Recent results from the NA62 Experiment

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Main goal of the NA62 experiment:

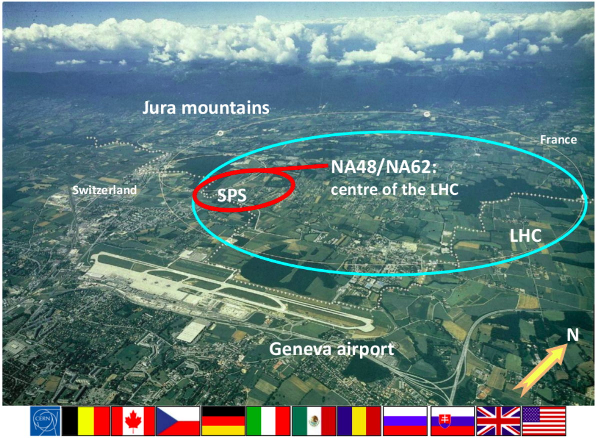
- Measurement of the Branching fraction of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay

Precision measurements:

- $K^+ \to e^+ \nu\gamma$ (SD$^+$)
- $K^+ \to \pi^+ \ell^+ \ell^-$ - Lepton Universality test
- $K^+ \to \pi^+ \pi^+ \pi^- \gamma$
- $K^+ \to \mu^+ \nu \mu^+ \mu^-$

BSM searches in the kaon mode:

- Search for Heavy Neutral Leptons in $K^+ \to e^+ N$, $K^+ \to \mu^+ N$, $\pi^+ \to e^+ N$ decays
- LFV, LNV studies in $K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \mu^- \nu e^+ e^+$ and $K^+ \to \pi^0 \pi \mu e$ decays



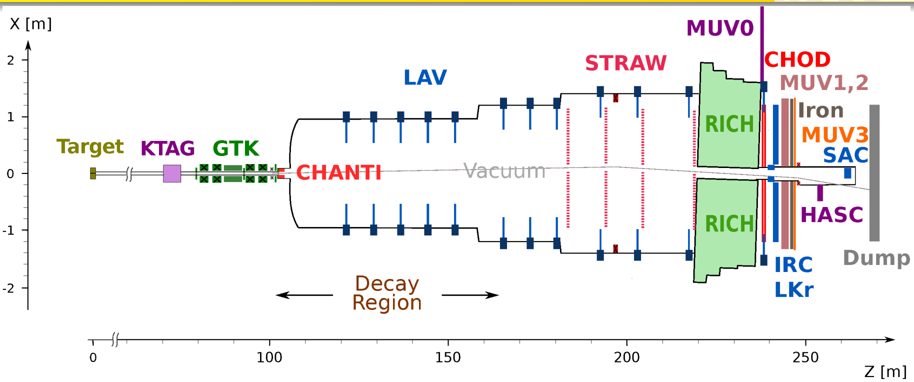
Kaon decay in flight experiments.

NA62: ~**300** 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	
NA48/2	2003: K^+/K^-	
	2004: K^+/K^-	
NA62 (R_K phase)	2007: $K^\pm_{e2}/K^\pm_{\mu2}$	tests
	2008: $K^\pm_{e2}/K^\pm_{\mu2}$	tests
NA62	2014: pilot run	
	2015: commissioning run	
	2016 – 18 : $K^+ \to \pi^+ \nu\nu$ run	
	2021 – 26: $K^+ \to \pi^+ \nu\nu$ run	

NA62 Detector layout



SPS Beam:

- 400 GeV/c protons
- 1.9×10^{12} p/spill
- 3.5 s spill
- $\sim 10^{18}$ POT/year

Secondary beam:

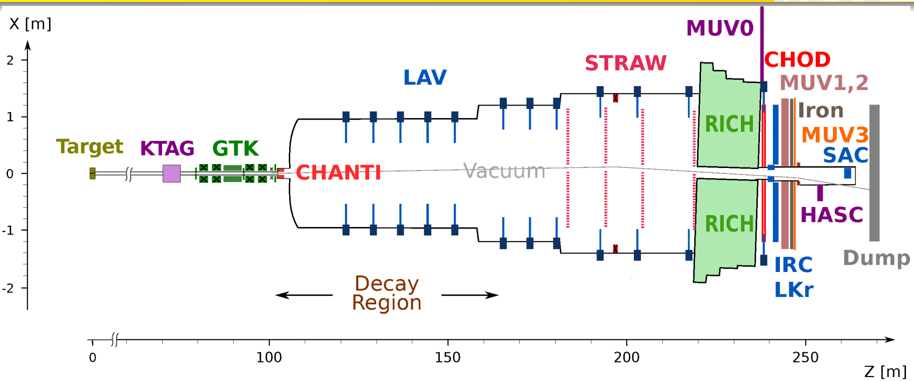
- 75 GeV/c momentum, 1% RMS
- 100 μrad divergence (RMS)
- $60 \times 30\ \mathrm{mm}^2$ transverse size
- $K^+(6\%)/\pi^+(70\%)/p(24\%)$
- 450 MHz of particles at GTK3

Decay Region

- 60 m long fiducial region
- ~ 3 MHz K^+ decay rate
- Vacuum $\mathcal{O}(10^{-6})$ mbar

[The NA62 Collaboration, JINST 12 (2017) P05025]

NA62 Detector layout



Upstream detectors (K^+)

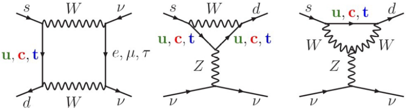
- **KTAG:** differential Cherenkov counter for K^+ ID
- **GTK:** Si pixel beam tracker
- **CHANTI:** Anti-counter for inelastic beam-GTK3 interactions

[The NA62 Collaboration, JINST 12 (2017) P05025]

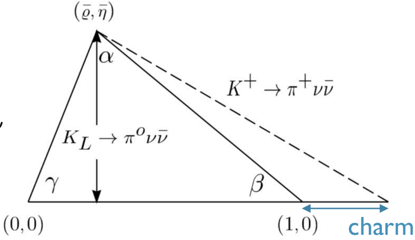
Downstream detectors (π^+)

- **STRAW:** track momentum spectrometer
- **CHOD:** scintillator hodoscopes
- **LKr/MUV1/MUV2:** Calorimeters
- **RICH:** Cherenkov counter for $\pi/\mu/e$ ID
- **LAV/SAC/IRC:** Photon veto detectors
- **MUV3:** Muon detector

- **FCNC loop process**
  - **s $\to$ d coupling** and highest CKM suppression (BR$\sim |V_{ts} \times V_{td}|^2$)



- **Very clean theoretically**
  - Short distance contribution and no hadronic uncertainties
  - Hadronic matrix element extracted from well-known decay $K^+ \to \pi^0 e^+ \nu$
  - Theoretical error budget dominated by CKM parameters



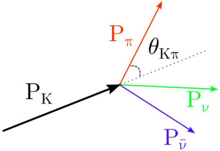
- **SM predictions**

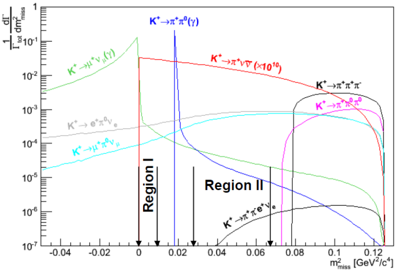
	[Buras et al. EPJC 82 (2022) 7, 615]	[D'Ambrosino et al. JHEP 09 (2022) 148]
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) =$	$(8.60 \pm 0.42) \cdot 10^{-11}$	$(7.86 \pm 0.61) \cdot 10^{-11}$
$\mathcal{B}(K^0_L \to \pi^0 \nu\bar{\nu}) =$	$(2.94 \pm 0.15) \cdot 10^{-11}$	$(2.68 \pm 0.30) \cdot 10^{-11}$

$K^+ \to \pi^+ \nu \bar{\nu}$: Analysis strategy

Kaon decays in flight

- **Signal:** Time and space $K^+ - \pi^+$ matching
- **Regions defined by:** $m^2_{miss} = (P_K - P_\pi)^2$
- The analysis is mostly cut based
- **Blind analysis:** Signal and background ctrl regions are kept blind throughout the analysis





Main background sources

Decay mode	BR	Main rejection tools
$K^+ \to \mu^+ \nu (\gamma)$	63%	$\mu-$ID + kinematics
$K^+ \to \pi^+ \pi^0 (\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+ \pi^+ \pi^-$	6%	multi + kinematics
$K^+ \to \pi^+ \pi^0 \pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+ \nu_e$	5%	$e-$ID + γ-veto
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3%	$\mu-$ID + γ-veto

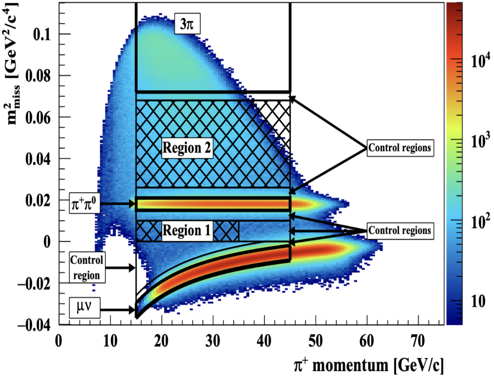
Requirements

- $\mathcal{O}(100)$ ps timing between sub-detectors
- $\mathcal{O}(10^4)$ background suppression with kinematics
- $\mathcal{O}(10^7)$ μ-suppression ($K^+ \to \mu^+ \nu$)
- $> (10^7)$ π^0-suppression ($K^+ \to \pi^+ \pi^0$,$\pi^0 \to \gamma\gamma$)

Signal regions

- Three different ways to calculate m_{miss} to avoid mis-reconstruction:
  - $m^2_{miss} = (STRAW,\ GTK)$
  - $m^2_{miss} = (RICH,\ GTK)$
  - $m^2_{miss} = (STRAW,\ Beam)$

[JHEP 06 (2021) 093]

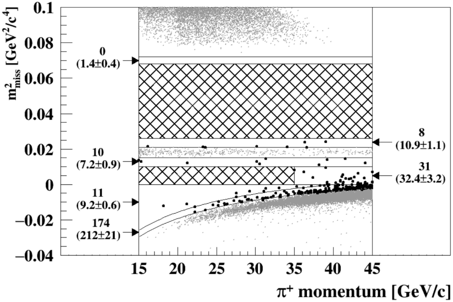


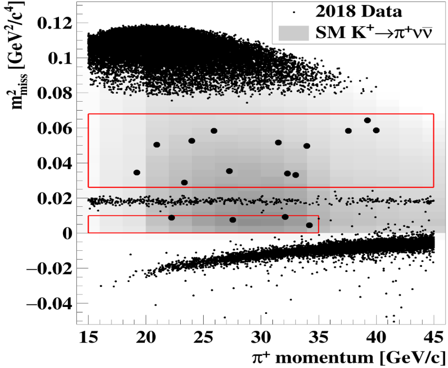
Selection

- Single track in final state topology matched with upstream K^+
- π^+ identification
- Photon rejection
- Multi-track rejection
- $105 < Z_{vertex} < 165$ m
- $15 < P_{\pi^+} < 35$ GeV$/c$ in R1
  $15 < P_{\pi^+} < 45$ GeV$/c$ in R2
  (best μ/π discrimination in RICH & to leave at least 30 GeV of E_{miss})

Performance

- $\varepsilon(\mu) = 1.3(2) \cdot 10^{-8}$ (73% π^+ efficiency)
- $\varepsilon(\pi^0) = (1.72 \pm 0.07) \cdot 10^{-8}$
- $\sigma(m_{miss}) = 1 \cdot 10^{-3}$ GeV$^2/c^4$
- $\sigma(t) \sim \mathcal{O}(100)$ ps



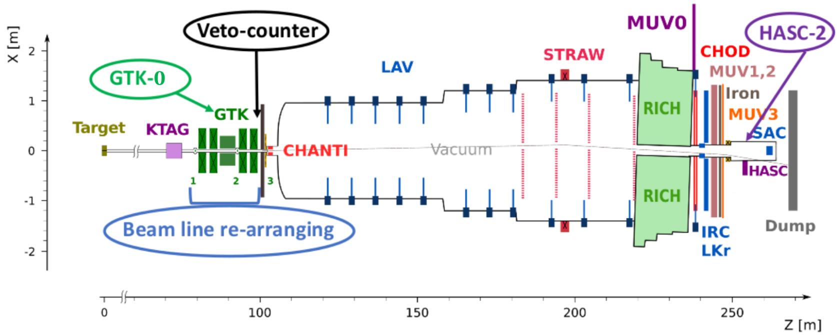


Validation: Observed (expected) events in control regions in bins of π^+ momentum.

Data sample	2016	2017	2018	2016-18
Expected SM signal	0.267 ± 0.02	2.16 ± 0.13	7.58 ± 0.40	10.01 ± 0.42
Expected background	$0.152^{+0.093}_{-0.035}$	1.46 ± 0.33	$5.42^{+0.99}_{-0.75}$	$7.03^{+1.05}_{-0.82}$
Observed events	1	2	17	20
	[PLB 791 (2019) 156-166]	[JHEP 11 (2020) 042]	[JHEP 06 (2021) 093]	

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$ **(3.4σ significance)**

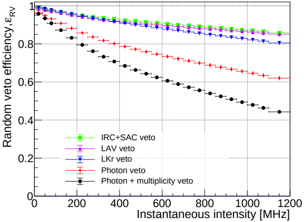
Run2 upgrade and Single Event Sensitivity (S.E.S.)

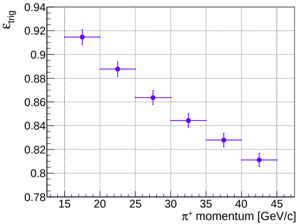


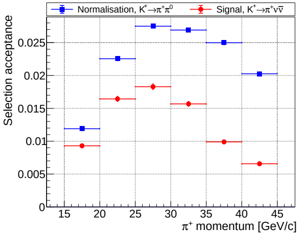
$$N^{exp}_{\pi\nu\nu} \approx N_{\pi^+\pi^0} \cdot \varepsilon_{RV} \cdot \varepsilon_{trigger} \cdot \frac{A_{\pi\nu\nu}}{A_{\pi^+\pi^0}} \cdot \frac{\mathcal{B}(\pi\nu\nu)}{\mathcal{B}(\pi^+\pi^0)} \quad \Rightarrow \quad S.E.S. = \frac{\mathcal{B}(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}}$$

- Normalization channel: $K^+ \to \pi^+\pi^0$
- ε_{RV} - Random Veto - efficiency loss due to accidental activity
- Ratio of $\pi\nu\nu$ and $\pi^+\pi^0$ acceptances allows cancellation of systematic effects
- Computation in bins of π^+ momentum and instantaneous beam intensity

2021+22 Single Event Sensitivity (S.E.S.)



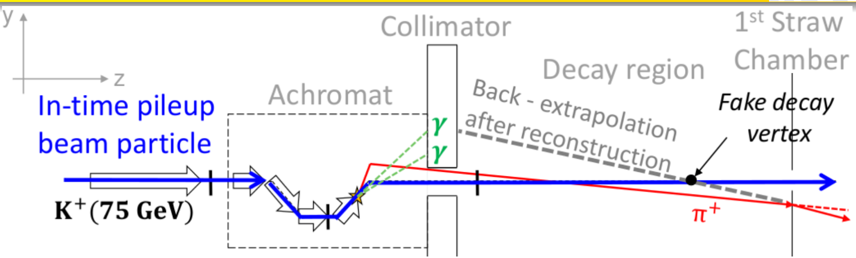




$$N^{exp}_{\pi\nu\nu} \approx N_{\pi^+\pi^0} \cdot \varepsilon_{RV} \cdot \varepsilon_{trigger} \cdot \frac{A_{\pi\nu\nu}}{A_{\pi^+\pi^0}} \cdot \frac{\mathcal{B}(\pi\nu\nu)}{\mathcal{B}(\pi^+\pi^0)} \quad \Rightarrow \quad S.E.S. = \frac{\mathcal{B}(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}}$$

- $S.E.S. = (0.85\pm0.03)\times10^{-11} \xrightarrow{B^{SM}_{\pi\nu\bar{\nu}}=8.4\times10^{-11}} N^{SM}_{\pi\nu\bar{\nu}} = 9.91\pm0.34$
- $N^{SM}_{\pi\nu\bar{\nu}}$ per SPS spill: 2.5×10^{-5} in 2022
  - Was 1.7×10^{-5} in 2018 $\rightarrow$ signal yield increased by 50%
- Sensitivity for $\mathcal{B} \sim \sqrt{S+B/S} = 0.5$
  - Similar but improved with respect to 2018 analysis for same amount of data

$K^+ \to \pi^+ \nu \bar{\nu}$: 2021+22 Backgrounds

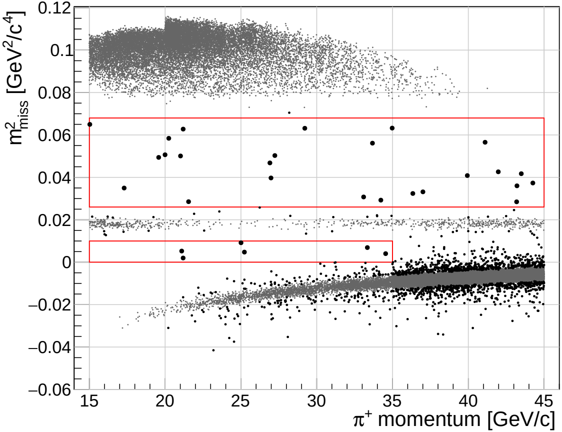


Upstream background:

- Kaon decays upstream so that only a pion enters the decay region
- In-time pileup beam particle present (tagged in KTAG and GTK)
- Upstream pion enters the decay region and scatters in the first STRAW chamber

Background type	$N_{background}$
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \pi^+\pi^- e^+\nu$	$0.89^{+0.34}_{-0.28}$
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
$K^+ \to \pi^0\ell^+\nu$	< 0.001
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.1^{+2.1}_{-1.9}$

2021+2022 Data set



Expected signal:

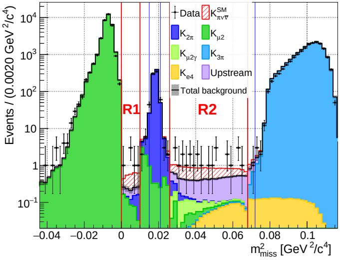
$$N^{SM}_{\pi\nu\bar{\nu}} = 9.91 \pm 0.34$$

Expected background:

$$N_{Bkg} = 11.1^{+2.1}_{-1.9}$$

Observed events: **31**

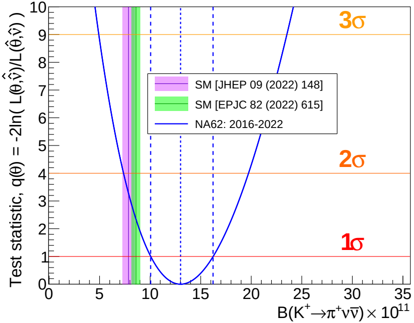
1D projection with differential background predictions & SM signal expectation [not a fit]:

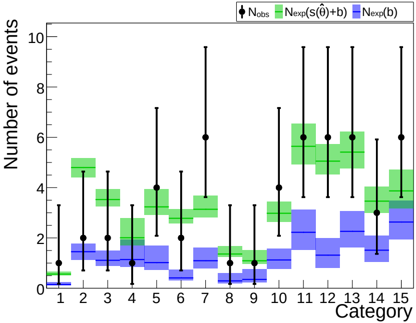


Combining NA62 results: 2016—22

- Integrating 2016—22 data: $N_{Bkg} = 18^{+3}_{-2}$, $N_{observed} = 51$
- **Background-only hypothesis** p–value $= 2 \times 10^{-7}$

  $\Rightarrow$ **significance** $Z > 5$

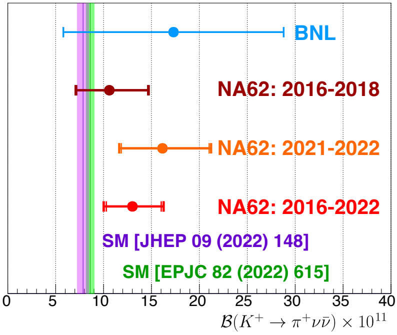


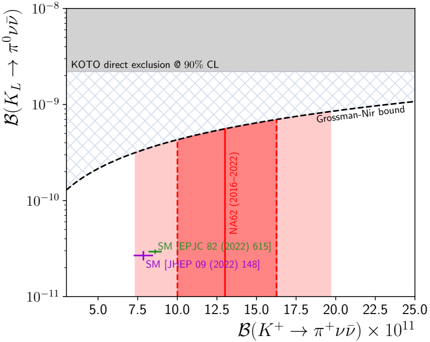


$$\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11} = (13.0(^{+3.0}_{-2.7})_{stat}[^{+1.3}_{-1.3}]_{syst}) \times 10^{-11}$$

[JHEP 02 (2025) 191]

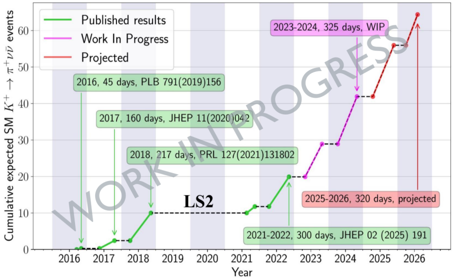
Results in context





- NA62 results consistent; fractional uncertainty reduced from 40% to 25%
- Central value moved up (now $1.5 - 1.7\sigma$ above SM)
- Bkg-only hypothesis rejected with significance $Z > 5$
- Observation of the decay with BR consistent with the SM, within 1.7σ
- Need full NA62 data-set to clarify SM agreement or tension

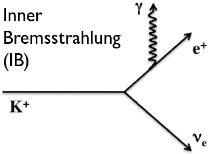
Prospects and Plans

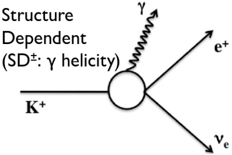


- Optimal intensity set (using 2021–23 data)
- Higher signal yield and efficiency
- Full sample by end of 2026
- $\sim 3\times$ current published results
- BR uncertainty target $< 20\%$ (stat + analysis improvements)
- Study kinematic distributions (shapes)

- 2021: $\sim 1/4$ of spill removed due to spike in intensity at start of spill (DQ degraded)
- WIP prospects for 2023–24 from 2025 SPSC report – analysis as for published 2021–22 result.
- 2025–26 are PROJECTIONS assuming $N_{\pi\nu\bar{\nu}}$/day is the same as for 2024.

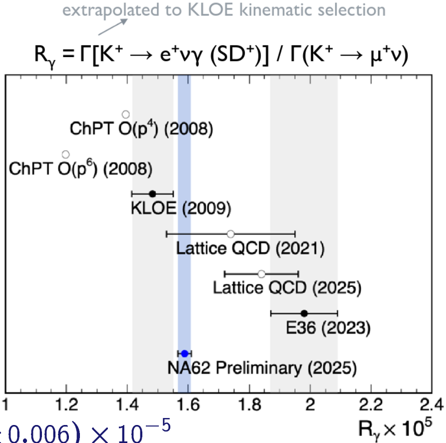
Dataset	2022	2023	2024
Number of spills $[10^3]$	326	363	519
$<$ Beam intensity $>$ [GHz]	0.57	0.48	0.41
$< N_{\pi\pi}/\text{spill} >$ $[10^2]$	4.9	4.7	4.4
N_K $[10^{12}]$	2.3	2.5	3.3
ε_{RV}	0.63	0.68	0.73
$N_{\pi\nu\nu}$	8	9	13
$N_{\pi\nu\nu}/\text{spill}$ $[10^{-5}]$	2.5	2.5	2.6
$B_{\text{total}}/N_{\pi\nu\nu}$	1.1	1.1	1.0





- Dataset: 2017–2018
- Normalization: $K^+ \to e^+\nu\pi^0$
- Backgrounds: $K^+ \to e^+\nu\pi^0$, $K^+ \to e^+\nu\gamma(SD^-)$, $K^+ \to e^+\nu$, $K^+ \to \pi^+\pi^0$
- Kinematic selection: $X = \frac{2E_e^*}{m_K} > 0.2$, $Y = \frac{2E_\gamma^*}{m_K} > 0.93$ (where SD^+ dominates)
- 3.5× improvement in statistical uncertainty

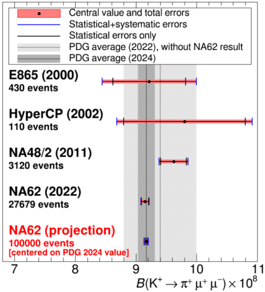
- $B/S \sim 0.4\%$ contributes little to total uncertainty
- R_γ precision improved 10× w.r.t. PDG average

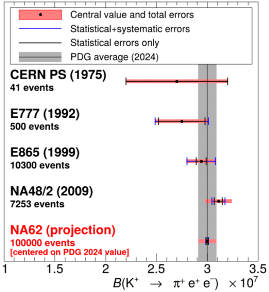


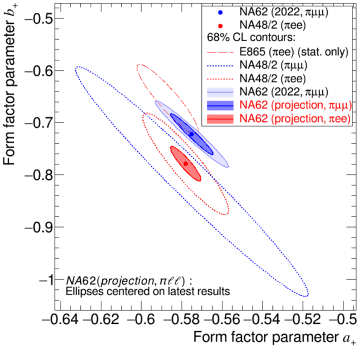
$$\mathcal{B}(K^+ \to e^+\nu\gamma(\mathrm{SD}^+)) = (0.466 \pm 0.006) \times 10^{-5}$$

$K^+ \to \pi^+ \ell^+ \ell^-$ - Final Dataset Projections

Expect $>$100k events per channel,
with negligible background
and $\sim$0.3% systematic uncertainty





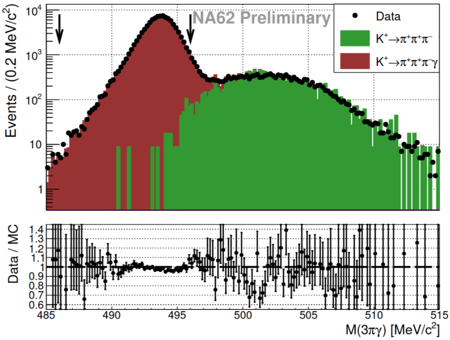


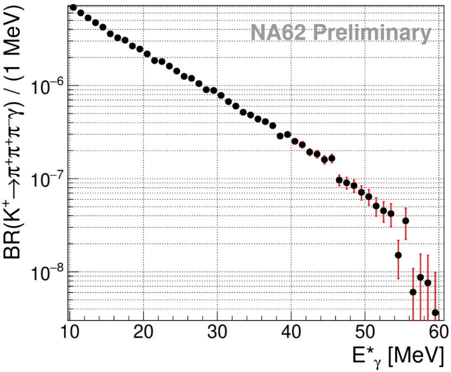
JHEP11 (2022) 011

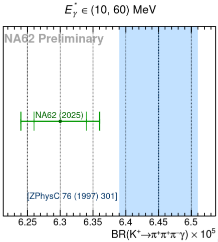
Total (a_+, b_+) errors
expected to improve by
$\sim 1.5\times$ for $\pi\mu\mu$ and
$\sim 3\times$ for πee with respect
to current best results

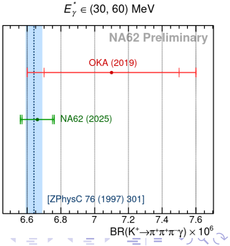
$$\frac{d\Gamma}{dz} \propto G_F M_K^2 \,(a + bz) + W_{\pi\pi}(z), \;\; z = \frac{m^2_{\ell^+\ell^-}}{M_K^2}$$

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



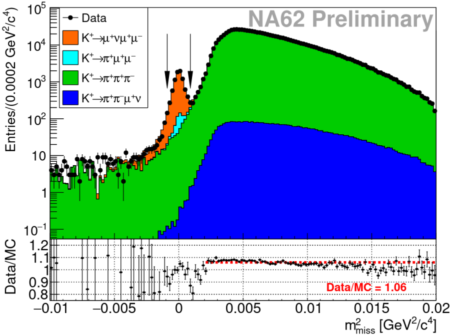






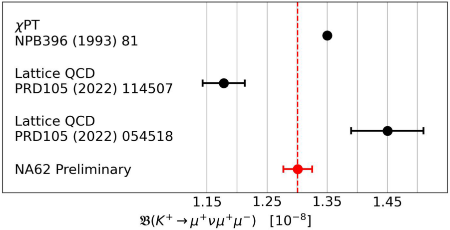
- Dataset 2017-18
- Normalization channel: $K^+ \to \pi^+\pi^+\pi^-$
- First measurement in $10 < E^*_\gamma/MeV < 30$
- Bkg $< 0.2\%$ for $E^*_\gamma > 10$ MeV
- Good agreement with OKA and with theory

$K^+ \to \mu^+ \nu \mu^+ \mu^-$



- Dataset 2017-24 ($N_K = 1.4 \times 10^{13}$)
- Normalization channel: $K^+ \to \pi^+ \mu^+ \mu^-$
- Signal data candidates: 8227
- Background contamination: $892 \pm 11_{stat} \pm 54_{syst}$
- Bkg mechanisms: π decay in flight, mis-ID

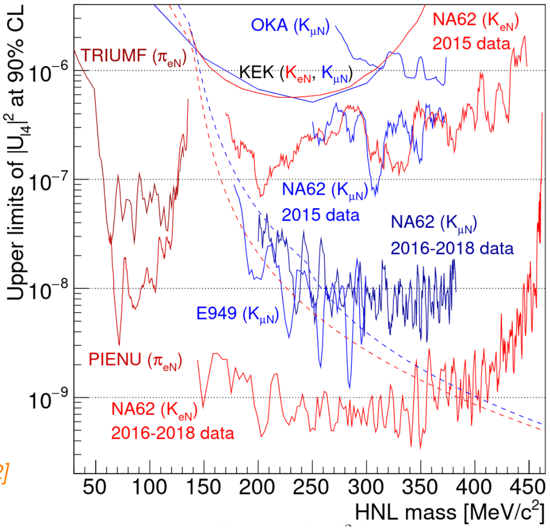
- First observation of last missing $K^+ \to \ell^+ \nu \ell^+ \ell^-$ decay
- Spectrum agrees with $\mathcal{O}(p^6)$ χPT prediction
- Potential analysis extension: search for a promptly-decaying BSM vector/scalar particle X: $K^+ \to \mu^+ \nu X$; $(X \to \mu^+ \mu^-)$



$$\mathcal{B}(K^+ \to \mu^+ \nu \mu^+ \mu^-) = (1.301 \pm 0.024) \times 10^{-8}$$

Results of HNL search

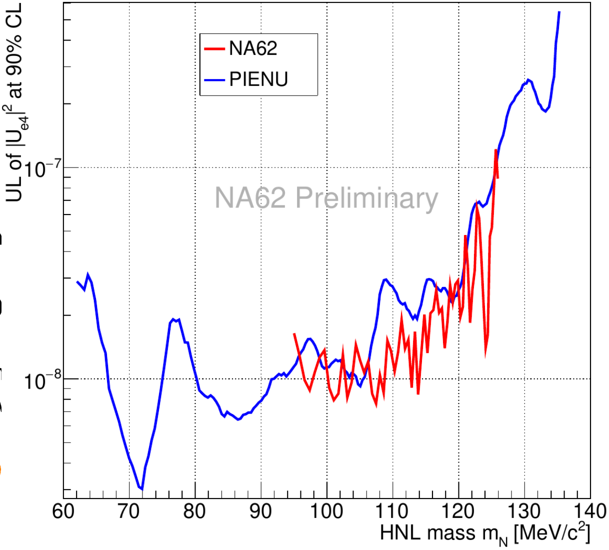
- Improvement over earlier production searches by up to two orders of magnitude in terms of $|U_{\ell 4}|^2$.
- For $|U_{e4}|^2$, the BBN-allowed range excluded up to 350 MeV. *[NPB 590 (2000) 562]*
- For $|U_{\mu 4}|^2$, reached BNL-E949 sensitivity, and extended the HNL mass range to 384 MeV.
- New upper limit at 90% CL: $\mathcal{B}(K^+ \to \mu^+ \nu\nu\nu) < 1.0 \times 10^{-6}$. Similar limits on $\mathcal{B}(K^+ \to \mu^+ \nu X)$, with $X =$ invisible. *[Theory: PRL 124 (2020) 041802]*
- Full Run 1 data set.



[Phys. Lett. B 816 (2021) 136259]

Results of HNL search

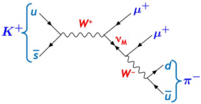
- Improvement over earl ... le in terms of $|U_{\ell 4}|^2$.
- For $|U_{e4}|^2$, the BBN-allowed range excluded up to 350 M
  [NPB 590 (2000) 562]
- For $|U_{\mu 4}|^2$, reached BNL-E949 sensitivity, extended the HNL ma range to 384 MeV.
- New upper limit at 90 CL: $\mathcal{B}(K^+ \to \mu^+ \nu\nu\nu)$ 1.0×10^{-6}. Similar lin on $\mathcal{B}(K^+ \to \mu^+ \nu X)$, \ $X =$ invisible.
  [Theory: PRL 124 (2020)
- Full Run 1 data set.



NP searches in kaon decays

- Search for Majorana neutrinos in LNV $K^+ \to \pi^- \ell^+ \ell^+$ decays

  [Asaka-Shaposhnikov model (νMSM) [PLB 620 (2005) 17]]



  - DM + Baryon Asymmetry + low mass of SM ν
    can be explained by adding three sterile Majorana neutrinos to the SM
  - Searches for LNV in 3-track decays:
    - LNV decays improving over PDG limits:

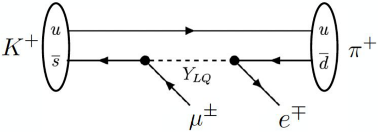
      $\mathcal{B}(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ @90% CL *[PLB 830 (2022) 137172]*

      $\mathcal{B}(K^+ \to \pi^- \pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ @90% CL

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

      $\mathcal{B}(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11}$ @90% CL *[PLB 838 (2023) 137679]*

- Search for LNV/LFV in $K^+ \to \pi \mu e$, $K^+ \to \pi^0 \pi \mu e$ decays
  - Experimental signature:
    3 charged tracks with $\pi^\pm \mu^\mp e^+$
  - BR measured relative to normalization channel $K^+ \to \pi^+ \pi^+ \pi^-$



$\mathcal{B}(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11}$

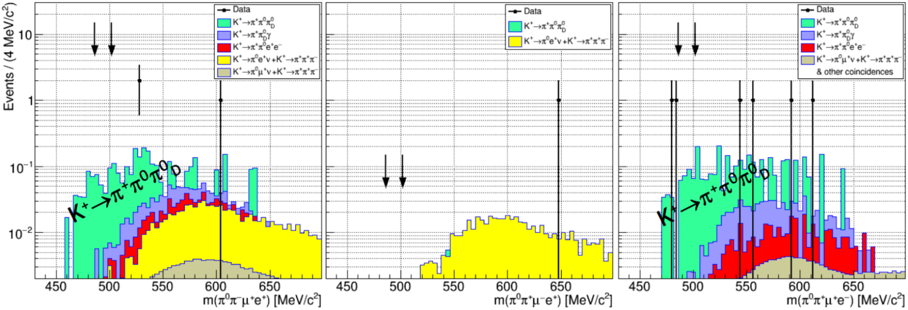
$\mathcal{B}(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11}$

$\mathcal{B}(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10}$ *[PRL 127 (2021) 131802]*

1 order of magnitude improvements compared to previous searches.
Upper limits at 90% CL.

$K^+ \to \pi^0 \pi \mu e$

$K^+ \to \pi^0 \pi^- \mu^+ e^+$ $\quad$ $K^+ \to \pi^0 \pi^+ \mu^- e^+$ $\quad$ $K^+ \to \pi^0 \pi^+ \mu^+ e^-$



Decay mode	Expected bkg	Observed	UL of BR at 90% CL
$K^+ \to \pi^0 \pi^- \mu^+ e^+$	0.33 ± 0.07	0	2.9×10^{-10}
$K^+ \to \pi^0 \pi^+ \mu^- e^+$	0.004 ± 0.003	0	3.1×10^{-10}
$K^+ \to \pi^0 \pi^+ \mu^+ e^-$	0.29 ± 0.07	0	5.0×10^{-10}

[PLB859 (2024) 139122]

Conclusion

- First observation of $K^+ \to \pi^+ \nu\bar{\nu}$ decay:

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11} = (13.0(^{+3.0}_{-2.7})_{stat}[^{+1.3}_{-1.3}]_{syst}) \times 10^{-11}$$

  - The smallest BR ever measured at 5σ signal significance [JHEP 02 (2025) 191]
  - Expect $< 20\%$ precision with the final 2016 – 2026 dataset
- First observation of $K^+ \to \mu^+ \nu \mu^+ \mu^-$:

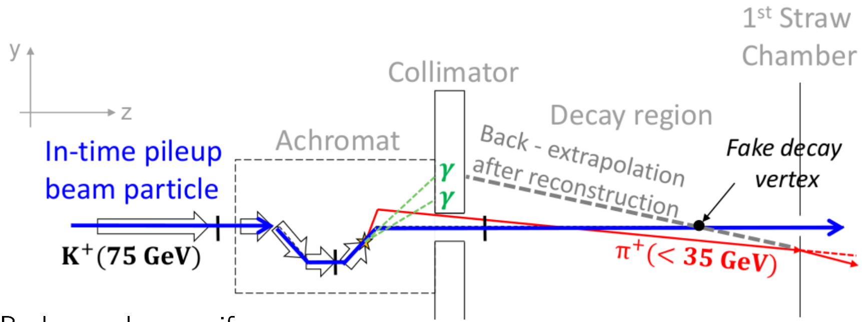
$$\mathcal{B}(K^+ \to \mu^+ \nu \mu^+ \mu^-) = (1.301 \pm 0.024) \times 10^{-8}$$

- $K^+ \to e^+ \nu \gamma$ and $K^+ \to \pi^+ \pi^+ \pi^- \gamma$ studied with unprecedented precision
- BSM physics in kaon decays:
  - Searches for $K^+ \to \ell^+ N$, $K^+ \to \mu^+ \nu X$ and $\pi^+ \to e^+ N$ decays [PLB 816 (2021) 136259]
  - LFV/LNV searches in $K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \mu^- \nu e^+ e^+$ & $K^+ \to \pi^0 \pi \mu e$ decays [PLB 830 (2022) 137172], [PLB 797 (2019) 134794] [PLB 838 (2023) 137679], [PRL 127 (2021) 131802]
- The full 2016 – 2026 dataset will allow for stringent tests of the SM

Stay tuned!

Spares

Upstream background



Background source if:

- a kaon decays upstream, and only a pion enters in the decay region;
- there is an in-time pileup beam particle (in KTAG and GTK);
- the upstream generated pion enters in the decay region and is scattered in the first STRAW chamber.

In 2018 collimator was replaced to remove early decays mechanism and data are split in subsets S1/S2 (Old/New collimator, ∼ 20%/80% of 2018 data). It allows to relax some cuts for S2, while keeping the S/B ratio same as for S1.

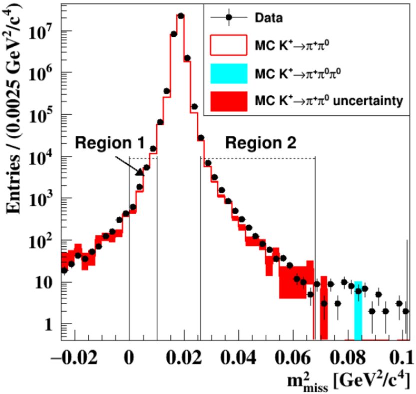
Background from kaon decays

Data in *bkg* region after $\pi\nu\nu$ selection:γ-rejection applied

$$N^{exp}_{bkg}(region) = N(bkg) \cdot f^{kin}(region); \quad bkg = \pi^+\pi^0 \text{ or } \mu^+\nu$$

Expected *bkg* in signal regions after $\pi\nu\nu$ selection

Fraction of *bkg* in signal region measured on control data



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