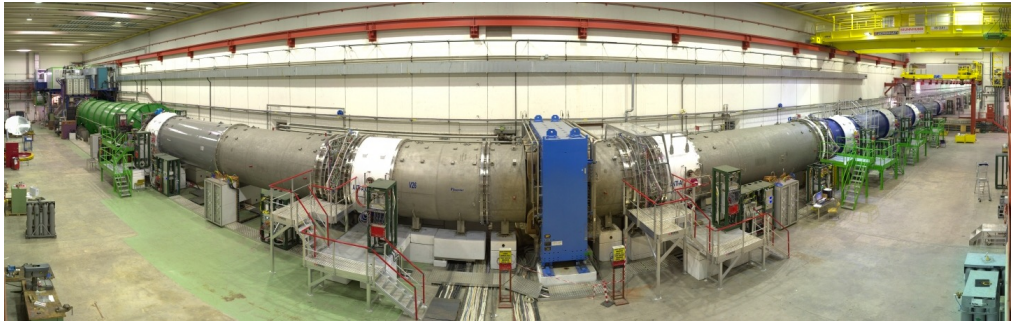

Searches for LF/LN violation and hidden sectors in kaon decays at the NA62 experiment

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SUSY 2024 - Theory meets experiments

The 31st International Conference on Supersymmetry and Unification of Fundamental Interactions

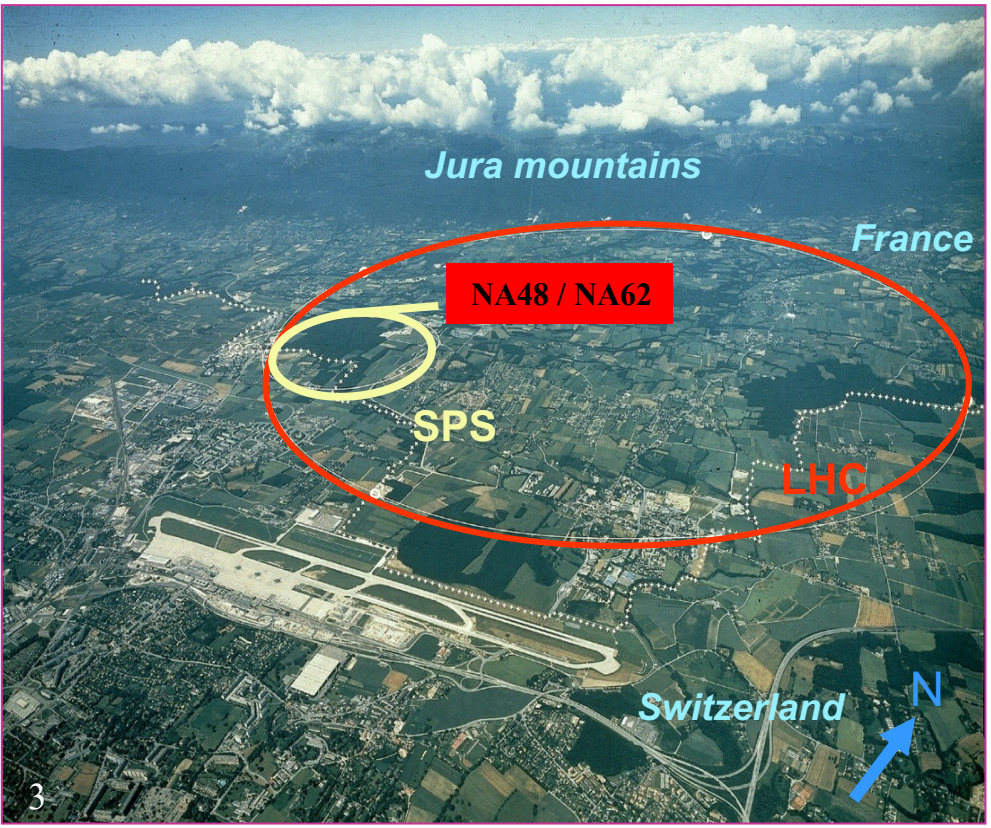
Madrid (IFT) 10-14 June 2024

* On behalf of the NA62 Collaborations

★ The NA62 experiment at the CERN kaon beam facility

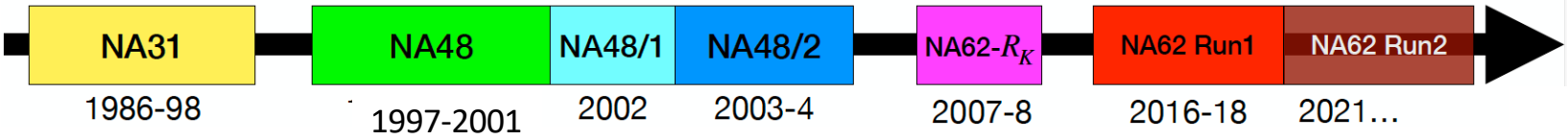
The NA62 experiment at CERN

A fixed target experiment at the CERN SPS dedicated to the study of rare decays in the kaon sector.



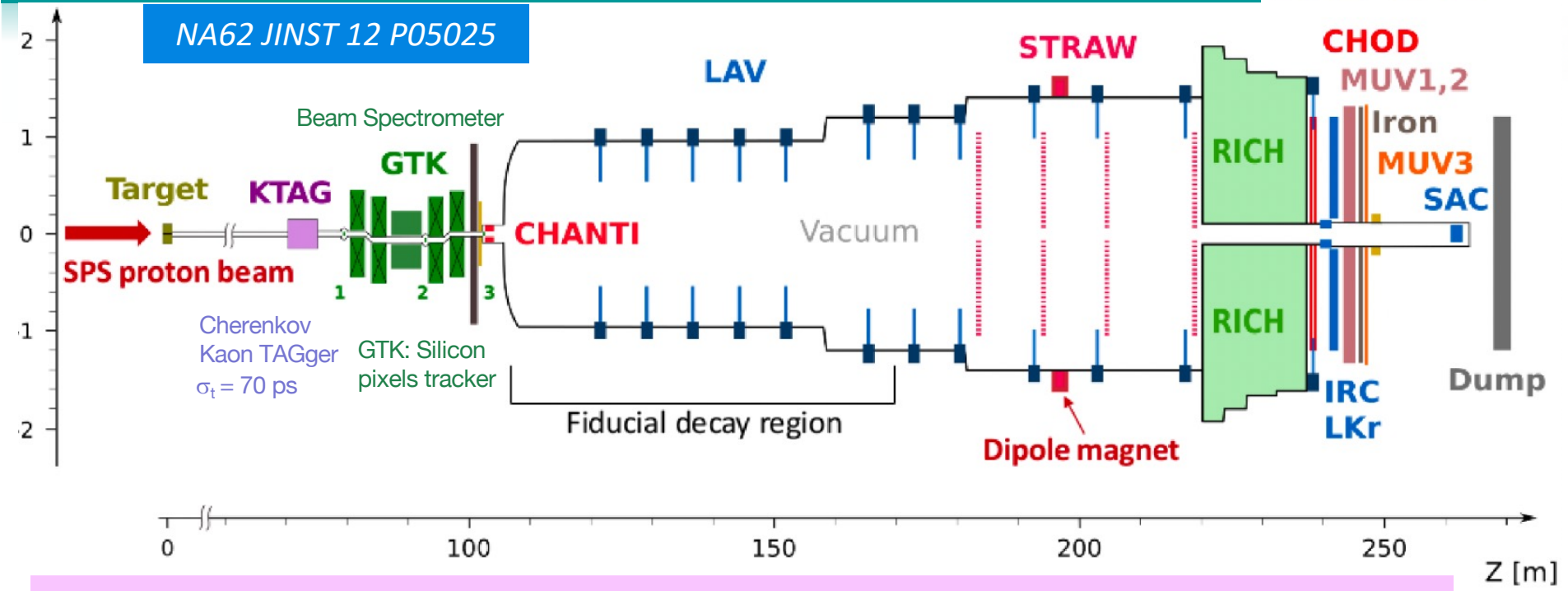
- Detector installation completed in 2016
- Physics runs in 2016, 2017 and 2018
- Data taking resumed in July 2021, approved up to CERN Long-Shutdown-3…
- Main goal: BR($K^+ \to \pi^+ \nu\bar{\nu}$) measurement
- Broad physics program thanks to unprecedented statistics for many decay modes

~300 physicists from 31 institutes in 11 countries



The NA62 kaon beam

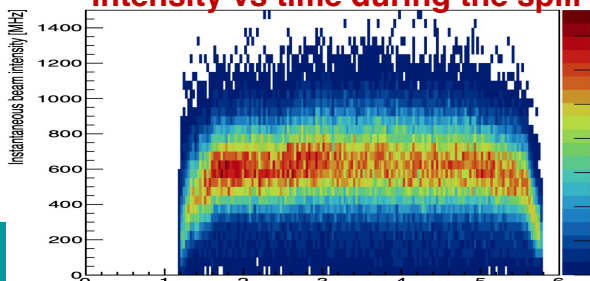
NA62 JINST 12 P05025



- SPS beam: 400 GeV/c proton on beryllium target, 3 10^{12} /spilL
- 75 ± 1 GeV/c unseparated secondary hadron beam (70% pions, 24% protons, 6% kaons)
- **Decay in-flight technique**: the high energy kaons decay in a ~60 m fiducial region
- Beam rate: 600 MHz; K^+ rate ~ 35 MHz; 4 MHZ K^+ decays in the fiducial volume

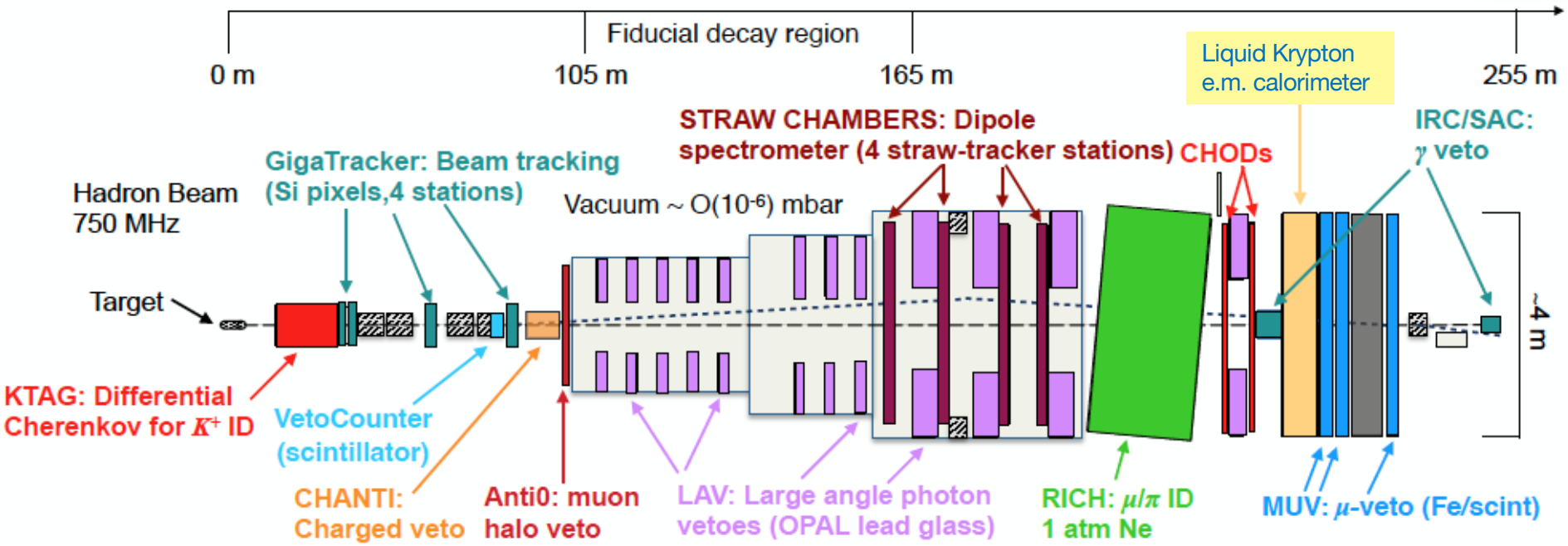
- ✓ One year ~ 2 10^{18} protons on target ~ 5 10^{12} K^+ decays
- ✓ Beam structure: ideally, uniform over a 4.8 s long spill
- ✓ In practice, significant variations of instantaneous beam intensity during the spill

Intensity vs time during the spill



The NA62 detector

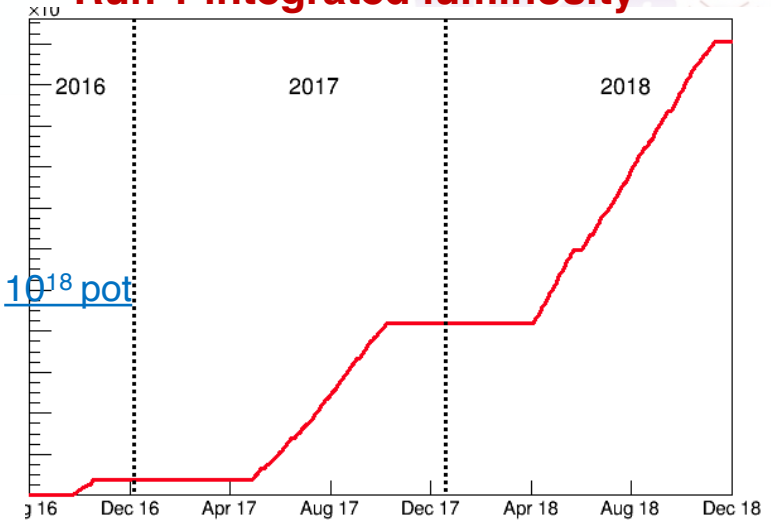
JINST 12 (2017) 05, P05025



- Beam Si pixel spectrometer (**GTK**)
- Decay products magnetic spectrometer (**STRAW**)
- Particle identification system (**KTAG, RICH, MUVs**)
- **LKr**: electromagnetic calorimeter
- Veto system (**LAV, iRC, SAC, CHANTI, MUV, HASC**)
- CHOD: scintillator hodoscopes
- Multi level (**L0, L1, L2**) trigger

NA62 datasets

Run 1 integrated luminosity



- Run 1 (2016–18): $N_K \sim 10^{13}$ useful K^+ decays with the main trigger
  - Sample 2016 (30 days, ~ 1.3×10^{12} ppp): 2×10^{11} useful K^+ decays
  - Sample 2017 (160 days, ~1.9×10^{12} ppp): 2×10^{12} useful K+ decays
  - Sample 2018 (217 days, ~2.3×10^{12} ppp): 4×10^{12} useful K+ decays
- Run 2 (2021–…): in progress (up to 3×10^{12} ppp), approved till 2025

- Currently: ~ $2\ 10^{18}$ pot/year, ~ $5\ 10^{12}$ K^+ decays/year
- Beam-dump mode: ~ $4\ 10^{17}$ pot collected so far

Precision measurement
Search for new physics with precision measurement to test the Standard Model.

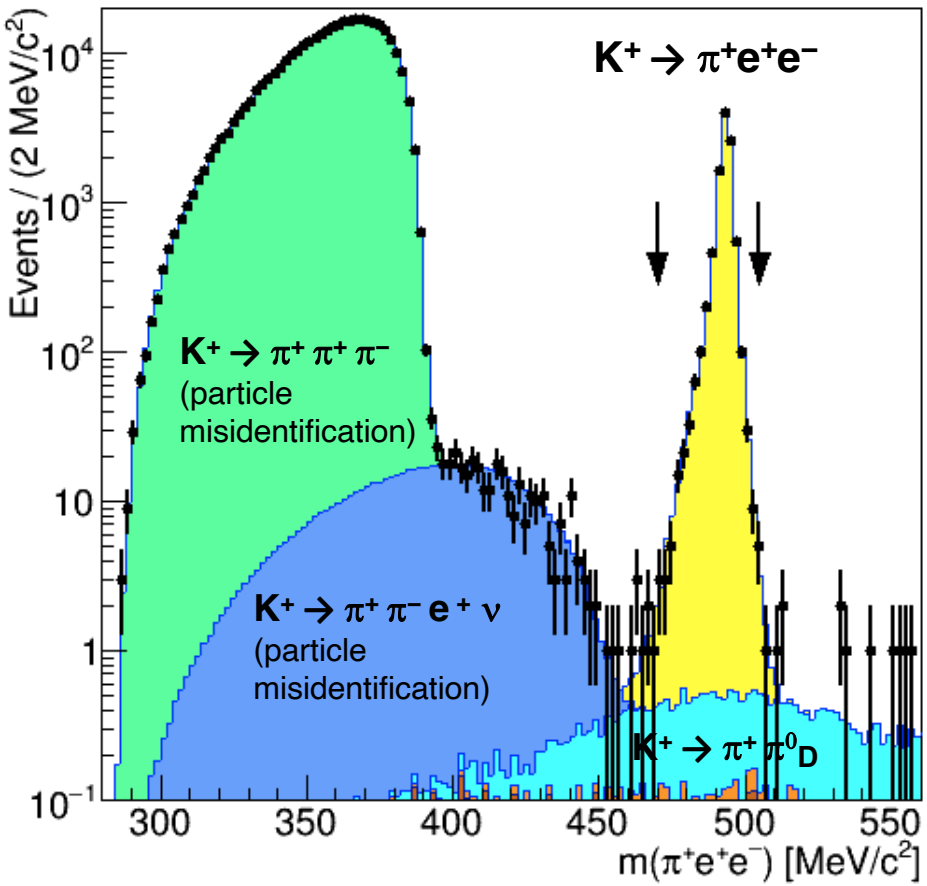
Flavor Physics
Search for lepton flavor & lepton number violation, rare & forbidden decays.

Dump mode: Hidden sector Physics
Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long –lived particles.

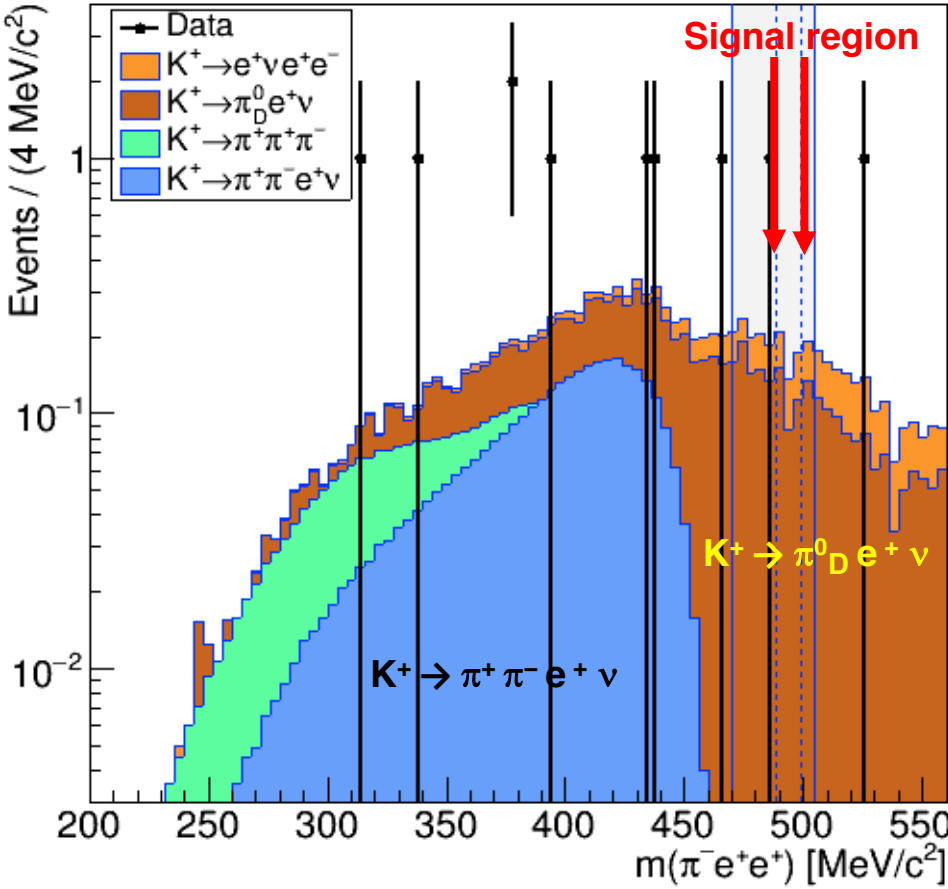
★ Searches for Lepton Flavour and Lepton Number violation in kaon decays

Searches for $K^+ \to \pi^- e^+ e^+$

SM selection: m($\pi^+ e^+ e^-$)



LNV selection: m($\pi^- e^+ e^+$)



Candidates observed: **11041**

BR($K^+ \to \pi^+ e^+ e^-$) = (3.00 ± 0.09) × 10^{-7}

K^+ decays in FV: **(1.015 ± 0.032) × 10^{12}**

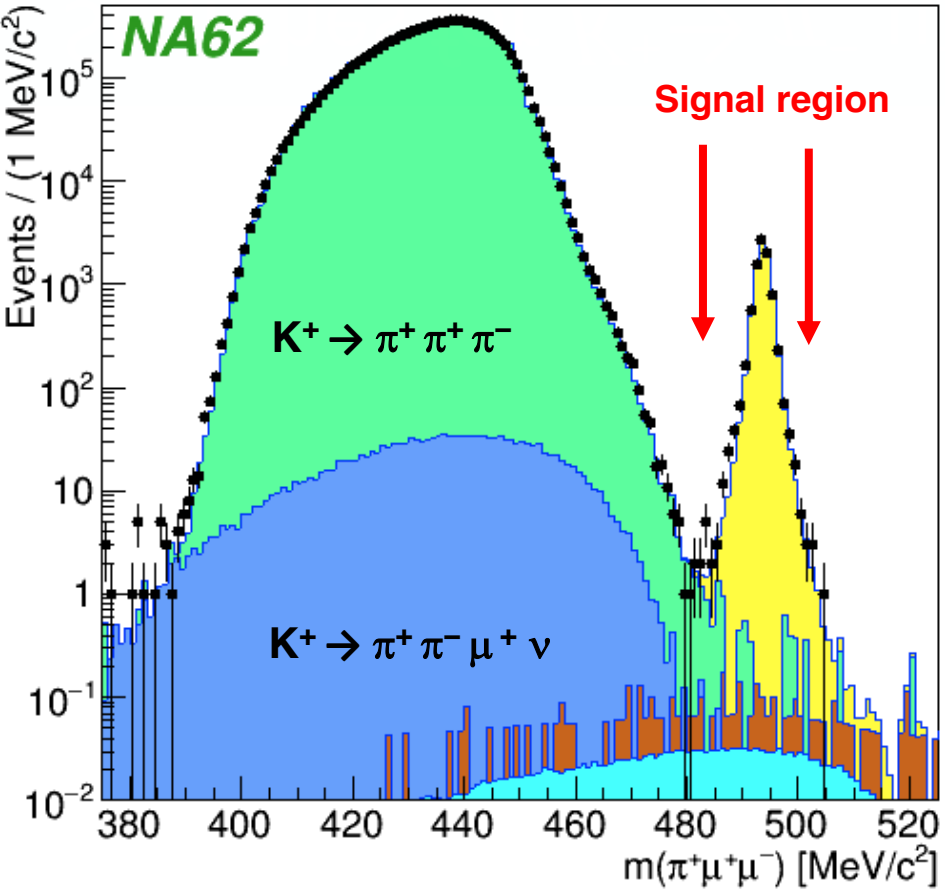
Expected background: **0.43 ± 0.09** evt

Candidates observed: **0**

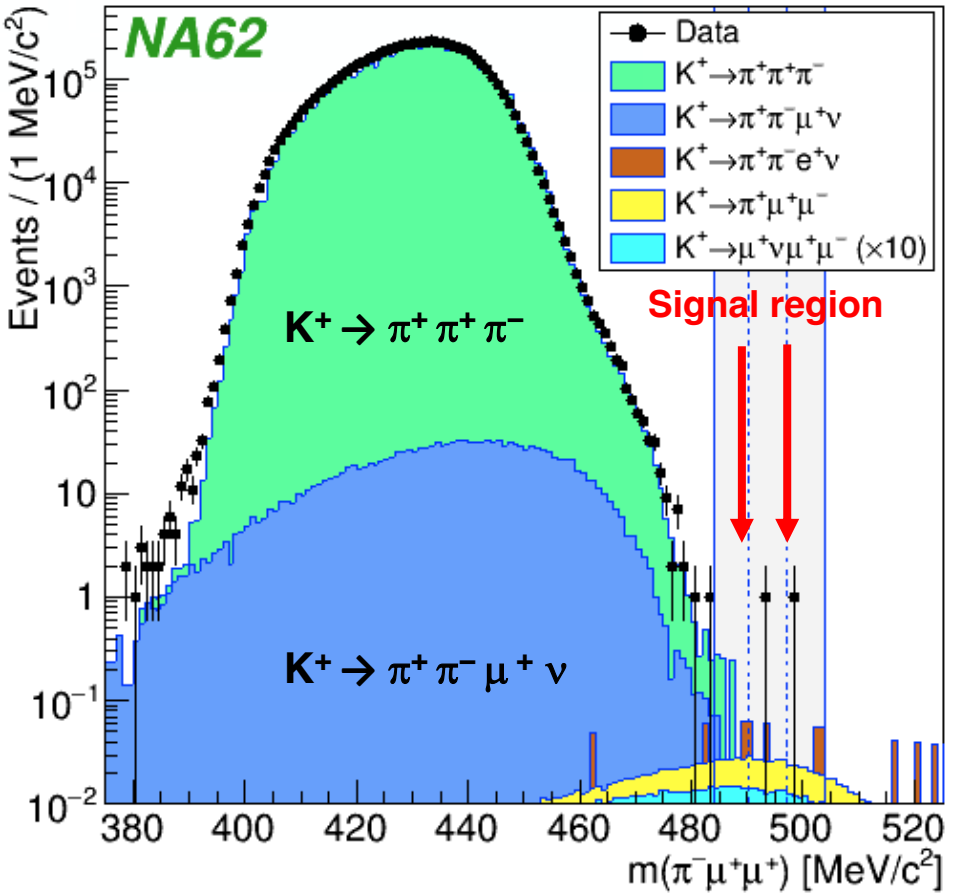
BR($K^+ \to \pi^- e^+ e^+$) < 5.3 × 10^{-11} at 90% CL

Searches for $K^+ \to \pi^- \mu^+ \mu^+$

SM selection: m($\pi^+ \mu^+ \mu^-$)



LNV selection: m($\pi^- \mu^+ \mu^+$)



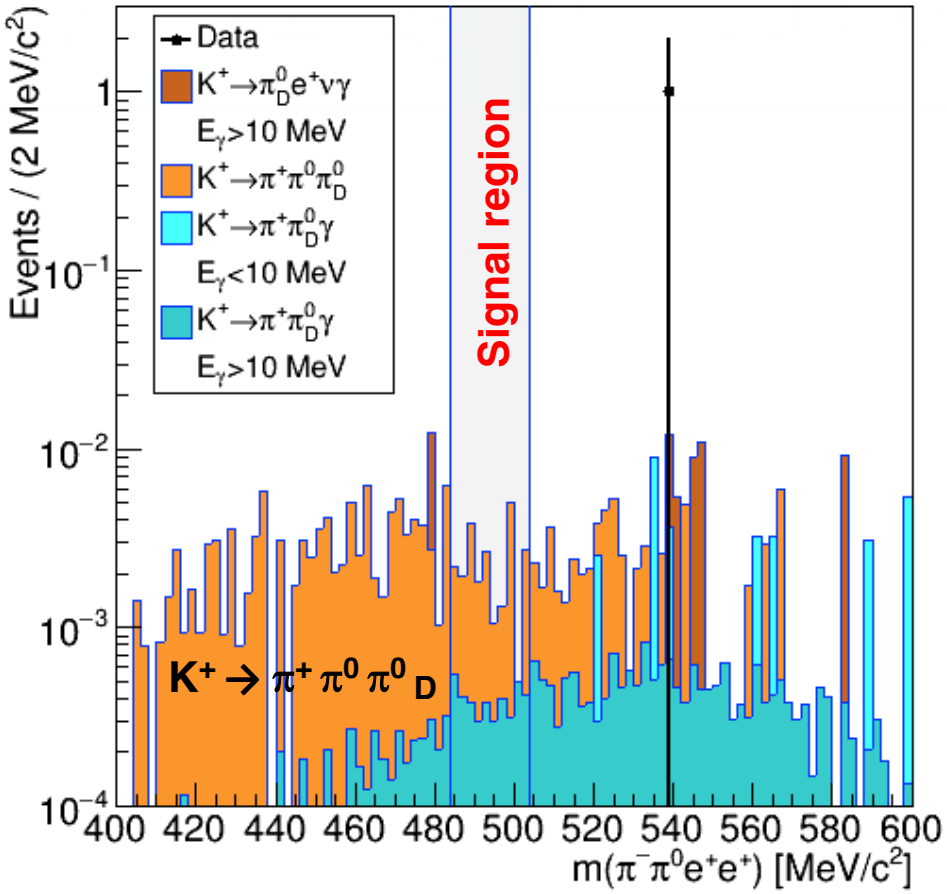
Candidates observed: **8357**
Background: **0.07%**
BR($K^+ \to \pi^+ \mu^+ \mu^-$) = (0.962 ± 0.025) × 10^{-7}
K^+ decays in Fid.Volume: **(7.94 ± 0.23) × 10^{11}**

Expected background: **0.91 ± 0.41** evt
Candidates observed: **1**
BR($K^+ \to \pi^- \mu^+ \mu^+$) < 4.2 × 10^{-11} at 90% CL

PLB 797 (2019) 134794

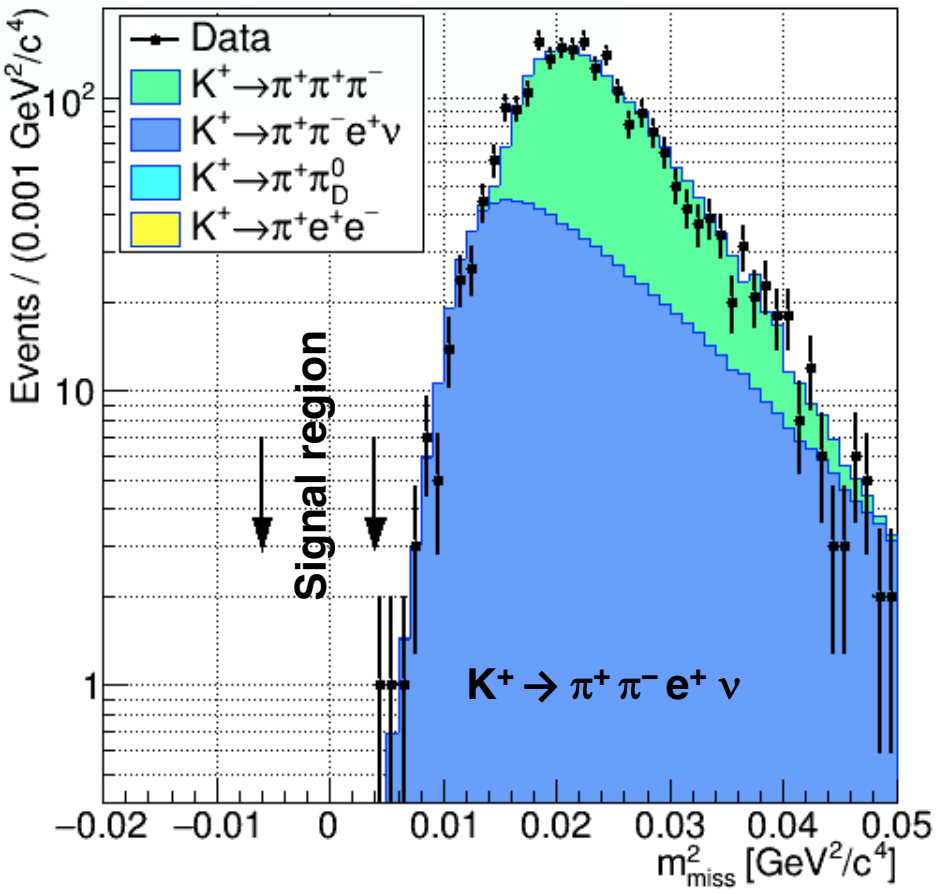
$K^+ \to \pi^- \pi^0 e^+ e^+$ and $K^+ \to \mu^- \nu e^+ e^+$

$m(\pi^-\pi^0 e^+e^+)$



Expected background: **0.044±0.020** evt
Candidates observed: **0**
BR($K^+ \to \pi^- \pi^0 e^+ e^+$) < 8.5 × 10^{-10} at 90% CL

Squared missing mass, $(P_K - P_\mu - P_{e1} - P_{e2})$



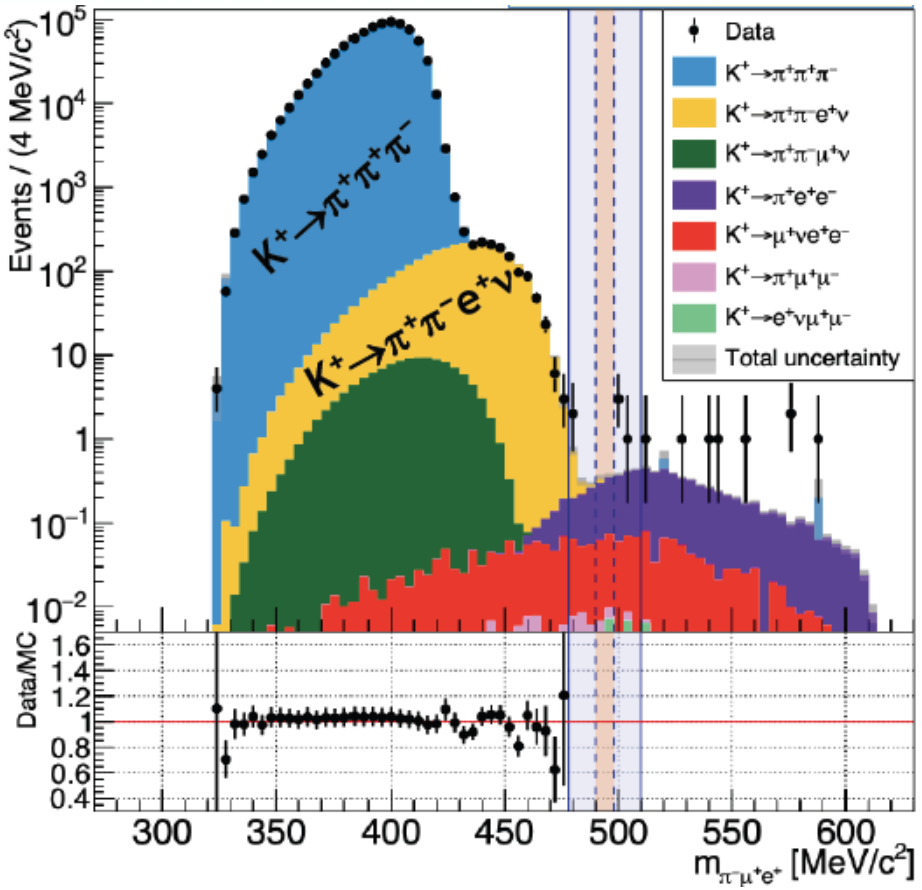
Expected background: **0.26±0.04** evt
Candidates observed: **0**
BR($K^+ \to \mu^- \nu e^+ e^+$) < 8.1 × 10^{-11} at 90% CL

PLB 830 (2022) 137172
PLB 838 (2023) 137679

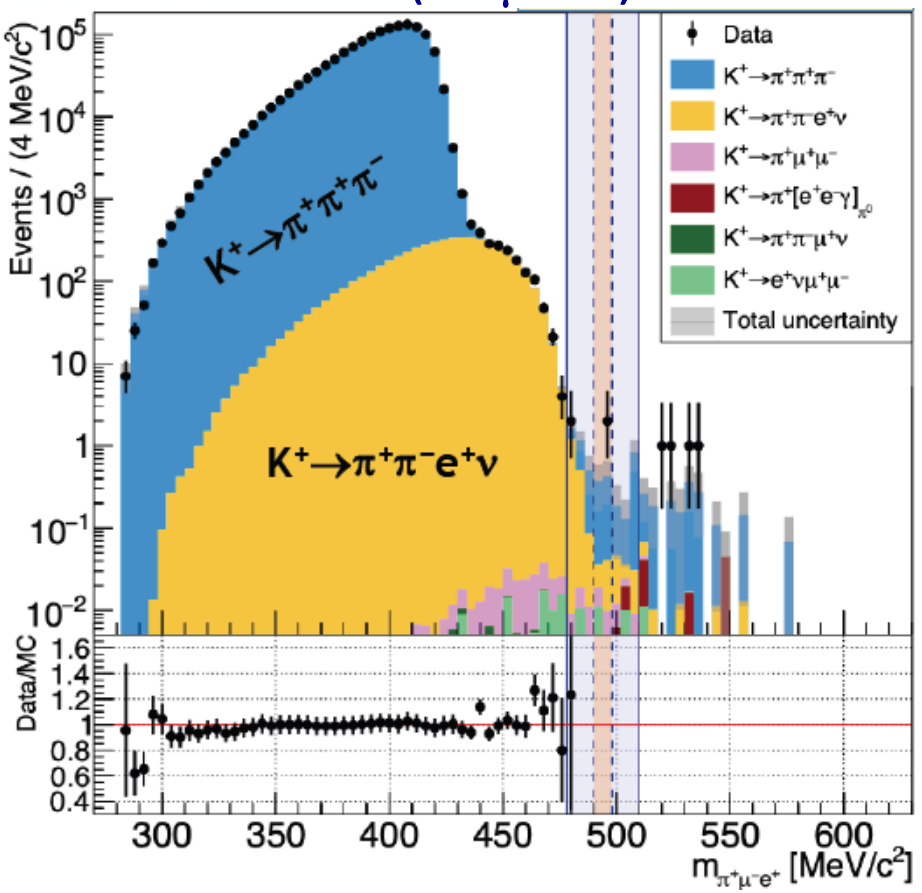
Search for $K^+ \to \pi\,\mu\,e$ decays

PRL 127 (2021) 131802

LNV: m($\pi^-\,\mu^+\,e^+$)



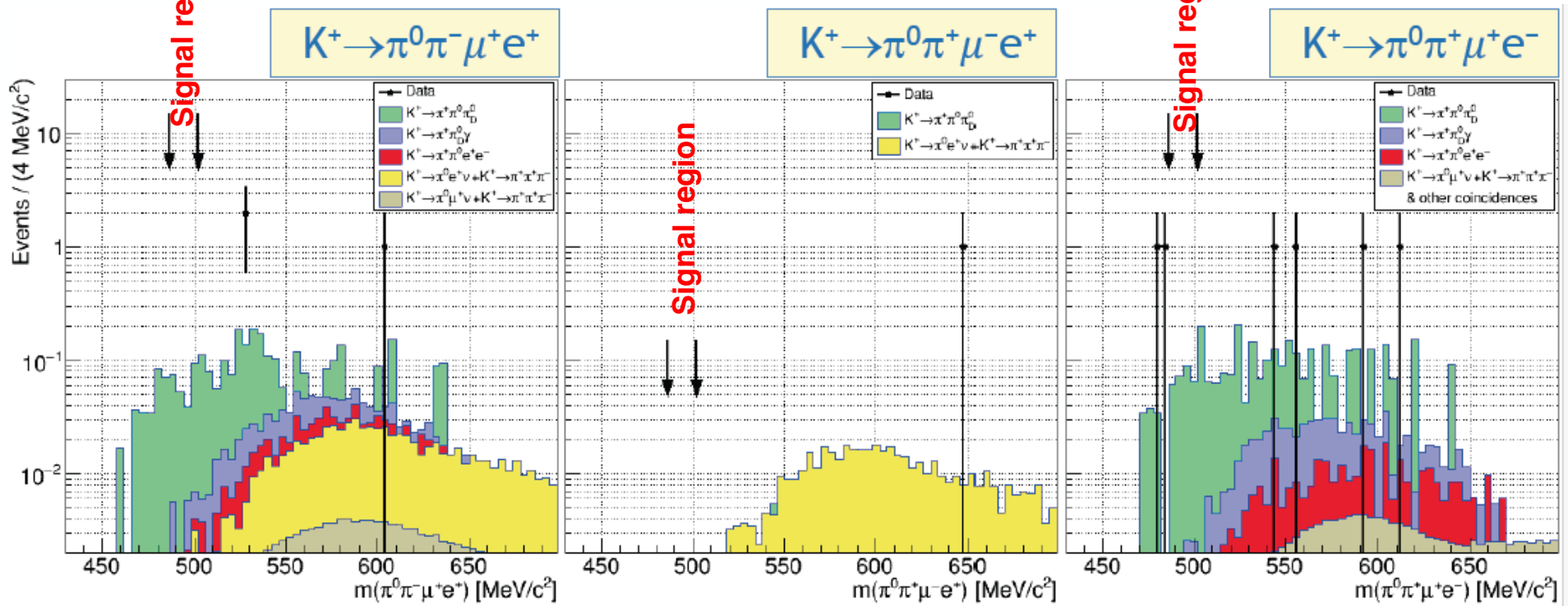
LFV: m($\pi^+\,\mu^-\,e^+$)



K^+ decays in FV: $(1.33 \pm 0.02) \times 10^{12}$
Expected background: 1.07 ± 0.20 evt
Candidates observed: 0
BR($K^+ \to \pi^-\,\mu^+ e^+$) < 4.2×10^{-11} at 90% CL

Expected background: 0.92 ± 0.34 evt
Candidates observed: 2
BR($K^+ \to \pi^+ \mu^- e^+$) < 6.6×10^{-11} at 90% CL
BR($\pi^0 \to \mu^- e^+$) < 3.2×10^{-10} at 90% CL

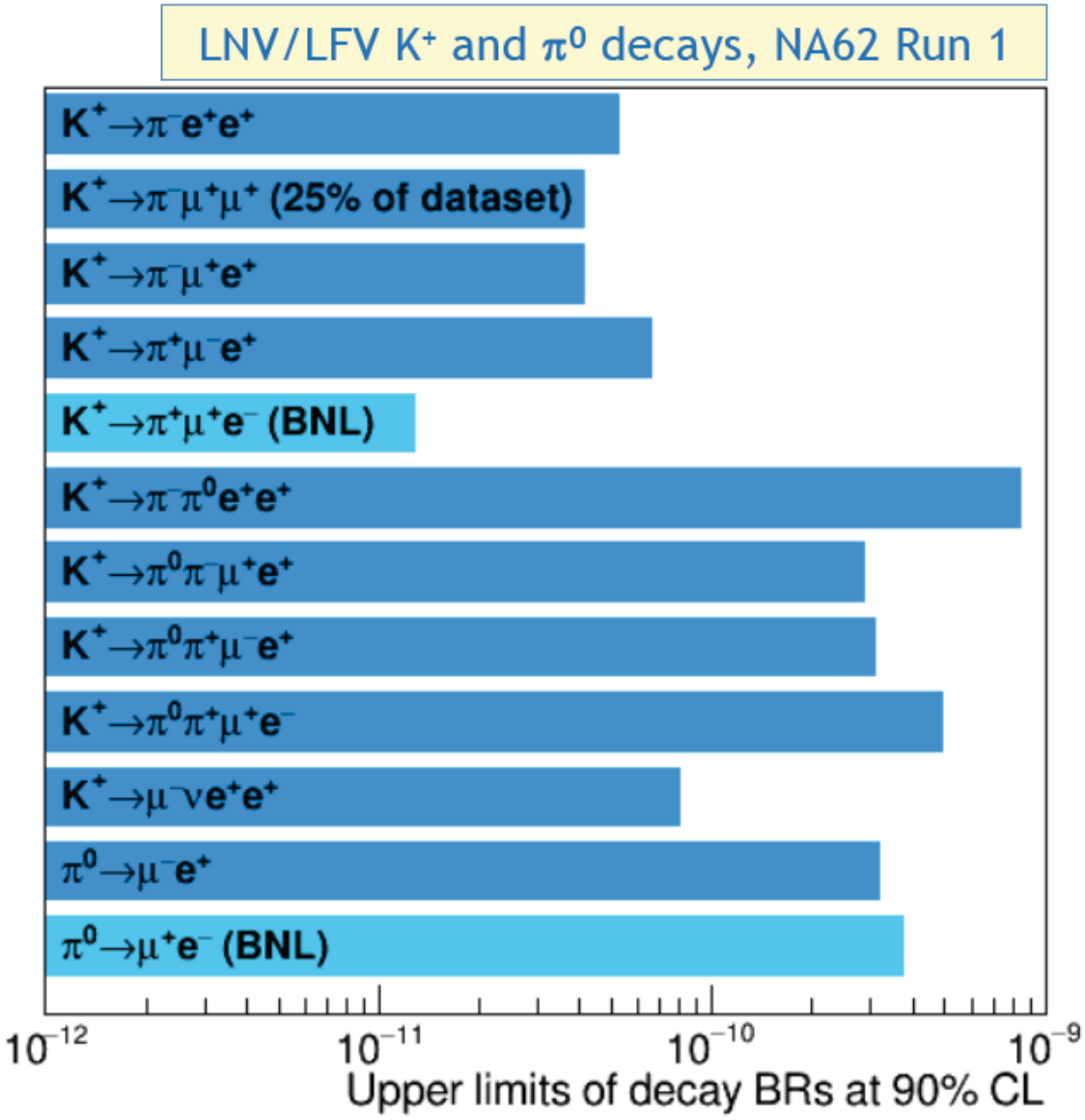
Search for $K^+ \to \pi^0\pi\mu e$ decays



Mode	Expected background	Candidates observed	Upper limit 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}

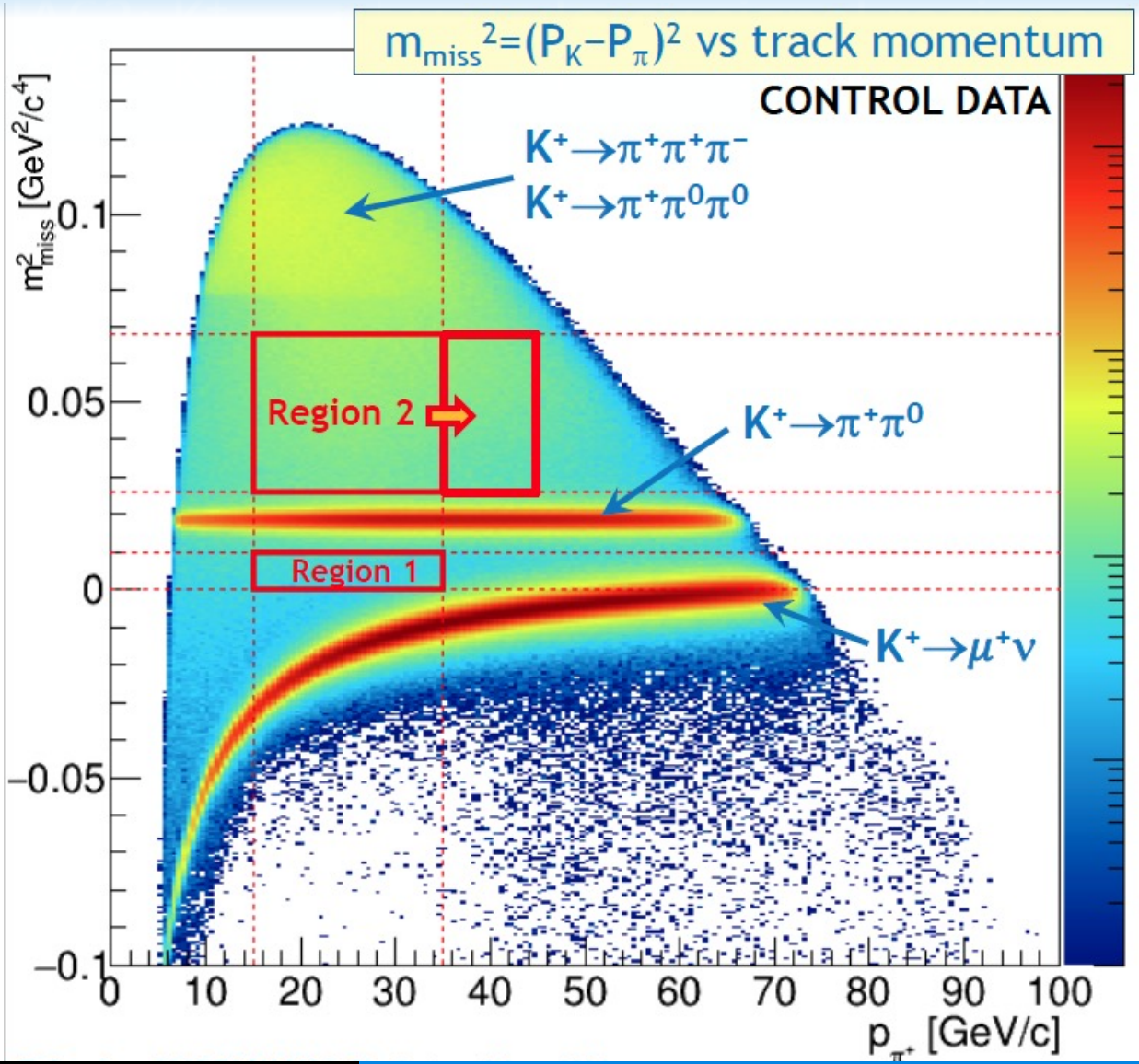
3 new results! to be published

Summary: LFV/LNV searches



★ Searches for Hidden Sectors in kaon decays

NA62: $K^+ \to \pi^+ \nu \bar{\nu}$ decay signal regions



Main K^+ decay modes (>90% of BR) rejected kinematically.

Resolution on m^2_{miss}: $\sigma=1.0\times10^{-3}$ GeV^4/c^2.

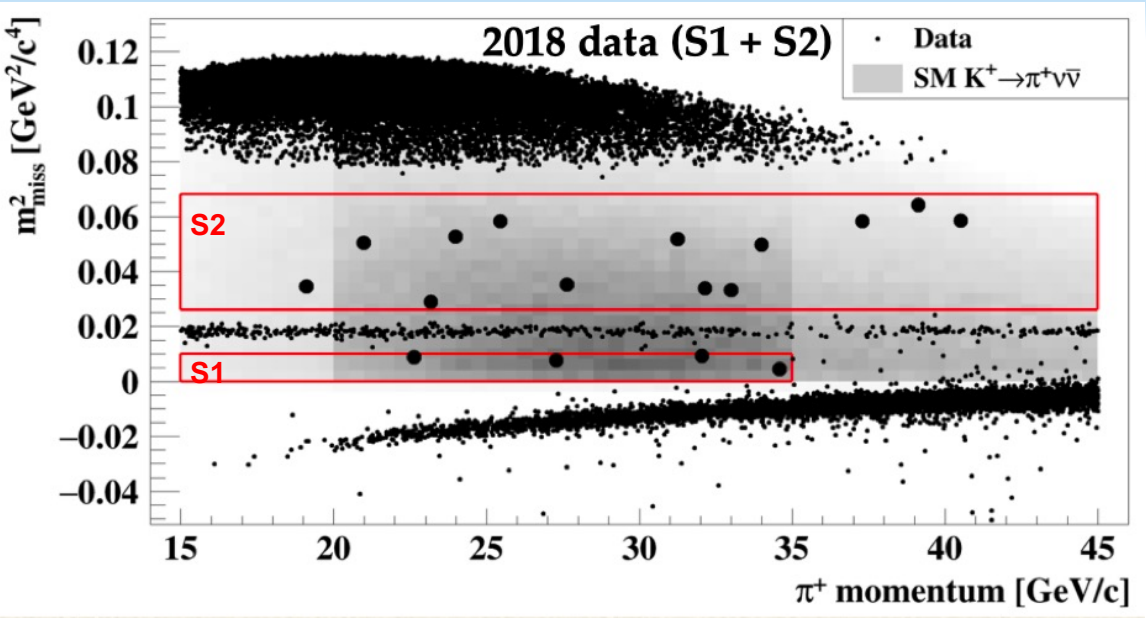
Measured kinematic background suppression:

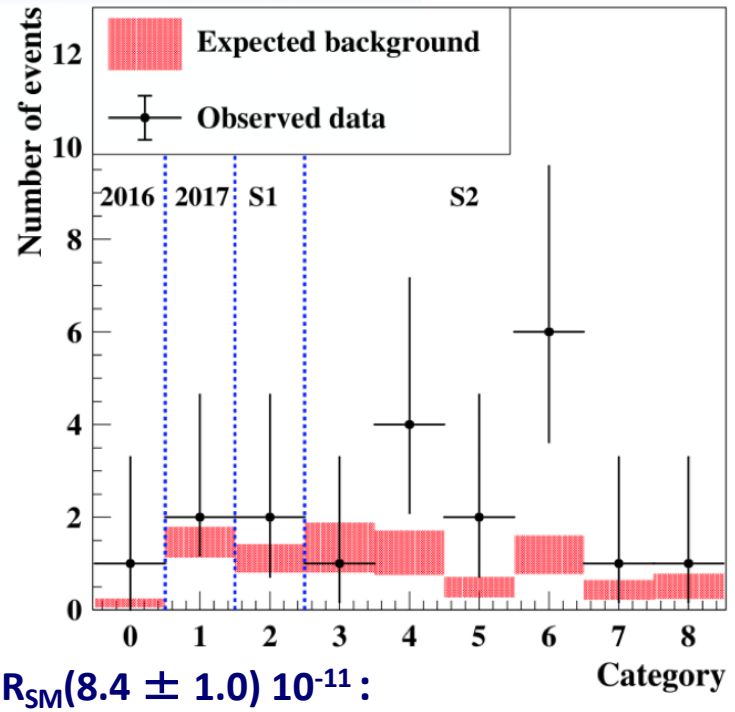
- ✓ $K^+\to\pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

Further background suppression:

- ✓ PID (calorimeters & RICH): μ suppression ~10^{-8}, π efficiency = 64%.
- ✓ Hermetic photon veto: $\pi^0\to\gamma\gamma$ rejection factor = 1.4×10^{-8}.

NA62 results from Run 1 (2016-2018)





- **20 events observed in the signal region**
- Combining the complete Run 1 data set and assuming $BR_{SM}(8.4 \pm 1.0)\ 10^{-11}$:

$N^{exp}_{\pi\nu\nu} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

$N^{exp}_{background} = 7.03\ ^{+1.05}_{-0.82}$

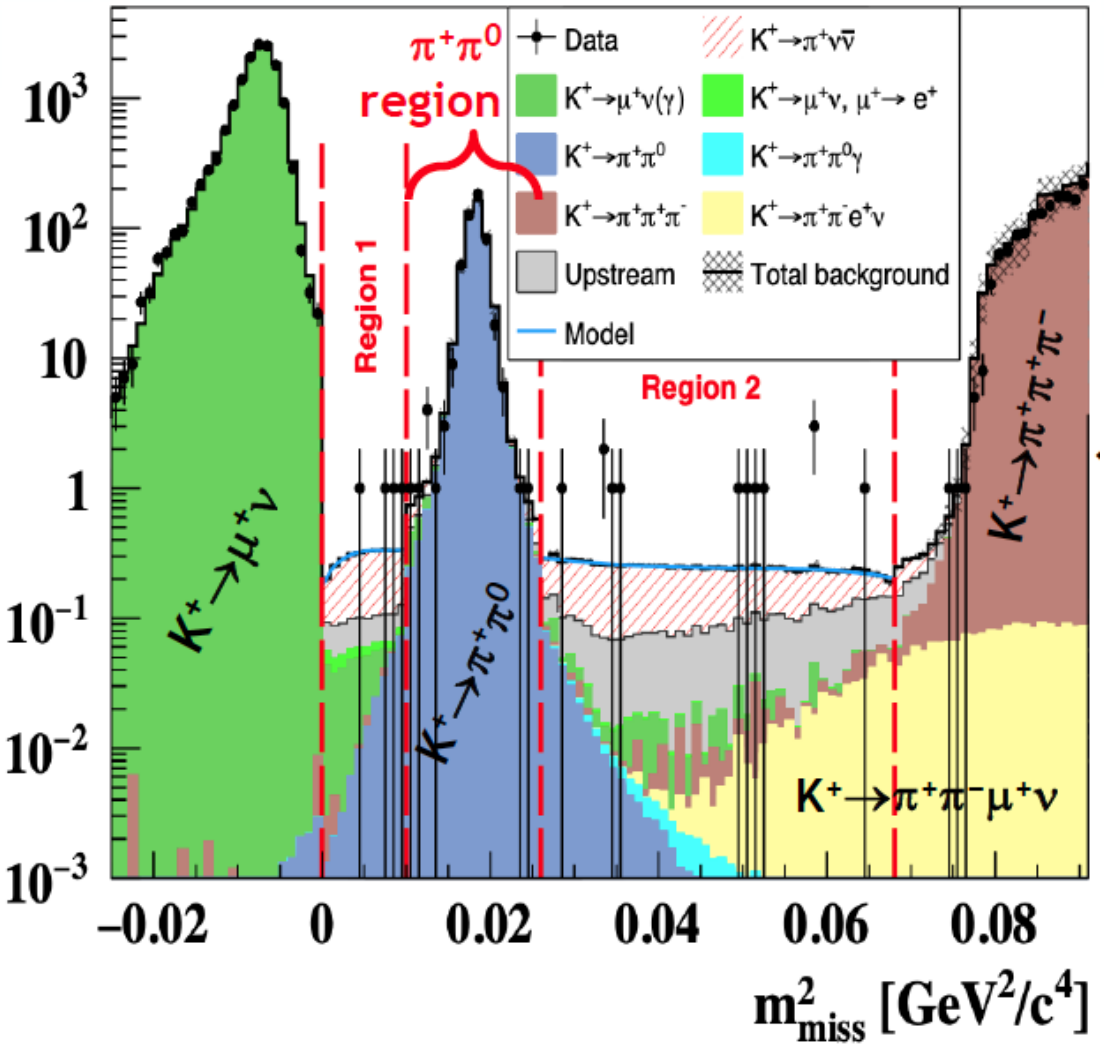
$SES = (0.839 \pm 0.053_{syst}) \times 10^{-11}$

JHEP 06 (2021) 093

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

Hidden sectors with $K^+ \to \pi^+ \nu \bar{\nu}$

Squared missing mass (2018 data)



- Signal regions R1,R2: search for $K^+ \to \pi^+ X$ (X=invisible), $0 < m_X < 110$ MeV/c^2 and $154 < m_X < 260$ MeV/c^2.
  - Interpretation: dark scalar, ALP, QCD axion, axiflavon.
  - Main background: $K^+ \to \pi^+ \nu\nu$

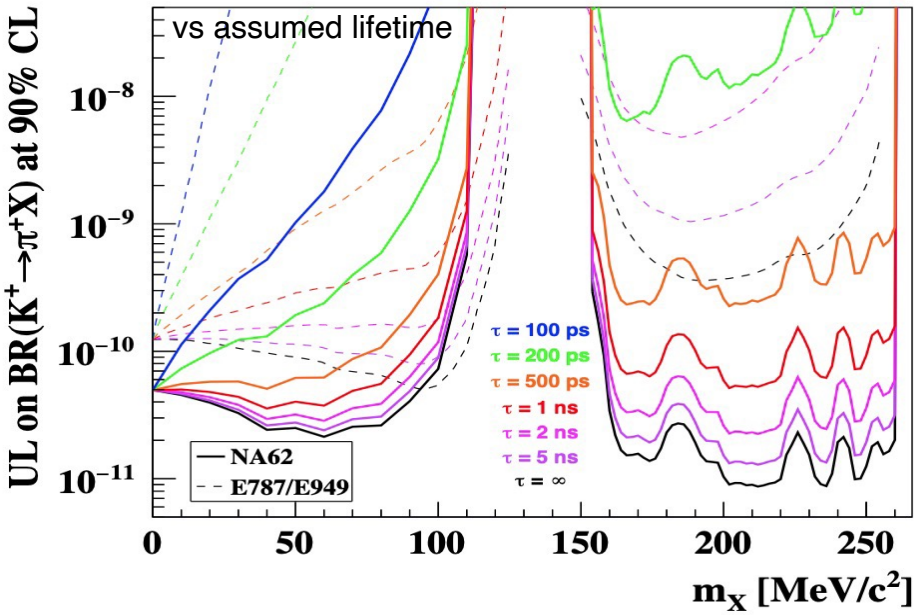
- Search for $\pi^0 \to$ invisible in the $\pi^+\pi^0$ region
  - Negligible SM rate ($\pi^0 \to 4\nu$)
  - Observation = BSM physics.
  - Reduction of $\pi^0 \to \gamma\gamma$ background: optimised π^+ momentum range.
  - Interpretation as $K^+ \to \pi^+ X$ with m_X between R1 and R2.

JHEP 06 (2021) 93

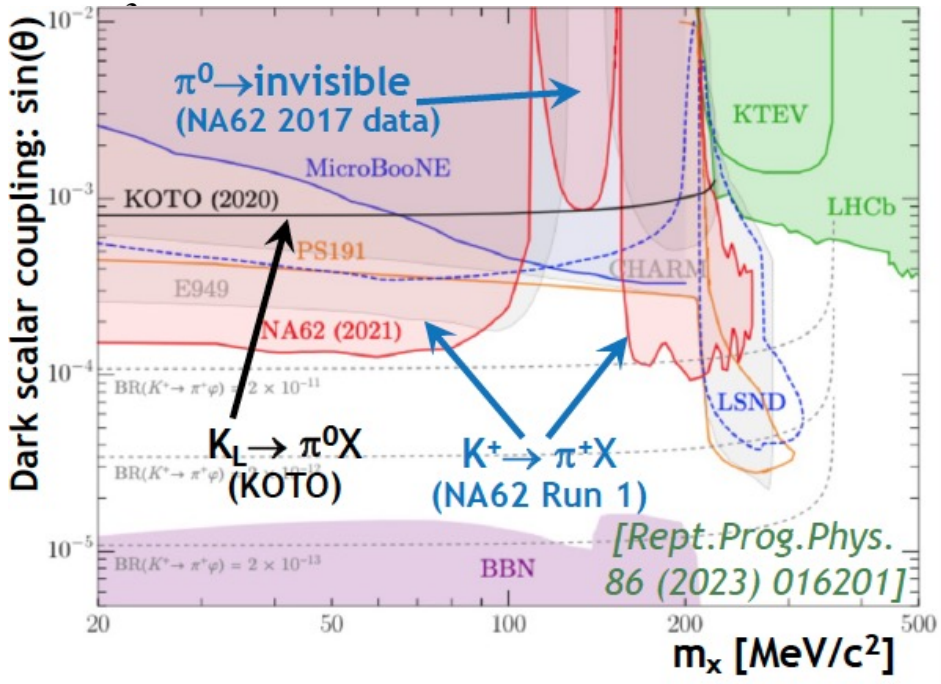
JHEP 02 (2021) 201

Results: search for $K^+ \longrightarrow \pi^+ X$

UL at 90% CL of BR($K^+ \rightarrow \pi^+ X$) vs m_X



Dark scalar searches below the K mass

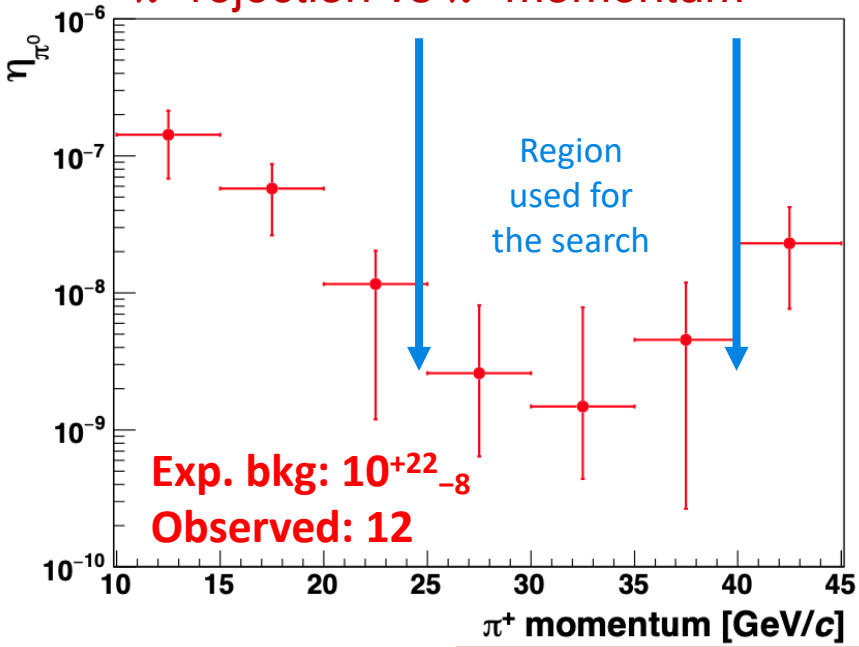


- Mass resolution is $\delta m_X \sim 40$ MeV/c^2 at m_X=0, and improves with m_X
- Upper limits of BR($K^+ \rightarrow \pi^+ X$) established depending on X mass and lifetime
- Improvement on **BNL-E949** *[PRD79 (2009) 092004]* over most of m_X range
- Interpretation shown here: the dark scalar model
- Note the **KOTO** result based on 2016−18 data. *[PRL125 (2021) 021801]*

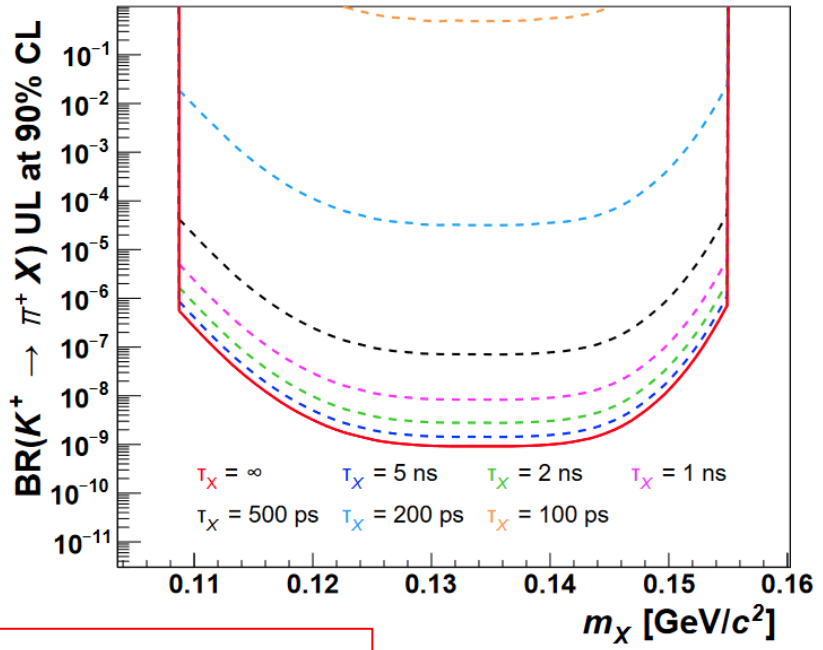
$K^+ \to \pi^+\pi^0$ with $\pi^0 \to$ invisible

- Basic event selection same as for $K^+ \to \pi^+\nu\nu$ decays
- Rejection of ($K^+ \to \pi^+\pi^0(\gamma)$, $\pi^0 \to \gamma\gamma$) decays: simulations based on single-photon efficiency *[JHEP 02 (2021) 201].*
- Validates π^0 rejection estimates for BR($K^+ \to \pi^+\nu\nu$) measurement
- 2017 data only – reaching limits from photon veto inefficiency
- $K_{\pi\nu\nu}$ trigger and selection used, with $0.015 < m^2_{miss} < 0.021$ GeV$^2/c^4$

π^0 rejection vs π^+ momentum



UL at 90% CL of BR($K^+ \to \pi^+$ X) vs m_X

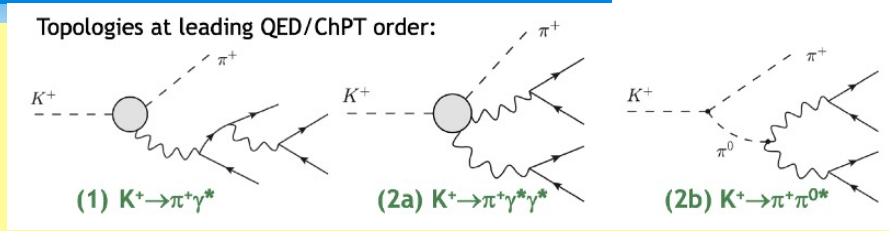


BR($\pi^0 \to$ invisible) < 4.4 x 10^{-9} at 90% CL

Pair production of exotic states - $K^+ \to \pi^+ e^+ e^- e^+ e^-$

Theory: SM allowed

$BR = 7.2 \pm 0.7 \times 10^{-11}$ (outside π^0 pole)



Dark sector probe:

$K^+ \to \pi^+ aa$ with $a \to e^+e^-$ QCD axion, e.g. m_a = 17 MeV $BR = 1.7 \times 10^{-5}$

$K^+ \to \pi^+ S$ with $S \to A'A'$ dark scalar and $A' \to e^+e^-$ dark photon ($m_S > 2mA'$)

Goal: Search for: 1) SM process ($K_{\pi 4e}$); 2) QCD di-axion; 3) Dark cascade

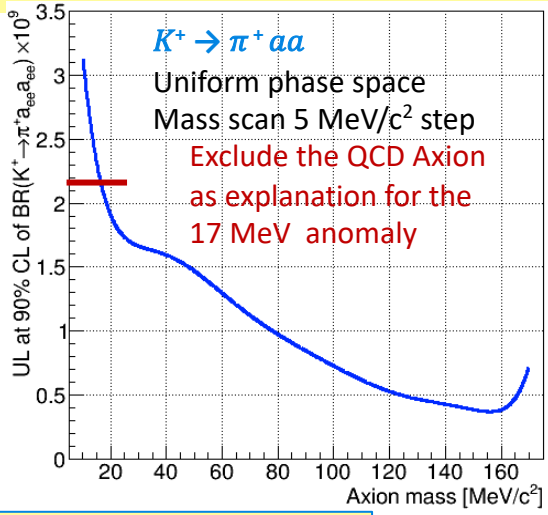
Signal: $\boldsymbol{K_{\pi 4e}}$ and $\boldsymbol{K^+ \to \pi^+ aa}$ "Dark")

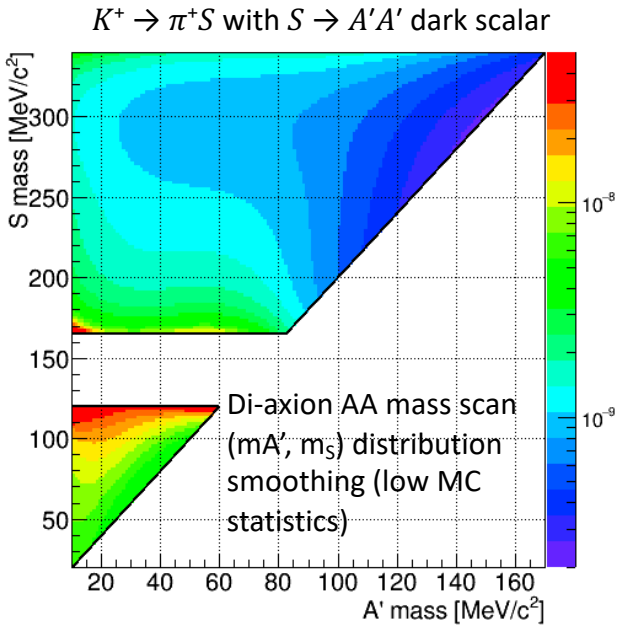
Same selection as $K_{\pi 4e}$

Choice of the optimal e^+e^- mass pair

Condition on m_{ee}

Normalization: $K^+ \to \pi^+ \pi^0{}_{DD}$





SM: BR($K_{\pi 4e}$) < 1.4 10^{-8} @90% CL

Limits on $K^+ \to \pi^+ aa$ and $Dark$ cascade

PLB 846 (2023) 138193

Results: HNL production

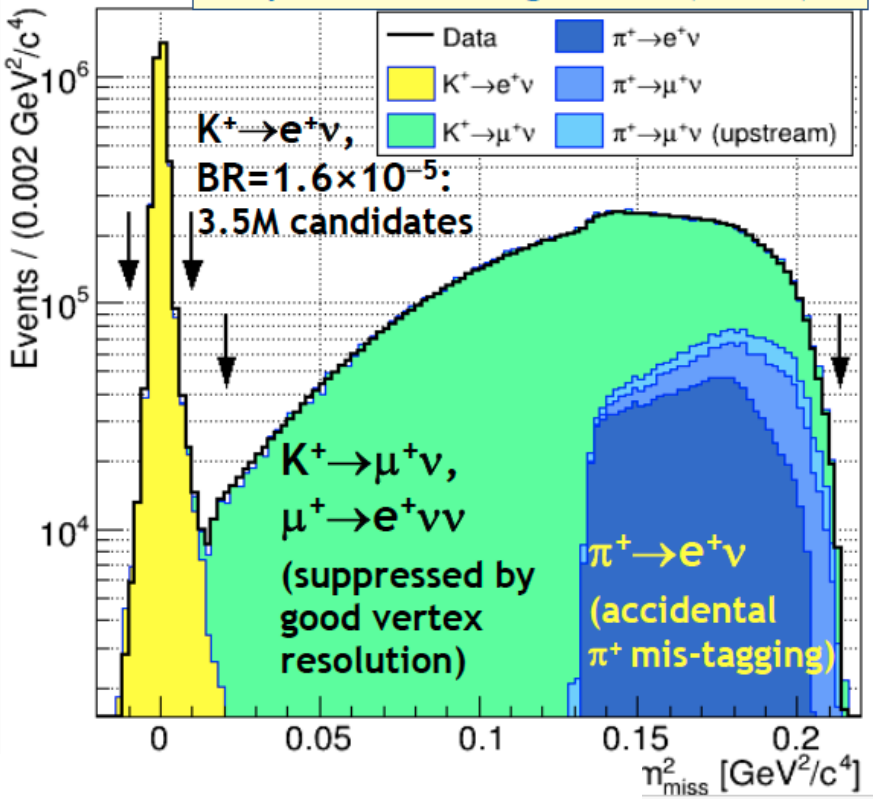
NA62 RUN1

- Trigger lines: $K_{\pi\nu\nu}$ for $K^+\to e^+N$; Control/400 for $K^+\to\mu^+N$.
- Numbers of K^+ decays in fiducial volume: $N_K=3.5\times10^{12}$ in the positron case; $N_K=4.3\times10^{9}$ in the muon case.
- Squared missing mass: $m^2_{miss}=(P_K-P_\ell)^2$, using STRAW and GTK trackers.
- HNL production signal: **a spike above continuous missing mass spectrum**.

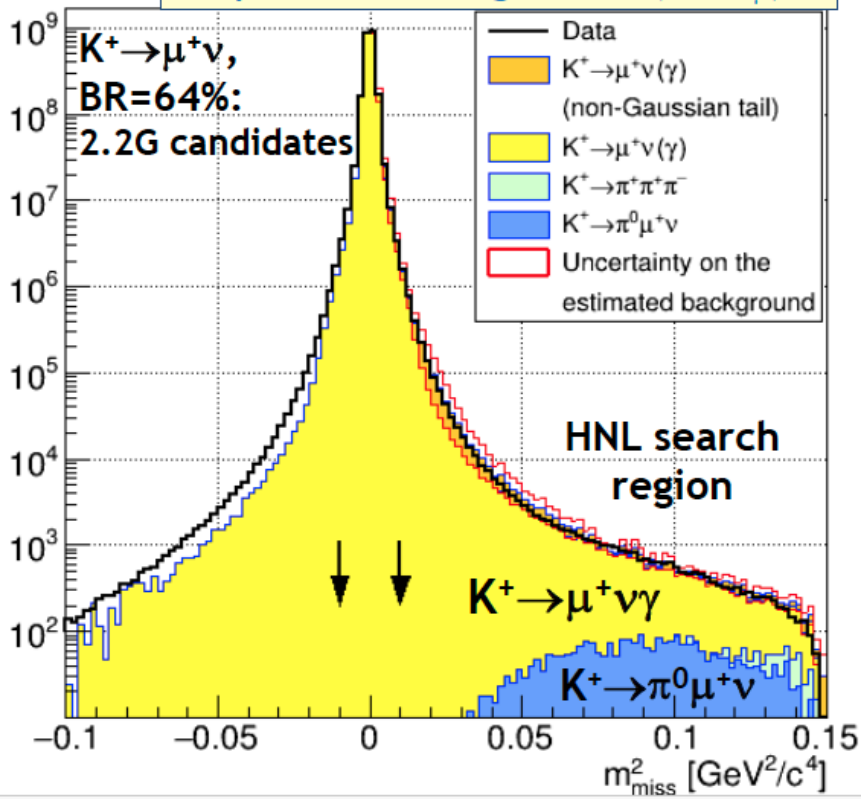
PLB 807 (2020) 135599

PLB 816 (2021) 136259

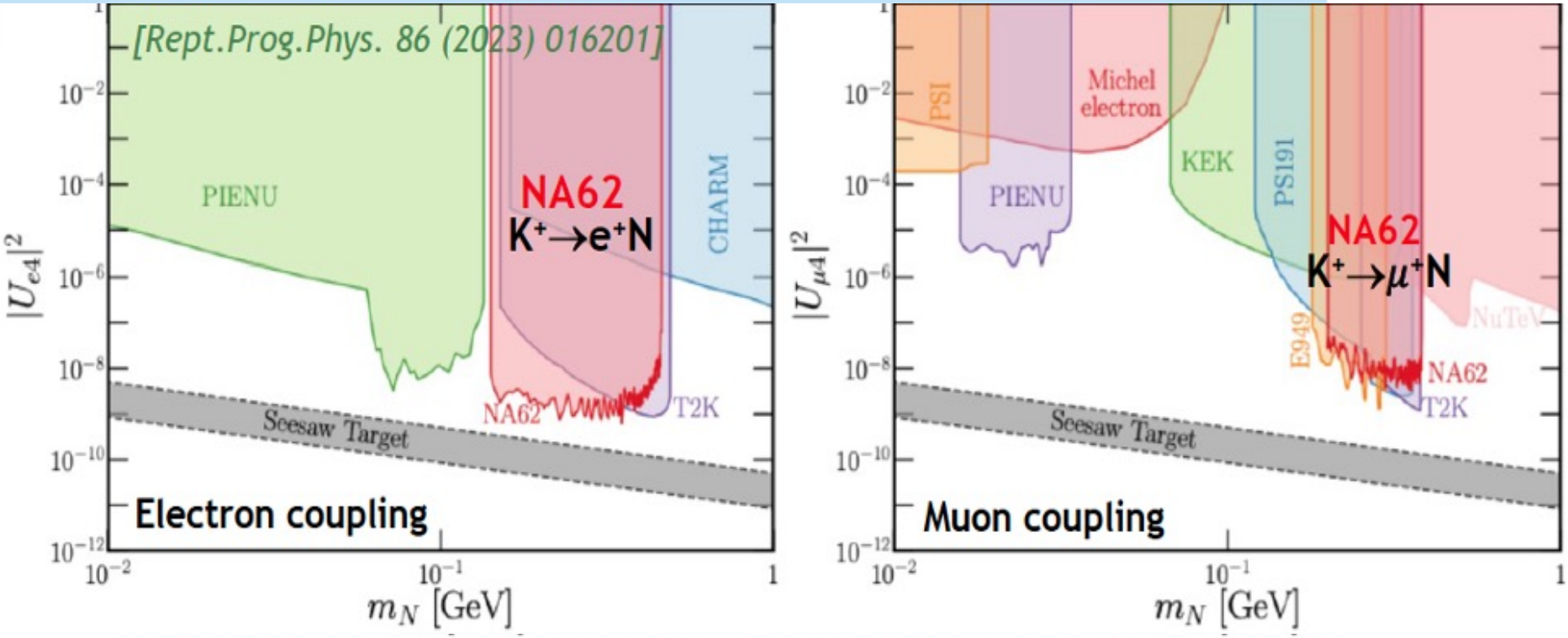
Squared missing mass: $(P_K-P_e)^2$



Squared missing mass: $(P_K-P_\mu)^2$



Results: HNL production



- For $|U_{e4}|^2$, complementary to search for $\pi^+ \to e^+N$ at PIENU.
- For $|U_{\mu 4}|^2$, complementary to search for $K^+ \to \mu^+N$ at BNL-E949.
- In both cases, complementary to HNL *decay* searches at T2K.
- Future kaon and pion experiments will approach the seesaw bound.

- An upper limit at 90% CL: $BR(K^+ \to \mu^+\nu\nu\nu) < 1.0 \times 10^{-6}$, and similar limits of $BR(K^+ \to \mu^+\nu X)$, with X=invisible.

PLB 807 (2020) 135599

PLB 816 (2021) 136259

Summary

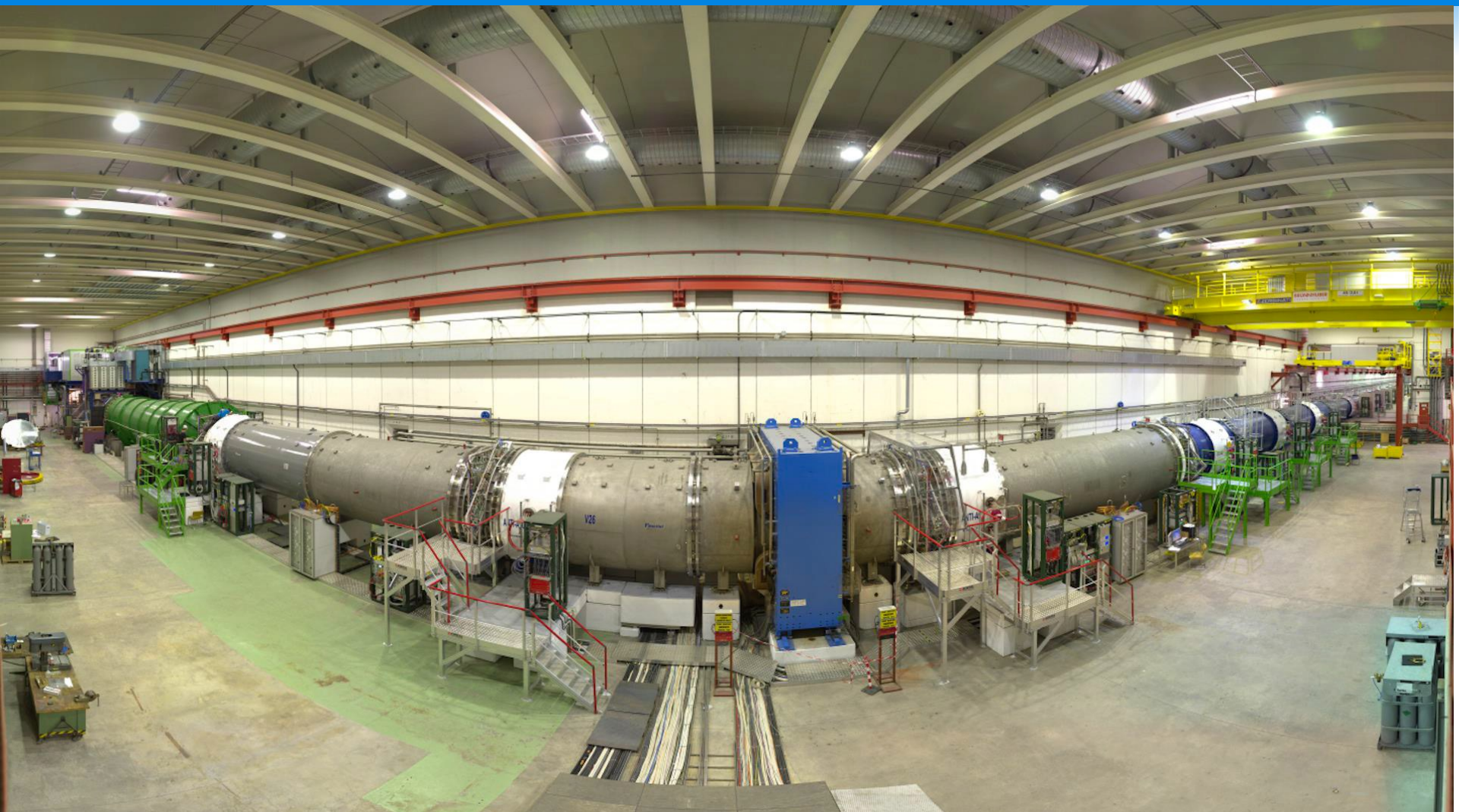
Physics program with charged kaons successfully pursued at CERN SPS by NA62.
Run 2 (2021–): in progress (up to 3×10^{12} ppp), approved till 2025.

- Kaon decays: a unique probe for new physics
  - ✓ Large decay samples are available (~10^{13} decays)
  - ✓ Often simple and clean final states, low backgrounds
- NA62 at CERN is collecting data from 2016 till at least 2025
  - ✓ World's largest multi-purpose sample of K^+ decays
  - ✓ First measurement of the ultra-rare $K^+ \to \pi^+ \nu\nu$ decay

- NA62 LFV/LNV programme: stringent limits on 10 decay modes

- Searches for hidden sectors in kaon decays at NA62 address a range of PBC benchmark scenarios
  - ✓ $K^+ \to \pi^+ X_{invisible}$: dark scalar and ALP $K^+ \to \ell^+ N$: heavy neutral leptons

Thank you for your attention



NA62 published results

- *Search for leptonic decays of the dark photon at NA62*, arXiv: 2312.12055 [hep-ex] (2023), submitted to Phys. Rev. Lett.
- *Measurement of the* $K^+ \to \pi^+\gamma\gamma$ *decay*, Phys. Lett. B. 850 (2024) 138513.
- *Search for* K^+ *decays into the* $\pi^+e^+e^-e^+e^-$ *final state*, Phys. Lett. B. 846 (2023) 138193.
- *A study of the* $K^+ \to \pi^0e^+\nu\gamma$ *decay*, JHEP 09 (2023) 040.
- *Search for dark photon decays to* $\mu^+\mu^-$ *at NA62*, JHEP 09 (2023) 035.
- *A search for the* $K^+ \to \mu^-\nu e^+e^+$ *decay*, Phys. Lett. B 838 (2023) 137679.
- *A measurement of the* $K^+ \to \pi^+\mu^+\mu^-$ *decay*, JHEP 11 (2022) 011.
- *Searches for lepton number violating* $K^+ \to \pi^-(\pi^0)\, e^+e^+$ *decays*, Phys. Lett. B 830 (2022) 137172.
- *Search for Lepton Number and Flavor Violation in* K^+ *and* π^0 *Decays*, Phys. Rev. Lett. 127 (2021) 131802.
- *Measurement of the very rare* $K^+ \to \pi^+\nu\bar{\nu}$ *decay*, JHEP 06 (2021) 093.
- *Search for* K^+ *decays to a muon and invisible particles*, Phys. Lett. B 816 (2021) 136259.
- *Search for a feebly interacting particle* X *in the decay* $K^+ \to \pi^+X$, JHEP 03, (2021) 058.
- *Search for* π^0 *decays to invisible particles*, JHEP 02, (2021) 201.
- *An investigation of the very rare* $K^+ \to \pi^+\nu\bar{\nu}$ *decay*, JHEP 11 (2020) 042.
- *Search for heavy neutral lepton production in* K^+ *decays to positrons*, Phys. Lett. B 807 (2020) 135599.
- *Searches for lepton number violating* K^+ *decays*, Phys. Lett. B 797 (2019) 134794.
- *Search for production of an invisible dark photon in* π^0 *decays*, JHEP 1905 (2019) 182.
- *First search of* $K^+ \to \pi^+\nu\bar{\nu}$ *using the decay-in-flight technique*, Phys. Lett. B 791 (2019) 156.
- *Search for heavy neutral lepton production in* K^+ *decays*, Phys. Lett. B 778 (2018) 137.

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