# Dark Sector at NA62 experiment

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**Consiglio di Sezione**

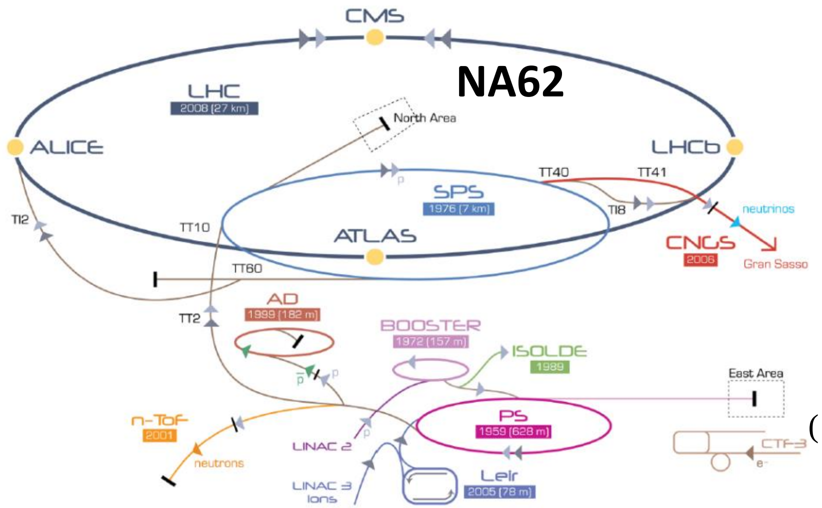
**16 Gennaio 2018**

# Outline

- NA62 experiment
- Hidden sector searches at NA62
- Expected sensitivities for the hidden sector
- Conclusions

# NA62 experiment

High-intensity facility designed to study rare kaon decays




~ 200 participants

29 institutions from 13 countries

Main goal: BR $(K^+ \to \pi^+ \nu\bar{\nu})$ measurement with 10% precision

SM prediction: $\mathrm{BR}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (8.4 \pm 0.1) \times 10^{-11}$

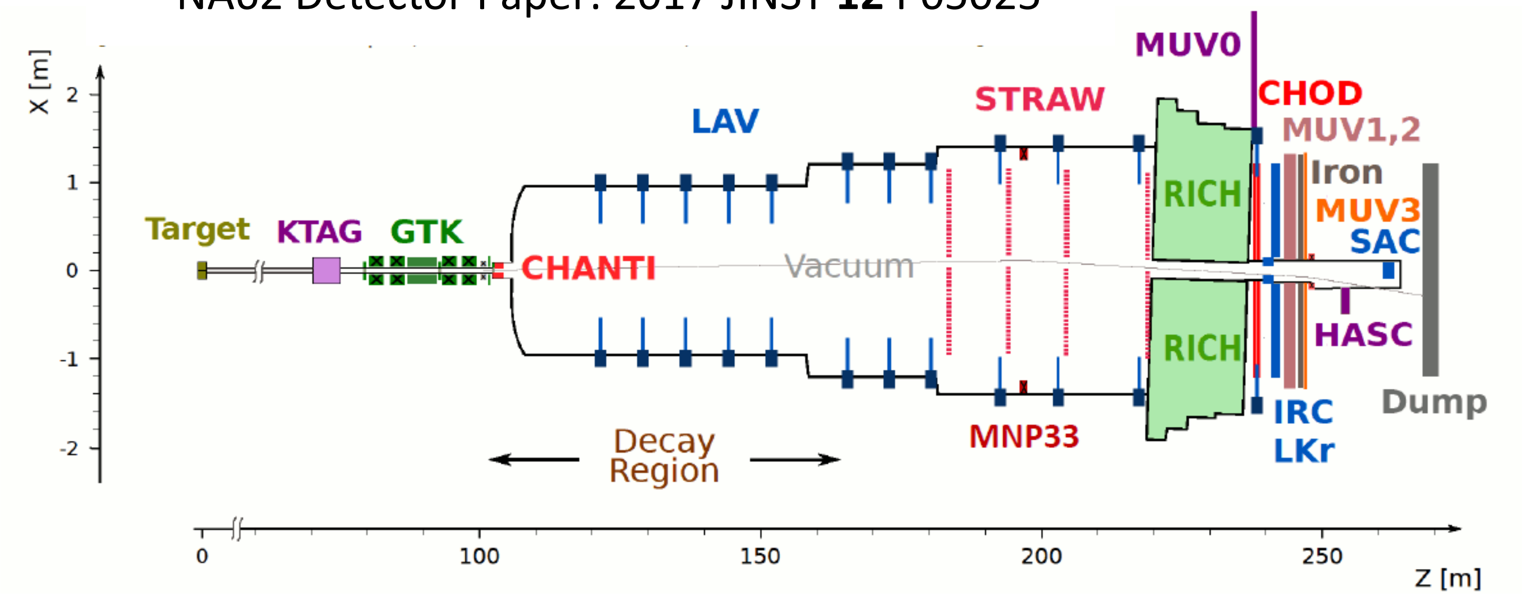
*[Buras et al. JHEP 1511 (2015) 33]*

Experimental status (E787,E949): $\mathrm{BR}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$

*[Phys. Rev. D 77, 052003 (2008), Phys. Rev. D79, 092004 (2009)]*

# NA62 layout

NA62 Detector Paper: 2017 JINST **12** P05025



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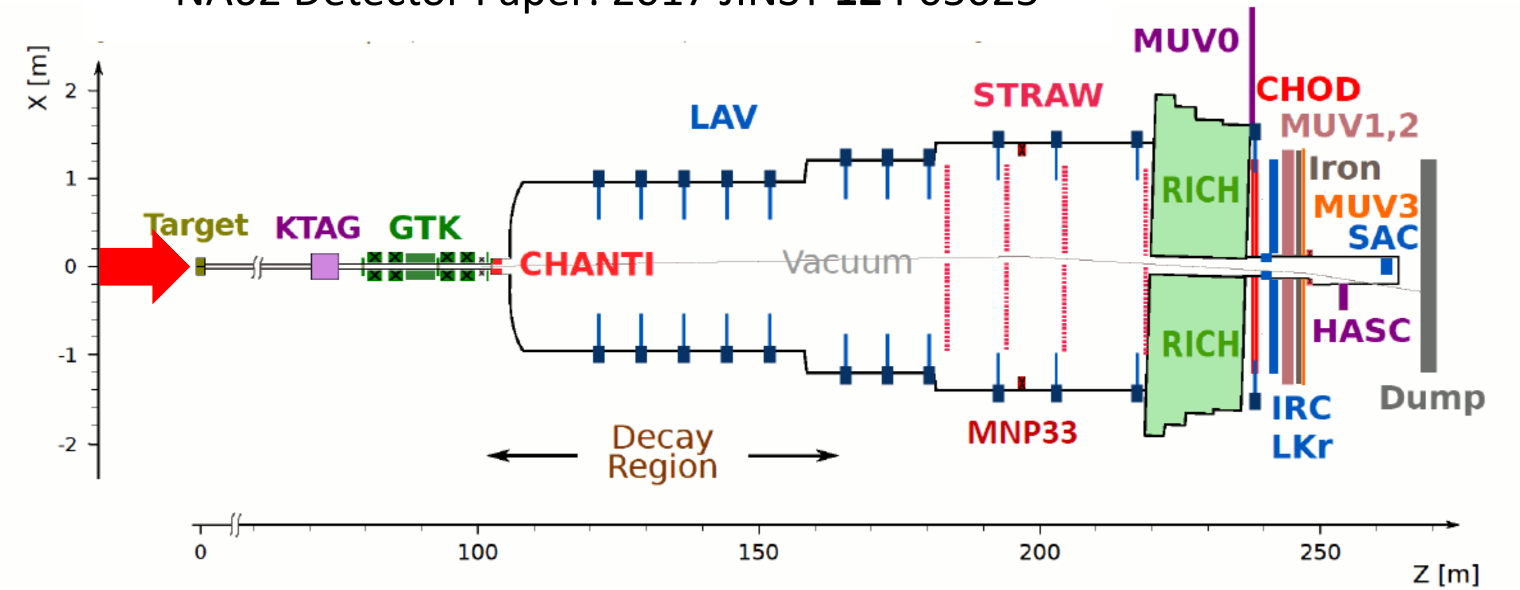


SPS protons:

400 GeV

$10^{12}$PoT/s on spill

3.5 s spill

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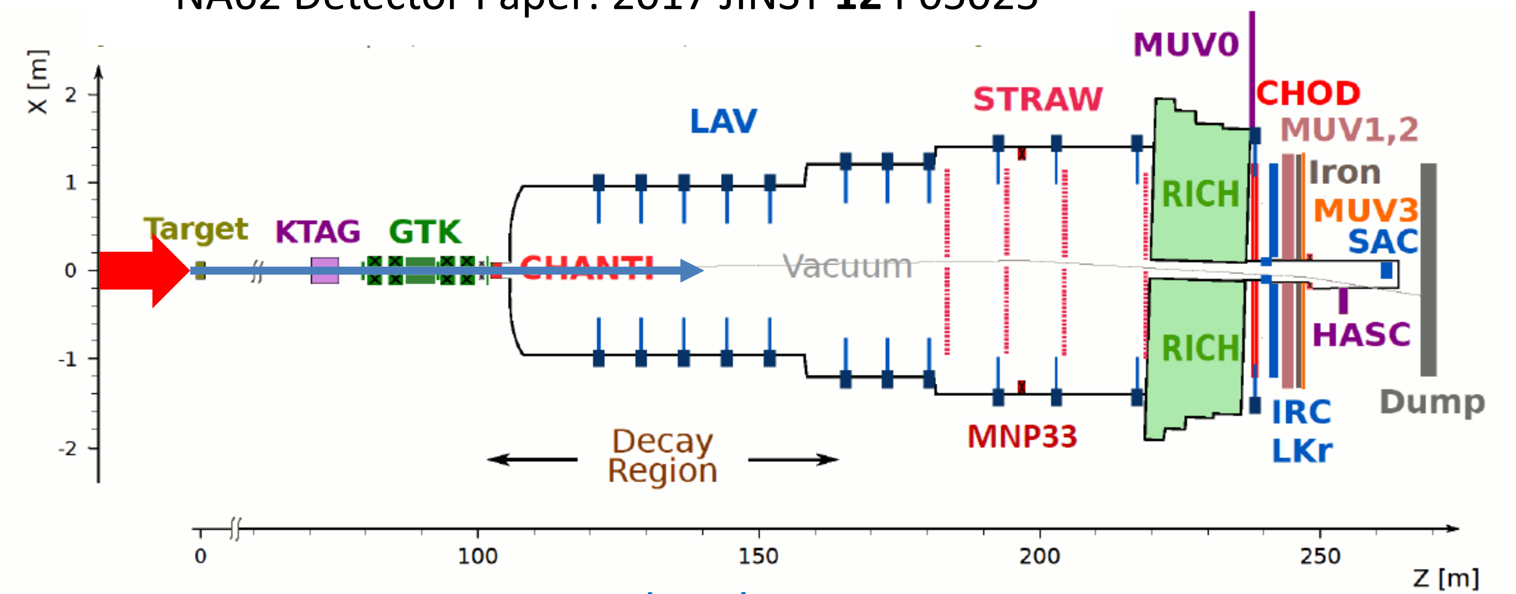


SPS protons:

400 GeV

$10^{12}$PoT/s on spill

3.5 s spill

Secondary beam:

75GeV/c, $\Delta p/p \sim 1\%$

100 $\mu$rad

K(6%), $\pi$(70%), p(23%)

$33\times10^{11}$ (750 MHz at GTK3)

$60\times30$ $mm^2$

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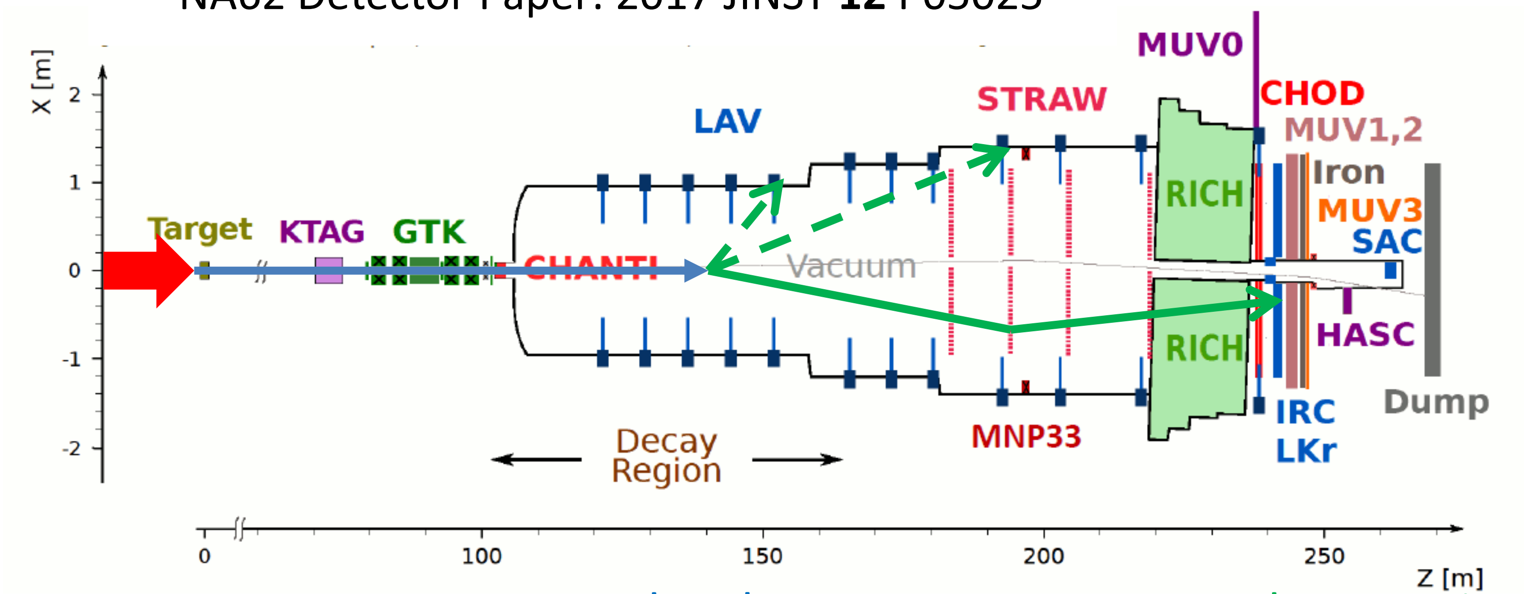


| SPS protons: | Secondary beam: | Kaon decay region: |
| --- | --- | --- |
| 400 GeV | 75GeV/c, $\Delta p/p \sim 1\%$ | 60 m length |
| $10^{12}$PoT/s on spill | 100 $\mu$rad | $\sim$ 5 MHz |
| 3.5 s spill | K(6%), $\pi$(70%), p(23%) | O($10^{-6}$) mbar |
| | $33\times10^{11}$ (750 MHz at GTK3) | |
| | $60\times30$ mm$^2$ | |

# NA62 layout

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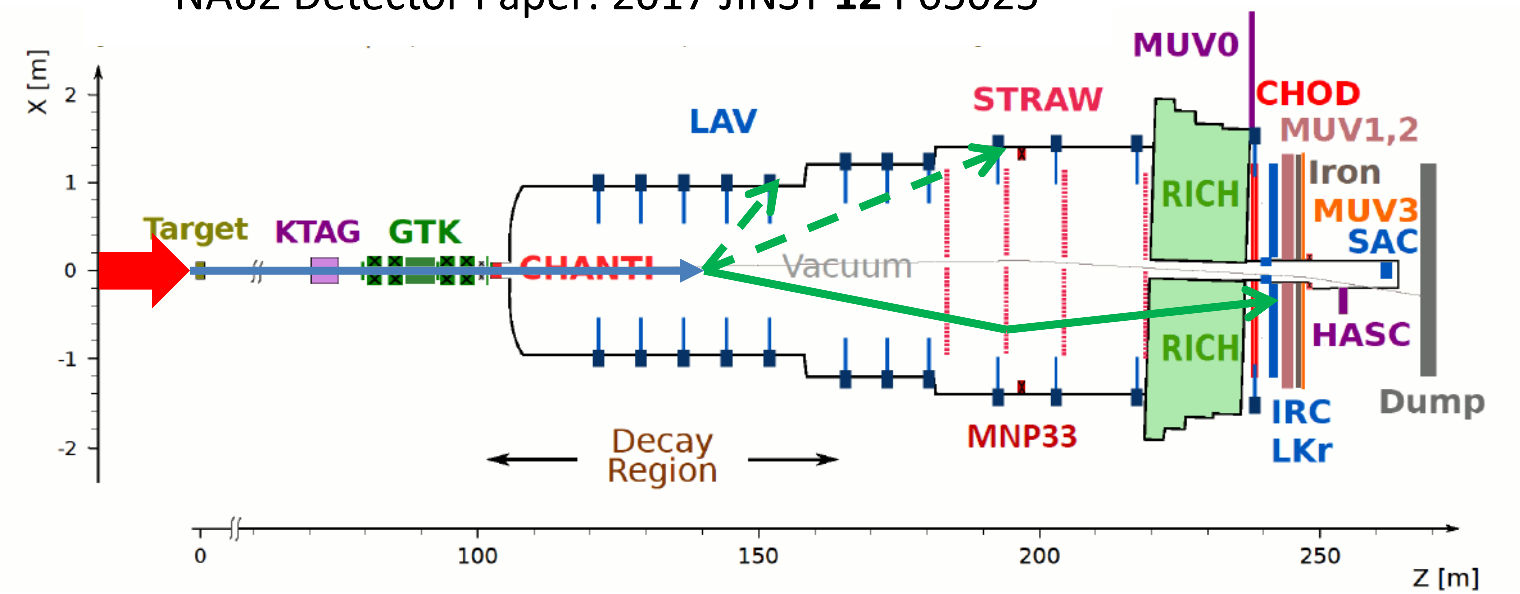



NA62 Keystone

| | |
|---|---|
| O (100 ps) | Timing between sub-detectors |
| $O(10^4)$ | Background suppression via kinematics reconstruction |
| $> 10^7$ | Muon suppression for $15 < p(\pi^+) < 35$ GeV/c |
| $> 10^7$ | $\pi^0$ rejection for $E(\pi^0) > 40$ GeV |

# NA62 timescale for $K^+ \to \pi^+ \nu\bar{\nu}$

## 2015

L0 trigger commissioning

Tested up to nominal intensity, $3.3 \cdot 10^{12}$ PoT/spill, 3.5s effective spill length

## 2016

L1 trigger/detector final commissioning

Stable running at 20% of the nominal beam intensity

Reach SM-expectation sensitivity, $O(10^{-10})$

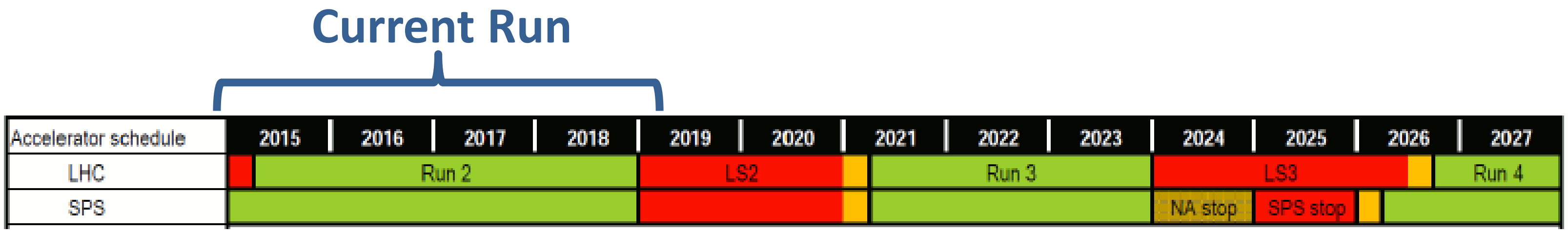
## 2017

Stable running at 60% of the nominal intensity, $\sim 3\times10^{12}$ $K^+$ decays collected

Improve (by much) on present state of the art (BNL measurement)

## 2018

Expect similar conditions as 2017, might incrementally increase intensity



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# NA62 physics besides $K^+ \to \pi^+ \nu\bar{\nu}$

**Such high-intensity, high-performance setup suited for other New Physics searches:**

- Lepton flavor violation (LFV) and lepton number violation (LNV) studies

  $10^{13}$ **$K^+$** $\to$ single event sensitivity (SES) ~ $10^{-12}$ (~$10^2$ improvement on past results)
- Ultra-rare/forbidden $\pi^0$ decays

  $10^{11}$ tagged **$\pi^0$** $\to$ SES ~ $10^{-10}$ (~$10^2$ improvement on chiral perturbation theory studies from other kaon decays)

**Trigger bandwidth for final states other than "$\pi^+$ + $E_{miss}$" (for $K^+ \to \pi^+ \nu\nu$) is limited:**

**Some LFV/LNV studies can be performed because involve low-bandwidth trigger**

- 3 daughter tracks at SES ~ $10^{-11}$: $K^+ \to \pi^+ \mu^\pm e^\mp$, $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^\pm \mu^+ \mu^+$

**Others because can be made in parasitic mode with the main trigger:**

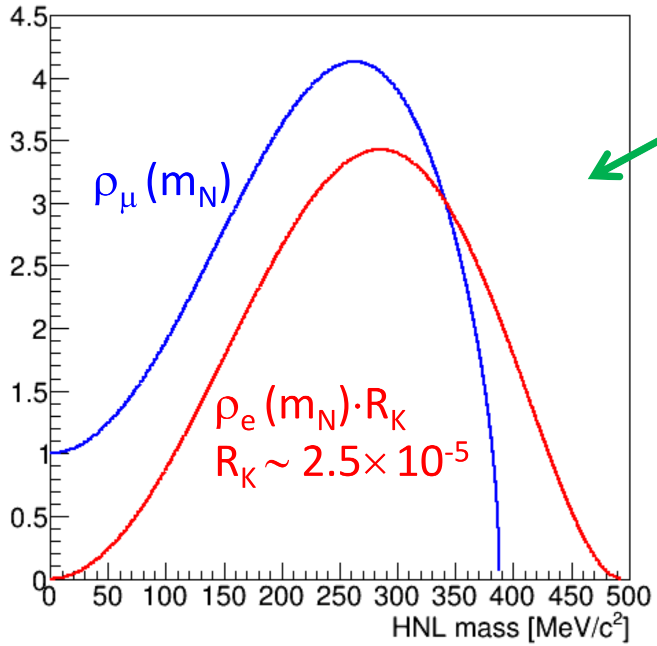
- Search for heavy neutral leptons (HNLs) in $K^+ \to \mu^+ \nu_h$, $K^+ \to e^+ \nu_h$
- Search for **$\pi^0$** $\to$ *invisible*, NA62 sensitive at $10^{-8}$ or better

# HNLs in kaon decays

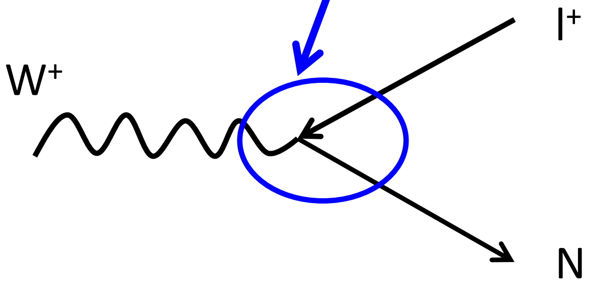
HNLs with mass $m_N < (m_K - m_e)$ can be produced in $K^+$ decays: $K^+ \rightarrow l^+ N$ ($l = e, \mu$)

Kinematic enhancement factor

$$\Gamma\left(K^+ \rightarrow l^+ N\right) = \Gamma\left(K^+ \rightarrow l^+ \nu_l\right) \cdot \rho_l\left(m_N\right) \cdot \left|U_{l4}\right|^2$$




Mixing matrix element: lepton-HNL coupling



# HNLs search in NA48/2 and NA62

Two different strategies can in principle be used in the HNLs search:

- Look for peaks in the missing mass spectra of two-body decays: $K^+ \to l^+ N$ ($l=e,\mu$)

$$\Gamma\left(K^+ \to l^+ N\right) = \Gamma\left(K^+ \to l^+ \nu_l\right) \cdot \rho_l\left(m_N\right) \cdot \left|U_{l4}\right|^2$$

$K^+ \to \mu^+ N$ (NA62-$R_K$) *[Phys. Lett. B772 (2017) 712-718]*

$K^+ \to e^+ N$, $K^+ \to \mu^+ N$ (NA62 2015) *[arXiv:1712.00297 [hep-ex], Accepted by Phys. Lett. B]*

- Look for HNLs decay products: $N \to \pi^0 \nu$, $N \to \pi \mu$, $N \to \pi e$, $N \to \nu\nu\nu$
  (dominant decays for $m_N < 500$ MeV/$c^2$)

$$\Gamma\left(\mathrm{N} \to \mathrm{SM\ particles}\right) \sim \left|U_{l4}\right|^2 \cdot m_N^3$$

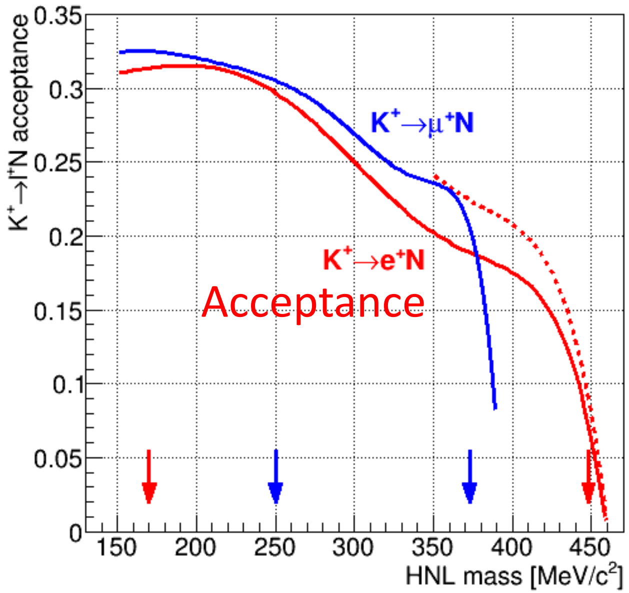
usually performed in beam dump experiments

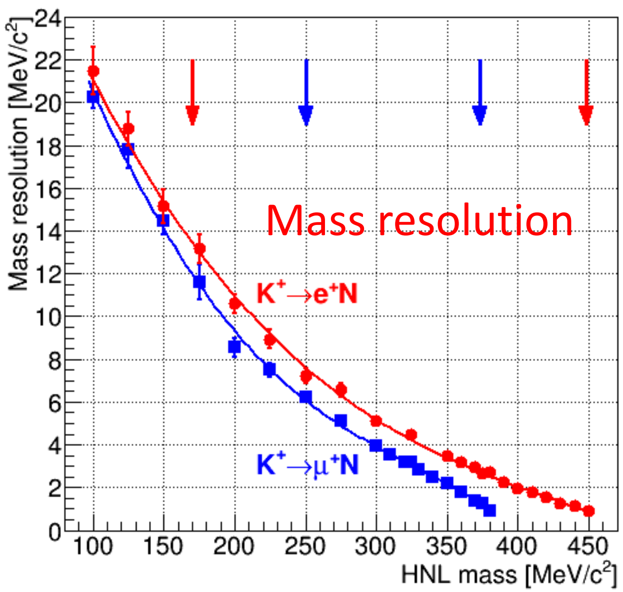
can also be studied in LNV decays with $\Delta L = 2$

$K^\pm \to \pi\mu\mu$ (NA48/2) *[Phys. Lett. B769 (2017) 67-76]*

# NA62 2015 HNLs search

- Peak search in $K^+ \to l^+N$ selected sample looking at $m_{miss}=(p_K - p_l)^{1/2}$
- Signal region: $250 < m_{miss} < 373$ MeV/$c^2$ ($K_{\mu 2}$), $170 < m_{miss} < 448$ MeV/$c^2$($K_{e2}$)
- Minimum bias data at 1% nominal intensity
- No beam tracker $\to$ average momentum using $K^+ \to \pi^+\pi^+\pi^-$
- $N_K \sim 3\times10^8$ in fiducial volume
- Dedicated Heavy Neutrino MC to evaluate acceptance and $m_{miss}$ resolution

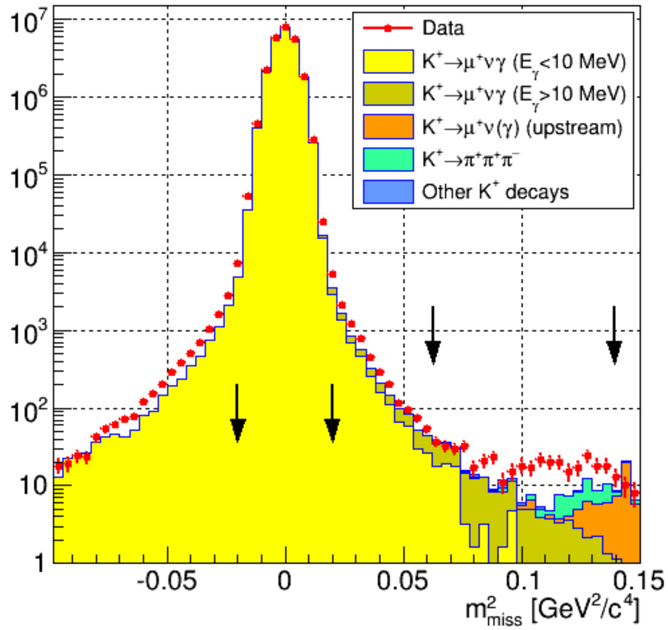


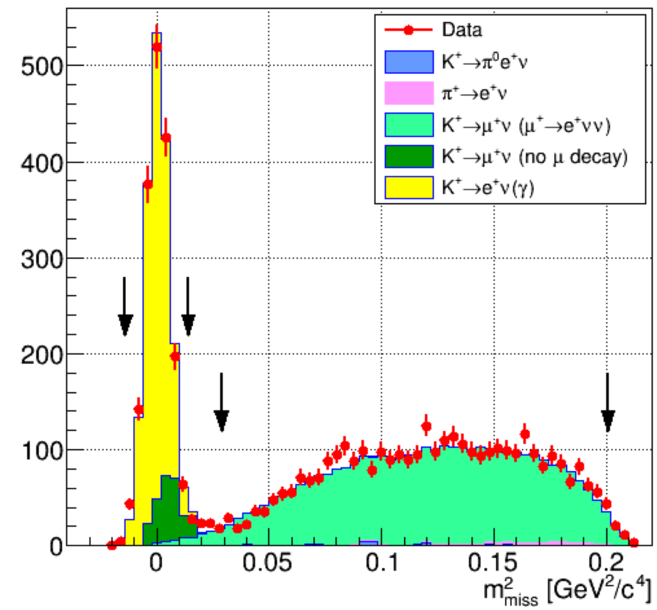



# NA62 2015 HNLs search

Most of the selection conditions are common for the $K^+ \to \mu^+N$ and $K^+ \to e^+N$
Differences mainly in trigger and particle identification criteria

Background studies based on MC simulation



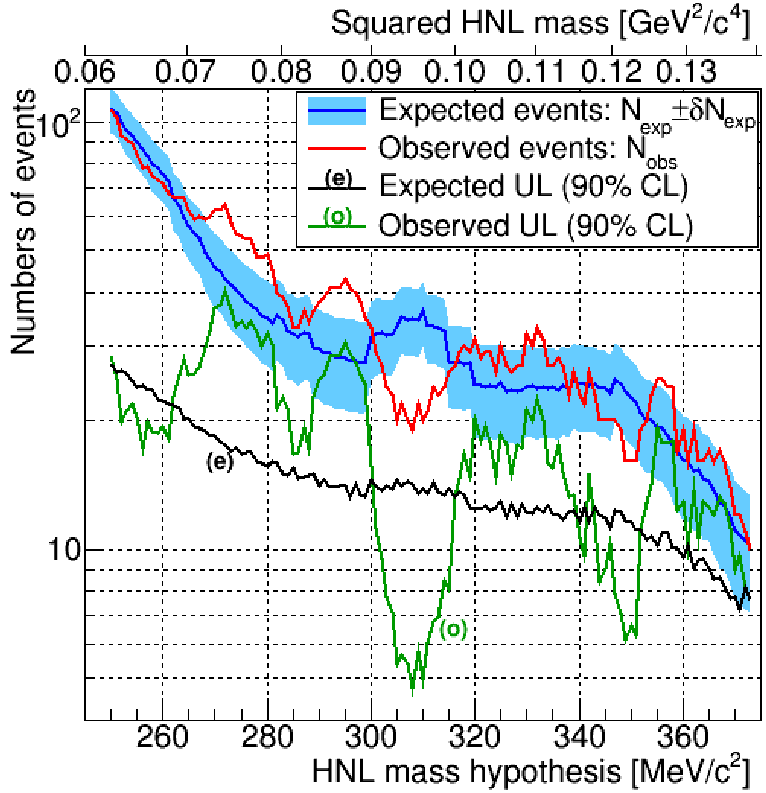



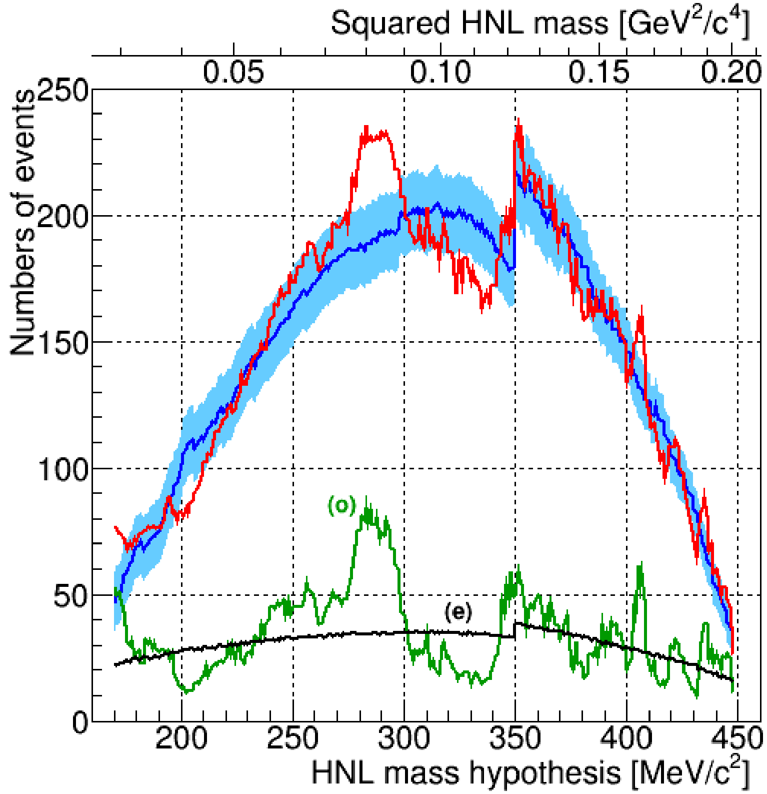

Data-driven background estimates used for the HNL search

- $K^+ \to l^+N$ search based on a HNL mass scan in the $m_{miss}$ data spectra
- Step of the mass scan fixed at 1 $MeV/c^2$

# NA62 2015 HNLs results

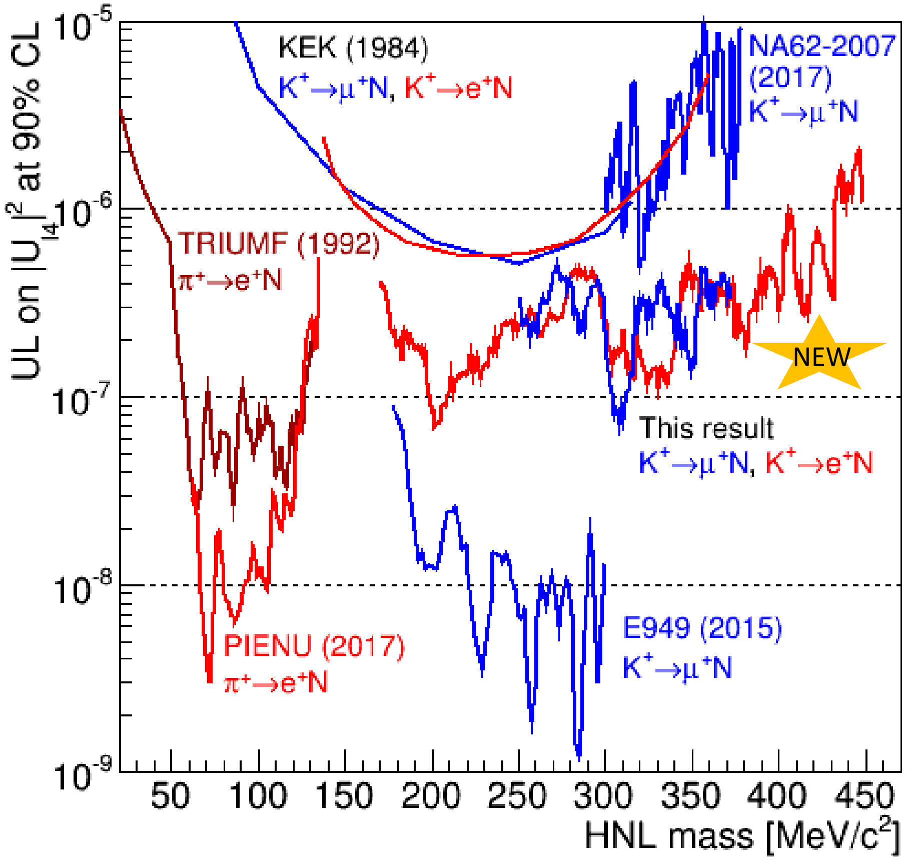
Rolke-Lopez method to get $UL(N_{sig})$



# World limit on $|U_{l4}|^2$

Limits from production searches




- Upper limits on the HNL mixing parameters $|U_{l4}|^2$ established between $10^{-7}$ and $10^{-6}$
- Extended mass range for $|U_{e4}|^2$

Prospects

$K^+ \to e^+N$ analysis on NA62-2016 data well advanced.
Expected major improvements due to higher beam intensity and fully commissioned beam tracker

$|U_{e4}|^2$ limit expected to decrease by 1-2 orders of magnitude by the end of NA62 run

# NA62 future projects

NA62 officially approved up to LS2$\rightarrow$ measuring BR ($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) with 10% accuracy

Before LS2 (2018)

many searches in the hidden sector using the kaon beam

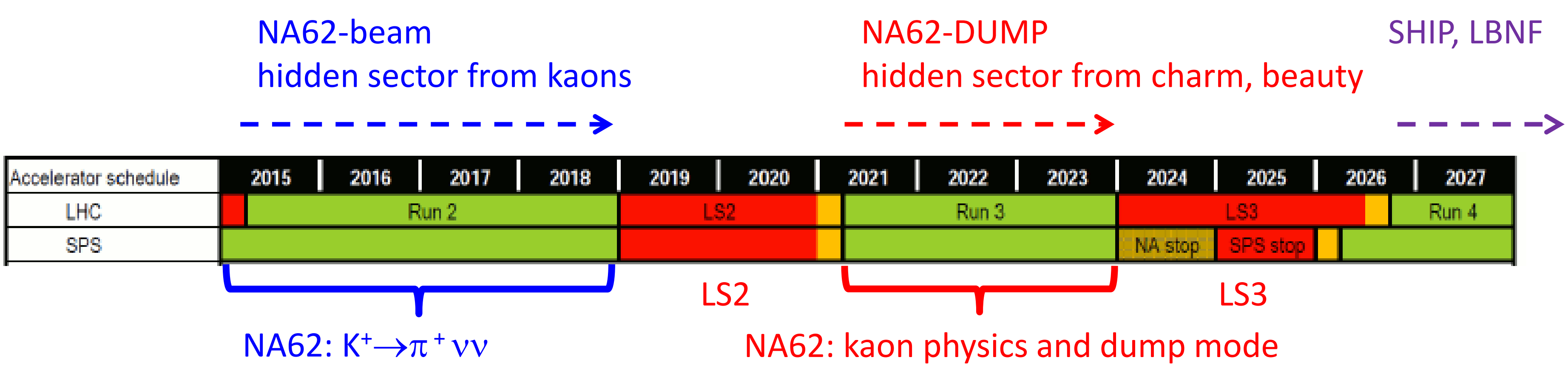
After LS2 (2020+)

refine $\pi\nu\nu$ measurement

run NA62 in beam-dump mode to search for hidden particles (**Heavy Neutral Leptons, Dark Photons, Dark Scalars, Axion/Axion-Like Particles**) from charm and beauty decays

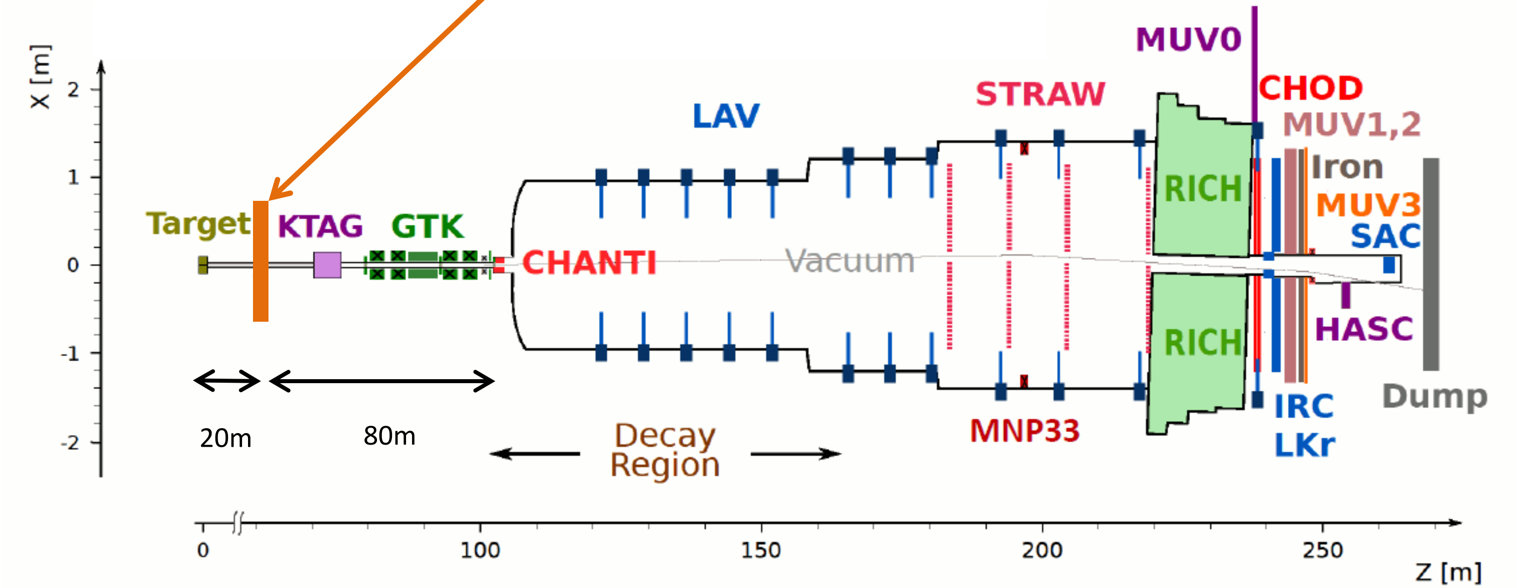
$\rightarrow$ Minimal upgrade to the present set-up under study, proposal in preparation

$\rightarrow$ Actively contributing to the Physics Beyond Collider Working Groups



# NA62 in dump mode

Beam defining collimators (TAX1 and TAX2)
~ 11 $\lambda_I$ Cu-based  can be used as a dump




Easy switch between $K^+$ beam and proton dump mode with TAXes

**$10^{18}$ PoT/nominal year**: $10^{12}$PoT/s on spill, 100 days/year, 60% run efficiency

**$10^{15}$ $D_{(S)}$, $10^{14}$ K, $10^{18}$ $\pi^0/\eta/\eta'/\Phi/\rho/\omega$ with ratios 6.4/0.68/0.07/0.03/0.94/0.95 (B mesons too)**

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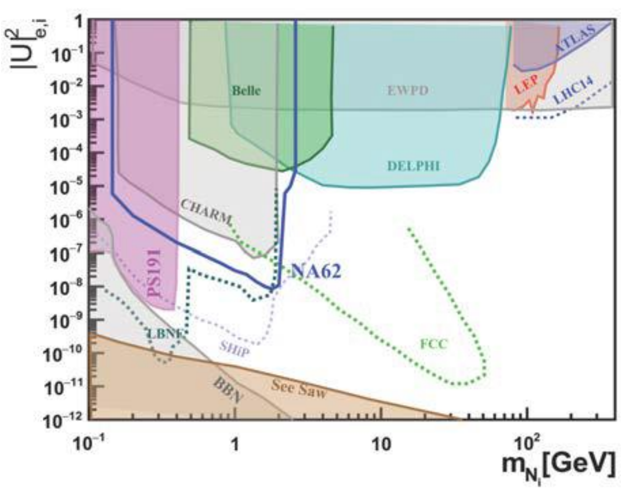
# NA62 projected sensitivity: HNLs

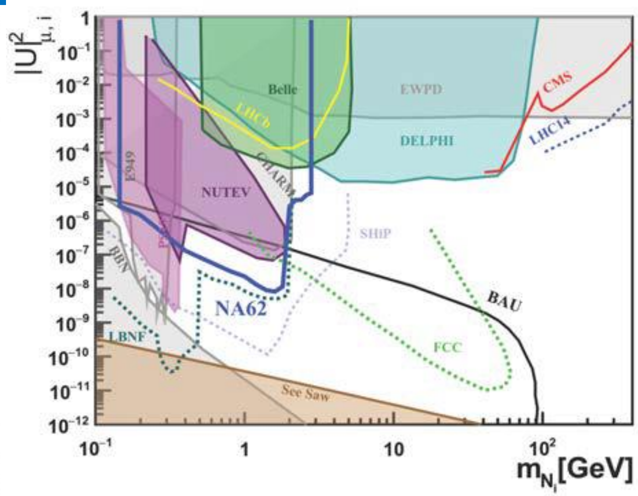
NA62 sensitivity with $10^{18}$ PoT in dump mode

- Search for two-track final states, including open channels
- Assume zero background
- Separately address 3 extreme coupling scenarios

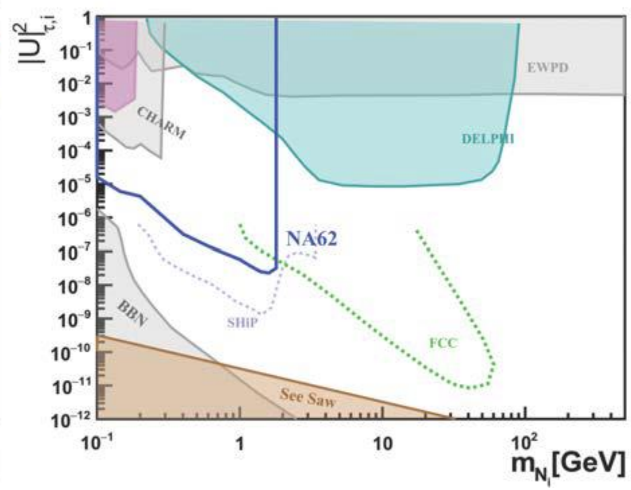
Scenario 1 — $U^2_e$ enhanced




Scenario 2 — $U^2_\mu$ enhanced




Scenario 3 — $U^2_\tau$ enhanced

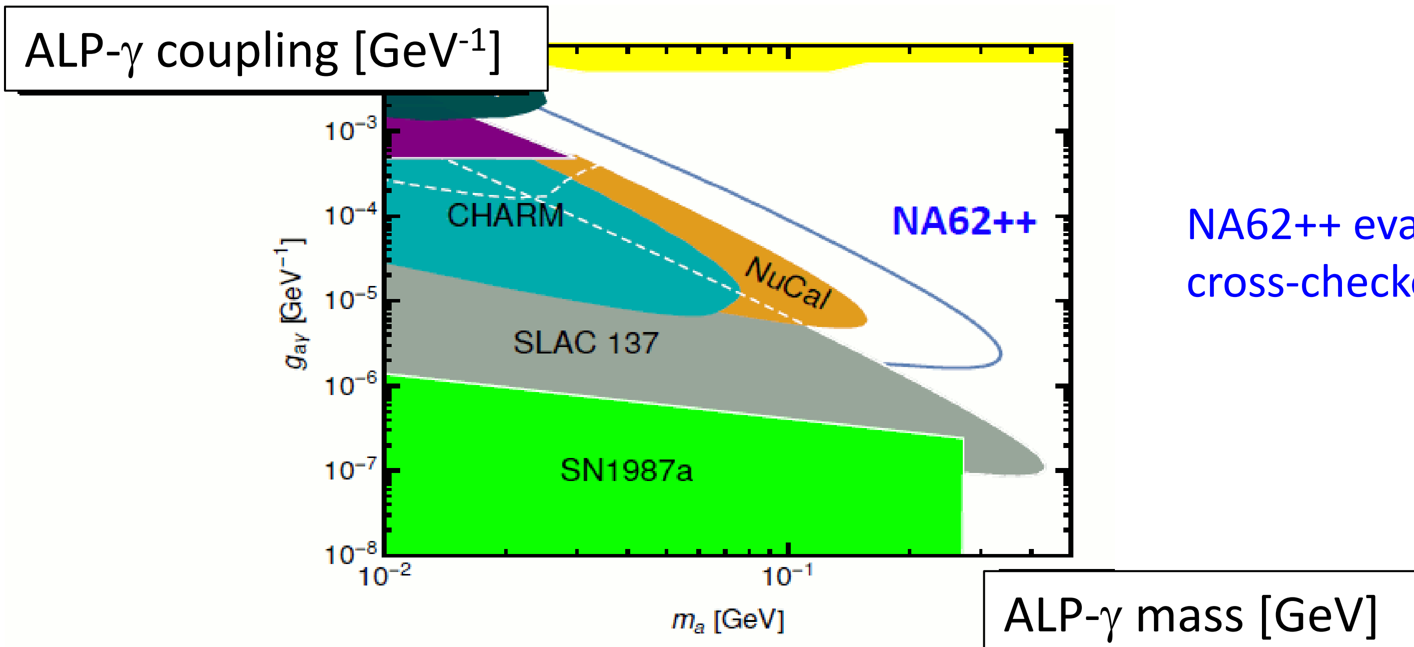



Zero background has been proven at $4\times10^{15}$ PoT and fully reconstructed final states

# NA62 projected sensitivity: ALPs

NA62 sensitivity with $10^{18}$ PoT in dump mode

- Study ALP Primakoff production from interaction onto TAX
- Search for ALP-decay to $\gamma\gamma$ in the NA62 fiducial volume
- Account for geometrical acceptance
- Assume zero-background



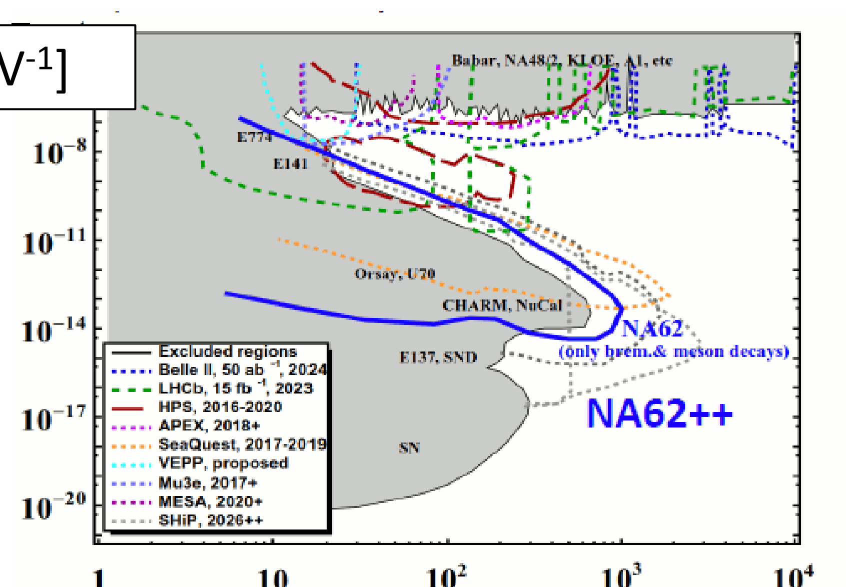

NA62++ evaluation cross-checked with full MC

# NA62 projected sensitivity: DPs

NA62 sensitivity with $10^{18}$ PoT in dump mode

- Study DP production (meson decays , bremmsstrahlung) from interaction onto target
- Search for DP-decay to ee, $\mu\mu$ in the NA62 fiducial volume
- Account for geometrical acceptance
- Assume zero-background

DP-$\gamma$ coupling [GeV$^{-1}$]




ALP-$\gamma$ mass [GeV]

NA62++ evaluation cross-checked with full MC

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# Conclusions

- NA62 approved to run until 2018 (LS2) with the main goal of measuring $BR(K^+ \to \pi^+ \nu\bar{\nu})$ with 10% accuracy
- Before LS2 (2018): searches in the hidden sector performed using the kaon beam. Short periods in dump mode also scheduled
- After LS2 there is a window of opportunity to run NA62 in beam-dump mode to collect $10^{18}$ PoT (~80 days @ full intensity) to search for hidden particles from charm / beauty decays
- Preliminary studies with data taken in beam and beam-dump modes show that the background can be kept under control for fully reconstructed final states. Improvements in the setup are currently under consideration to optimize the detector performances.