The 27th International Workshop on Weak Interactions and Neutrinos

Exotic searches at the NA62 experiment at CERN

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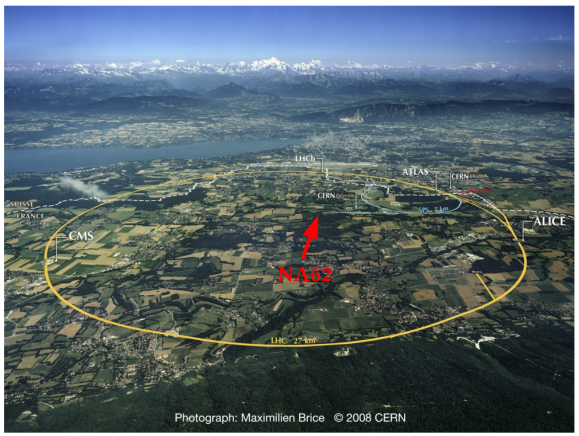
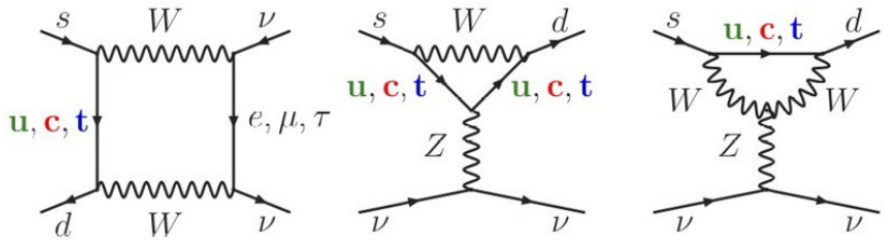
Outline

- NA62 experiment
- Heavy Neutral Lepton (HNL) production searches
- Dark Photon (DP) production searches
- Axion-Like Particle (ALP) searches
- Future prospects

The NA62 experiment

- Fixed-target experiment at CERN SPS
- 2015-2018: measure BR of rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$
- Strongly suppressed FCNC, sensitive to New Physics and with theoretically clean prediction: $BR_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \cdot 10^{-11}$ ***[JHEP11 033 (2015)]***
- BNL (E949, E787): $BR_{BNL}(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$ ***[Phys. Rev. D 79, 092004 (2009)]***
- NA62 limit with 2016 data sample (analysis of 2017-18 sample ongoing): $BR_{NA62}(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \cdot 10^{-10}$ @ 95% CL ***[arXiv:1811.08508v2 (2019)]***

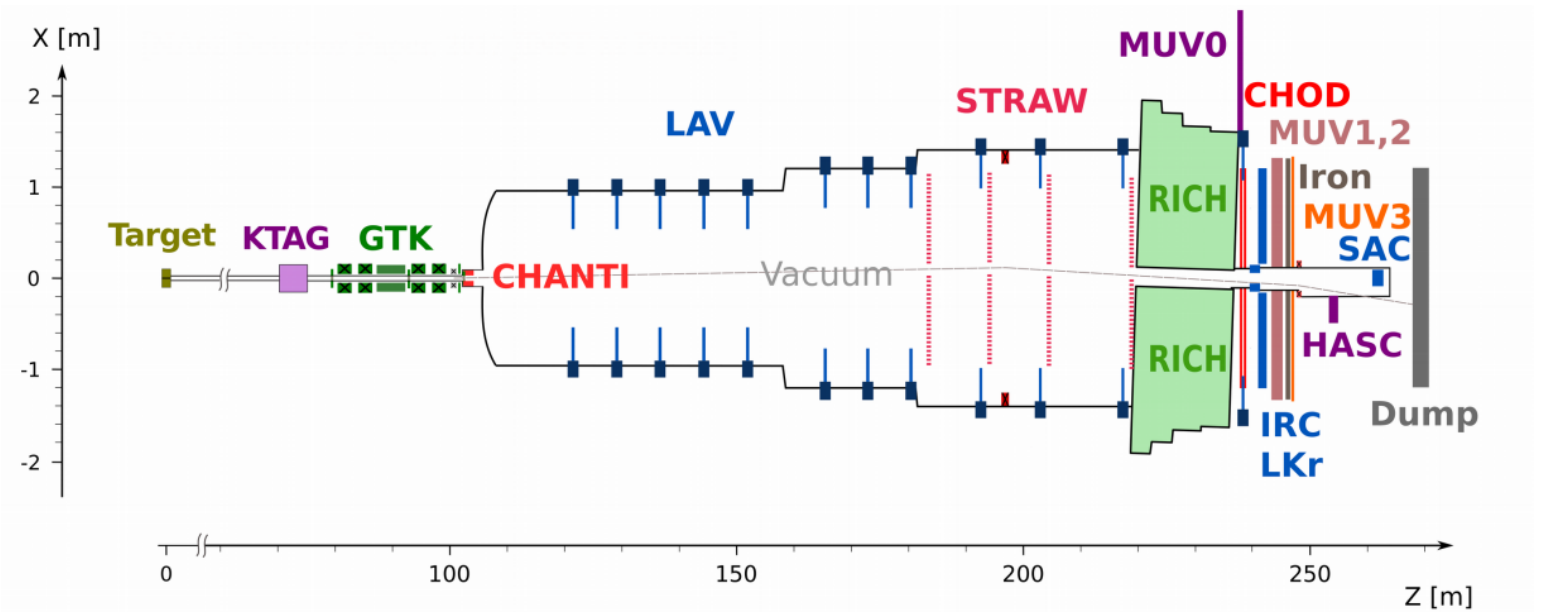




- 2015-2018: broad program of exotic (BSM) physics with LNV/LFV in K decays and weakly-interacting massive mediators (HNL, DP, ALP)

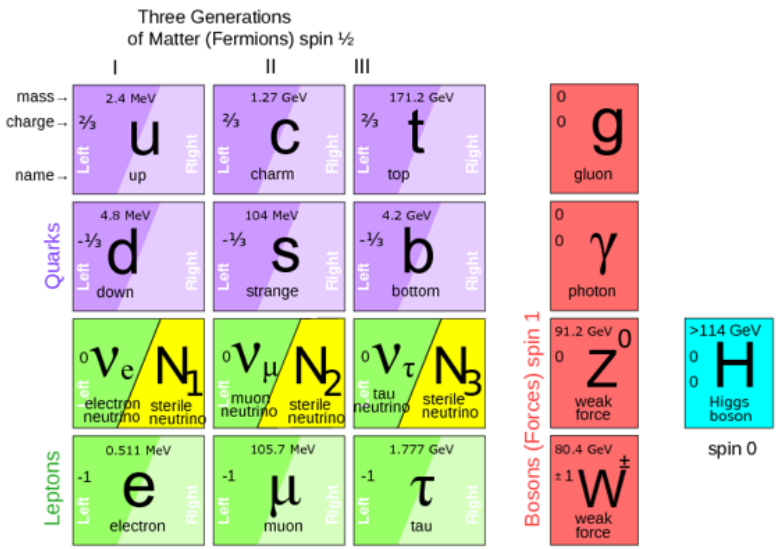
The NA62 experimental setup

- SPS beam: 400 GeV/c SPS protons on Be target, $3 \cdot 10^{12}$ protons/spill (3.5 s spill)
- Secondary beam: 75 GeV/c momentum, 750 MHz (6% K^+, 70% π^+, 24% p and μ)
- Vacuum decay region: 60 m long, $\sim$ 5 MHz K^+ decay rate, in-flight kaon decay technique
- Redundant particle ID and high-rate, high-resolution tracking systems
- High-efficiency veto systems for photons, muons and charged particles



HNL - Theoretical framework

- Neutrino Minimal Standard Model (SM extension) accounting for neutrino masses and oscillations, dark matter and Baryon Asymmetry of the Universe (BAU)
- See-saw mechanism $\rightarrow$ 3 additional right-handed, singlet, Majorana/Dirac HNLs
- Lightest HNL of mass O(10 keV/c^2) is candidate for DM
- Heaviest HNLs of mass O(1 GeV/c^2) are degenerate but almost equal
- Production and decay modes same as SM ones, scaled by coupling factor $|U_{l4}|^2$ and kinematic factor $\rho_l(m_N)$ (phasespace + helicity)

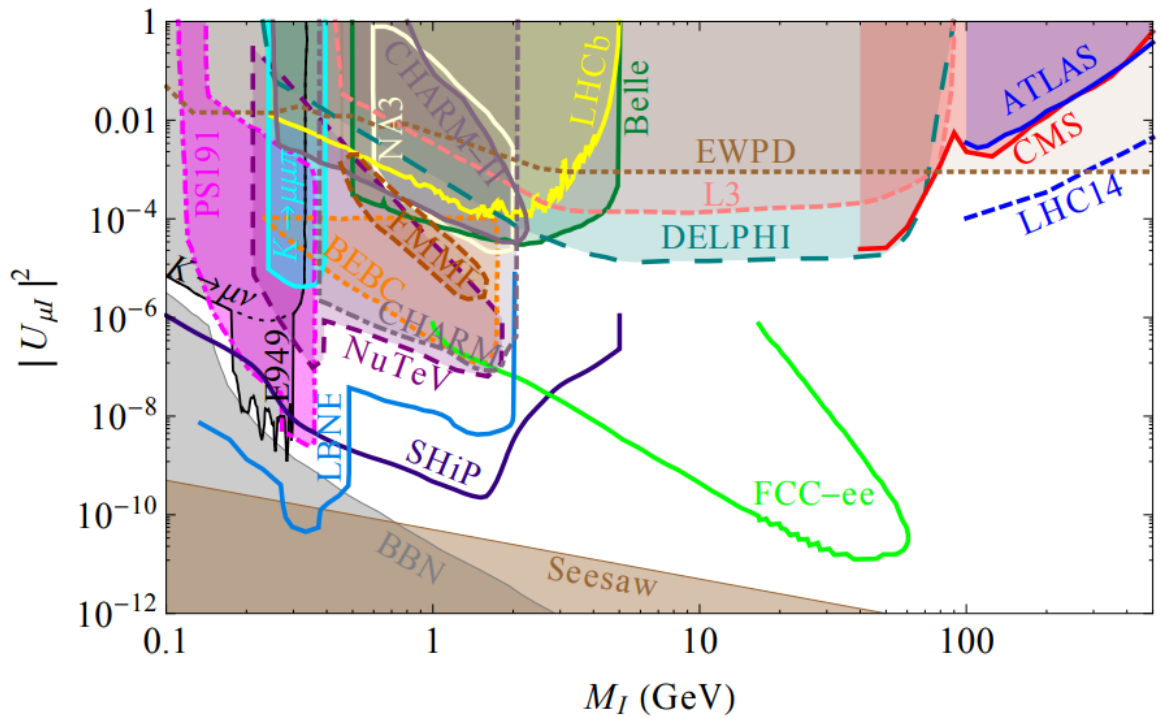


$$\mathcal{B}(K^+ \rightarrow \ell^+ N) = \mathcal{B}(K^+ \rightarrow \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_{\ell 4}|^2$$

Phys. Rev. D24 1232 (1981)

HNL - Experimental techniques for searches

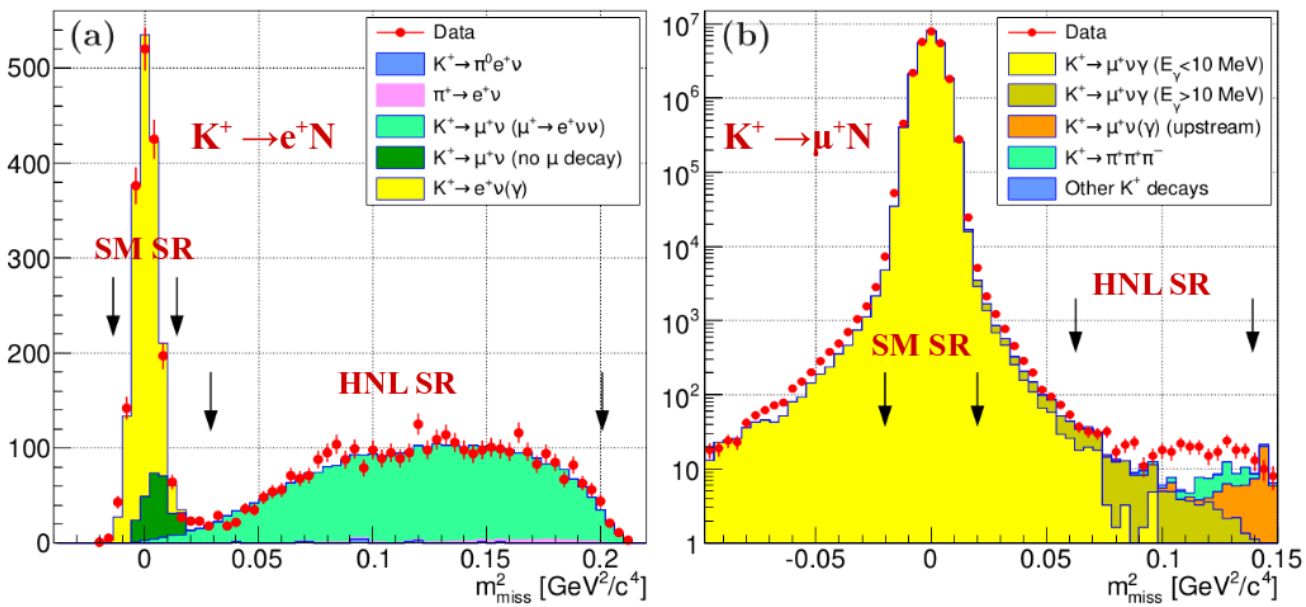
- Production searches look for peaks in squared missing mass distribution $m^2_{miss} = (P_{in} - P^{vis}_{fin})^2$ (TRIUMF, NA62, KEK, E949), decay-model independent $\rightarrow$ sensitive to long-lived HNLs
- Decay searches (CHARM and PS191), coupling- and decay-model dependent $\rightarrow$ sensitive to short-lived HNLs
- Limits on coupling between HNL and muon vs HNL mass



Rep. Prog. Phys. 79 124201 (2016)

HNL - Production searches in kaon decays at NA62 - I

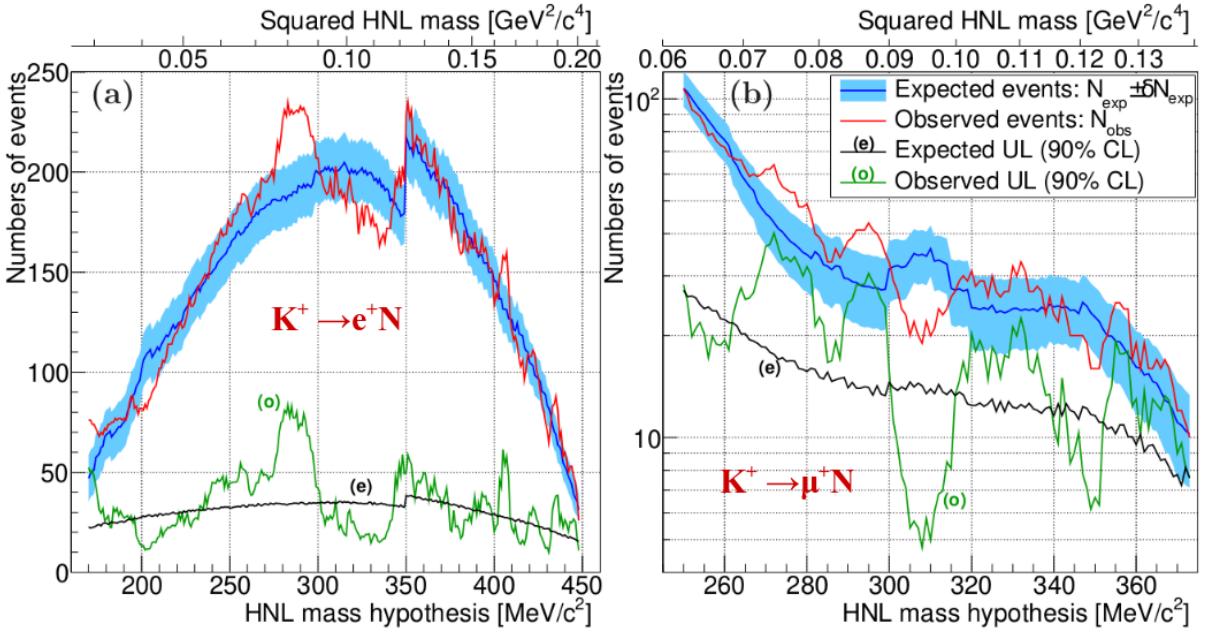
- Peak searches in squared missing mass of $K^+ \to l^+ N$ decays ($l = e, \mu$): $m^2_{miss} = (P_K - P_l)^2$
- NA62 2015: 5 days data-taking @ 1% nominal beam intensity, $3(1) \cdot 10^8$ K decays in FV for $K^+ \to e^+(\mu^+)N$
- Single positively-charged track topology + kaon decay vertex close to beam axis + positron/muon ID through $\frac{E}{p}$
- m^2_{miss} SM signal region (peak around 0) and HNL signal region for e and μ selections



Phys. Lett. B778 137 (2018)

HNL - Production searches in kaon decays at NA62 - II

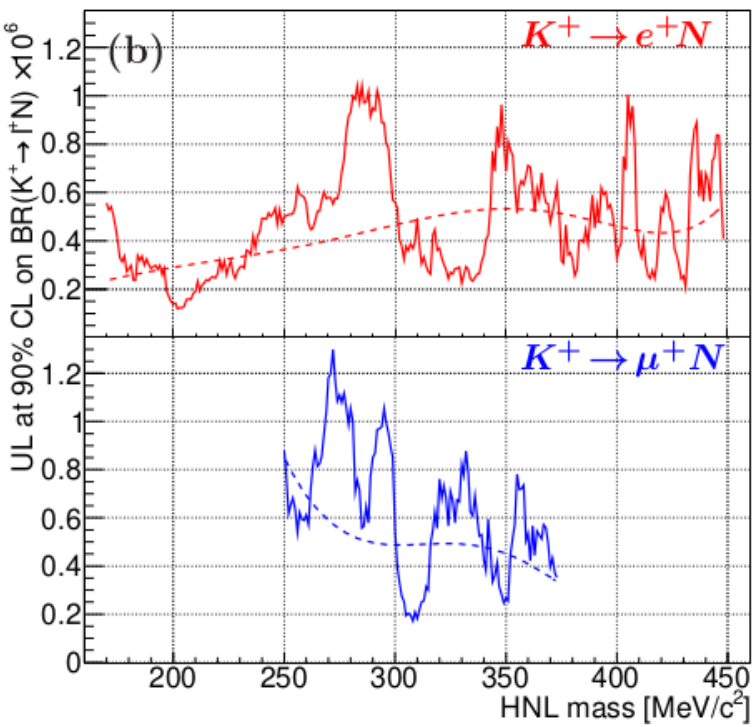
- Scan in squared missing mass with 1 MeV/c^2 step
- Data-driven background evaluation: polynomial fits to mass spectra outside signal windows
- Expected and observed number of events computed for each mass window
- CLs assuming poissonian/gaussian distributions for observed/expected number of events (Rolke-Lopez method)
- Local signal significance never exceeds 3 σ: no HNL signal is observed

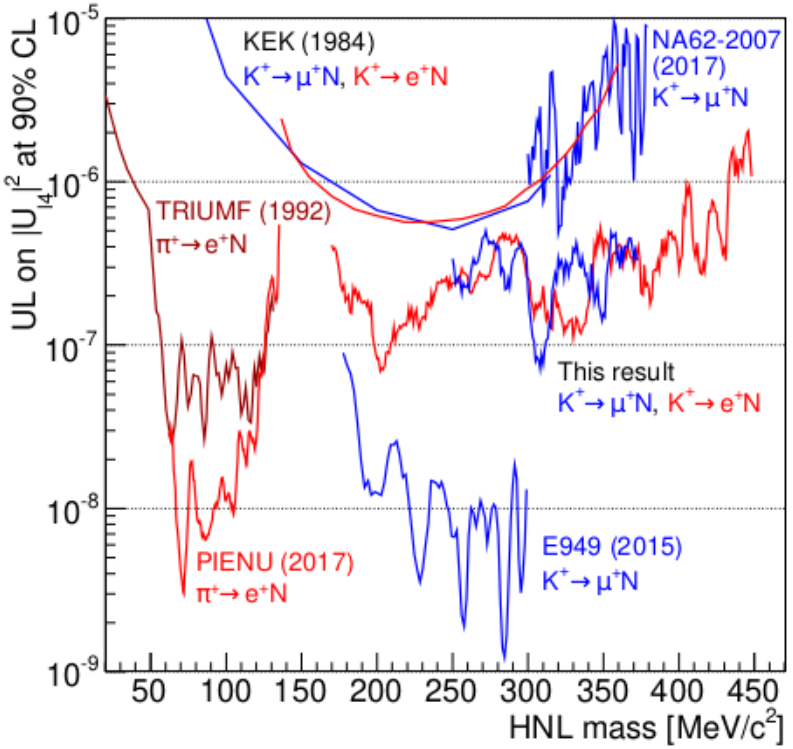


Phys. Lett. B778 137 (2018)

HNL - Production searches in kaon decays at NA62 - III

- From $N_{obs} \rightarrow$ UL on $BR(K^+ \rightarrow l^+ N)$ vs $m_N \rightarrow$ UL on $|U_{l4}|^2$ vs m_N
- Improved limits for $|U_{e4}|^2$ in 170 MeV/$c^2 \leq m_N \leq$ 448 MeV/c^2 ***[Phys. Lett. B778 (2018) 137]***
- Improved limits for $|U_{\mu 4}|^2$ in 300 MeV/$c^2 \leq m_N \leq$ 373 MeV/c^2 ***[Phys. Lett. B778 (2018) 137]***
- O(10) improvement foreseen with current NA62 data (2016-2018)

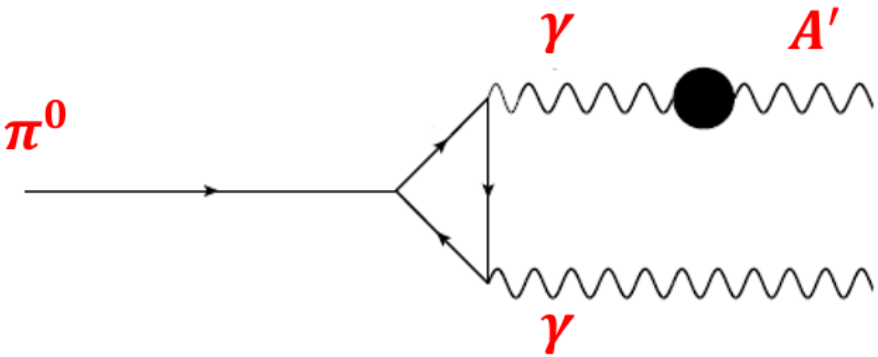




Phys. Lett. B778 137 (2018)

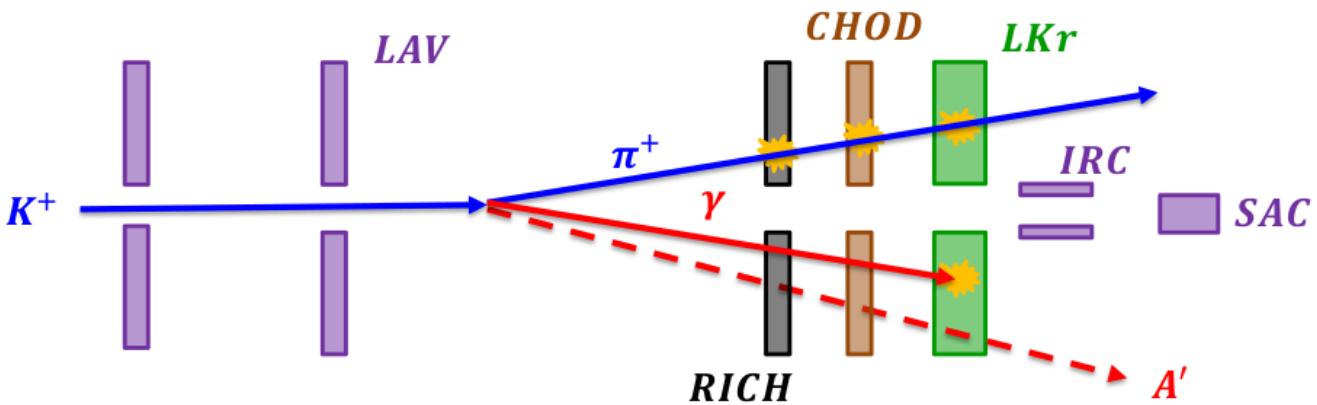
DP - Theoretical framework

- Weakly-interacting BSM particle below EW scale introducing extra U(1) gauge symmetry
- Corresponding gauge vector boson (DP) A' produced in $K^+ \to \pi^+\pi^0, \quad \pi^0 \to \gamma A'$
- Process is same as SM one, but scaled by coupling factor ϵ^2 and kinematic factor



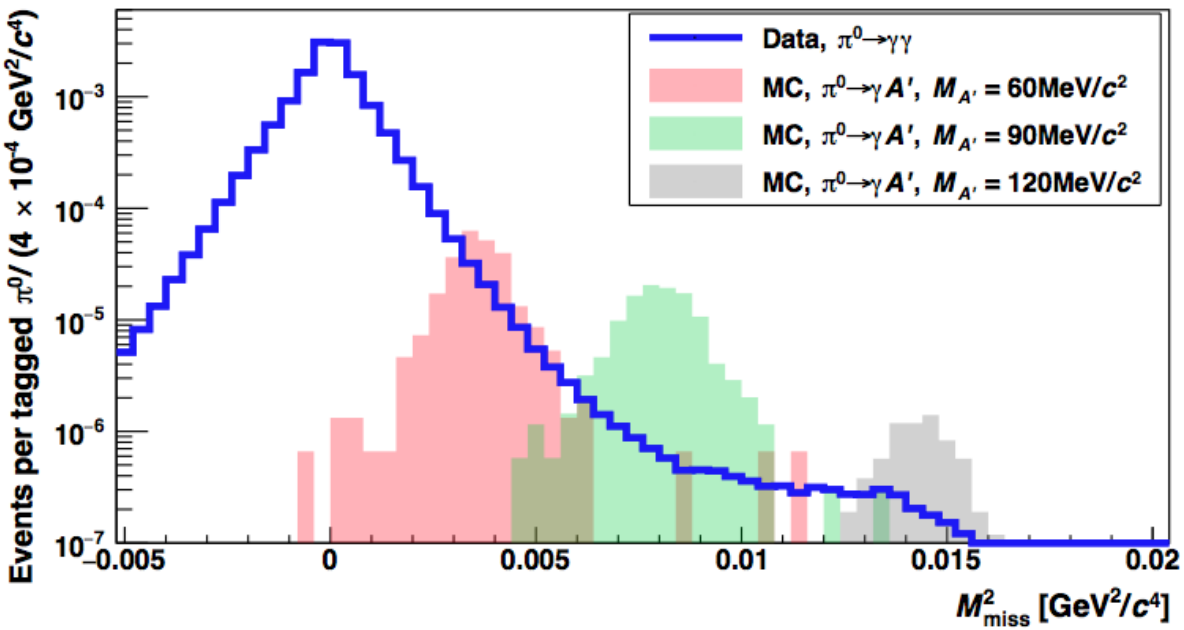
$$\mathrm{BR}\left(\pi^0 \to A'\gamma\right) = 2\epsilon^2 \left(1 - \frac{M_{A'}^2}{M_{\pi^0}^2}\right)^3 \times \mathrm{BR}\left(\pi^0 \to \gamma\gamma\right)$$

Phys. Lett. B 166 196 (1986)



DP - Production searches in kaon decays at NA62 - I

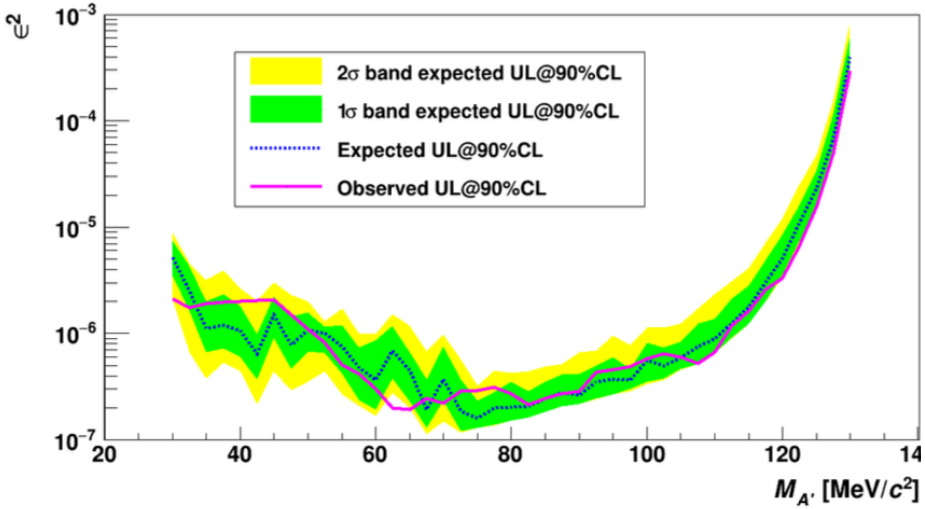
- Peak searches in squared missing mass $m^2_{miss} = (P_K - P_\pi - P_\gamma)^2$ on 2016 data
- Single positively-charged track topology + single photon in veto system + missing momentum pointing towards EM calorimeter
- Main background (data driven): $K^+ \to \pi^+\pi^0, \quad \pi^0 \to \gamma\gamma$ with one photon undetected
- Scan in squared missing mass → expected and observed number of events for each mass window

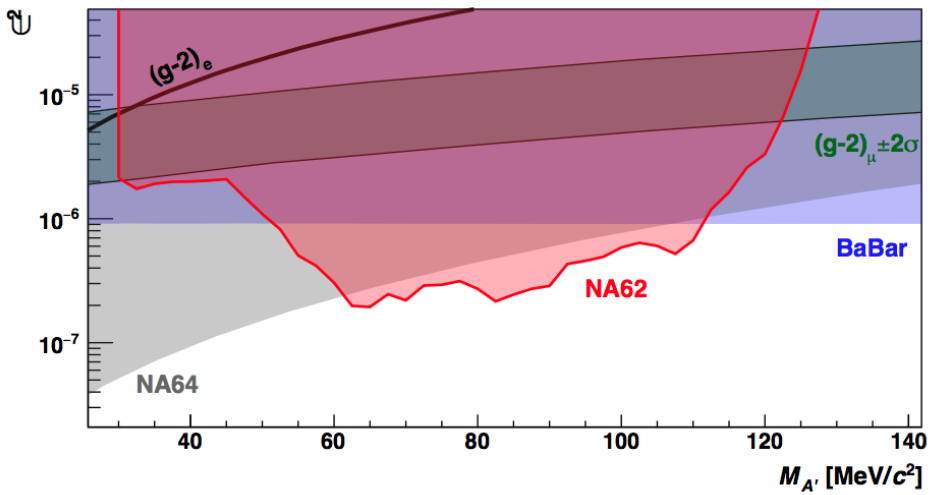


arxiv:1903.08767 (2019)

DP - Production searches in kaon decays at NA62 - II

- CLs assuming zero-background hypothesis
- No statistically significant excess observed
- Upper limits @ 90% CL
- Improvements on previous limits over mass range 60-110 MeV/c^2

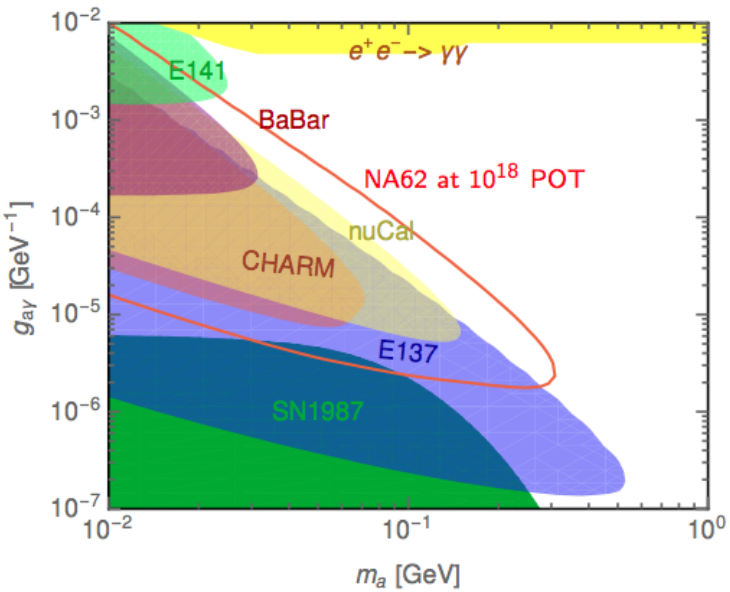




arxiv:1903.08767 (2019)

ALP - Decay searches at NA62

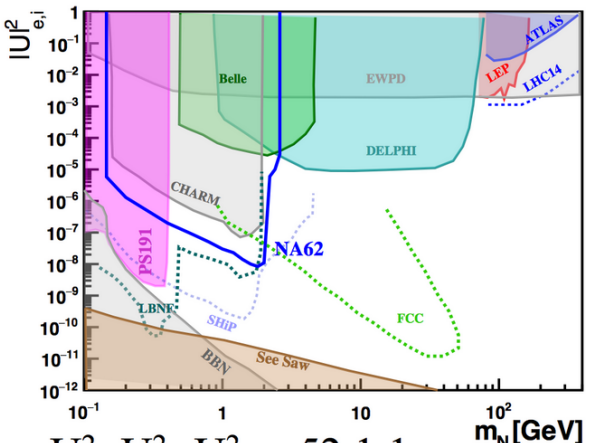
- Good candidate for cold dark matter, produced via elastic scattering of beam proton dumped onto NA62 Cu collimators (Primakoff effect)
- Decay searches can be performed for $A \to \gamma\gamma$ in MeV/c^2-GeV/c^2 mass range
- Ongoing analysis of 2017-2018 data taken in beam-dump mode (closed beam collimators) with $2 \cdot 10^{16}$ Protons on Target (POT)
- Expected sensitivity in zero-background hypothesis in the plane ALP coupling to photons vs ALP mass (projection for 10^{18} POT)



arXiv:1904.02091v1 (2019)

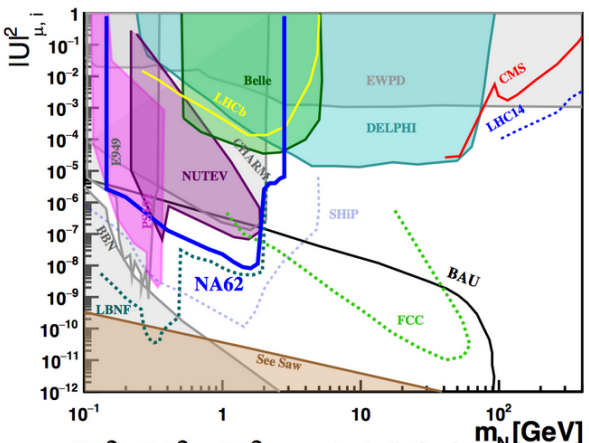
Future prospects at NA62 - I

- 2019-2020: CERN Long Shutdown $\rightarrow$ minimal detector and beamline upgrades for NA62
- 2021-2023: resume $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ data-taking (under approval)
- 2021-2023: run in beam-dump mode $\rightarrow$ remove target, dump proton beam on Cu collimators $\rightarrow$ direct production in dump + indirect production through intermediate K, D, B
- 5 year (10^{18} POT) timescale sensitivity projections by Physics Beyond Colliders (PBC)-BSM group (current vs prospects)
- HNL decay searches to visible final states for three benchmark scenarios *[JHEP0710 015 (2007)]*



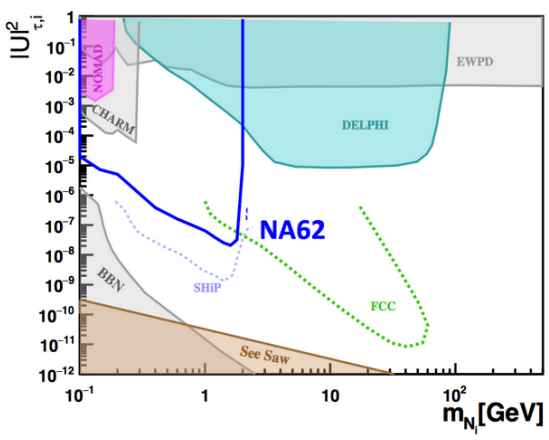
$U^2_e : U^2_\mu : U^2_\tau = 52:1:1$

Normal hierarchy of active ν masses



$U^2_e : U^2_\mu : U^2_\tau = 1:16:3.8$

Normal hierarchy of active ν masses



$U^2_e : U^2_\mu : U^2_\tau = 0.061:1:4.3$

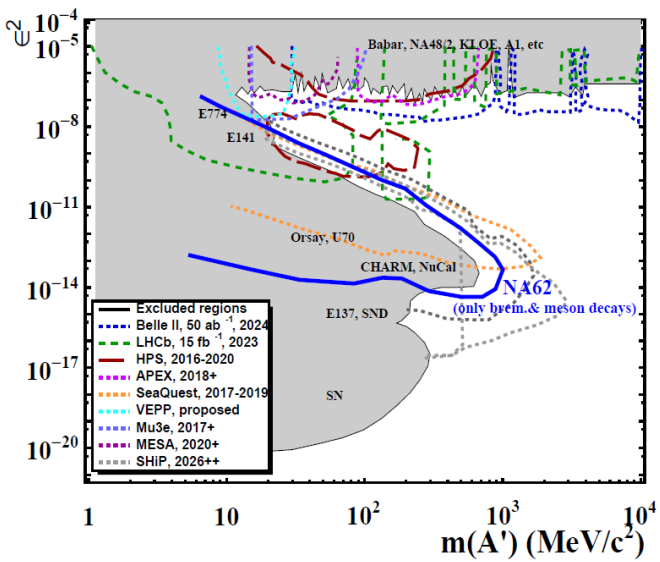
Normal hierarchy of active ν masses

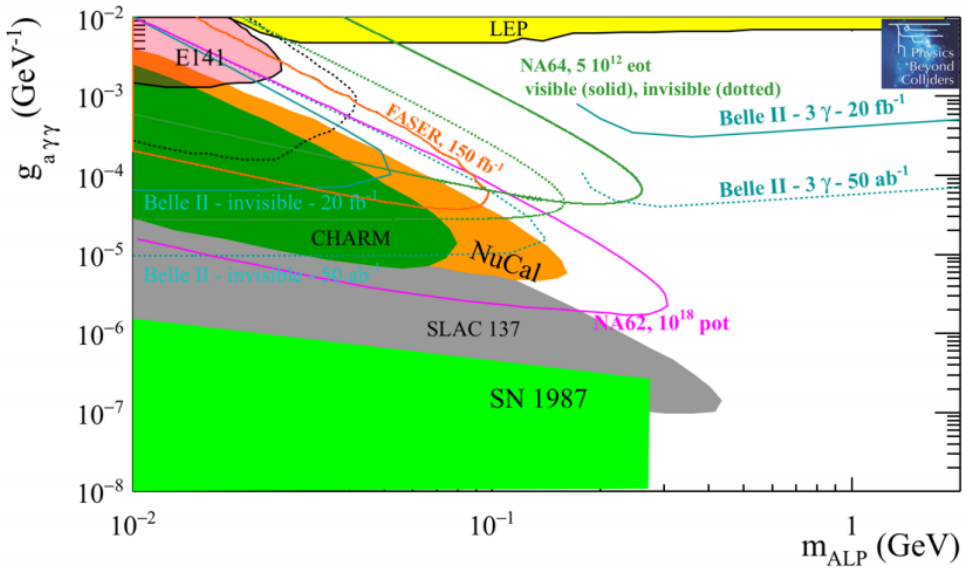
arXiv:1901.09966v2 (2019)

Future prospects at NA62 - II

- DP decay searches to visible final states: $A' \to e^+e^-, \mu^+\mu^-$ (NA62)
- ALP decay searches to visible final states: $A \to \gamma\gamma$ (NA62)

- Several other prospects by PBC-BSM group
- DP decay searches to invisible final states (WIMP): $A' \to \chi\bar{\chi}$ (not @ NA62)
- ALP decay searches to visible final states: $A \to f\bar{f}$ (not @ NA62)





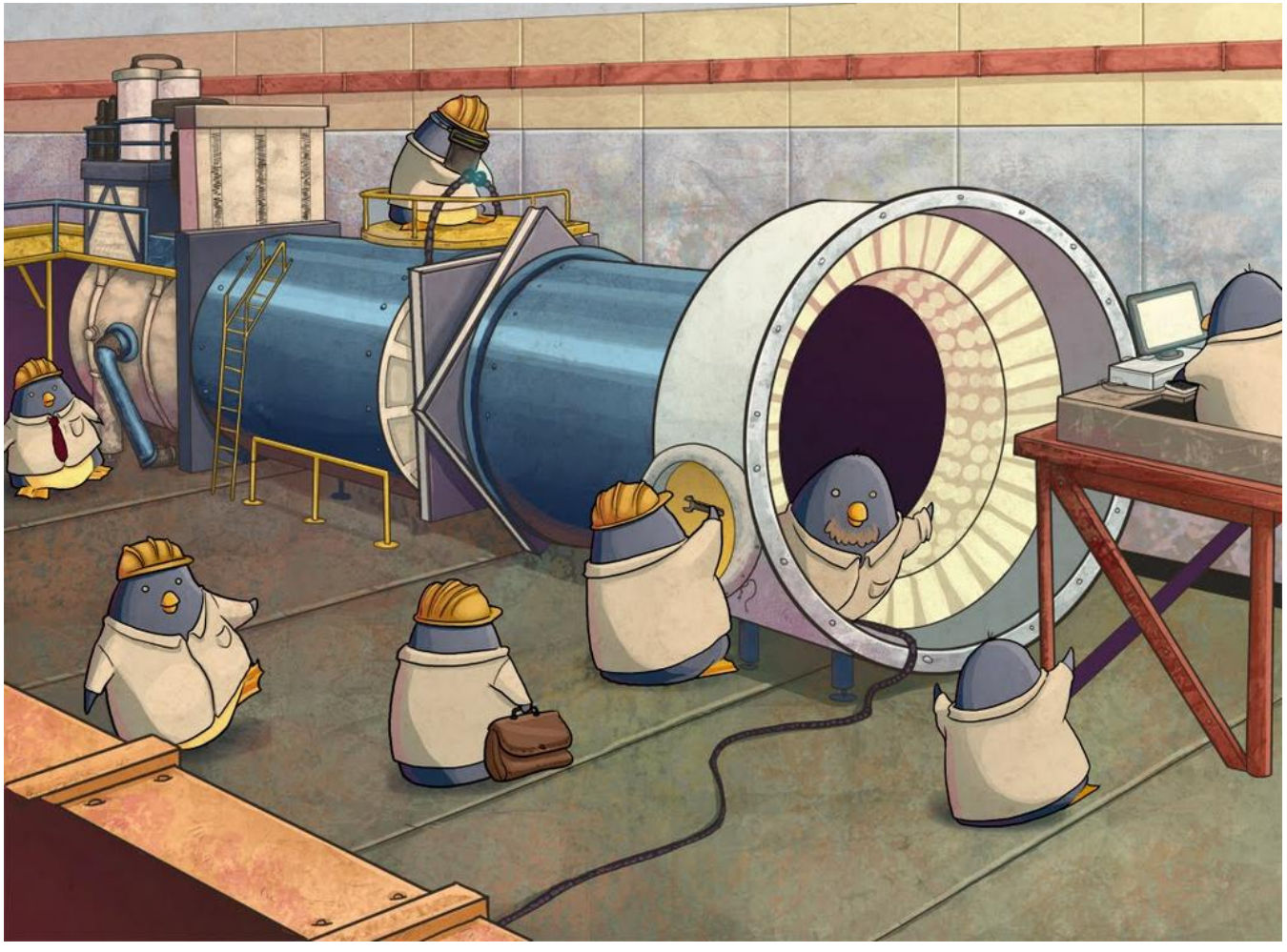
arXiv:1901.09966v2 (2019)

Conclusions

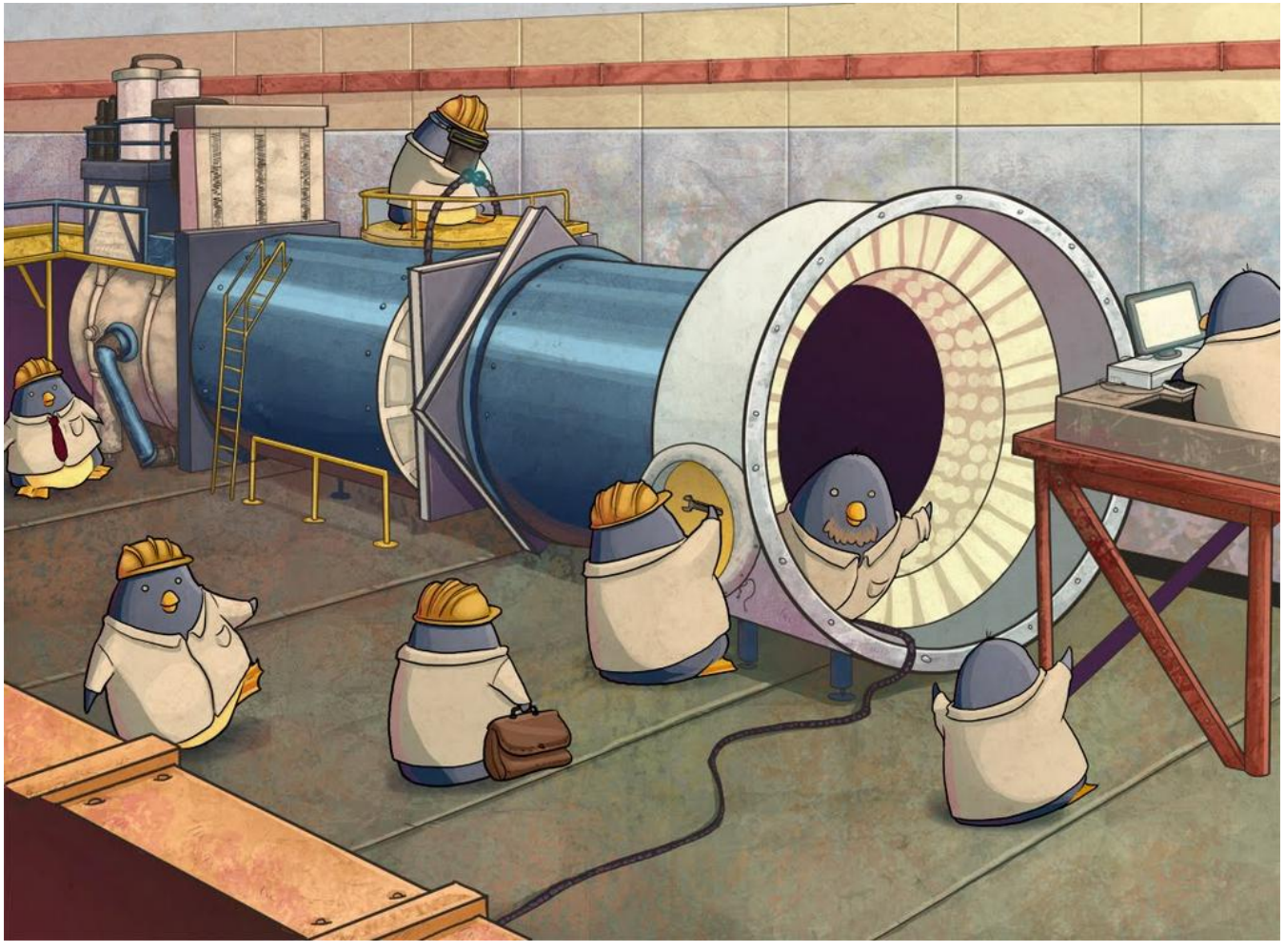
- Novel NA62 decay-in-flight technique works
- $BR_{NA62}(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \cdot 10^{-10}$ @ 95% CL (2016 data sample)
- 2017-2018 data analysis ongoing
- Continuation of data-taking for 2021-2023 under approval

- Broad exotic physics program studied parasitically (in presence of K beam) and in beam-dump mode
- Improved upper limits on HNL and DP production searches in K decays with partial data samples
- Expected improvements on several hidden-sector mediators with current and 2021-2023 data samples

Thank you for your attention!

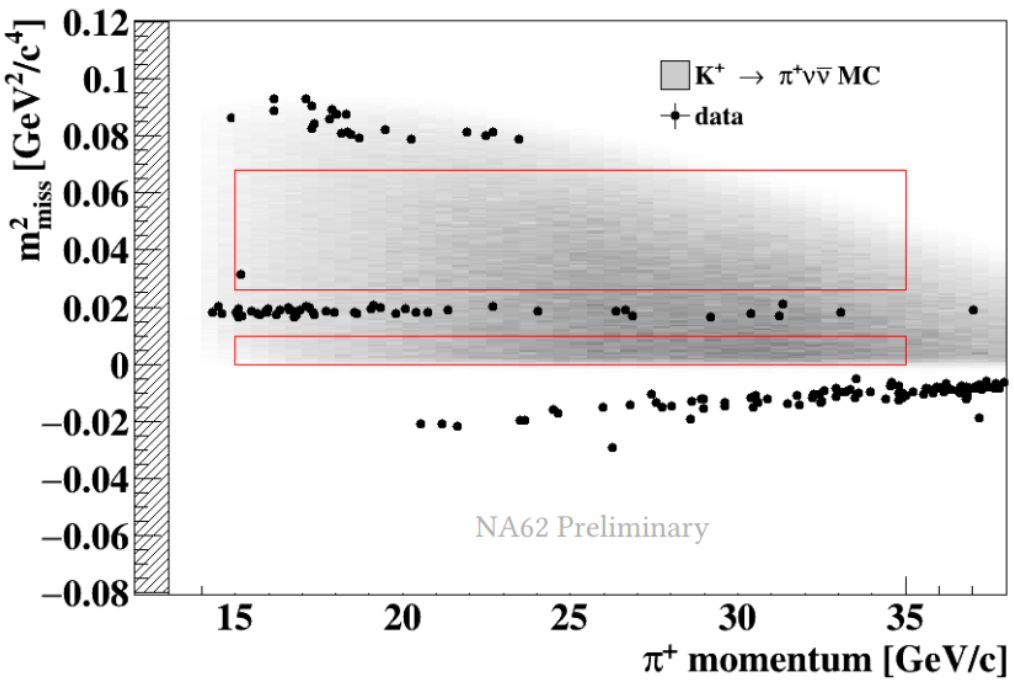


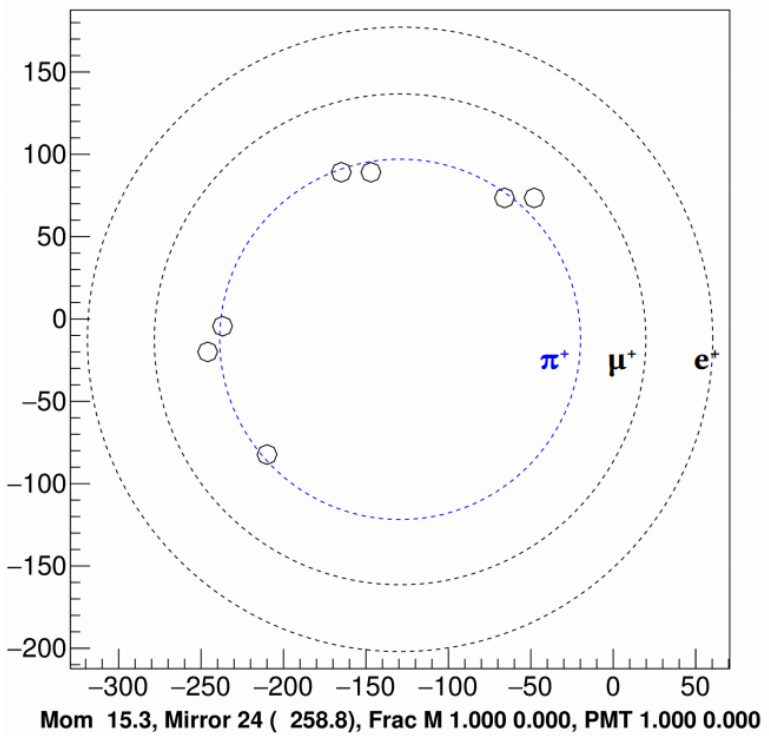
Backup slides



Measurement on 2016 data sample

- $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (28^{+44}_{-23}) \cdot 10^{-11}$ @ 68% CL
- $BR(K^+ \to \pi^+ \nu\bar{\nu}) < 11 \cdot 10^{-10}$ @ 90% CL
- $BR(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \cdot 10^{-10}$ @ 95% CL

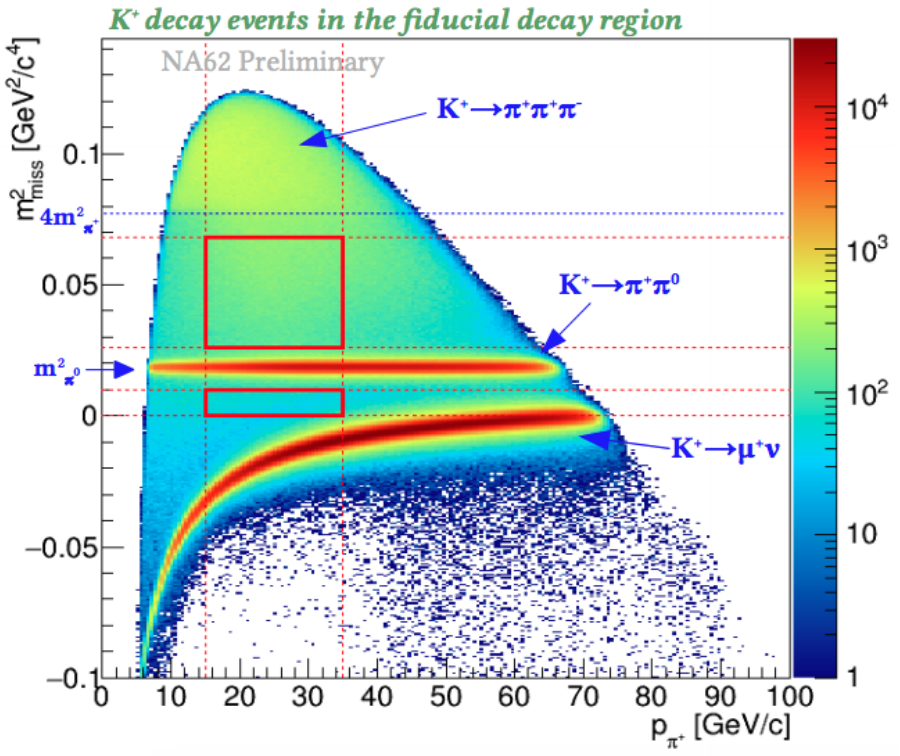


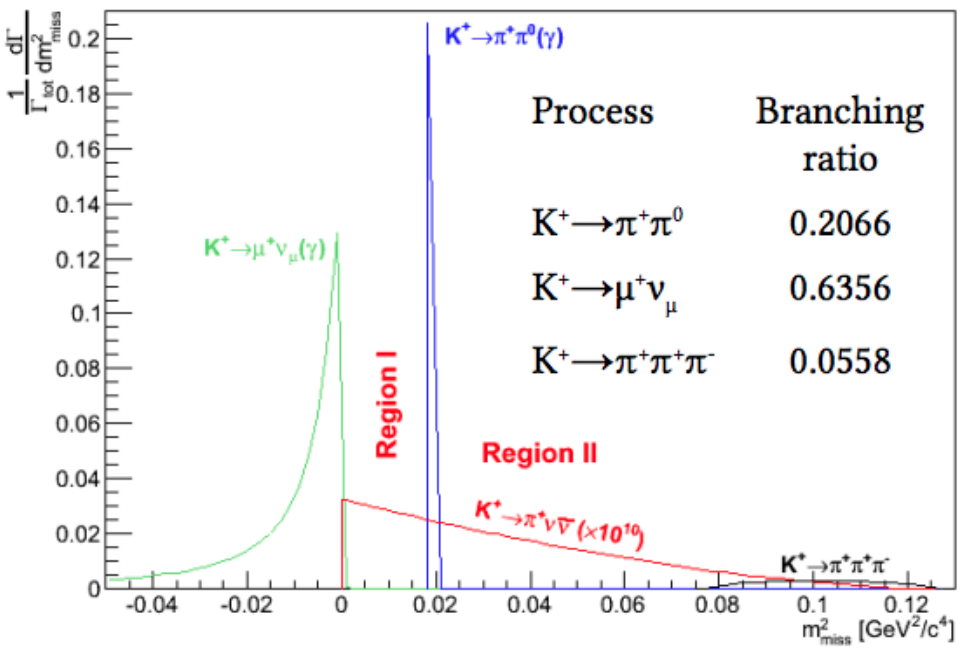


Phys. Rev. D 79, 092004 (2009)

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

- Decay-in-flight technique: $m^2_{miss} = (P_K - P_\pi)^2$
- Single positively-charged track topology (15 GeV/$c \leq p_\pi \leq$ 35 GeV/c)
- Timing between upstream and downstream detectors O(100) ps





arXiv:1811.08508v2 (2019)

$K^+ \to \pi^+ \nu\bar{\nu}$ - Background summary

Process	Expected events in R1 + R2
$K^+ \to \pi^+ \nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.029_{syst} \pm 0.032_{ext}$
$K^+ \to \pi^+ \pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+ \nu_\mu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+ \pi^- \pi^+$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream background	$0.050^{+0.090}_{-0.030}$
Total background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

arXiv:1811.08508v2 (2019)

Parasitic mode vs beam-dump mode at NA62

- Exotic searches in parasitic mode, performed in presence of K beam: SPS protons on Be target $\rightarrow$ indirect exotic production through intermediate K,D,B
- Exotic searches in beam-dump mode: Be target removed $\rightarrow$ SPS protons on Cu beam collimators $\rightarrow$ direct exotic production in dump + indirect exotic production through intermediate K,D,B