Searches for beyond the standard model physics with the ArgoNeuT experiment

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Introduction

Accelerator neutrino experiments are exposed to high-energy, high-intensity beams:

- could produce various long-lived BSM particles
- can search for their decay using neutrino detectors, such as ArgoNeuT

This talk will give an overview of several recent BSM searches performed with the ArgoNeuT experiment:

- millicharged particles
- heavy neutral leptons
- heavy QCD axions

Each search was performed working directly in collaboration with theorists

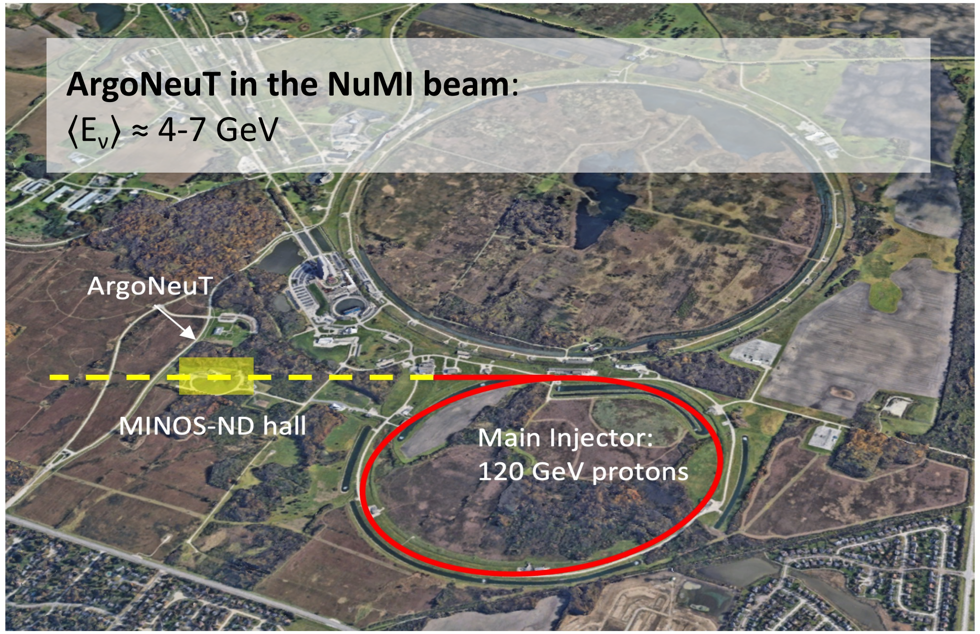
The ArgoNeuT Experiment

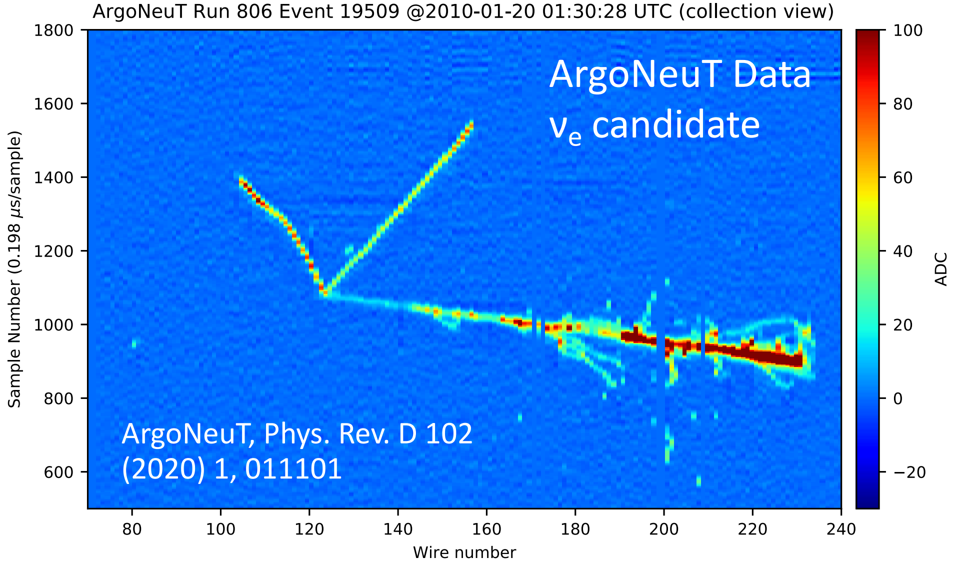
First Liquid Argon Time Projection Chamber (LArTPC) in a neutrino beam in the US:

- exposed to 120 GeV NuMI beam, ~1km from target
- collected data 2009-2010, ~5-month physics run
- $1.25{\times}10^{20}$ POT, ~7000 neutrino interactions
- sensitivity to BSM particles produced in beam

Designed as a test experiment… but producing physics results:

- multiple first ν-argon cross-section measurements
- BSM searches: millicharged particles, heavy neutral leptons and heavy QCD axions
- along with extensive detector R&D

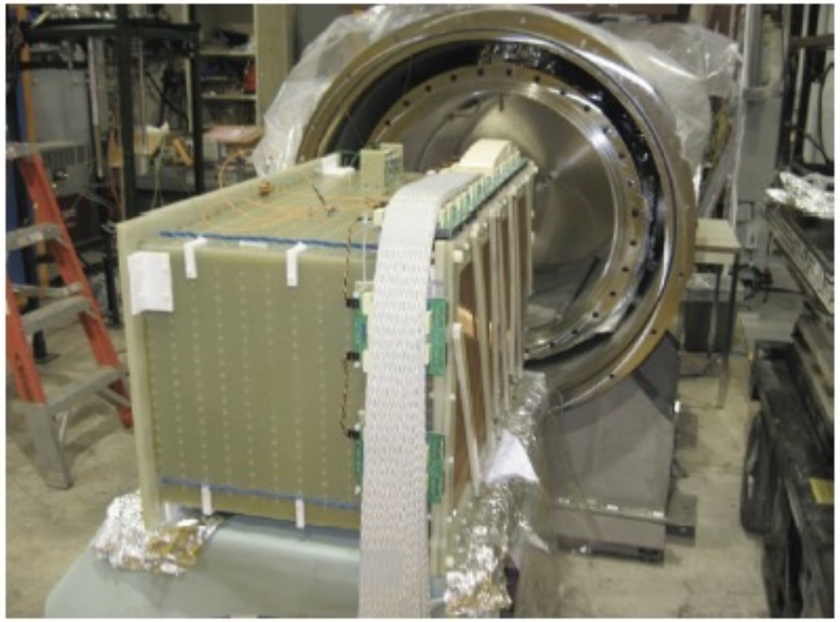


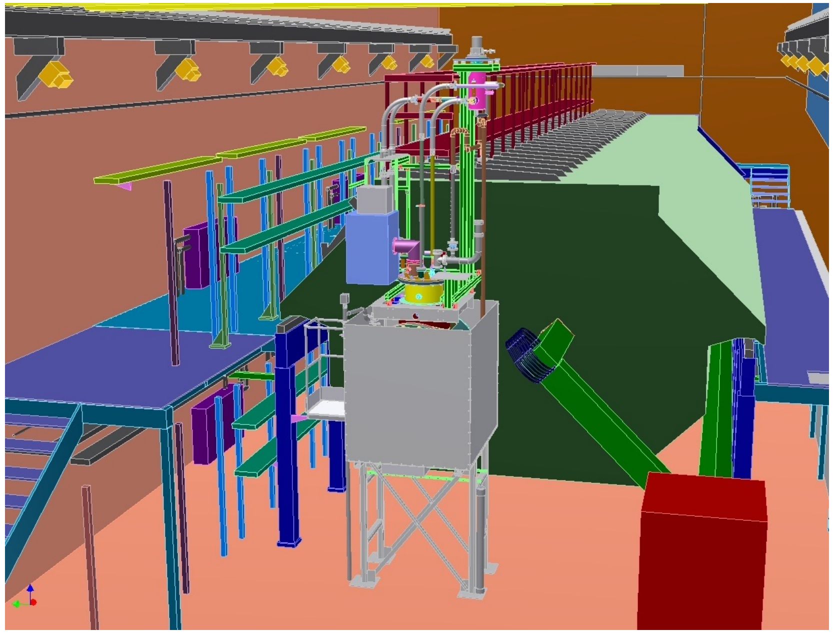


The ArgoNeuT detector

0.24 ton Liquid Argon Time Projection Chamber:

- 40 (h) × 47 (w) × 90 (l) cm^3
- two wire planes, 4mm wire spacing

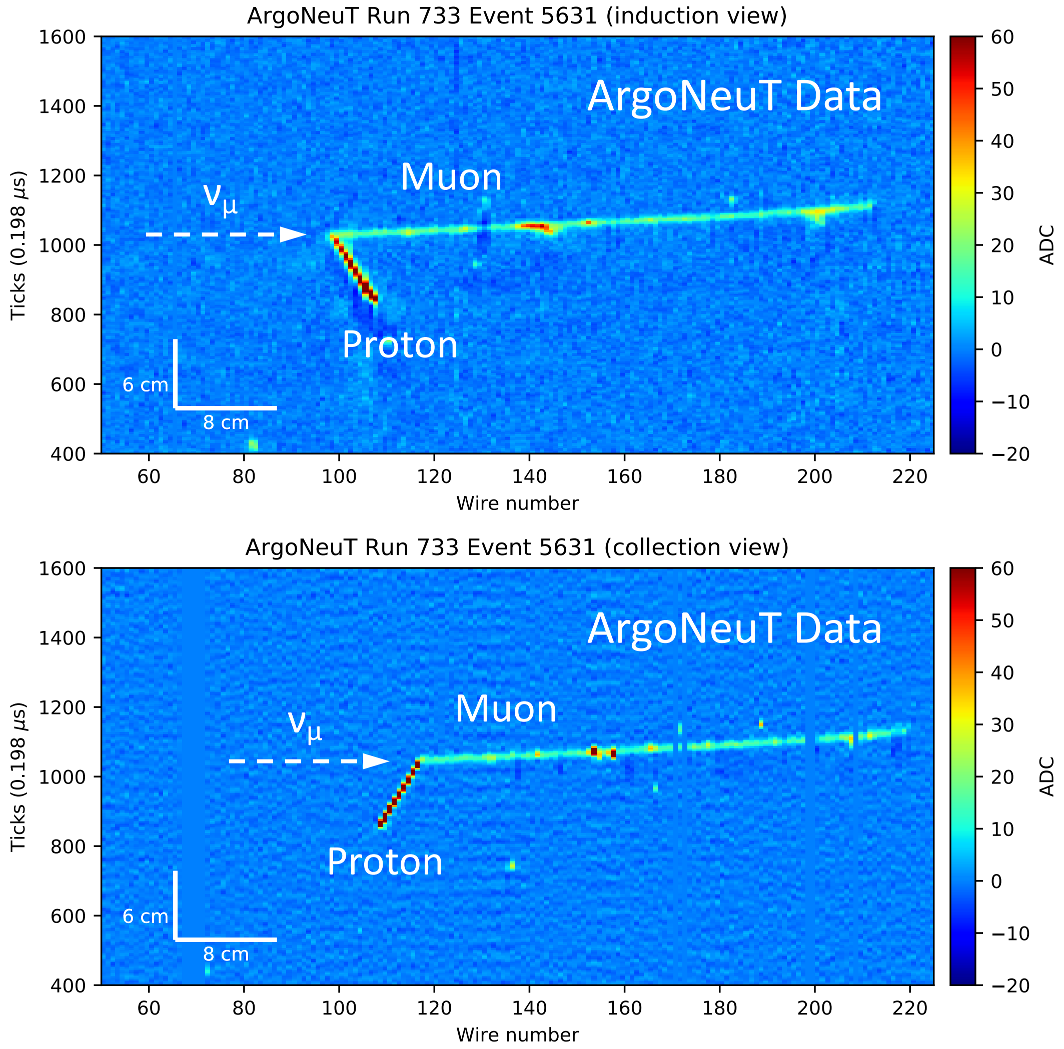




Upstream of MINOS near detector (MINOS-ND):

- large magnetized steel and scintillator strip spectrometer, 3.8 (h) × 4.8 (w) × 16.6 (l) m^3
- used to identify muons by matching tracks exiting ArgoNeuT with tracks in the MINOS-ND

LArTPC technology: 3D imaging and calorimetry

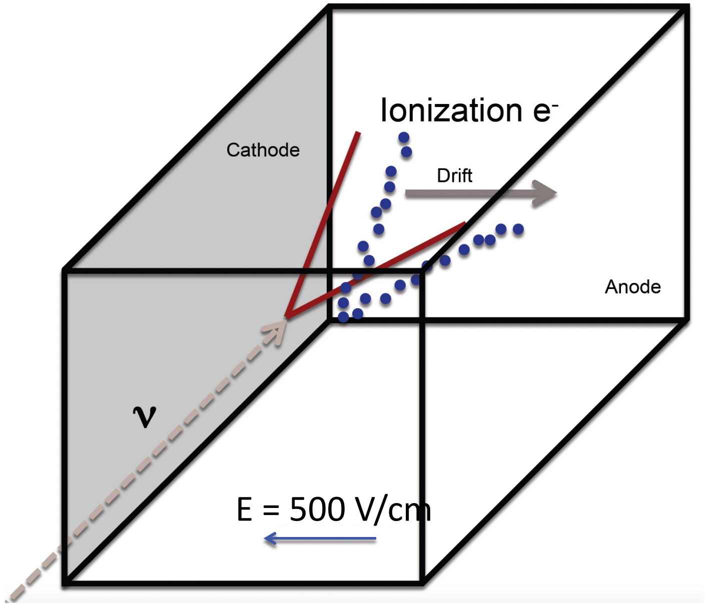


Two 2D views, with ~4 mm scale resolution

→ 3D track and shower reconstruction

Total charge proportional to the deposited energy

→ calorimetry + particle identification based on dE/dx



Millicharged particles

Millicharged particles (mCP):

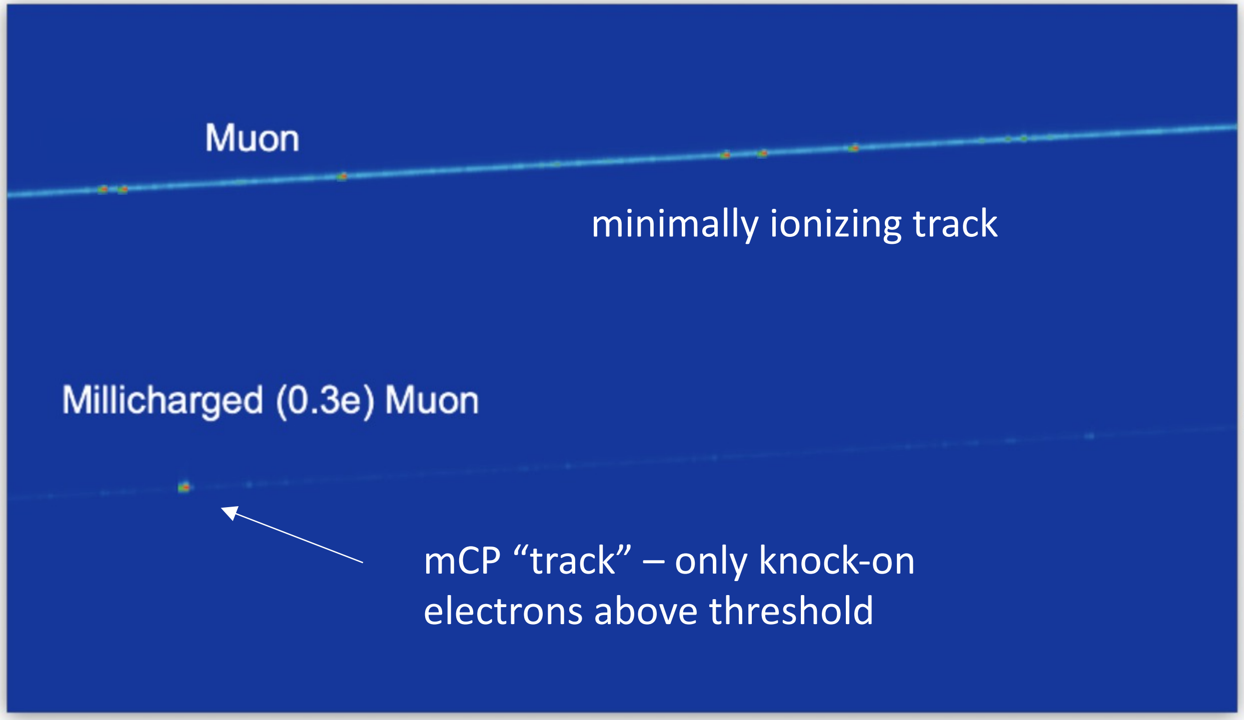
- electric charge **Q = ε · e** , where **ε << 1**
- could be produced in neutrino beam, from meson decays

mCP "track" below LArTPC detection threshold:

- only see knock-on electrons that create isolated energy deposits above threshold
- mCP signal: one or more isolated blips of ionization charge

Low energy threshold is key:

- **300 keV** in ArgoNeuT
- ArgoNeuT, Phys. Rev. D 99 (2019) 1, 012002

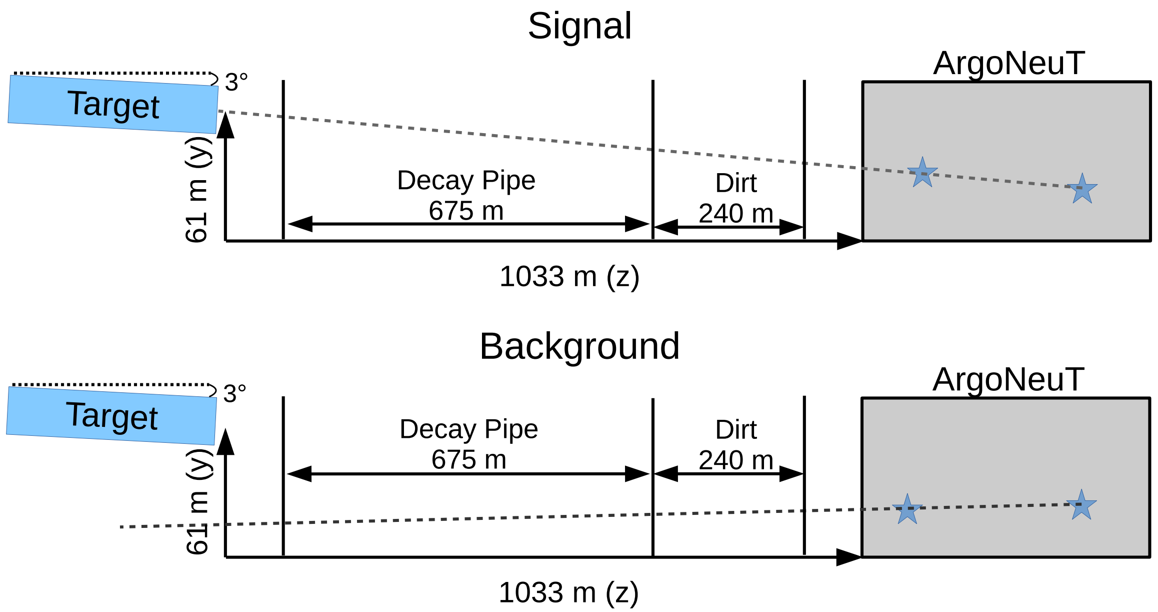


Selecting mCP in ArgoNeuT

Search in "empty" events in ArgoNeuT data, without tracks or showers from neutrino interactions:

- 3,259,427 events, 1.0×10^{20} protons-on-target (POT)

Minimal energy loss and deflections during propagation – mCP points back towards beam



Signal: double-hit event, points back to beam target

Background: hits do not point back to beam target

mCP search results

ArgoNeuT millicharged particle search:

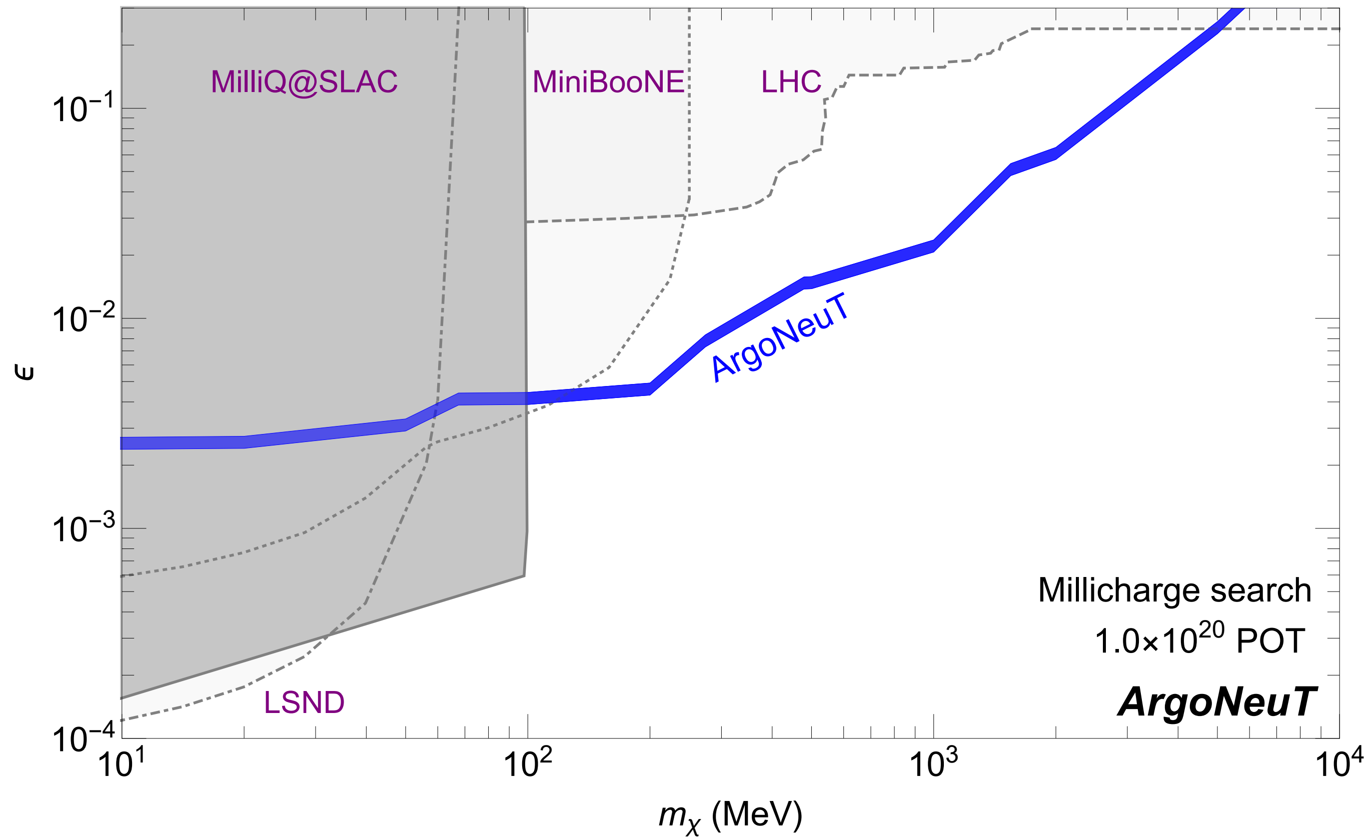
- lead analyzer: I. Lepetic
- theorists: R. Harnik, Z. Liu

mCP search results:

- one event observed, consistent with background expectation
- exclude large region of unexplored parameter space at 95% CL

First search for mCP in a LArTPC:

- JHEP 07 (2019) 170 (Theory)
- Phys. Rev. Lett. 124 131801 (2020) (ArgoNeuT + Theory)



Heavy neutral leptons

120 GeV protons at NuMI enables production of HNLs with masses up to ~ 1 GeV

- long-lived relative to experimental lengths – can propagate to ArgoNeuT, then can search for their decay

Consider **tau-coupled** scenario:

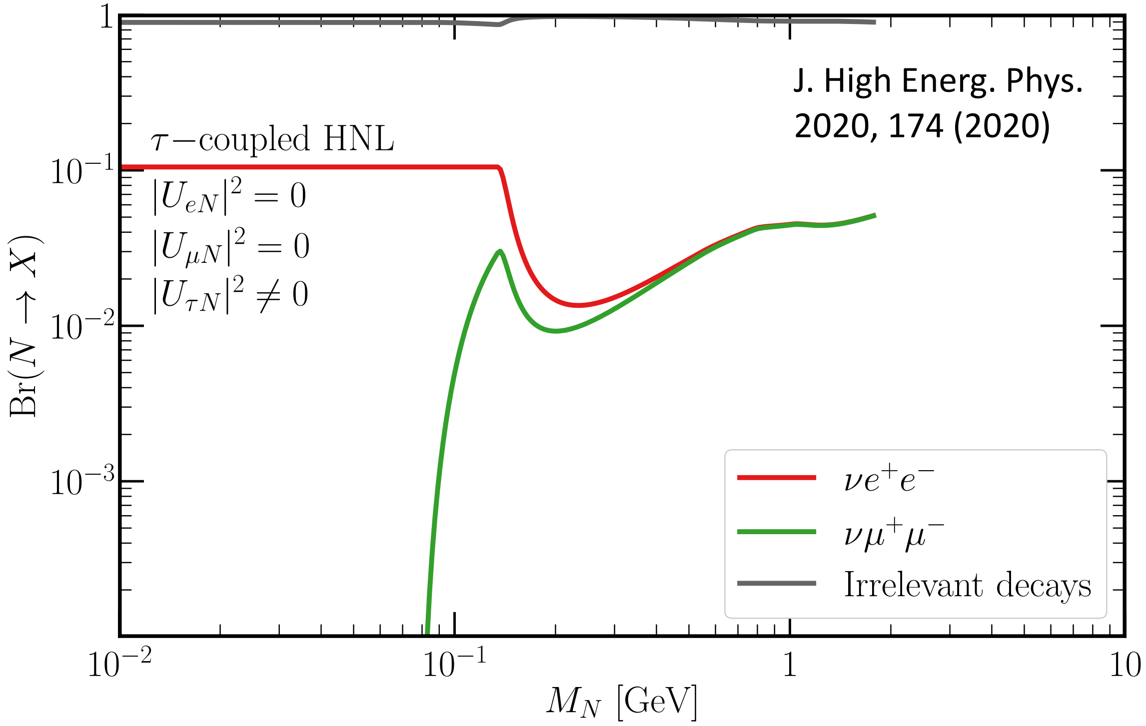
- i.e. $|U_{\tau N}|^2 \neq 0$ and $|U_{eN}|^2 = |U_{\mu N}|^2 = 0$
- produced from $\tau^{\pm}$ decays:

$$D_{(s)}^{+/-} \rightarrow \tau^{+/-} + \nu_{\tau} \qquad \tau^{+/-} \rightarrow N + X^{+/-}$$

where $X^{\pm}$ are SM particles, e.g. $\pi^{\pm}$

Significant decay modes:

$N \longrightarrow \nu\, e^+ e^-$ and $\mathbf{N \longrightarrow \nu\, \mu^+ \mu^-}$



For model details see:
Berryman et al. JHEP 02 (2020) 174
Coloma et al. Eur. Phys. J. C, 81(1):78, 2021

Heavy QCD axions

120 GeV protons at NuMI also enables production of heavy axions with masses up to ~ 1 GeV

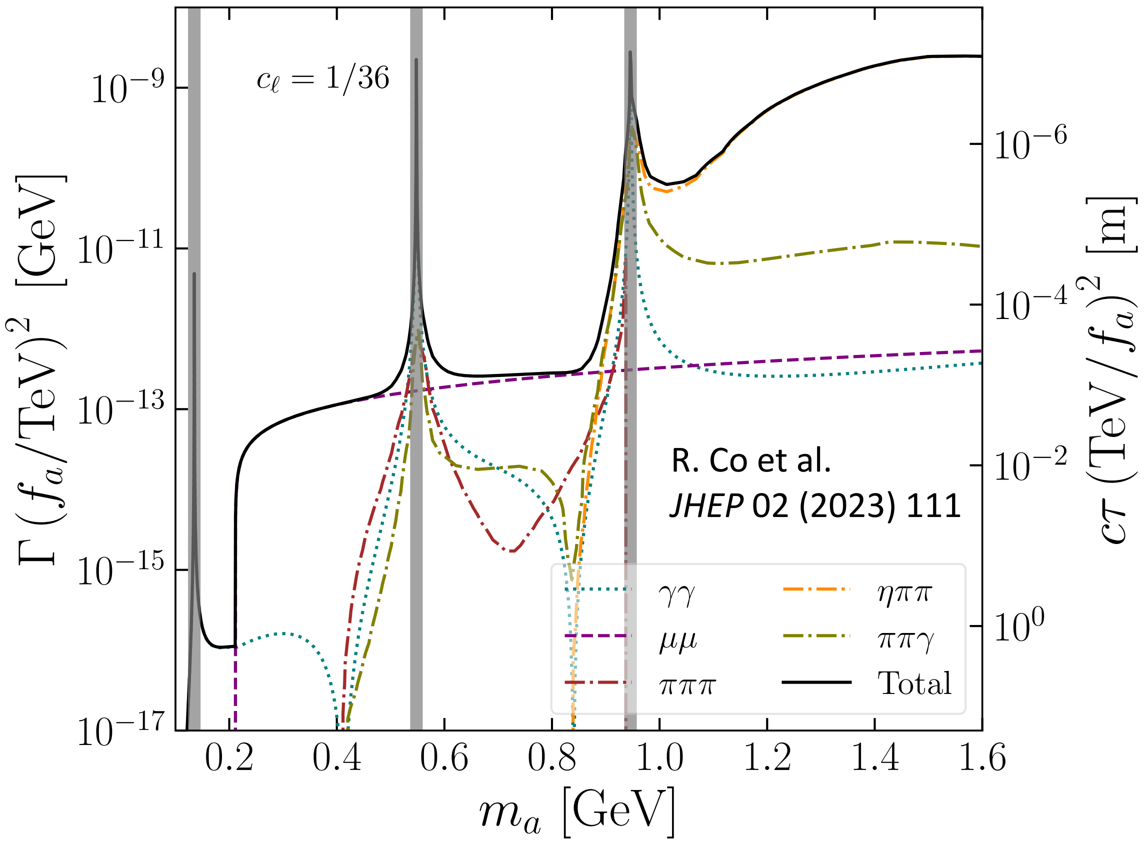
- can also be long-lived relative to experimental lengths --> can search for their decays in ArgoNeuT

Consider model with couplings to SM gauge bosons + coupling to leptons (allowing leptonic final states)

Production from mixing with π^0, η and η′ mesons

Significant decay modes: γγ, ee, **μμ** + hadronic modes

Contributions depend on axion-lepton coupling strength, two benchmark scaling: c_l = 1/36 and 1/100



For model details see:

K. Kelly et al. Phys. Rev. D 103 (2021) 9, 095002

R. Co et al. *JHEP* 02 (2023) 111

Di-muon signatures in ArgoNeuT

HNLs and heavy axions are very different models… but can produce similar decay signatures in ArgoNeuT:

HNLs decaying to muon pair $N \longrightarrow \nu\, \mu^+ \mu^-$:

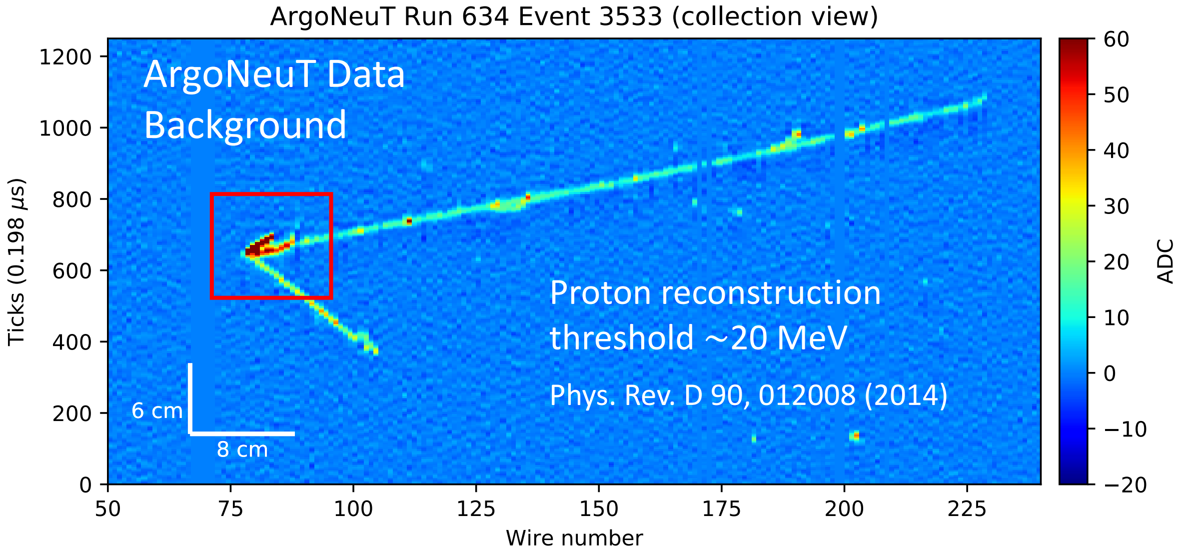
- average muon energy: ~ 7 GeV
- average opening angle: ~ 3 deg

Axions decaying to muon pair $a \longrightarrow \mu^+ \mu^-$:

- average muon energy: ~ 20 GeV
- average opening angle: ~ 2.5 deg

ArgoNeuT + MINOS-ND ideal for $\mu^+ \mu^-$ signatures:

- ArgoNeuT LArTPC: vertex identification and reconstruction of low energy particles – allows identification of backgrounds
- MINOS-ND muon spectrometer: muon charge reconstruction + charged pion rejection
- combination of detectors allows us to select these events with *near zero background*

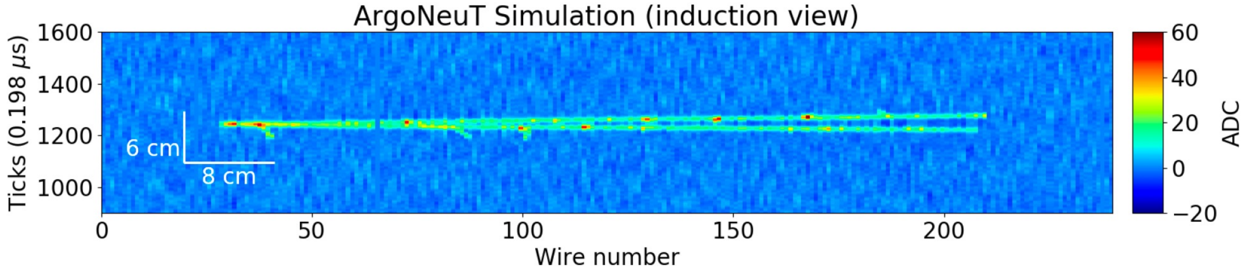


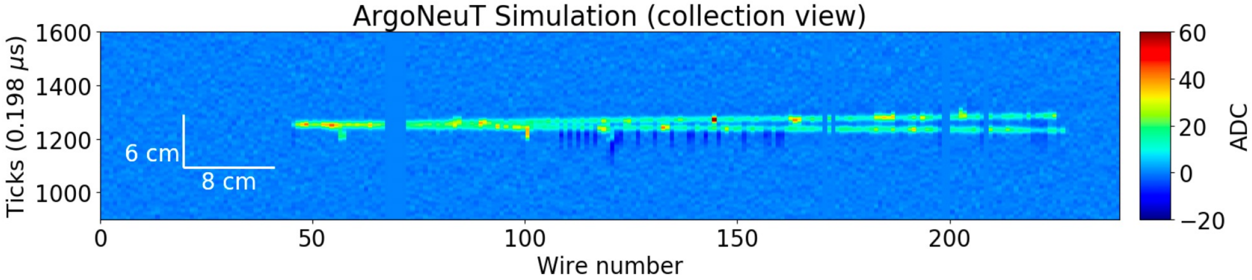
Di-muon signatures in ArgoNeuT

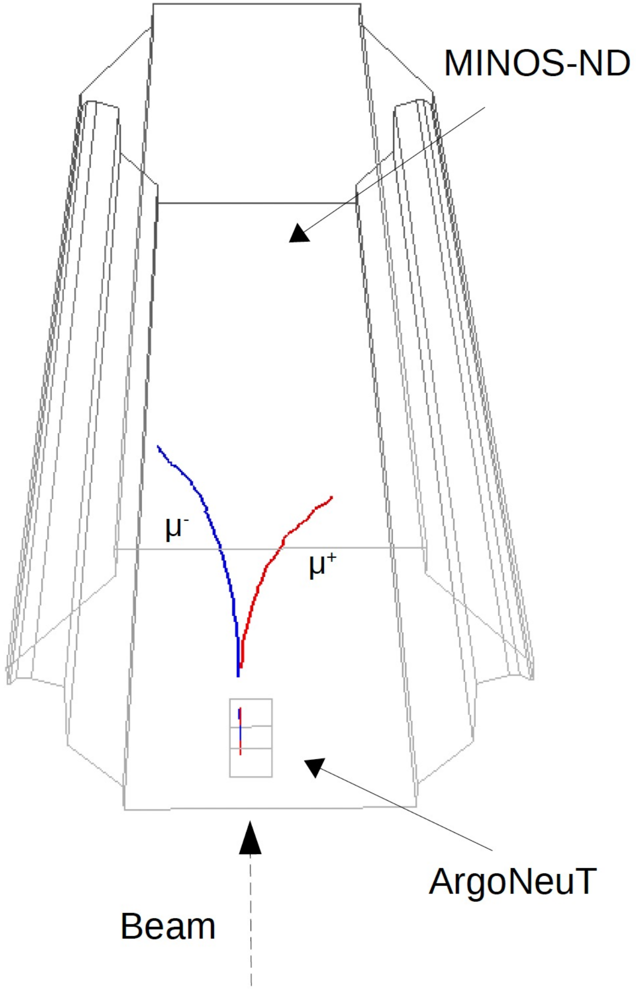
Two different signatures, depending on how forward going the muons are:

1. **two MIP dE/dx tracks** in ArgoNeuT, match to **two tracks** in MINOS-ND
2. **single double-MIP dE/dx track** in ArgoNeuT, matches to **two tracks** in MINOS-ND

Signature 1: *Two-track* event [simulation]







Di-muon signatures in ArgoNeuT

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1. **two MIP dE/dx tracks** in ArgoNeuT, match to **two tracks** in MINOS-ND
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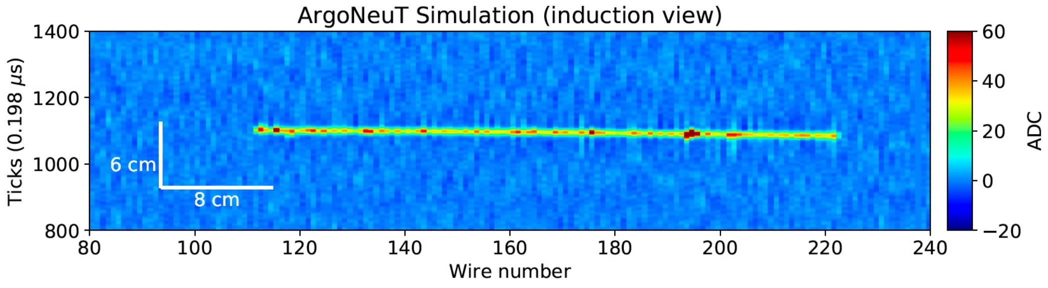
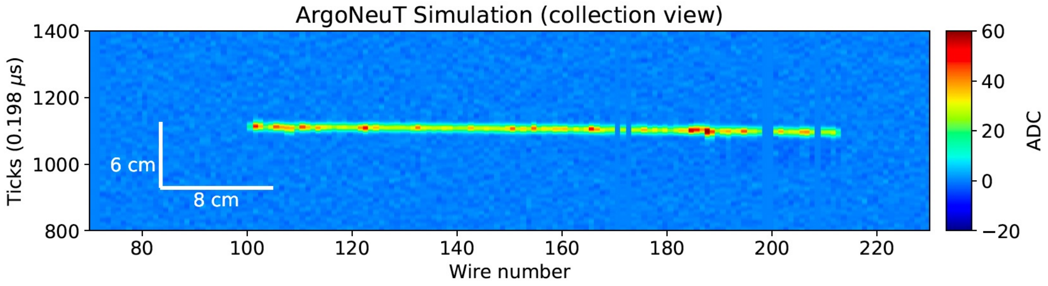
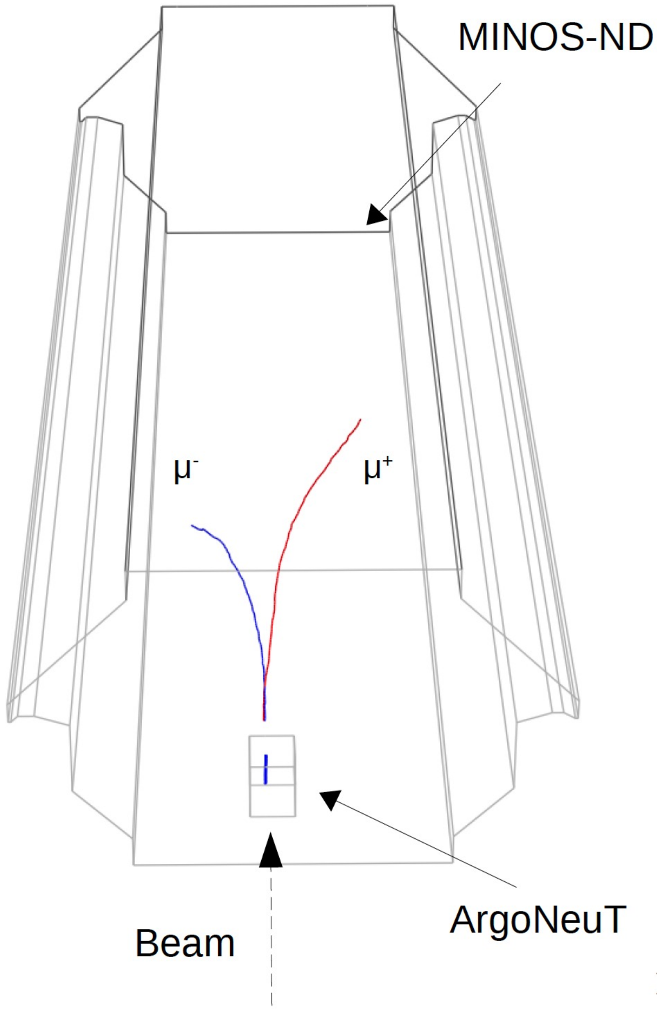
Signature 2: *Double-MIP* event [simulation]







Selecting HNLs and heavy axions in ArgoNeuT

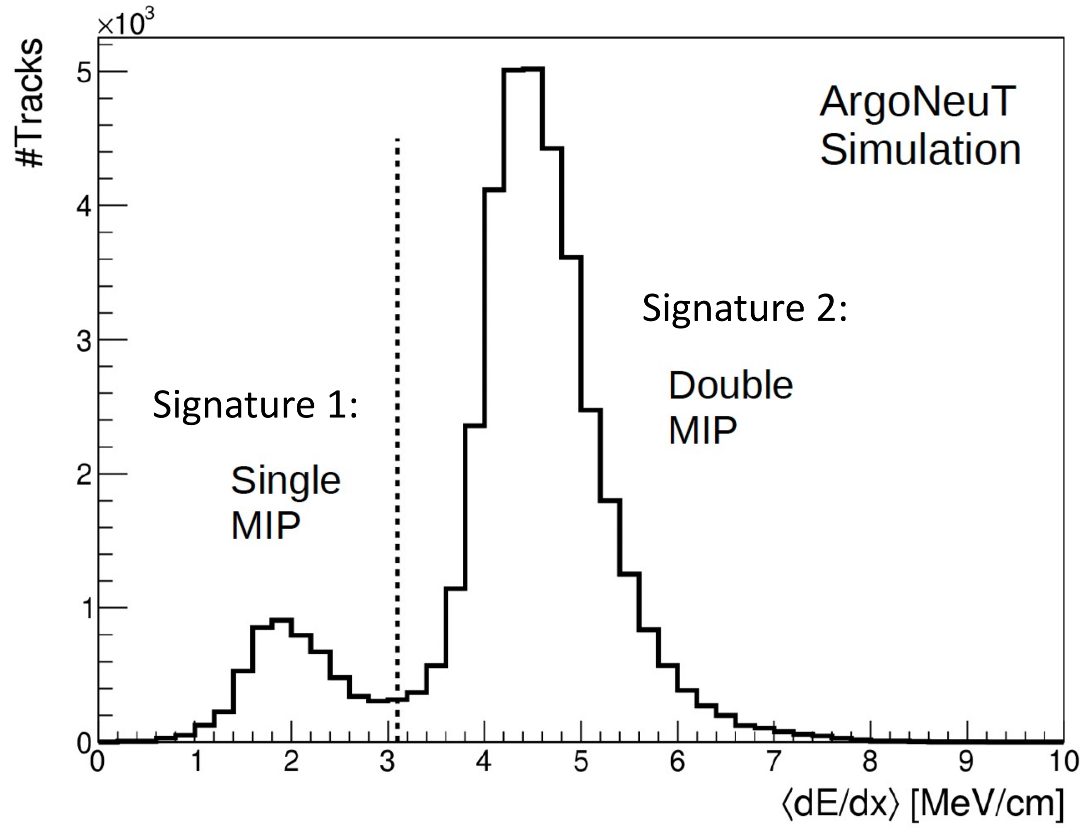
Select highly forward-going muons in ArgoNeuT by average dE/dx at start of tracks:

- minimally ionizing particle (MIP), dE/dx ~ 2 MeV/cm
- overlapping muons ~ 2 x MIP dE/dx

Match to two-tracks in the MINOS-ND:

- oppositely charged
- pion rejection based on dE/dx and length
- use timing information to avoid mis-matching

Selections tuned using simulation for each model to account for differing kinematics



HNL search results

ArgoNeuT tau-coupled HNL search:

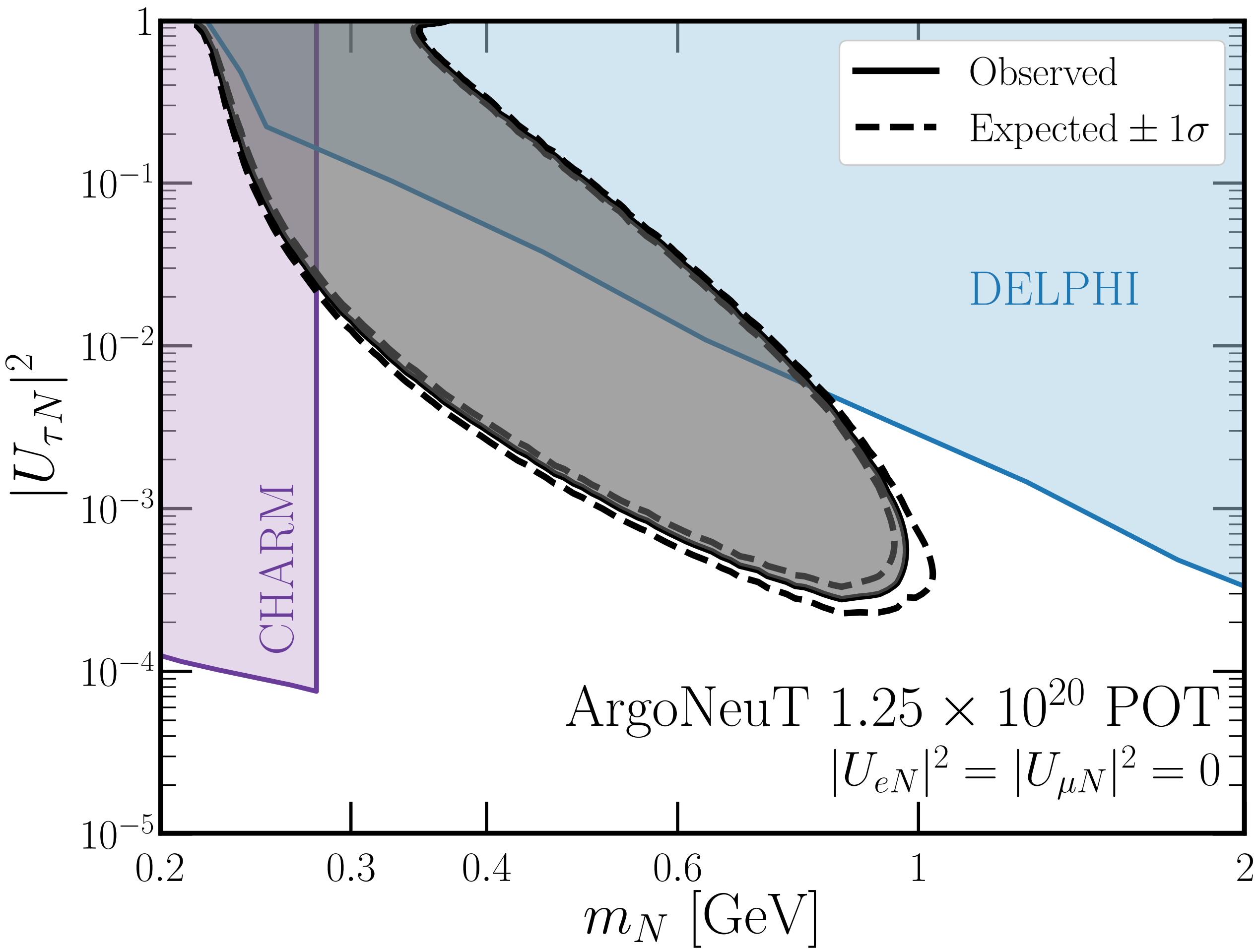
- lead analyzer: P. Green
- theorists: K. Kelly, A. de Gouvêa

HNL search results:

- 0 events observed in data, consistent with background expectation
- exclude large region of unexplored parameter space of tau-coupled HNLs at 90% CL

First search for tau-coupled HNLs in a LArTPC:

- Phys. Rev. Lett. 127, 121801 (2021) (ArgoNeuT + Theory)



Axion search results

ArgoNeuT heavy QCD axion search:

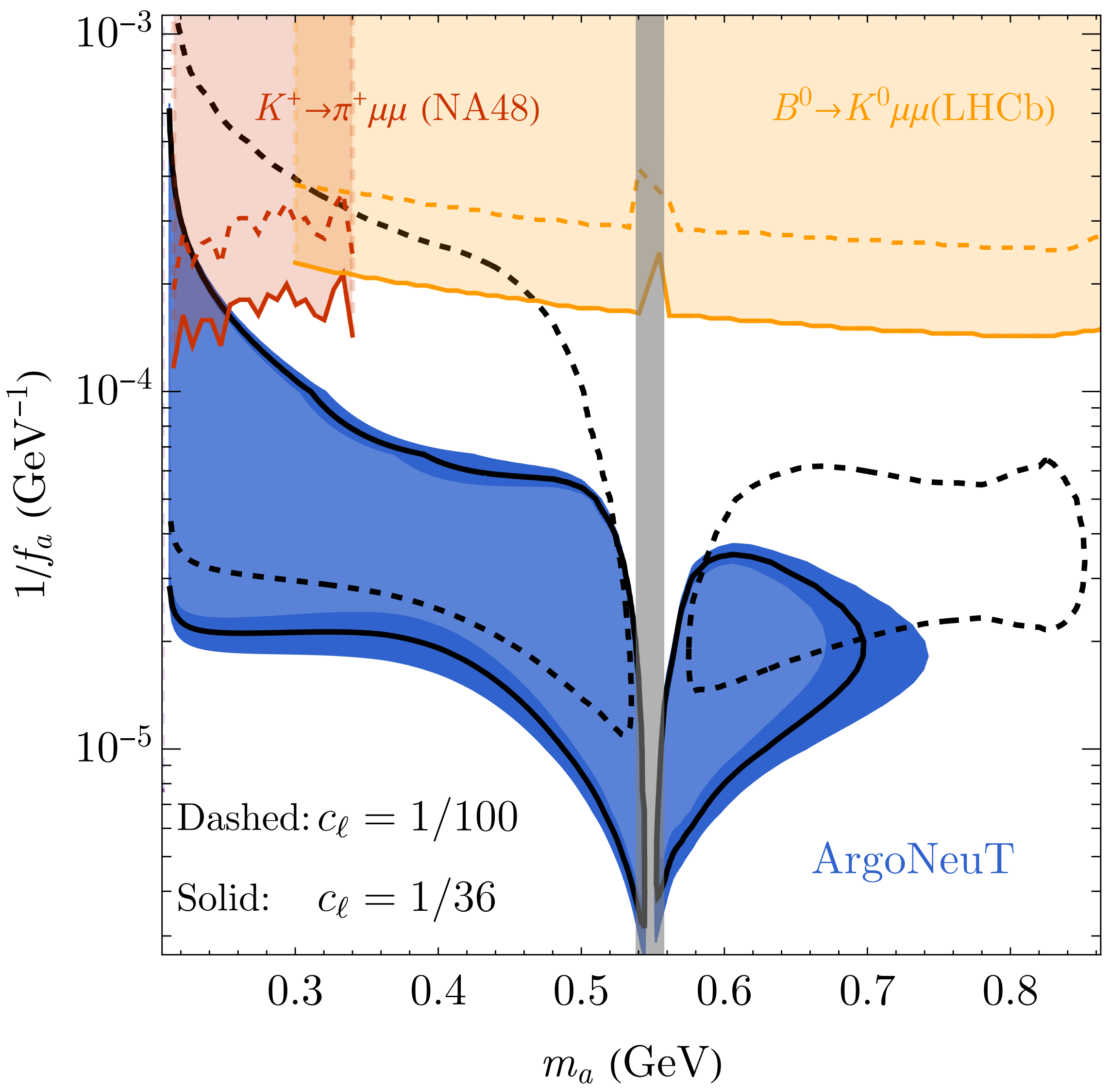
- lead analyzer: P. Green
- theorists: R. Co, R. Harnik, K. Kelly, S. Kumar, Z. Liu, K. Lyu

Axion search results:

- 0 events observed in data, consistent with background expectation
- exclude large region of unexplored parameter space at 95% CL, evaluated at two benchmark axion-lepton couplings

First search for heavy QCD axions in a LArTPC

- Phys. Rev. Lett. 130, 221802 (2023) (ArgoNeuT + Theory)



Conclusions

ArgoNeuT has performed multiple recent searches for long-lived BSM particles:

- millicharged particles: Phys. Rev. Lett. 124 131801 (2020)
- heavy neutral leptons: Phys. Rev. Lett. 127, 121801 (2021)
- heavy QCD axions: Phys. Rev. Lett. 130, 221802 (2023)

First searches of their kind in LArTPC neutrino detectors:

- developed techniques to select new signatures
- set world-leading constraints

All three analyses performed working directly with theorists:

- close collaboration between experiment and theory key to success

Backups

Electron and muon-coupled HNLs

ArgoNeuT can also apply constraints to electron- and muon-coupled HNL models:

- significantly less sensitive to these scenarios, N ⟶ ν $\mu^+ \mu^-$ subdominant channel