Pion Production Cross Sections and Rare Searches with MicroBooNE

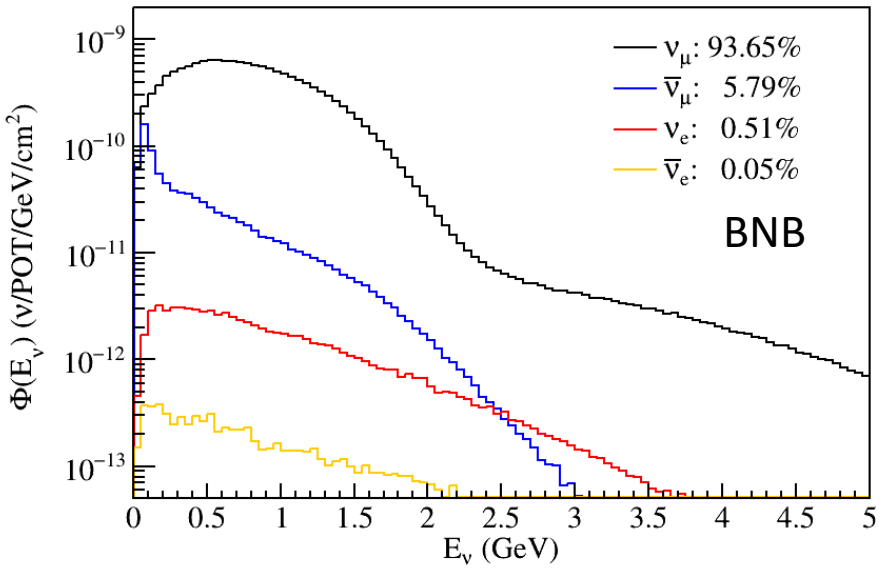
Patrick Green, on behalf of the MicroBooNE collaboration

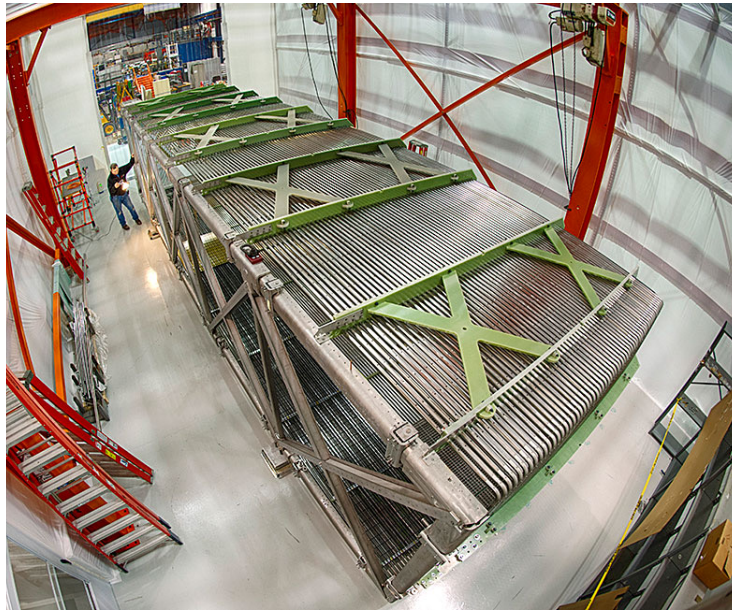
University of Oxford

MicroBooNE experiment

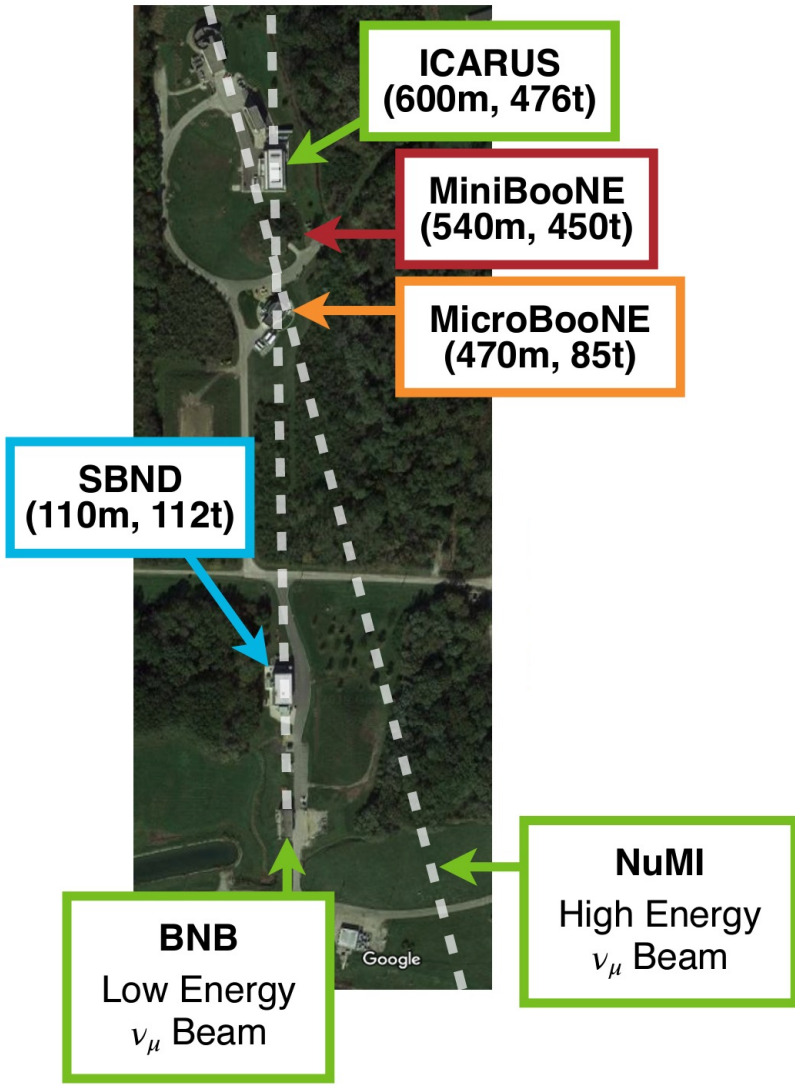
MicroBooNE is an 85-tonne active mass LArTPC at Fermilab, US:

- fully active tracking calorimeter, mm-level resolution and low thresholds
- two neutrino beams: BNB (8 GeV, on-axis), NuMI (120 GeV, 8° off-axis)
- 5 years of beam data 2015-2020, over 500k neutrino-Argon interactions





Fermilab Neutrino Campus



Neutrino interaction measurements at MicroBooNE

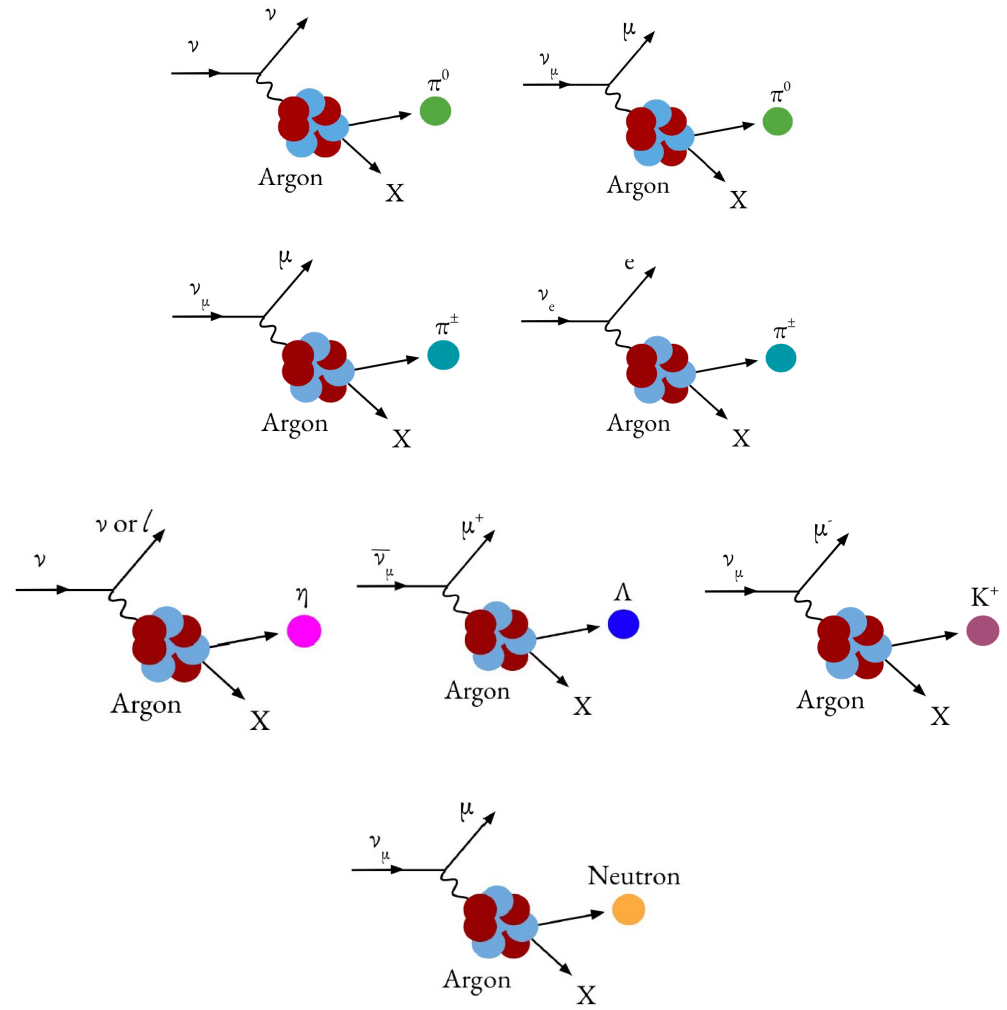
MicroBooNE has an extensive neutrino interaction cross-section measurement program:

- over 20 published measurements
- many more ongoing, including first full data-set analyses

Previous MicroBooNE cross-section talk focused **ν**-Ar inclusive and pion-less measurements (D. Barrow)

This talk:

1. **ν**-Ar pion topologies, as probe of resonant production
2. rare processes including η, Λ and K production
3. neutrino-induced neutron identification



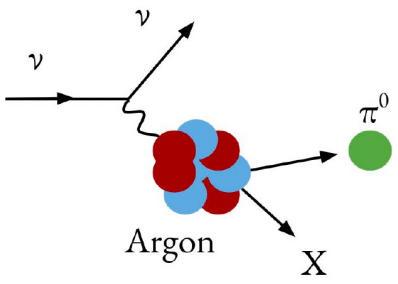
π^0 production measurements

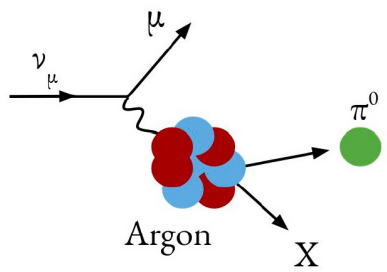
Charged and neutral current π^0 production measurements on Argon performed with MicroBooNE:

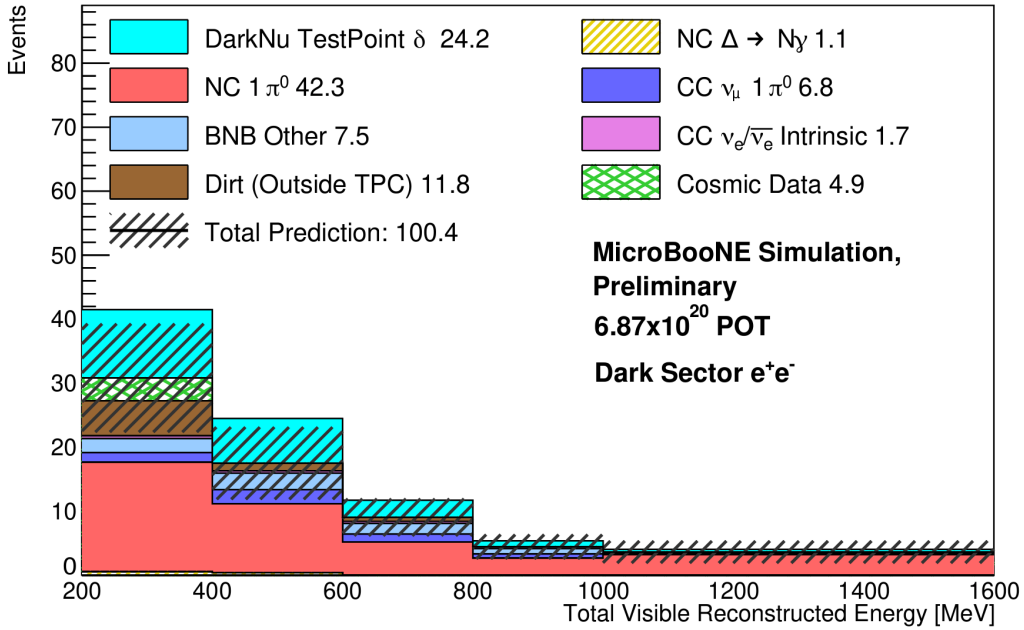
- production dominated by Δ(1232) resonances, allows us to probe the modelling of this process

Plays significant role in ν_e appearance studies

Forms dominant background for single photon and e^+e^- beyond the standard model searches



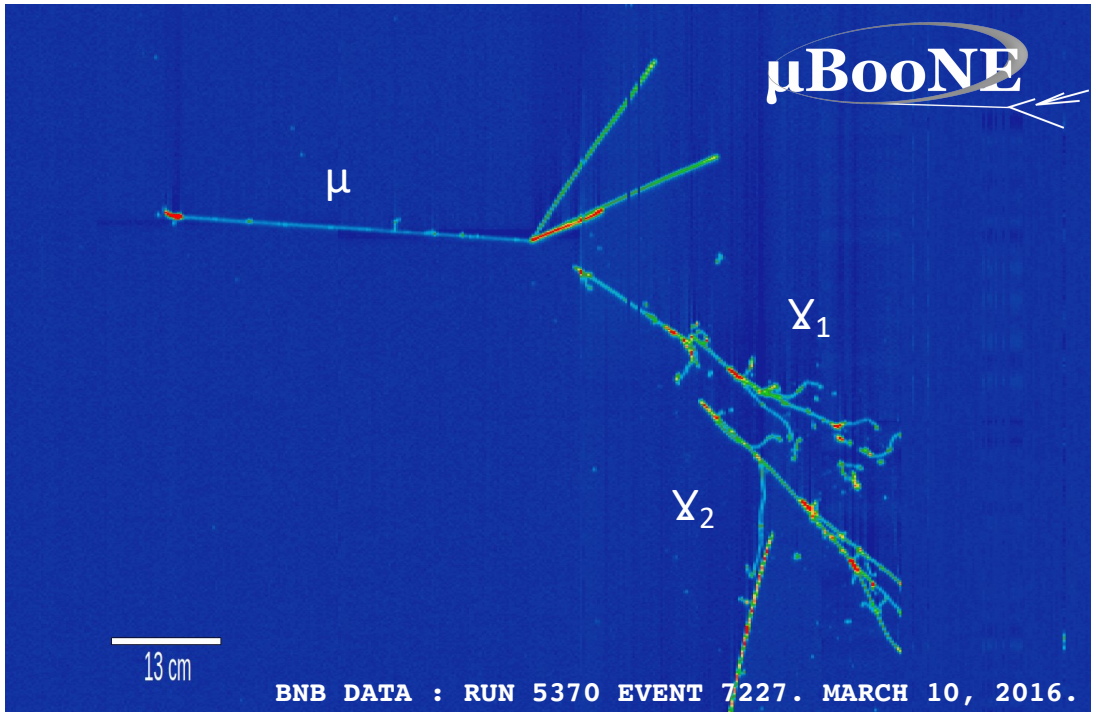




See talks by F. Gao and E. Yandel

Charged-current π^0 measurement

arXiv: 2404.09949



Select: $\boldsymbol{\nu_\mu}$ + Ar → $\boldsymbol{\mu^-}$ + π^0 + 0 $\pi^\pm$ + X

- muon candidate
- two photon shower candidates
- no charged pions, any number nucleons

1392 candidate events, with 69% purity

- 6.86×10^{20} POT, runs 1-3 data

Extract differential cross-sections in:

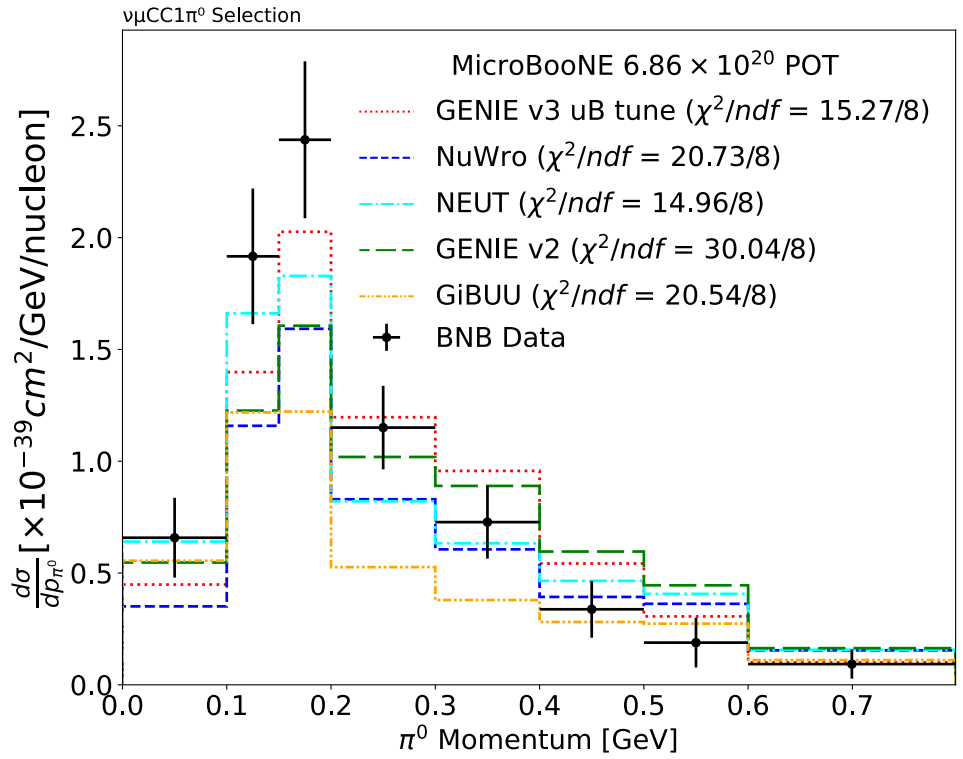
- π^0 and $\boldsymbol{\mu}$ momentum and angle
- $\boldsymbol{\mu}$ - π^0 opening angle

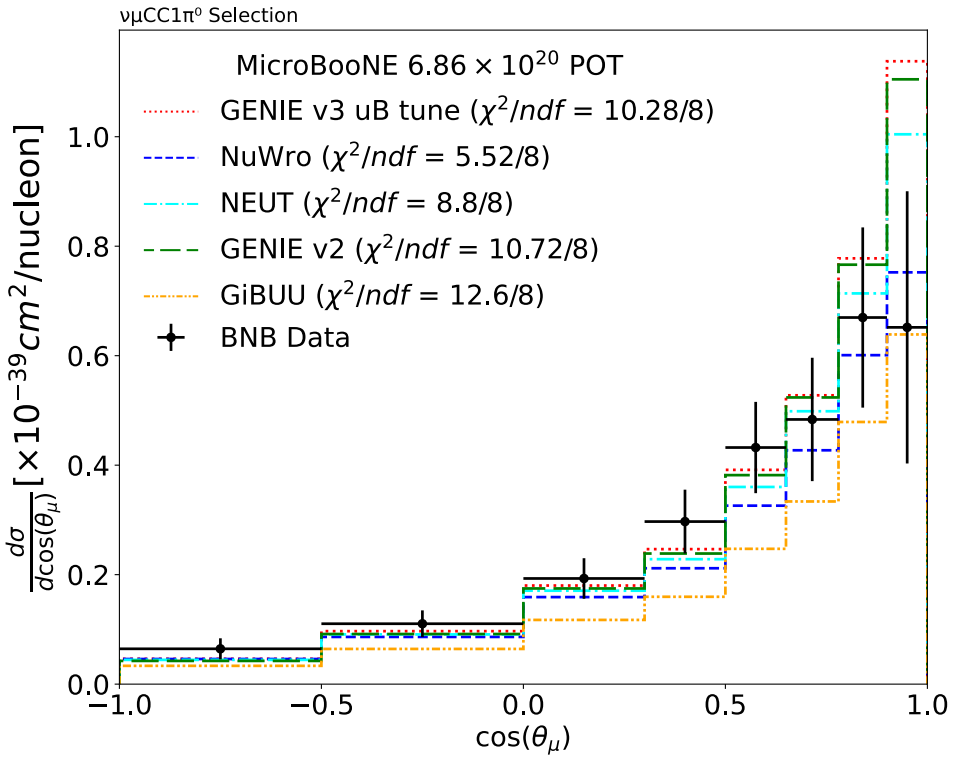
Charged-current π^0 measurement

arXiv: 2404.09949

Mismodeling identified in π^0 momenta and forward muon angles

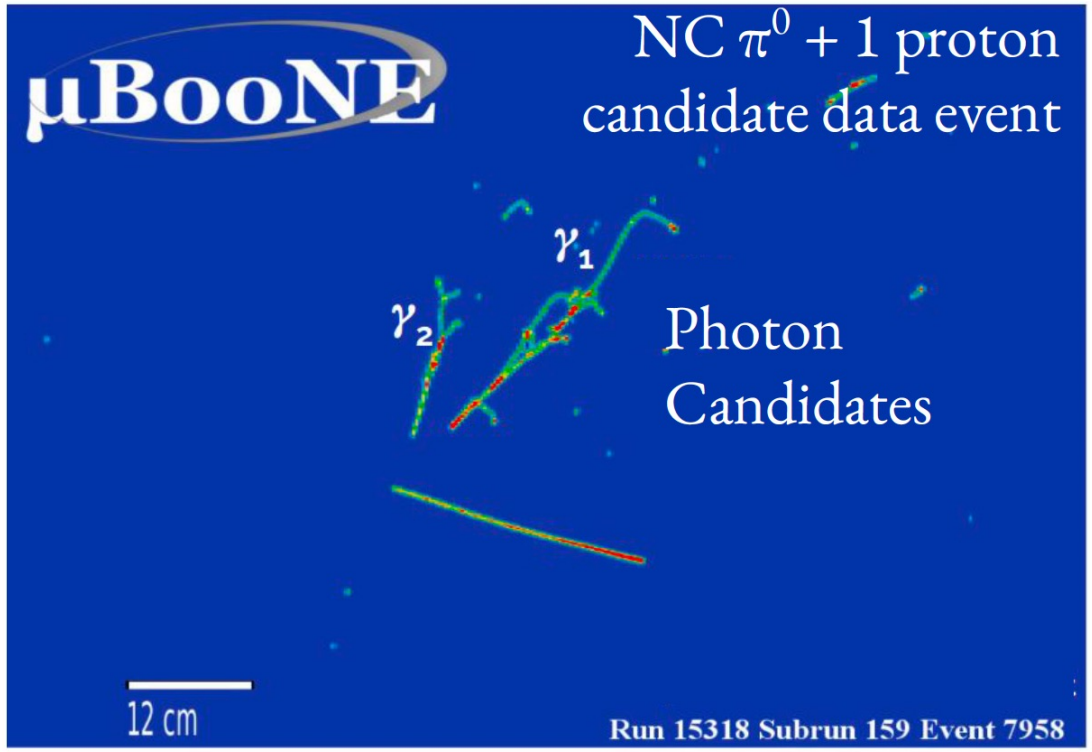
- consistent with shortcomings at low momentum transfer observed on other targets (MiniBooNE, MINERvA)





Neutral current π^0 measurement

arXiv: 2404.10948



Select: $\nu + Ar \rightarrow \nu + \pi^0 + X$

- two photon shower candidates
- candidate events split into 0 proton and N protons, 35 MeV KE threshold

4971 candidate events, 54% purity

- 6.4×10^{20} POT, runs 1-3 data

Split into 3519 0p and 1452 Np candidates

Measure:

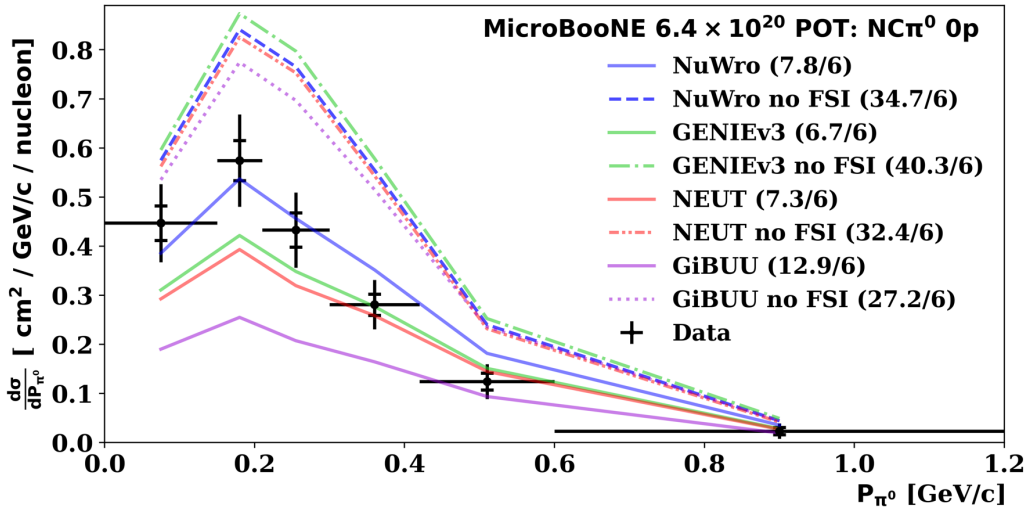
- single differential cross-section in π^0 momentum separately for 0p and Np
- double differential cross-section in π^0 momentum and angle for combined sample

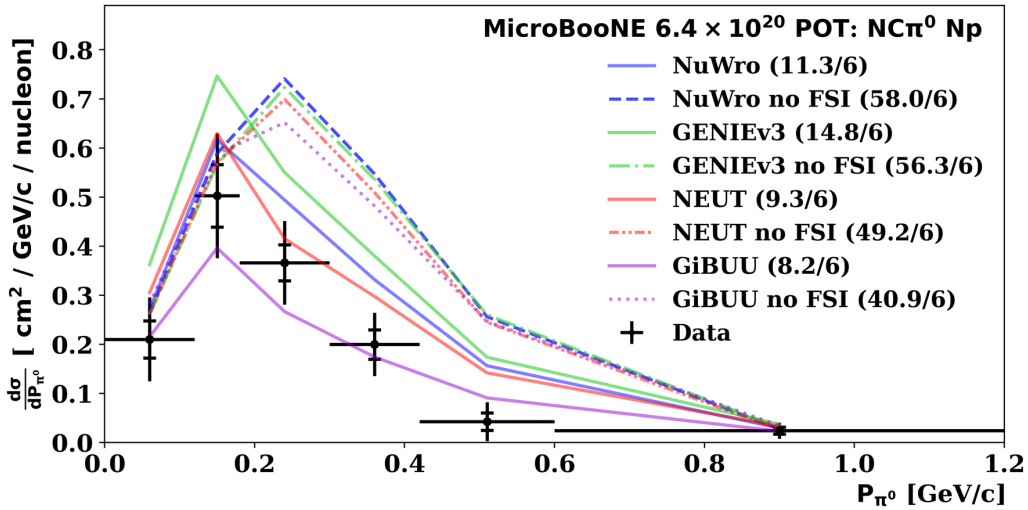
Neutral current π^0 measurement

arXiv: 2404.10948

Separate single-differential measurements for 0p and Np samples

Clear overprediction without effects of final-state-interactions (FSI)



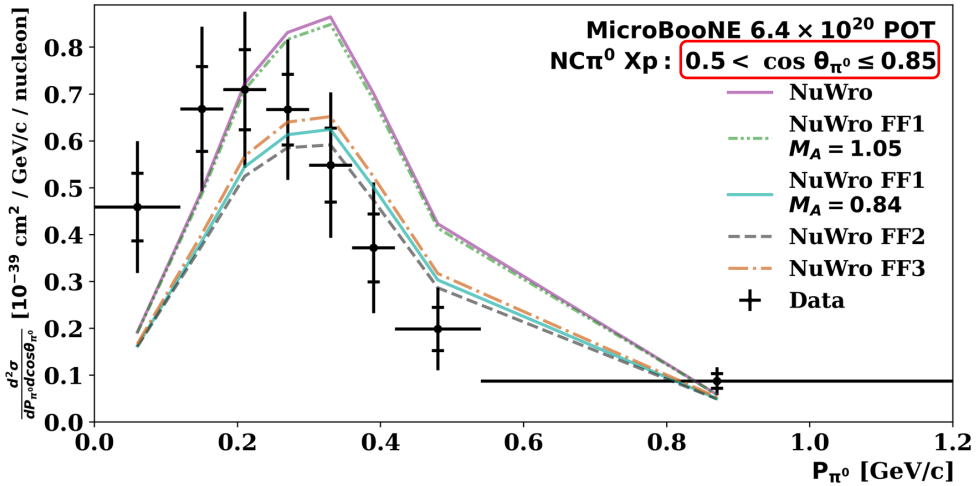


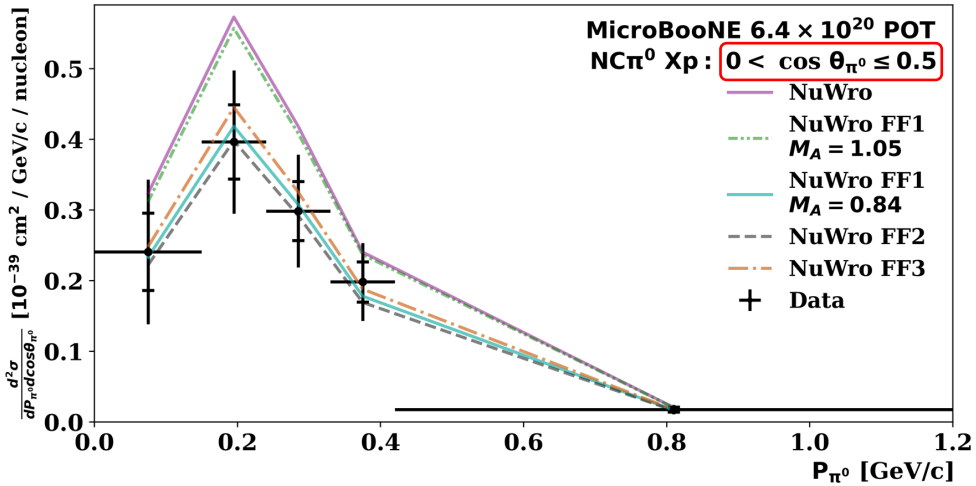
Neutral current π^0 measurement

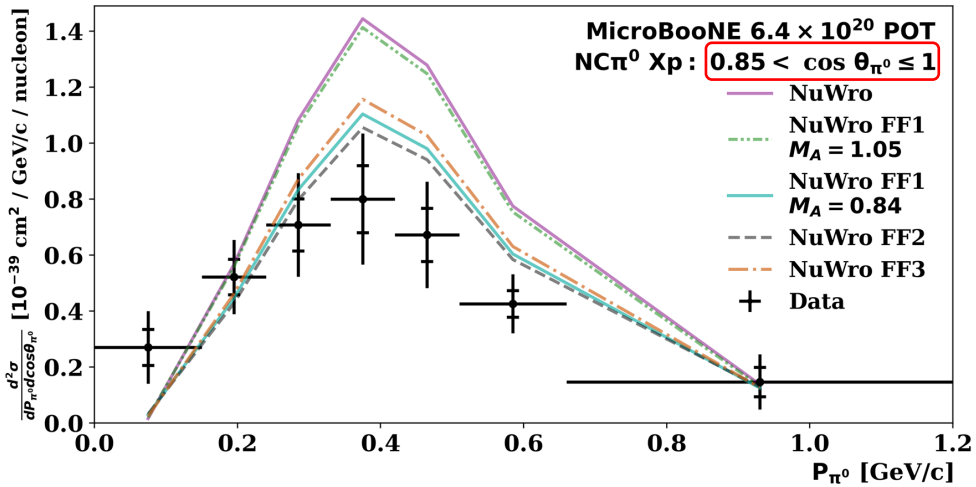
arXiv: 2404.10948

First double-differential cross-section measurement in π^0 kinematics (momentum, angle):

- enhanced sensitivity to mismodelling in different regions of phase space
- systematic overprediction compared to data
- sensitivity to form factor modeling







Charged pion measurements

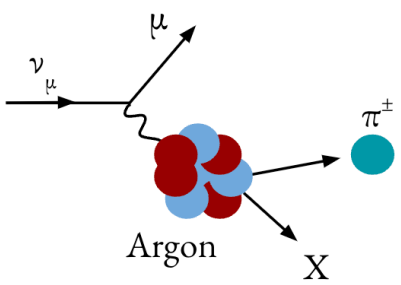
MicroBooNE $\pi^{\pm}$ measurements using full data-set on-going:

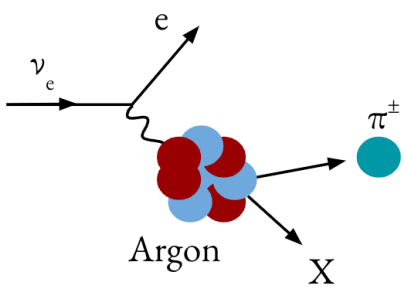
- ν_μ CC $1\pi^{\pm}$ using BNB beam, 11.14×10^{20} POT
- ν_e CC $1\pi^{\pm}$ using NuMI beam, 18.85×10^{20} POT

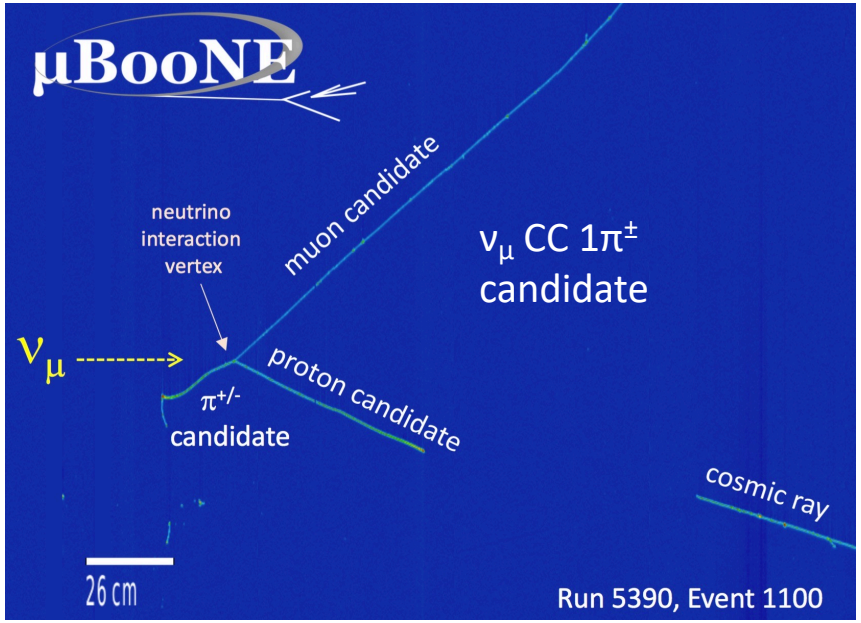
$\pi^{\pm}$ production will one of the dominant channels in DUNE:

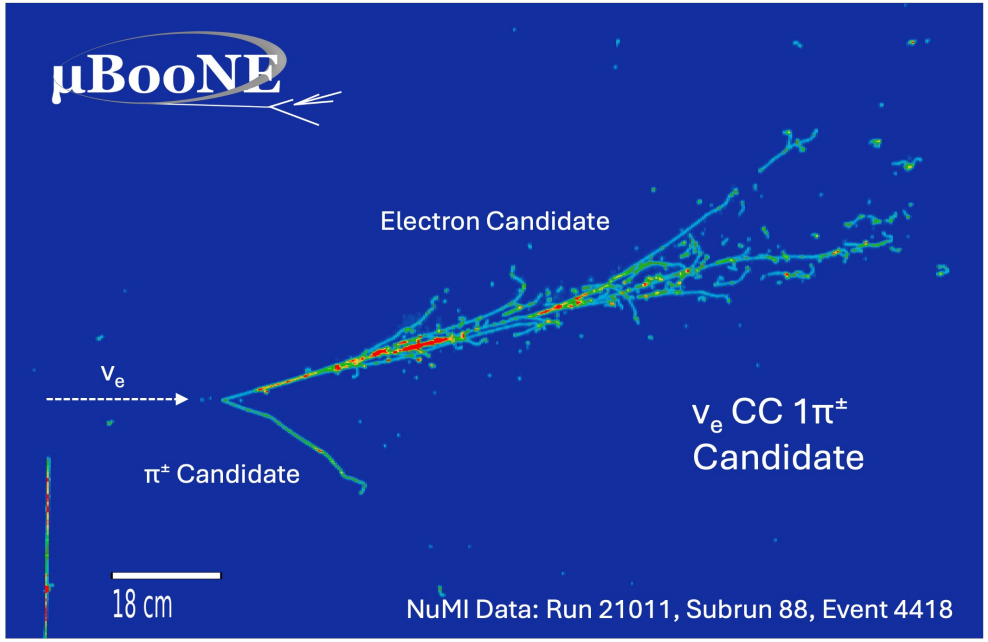
- precision measurements on argon critical

First measurements from MicroBooNE coming very soon!

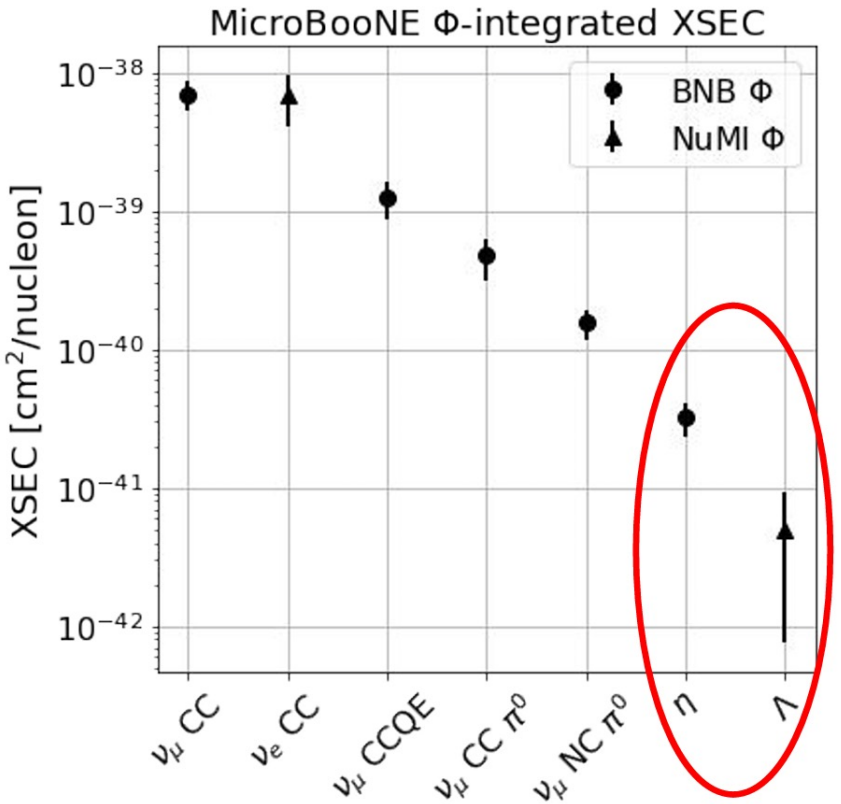








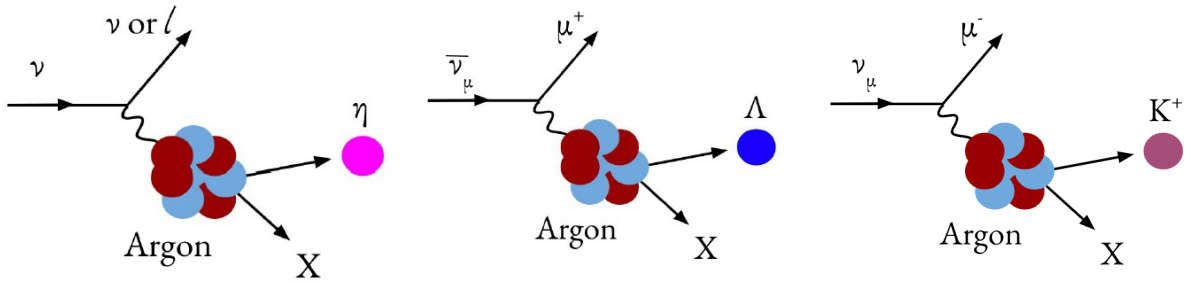
Rare processes measurements



High-precision era requires accurate understanding of cross-sections of even rarest processes that can form backgrounds for searches

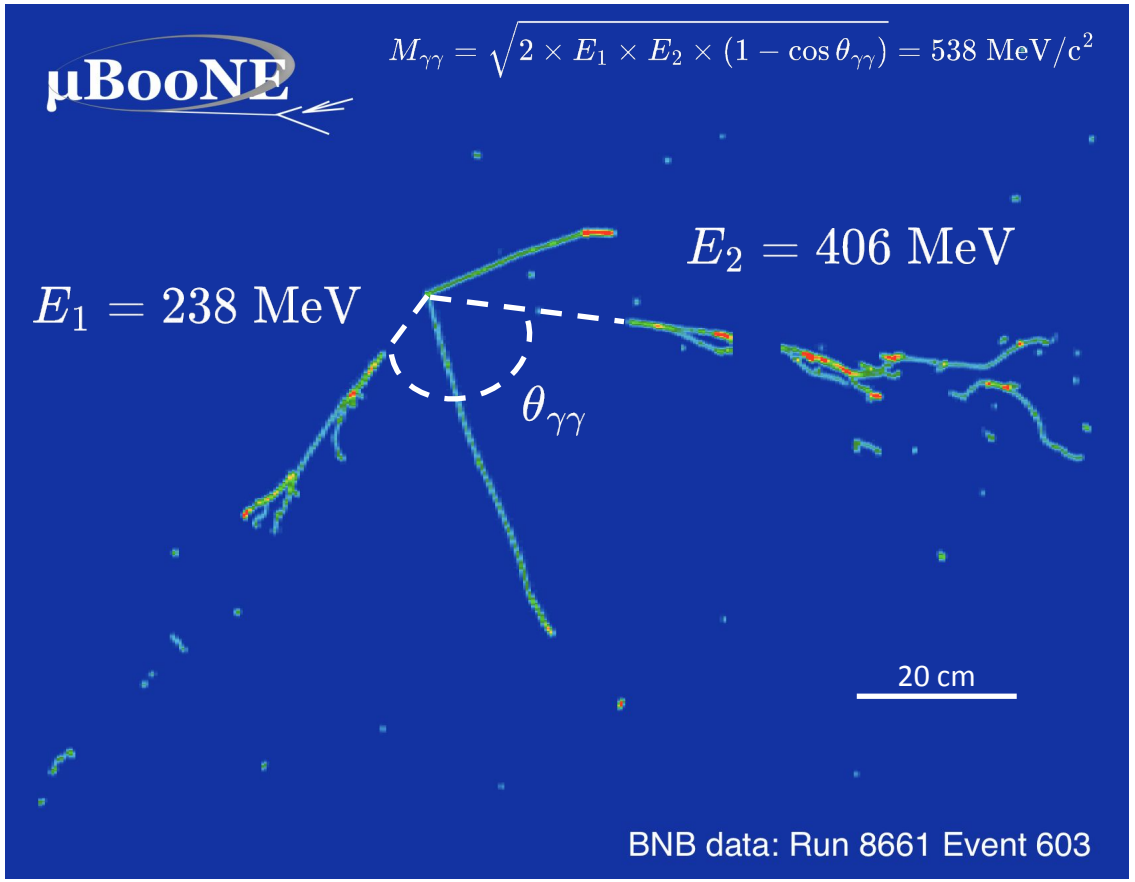
Orders of magnitude lower cross-sections than previous measurements

Require development of novel reconstruction and selection techniques, pushing capabilities of LArTPCs



η meson production

Phys. Rev. Lett. 132, 151801 (2024)



Powerful probe of resonances beyond Δ(1232)

- production in MicroBooNE dominated by N(1535) resonance

Select η → γγ:

- separate from π^0 → γγ via invariant mass
- 93 candidate events, with 49.9% purity
- 6.79×10^{20} POT, runs 1-3 data

η meson production

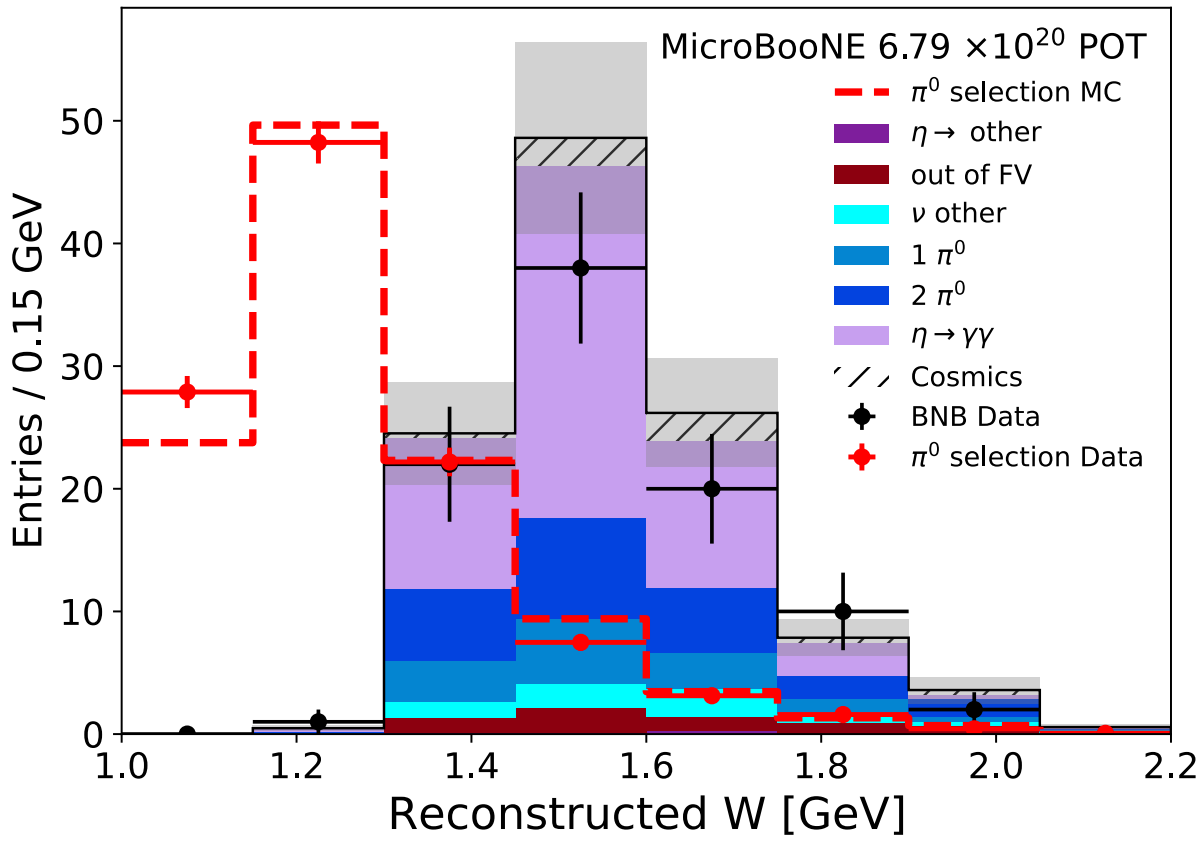
Phys. Rev. Lett. 132, 151801 (2024)

First measurement with a LArTPC detector:

- $\sigma = 3.22 \pm 0.84$ (stat.) ± 0.86 (syst.) $\times 10^{-41}$ cm^2/nucleon

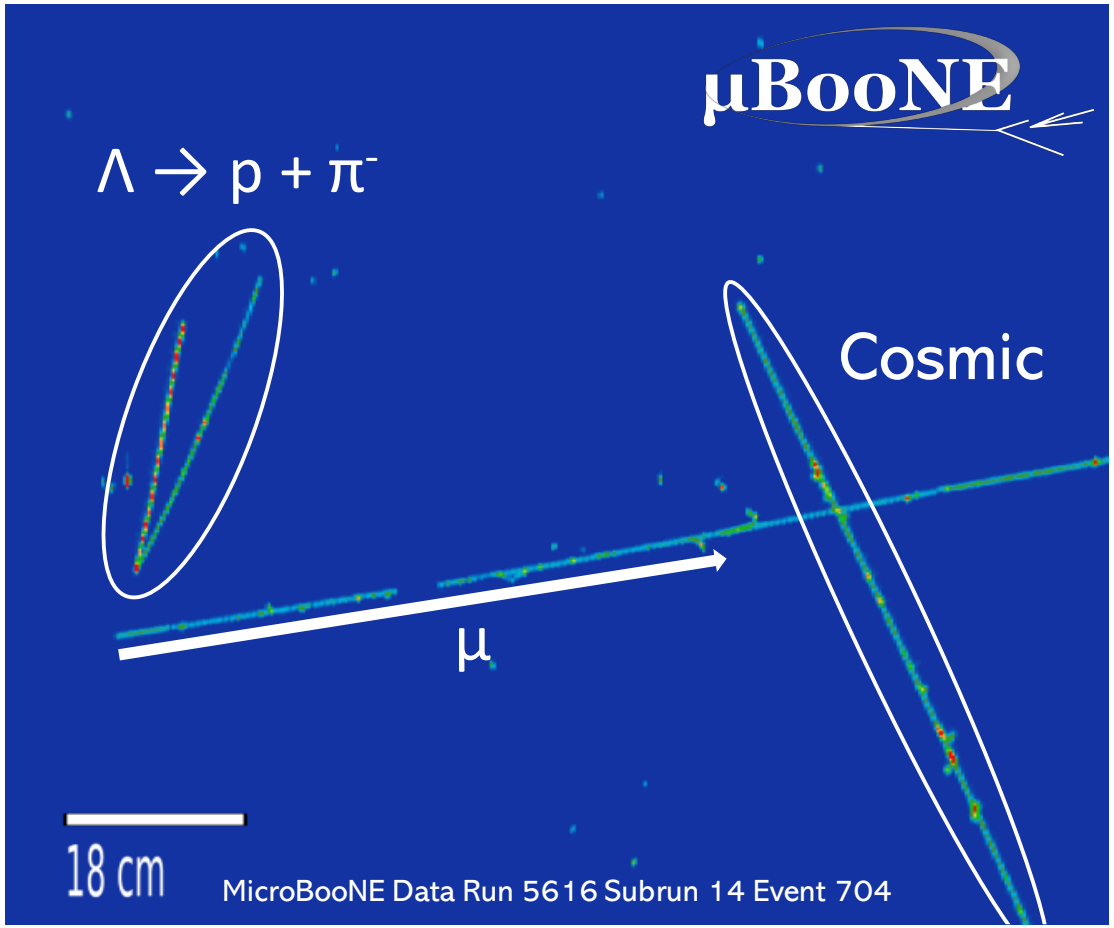
Provides input for proton decay channels ($p \rightarrow e^+ \eta$ and $p \rightarrow \mu^+ \eta$)

Novel tool for calibration electromagnetic showers in GeV scale accelerator neutrino experiments



Λ baryon production

Phys. Rev. Lett. 130, 231802 (2023)



Extremely rare process:

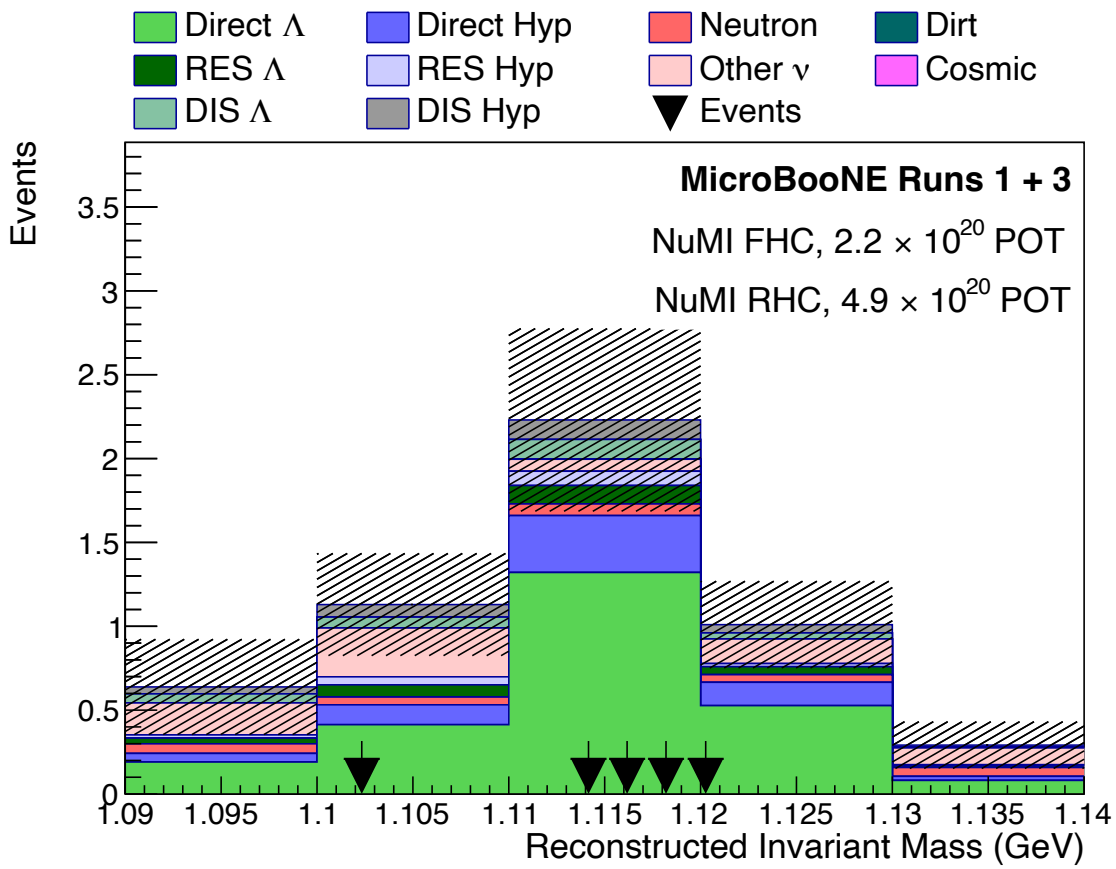
- Cabibbo suppressed
- only produced in anti-neutrino interactions → make use of NuMI beam data due to availability of RHC data

Novel selection technique developed:

- 5 candidate events
- 2.2×10^{20} POT FHC, 4.9×10^{20} POT RHC (NuMI beam runs 1 + 3)

Λ baryon production

Phys. Rev. Lett. 130, 231802 (2023)



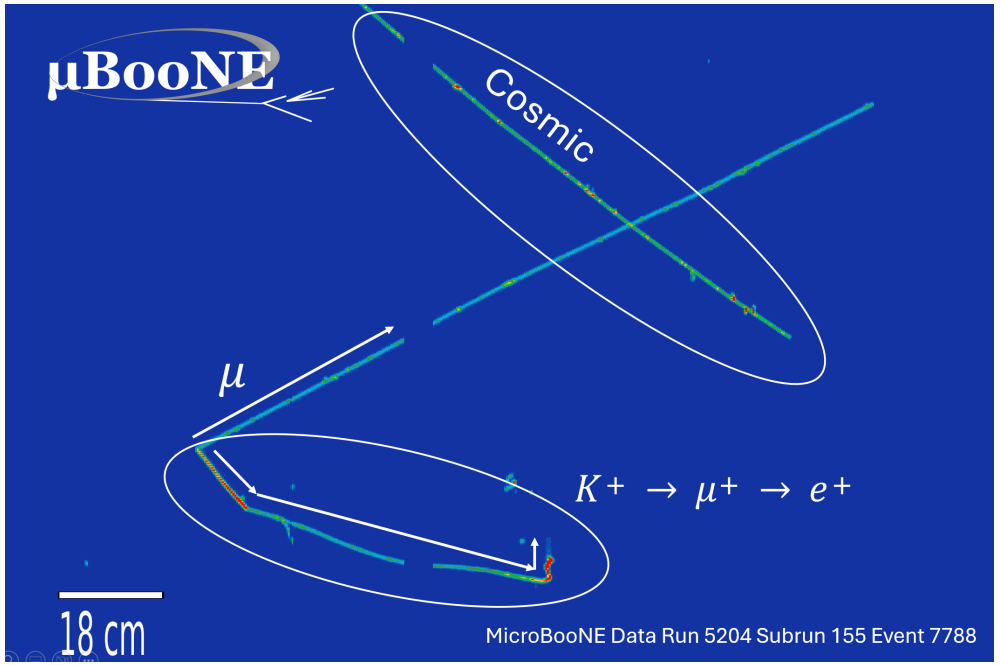
First measurement with a LArTPC detector:

- $\sigma = 2.0^{+2.2}_{-1.7} \times 10^{-40} \frac{\mathrm{cm}^2}{\mathrm{Ar}}$

Important input to hyperon interaction modelling

Potential background in proton decay searches, secondary interaction can mimic p → K ν signature

K^+ production



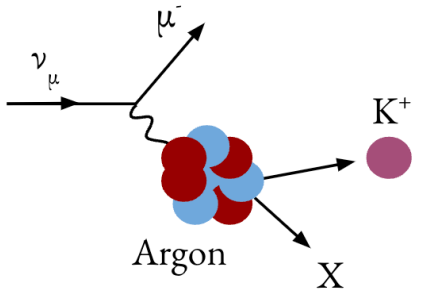
First MicroBooNE K^+ production measurement on-going:

- $\nu_\mu + Ar \rightarrow \mu^- + K^+ + X$

  where $K^+ \rightarrow \mu^+ \rightarrow e^+$

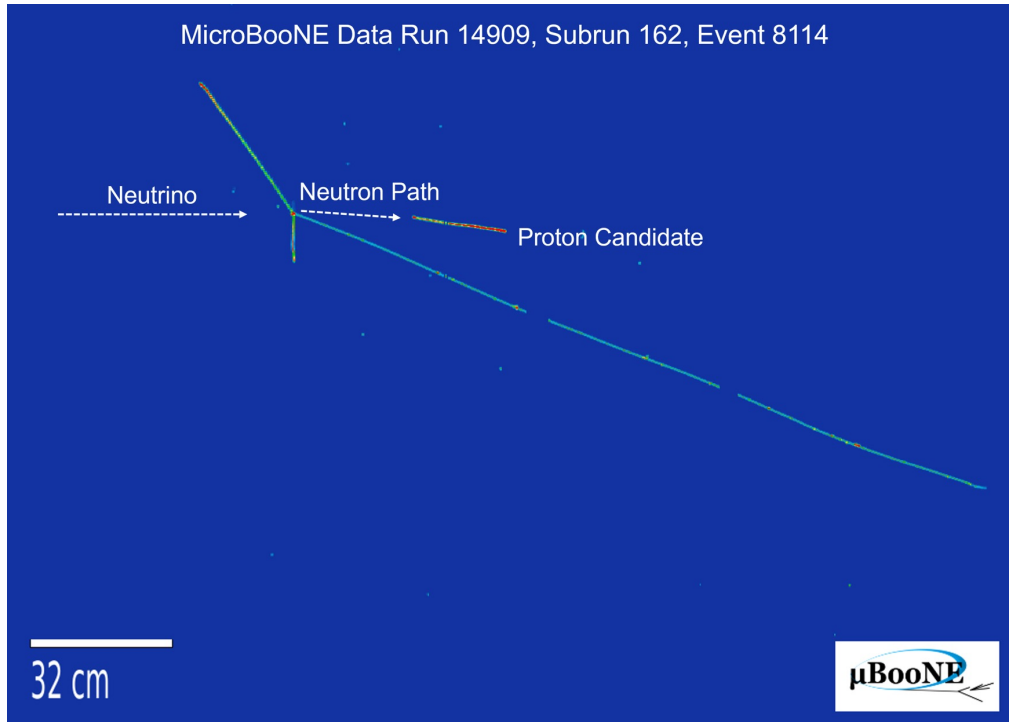
Provides input for proton decay searches, $p \rightarrow K^+ \nu$

See poster by J. Rodriguez



Neutrino-induced neutron identification

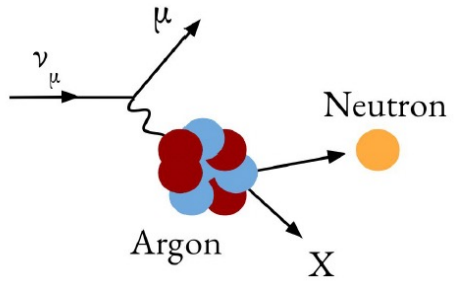
arXiv: 2406.10583



Neutrons produced in neutrino interactions are extremely challenging to reconstruct, predominantly escape the detector without any visible signature

Undetected neutrons are source of “missing energy” leading to biases in neutrino energy reconstruction

Novel neutrino-induced neutron detection method developed using secondary proton tracks



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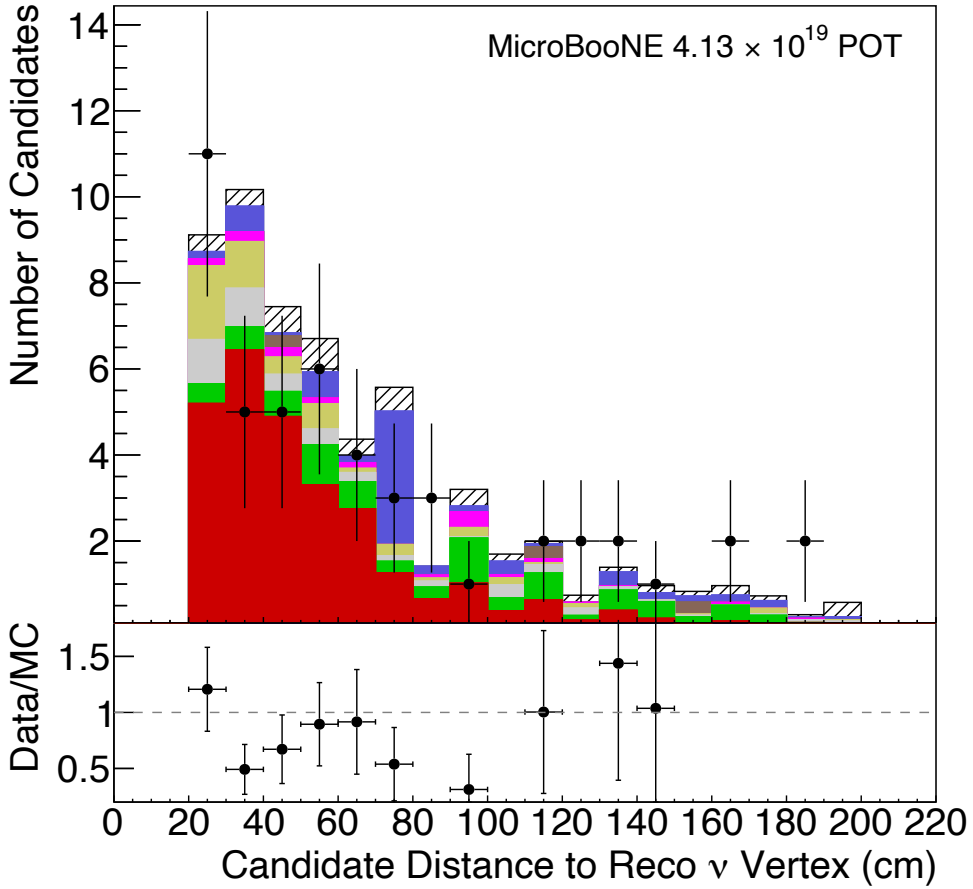
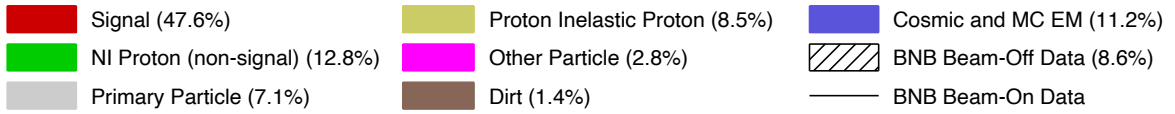


Identify sample of neutron candidates:

- 48% purity for primary neutrons
- validated with small fraction of data, 4.13 × 10^{19} POT

Detection method applicable to any LArTPC detector

In future, plan to extend to full data-set and perform measurement of neutrino-induced neutron production rates and kinematics



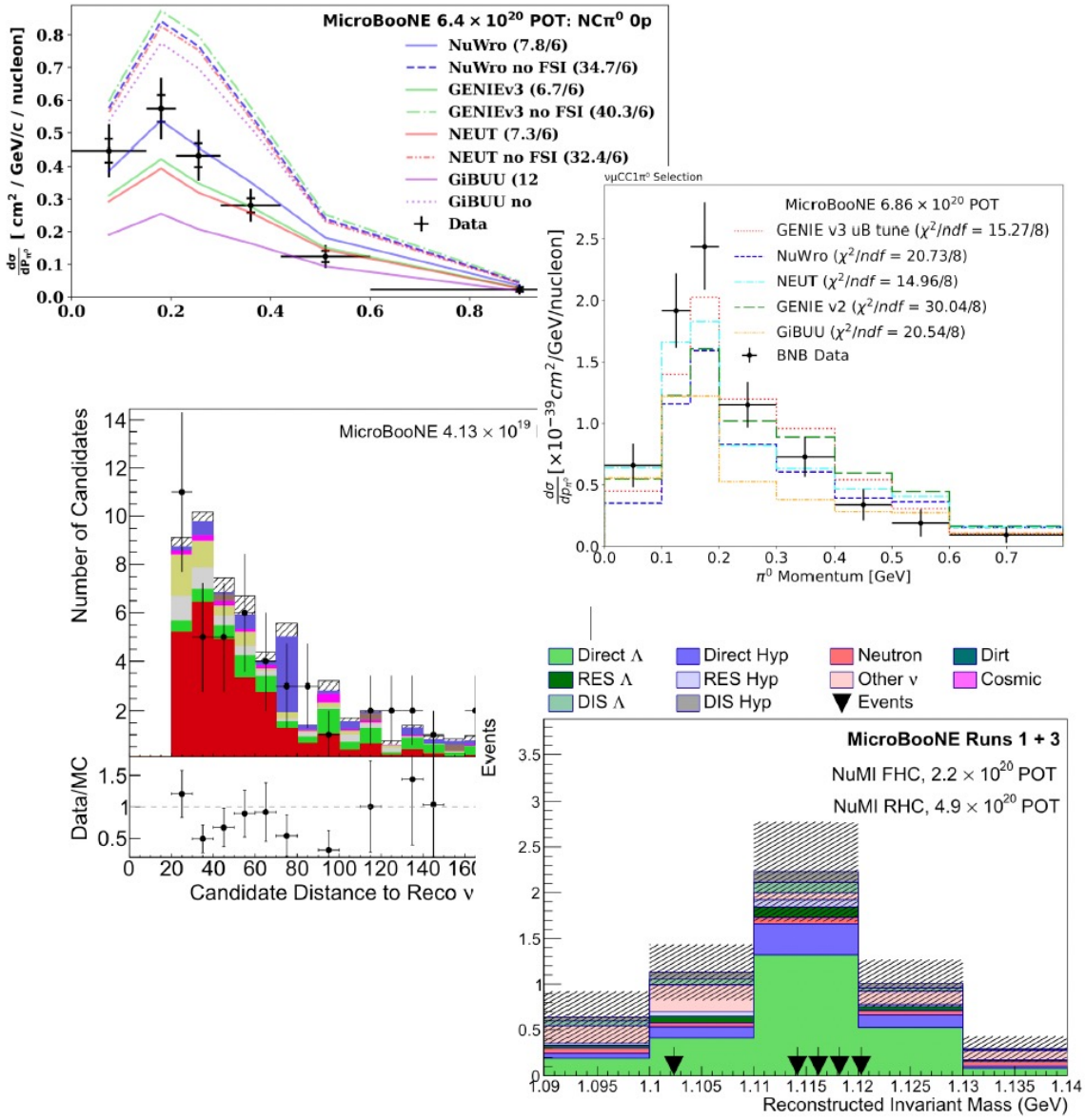
Summary

MicroBooNE has an extensive program of cross-section and rare process analyses

Over 20 published analyses, many more on-going including first full data-set measurements

- 2 ✕ statistics of existing analyses

First charged pion and kaon production measurements coming very soon!



Backups

MicroBooNE LArTPC

Fully active tracking calorimeter

3 planes of wires, collecting ionization charge

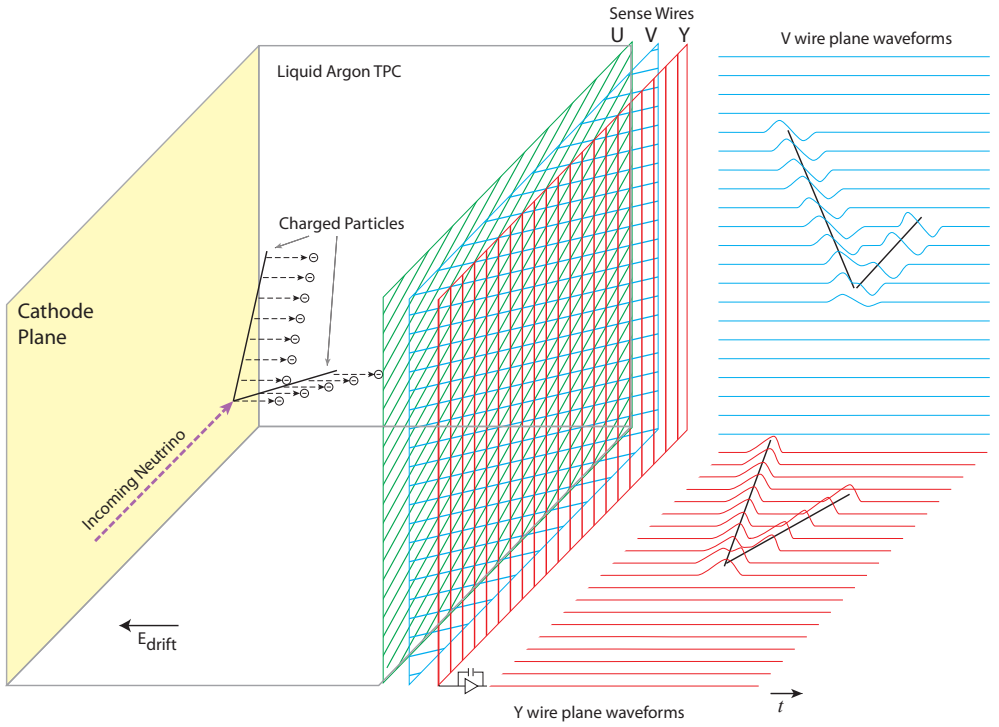
- vertical, +60° and -60° with 3mm wire spacing
- 2.6m drift length, E_{drift} = 273 V/cm

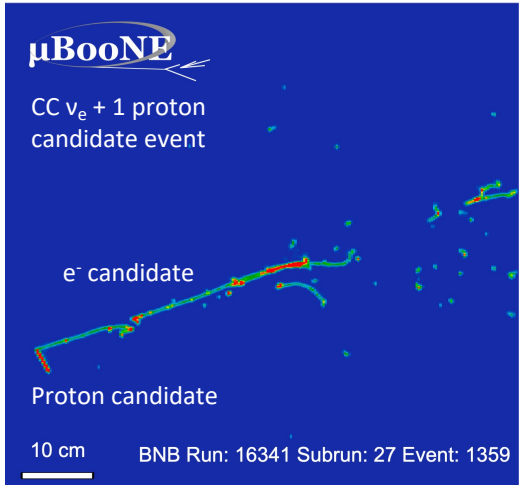
32 PMTs, collecting scintillation light

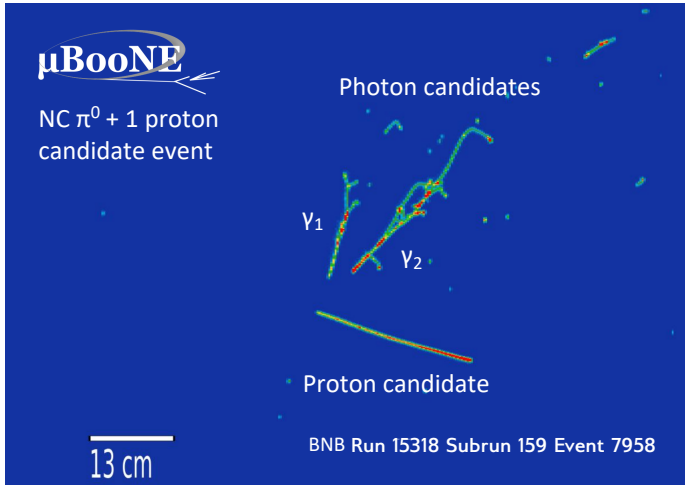
- located behind the wire planes at the anode

Precision neutrino measurements at scale:

- mm-level resolution, low thresholds
- excellent particle identification



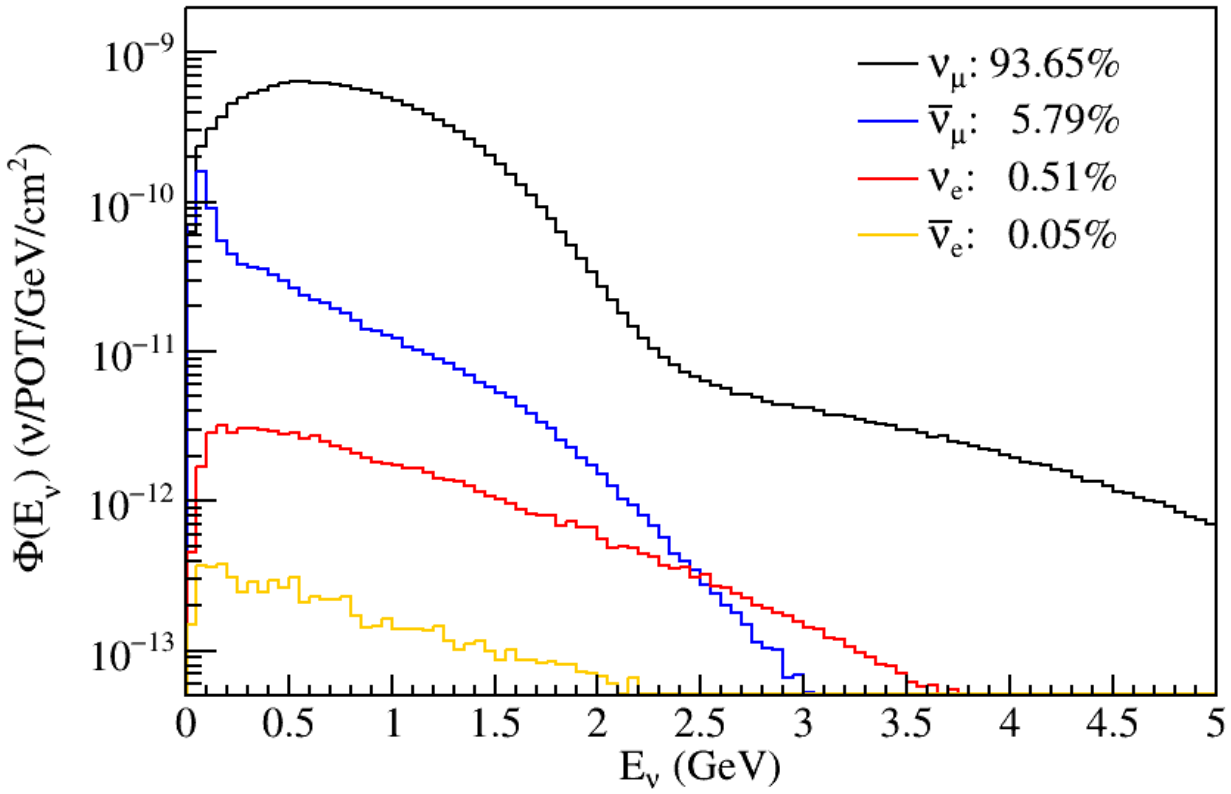




BNB Flux

BNB flux @ MicroBooNE

- 8 GeV beam, on-axis
- $\langle E_\nu \rangle$ = 0.8 GeV



NuMI Flux

MICROBOONE-NOTE-1129-PUB.pdf

NuMI flux @ MicroBooNE

- 120 GeV beam, ~8° off-axis
- $\langle E_\nu \rangle$ = 0.65 GeV