Measurements of Electron-Neutrino Interactions in MicroBooNE

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Outline

- Why do we care about electron-neutrino measurements (and particularly on argon)
- MicroBooNE and its beams
- ν_e CC inclusive measurements using the NuMI beam
- ν_e CC measurement using the BNB
- Future outlook.

Big Questions in Neutrino Physics

- The questions below, are what is currently driving the field of experimental neutrino physics

- ***how much do neutrinos weigh?***
- ***what is the nature of the ν?***

β decay and $0\nu\beta\beta$ decay

- ***which neutrino is the heaviest and which is the lightest (MH)?***
- ***do neutrinos violate CP?***

long-baseline neutrinos

- ***is our picture correct?***
- ***are there more than 3 kinds of neutrinos?***

short-baseline neutrinos

ν_e appearance in 0.1-10GeV Range! e.g. in LArTPCs

Looking back to last NuINT

ν_e cross sections on argon circa last NuINT

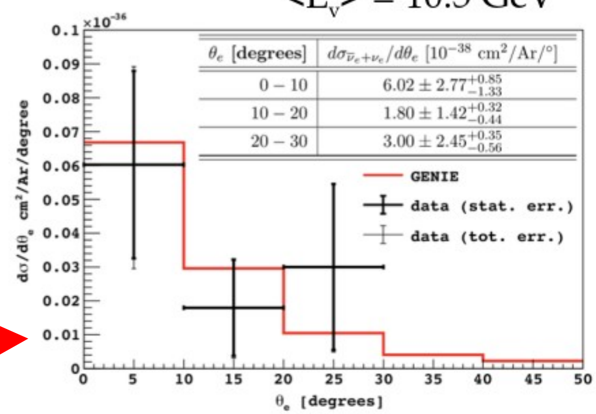
All ν_e measurements ca. early 2020

Experiment	Target	Type	Reference
Gargamelle	CF3Br	Inclusive	*Nuclear Physics B*, vol. 133, no. 2, 1978
T2K	C, H_20	Inclusive	*Phys. Rev. Lett.*, vol. 113, 2014 *Phys. Rev. D*, vol. 91,2015. *Journal of HEP*, vol. 2020, no. 10, 2020
MINERvA	$(C_8H_8)_n$	Exclusive	*Phys. Rev. Lett.*, vol. 116, 2016.
ArgoNeuT	Ar	Inclusive	*Phys. Rev. D*, vol. 102, 2020.

Only one on Ar, with 13 $\nu_e + \bar{\nu}_e$ events

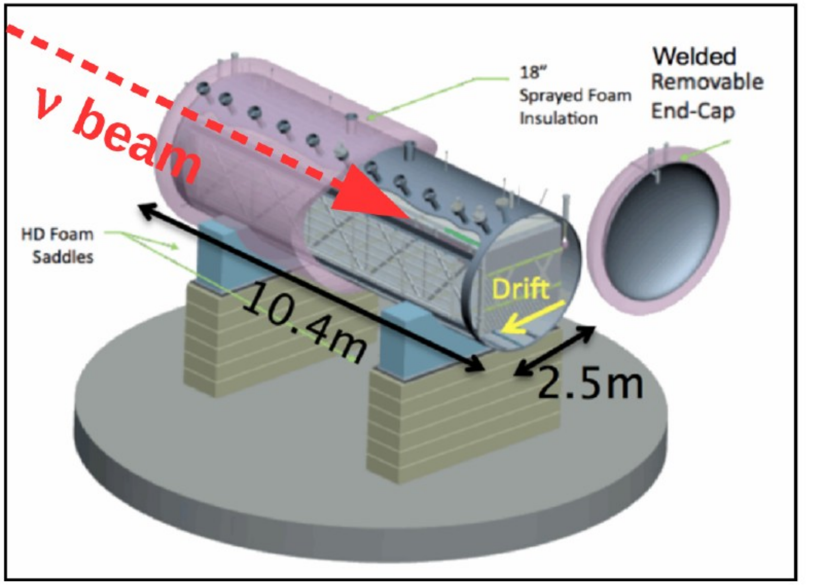
$\langle E_\nu \rangle = 4.3$ GeV

$\langle E_{\bar{\nu}} \rangle = 10.5$ GeV

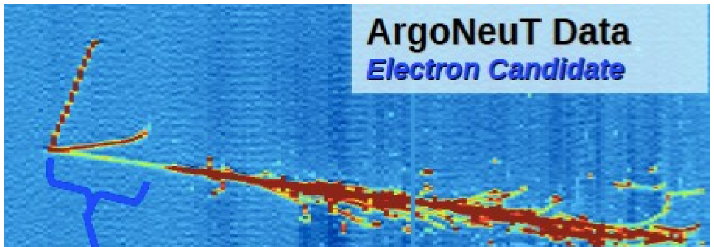


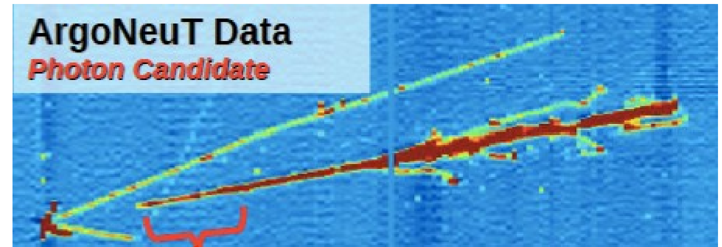
MicroBooNE at a glance

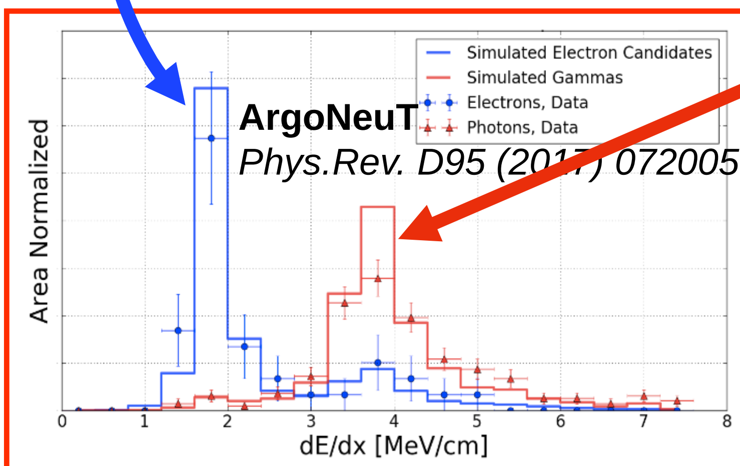
- See Xin's talk on Monday for overview.
- 170 tons of LAr (90 tons active).
- Scintillation light detected by PMTs provides signal timing.
- Longest running LArTPC in a neutrino beam.
- Able to detect neutrinos from two beams.
- LArTPC, and so excellent electron-photon separation capabilities.



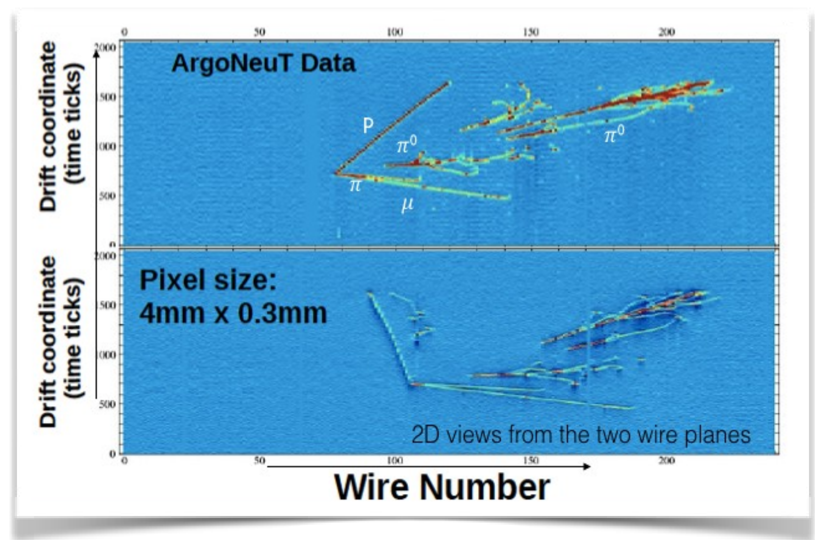
Measuring ν_e in liquid argon





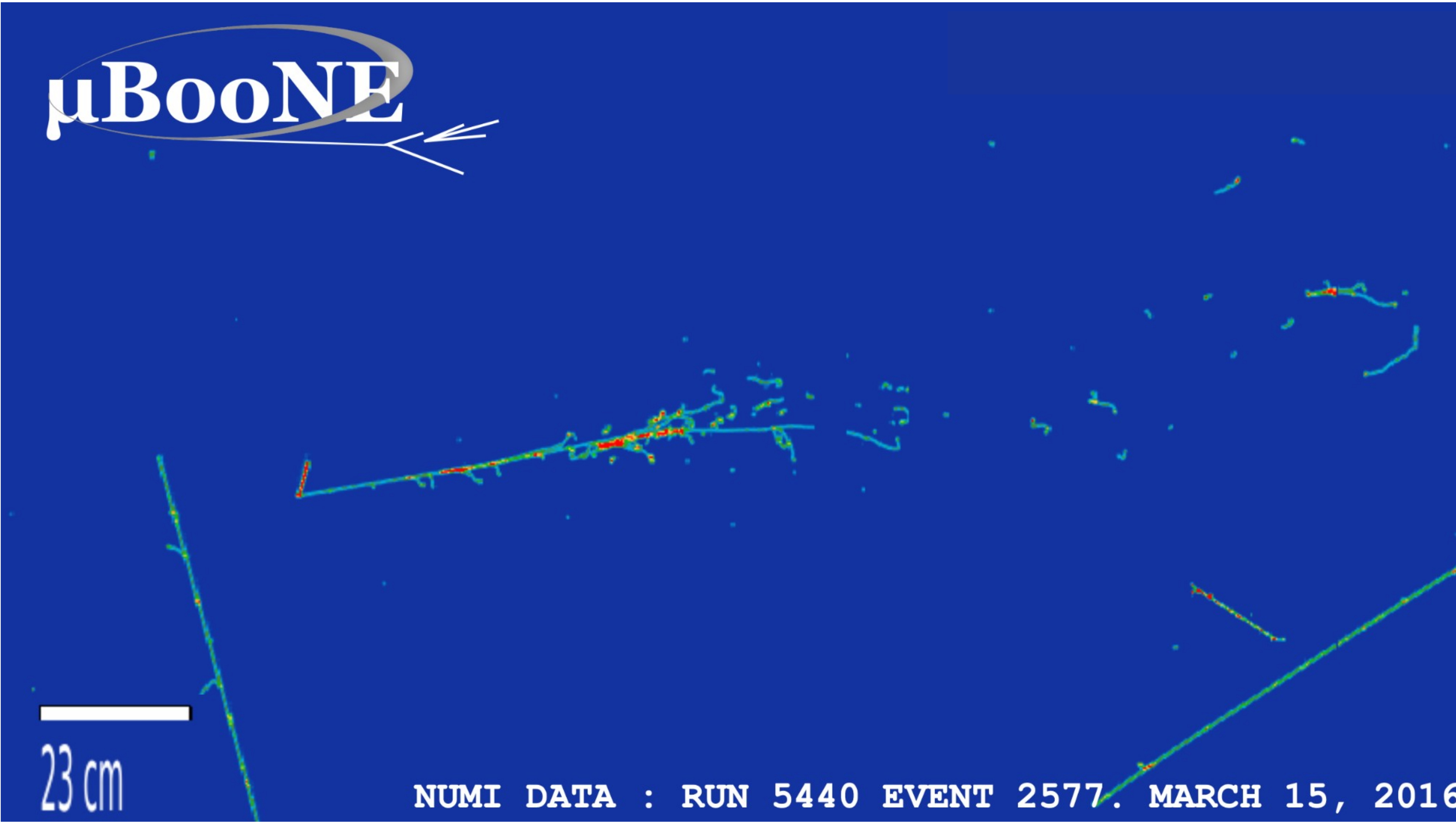


Double handle: topology and dE/dx

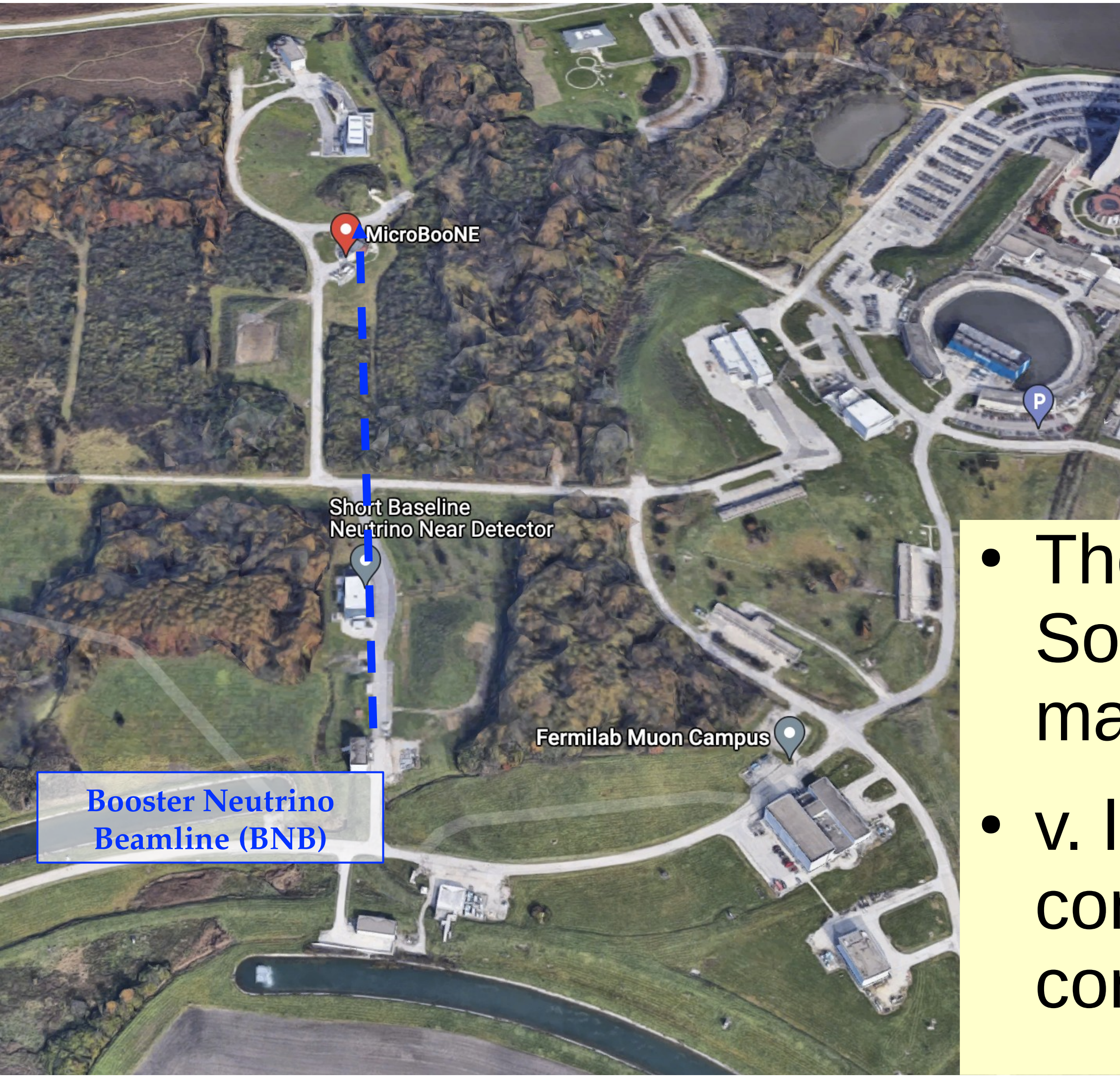


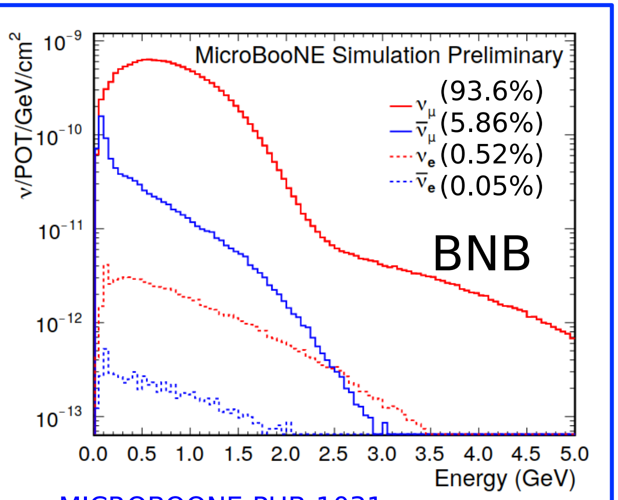
The LArTPC is an excellent tool for electron/photon separation

ν_e in MicroBooNE



MicroBooNE and its beams

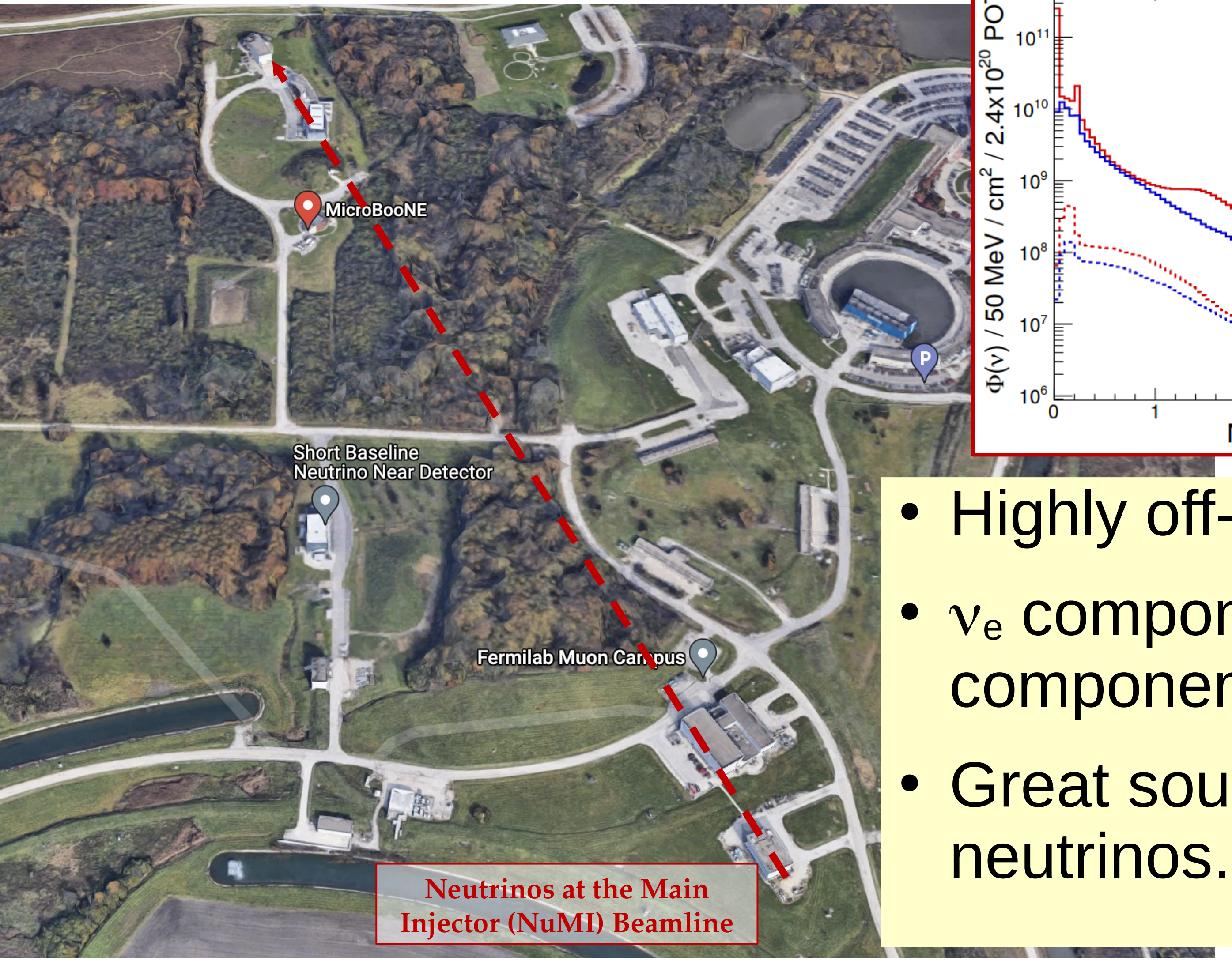


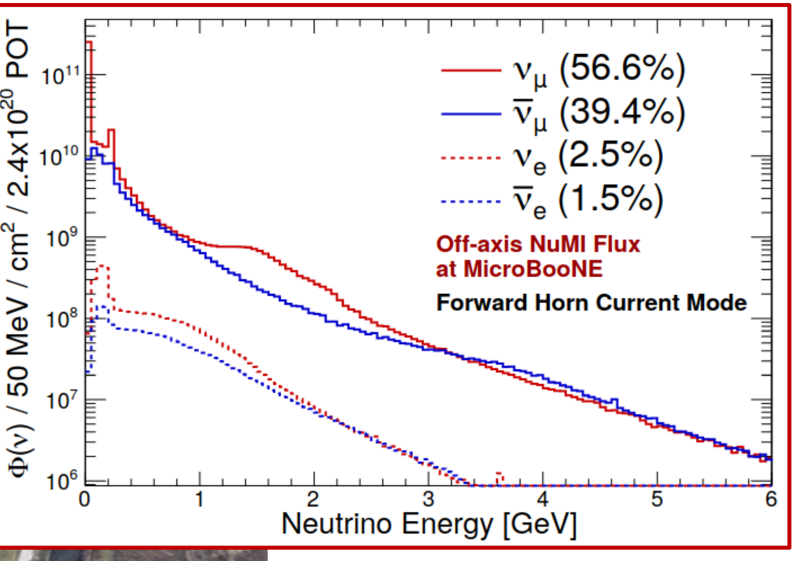


MICROBOONE-PUB-1031

- The on-axis beam. Source of neutrinos for majority of analyses.
- v. low intrinsic ν_e component (<1%), $\bar{\nu}_e$ component even smaller.

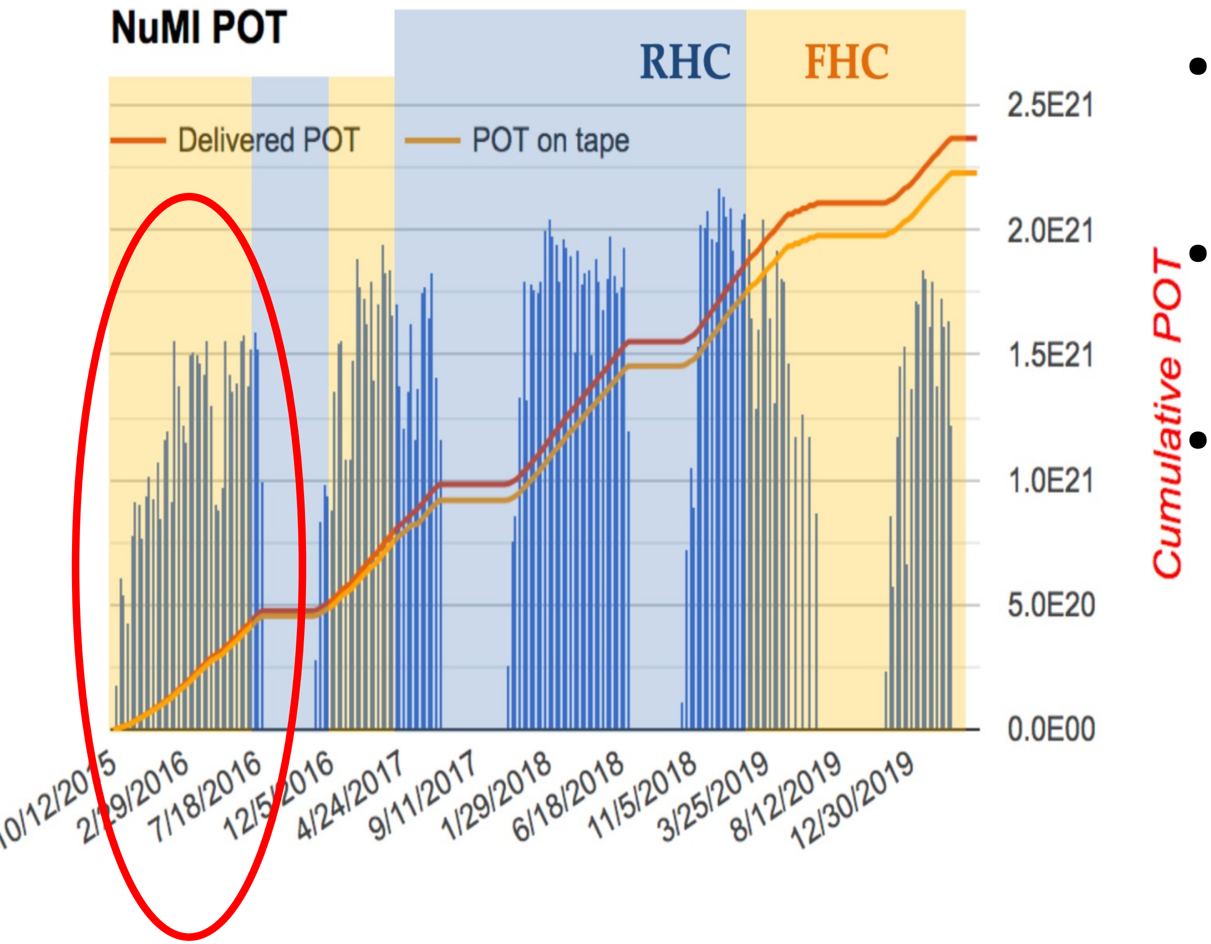
MicroBooNE and its beams (2)





- Highly off-axis (8°).
- ν_e component 5xBNB, $\bar{\nu}_e$ component comparable.
- Great source of electron neutrinos.

NuMI beam in MicroBooNE



- Total NuMI POT on tape 2.3x10^{21}
- In this talk: uB run 1 (Med. Energy, FHC).
- The Package to Predict FluX (PPFX) constraints hadron production uncertainties *[Phys.Rev.D 94 (2016) 9, Aliaga et al]*

1. Flux Averaged Inclusive $\nu_e + \bar{\nu}_e$ CC

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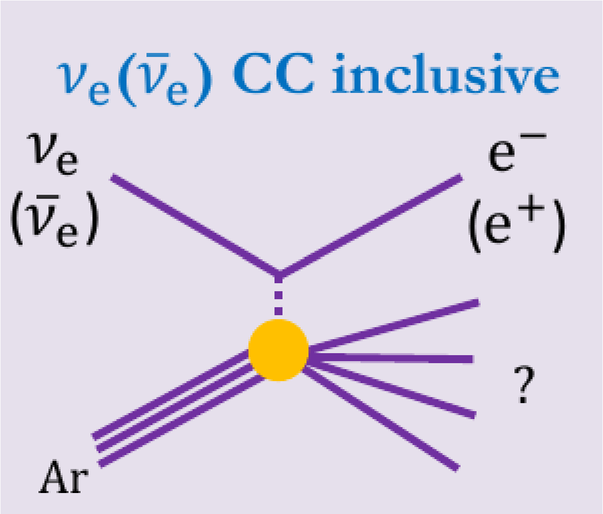
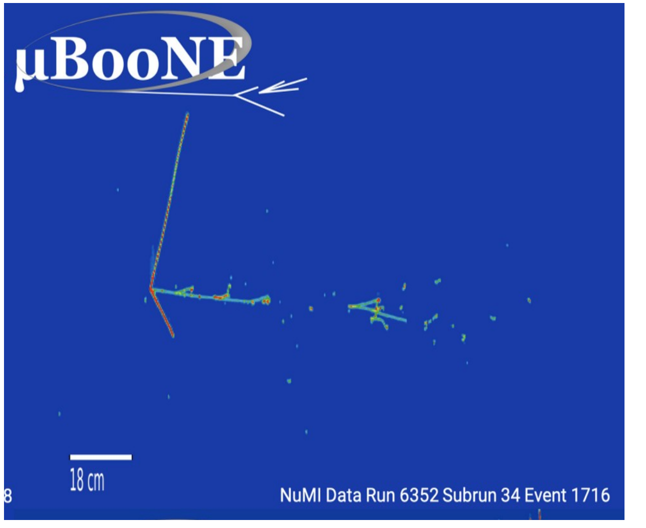
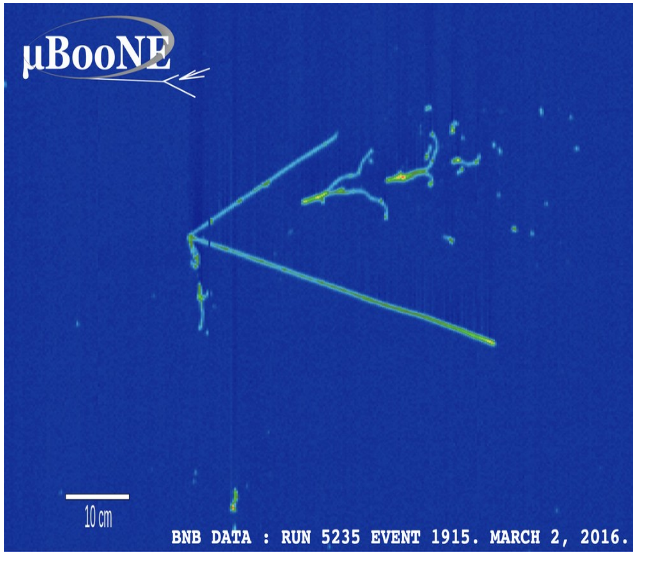


The measurement

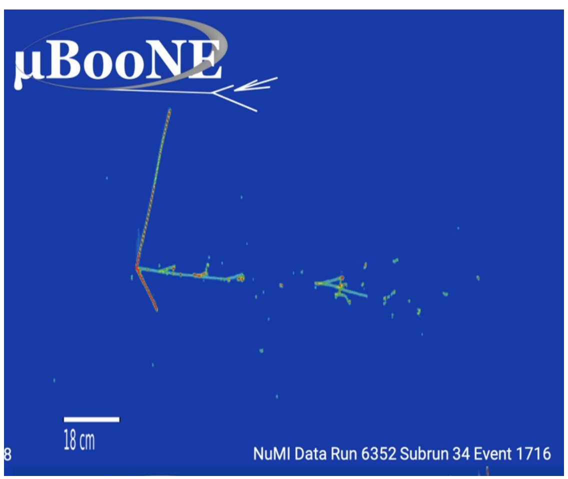
- "1st Generation" MicroBooNE measurement
- Beam simulated using FLUGG.
- Using CORSIKA to simulate cosmics.
- Signal: All ν_e and $\bar{\nu}_e$ interactions with energy greater than 250 MeV

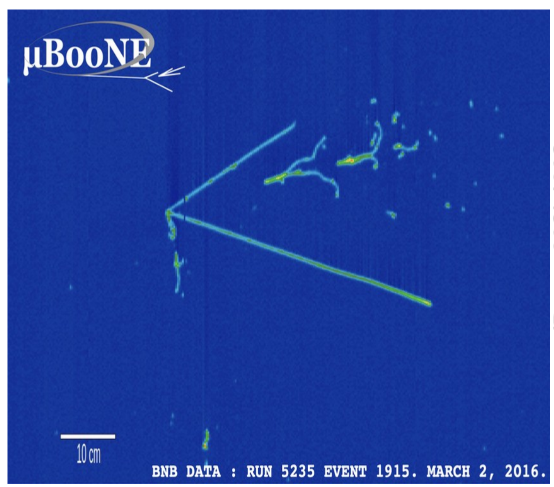


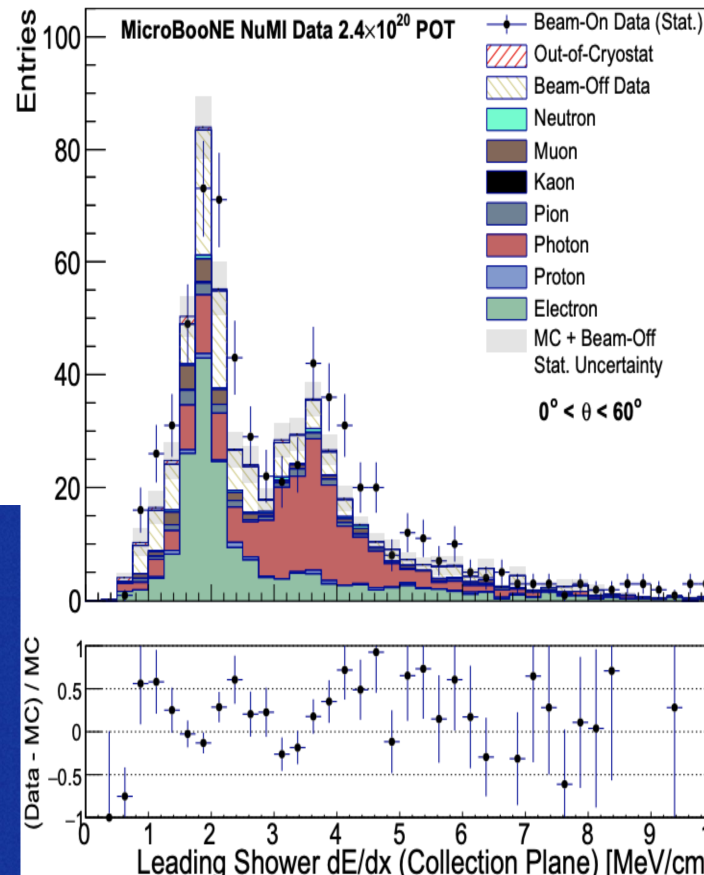


Automated e/γ separation

- First demonstration of a fully automated e/γ discrimination based on shower dE/dx & vertex distance.
- dE/dx observed to provide more discriminating power than vertex distance (analysis specific).



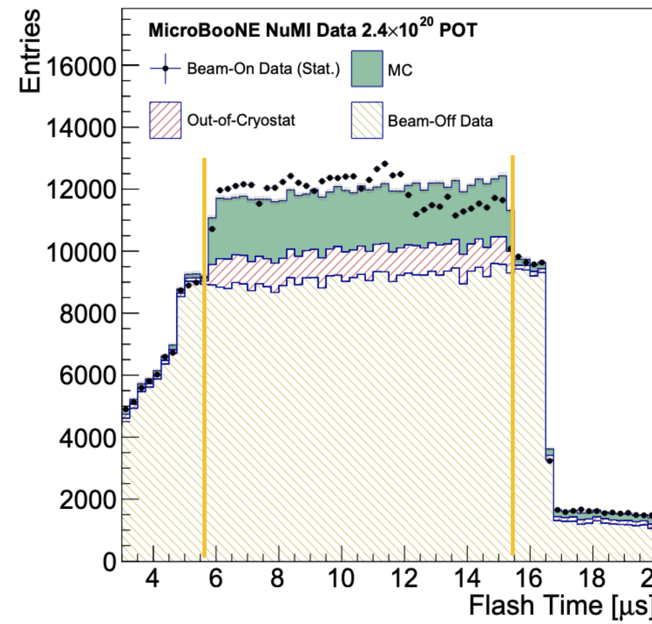


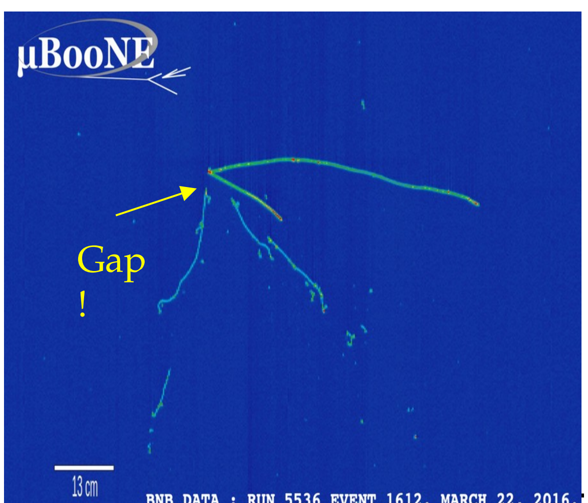


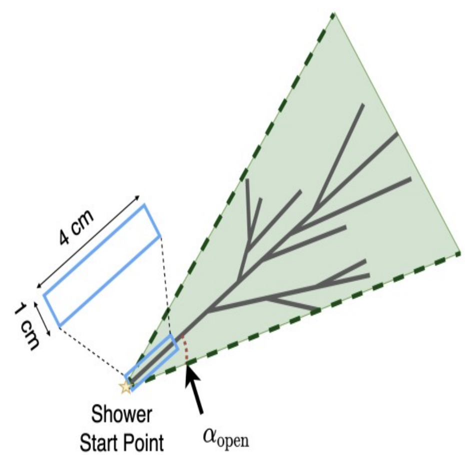
Selection

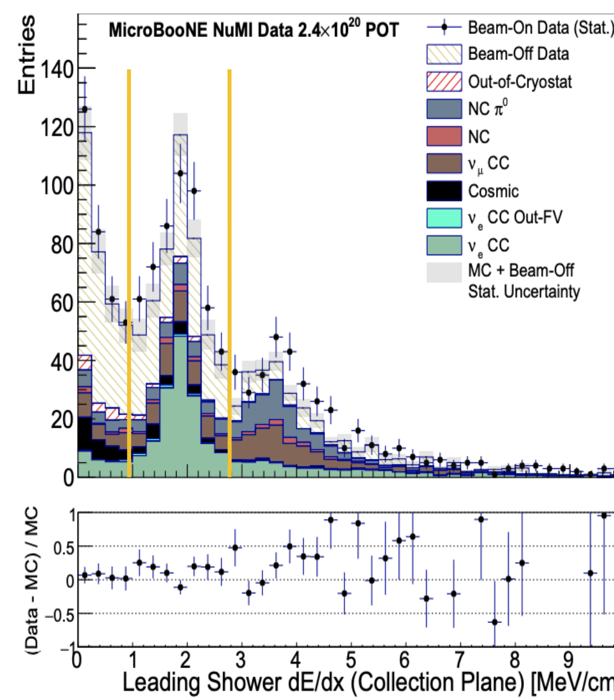
Selection (main points):

- Require optical beam flash within the beam window
- 1 or more showers
- Vtx-leading shower distance < 4 cm
- Leading shower “physics”:
  - 1.4 MeV/cm < trunk dE/dx < 3 MeV/cm
  - 3^{o} < Opening angle < 15^{o}





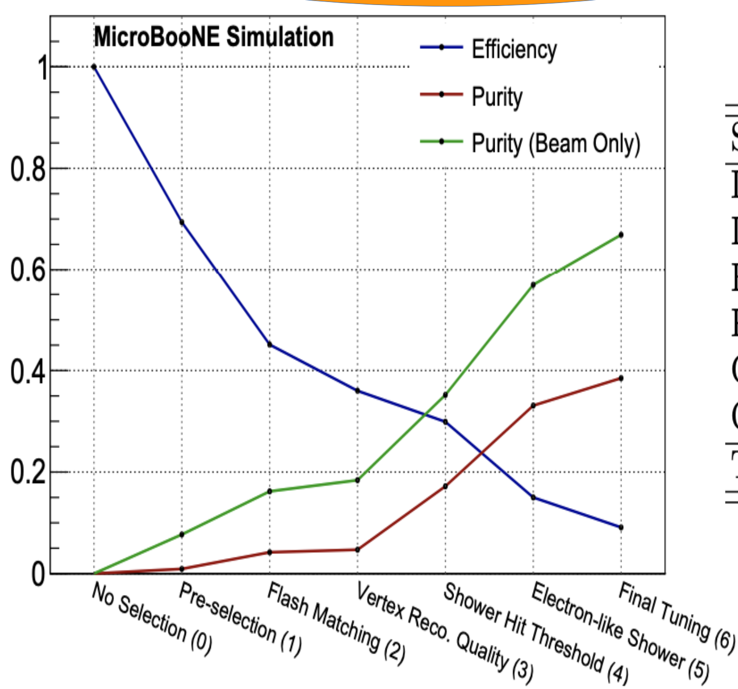




Final Result

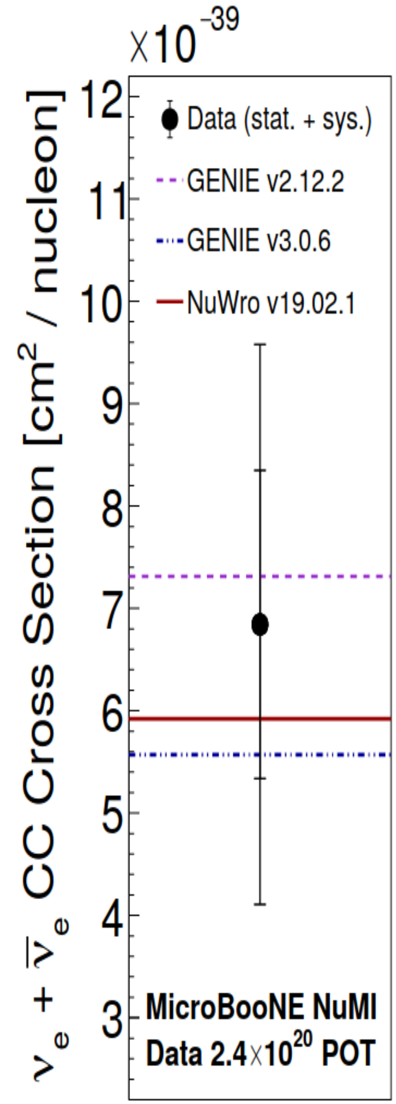
$$\langle\sigma\rangle = 6.84 \pm 1.51\,(\text{stat.}) \pm 2.33\,(\text{sys.}) \times 10^{-39}\ \frac{\text{cm}^2}{\text{nucleon}}$$

Overall purity: 38%
Overall efficiency: 9%
Cosmic ray contamination reduced by a factor of 10^5



22% statistical uncertainty

Systematic Source	Relative Uncertainty [%]
Interaction	10
Detector Response	23
Beam Flux	22
POT Counting	2
Cosmic Simulation	4
Out-of-Cryostat Simulation	6
Total	34



2. Single differential Inclusive $\nu_e+\overline{\nu}_e$ CC

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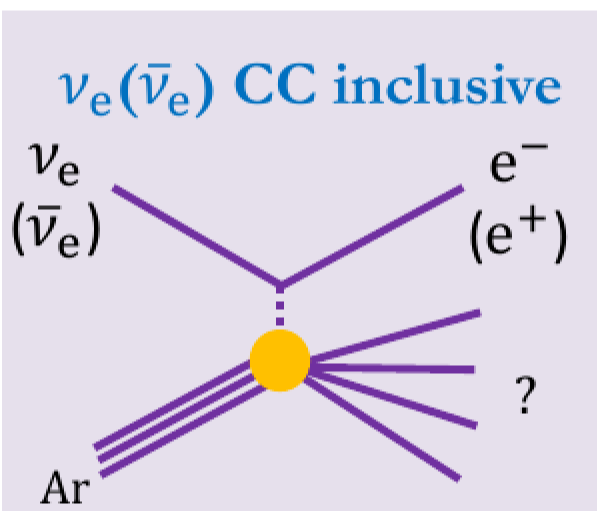
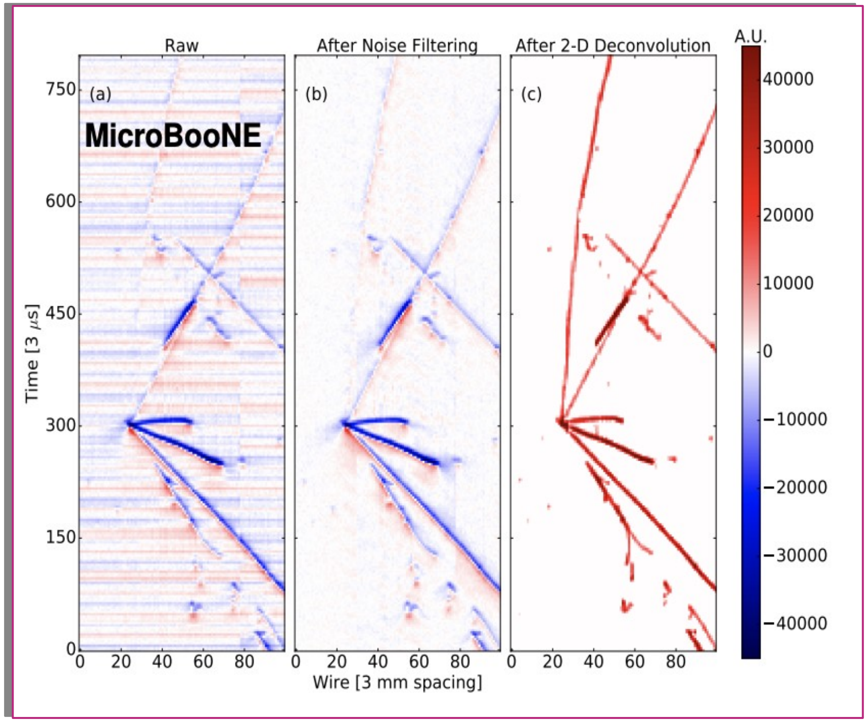


First ν_e differential c-s on Ar in lepton energy!

Improving the analysis

- “2nd generation” MicroBooNE Analysis
- Improved by:
  - Better signal processing and reconstruction, JINST 13, P07007 (2018) JINST 13, P07007 (2018).
  - Cosmic backgrounds now estimated using overlays.
  - Beam simulation using G4NUMI
  - Using GENIE v.3 tuned to T2K CC0π data.
  - Improved signal reconstruction.
- Signal: All ν_e and $\bar{\nu}_e$ interactions with energy greater than 60 MeV and charged lepton energy > 120 MeV



New Selection chain

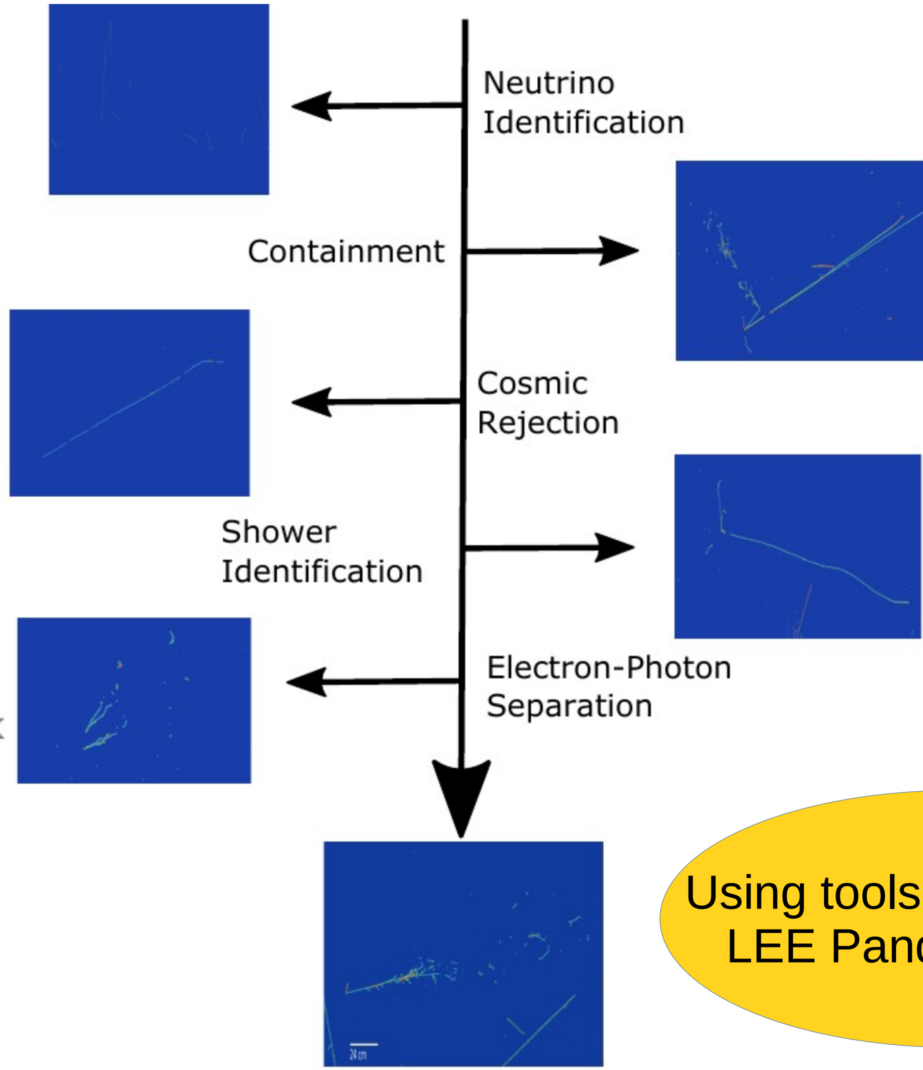
1. Slice ID
2. Shower in Neutrino Slice

3. Fiducial Volume Boundary
4. Contained Fraction

5. Topological Score
6. Cosmic IP

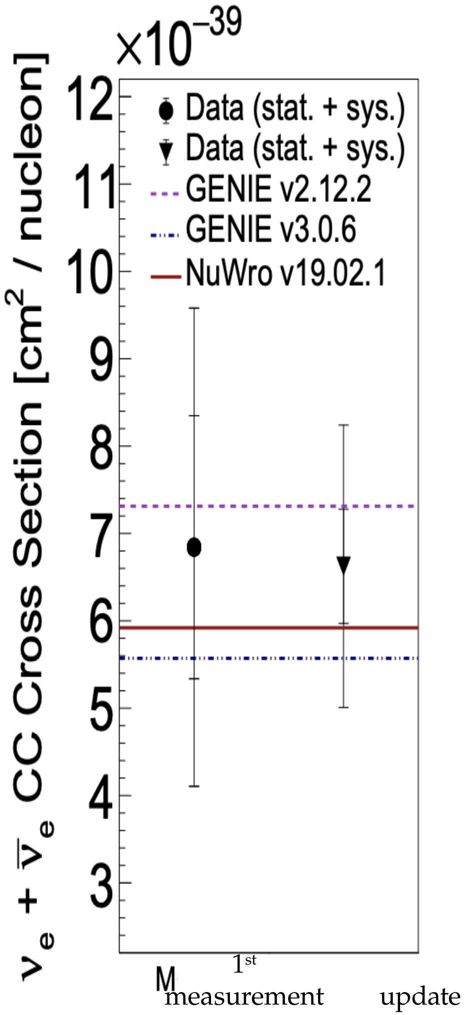
7. Shower Score
8. Hit Ratio

9. Moliere Angle
10. 2D: Shower distance, dE/dx
11. dE/dx (no tracks)



Using tools developed for LEE Pandora analysis

Comparison



After model improvement, reconstruction retuning & update selection:

- Consistent results (CV within 3%),
- halved uncertainties
- Increased purity (38% → 72%)
- Increased efficiency (9 → 21%)

1st measurement

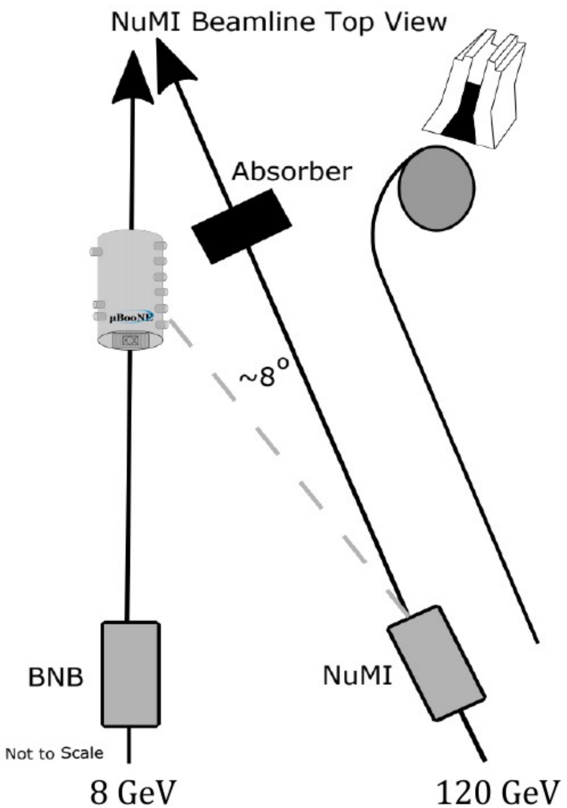
Systematic Source	Relative Uncertainty [%]
Interaction	10
Detector Response	23
Beam Flux	22
POT Counting	2
Cosmic Simulation	4
Out-of-Cryostat Simulation	6
Total	34

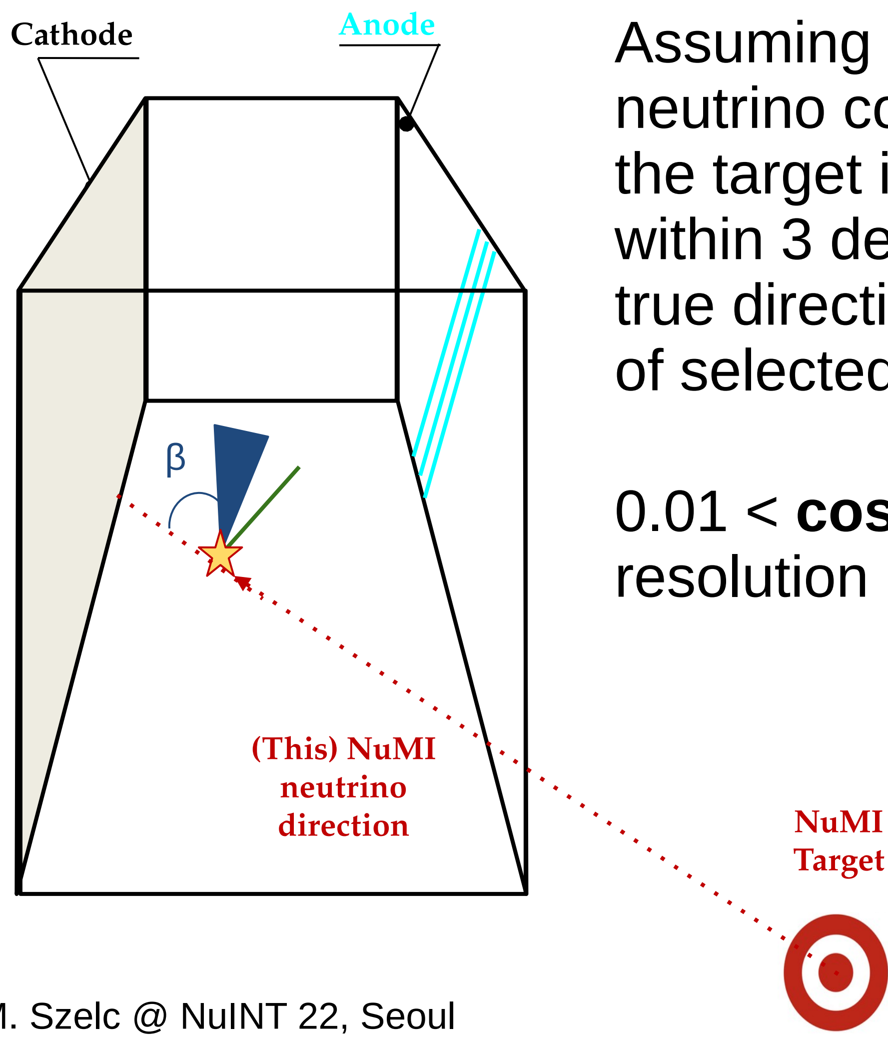
Update

Source of Uncertainty	Relative Uncertainty [%]
Beam Flux	17.4
Detector	6.8
Cross Section	5.8
POT Counting	2.0
Out-of-Cryostat	1.8
Proton/Pion Reinteractions	1.2
Beam-off Normalization	0.1
Total Systematic Uncertainty	19.8
MC Statistics	0.8
Data Statistics	10.0
Total Uncertainty	22.2

Differential cross section

- Variables: lepton energy and angle.

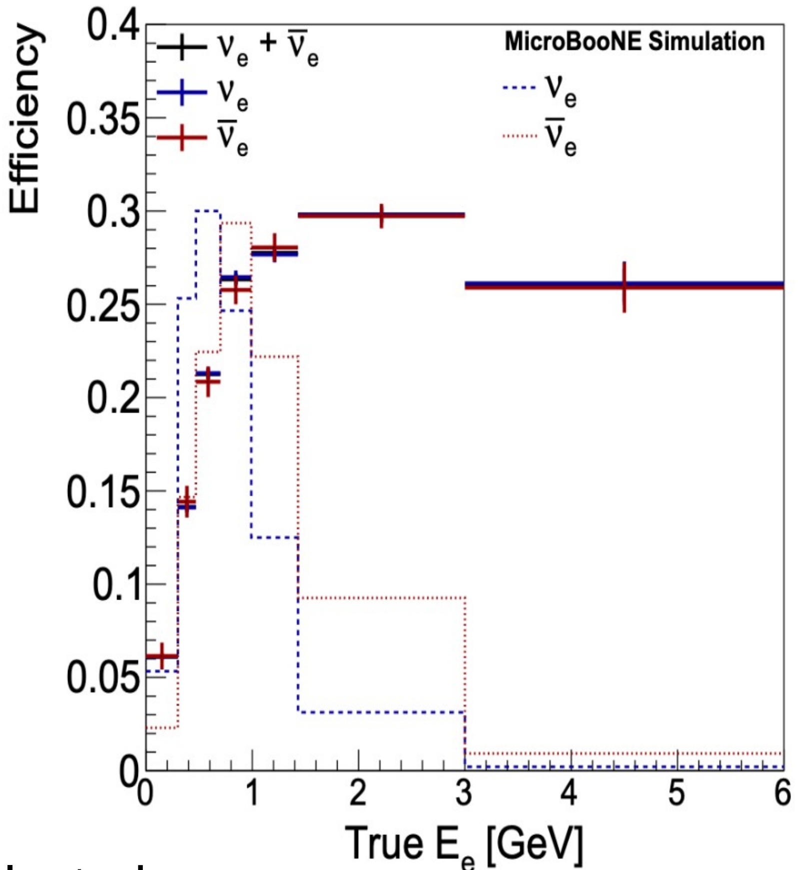


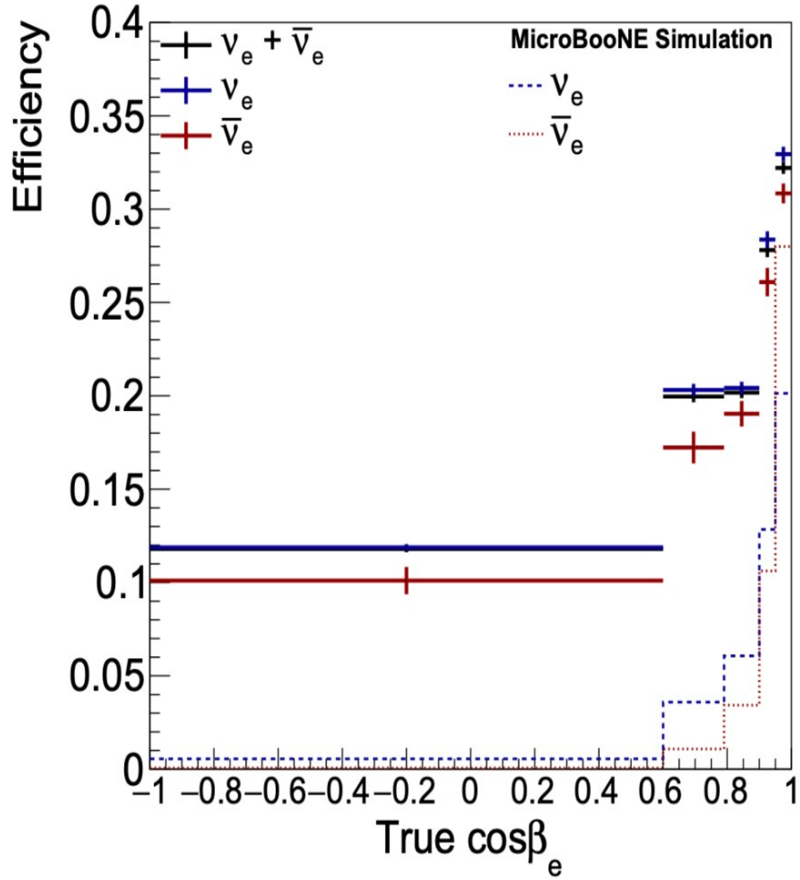


Assuming that neutrino comes from the target is correct within 3 degrees from true direction for 95% of selected ν_e

0.01 < **cosβ** resolution < 0.05

Event Selection and Performance

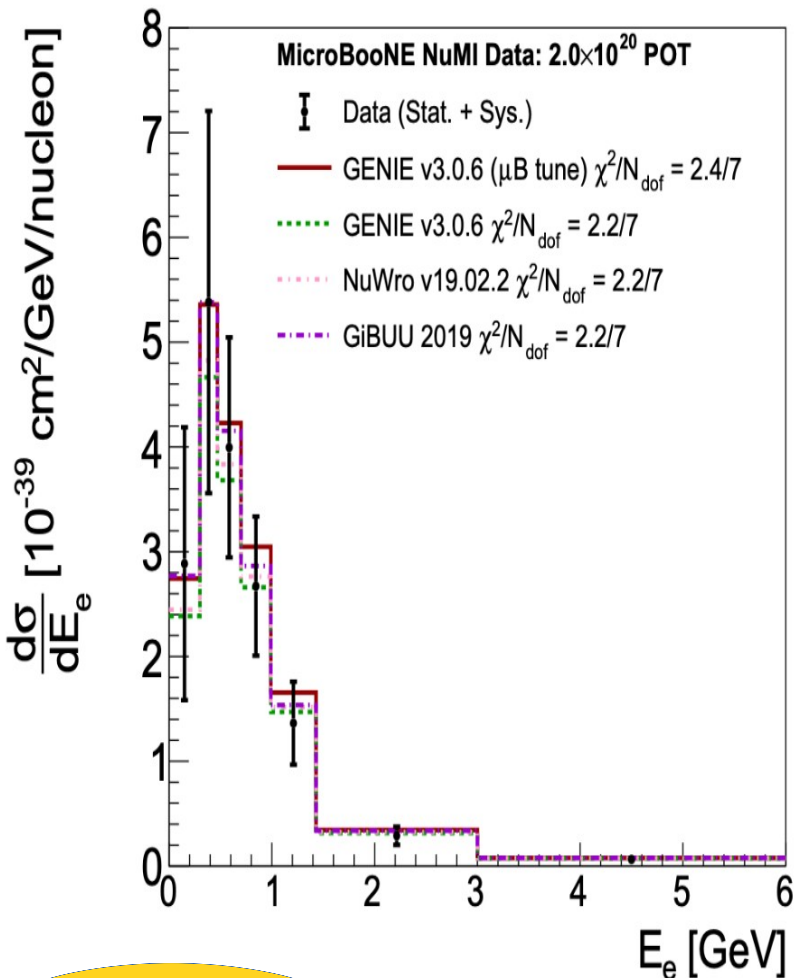


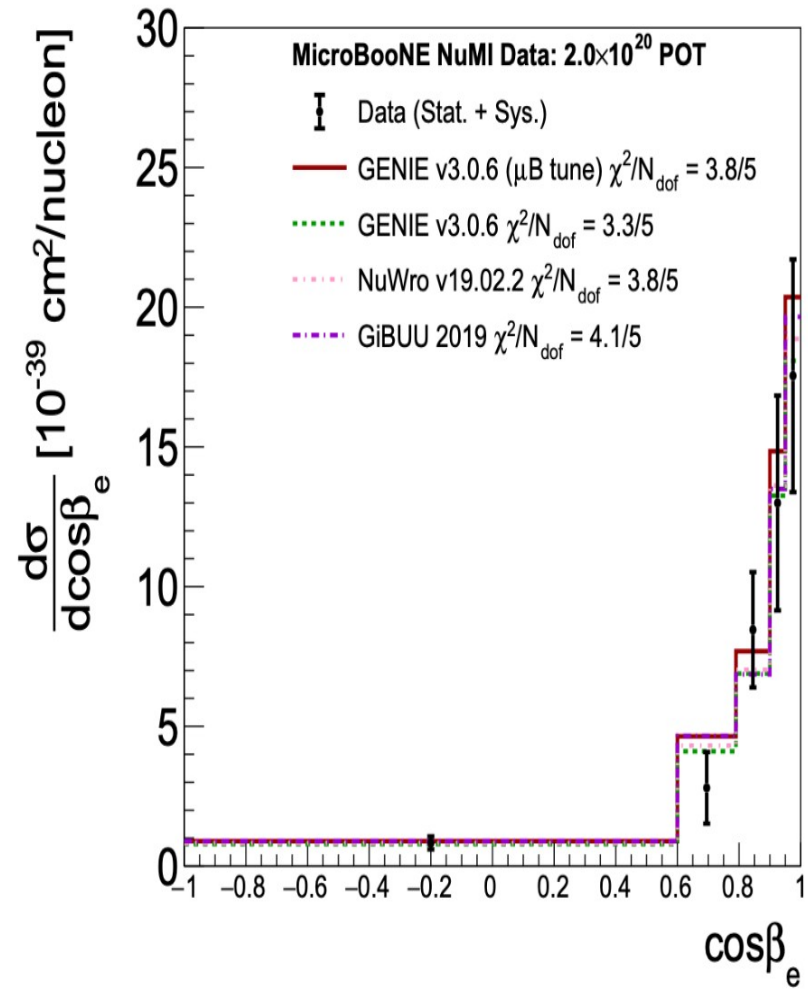


243 selected candidates.
purity: 72%
Avg efficiency: 21%

Main backgrounds:
→ cosmics 8%
→ non-ν_e containing π^0 11%
→ interactions outside FV 7%

Cross Section Results

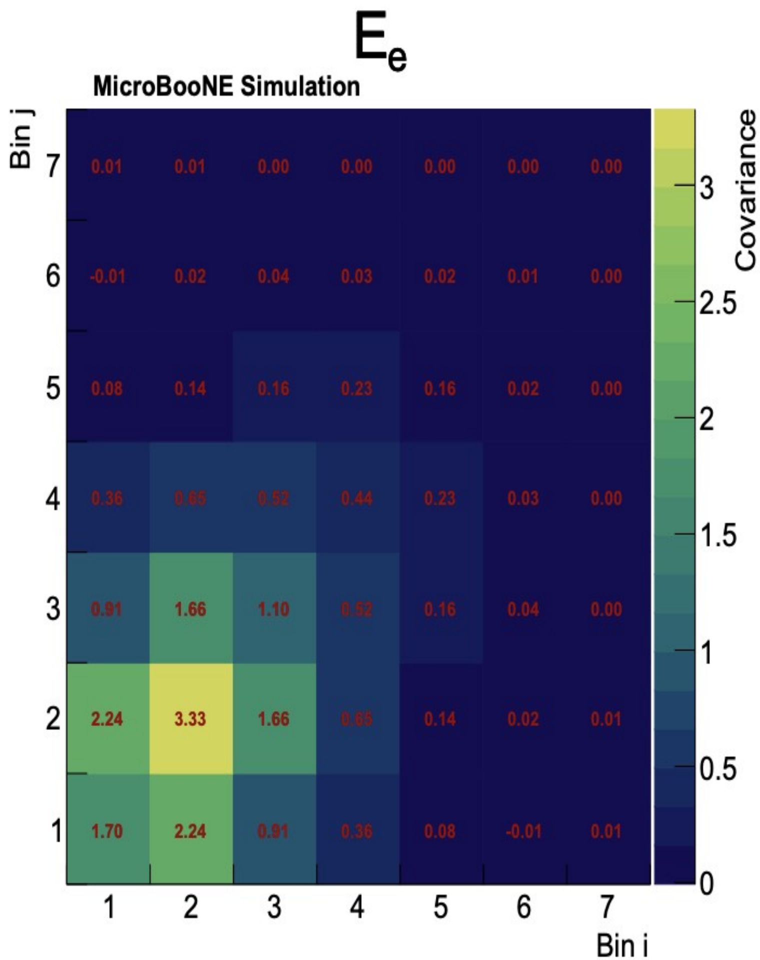


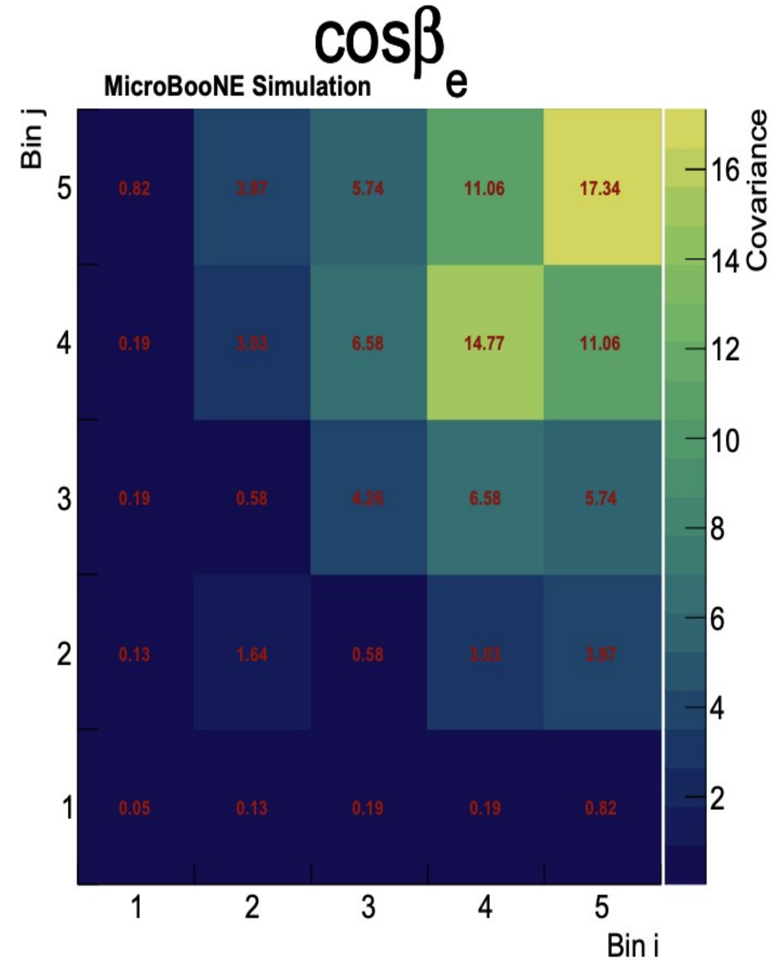


Wiener-SVD unfolded

Good data – MC agreement

Unfolded data-covariance matrix





supplemental material

3. Differential pionless ν_e CC cross section using BNB

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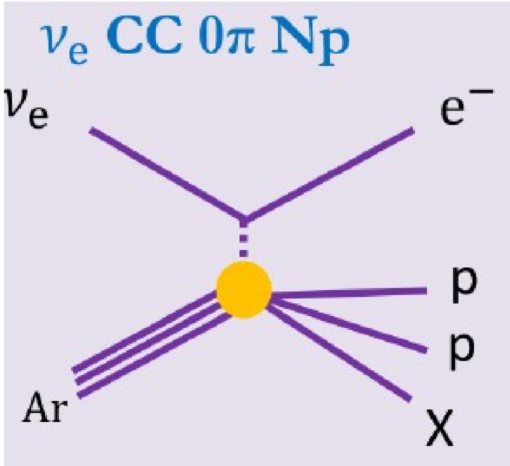
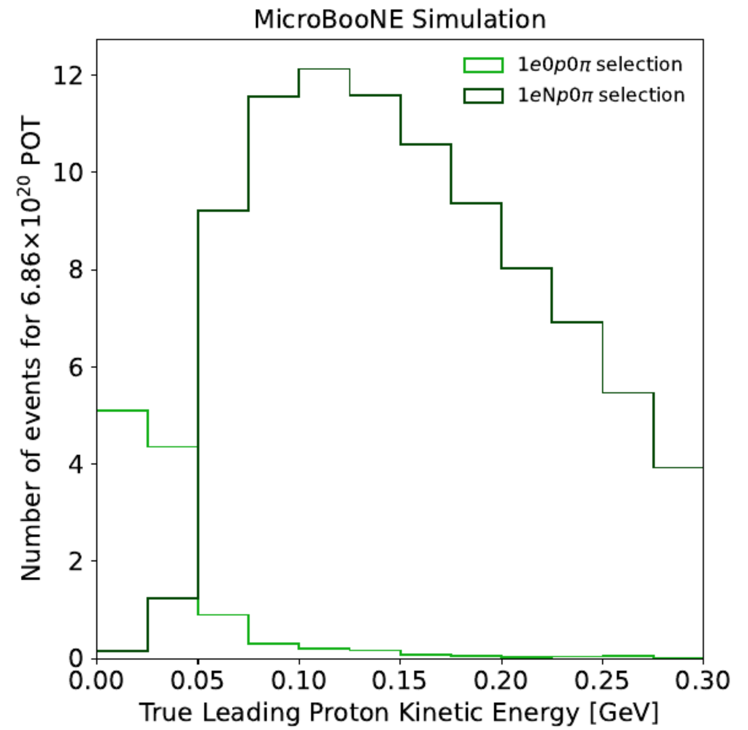


First exclusive ν_e c-s on argon!

Measurement

- "2nd generation" MicroBooNE analysis
- Using the BNB and reconstruction framework developed for the LEE.
- Using Run 1-3 data.
- Using overlays for cosmics.
- Signal: CC ν_e interactions with:
  - $KE_e > 30$ MeV, $KE_\pi < 40$ MeV
- Two selection chains depending on presence of protons (i.e. $KE_p > 50$ MeV).
  - For **1e0p0π** chain phase space restricted to: $\cos\theta_e > 0.6$ && $E_e > 0.51$ GeV to enhance purity.
- ~100+10 events expected (+ ~30+8 background events).



Same Selection chain as NUMI 1d

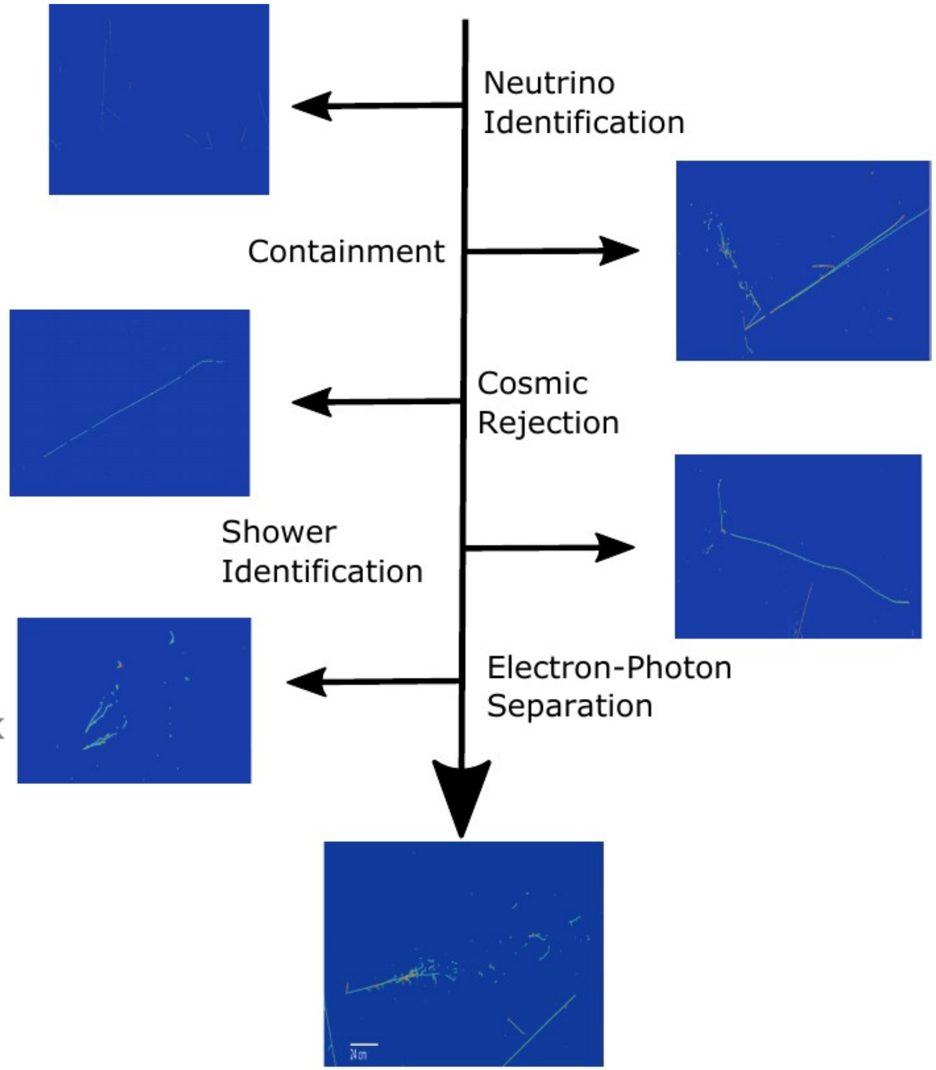
1. Slice ID
2. Shower in Neutrino Slice

3. Fiducial Volume Boundary
4. Contained Fraction

5. Topological Score
6. Cosmic IP

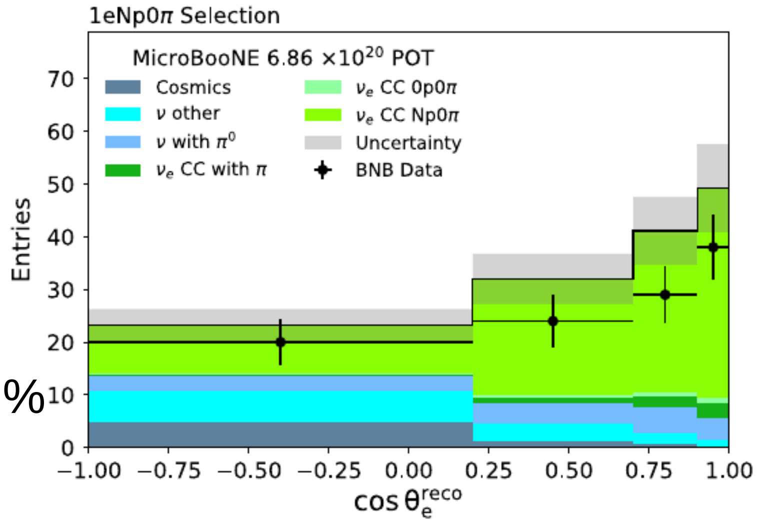
7. Shower Score
8. Hit Ratio

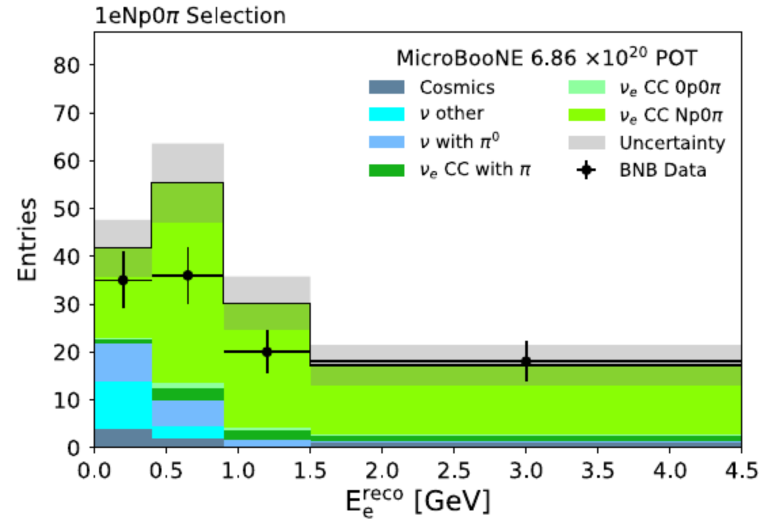
9. Moliere Angle
10. 2D: Shower distance, dE/dx
11. dE/dx (no tracks)

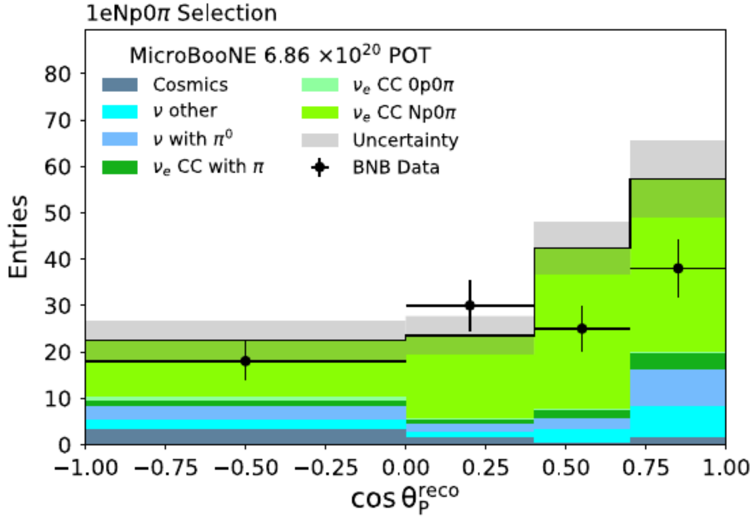


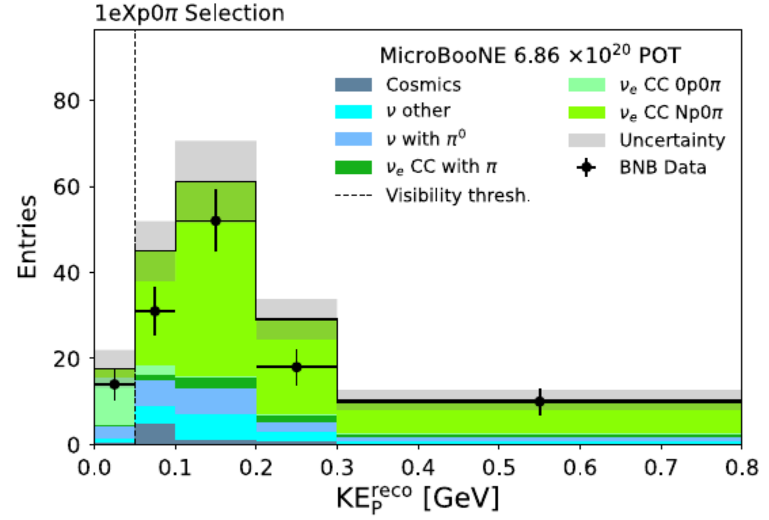
Selection Results

- **1eNp0π**:
  efficiency: 17%
  purity: 69%
- **1e0p0π**:
  efficiency: 12%
  purity: 65%

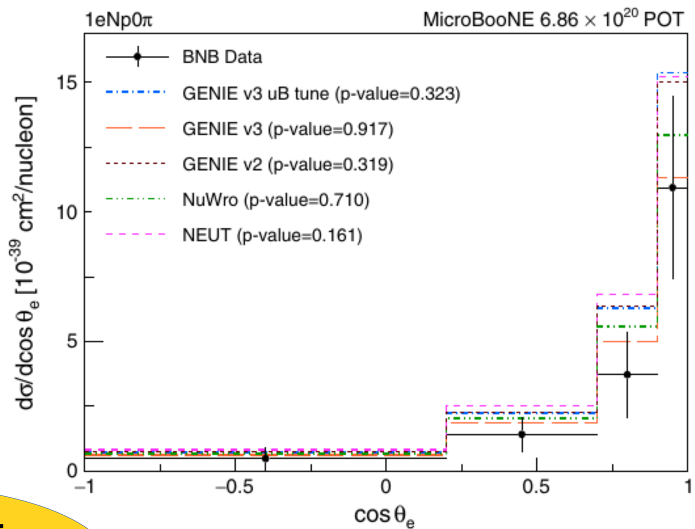


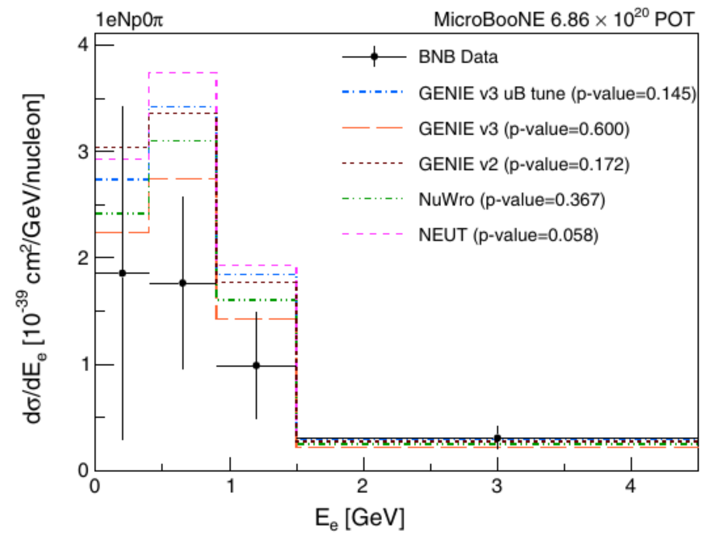






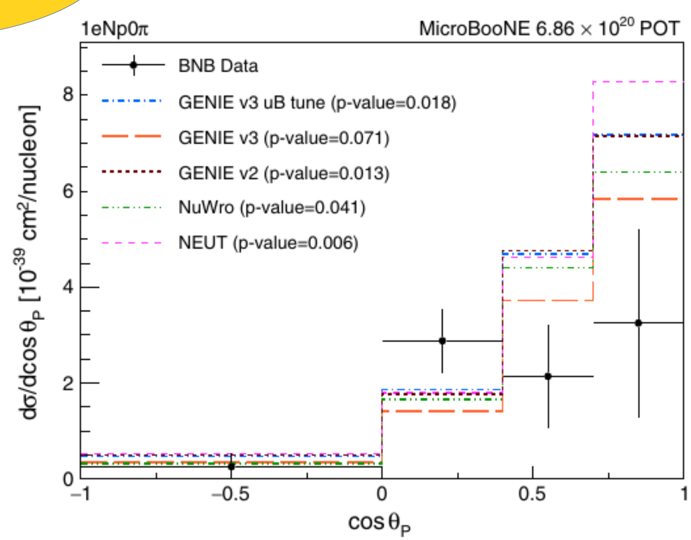
Cross section results

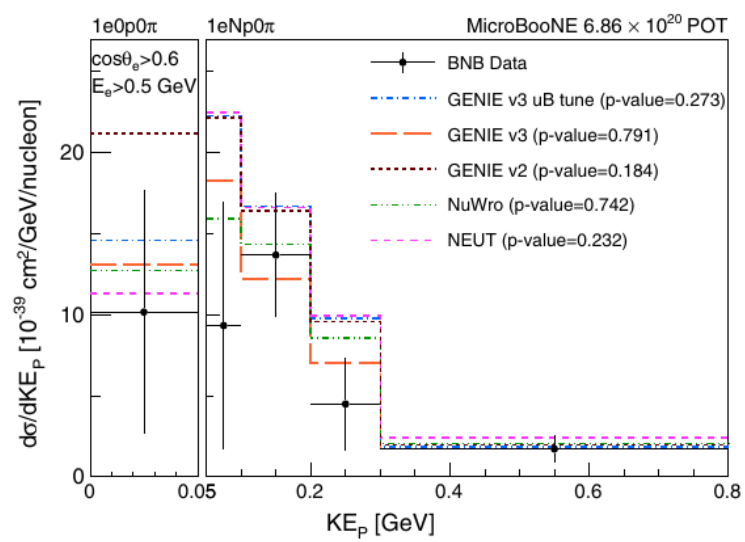




d'Agostini unfolded

Reasonable data – MC agreement





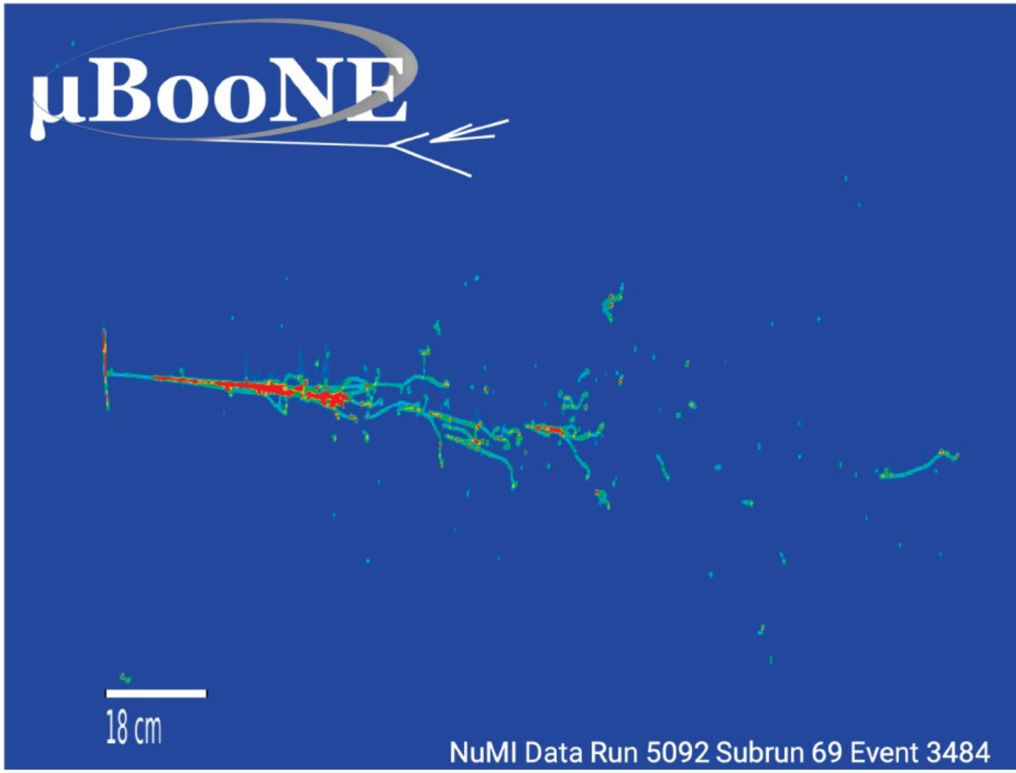
Covariance matrices in supplemental material

Summary and Outlook

- MicroBooNE is leading the way in electron-neutrino cross sections on argon.
- We have the largest electron-neutrino sample on argon to date.
- 3 measurements since last NuINT.
- More coming soon, including using the whole MicroBooNE data set!

감사합니다

- Upcoming MicroBooNE ν_e analyses:
  - ν_e CC 0π Np (NuMI)
  - $\bar{\nu}_e$ CC Inclusive (NuMI)
  - ν_e/ν_μ ratio (NuMI)
  - Full dataset analyses



Backup slides

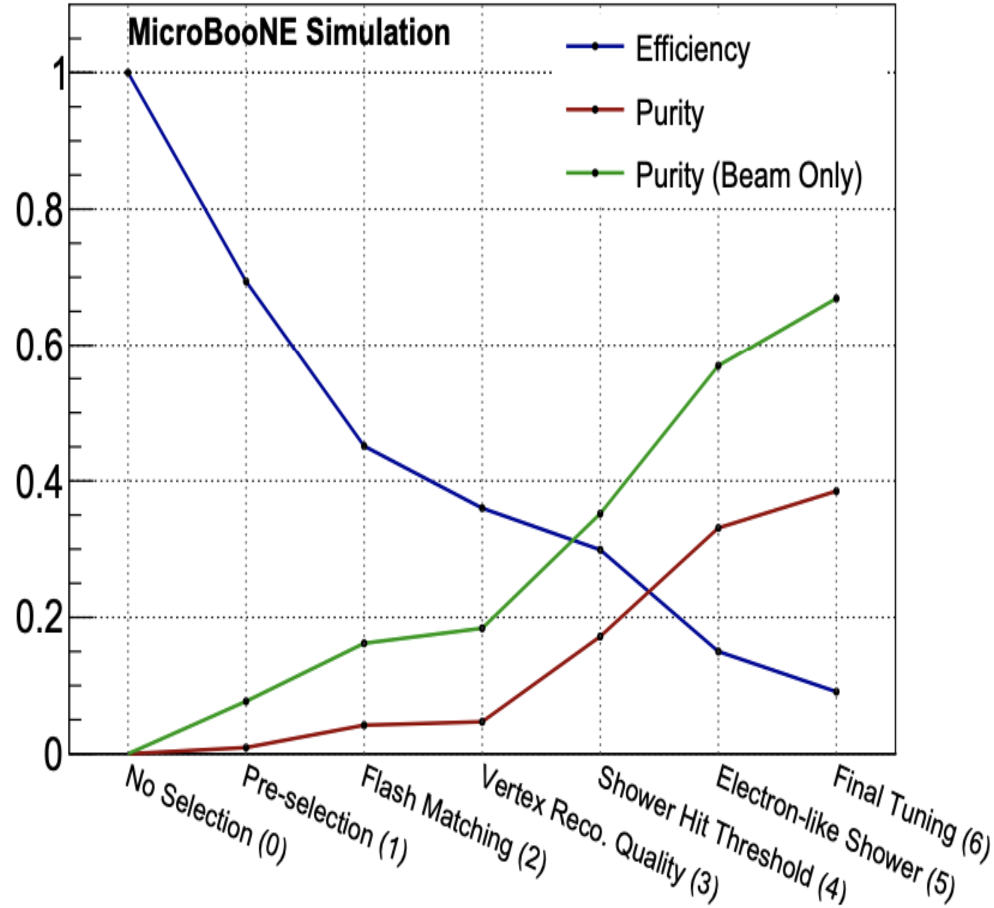
Selection Performance

- Overall purity: 38%

  Overall efficiency: 9%

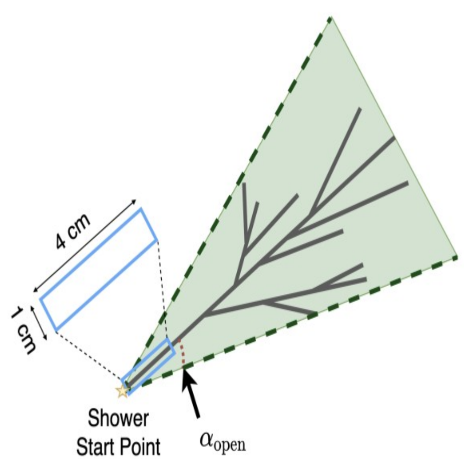
  Cosmic ray contamination decreases by a factor of 10^5 wrt initial selection stage… yet, cosmic rays represent the major background contribution to the analysis: 1:1 with signal

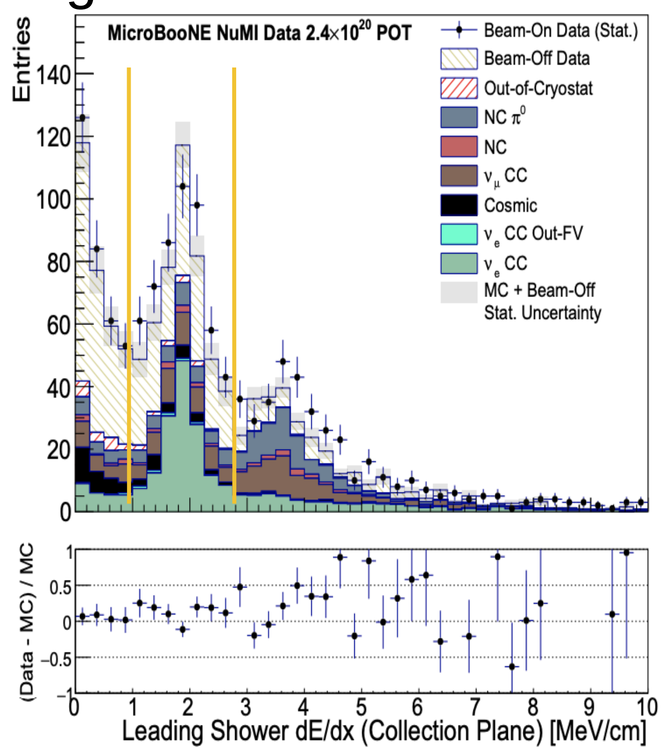
  → highlights the need of targeted cosmic ray removal (done in updated analysis)

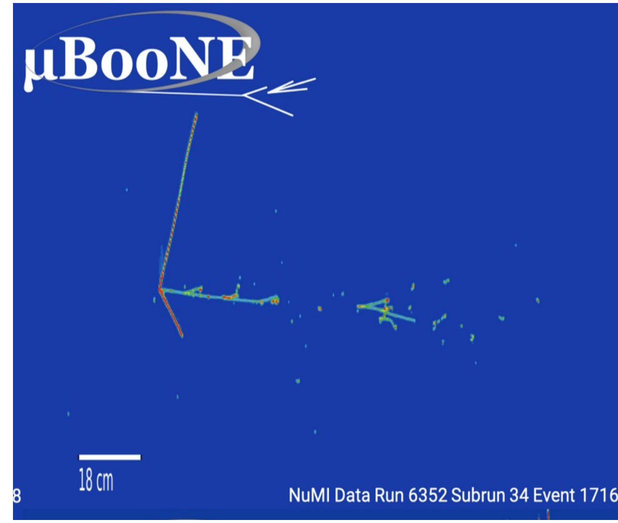


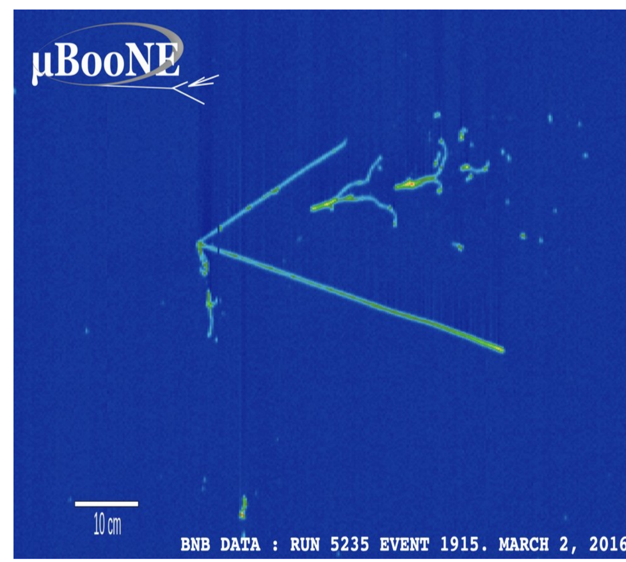
Selection cont'd

- Leading shower quality: 200+ total & 80+ collection hits
- Leading shower "physics":
  - 1.4 MeV/cm < trunk dE/dx < 3 MeV/cm
  - 3^{o} < Opening angle < 15^{o}







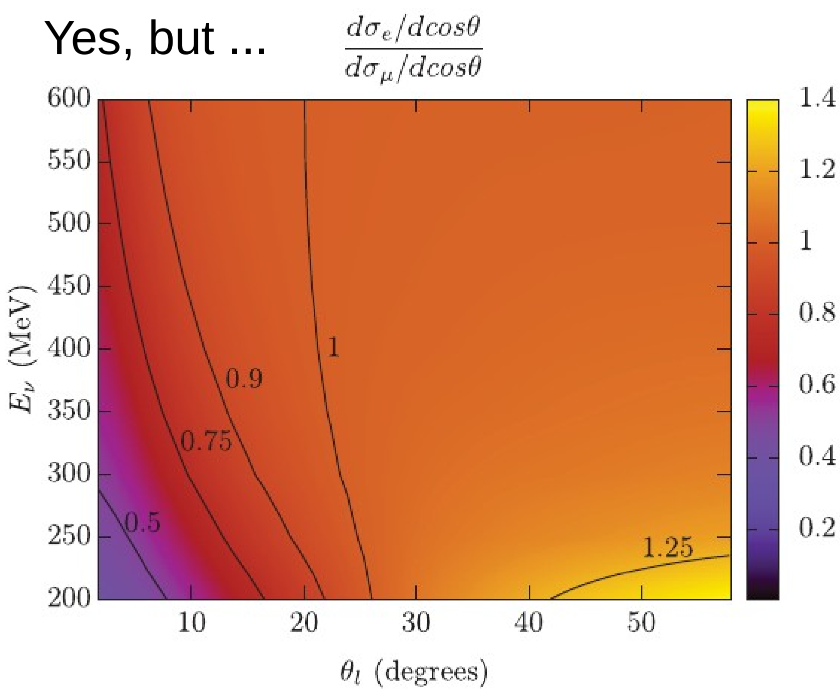


Why measure ν_e cross sections?

Many ν_μ measurements exist – much easier to produce ν_μ at accelerator energies.

Can't we use lepton universality and de done with it?

Yes, but ...



- Flavour-dependent effects due to the different lepton mass and uncertainties in nucleon form factors can be up to 5-10%: [Phys.Rev.D 86 (2012) 053003, PhysRevLett.123.052501, arXiv:2105.07939 https://arxiv.org/abs/2204.11379]
- Radiative part of these effects is not implemented in ν-generators.
- Direct measurements of ν_e cross sections could provide tests of lepton universality.
- Testing ground for ν_e reconstruction.