Search for exotic decays with NA62

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SUSY2019, CORPUS CHRISTI, TEXAS

Outline

Motivation for exotic decay searches

Introduction to the NA62 experiment

Recent results from NA62

Prospects of the NA62++ experiment

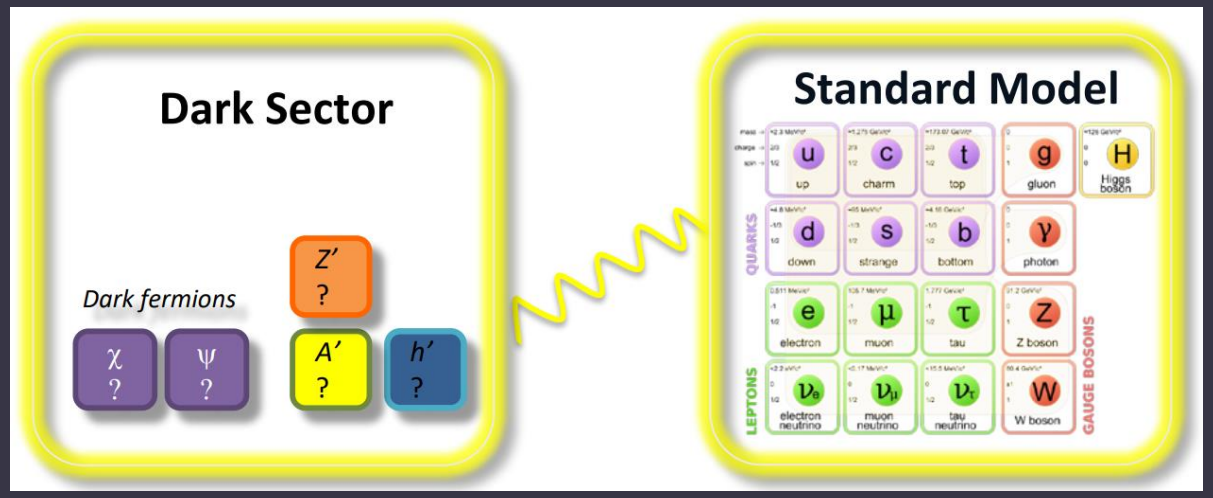
The NA62 detector

Motivation

No convincing signature of new physics discovered at the energy frontier (LHC)

Shift in interest towards the intensity frontier

Searches for light particles with feeble coupling to the SM (dark sector portals)



Motivation

No convincing signature of new physics discovered at the energy frontier (LHC)

Shift in interest towards the intensity frontier

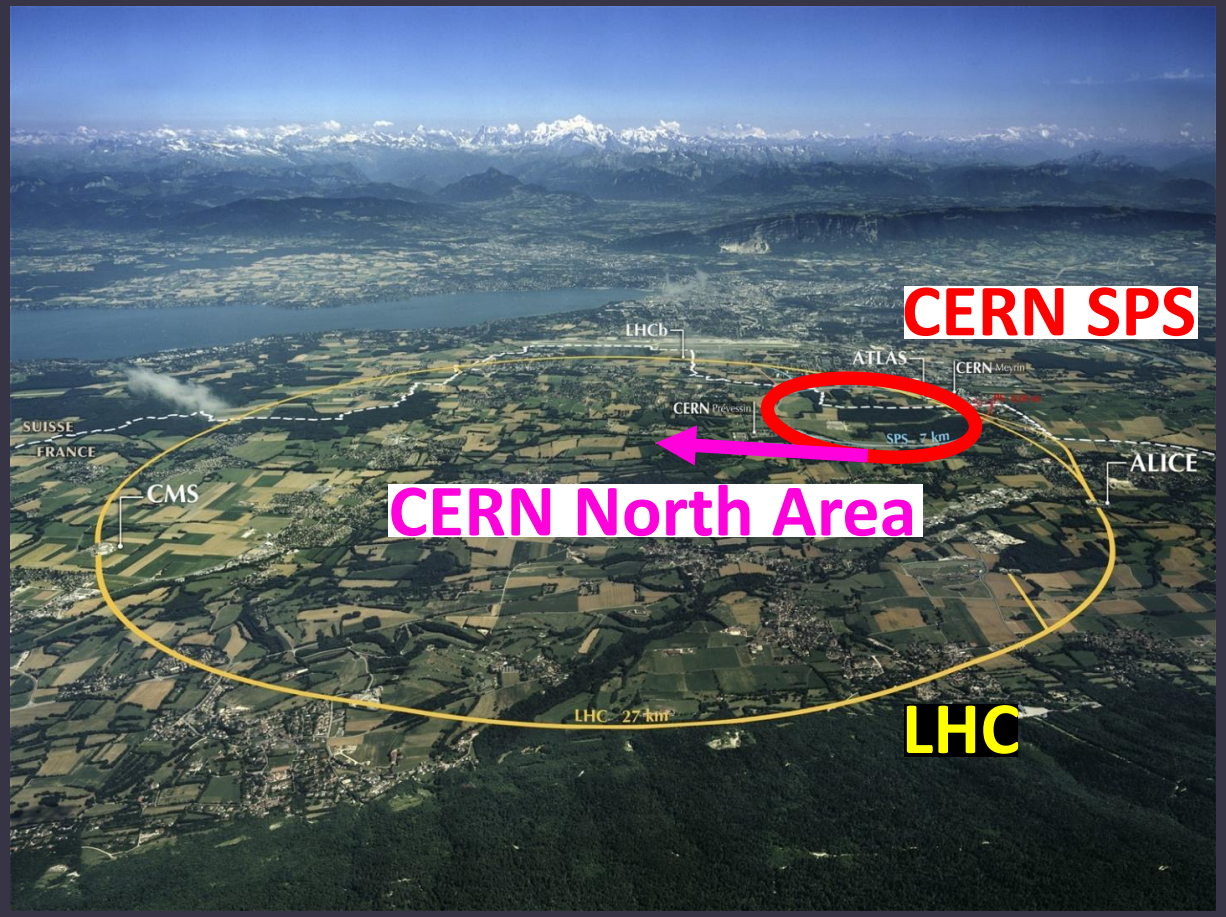
Searches for light particles with feeble coupling to the SM (dark sector portals)

Including: dark photon (A'), dark scalars (S), axion-like particles (ALP), heavy neutrino (N)

All of these could be discovered in the NA62 experiment at CERN

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$

The NA62 experiment at CERN



The NA62 collaboration has about 200 members from 28 institutes around the world

Data-taking between 2015 and 2018,

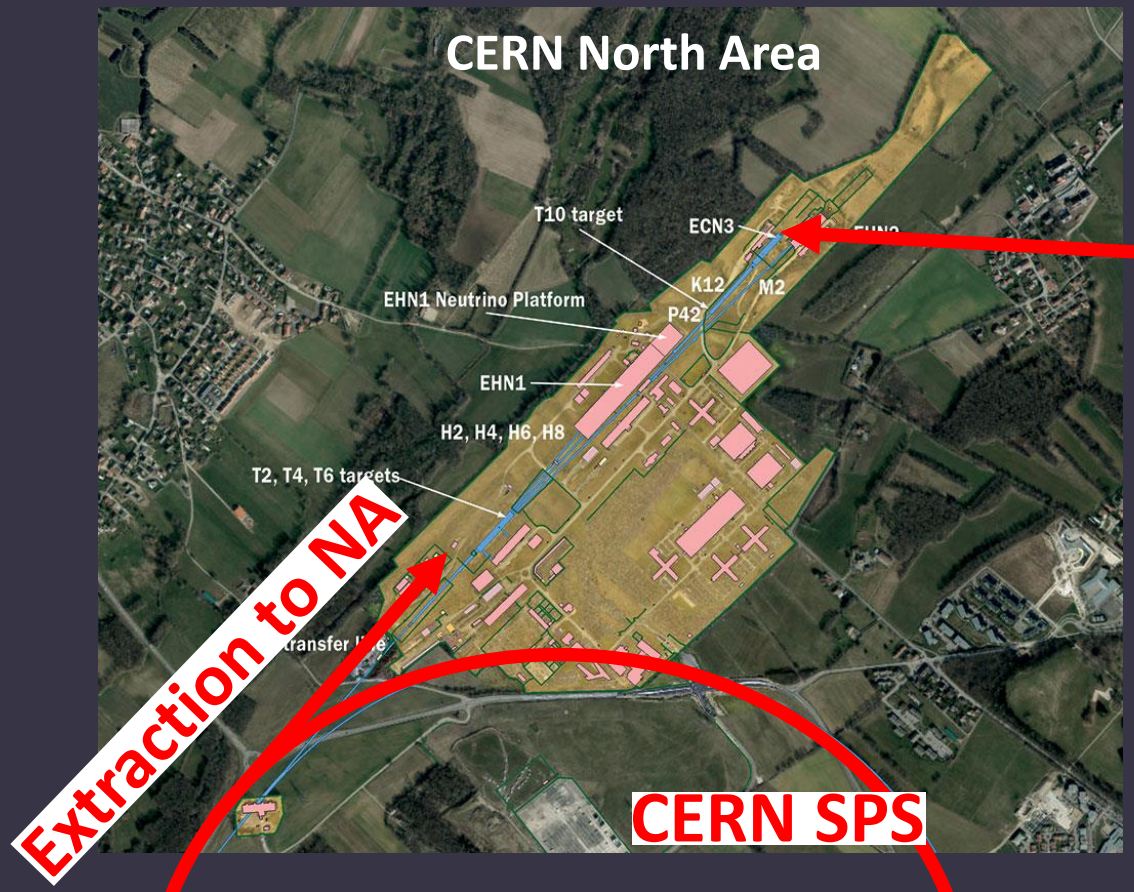
with more anticipated in 2021 – 2023

Broad physics programme:

- Main physics goal: $\mathrm{B}(K^+ \to \pi^+ \nu\bar{\nu})$
- Rare/forbidden kaon decays
- Exotic processes

New results
Talk by J. Pinzino
Wed 15:40

The NA62 experiment



The CERN North Area is host to several experiments

- NA61, **NA62**, NA64, ProtoDUNE, …

For **NA62:**

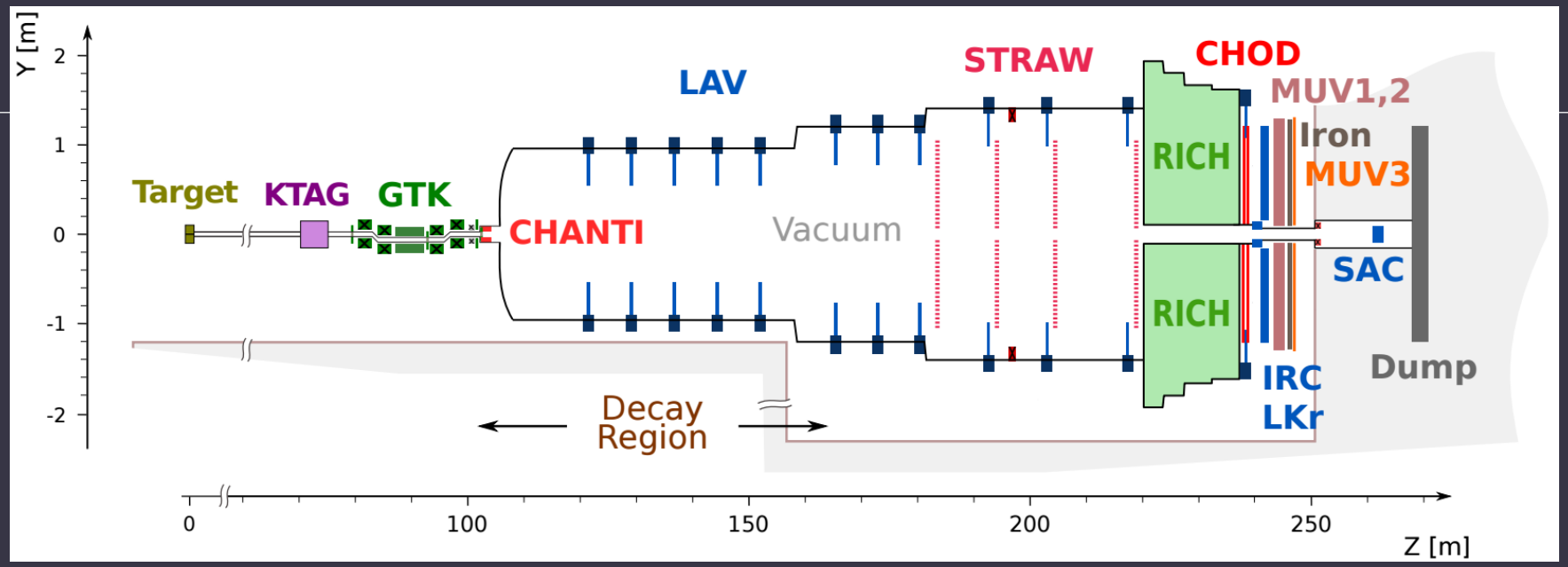
400 GeV/c protons impinge on the T10 target

- 10^{12} protons on target per spill
- Typically two 5 second spills every 32 seconds

Produces a beam of positive secondary hadrons

- Momentum selected at $p = 75\ \mathrm{GeV}\ \pm 1\%$
- $750\ \mathrm{MHz}$ of particles in the beam (6% K^+ fraction)

The NA62 experiment



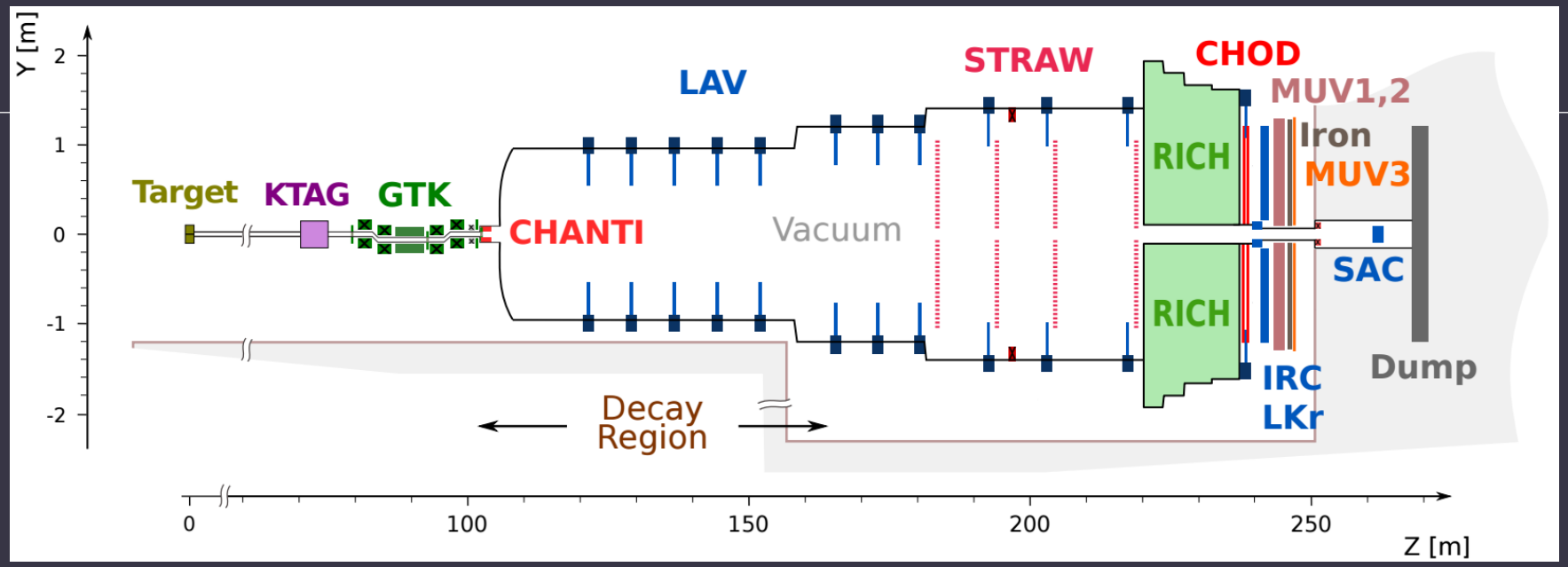
Beam measurement

- **KTAG:** K^+ tagging, $\sigma_t = 70$ ps
- **GTK:** beam spectrometer, $\sigma_t = 200$ ps
  $\sigma_p = 0.2\%$
- **CHANTI:** veto for scattered particles
- **Vacuum:** fiducial decay volume

Daughter particle measurements:

- **STRAW:** spectrometer, $\sigma_p = (0.3 \oplus 0.005 \cdot p)\%$ [GeV]
- **CHOD:** hodoscope, $\sigma_t = 200$ ps
- **RICH, LKr:** particle identification (π / μ / e)
- **LAV/LKr/IRC/SAC:** fully hermetic photon vetoes
- **MUV1,2,3:** muon vetoes

The NA62 experiment



About 20% of K^+ decay inside the fiducial volume (5 MHz of K^+ decays)

From 2 years running at nominal intensity:

- Observe $O(10^{13})$ K^+ decays in fiducial volume
- Observe $O(10^{12})$ π^0 decays, since $B(K^+ \to \pi^+\pi^0) \approx 20\%$

Huge data samples and powerful detector make NA62 a perfect laboratory for exotic searches

Search for heavy neutrino production

Phys. Lett. B 778 (2018) 137

Analysis principle:

- Heavy neutrinos produced in $K^+ \to \ell^+ N, (\ell = e, \mu)$ due to mixing with SM neutrinos
- N long lived and escapes the detector
- $B(K^+ \to \ell^+ N) = B(K^+ \to \ell^+ \nu) \cdot \rho_{\ell(m_N)} \cdot |U_\ell|^2$

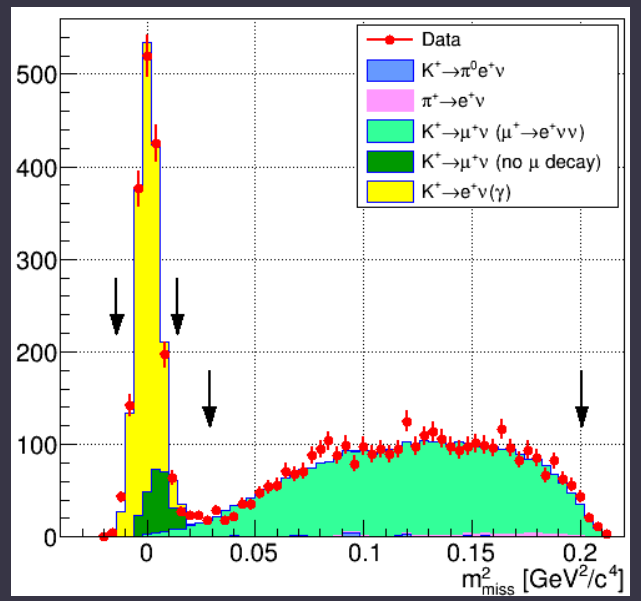
  $\rho_\ell(m_N)$ is a phase-space factor

  U_ℓ is the mixing strength

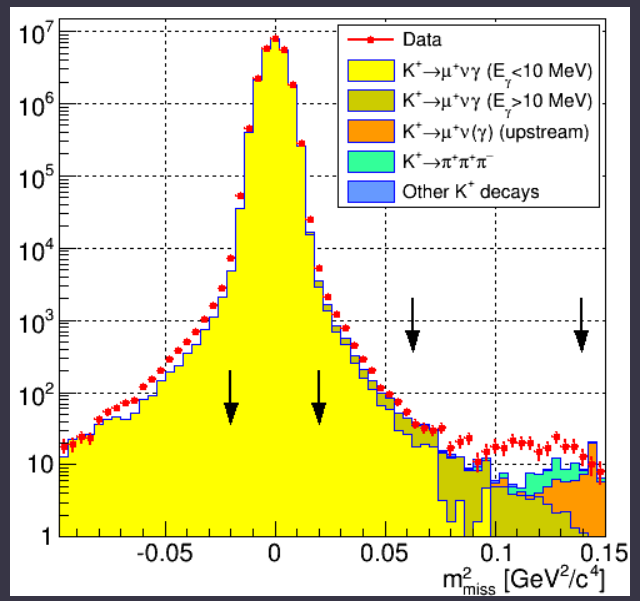
Search strategy:

1. Search for excess in missing mass spectrum:
   $$m^2_{miss} = (P_K - P_\ell)^2 = m^2_N$$
2. Count n_{sig} in sliding mass window across m^2_{miss}
3. Convert n_{sig} to limit on $|U_\ell|$

$K^+ \to e^+ N$



$K^+ \to \mu^+ N$



Search for heavy neutrino production

Phys. Lett. B 778 (2018) 137

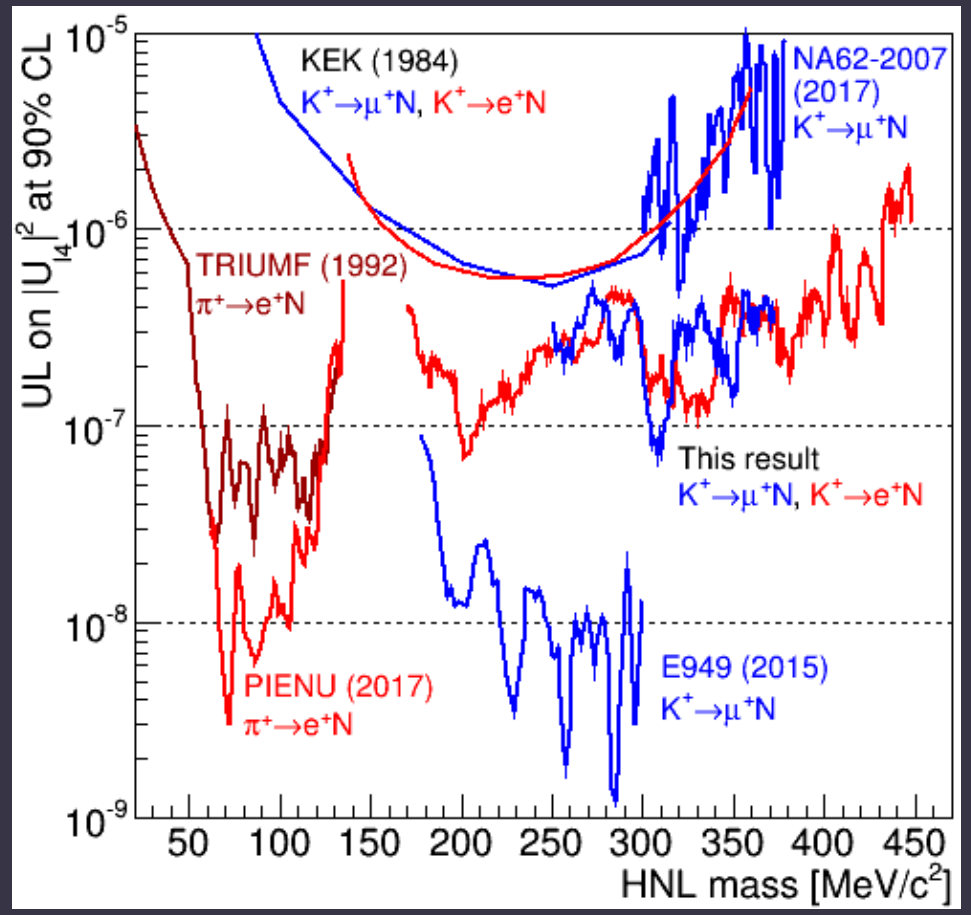
Data used:

- Number of K^+ are $n_K^e = 3 \times 10^8$ and $n_K^\mu = 1 \times 10^8$
- Collected over five days in 2015 with a minimum-bias trigger running at $\sim 1\%$ nominal intensity

Results:

- Limits on n_{sig} set using Rolke-Lopez method
- Limits on $|U_\ell|$ at $O(10^{-7})$ for both electron and muon modes
- Improved limits on $|U_e|$ from $170 - 448\ \mathrm{MeV/c^2}$
- Improved limits on $|U_\mu|$ above $300\ \mathrm{MeV/c^2}$

Future prospects very promising: $|U_\ell| < 10^{-8}$



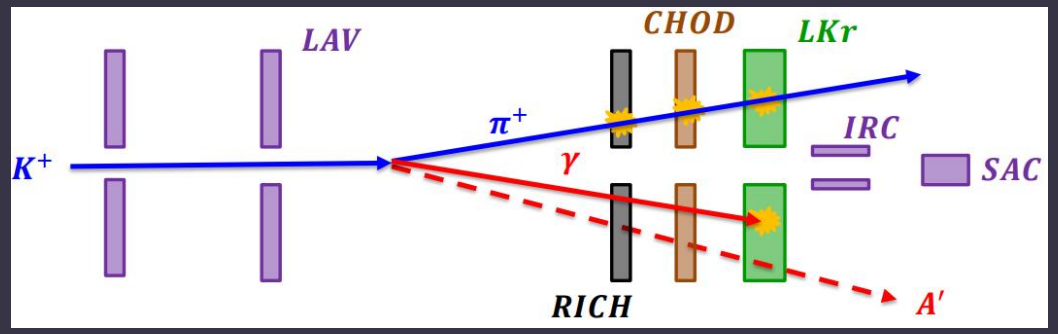
Search for A' in π^0 decays

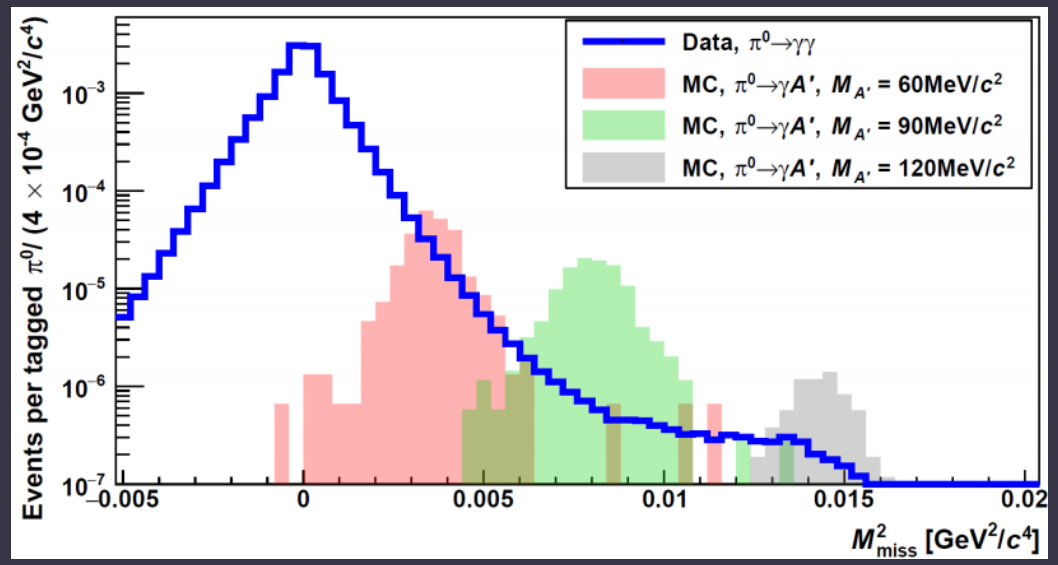
CERN-EP-2019-048, arxiv:1903.08767 (accepted by JHEP)

Analysis principle:

- Dark photon produced in π^0 decay: $K^+ \to \pi^+\pi^0,\ \pi^0 \to \gamma A'$ through kinematic mixing with the SM photon
- Rate driven by mixing strength ϵ:

$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F_{\mu\nu}^{QED} F_{dark}^{\mu\nu}$$





Search strategy:

1. Search for excess of events in missing mass spectrum:
$$m_{miss}^2 = \left(P_K - P_\pi - P_\gamma\right)^2 = m_{A'}^2$$
2. Count n_{sig} in sliding mass window across m_{miss}^2
3. Convert n_{sig} to limit on ϵ

Search for A' in π^0 decays

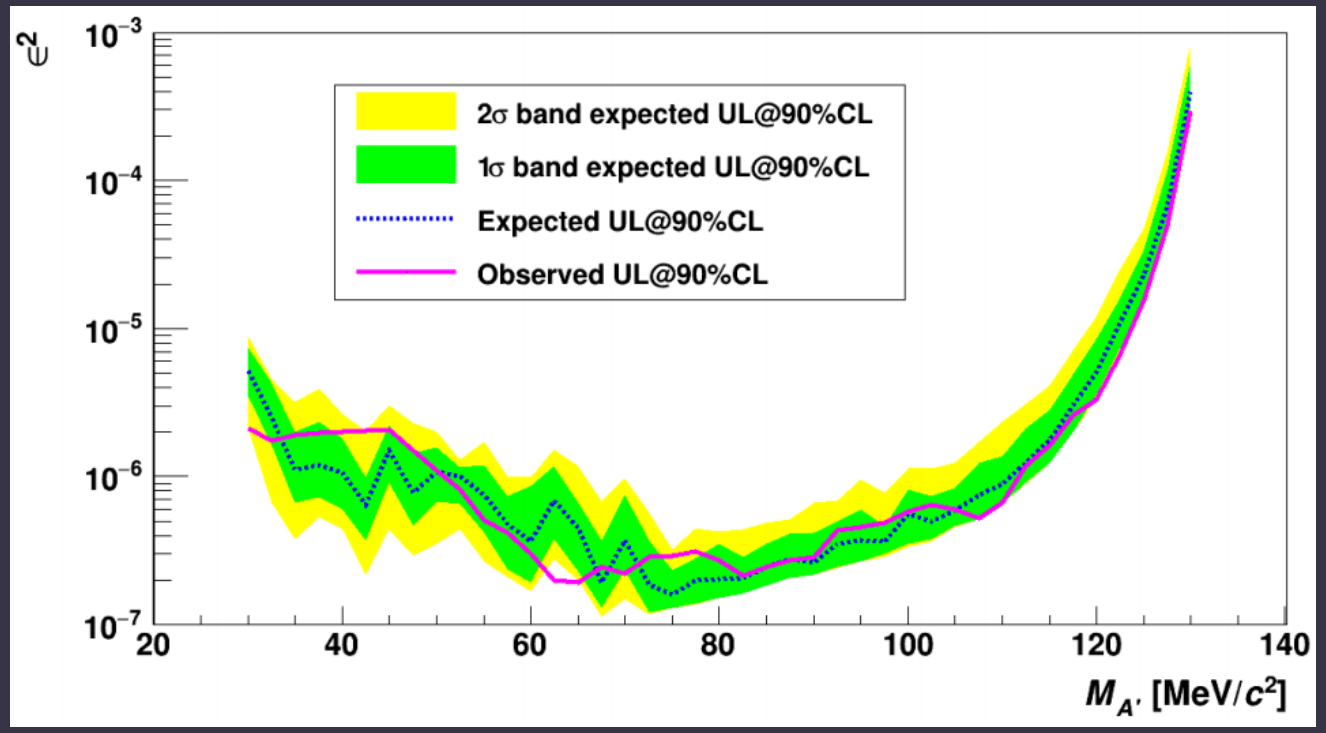
CERN-EP-2019-048, arxiv:1903.08767 (accepted by JHEP)

Data used:

- A subsample of the 2016 data
- About 1% of data collected from 2016 – 2018

Limit setting:

- CLs method used to set limits on ϵ^2 at 90% CL
- No statistically significant excess was observed



Search for A' in π^0 decays

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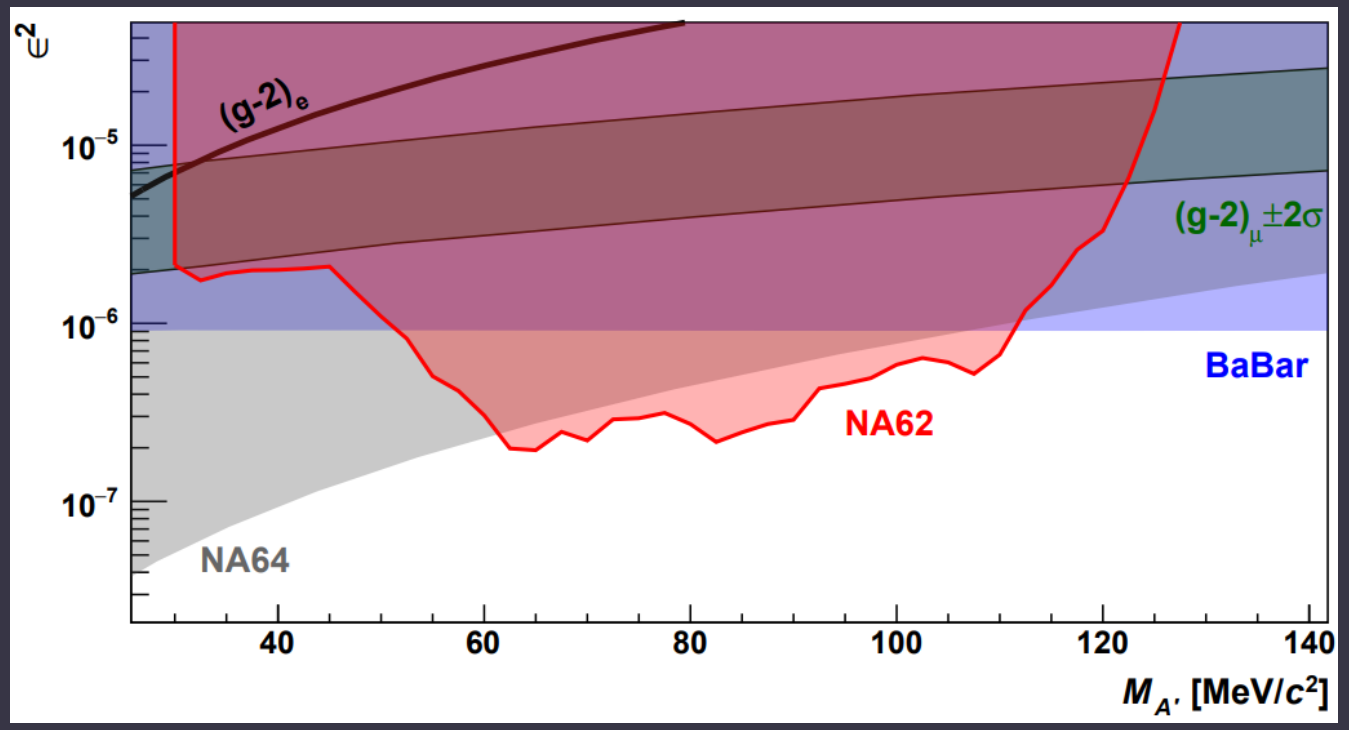
Data used:

- A subsample of the 2016 data
- About 1% of data collected from 2016 – 2018

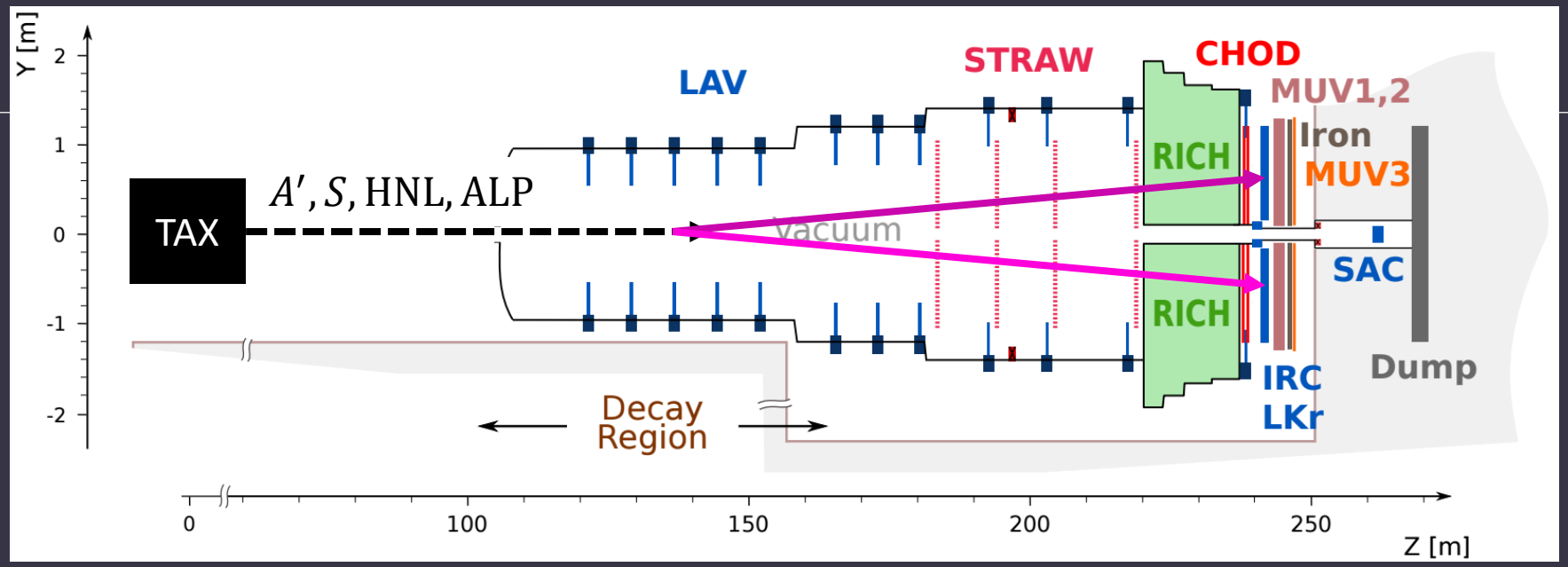
Limit setting:

- CLs method used to set limits on ϵ^2 at 90% CL
- No statistically significant excess was observed
- Improved limits from $60 - 110\ \mathrm{MeV/c^2}$



Also sets world's best upper limit on $B(\pi^0 \to \gamma\nu\bar{\nu}) < 1.9 \times 10^{-7}$ (more than 3 orders of magnitude improvement)

The NA62++ experiment



The NA62++ experiment uses the same NA62 apparatus in a "beam dump" mode

- T10 target is removed, the beam is dumped onto copper 'TAX' collimators (takes ~10 minutes to set up)
- All hadrons are absorbed in the TAX material, but dark sector particles can pass into the fiducial volume

NA62++ can collect $O(10^{18})$ protons on target (POT) in $O(3)$ months (protons at $p = 400$ GeV/c)

Possibility to run in this mode in 2023

The NA62++ experiment

PBC BSM working group report. arxiv:1901.09966

The physics prospects of NA62++ have been studied as part of the

'Physics Beyond Colliders – Beyond the Standard Model' working group

The following slides show NA62++ prospects assuming $O(10^{18})$ POT

The limits are set at 90% CL, and are compared to other results expected on a 5-year timescale

The results of background studies based on $O(10^{16})$ POT are included in the limits

Improvements to the NA62++ setup (upstream veto, beamline modifications, higher intensity) are not included here, but initial studies are promising

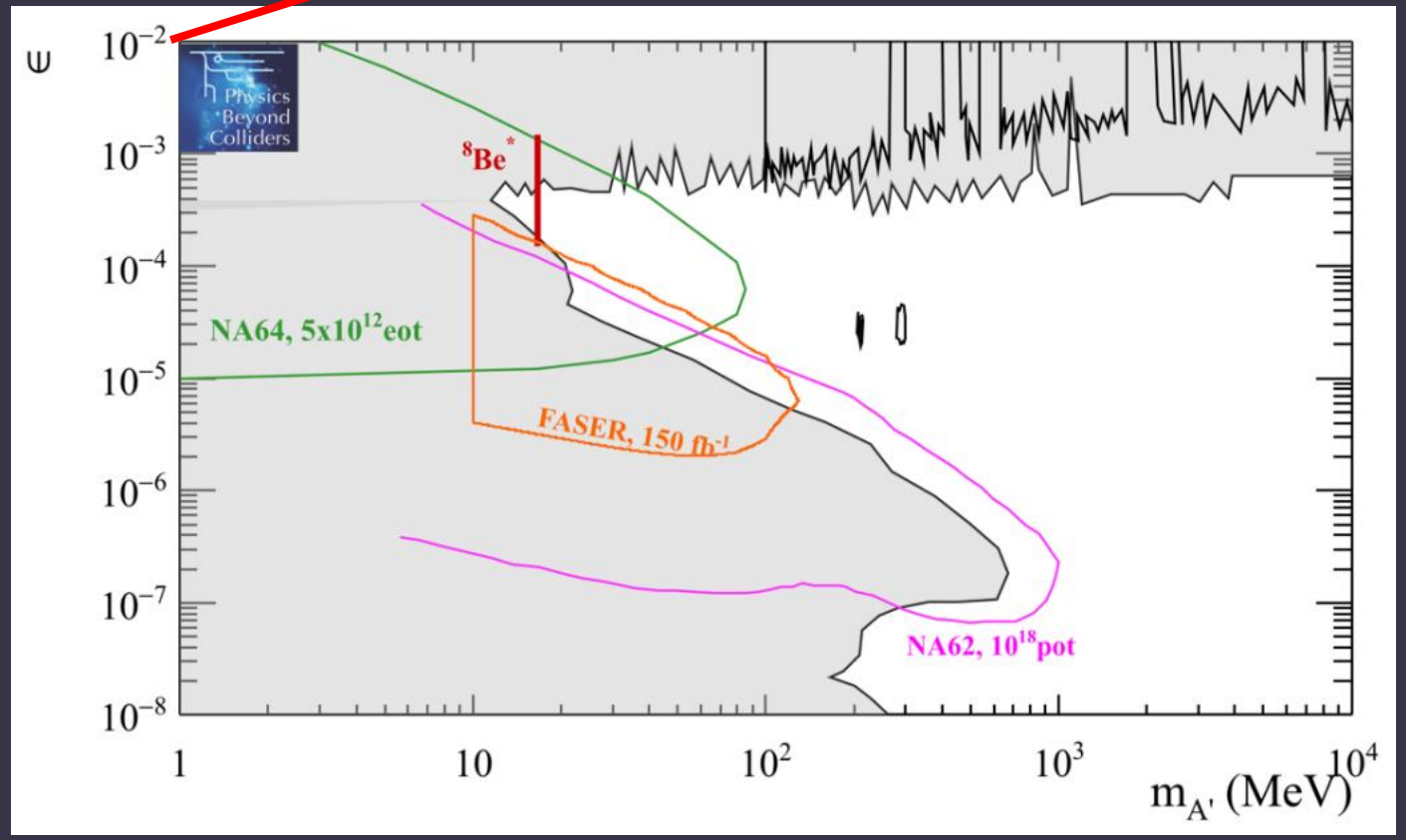
Dark photon A' decaying visibly

Strength of mixing with SM photon

NA62++ can improve limits on the A' parameter space

$A' \to \mu^+\mu^-$ and $A' \to e^+e^-$ included here

NA62 limits comparable with those possible at SeaQuest (not shown here)



mass of the dark photon

Dark scalar S

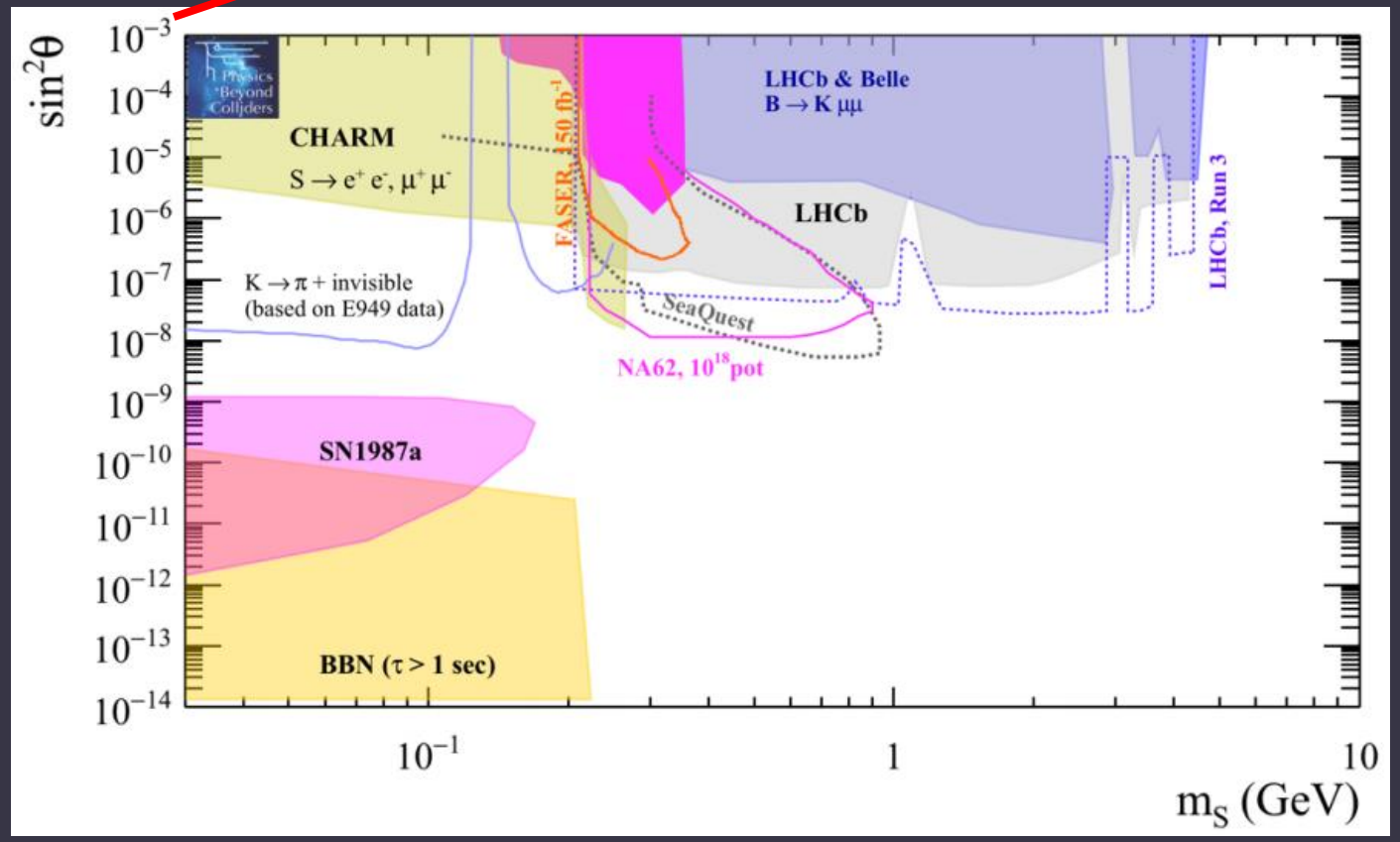
Strength of mixing with SM Higgs

NA62++ can improve limits on the S parameter space

$S \to \mu^+\mu^-$ important here

NA62 limit comparable with those possible at SeaQuest

Also $K^+ \to \pi^+ inv$ and $K^+ \to \pi^+ S, S \to \mu^+\mu^-$ accessible to NA62 in K^+ mode



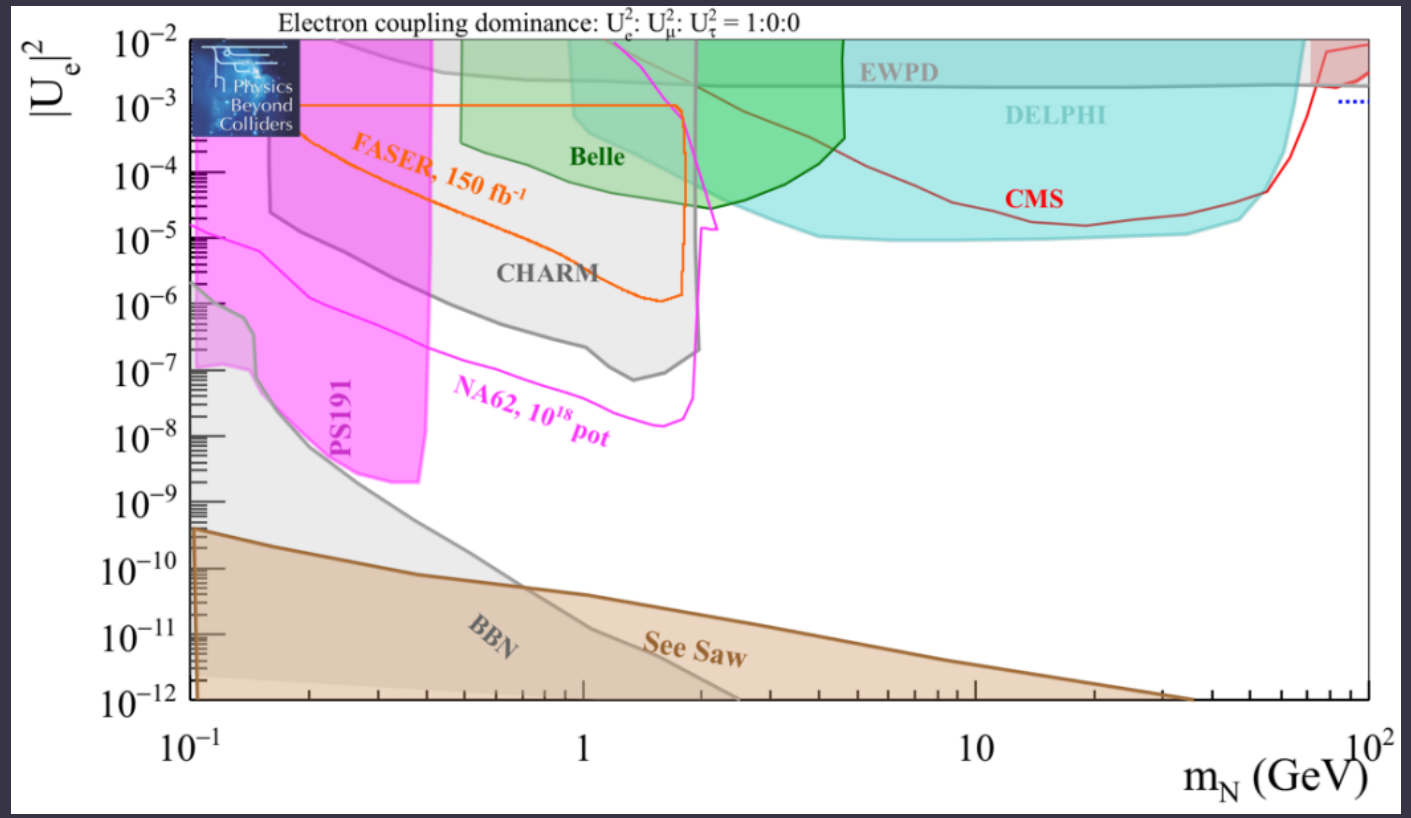
mass of the dark scalar

Heavy neutrino N

Electron coupling dominance: $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 0 : 0$

NA62++ can improve limits on the N parameter space

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



Heavy neutrino N

Muon coupling dominance: $U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 0$

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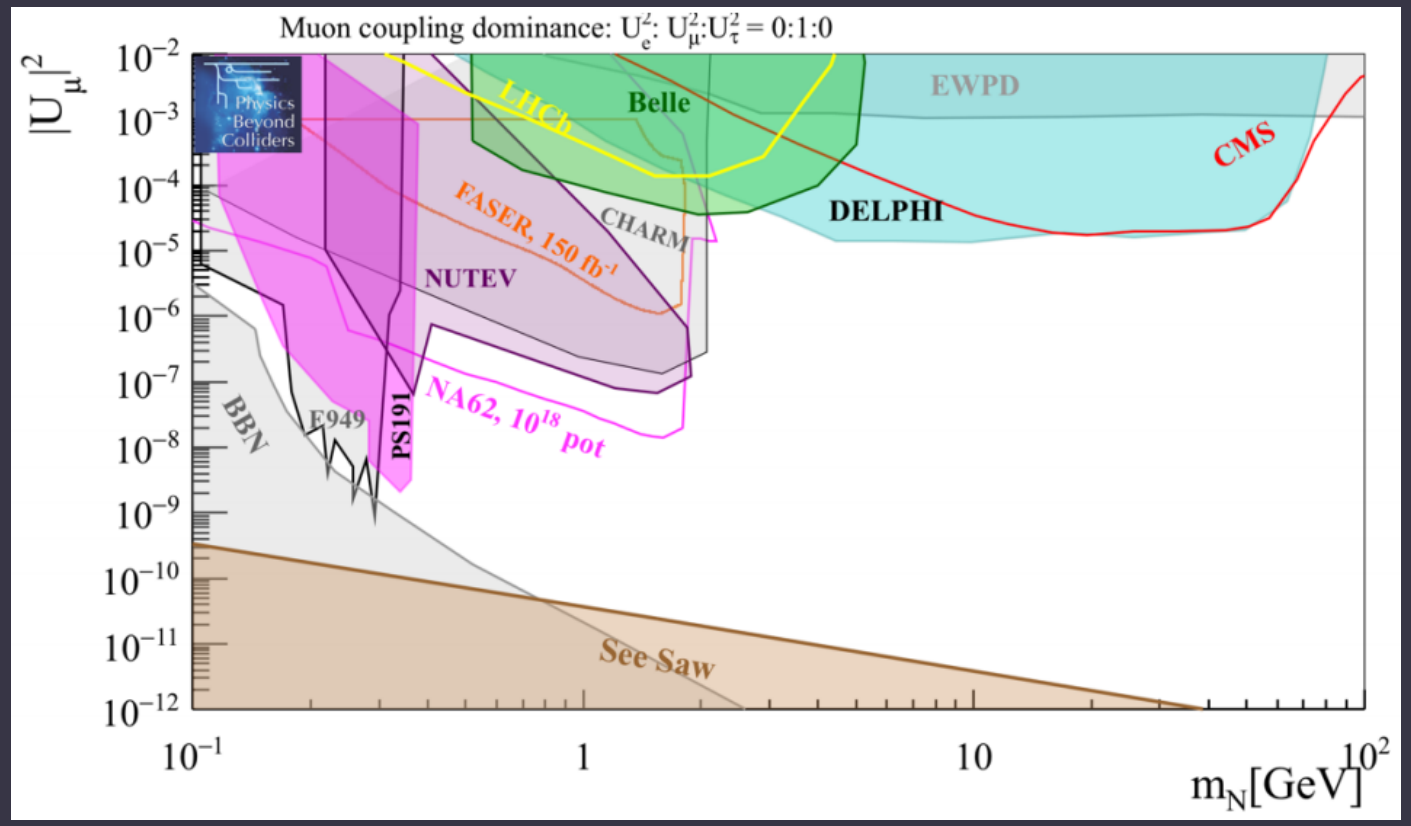

Heavy neutrino N

Tau coupling dominance: $U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 0 : 1$

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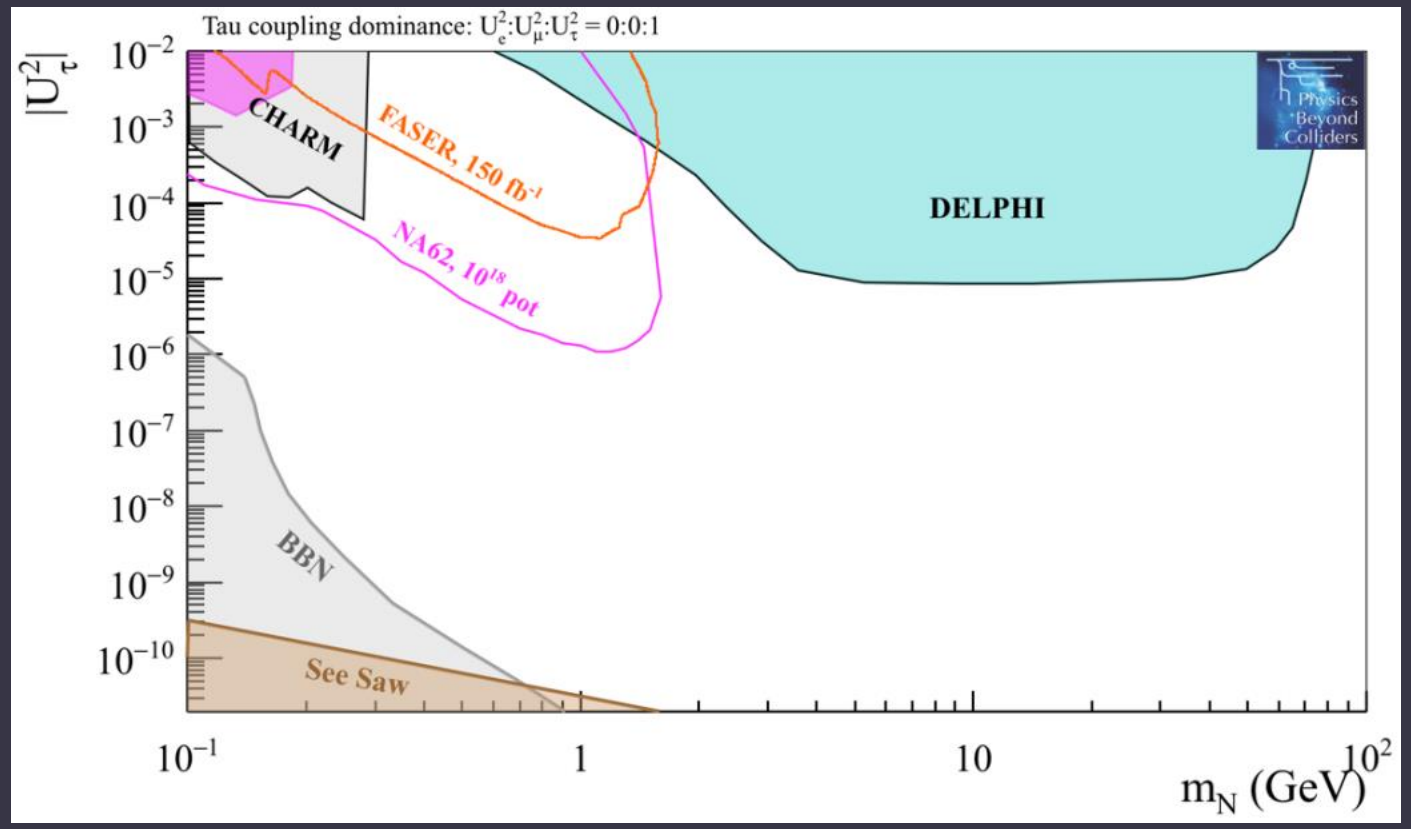
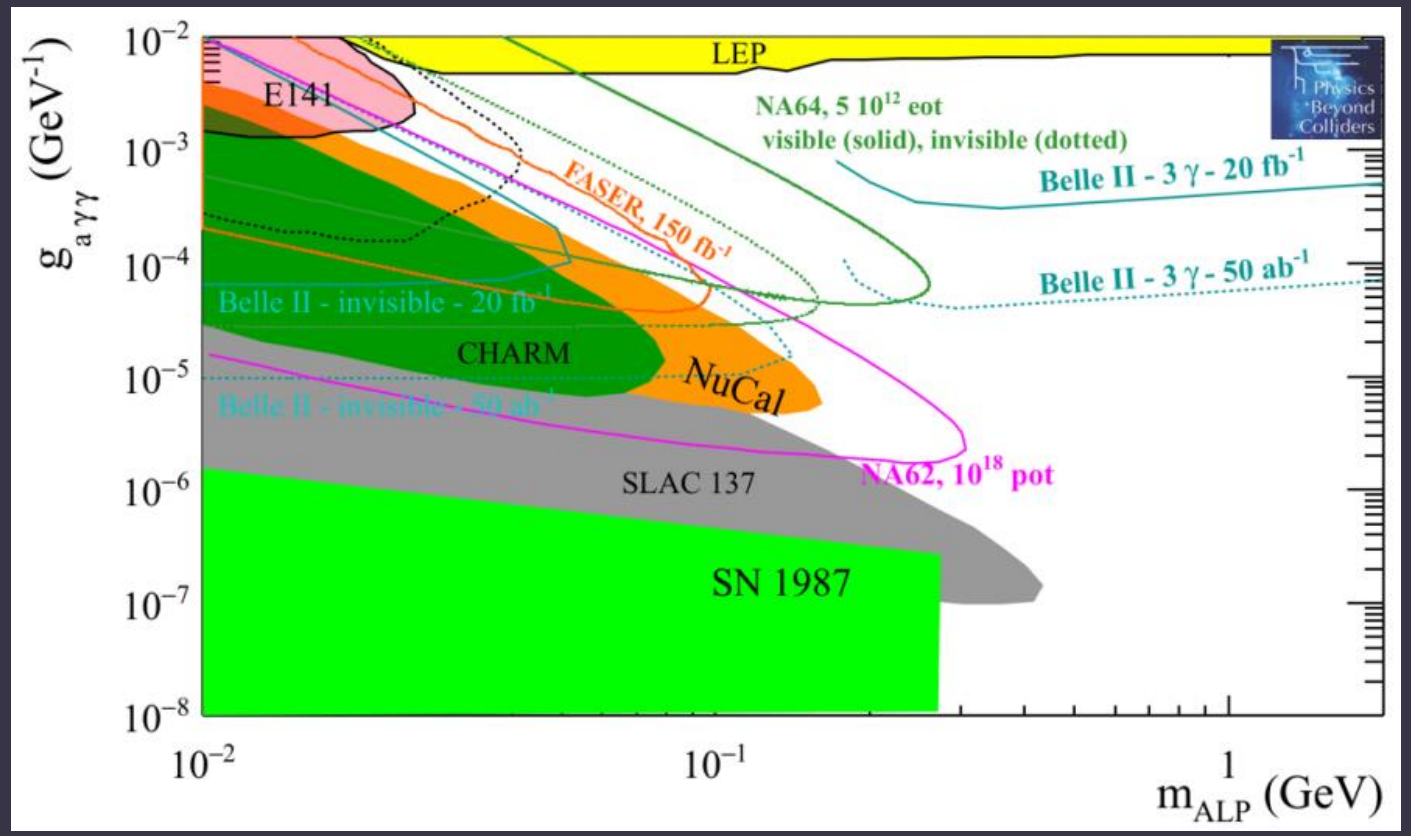


ALP with photon couplings

NA62++ can improve limits on the *ALP* parameter space

Limits for *ALPs* with gluon and fermion couplings currently being computed



Summary

The NA62 experiment is a powerful laboratory to make searches for exotic decays

Results of recent searches for the exotic decays $K^+ \to \ell^+ N$ and $\pi^0 \to \gamma A'$ were presented

Worlds-best limits have been set on both the N and A' parameter spaces respectively

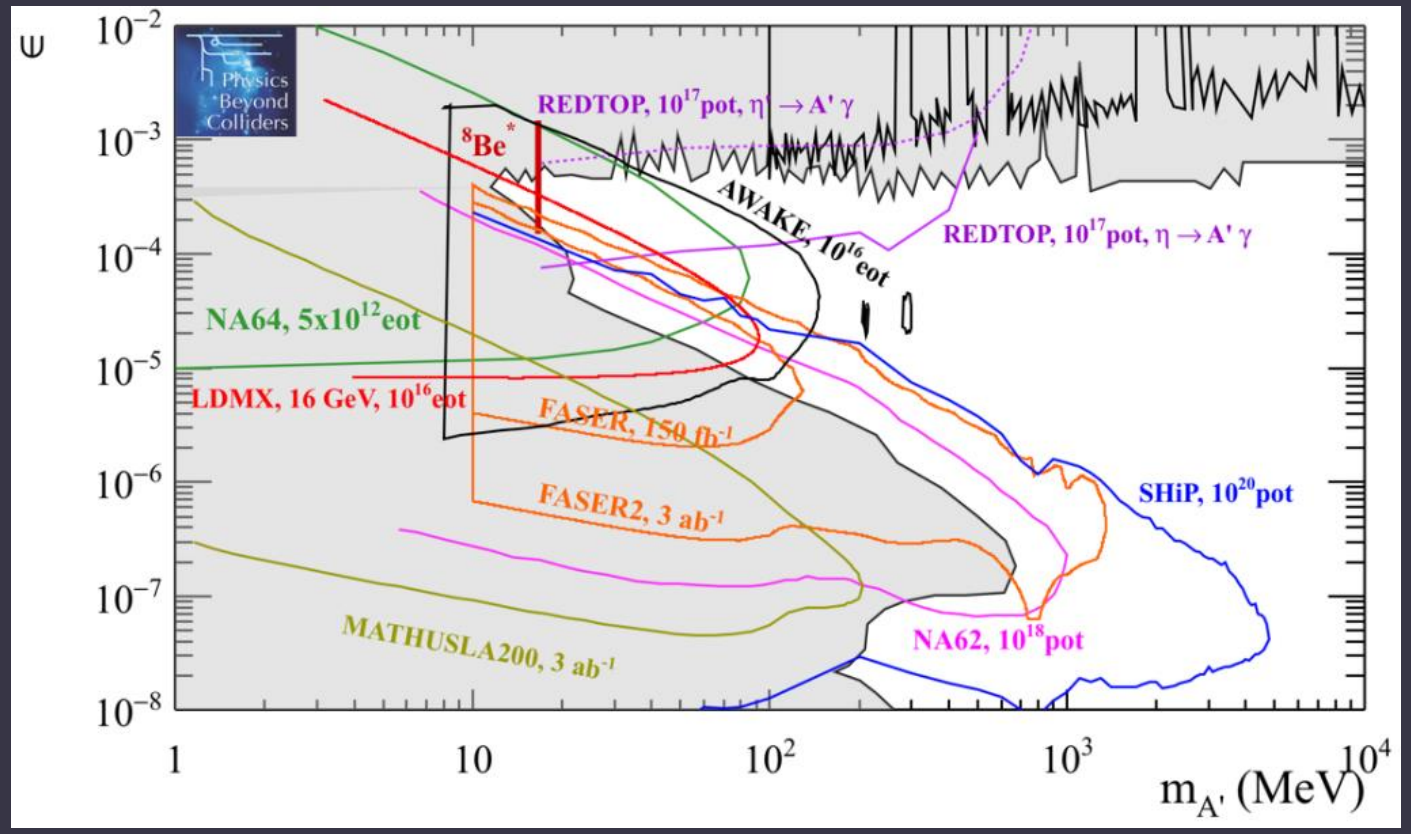
The prospects for the NA62++ "dump mode" experiment were presented

Searches for exotic decays at NA62++ can improve limits in a variety of models, including dark photons (A'), dark scalars (S), axion-like particles (ALP), heavy neutrinos (N)

Dark photon decaying visibly

15-year timescale

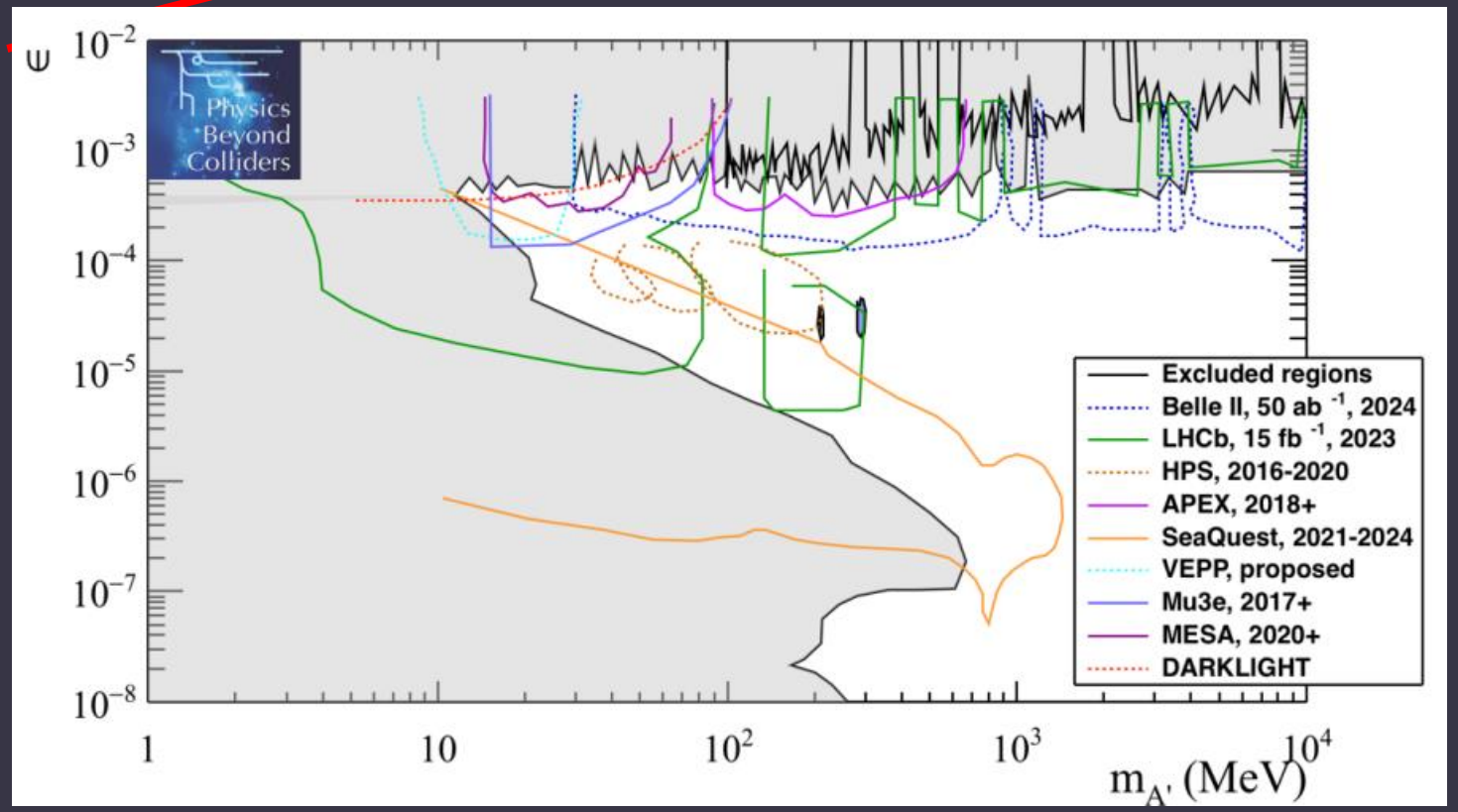
SeaQuest limit ≈ FASER2



Dark photon A' decaying visibly

Strength of mixing with SM photon

Non-PBC limits (15 years)

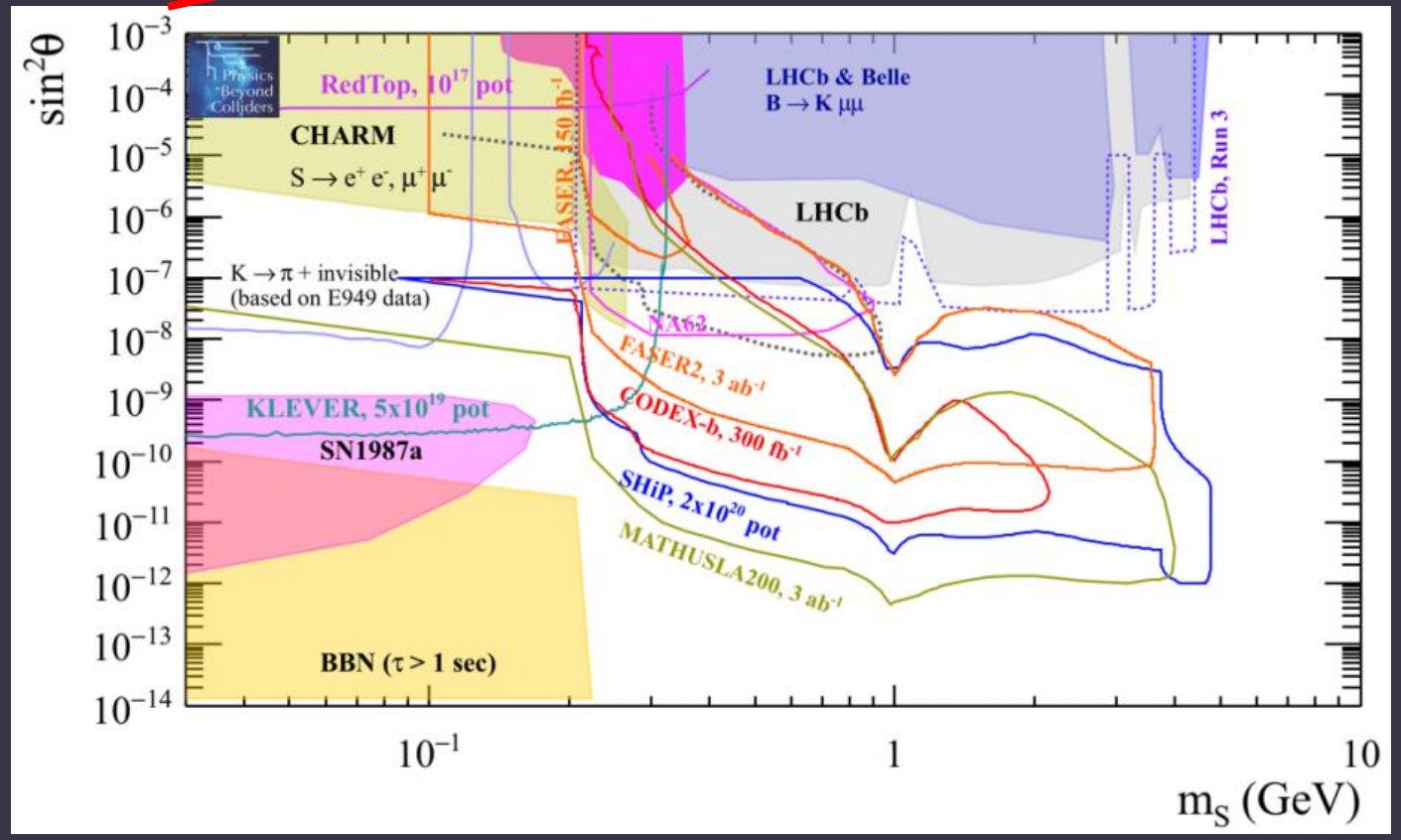


mass of the dark photon

Dark scalar S

Strength of mixing with SM Higgs

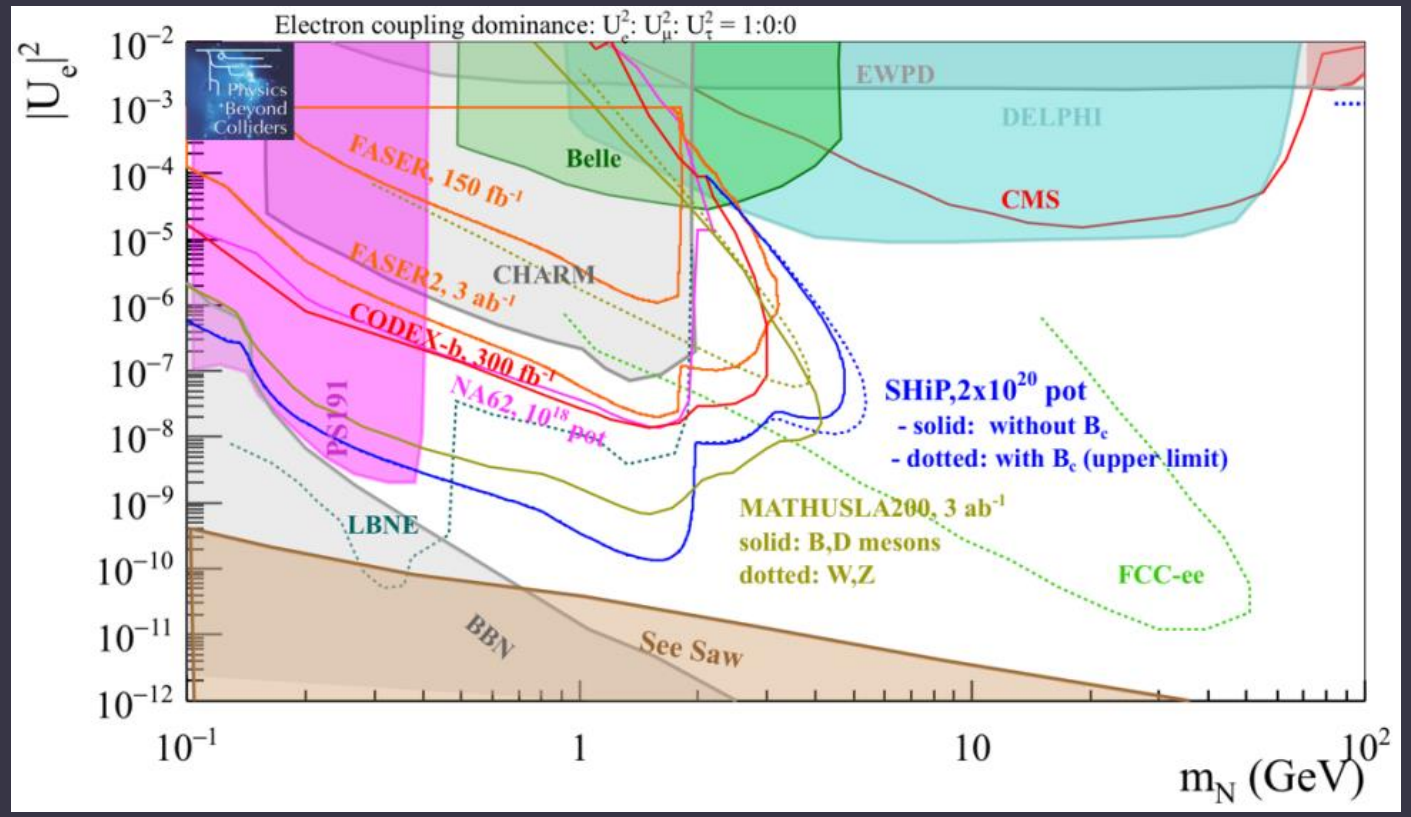
15 year timescale



Heavy neutral leptons

Electron coupling dominance: $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 0 : 0$

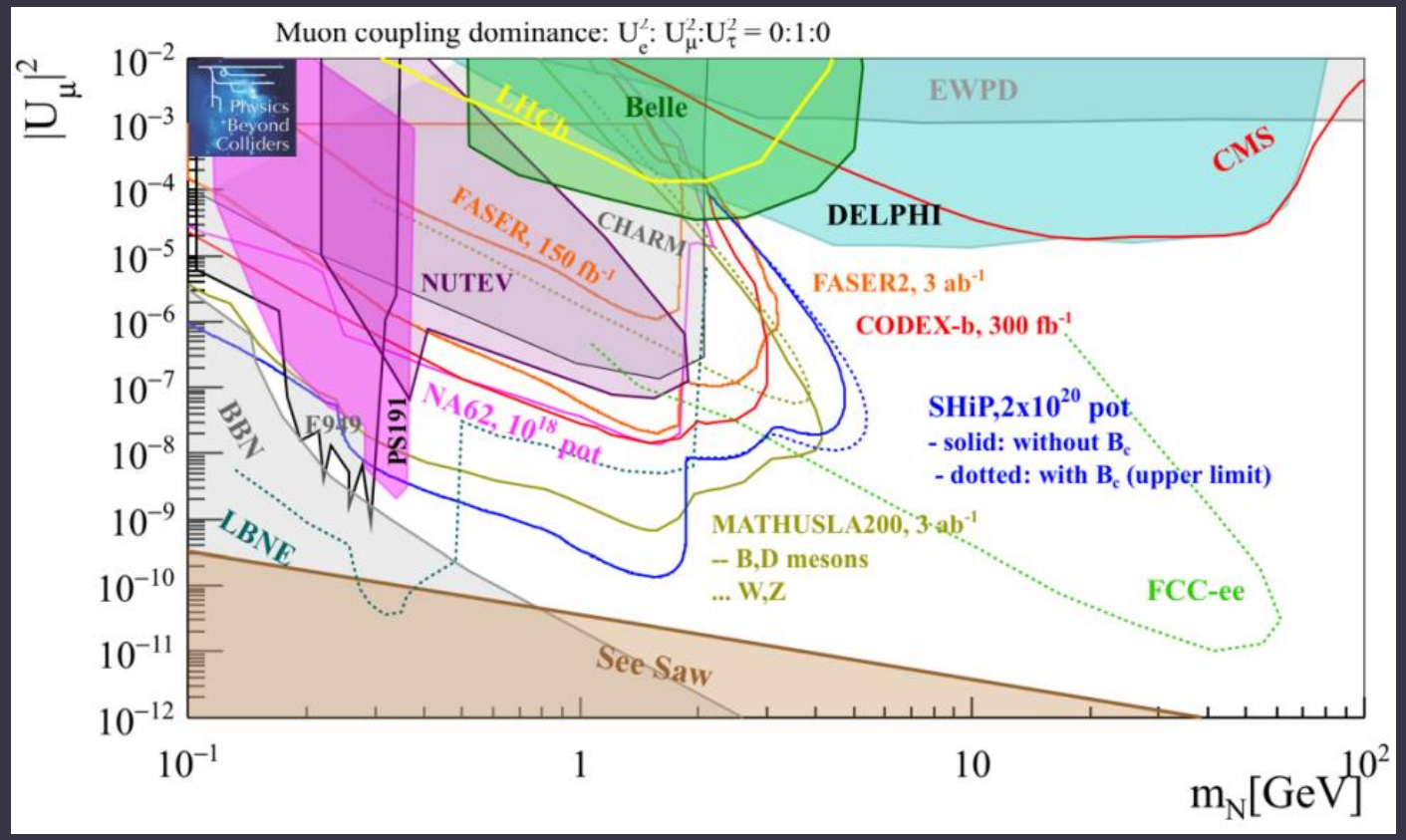
15 year timescale



Heavy neutral leptons

Muon coupling dominance: $U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 0$

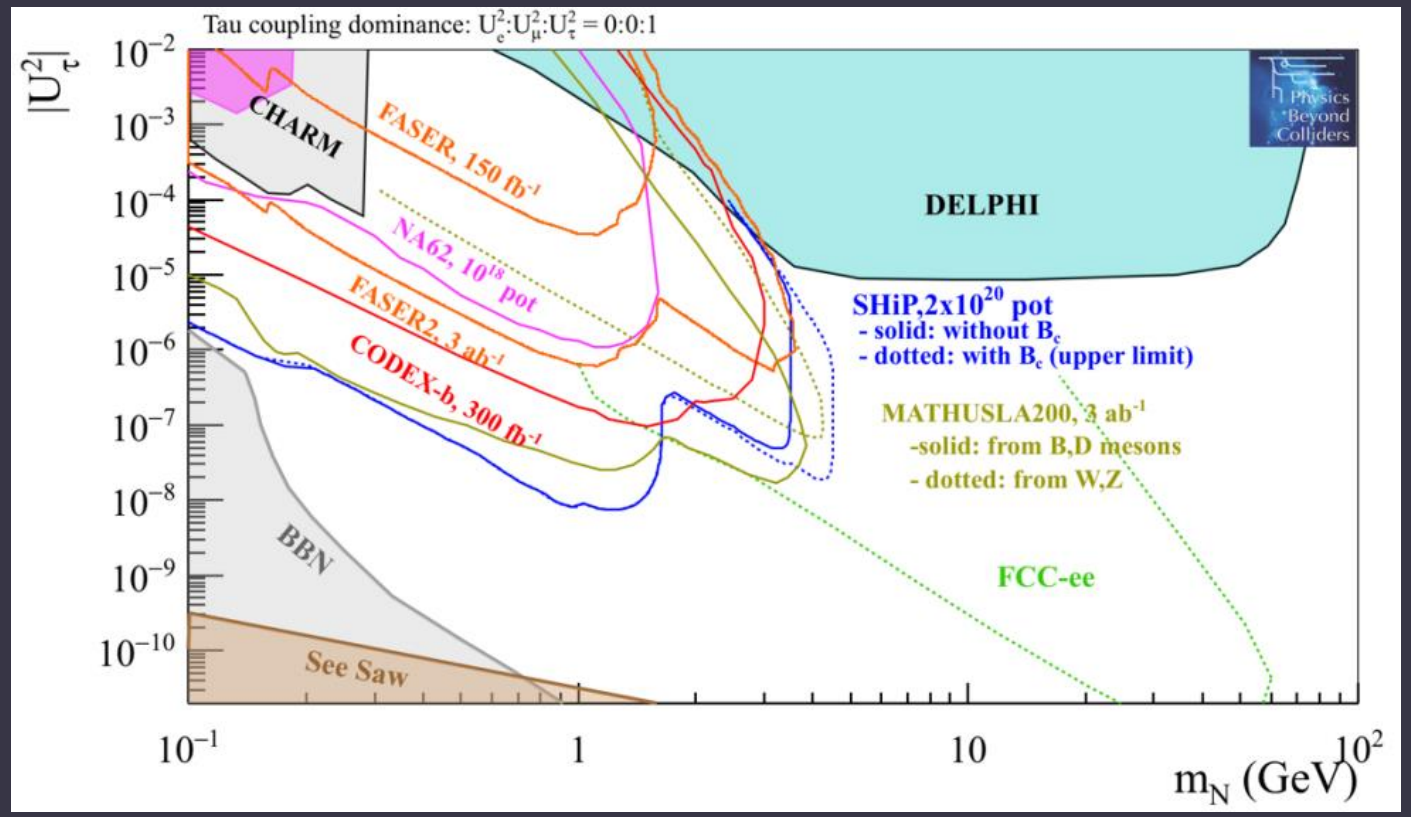
15 year timescale



Heavy neutral leptons

Tau coupling dominance: $U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 0 : 1$

15 year timescale



ALP with photon couplings

15 year timescale