# MicroBooNE Recent Cross Section Results

Michael Kirby, Fermilab/Scientific Computing Division

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APS Division of Particles & Fields 2019 - Northeastern University

# How does MicroBooNE fit into the neutrino picture?

Short Baseline Accelerator Neutrino Program

- resolve anomalies from LSND/MiniBooNE
- MicroBooNE first experiment in the program
- utilize Booster Neutrino Beam
- LArTPC - improved coverage, energy threshold, and particle identification

Measurements of ν-Ar cross sections

- comparison with numerous predictions
- allows MicroBooNE to tune interaction, nuclear, and final state models to match data
- improve determination of incident ν energy for neutrino oscillation measurements

Liquid Argon TPC detector research and development for future experiments

Non-Accelerator based physics R&D (SN, p decay)

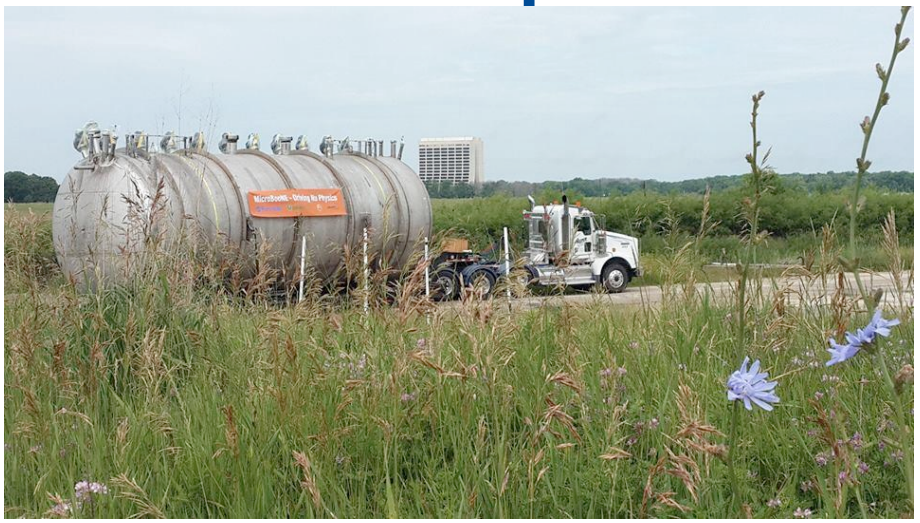
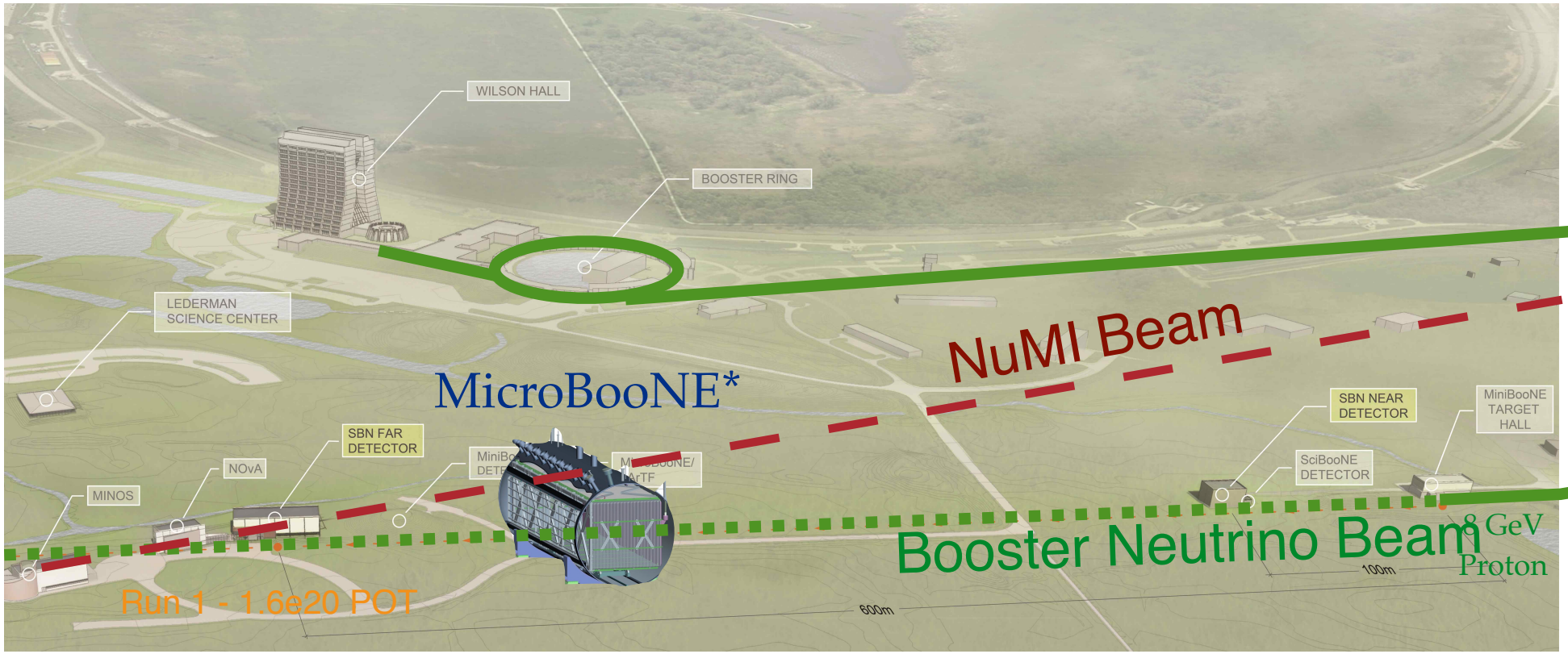
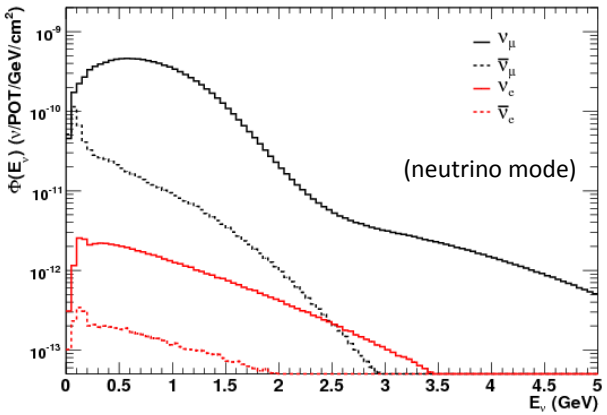


Photo by my mom

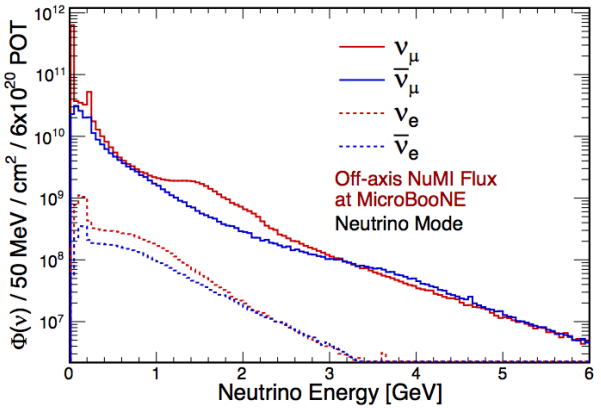
Photo by Reidar Hahn

# MicroBooNE and the NuMI Beam




470m Baseline
<$E_\nu$> = 850 MeV
$\nu_e$ < 1% flux




NuMI Beam Line
8° Off Axis
$\nu_e$ ≈5% flux



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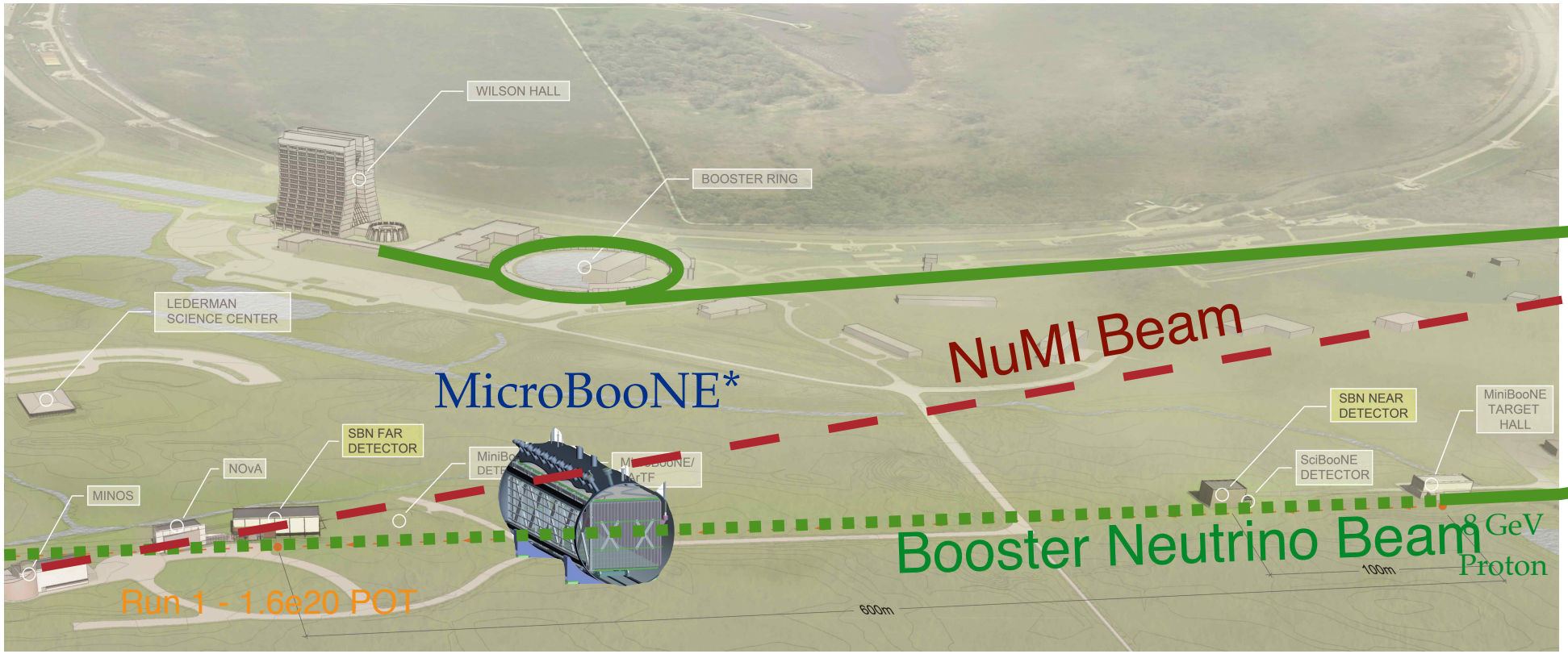
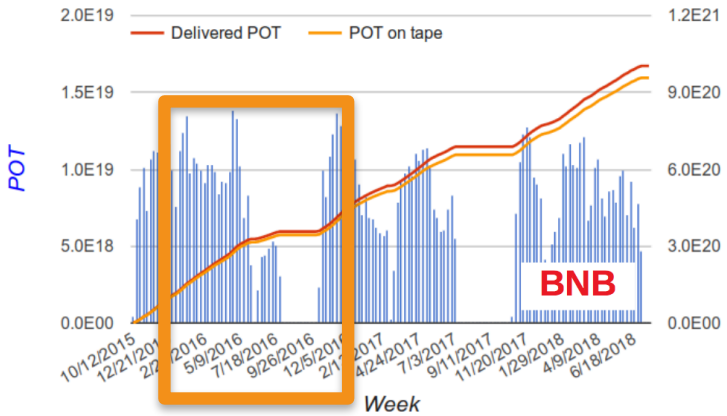
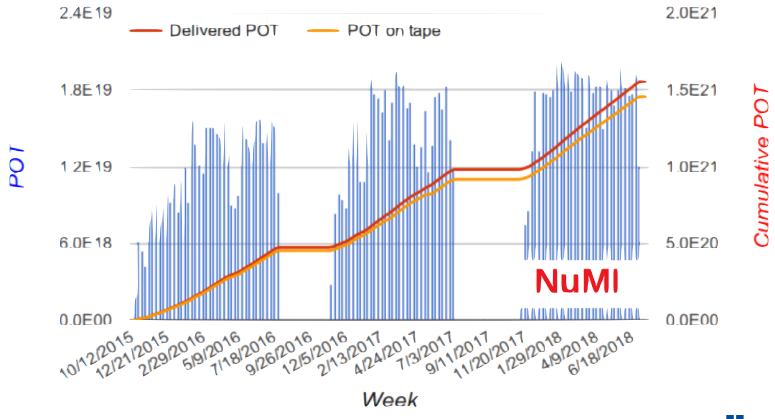
*not to scale or correct orientation

# MicroBooNE and the NuMI Beam






Run 1 - 1.6e20 POT

*not to scale or correct orientation

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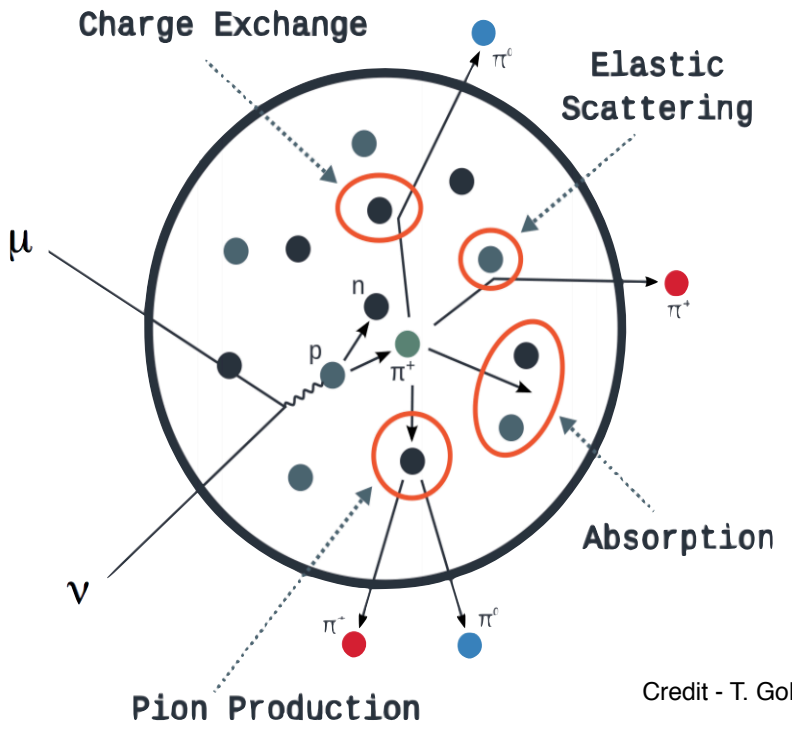
# Neutrino - Nucleon interaction

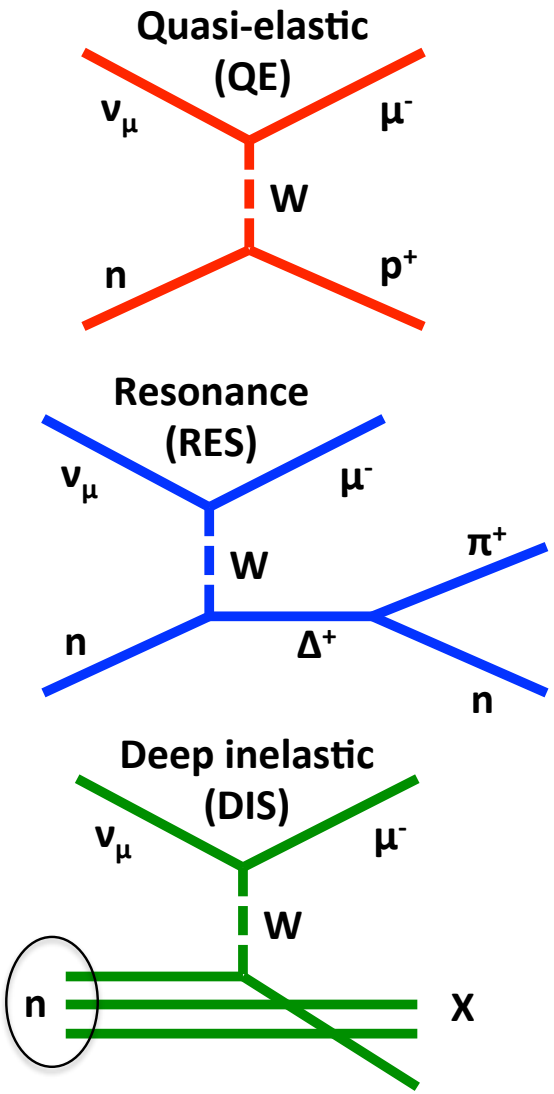
$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Determination of the incident neutrino is based upon interpretation of reconstructed final-state objects through interaction model
- Nuclear model
- Nucleon correlations
- Final-state interactions
- All of this before the particles exit the nucleus and interact in the detector

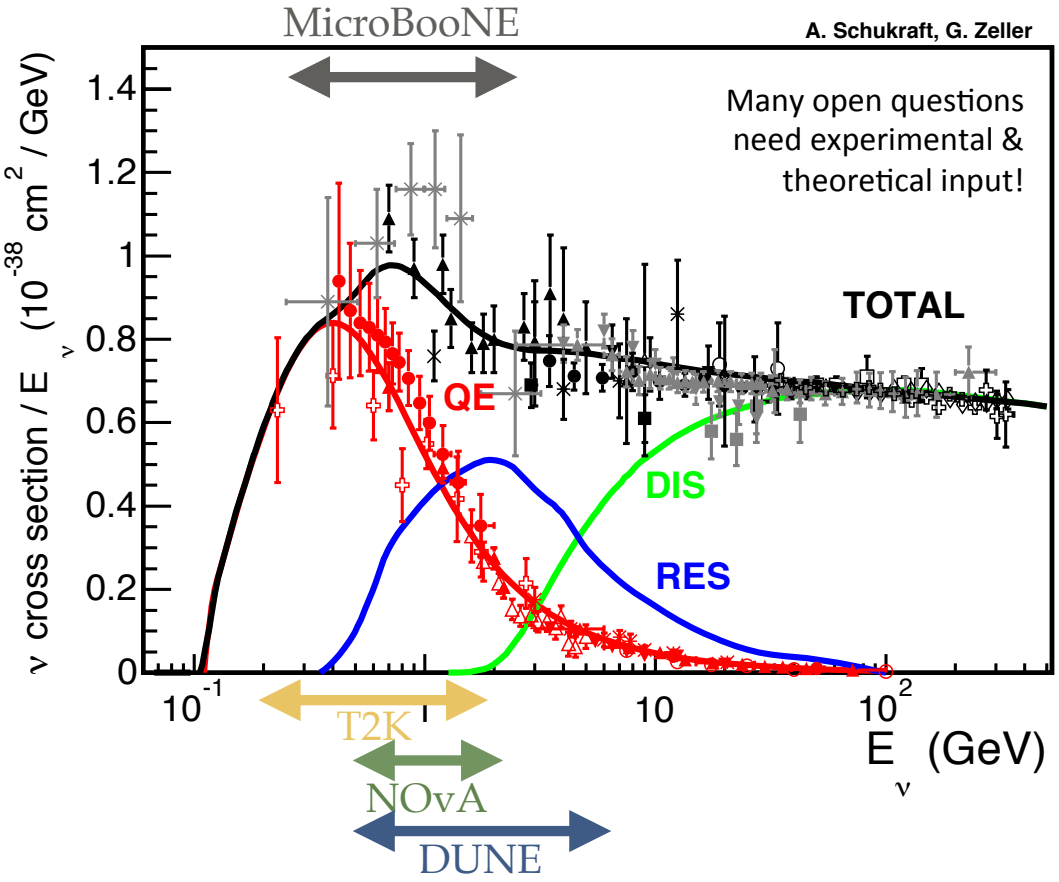



Credit - T. Golan

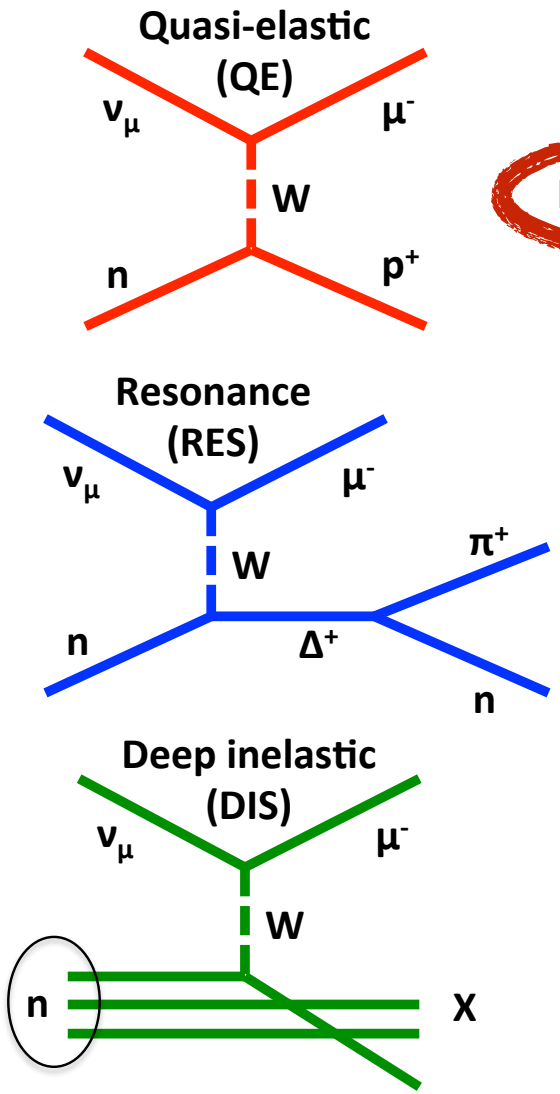
# Neutrino-nucleon interactions



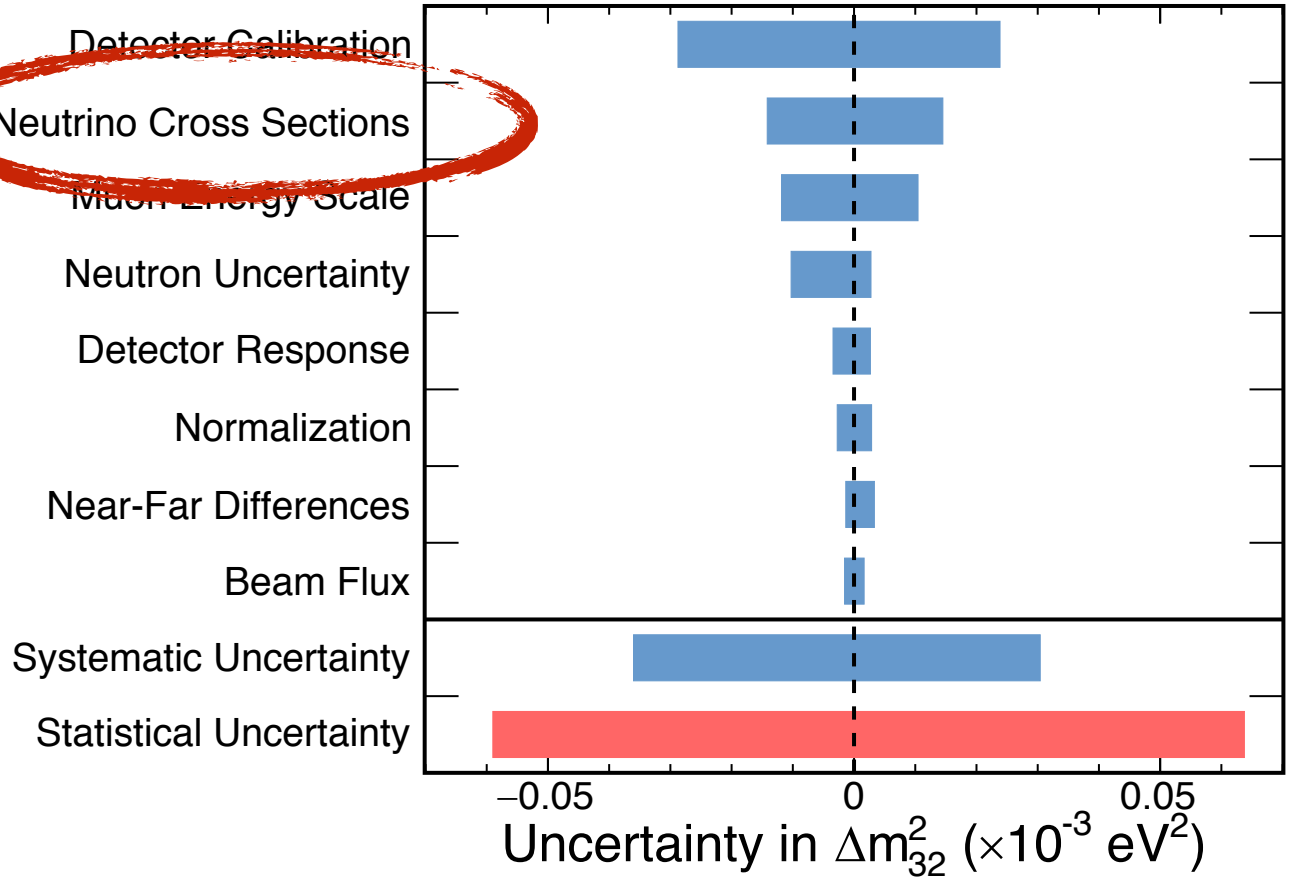

Lots of interesting (nuclear) physics over all energy ranges.



# Neutrino-nucleon interactions

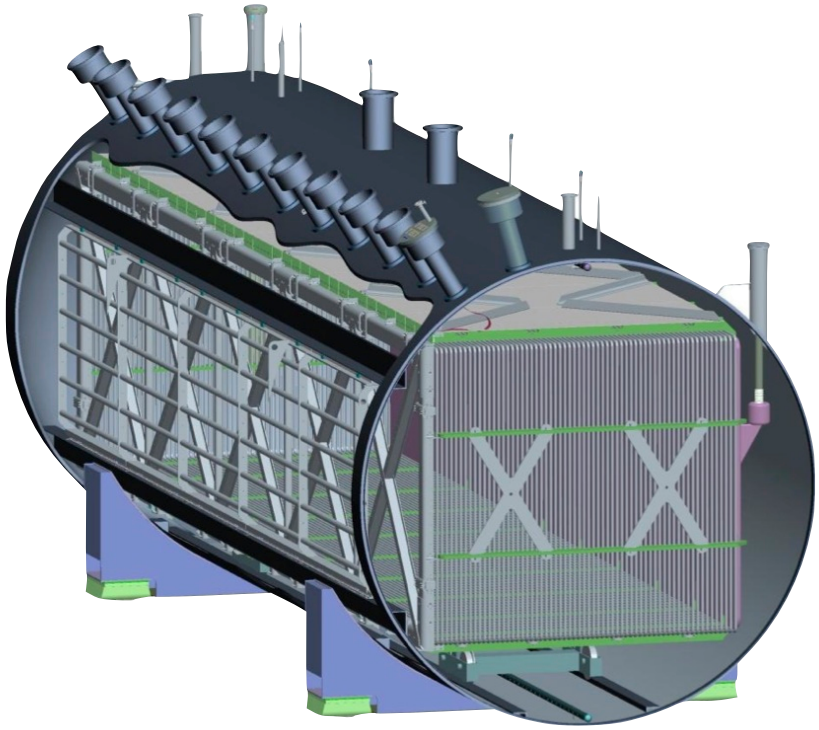



NOvA Preliminary




Alex Himmel, Fermilab W&C June 15, 2018

# MicroBooNE Detector



- 85 t active volume
- 2 induction planes (±60°)
- 1 collection plane (vert)
- 2.3 ms drift time
  - 70 kV - 2.5m drift
- 32 PMTs for trigger and t0

JINST 12, P02017 (2017)

## Liquid Argon TPC

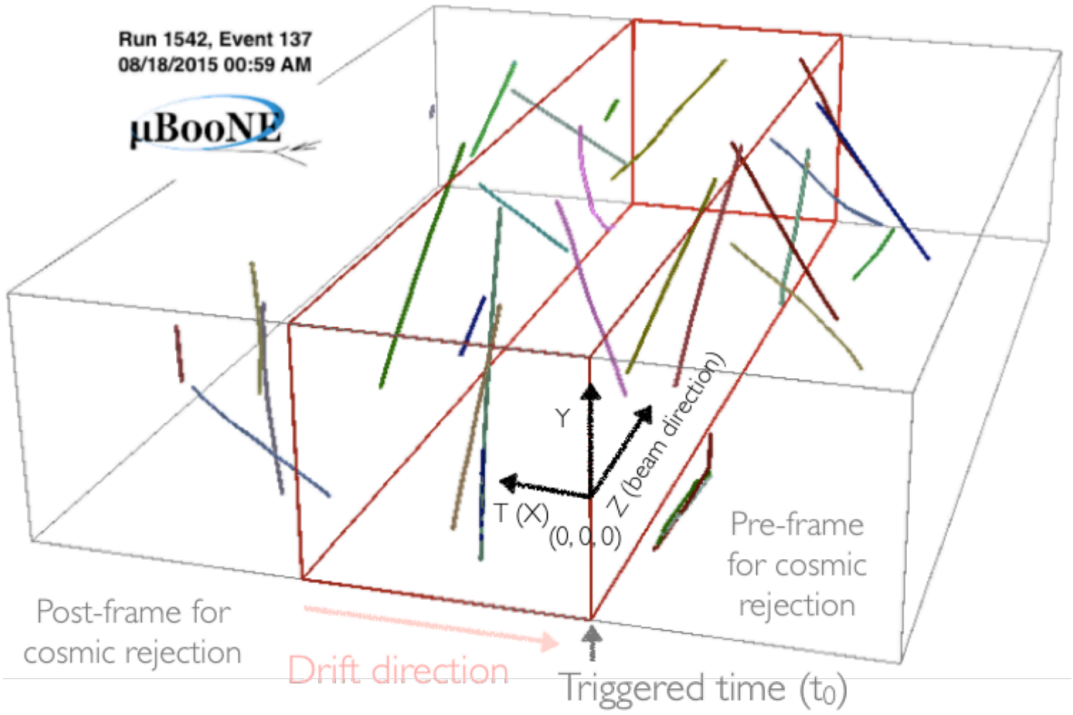
### Strengths

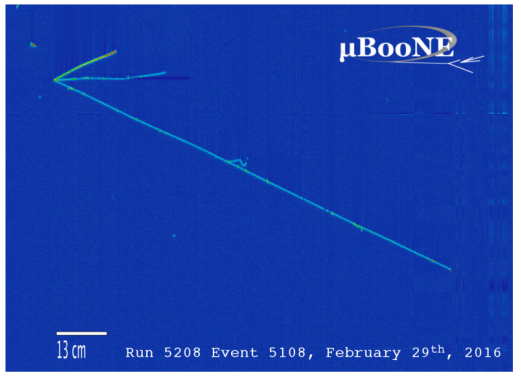
- full $4\pi$ coverage
- mm scale resolution
- Fully active calorimetry
- lower energy threshold than any other accelerator $\nu$-detectors

### Challenges

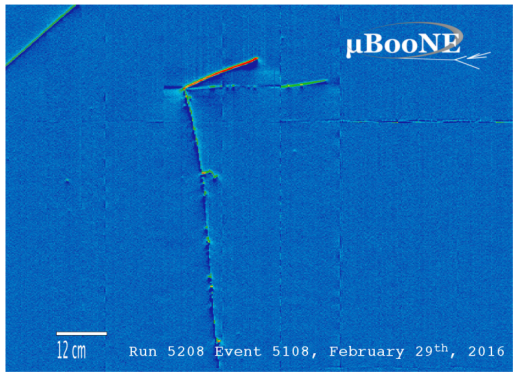
- argon purity - electron lifetime
- uniformity of E-field
- neutron identification
- target atom contains 40 nucleons

# MicroBooNE event reconstruction

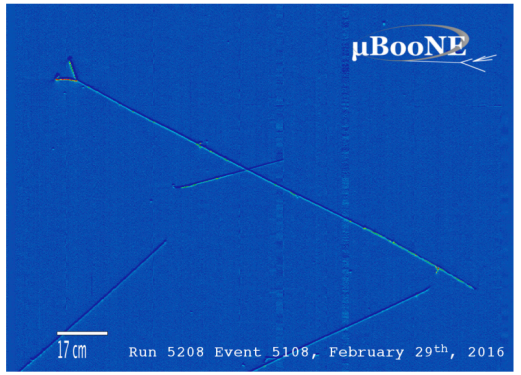



(a) Collection plane (Y)




(c) Induction plane (U)




(e) Induction plane (V)

Readout Time

Chan #

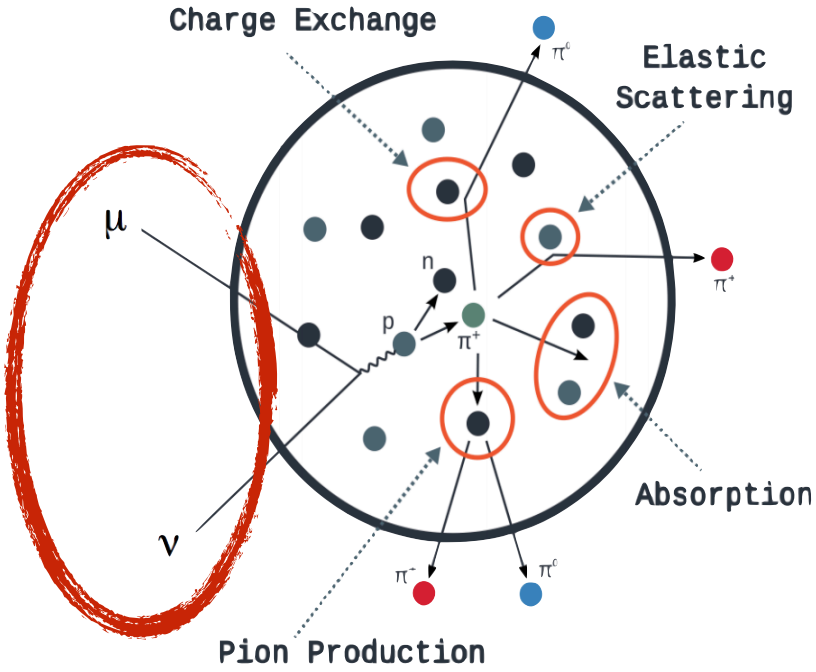
Surface detector - reject dominant cosmic tracks

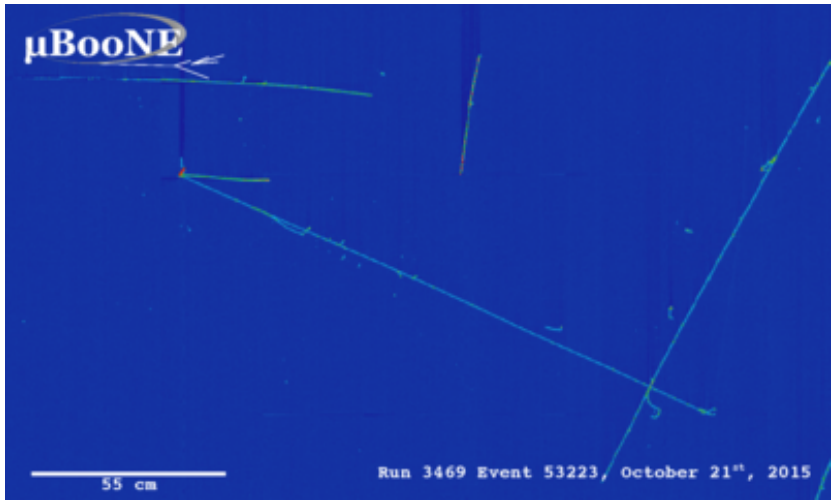
Reconstruct interaction vertex

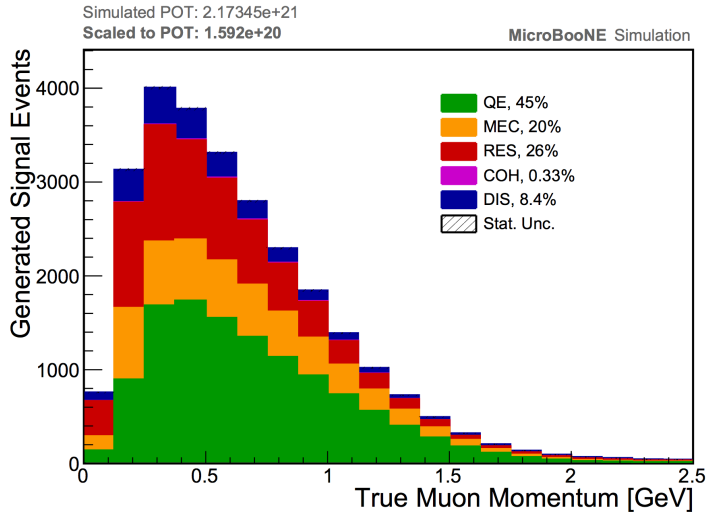
Particle identification - $\mu$, e, p, $\pi^o$, $\gamma$

# Inclusive $\nu_\mu$ cross section measurement

- Identify muon track from neutrino vertex
- high efficiency recontruction
- purity - test rejection of cosmic tracks
- Full 4π coverage of interaction vertex
- Largely independent of hadron activity/ FSI, but sensitive to nuclear & interaction model
- important first step towards tuning models
- can be used as constraint for $\nu_e$ beam composition



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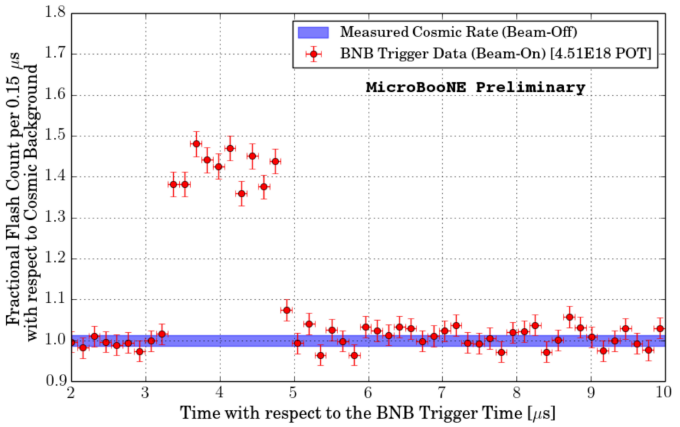
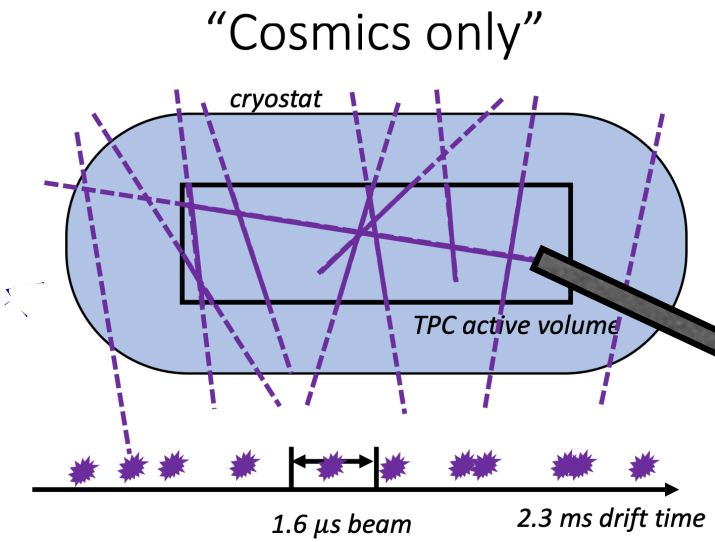
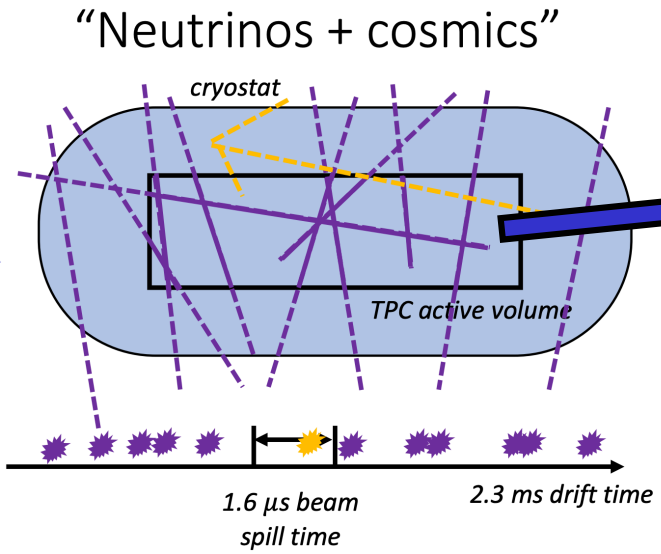
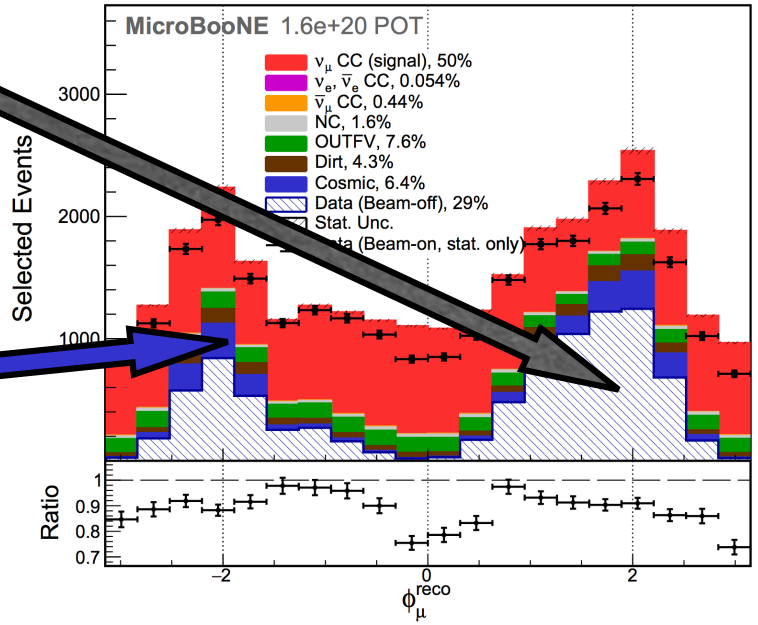
# Cosmic background rejection

- "cosmic only" - can be measured directly from off-beam triggers
- "neutrino + cosmic" - track from cosmic interaction is associated with flash from neutrino interaction outside of active volume
- Totally rejection factor of 99.99% achieved

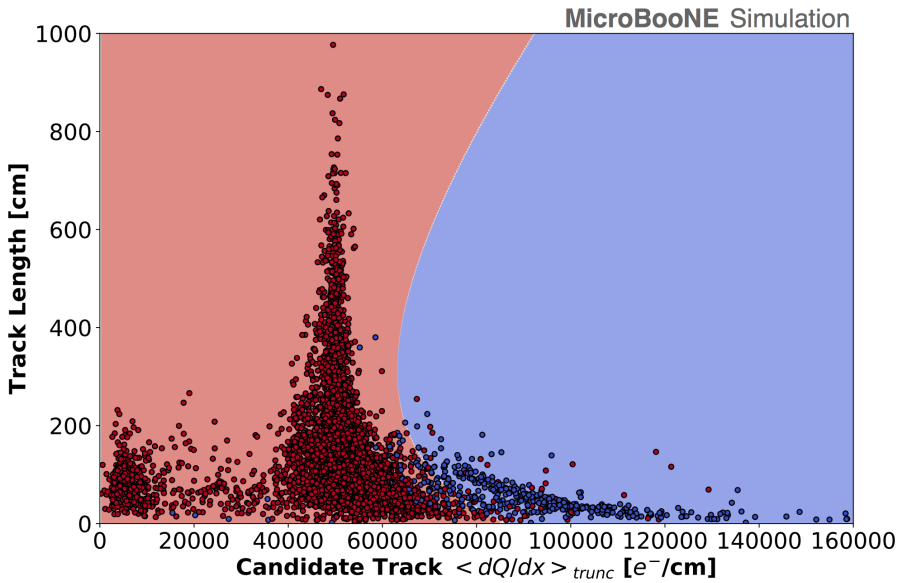


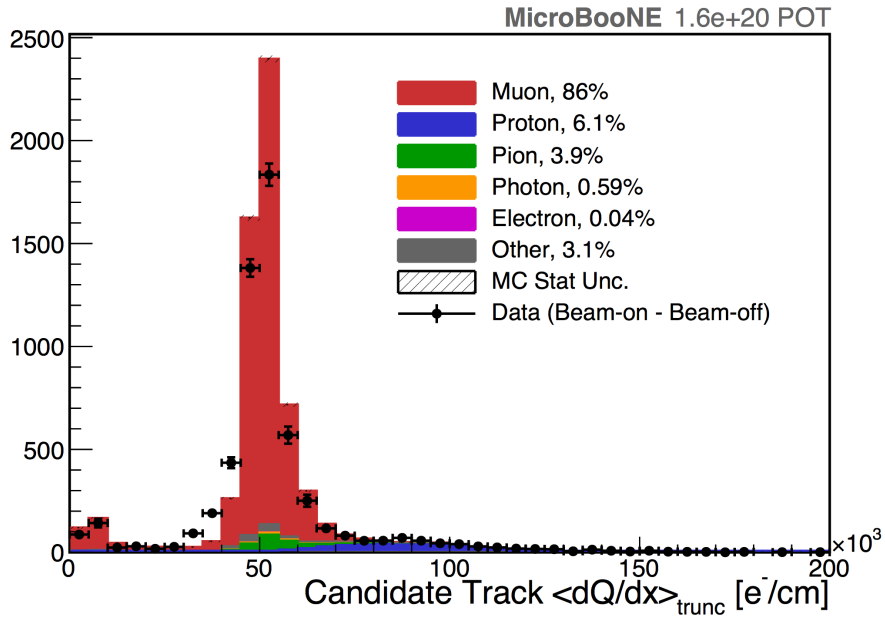



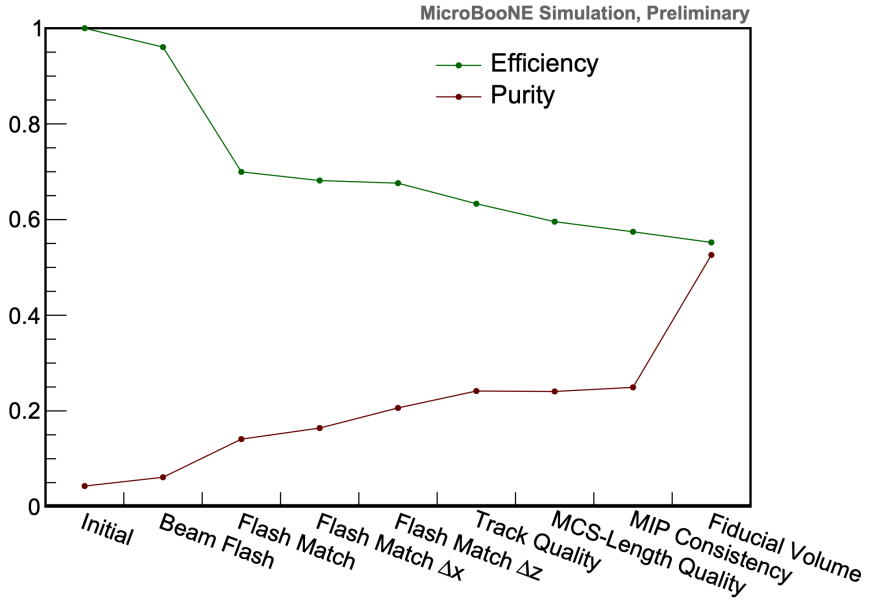



# Muon Candidate Track Identification

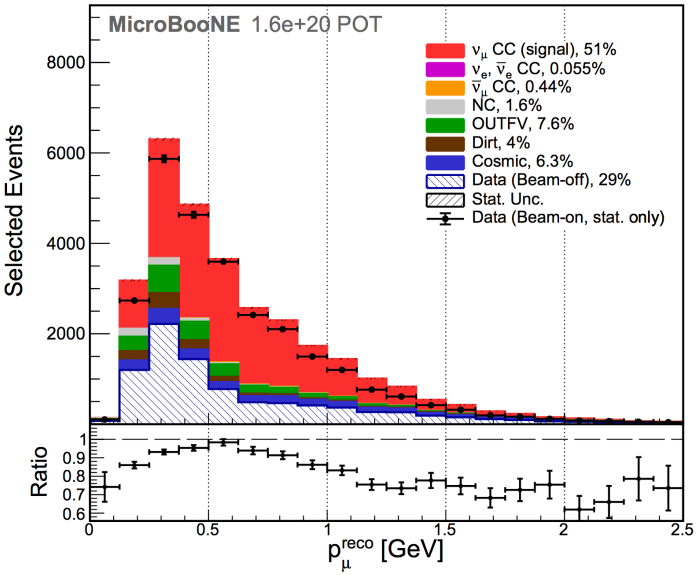


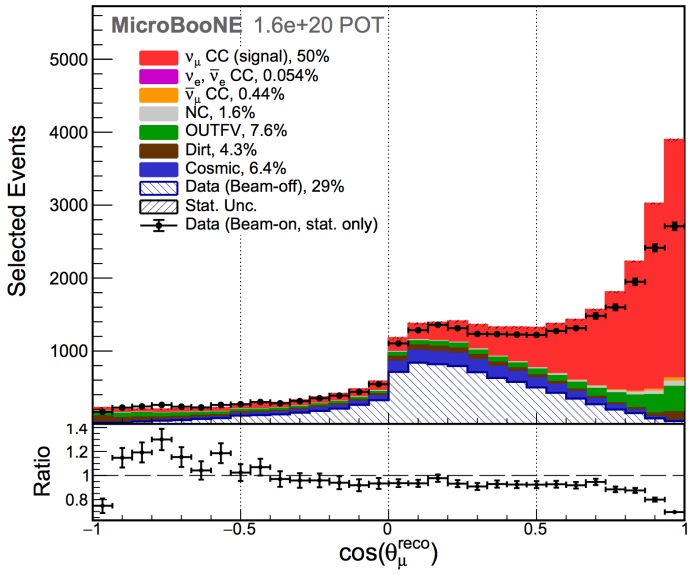

- Multiple Coulomb Scattering to eliminate broken tracks
- truncated dQ/dx of the track consistent with MIP
- Eff = 55%, purity 53%

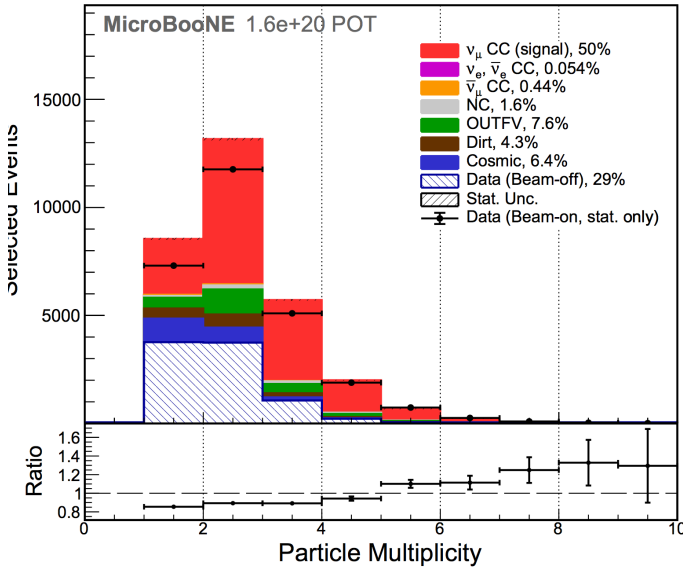


# Muon Candidate Distributions




- GENIE prediction from v2.12.2 with empirical MEC
- Some tension in the forward region
- high efficiency and acceptance allows for this to be base sample of other selections



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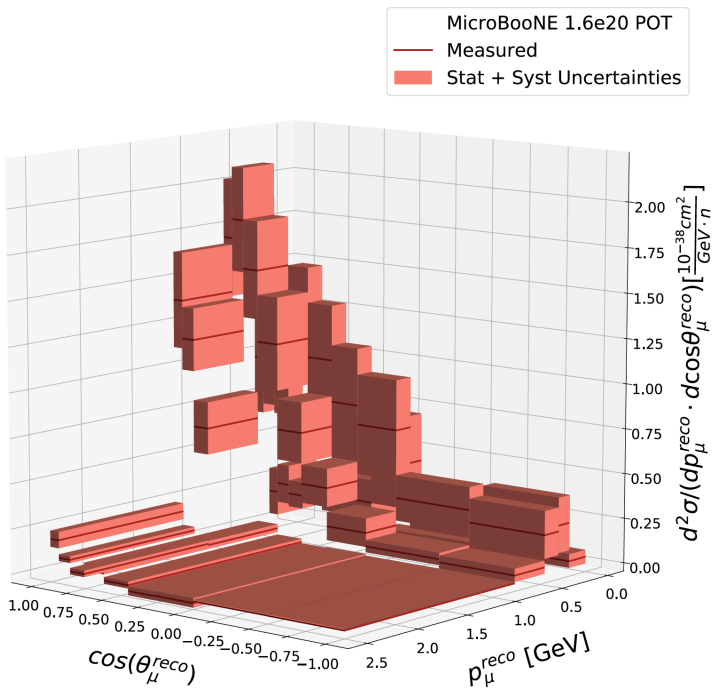
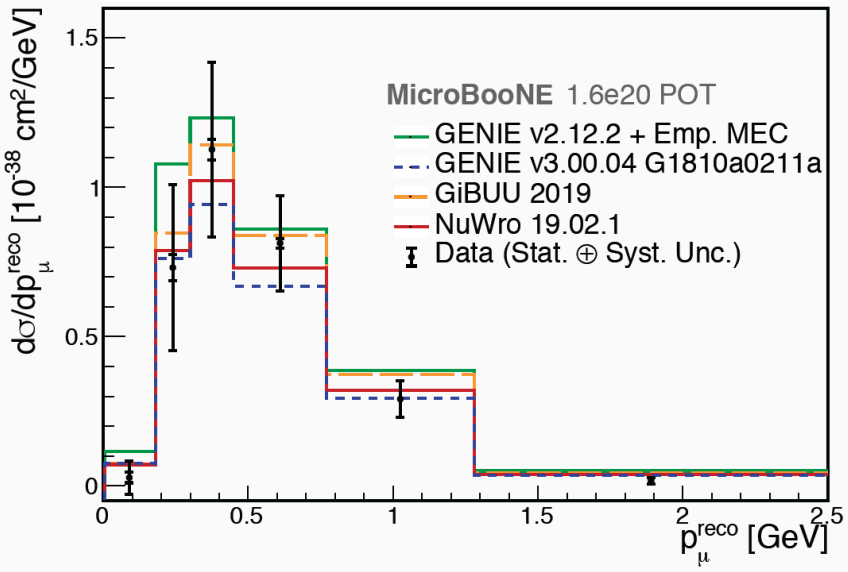
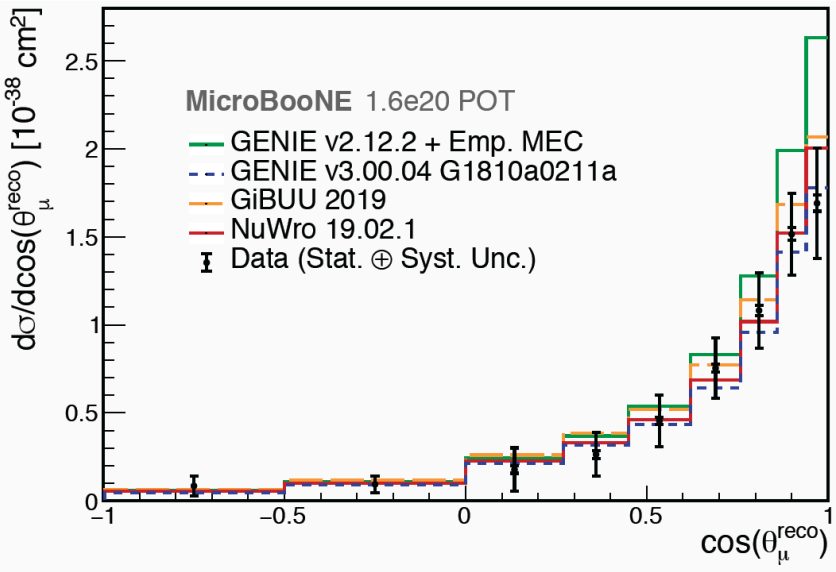
# $\nu_\mu$-Ar Inclusive Cross-Section Measurement

- First double differential cross section - $p_\mu$ vs $\cos(\theta_\mu)$
- Single differential cross sections - $p_\mu$ and $\cos(\theta_\mu)$
- tested with different neutrino event generators
- greatest tension exists at forward muon production
- forwarded folded analysis and publication of migration matrices allows for independent comparison with new models

Submitted to PRL, arXiv:1905.09694



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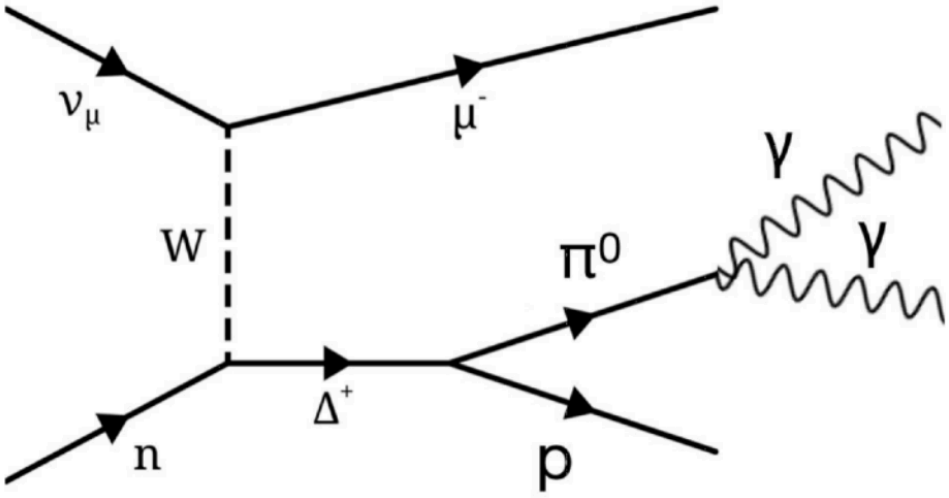
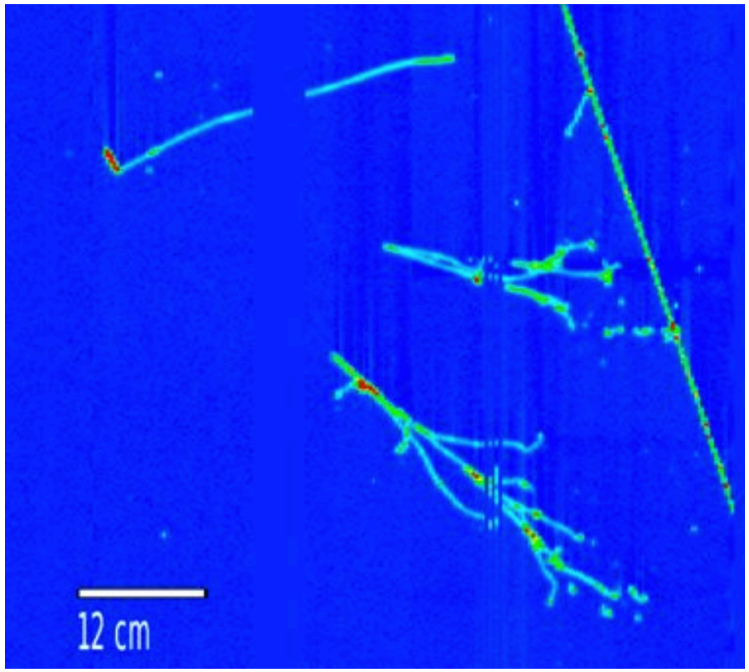
# Moving to more complicated topology -> CC $\pi^0$ Cross Section

- dominate production is from decay of Δ to π0
- important for neutrino-argon interactions, FSI, and detector performance
- Reconstruct a electromagnetic shower associated with vμ vertex
- select photon showers and separate from electrons
- shower and vertex reconstruction resolution

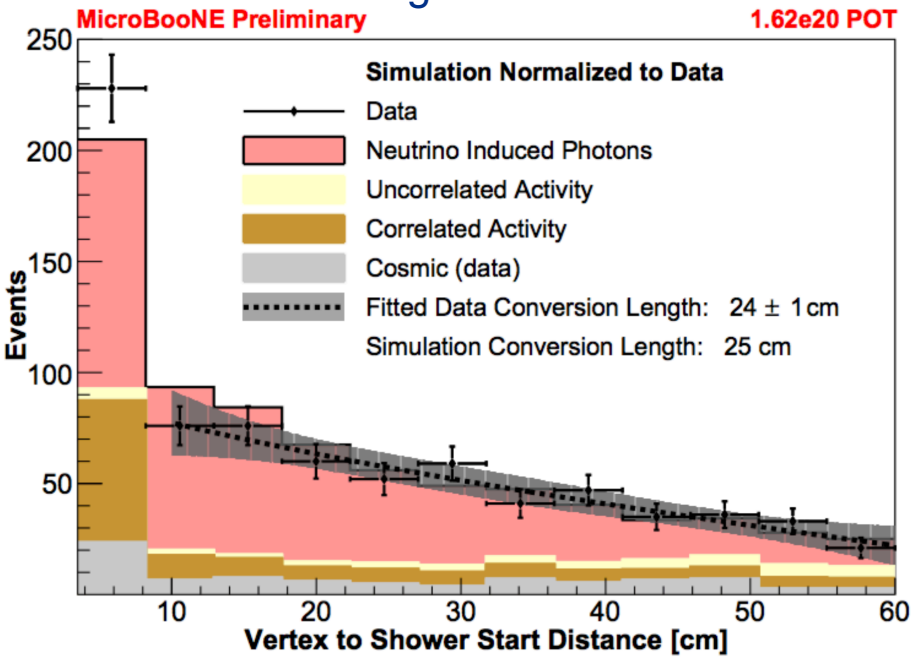


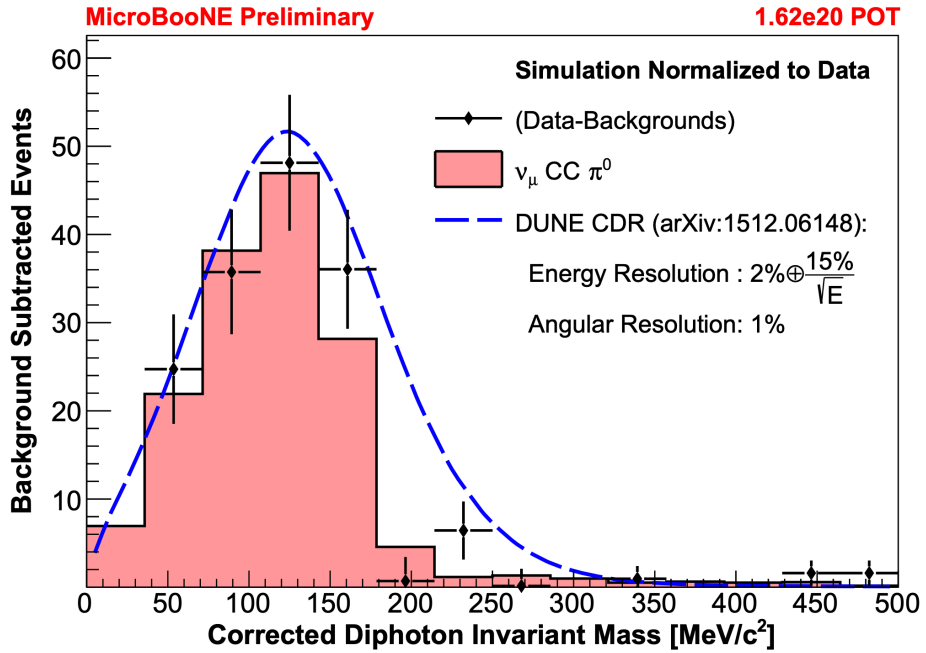
# CC $\pi^0$ candidate selection

- Fit the shower conversion length to confirm $\gamma$ selection
- Measured conversion length agrees with simulation
- Single shower - higher efficiency
- Two shower - higher purity
  - energy correction from simulation
  - hit thresholds correction
  - clustering efficiency
  - consistent with $\pi^0$ mass

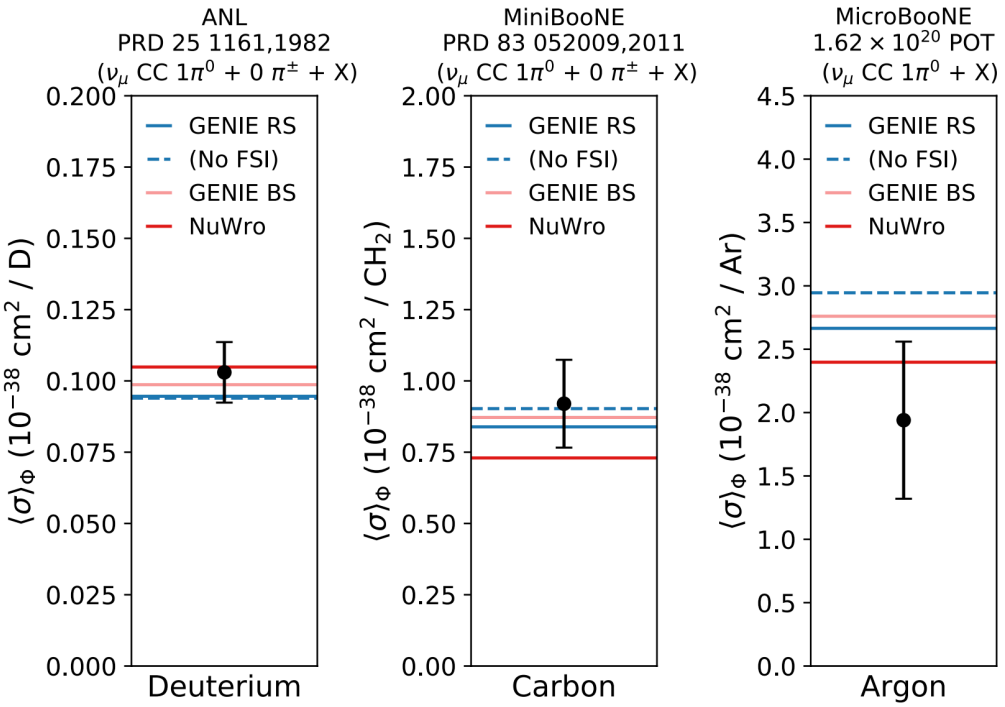
Single Shower Selection

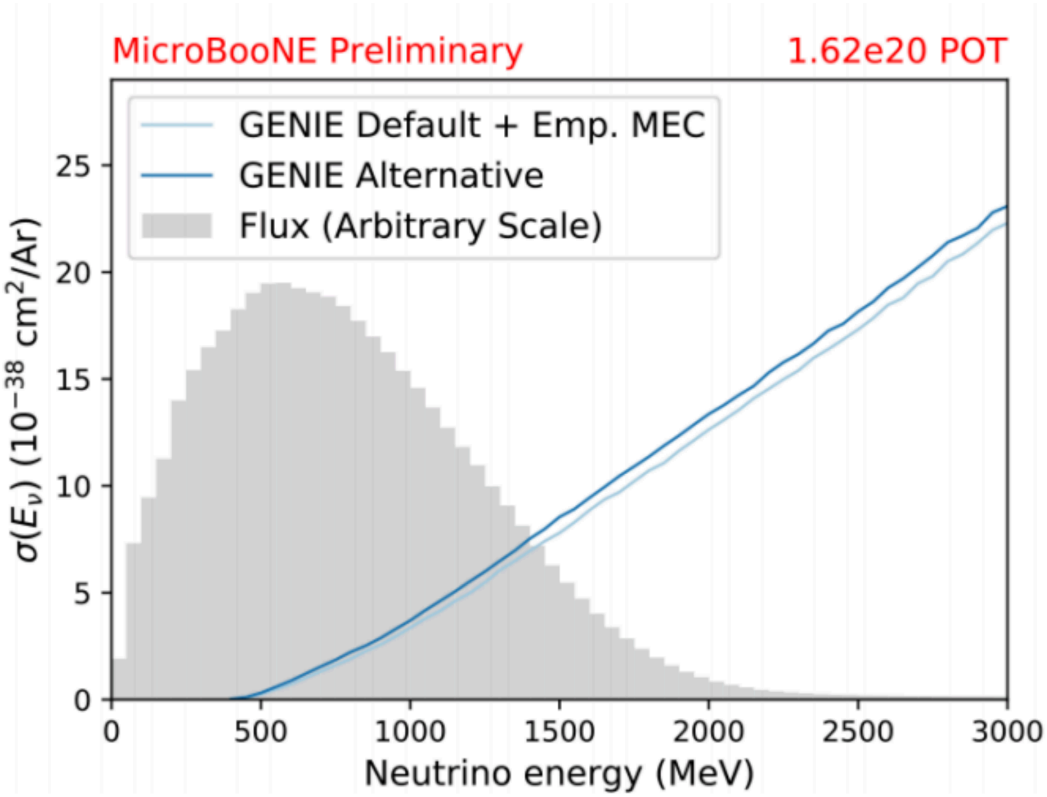



Two Shower Selection



# Final CC π⁰ Cross Section

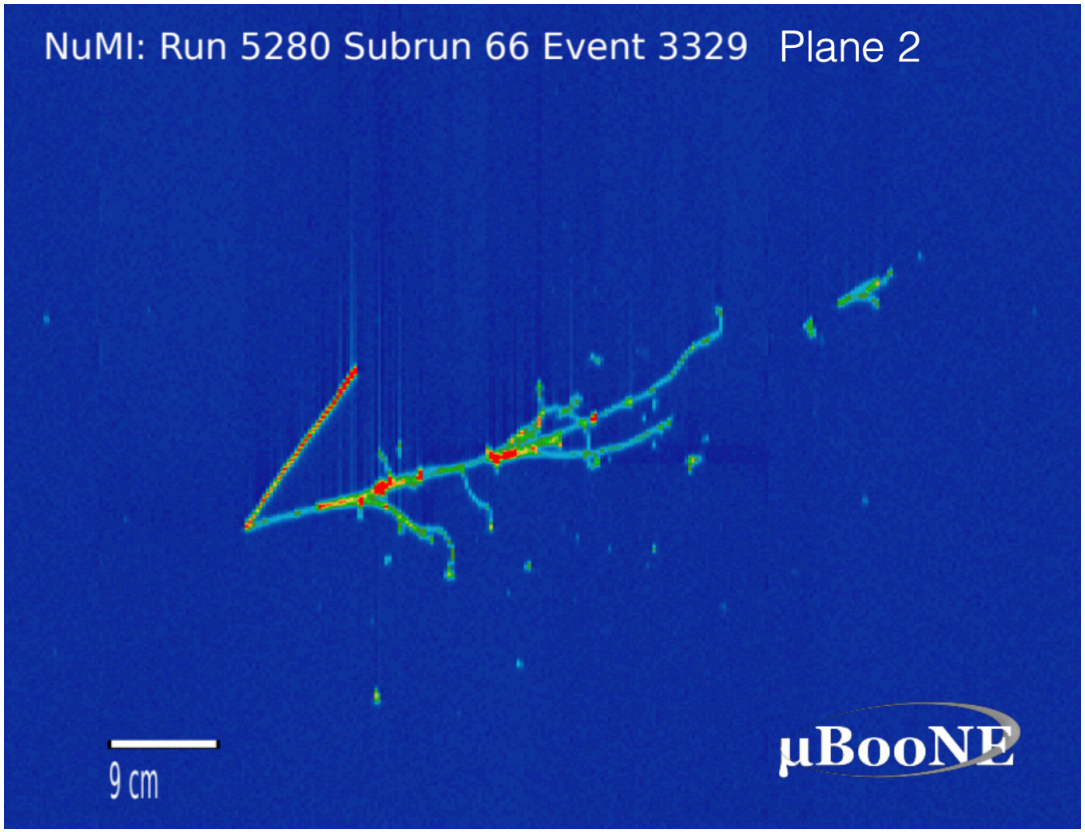


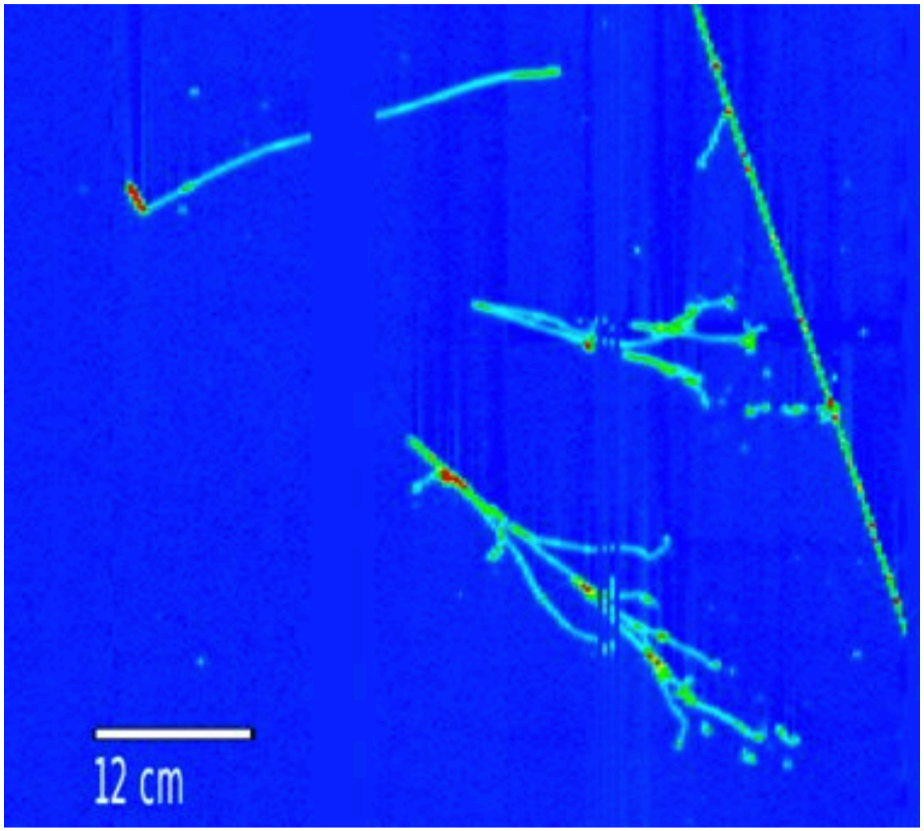




$$\left\langle \sigma^{\nu_\mu \mathbf{CC}\pi^0} \right\rangle_\Phi = (1.94 \pm 0.16\ [\text{stat.}] \pm 0.60\ [\text{syst.}]) \times 10^{-38}\ \frac{\text{cm}^2}{\text{Ar}}$$

Phys. Rev. D99, 091102(R) (2019)

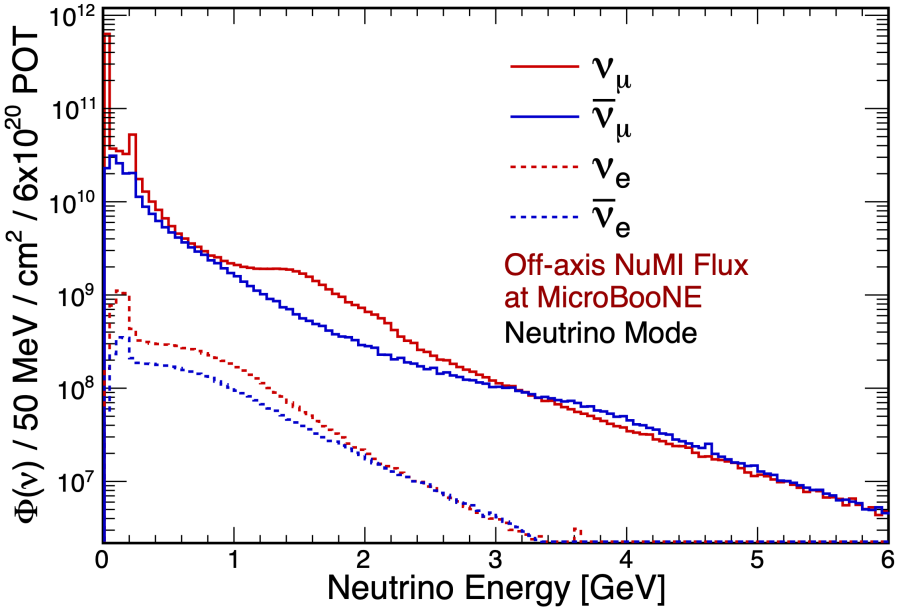
# What about electrons?

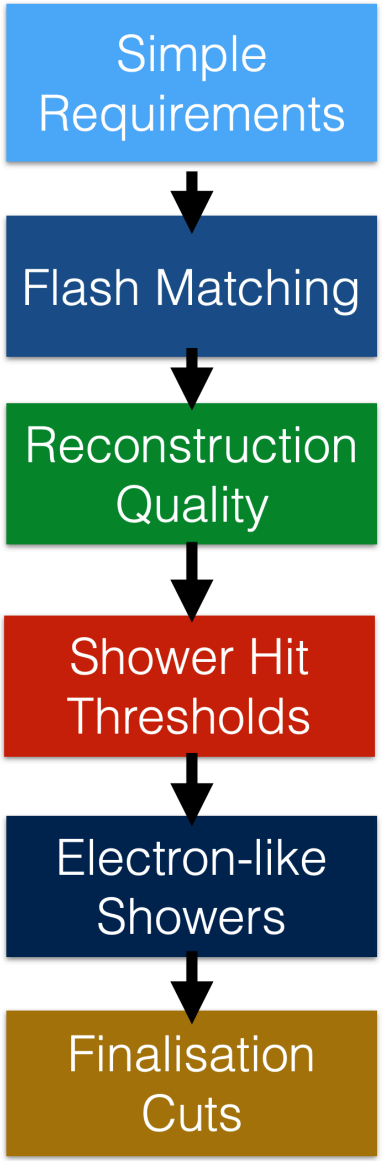


# Reconstruction of $\nu_e$ interactions from the NuMI Beam

- Golden channel for $\nu$ oscillation measurements
- first measurement of $\nu_e$-Ar
- 5% $\nu_e$ beam composition
- NuMI spectrum (640 MeV)



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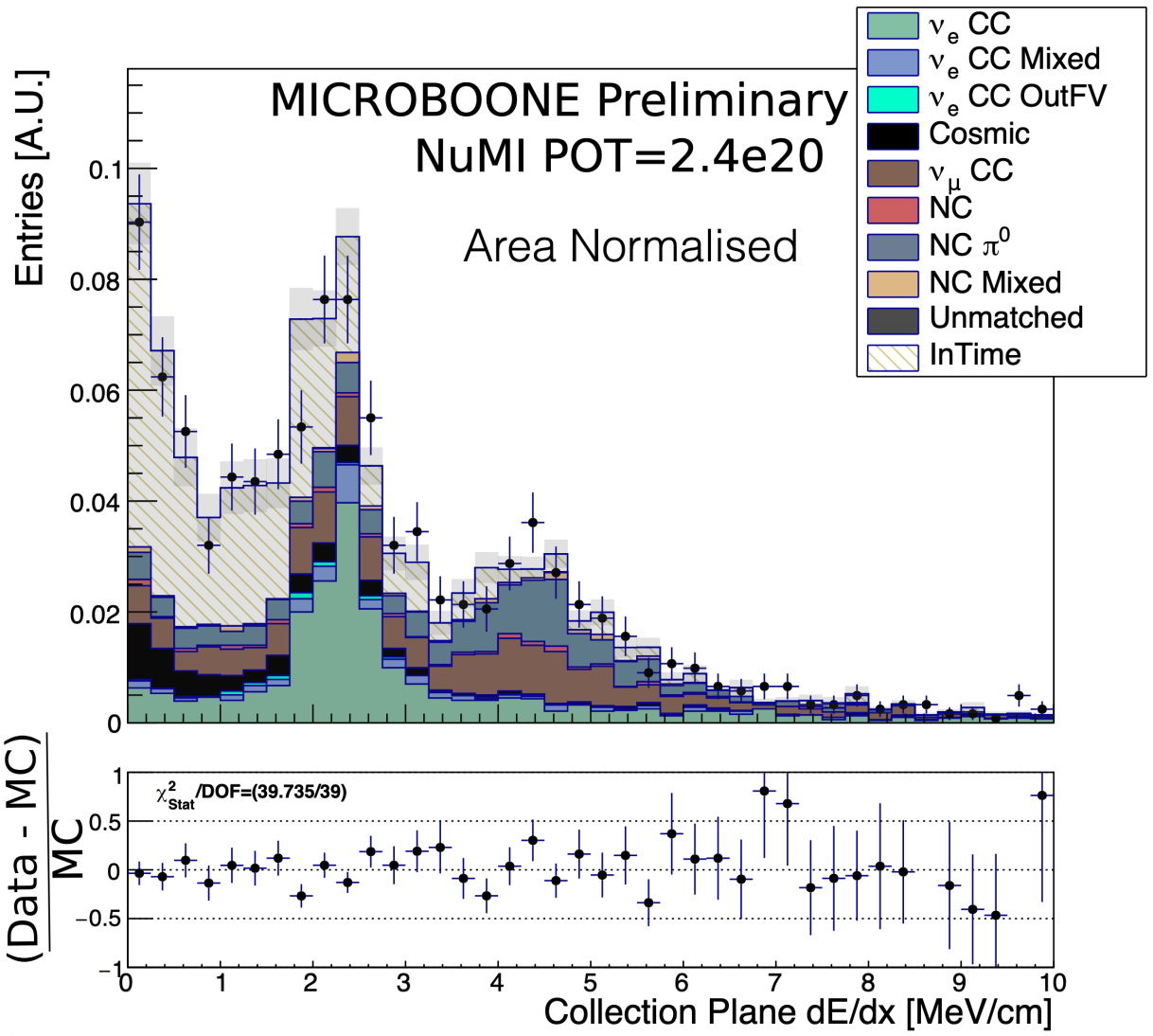
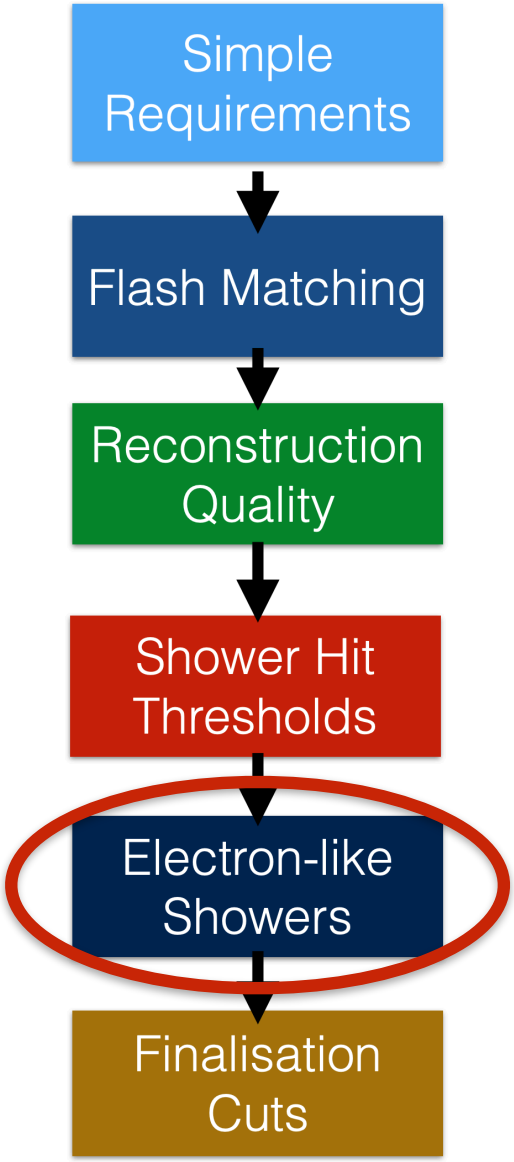
# Selection of $\nu_e$ candidates



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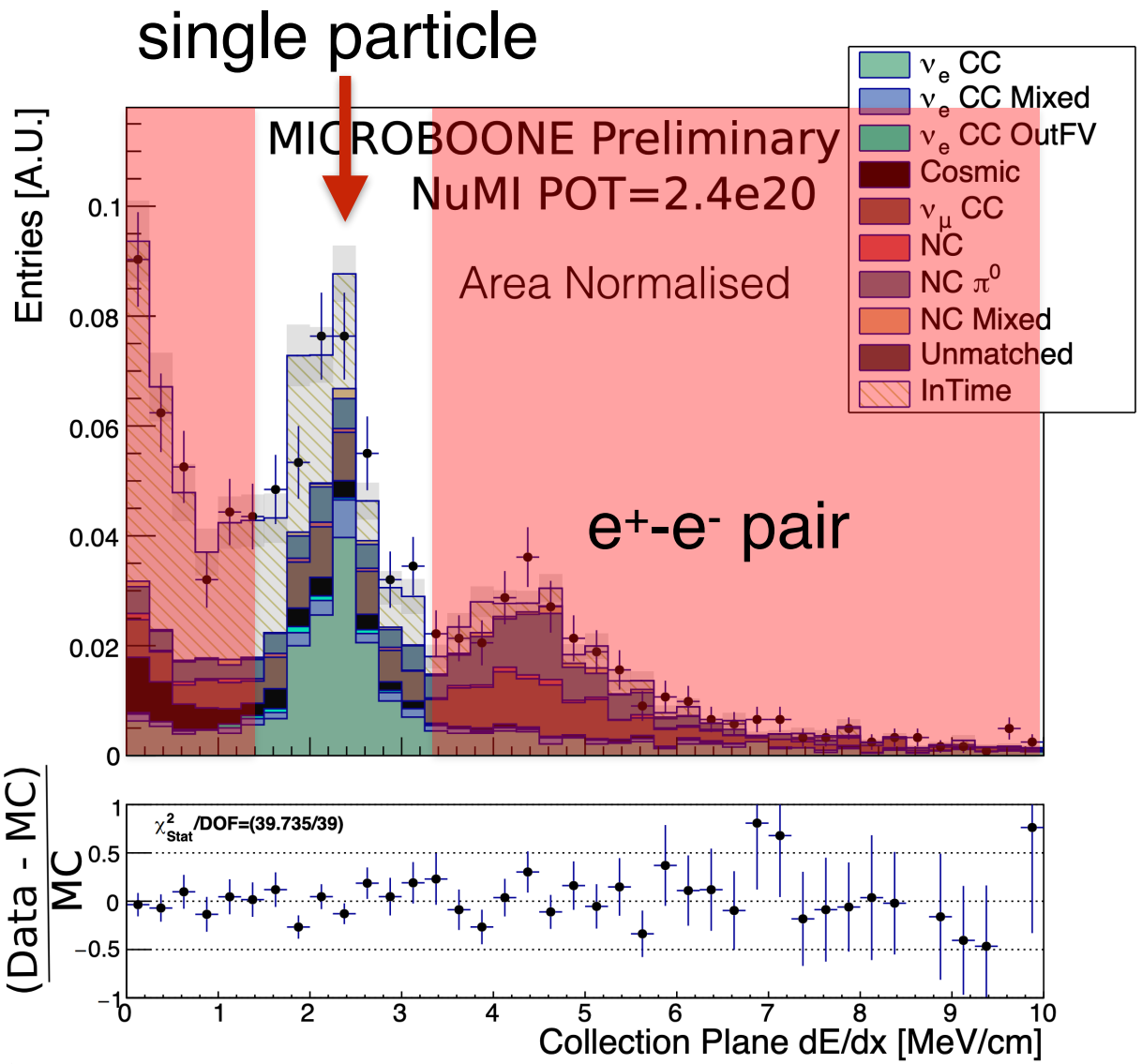
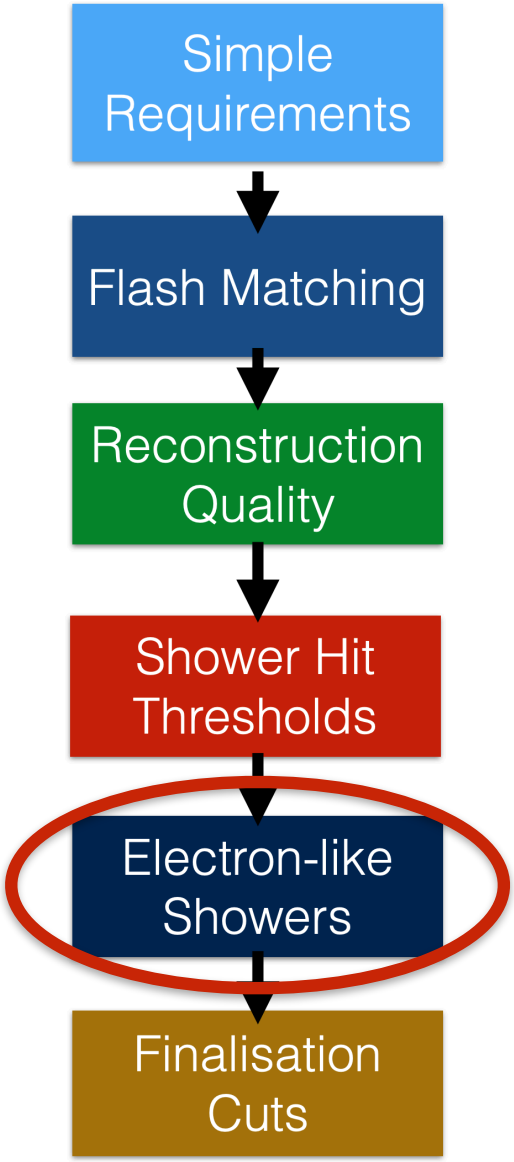
# Selection of $\nu_e$ candidates



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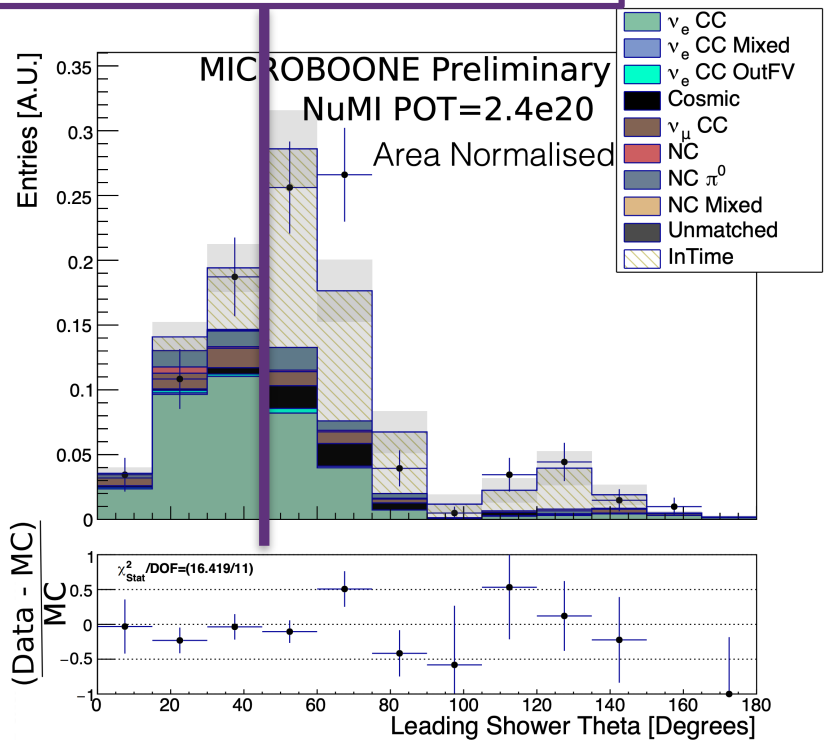
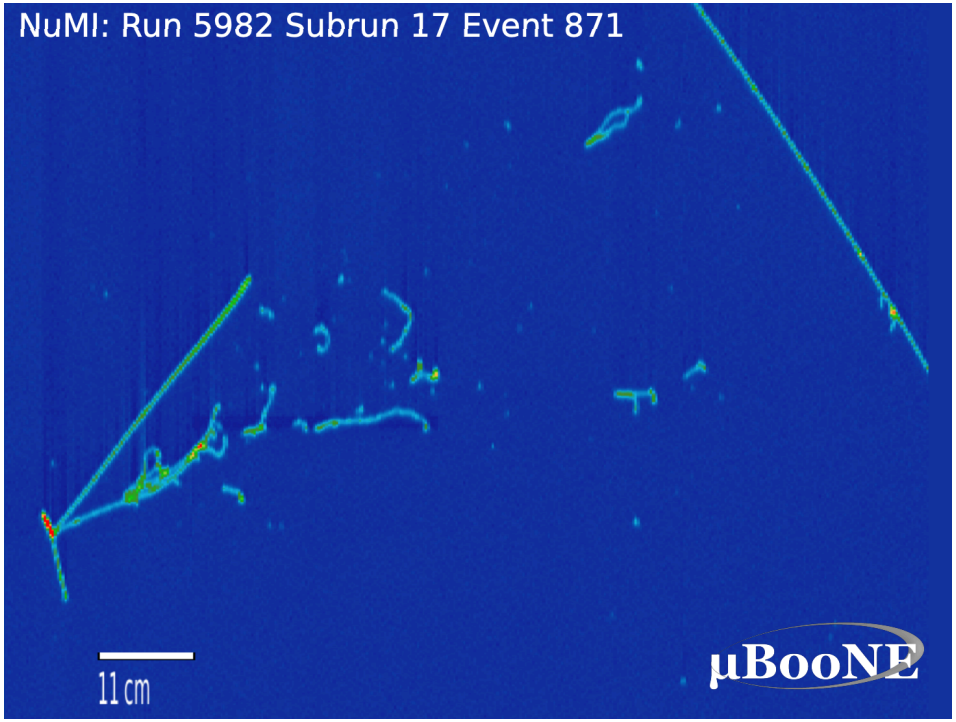
# Selection of $\nu_e$ candidates

NuMI Target Direction



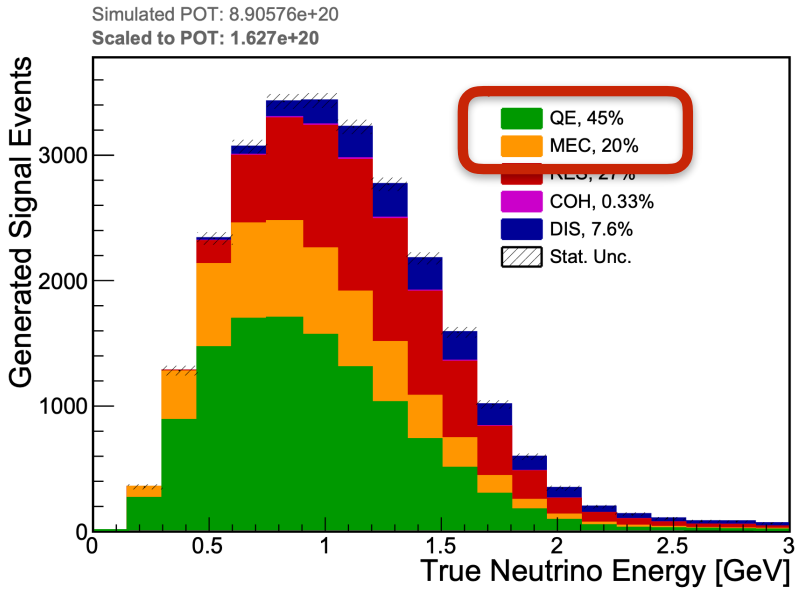



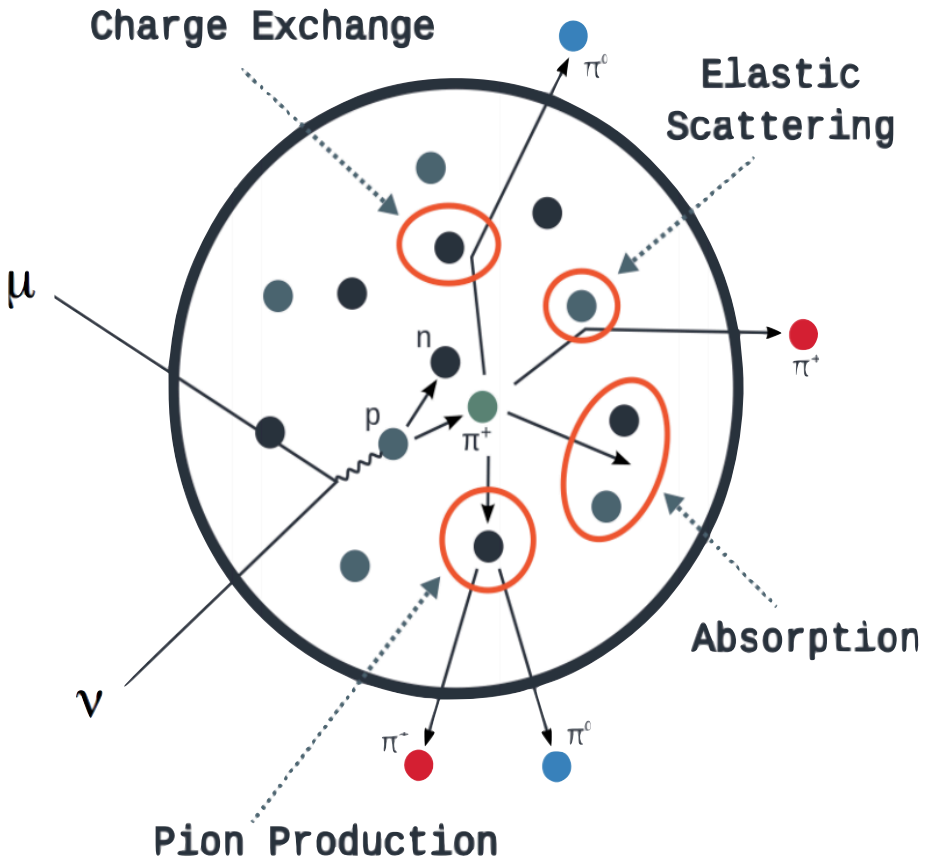

- can isolate single-e peak from the $e^+$-$e^-$ pairs from photons
- events aligned with collection plane will be recovered with use of the induction planes

**MICROBOONE-NOTE-1054-PUB**

# Neutrino - Nucleon interaction

- determination of the incident neutrino is based upon interpretation through nuclear model of reconstructed final-state objects



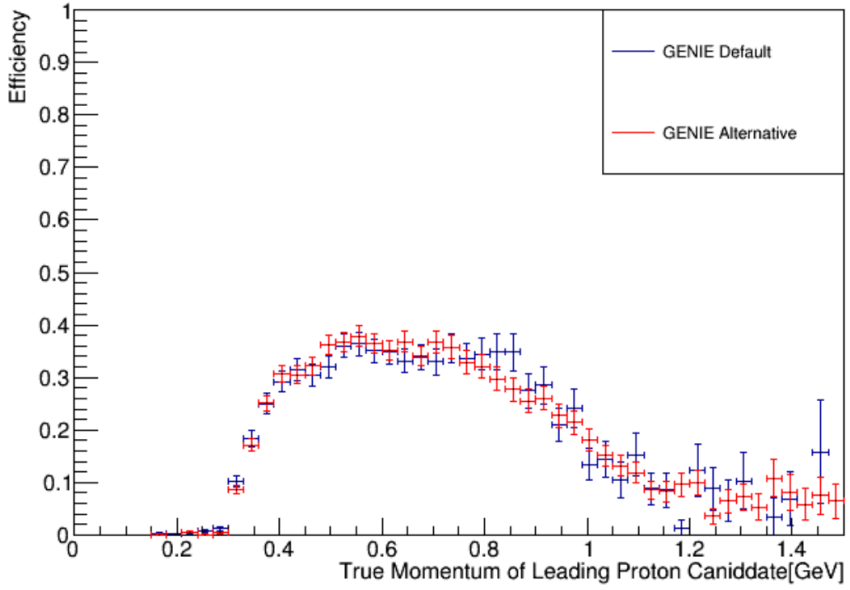



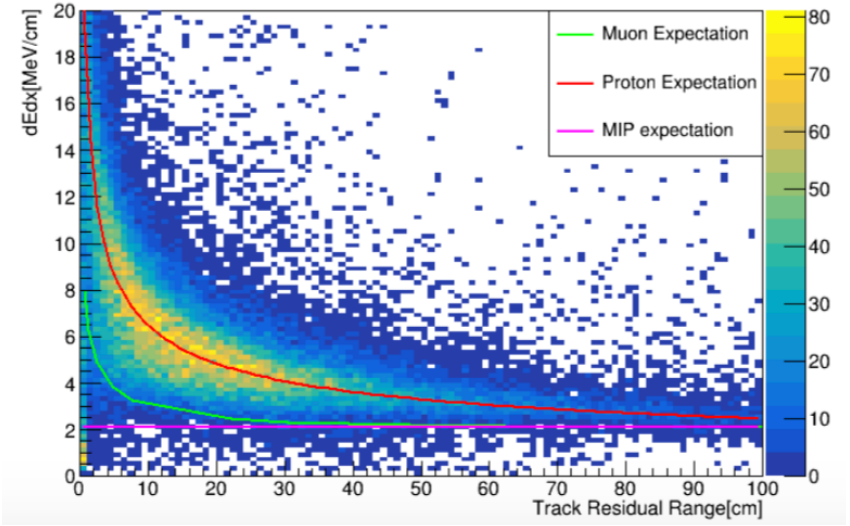
# Proton Identification Algorithm (PID)

$$PID = \chi^2_{\mathrm{proton}}/ndof = \sum_{hit}\left(\frac{(dE/dx_{measured} - dE/dx_{theory})}{\sigma_{dE/dx}}\right)^2/ndof$$

**Select tracks ≥ 5 hits**
**correct dE/dx for electron recombination**
**use only the collection plane currently**
**Calculate $\chi^2$(dE/dx) with proton expectation**

| Experiment | Threshold |
|---|---|
| T2K | 0.5 GeV/c |
| MINERvA | 0.45 GeV/c |
| MicroBooNE | 0.3 GeV/c |




Proton Candidates



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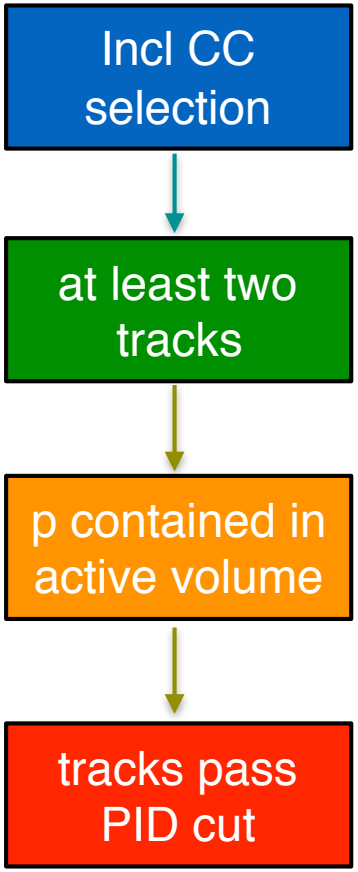
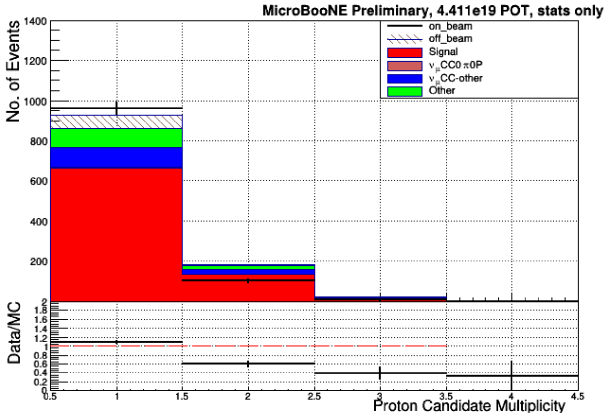
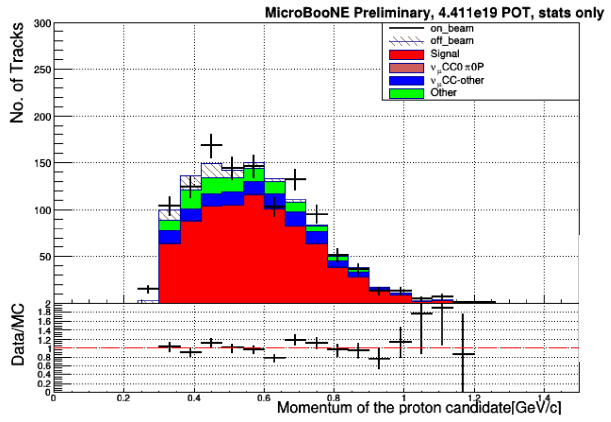
# Proton Multiplicity in $\nu_\mu$ CC 0π

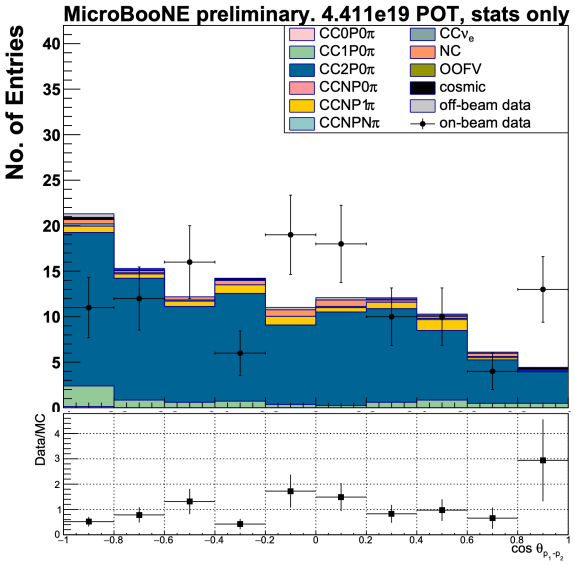
## CC1$\mu$Np Selection



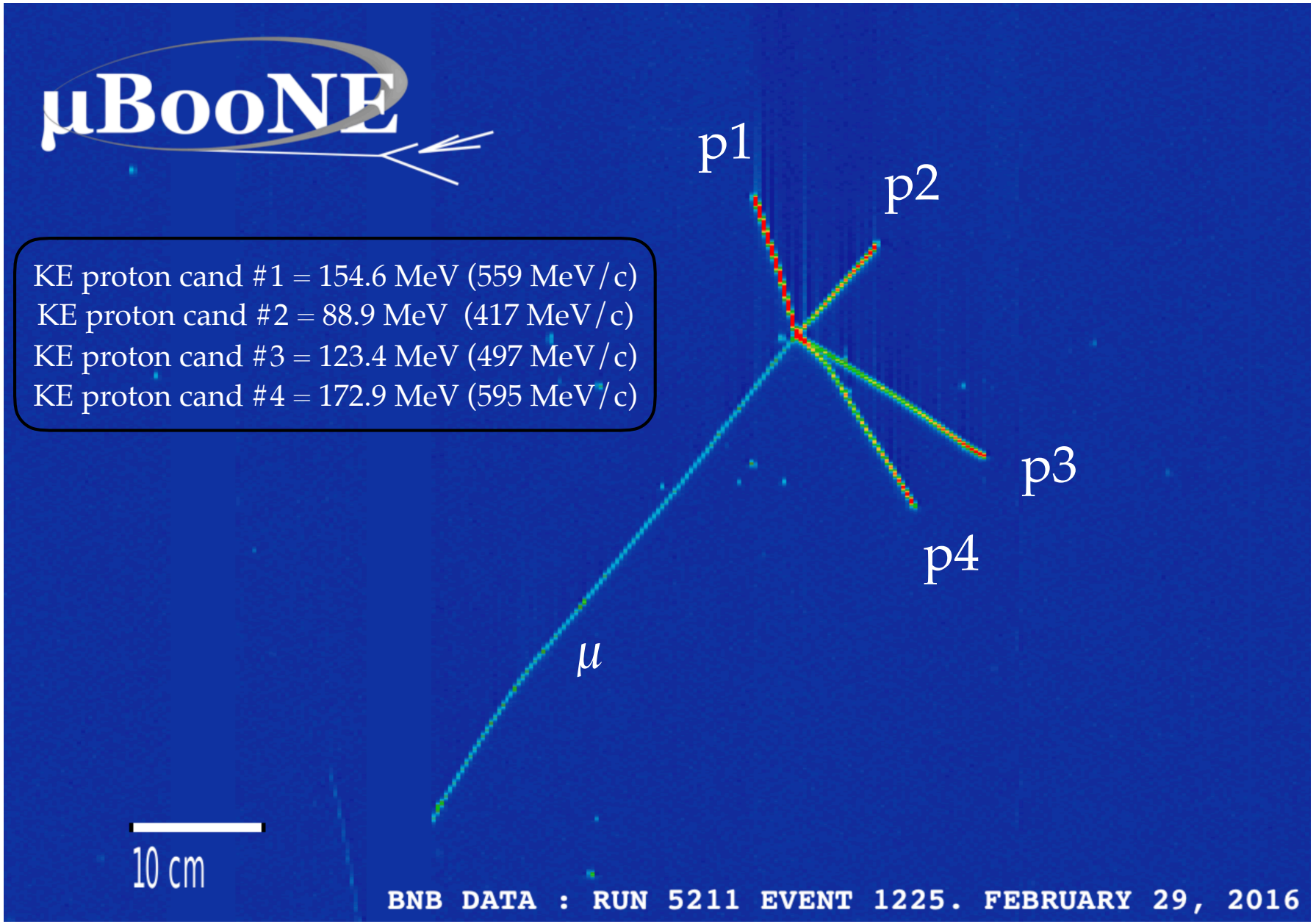

## CC1$\mu$2p Selection




**MICROBOONE-NOTE-1056-PUB**

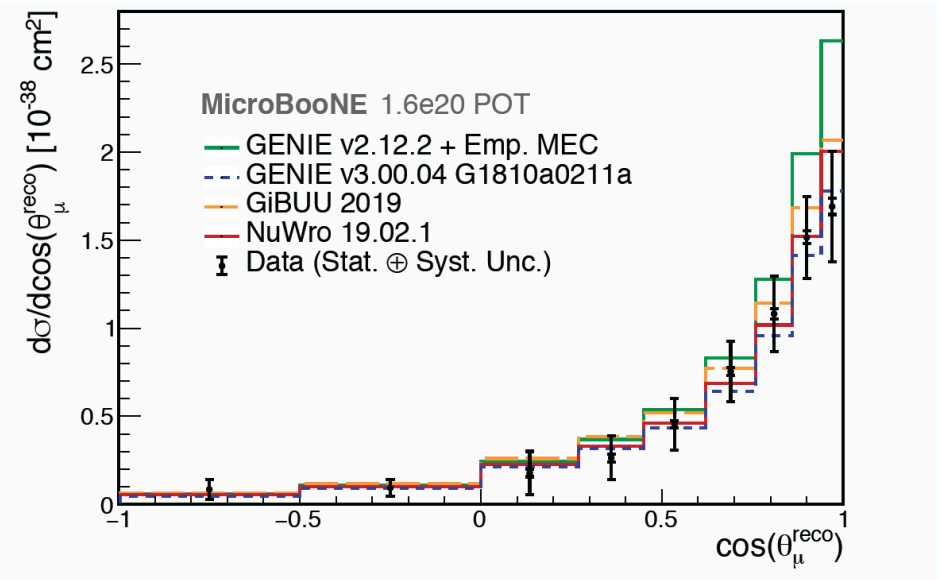
- proton momenta > 300 MeV/*c*
- Currently performing shape-only/stat uncertainty only
- systematic uncertainties, abs. normalization, and more than 3x the data soon
- separate analysis focused on CC1$\mu$2p selection

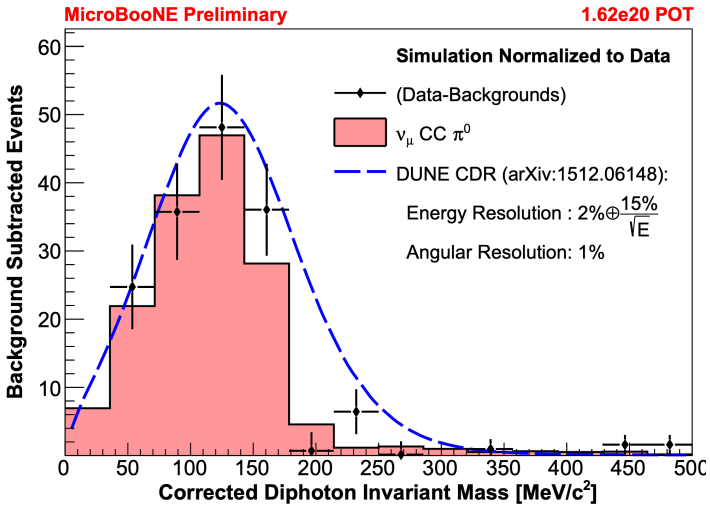
# An impressive event

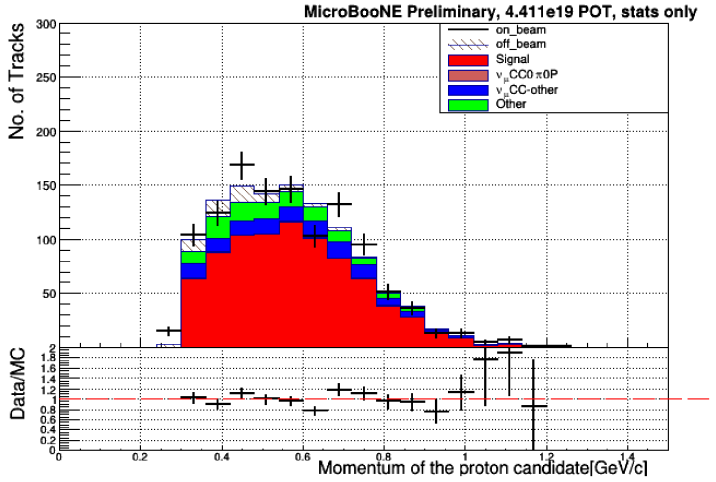


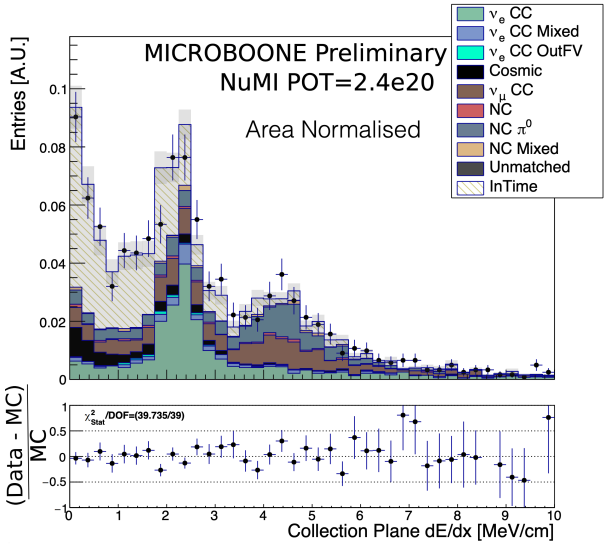
# Conclusions

- MicroBooNE is breaking new ground in measurements of neutrino-nucleon cross sections
- first double/single differential cross-section $\nu_\mu$-Argon
- Cosmic rejection, particle identification, vertex reconstruction
- continue to extend the understanding neutrino interactions and develop tuned interaction model matching $\nu$-Ar data
- Already have sensitivity to exclude existing models



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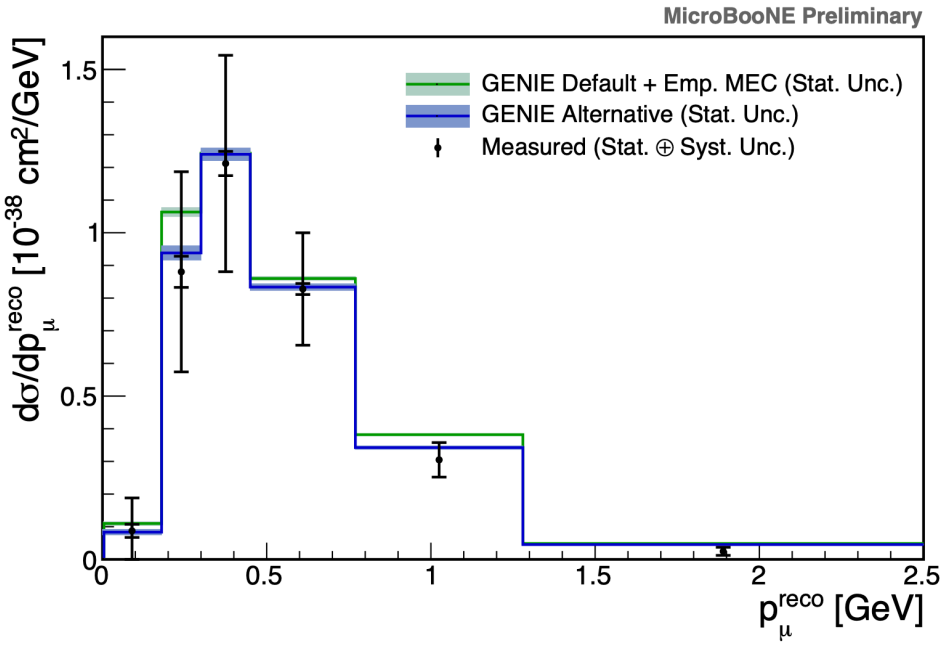
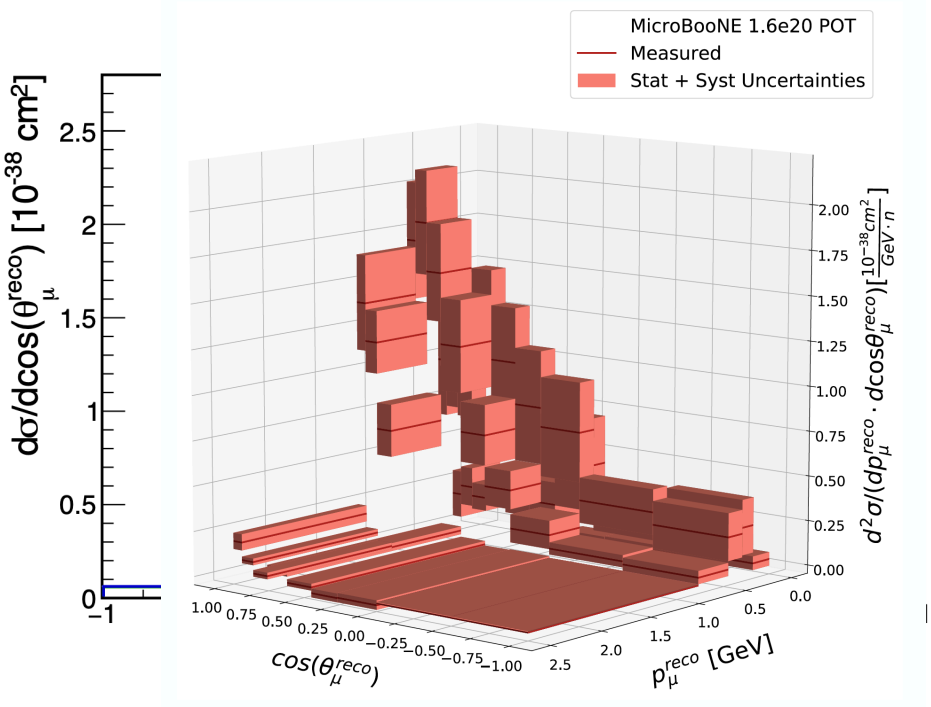
# Backup slides

# First double-differential $\nu_\mu$-Ar Cross-Section Measurement

## The final single-differential $\nu_\mu$ CC inclusive cross section on argon




| Error Source | Method | Estimated Relative Uncertainty |
|---|---|---|
| Beam Flux | Estimated with multisim variations | 12% |
| Cross Section Modeling | Estimated with multisim variations | 4% |
| Detector Response | Estimated with unisim variations | 19% |
| POT Counting | Toroids Resolution | 2% |
| Cosmics (in-time) | Estimated from data-driven cosmic model | 7% |
| Cosmics (out-of-time) | Estimated from off-beam statistics | 1% |
| Beam Timing Jitter | Estimated from on- minus off-beam flashes | 4% |



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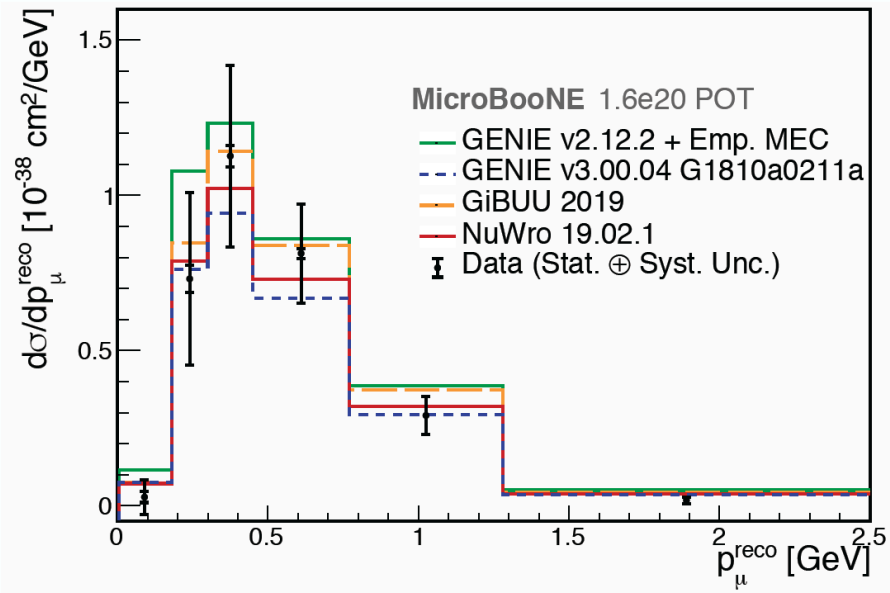
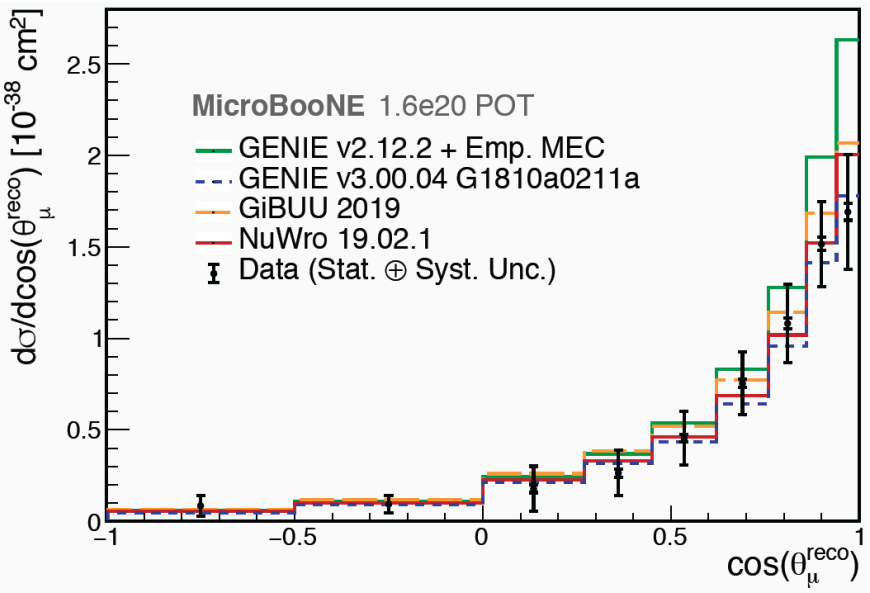
# Cross Section Measurement

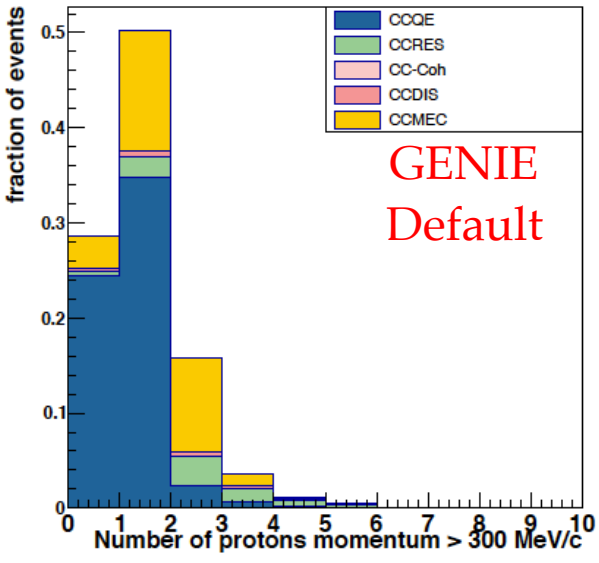


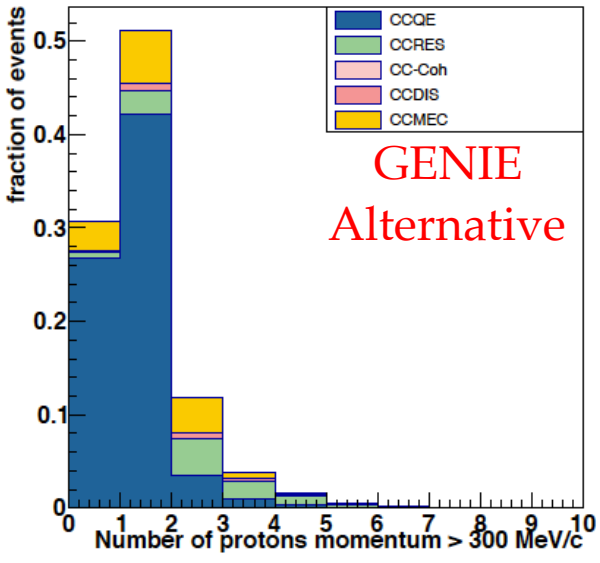



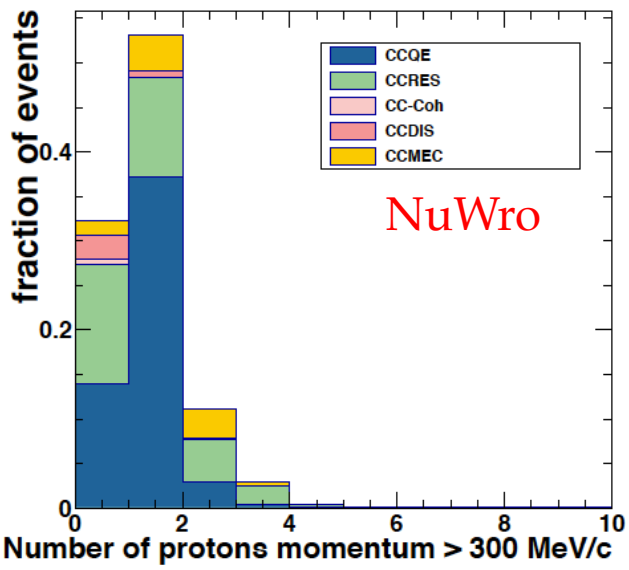

| Model Element | GENIE v2 + MEC (v2.12.2) | GENIE v3 (v3.00.04 G1810a0211a) | NuWro (19.02.1) | GiBUU (2019) |
|---|---|---|---|---|
| **Nuclear Model** | Bodek-Ritchie Fermi Gas [1] | Local Fermi Gas [2, 3] | Local Fermi Gas [2, 3] | Consistent nuclear medium corrections throughout. Also uses a LFG model for nucleon momenta, a separate MEC model [11], and propagates final state particles according to the Boltzmann-Uehling-Uhlenbeck equations [11] |
| **Quasi-elastic** | Llewellyn-Smith [4] | Nieves [2, 3] | Nieves [2, 3] | |
| **MEC** | Empirical [5] | Nieves [2, 3] | Nieves [2, 3] | |
| **Resonant** | Rein-Seghal [6] | Berger-Seghal [7] | Berger-Seghal [7] (pion production from [9]) | |
| **Coherent** | Rein-Seghal [6] | Berger-Seghal [7] | Berger-Seghal [7] | |
| **FSI** | hA [8] | hA2018 [8] | Oset [10] | |

# Neutrino - Nucleon interaction

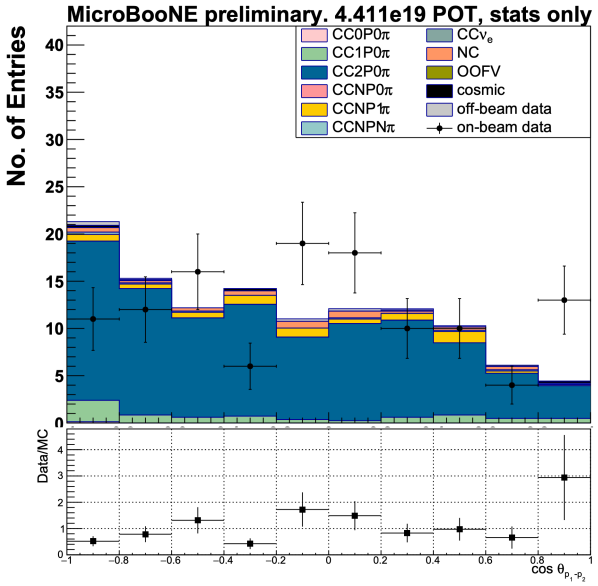
- MicroBooNE interactions are dominated by CCQE and CCMEC interactions
- large variation in QE and MEC models across numerous theoretical predictions and generators
- low-energy protons offer an excellent probe into intra-nuclear re-scattering and correlated-nucleon interactions

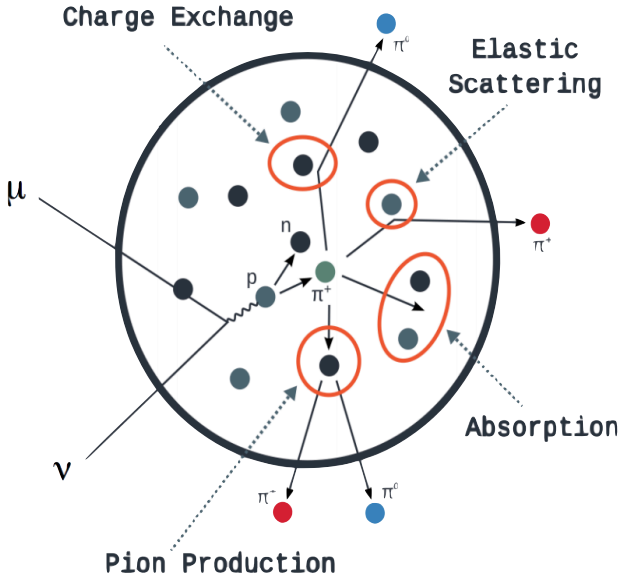


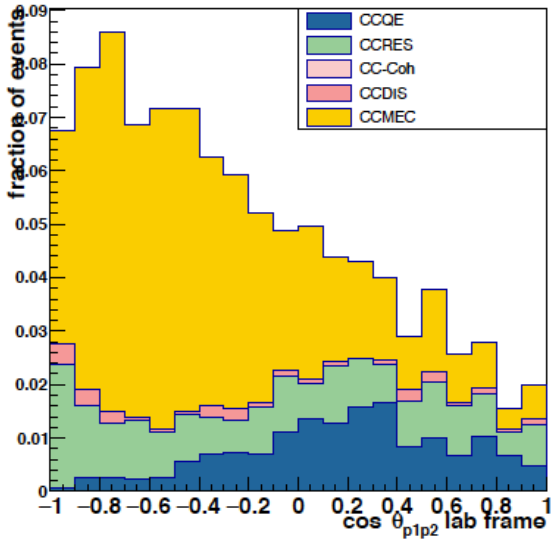



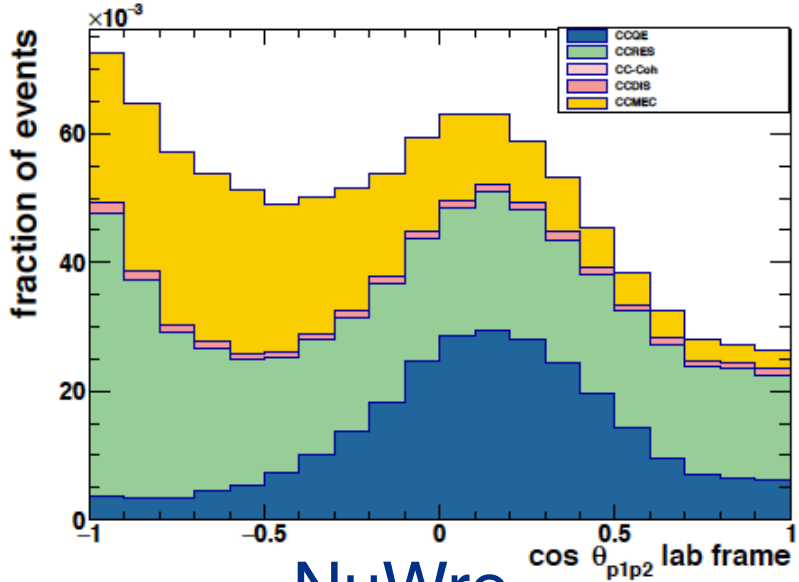
# CC1$\mu$2P Opening angle distribution




GENIE Default




NuWro



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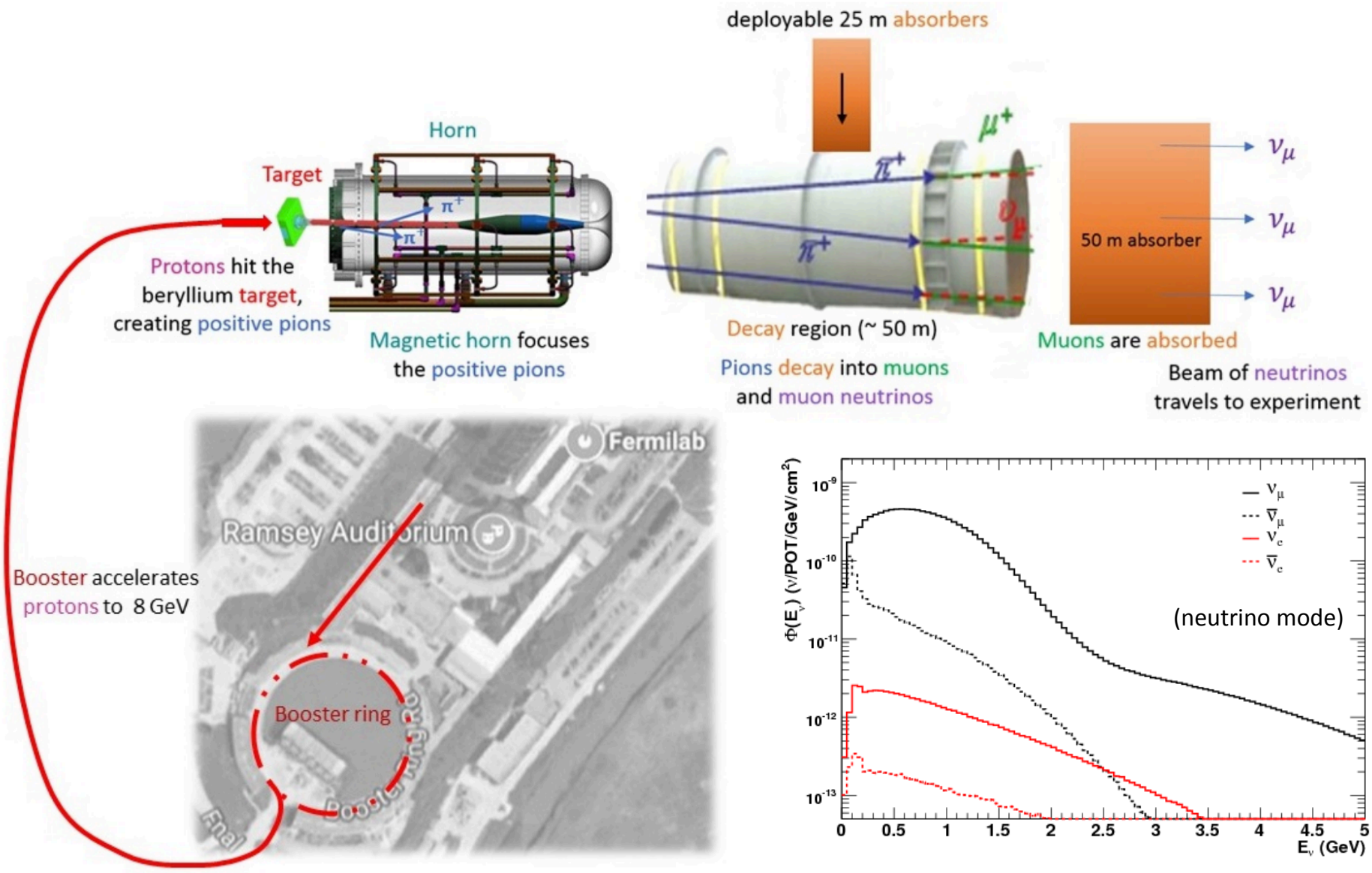
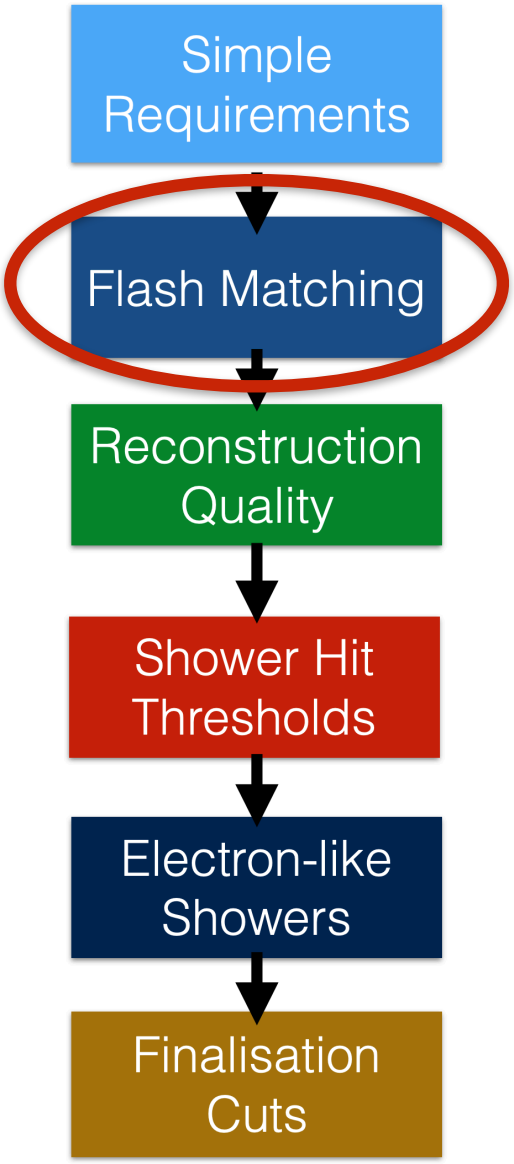
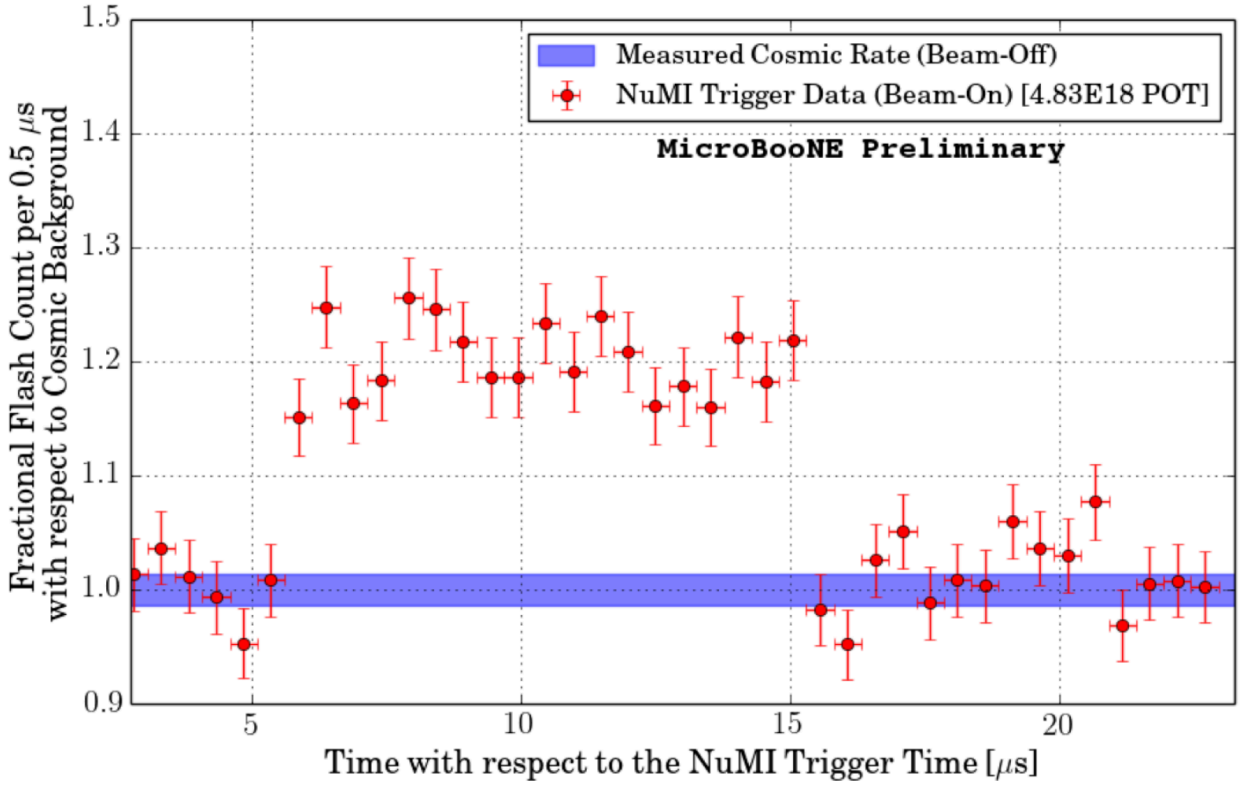
# Booster Neutrino Beam production



# Selection of $\nu_e$ candidates



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# Selection of $\nu_e$ candidates