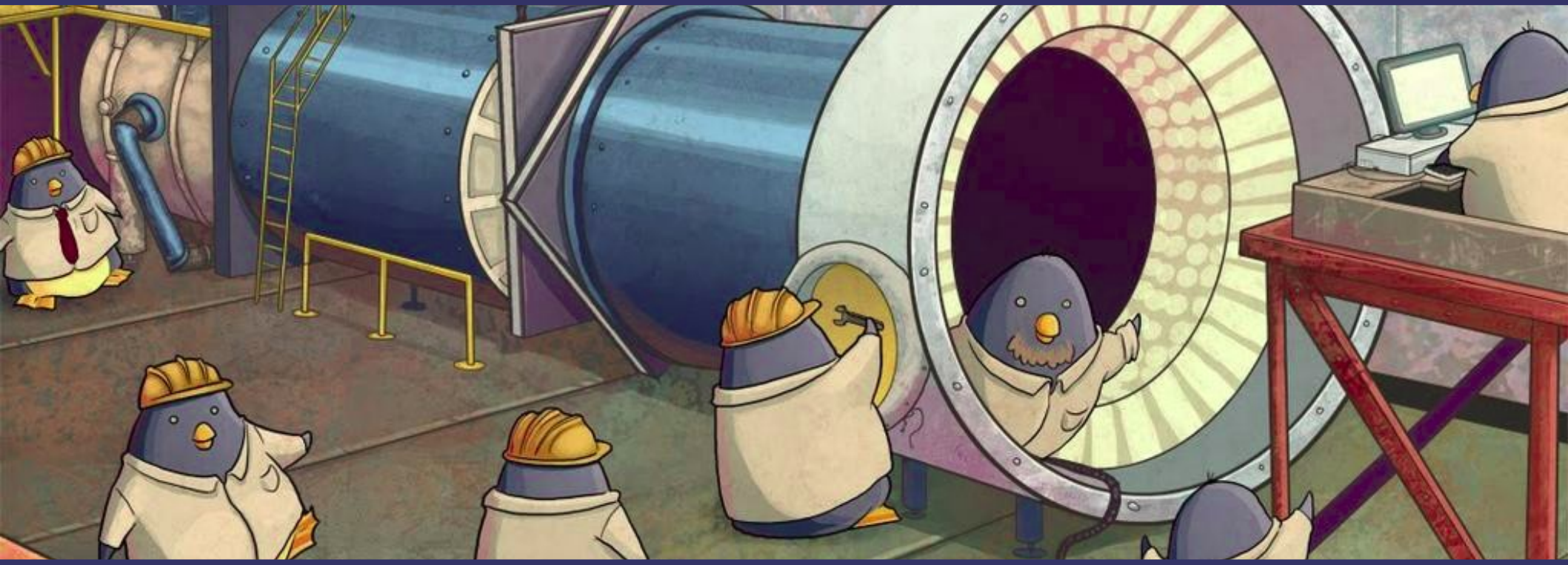
Conference on Flavour Physics and CP violation (FPCP)



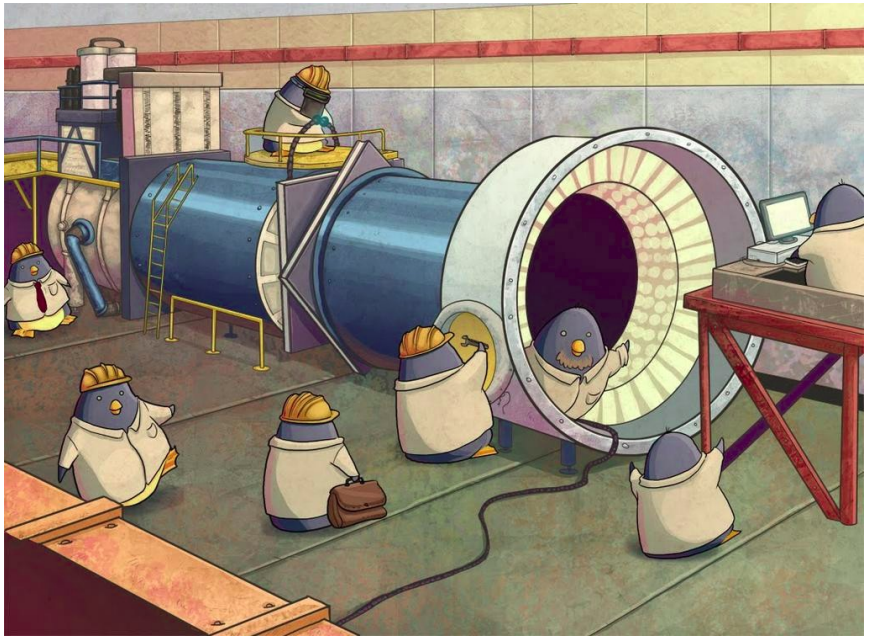
Search for exotic decays in NA62

Alina Kleimenova
(Université catholique de Louvain)
on behalf of NA62 Collaboration

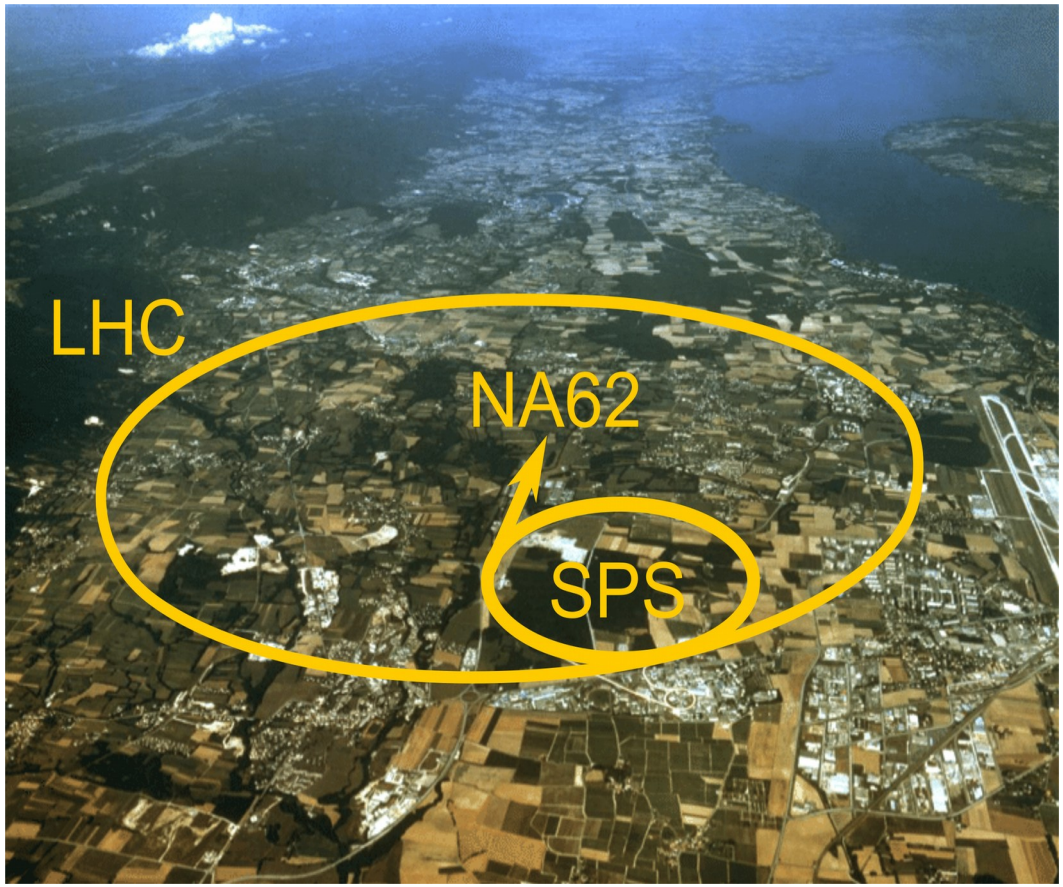
FPCP 2020, 10th June

Outline

- The NA62 experiment at the CERN SPS
- NA62 exotics searches:
  - Heavy Neutral Lepton (HNL) searches
  - Dark Photon (DP) searches
  - Future prospects
- Summary



The NA62 experiment



~30 institutes, ~200 participants from:

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

NA62 – fixed target kaon experiment at CERN SPS

Main goal: measurement of the BR($K^+ \to \pi^+ \nu\bar{\nu}$) with 10% precision using novel kaon-in-flight technique.

Theoretical prediction:

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$

[Buras et al., JHEP11(2015)033]

Experimental result before NA62:

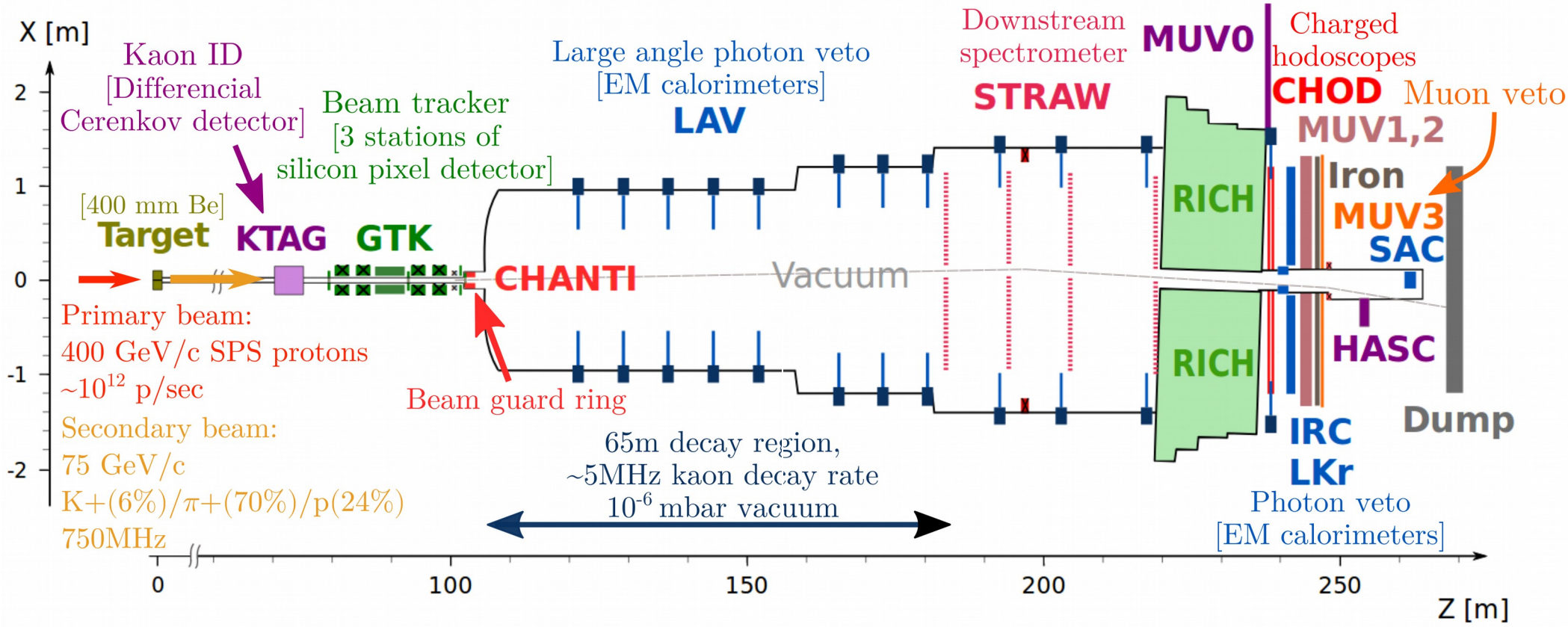
$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$

[Phys. Rev D 79, 092004 (2009)]

Broader physics program:

- Rare/forbidden kaon decays
- Searches for **exotic processes**

Detector overview

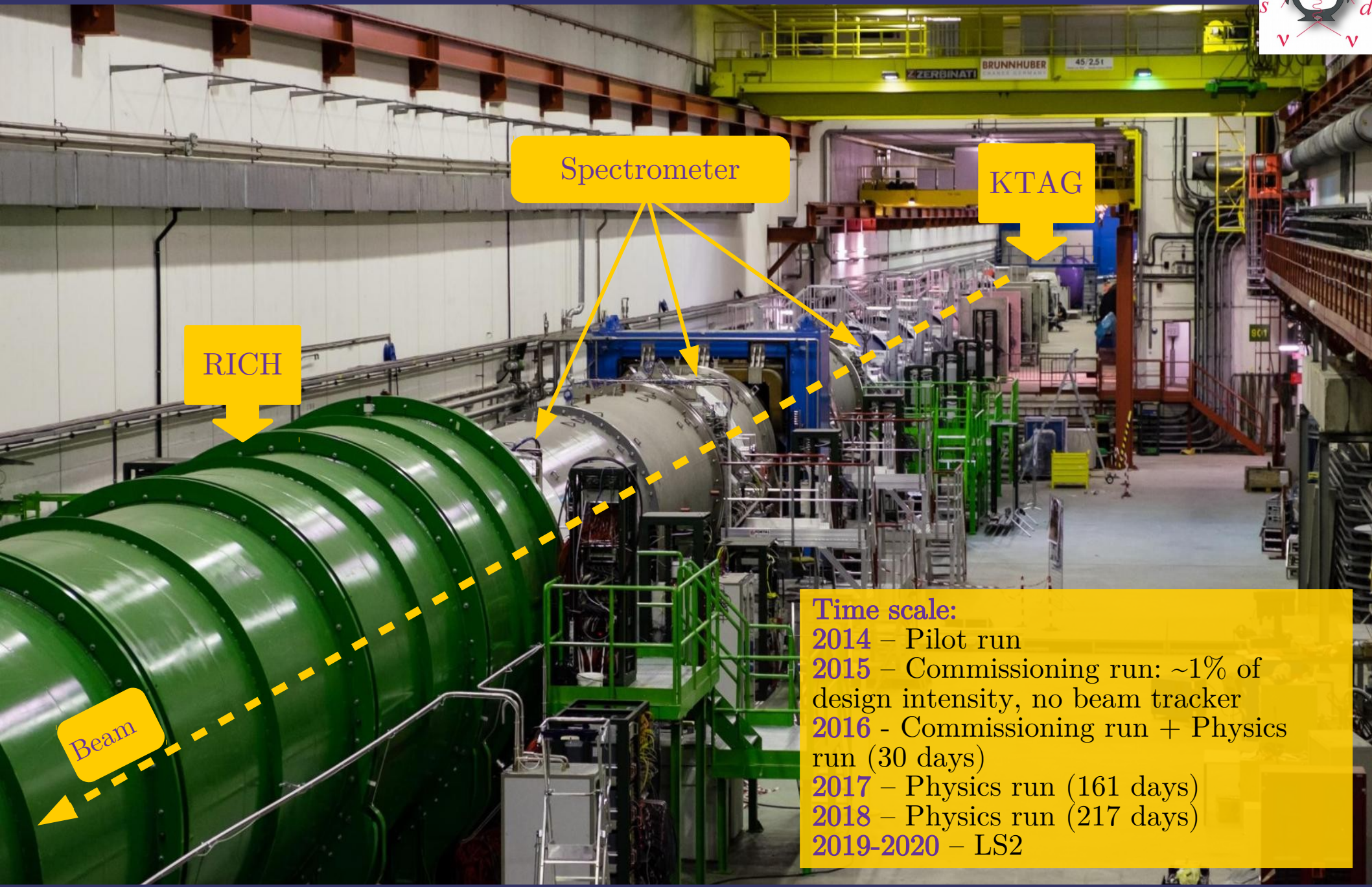


Performances:

- GTK-KTAG-RICH time resolution: $O(100$ ps$)$
- $O(10^4)$ background suppression from kinematics
- $O(10^7)$ muon rejection for 15 $<p(\pi^+)<$ 35 GeV
- $O(10^8)$ π^0 rejection of for $E(\pi^0)>$ 40 GeV

[NA62 Detector Paper, JINST 12 (2017), P05025]

NA62



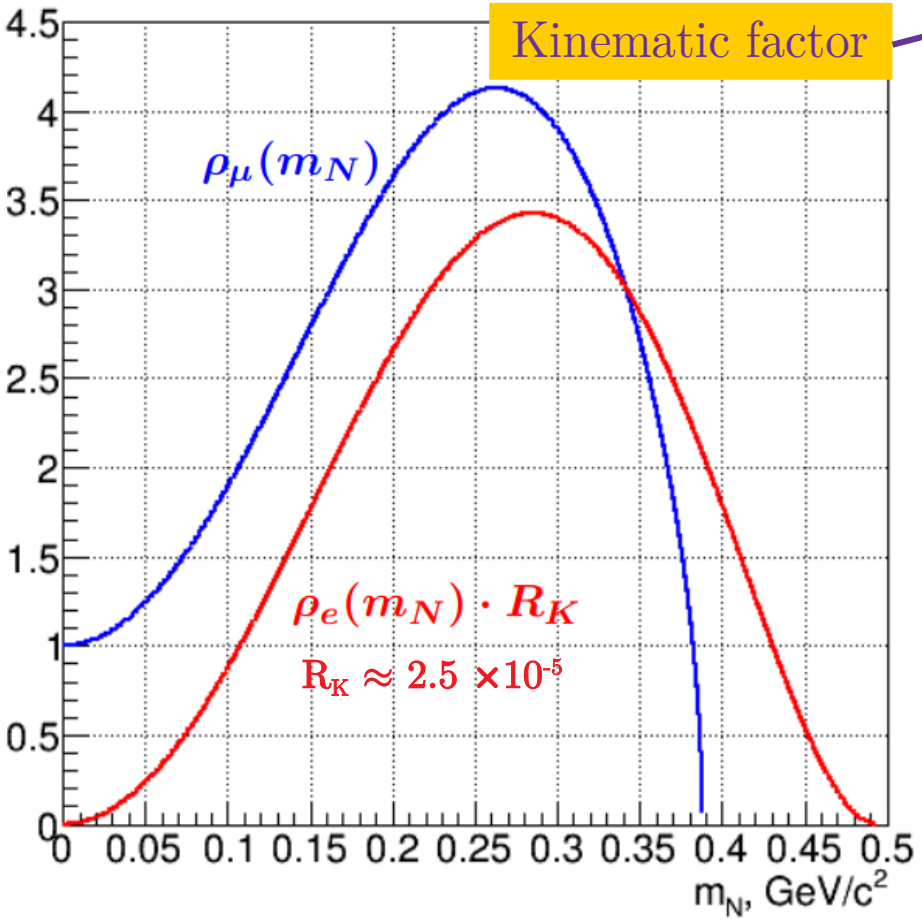
Time scale:
2014 – Pilot run
2015 – Commissioning run: ~1% of design intensity, no beam tracker
2016 - Commissioning run + Physics run (30 days)
2017 – Physics run (161 days)
2018 – Physics run (217 days)
2019-2020 – LS2

HNL searches in kaon decays

$$\Gamma(K^{\pm} \to l^{\pm} N) = \Gamma(K^{\pm} \to l^{\pm} \nu_l) \rho(m_N) \, |U_{l4}|^2$$

[R. Shrock PLB96 (1980) 159]

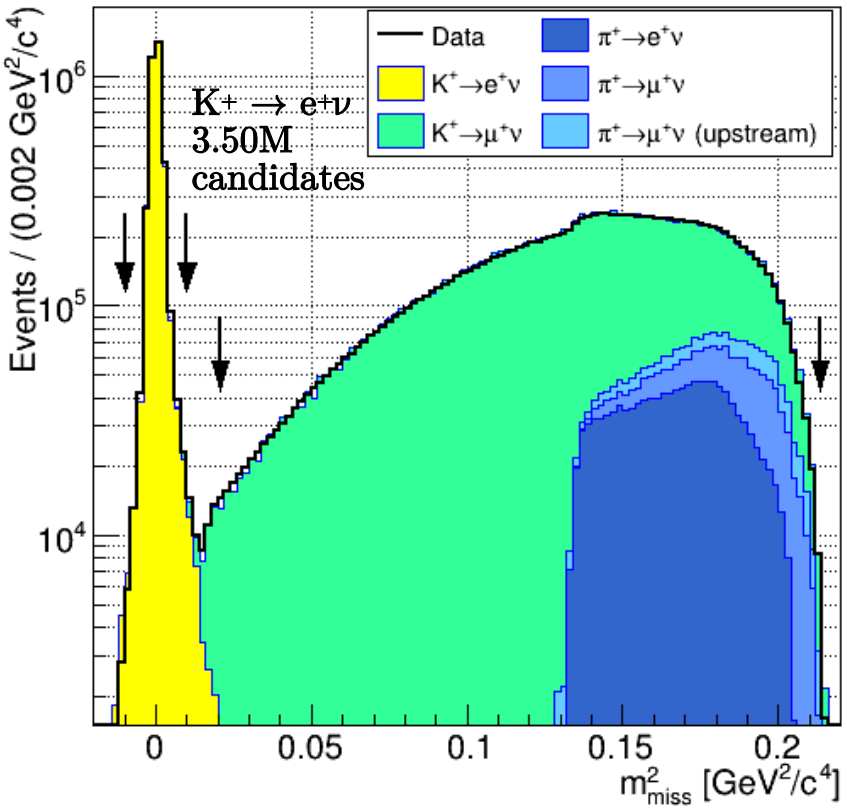
Kinematic factor

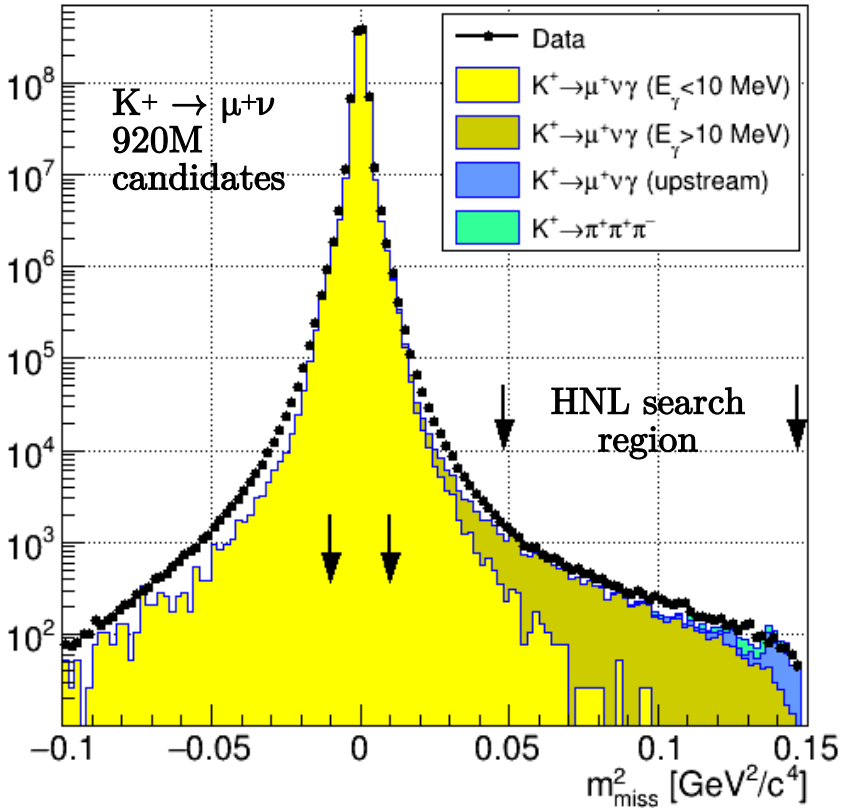


- HNL production is enhanced wrt SM decays
- Large f ~10^5 enhancement in the $K^+ \to e^+ N$ case: helicity suppression is relaxed.

HNL searches in kaon decays

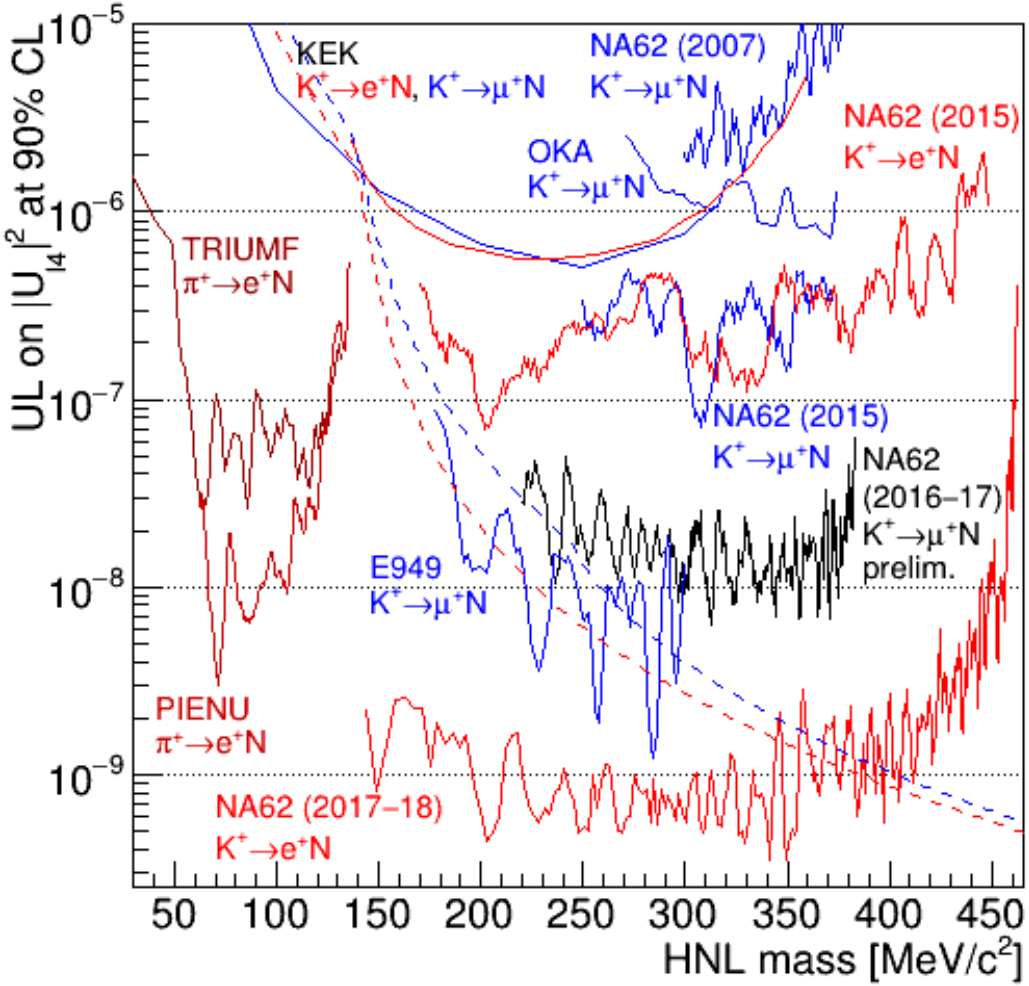
- **Data:** 2016+2017 for muon mode and 2017+2018 for positron mode
- **Triggers used:** the main $K_{\pi\nu\nu}$ for $K^+ \longrightarrow e^+N$; **Control** (min bias)/400 for $K^+ \longrightarrow \mu^+N$.
- Numbers of K^+ decays in the fiducial volume: $N_K=(3.52\pm0.02)\times10^{12}$ in **positron** case; $N_K=(4.29\pm0.02)\times10^{9}$ in **muon** case.
- **Peak searches in the squared missing mass**: $m^2_{miss}=(P_K - P_\ell)^2$, where P_K is kaon 4-momentum measured using GTK, and P_ℓ is lepton 4-momentum measured using STRAW.





HNL production search summary

NA62 collaboration, Phys.Lett.B778 (2018) 137
arXiv:2005.09575



- No HNL signal was observed
- Full data set for positron mode and ~1/3 of the data set for muon mode.
- Improvements over earlier production searches by up to 2 order of magnitude
- Muon case: sensitivity approaches E949. Search extends to 383 MeV/c^2
- Positron case: the BBN-allowed range is excluded up to 340 MeV/c^2

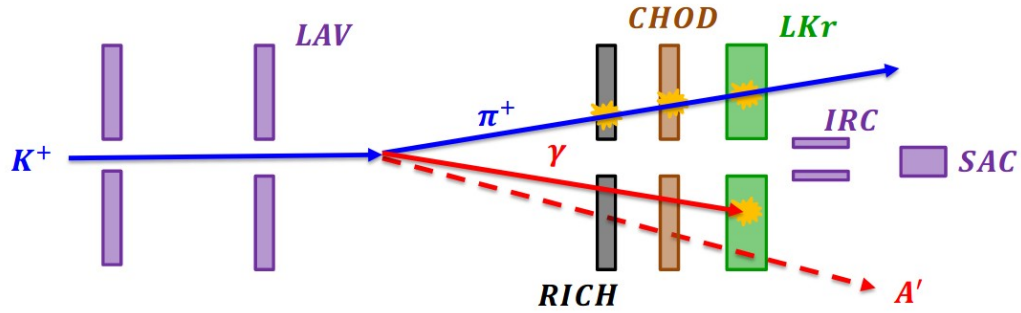
Dark photon searches in π^0 decays

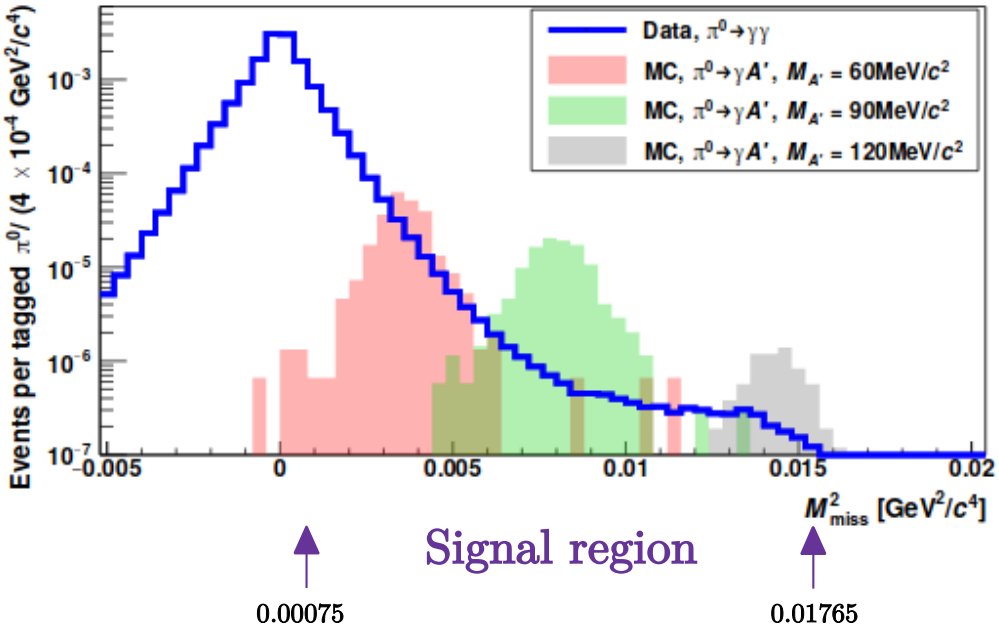
Dark photon produced in **π^0 decay** via **kinetic mixing ϵ** with SM photon $K^+ \to \pi^+\pi^0$, $\pi^0 \to A'\gamma$:

$$\mathcal{B}(\pi^0 \to \gamma A') = 2\epsilon^2 \left(1 - \frac{m^2_{A'}}{m^2_{\pi^0}}\right)^3 \mathcal{B}(\pi^0 \to \gamma\gamma)$$

where A'$\to$ invisible or long lived

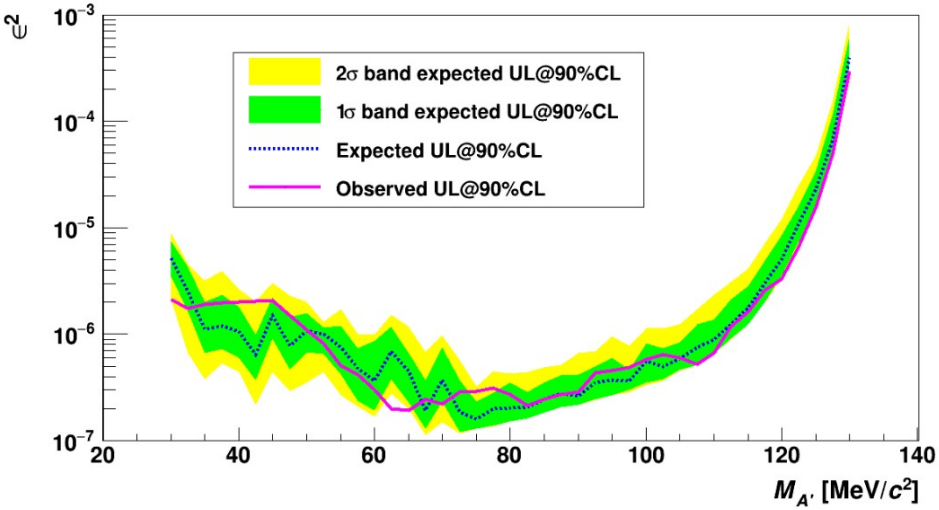
- **Data:** 5% of 2016 data (1% of full available statistics)
- **Trigger:** main $K_{\pi\nu\nu}$ trigger
- **Selection:** Tag π^0 of known momentum from $K^+ \to \pi^+\pi^0$ and select events with $\pi^0 \to \gamma$ + invisible
- **Peak searches in the missing mass spectrum**: $m^2_{miss} = (P_K - P_\pi - P_\gamma)^2$

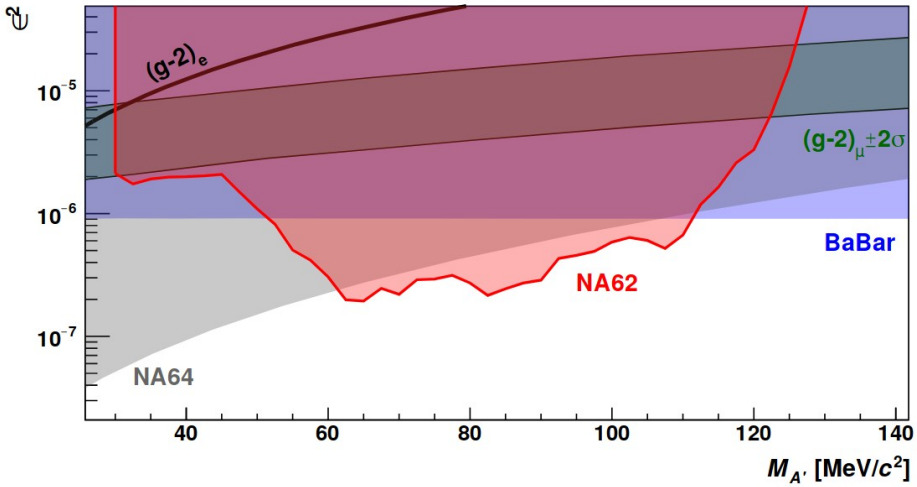




Dark Photon – 2016 result

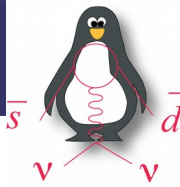
JHEP 05 (2019) 182





- No DP signal was observed
- Improved limits on ϵ^2 in 60-110 MeV/c^2 range (already covered by NA64 [PRL 123, 121801])
- Set 3 orders of magnitude better upper limits on:

$$\mathcal{B}(\pi^0 \to \gamma\nu\bar{\nu}) < 1.9 \times 10^{-7}$$



Future prospects: NA62++

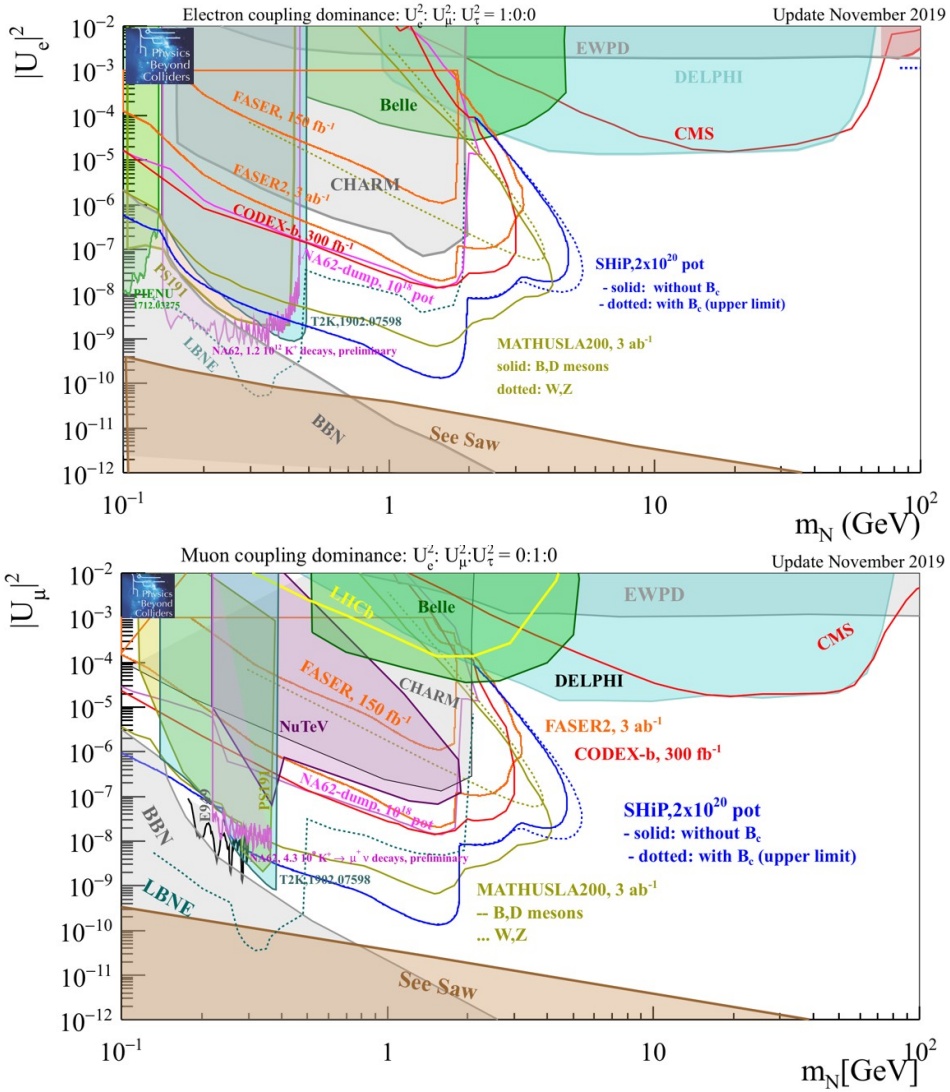
- The NA62++ experiment uses the same NA62 apparatus in a "beam dump" mode
  - NA62++ can collect O(10^{18}) protons on target (POT) in O(3) months
  - Possibility to run in this mode in 2023
- The physics prospects of NA62++ have been studied as part of the 'Physics Beyond Colliders – Beyond the Standard Model' working group [arxiv:1901.09966]
- The following slide shows NA62++ prospects assuming **O(10^{18}) POT** and **negligible background**
- **The limits are set at 90% CL**

Note:

- The results of studies based on **O(10^{16}) POT** show negligible background level
- A detailed, G4-based MC simulation developed within the PBC reproduces the distribution of single-track background events
- Improvements to the NA62++ setup (upstream veto, beamline modifications, higher intensity) are not included here, but initial studies are promising

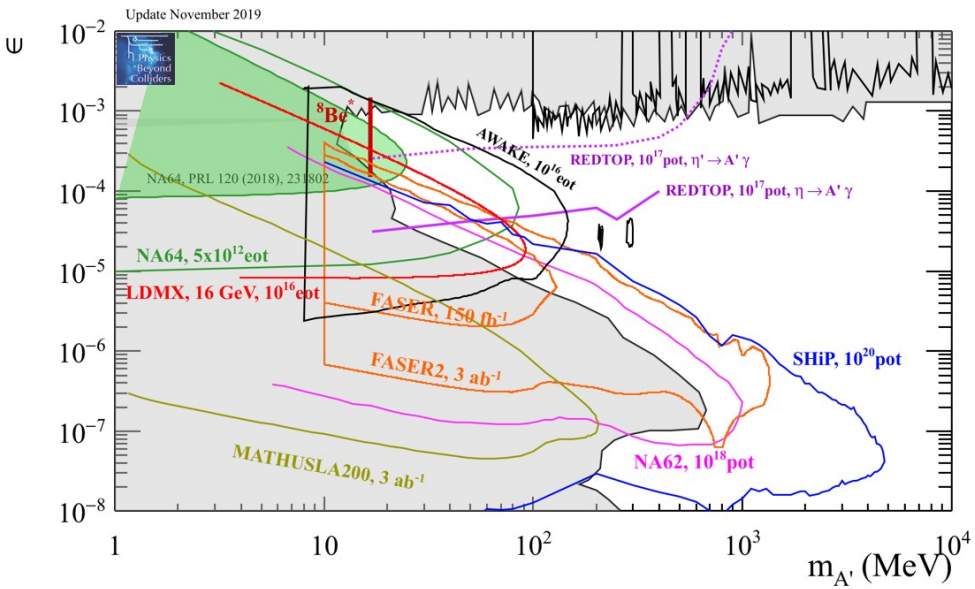
HNL decay searches

- HNL decay searches to visible final states with at least two charged tracks, where HNL produced in leptonic decays of B and D mesons
- Expected sensitivity in the plane HNL coupling to one SM generation vs HNL mass
  - account for acceptance
  - zero-background assumption



[PBC-BSM report, arXiv:1901.09966][arXiv:1801.04207]

Dark photon decay searches

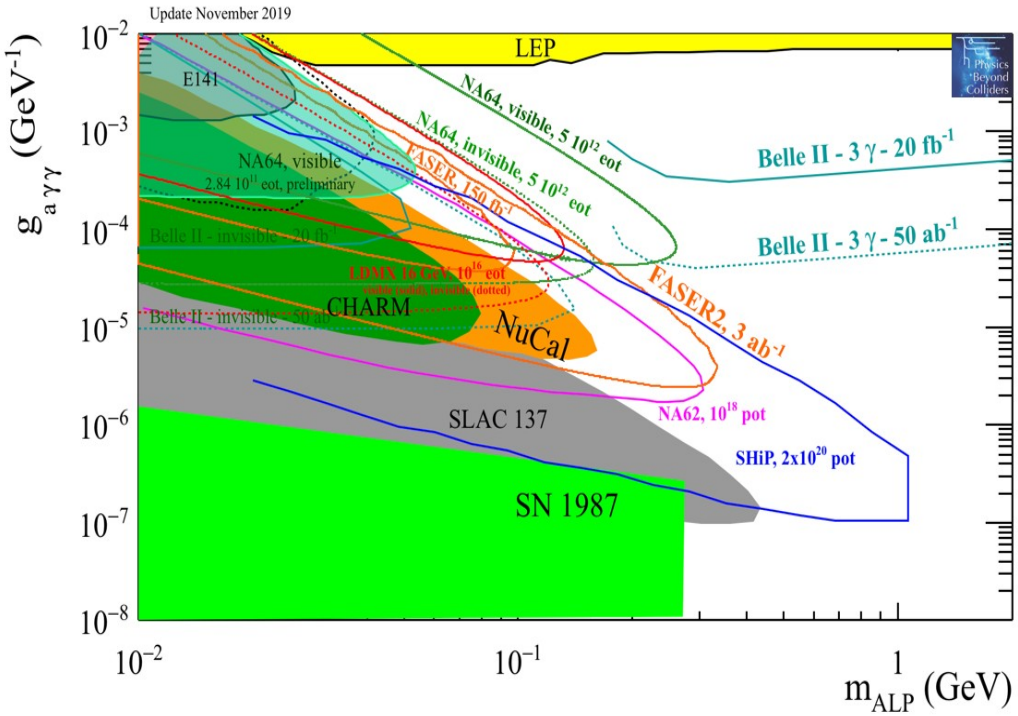


- Decay searches for A' $\to$ ll
- Expected sensitivity in the plane A' mixing with SM photons vs A' mass :
  - account for geometrical acceptance
  - zero-background assumption
- Sensitivity expected to be higher than shown:
  - including direct QCD production of A'
  - Including A' production in the collimator (here, only target)

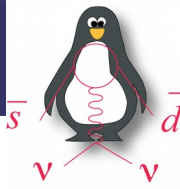
[PBC-BSM report, arXiv:1901.09966]

ALP decay searches

- Decay searches for $a \to \gamma\gamma$, where a produced via elastic scattering of beam proton dumped onto collimator material
- Analysis of 2017-2018 data is ongoing ($2 \cdot 10^{16}$ POT) – first results are expected very soon!
- Expected sensitivity in the plane ALP coupling to photons vs ALP mass
  - account for geometrical acceptance
  - zero-background assumption

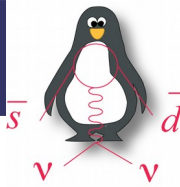


[PBC-BSM report, arXiv:1901.09966]

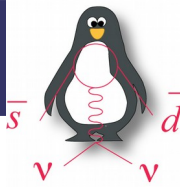


Summary

- The NA62 experiment is a powerful laboratory to make searches for exotic particles in both production and decay modes:
  - Final upper limits on HNL mixing parameters in positron case and preliminary upper limits in the muon case
  - Preliminary new limit on dark photon coupling
  - Further results and useful studies will be obtained with the NA62 full data set analysis (2016-2018)
- The prospects for the NA62++ "dump mode" experiment were presented:
  - Searches for exotic decays at NA62++ can improve limits in a variety of models, including Heavy neutral leptons (HNL), dark photons (A′), and axion-like particles (ALP)

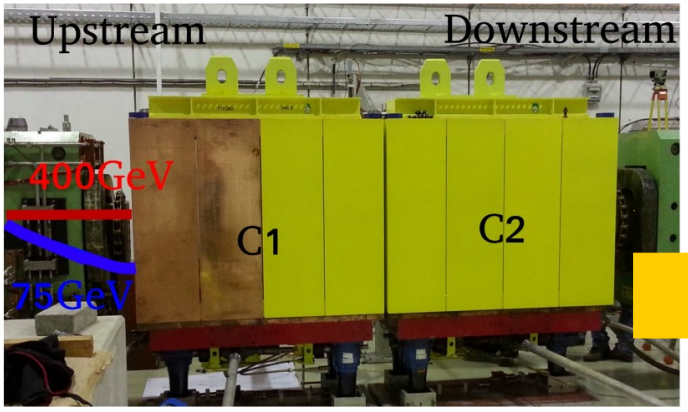


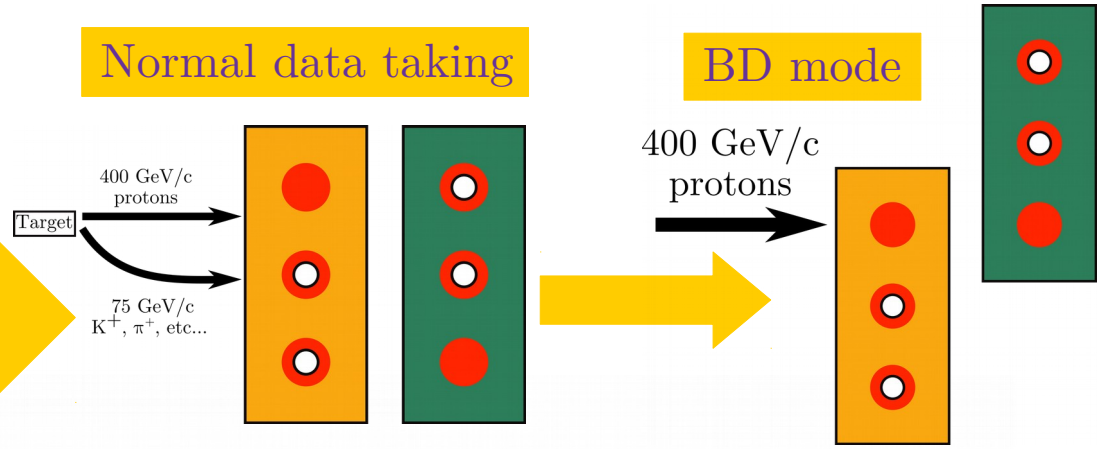
Thank you!

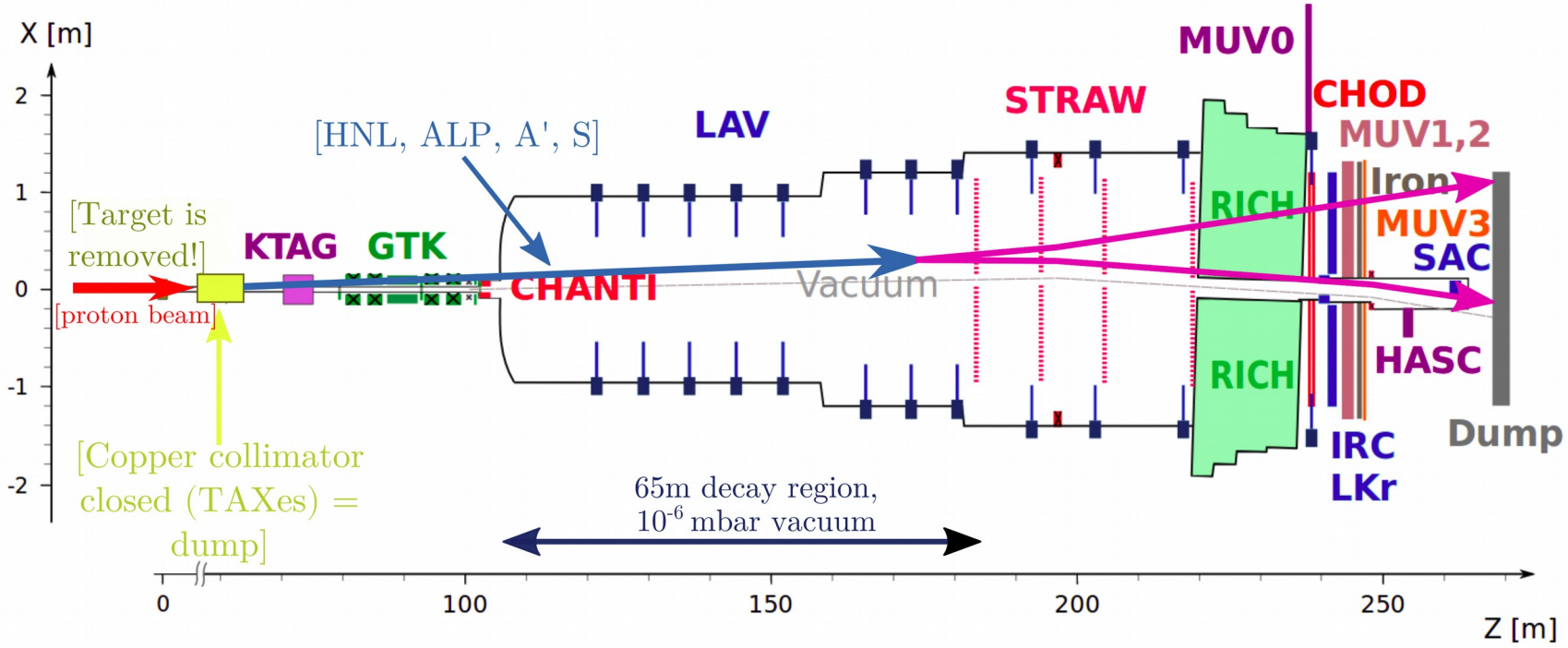


[Backup slides]

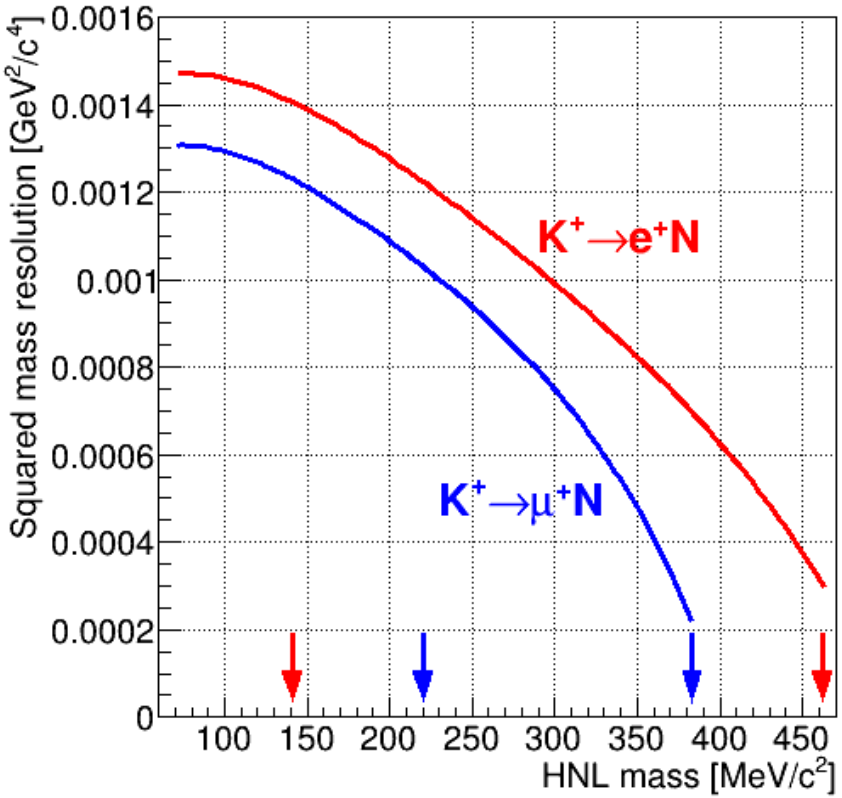
Beam dump mode of NA62

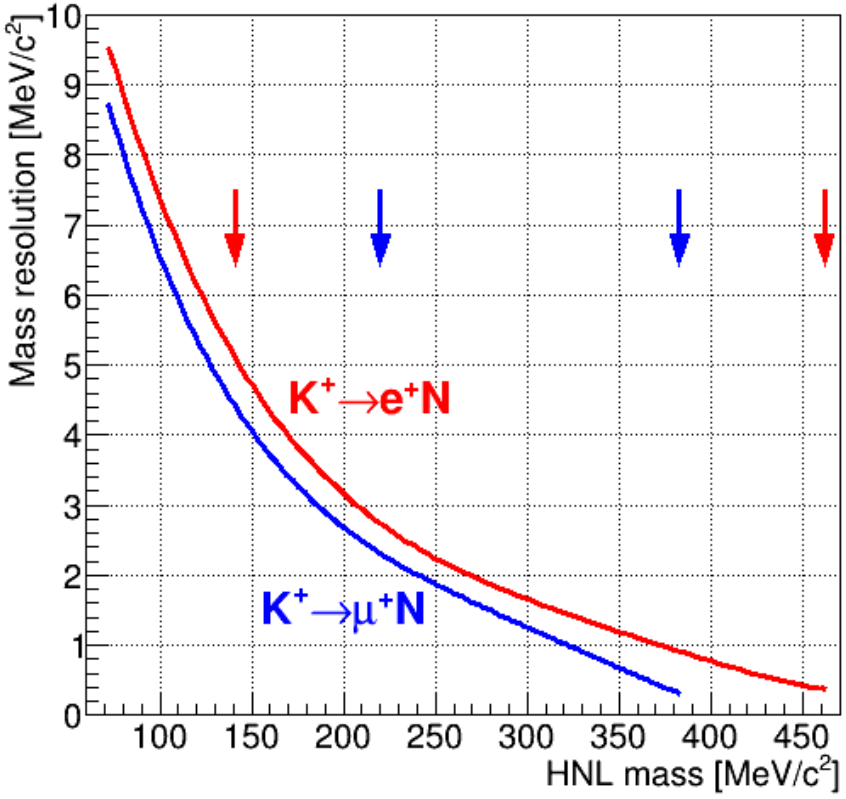






HNL production searches: mass resolution



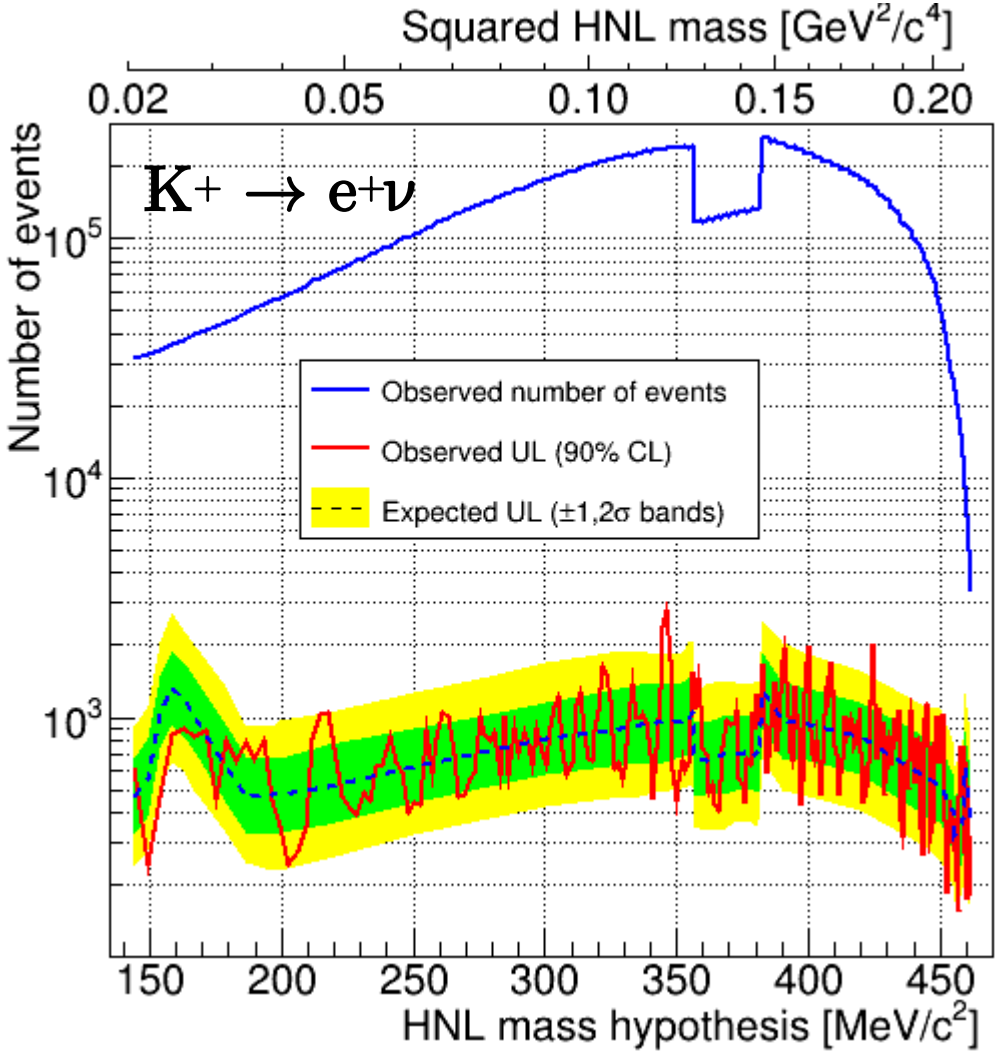


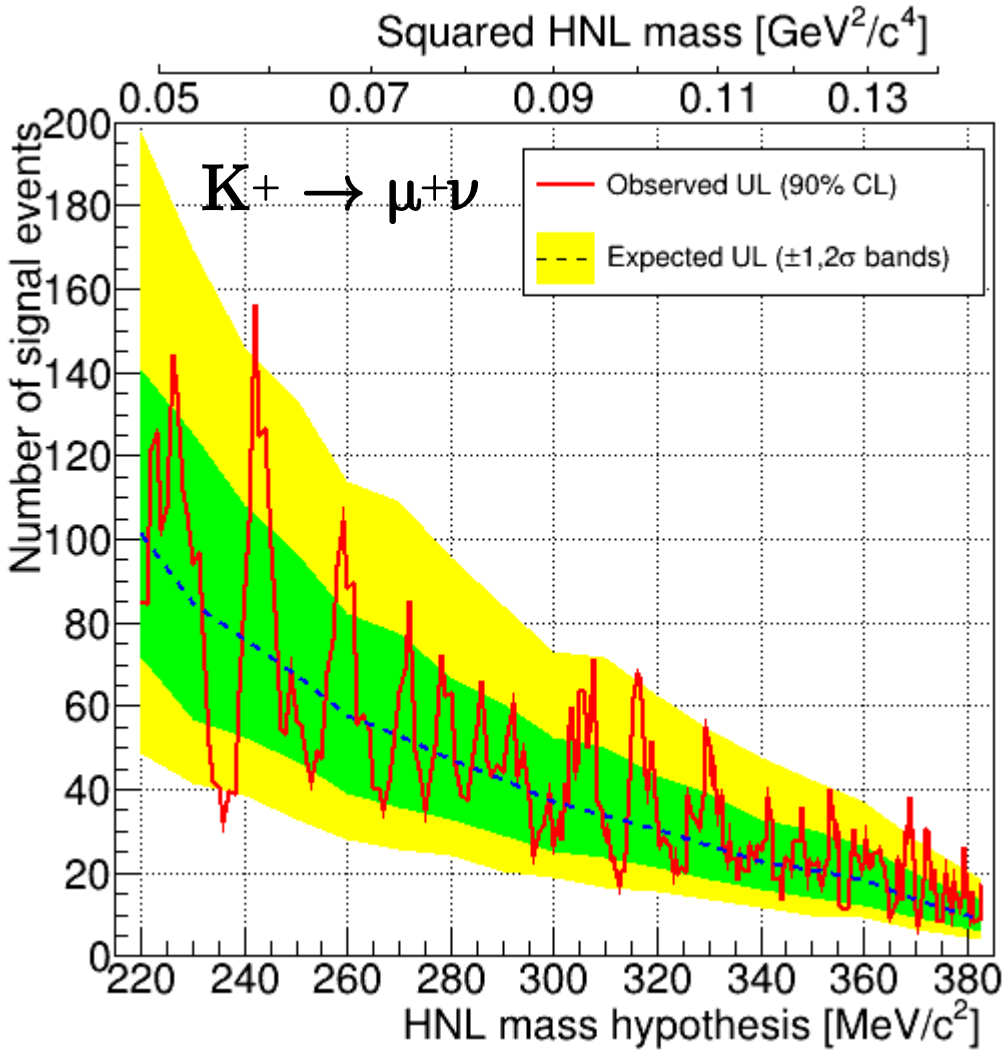
- "mass window" for the mass scan procedure: $|m-m_N|<1.5\sigma_m$: background is proportional to mass resolution.

Mass scan procedure

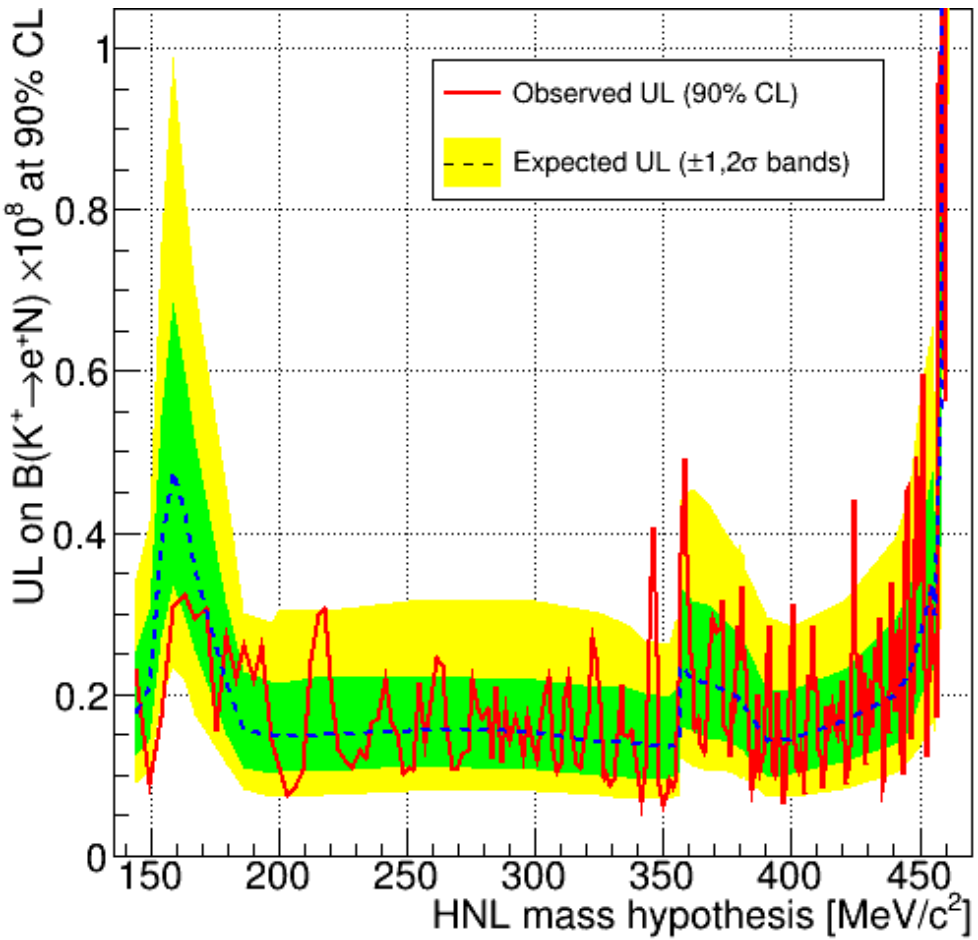
- HNL mass range: 141–462 (220–383) MeV/c2 in the Ke_2 ($K\mu_2$) case.
- Scan step:
  - $\sigma_m/2$ in the Ke_2 case;
  - 1 (0.5) MeV/c2 below (above) m_N=300 MeV/c2 in the $K\mu_2$ case.
- Number of mass hypotheses tested: 264 (247) in the Ke_2 ($K\mu_2$) case.
- Signal region half-width: $1.5\sigma_m$.
- In each mass hypothesis m_0, background (and its stat. error) determined from the data (polynomial fits in sidebands: approx $1.5\sigma_m<|m-m_0|<12\sigma_m$).
- Limits on $|U\ell 4|^2$: CL_S comparison of observed vs expected event counts.

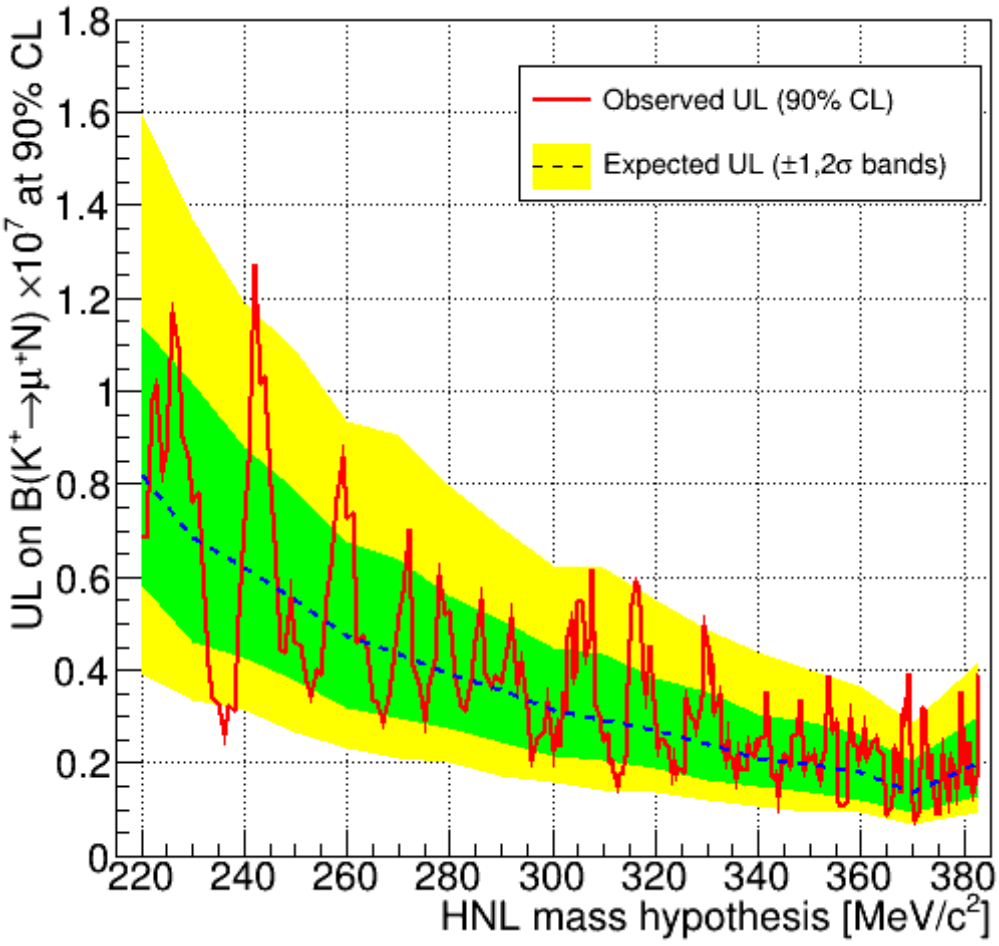
HNL production searches: ULs on numbers of signal events, 90%CL





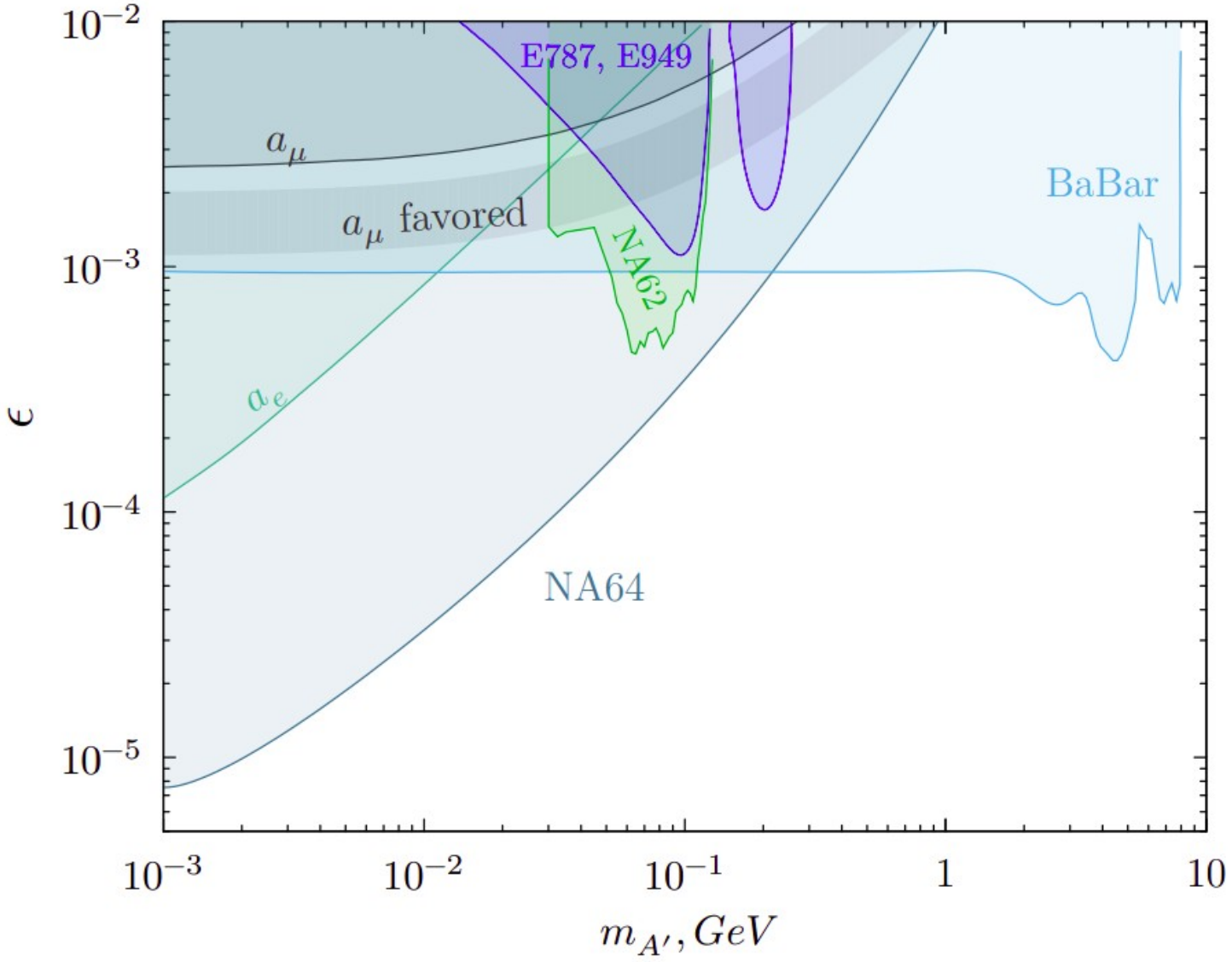
HNL production searches: ULs on BR(K→ l⁺N), 90%CL





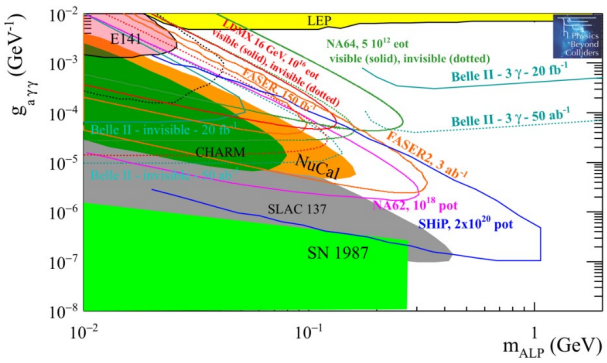
- Maximum local significance **3.6** for m_N=346MeV/c²
- Global significance: **2.2**

Dark Photon – NA64



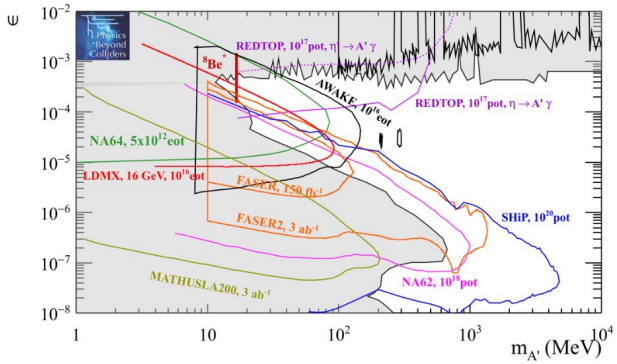
Future prospects 10-15 years scale

Coupling to SM photon



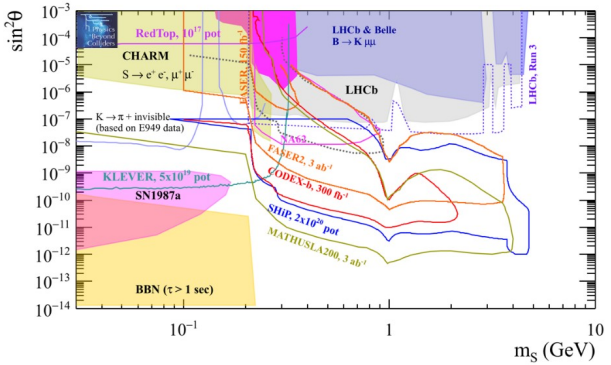
$a \to \gamma\gamma$

Mixing with SM photon



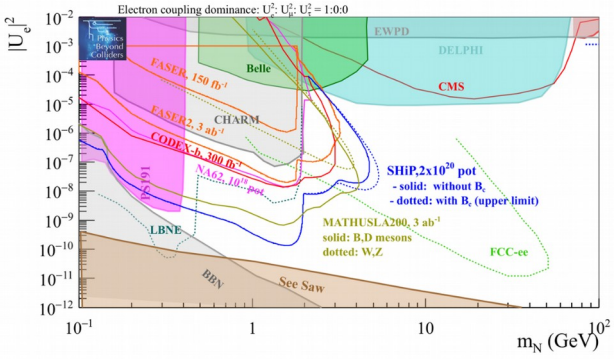
$A' \to ll$

Mixing with SM Higgs

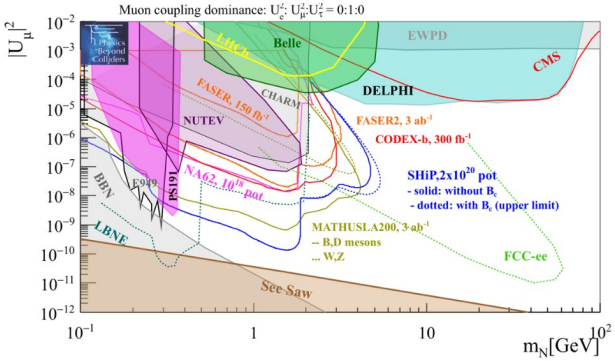


$S \to ll$

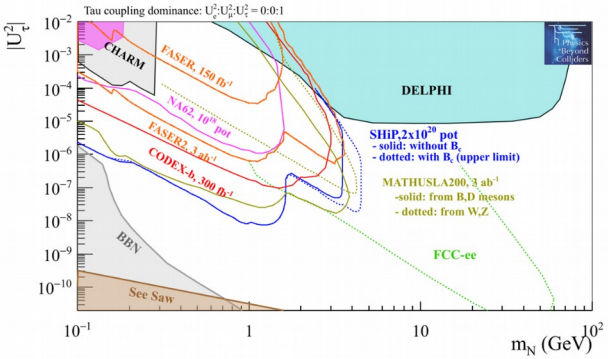
Electron coupling dominant



Muon coupling dominance



Tau coupling dominance



All HNL decays with at least two charged tracks are considered, assuming zero background

[PBC-BSM report, arXiv:1901.09966]