Measurement of the very rare $K^+ \to \pi^+ \nu \overline{\nu}$ decay

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On behalf of the NA62 Collaboration

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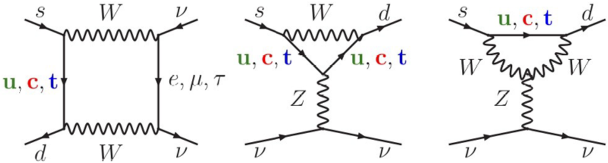
$K^+ \to \pi^+ \nu\bar{\nu}$: theoretical status



- FCNC loop process - rare meson decay naturally suppressed by the GIM mech.
- Sensitive to contributions of physics BSM
  - **MSSM** [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27], [Isidori et al. JHEP 0608 (2006) 064]
  - **Custodial Randall-Sundrum** [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
  - **Simplified Z, Z' models** [Buras et al. High Energ. Phys. (2015)166], [Aebischer et al. JHEP12 (2020)097]
  - **Littlest Higgs with T-parity** [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
  - **LFU violation models** [Bordone, M., Buttazzo, D., Isidori, G. et al. Eur. Phys. J. C (2017) 77: 618]
  - **Leptoquarks** [Fajfer,Kosnik,Vale Silva,Eur. Phys. J.C78, 275 (2018)]

- SM prediction [Buras.et.al., JHEP11(2015) 033]:

$$\mathcal{B}_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

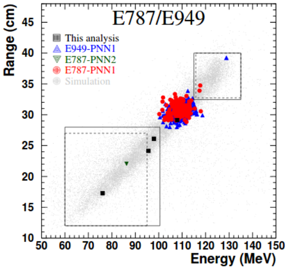
  - Uncertainty coming mostly from CKM parameters (γ, $|V_{cb}|$)
  - In agreement with the very recent result [Brod,Gorbahn,Stamou,arXiv:2105.02868]

$K^+ \to \pi^+ \nu \overline{\nu}$: experimental status

Previous measurement at BNL:

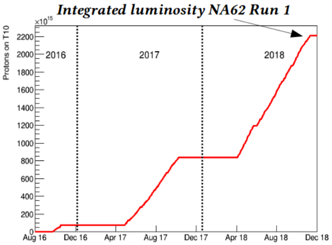
- Experiments E787 and E949
- Technique: stopped kaon beam, decays at rest
- Final results published in 2009
  [E949, Phys.Rev.D 79, 092004 (2009)]
- Observed 7 events in total
- Branching fraction measurement:

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

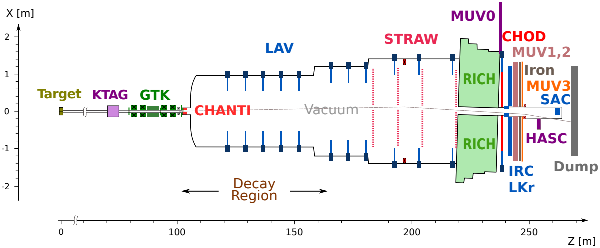


New measurement at CERN ***(this talk)*****:**

- NA62 collaboration
- Technique: kaon decays in flight
- Data taking in 2016 - 2018 (Run 1)
- Integrated luminosity: 2.2×10^{18} POT
  $\Rightarrow 3 \times 10^{12}$ K^+ decays



NA62 Beam and Detector



[JINST 12(2017) P05025]

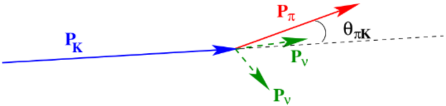
Beam:

- 400 GeV/c primary proton beam from SPS
- $2{\times}10^{12}$ protons per 3.5 s spill
- Beryllium target
- Secondary hadron beam, $\sim$ **75 GeV/c**, content: $\boldsymbol{K}^+$ (6%), π^+ (70%), p (24%)
- 75 m long decay region, vacuum
- Kaon decay rate $\sim$ 3 MHz

Detectors:

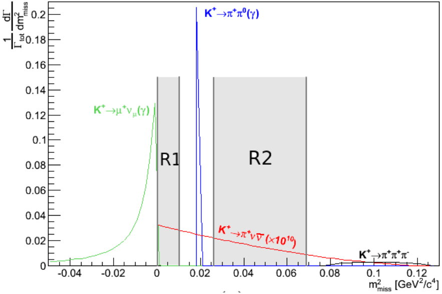
- KTAG - Cherenkov det., K^+ tagging
- GTK - beam spectrometer
- STRAW - downstream spectrometer
- CHOD - charged particle hodoscope
- LAV, IRC, SAC - photon veto
- RICH, LKr - Cherenkov detector and calorimeter for PID
- MUV3 - muon veto
- CHANTI, HASC, MUV0-2

$K^+ \to \pi^+ \nu \bar{\nu}$ at NA62: measurement and analysis strategy



- PNN and min-bias trigger streams
- Blind analysis
- Signal normalized to $K^+ \to \pi^+ \pi^0$
- Two signal regions (R1, R2)

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



Keystones:

- Time coincidence resolution $\mathcal{O}(100\text{ ps})$
- Kinematic background suppression $\sim \mathcal{O}(10^4)$
- PID background suppression:
  - μ^+ (from $K_{\mu 2}$) $> 10^7$
  - π^0 (from $K_{2\pi}$) $> 10^7$

Signal selection strategy:

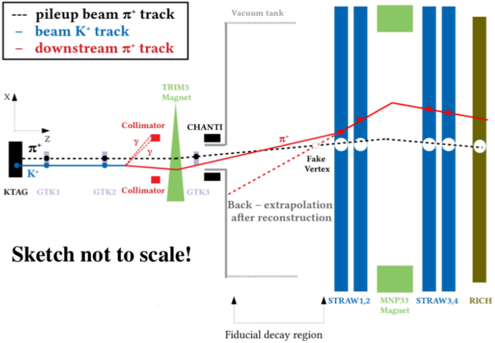
- Kaon tagging
- Kaon and pion momentum reconstruction
- Kaon-pion matching
- π^+ identification
- Background suppression

$K^+ \to \pi^+\nu\bar{\nu}$ at NA62: backgrounds

- **K^+ decays**

Decay channel	Branching fraction [PDG]	Estimated with
$K^+ \to \mu^+\nu$ ($K_{\mu 2}$)	$(63.56 \pm 0.11) \times 10^{-2}$	data
$K^+ \to \pi^+\pi^0$ ($K_{2\pi}$)	$(20.67 \pm 0.08) \times 10^{-2}$	data
$K^+ \to \pi^+\pi^+\pi^-$ ($K_{3\pi}$)	$(5.583 \pm 0.024) \times 10^{-2}$	data, MC
$K^+ \to \pi^+\pi^- e^+\nu$ (K_{e4})	$(4.247 \pm 0.024) \times 10^{-5}$	MC
Other		MC

- **Upstream events** $\longrightarrow$ data-driven estimation



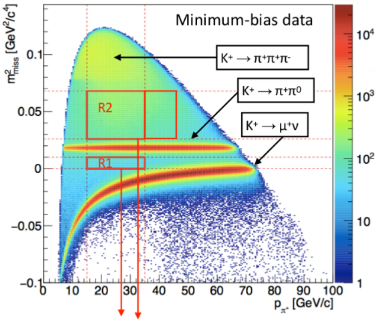
Dominant background in 2017 and 2018 data.

Changes in 2018 data taking and analysis

- **Replacement of the final collimator**
  - to suppress upstream events
  - installed in June 2018
  - 2018 data divided into S1 (old collimator, 20%) and S2 (new collimator, 80%)

- **Signal selection optimization**
  - Signal region 2 extended to 45 GeV
  - Relaxed criteria against upstream background, use BDT
  - PID conditions optimized in bins of π^+ momentum
  - Enlargement of the fiducial volume
  - Improvement of γ and multi-track veto

$\Rightarrow$ **Increase in signal acceptance**

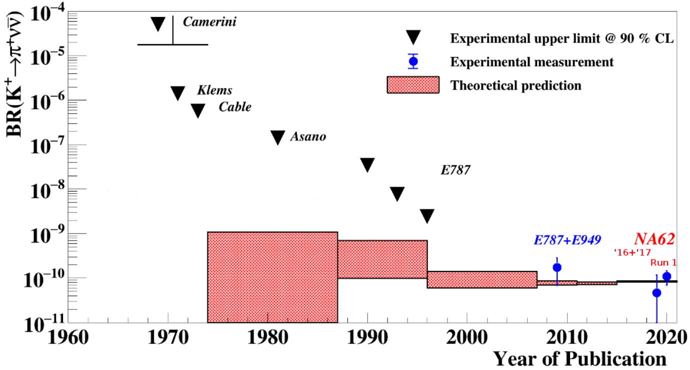


Kinematic cuts to define signal regions R1 and R2

$K^+ \to \pi^+ \nu \bar{\nu}$ at NA62: results

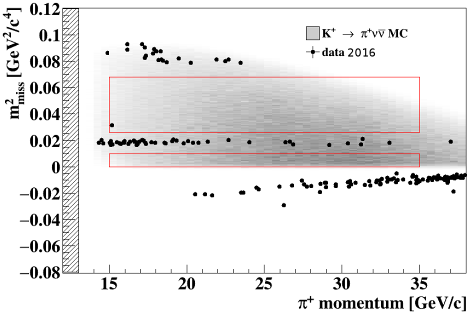
	2016 data	2017 data	2018 S1 data	2018 S2 data
SES ($\times 10^{10}$)	3.15 ± 0.24	0.39 ± 0.02	0.54 ± 0.04	0.14 ± 0.01
$A(\pi\nu\nu) \times 10^2$	4.0 ± 0.4	3.0 ± 0.3	4.0 ± 0.4	6.4 ± 0.6
$N_{exp}(\pi\nu\nu)$	0.27 ± 0.04	2.16 ± 0.13	1.56 ± 0.10	6.02 ± 0.39
$N_{exp}(bkg)$	$0.15^{+0.093}_{-0.035}$	1.46 ± 0.33	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
$N_{observed}$	1	2	2	15

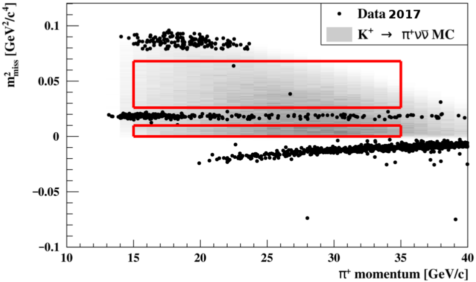
$$\mathcal{B}^{NA62}_{16+17+18}(K^+ \to \pi^+ \nu \bar{\nu}) = (\mathbf{1.06^{+0.40}_{-0.34}}|_{stat} \pm \mathbf{0.09}_{syst}) \times \mathbf{10^{-10}} @ \ 68\% \ \text{CL}$$

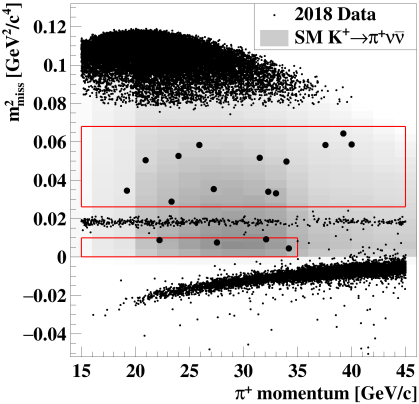


[NA62 Collab., JHEP06(2021)093]

$K^+ \to \pi^+\nu\bar{\nu}$ at NA62: results





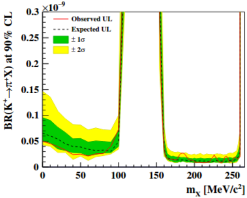


[NA62 Collab.,Phys.Lett.B791, 156(2019)],
[NA62 Collab.,JHEP11(2020)042],
[NA62 Collab.,JHEP06(2021)093]

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

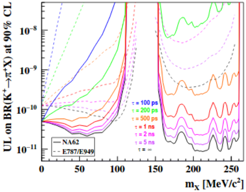
Interpretation of $K^+ \to \pi^+ \nu\overline{\nu}$ result in terms of $K^+ \to \pi^+ X$, $X \to$ *invis*.

- X is a scalar or pseudo-scalar particle
- Same signature as $K^+ \to \pi^+ \nu\overline{\nu}$
- Two body decay $\Rightarrow$ peak in m^2_{miss} spectrum at m^2_X



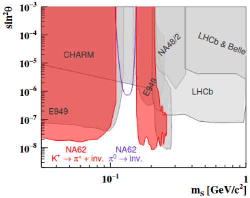
Peak search:

- Using sample selected in $K^+ \to \pi^+ \nu\overline{\nu}$ measurement
- Peak search with fully frequentist hypothesis testing via shape analysis of m^2_{miss} distribution
- Dominant background is $K^+ \to \pi^+ \nu\overline{\nu}$



Results evaluated for [NA62 Collab., JHEP06(2021)093]:

- stable or invisibly decaying particle X (top)
- X decaying to visible SM particles (center)
  - Exclusion limits in BC4 model [Beacham et al., J.Phys.G 47, 010501 (2020)] with X = dark scalar mixing with Higgs boson (bottom)



Prospects for Run 2

Goal: $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})$ measurement with $\mathcal{O}(10\%)$ precision

- **Data-taking re-started in July 2021**
- Expected to run at full intensity until LS3

Focus on:

- Analysis optimization for full intensity
- Upstream background reduction
  - optimized beam achromat
  - additional beam spectrometer station
  - new veto counter
- Reduction of background from kaon decays
  - new calorimeter on the side of beam pipe

Conclusions

Complete result from Run 1 (2016+2017+2018):

- Observed events: 20
- Expected background: ~ 7
- $\mathcal{B}(K^+ \to \pi^+ \nu \overline{\nu}) = (1.06^{+0.40}_{-0.34}|_{stat} \pm 0.09_{syst}) \times 10^{-10}$ **@ 68% CL**

$\Rightarrow$ **most precise measurement so far**

$\Rightarrow$ **3.4σ significance**

$\Rightarrow$ **looking forward to NA62 Run 2 data**