New Physics with Exotic and Long-Lived Particles: A Joint ICISE-CBPF Workshop
1 – 6 July 2019
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Searches for exotic particles at NA62 (CERN)

On behalf of the NA62 collaboration

UCLouvain
Institut de recherche en mathématique et physique

Artur Shaikhiev (artur.shaikhiev@cern.ch)
Université catholique de Louvain, Belgium
Institute for Nuclear Research, Moscow

Outline

- NA62 experiment
- Exotic searches:
  - Heavy Neutral Leptons (HNL)
  - Dark Photon
  - Axion-Like Particles (ALP)
  - Dark scalars S
- Summary

NA62 experiment (decay-in-flight)

- Main goal is measure ultra rare kaon decay $K^+ \to \pi^+ \nu\nu$ with 10% precision
- SM prediction:

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

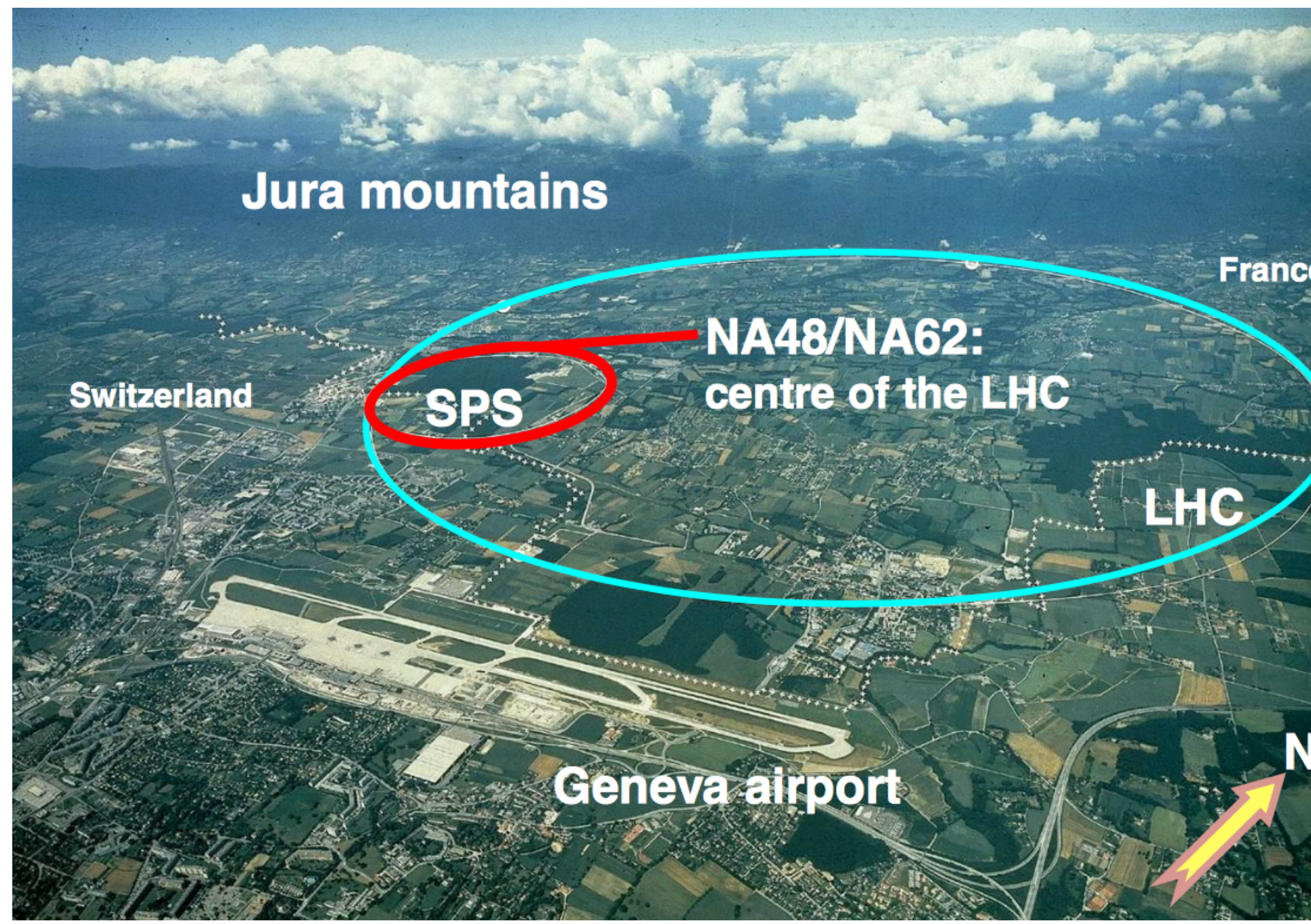
[Buras et al., JHEP 1511 (2015) 033]

- Experimental value

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

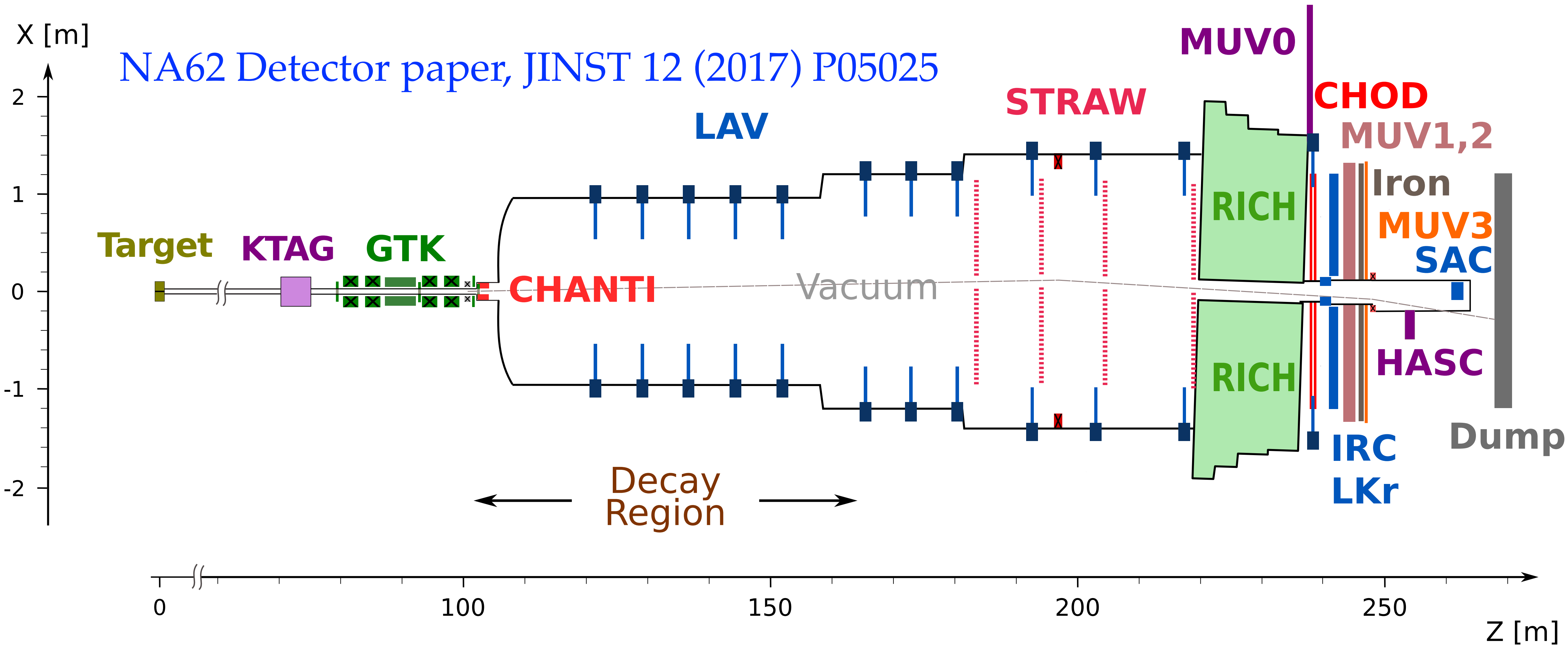
[E949/E787 PRL 101 (2008) 191802]

- Sensitive to New Physics



27 institutes, ~200 participants form: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax-GMU, Ferrara, Firenze,Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Torino, TRIUMF, Vancouver UBC

The NA62 detector



- Kaon ID and direction (KTAG, GTK, CHANTI)
- Pion ID and direction (STRAW, CHOD, RICH)
- Photon veto (LAV, LKr, IRC, SAC)
- Muon veto (MUV1,2,3)

Secondary beam

- Momentum 75 GeV/c
- Composition: K^+(6%), π^+(70%), p(24%)

Data collection

2014	2015	2016	2017	2018	2019-2020
Pilot Run	Commissioning	Commissioning + Physics Run	Physics Run	Physics Run	LS2 Long shutdown 2

2015: 1% of nominal intensity, ~3×10^8 kaon decays
2016: 40% of nominal intensity, ~5×10^{11} kaon decays recorded
2017+2018: 60% of nominal intensity, > 8×10^{12} kaon decays on the tape
— better data quality assessment
— higher data taking efficiency

Trigger streams:

- $\pi\nu\nu$ trigger: 1 track, γ/μ veto
- Control trigger: samples for normalization, background estimation
- 3-track triggers: samples for lepton flavour violation study

Beyond the Standard Model

Neutrino oscillation

Baryon asymmetry of the Universe

Dark matter and dark energy

There is New Physics beyond the Standard Model, but we don't know exactly what is it

Search for New Physics:

- Study of rare decays of the SM particles (like $K^+\to\pi^+\nu\nu$)
  - Phys.Lett.B791 (2019) 156-166 ($K^+\to\pi^+\nu\nu$)
- Search for new particles (HNL, ALP, dark photon etc.)
  - Phys.Lett.B791 (2018) 137-145 (HNL)
  - JHEP 05 (2019) 182 (dark photon)
- Search for forbidden (in the SM framework) processes
  - arXiv:1905.07770, submitted to Phys.Lett.B (LNV in K^+ decays)

This talk

Heavy Neutral Leptons (HNL)

- The νMSM (Asaka et al., Phys.Lett.B 620 (2005) 17) is an extension of the SM to explain simultaneously neutrino oscillations, dark matter and baryon asymmetry of the Universe.
  - SM + 3 right-handed sterile neutrinos:
    - N_1: m_1 ~ 10 keV — dark matter candidate
    - $N_{2,3}$: $m_{2,3}$ ~ 100MeV — 100 GeV — baryon asymmetry
- Production in the meson decays, for example $K^+ \to l^+ N$ $(l=e,\mu)$ (but we also are able to search for HNL decays)

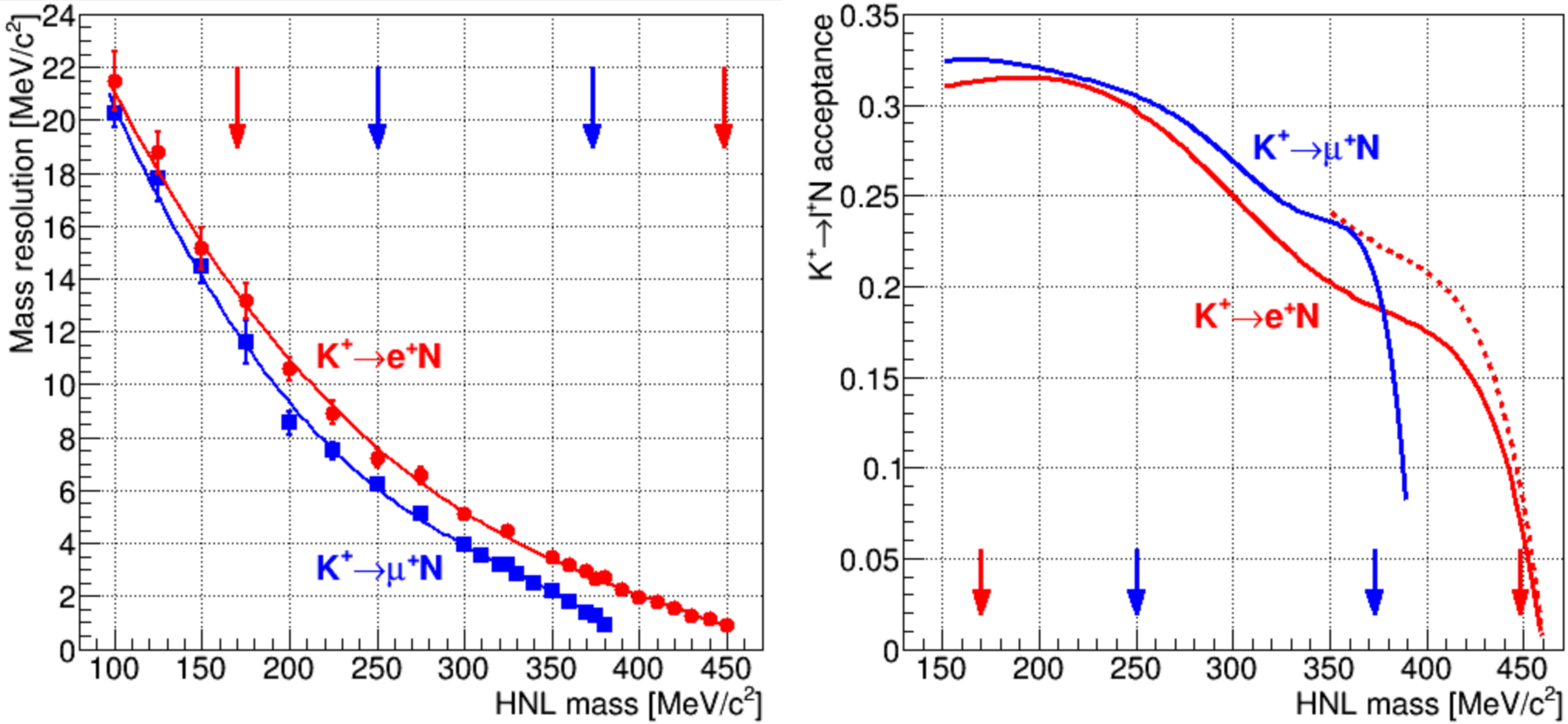
$$\Gamma(M^+ \to l^+ \nu_H) = \rho \times \Gamma(M^+ \to l^+ \nu_l) \times |U_{lH}|^2$$

R.E.Shrock, Phys.Rev.D24 1232 (1981)

Heavy Neutral Leptons (HNL)

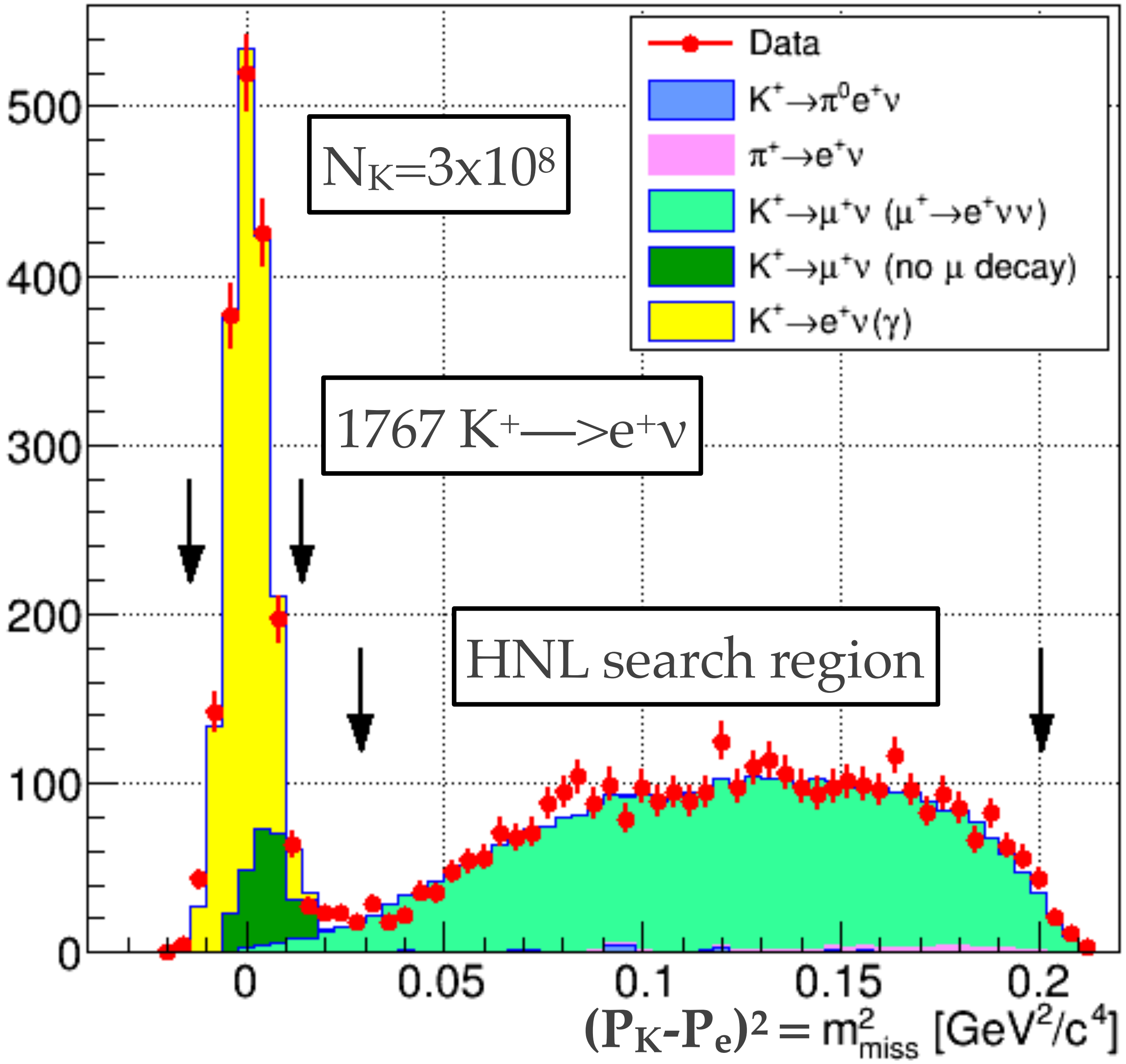
- Peak search in the missing mass distribution $(P_K-P_l)^2$, P_K is kaon four-momentum, P_l is lepton four-momentum
- 2015 minimum bias data (~1% of intensity)
- Kaon decays in the fiducial volume: ~3×10^8 $K^+\to e^+\nu$, ~1×10^8 $K^+\to\mu^+\nu$
- Beam tracker (GTK) is not available: kaon momentum is estimated as beam average
- Polynomial fit of the background (data-driven expected background)
- Upper limit for each mass is obtained from numbers of observed and expected events and their uncertainties

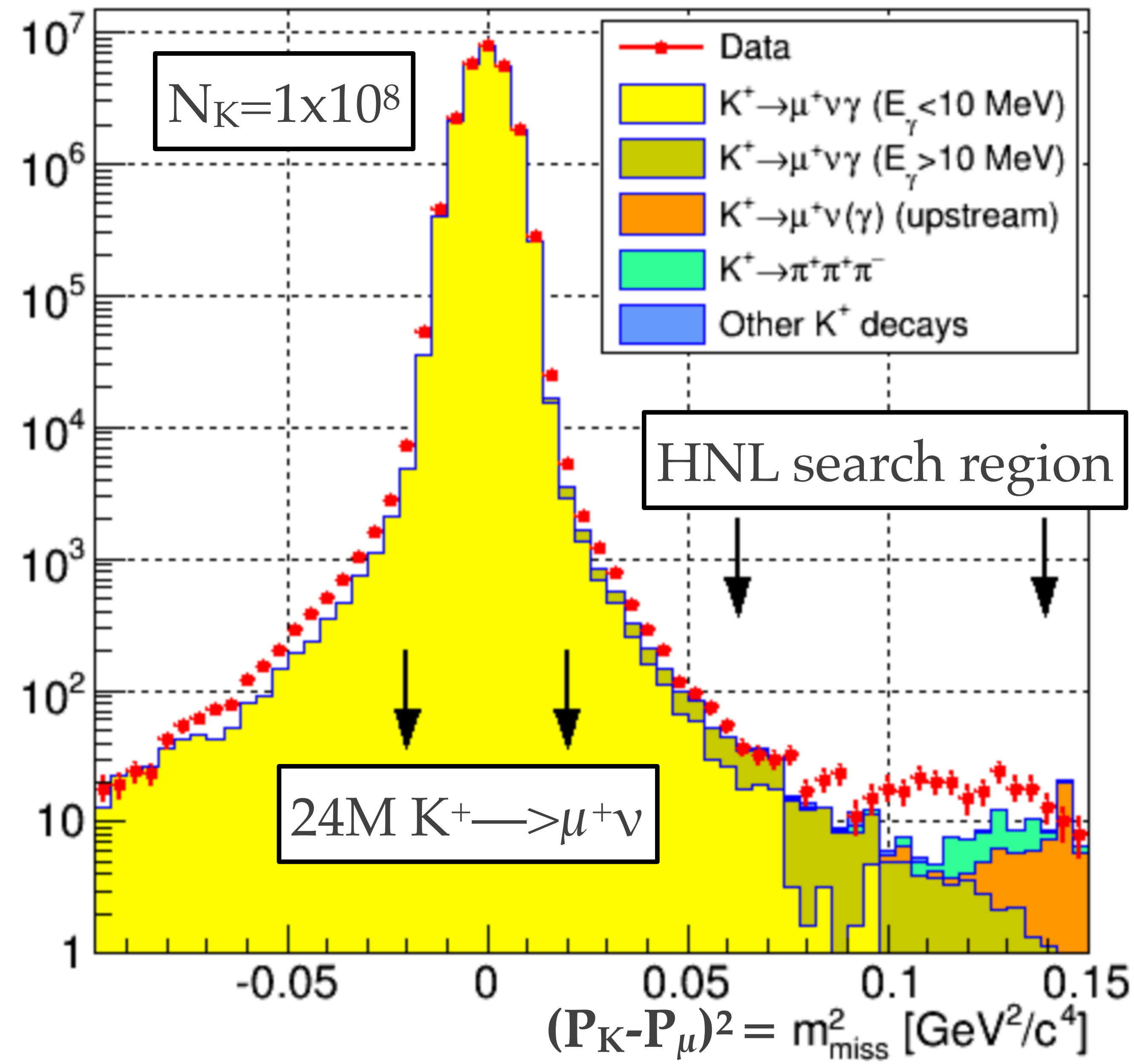
Acceptance and Resolution



- HNL mass scan in steps of 1 MeV/c^2
- Search window of $\pm 1.5\sigma_{m_N}$ (HNL mass resolution): n_{obs}
- Estimate background, n_{exp}, by fitting data events outside signal search region
- Uncertainties on n_{exp} evaluated using Monte Carlo simulation

Heavy Neutral Leptons (HNL)



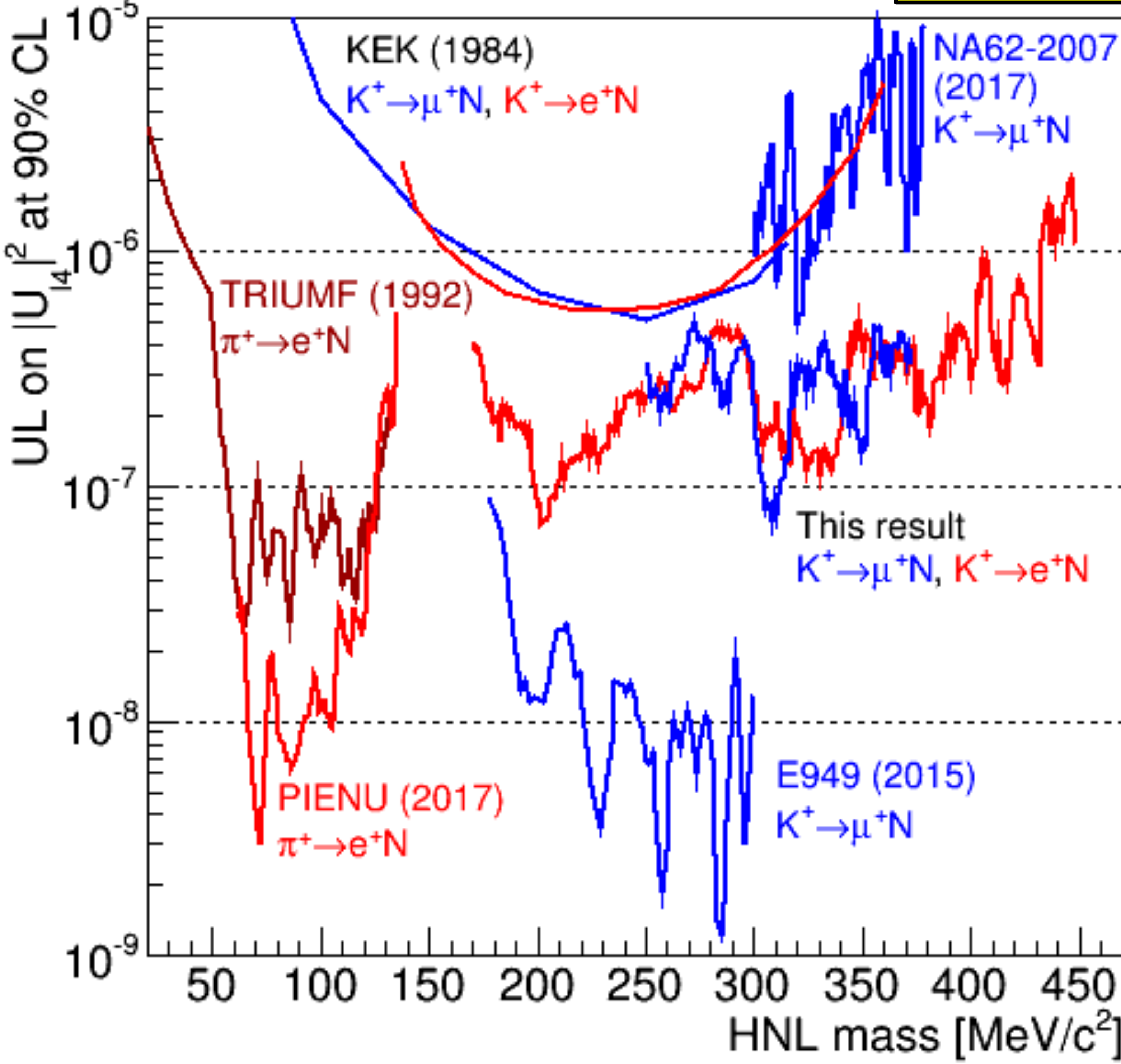


- Look for peak in the HNL region of $m_{miss}^2 = (P_{K^+} - P_{l^+})^2$, $(l = e, \mu)$
- HNL mass signal region:
  - e^+: $170 < m_N < 448$ MeV/c²
  - μ^+: $250 < m_N < 373$ MeV/c²

$$N_l^K = \frac{N_l^{SM\ region}}{A_l \times BR(K^+ \to l^+ \nu_l)}$$

HNL Results

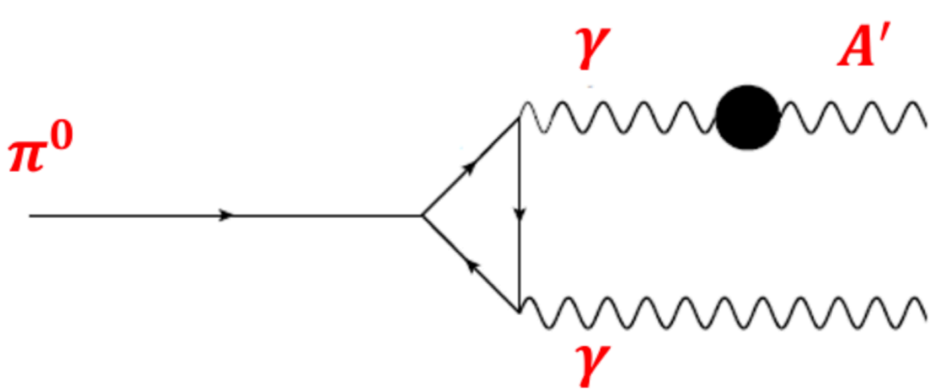
NA62 collaboration, Phys.Lett.B778 (2018) 137



- No signal observed
- Currently analysing 2016—2018 data: expect more strong limits due to using GTK and much more statistics
- Close related study: $K^+ \to l^+ \nu\nu\nu$ and $K^+ \to l^+ \nu X$, X is invisible

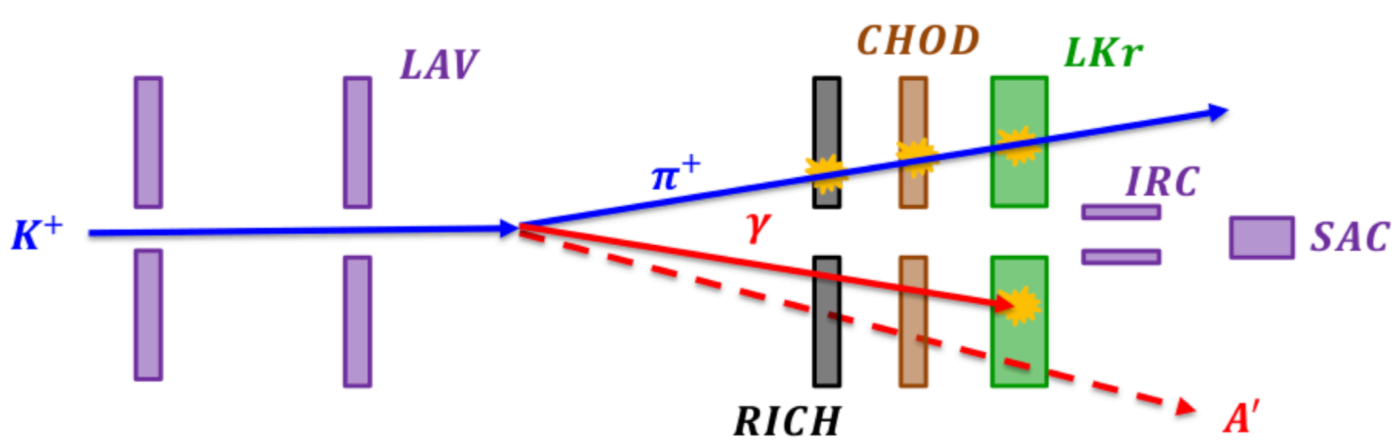
Dark photon searches in π^0 decays

- Weakly interacting hypothetical particle below EW scale introducing U(1) gauge symmetry
- Dark photon A′ produced in π^0 decay via kinetic mixing ε with SM photon in the decay chain $K^+ \to \pi^+\pi^0, \pi^0 \to A'\boldsymbol{\gamma}$
- A′ is invisible or long-lived



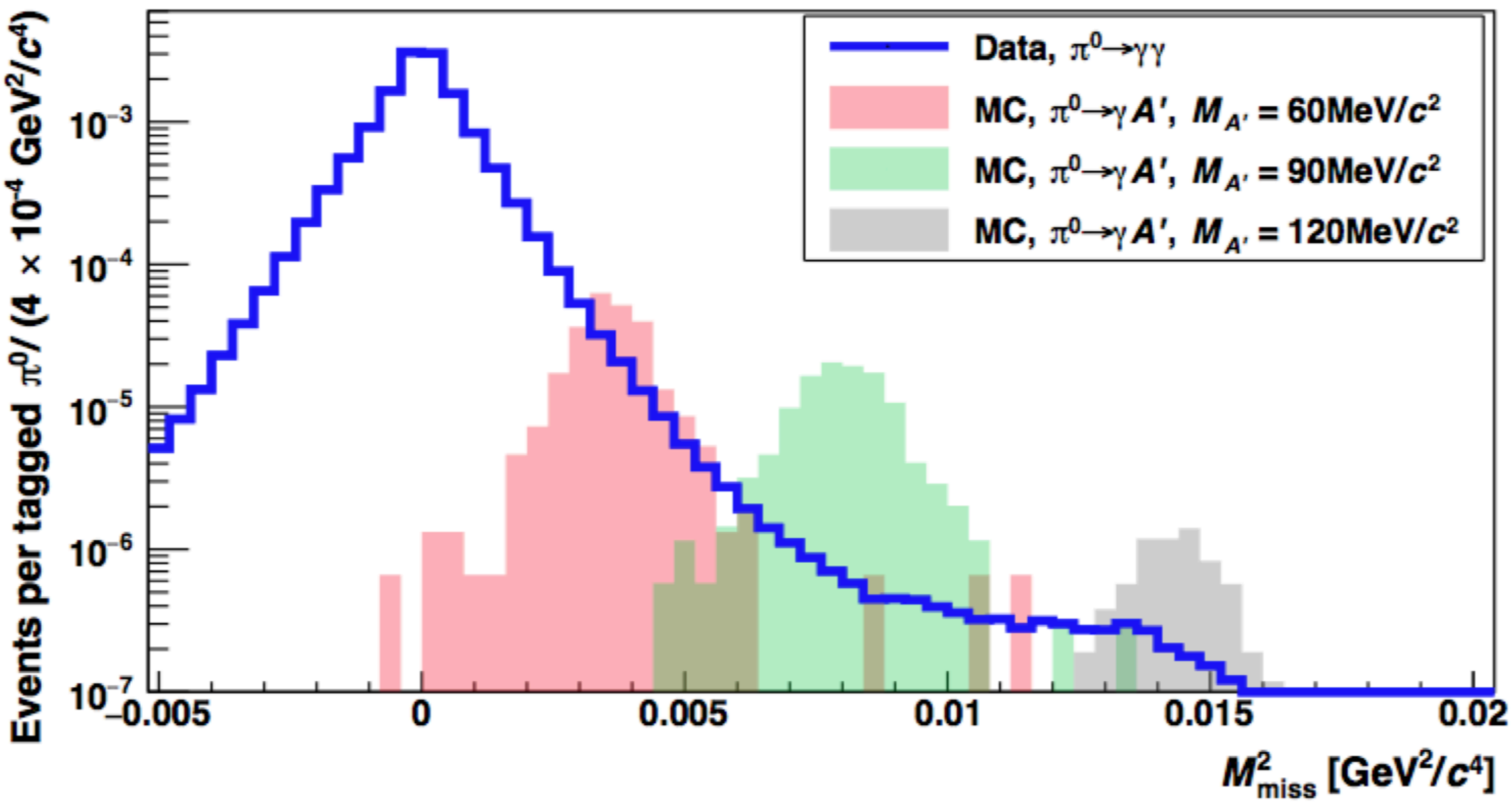
$$\mathrm{BR}\left(\pi^0 \to A'\gamma\right) = 2\epsilon^2 \left(1 - \frac{M_{A'}^2}{M_{\pi^0}^2}\right)^3 \times \mathrm{BR}\left(\pi^0 \to \gamma\gamma\right)$$

Phys. Lett. B 166 196 (1986)

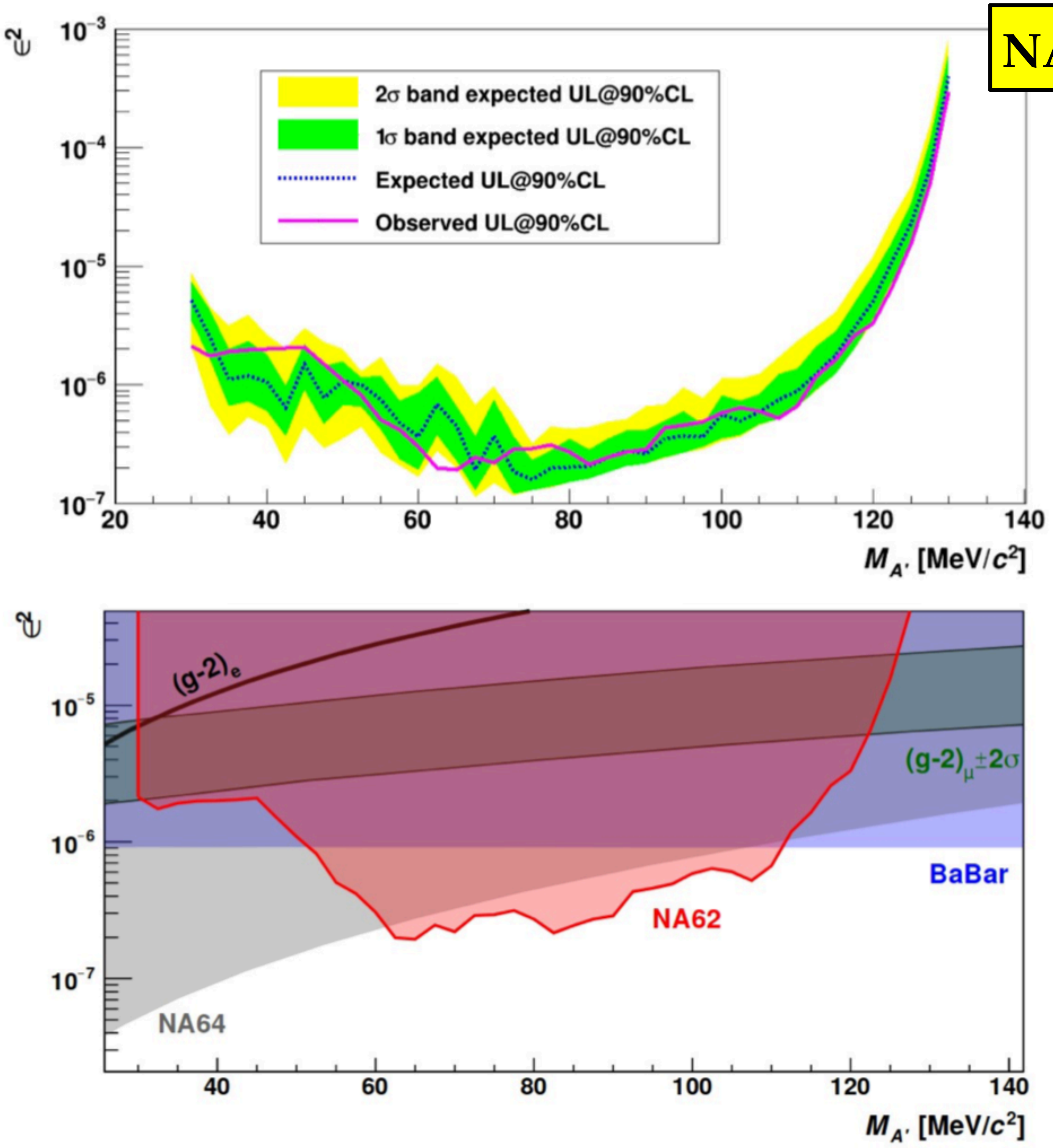


Dark photon searches in π^0 decays

- 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 $\to$ expected and observed number of events for each mass window



Dark photon result



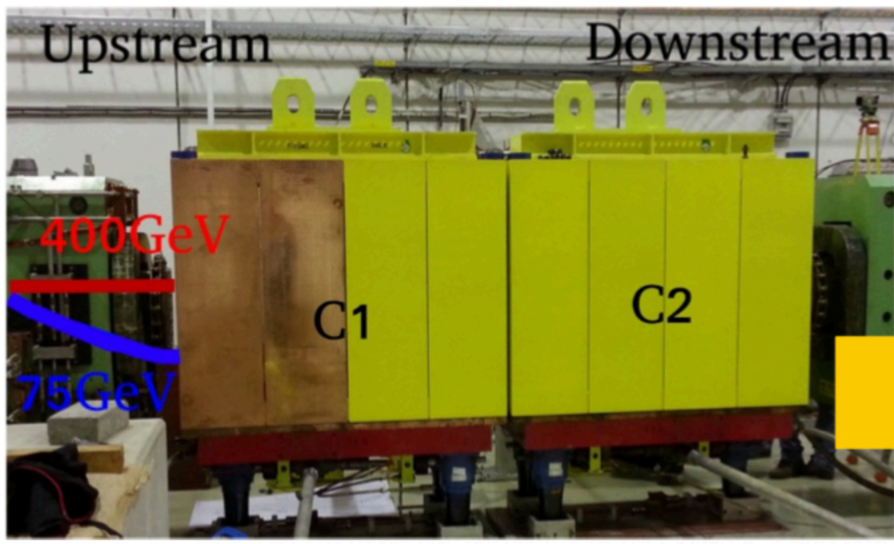
NA62 collaboration, JHEP 05 (2019) 182

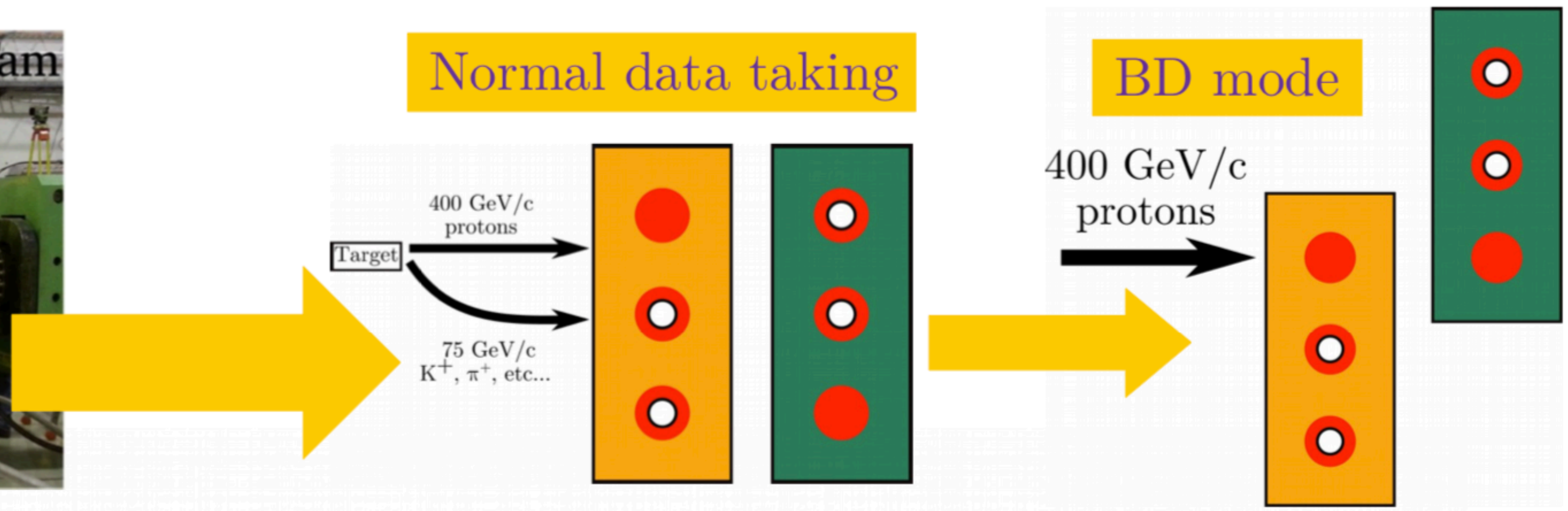
- No signal observed
- Improved limits on ε² in 60—110 MeV / c² range
- Set new upper limit on

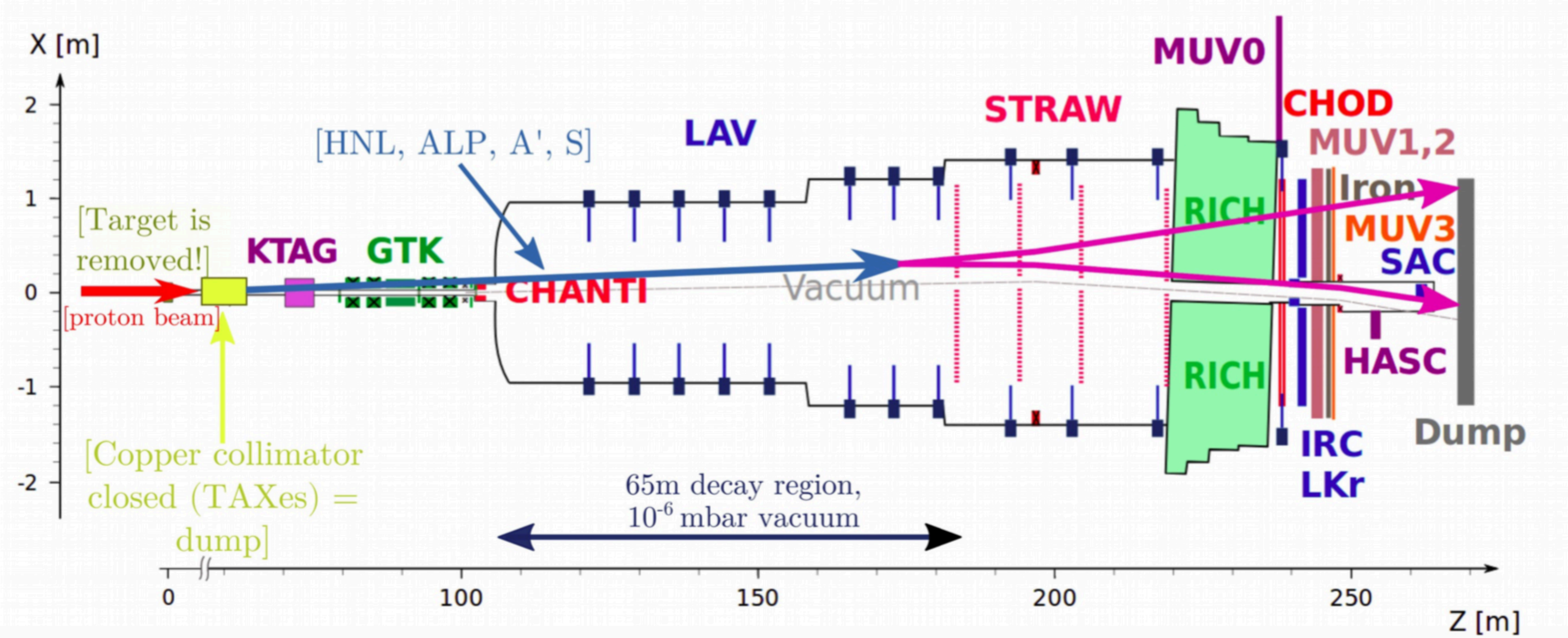
$$\mathcal{B}(\pi^0 \to \gamma\nu\bar{\nu}) < 1.9 \times 10^{-7}$$

Improving the current limit by more than three orders of magnitude

NA62 in Beam Dump mode





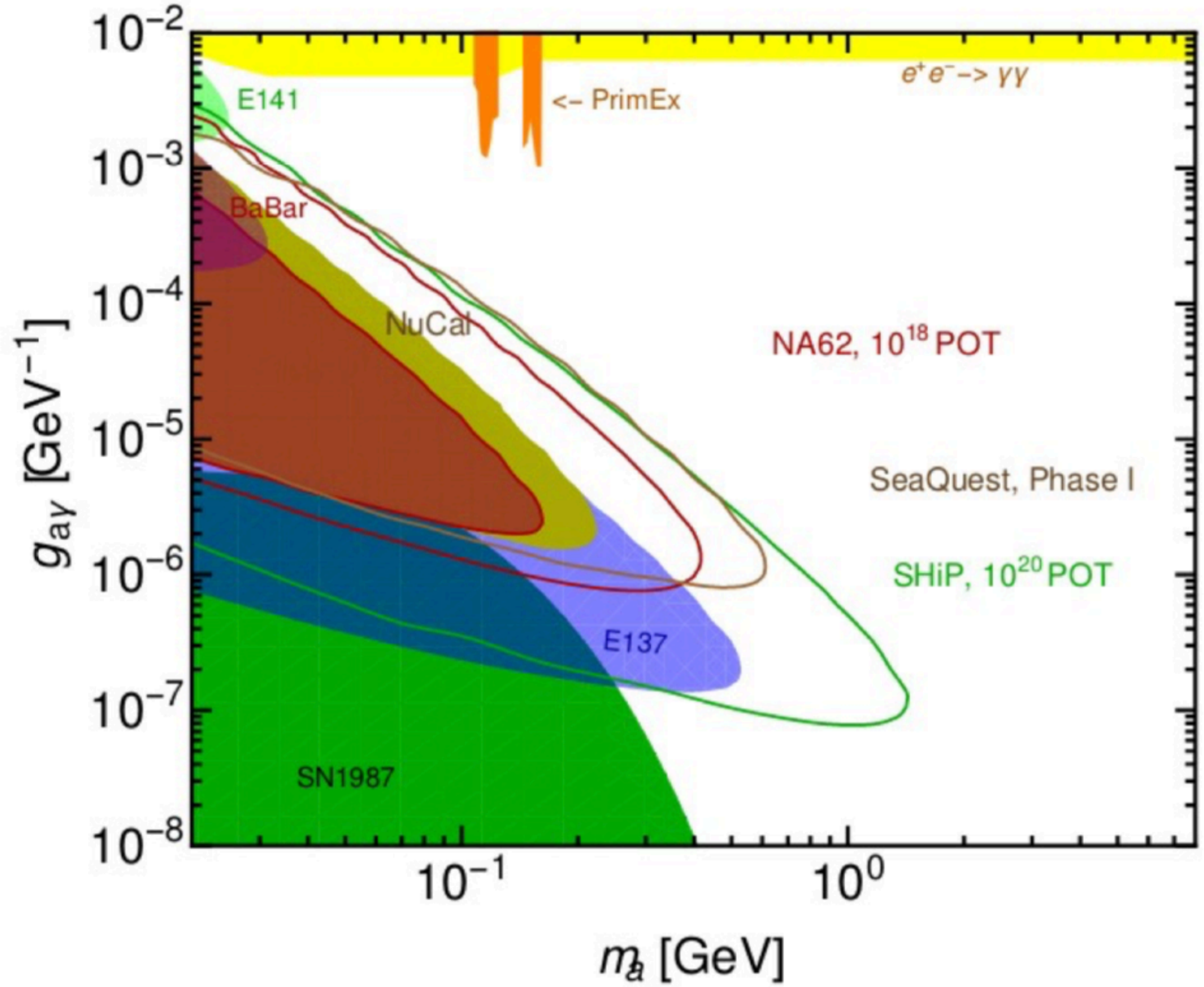


NA62++ project

- The NA62++ uses the same NA62 apparatus in BeamDump mode
  - Can collect $O(10^{18})$ protons on target (POT) in O(3) month (protons at $p=400\,GeV/c$)
  - 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 slides show NA62++ prospects assuming $O(10^{18})$ POT and zero background
- The limits are set at 90%C.L., and are compared to other results expected on 5-year timescale
- The results of studies based on $O(10^{16})$ POT show negligible background
- Improvements to NA62++ setup (upstream veto, beam line modifications, higher intensity) are not included here, but initial studies are promising

ALP decay search

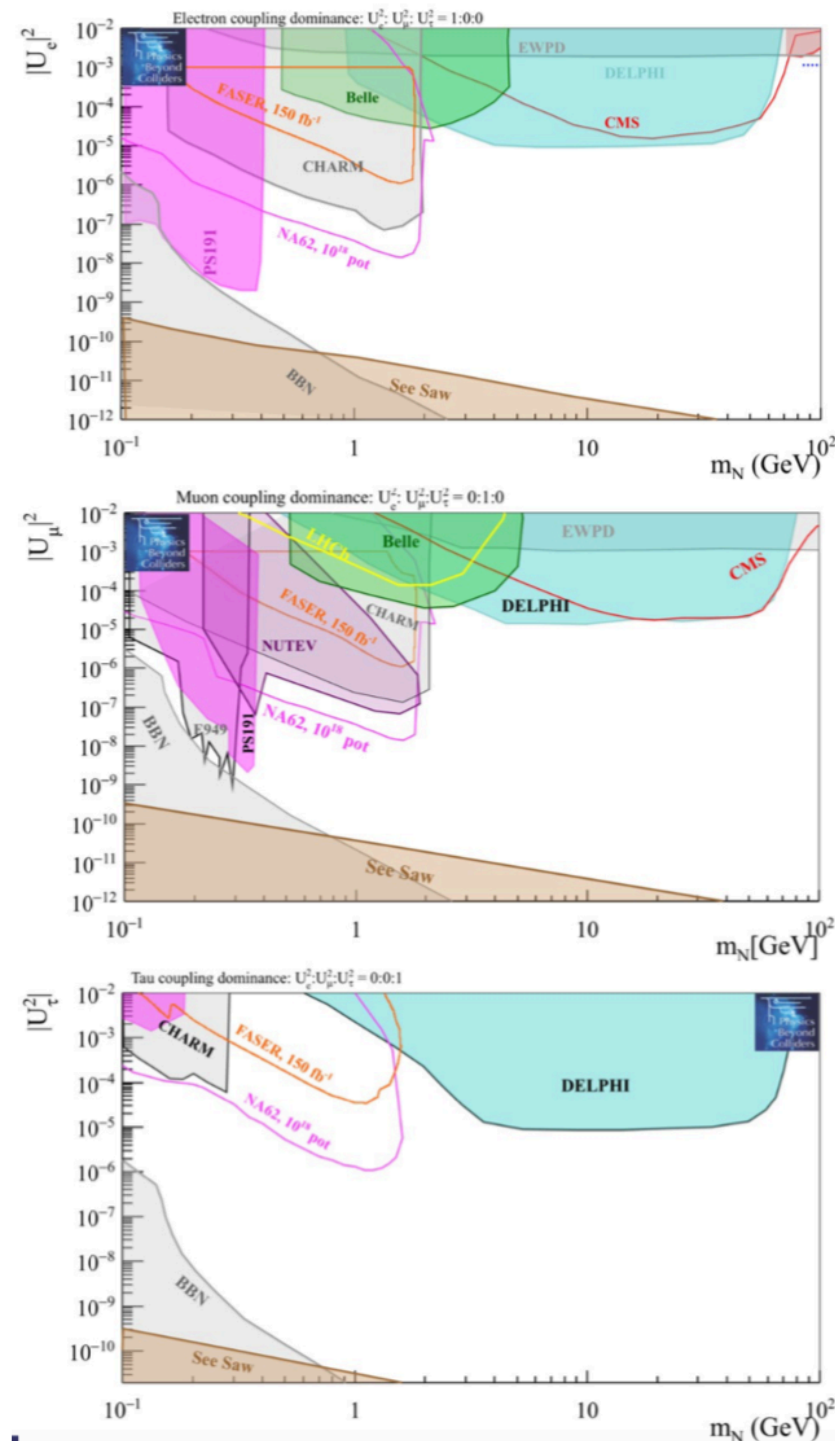
- Good candidate for cold dark matter, produced via elastic scattering of beam proton dumped onto NA62 Cu collimators (Primakoff effect)
- Decay searches can be performed for $A \to \gamma\gamma$ in MeV/c^2-GeV/c^2 mass range
- Ongoing analysis of 2017-2018 data taken in beam-dump mode (closed beam collimators) 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:1904.02091

HNL decay searches

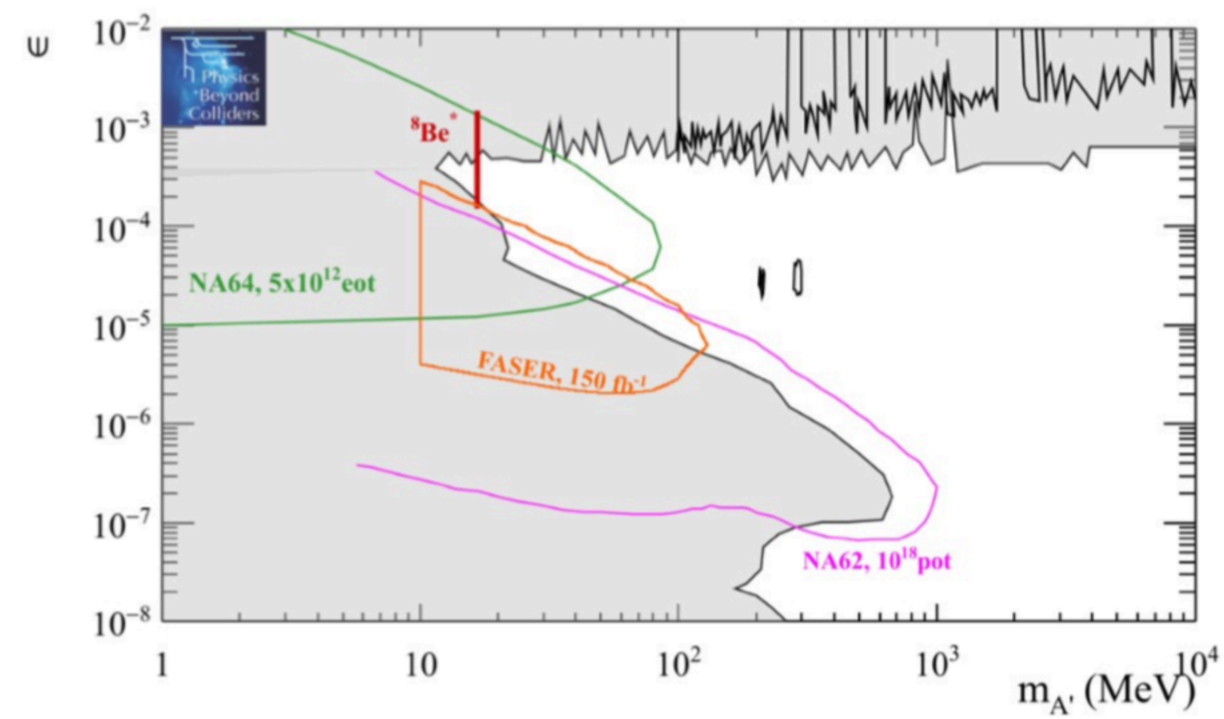
- HNL decay searches to visible final states with at least two charged tracks. HNL are produced in B,D meson decays
- Expected sensitivity in the plane HNL coupling to one SM generation vs HNL mass (zero background assumption)



arXiv:1901.09966, arXiv:1801.04207

Dark photon decay searches

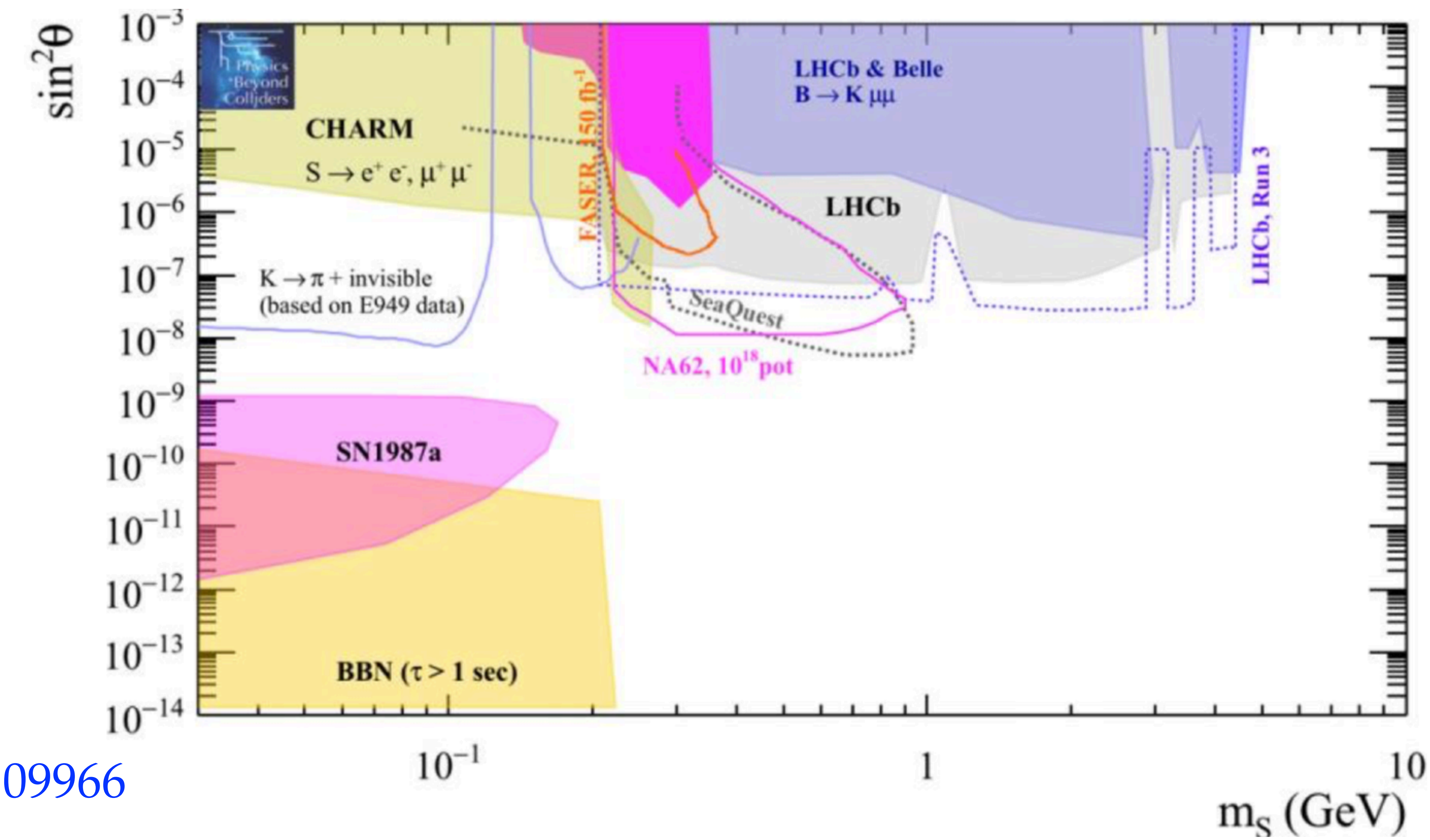
- Search for $A' \to l^+ l^-$
- Expected sensitivity in the plane A′ mixing with SM photon vs A′ mass (zero background assumption)
- Sensitivity expected to be higher than shown due to
  - including direct QCD A′ production
  - including A′ production in the collimator (here only target)



arXiv:1901.09966

Dark scalar S decay searches

- NA62++ can improve limits on S parameter space
- Expected limit is comparable with those possible at SeaQuest
- Also $K^+ \to \pi^+$ + invisible and $K+ \to \pi^+ S$, $S \to \mu^+\mu^-$ accessible to NA62 in K^+ mode



arXiv:1901.09966

Summary

- The NA62 experiment is a powerful laboratory to make searches for exotic particles in both production and decay modes
  - World best upper limits on HNL and Dark photon mixing parameters have been set
  - Improved results are expected after full data set analysis (2016–2018)
  - NA62 will continue to take data after LS2 in kaon mode
- The prospects for the NA62++ “dump mode” experiment were presented
  - Improvements on limits in a variety of models including HNL, dark photons, ALP, dark scalar are expected
  - Possibility to run in BeamDump mode in 2023