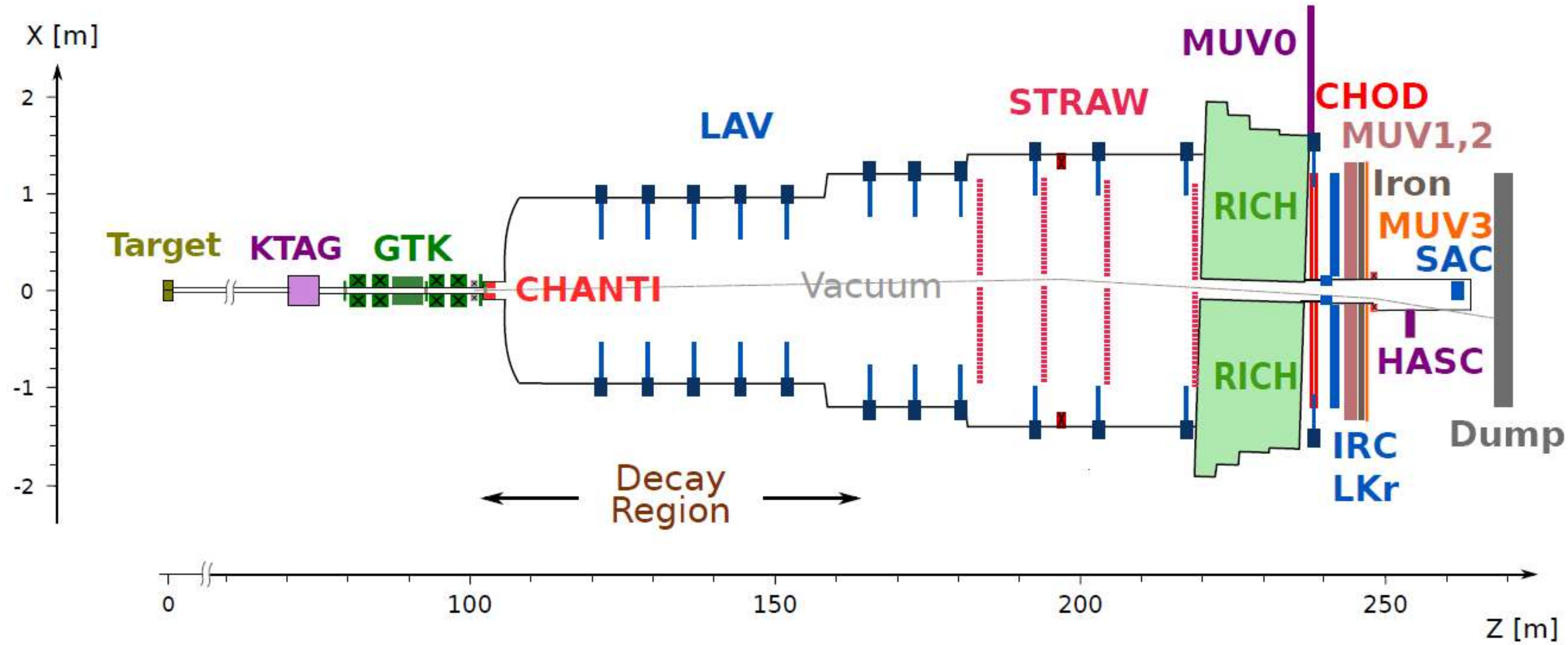
Particle identification

Identify kaons in the beam
Identify positrons
Additional π/μ rejection [$O(10^2)$]

Precise sub-ns timing

Kaon-pion time association
To reduce pileup

The NA62 detector



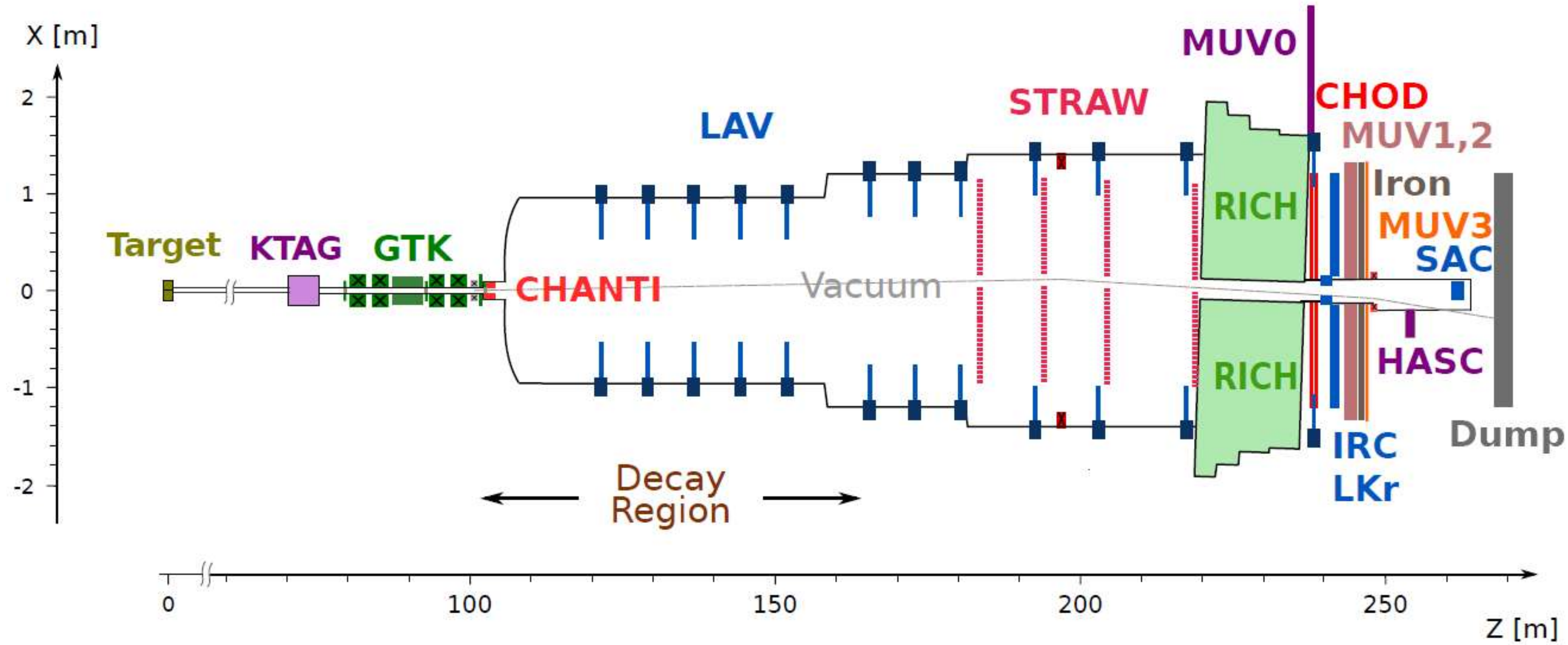
Beam	
Momentum	75 GeV/c, 1% bite
Divergence (RMS)	100 μrad
Transverse Size	$60 \times 30 mm^2$
Composition	K+ 6%, π+ 70%, p 24%
Nominal Intensity	33×10^{11} ppp (750 MHz at GTK3)

Fiducial region

60 m decay region
10^{-6} mbar vacuum
Downstream rate ~ 10 MHz

Detector description:
JINST 12 P05025 (2017), arxiv:1703.08501

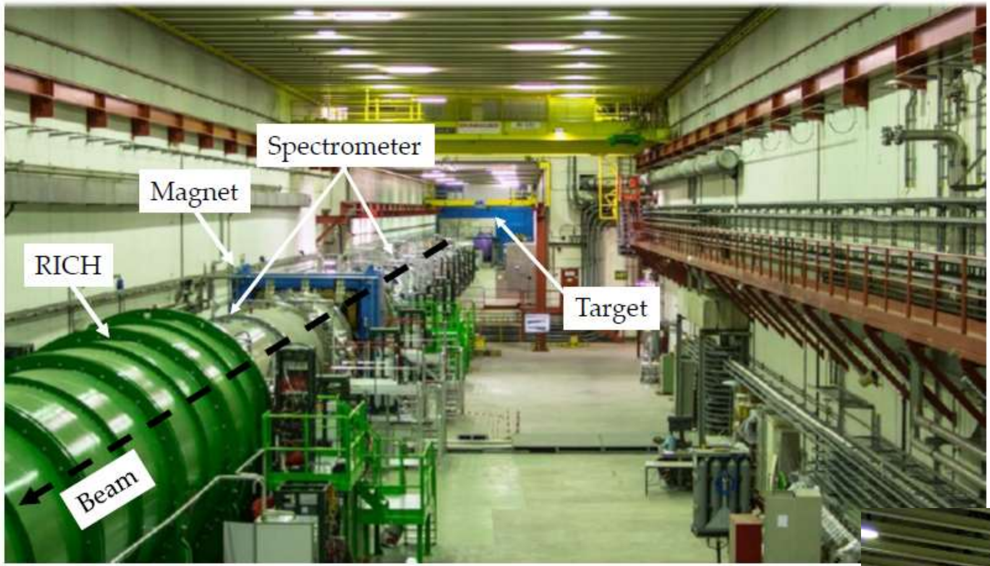
The NA62 detector



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

Downstream detectors (π^+)	
STRAW	Track spectrometer
CHOD	Scintillator hodoscopes
LKr/MUV1/MUV2	Calorimetric system
RICH	Cherenkov for $\pi/\mu/e$ ID
LAV/LKr/IRC/SAC	Photon veto
MUV3	Muon veto

NA62 runs



2014: Pilot run

2015: Commissioning run

2016: Commissioning and physics run

Result published:
Phys. Lett. B 791 (2019) 156

2017: 160 days of data taking

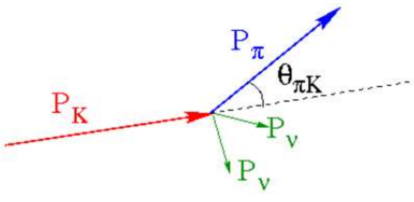
Result published:
JHEP 11 (2020) 042

2018: 217 days of data taking

Result published:
JHEP 06 (2021) 093

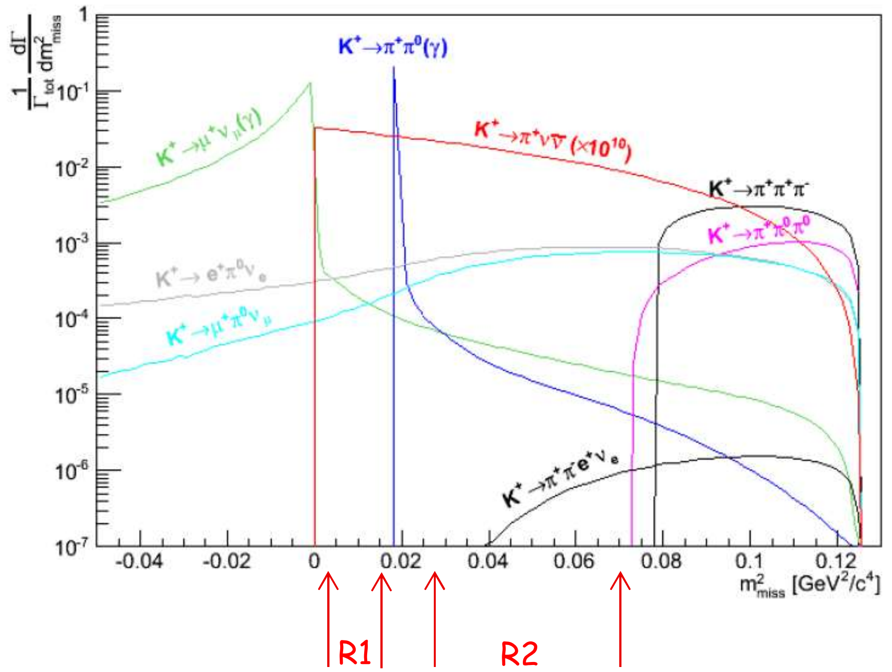
K^+ decay in-flight

- Signature: one incident kaon, 1 charged output track
- Missing mass distributions: $m^2_{miss} = (P_K - P_{track(hyp\ \pi^+)})^2$
- Define two regions in m^2_{miss} to accept candidate events
- 65 m long decay fiducial region, $15 < P\pi < 35$ GeV/c
- Particle ID (Cherenkov detectors, calorimeters)
- Photon Veto



- Backgrounds:
  - Accidental beam activity
  - K+ decay modes:

$K^+ \to \pi^+\pi^0\ (\gamma)$	Br = 0.2067
$K^+ \to \mu^+\nu\ (\gamma)$	Br = 0.6356
$K^+ \to \pi^+\pi^+\pi^-$	Br = 0.0558
$K^+ \to \pi^+\pi^-e^+\nu$	Br = 4.25×10^{-5}

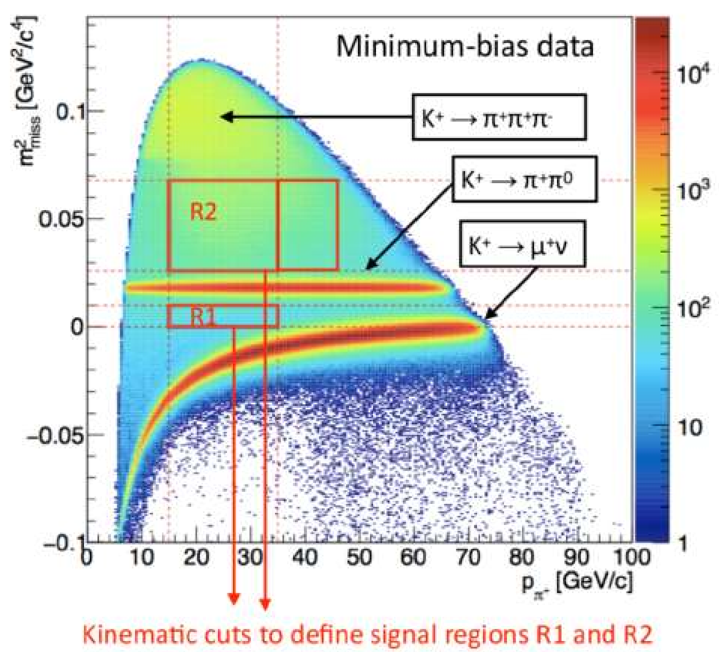


Data analysis

- Analysis steps
  - Selection
  - Determination of single event sensitivity (SES)
  - Estimation and validation of the expected background
  - Un-blinding of the signal regions

- Selection
  - K^+ decay into one charged particle
  - π^+ identification
  - Photon rejection
  - Multi track rejection

- Performances
  - GTK-KTAG-RICH timing: O(100 ps)
  - π^+ ID: $\varepsilon_\mu = 10^{-8}$; $\varepsilon_{\pi+}$ ~64%
  - π^0 rejection $\varepsilon_{\pi 0}$ = ~$1.4 \cdot 10^{-8}$
  - $\sigma(m^2_{miss}) \sim 10^{-3}$ GeV^2/c^4



Single Event Sensitivity (SES)

- Determine Kaon flux from $K^+ \to \pi^+\pi^0$ selected with control trigger (downscale 400)
- Use the same $\pi\nu\nu$ selection, but without photon and multiplicity rejection and with missing mass cut modified

- Average random veto efficiency ε_{RV} = (66±1)%
- Average trigger efficiency ε_{trig} = (88±4)%
- Both efficiencies function of the instantaneous beam intensity, measured from the sidebands of the time distributions in the GTK
- All computations done in momentum bins and then summed

$$N_{\pi\nu\nu}^{\exp} = N_{\pi\pi}\varepsilon_{RV}\varepsilon_{trig}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{BR(\pi\nu\nu)}{BR(\pi\pi)} \qquad SES = \frac{BR(\pi\nu\nu)}{N_{\pi\nu\nu}^{\exp}}$$

Single Event Sensitivity (SES)

Integrated over beam intensity and π^+ momentum

$$SES = (0.111 \pm 0.007) \times 10^{-10} \quad N_{\pi\nu\nu}^{exp} = 7.58 \pm 0.40_{syst} \pm 0.75_{ext}$$

External error from SM prediction for BR = $(0.84 \pm 0.10)*10^{-10}$

Error budget	
Source	Uncertainty
Trigger efficiency	5%
MC Acceptance	3.5%
Random veto efficiency	2%
Instantaneous intensity	0.7%
Normalization background	0.7%
Total	6.5%

Background suppression

Data driven estimation
$K^+ \to \pi^+\pi^0$ (γ), $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^+$:

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

Expected events in the signal region, $\pi\nu\nu$ selection

Data in $\pi^+\pi^0$ ($\mu^+\nu$) region, $\pi\nu\nu$ selection (including π^0 rejection)

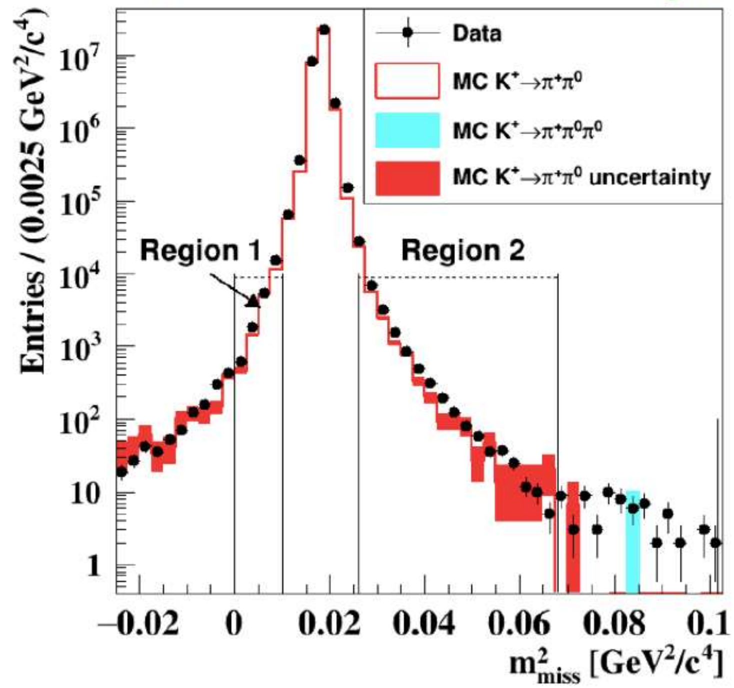
Fraction of $\pi^+\pi^0$ ($\mu^+\nu$) in signal region measured on control data

$$N_{\mu\nu}^{exp}(region) = N(\mu^+\nu) f^{kin}(region)$$

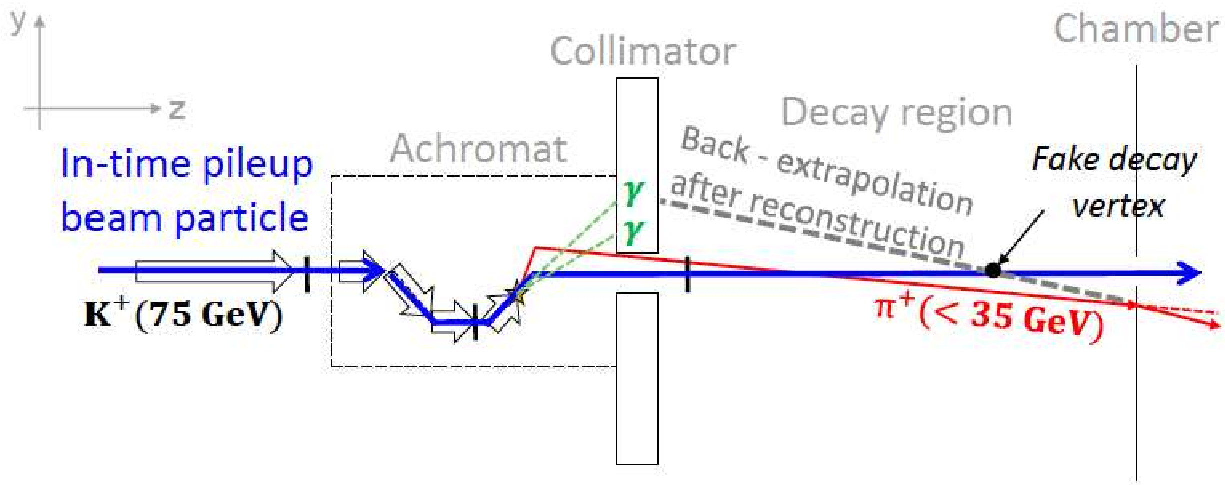
$K^+ \to \pi^+\pi^+\pi^-$: Same procedure, but kinematic tails estimated with MC

$K^+ \to \pi^+\pi^- e^+ \nu e$, $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^0 \ell^+ \nu$: evaluation only with MC simulations normalized to the SES

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



Upstream background



K^+ decay/interaction in the achromat
Photons blocked by the collimators

← Use inverted K-π matching to counts event from data

π^+ detected in the straw, but it has scattered

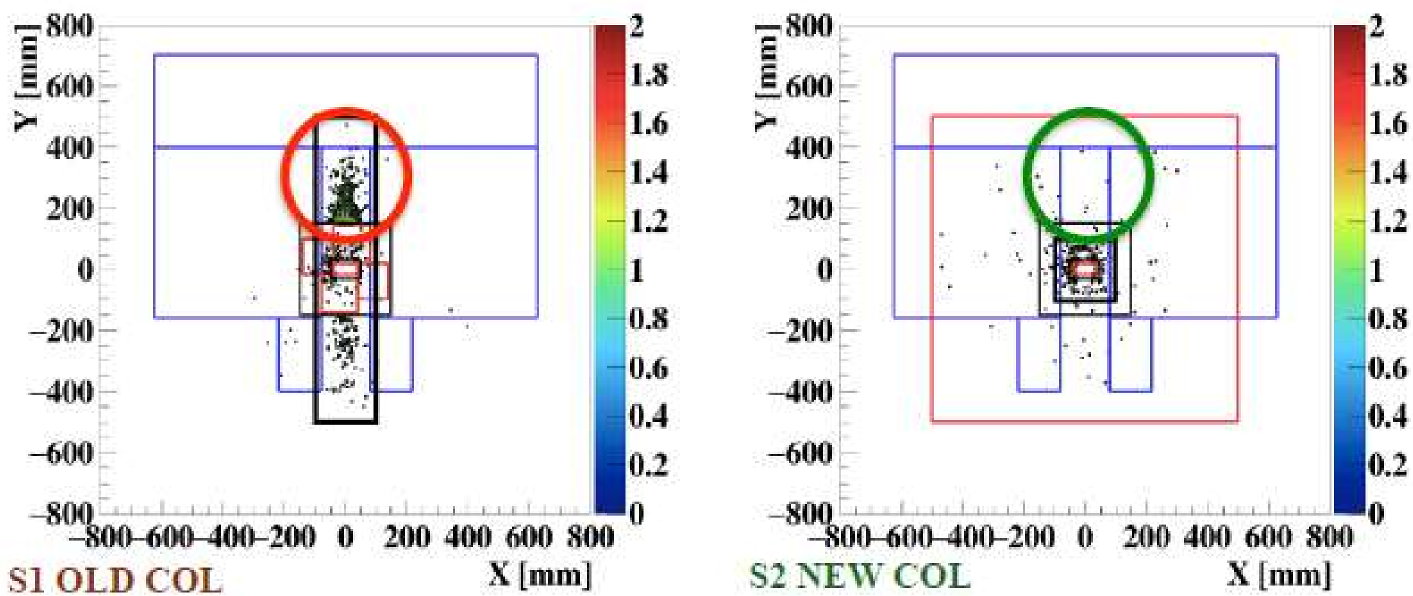
Back extrapolation gives a fake vertex in the fiducial zone with an in-time pileup K^+

← Estimation of the probability of occurrence from data/MC

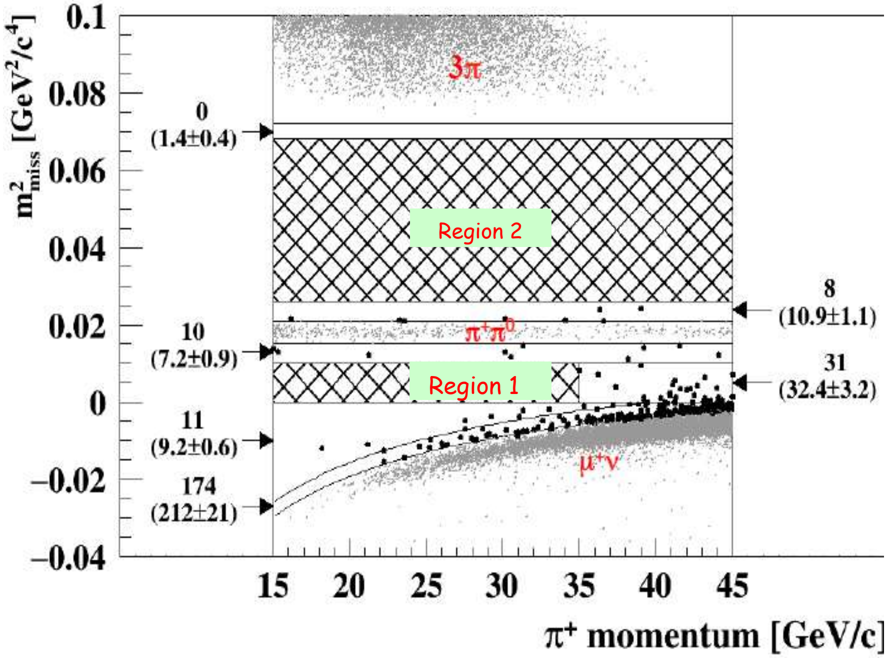
Upstream background

In 2018 a new collimator was installed to help reducing upstream background

Below track extrapolation at collimator in an enriched sample of upstream events



Background evaluation



Estimation of the background using data
Validation in 6 control regions with blind analysis

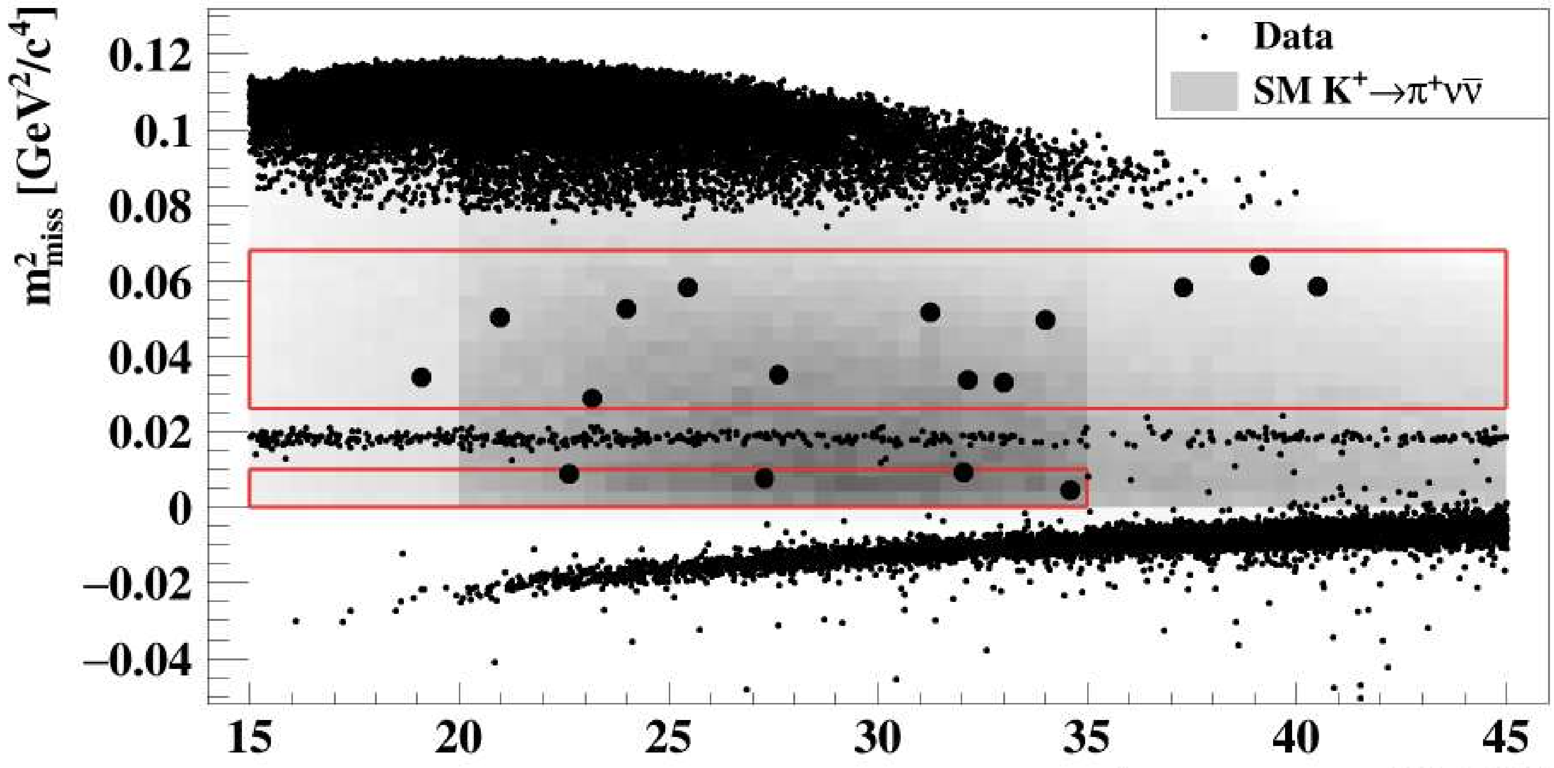
After unmasking control regions good agreement between expected and observed events

Background estimates summed over Region 1 and Region 2

Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

$$Total\ background = 5.42^{+0.99}_{-0.75}$$

Opening the box



[JHEP 06 (2021) 096]

17 candidates observed

7.58 ± 0.85 SM signal events expected with a background of $5.42^{+0.99}_{-0.75}$ events

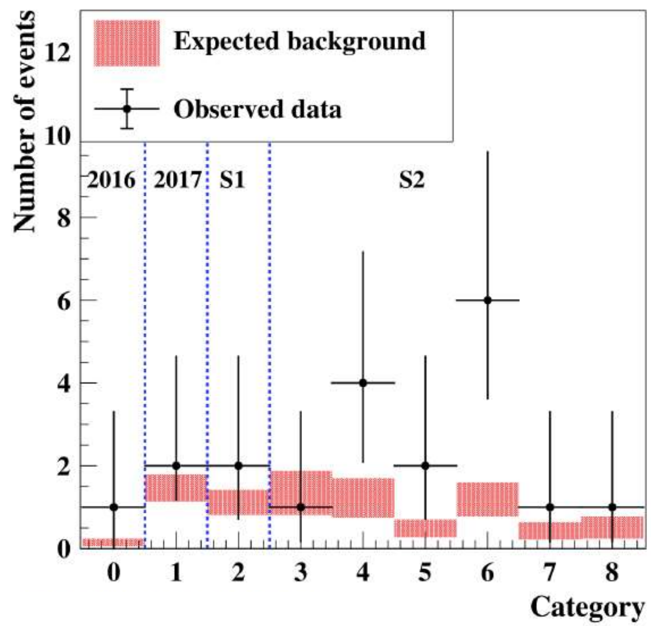
$K^+ \rightarrow \pi^+\nu\nu$ 2016+2017+2018 combined result

	2016	2017	2018
Observed candidates	1	2	17
Single event sensitivity	$(3.15 \pm 0.24)\cdot 10^{-10}$	$(3.89 \pm 0.21)\cdot 10^{-11}$	$(1.11 \pm 0.07)\cdot 10^{-11}$
Expected SM signal	0.267 ± 0.038	2.16 ± 0.29	7.58 ± 0.85
Expected background	0.152 ± 0.090	1.46 ± 0.33	$5.42^{+0.99}_{-0.75}$

20 events observed in signal regions
P(bkg only) = $3.4*10^{-4}$
3.4 σ significance

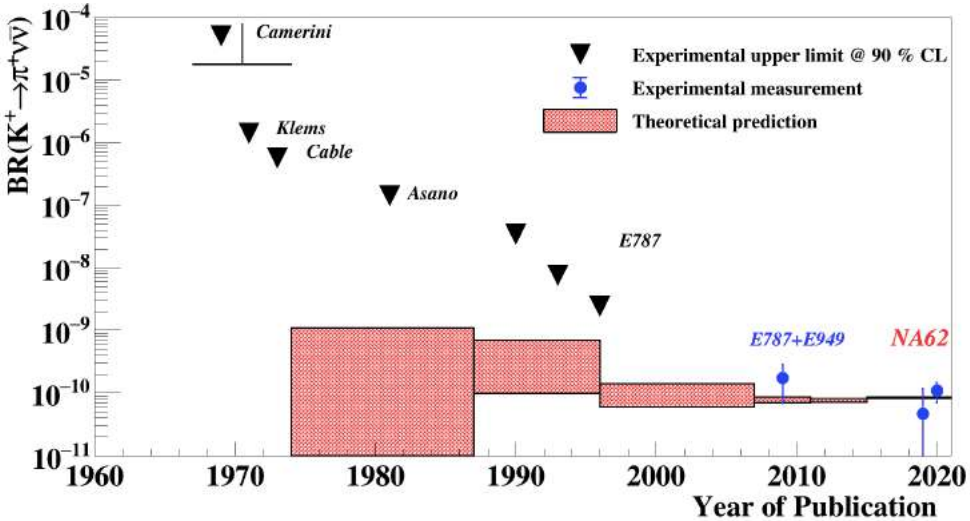
9 categories: 2016, 2017, 2018 oldcol (S1) and 6 for 2018 newcol (S2)

Maximum log-likelihood fit using signal and background expectations in each category



$$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}\Big|_{stat} \pm 0.9_{syst}) \times 10^{-11} (68\%\ CL)$$

The result



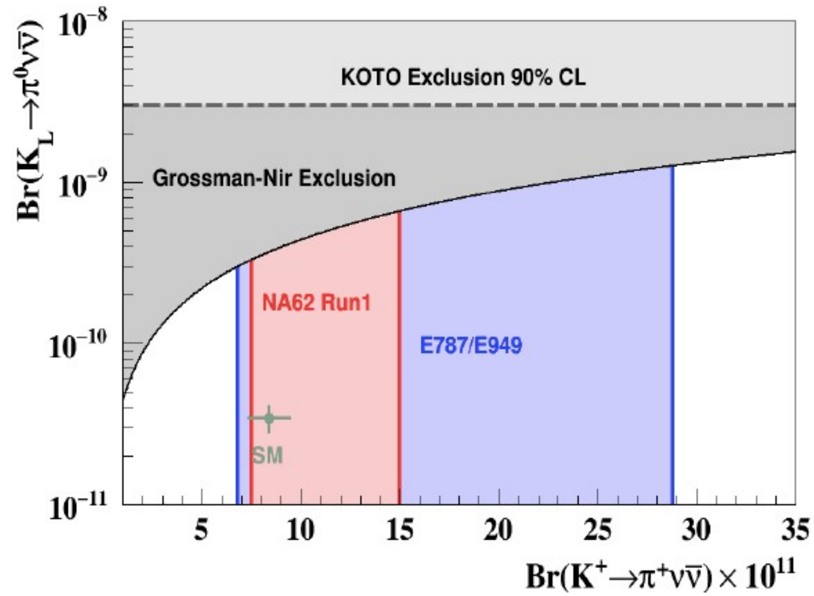
Most precise measurement of the $K^+ \to \pi^+\nu\nu$ decay rate

Strongest evidence so far ($3.4\ \sigma$) for its existence

Part of parameter space already ruled out

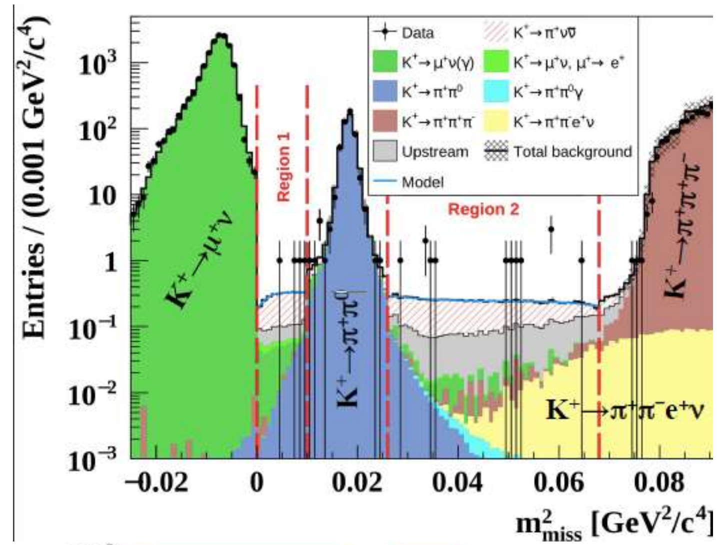
Exclusion of large $BR(K^+ \to \pi^+\nu\nu)$ deviations from SM excluded

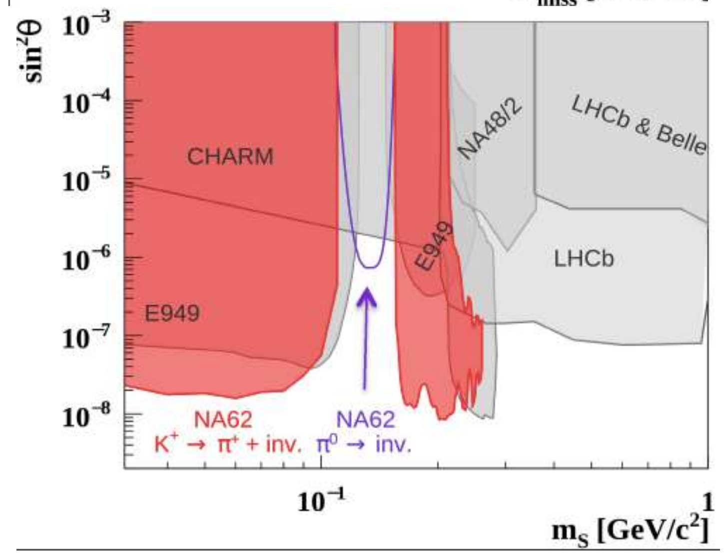
Grossman-Nir limit:
$BR(K_L \to \pi^0\nu\nu) < 4.3 \times BR(K^+ \to \pi^+\nu\nu)$



$K^+ \to \pi^+ X$, X invisible

- Search for feebly interacting particles in several models
  - Dark scalar mixing with Higgs boson
  - Scalars, like Alps, QCD axion, axiflavon
- Use the background shapes of $\pi\nu\nu$ analysis: consider as SM background
- Peak search using the m^2_{miss} observable for M_X in the 0-260 MeV/c^2 range
- Improvements on previous limits over most of the M_X range
- 90% UL on BR($K+ \to \pi^+ X$) in (10^{-11}-10^{-10})
- Exclusion limits for dark scalars
  - Production and decay driven by mixing with Higgs
  - Assuming X decays only to visible SM particles, then lifetime inversely proportional to the mixing
- Stringent constraints on the allowed region in the (M_X, $\sin^2\theta$) plane





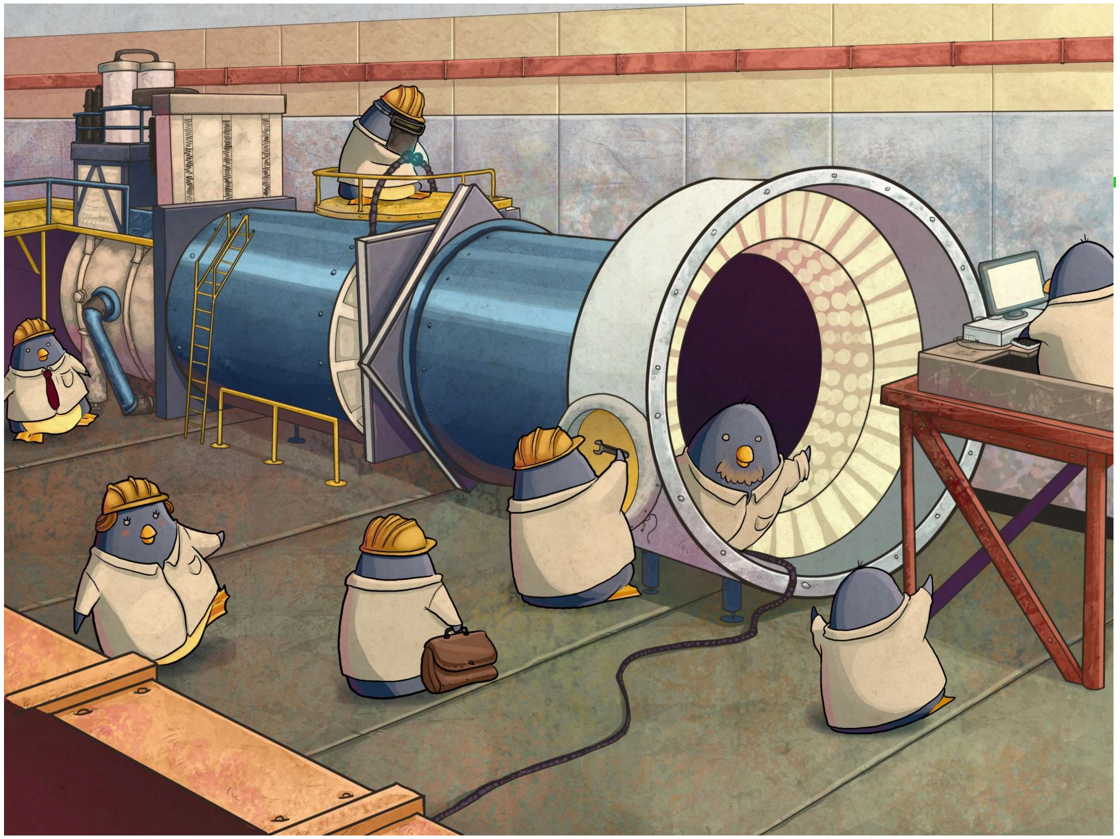
Conclusions

- The 2016-2017-2018 NA62 combined result for $K^+ \to \pi^+ \nu\nu$ has been presented
  - 20 events found

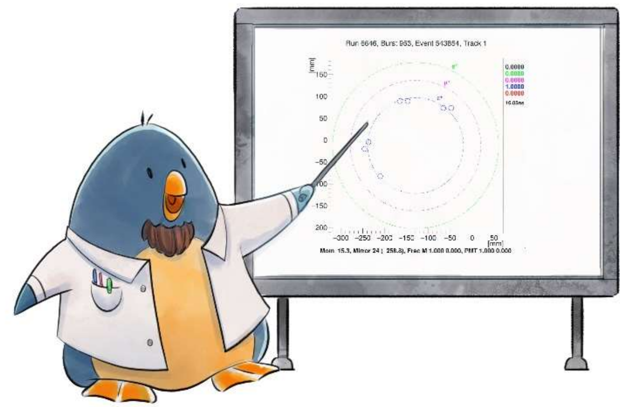
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}\Big|_{stat} \pm 0.9_{syst}) \times 10^{-11} (68\%\ CL)$$

- The experimental setup has been updated for the next data taking (2021-2025)
  - Data taken in 2021, 2022 run just started
  - New veto counter to further reduce upstream background
  - Upstream scintillator plane to help in reducing muon background in dump mode
  - Second HASC module to improve π^0 and 3π backgrounds

- Search for $K^+ \to \pi^+ X$, X invisible
  - Improvement on the upper limit for the branching ratio
  - Stringent constraints on the allowed region in the $(M_X, \sin^2\theta)$ plane



Artist's view of the past installation activity…



Thank you!

… and of the current analysis work…