Improved constraints on Heavy Neutral Leptons and Heavy QCD Axions from the ArgoNeuT Experiment

Patrick Green, on behalf of the ArgoNeuT collaboration

In collaboration with A. de Gouvêa and K. Kelly (HNL search)
R. Co, R. Harnik, K. Kelly, S. Kumar, Z. Liu, and K. Lyu (Axion search)

Phys. Rev. Lett.
127, 121801 (2021)
[arXiv: 2106.13684]

arXiv: 2207.08448

Introduction

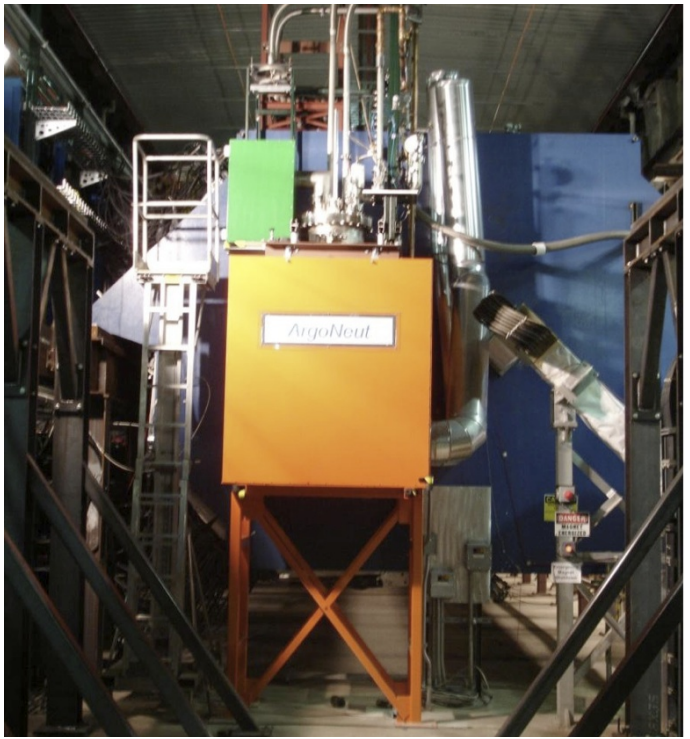
Heavy neutral leptons and heavy QCD axions are both proposed extensions to the Standard Model:

- provide possible explanations for various unresolved puzzles
- heavy neutral leptons: neutrino mass, dark matter…
- heavy QCD axions: strong CP problem, axion quality problem…

Could be produced in neutrino beams, and their decays searched for in neutrino detectors:

- such as the ArgoNeuT detector

This talk will present searches for heavy neutral leptons and heavy QCD axions performed with the ArgoNeuT experiment



- The ArgoNeuT experiment
- Models, production and decay
- Simulation and signature
- Selection
- Backgrounds and systematics
- Results

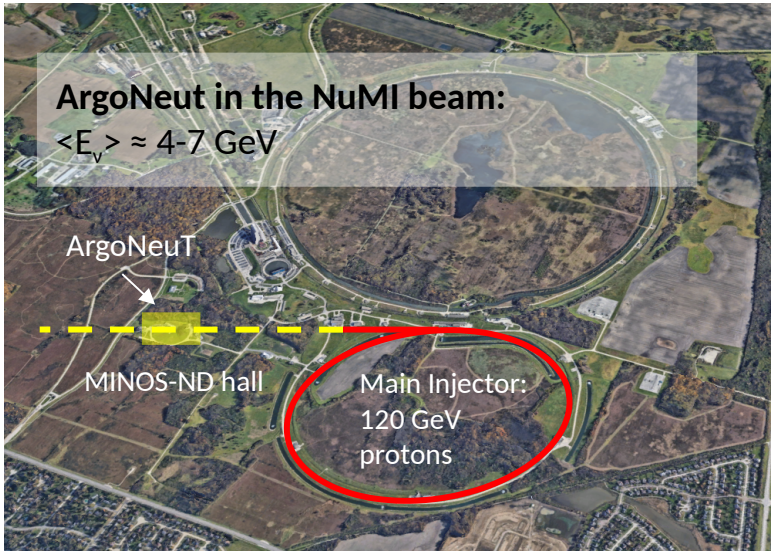
The ArgoNeuT experiment

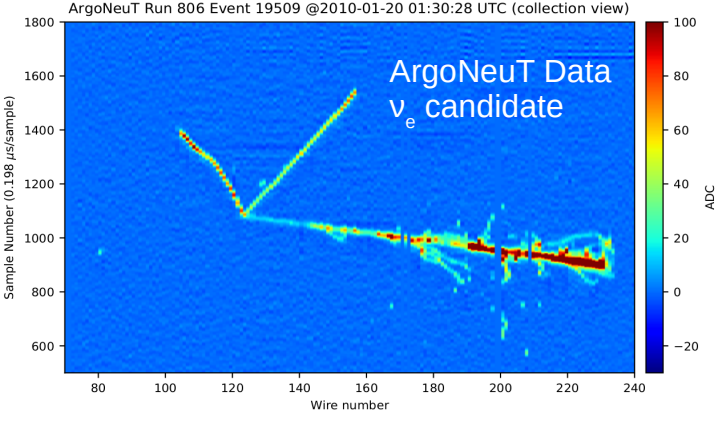
First Liquid Argon Time Projection Chamber (LArTPC) in a neutrino beam in the US:

- located along the NuMI beam, ~1km from the beam target
- collected data 2009-2010, ~4.5 month run
- 1.25e20 POT, ~7000 neutrino interactions

Designed as a test experiment… but producing physics results:

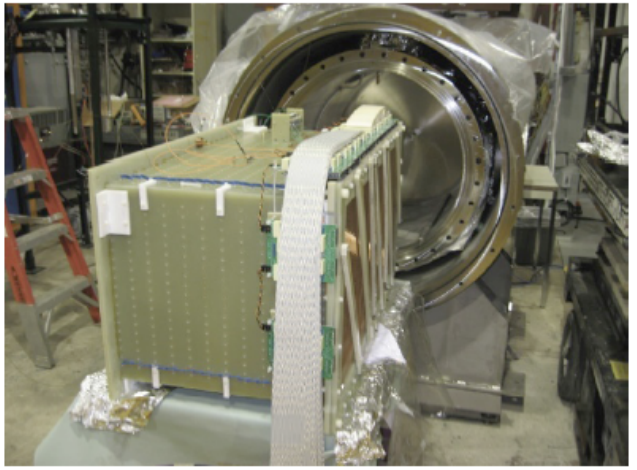
- several first ν-Ar cross-section measurements
- BSM searches: millicharged particles, heavy neutral leptons, heavy QCD axions
- along with extensive detector R&D





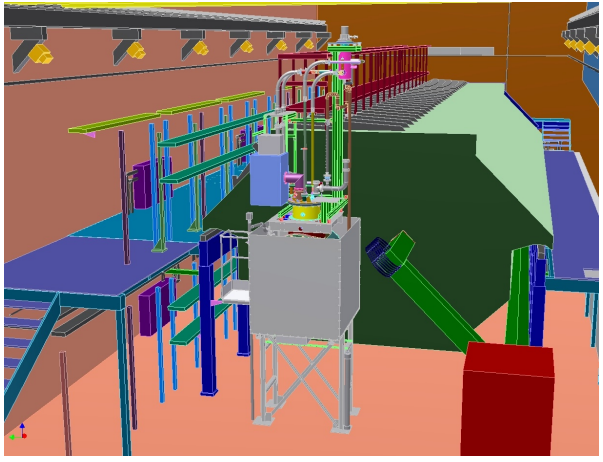
R. Acciarri et al., Phys. Rev. D 102 (2020) 1, 011101

The ArgoNeuT detector



0.24 ton LArTPC:

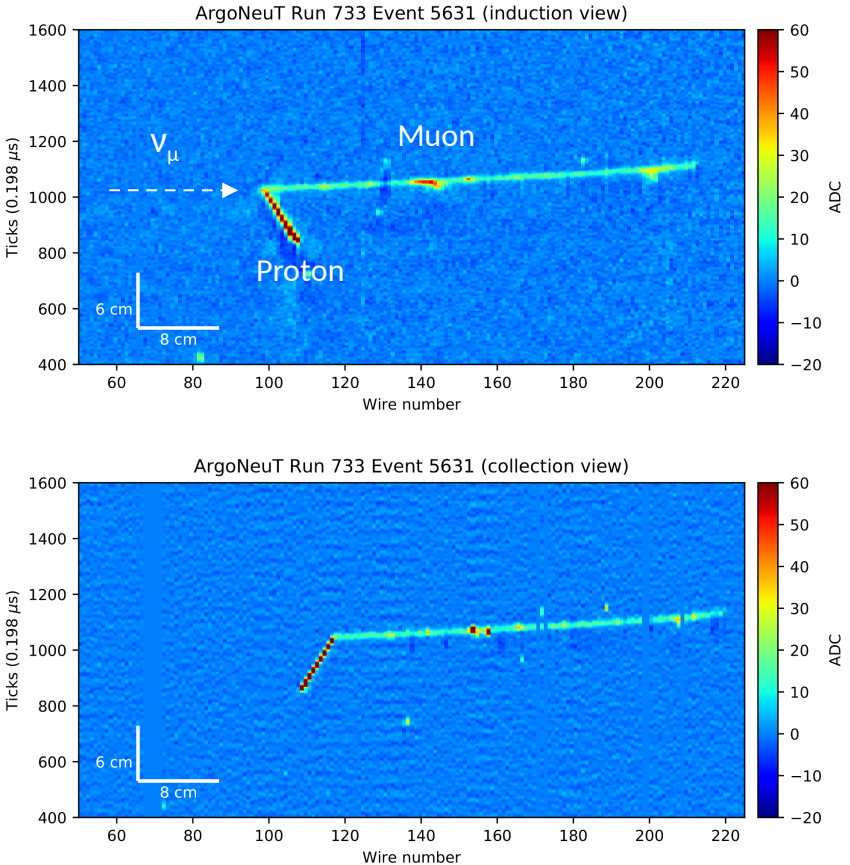
- 40(h)x47(w)x90(l) cm^3 instrumented volume
- two wire planes collect drifted ionisation charge
- 4mm wire spacing



Upstream of the MINOS near detector:

- large magnetised steel and scintillator strip spectrometer
- used to identify muons – tracks exiting ArgoNeuT are matched with tracks reconstructed in the MINOS-ND

LArTPC technology: 3D imaging and calorimetry



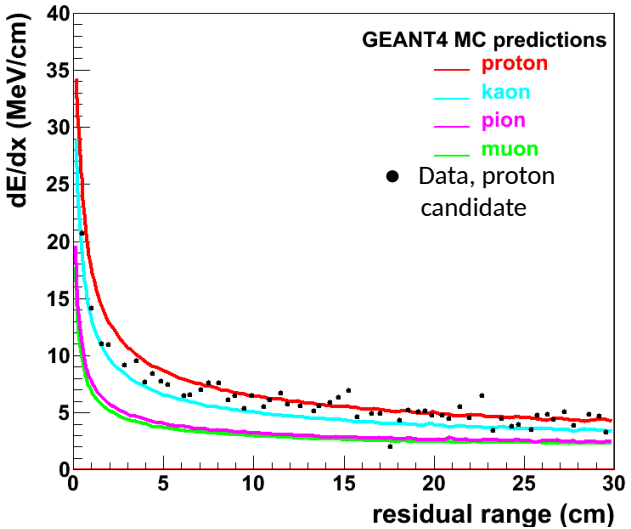
Two 2D views, with ~4 mm scale resolution

–> 3D Track/Shower reconstruction

Total charge proportional to the deposited energy

–> Calorimetry

Particle identification based on dE/dx:



ArgoNeuT
JINST 7 P10019
(2012)

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Heavy neutral lepton and heavy QCD axion models

Heavy neutral lepton (HNL) model:

- simple extension to SM introducing a HNL, N
- mass m_N ~ 100 MeV – 1 GeV and mixes with SM neutrinos via new non-zero mixing angle
- consider tau-coupled scenario, i.e. $|U_{\tau N}|^2 \neq 0$ and $|U_{eN}|^2 = |U_{\mu N}|^2 = 0$

P. Coloma et al. Eur. Phys. J. C, 81(1):78, 2021

Heavy QCD axion model:

- introduce heavy QCD axion, a
- consider couplings with gluons + other SM gauge bosons and leptons
- mass m_a ~ 100 MeV – 1 GeV and mixing angle θ_a with the SM neutral pseudoscalar mesons

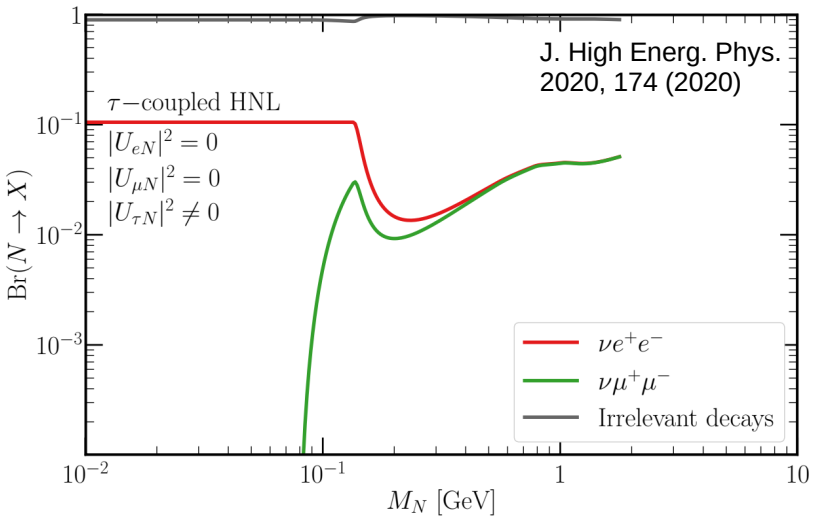
K. Kelly, S. Kumar and Z. Liu Phys. Rev. D 103 (2021) 9, 095002

Very different models... but can produce similar decay signatures in ArgoNeuT

Decay modes

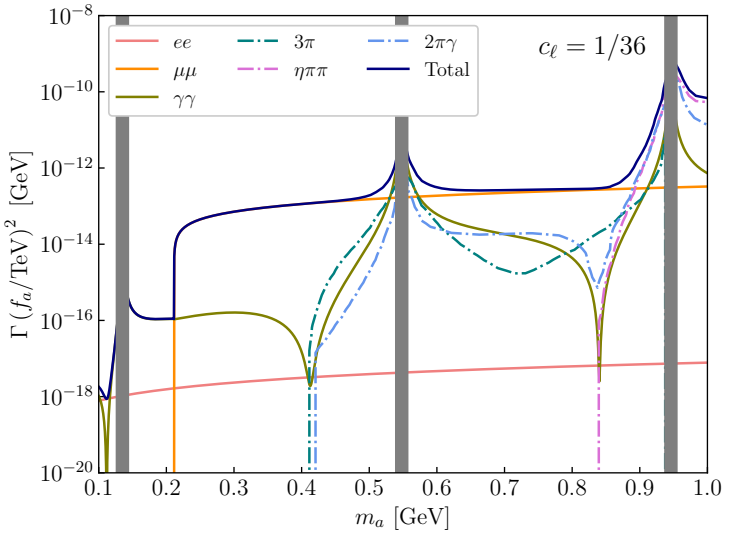
Heavy neutral leptons (tau-coupled):

- decay to νee and νμμ + various non-detectable channels such as ννν
- in ArgoNeuT search for: $N \rightarrow \nu_\tau + \mu^+ + \mu^-$



Heavy QCD axions:

- decay to ee, μμ, γγ + hadronic modes
- contributions depend on axion-lepton coupling, c_l: two benchmark scenarios $c_l = 1/36$ and $c_l = 1/100$
- in ArgoNeuT search for: $a \rightarrow \mu^+ + \mu^-$



Production in the NuMI beam

Heavy neutral leptons:

- proton—fixed-target collisions produce flux of D and D_s mesons
- D / D_s decay to τ leptons, then subsequently decay to tau-coupled HNLs

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

$$\tau^{+/-} \rightarrow N + X^{+/-}$$

where $X^{+/-}$ are SM particles e.g. $\pi^{+/-}$

Heavy QCD axions

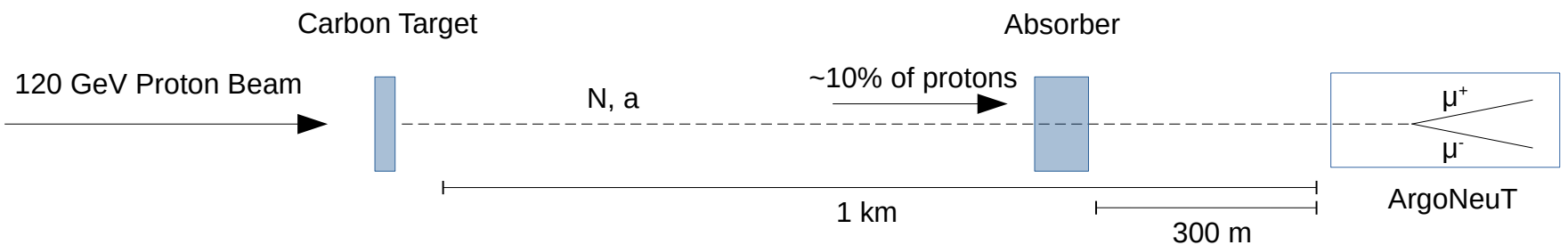
- proton—fixed-target collisions produce flux of π^0, η and η' mesons
- non-zero mixing angle, θ_{aM}, results in flux of axions

$$\theta_{aM} = \frac{f_\pi}{f_a} \frac{C_{aM}}{m_a^2 - m_M^2}$$

where $M = \pi, \eta, \eta'$

Mass range ~100 MeV – 1 GeV

~10% of protons reach the NuMI absorber, where production also occurs



Why perform these searches with ArgoNeuT?

Exposed to high-energy 120 GeV NuMI beam:

- enables production of heavy neutral leptons and heavy QCD axions with masses up to approximately the 1 GeV scale

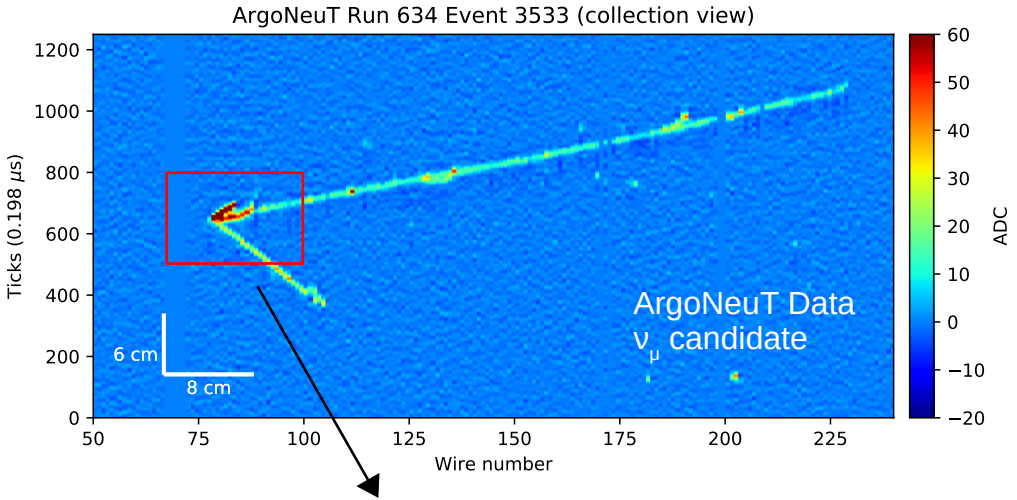
LArTPC detector technology:

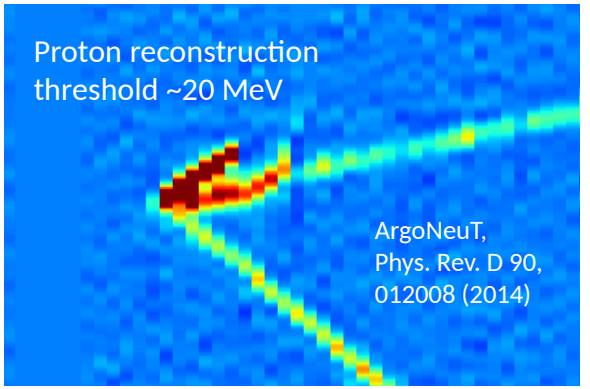
- excellent vertex identification and reconstruction of low energy particles
- allows identification and removal of backgrounds

Upstream of the MINOS near detector:

- magnetic field allows muon charge reconstruction
- aids distinguishing pions and muons, difficult in LArTPCs

Ideal combination of detectors to search for $\mu^+ \mu^-$ signature





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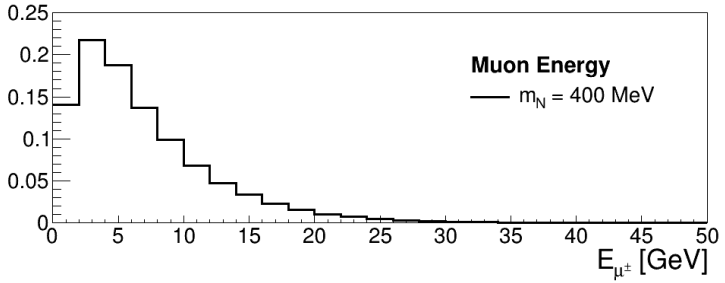
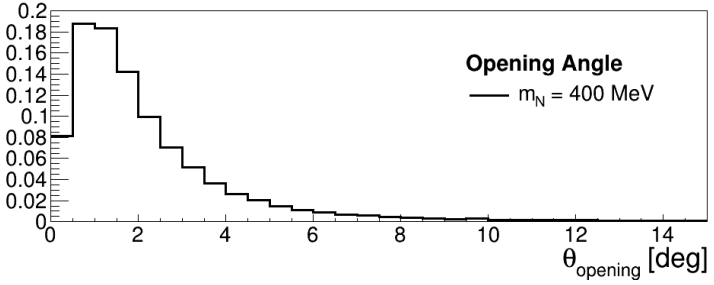
HNL and axion simulation

Dedicated simulations performed for both heavy neutral leptons and heavy QCD axions:

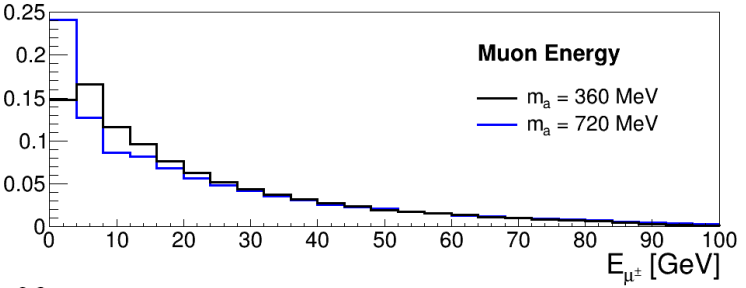
- production using pythia8 + standard ArgoNeuT and MINOS simulation and reconstruction chains
- resulting muons energetic and highly forward-going – may be reconstructed as overlapping in ArgoNeuT

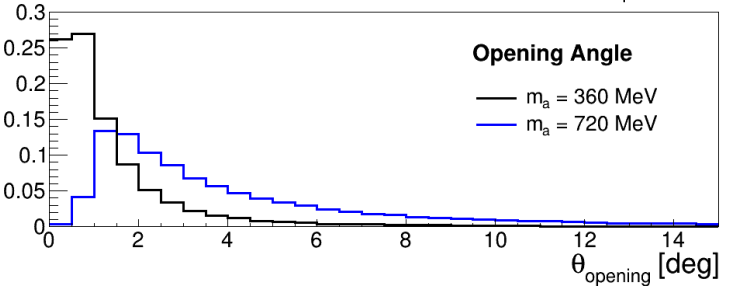
Heavy neutral leptons





Heavy QCD axions



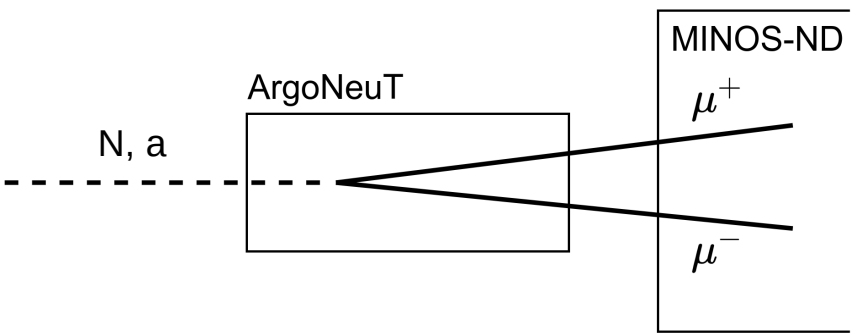


Signatures in ArgoNeuT

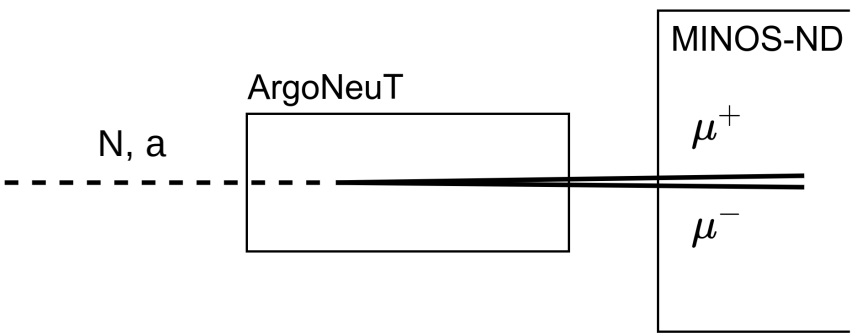
Consider two different signatures, depending on how forward going the muons are:

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

Two-track Event



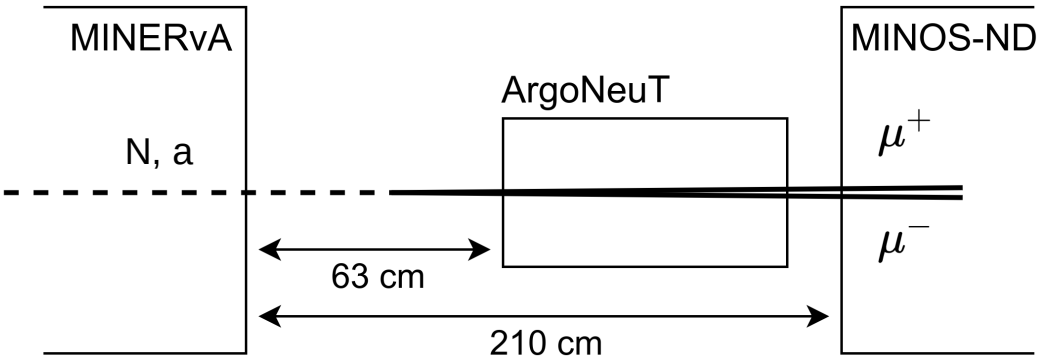
Double-MIP Event



Decays in the cavern upstream of ArgoNeuT

Also consider decays occurring in the cavern upstream of ArgoNeuT:

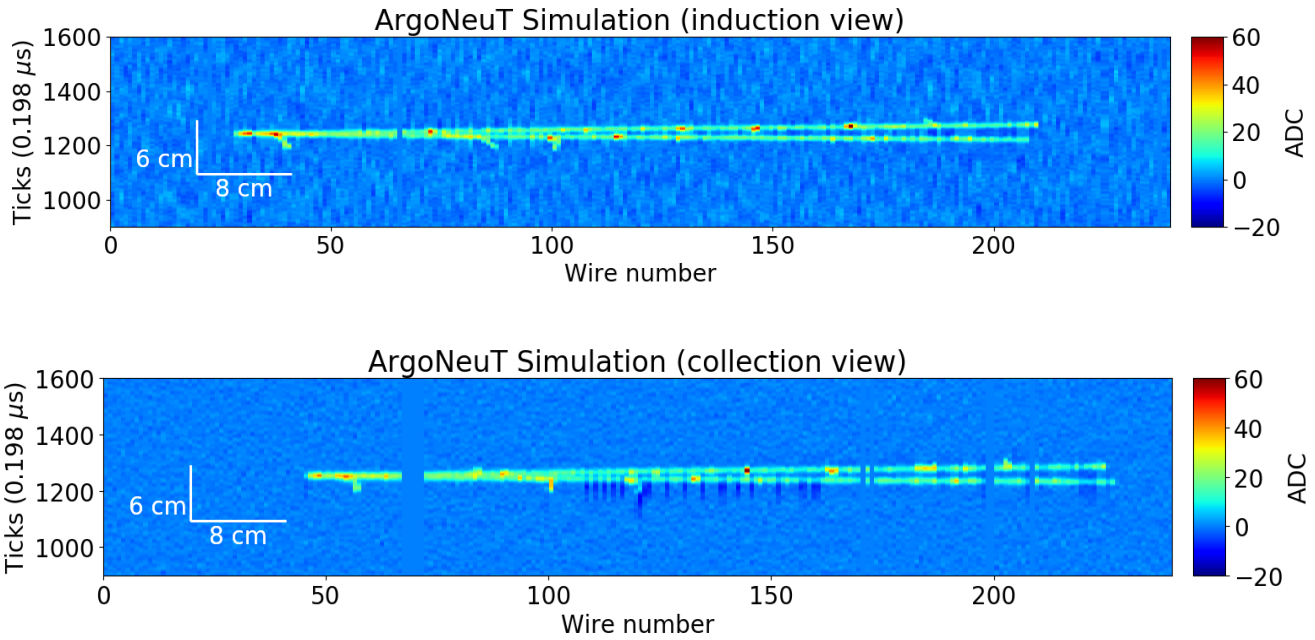
- region between ArgoNeuT and end of MINERvA detector (under construction during ArgoNeuT running)
- select double-MIP signature only, distinct from background neutrino-induced muons

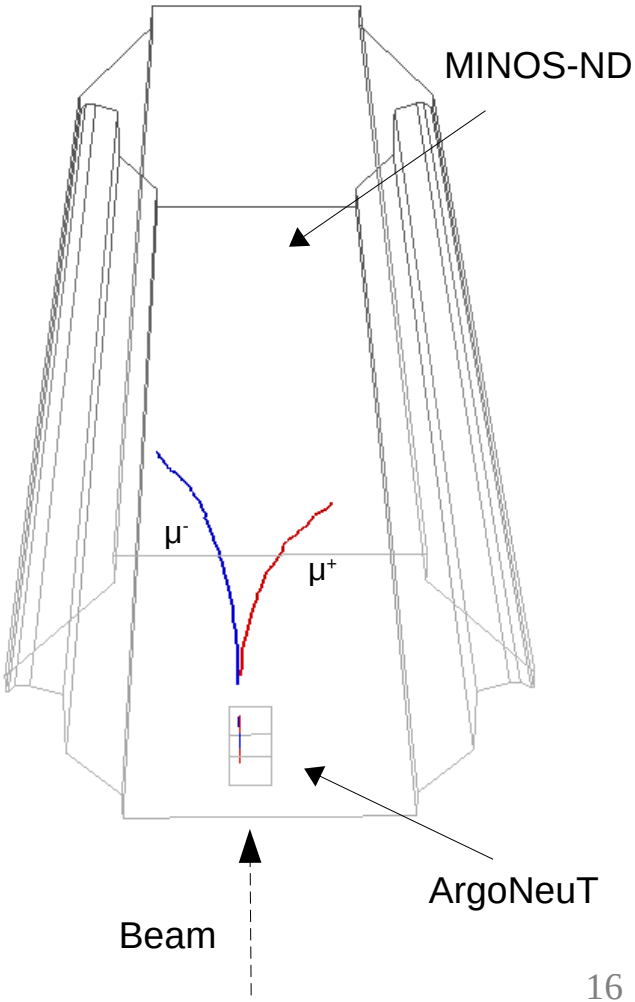


Simulated decay: two-track topology

Example simulated *two-track* signature event:

- two distinct muon tracks in ArgoNeuT that match to MINOS-ND

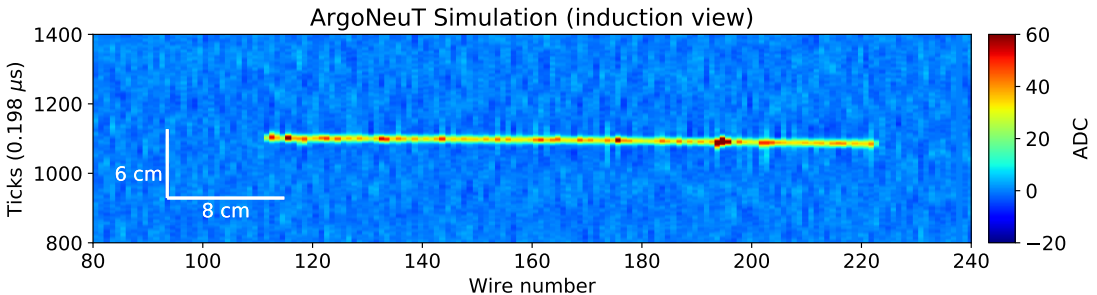


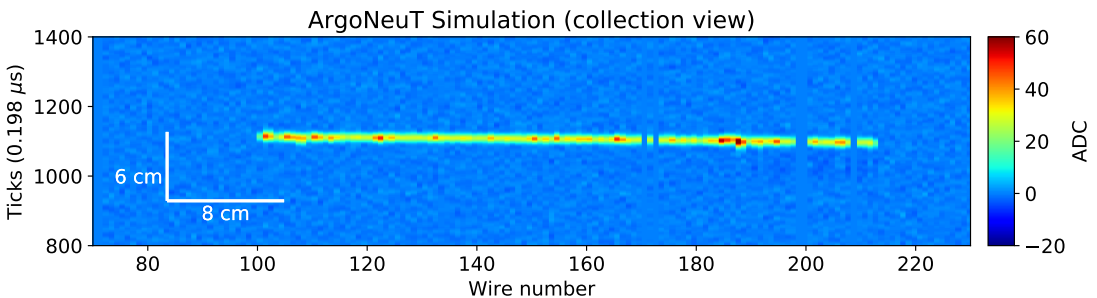


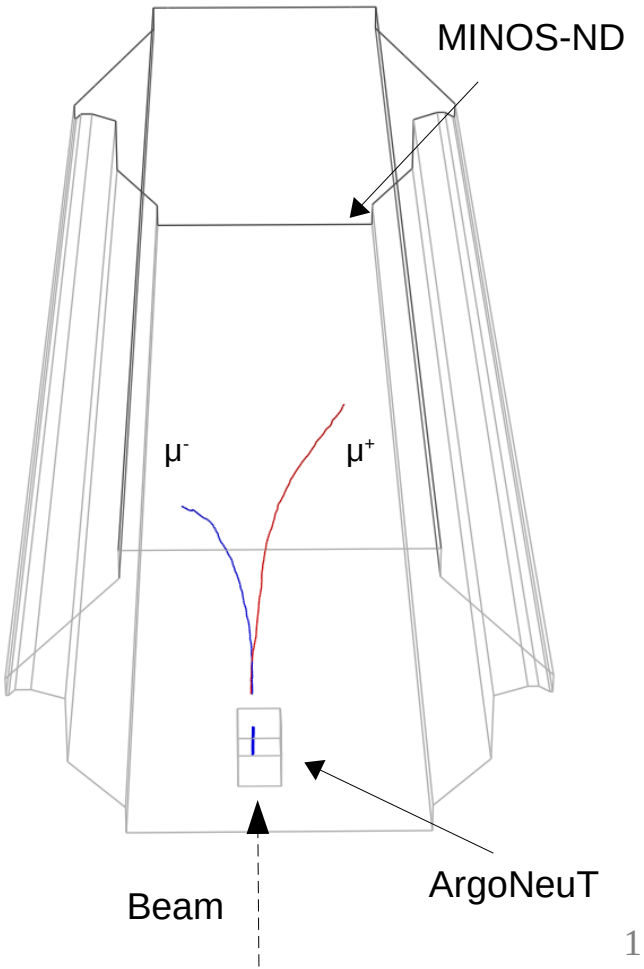
Simulated decay: double-MIP topology

Example simulated *double-MIP* signature event:

- single track in ArgoNeuT that matches to two tracks in MINOS-ND







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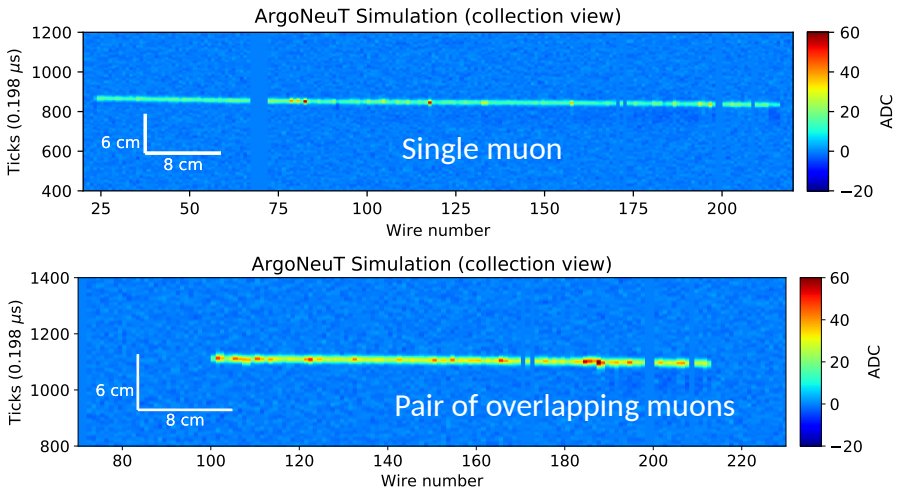
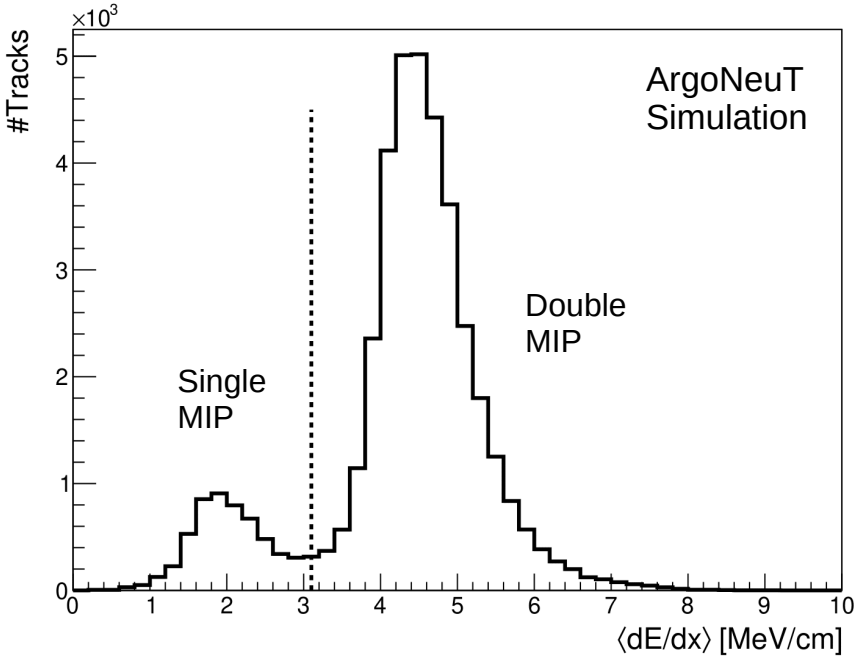
Identifying overlapping muon pairs

Strongest identifier of whether overlapping muons are present provided by the *dE/dx*:

- minimally ionising particle dE/dx ~ 2 MeV/cm
- overlapping muons ~2 x MIP dE/dx

MIP and double-MIP tracks easily distinguishable





Selection in ArgoNeuT

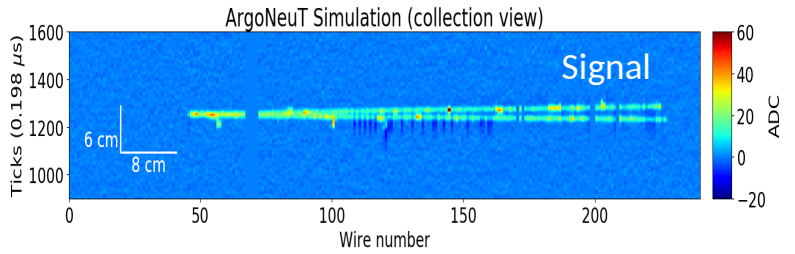
Two-track signature:

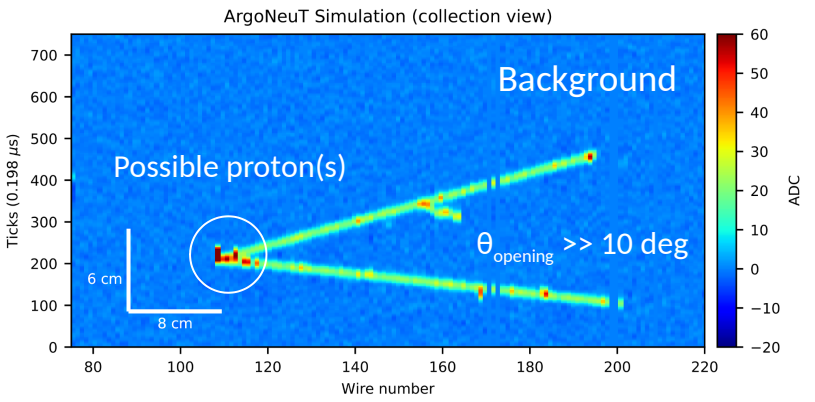
- two tracks that originate from a common vertex within fiducial volume + exit towards MINOS-ND
- both tracks have mean *dE/dx* < 3.1 MeV/cm
- small opening angle between them

Double-MIP signature:

- *dE/dx* > 3.1 MeV/cm over first 5 cm of track
- small angle with respect to the beam direction

Selections tuned using simulation for each model





MINOS-ND matching

MINOS-ND matching:

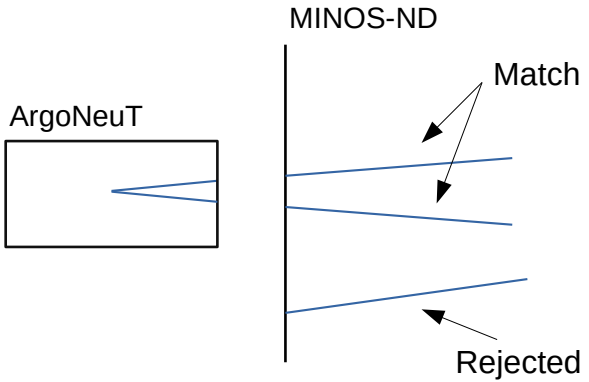
- each ArgoNeuT track projected to start of MINOS-ND
- position and angular offset to each MINOS-ND track calculated, matches if within tolerance

Selection in MINOS-ND:

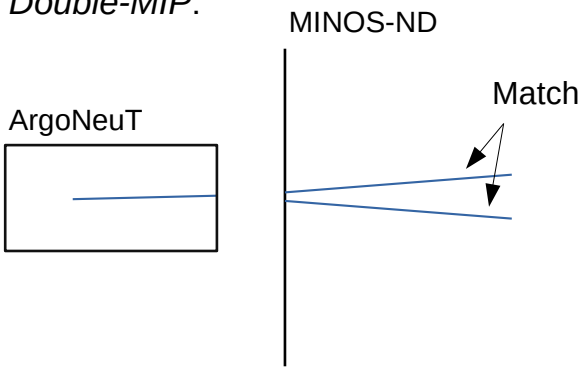
- tracks in-time, $|\Delta t_0| < 20$ ns
- tracks reconstructed with opposite charges
- both tracks muon-like: track length and MIP dE/dx

As before, selections tuned using simulation for each model

Two track:



Double-MIP:

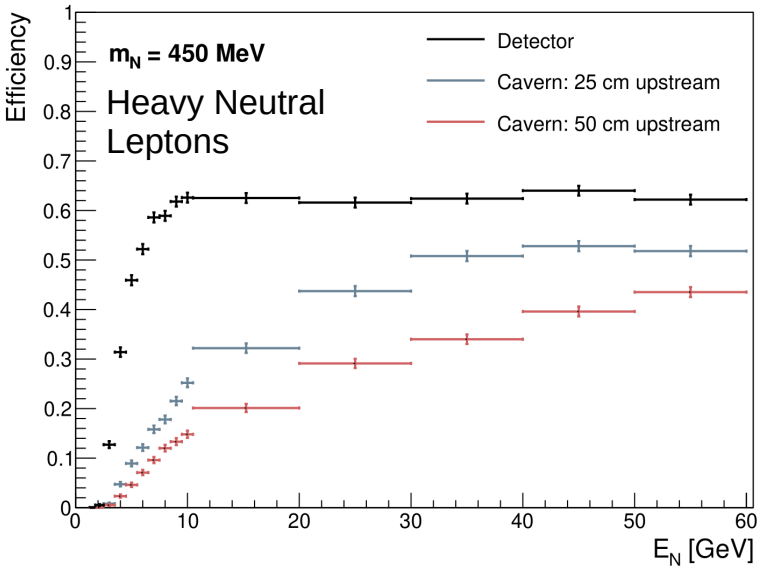


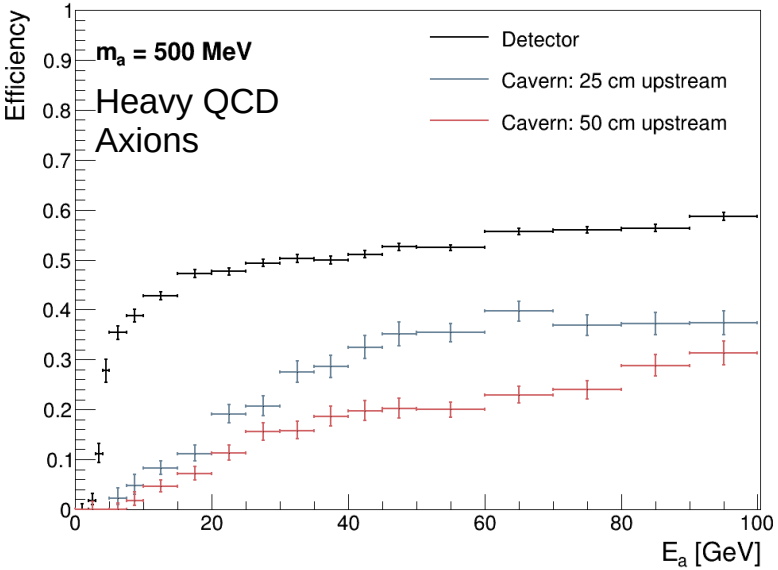
Selection efficiency

Decays-inside-detector efficiencies:

- ~50-60% at high energies, slightly lower in axion case
- sharp decline at lower energies, muons have insufficient energy to reach the MINOS-ND

Decays-inside-cavern efficiencies lower – only select most forward-going muon pairs





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Background expectation

Background simulation:

- GENIE neutrino generator (detector and cryostat)
- data-driven model of through-going muons

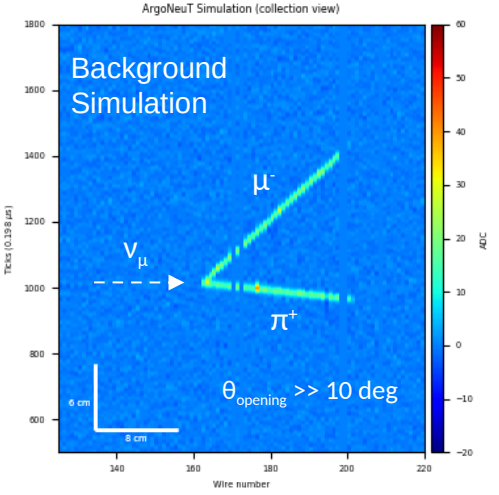
Dominant source of background:

- ν_μ interactions with minimal additional vertex activity and/or incorrectly matched additional neutrino-induced through-going muons in MINOS-ND

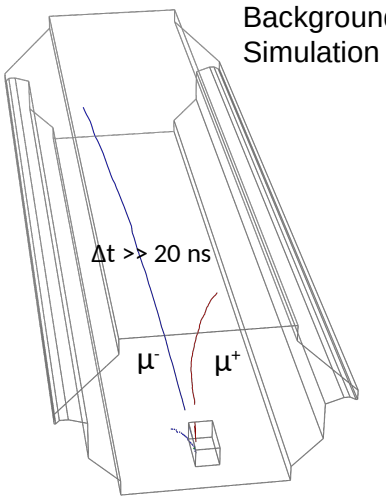
Typically topologically distinct and/or matched to out-of-time tracks in MINOS-ND – can be removed

Total background expectation small – very clean signature:

Model	Predicted Events
Heavy Neutral Leptons	0.4 ± 0.2
Heavy QCD Axions	0.1 ± 0.1



Topologically distinct, opening angle too large



Matched muon tracks out of time, from different interactions/decays

Systematic uncertainties

Heavy neutral leptons:

- dominated by uncertainty in HNL flux
- due to uncertainty in D / D_s production + uncertainty on branching ratio to τ leptons

Systematic Uncertainty	Impact [%]
HNL flux	20.8
Reconstruction effects	0.5
Selection efficiency	3.3
Instrumented volume	2.2
POT counting	1.0
Total	21.2

Heavy QCD axions:

- dominated by uncertainty in axion flux
- primarily due to theoretical uncertainties arising from QCD calculations
- depends on the coupling strengths chosen

Systematic Uncertainty	Impact [%]
Axion flux	~30
Reconstruction effects	0.5
Selection efficiency	3.3
Instrumented volume	2.2
POT counting	1.0
Total	~30.3

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Applying to data

Selections applied to ArgoNeuT data-set:

- 1.25e20 POT, anti-neutrino mode beam

0 events observed in data

- consistent with background expectations

Allows exclusion constraints to be set...

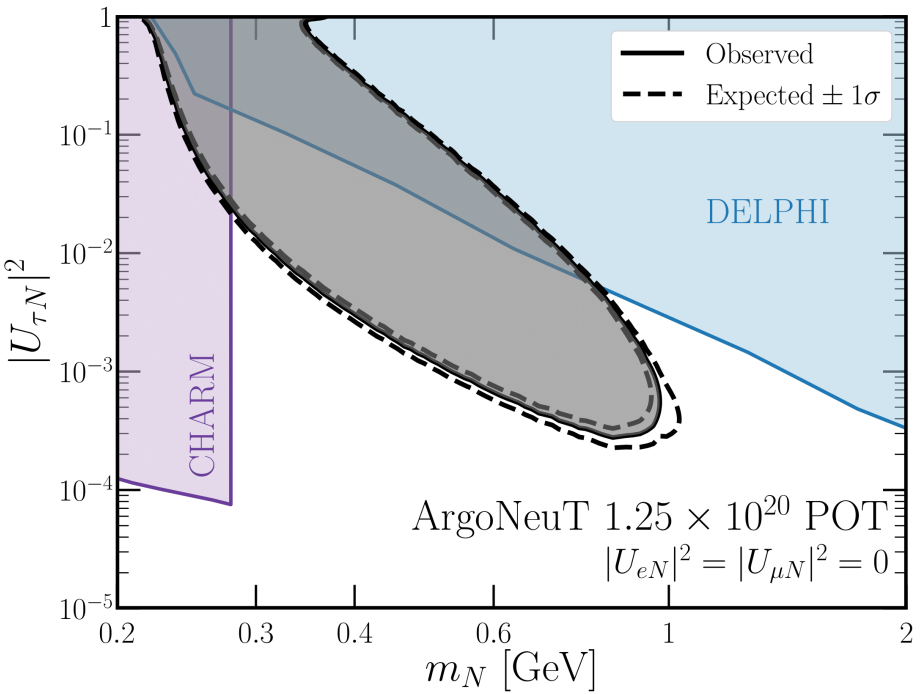
Heavy neutral leptons

ArgoNeuT HNL constraint:

- region of parameter space excluded at 90% CL (solid black line, gray shaded region)
- uncertainty on expected constraint (dashed line)

Existing limits from CHARM (purple) and DELPHI (blue) also shown

Set new exclusion constraint on tau-coupled HNLs with masses m_N = 280 – 970 MeV



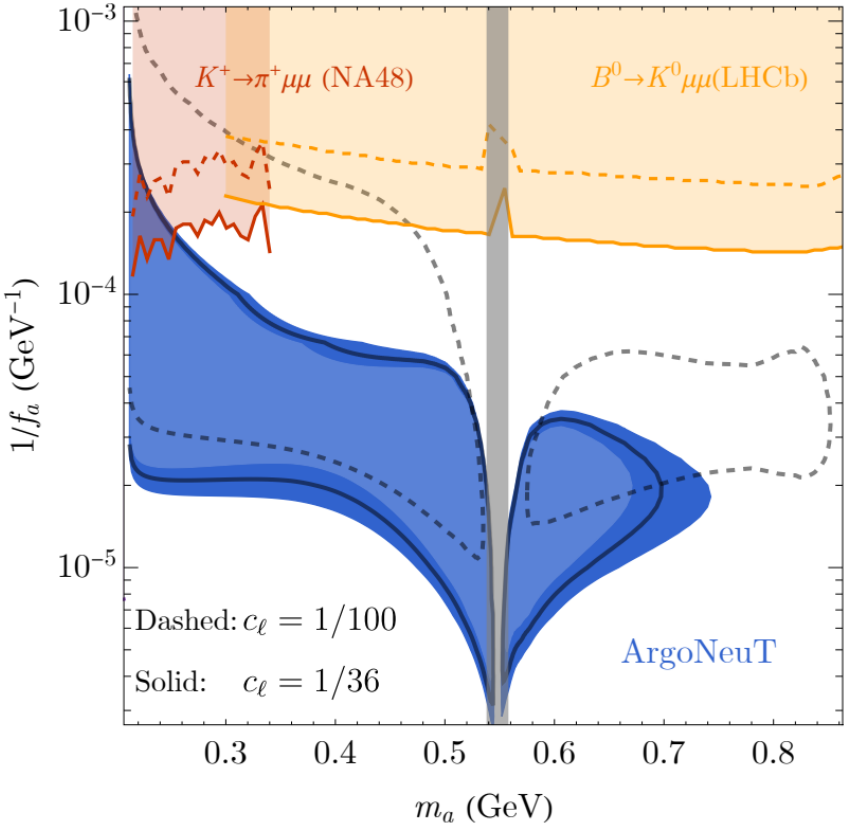
Heavy QCD axions

ArgoNeuT heavy QCD axion constraint:

- 95% CL exclusion constraints for c_l = 1/36 (solid contour, blue shaded region) and c_l = 1/100 (dashed contour)
- uncertainty on expected constraint shown for c_l = 1/36 (dark blue shaded region)

Existing limits re-cast from NA48 (red) and LHCb (orange) for both benchmark models

Set new exclusion constraints for heavy QCD axions with m_a ~ 0.2 – 0.9 GeV and axion decay constant f_a ~ 10 TeV



Summary and conclusions

Searches for heavy neutral leptons and heavy QCD axions have been performed using the ArgoNeuT detector:

- produced in NuMI neutrino beam from $\tau^{\pm}$ decay (HNLs) and meson-mixing (axions)
- heavy neutral lepton decay signature: $N \rightarrow \nu\ \mu^+\ \mu^-$
- heavy QCD axion decay signature: $a \rightarrow \mu^+\ \mu^-$

Observe 0 events in ArgoNeuT data, allowing new exclusion constraints to be set:

- tau-coupled heavy neutral leptons: m_N = 280 – 970 MeV
- heavy QCD axions: m_a = 0.2 – 0.9 GeV, with f_a ~ 10 TeV

First searches for each of these models in LArTPC neutrino detectors:

- techniques developed could be employed in future searches using LArTPC detectors, e.g. DUNE

Heavy neutral lepton search: Phys. Rev. Lett. 127, 121801 (2021) [arXiv: 2106.13684]

Heavy QCD axion search: arXiv: 2207.08448

Back-up

Heavy Neutral Lepton and Heavy QCD Axion energies

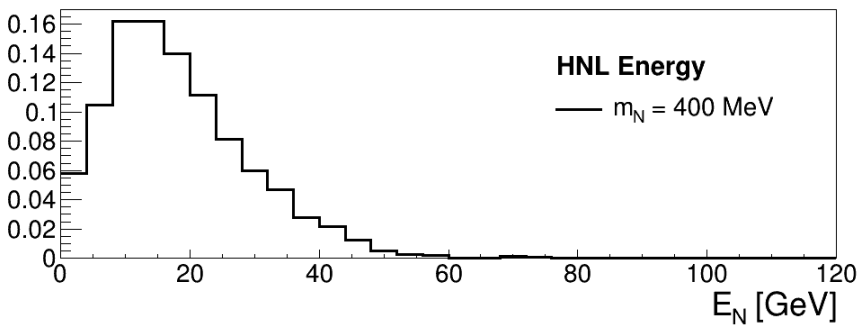
Tau-coupled Heavy Neutral Leptons:

- average energy ~ 20 GeV, produced up to around 60 GeV

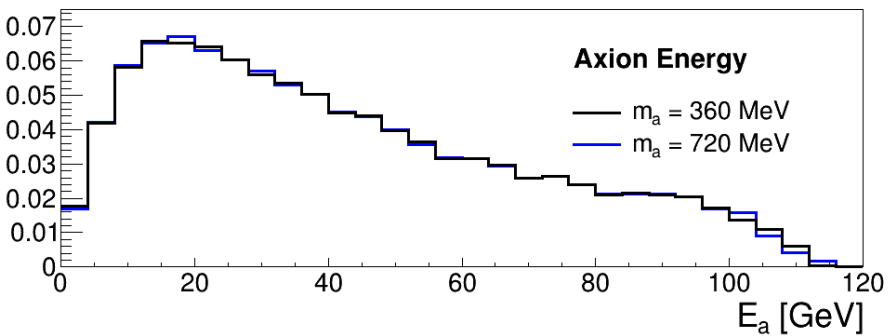
Heavy QCD Axions:

- average energy ~ 40 GeV, production possible up to nearly beam energy

Heavy Neutral Leptons



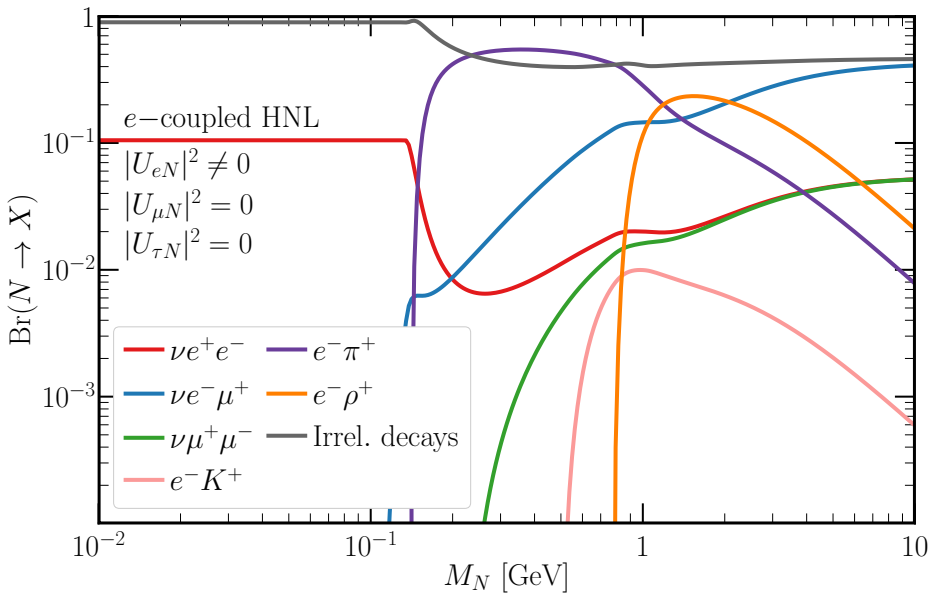
Heavy QCD Axions

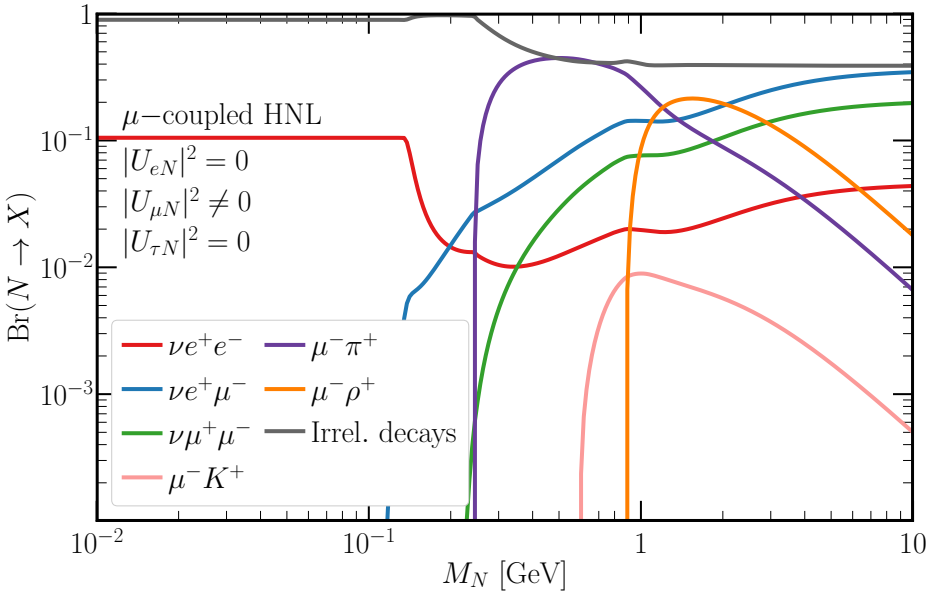


Electron/muon-coupled HNLs: branching ratios

HNL scenarios where $|U_{eN}|^2 \neq 0$ or $|U_{\mu N}|^2 \neq 0$, in each case assuming mixing to the other flavors is zero

Dimuon channel subdominant to eπ (electron-coupled) and μπ (muon-coupled) in mass range of interest – ArgoNeuT has less sensitivity to these scenarios



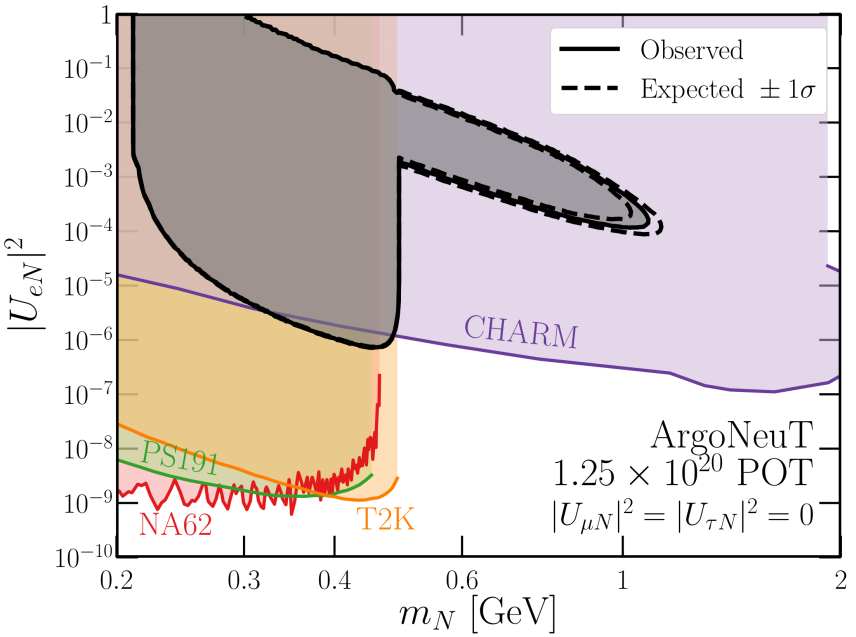


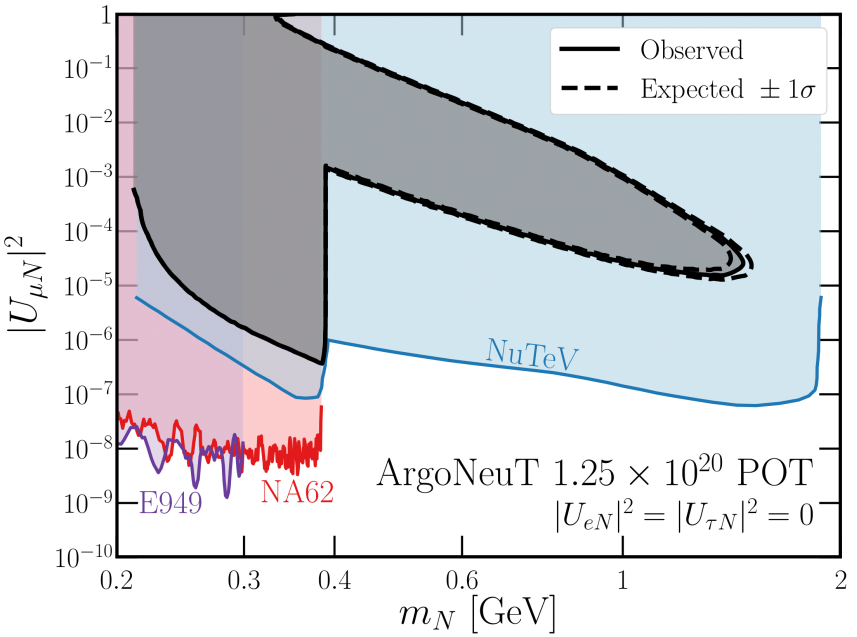
Electron/muon-coupled HNLs: sensitivity

HNL scenarios where $|U_{eN}|^2 \neq 0$ or $|U_{\mu N}|^2 \neq 0$, in each case assuming mixing to the other flavors is zero

Parameter space excluded at 90% CL (solid black line)

ArgoNeuT sensitivity to these models is significantly poorer than existing limits

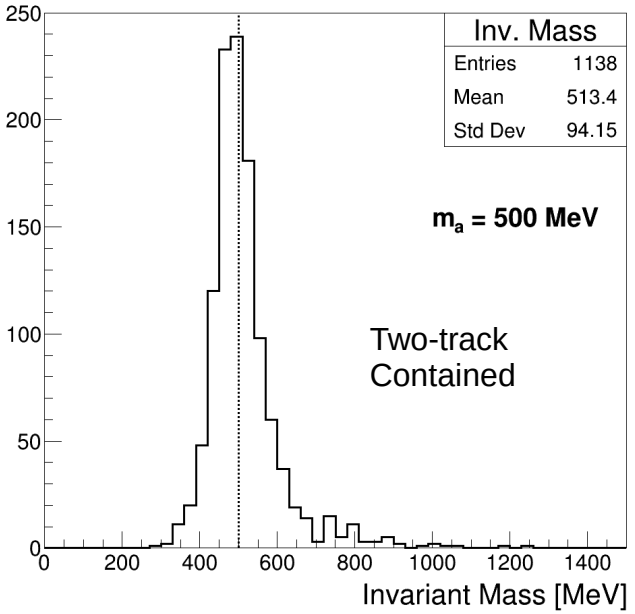


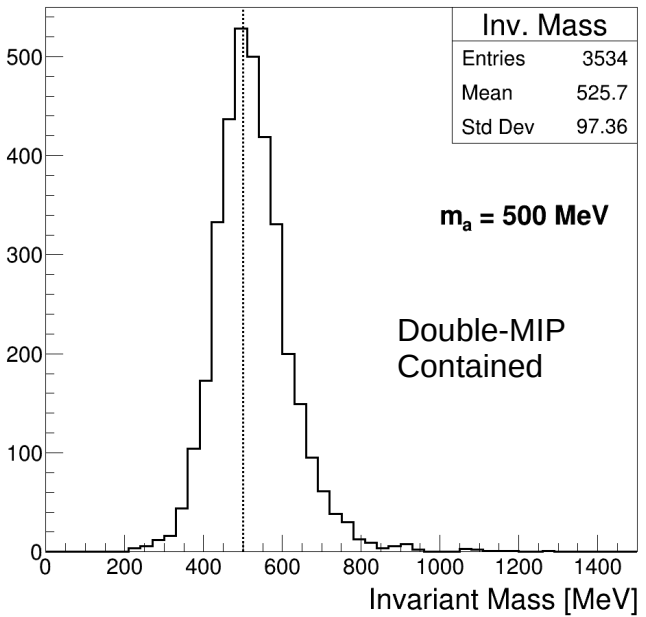


Heavy QCD Axion invariant mass

Heavy QCD Axion decay two-body – invariant mass could provide powerful tool if signal observed:

- muon trajectories reconstructed in ArgoNeuT and momentum in the MINOS-ND
- axion invariant mass resolution: ~100 MeV contained in MINOS-ND, ~200 MeV exiting MINOS-ND

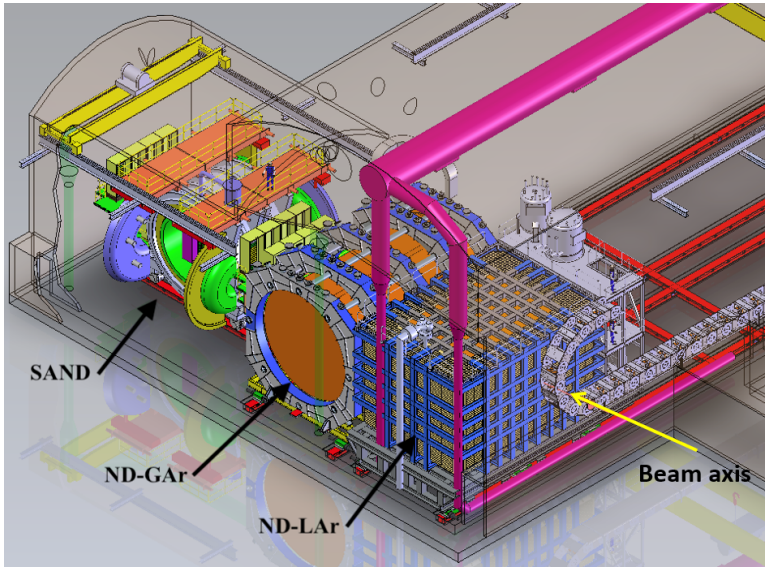


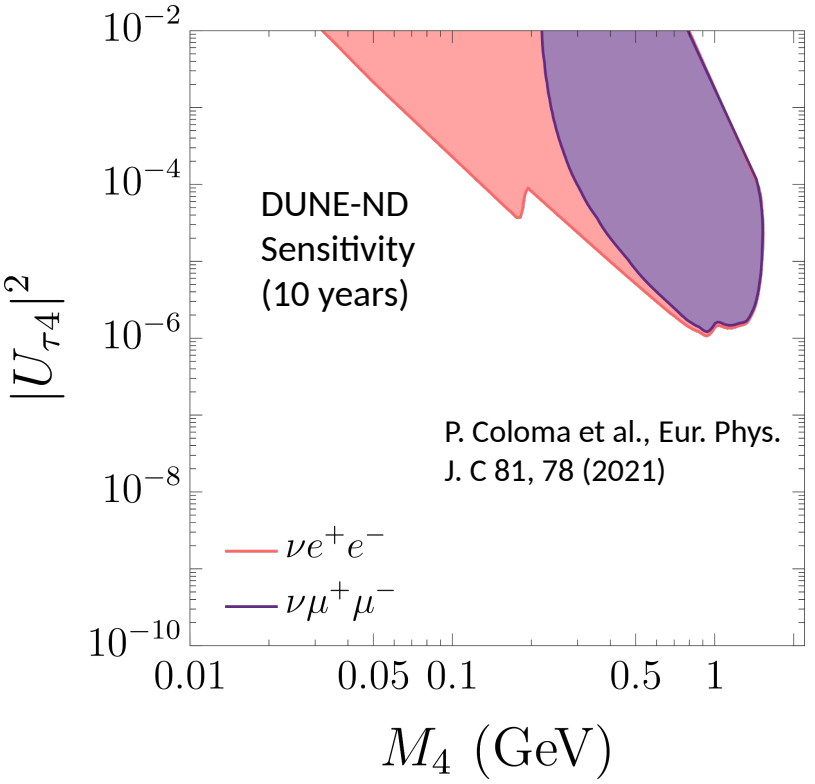


Future searches for tau-coupled HNLs in LArTPCs

DUNE near detector:

- sensitive to large region of unexplored phase space
- modular LArTPC and magnetised GArTPC -- could employ similar techniques to search for μ+ μ-





Future searches for heavy QCD axions in LArTPCs

DUNE near detector also sensitive to heavy axions:

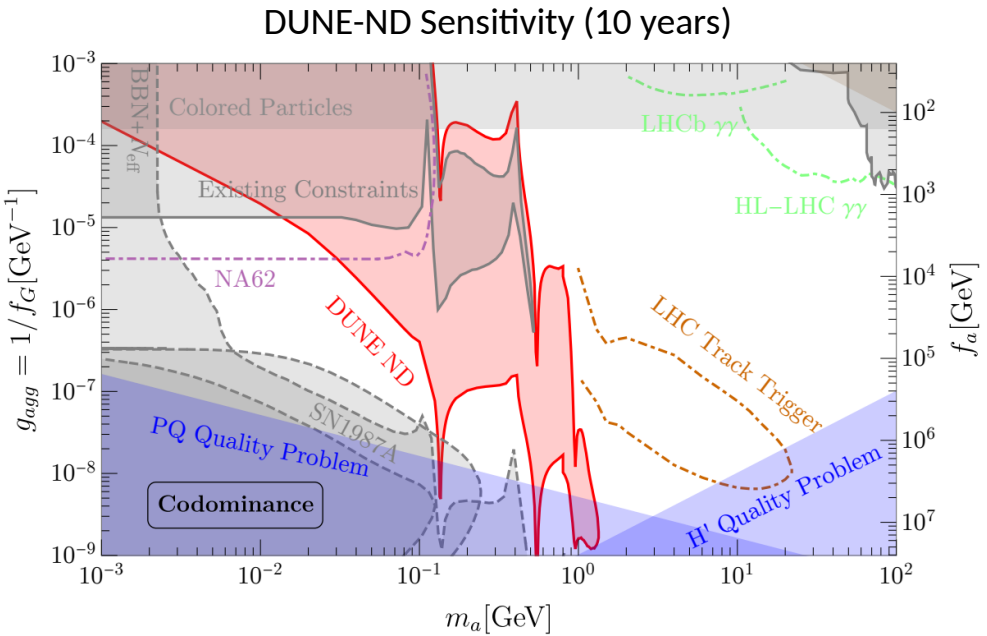
- able to probe large region of parameter space

SBN detectors (SBND, MicroBooNE, ICARUS):

- either using off-axis NuMI beam, or could be sensitive to lower masses using 8 GeV BNB beam

Other “axion-like” models also been considered:

- ArgoNeuT ALPs – arXiv: 2202.12317 (re-cast)
- MicroBooNE ALPs – arXiv: 2202.03447 (re-cast)



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