First constraints on Heavy QCD Axions with a Liquid Argon Time Projection Chamber using the ArgoNeuT experiment

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In collaboration with R. Co, R. Harnik, K. Kelly, S. Kumar, Z. Liu, and K. Lyu

Introduction

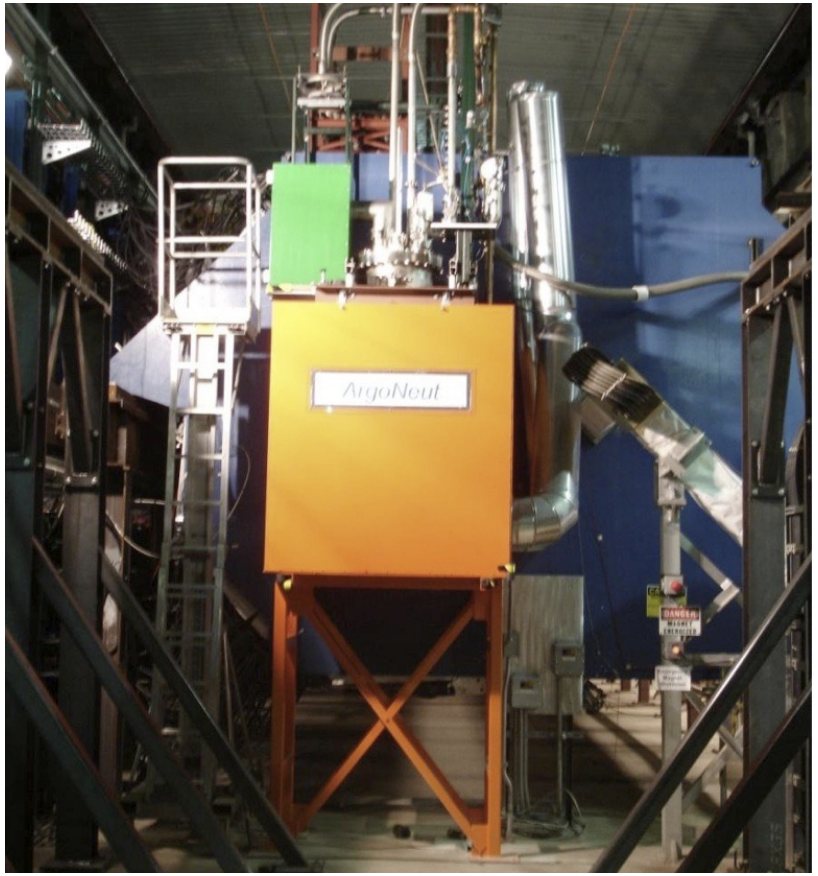
Heavy QCD axions are a proposed extension to standard model

- heavier version of conventional light QCD axions
- provide mechanism to resolve the *strong CP problem*
- avoid fine-tuning of light axions: *axion quality problem*

Potentially produced in neutrino beams, during high-energy proton—fixed-target collisions

Search for their subsequent decays in neutrino detectors:

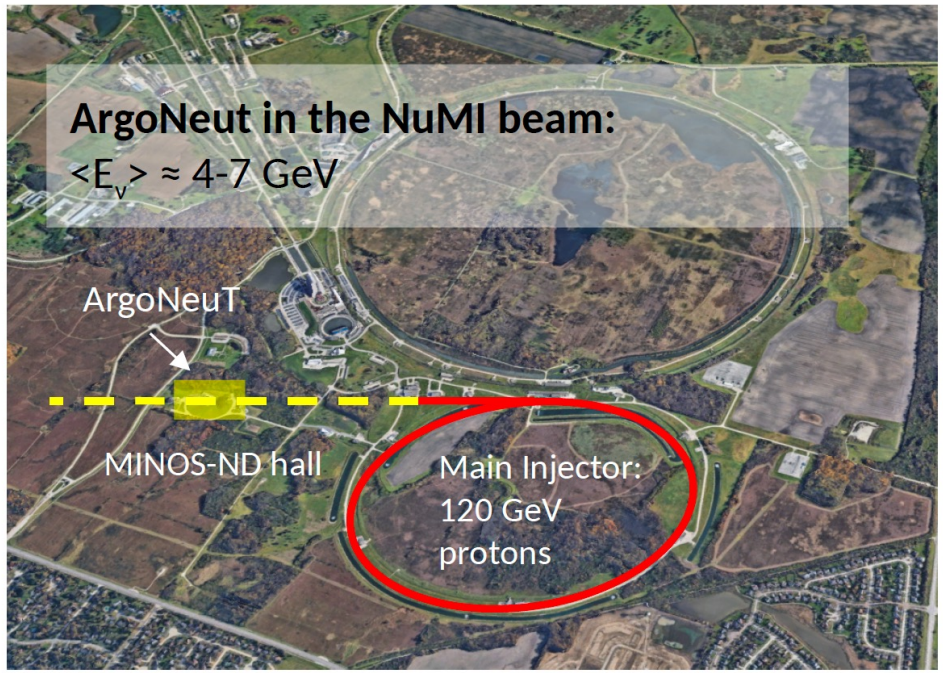
- ArgoNeuT experiment



ArgoNeuT experiment

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

- located along the NuMI beam, ~1km from target
- collected data 2009-10, 1.25×10^{20} POT



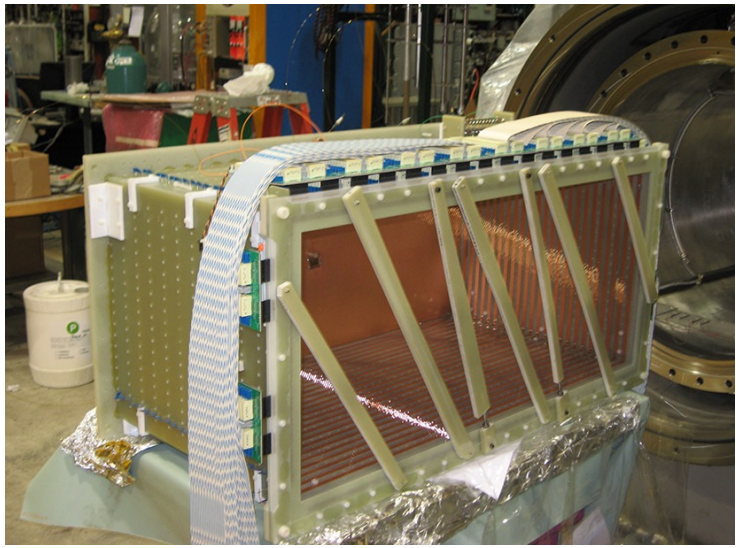
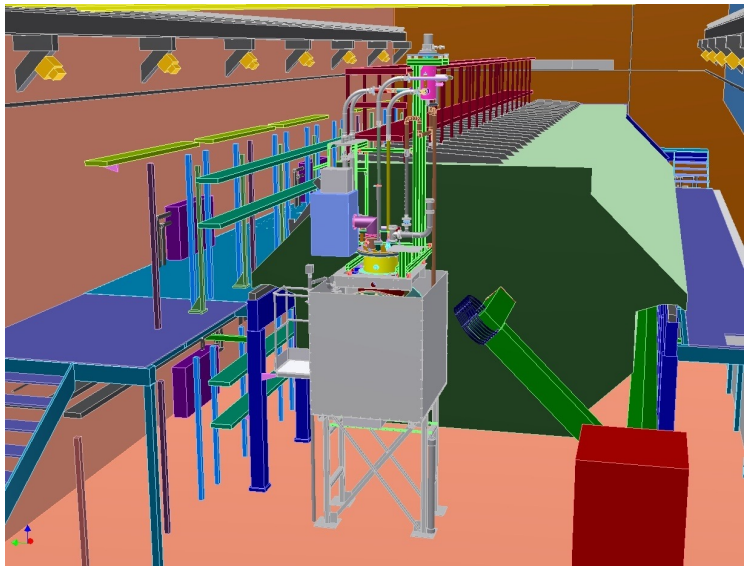


Table-top sized TPC:

- 0.24 ton LAr
- 40×47×90 cm^3
- two wire planes, 4mm wire spacing



Upstream of MINOS near detector:

- magnetised steel and scintillator strip
- muon spectrometer

BSM searches in ArgoNeuT

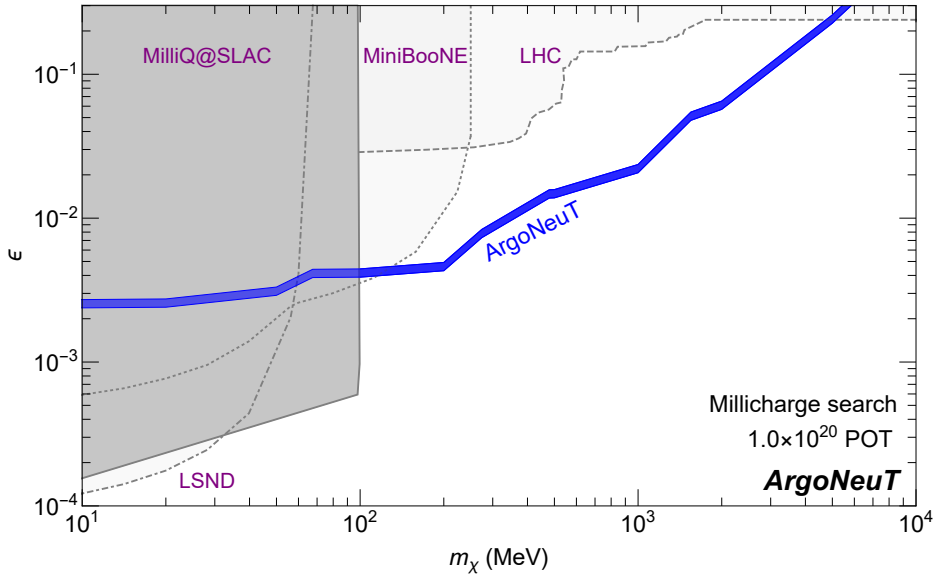
ArgoNeuT data-set very useful for searches for BSM physics:

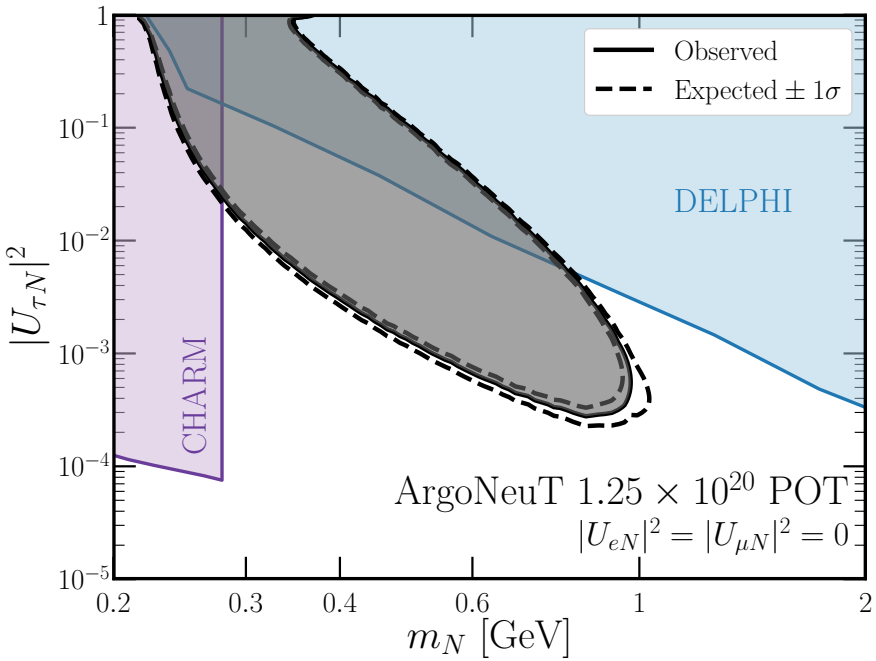
- NuMI beam, on-axis: high-energy, high intensity
- liquid argon TPC + magnetized spectrometer: unique among current liquid argon neutrino experiments

Performed multiple BSM searches in recent years:

- millicharged particles: Phys. Rev. Lett. 124 131801 (2020)
- heavy neutral leptons: Phys. Rev. Lett. 127 121801 (2021)

Direct collaboration between theory and experiment





Heavy QCD axions: model and production

Heavy QCD axion model:

- MeV-GeV scale heavy axion, *a*
- couples with gluons + other SM gauge bosons
- allow coupling with leptons via DFSZ model

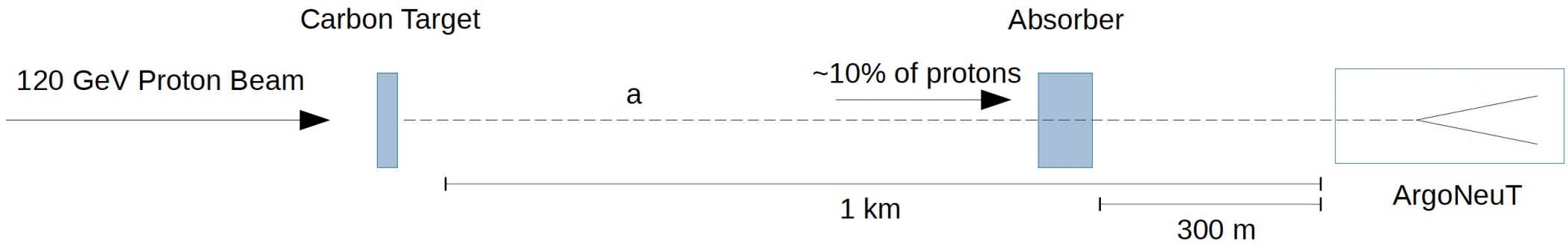
For model details see:

- K. Kelly et al. Phys. Rev. D 103 (2021) 9, 095002
- R. Co et al. *JHEP* 02 (2023) 111

Production in NuMI beam mixing with π^0, η and η' mesons

- masses up to ~ 1 GeV, production in beam target + absorber

Can be long-lived relative to experimental lengths: propagate to ArgoNeuT detector before decaying



Heavy QCD axions: decay

Many different possible heavy axion decay modes:

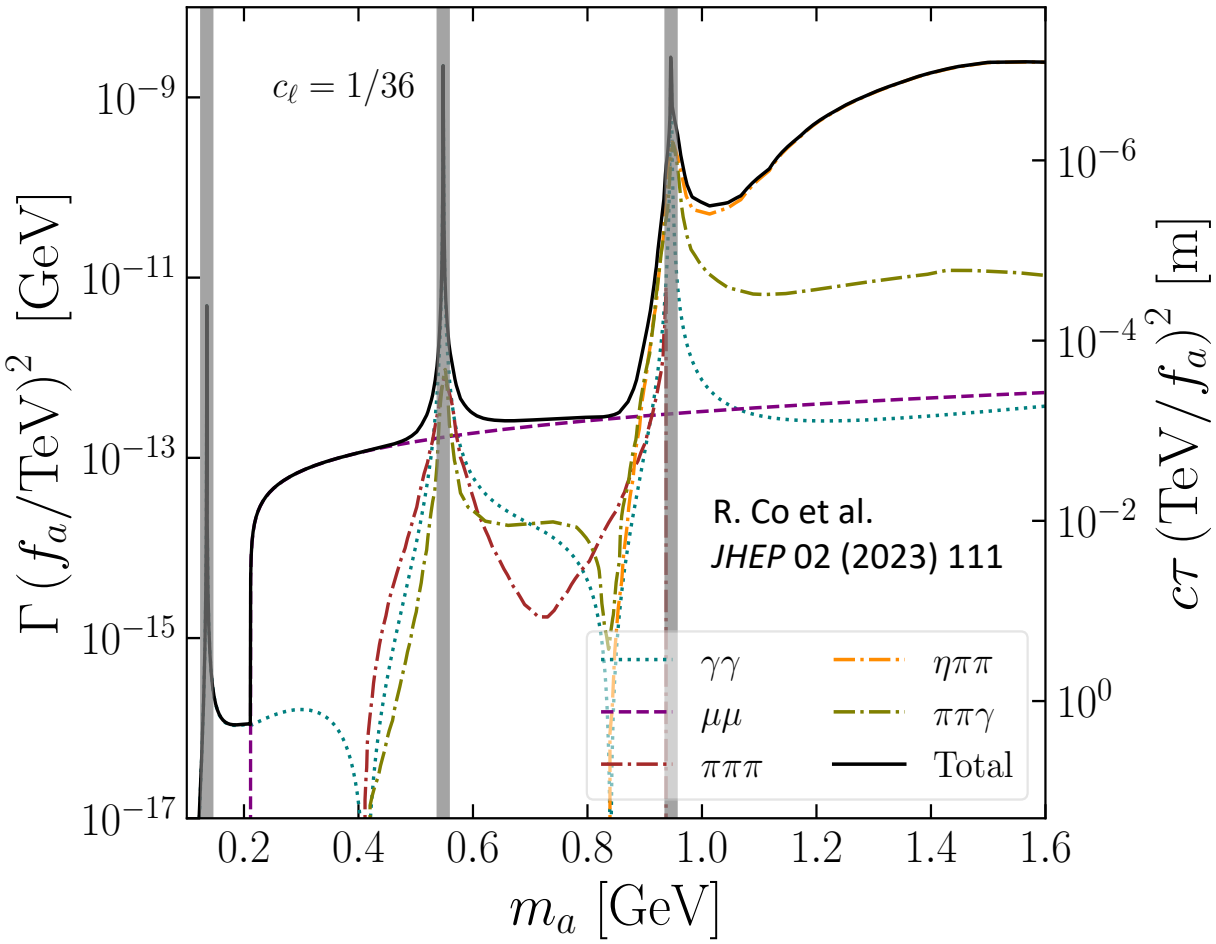
- relative contributions depend on choice of coupling strength weights in model
- "co-dominance" scenario: gauge-boson coupling weights equal and set to 1
- two benchmark small axion-lepton coupling weights: $c_l = 1/36$ and $c_l = 1/100$

In ArgoNeuT search for: $a \rightarrow \mu^+\mu^-$

- dominant channel up to $m_a \sim 1$ GeV

Muons energetic and highly forward-going:

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



Why ArgoNeuT?

ArgoNeuT + MINOS-ND ideal for $a \rightarrow \mu^+\mu^-$

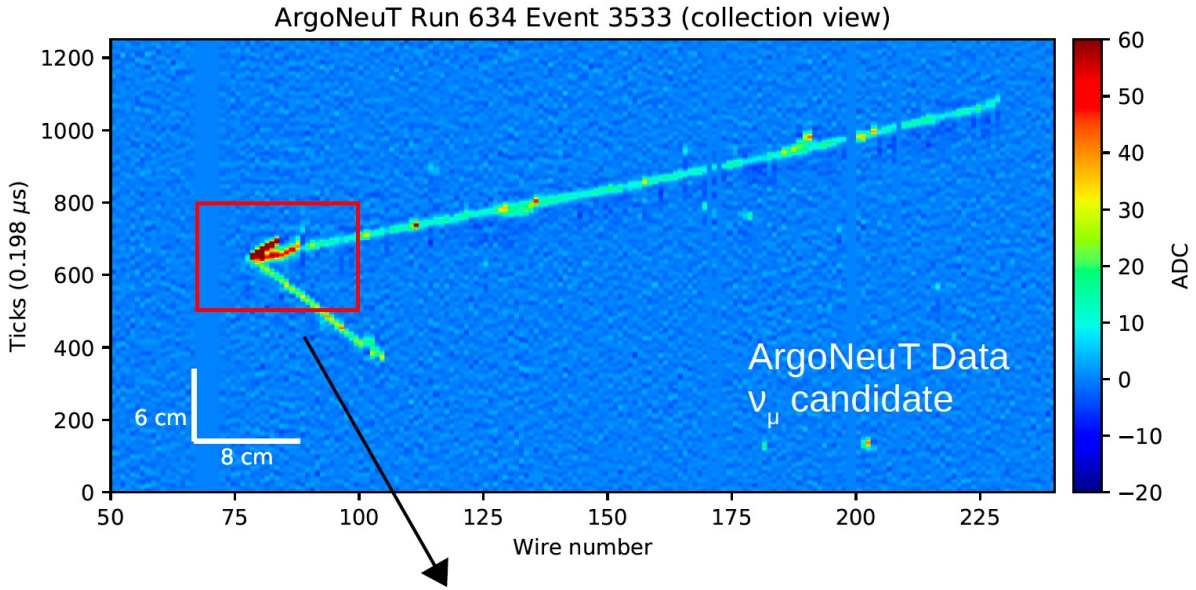
ArgoNeuT LArTPC:

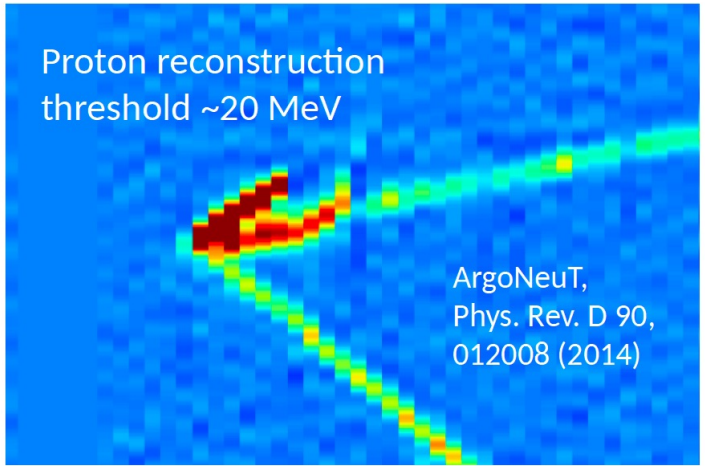
- excellent vertex identification and reconstruction of low energy particles
- allows rejection of neutrino backgrounds

MINOS-ND muon spectrometer:

- muon charge reconstruction
- charged pion rejection through matching

Combination of detector technologies allows us to select this signature with *near zero background*



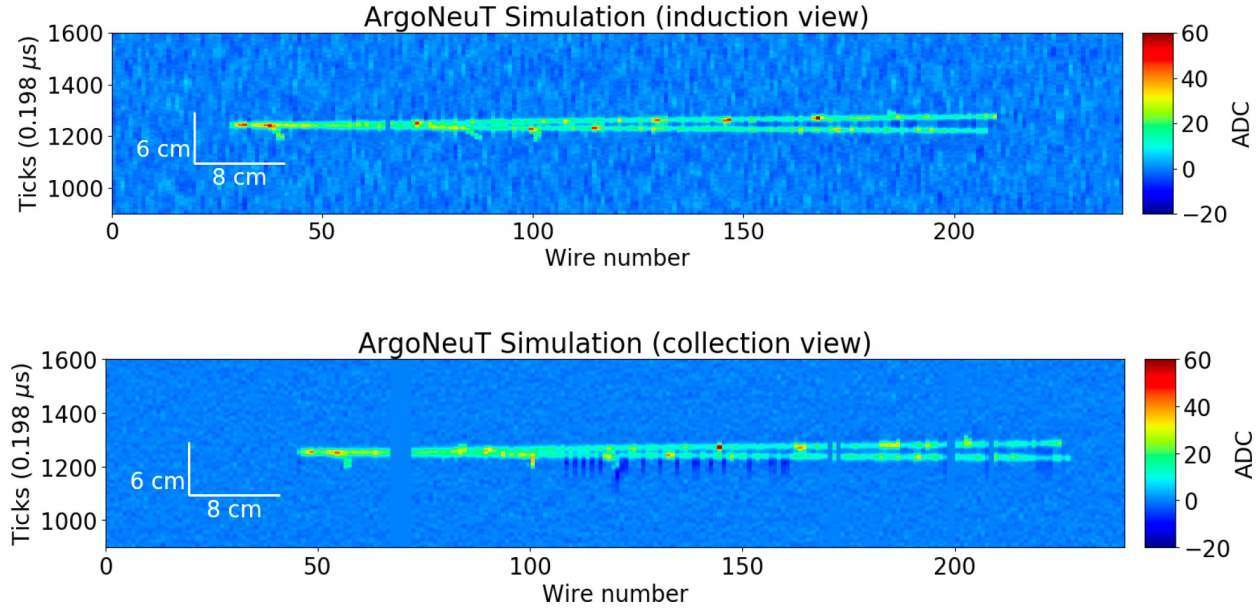


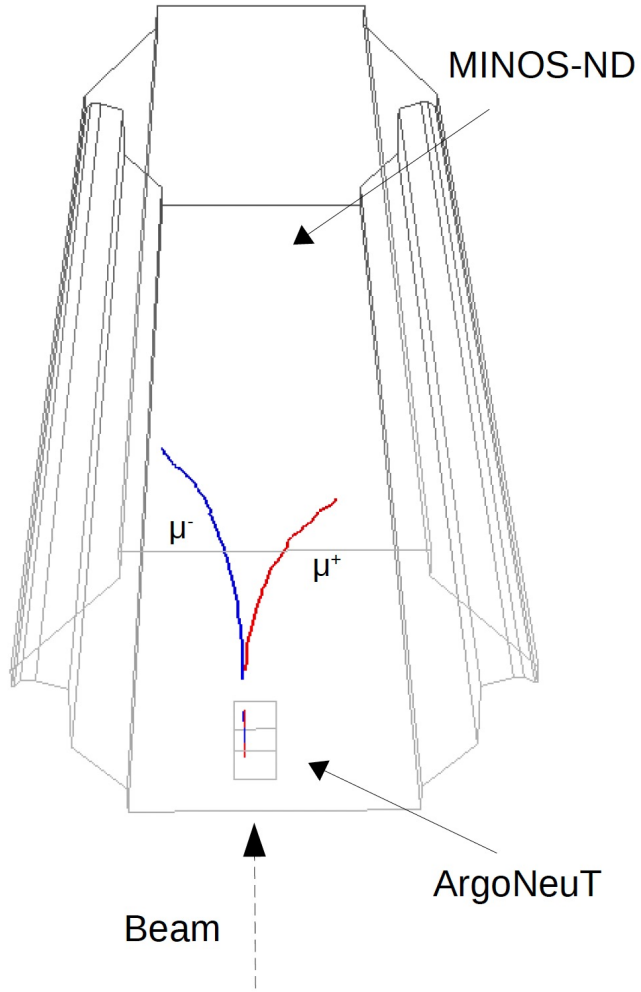
Di-muon signatures in ArgoNeuT

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]





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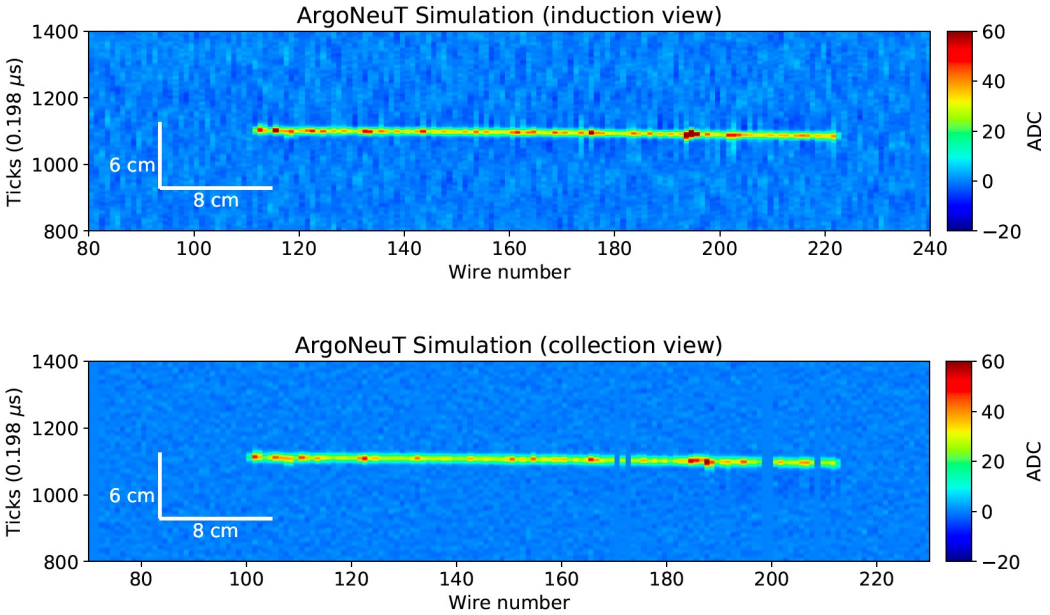
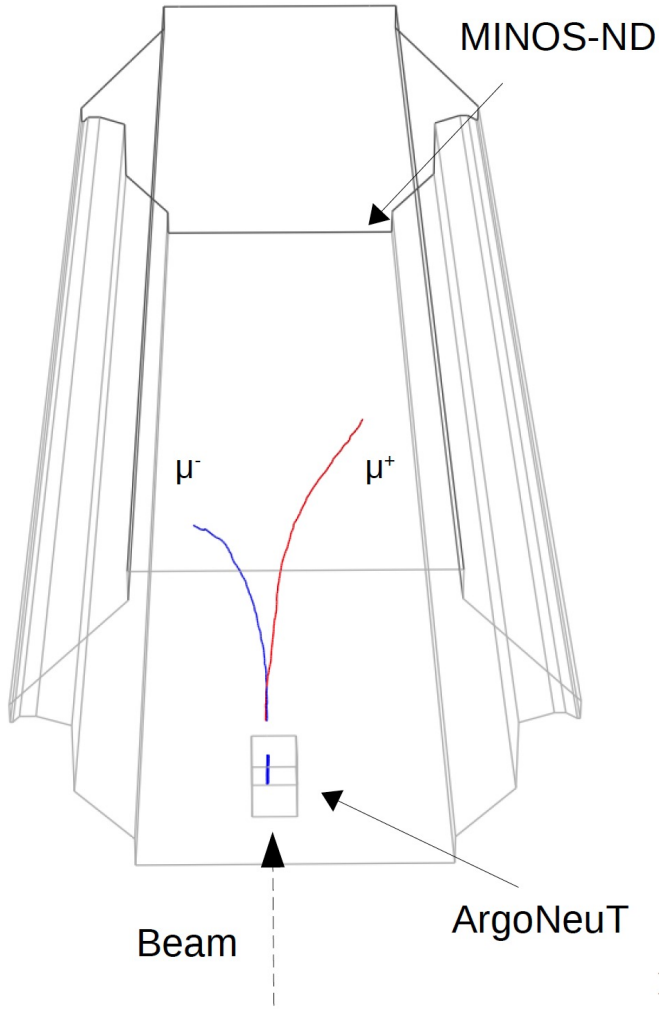
Signature 2: *Double-MIP* event [simulation]





Selecting heavy axions in ArgoNeuT

Use techniques developed for ArgoNeuT's previous heavy neutral lepton search ($N \longrightarrow \nu\ \mu^+\ \mu^-$):

- tuned using dedicated heavy axion simulation

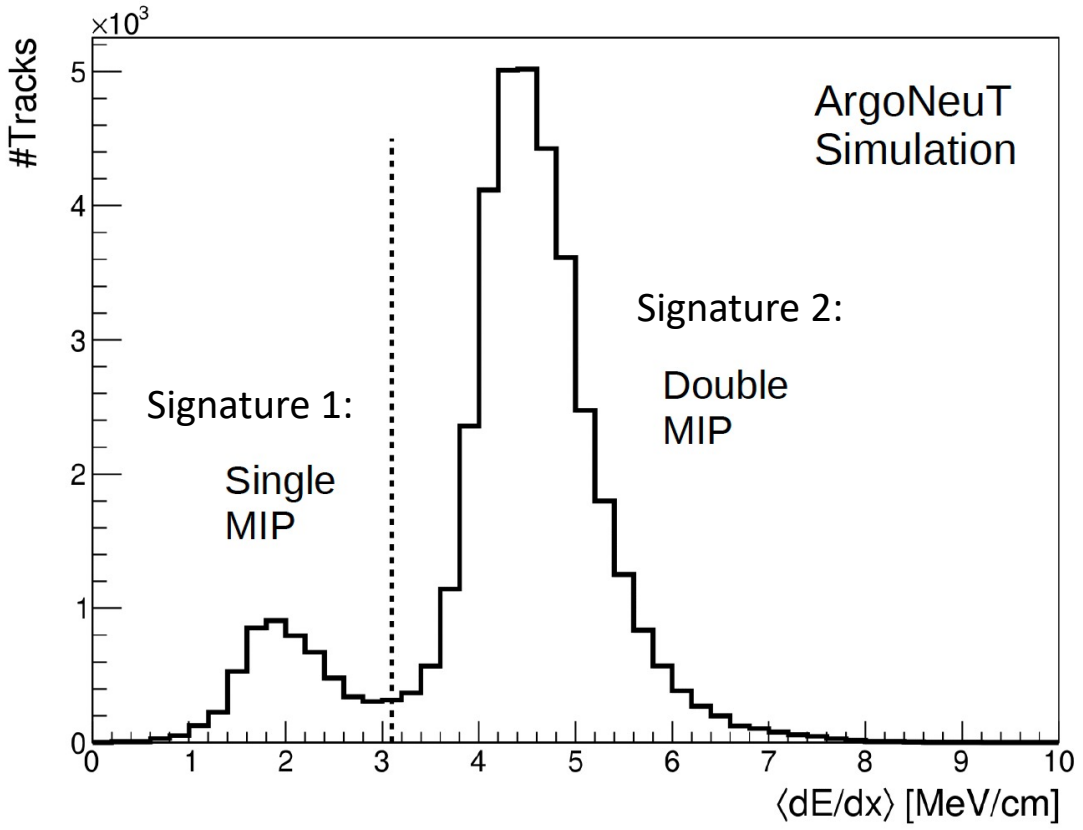
Select highly forward-going muons in ArgoNeuT by average dE/dx at start of tracks:

- 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
- use timing information to avoid mis-matching

Selection efficiency ~50%, but sharp decline at low energies where muons don't reach MINOS-ND



Backgrounds and systematics

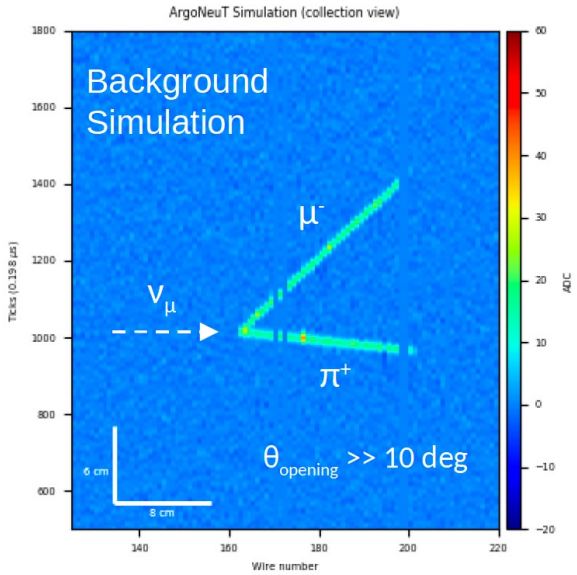
Backgrounds simulated using GENIE, along with a data-driven model of through-going muons:

- dominant source of background: CC ν_μ interactions producing single charged pion, may be mismatched in MINOS-ND
- topologically distinct and/or out-of-time in MINOS-ND – removed during selection

Total background expectation small: 0.1 ± 0.1 events

Systematic uncertainties:

- dominated by uncertainty in axion flux: theoretical uncertainties in meson production + axion-meson coupling
- suite of experimental systematic uncertainties also evaluated, but subdominant



Topologically distinct, opening angle too large

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

Results

Zero events observed in ArgoNeuT data:

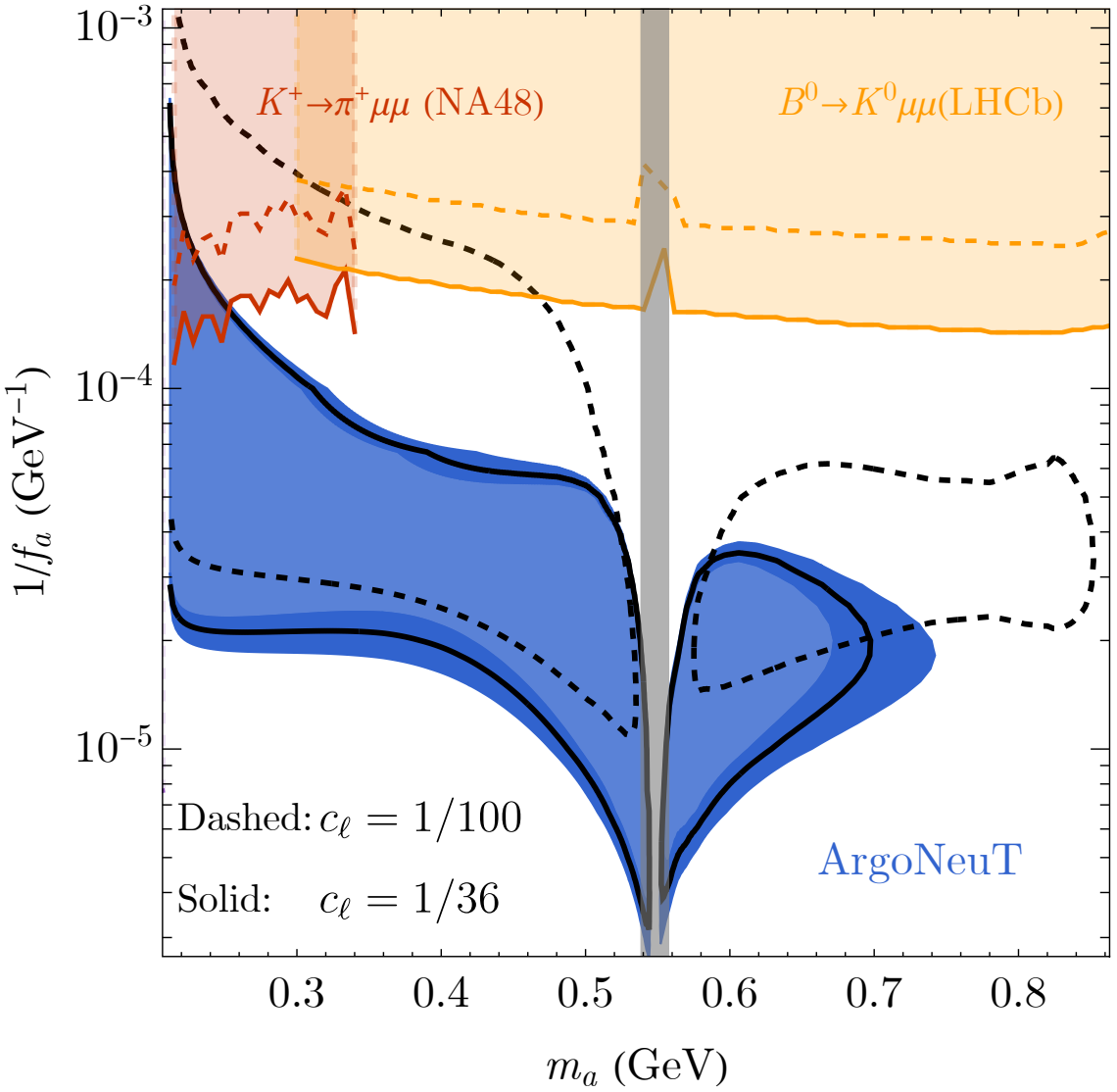
- consistent with background expectation

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 leading exclusion constraints for mass $m_a \sim$ 0.2 – 0.9 GeV and decay constant $f_a \sim$ 10 TeV



Conclusions

Search for heavy QCD axions has been performed using the ArgoNeuT experiment:

- produced in the NuMI beam from meson-mixing
- heavy QCD axion signature: $\mathbf{a \longrightarrow \mu^+ \mu^-}$

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

- leading constraint axion mass $m_a \sim 0.2 – 0.9$ GeV and axion decay constant $f_a \sim 10$ TeV

First search for heavy QCD axions in a LArTPC neutrino detector:

- techniques developed could be employed in future searches using LArTPCs, e.g. DUNE, SBN…

Results published: Phys. Rev. Lett. 130, 221802 (2023)

Backups

Heavy QCD axion couplings

Relative contributions depend on choice of coupling strengths in model:

- consider “co-dominance” scenario:

$$c_1 = c_2 = c_3 = 1$$

$$\mathcal{L}_{\text{gauge}} = \frac{c_3 \alpha_3}{8\pi f_a} a G\tilde{G} + \frac{c_2 \alpha_2}{8\pi f_a} a W\tilde{W} + \frac{c_1 \alpha_1}{8\pi f_a} a B\tilde{B}$$

- two benchmark small axion-lepton couplings:

$$c_l = \frac{1}{36}, \qquad c_l = \frac{1}{100}$$

$$\mathcal{L}_{\text{lepton}} = \sum_{\ell=e,\mu,\tau} \frac{\partial_\mu a}{2f_a} \left(c_{V\ell} \bar{\ell}\gamma^\mu \ell + c_{A\ell} \bar{\ell}\gamma^\mu \gamma_5 \ell \right)$$

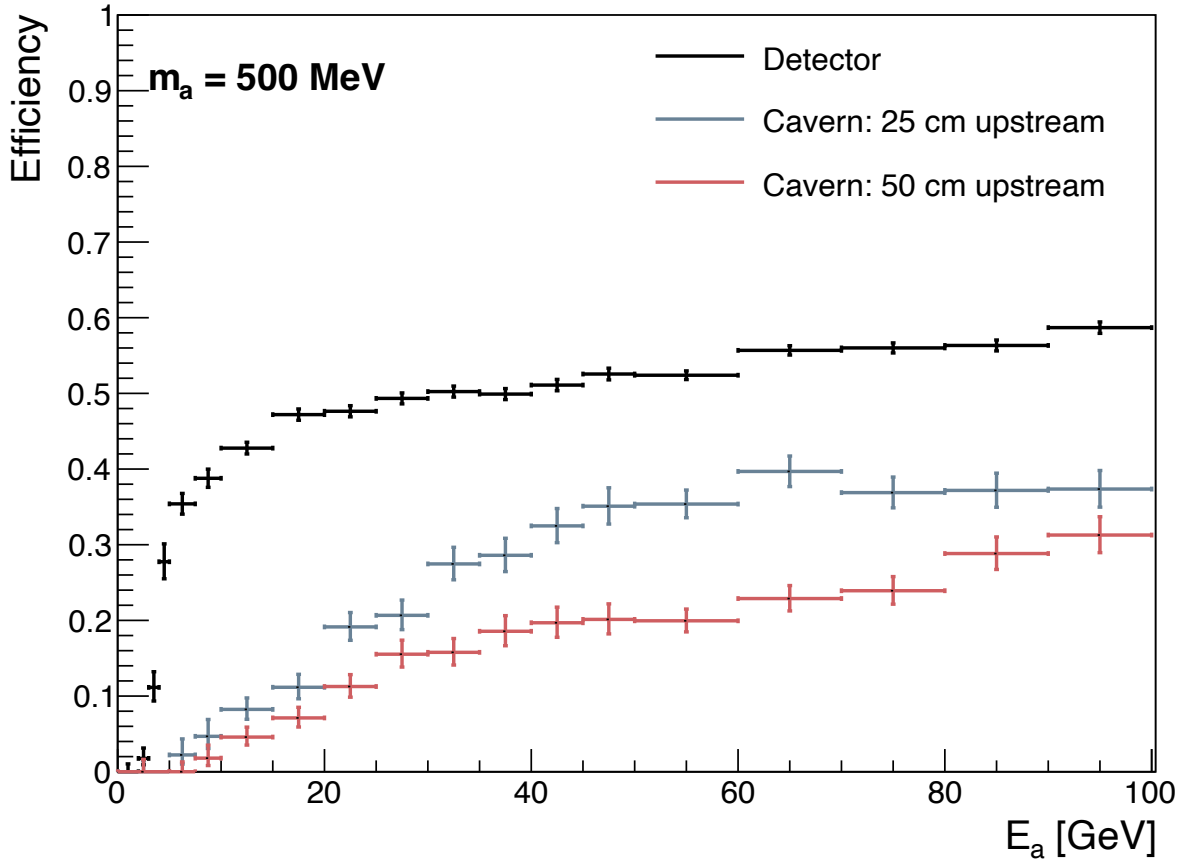
Heavy QCD axion selection efficiency

Decays-inside-detector:

- efficiency ~50% at high energies
- sharp decline at lower energies, muons have insufficient energy to reach MINOS-ND

Decays-inside-cavern (signature 2 only):

- efficiencies lower, only select most forward-going muon pairs



Future searches in LArTPC experiments

Current and up-coming LArTPC experiments are expected to have significant sensitivity to these models:

- SBN program detectors at Fermilab (SBND, MicroBooNE, ICARUS) – multiple searches already on-going!
- DUNE near detector – modular design LArTPC + magnetized spectrometers, could employ similar techniques