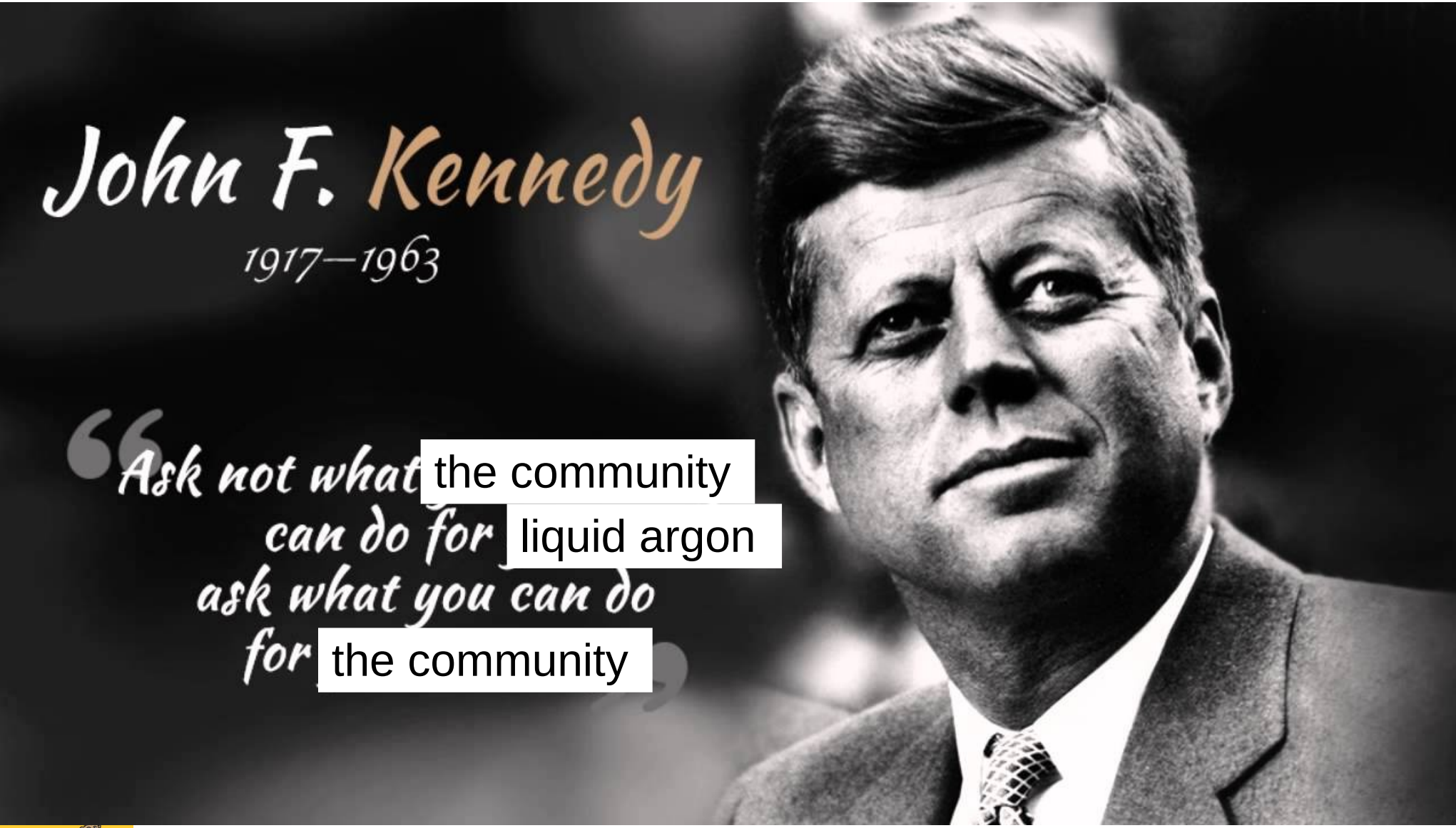
What current liquid argon experiments can do for you

Andrew Furmanski

ECT* workshop

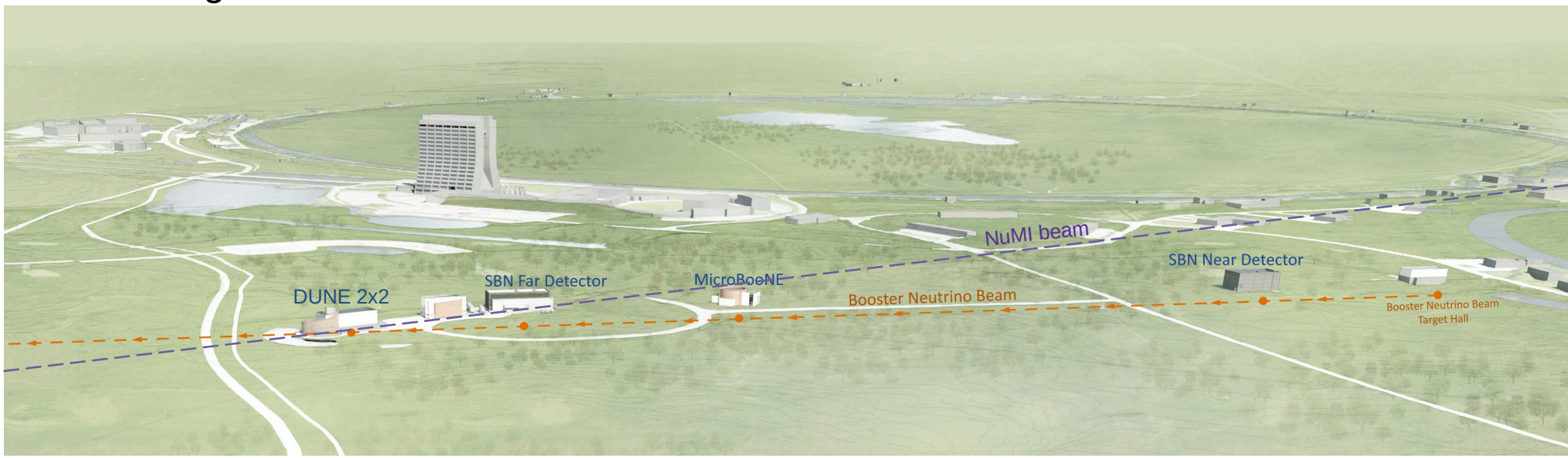
21st October 2024


John F. Kennedy
1917—1963
“Ask not what the community can do for liquid argon ask what you can do for the community”


Help From
LArLArLAND

The (LAr) Landscape

- I will discuss (almost) exclusively LArTPC neutrino detectors at Fermilab
  - SBND, MicroBooNE, ICARUS
  - DUNE “2x2”
  - ArgoNeuT



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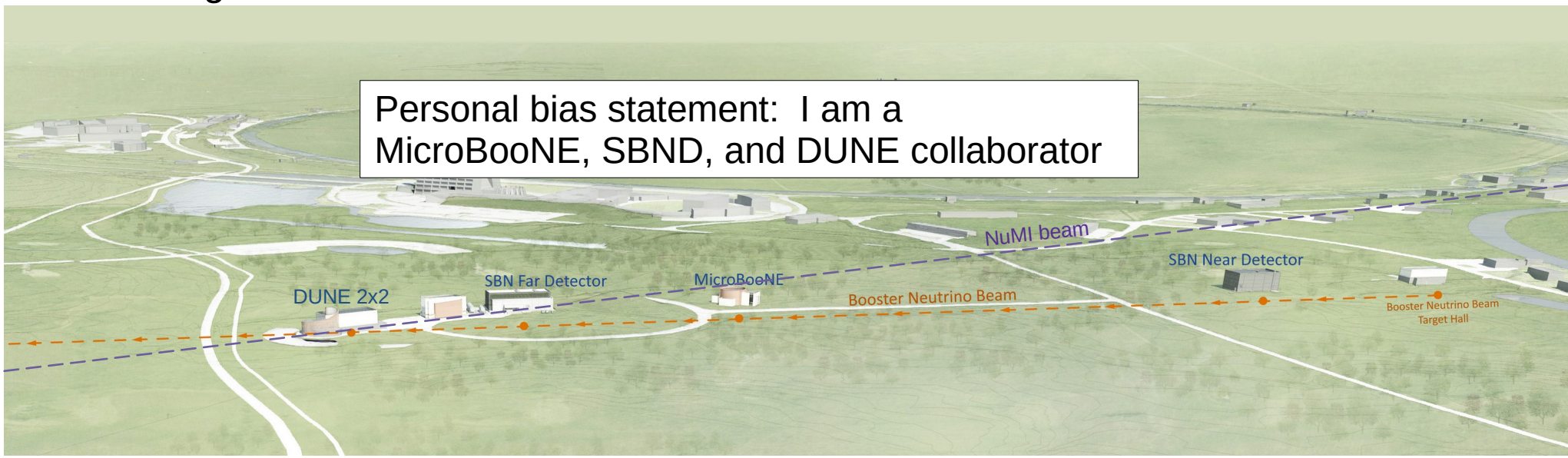
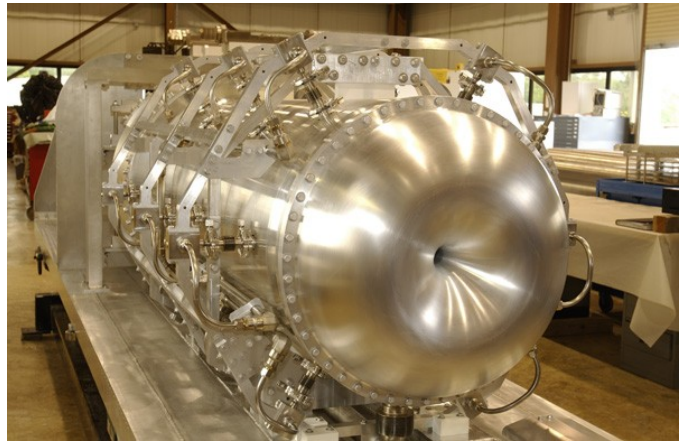
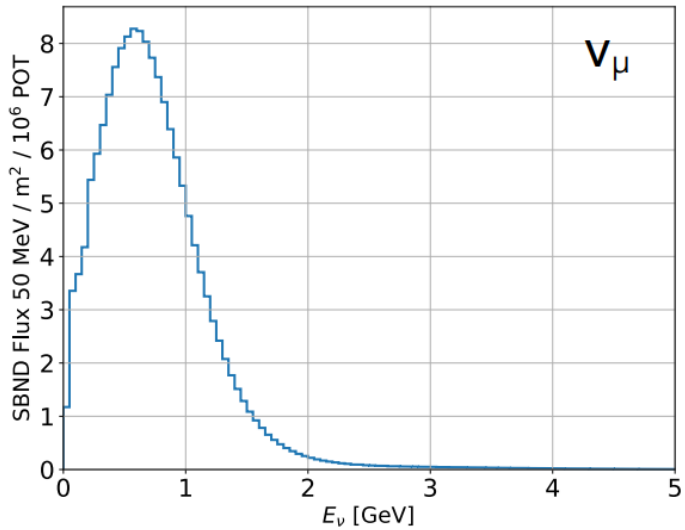


The Booster Neutrino Beam

- 8GeV proton beam
  - Directly from Fermilab Booster
- Berylium target
- Single focusing horn
- 50 decay pipe
- 600 MeV peak, 800 MeV mean
- 0.5% electron neutrino contamination



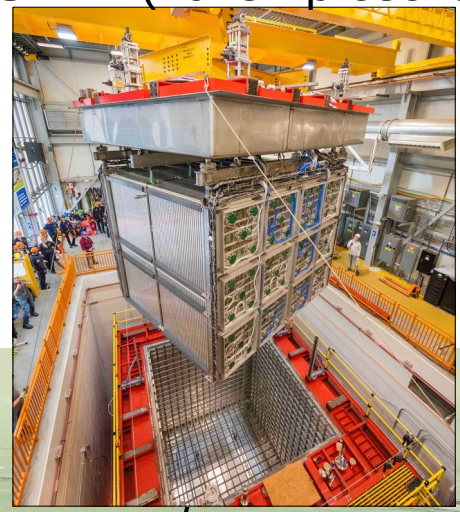


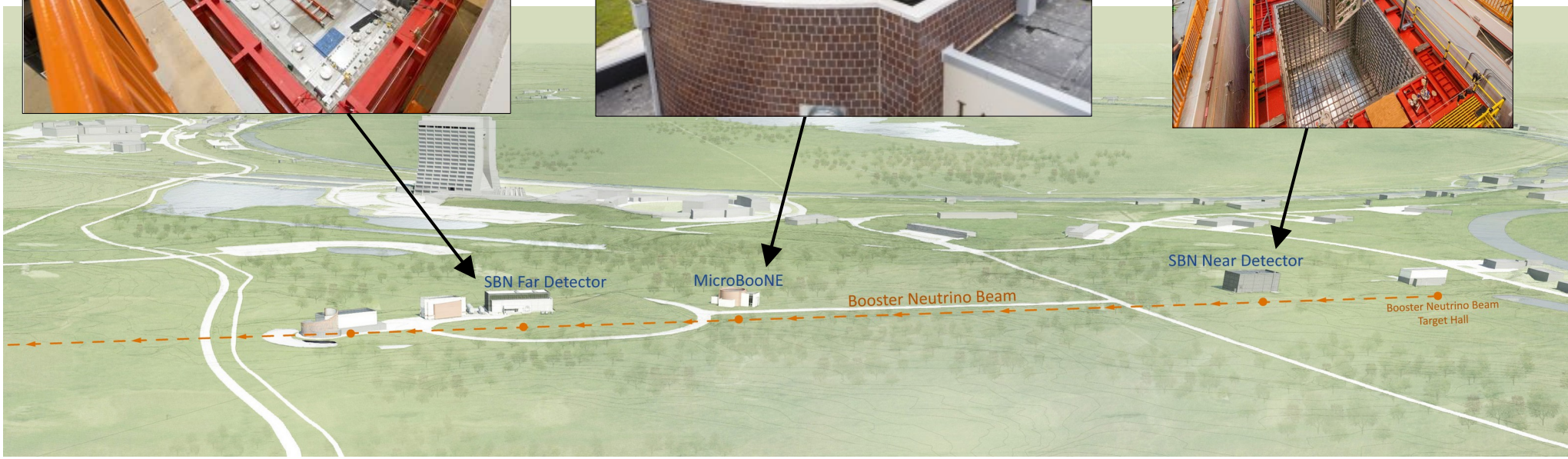
BNB experiments

ICARUS (2021 - present)

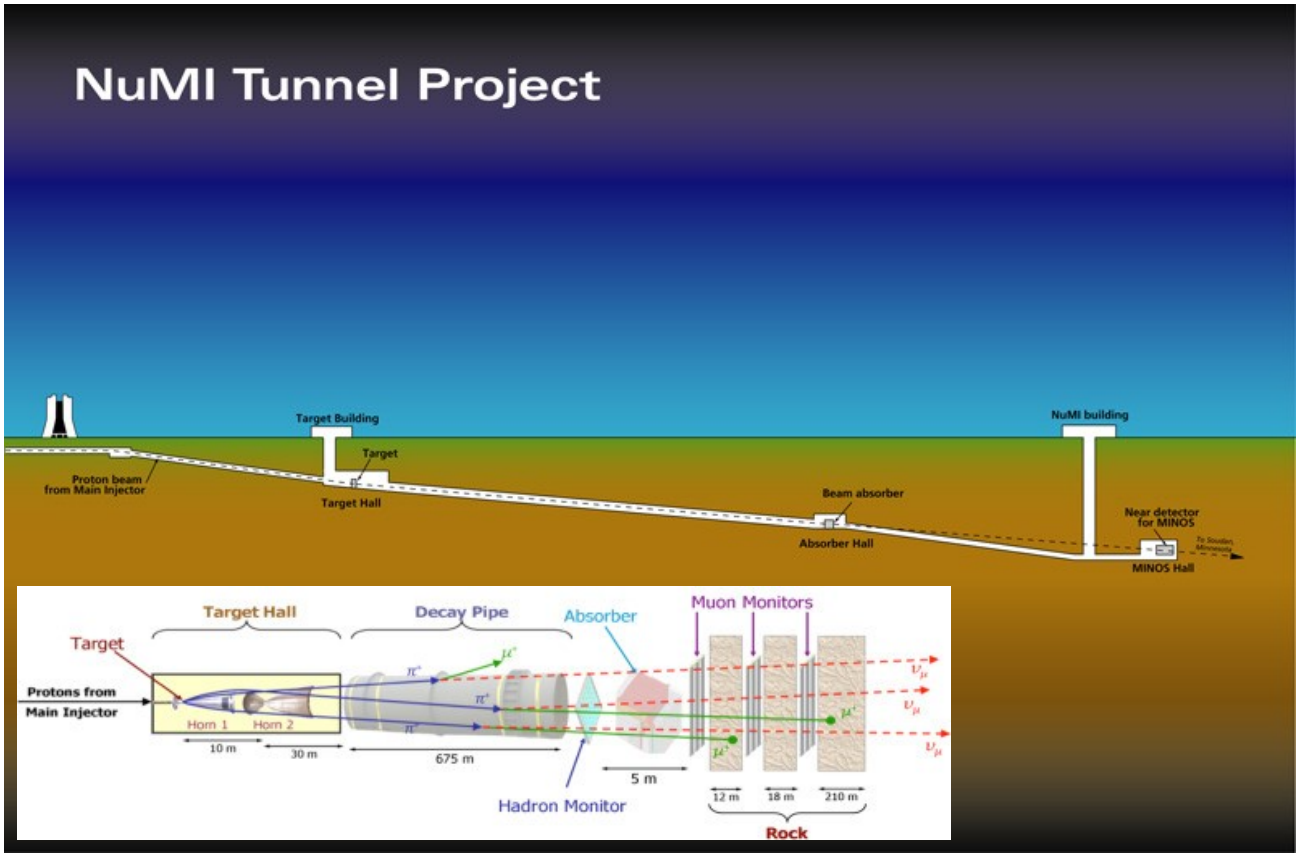
MicroBooNE (2015 - 2021)

SBND (2023 - present)

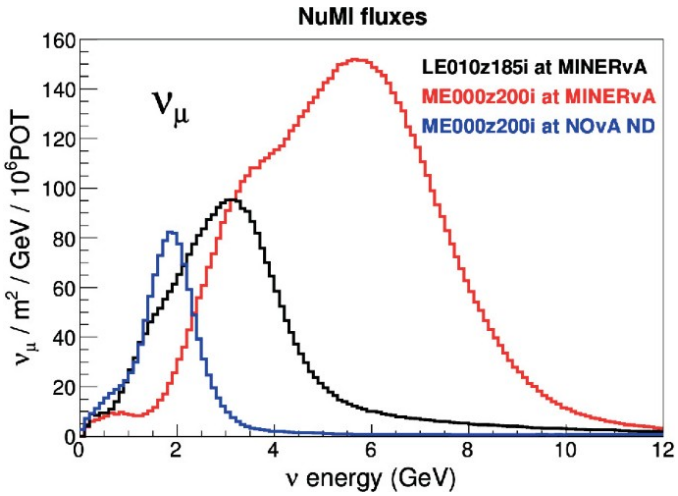




Neutrinos from the Main Injector

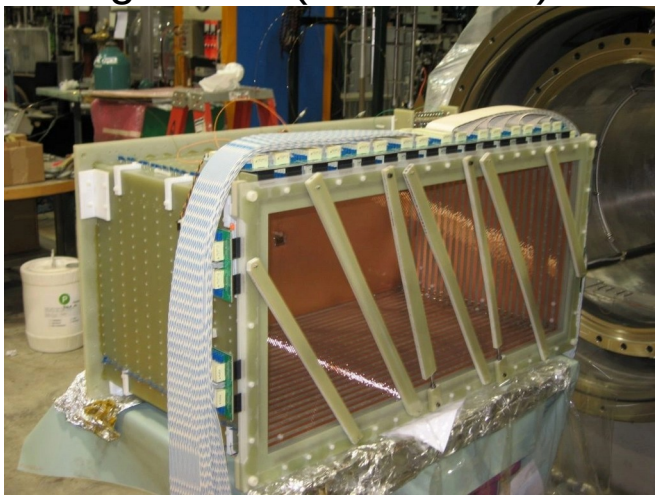


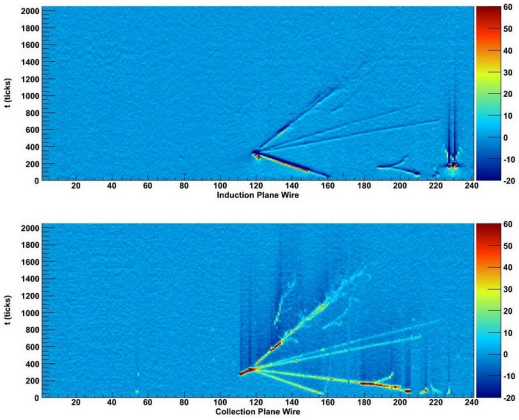
- NuMI beam built for MINOS
- 120 GeV protons
- Graphite target
- Two horns
- ~600m decay pipe
- Currently operating in “medium energy” tune, peak flux at ~7GeV



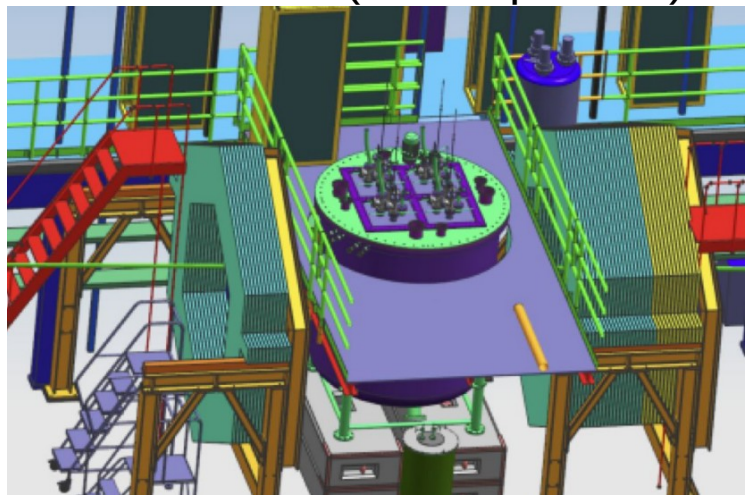
NuMI experiments

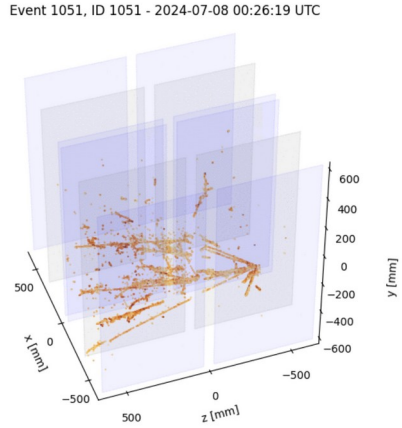
ArgoNeuT (2009-2010)



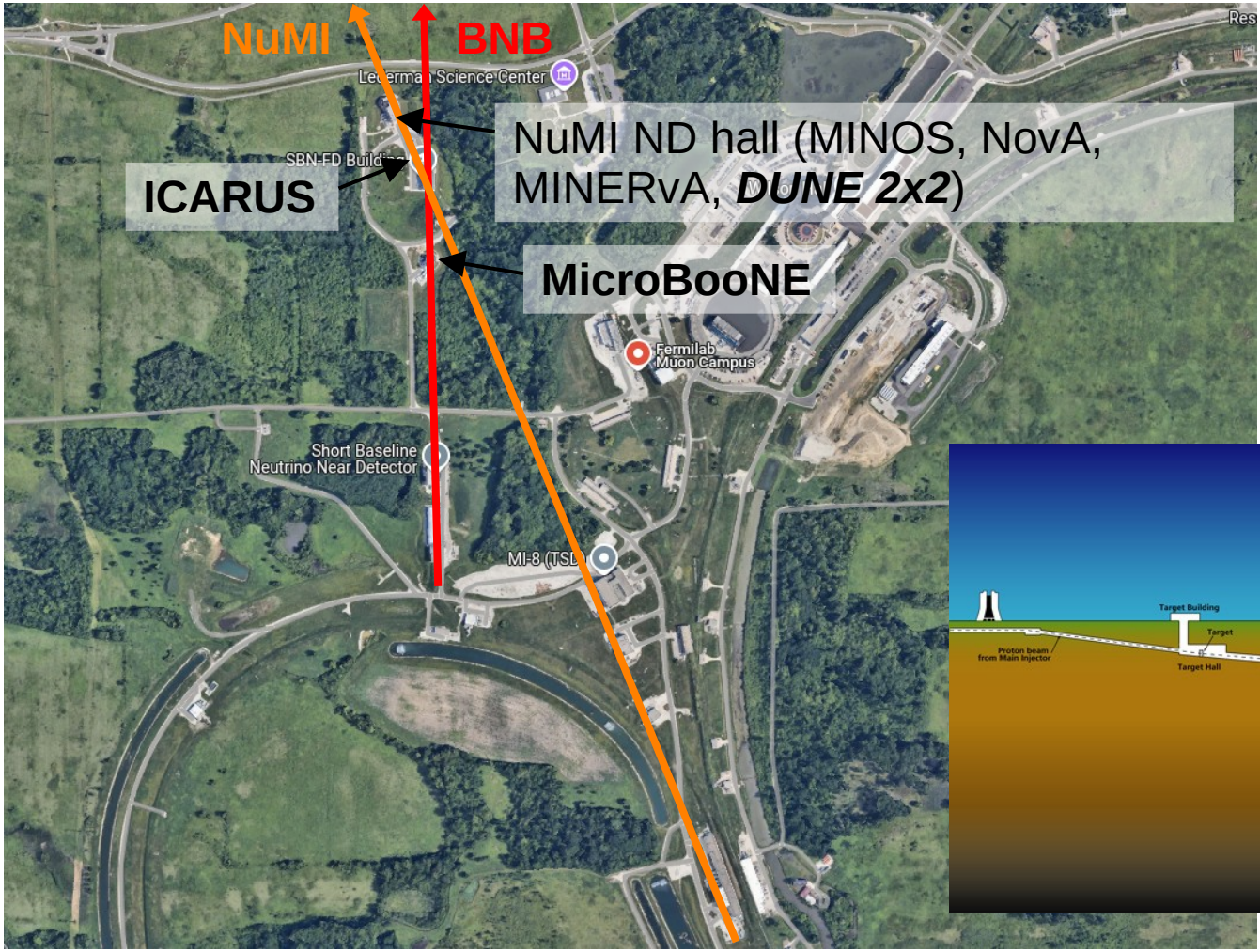


DUNE 2x2 (2024 - present)

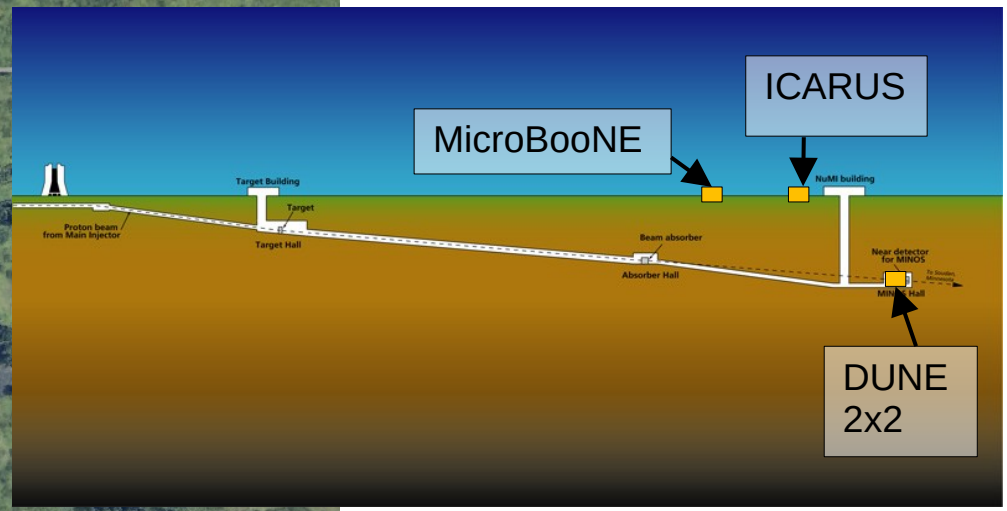




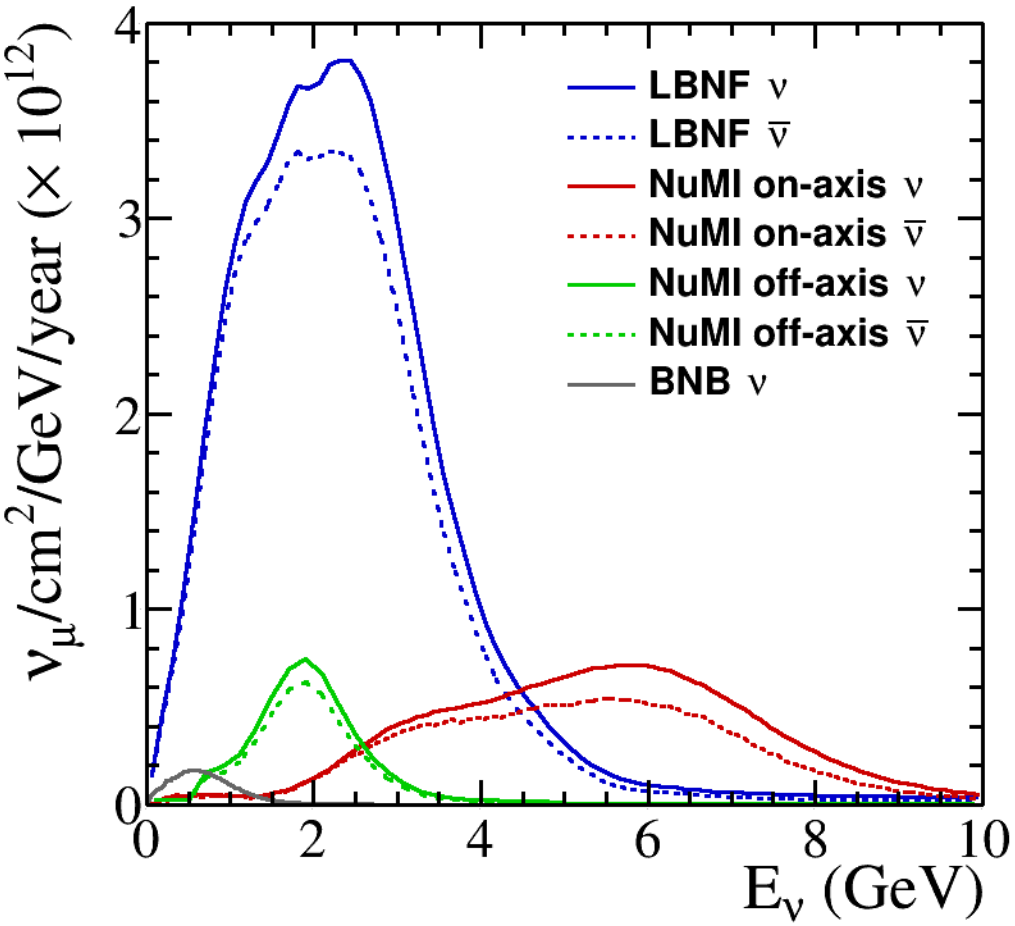
But wait, there's more!



- MicroBooNE and ICARUS exposed to (far) off-axis NuMI beam
- MicroBooNE furthest at 8 degrees



Energy Spectra



- BNB measurements cover low edge of DUNE flux
- NuMI (2x2) measurements cover high tail
- We won't get much data at the DUNE peak energies

What uncertainties matter?

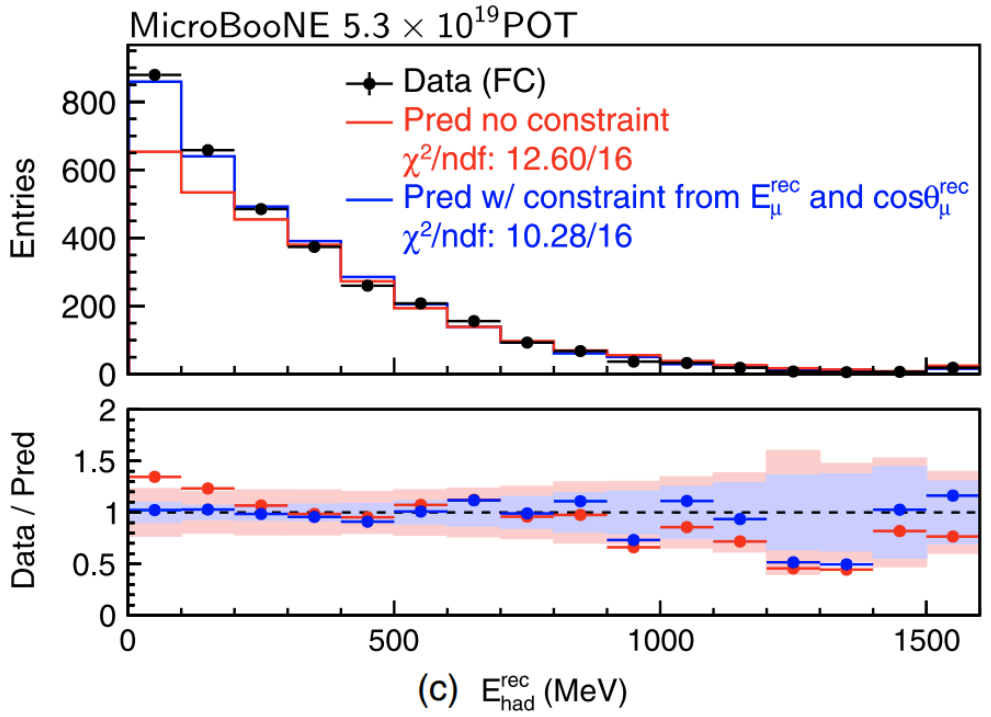
- For DUNE, neutrino energy estimation expected to rely on measuring all particles
- Corrections needed for:
  - Neutrons
  - Re-scattering pions and protons
    - Proton/pion confusion misses/adds pion mass
    - Energy loss in inelastic scatters
  - Any energy loss to nucleus, low-energy particles, etc
- No data will be at the right neutrino energy – focus on measuring things sensitive to FSI, missing energy, and generally test models as completely as possible

Existing data

- ArgoNeuT published 6 cross section measurements
  - Limited statistics, but still helpful
- MicroBooNE have 20 published cross section measurements
  - Mainly from BNB, but some NuMI
- I'll briefly highlight some of the most relevant for the future

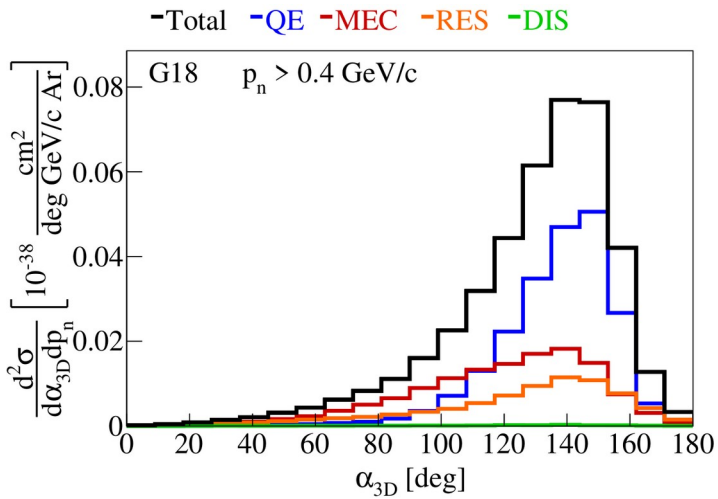
Missing Energy Search

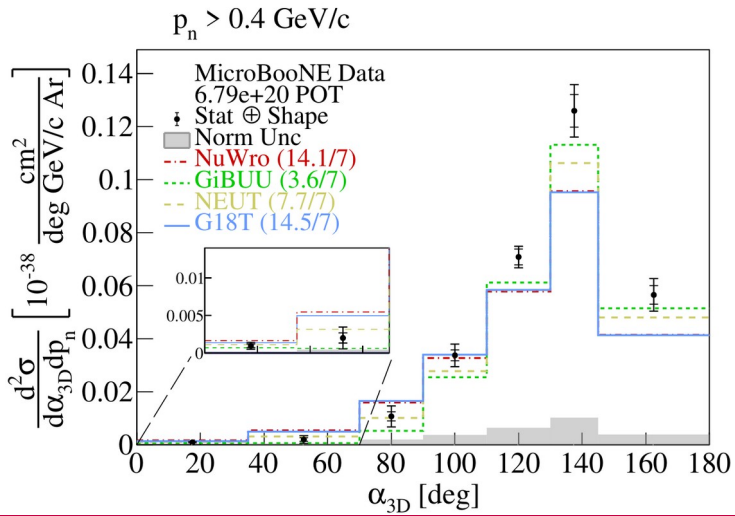
- Measure muon kinematics
- Build correlations with hadronic energy from MC
- Constrain hadronic energy prediction using measured muon kinematics
- If the model has too much or too little missing energy, the correlations will be wrong



Missing Momentum Measurement

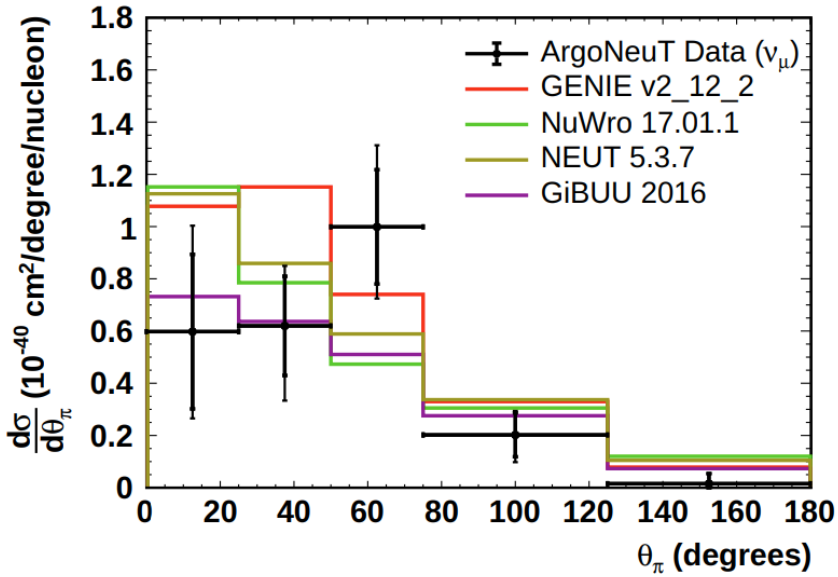
- Single-proton events, measure missing momentum (magnitude and direction)
- High missing momentum, direction distribution **sensitive to proton FSI**, and MEC/RES contributions
- Indication that only GiBUU has sufficient proton rescattering

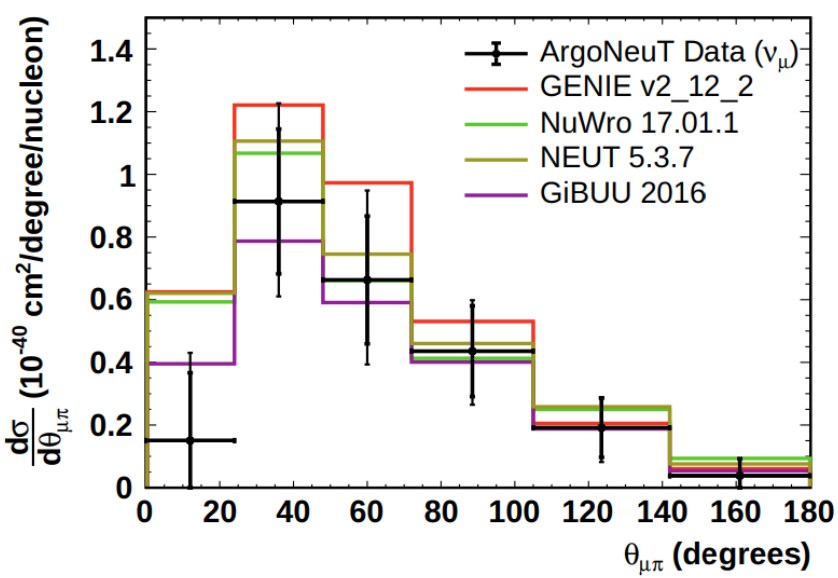




Charged pions

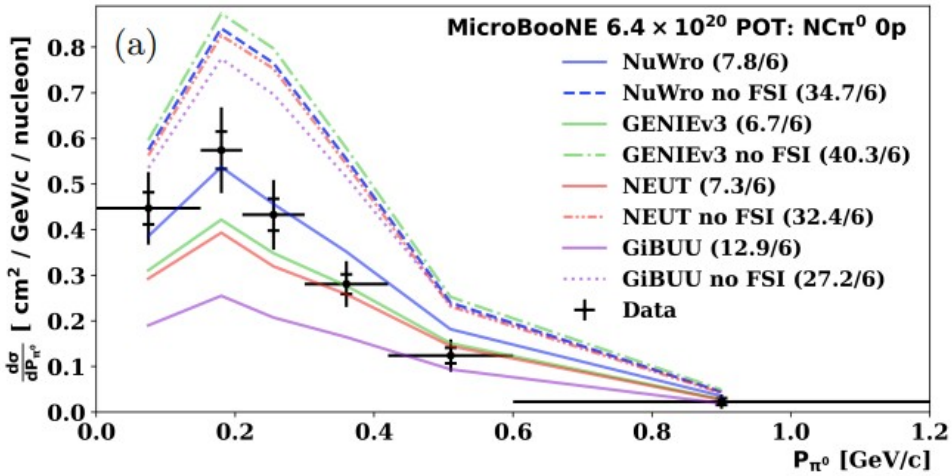
- One measurement so far, from ArgoNeuT
- Purity very low (10%) as pions and protons regularly uncontained

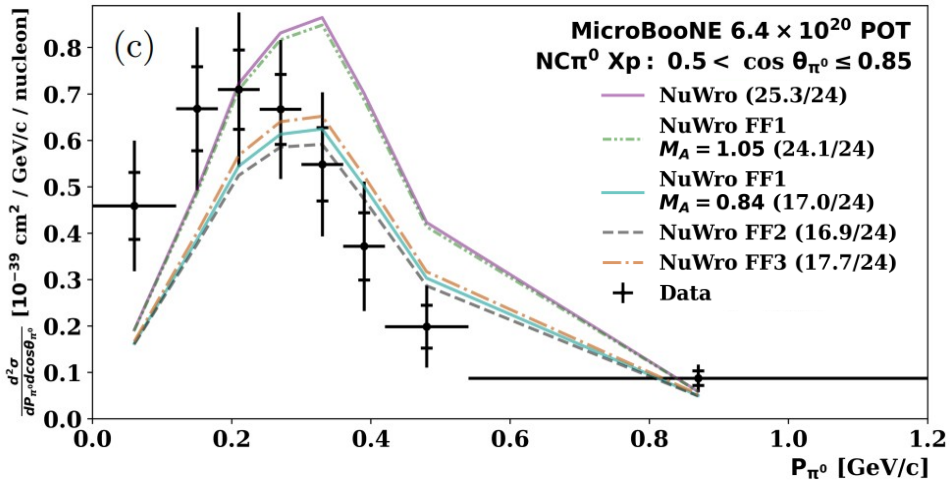


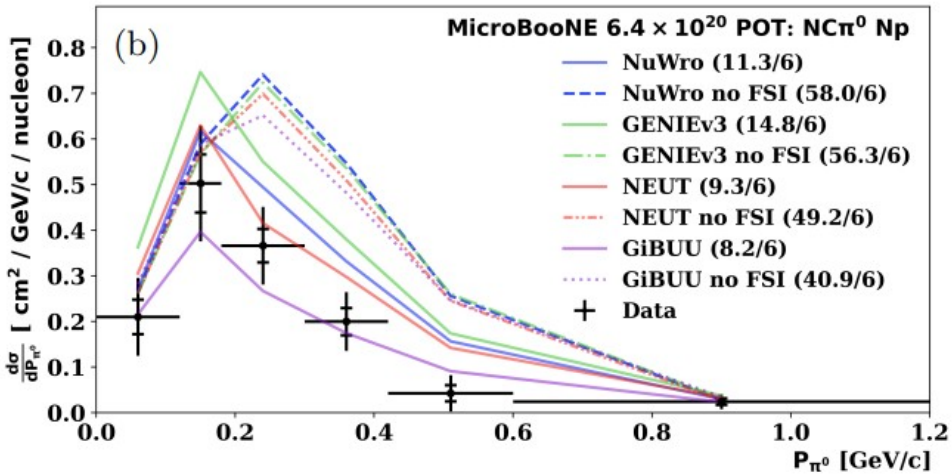


Neutral pions

- Almost 5000 NCπ^0 events
- Double-differential in π^0 kinematics
- Also separated by presence or absence of accompanying protons
- Clear impact of pion FSI

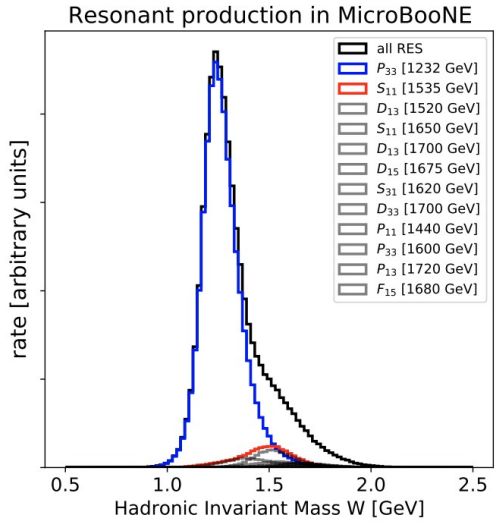


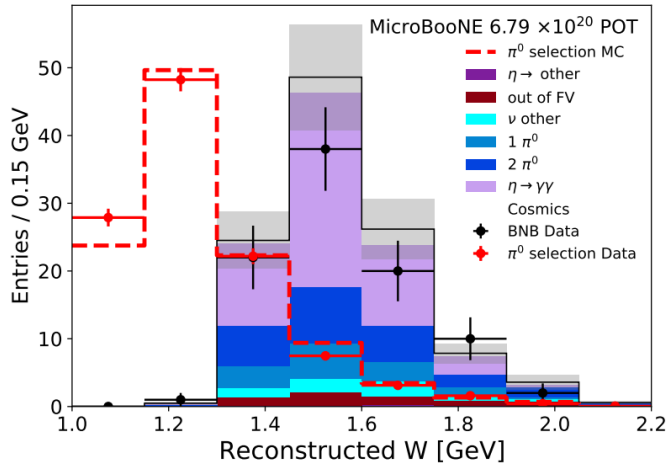




Heavier mesons

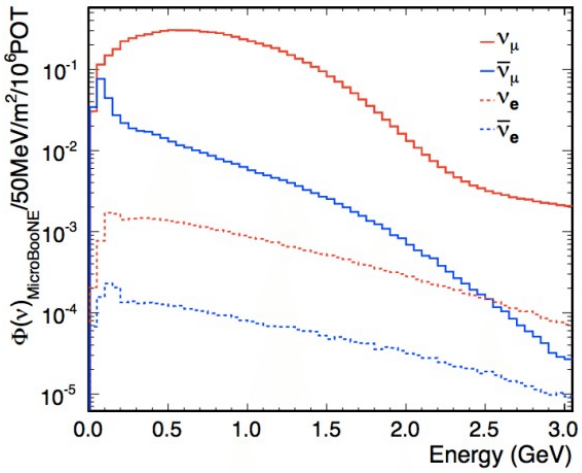
- Mesons heavier than pions can't be produced by a Δ(1232) resonance
- Measurement of η production sensitive to higher order resonances
- Can't easily separate this contribution with pions

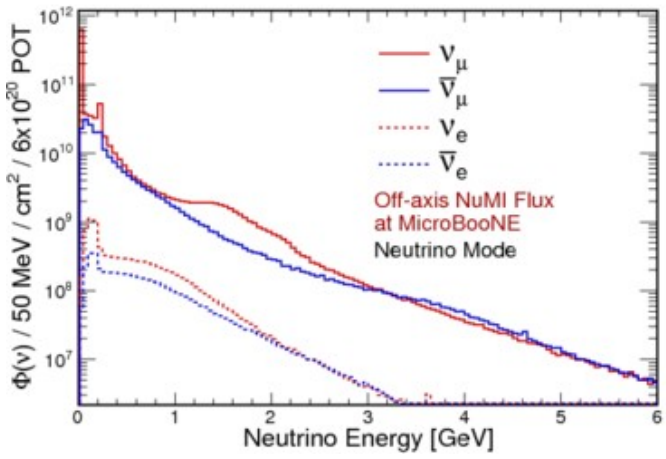




Electron neutrinos

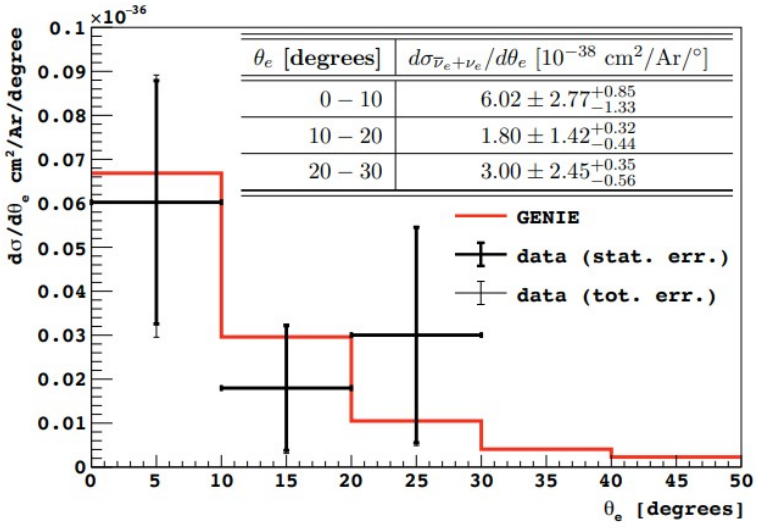
- Electron neutrinos are hard to come by
- NuMI has much higher ν_e contamination than BNB
  - Higher proton energy → more kaons → more electron neutrinos
- This is true both on- and off-axis

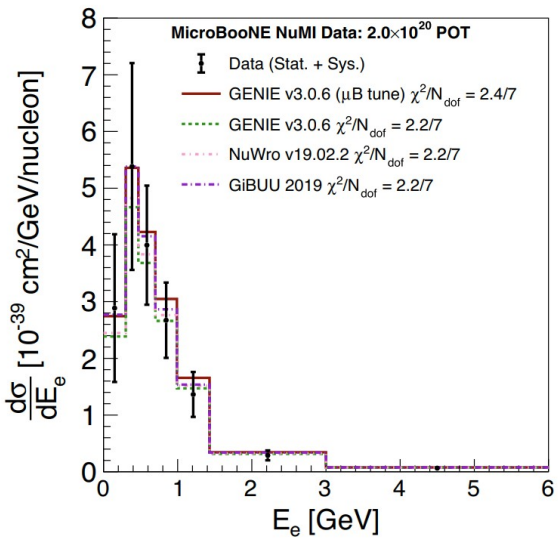


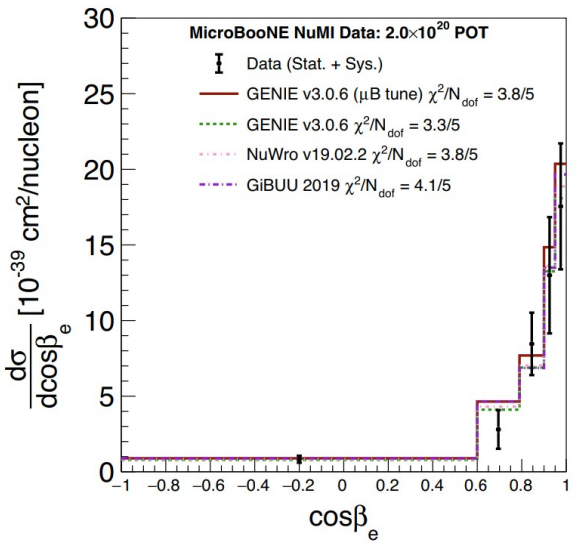


NuMI measurements

- 13 events from ArgoNeuT
- ~200 events from MicroBooNE
- Both neutrino/antineutrino mixes
  - No charge ID, and for MicroBooNE, large wrong-sign contamination

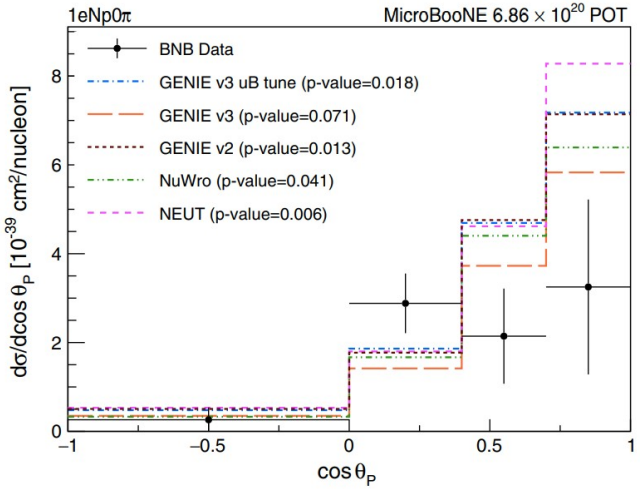


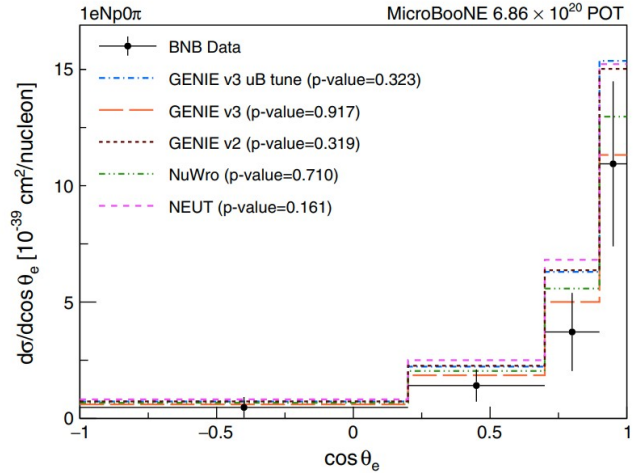




BNB measurements

- BNB measurement lower statistics
  - Only 0.5% electron neutrinos
- But pure(ish) neutrino
- Measurement is pionless, and includes proton kinematics



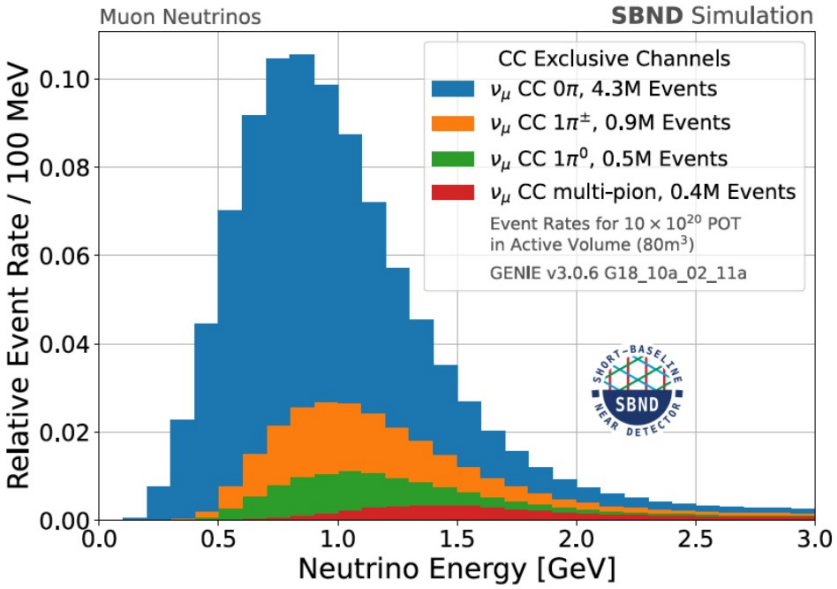


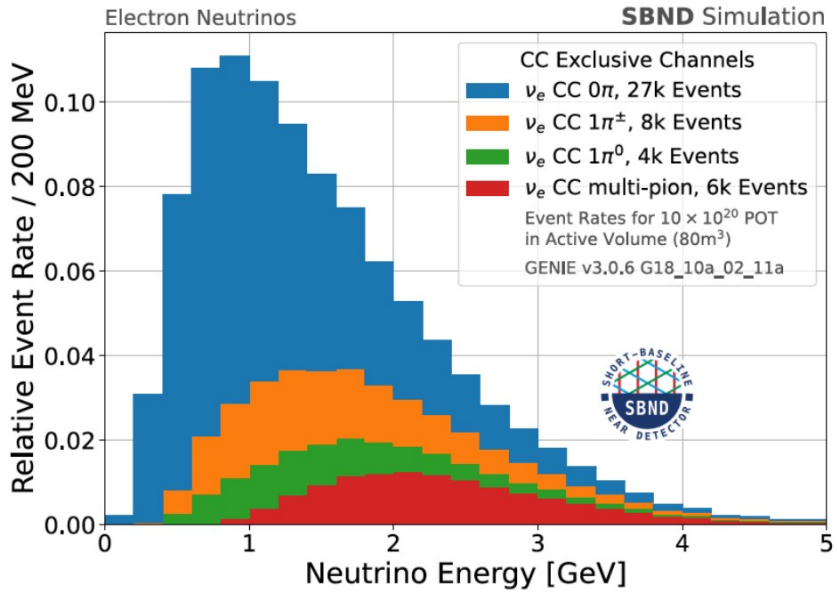
Improvements on the way

- Future measurements will begin to include:
  - Higher statistics
  - Reduced uncertainties
  - Correlated measurements
  - Additional neutrino fluxes
  - More particles

SBND statistics

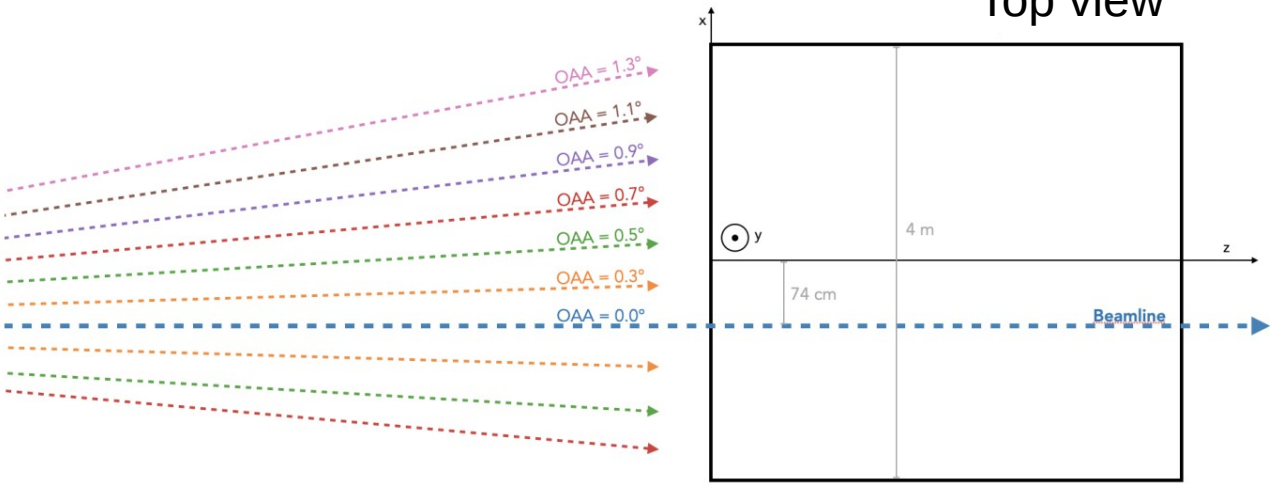
- SBND is ***very*** close to the beam
- Millions of neutrino interactions per year
- 30x MicroBooNE dataset



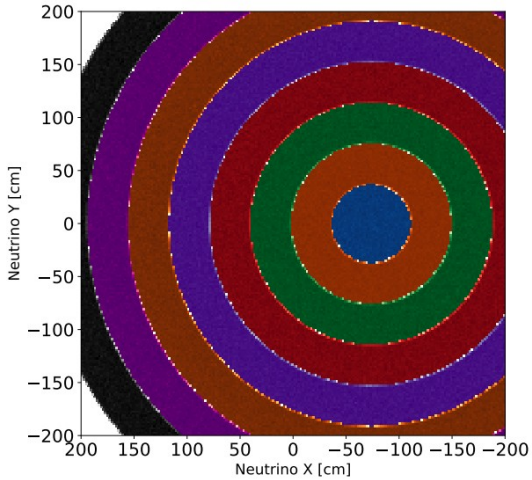


SBND-PRISM

Top view



Beam view



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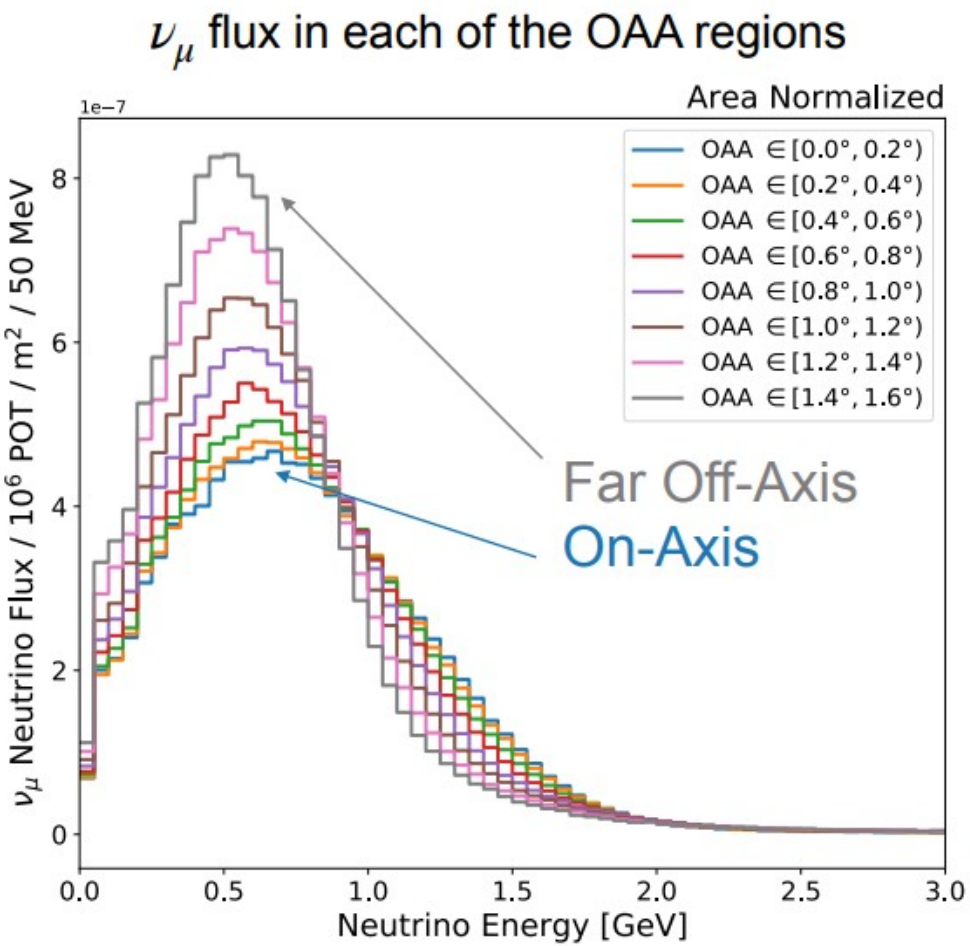
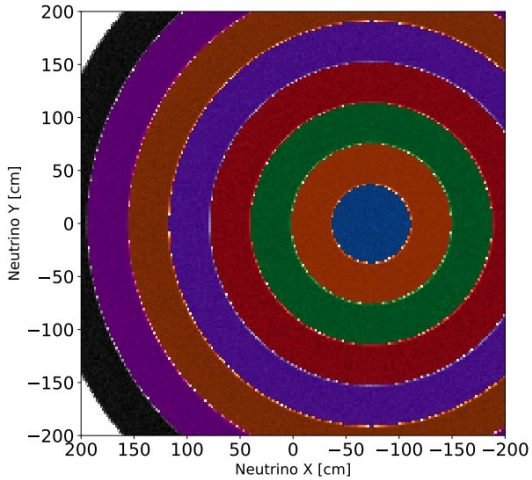


Beam view

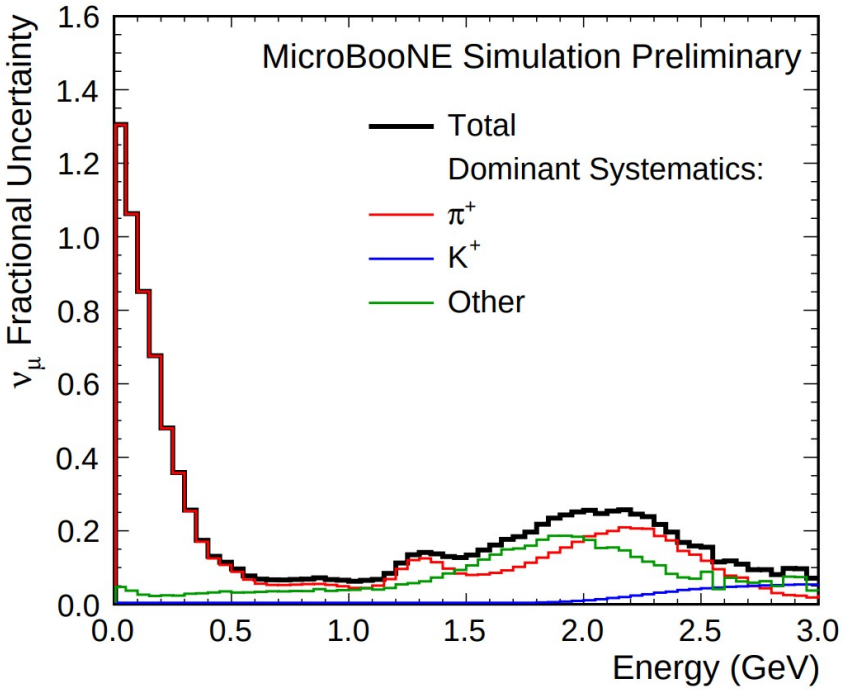


Vary energy dependence by scanning position in detector

Constrain energy dependence of cross sections directly

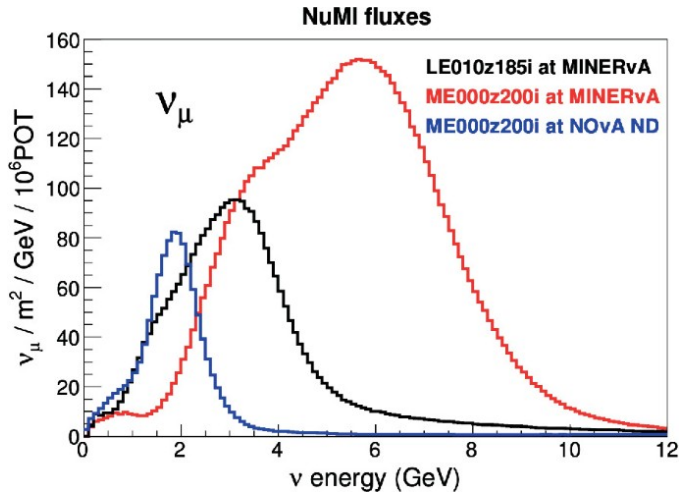
BNB flux uncertainties

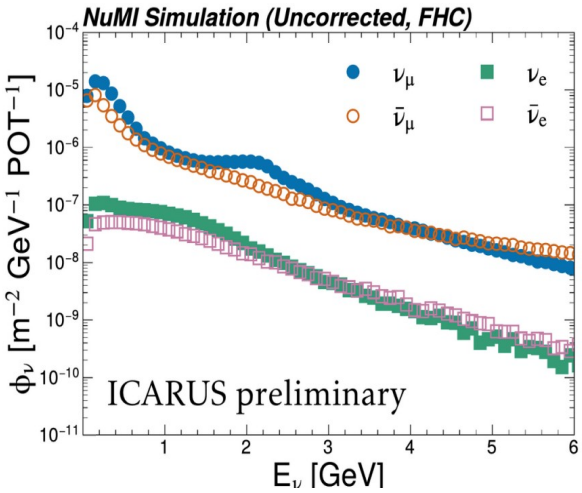
- Pion production in p-Be interactions dominates BNB uncertainty
- Primarily unconstrained phase space (low momentum, high angle pions)
- New data from NA61/SHINE and EMPHATIC is expected to reduce this
- Hope to combine with in-situ v-e scattering constraint at SBND (around 500 events expected)

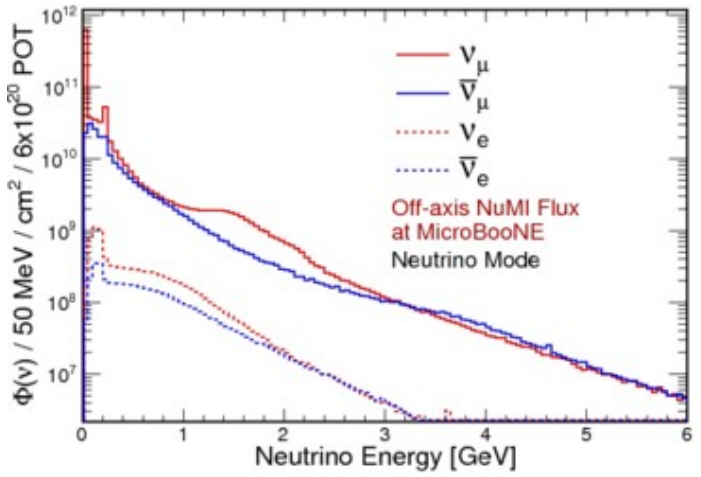


The many NuMI fluxes

- DUNE 2x2, ICARUS, and MicroBooNE see three different, correlated neutrino fluxes

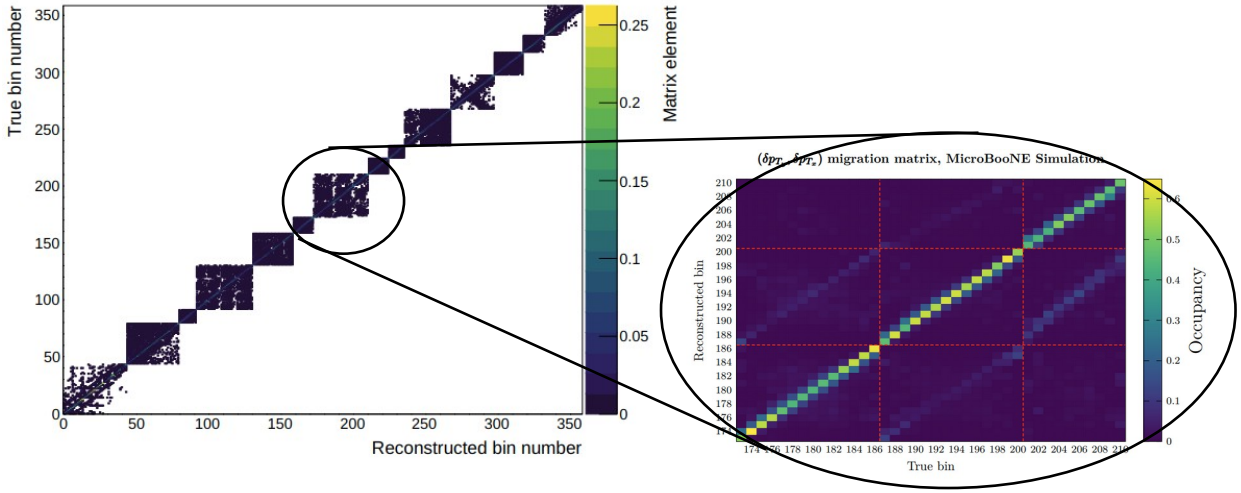


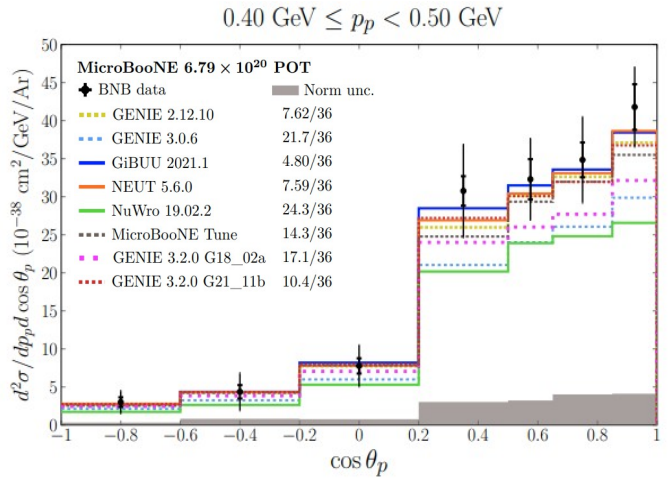




Correlations

- Recent MicroBooNE measurements demonstrate including correlations between:
  - Different 1D/2D projections of the same events
  - Different final states





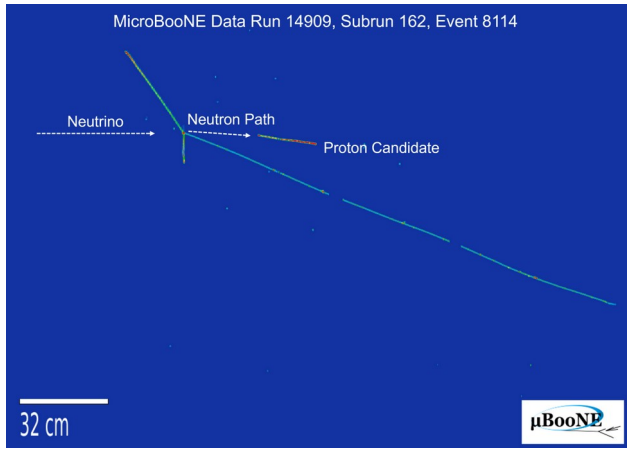
Model	χ^2 / 359 bins
GENIE 3.0.6	1859
NEUT 5.6.0	2582
MicroBooNE Tune	2673
GENIE 3.2.0 G21_11b	2947
GiBUU 2021.1	4836
NuWro 19.02.1	5315
GENIE 3.2.0 G18_02a	5724
GENIE 2.12.10	7799

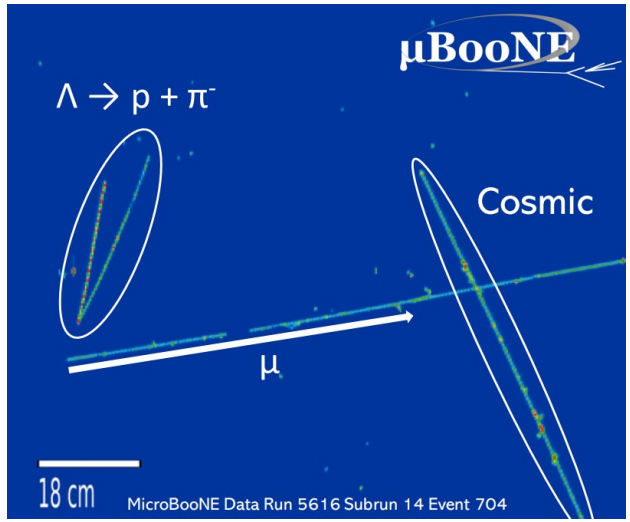
Future correlations

- Hope to include correlations across multiple analyses in future
- SBND-PRISM will include correlations between different energy spectra from the BNB
- In principle, with the right agreements in place… same measurement at MicroBooNE and ICARUS in correlated but different NuMI spectra!

New signatures

- More charged pions
  - Challenging due to hadronic interactions
  - Lots of these at DUNE 2x2!
- Neutrons
  - Challenging due to lack of interactions
  - Some *chance of measuring neutron energy* in DUNE 2x2 with optical segmentation
- Strange particles
  - Maybe won't be game-changing, but it's fun!



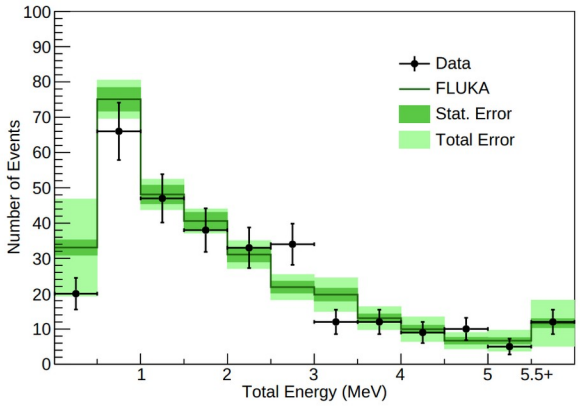


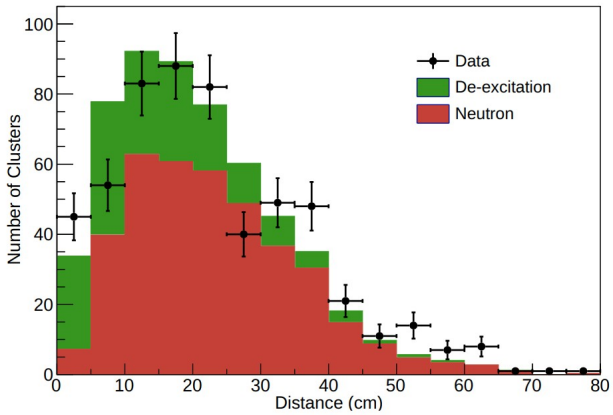
Things I can’t promise

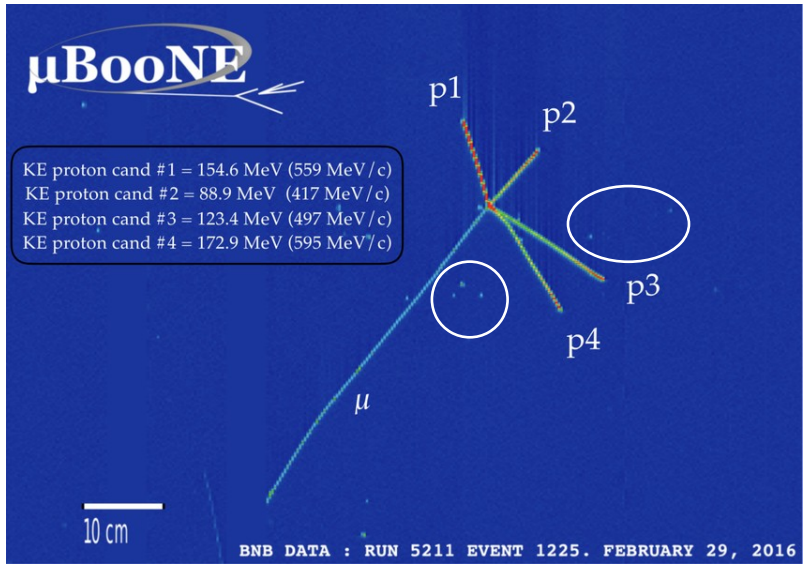
- Some signatures can in principle be measured
- These analyses are challenging and I can’t guarantee they’ll be done
- But they’d certainly be interesting and useful...

De-excitation photons

- Nucleus left in excited state
- Nucleus de-excites, producing MeV-scale photons
- We can see these, and in principle we can measure their energies
- There's information here, if we can figure out what to do with it



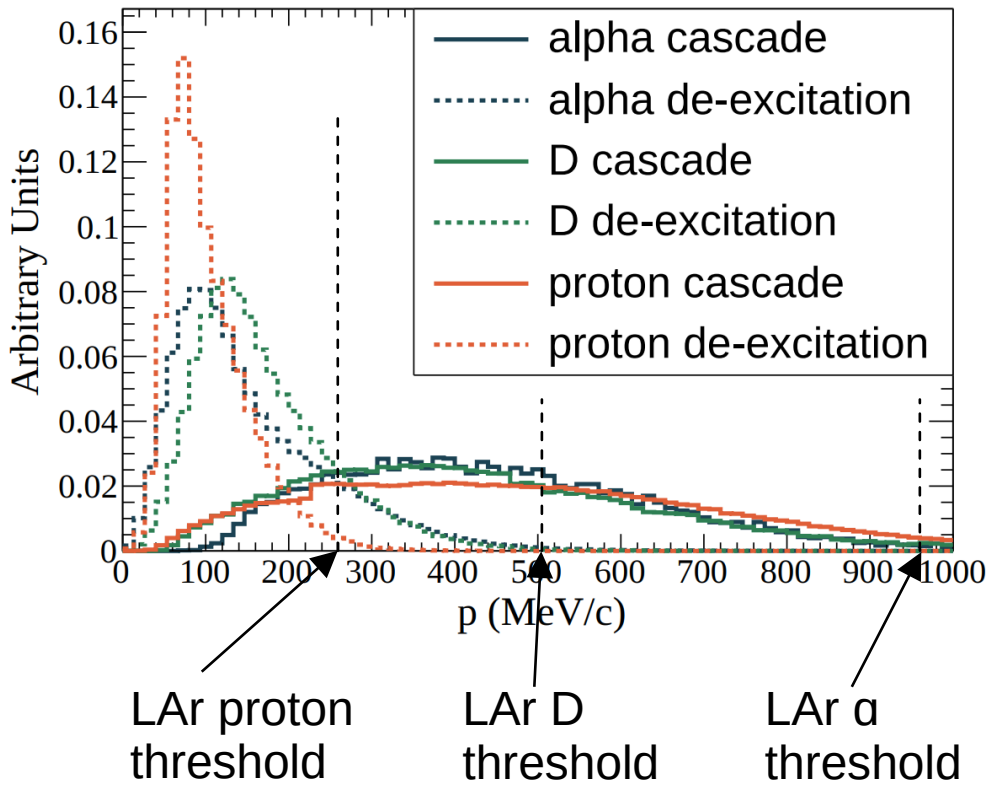




Nuclear Fragments

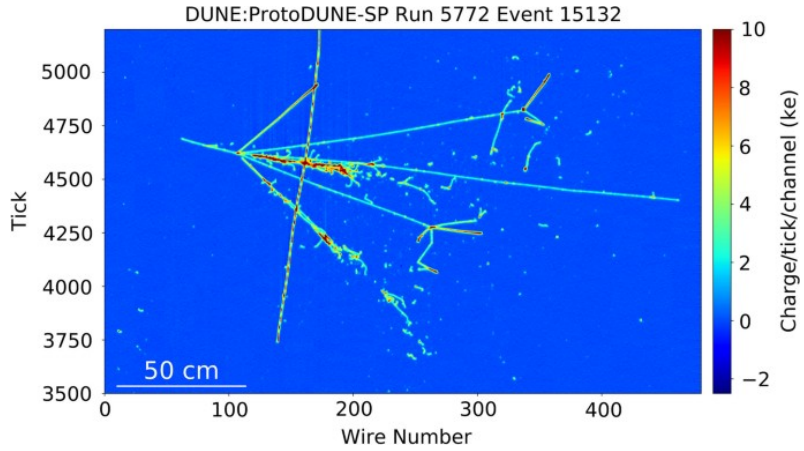
Caveat: figure is for T2K flux on carbon...

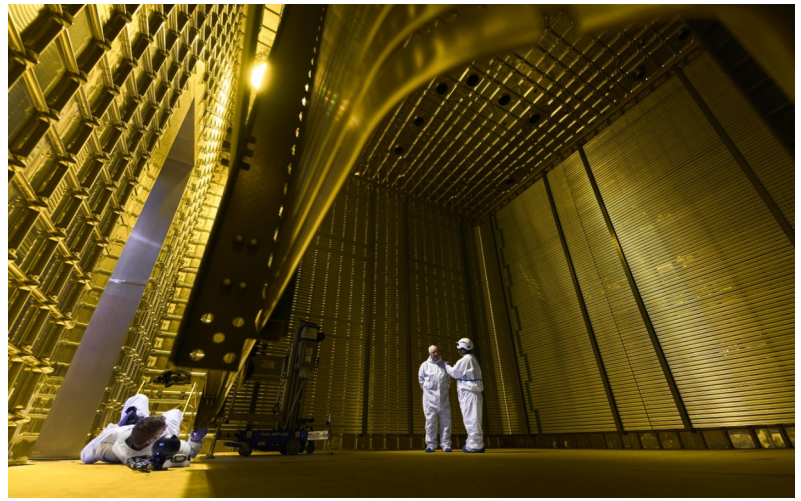
- *Some* nuclear fragmentation might be visible above threshold
- Particularly deuterons, but a few alphas
- SBND, should get enough events to measure the tail of this distribution
  - DUNE 2x2 might see a harder spectrum with higher neutrino energies
- We now have some predictions of these spectra – what uncertainties are reduced by measuring these?



Non-neutrino liquid argon

- ProtoDUNE measurements of secondary interactions
- Reduce detector response uncertainties
- Potentially provide data to constrain FSI through h-Ar interactions





Timelines

- ArgoNeuT data collection ended in 2010
- MicroBooNE data collection ended in 2021
  - First analyses using full dataset have been released, more to come
- SBND, ICARUS, DUNE 2x2 all expect to collect data until Fermilab long shutdown (2027)