



The University of Manchester

Light and Dark in Liquid Argon Time Projection Chamber Neutrino Detectors

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Science and
Technology
Facilities Council

Introduction

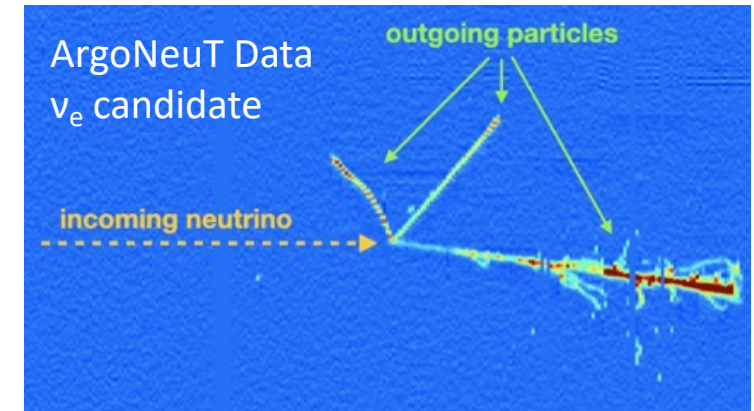


Liquid argon time projection chamber (LArTPC) neutrino detectors:

- high resolution imaging of neutrino interactions, precision neutrino physics
- set to answer the largest open questions: mass hierarchy, CP violation

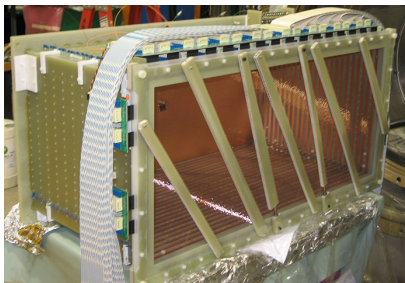
Rapidly increasing in scale – leading to significant computational challenges

Powerful tools to search for beyond the standard model physics



ArgoNeuT

- 0.24 ton
- 2009-10



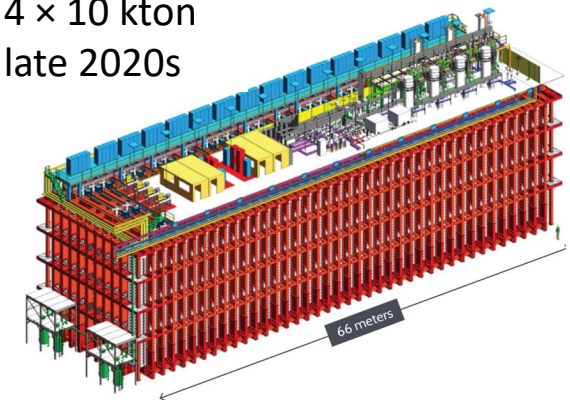
SBN Program

- (SBND, μ BooNE, ICARUS)
- O(100 ton)
- present



DUNE

- 4 × 10 kton
- late 2020s



Thesis overview

Scintillation light modelling in LArTPC neutrino detectors:

- developer of semi-analytical light simulation model
- SBND, DUNE, MicroBooNE
- Eur. Phys. J. C 81 (2021) 4, 349

LArTPC processing on high performance computers:

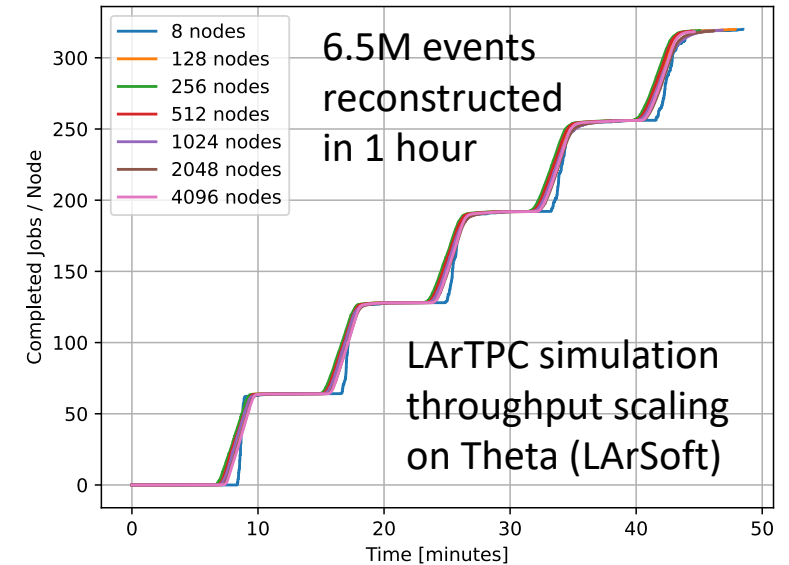
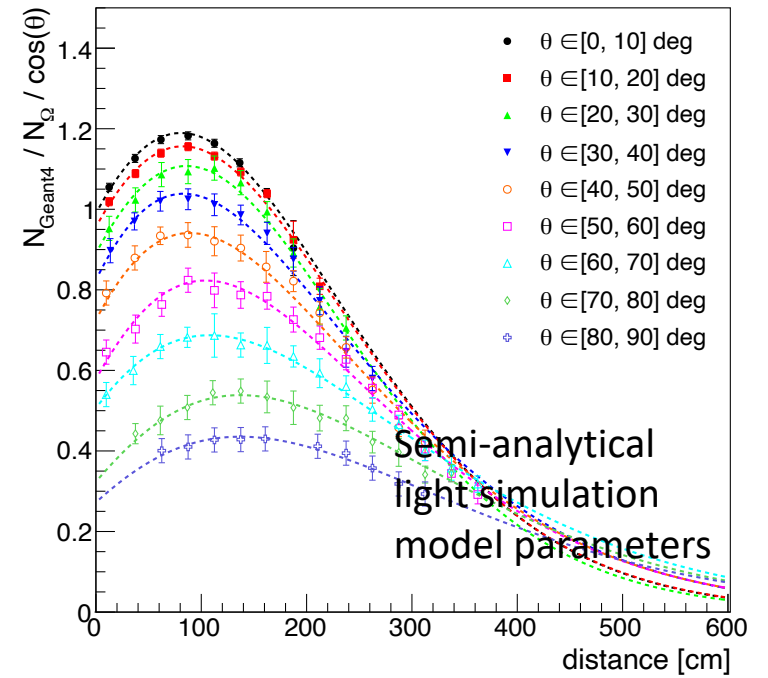
- SBND, using Theta HPC @ Argonne

Beyond the standard model searches with ArgoNeuT:

- Heavy Neutral Leptons and Heavy QCD Axions
- Phys. Rev. Lett. 127, 121801 (2021)
- Phys. Rev. Lett. 130, 221802 (2023)

Addressing computational challenges faced by large scale LArTPCs

Demonstrating power of LArTPCs for dark-sector searches



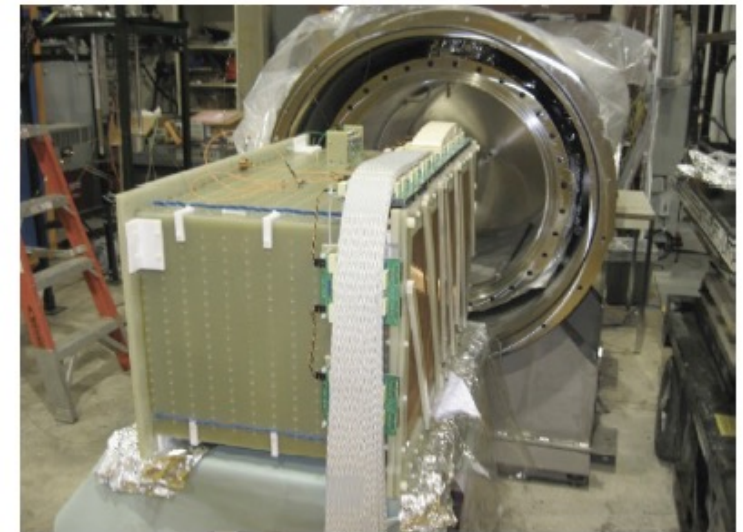
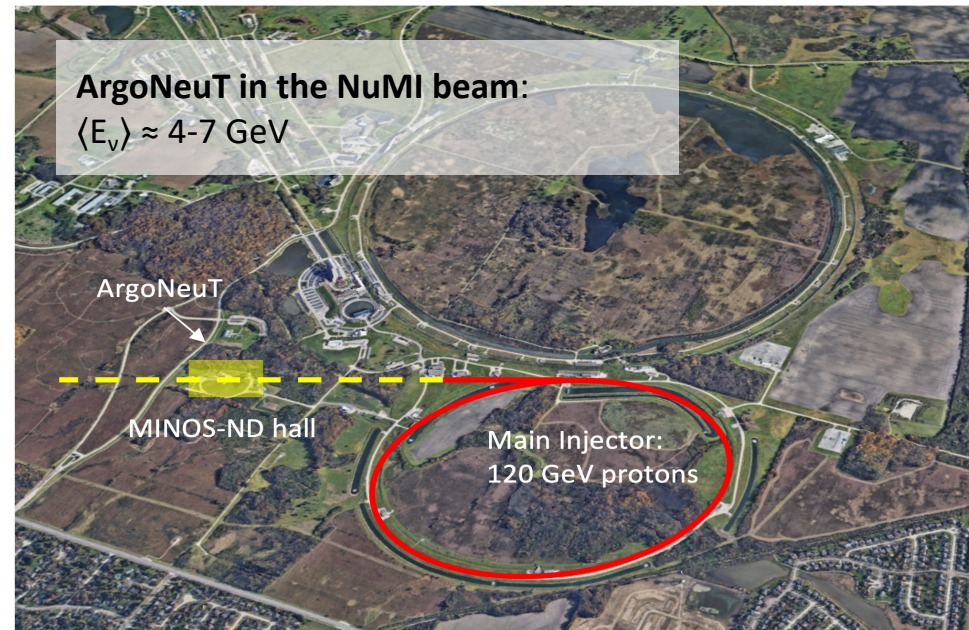
The ArgoNeuT experiment

First LArTPC in a neutrino beam in the US:

- 120 GeV NuMI beam, ~1km from target
- 0.24 ton LAr volume, table-top-sized TPC
- 2009-2010, ~5-month physics run
- MINOS near detector: muon spectrometer

High-energy, high-intensity neutrino beam:

- ideal for searching for beyond the standard model physics
- collaborate directly with theorists



HNLs and heavy QCD axions

High-energy-proton—fixed-target collisions at NuMI (120 GeV):

- production of HNLs and heavy axions, masses up to ~ 1 GeV
- long-lived – can propagate to ArgoNeuT, then search for decays

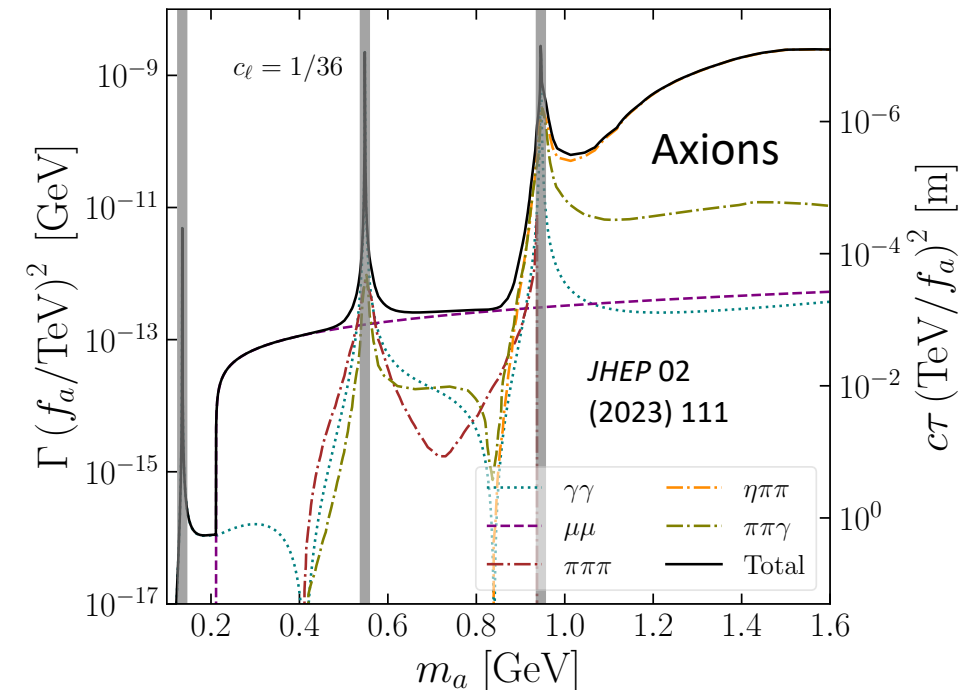
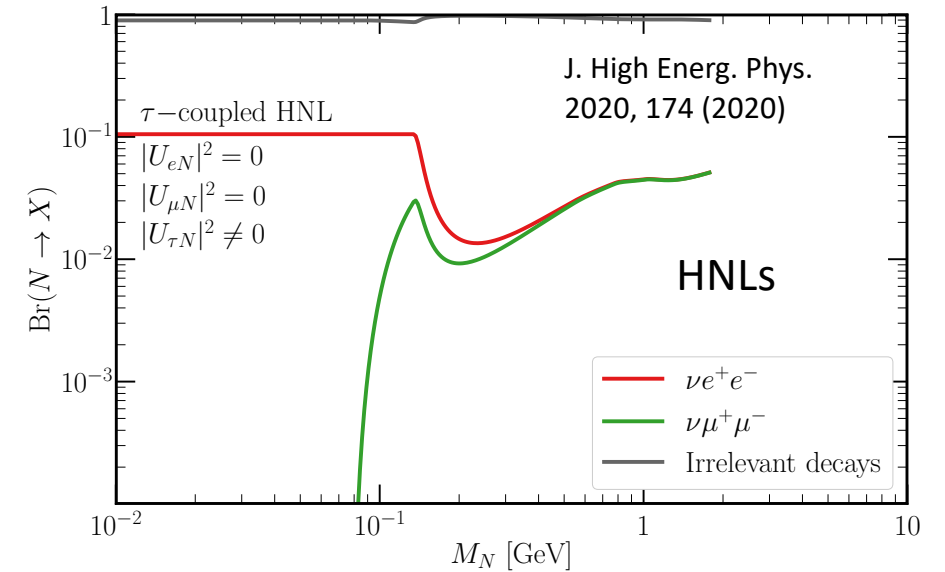
Very different models, but can produce similar decay signatures:

- HNLs (tau-coupled): $\mathbf{N} \rightarrow \nu \mu^+ \mu^-$
- Heavy QCD axions: $\mathbf{a} \rightarrow \mu^+ \mu^-$

ArgoNeuT is uniquely capable of searching for $\mu^+ \mu^-$ signatures:

- ArgoNeuT: high-resolution LArTPC – rejection of neutrino backgrounds
- MINOS-ND: charge reconstruction and pion rejection

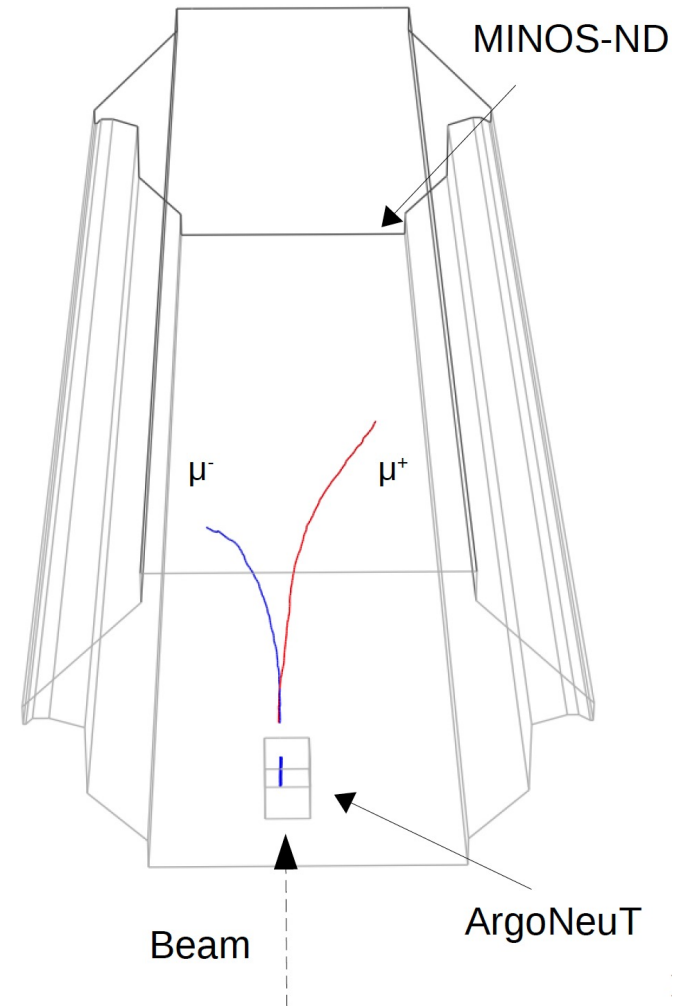
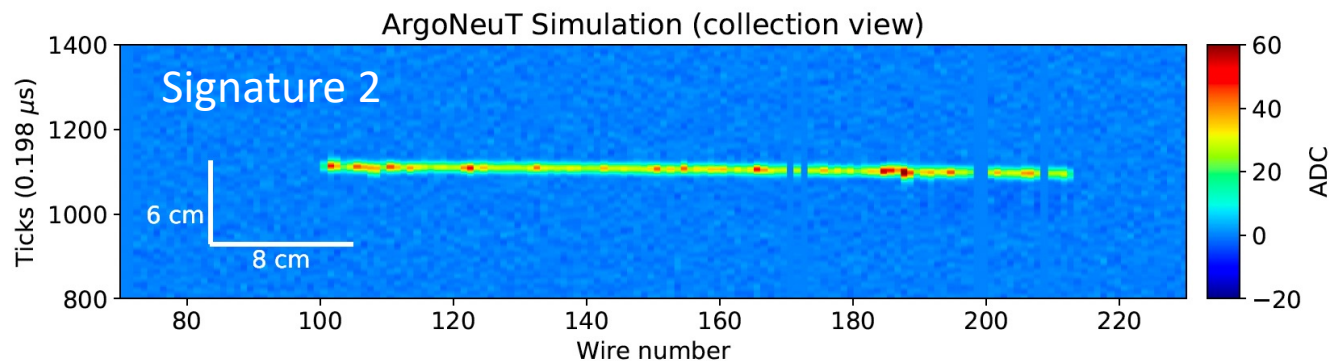
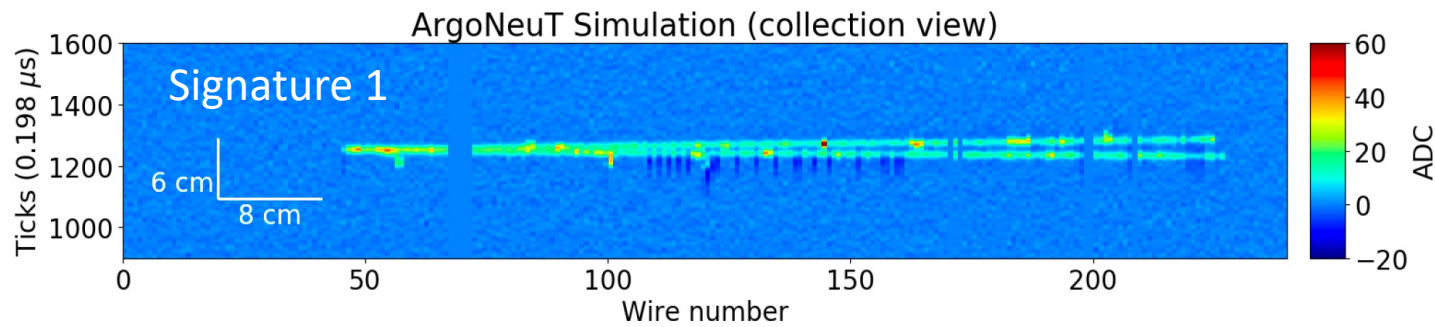
First time $\mu^+ \mu^-$ signature searched for in a LArTPC neutrino detector



Selecting di-muon signatures in ArgoNeuT

Highly-boosted muons often overlap in ArgoNeuT:

- developed novel technique to identify overlapping muons using dE/dx
- match to MINOS-ND where muons separated by magnetic field



Results – heavy neutral leptons (tau-coupled)

ArgoNeuT heavy neutral lepton search:

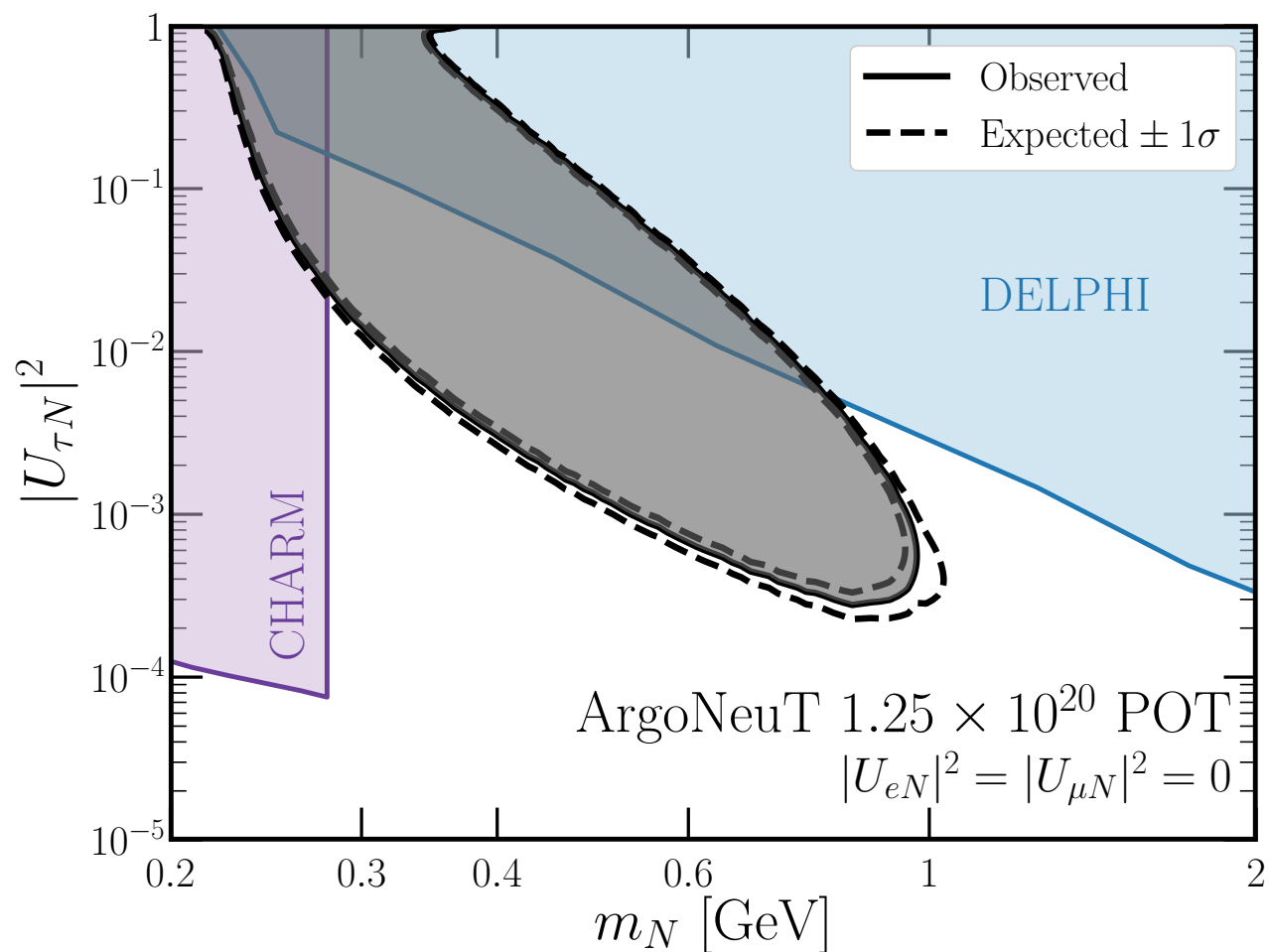
- 0 events observed in data
- world-leading constraint on tau-coupled HNLs (at time of analysis)

First search for tau-coupled HNLs in a LArTPC

First search for di-muon signature in a LArTPC

Phys. Rev. Lett. 127, 121801 (2021)

- ArgoNeuT + K. Kelly, A. de Gouvêa



Results – heavy QCD axions

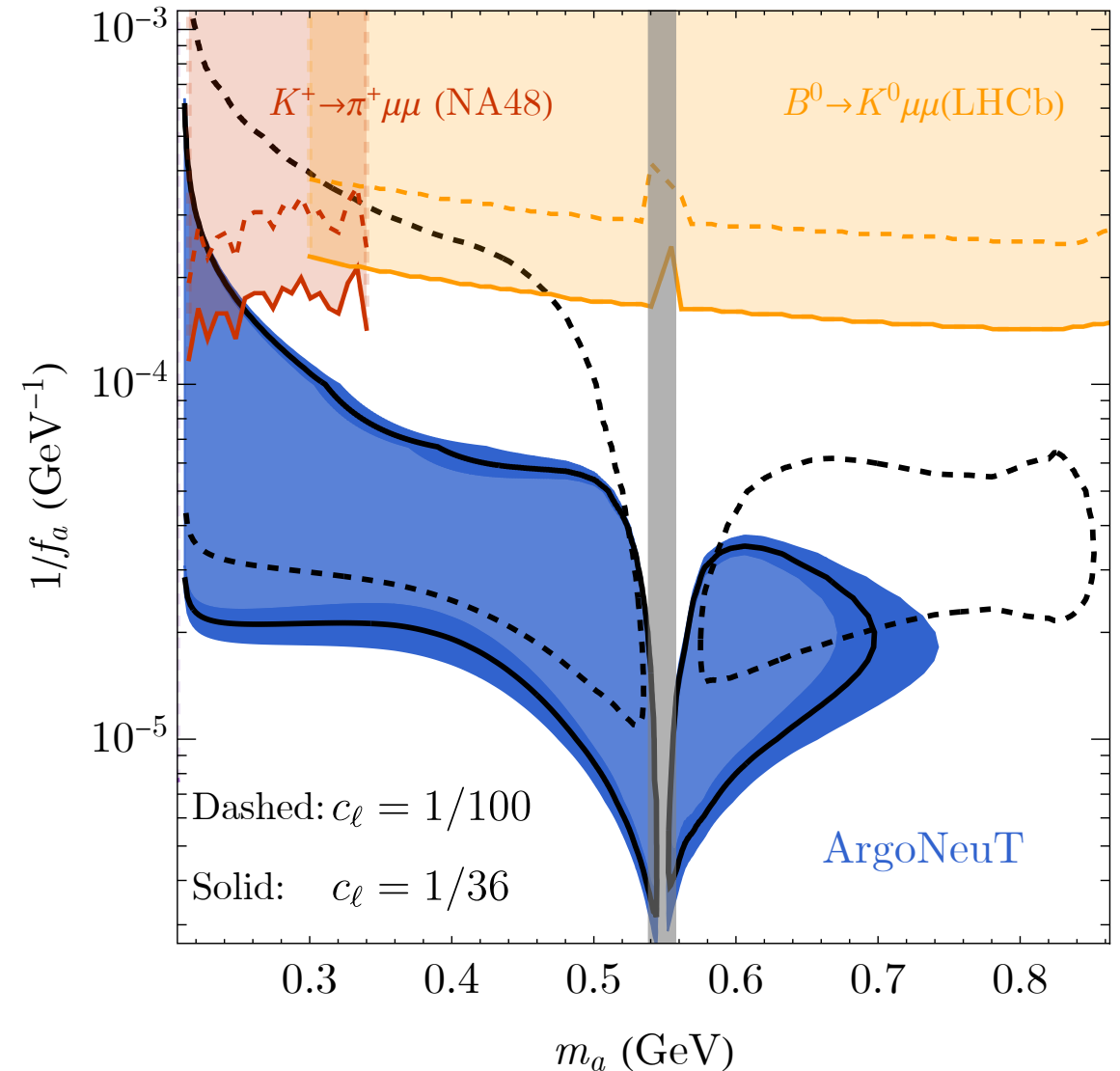
ArgoNeuT heavy QCD axion search:

- 0 events observed in data
- world-leading constraint on heavy QCD axions, evaluated for two benchmark axion-lepton couplings

First search for heavy QCD axions in a LArTPC

Phys. Rev. Lett. 130, 221802 (2023)

- ArgoNeuT + R. Co, R. Harnik, K. Kelly, S. Kumar, Z. Liu, K. Lyu
- editors' suggestion



Summary

I was a key developer of a model to simulation scintillation light in large scale LArTPCs

- enables simulation on the scale of DUNE
- [Eur. Phys. J. C 81 \(2021\) 4, 349](#)

I performed multiple searches for BSM physics with the ArgoNeuT experiment

- Heavy Neutral Leptons:
[Phys. Rev. Lett. 127, 121801 \(2021\)](#)
- Heavy QCD Axions:
[Phys. Rev. Lett. 130, 221802 \(2023\)](#)

First of their kind in LArTPC neutrino detectors:

- pave the way for future searches in upcoming experiments – SBN, DUNE

Predicting transport effects of scintillation light signals in large-scale liquid argon detectors

Diego Garcia-Gomez^{1,a}, Patrick Green², Andrzej M. Szelc^{2,3,b}

PHYSICAL REVIEW LETTERS **127**, 121801 (2021)

New Constraints on Tau-Coupled Heavy Neutral Leptons with Masses $m_N = 280\text{--}970$ MeV

R. Acciarri,¹ C. Adams,² J. Asaadi,³ B. Baller,¹ V. Basque,¹ F. Cavanna,¹ A. de Gouvêa,⁴ R. S. Fitzpatrick,⁵ B. Fleming,⁶ P. Green^{7,*}, C. James,¹ K. J. Kelly,¹ I. Lepetic,⁸ X. Luo,⁹ O. Palamara,¹ G. Scanavini,⁶ M. Soderberg,¹⁰ J. Spitz,⁵ A. M. Szelc,¹¹ W. Wu,¹ and T. Yang¹

(ArgoNeuT Collaboration)

PHYSICAL REVIEW LETTERS **130**, 221802 (2023)

Editors' Suggestion

First Constraints on Heavy QCD Axions with a Liquid Argon Time Projection Chamber Using the ArgoNeuT Experiment

R. Acciarri,¹ C. Adams,² B. Baller,¹ V. Basque,¹ F. Cavanna,¹ R. T. Co,^{3,4} R. S. Fitzpatrick,⁵ B. Fleming,⁶ P. Green^{7,8,*}, R. Harnik,¹ K. J. Kelly,⁹ S. Kumar,^{10,11} K. Lang,¹² I. Lepetic,¹³ Z. Liu,^{3,†} X. Luo,¹⁴ K. F. Lyu,³ O. Palamara,¹ G. Scanavini,⁶ M. Soderberg,¹⁵ J. Spitz,⁵ A. M. Szelc,¹⁶ W. Wu,¹ and T. Yang¹

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