Searches for hidden sectors and LFV/LNV in kaon decays

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Outline

1) The NA62 experiment at CERN
2) Searches for hidden sectors in K^+ decays
3) Searches for lepton flavour/number violating K^+ decays
4) Summary

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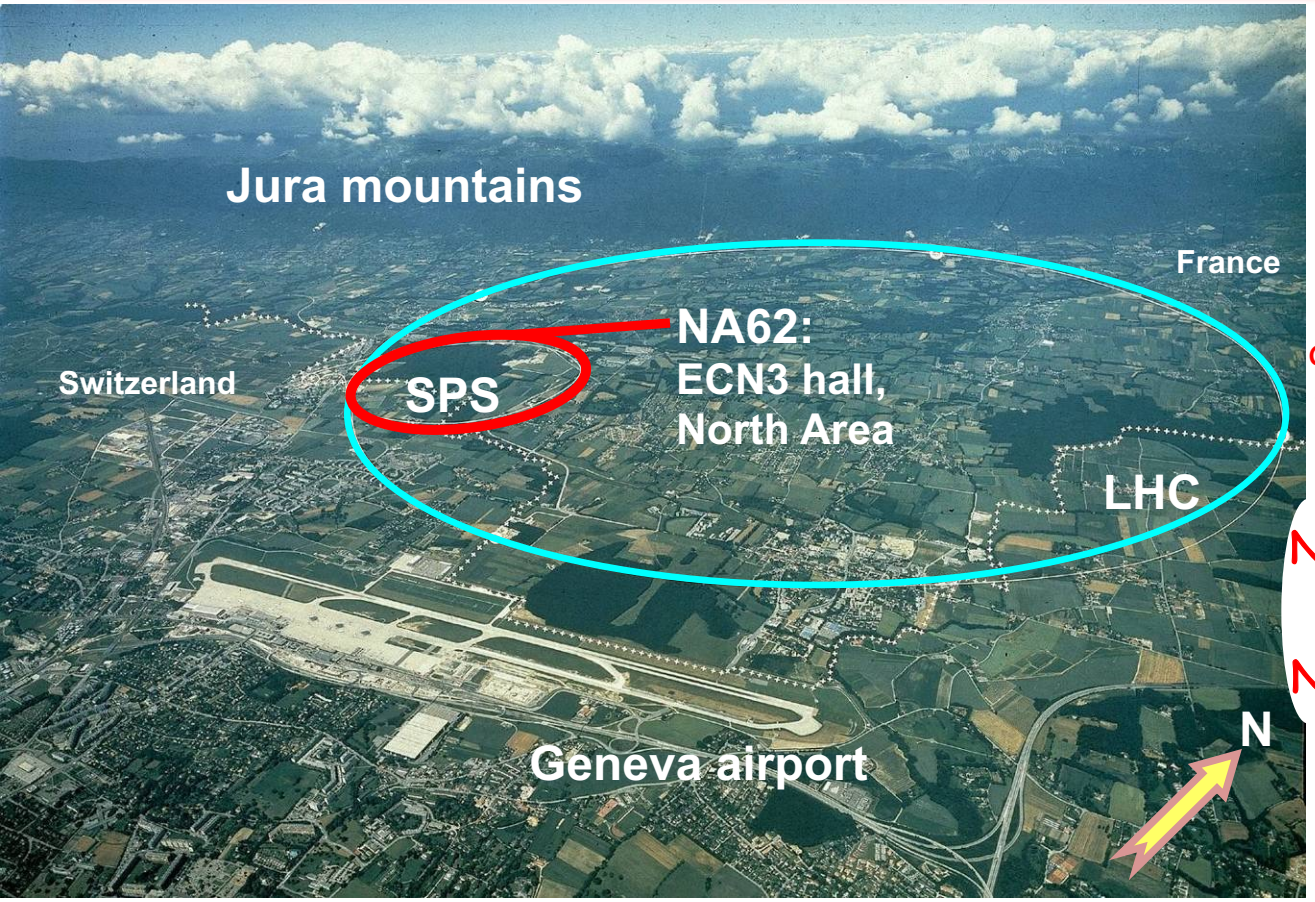
Kaon experiments at CERN



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 run
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests

NA62
- 2015: commissioning
- 2016-18: physics run 1
- 2021-: physics run 2

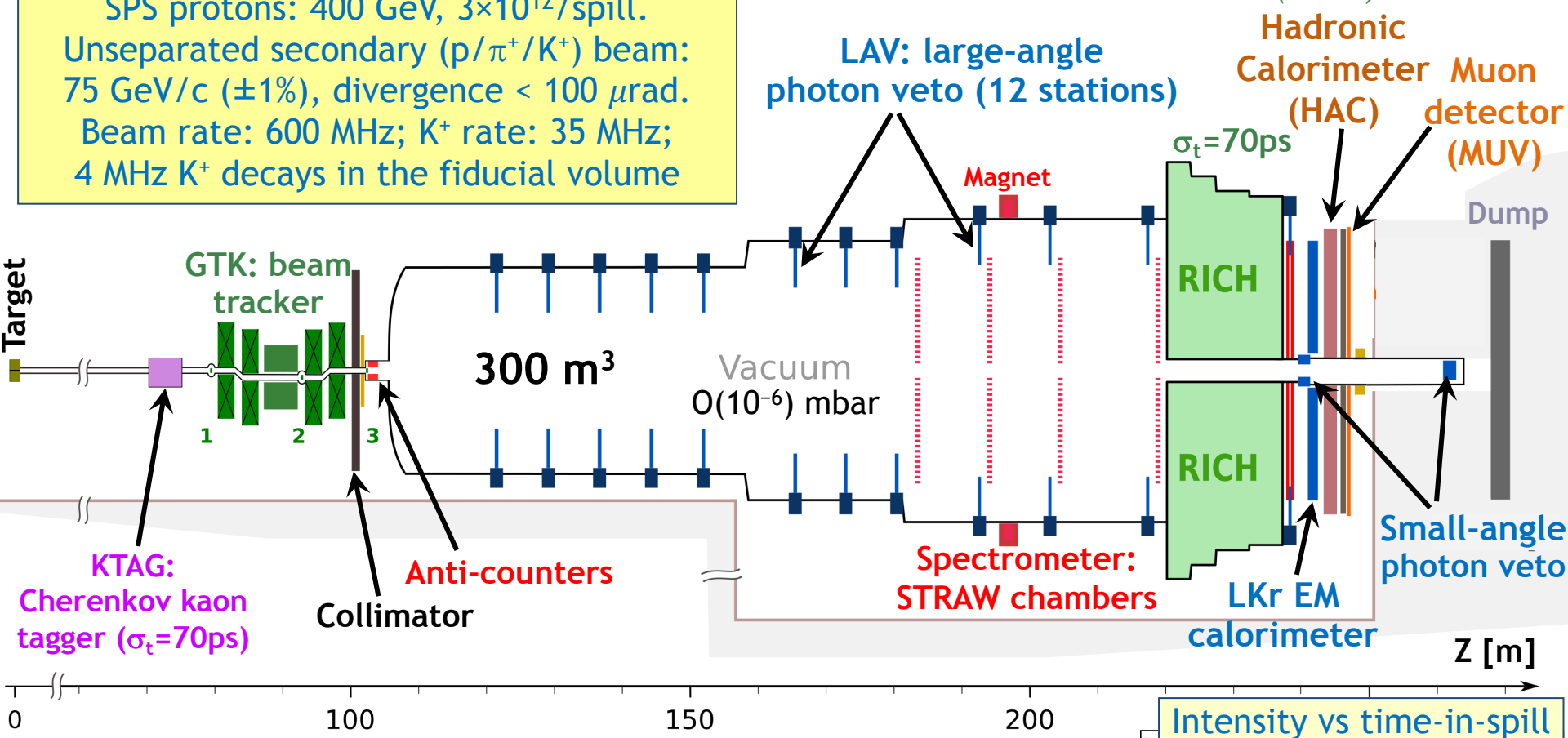
Main NA62 goal: $K^+ \to \pi^+ \nu\nu$ measurement to 15% precision using the decay-in-flight technique.

Currently ~300 participants from ~30 institutions.

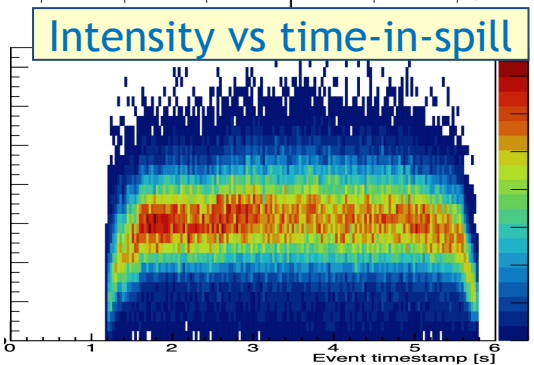
The NA62 setup

SPS protons: 400 GeV, 3×10^{12}/spill.
Unseparated secondary ($p/\pi^+/K^+$) beam:
75 GeV/c (±1%), divergence < 100 μrad.
Beam rate: 600 MHz; K^+ rate: 35 MHz;
4 MHz K^+ decays in the fiducial volume

JINST 12 (2017) P05025

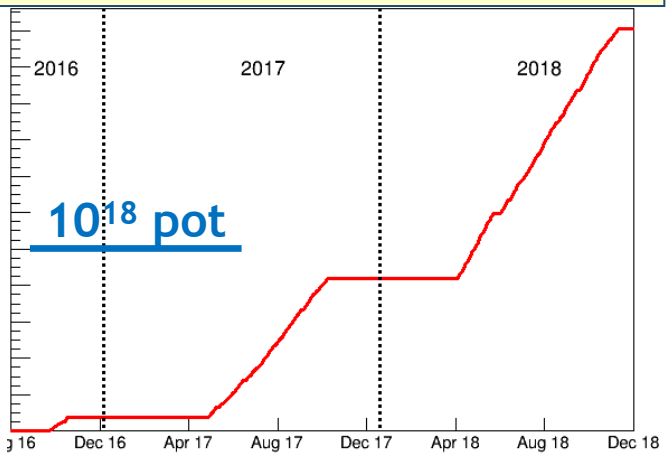


- One year ≈ 2×10^{18} protons on target ≈ 5×10^{12} K^+ decays.
- Beam structure: ideally, uniform over a 4.8 s long spill.
- In practice, significant variations of instantaneous beam intensity during the spill.



NA62 datasets

Run 1 integrated luminosity



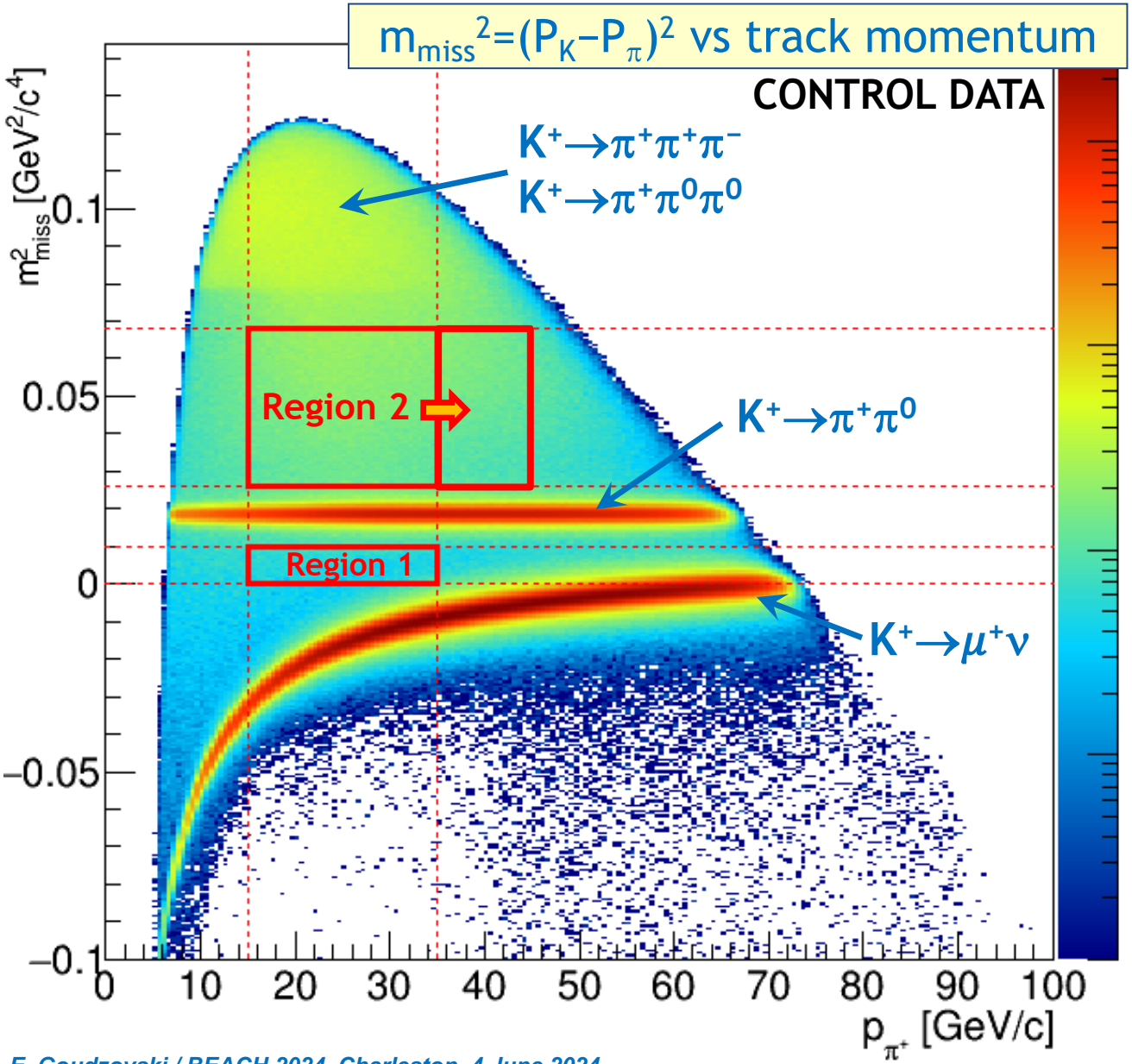
Currently: ~2×10^{18} pot/year,
~5×10^{12} K^+ decays/year

Beam-dump mode:
4×10^{17} pot collected so far

- 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.

Searches for hidden sectors in kaon decays

NA62: $K_{\pi\nu\nu}$ 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:

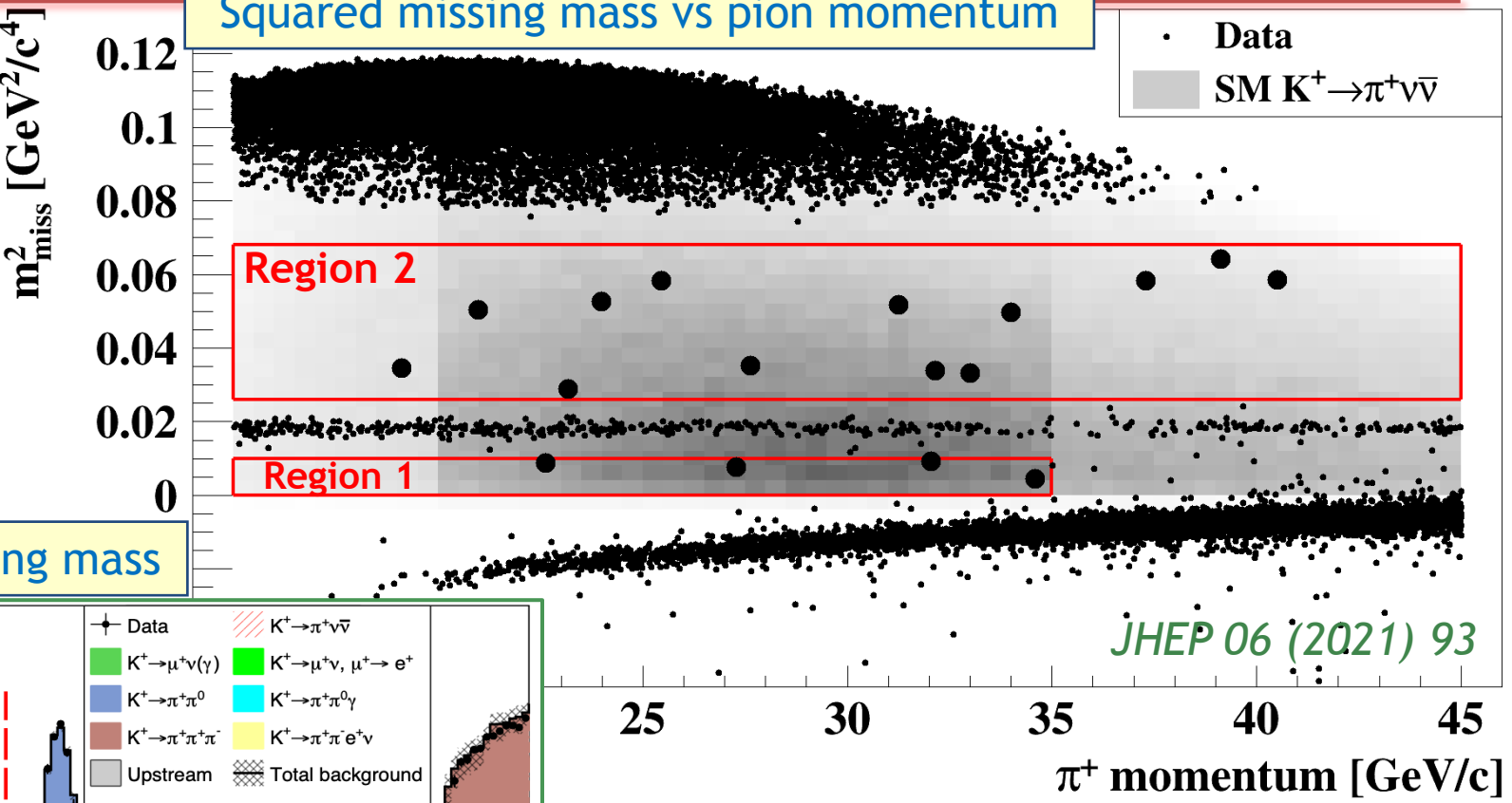
- ✓ $K^+\to\pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

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}.

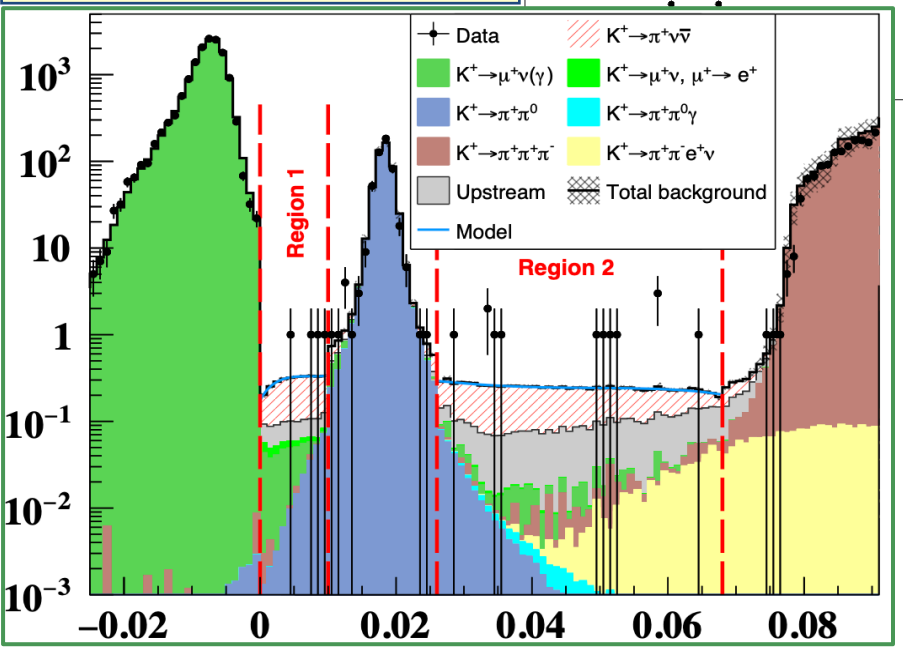
NA62 2018 data (=most of Run 1)

Squared missing mass vs pion momentum



JHEP 06 (2021) 93

Squared missing mass



Full Run 1 data set:

Candidates observed: **20** (17 in 2018 data)

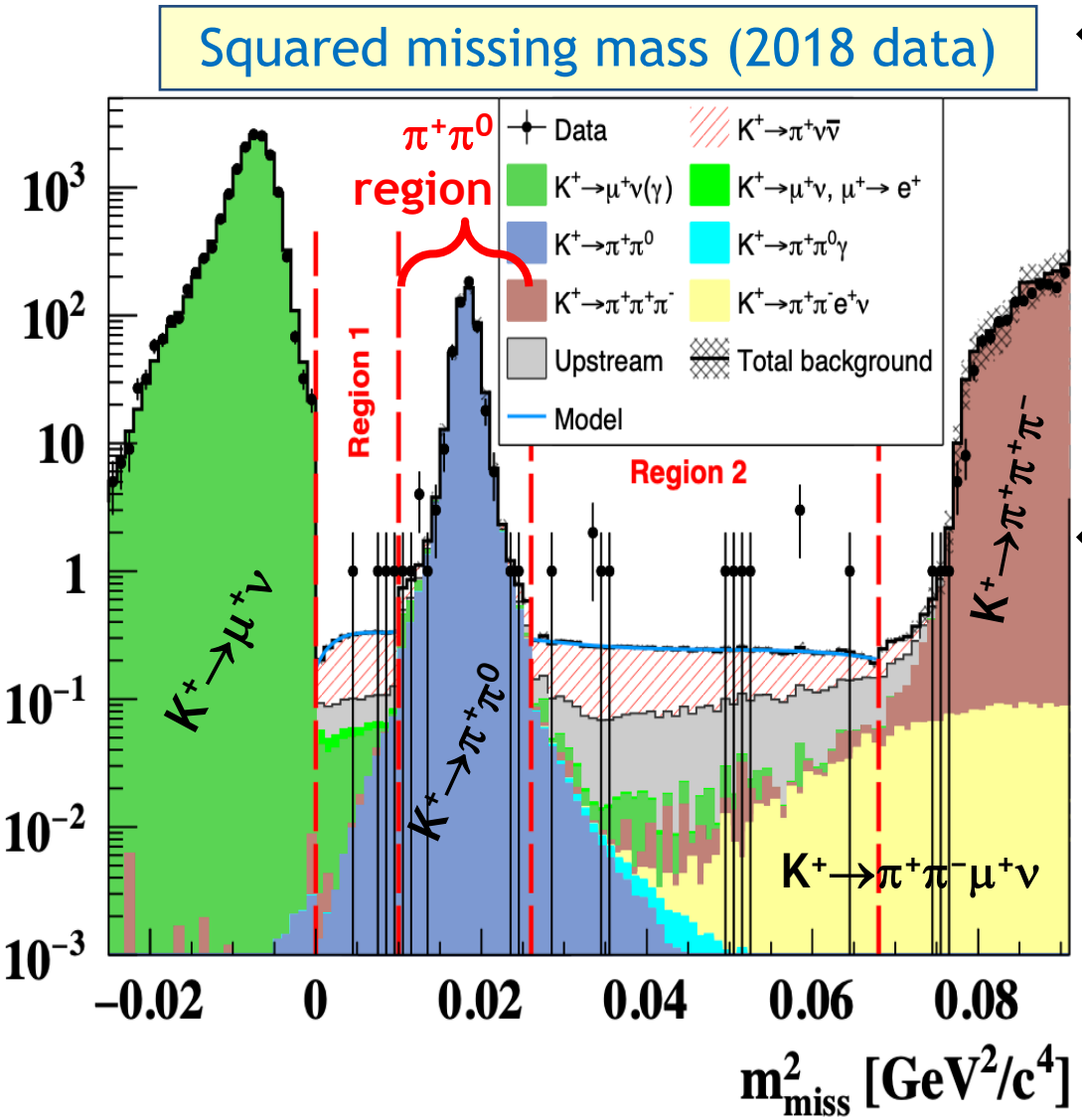
Expected background: $7.03^{+1.05}_{-0.82}$

Expected SM $K_{\pi\nu\nu}$ events:

$10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

Hidden sectors with $K^+ \to \pi^+ \nu\nu$

JHEP 06 (2021) 93, JHEP 02 (2021) 201



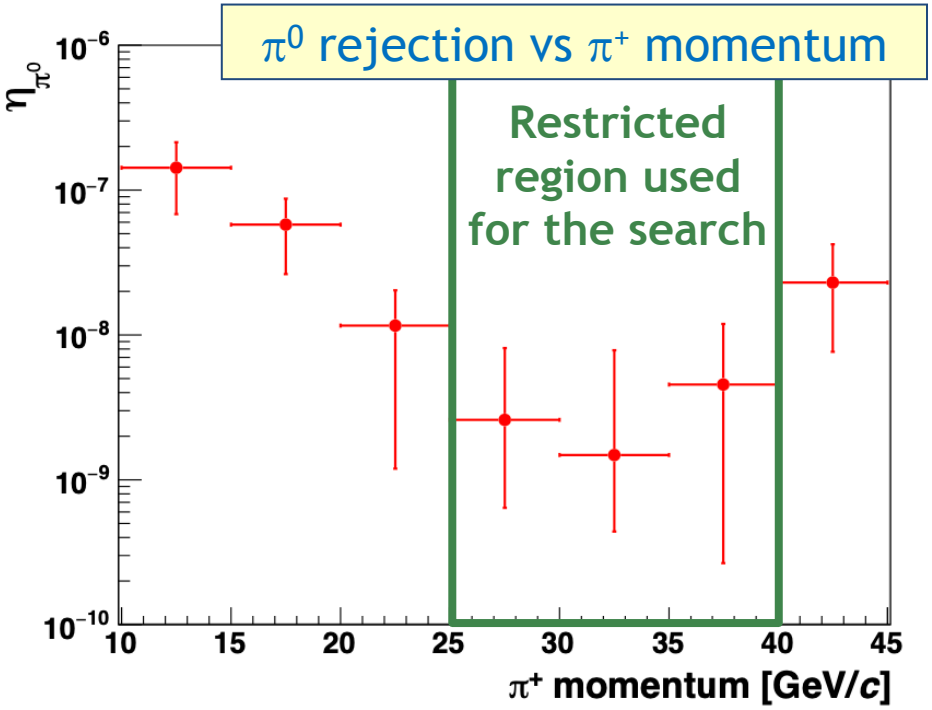
- Signal regions **R1**,**R2**: search for $K^+ \to \pi^+ X$ (X=invisible), $0 \le m_X \le 110$ MeV/c^2 and $154 \le m_X \le 260$ MeV/c^2.
  - ✓ Interpretation: dark scalar, ALP, QCD axion, axiflavon.
  - ✓ Main background: $K^+ \to \pi^+ \nu\nu$.
- The $\pi^+\pi^0$ region: search for $\pi^0 \to$ invisible.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

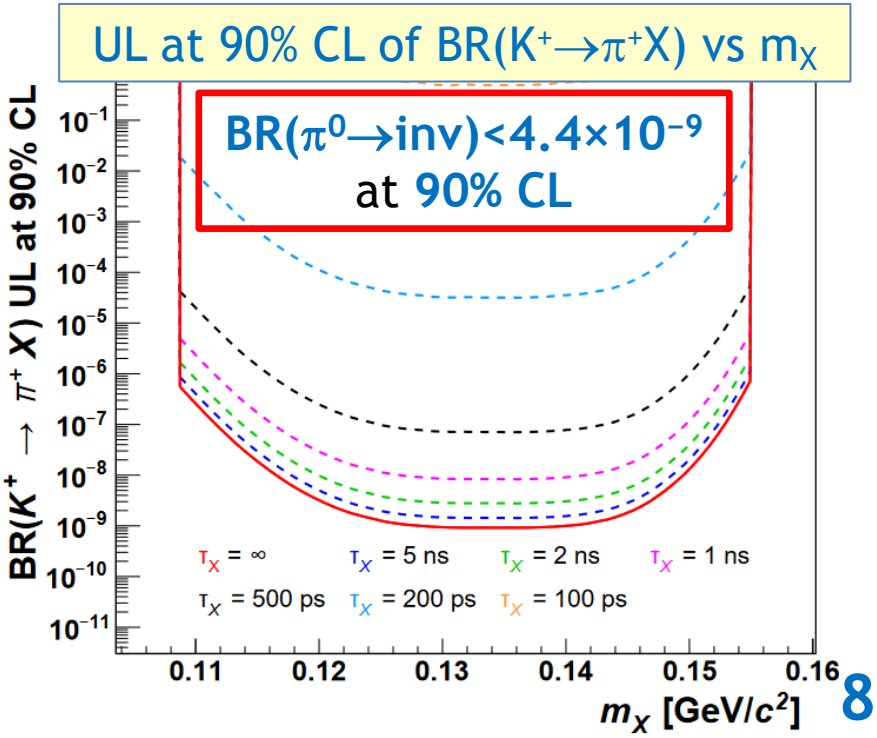
Search for $\pi^0 \to$ invisible

- Rejection of ($K^+ \to \pi^+\pi^0(\gamma)$, $\pi^0 \to \gamma\gamma$) decays: simulations based on single-photon efficiency measurements with $K^+ \to \pi^+\pi^0$ decays. *JHEP 02 (2021) 201*
- Rejection of $\pi^0 \to \gamma\gamma$ decays for $K^+ \to \pi^+\nu\nu$ analysis: $\varepsilon \approx 10^{-8}$.
- For $\pi^0 \to$ invisible search ($25 < p_\pi < 40$ GeV/c): $\varepsilon = (2.8^{+5.9}_{-2.1}) \times 10^{-9}$

Search for $\pi^0 \to$ invisible: (~10% of NA62 Run 1 dataset, 4×10^9 tagged π^0 mesons)

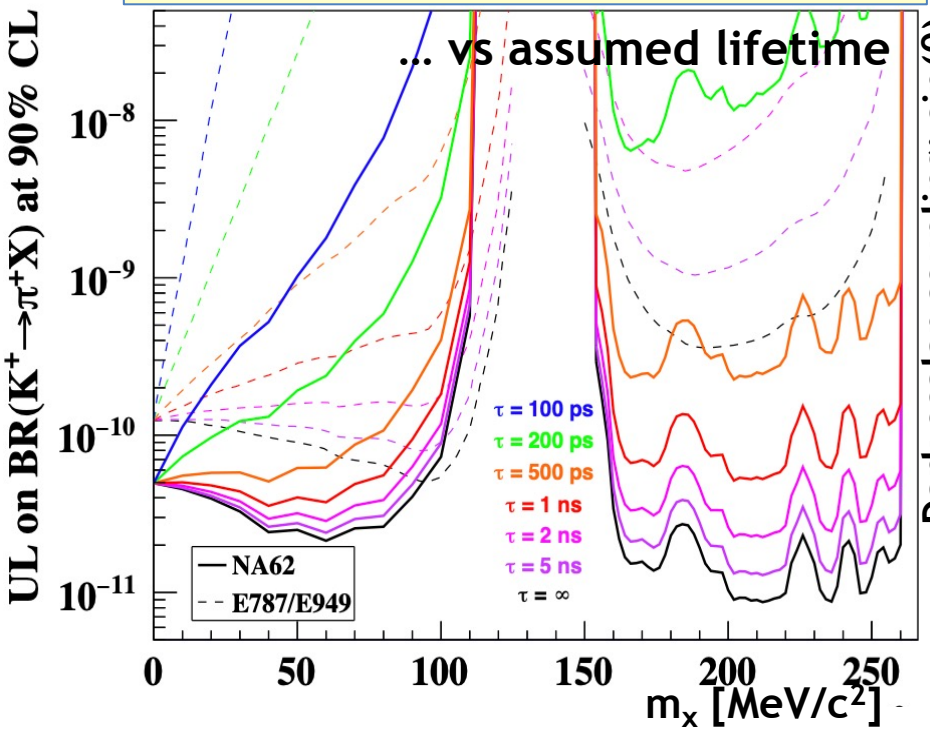
- $K_{\pi\nu\nu}$ trigger and selection used, with $0.015 < m^2_{miss} < 0.021$ GeV^2/c^4.
- Expected $\pi^0 \to \gamma\gamma$ events: 10^{+22}_{-8}, events observed: 12.



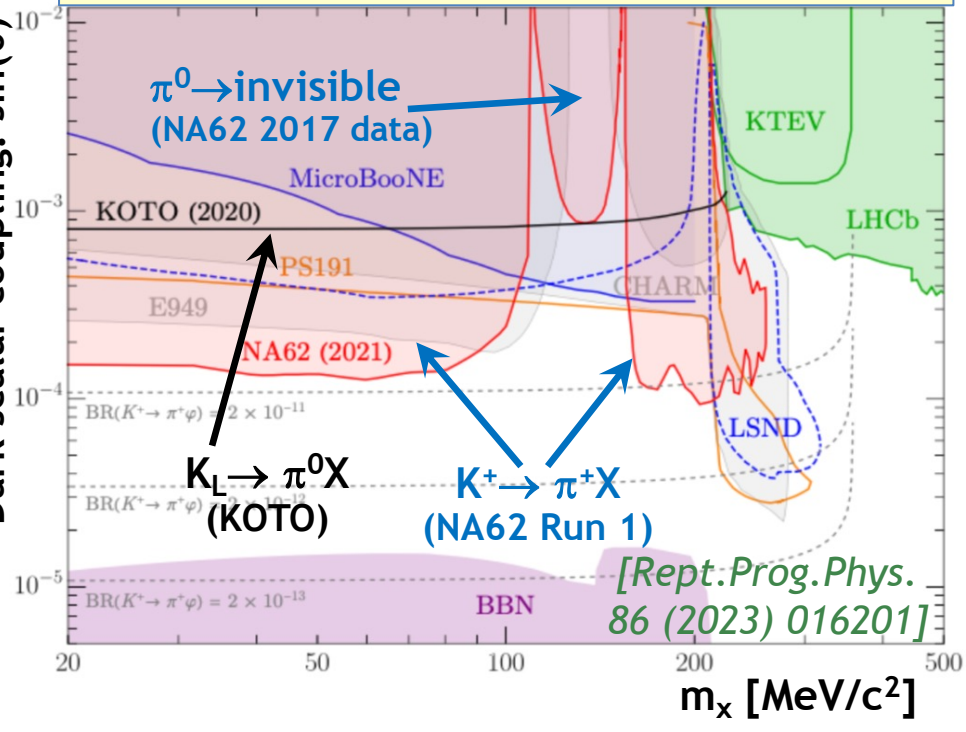


Results: search for $K^+ \to \pi^+ X$

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



Dark scalar searches below the K mass

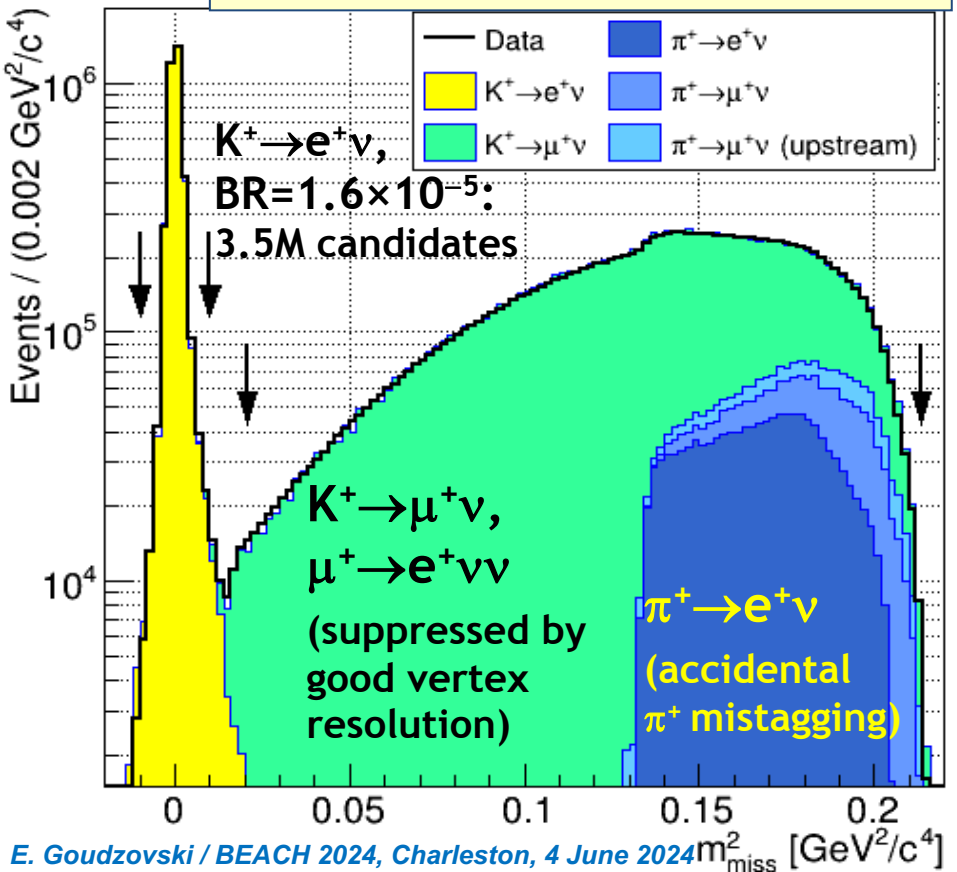


- Mass resolution: $\delta m_X \sim 40$ MeV/c^2 at $m_X=0$, improving at higher m_X.
- Upper limits of $BR(K^+ \to \pi^+ X)$ established depending on X mass and lifetime.
- Improvement on BNL-E949 *[PRD79 (2009) 092004]* over most of m_X range.
- Interpretation shown here: the dark scalar model.
- Note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

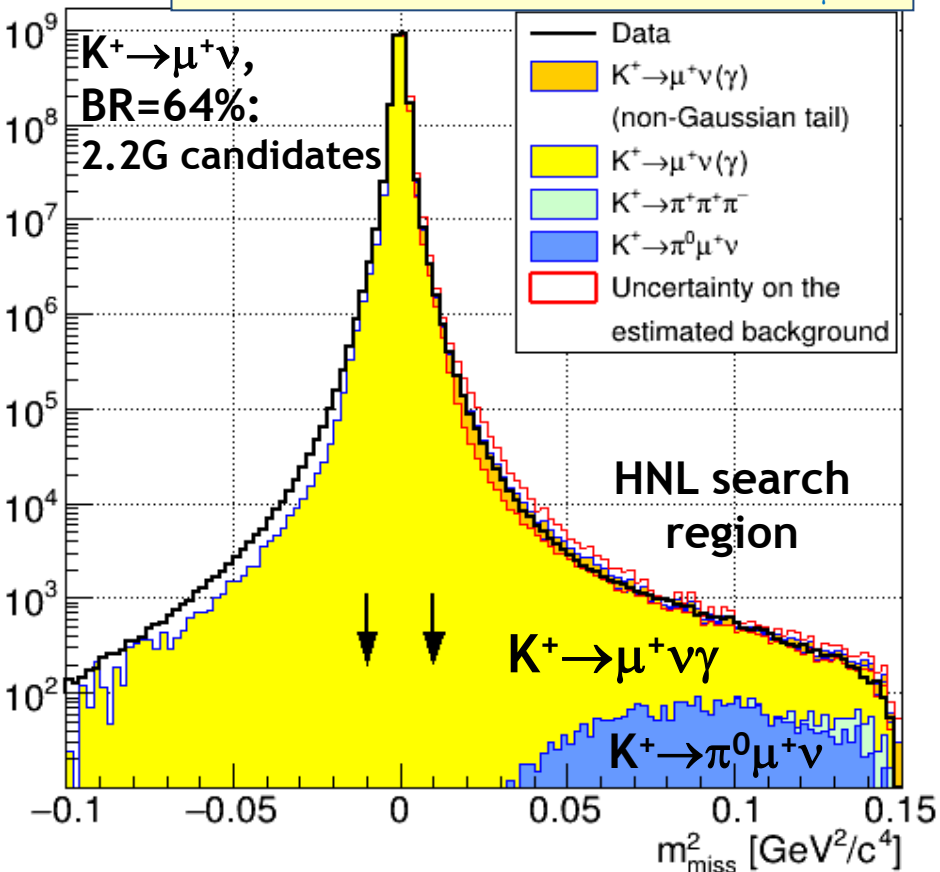
HNL production: NA62 Run 1

- Trigger lines: $K_{\pi\nu\nu}$ for $K^+ \to e^+N$; Control/400 for $K^+ \to \mu^+N$. *PLB807 (2020) 135599*, *PLB816 (2021) 136259*
- 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**.

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

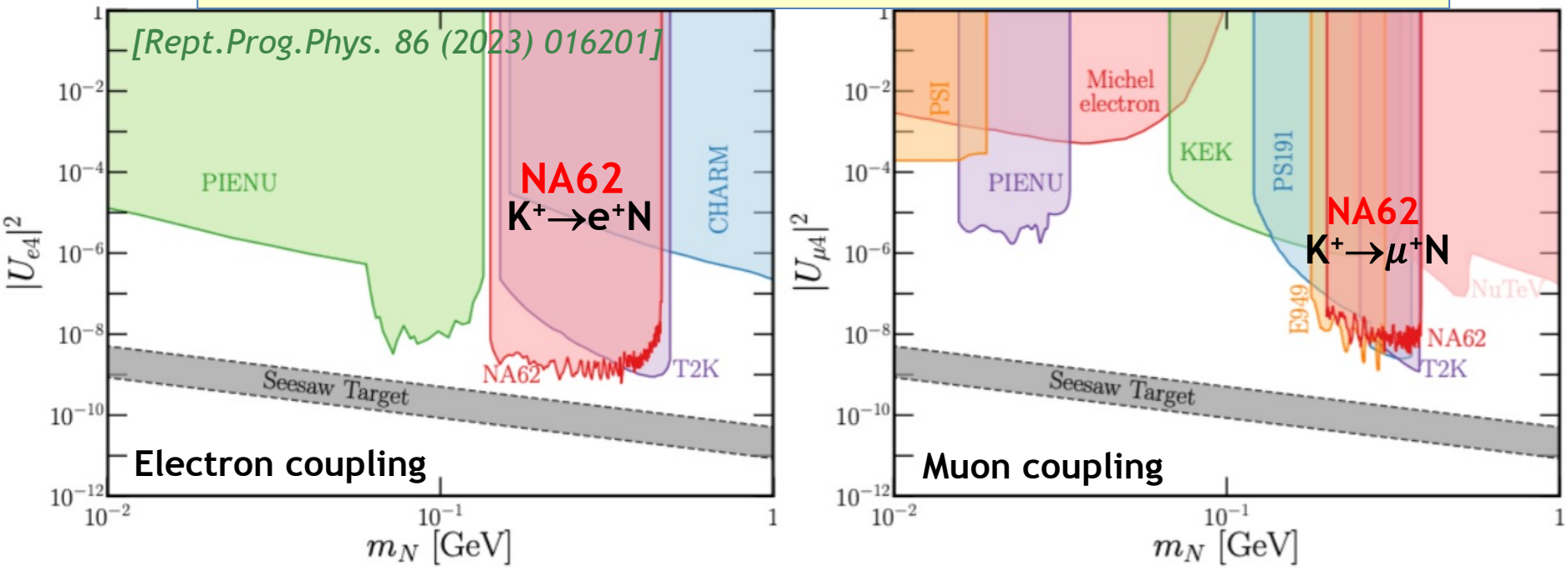


Squared missing mass: $(P_K - P_\mu)^2$



HNL production: results

BC6,7: $|U_{\ell 4}|^2$ limits vs m_{HNL} from production & decay searches



- 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 pion experiments might reach the seesaw bound.

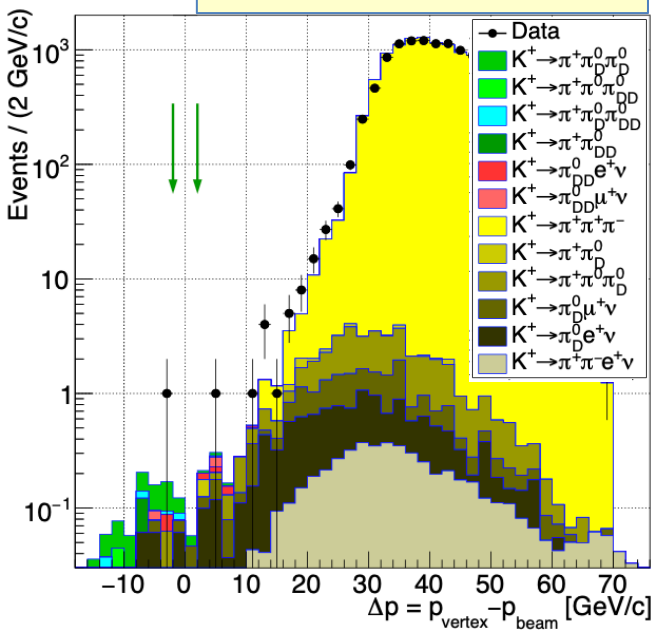
- Upper limit at 90% CL: $BR(K^+ \to \mu^+ \nu\nu\nu) < 1.0 \times 10^{-6}$, and similar limits of $BR(K^+ \to \mu^+ \nu X)$, with X=invisible.

[PLB 807 (2020) 135599; PLB 816 (2021) 136259]

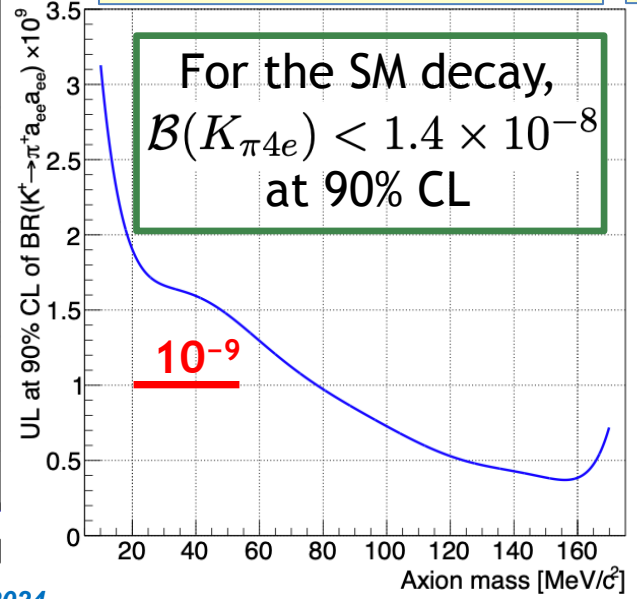
Pair-production of exotic states

- NA62 Run 1, multi-electron trigger, $N_K = 8.6\times10^{11}$. *PLB846 (2023) 138193*
- Production and prompt decays of axion pairs, $K^+\to\pi^+aa$, $a\to e^+e^-$: exclusion of the QCD axion explanation for the "17 MeV anomaly".
  - ✓ Expect $BR(K^+\to\pi^+aa)>2\times10^{-8}$ for $m_a=17$ MeV.
    [Alves, PRD103 (2021) 055018; Hostert and Pospelov, PRD105 (2022) 015017]
- Prompt dark cascade involving a dark scalar (S) and dark photons (A'): $K^+\to\pi^+S$, $S\to A'A'$, $A'\to e^+e^-$.
- The SM decay: $BR_{SM}(K^+\to\pi^+e^+e^-e^+e^-)=(7.2\pm0.7)\times10^{-11}$ [Husek, PRD106 (2022)]

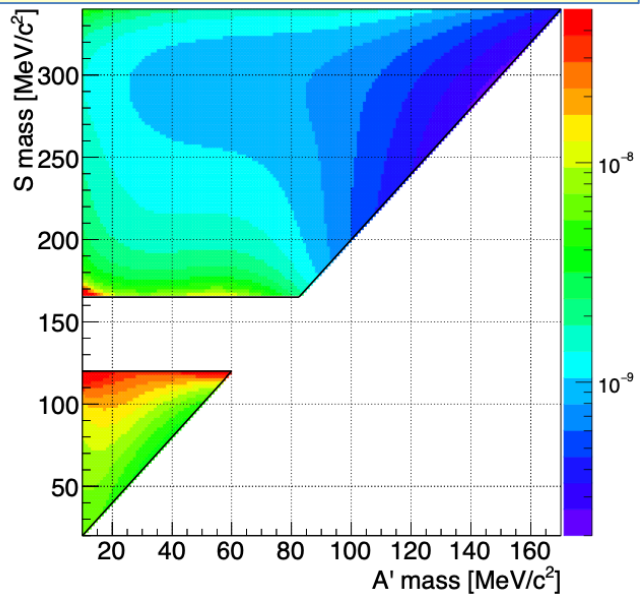
Momentum excess



UL at 90% CL of $BR(K^+\to\pi^+a_{ee}a_{ee})$ vs m_a



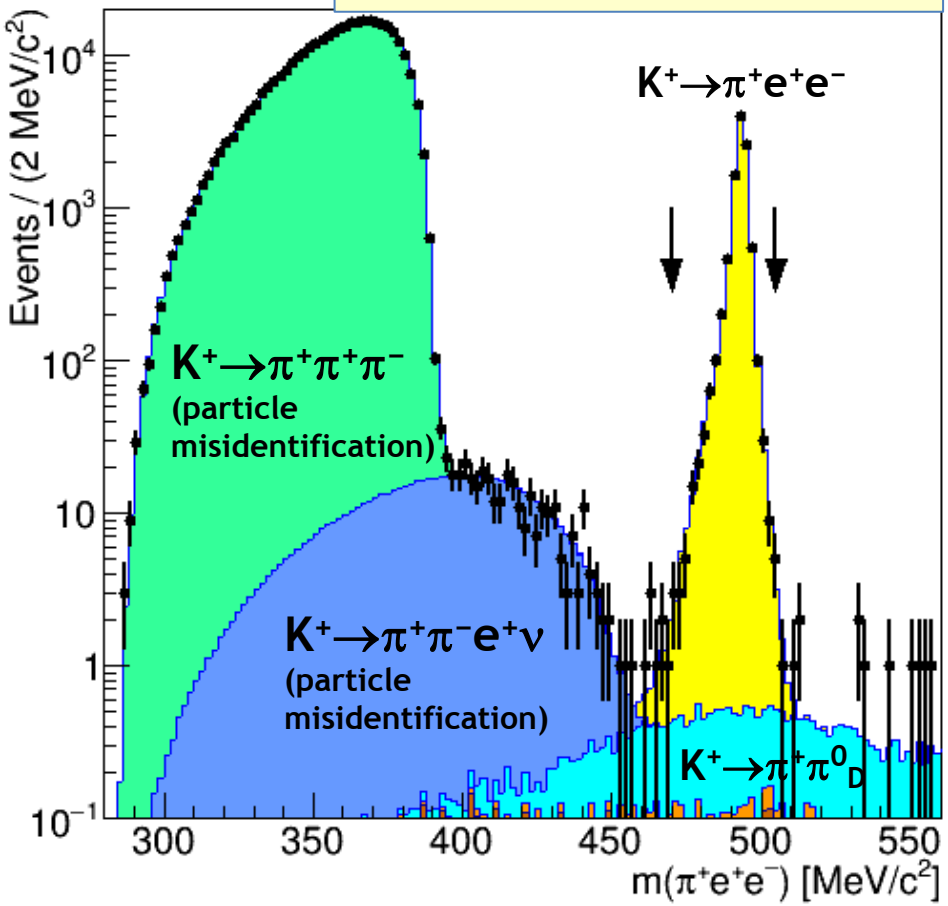
UL of $BR(K^+\to\pi^+S, S\to A'_{ee}A'_{ee})$ vs $(m_{A'}, m_S)$



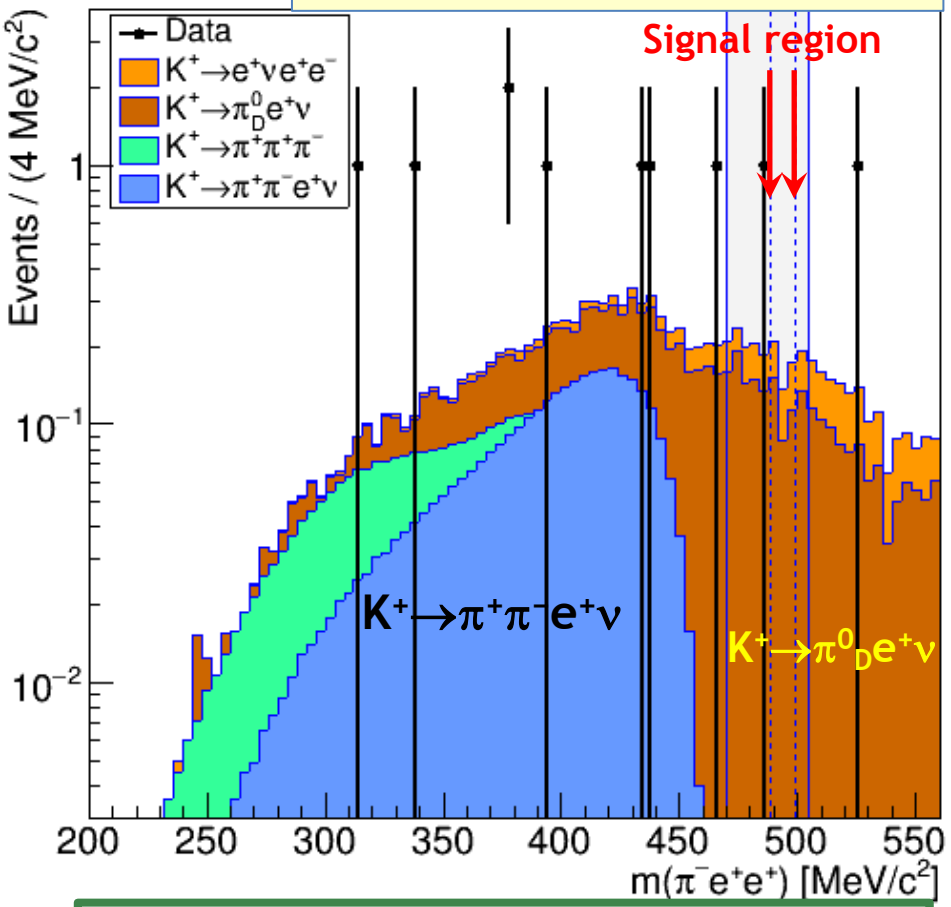
Searches for LFV/LNV in kaon decays

Search 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)×10¹²**

Expected background: **0.43±0.09** evt

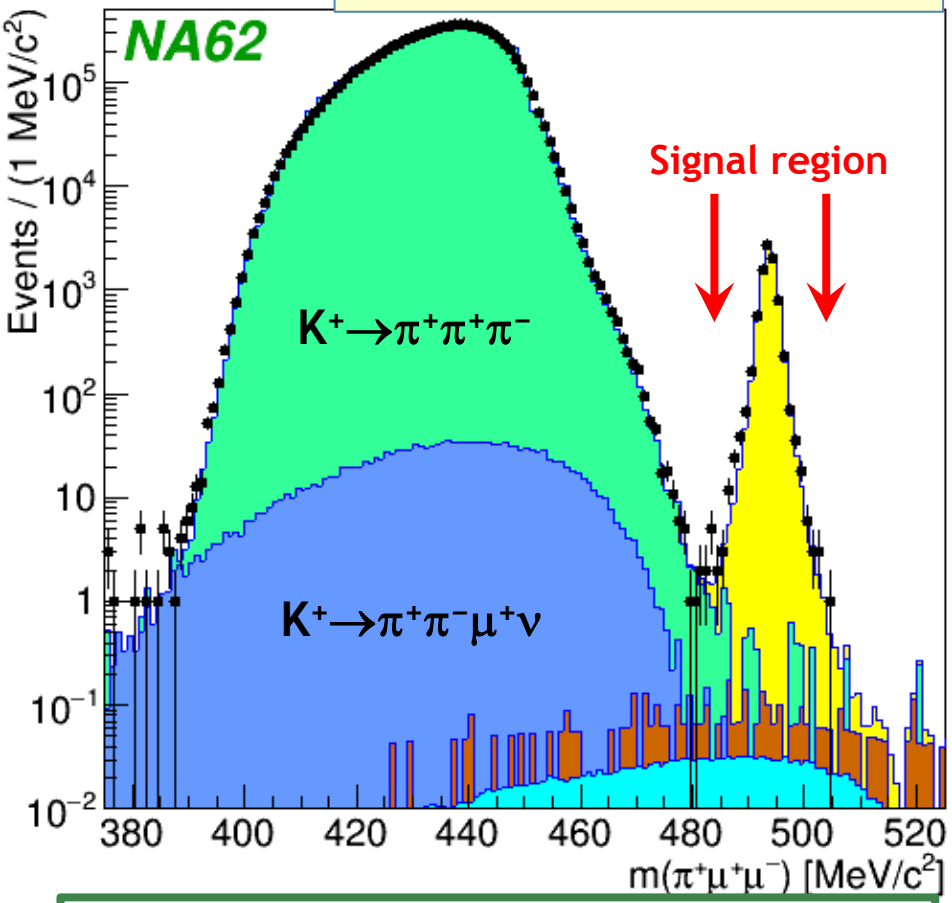
Candidates observed: **0**

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

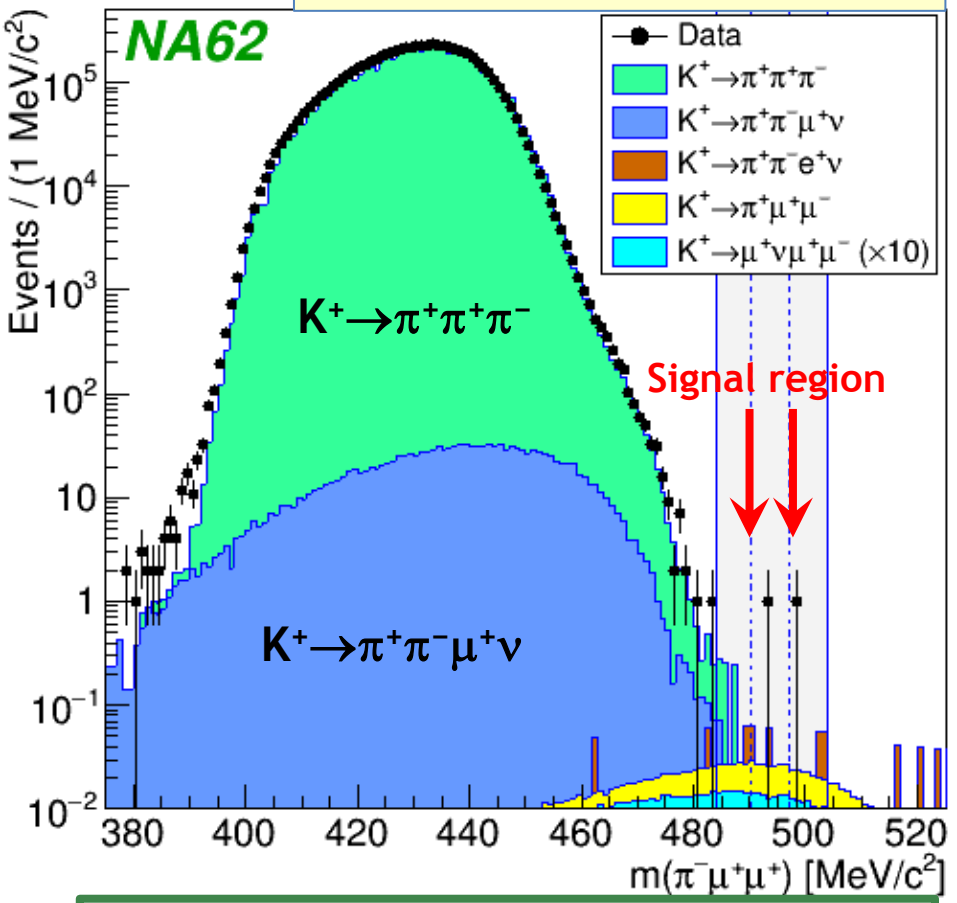
PLB830 (2022) 137172

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

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



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



Candidates (25% of Run 1 data): **8357**
Background: **0.07%**
BR($K^+ \to \pi^+\mu^+\mu^-$) = (0.962±0.025)×10^{-7}
K^+ decays in FV: (7.94±0.23)×10^{11}

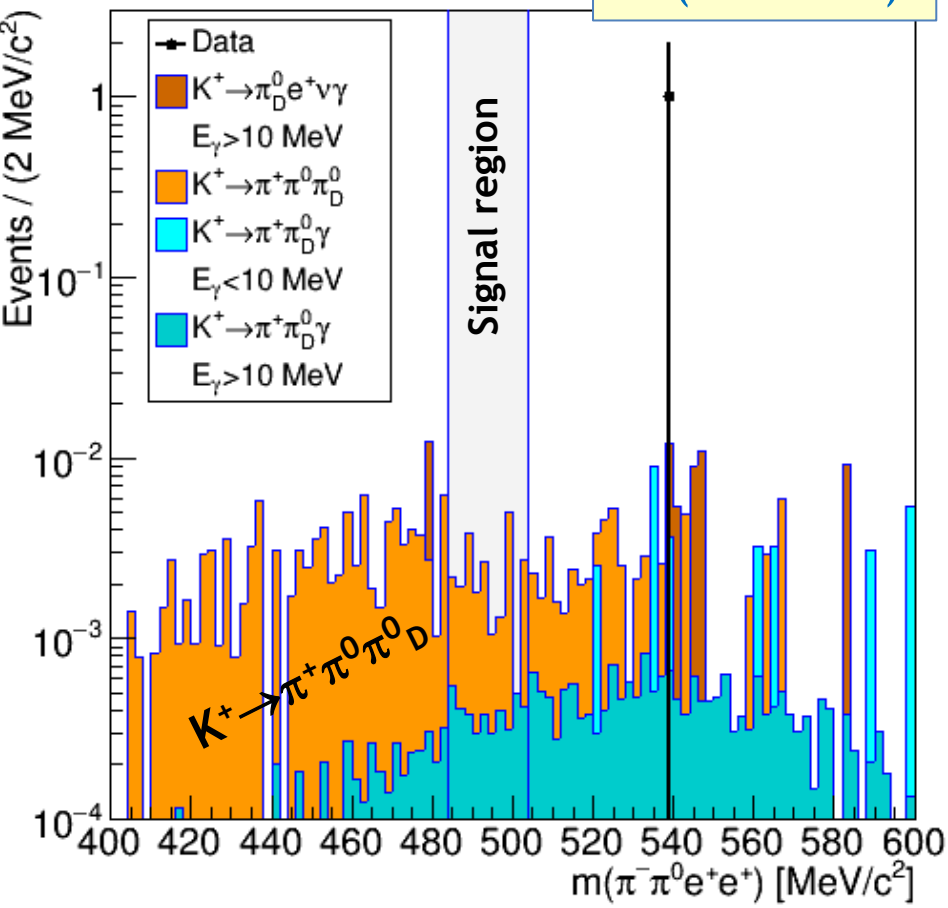
Expected background: **0.91±0.41** evt
Candidates observed: **1**
BR($K^+ \to \pi^-\mu^+\mu^+$)<4.2×10^{-11} at 90% CL

PLB797 (2019) 134794

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

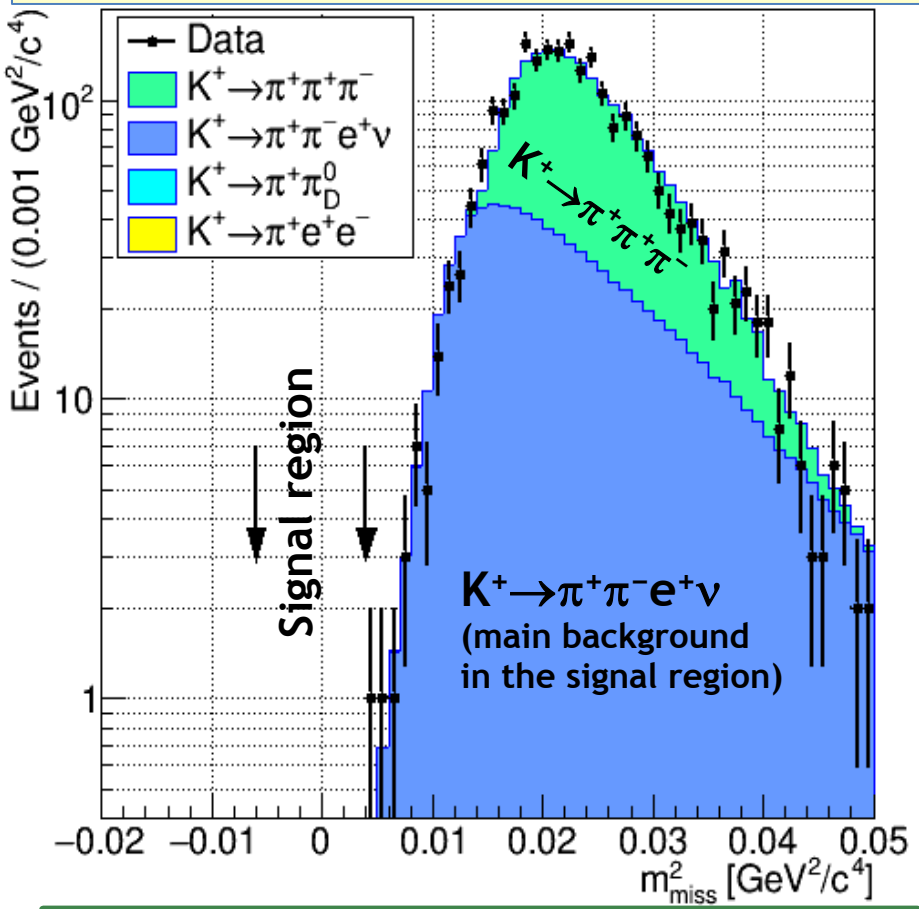
PLB830 (2022) 137172
PLB838 (2023) 137679

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



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, $(P_K - P_\mu - P_{e1} - P_{e2})^2$

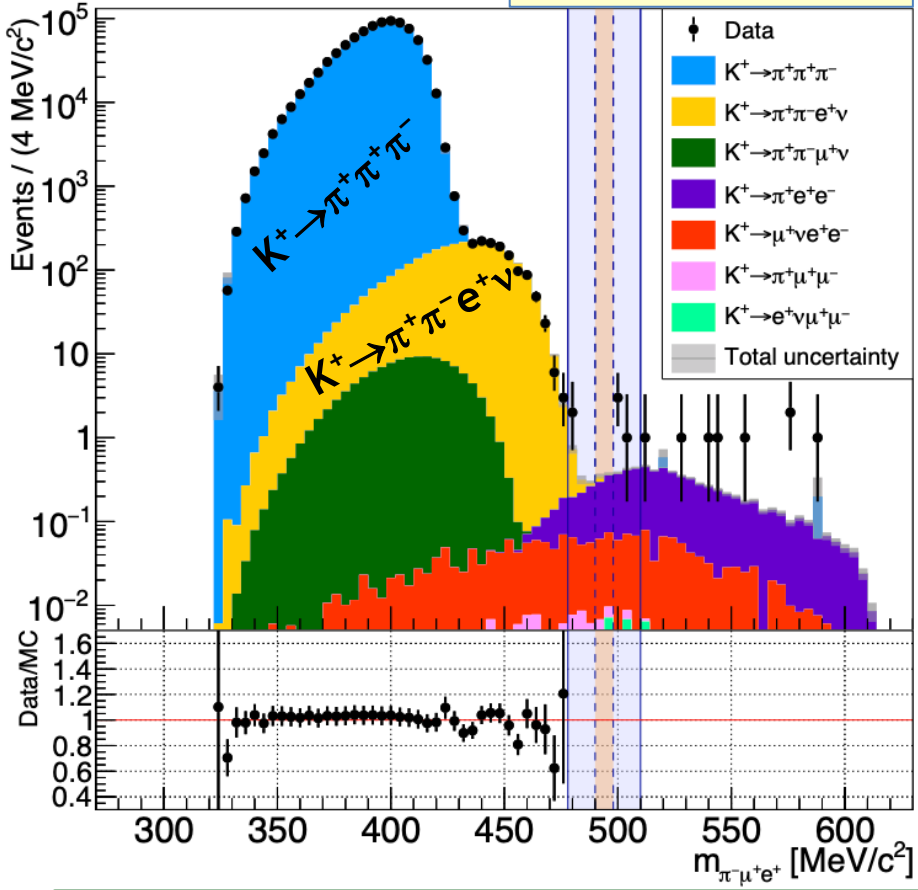


Expected background: **0.26±0.04** evt
Candidates observed: **0**
BR($K^+ \to \mu^- \nu e^+ e^+$)<8.1×10^{-11} at 90% CL

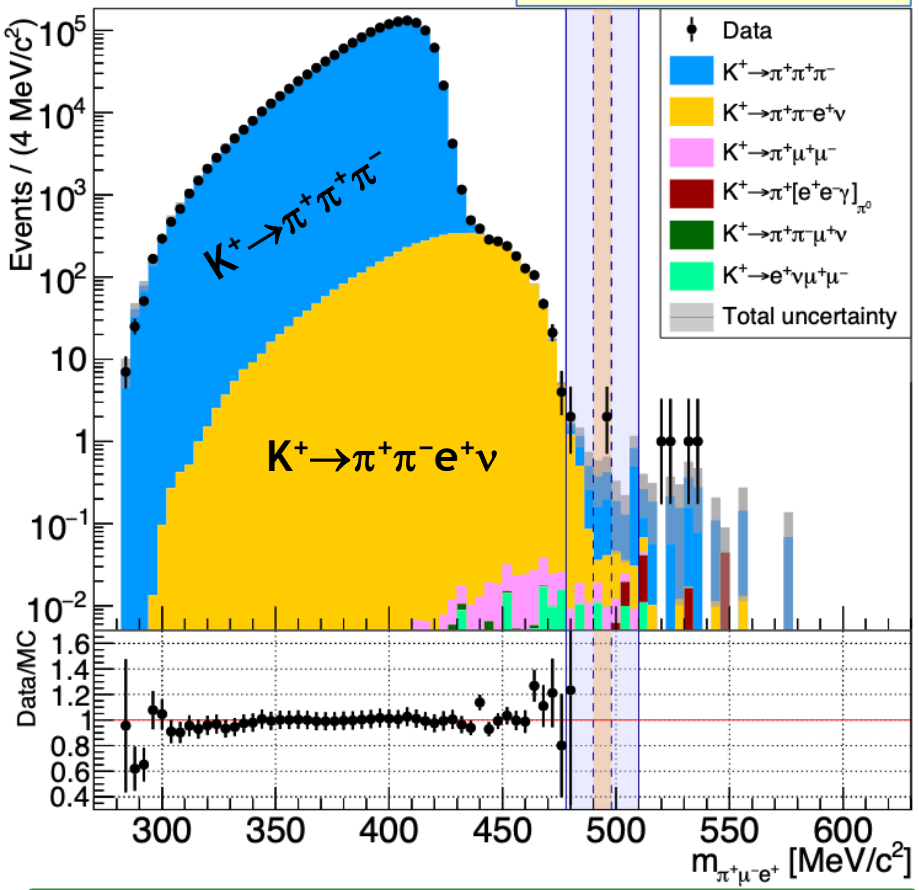
Search for $K^+ \to \pi\mu e$ decays

PRL 127 (2021) 131802

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



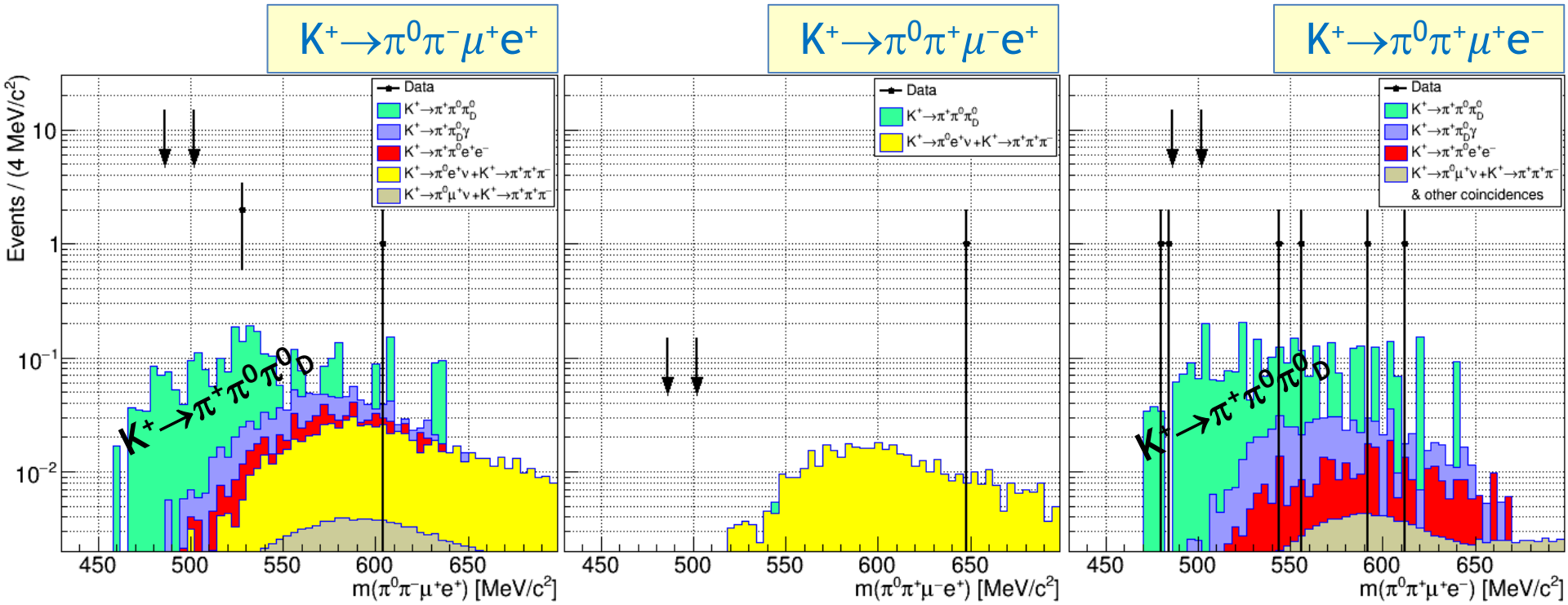
LFV: $m(\pi^+\mu^-e^+)$



K^+ decays in FV: $(1.33\pm0.02)\times10^{12}$
Expected background: 1.07 ± 0.20 evt
Candidates observed: 0
$BR(K^+\to\pi^-\mu^+e^+)<4.2\times10^{-11}$ at 90% CL

Expected background: 0.92 ± 0.34 evt
Candidates observed: 2
$BR(K^+\to\pi^+\mu^-e^+)<6.6\times10^{-11}$ at 90% CL
$BR(\pi^0\to\mu^-e^+)<3.2\times10^{-10}$ at 90% CL

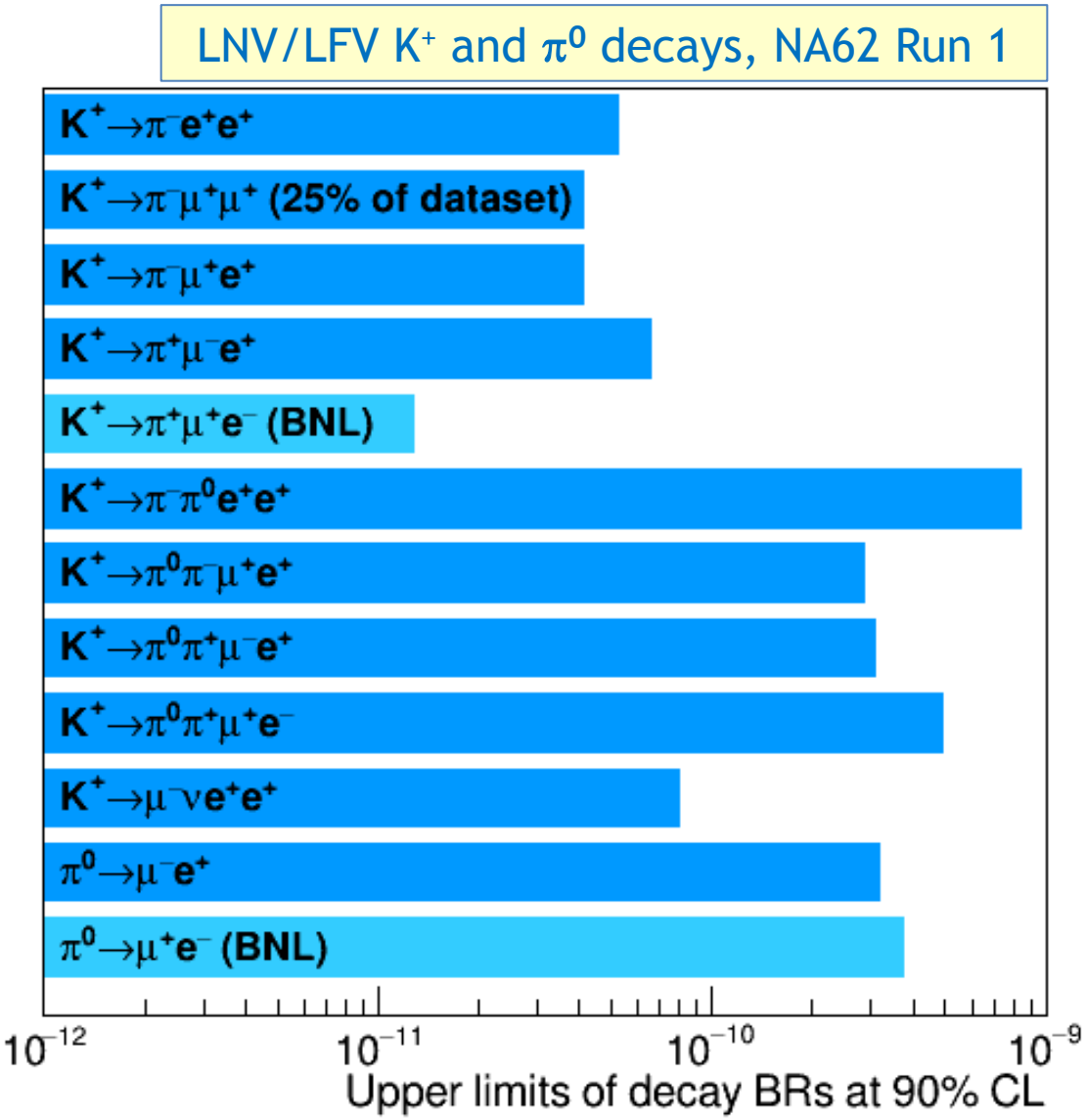
Search for $K^+ \to \pi^0 \pi \mu e$ decays



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}

[First presented at BEACH 2024, to be published]

LFV/LNV K^+ decays: state of the art



Summary

- Kaon decays: a unique probe for new physics.
  - ✓ Large decay samples are available (~10^{13} decays).
  - ✓ Often simple and clean final states, low backgrounds.
  - ✓ Kaon SM decay width is suppressed wrt heavy mesons.

- NA62 at CERN is collecting data from **2016** till at least **2025**.
  - ✓ World's largest multi-purpose sample of K^+ decays.
  - ✓ The final K^+ decay experiment, in the observable future.
  - ✓ First measurement of the ultra-rare $K^+ \to \pi^+ \nu\nu$ decay.

- Searches for hidden sectors in kaon decays at NA62 address a range of PBC benchmark scenarios.
  - ✓ $K^+ \to \pi^+ X_{inv}$: dark scalar (BC4) and ALP (BC10,11).
  - ✓ $K^+ \to \ell^+ N$: heavy neutral leptons (BC6,7).
  - ✓ Also non-minimal scenarios, e.g. $K^+ \to \pi^+ aa$.

- NA62 LFV/LNV programme: **10** decay modes addressed so far.