

# NA62 results and HIKE prospects on FIPs

Evgueni Goudzovski

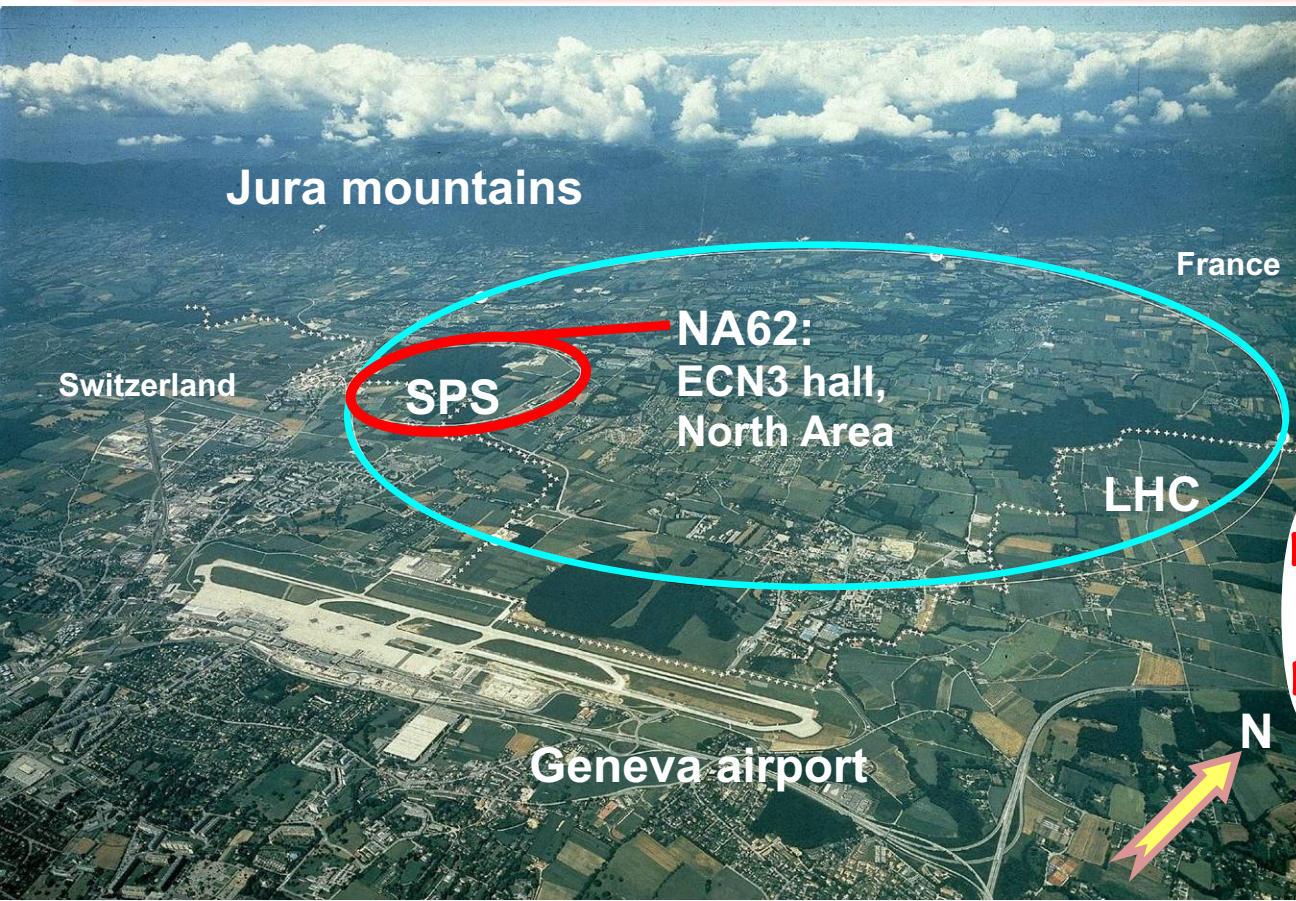
UNIVERSITY OF  
BIRMINGHAM

## Outline:

1. The NA62 experiment and the HIKE proposal
2. Dark scalar and ALP production in  $K^+/K_L$  decays (BC4,10)
3. Heavy neutral lepton production in  $K^+$  decays (BC6,7)
4. Results and prospects in beam-dump mode
5. Summary



# Kaon experiments at CERN



Main **NA62** goal:  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  measurement to **10%** precision with a novel decay-in-flight technique.

Currently **~300** participants from **~30** institutions.

## Earlier: NA31

1997:  $\epsilon'/\epsilon$ :  $K_L + K_S$

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**  
discovery of direct CPV

2002:  $K_S$ /hyperons

**NA48/1**

2003:  $K^+ / K^-$

**NA48/2**

2004:  $K^+ / K^-$

**NA62**  
 $R_K$  run

2007:  $K_{e2}^+ / K_{\mu2}^+$  | tests

2008:  $K_{e2}^+ / K_{\mu2}^+$  | tests

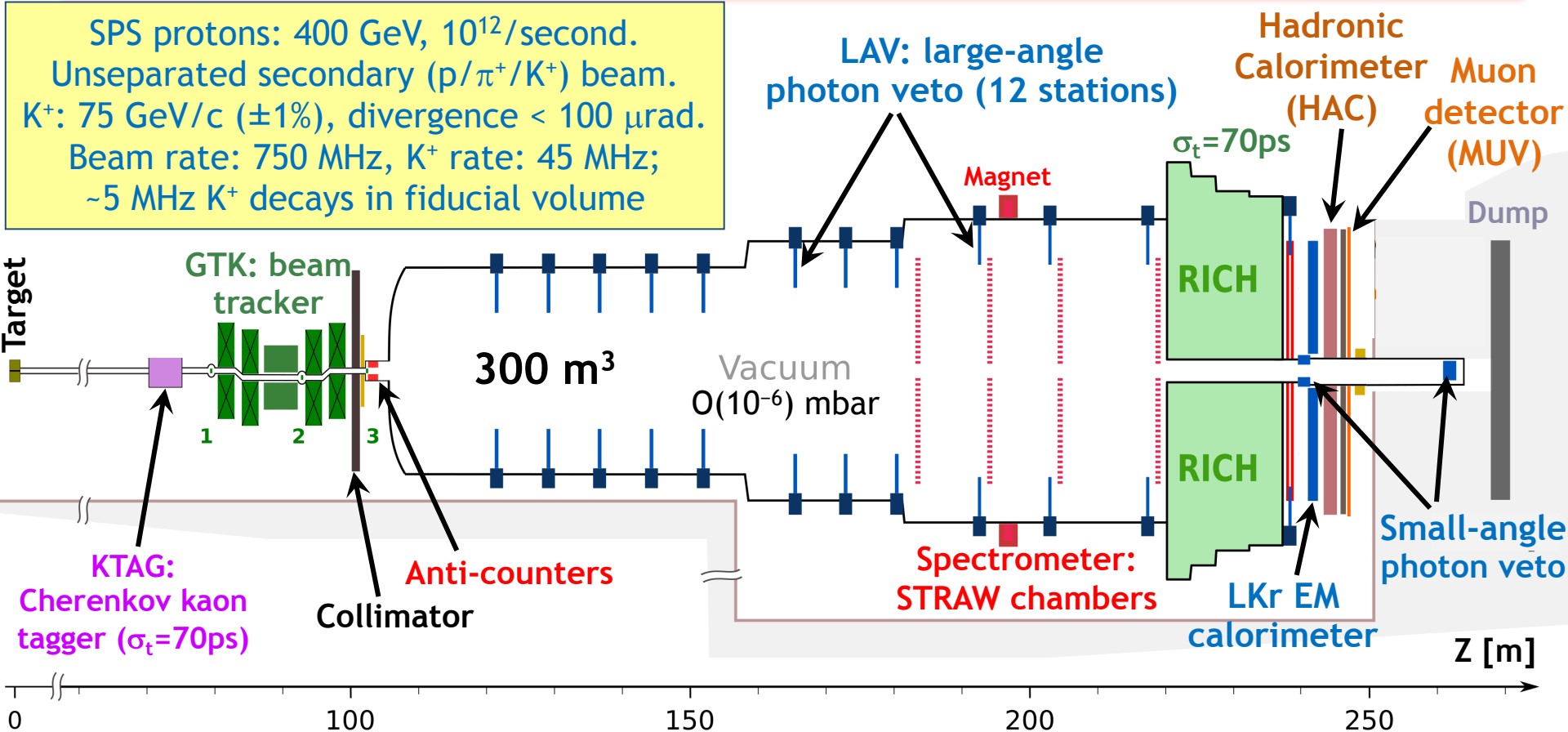
**NA62**

2015: commissioning

2016-18: physics run 1

2021-: physics run 2

# The NA62 experiment



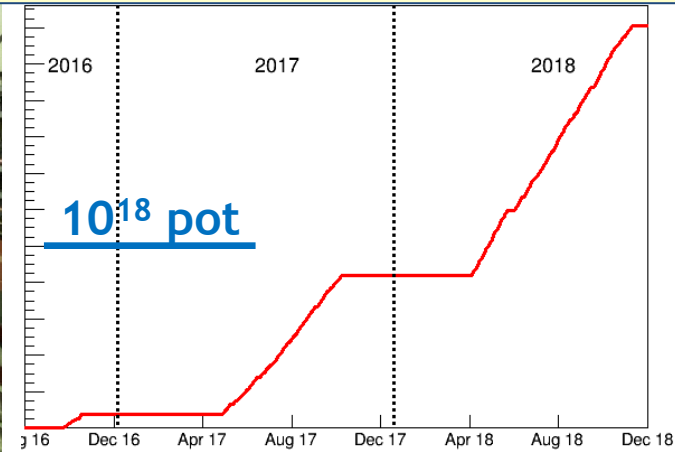
- ❖ In 2018, 1 year of operation  $\approx 10^{18}$  protons on target;  $4 \times 10^{12}$   $K^+$  decays.
- ❖ Single event sensitivities for  $K^+$  decays: approaching  $BR \sim 10^{-12}$ .
- ❖ Kinematic rejection factors:  $1 \times 10^{-3}$  for  $K^+ \rightarrow \pi^+ \pi^0$ ,  $3 \times 10^{-4}$  for  $K \rightarrow \mu^+ \nu$ .
- ❖ Hermetic photon veto:  $\pi^0 \rightarrow \gamma\gamma$  decay suppression (for  $E_{\pi^0} > 40$  GeV)  $\sim 10^{-8}$ .
- ❖ Particle ID (RICH+LKr+HAC+MUV):  $\sim 10^{-8}$  muon suppression.



# NA62 datasets



Run 1 integrated luminosity



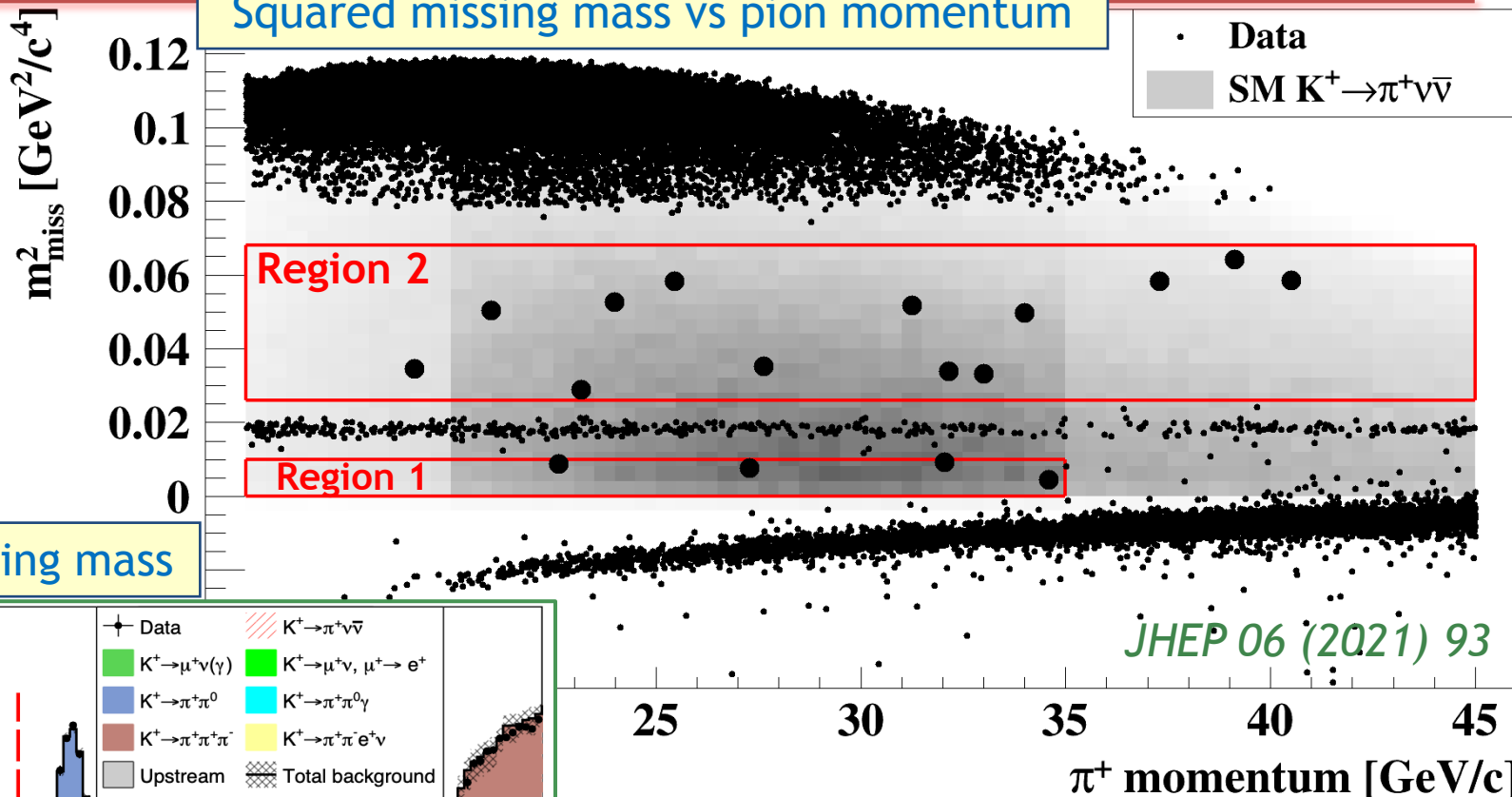
$2.2 \times 10^{18}$  pot collected

- ❖ Run 1 (2016–18): ~400 days of data collection in total.
  - ✓ Proton beam intensity:  $2.3 \times 10^{12}$  ppp in 2018.
  - ✓ Data sample in  $K^+$  mode:  $2.2 \times 10^{18}$  pot,  $6 \times 10^{12}$  useful  $K^+$  decays.
- ❖ Run 2 (2021–): approved till LS3, improved detector,  $3 \times 10^{12}$  ppp.
  - ✓ Expect much larger sample in  $K^+$  mode.
  - ✓ Beam-dump mode:  $1.4 \times 10^{17}$  pot collected, expect  $10^{18}$  pot by LS3.3

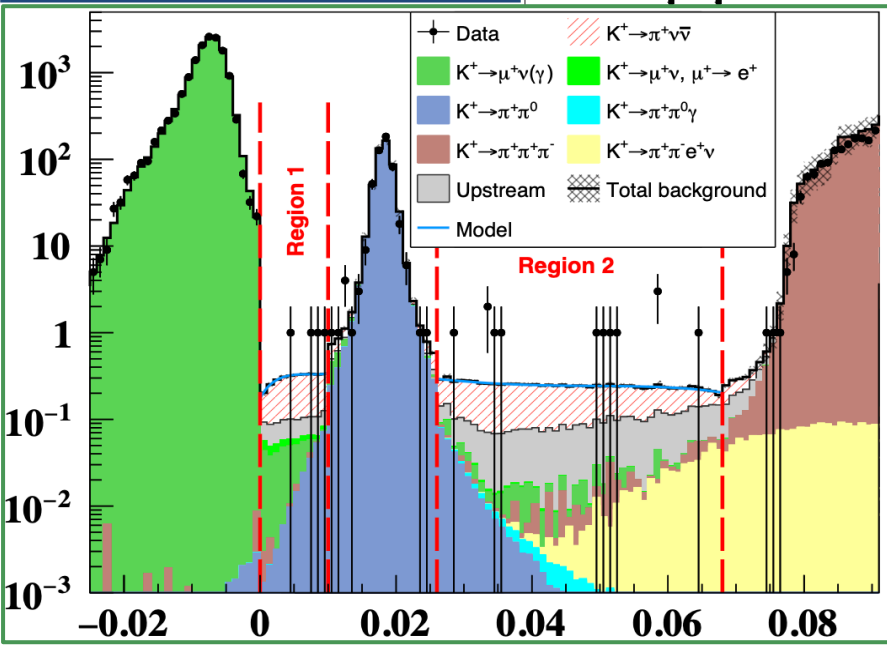
# The HIKE proposal at CERN

- ❖ SPS fixed target operation foreseen **until at least 2038**.
- ❖ **HIKE** (“*High-Intensity Kaon experiments*”):  
a long-term programme rare kaon decay programme at the SPS.
- ❖ Proton beam intensity required:  $2 \times 10^{13}$  ppp,  $1.2 \times 10^{19}$  pot/year.
- ❖ Experimental challenge:  $\sim 20$  ps time resolution for main detectors.
- ❖ A series of  $K^+$  and  $K_L$  decay experiments in the ECN3 (NA62) hall:
  - ✓ phase 1: a multi-purpose  $K^+$  decay experiment, focused on  $K^+ \rightarrow \pi^+ \nu \nu$  measurement to  $\sim 5\%$  precision;
  - ✓ phase 2: a multi-purpose  $K_L$  decay experiment with charged-particle detection and PID, focused on  $K_L \rightarrow \pi^0 \ell^+ \ell^-$ ;
  - ✓ phase 3: a dedicated  $K_L \rightarrow \pi^0 \nu \nu$  experiment (**KLEVER**).
- ❖ A few times  $10^{19}$  pot to be collected in beam dump mode, in conjunction with the **SHADOWS** off-axis experiment.
- ❖ Snowmass contributed paper: [arXiv:2204.13394](https://arxiv.org/abs/2204.13394).
- ❖ Submission of Lol to the SPSC: **November 2022**.

# NA62 Run 1 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ result



Squared missing mass



## Full Run 1 data set:

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

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

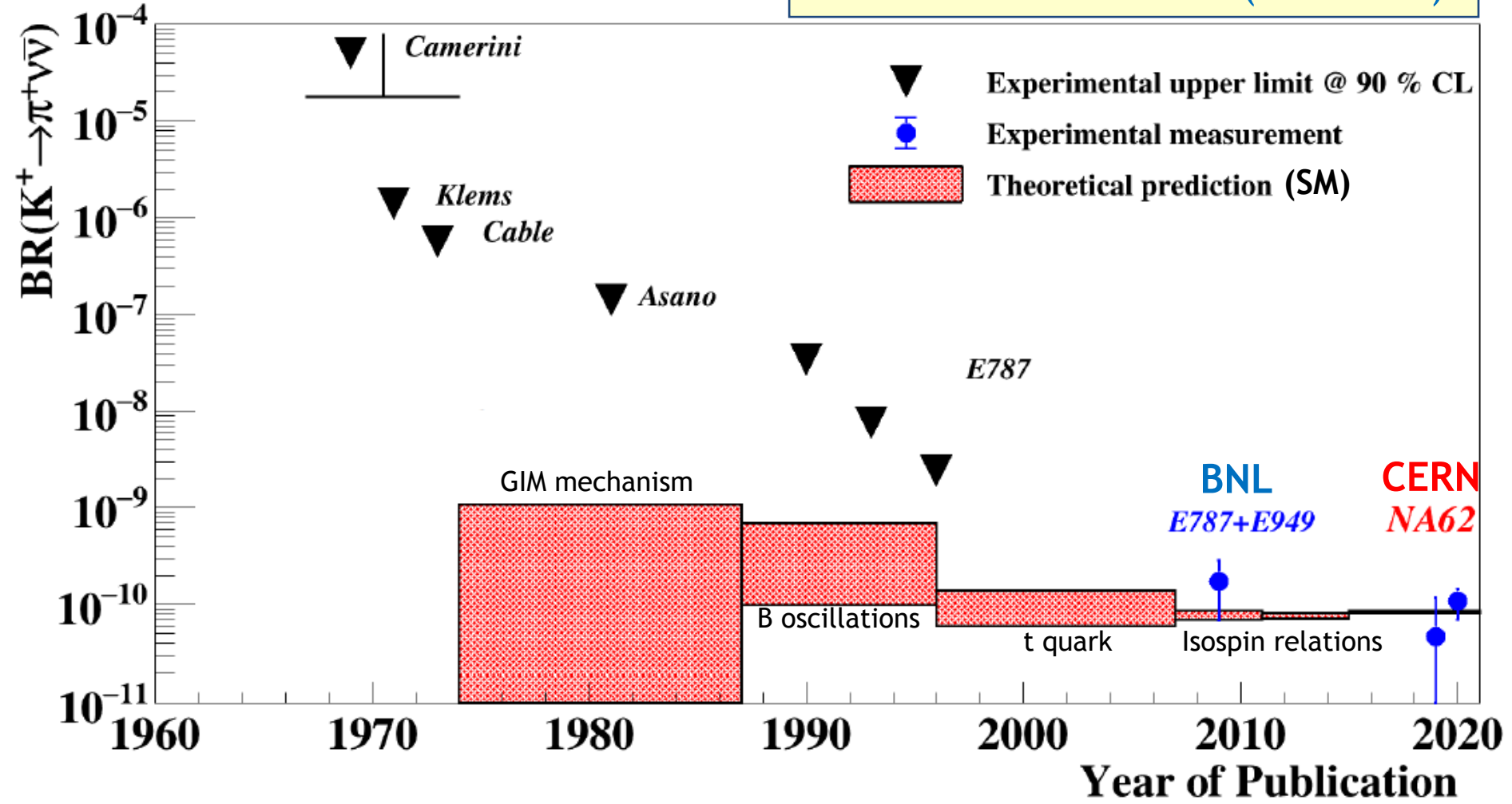
Expected SM events:

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

# History of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ searches

JHEP 06 (2021) 93

Time evolution of  $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

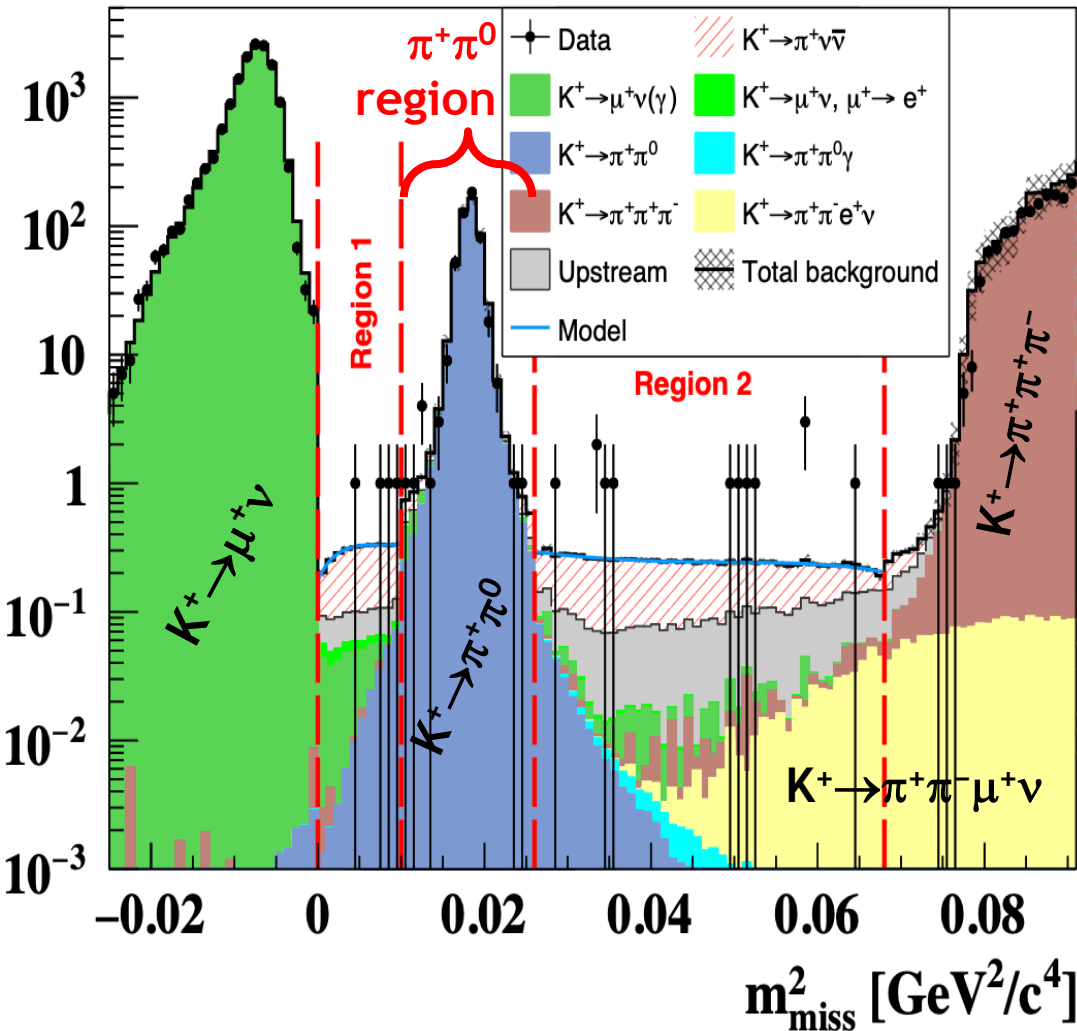


NA62 Run 1:  $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6_{-3.4}^{+4.0} |_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-11}$

(3.4 $\sigma$  significance)

# Hidden sectors with $K^+ \rightarrow \pi^+ \nu \nu$

Squared missing mass (NA62 2018 data)

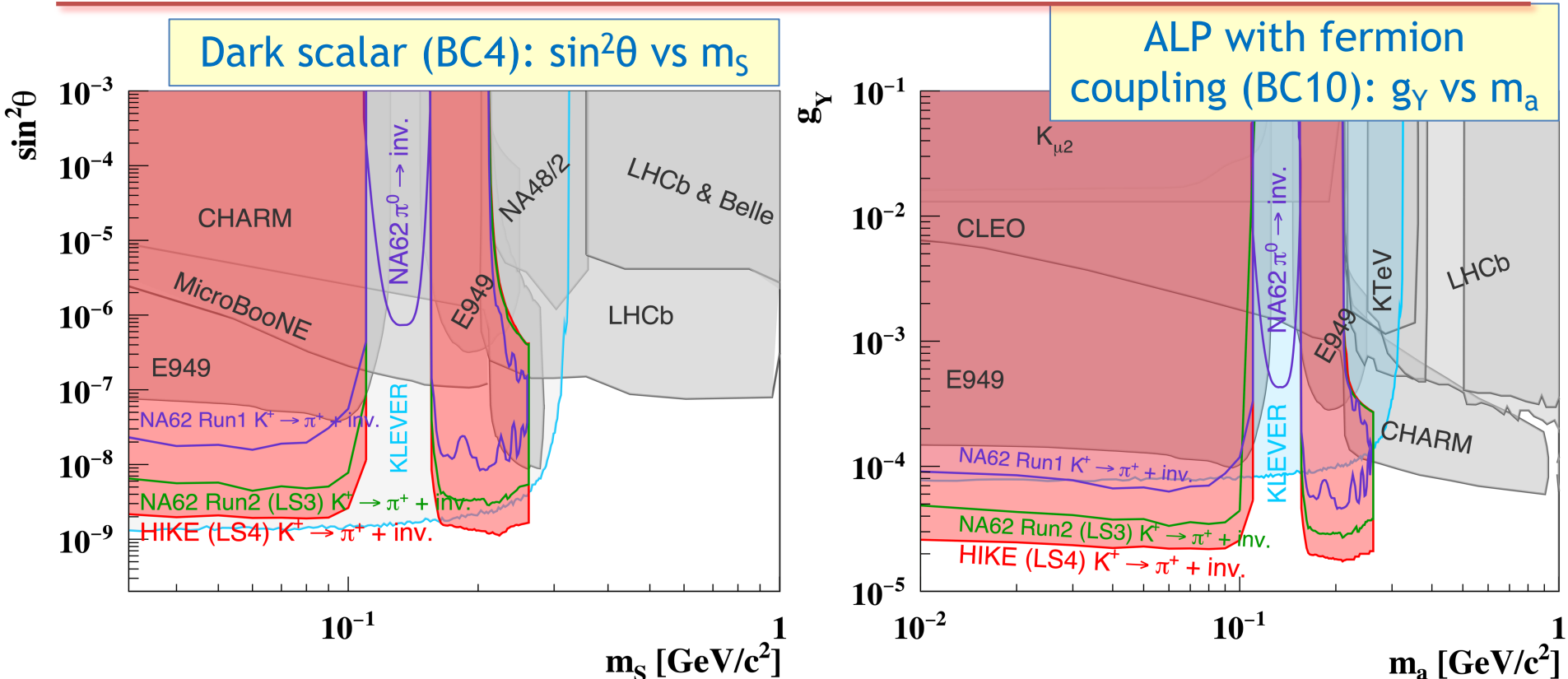


- ❖ Signal regions **R1, R2**: search for  $K^+ \rightarrow \pi^+ X$  ( $X$ =invisible),  $0 \leq m_X \leq 110 \text{ MeV}/c^2$  and  $154 \leq m_X \leq 260 \text{ MeV}/c^2$ .
  - ✓ Interpretation: dark scalar, ALP, QCD axion, axiflavor.
  - ✓ Main background:  $K^+ \rightarrow \pi^+ \nu \nu$ .

- ❖ The  $\pi^+ \pi^0$  region: search for  $\pi^0 \rightarrow$ invisible.
  - ✓ Tiny SM  $\pi^0 \rightarrow \nu \nu (\nu \nu)$  rates.
  - ✓ Observation = BSM physics.
  - ✓ Reduction of  $\pi^0 \rightarrow \gamma \gamma$  background: optimised  $\pi^+$  momentum range.
  - ✓ Interpretation as  $K^+ \rightarrow \pi^+ X$ , with  $m_X$  between R1 and R2.



# Dark scalar/ALP results & projections



- ❖ **NA62 Run 1**: published results.  
[JHEP 02 (2021) 201, JHEP 03 (2021) 58, JHEP 06 (2021) 93]
- ❖ **NA62 Run 2** projection: 5-fold increase in statistics wrt Run 1 assumed.  
[CERN-SPSC-2019-039]
- ❖ **HIKE** projection: 40-fold increase in statistics wrt Run 1 assumed.
- ❖ **KLEVER** projection ( $K_L \rightarrow \pi^0 X$ ): refined wrt FIPs 2020 report.

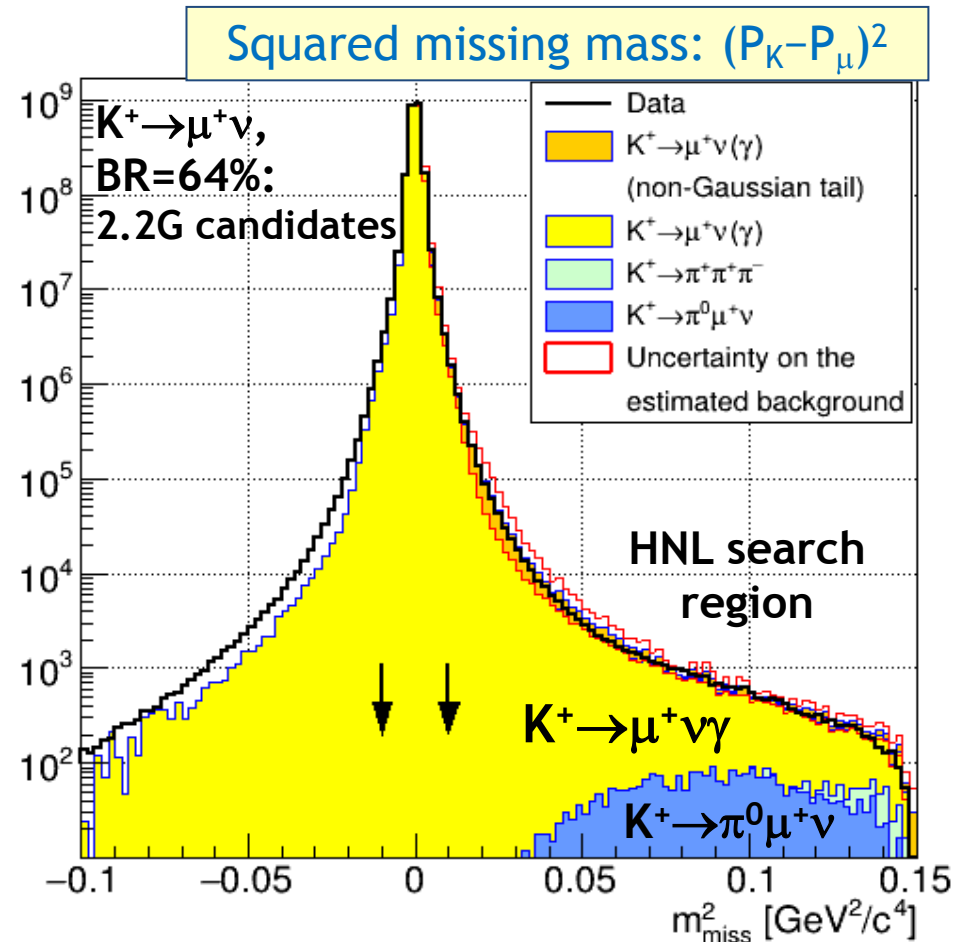
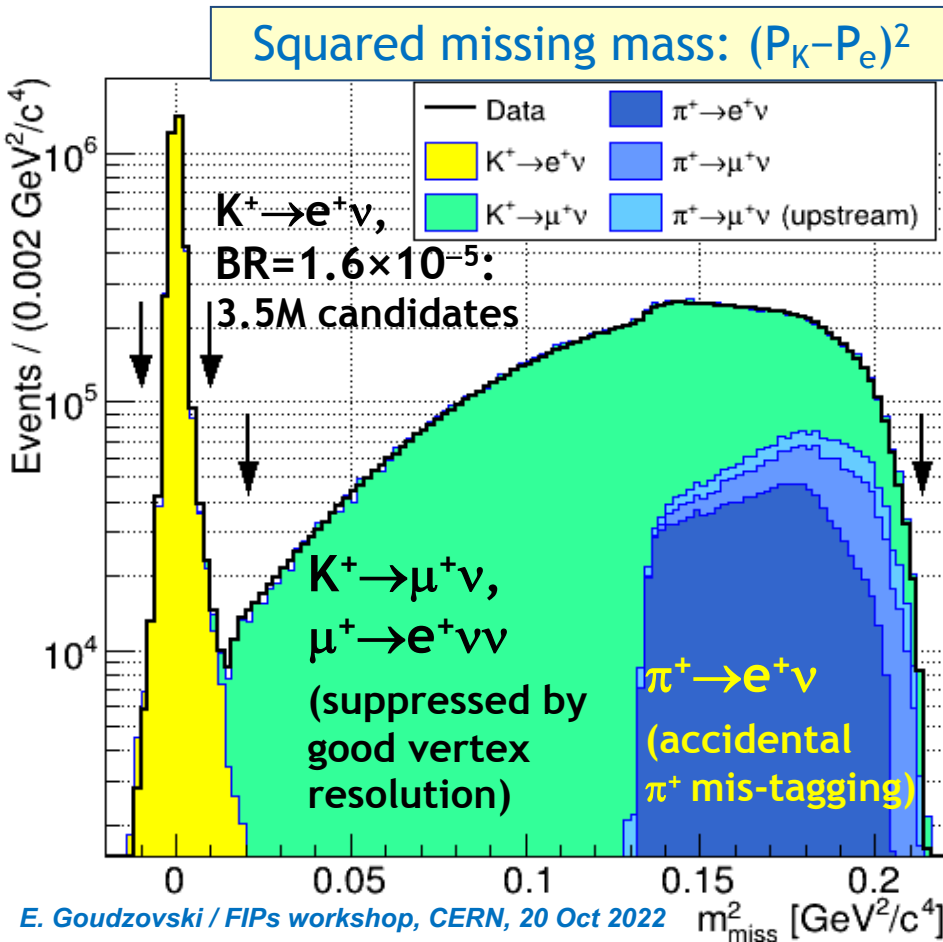
[EPJ C81 (2021) 1015]

# NA62 Run 1: HNL production search

PLB 807 (2020) 135599

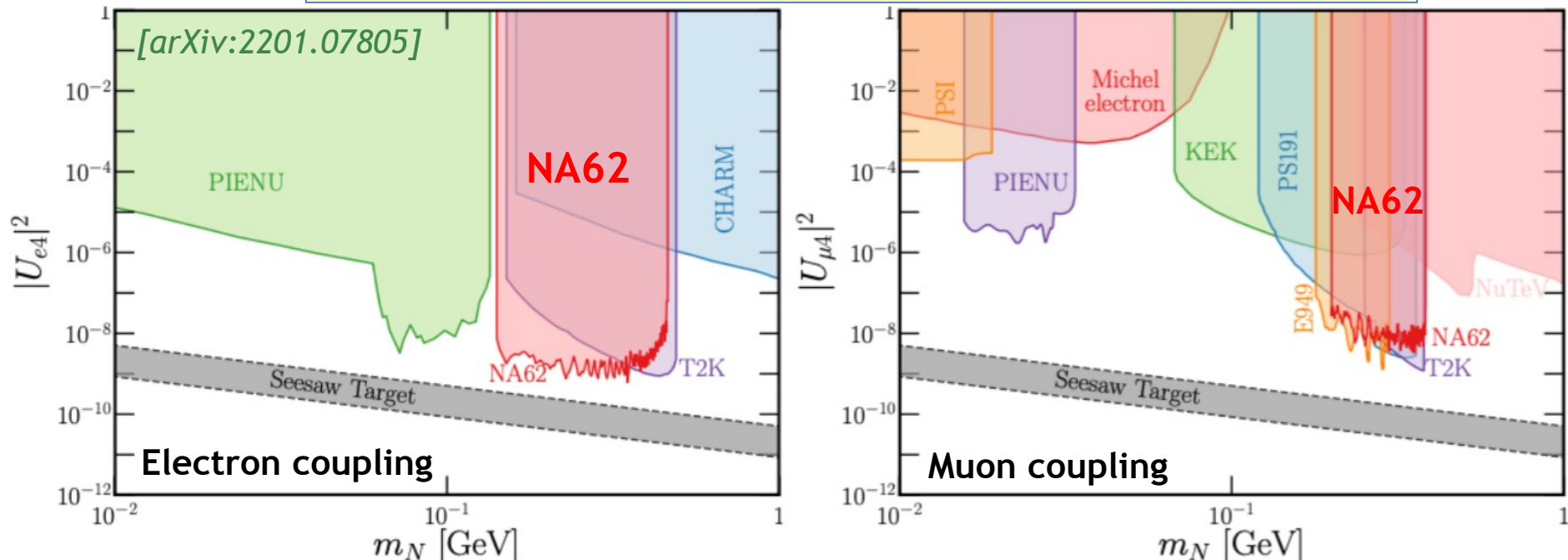
PLB 816 (2021) 136259

- ❖ Numbers of  $K^+$  decays in fiducial volume:  
 $N_K = (3.52 \pm 0.02) \times 10^{12}$  in positron case;  $N_K = (4.29 \pm 0.02) \times 10^9$  in muon case.
- ❖ Squared missing mass:  $m_{\text{miss}}^2 = (\mathbf{P}_K - \mathbf{P}_\ell)^2$ , using STRAW and GTK trackers.
- ❖ HNL production signal: **a spike above continuous missing mass spectrum.**



# NA62 Run 1: HNL exclusion

$|U_{e4}|^2$  limits vs  $m_{\text{HNL}}$  from production & decay searches



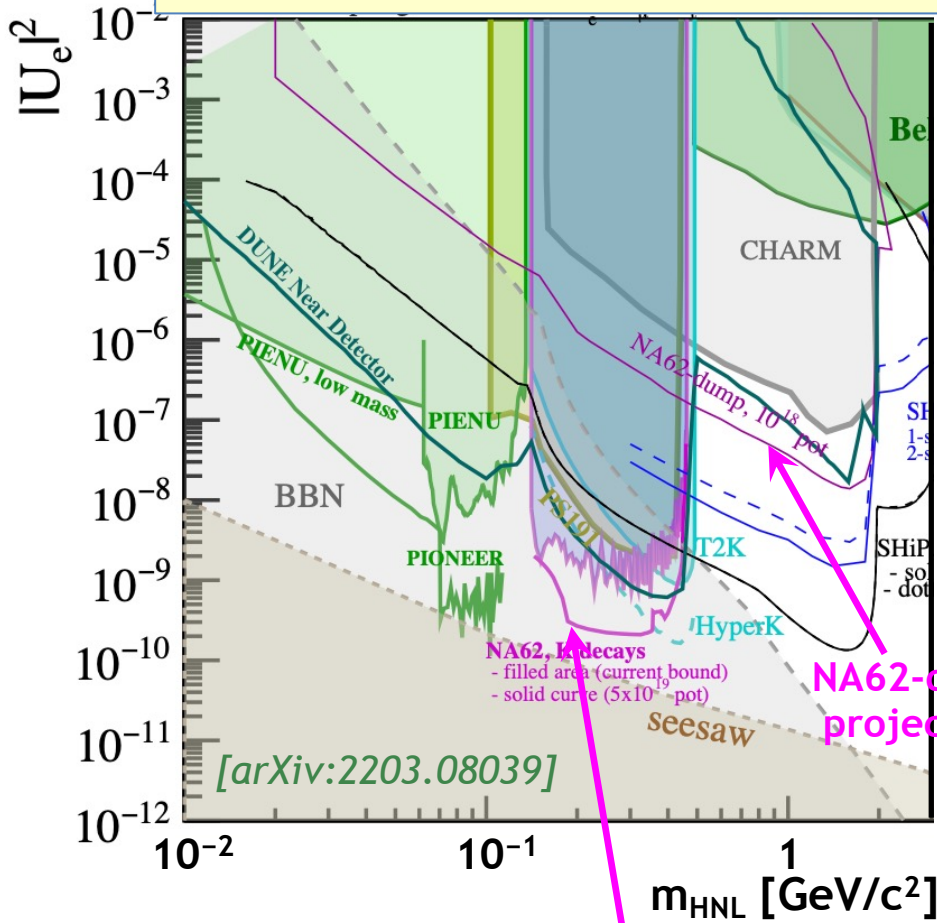
- ❖ For  $|U_{e4}|^2$ , complementary to search for  $\pi^+ \rightarrow e^+ N$  at PIENU.
- ❖ For  $|U_{\mu 4}|^2$ , complementary to search for  $K^+ \rightarrow \mu^+ N$  at BNL-E949.
- ❖ In both cases, complementary to HNL decay searches at T2K.
- ❖ Future kaon and pion experiments will approach the seesaw bound.
- ❖ An upper limit at 90% CL:  $\text{BR}(K^+ \rightarrow \mu^+ \nu \nu) < 1.0 \times 10^{-6}$ , and similar limits on  $\text{BR}(K^+ \rightarrow \mu^+ \nu X)$ , with  $X = \text{invisible}$ .

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

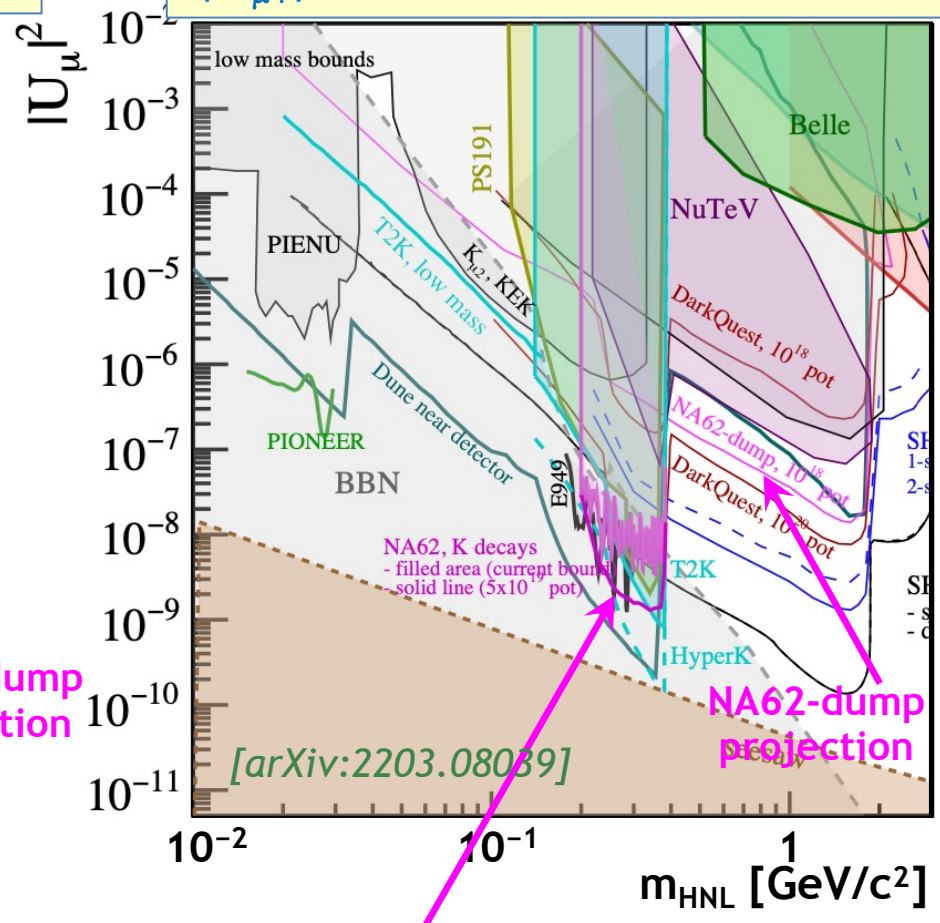
# HNL: HIKE $K^+$ phase projections

$|U_{e4}|^2$  limits vs  $m_{\text{HNL}}$  from production & decay searches

$|U_{e4}|^2$ : electron dominance assumed



$|U_{\mu 4}|^2$ : muon dominance assumed



❖ Official **HIKE projections**, published in the Snowmass HNL white paper.

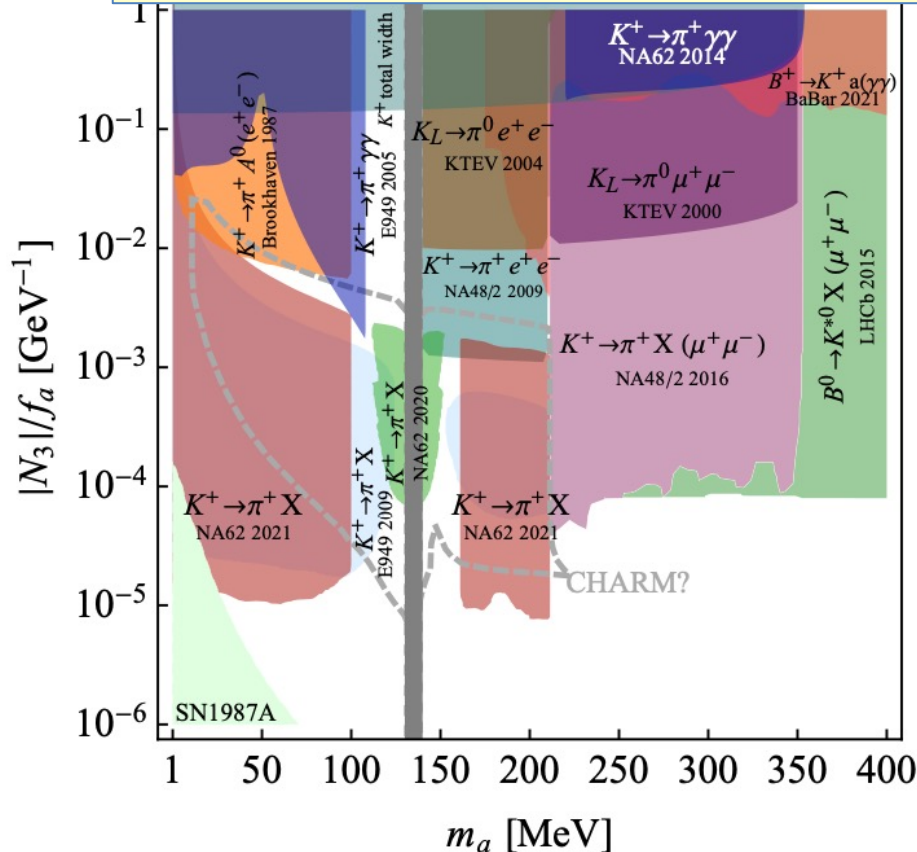
[arXiv:2203.08039]



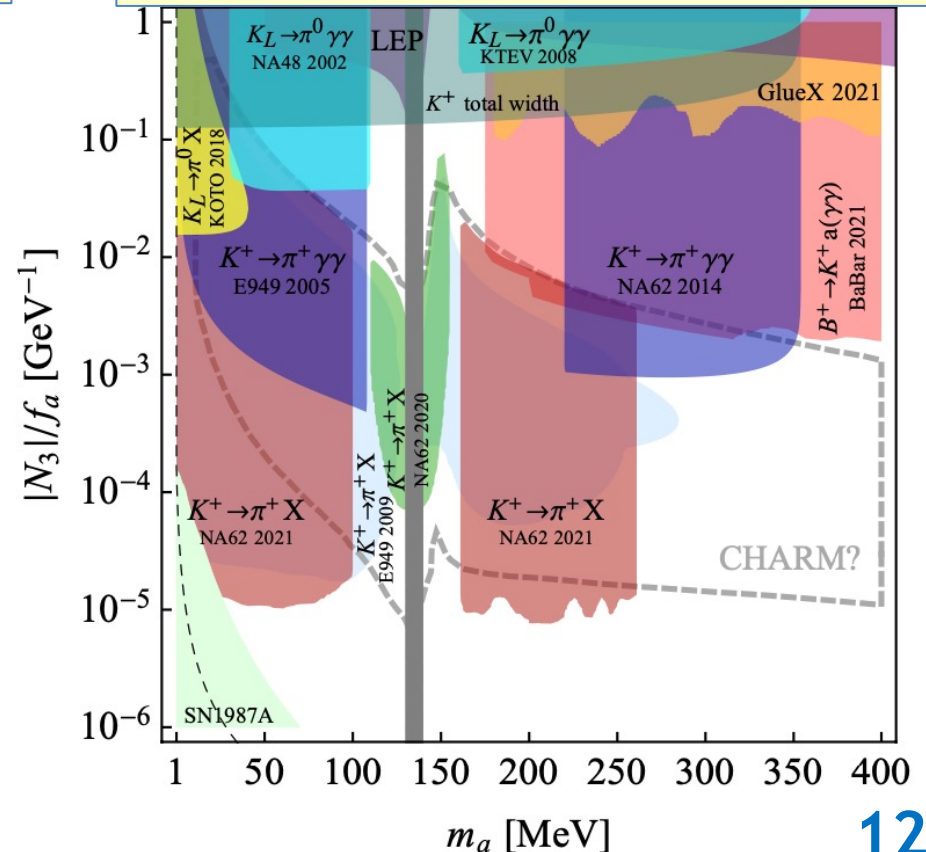
# Other opportunities in $K^+$ decays

- ❖ Review of hidden-sector models to be probed with rare K decays: [arXiv:2201.07805](https://arxiv.org/abs/2201.07805).
- ❖ Searches for prompt and displaced resonances in  $K^+ \rightarrow \pi^+ \ell^+ \ell^-$  and  $K^+ \rightarrow \pi^+ \gamma \gamma$  spectra: unique probes into ALP phase space.

ALP coupling vs mass, via  $K \rightarrow \pi \ell \ell$



ALP coupling vs mass, via  $K \rightarrow \pi \gamma \gamma$

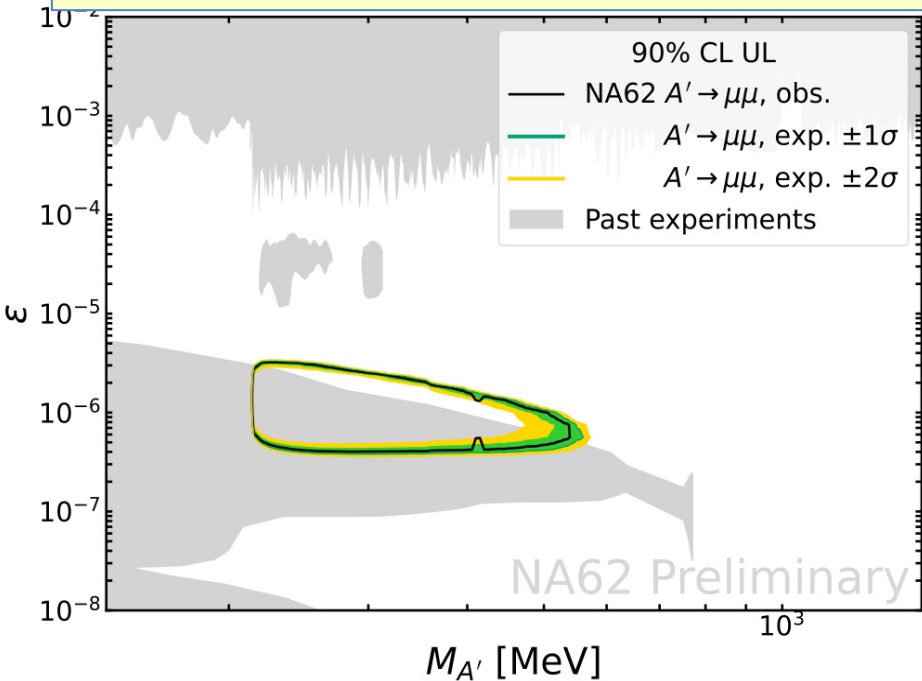


# NA62 in beam-dump mode

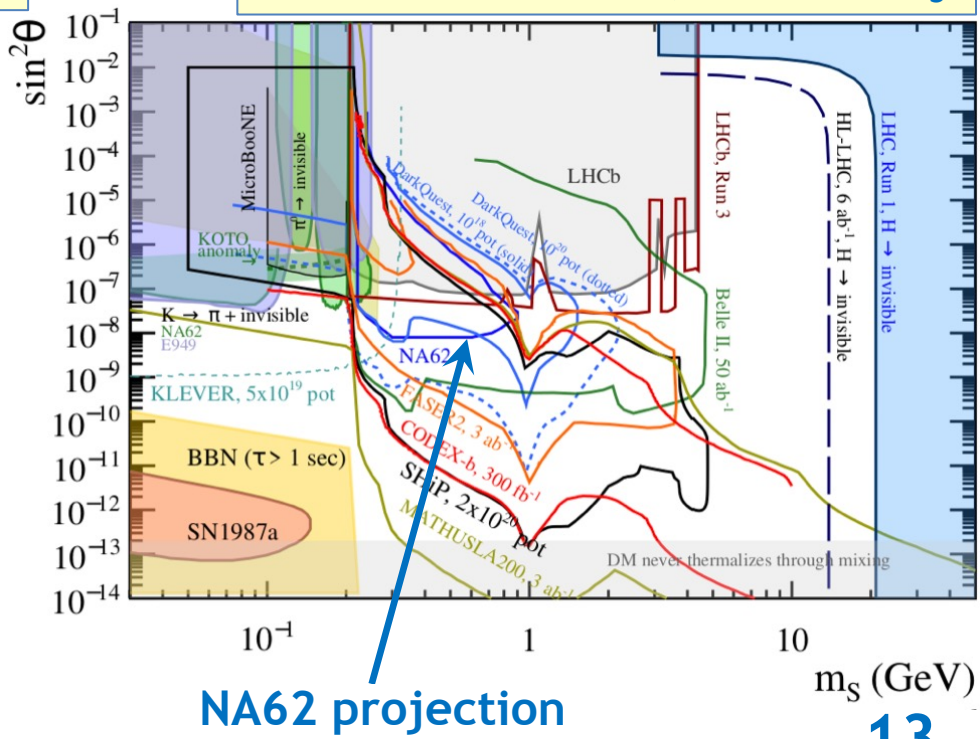
- ❖ *Preliminary NA62 result*: search for dark photon decays ( $A \rightarrow \mu^+ \mu^-$ ) with  $1.4 \times 10^{17}$  pot collected in beam-dump mode.
- ❖ Dark photon production mechanisms: bremsstrahlung, meson-mediated.

NA62 projection (by LS3) for  $10^{18}$  pot in dump mode

BC1: dark photon exclusion:  $\epsilon$  vs  $m_{A'}$



BC4: DS exclusion,  $\sin^2\theta$  vs  $m_S$



- ❖ Kaon decay experiments **NA62/HIKE**: an essential part of flavour-physics programme (European Strategy Update 2020).
- ❖ **NA62 Run 1** dataset (**2016–18**) is equivalent to  $6 \times 10^{12}$   $K^+$  decays.
- ❖ **NA62 Run 2** is progress (**2021–LS3**): expect much larger  $K^+$  decay dataset; improved detector.
- ❖ The **HIKE proposal**: next-generation rare kaon decay experiments with high-intensity  $K^+$  and  $K_L$  beams.
- ❖ DS, ALP, HNL *production* searches with **NA62 Run 1** dataset:  
[JHEP 02 (2021) 201; JHEP 02 (2021) 201; JHEP 06 (2021) 93;  
PLB 807 (2020) 135599; PLB 816 (2021) 136259]
- ❖ DP *decay* search with **NA62 Run 2 (2021)** beam-dump dataset: preliminary result, to be published soon.
- ❖ Solid future **NA62/HIKE** projections are available for many scenarios.