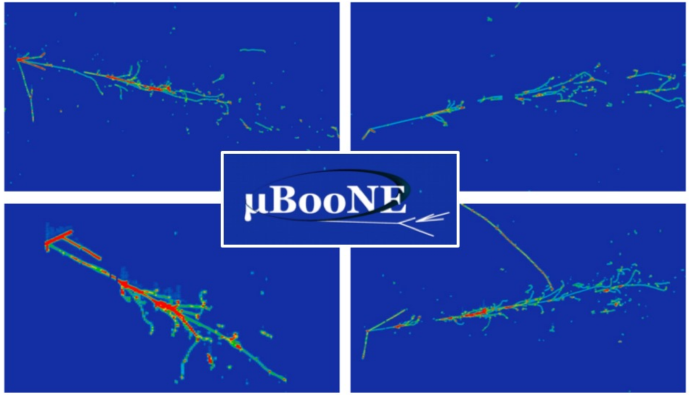
Report from the MicroBooNE Collaboration



Justin Evans (Manchester)

Bonnie Fleming (Yale)

µBooNE

MANCHESTER
1824
The University of Manchester

Introduction

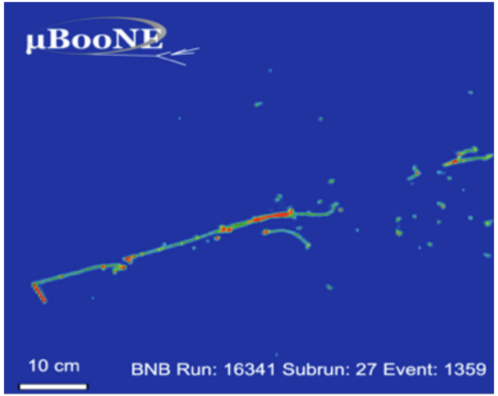
Our first search for a low-energy excess

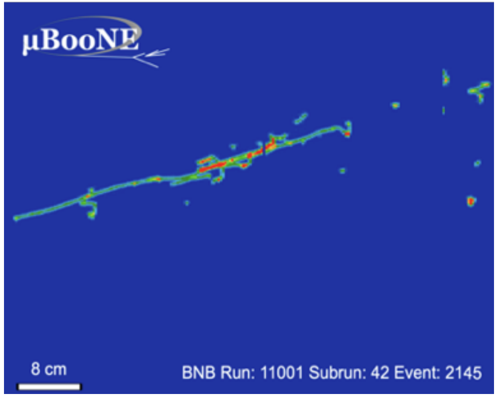
- Electron and photon channels

A clear demonstration that liquid argon is the technology of choice for precision neutrino physics

We are looking forwards to our next phase of analyses

- Already planning for a very exciting future for MicroBooNE





First low-energy excess search

Four independent analyses

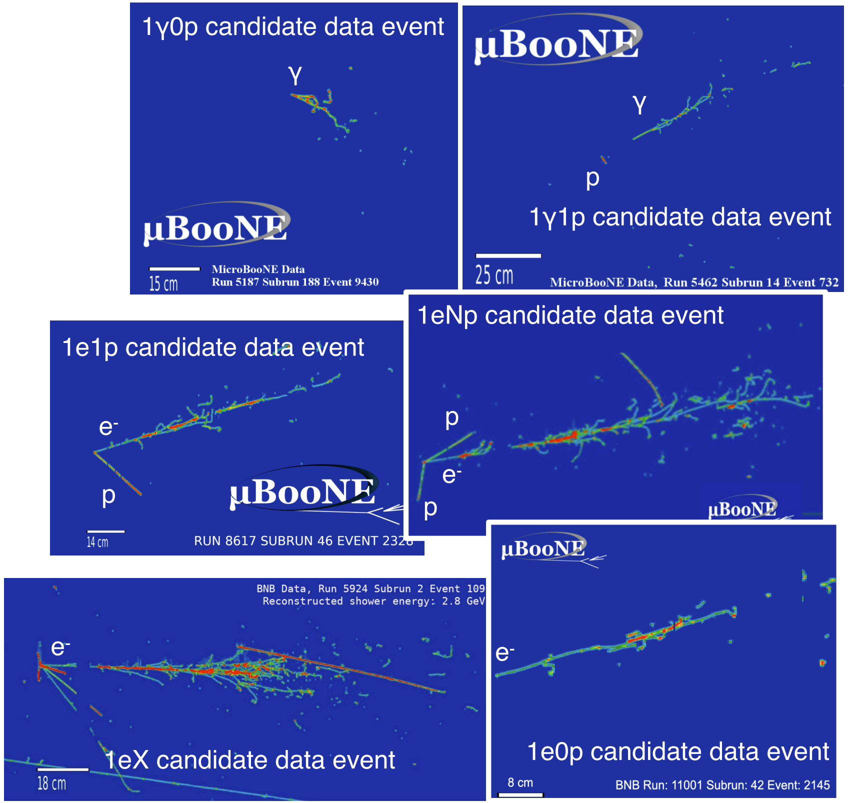
- Targeting six different final states

Single-photon analysis

- NC $\Delta \rightarrow N\gamma$ hypothesis
- 1γ0p, 1γ1p

Searches for a ν_e excess

- Quasi-elastic kinematics (1e1p)
- MiniBooNE-like final states (1eNp, 1e0p)
- All ν_e final states (1eX)



µBooNE

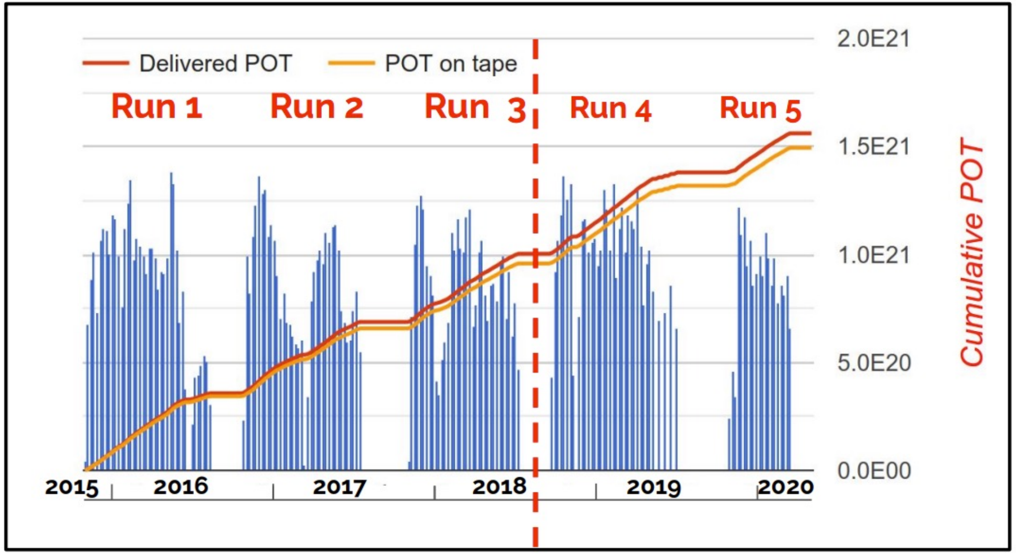
Data sample

Data from Runs 1–3, take Feb 2016 – Jul 2018

- Overlaps with MiniBooNE ν-mode running

Exposure of ~7x10^{20} protons on target

Represents ~1/2 of the full MicroBooNE data sample



Ingredients for the excess search

Flux simulation

MiniBooNE excess model

Neutrino interaction modeling

Detector response model

Calibrations

Systematic uncertainty evaluation

Multiple reconstruction frameworks

Event selections

Data-driven ν_e rate prediction 'ν$_\mu$ constraint'

Validation sidebands

Blind analyses

Results

Related publications from 2021:
Neutrino interactions: arXiv:2110.14028
Systematics: arXiv:2111.03556
Reconstruction: arXiv:2101.05076 (PRA), 2110.13961
Sidebands: 2110.11874, 2109.02460 (JHEP)
LEE Results: arXiv:2110.00409, 2110.14054, 2110.14080, 2110.14065, 2110.13978
Plus other recent papers:
Cross-sections: arXiv:2101.04228 (PRD), 2109.06832, 2110.14023
BSM searches: arXiv:2106.00568 (PRL)
Detector: arXiv:2104.06551 (JINST)

First inclusive differential ν_e cross-sections on argon
W&C seminar on 14th January

MicroBooNE Papers

2017 2018 2019 2020 2021

12 new papers since the last PAC!

23 papers in 2021 so far

Novel approach for evaluating detector-related uncertainties in a LArTPC using MicroBooNE data
First measurement of energy-dependent inclusive muon neutrino charged-current cross sections on argon with the MicroBooNE detector
Search for an anomalous excess of inclusive charged-current ν_e interactions without pions in the final state with the MicroBooNE experiment
Search for an anomalous excess of charged-current quasi-elastic ve interactions with the MicroBooNE experiment using deep-learning-based reconstruction
New theory-driven GENIE tune for MicroBooNE
Search for an anomalous excess of inclusive charged-current ν_e interactions in the MicroBooNE experiment using Wire-Cell reconstruction
Search for an excess of electron neutrino interactions in MicroBooNE using multiple final state topologies
Wire-Cell 3D pattern recognition techniques for neutrino event reconstruction in large LArTPCs
Electromagnetic shower reconstruction and energy validation with Michel electrons and π^0 samples for the deep-learning-based analyses in MicroBooNE
Search for neutrino-induced NC Δ radiative decay in MicroBooNE and a first test of the MiniBooNE low-energy excess under a single-photon hypothesis
First measurement of inclusive electron-neutrino and antineutrino charged current differential cross sections in charged lepton energy on argon in MicroBooNE
Calorimetric classification of track-like signatures in liquid argon TPCs using MicroBooNE data
Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector
Measurement of the Longitudinal Diffusion of Ionization Electrons in the Detector
Cosmic Ray Background Rejection with Wire-Cell LAr TPC Event Reconstruction in the MicroBooNE Detector
Measurement of the Flux-Averaged Inclusive Charged Current Electron Neutrino and Antineutrino Cross Section on Argon using the NuMI Beam in MicroBooNE
Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC
Semantic Segmentation with a Sparse Convolutional Neural Network for Event Reconstruction in MicroBooNE
High-performance Generic Neutrino Detection in a LAr TPC near the Earth's Surface with the MicroBooNE Detector
Neutrino Event Selection in the MicroBooNE LAr TPC using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching
A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector
The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos
Measurement of Differential Cross Sections for Muon Neutrino CC Interactions on Argon with Protons and No Pions in the Final State
Measurement of Space Charge Effects in the MicroBooNE LAr TPC Using Cosmic Muons
First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector
Search for heavy neutral leptons decaying into muon-pion pairs in the MicroBooNE detector
Reconstruction and Measurement of O(100) MeV Electromagnetic Activity from Neutral Pion to Gamma Gamma Decays in the MicroBooNE LArTPC
A Method to Determine the Electric Field of Liquid Argon Time Projection Chambers Using a UV Laser System and its Application in MicroBooNE
Calibration of the Charge and Energy Response of the MicroBooNE Liquid Argon Time Projection Chamber Using Muons and Protons
First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Enu ~0.8 GeV with the MicroBooNE Detector
Design and Construction of the MicroBooNE Cosmic Ray Tagger System
Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector
First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE detector
A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions
Ionization Electron Signal Processing in Single Phase LArTPCs II: Data/Simulation Comparison and Performance in MicroBooNE
Ionization Electron Signal Processing in Single Phase LArTPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation
The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector
Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter
Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC
Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC
Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering
Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber
Design and Construction of the MicroBooNE Detector

Very strong track record of papers since 2017

- ~ ½ JINST
- ~ ½ Phys Rev, EPJC

Systematic uncertainties

We have made the first complete assessment of systematic uncertainties in a LArTPC

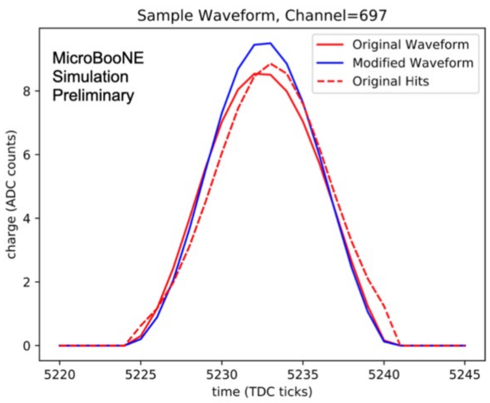
- Years of work have come to fruition

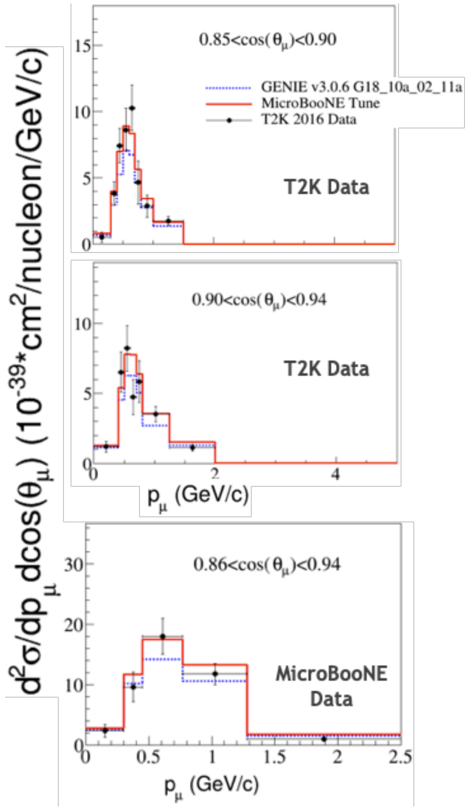
Detector uncertainties

- Novel data-driven technique using wire responses
- **arXiv:2111.03556**
- Plus evaluations of space charge, recombination, optical model & GEANT4 uncertainties

Developed our own ‘MicroBooNE GENIE tune’

- Fit to 2016 T2K ν_μ CC0π data taken at similar energies
- Tune CCQE and CC2p2h models
- Varying >50 parameters to assess interaction uncertainties
- **arXiv:2110.14028**

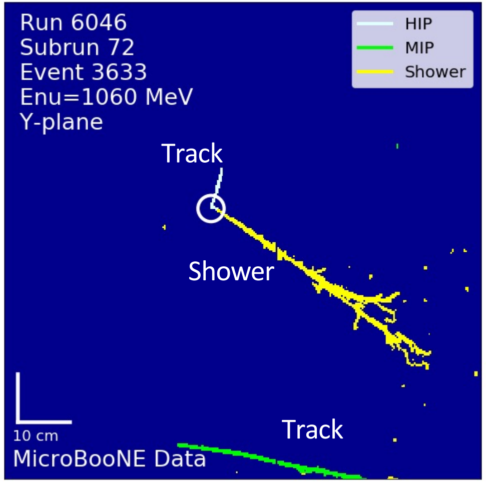




Three independent reconstruction frameworks

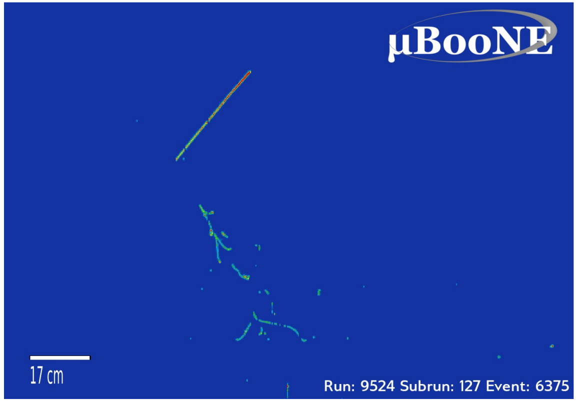
Deep-learning-based

- Semantic segmentation & CNNs
- 1e1p topology



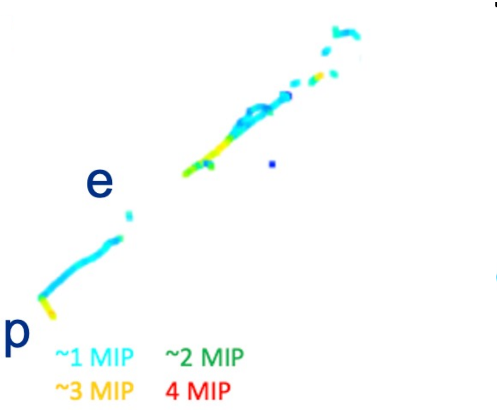
Pandora-based

- Single-photon search ($1\gamma1p$, $1\gamma0p$)
- Pionless electron search (1eNp, 1e0p)



Wire-Cell-based

- Tomographic techniques & 3D imaging
- Fully inclusive electron search



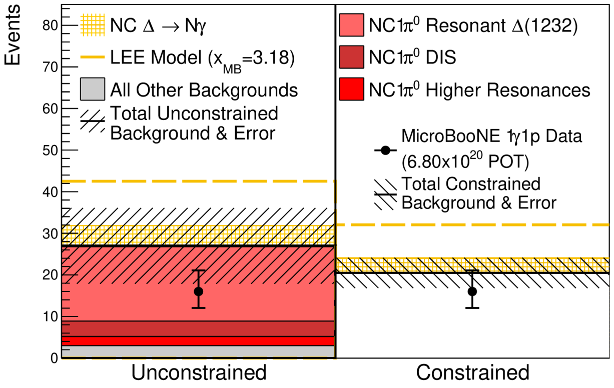
Single-photon results

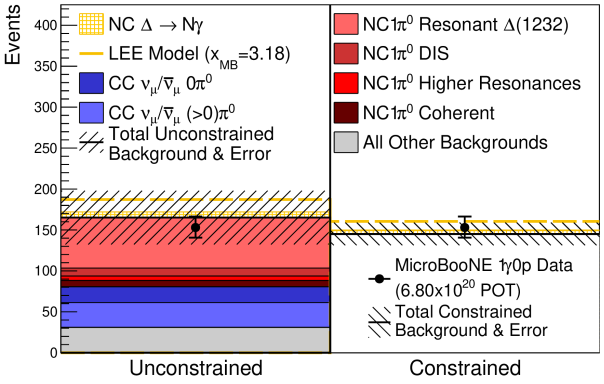
- No evidence for an enhanced rate of single photons from NC $\Delta \rightarrow N\gamma$ decay above nominal GENIE expectations

- One-sided bound on the normalisation of NC $\Delta \rightarrow N\gamma$ events of $x_\Delta < 2.3$ (90% C.L.)

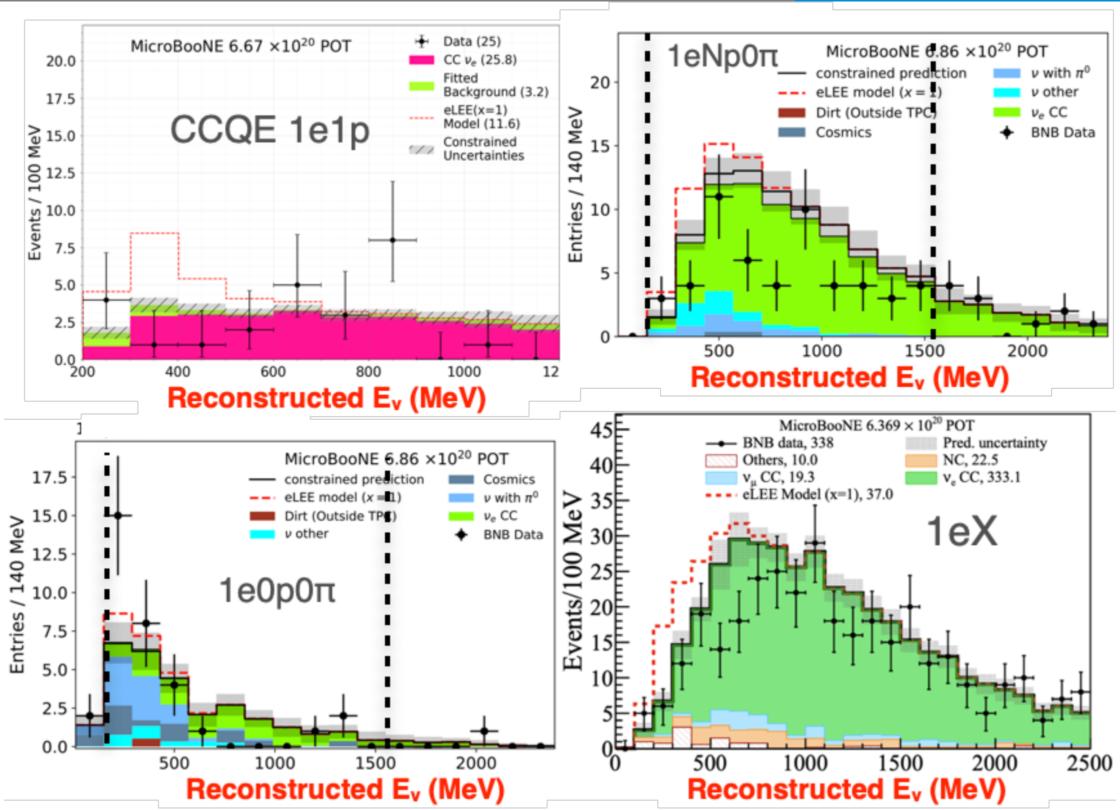
$$\mathcal{B}_{\text{eff}}(\Delta \to N\gamma) < 1.38\% \quad \text{(90\% C.L.)}$$

- More than 50 times better than the world's previous limit



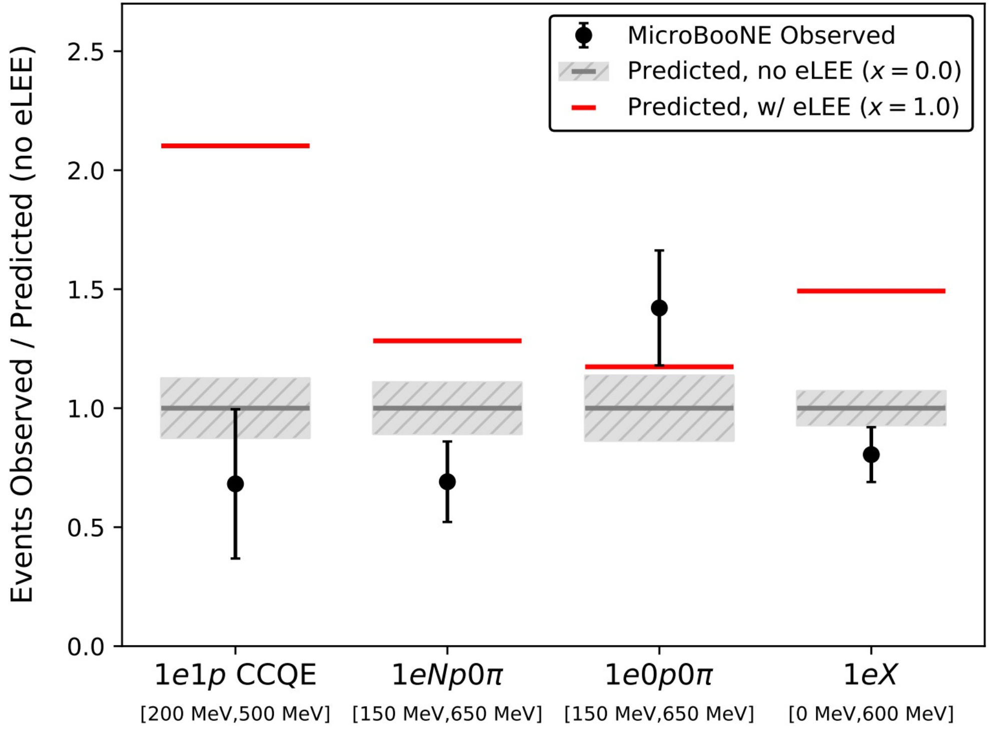


Electron results



Electron results

- Observe ν_e candidate event rates in agreement with, or below, the predicted rates
- Reject the hypothesis that ν_e CC interactions are fully responsible for the MiniBooNE excess at >97% C.L. in all analyses
- The MiniBooNE excess is not solely ν_e, so there is much more to understand!



µBooNE

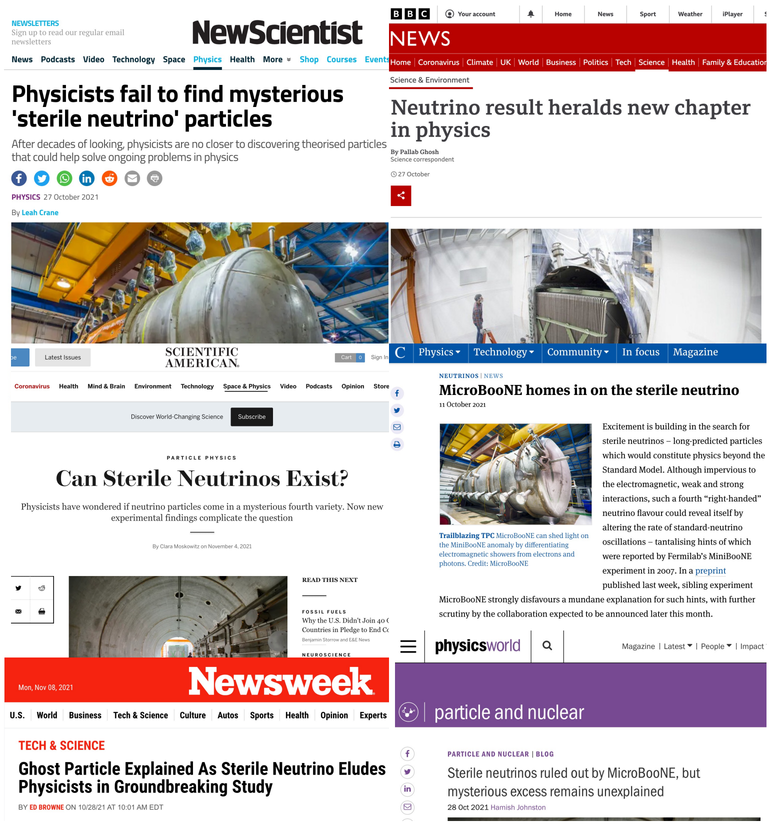
Media reach

Our results and press release had a media reach of 600M

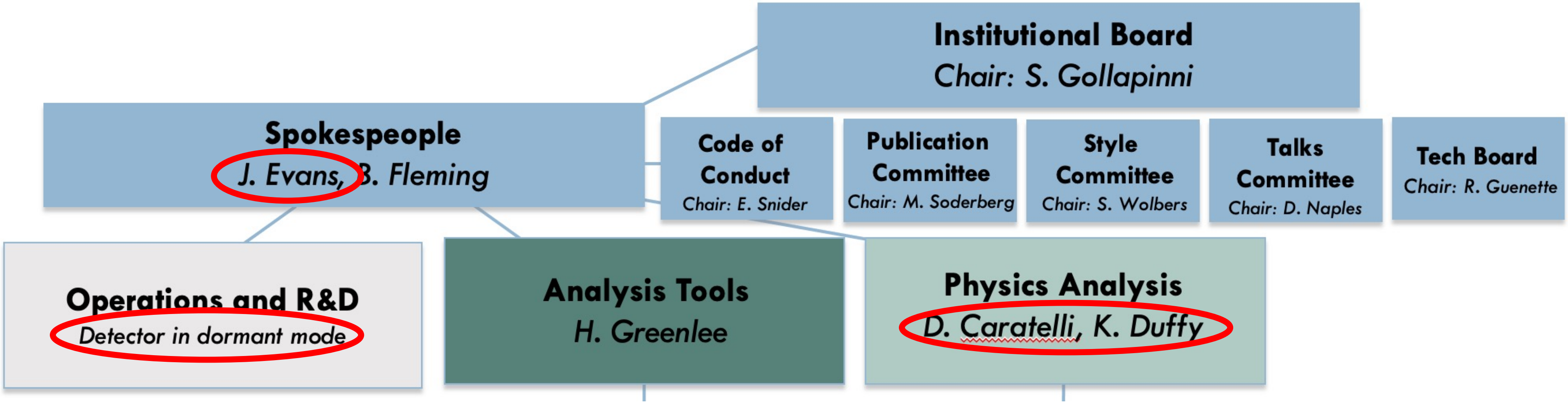
- Many thanks to the Fermilab Office of Communications

Significant BBC coverage

New Scientist, Physics World, CERN Courier, Scientific American, Newsweek, Nature Briefing…



Leadership changes



New co-spokesperson: Justin Evans (Manchester)

- Election for Bonnie's successor to begin shortly

New physics coordinators: David Caratelli (UCSB) & Kirsty Duffy (Oxford)

Run-coordinator role is now retired

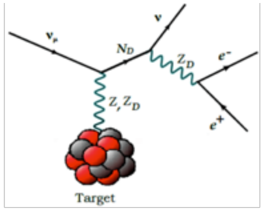
What next? Evolving theory landscape…

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - *[13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)*
  - *[14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141*
- New resonance matter effects
  - *[5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - *[7] Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
- Decay of heavy sterile neutrinos produced in beam
  - *[4] Gninenko, Phys.Rev.D83:015015,2011*
  - *[12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)*
  - *[15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)*
  - *[11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - *[1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *[2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531*
  - *[3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *[10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *[6] Abdallah, Gandhi, Roy, Phys. Rev. D 104, 055028 (2021)*
- Decay of axion-like particles
  - *[8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)*
- A model-independent approach to any new particle
  - *[9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)*

Produces true electrons

Produces true photons

Produces e^+e^- pairs



PRL 121, 241801 (2018)

- Many of these models predict more complex final states (e^+e^-) and/or differing levels of hadronic activity

→ *The hadronic state is becoming increasingly more important as a model discriminator*

- We are fortunate that LArTPCs are sensitive to these possibilities

μBooNE

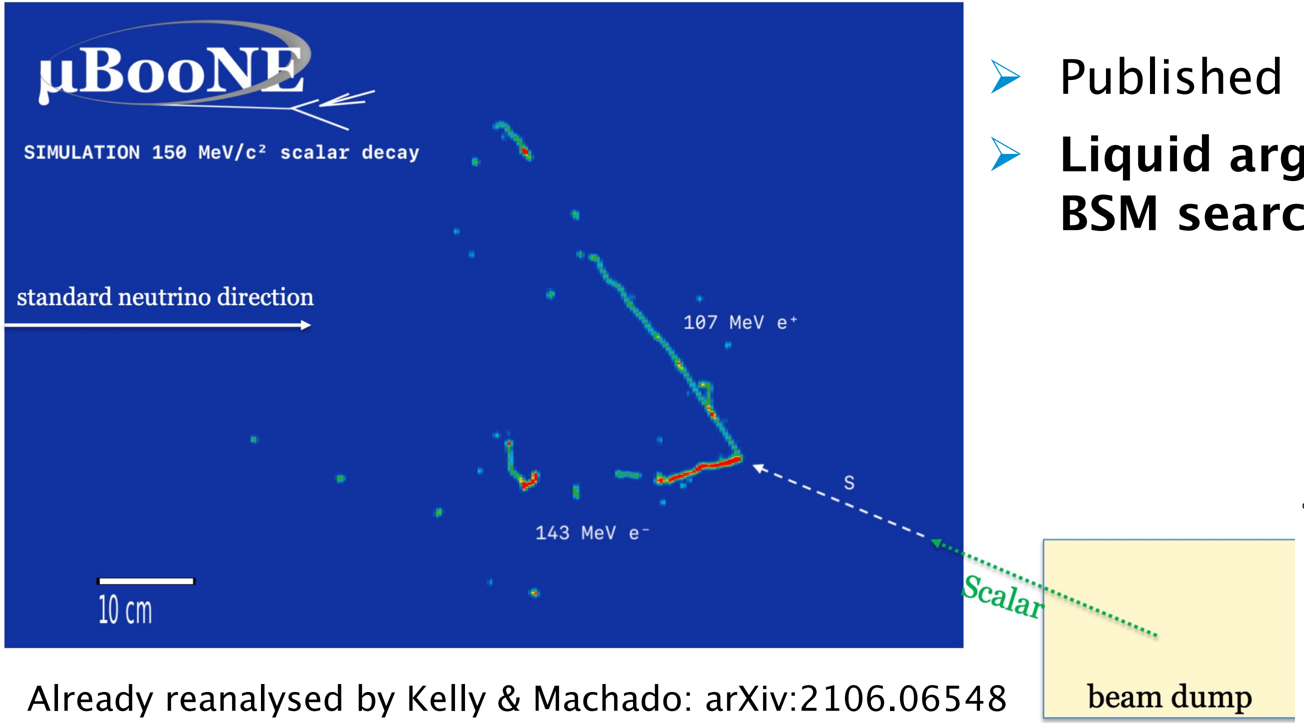
What next? Evolving theory landscape…

Already started probing with first LEE results

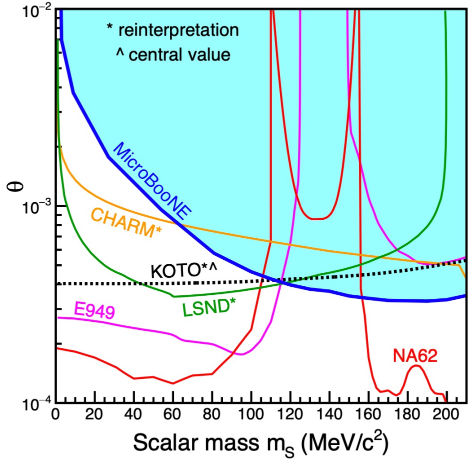
Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma0p$	$1\gamma1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [2,3]	✔ [2,3]	✔ [1,2,3]	✔ [1,2,3]	✔ [1,2,3]
More complex higgs *					✔ [10]	✔ [10]	✔ [6,10]	✔ [6,10]	✔ [6,10]
Axion-like particle *					✔ [8]		✔ [8]		
Res matter effects	✔ [5]	✔ [5]	✔ [5]	✔ [5]					
SM γ production							✔	✔	✔

*Requires heavy sterile/other new particles also

Interlude: Higgs-portal scalar boson search

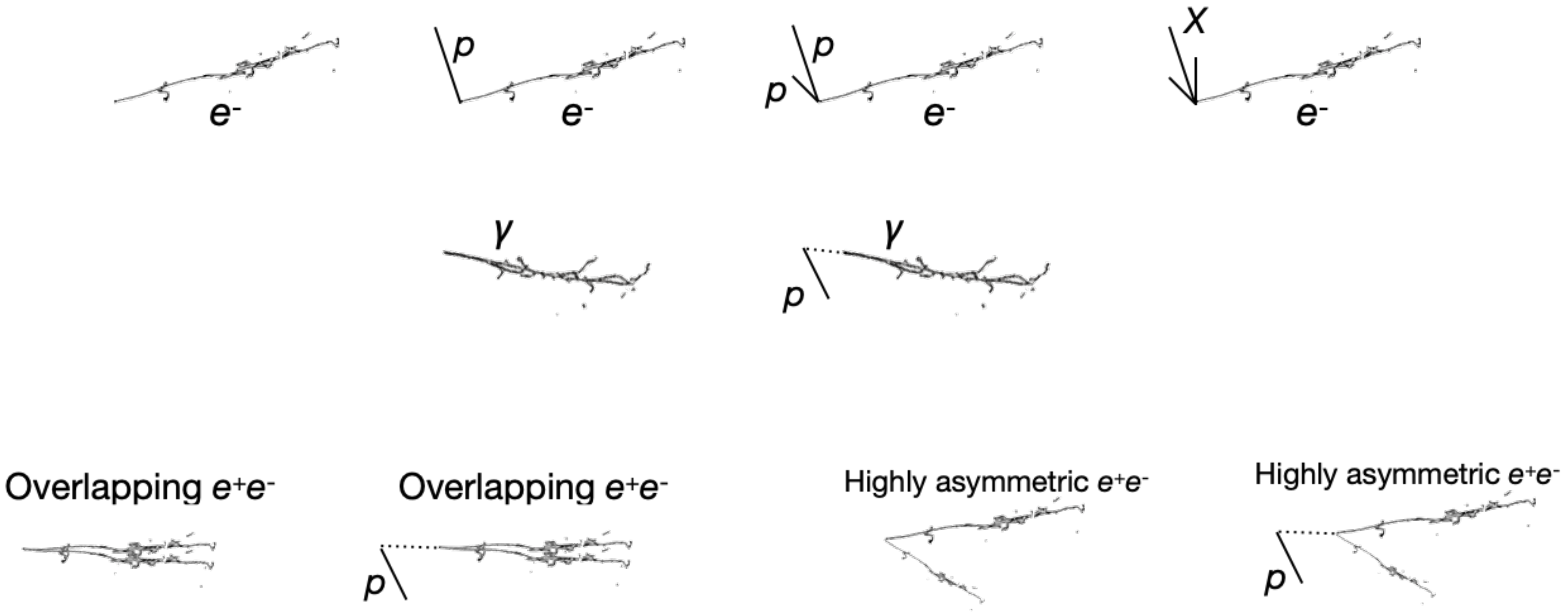


- ➢ Published in Phys. Rev. Lett.
- ➢ **Liquid argon is becoming a BSM search factory**



- ➢ Already reanalysed by Kelly & Machado: arXiv:2106.06548
- ➢ **W&C seminar on 21st January 2022**

Landscape of final state topologies



Planning for the future

We have merely begun exploring the landscape of short-baseline physics available to LArTPCs

- We have many more analyses on the horizon, and half our data still left to analyse

Later this week, we will have a **MicroBooNE Phase II workshop**

- Setting out the collaboration's physics vision for the coming years
- Understanding the resource requirements and our available effort

See Pedro Machado's talk on broader SBN engagement with the theory community

Developing these analyses on MicroBooNE data gives us a head start for the SBN and DUNE physics programmes

We are also putting our tools into a form that are easily useable can be passed on to SBN and DUNE

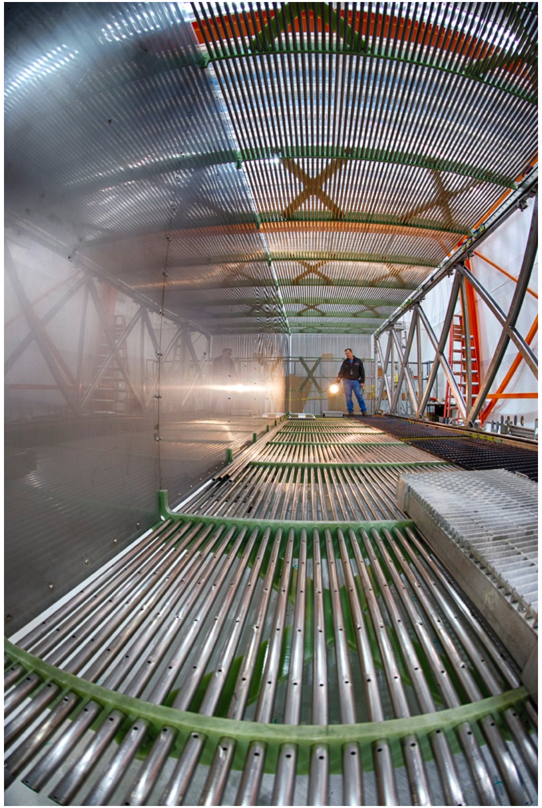
Detector R&D

MicroBooNE detector now in dormant mode

Before powering down, we took a number of R&D runs

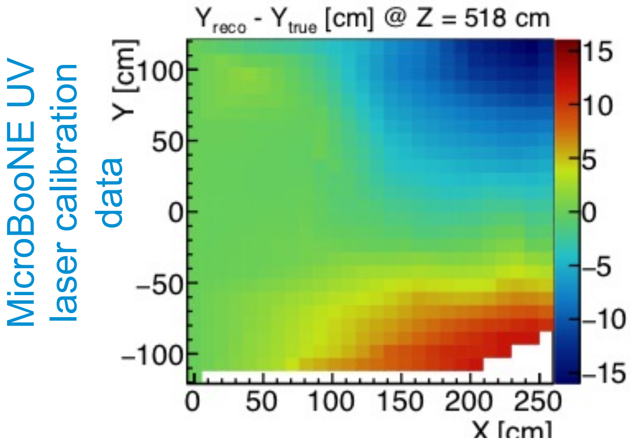
- Raising high voltage to 128 kV
- Single photoelectron rate as a function of HV
- Reversing HV polarity
- Radon doping
- Demonstrating new trigger system
- Laser grounding study
- Argon purity study

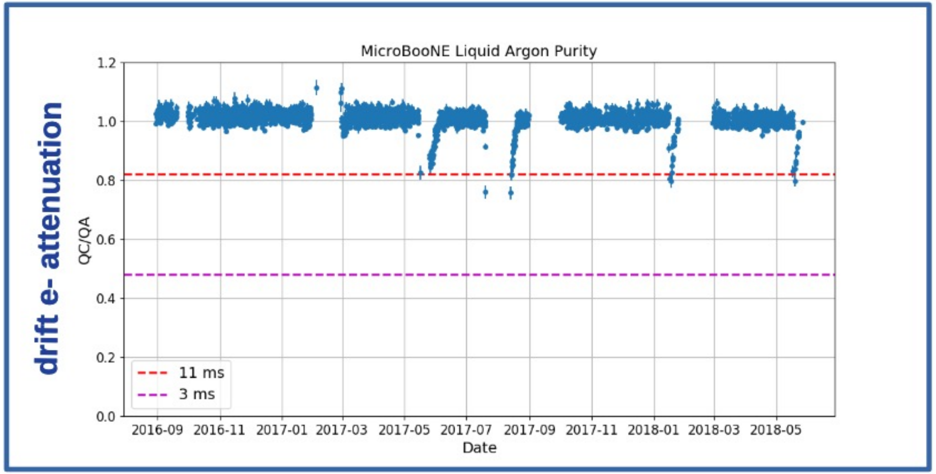
Now working to analyse and publish this data

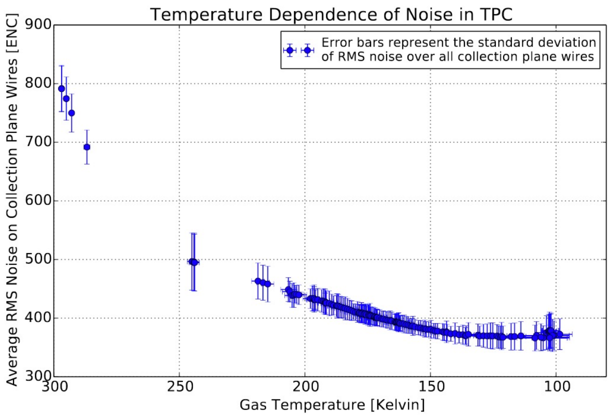


MicroBooNE's hardware R&D successes

- Successful development and long-term running of cold, low-noise electronics
- Excellent purity, x6 better than design, without evacuation
- Precision laser calibration system
- Signal processing calibration
- Stable, long-term running of large liquid argon detector – 2.5m drift distance, **500k interactions over 5 years**







μBooNE

Lessons Learned from MicroBooNE

- First use of cold front-end electronics in a LArTPC (JINST 12, P08003, 2017)
  - ASIC saturation: new generation ASICs now have additional input bias current settings
  - Wire vibrations: spacers have been added to support the anode wires in the design of new LArTPCs to reduce vibrations and wire motion from fluid flow
  - Misconfigured channels: additional electrostatic discharge protection has been added on the configuration pins in next generation ASICs
  - ASIC startup: design margin of the bandgap reference circuit has been increased in the new ASIC design to remove start-up problems
  - Electronics environment: additional attention is being paid to grounding during building construction (e.g., SBND, ICARUS) and during detector installation
  - Offline noise filtering: MicroBooNE noise filtering approach and code had an immediate impact on the analysis of DUNE 35 ton and ProtoDUNE data (JINST 12, P08003, 2017)
- Demonstration of very high argon purity without evacuation in a fully instrumented vessel (public note #1026)
  - Breakdown in high purity argon is a serious issue in the design of LArTPCs (JINST 9, T11004, 2014, JINST 9, P11001, 2014)
  - Very stable liquid argon purity can be achieved for years at a time with a properly designed cryogenics systems (public note #1026)
  - Argon delivery schedule should be well thought-out in advance; filling is the largest source of thermal gradients; can be controlled with heaters and gas flow
  - Learned that there is a trade-off between the requirements on argon purity and drift high voltage that has become an important part of planning for DUNE
- First use of a UV laser calibration system (public note #1055)
  - Electric field can be mapped using an in-situ steerable UV laser system; such a system is now under consideration for the DUNE far detector (JINST 9, T11007, 2014)
  - First high statistics measurement of space charge effects in a LArTPC comparing measurements from cosmics and UV laser (public note #1018)
  - UV laser system requires special maintenance – lessons learned from MicroBooNE experience are being communicated to SBND
  - Lessons learned for future UV laser system designs in LAr communicated in a public note to DUNE for TDR preparation (public note #1055)
- LArTPC calibrations and TPC signal processing
  - 2D-deconvolution improves reconstruction of particle tracks in liquid argon (JINST 13, P07006, 2018, JINST 13, P07007, 2018)
  - Multiple Coulomb scattering parameters tuned for argon (JINST 12, P10010, 2017)
  - Michel electron energy spectrum needs to be corrected for large radiative effects in argon (JINST 12, P09014, 2017)
  - Anode/cathode piercing muon tracks can be used to measure argon purity in real-time for detector monitoring and subsequent data analysis (public notes #2016, #1048)
  - ^{39}Ar beta decays as a possible calibration source for DUNE (public note #1050)
- Long Term LArTPC Operations
  - Lessons learned from commissioning MicroBooNE were documented and communicated to protoDUNE (MicroBooNE docdb #15878)
  - Developed means to inspect the integrity of wire planes inside a sealed cryostat (JINST 10, T08006, 2015)
  - Raised awareness of the need to be able to assess HV feedthrough connectivity during operations; developed novel means to use anode plane signals to assess real-time connectivity
  - Documented stability a LArTPC over years of operations (public note #1013)
  - MicroBooNE developed the first implementation of a continuous readout stream for supernova neutrino physics (JINST 12, P02017, 2017)
  - Serious thought should be given to the reduction of LArTPC data rates both through triggering and further development of data compression techniques
  - An unknown source of large single photoelectron rates can be present in a surface LArTPC which can impact triggering considerations and data rates; comparing rates with ProtoDUNE-SP
  - Experience from MicroBooNE operations led to plans for both overburden and cosmic ray taggers for the SBND and ICARUS detectors (JINST 14, P04004, 2019)
  - Developing CRT to TPC matching and sharing with SBN

MicroBooNE computing

We are the first LArTPC to produce complete data and Monte Carlo sets

- With a full suite of systematics

Thanks to SCD for incredible support for our processing and storage

We are now starting the push towards analysing Runs 4 and 5

- And the full NuMI data set

	2019 (actual)	2020 (actual)	2021 (actual YTD)	2022 (projected)	2023 (projected)
Cumulative storage needs (PB)	3.0	4.9	2.4	3.5	3.5
Grid computing needs (M CPU-Hr)	32.7	46.9	35.9	30	30

Summary

Our first searches for low-energy excesses are now released

- No evidence for excesses of ν_e or NC $\Delta \rightarrow N\gamma$

We have shown that liquid argon can perform precision neutrino physics analyses

- Multiple channels and topologies
- Reconstruction down to ~100 MeV
- Sidebands, systematics, detector response models, reconstruction algorithms…

We have demonstrated that the SBN programme, and DUNE, will produce world-class measurements from day one

We are now planning our next phase of analyses

- **MicroBooNE Phase II workshop happening later this week**