Measurement of Differential Cross Sections for ν_μ-Argon Charged-Current Interactions with Protons and no Pions in the Final State with the MicroBooNE Detector

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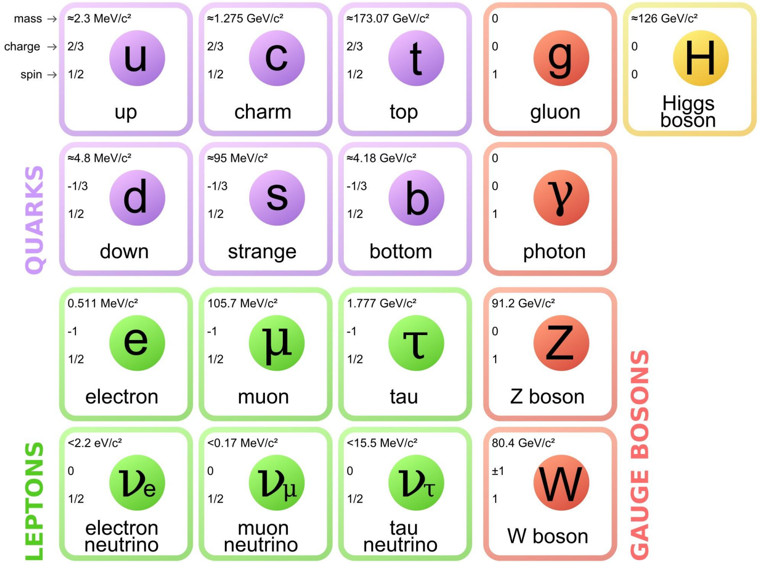
Joint Experimental-Theoretical Physics Seminar, Fermilab Nov 6, 2020

Outline

- Overview of neutrino oscillation
- Why neutrino Interactions are important to neutrino oscillations
- Liquid Argon Time Projection Chamber (LArTPC)
  - Detector Principles
  - MicroBooNE experiment
- New Charged Current 0 pion N protons (CC0πNp, N>0) Measurement
  - Signal and Background Definition
  - Systematic & Statistical Uncertainties
  - Cross section measurements

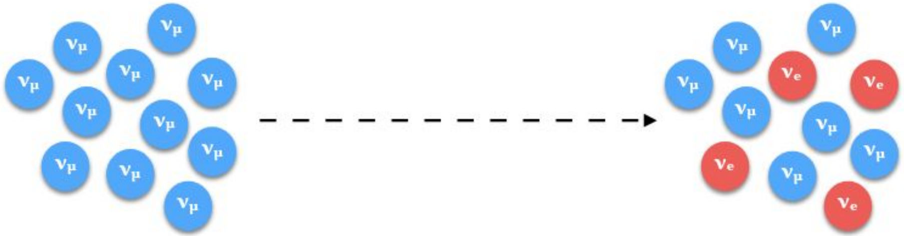
Neutrinos

Standard Model



- Neutrinos are massless and left-handed
- Only weak interactions

Beyond the Standard Model



- Neutrino Oscillation observed by experiments indicate that Neutrinos are massive
  - Important example of physics beyond standard model
  - Neutrino mass generation mechanism is uncertain (low mass)

Neutrino Oscillations

Mixing of flavor states:

$$|\nu_\alpha\rangle = \sum_{k=1}^{N+S} U^*_{\alpha k} |\nu_k\rangle$$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Time evolution of mass states:

$$|\nu_k(t)\rangle = \exp(-iE_k t)\, |\nu_k\rangle$$

Neutrino Oscillation Probability:

$$P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t)\rangle|^2$$
$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\frac{\Delta m^2_{ij} L}{4E})$$
$$+ 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\frac{\Delta m^2_{ij} L}{4E}),$$

Oscillation Probability*:

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

two neutrino flavors, for simplicity

Travel Distance

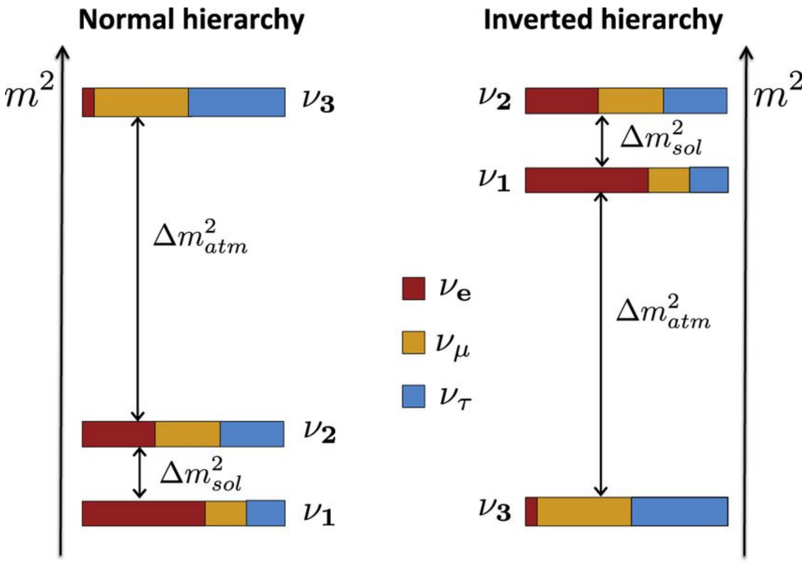
Mass splitting

Neutrino Energy

Neutrino Oscillations

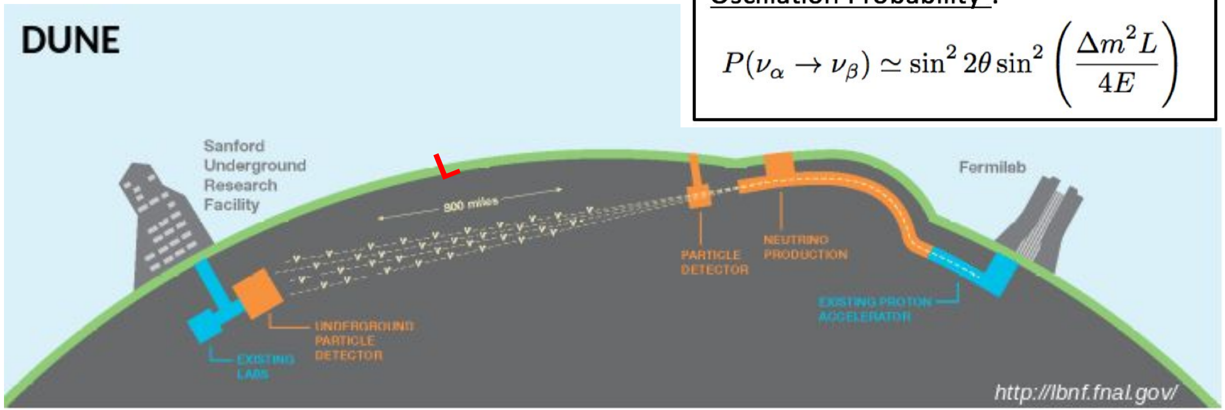
Key open questions in neutrino oscillations:

- What is the neutrino absolute mass and mass ordering?
  - Normal Hierarchy (NH) or Inverted Hierarchy (IH)?
- How much is CP violated in the neutrino sector?
  - Could explain matter/anti-matter asymmetry?
- Is the 3 flavor mixing matrix unitary
- Do sterile neutrinos exist?



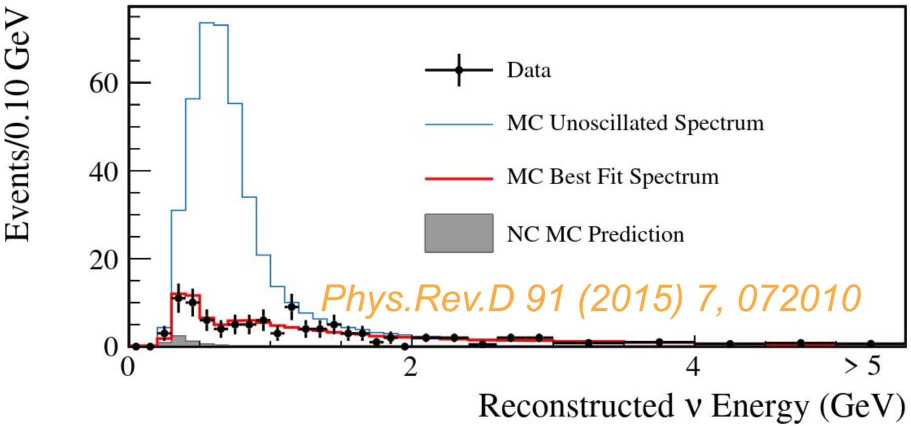
Neutrino Oscillation Experiments

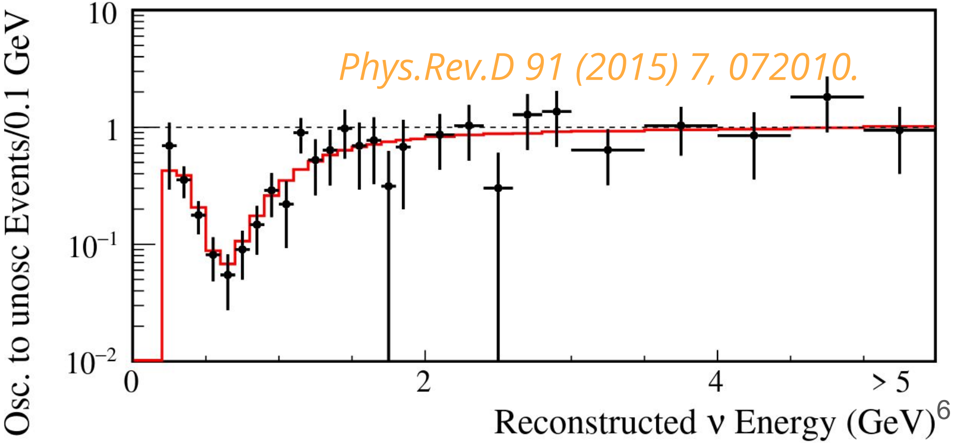
- Neutrino oscillation measurement of $\nu_\alpha \rightarrow \nu_\beta$
  - **Disappearance** of ν_α
  - **Appearance** of ν_β
- E.g. ν_α disappearance:
  - Detect ν through interaction in detector
  - Reconstruct neutrino spectrum E_ν



Oscillation Probability*:

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$





Neutrino Oscillations

Neutrino Event Rate:

$N_{FD}(\mathbf{E_\nu}) = \Phi(\mathbf{E_\nu}) \times \sigma(\mathbf{E_\nu}) \times \varepsilon \times \mathbf{P(\nu_\alpha \rightarrow \nu_\beta)}$

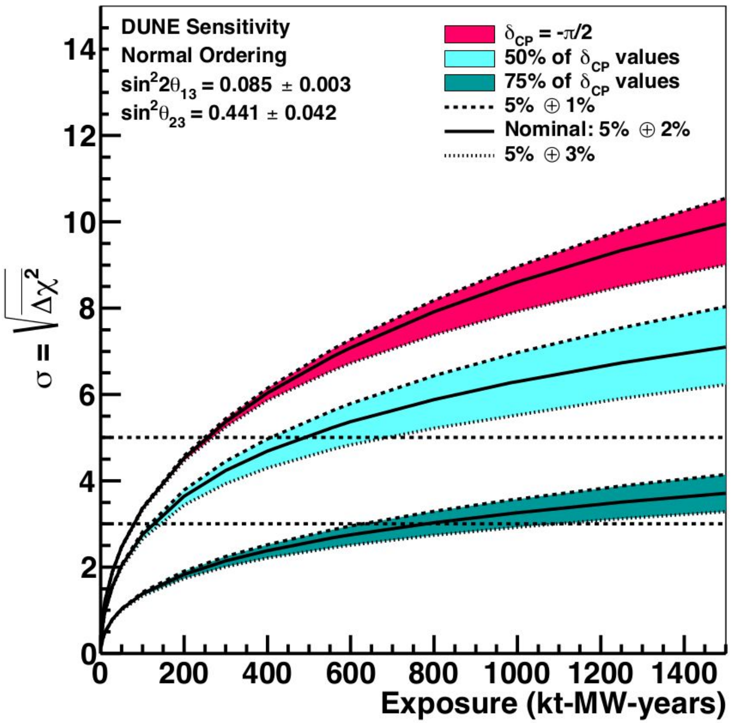
- $\Phi(\mathbf{E_\nu})$: Flux, $\sigma(\mathbf{E_\nu})$: Cross section
  ε: detector efficiency

NOvA: Systematic uncertainties on oscillation parameters

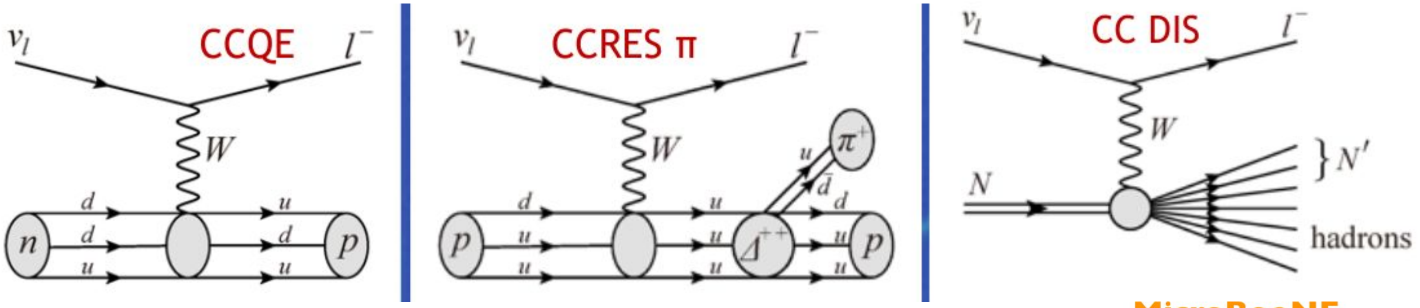
Source	$\sin^2\theta_{23}$ ($\times 10^{-3}$)	$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-5}$ eV$^2/c^4$)	δ_{CP} (π)
Calibration	+5.4 / -9.2	+2.2 / -2.6	+0.03 / -0.03
Neutron model	+6.0 / -13.0	+0.5 / -1.3	+0.01 / -0.00
Cross-sections	+4.1 / -7.7	+1.0 / -1.1	+0.06 / -0.07
E_μ scale	+2.3 / -3.0	+1.0 / -1.1	+0.00 / -0.00
Detector model	+1.9 / -3.2	+0.4 / -0.5	+0.05 / -0.05
Normalizations	+1.3 / -2.7	+0.1 / -0.2	+0.02 / -0.03
ND/FD diffs.	+1.0 / -4.0	+0.2 / -0.2	+0.06 / -0.07
Beam flux	+0.4 / -0.8	+0.1 / -0.1	+0.00 / -0.00
Total syst.	+9.7 / -20	+2.6 / -3.2	+0.11 / -0.12

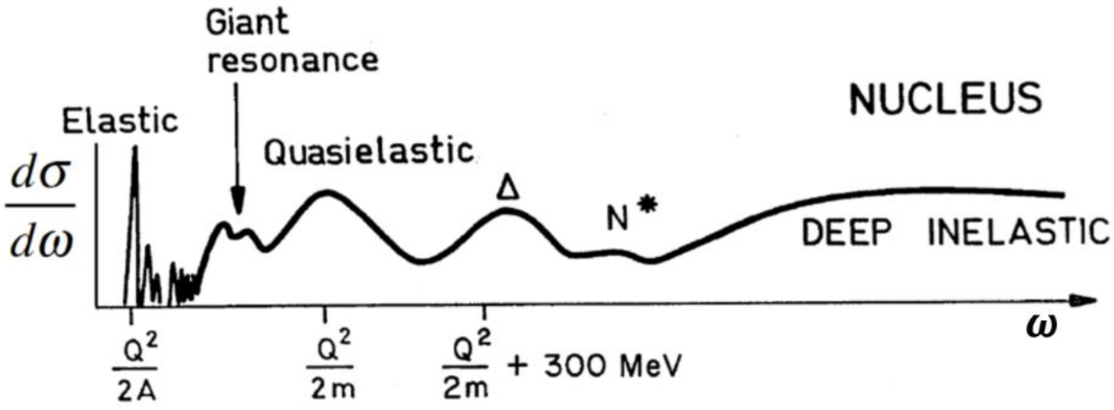
PRL 123, 151803 (2019) NOvA

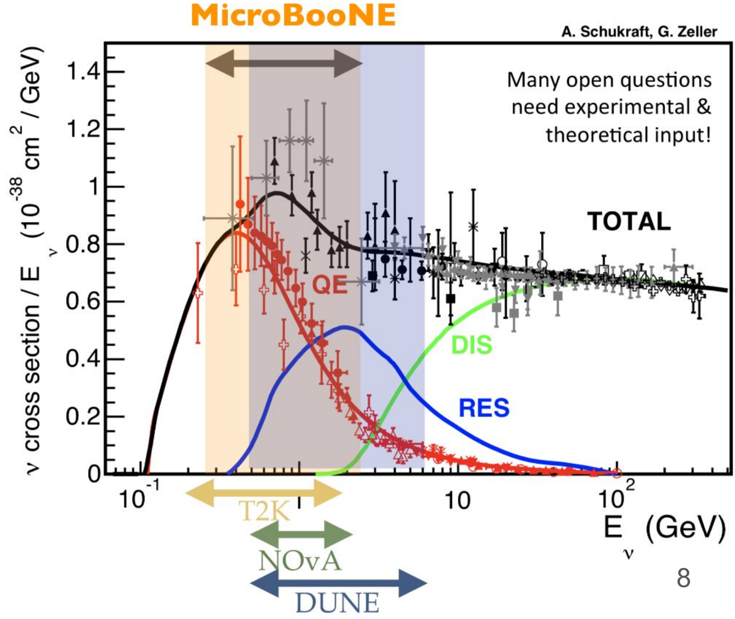
- DUNE needs uncertainties to be ~ few percent



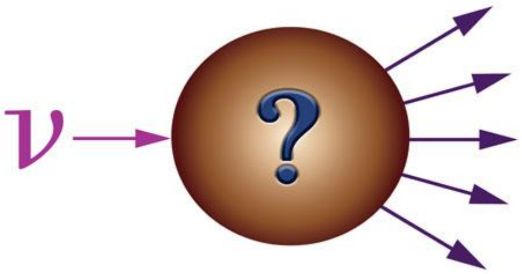
Neutrino Interactions

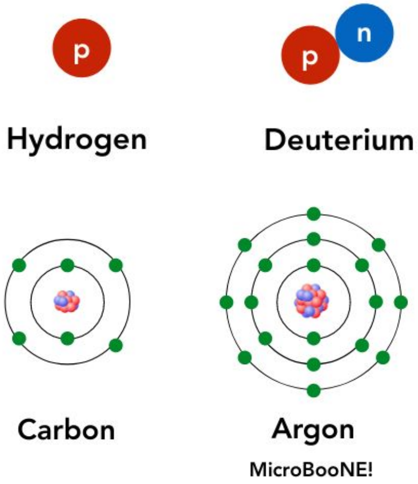






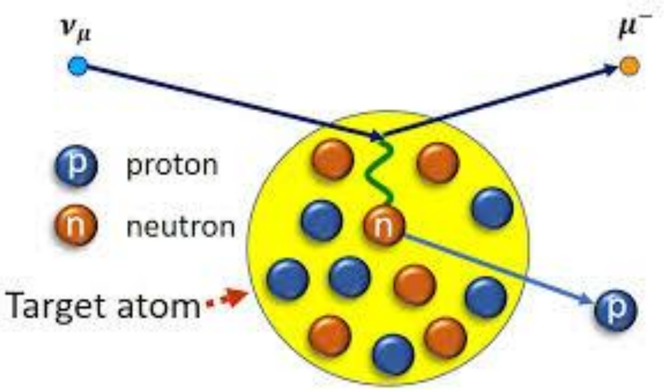
Nuclear Effects



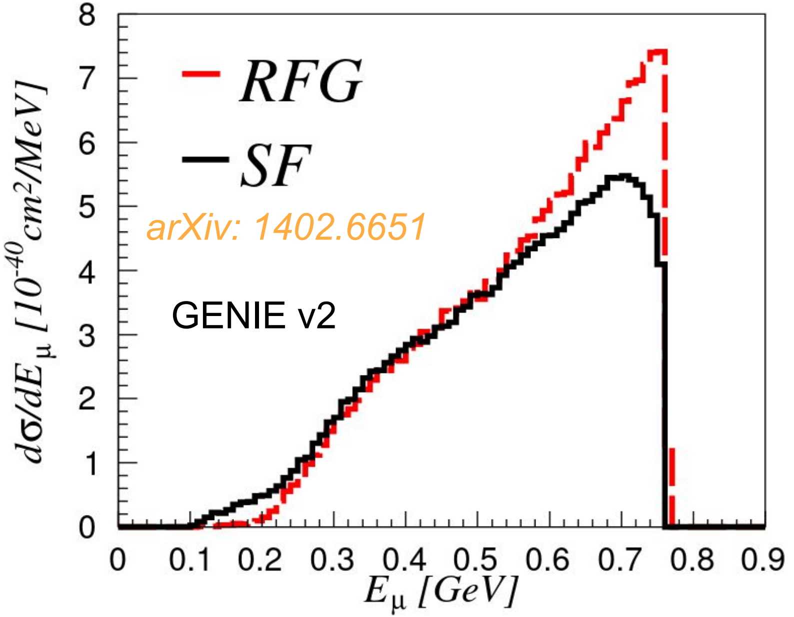


- 1970-1990's
  - Hydrogen/deuterium filled bubble chambers:
    - Experiments: ANL (hydrogen), BNL (hydrogen and deuterium)
    - Test the V-A nature of weak interactions
    - Measure nucleon axial vector form factor
- 1990-present
  - Complex nuclei as targets: C, Fe, **Ar**
  - Z ≠ N in Argon, neutrino and anti-neutrino QE could be different (arXiv: 1603.01072)
  - **Heavier targets have more complex nuclear effects**

Nuclear Effects - Fermi Motion



All the nucleons embedded in nucleus



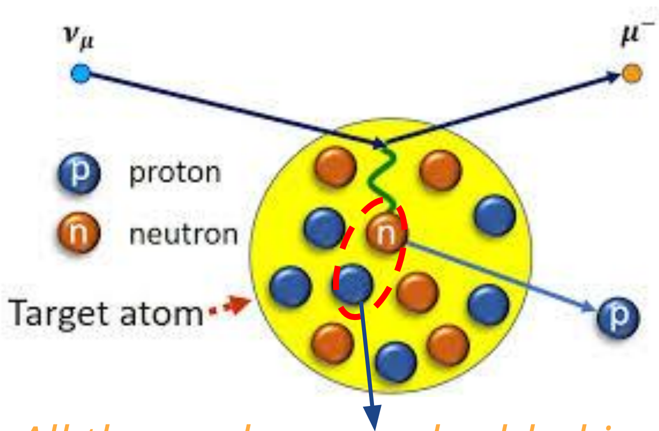
$$\nu + \mathrm{Ar} \rightarrow \mu + X$$

- Fermi Motion
  - Determines the momentum/removal energy of the nucleons
  - Models: Fermi Gas, Local Fermi Gas, Spectral functions ……
- Binding energy
  - Models: Constant or dependent on position

- CCQE interactions in GENIE with both FSI and pauli blocking included

arXiv: 1402.6651

Nuclear Effects - Nucleon Nucleon Correlations



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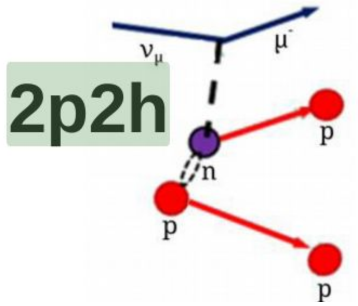
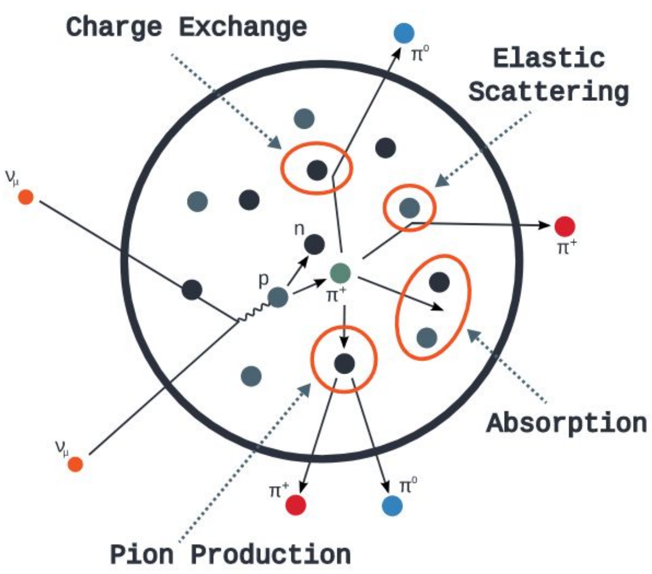


- Correlated Pair of Nucleons involved in neutrino interactions
  - Short Range Nucleon-Nucleon Correlations (<=1fm)
  - 2p2h (medium range)
  - Long range Nucleon-Nucleon Correlations (>1.2fm)
    - W boson absorption by the struck nucleons behaves differently
    - Suppression to the low momentum transfer (Q^2) events
    - Random Phase Approximation (RPA) with various approximations
- Two or more protons knocked out in neutrino interactions
  - Require a detector that can resolve hadrons - LArTPC

Nuclear Effects - Final State Interactions



Credit: T. Golan

Final State Interactions (FSI)

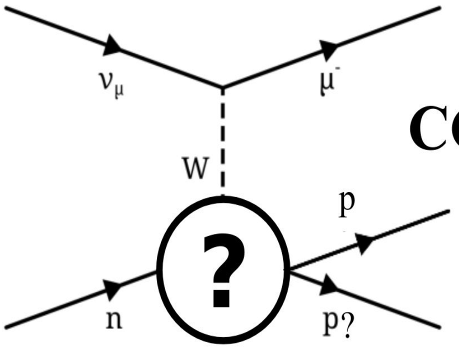
- Describe nucleon interactions with the residual nucleons before exiting nucleus, grows with A
- Impact on:
  - Final particle momentum
  - Final state particle multiplicity
- Models all semi-classical with corrections
  - Hadronic Cascade Model
  - Data-driven FSI model
  - BUU model (GiBUU)

ν Induced Charged Current 0 pion Interaction

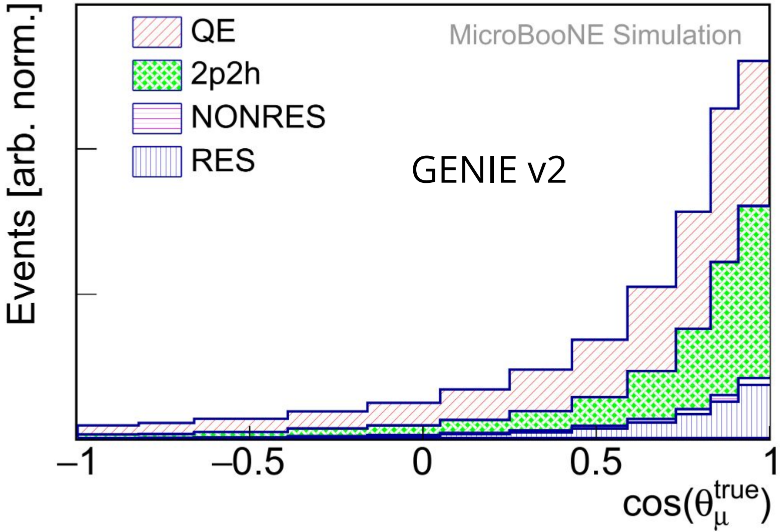
Motivations:

- The charged-current quasielastic (CCQE) interaction
  - Large cross section, “simple” process
  - Nuclear effects complicate things - CCQE very hard to measure directly

- CC0π or “CCQE-like” :
  - Closest proxy to CCQE, commonly used by MiniBooNE, T2K, MINERvA, etc.
  - Measuring protons tells us more about nuclear effects than lepton alone.
  - CC0πNp (N>0) is signal in this measurement
    - a Mixture of QE, 2p2h, NON-RESONANT and RESONANT pion production with pion absorption



CC0π+Np (N>0)



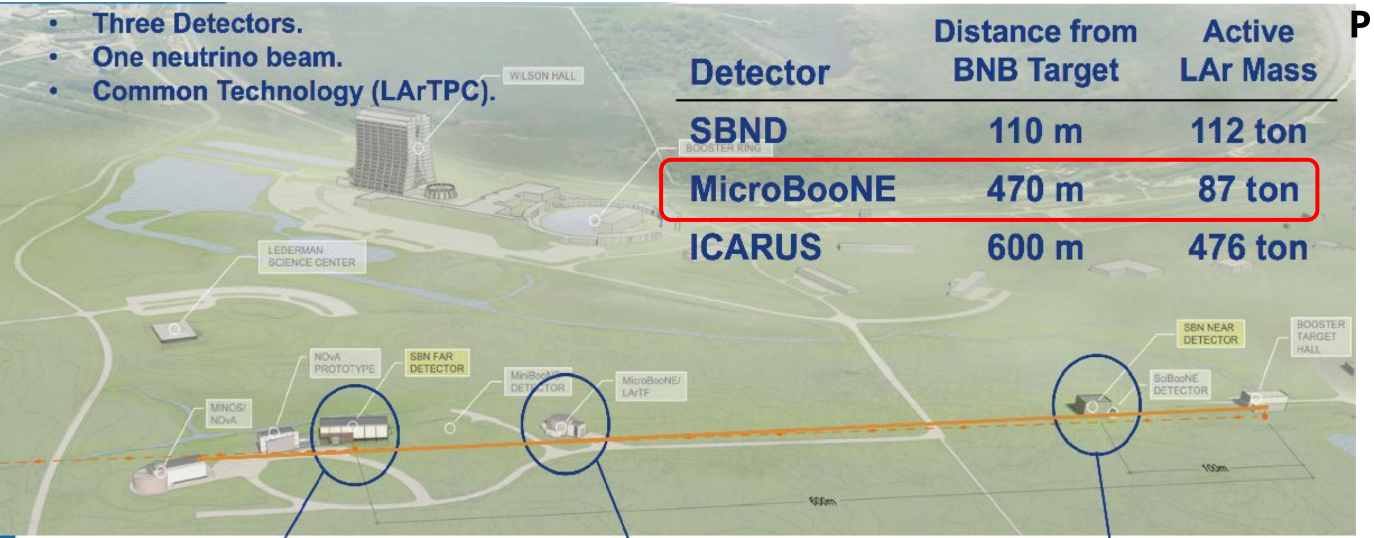
Previous CC0π Cross Section Measurements

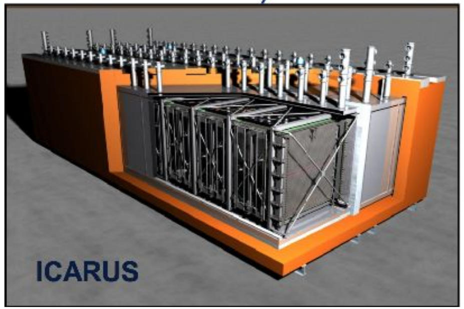
Experiment	Target	References	Comments	p_P Threshold
MiniBooNE	CH_2	PRD81:092005(2010)	Both CCQE and CC0π; no proton spectrum measurement	N/A
T2K	CH, H_2O	Phys. Rev. D98, 032003(2018)	Published proton momenta and multiplicity distributions	500 MeV/c
MINERvA	CH, Fe, Pb	Phys. Rev. Lett, 119,082001 (2017) Phys. Rev. D99, 012004 (2019)	Showed growing problems describing the magnitude of the data with increasing atomic number	450 MeV/c
MicroBooNE	Ar	Accepted by Phys. Rev. Lett	Emphasize CCQE-like with protons	300 MeV/c
MicroBooNE	**Ar**	**Submitted to Phys. Rev. D**	**Inclusive measurement with protons**	**300 MeV/c**

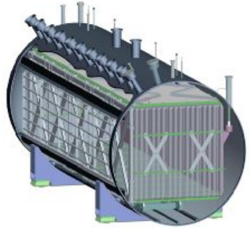
Short Baseline Neutrino Program (SBN)

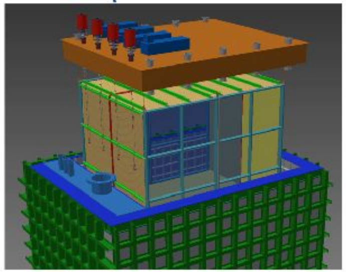
- Three Detectors.
- One neutrino beam.
- Common Technology (LArTPC).

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton






MicroBooNE


SBND

Primary Goals:

- Measure neutrino properties and neutrino oscillations
- Search for sterile neutrinos and test MiniBooNE and LSND anomaly
- MicroBooNE: **First large LArTPC detector in a ν beam in US with 5 years stable beam operation** (2015 until now)
- SBND & ICARUS are under construction or commissioning, will get improved data in the next few years

Short Baseline Neutrino Program (SBN)

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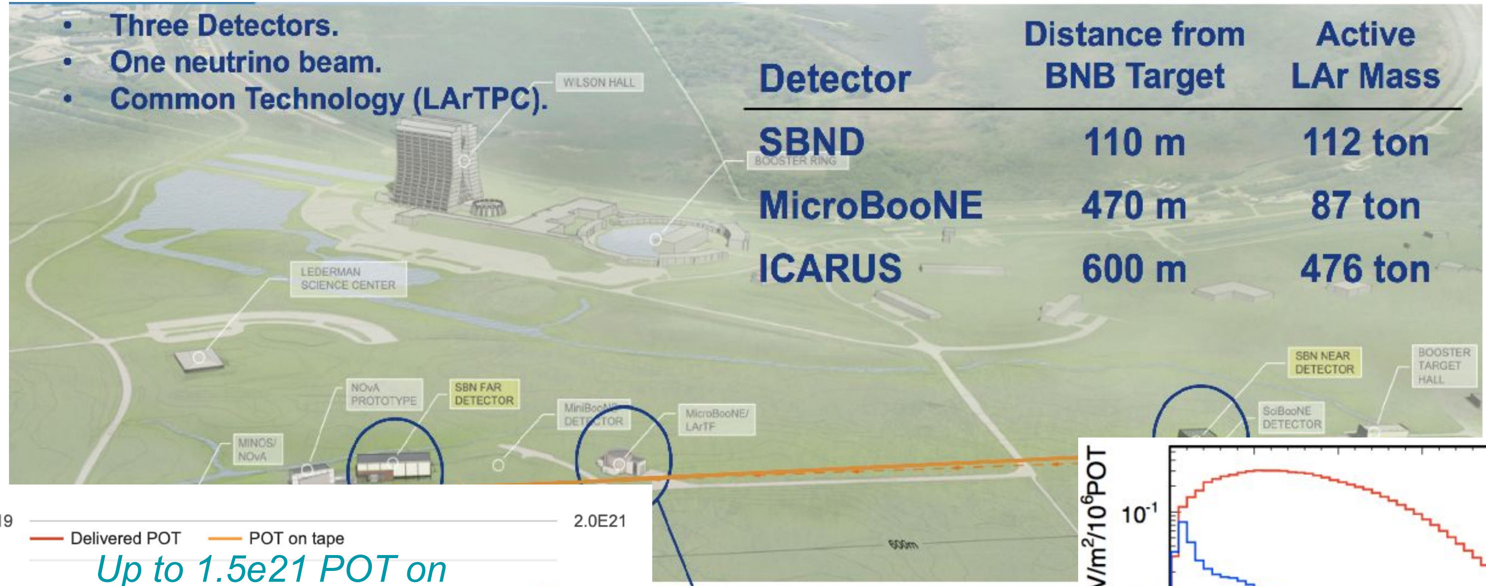
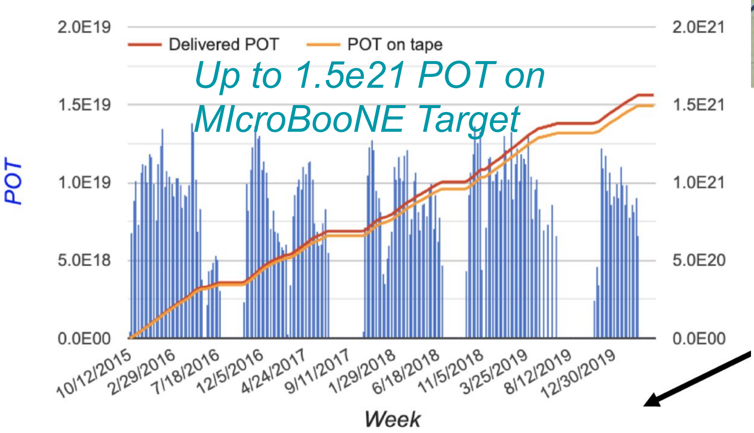
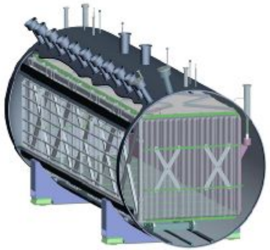
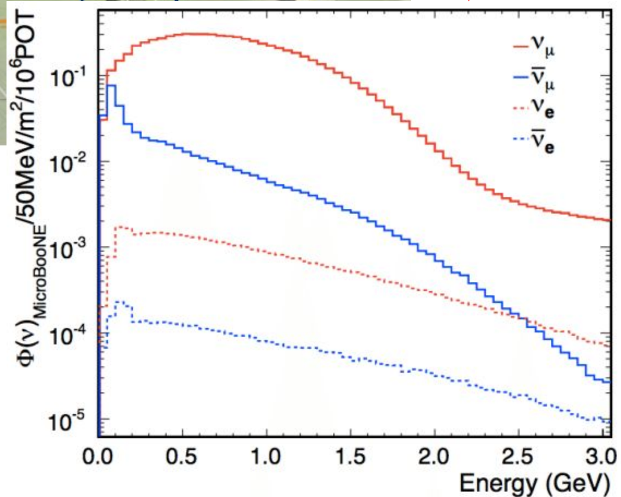


Booster Neutrino Beam Spectrum

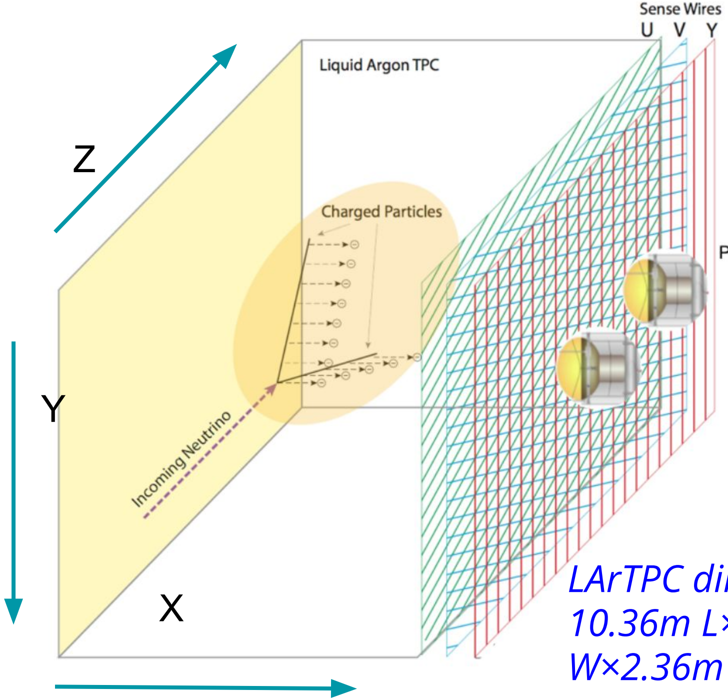




MicroBooNE

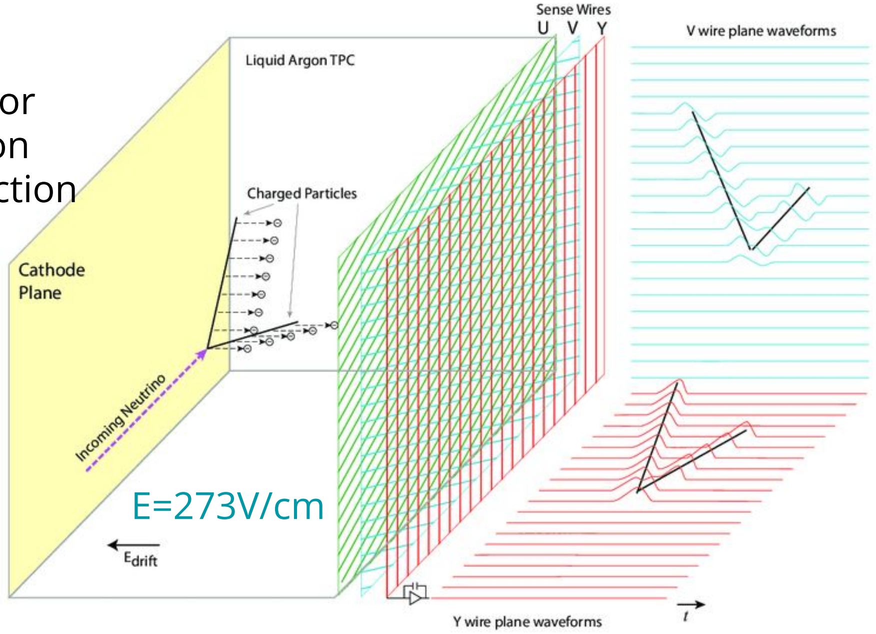


The Liquid Argon Time Projection Chamber

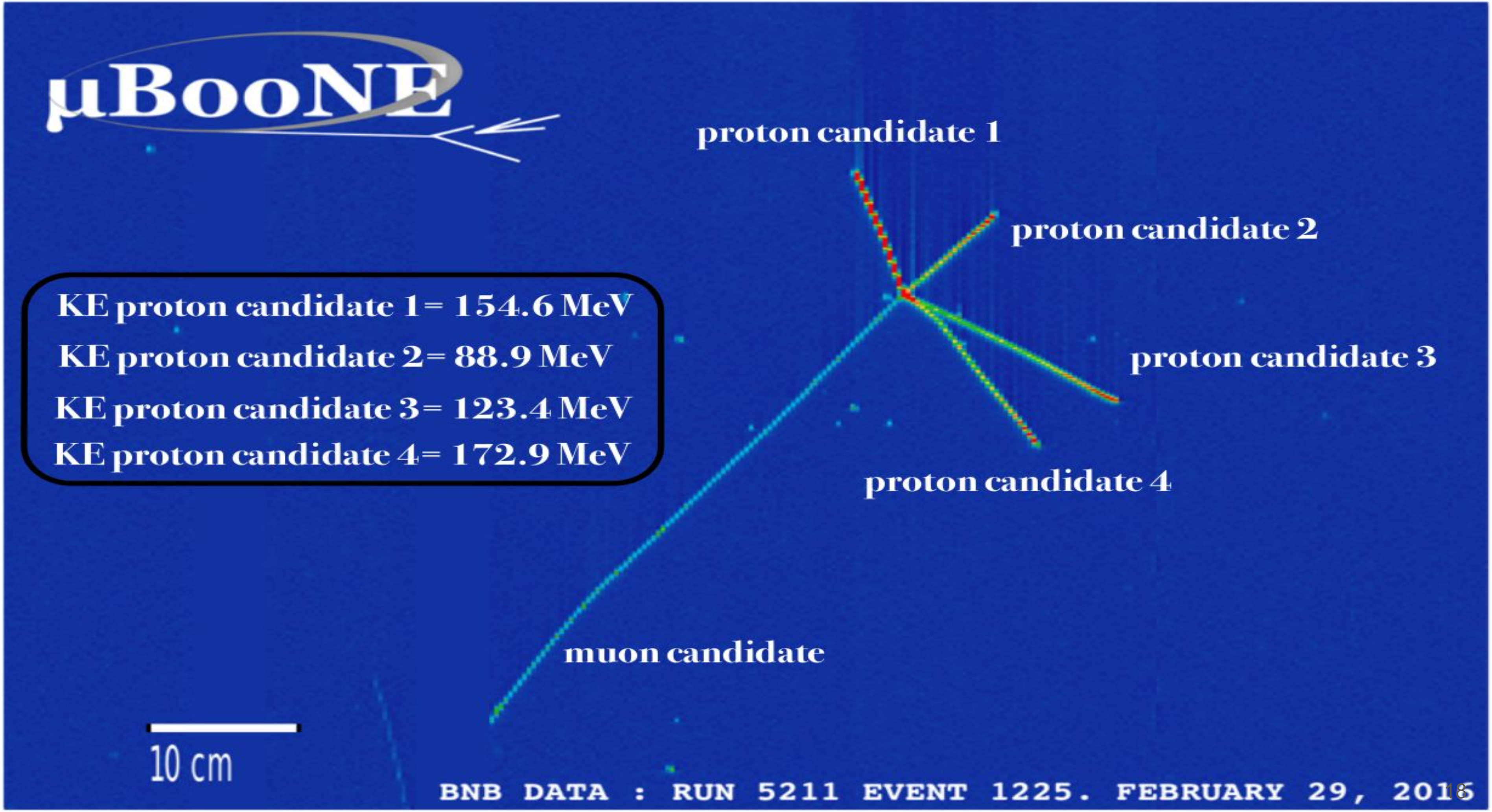


32 PMTs for Scintillation light detection

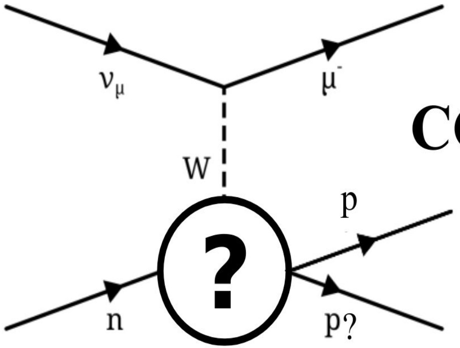
LArTPC dimension: 10.36m L×2.56m W×2.36m H



- Charged particles lose energy through Ar atom excitation (scintillation light) and ionization (drift electrons travel toward anode)
- Drift electrons are measured by wires
- 2 induction planes (+/-60 degrees with respect to Y axis) and 1 collection plane -> **3D reconstruction** from drift time (X) and Wire-plane matching (Y-Z)


μBooNE
proton candidate 1
proton candidate 2
proton candidate 3
proton candidate 4
muon candidate
KE proton candidate 1= 154.6 MeV
KE proton candidate 2= 88.9 MeV
KE proton candidate 3= 123.4 MeV
KE proton candidate 4= 172.9 MeV
10 cm
BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

Analysis Strategy



CC0π+Np (N>0)

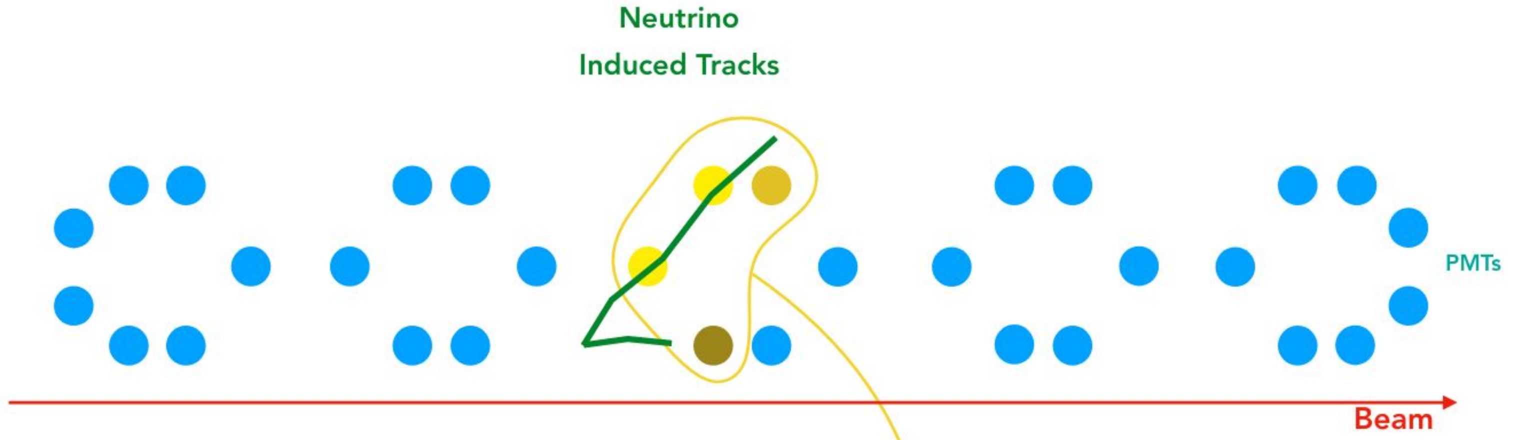
To select CC0πNp processes, we need

- Cosmic Removal
- Muon Identification
- Proton Identification
  - Distinguish proton from other particles
  - Further removal cosmics

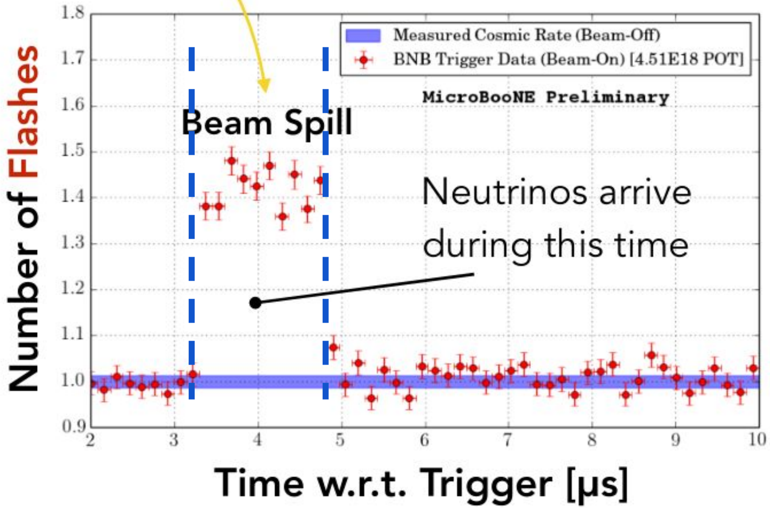
- Cosmic Removal and Muon Identification
  - Adopted from MicroBooNE CC inclusive analysis published in PRL*

* Phys. Rev. Lett. 123, 131801 (2019)

Cosmic Suppression with Optical Reconstruction

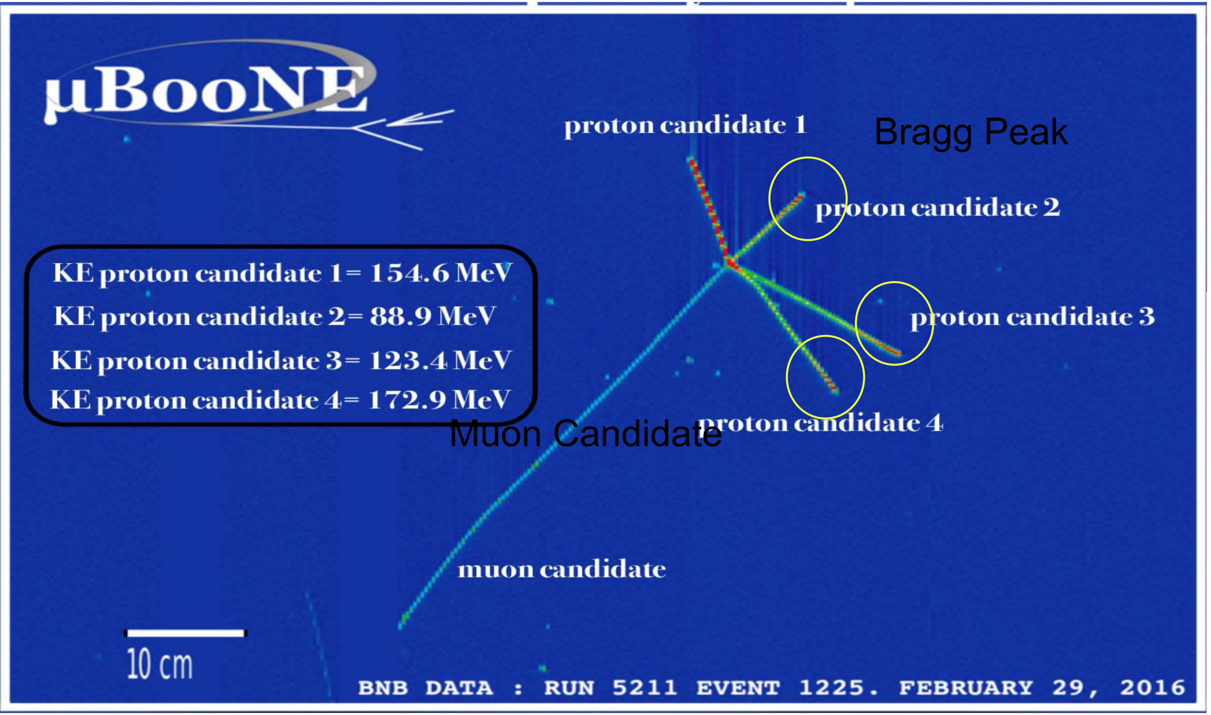


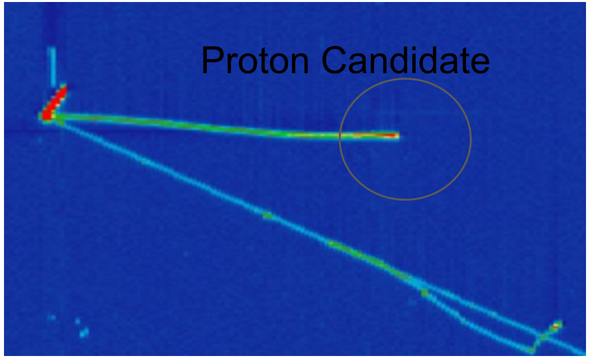
Neutrinos are delivered in spills that last for only **1.6 μs**. The light information (prompt) can be used to identify neutrino interactions during this spill.

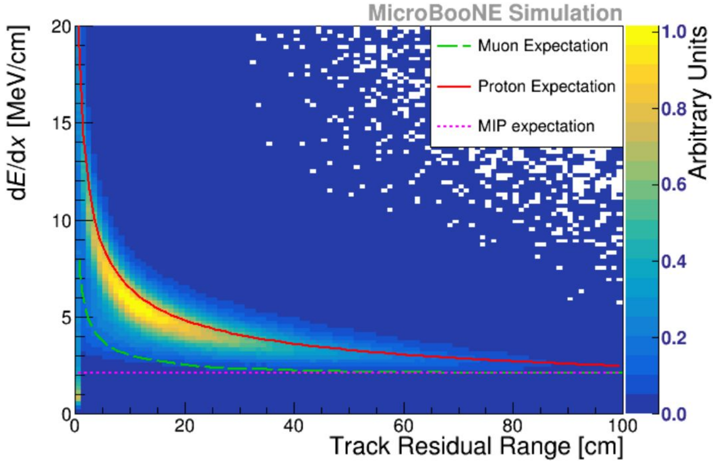


Credit: M. Del Tutto

Muon and Proton Identification





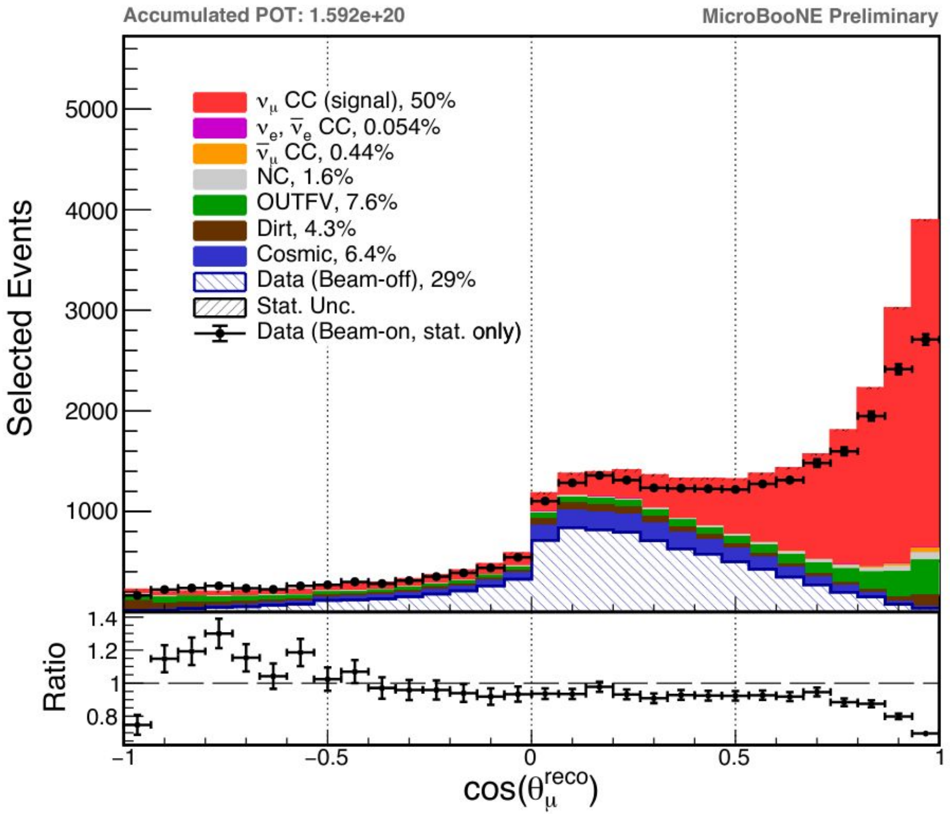


- dEdx is predicted by Bethe-Bloch formula
- Residual Range: distance from a reconstructed deposit (hit) to the stop point of a reconstructed track
- Particle identification is based on energy deposition per unit of length (dE/dx)

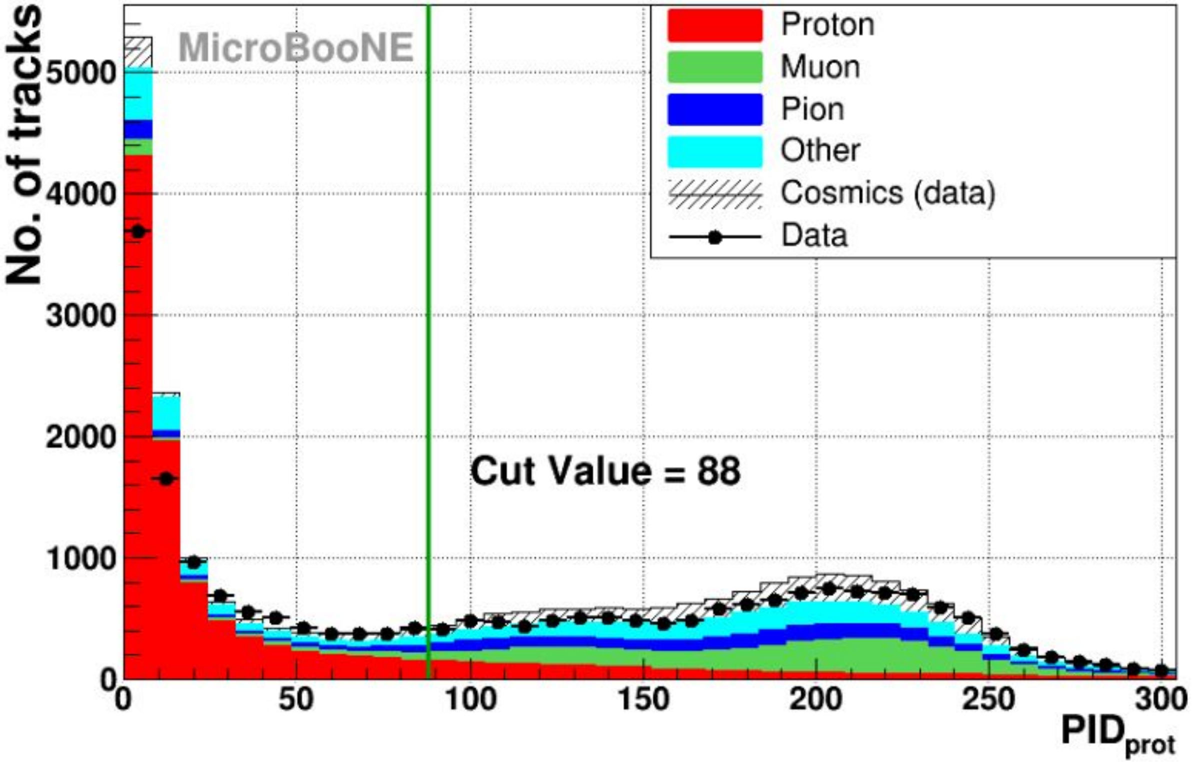
Muon Identification

Muon Identification comes from:

- MicroBooNE CCinclusive paper: [Phys. Rev. Lett. 123, 131801 (2019)]
- Muon candidate:
  - Longest track
  - Truncated mean dQdx vs residual range past minimum ionizing particle (MIP) consistency check
- Good cosmic removal efficiency
  - Over 99.9% removed
  - Need further cosmic removal

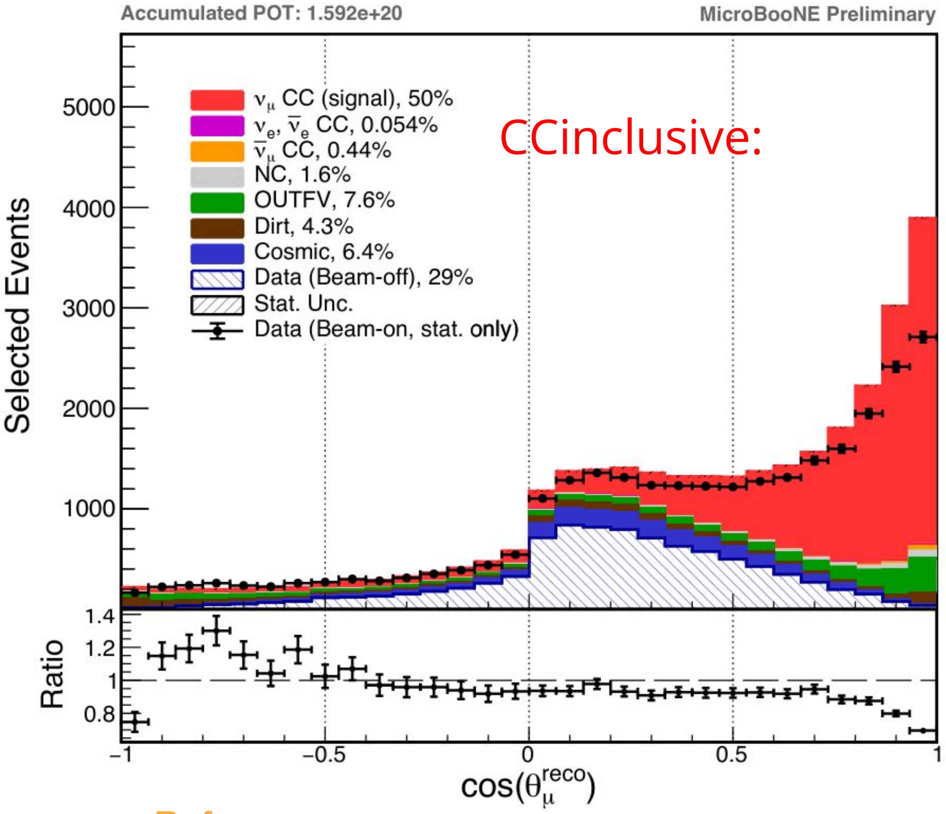


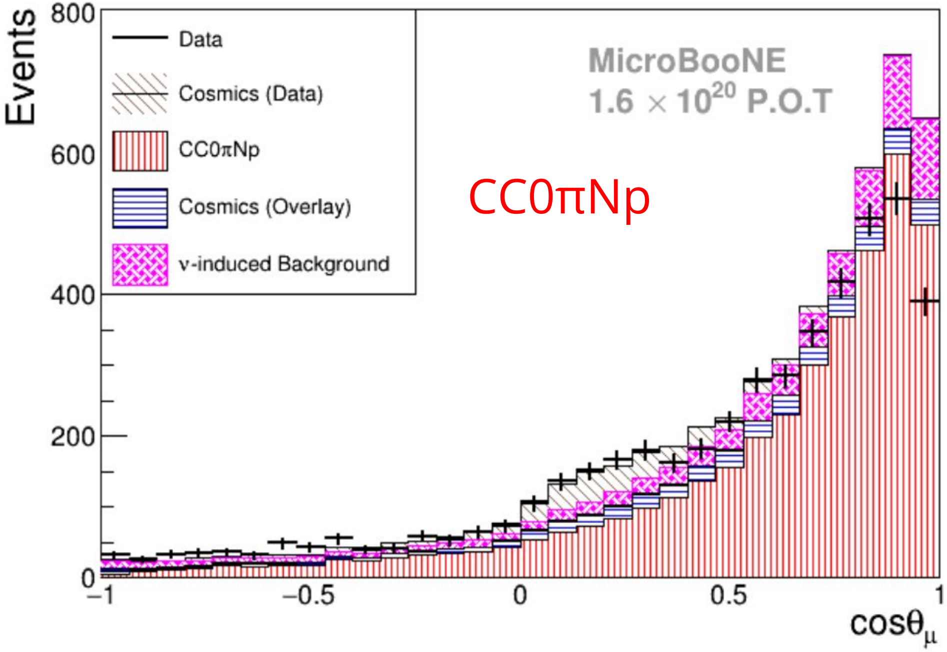
Proton Identification



- PID: a discriminator was constructed by comparing measured dEdx to theoretical predictions
- Proton-like: PID<88
- Further removes cosmics rays

Proton Identification





Reference: [Phys. Rev. Lett. 123, 131801 (2019)]

CCinclusive:

- Cosmic Removal+Muon ID

CC0πNp:

- Cosmic Removal+Muon ID+Proton ID

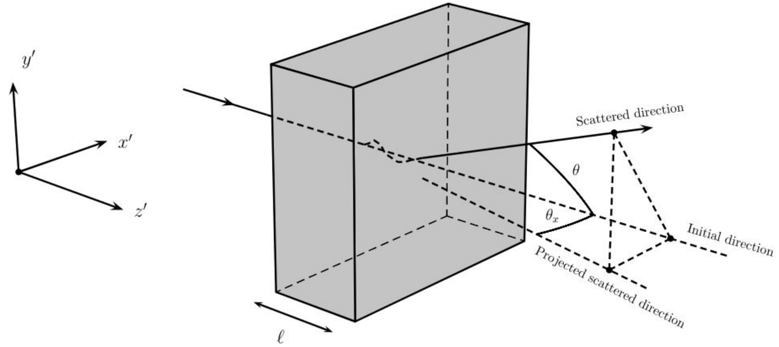
Momentum Reconstruction

Methods of momentum reconstruction in a LArTPC

- Range-based (only for contained tracks)
- Calorimetric (only for contained tracks)
- Multiple Coulomb Scattering (MCS)
  - Can be used for both contained and exiting particles

$$\sigma = \frac{S_2}{p\beta c} z \sqrt{\frac{l}{X_0}} \left[1 + \epsilon \cdot \ln\left(\frac{l}{X_0}\right) \right]$$

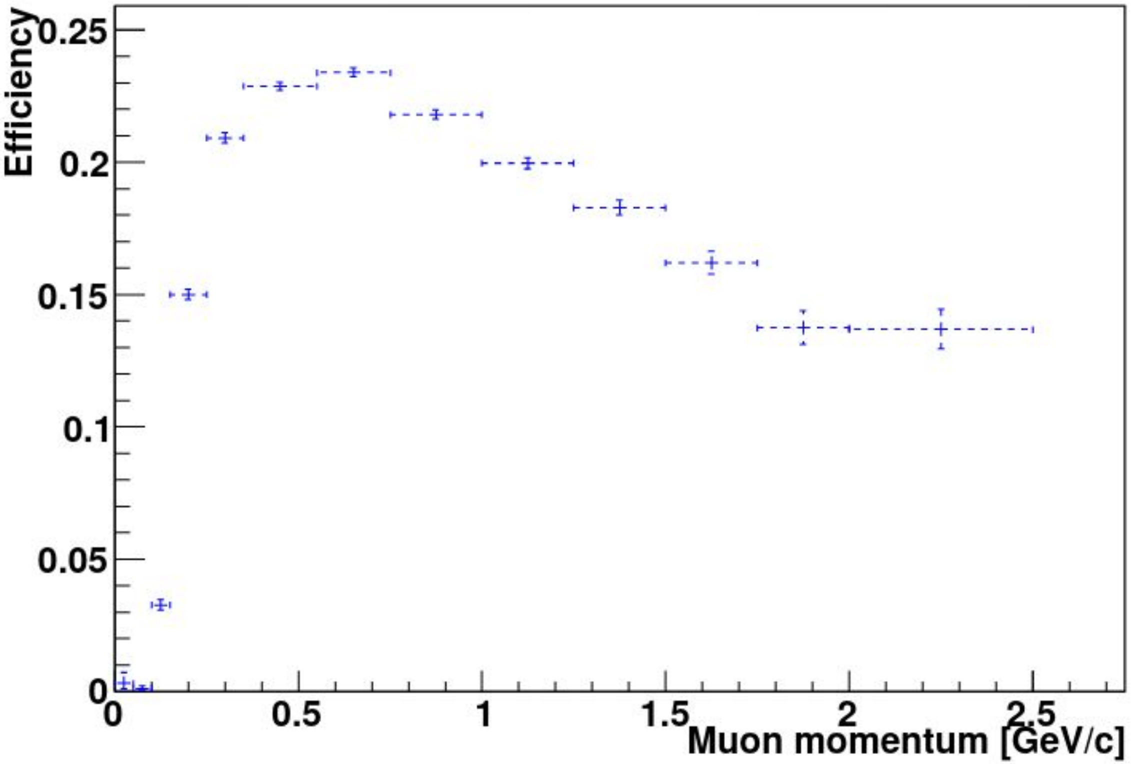
The RMS of the scattering angle σ is fit along the particle trajectory to estimate the momentum *p*



- **Muon candidates** momentum
  - The majority of BNB muons in MicroBooNE are exiting!
  - Range-based for contained; MCS for exiting
- **Proton candidates** momentum
  - Contained and Range-based

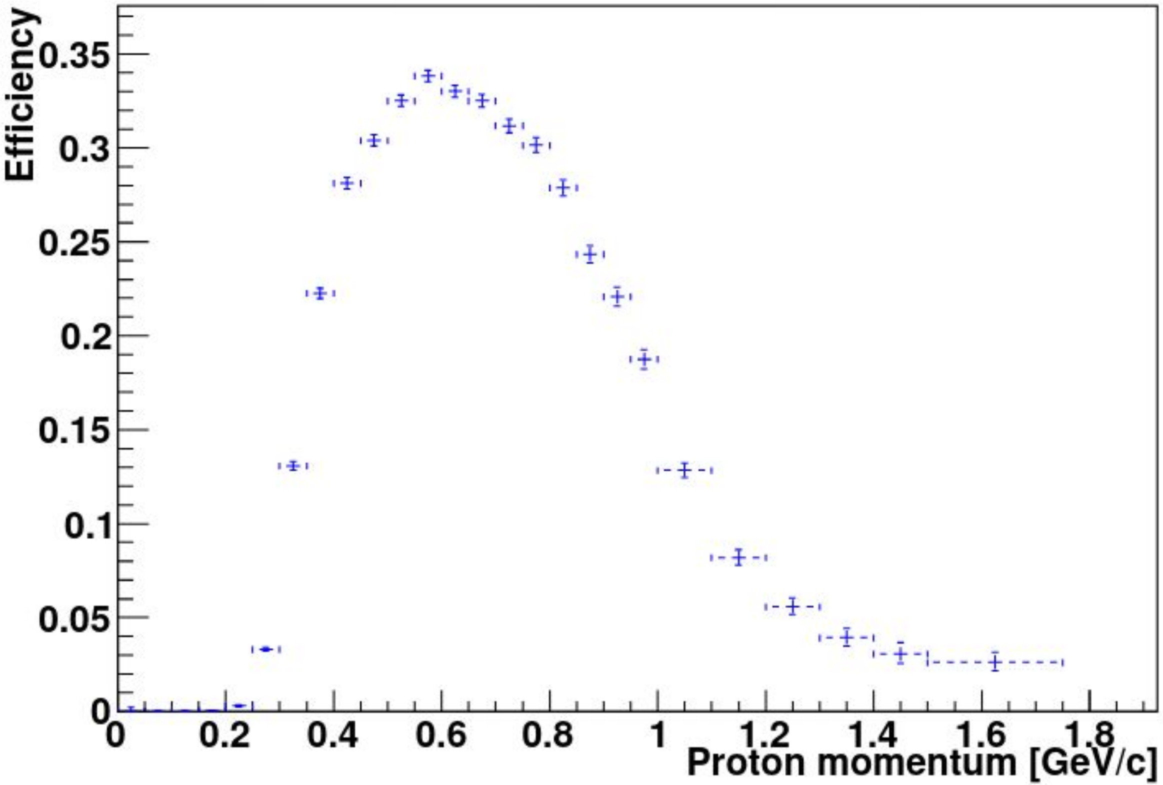
MCS Method Reference: JINST 12P10010(2017)

Phase Space Limits



- **Low momentum region (<100 MeV/c):** low reconstruction efficiency for short tracks

Phase Space Limits

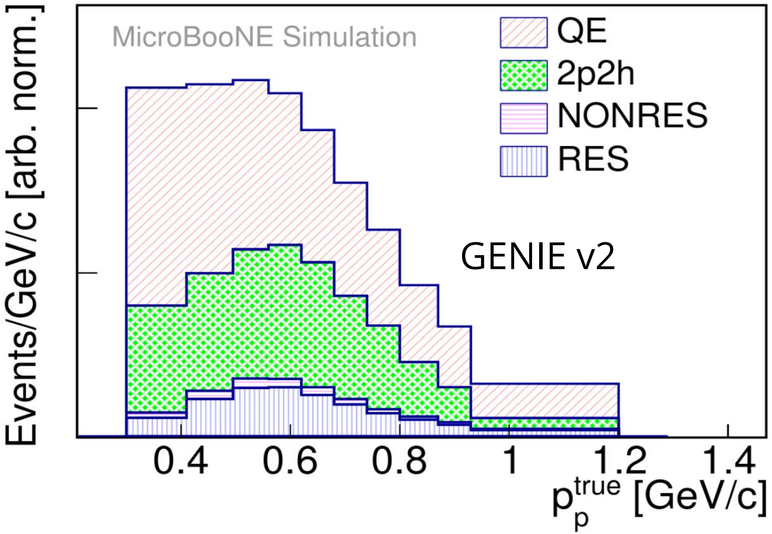


- **low momentum region (<300 MeV/c) :** low reconstruction efficiency due to short tracks
- **High momentum region(>1200 MeV/c) :** low reconstruction efficiency due to high re-interaction probability

Signal Definition and Motivations

Signal: one muon, N protons (N>0), no pions (charged or neutral) in the final state→ **CC0πNp**

- Muon momentum>100 MeV/c
- Leading proton (highest momentum) in range:
  - 300 MeV/c (KE=47 MeV) to 1200 MeV/c
- No momentum cuts to other proton candidates
- CCQE is strongest contributor, but not dominant



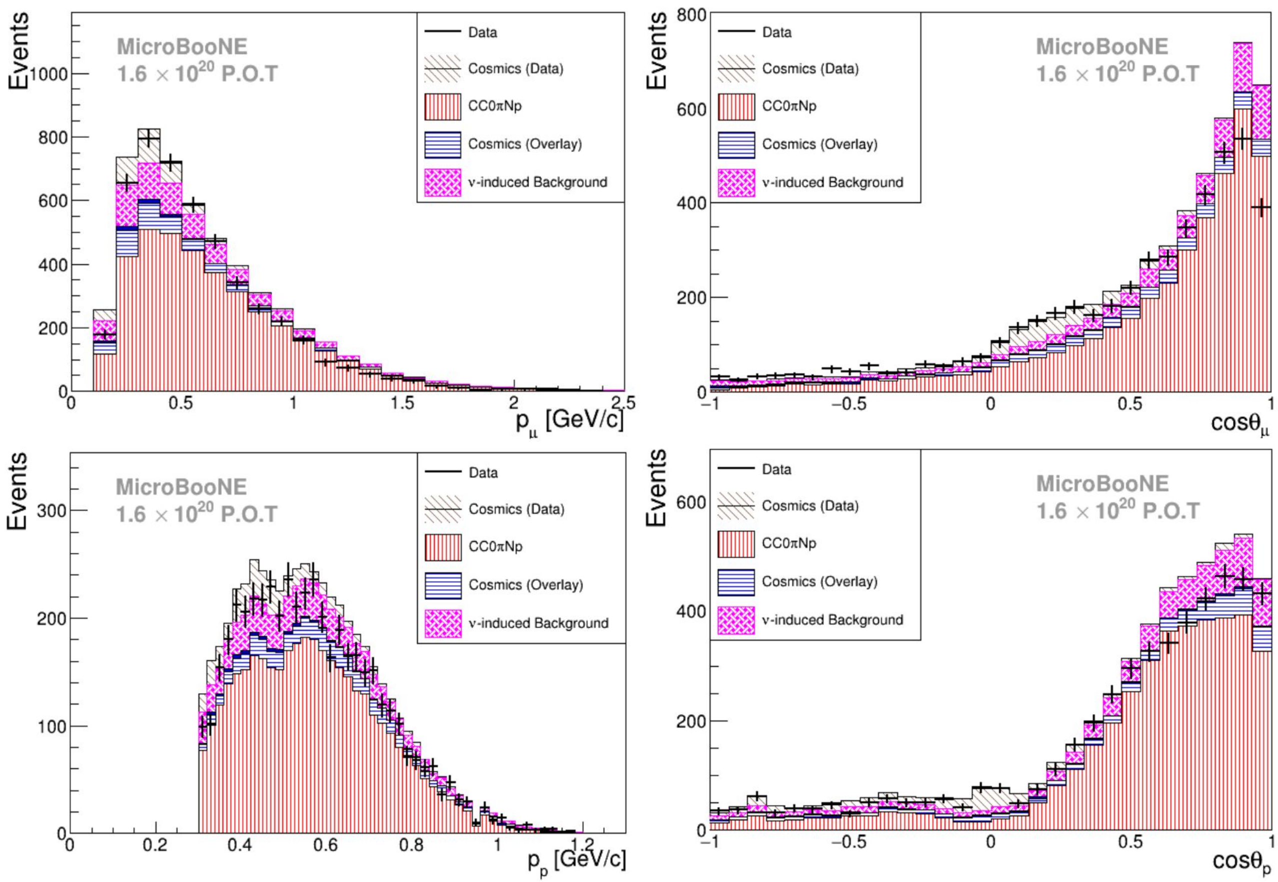
Signal definition

- matches current detector acceptance
- reduces model dependence, allowing more realistic tests of nuclear models

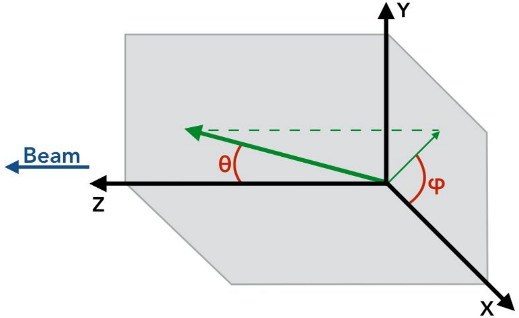
Comparison with CCQE-like (MicroBooNE W&C last Friday)

- Both emphasize importance of protons in signal definition
- CCQE-like signal definition/cuts more exclusive (1p vs. Np, kinematic cuts)
- Result is that CCQE-like has 81% CCQE, this analysis 54% CCQE

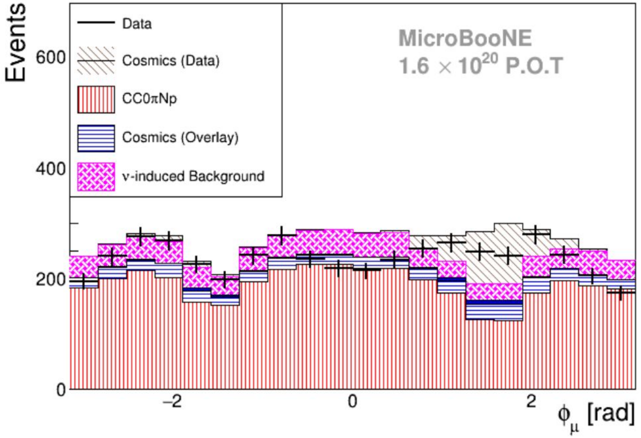
Kinematic Distributions

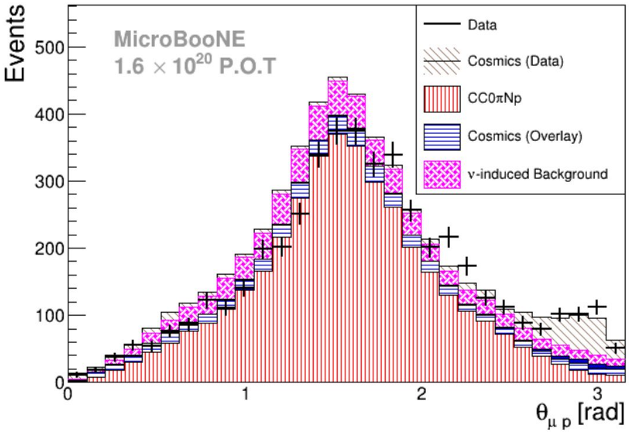


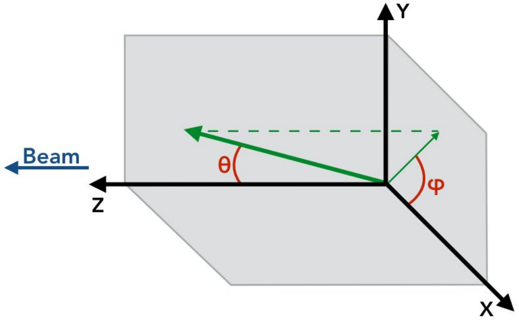
- Good efficiency and purity achieved (Purity: 71%| Efficiency: 29%)
- 4π angular coverage for both muon and proton
- Only leading proton is used in analysis
- Of all the selected events
  - 72% → 1 proton candidate
  - 22% →2 proton candidates
  - 6% →3 or more proton candidates

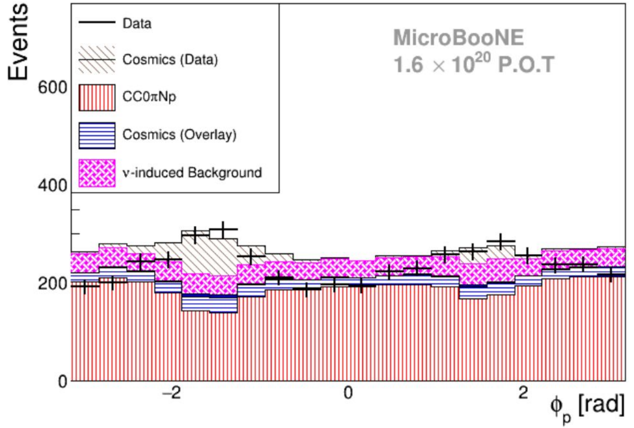


Kinematic Distributions



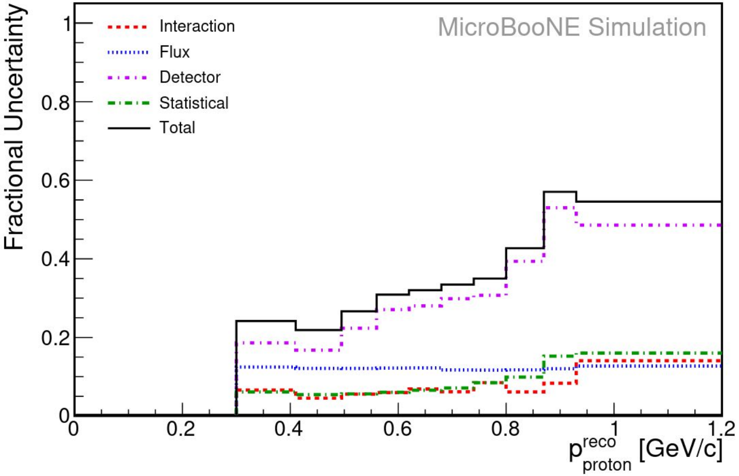


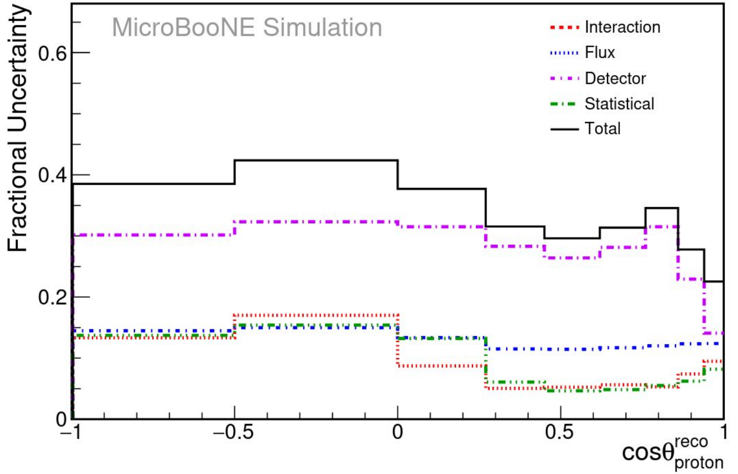




- Most remaining cosmics with the angle ~+/- 90 degrees with respect to x-z plane
- Cosmic track reconstructed as two tracks. Some **Muons with Bragg peak are misidentified as a proton candidate**. Rare occurrence, but many cosmics to cope with

Systematic Uncertainty





- Sources of Systematics
  - Neutrino interaction models
    - Parameters in GENIE cross section model and nuclear model varied within uncertainty with GENIE Reweight framework
    - Uncertainties from MEC and QE shape are included
  - Beam Flux Estimation
  - Detector Response **largest**
    - Diffusion, electron lifetime, space charge effect, dynamic induced charge
    - Dominated by Dynamic Induced Charge (DIC)
  - Statistical Uncertainty

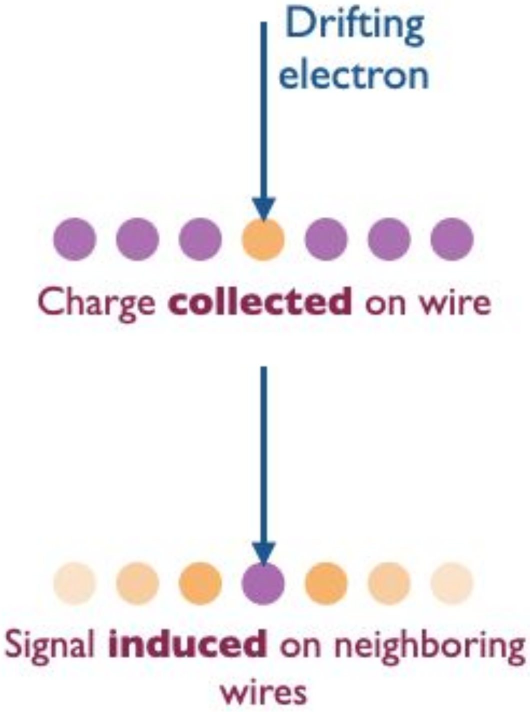
Dynamic Induced Charge

JINST 13 P07006 (2018)

JINST 13 P07007 (2018)

- Dominant uncertainty on this measurement
  - MC assumes drift electrons cause signal on only one wire
  - Not true! Nearby wires see charge by induction
  - Impacts on both muon and proton candidates
    - muon reconstruction efficiency
    - proton ID efficiency

- Updated simulation is being rolled out for new analyses with DIC correction



Credit: Kirsty Duffy

Cross Section Measurement

The single differential cross section in bin i is calculated as (using p_μ as an example):

$$\left(\frac{d\sigma}{dp_\mu}\right)_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu)_i}$$

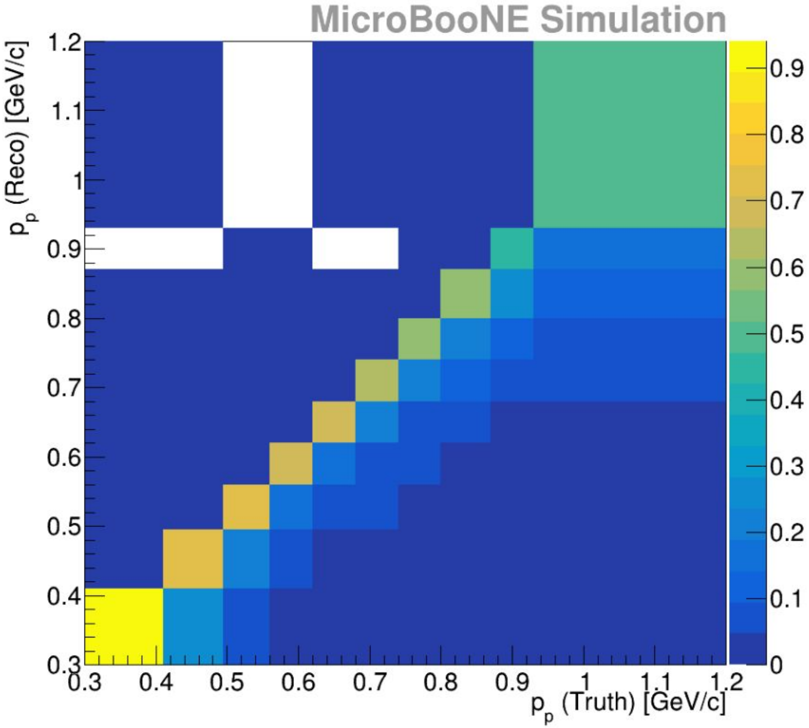
N_i	number of selected events in reconstructed bin i (data)
B_i	number of background events in reconstructed bin i (MC and cosmic data)
$\tilde{\varepsilon}_i$	overall efficiency (selection eff. x acceptance) in reconstructed bin i (MC)
N_{target}	number of target nucleons
Φ	muon neutrino flux (integrated over all energies)

- Forward folding method in cross section measurements as a function of five reconstructed variables
  - muon momentum (**p_μ**), muon angle (**$\cos\theta_\mu$**), leading proton momentum (**p_p**), leading proton angle (**$\cos\theta_p$**) and open angle between muon candidate and leading proton candidate (**$\theta_{\mu p}$**)

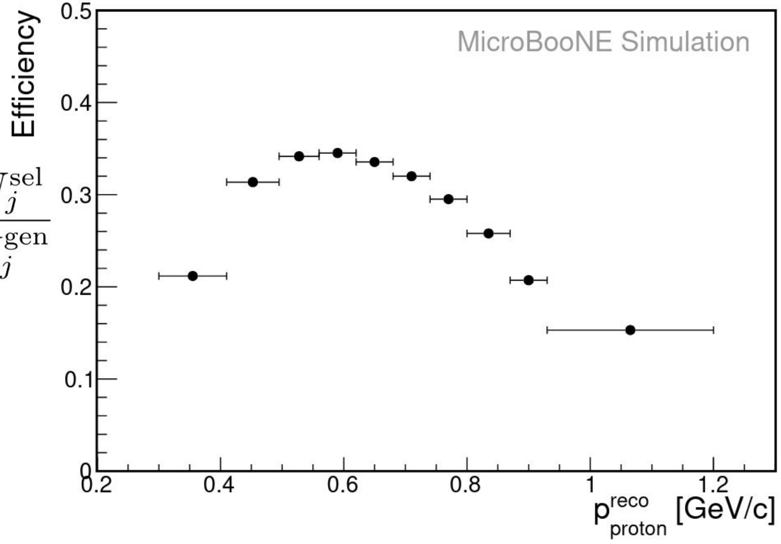
Cross Section Measurement

Differential Cross Section

$$\left(\frac{d\sigma}{dp_\mu}\right)_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu)_i}$$



$$\tilde{\epsilon}_i = \frac{\sum_{j=1}^{M} S_{ij} N_j^{\text{sel}}}{\sum_{j=1}^{M} S_{ij} N_j^{\text{gen}}}$$

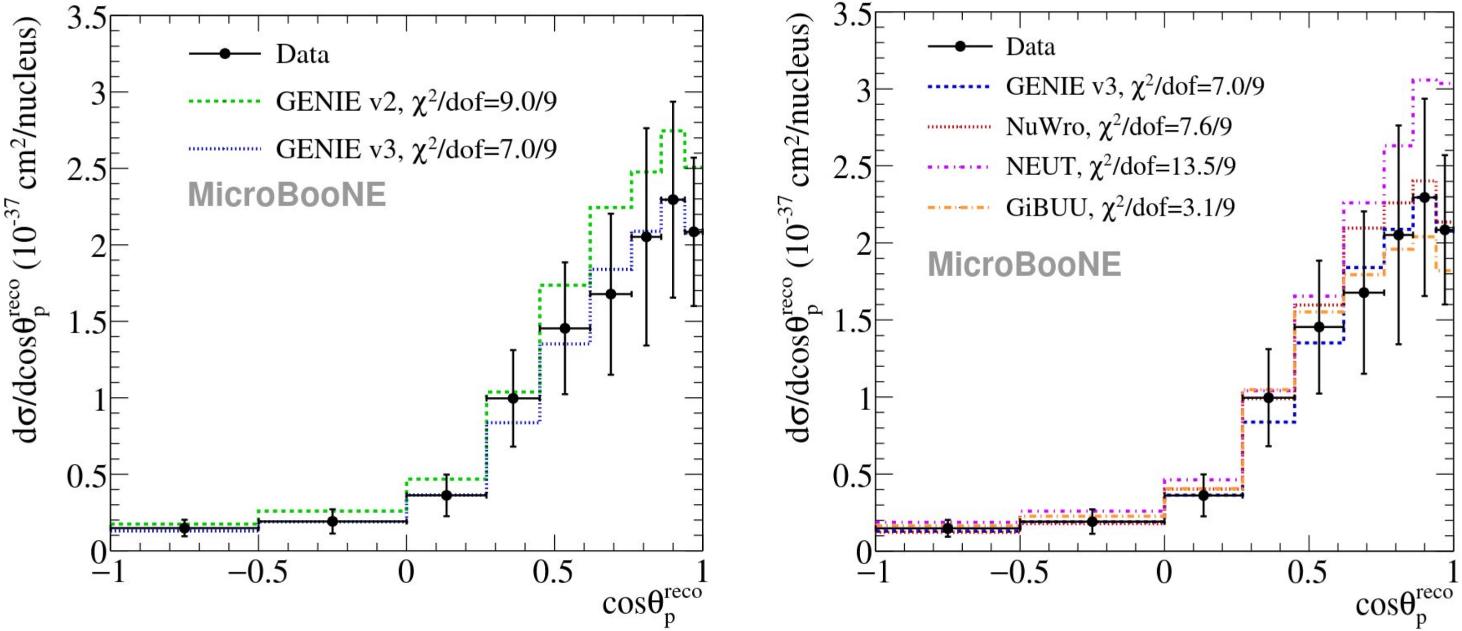


- Only statistical error shown in the efficiency distributions.

Model Sets of Generators in Use

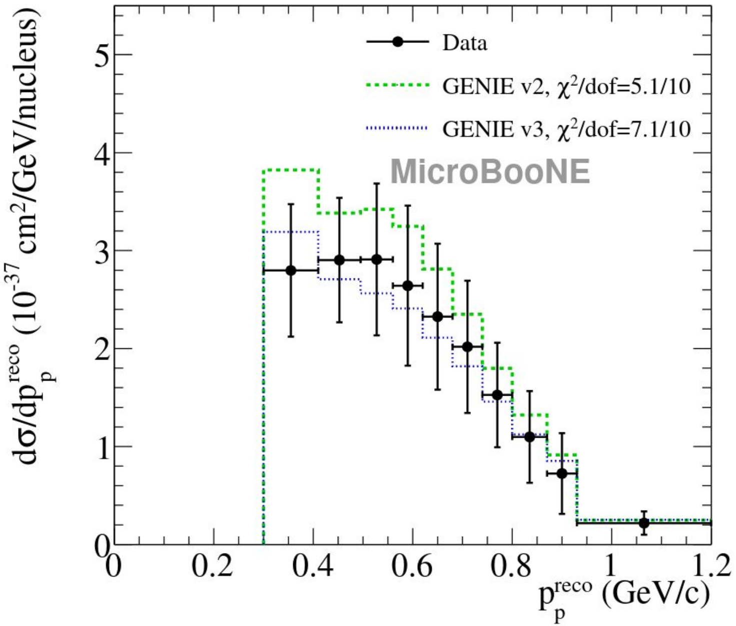
Model Element	GENIE v2+MEC v2.12.2*	GENIE v3 (v3.00.04 G1810a0211a)	NuWro 19.02.1	NEUT	GiBUU 2019
Nuclear Model	Bodek-Ritchie Fermi Gas [1]	Local Fermi Gas[2,3]	Local Fermi Gas[2,3]	Local Fermi Gas[2,3]	Consistent nuclear medium corrections throughout. Also uses a LFG model for nuclear modmenta, a separate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

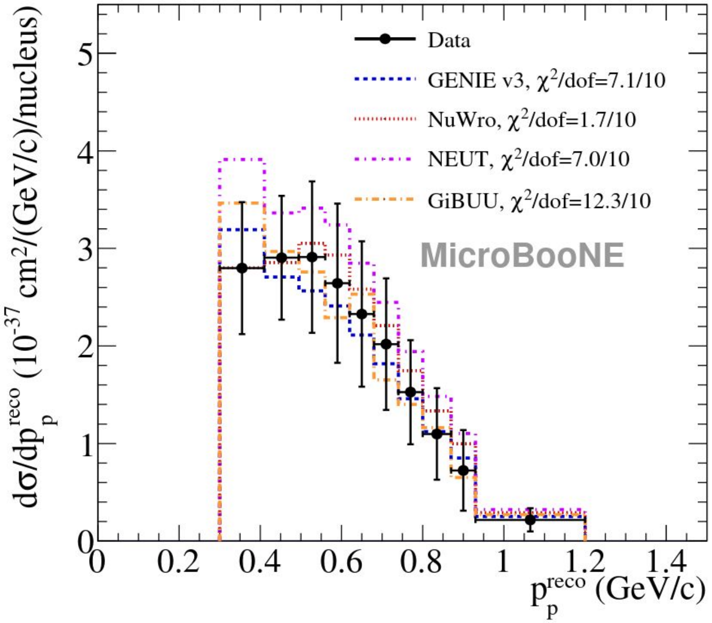
Cross Section Results - proton angle



- Left figure shows generator evolution; GENIE v3 results about 20% smaller than GENIE v2, better χ^2 (**Same for other variables**)
- χ^2 include correlations and the error bars have significant correlations
- Right figure compares data with recent generator results.
- Modern generators GENIE v3, NuWro and GiBUU all get better agreement with data than NEUT

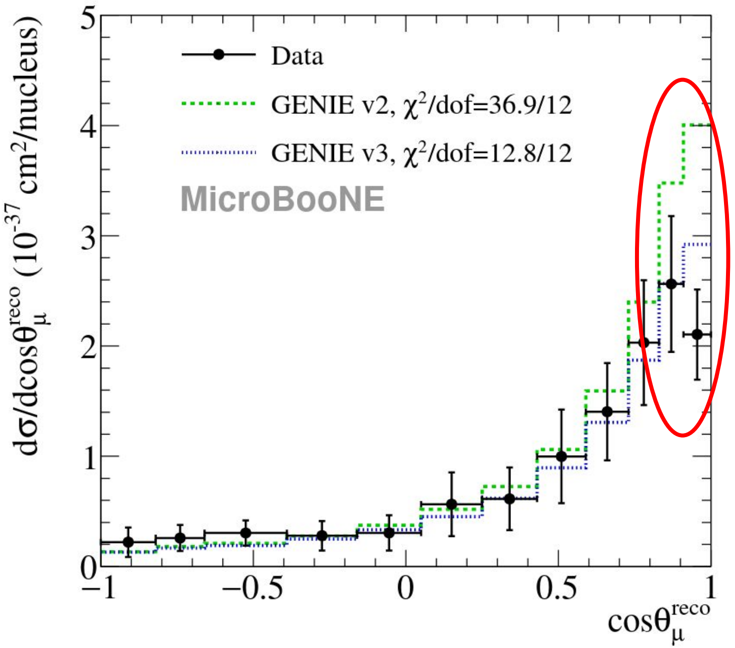
Cross Section Results - proton momentum

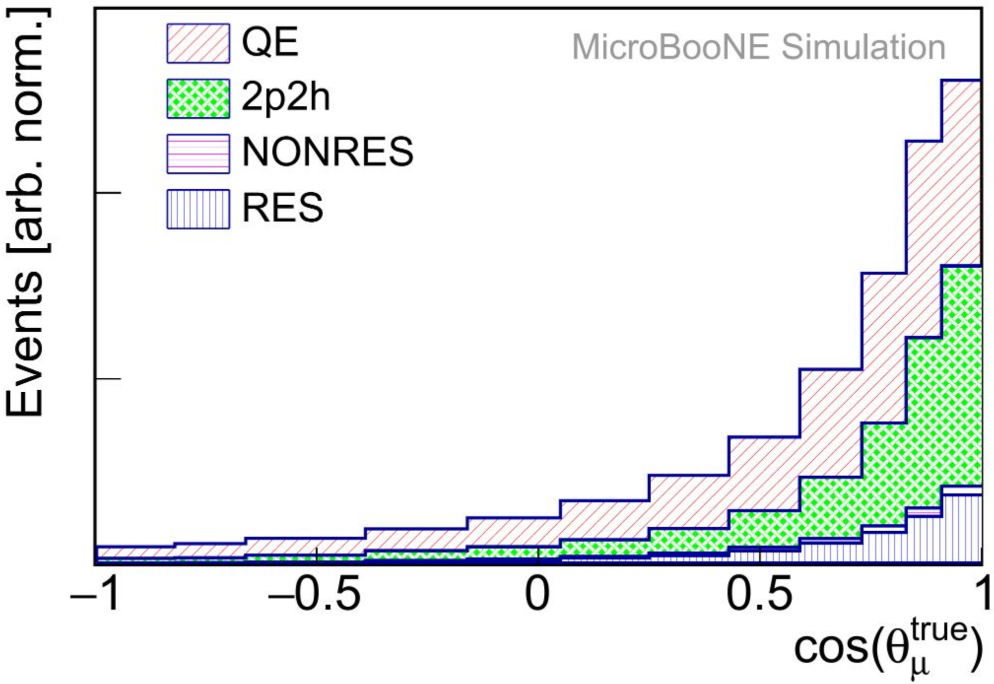




- Interesting because we go lower in momentum than previous experiments
- Models all match data reasonably well
- Some **divergence** for lowest momentum bin (0.3 to 0.41 GeV/c) with NEUT largest
- Data for even lower proton momentum will be very interesting, possible with liquid argon.

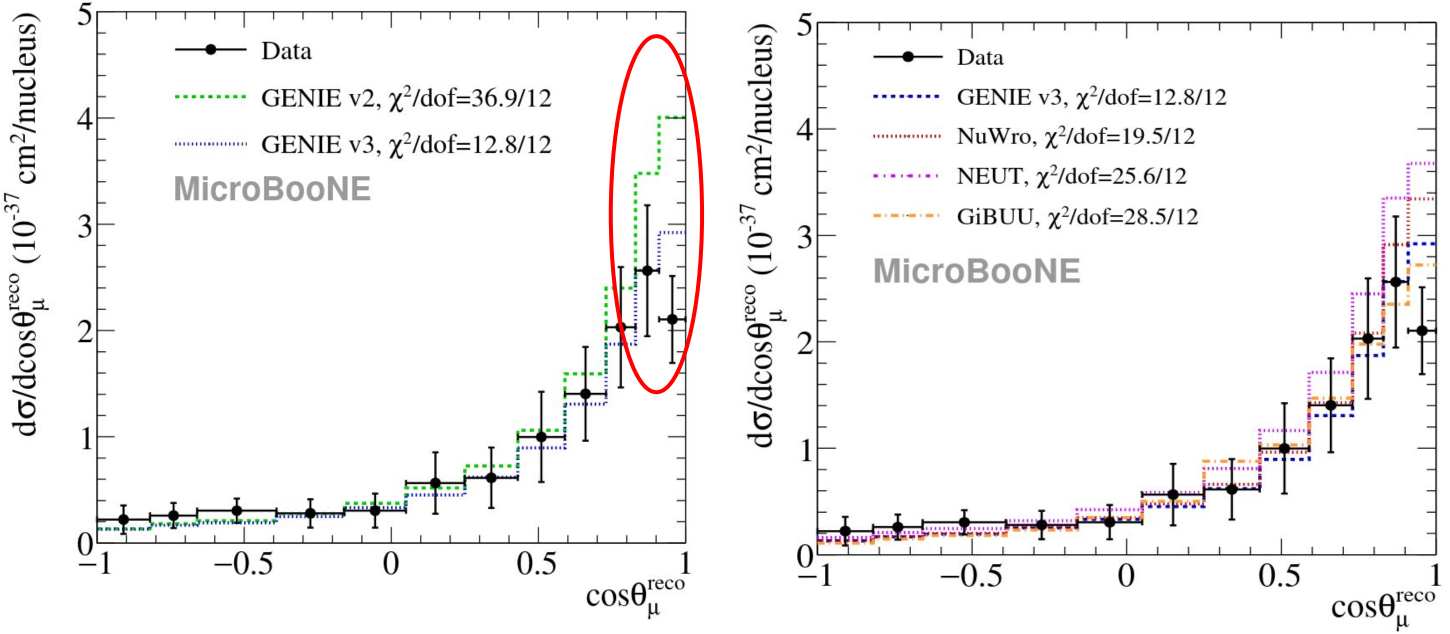
Cross Section Results - muon angle





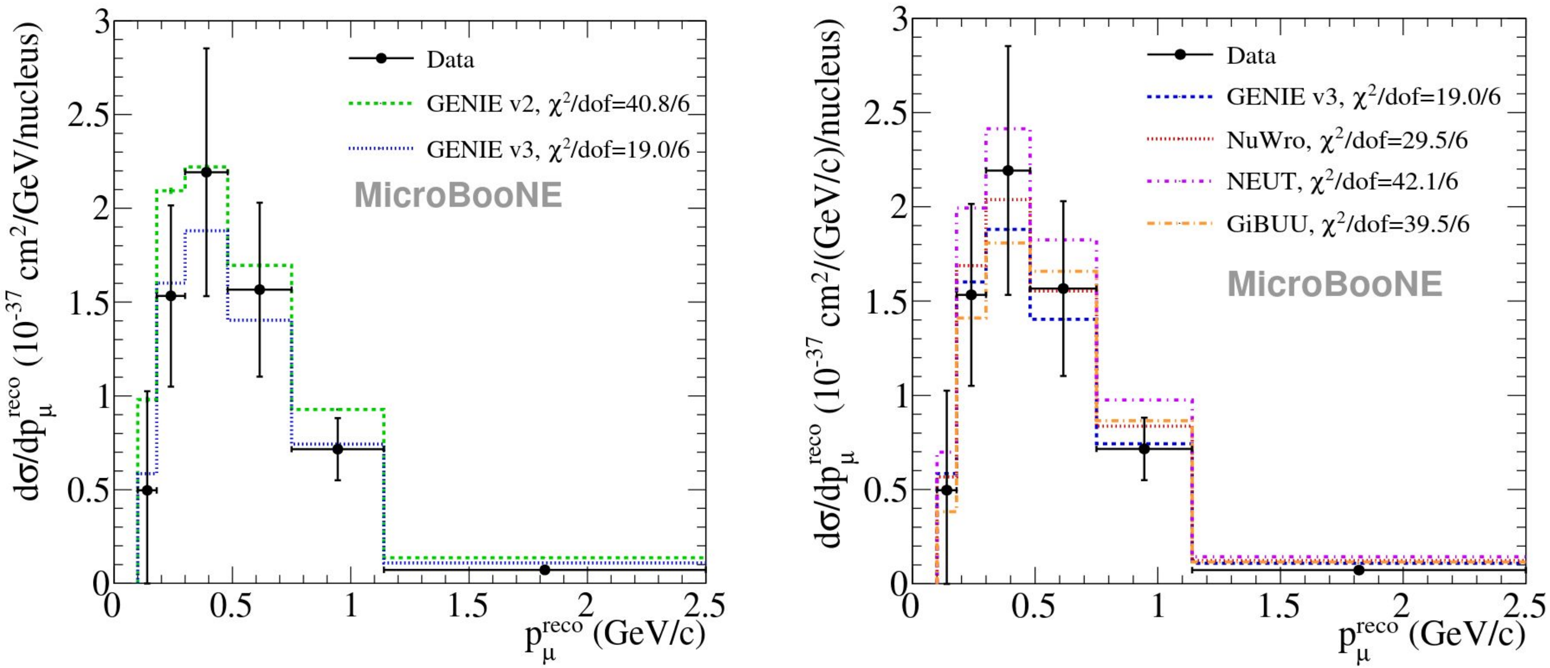
- Significant overprediction for most forward going muons seen for all models
  - Seen in the CC inclusive and CCQE-like measurements in MicroBooNE as well
  - 2p2h and nucleon-nucleon correlations (RPA) are important contributors, still uncertain.

Cross Section Results - muon angle



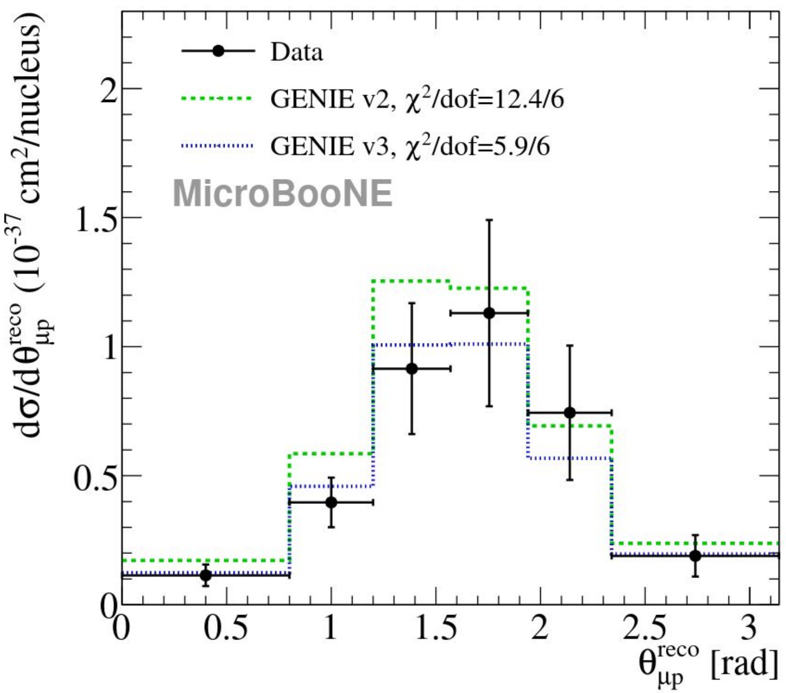
- Significant overprediction for most forward going muons seen for all models
  - Seen in the CC inclusive and CCQE measurements in MicroBooNE as well
  - 2p2h and nucleon-nucleon correlations (RPA) are important contributors, still uncertain.
  - New models do better, but don't go far enough

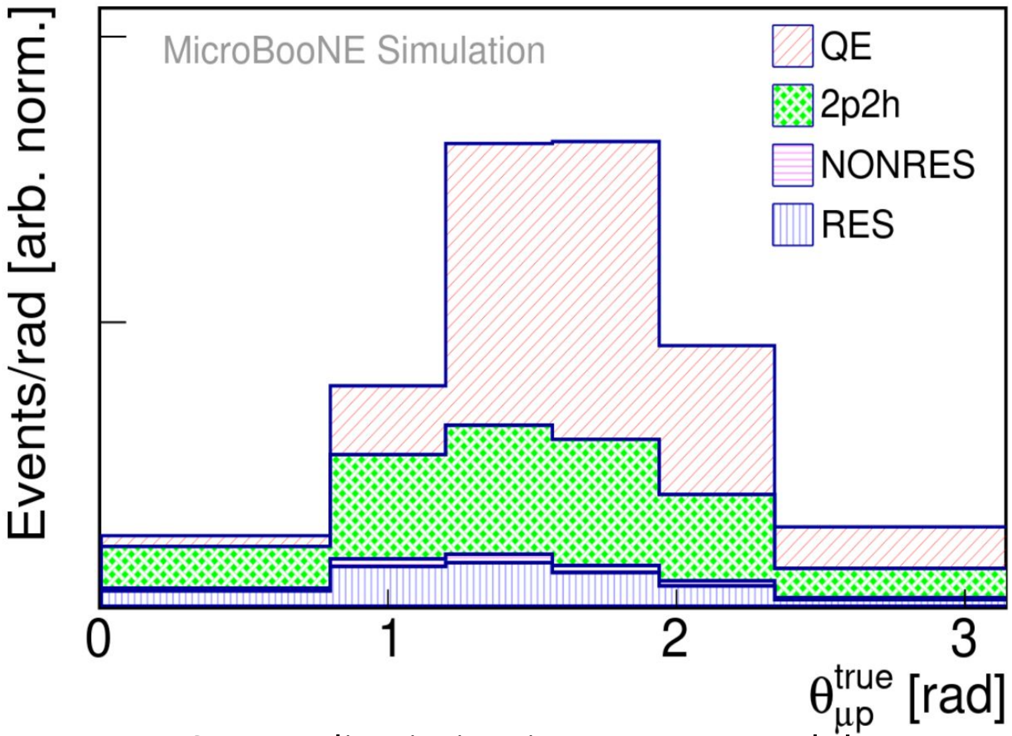
Cross Section Results - muon momentum



- Good overall agreement by eye, χ^2 is dominated by the last bin.
  - Similar to MicroBooNE CC inclusive analysis.

Cross Section Results - muon-proton opening angle

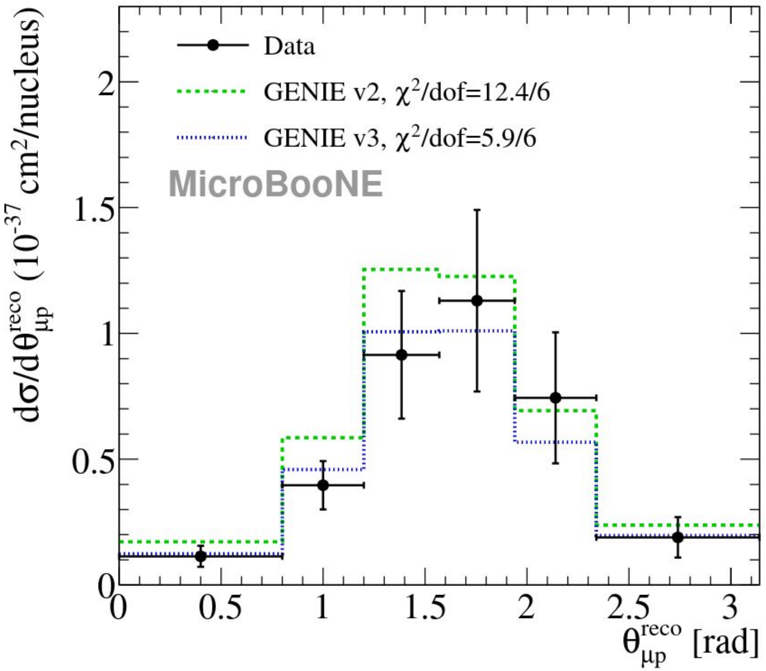


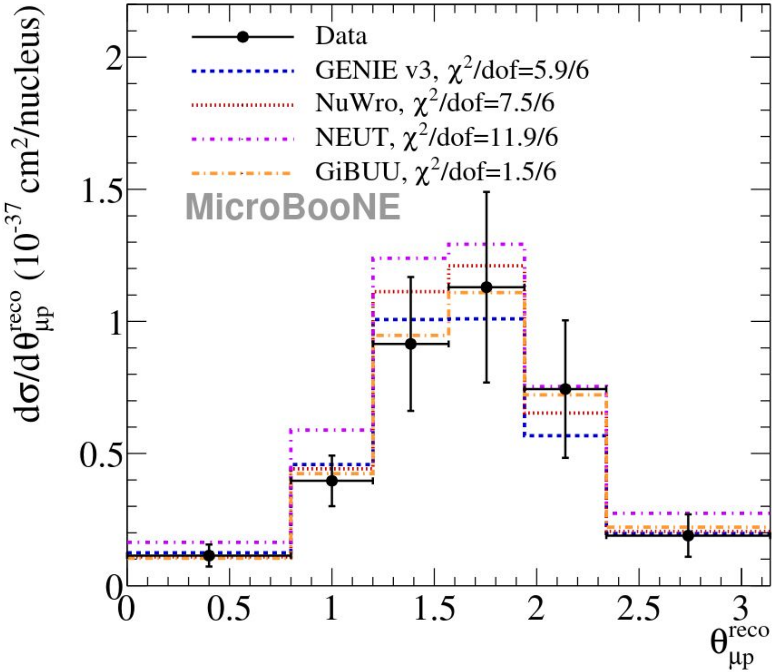


- Left figure shows generator evolution
- A slight shift for peak position

- Strong discrimination among models
  - CCQE : strongly peaked at ~π/2
  - Others: flatter

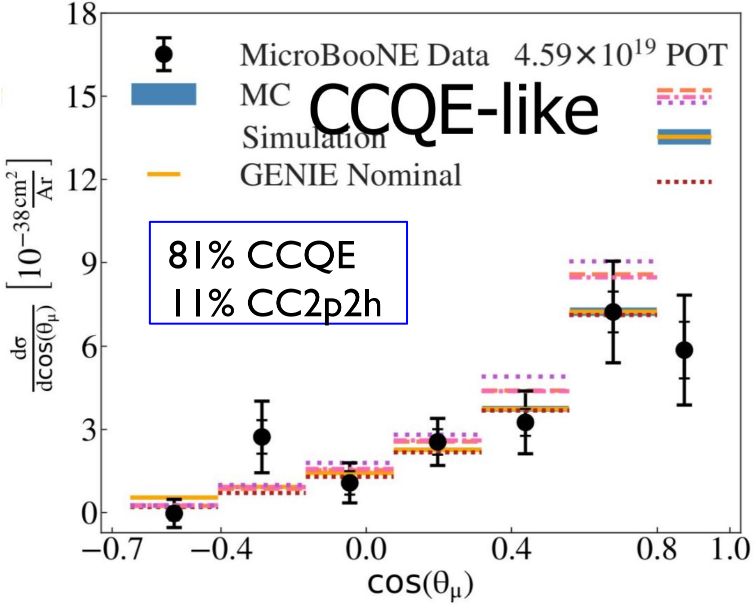
Cross Section Results - muon-proton opening angle

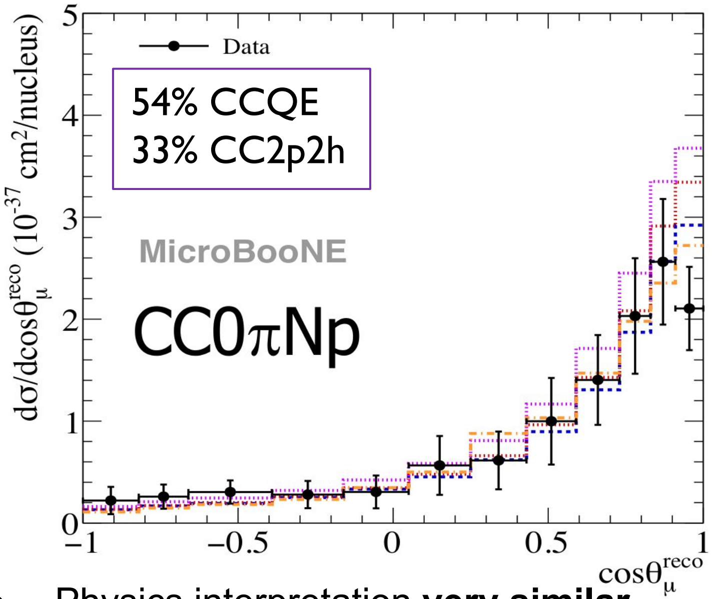




- Peak at π/2 comes from CCQE events, other mechanisms give flatter dependence
- Mix of QE, 2p2h, and pion production in modern generators mostly in agreement with data
- A slight shift for peak position, predicted by NuWro and GiBUU

MicroBooNE CC0πNp & CCQE-like are Complementary



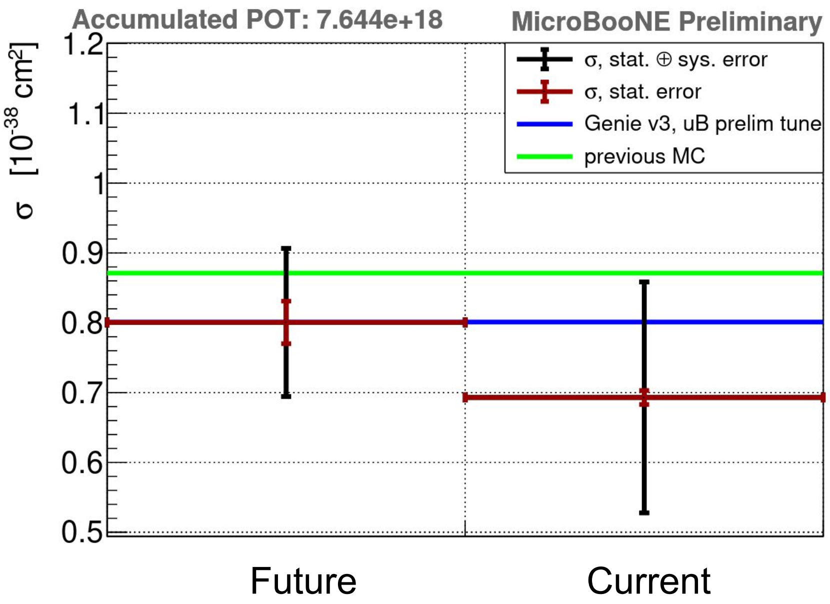


- Both emphasize importance of protons, similar events but difference in signal/cuts
- Both include QE, 2p2h, pion production
- CC0πNp has more inclusive signal
  - More events, larger systematic uncertainties
  - More phase space->less model dependence
  - Overall cross section ~3x larger, but less CCQE content
- Physics interpretation **very similar**
  - Shapes are similar, and both have suppression in most forward bin; calculations too large
  - CCQE-like discrepancy larger, hints problems is in CCQE (e.g. RPA)
- All will benefit from the complementarity

Future Prospects

- Increased statistics
    - Factor of 10 more data available,
- New ongoing analyses focusing on protons
    - Proton multiplicities (e.g. 2 proton measurements)
    - Lower proton momentum threshold
    - Double differential measurements
    - Transverse variable measurements
    - NC elastic cross section
- Cross section measurements using data from NuMI beam
    - High energy, different flux from BNB
- More accurate detector modeling
    - New detector simulation - much lower uncertainties

Drastically Reduced Systematics with New Simulation



Source	Current	Future
Detector response	16.2%	3.3%
Cross section	3.9%	2.7%
Flux	12.4%	10.5%
Dirt background	10.9%	3.3%
Cosmic ray background	4.2%	N/A
POT counting	2.0%	2.0%
CRT	N/A	1.7%
Total Sys. Error	23.8%	12.1%
Statistics	1.4%	3.8%
Total (Quadratic Sum)	**23.8%**	**12.7%**

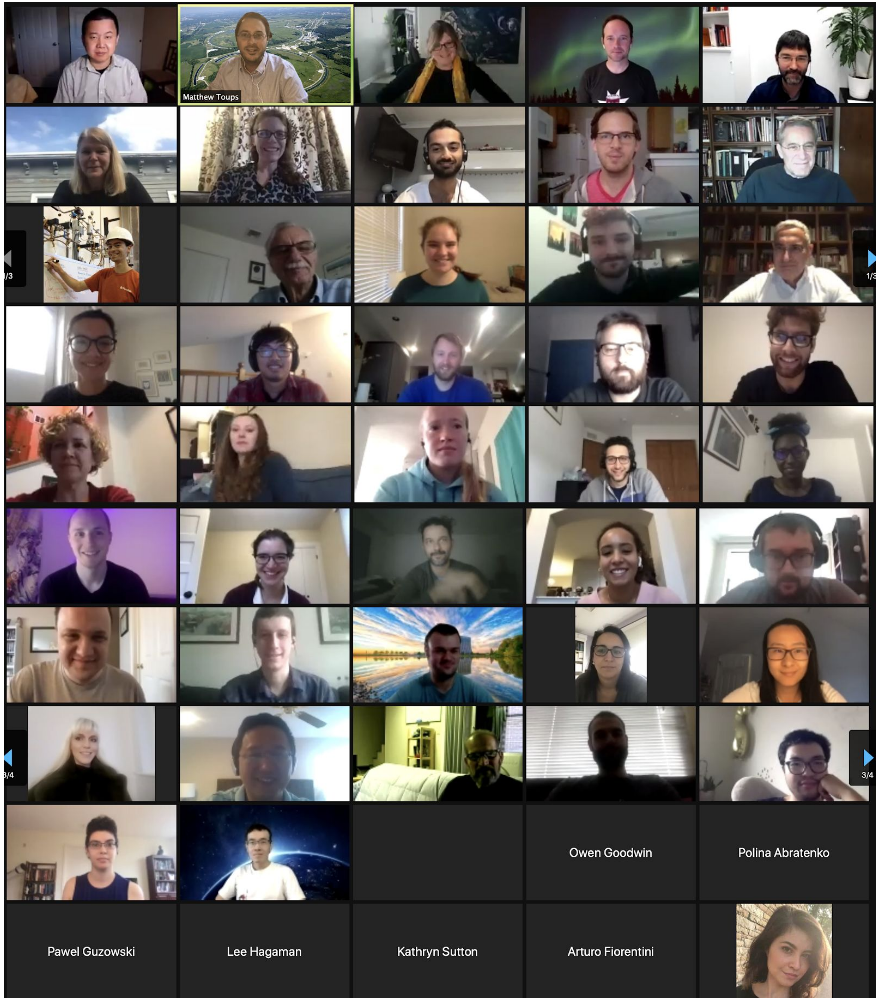
PRL 123, 131801 (2019)

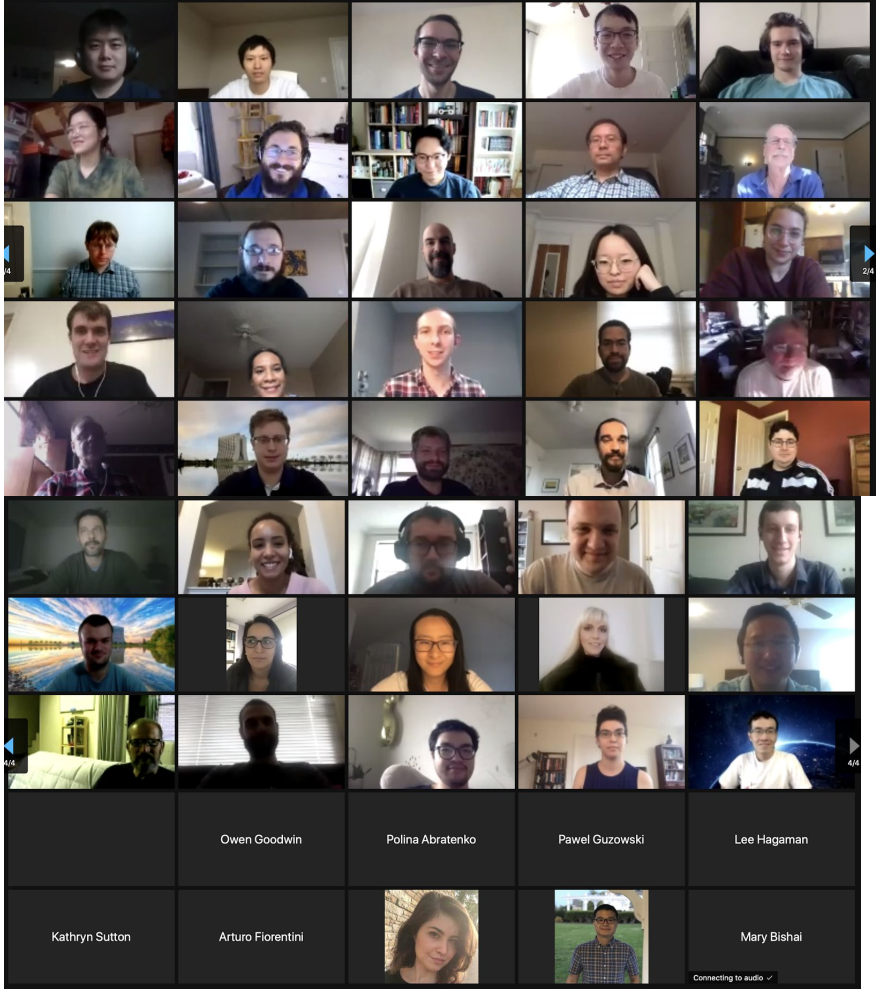
- New simulation drastically reduced uncertainties on CC inclusive analysis.
  - Similar behavior expected in CC0π with new simulation
- Figure shows the flux integrated cross section measurement from MicroBooNE Public Note*

* *MICROBOONE-NOTE-1075-PUB, MICROBOONE-NOTE-1069-PUB*

Summary and Conclusion

- New ν_μ charged current (CC) cross sections for Argon at E_ν~800 MeV
  - Paper preprint: http://arxiv.org/abs/2010.02390, submitted to PRD
  - One of a growing set from MicroBooNE **filling huge gap in argon cross section results**
  - This measurement completely **based on fully automatic event reconstruction**
  - **Loose signal definition** and **inclusive spectra** increases usefulness in testing models
  - **Emphasis on role of protons** - momentum and polar angle spectra for leading proton
- Compare data with results from many neutrino interaction generators (nuclear models)
  - New generation of models work significantly better than older models (GENIE v2)
  - **Models** were developed for carbon data, **mostly work well for argon**
  - **Overprediction at most forward muon angle** is biggest problem - evidence for strong dependence on nuclear effects (also low Q^2).
  - **Low Proton momentum threshold**
    - Increasing sensitivity to FSI
    - Additional studies on low momentum protons





Thank you very much for listening, I am happy to answer questions!

References

[1] Phys. Rev. D.24 (1981), p. 1400

[2] Phys. Rev. C.83 (2011), p. 045501

[3] Phys. Rev. D.88 (2018), p. 113007

[4] Phys. Rept. 3 (1972), p. 261

[5] AIP Conf. Proc. 1663 (2015), p. 030001

[6] Ann. Phys. 133 (1981), p. 79

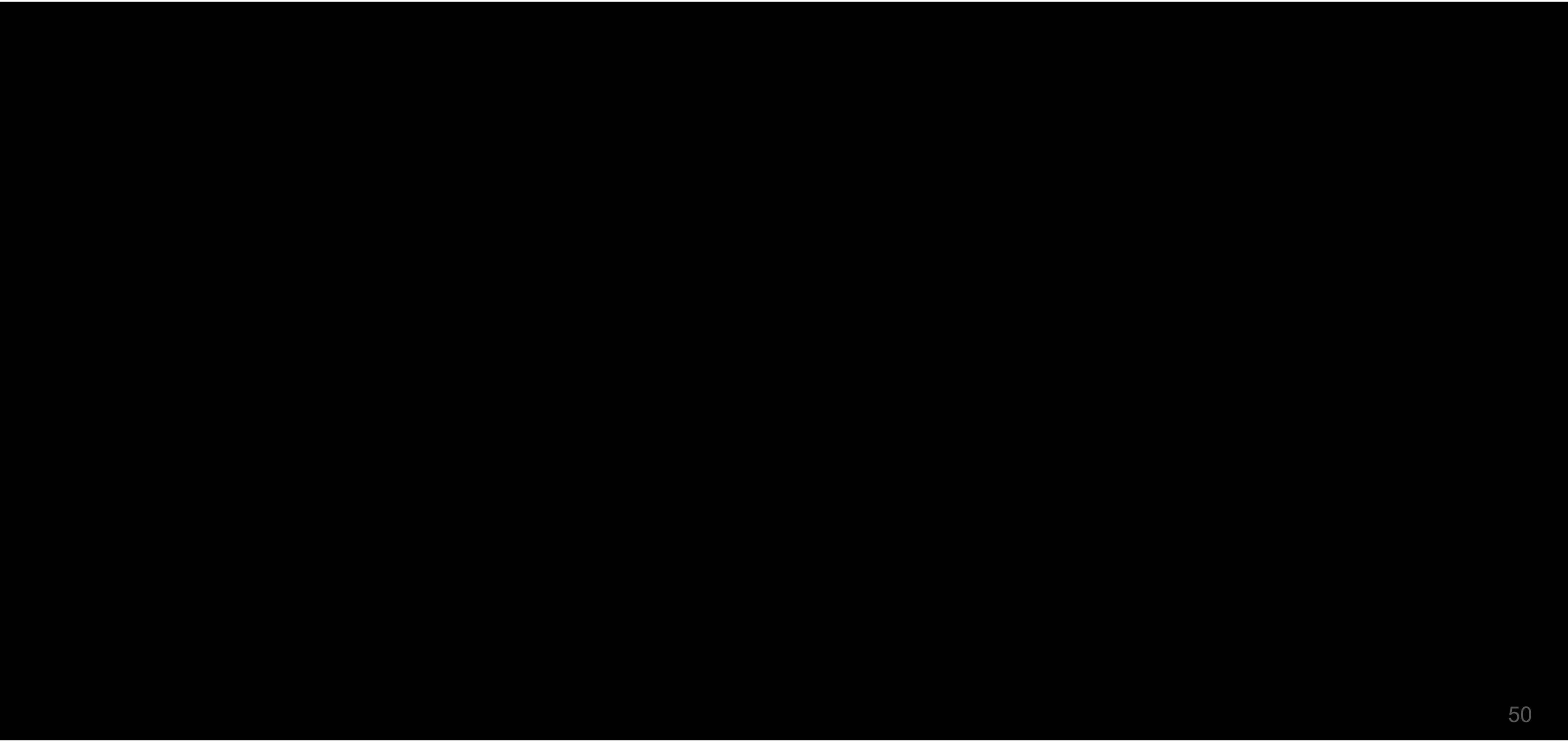
[7] Phys. Rev. D.79 (2009), p. 053003

[8] arXiv:1510.05494 [9] Phys. Rev. D 80, 093001 (2009)

[10] Nuclear Physics A 484, 557 (1988)

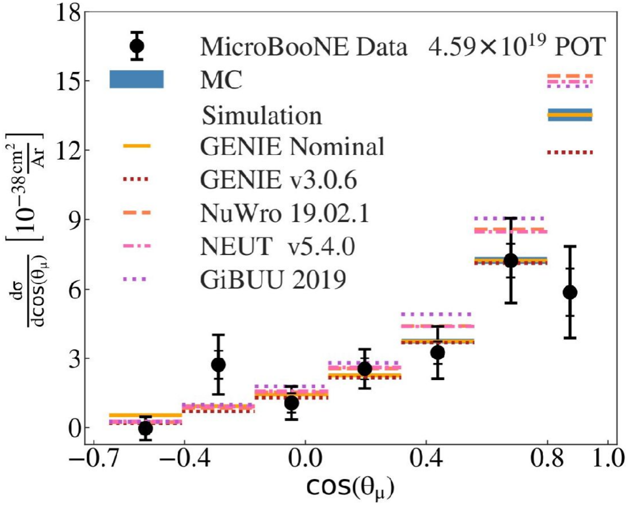
[11] Physics Reports 512, 1 (2012)

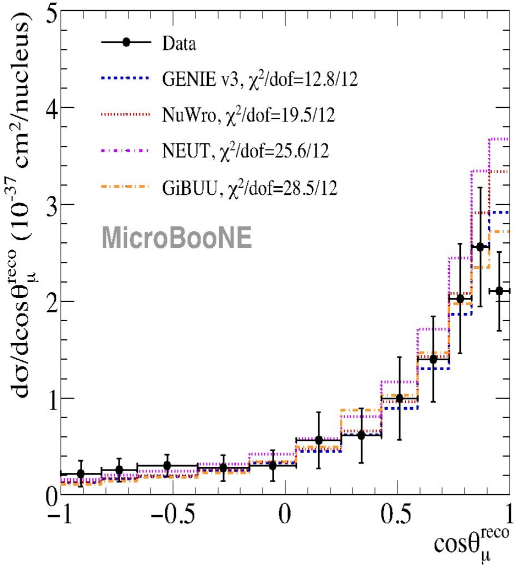
The Liquid Argon Time Projection Chamber



Cross section - $\cos(\theta_\mu)$

- Final result in variable interesting due to cosθ~1 issue
- CCQE-like has 29% of POT, more restrictive signal
  - Therefore, 410 events vs. 4736 events (Signal+Background for CC0πNp)
  - Overall cross section ~3x larger in CC0πNp
- However, shapes are similar, and both have suppression in most forward bin
- For both, calculations in this bin too large, but CCQE-like discrepancy larger





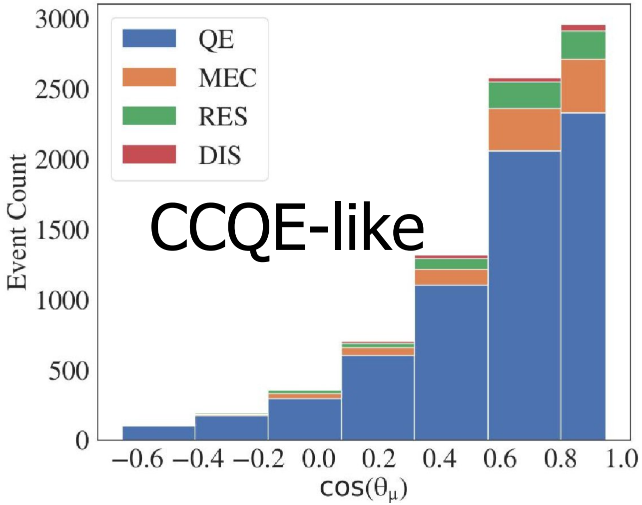
Signal definitions, cuts

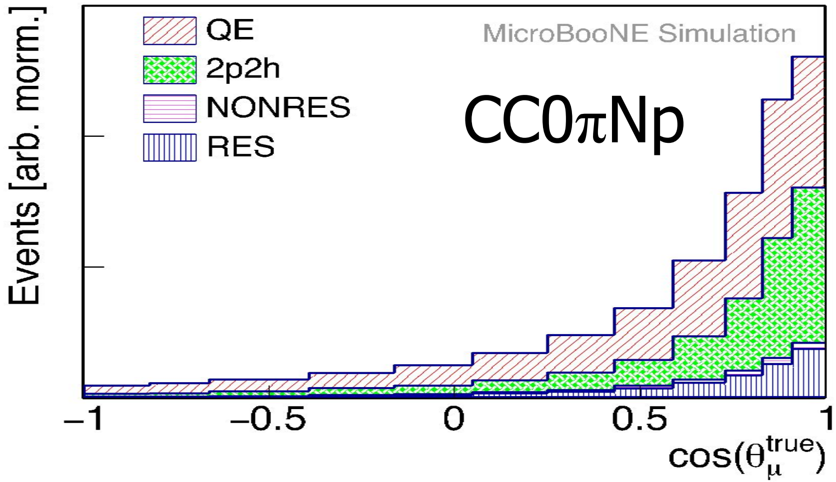
- Same:
  - muon, proton momentum threshold, tracking
  - Proton identification
- Similar:
  - proton high mom cutoff (1.0 vs. 1.2 GeV/c)
  - cosmic removal (overlay vs. Corsika)
- Different:
  - 1p vs. Np in signal
  - DIC treatment (correction vs. systematic error)
  - collinearity, coplanarity cuts
  - Transverse imbalance cut
  - folding/unfolding choice
  - proton containment

Compare event distributions by channel
Monte Carlo was GENIE v2.12.2

Interaction/fraction	CCQE-like	CC0πNp
QE	0.81	0.54
MEC	0.11	0.33
RES	0.07	0.11
DIS	0.01	0.02

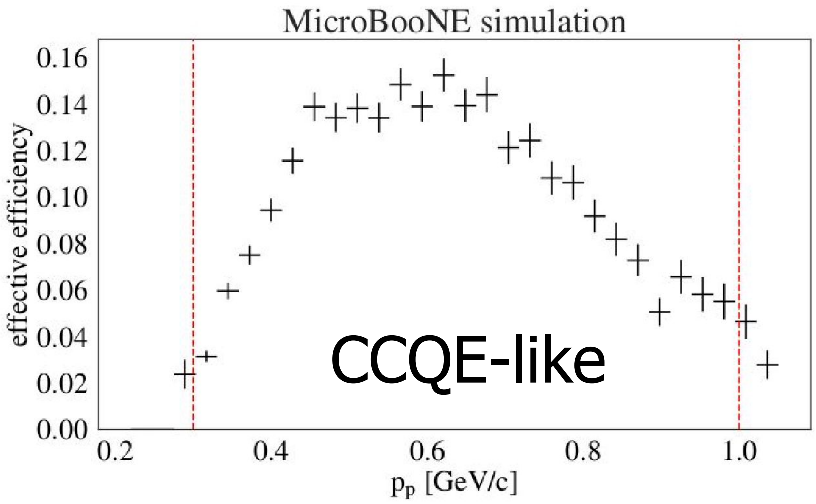
CCQE-like has significantly more CCQE, but getting 100% is very hard

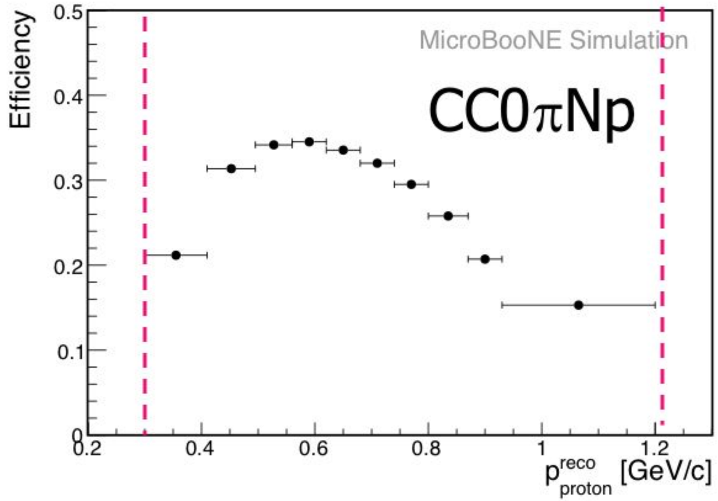




Compare efficiency - proton momentum

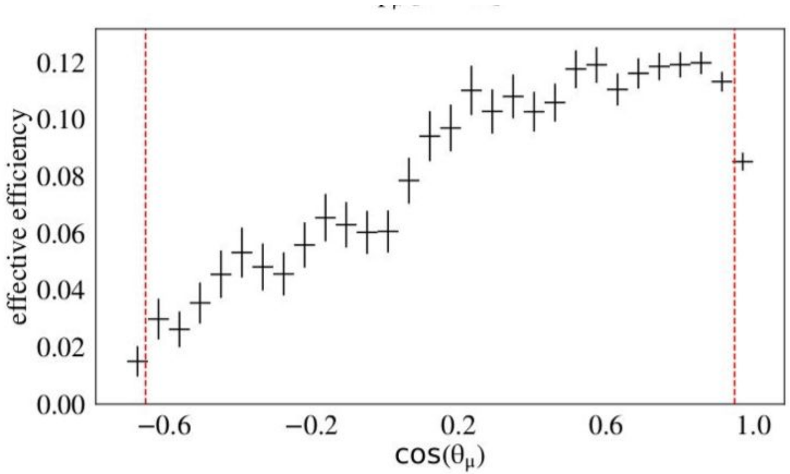
- CCQELike efficiency in true, CC0πNp eff in reco variables
  - We find smearing to be small effect, so likely doesn't matter
- Peak efficiency ~35% (CC0πNp) vs. 14%
- Efficiency more uniform in CC0πNp esp. at low momentum
- Both expected from more restrictive signal in CC0π1p

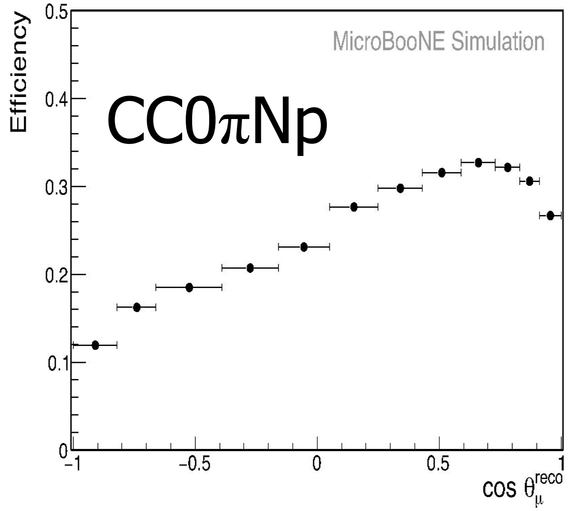




Compare efficiency – muon angle

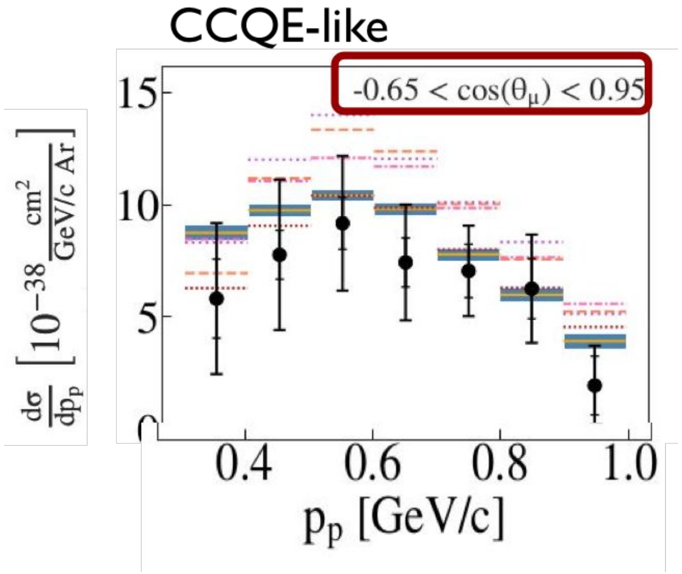
- Both have decreased efficiency at forward and backward angles
  - CCQE-like has cuts in angle, CC0πNp has none
- CC0πNp has larger efficiency

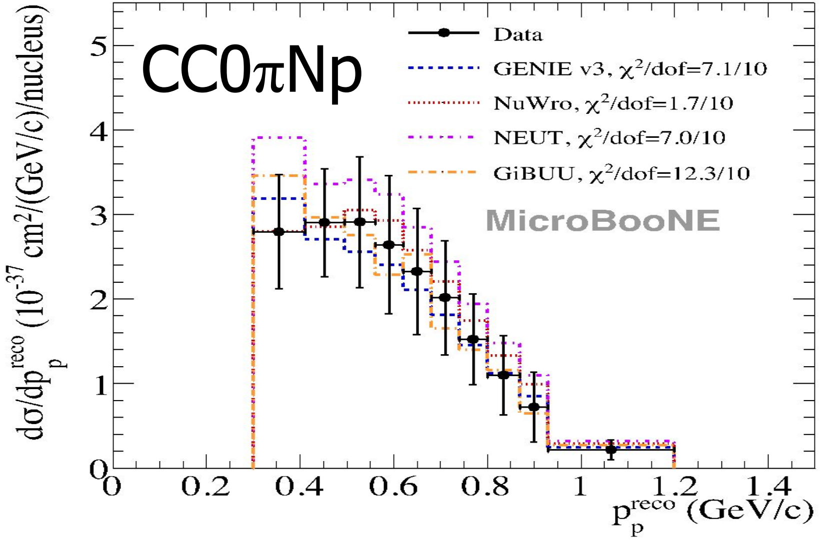




Cross section – proton momentum (p_p)

- Similar shapes, but more turnover at low p_p for CCQE-like
- Consistent with CC0πNp interaction breakdown





χ^2 comparison for GENIE nominal (v2)

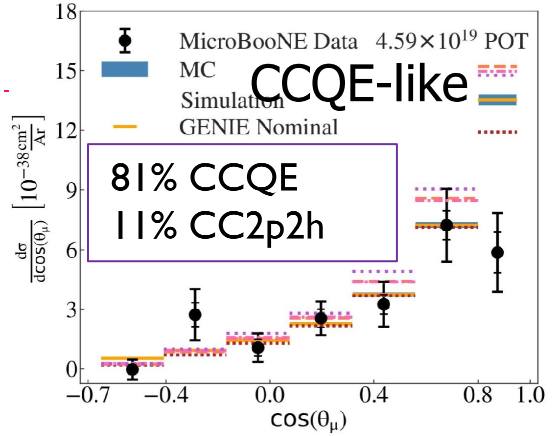
Variable/measurement	CCQE-like	CC0πNp
p_μ	14.2/7	40.8/6
$\cos(\theta_\mu)$	33.8/7	36.9/12
p_p	2.8/7	5.1/10
$\cos(\theta_p)$	12.4/7	9.0/9

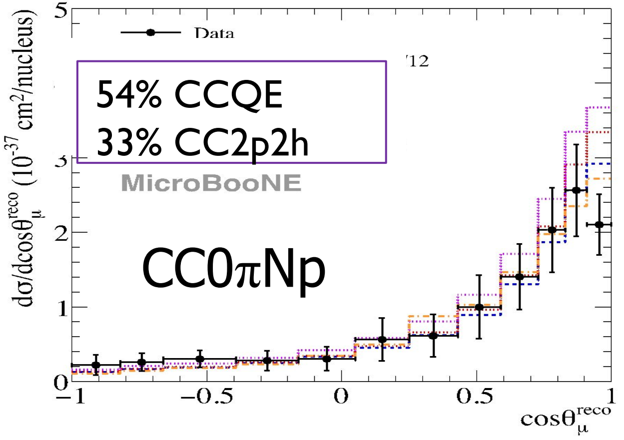
- CCQE-like has fewer bins except muon momentum
- Both analyses have worst χ^2 for $\cos(\theta_\mu)$ (ignoring p_μ which is dominated by highest momentum bin)
- Proton momentum has low χ^2 for both, reminding us that shape is tested here more than magnitude.

MicroBooNE CCQE-like and CC0πNp

Complementary analyses, similar physics

- Both emphasize importance of protons, similar events but different signal, cuts
- Both include QE, 2p2h, pion production.
- CC0πNp has more inclusive signal
  - more events, larger systematic uncertainty
  - More phase space, less model dependence
  - Overall cross section ~3x larger
- Physics interpretation very similar
  - Shapes are similar, and both have suppression in most forward bin; calculations too large
  - CCQE-like discrepancy larger, hints problems is in CCQE (e.g. RPA)
- Everyone benefits from this complementarity





MicroBooNE

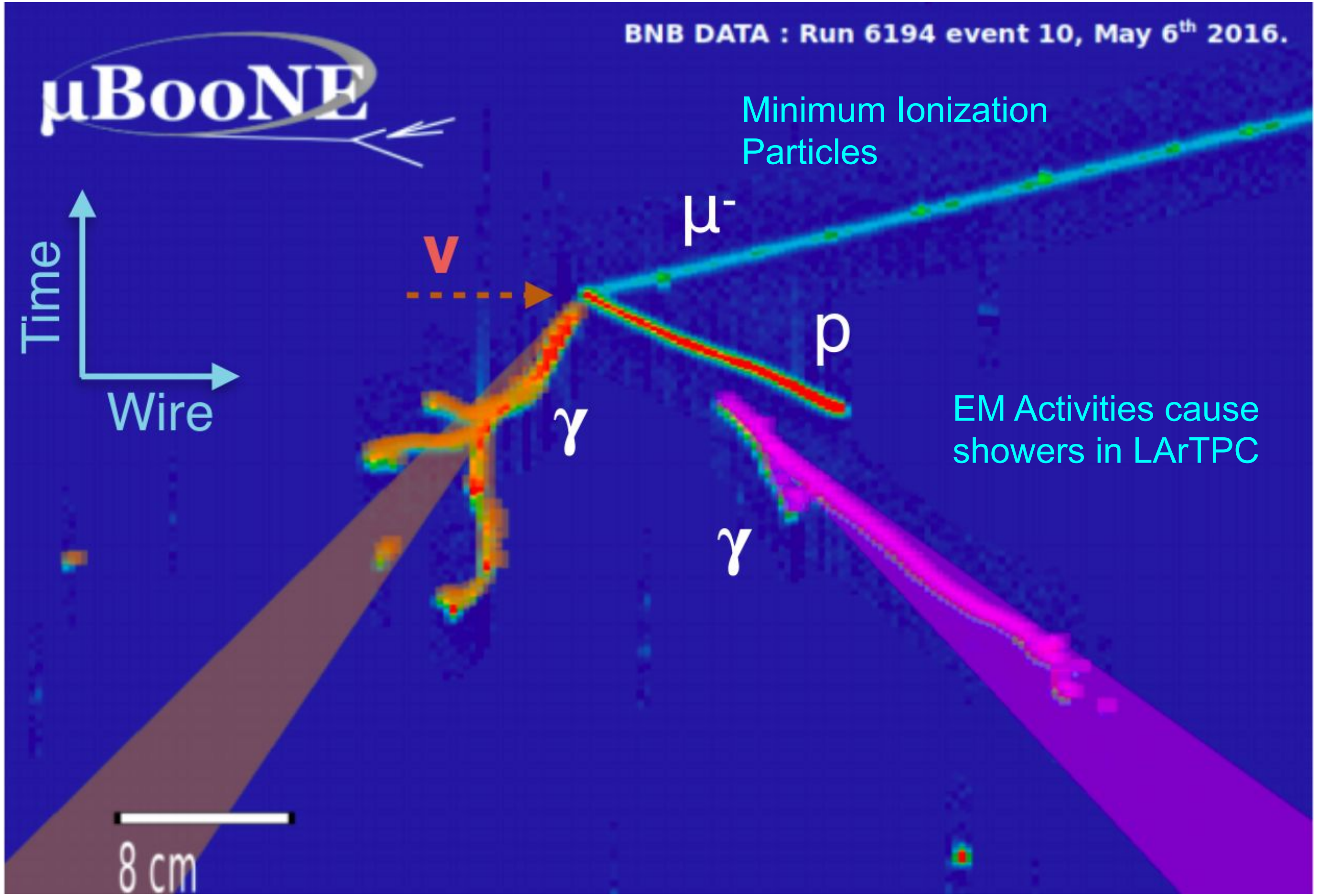
Near Surface Location -> Big Cosmic Backgrounds
Challenges for MicroBooNE analysis

- 90% of the triggered events have only cosmic activity
- Remaining 10% events have both cosmics and neutrinos in same event (20 cosmics and 1 neutrino)
- Half of the neutrino interactions occur outside the TPC

Systematic Uncertainty - Methodology

Methodology	
Event Based Re-weighting Method	Generation of re-simulated samples
● Re-weight factors were evaluated in either a “multisim” or or a “unisim” approach. ● Applied to: Neutrino Interaction Model, beam flux predictions, secondary hadronic interaction modeling	● Applied to: Detector Modeling Uncertainty

The Liquid Argon Time Projection Chamber



Neutrino Oscillation Probability

Mixing of flavor states

$$|\nu_\alpha\rangle = \sum_{k=1}^{N+S} U^*_{\alpha k} |\nu_k\rangle$$

Time evolution of mass state

$$|\nu_k(t)\rangle = \exp(-iE_k t)\,|\nu_k\rangle$$

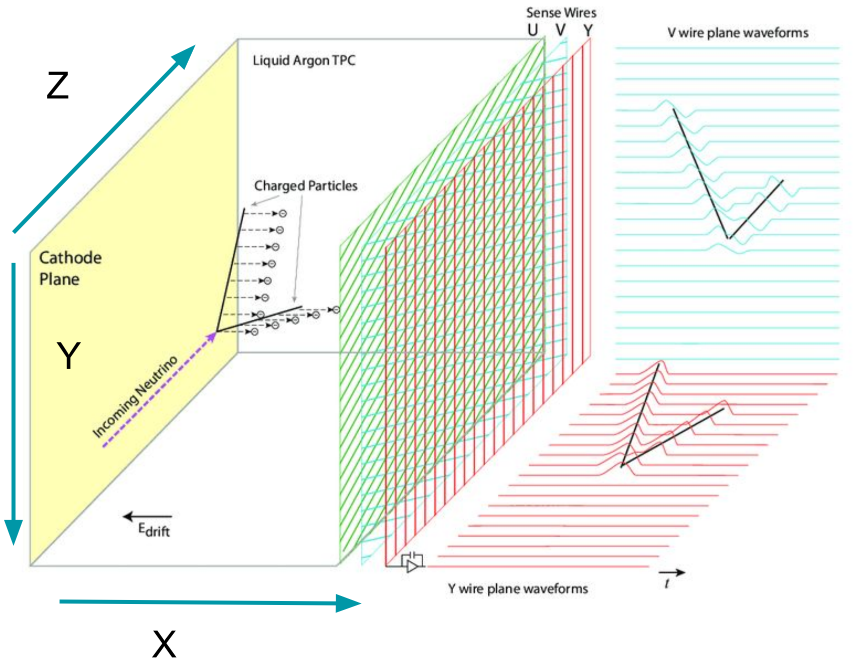
Transition amplitude

$$A_{\nu_\alpha \to \nu_\beta} \equiv A_{\alpha\beta} = \langle \nu_\beta | \nu_\alpha(t) \rangle = \sum_{k=1}^{N+S} U^*_{\alpha k} U_{\beta k}\ \exp(-iE_k t)$$

Transition probability

$$P_{\alpha\beta} = A^*_{\alpha\beta} A_{\alpha\beta} = \sum_{k,j=1}^{N+S} \underbrace{U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}}_{\equiv J^{\alpha\beta}_{kj}}\ \exp\left(-i(E_k - E_j)t\right)$$

The Liquid Argon Time Projection Chamber



Advantages:

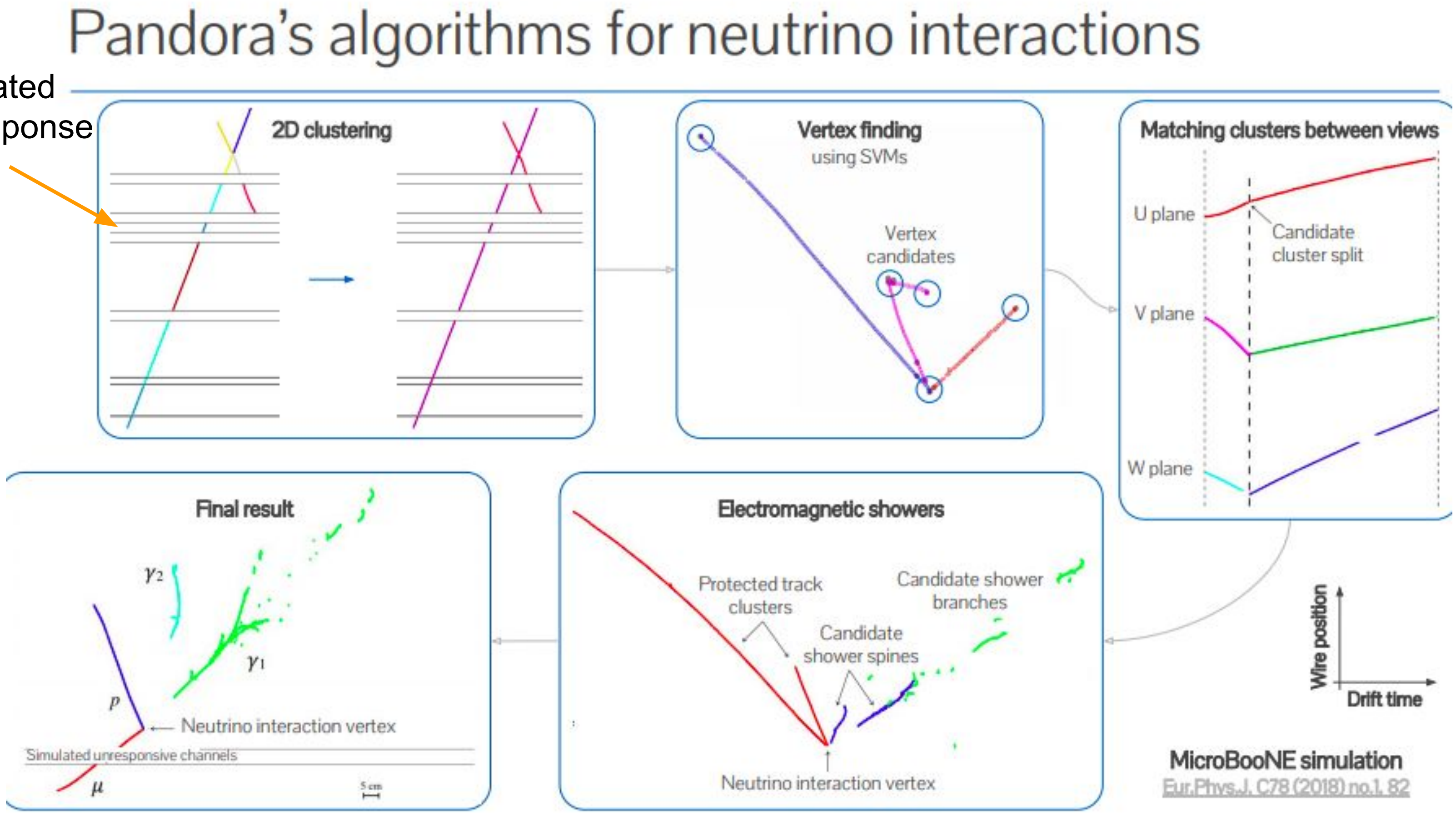
- High Z target + Large active volume -> a large amount of neutrino interactions compared lighter target
- High spatial resolution: 3mm wire pitch + ~mm vertex accuracy
- High calorimetric resolution: trace the charged particle ionization
- Strong particle identification
  - Tracks: muon, proton, charged pions kaons, etc
  - Showers: electron, gamma, pi0
  - Cold electronics -> Low noise

Challenges:

- New surface detector -> Cosmic background rejection
- High Z target means higher nuclear effects
- Non-uniform detector response: unresponsive channels, shorted wires

Pandora Algorithms for Reconstruction

Simulated un-response wires



Neutrino Interactions - Cross Sections

$$N_{\mathrm{FD}}^{\alpha\to\beta}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma_\beta^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}};\boldsymbol{p}_{\mathrm{reco}})$$

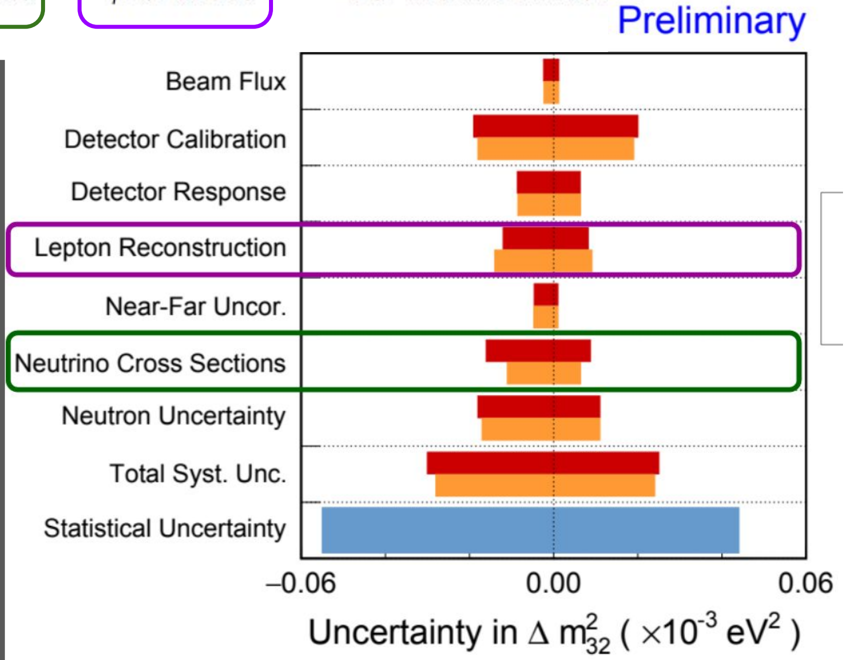
Neutrino Flux

- A sophisticated strategy for neutrino flux constraint has been developed in many neutrino experiments
  - MicroBooNE uses the same beam flux estimation from MiniBooNE from hadronic production
  - Models used in MiniBooNE are validated and refined using HARP data, HARP took data with the actual MiniBooNE extended replica target

Cross Sections

- Can be measured through neutrino interactions
- Consistently one of the major systematic uncertainty sources

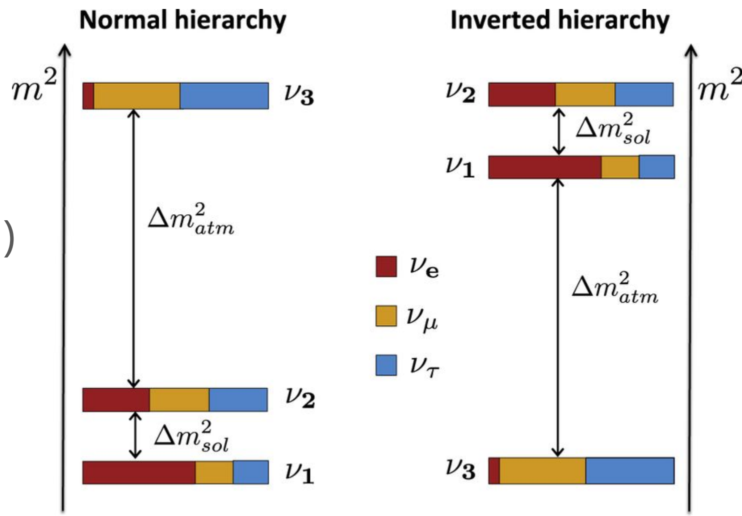
Efficiency: determined with MC model of detectors/physics



Credit: NOvA Collaboration

Open Questions about Neutrinos

- What is the neutrino absolute mass and mass ordering?
  - Is Δm^2 positive or negative? Mass hierarchy (MH) -> sign of Δm^2_{32}, Δm^2_{31}
  - Normal (NH): $m_3 > m_2 > m_1$
  - Inverted (IH): $m_2 > m_1 > m_3$
- Is there CP Violation in the lepton sector?
  - Is $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$?
  - Could explain matter/anti-matter asymmetry



Normal Hierarchy vs Inverted Hierarchy

Most Recent NOvA Result:

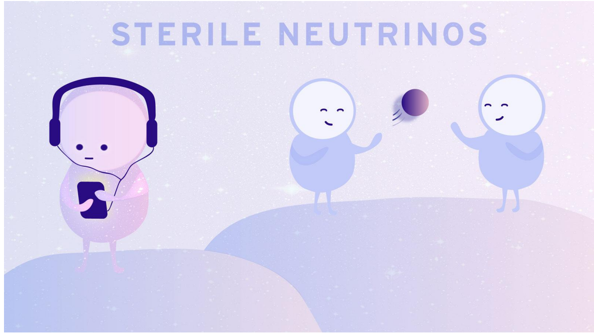
Best fit:

- $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$
- $\Delta m^2_{32} = (+2.41 \pm 0.07) \times 10^{-3}\,\mathrm{eV}^2/c^4$
- $\delta_{CP} = 0.82\,\pi$

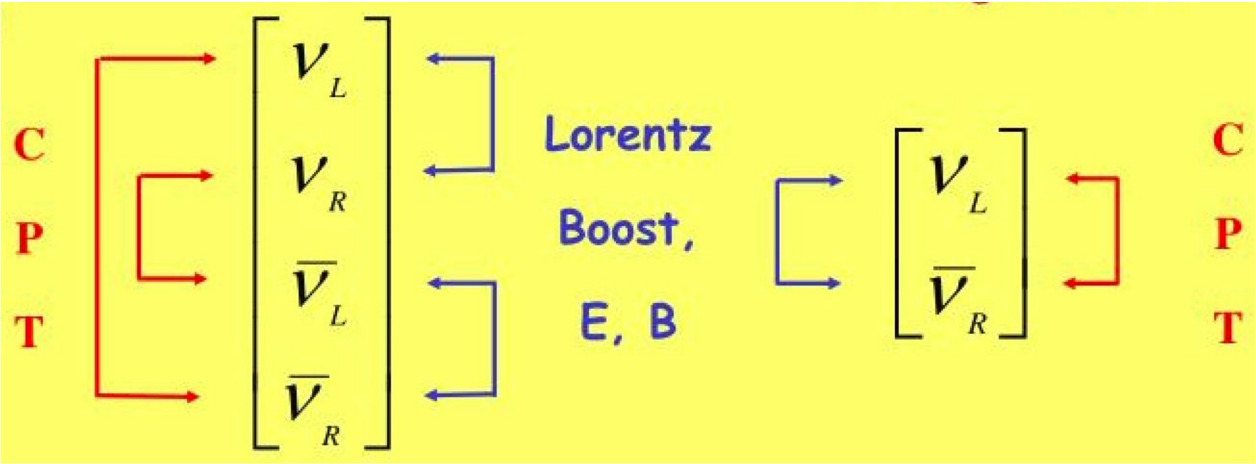
(NH)

Open Questions about Neutrinos

- Are the sterile neutrinos exist?
    - Dark matter: Sterile neutrino is a candidate
- What is the nature of neutrino mass generation mechanism?
    - Dirac or Majorana?
    - Why are the masses so small?



Dirac

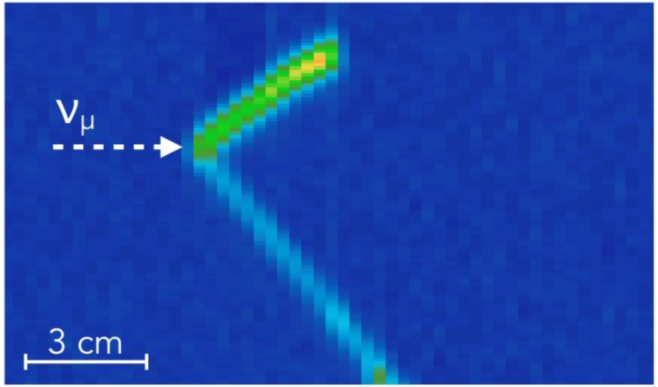


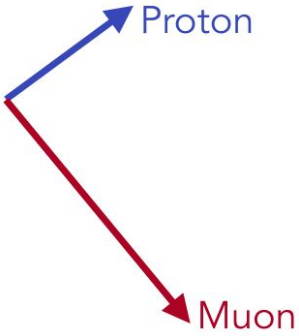
Majorana

Muon Identification

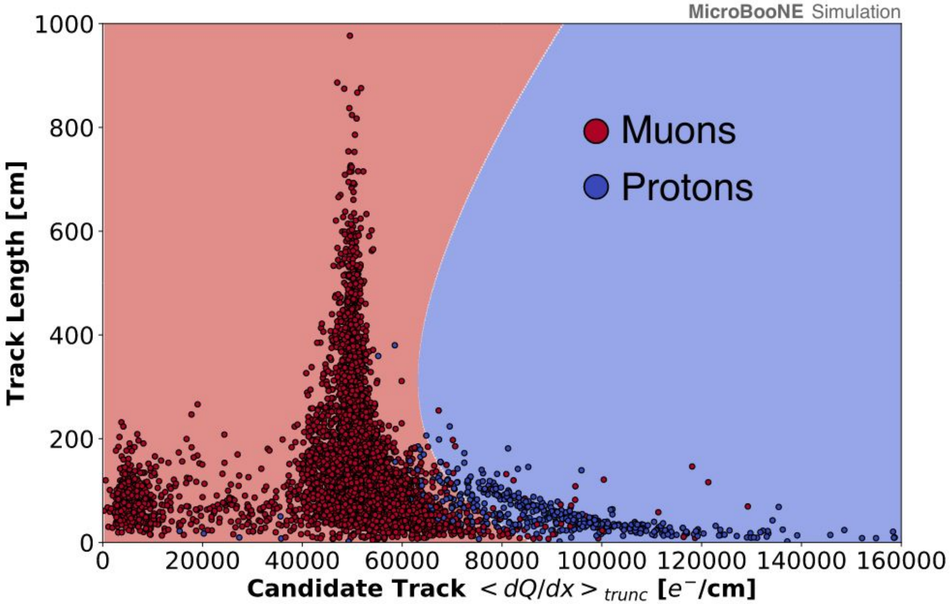
- Inherit from CC-inclusive cross section measurement
  - Developed optical strategy, first cosmic reductions

This can be used to ensure the selected track is a Minimum Ionising Particle (MIP) as the muon should be.

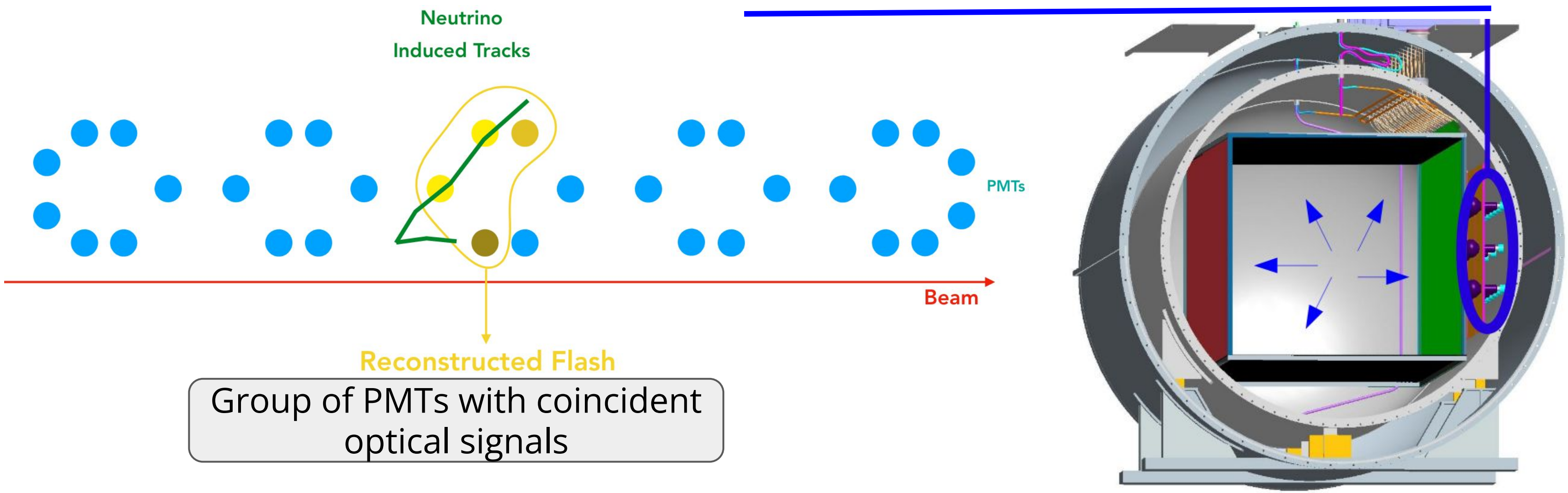




Reference: Phys. Rev. Lett. 123, 131801 (2019)

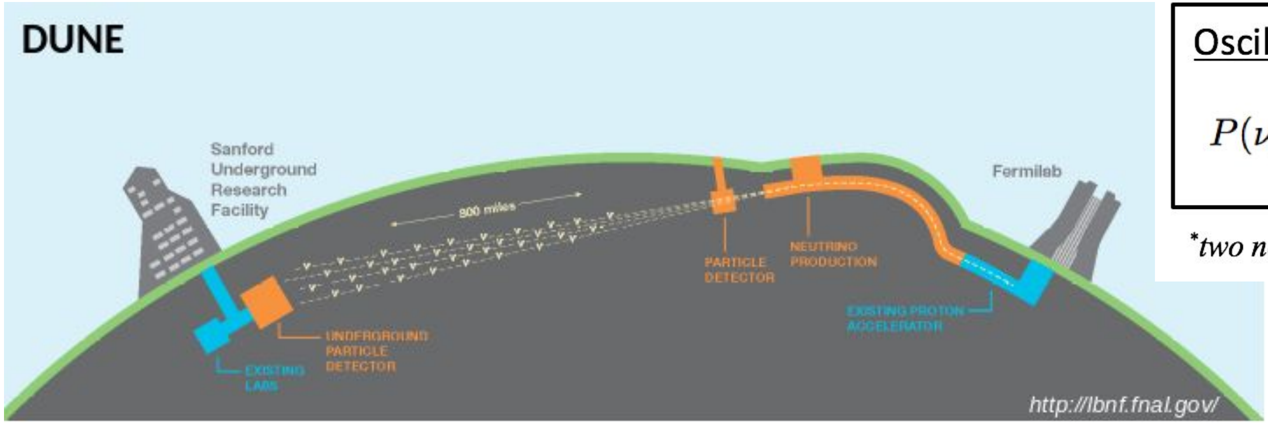


Optical Reconstruction



- Optical hits of the 32 PMTs with the same arrival time within the event are clustered into flashes.

Neutrino Oscillation Experiments



Oscillation Probability*:

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

**two neutrino flavors, for simplicity*

Experiments measure event rates which, for a given observable topology, can be naively computed as:

Event Rate at near detector:

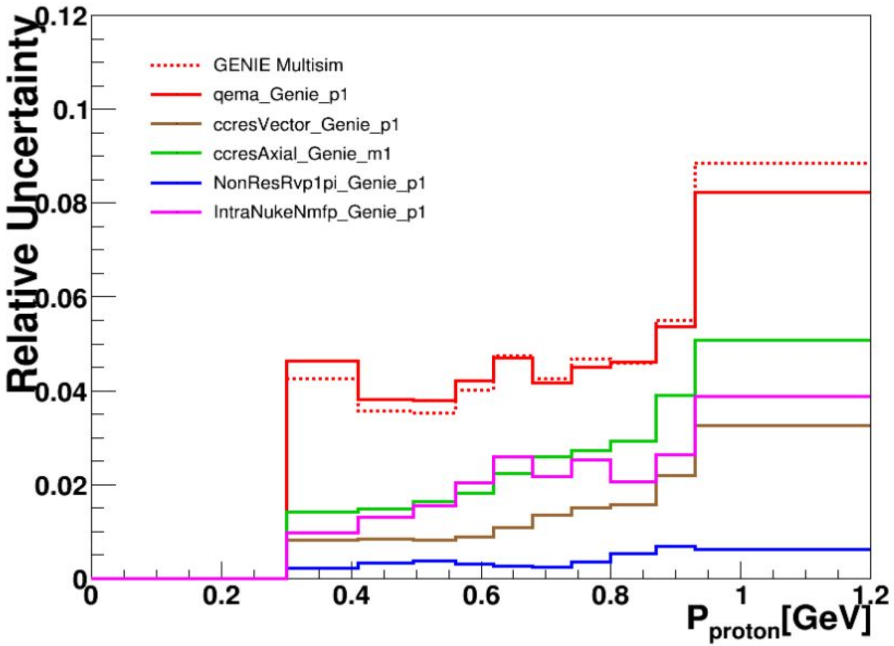
$$N^{\alpha}_{\mathrm{ND}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times \sigma^i_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})$$

Event Rate at far detector:

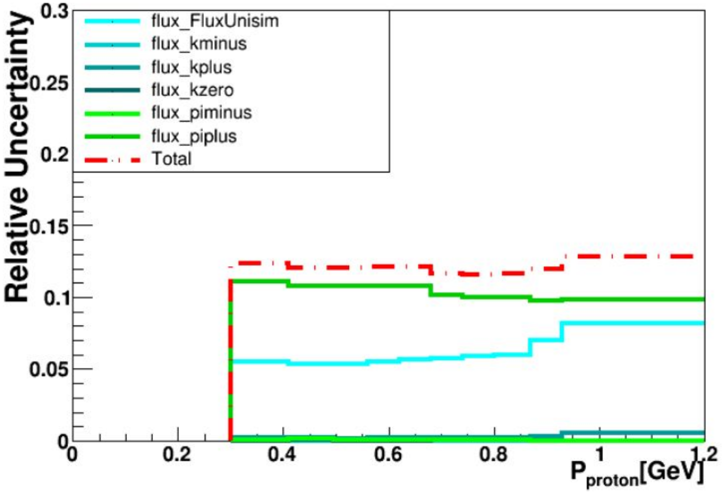
$$N^{\alpha\to\beta}_{\mathrm{FD}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma^i_\beta(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})$$

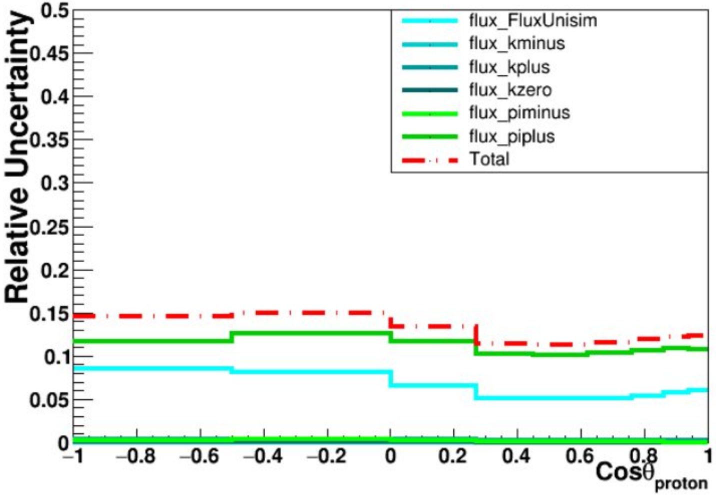
Interaction Model Uncertainty

- Arise from the parameterization of the models in our neutrino event generator GENIE (43 variations in total).
- Estimated by event-based reweighting method with GENIE reweighting framework.
- Figure shows the 5 most largest uncertainties from GENIE interaction model.
  - CCQE MA
  - CCRES vector and axial mass
  - Hadronic Model
- The largest uncertainty comes from CCQE M_A
  - Consistent with idea that the main background comes from neutrino interactions in the cryostat but outside the fiducial volume
  - Affect both signal rate and non-fiducial background



Beam Flux Uncertainty



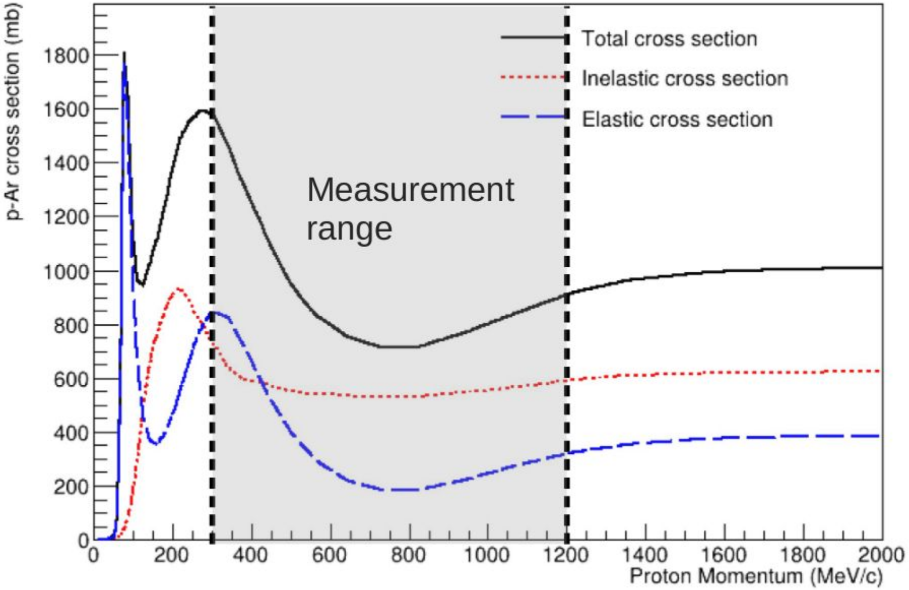


Hadronic: The hadron production rate uncertainties cover the rate of particles produced from protons striking the horn target with variations in π^+, π^-, K^+, K^-, K^0

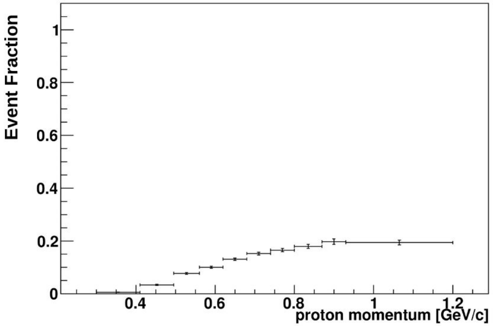
Non-hadronic: The uncertainty from focusing horn current measurements

Secondary Hadronic Interaction

- Uncertainty arises from hadrons (pions and protons) secondary interaction in the detector through hadronic interactions with nuclei.
  - elastically -> negligible
  - inelastically -> affect PID, energy resolution, etc
- These interactions can lead to the production of additional particles or large angle changes in particle trajectories that may lead to reconstruction algorithm failing to form a single, well-reconstructed track
- GEANT4 is used to propagate all hadrons through the detector medium based on a semi-classical cascade model



Fraction of elastic scattering of all the proton re-interactions



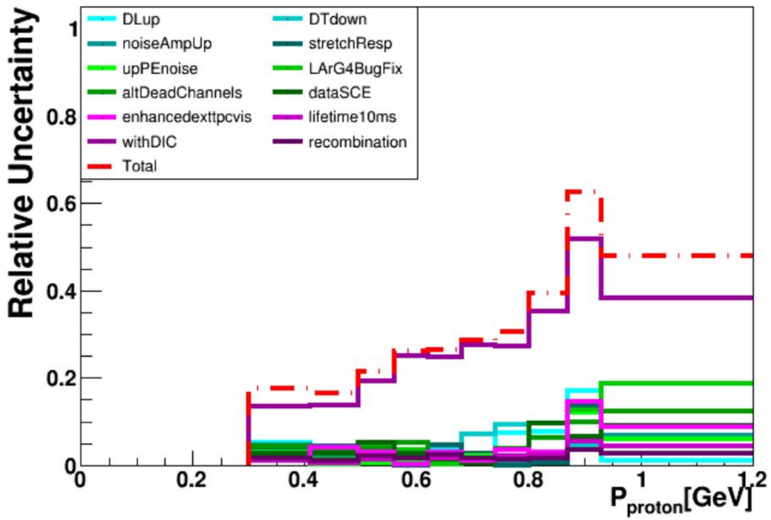
Detector Modeling Uncertainties

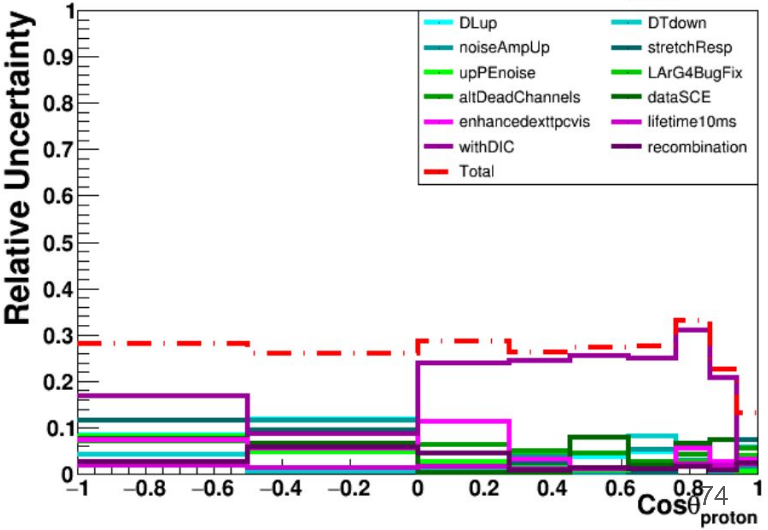
Detector Parameters Used to Evaluation Systematics
Drift electron diffusion both transverse and longitudinal Drift electron lifetime Drift electron recombination Space Charge Effect Dynamic Induced Charge (dominant) Electronics Response Photo-electron noise Recombination effects

To calculate systematics from detector response

- Generated MC samples for each one of these detector parameters and re-calculated the cross section σ^m
- The uncertainty has been evaluated as

$$E_{ij}^{\text{det}} = \sum_m \left(\sigma_i^{\text{CV}} - \sigma_i^m\right)\left(\sigma_j^{\text{CV}} - \sigma_j^m\right)$$





Methodology of Systematic Uncertainty

Multisim	Unisim

• Generating several MC replicas, each one called a “universe”
  ○ 1000 replicas generated in this analysis for different uncertainty
• Multiple parameters in the model are varied within their uncertainties
  ○ e.g. 43 parameters varied simultaneously when evaluate systematic from neutrino interaction model in GENIE
• Done through event reweighting, Requires only one MC run.
	• Changing one (detector) parameters at a time according to its uncertainty
	• Each parameter variation corresponds to a identical generated events but varied GEANT and detector simulation
	• The difference between the central value cross section and the cross section calculated with the new MC runs gives an indication of the systematic uncertainty on the cross section

Multisim Method

Central Value

$$\left\langle \frac{d\sigma^{cv}}{dx_\mu} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{target} \cdot \Phi_{\nu_\mu} \cdot (\Delta x_\mu)_i}$$

Reminder:

N_i: from data (doesn't change)

B_i: from MC (changes in every universe)

Universe *s*

$$\left\langle \frac{d\sigma^{s}}{dx_\mu} \right\rangle_i = \frac{N_i - B_i^s}{\tilde{\epsilon}_i^s \cdot N_{target} \cdot \Phi^s_{\nu_\mu} \cdot (\Delta x_\mu)_i}$$

$$\tilde{\epsilon}_i^s = \frac{\sum_{j=1}^{M} S_{ij}^s N_j^{s,\text{sel}}}{\sum_{j=1}^{M} S_{ij}^s N_j^{s,\text{gen}}}$$

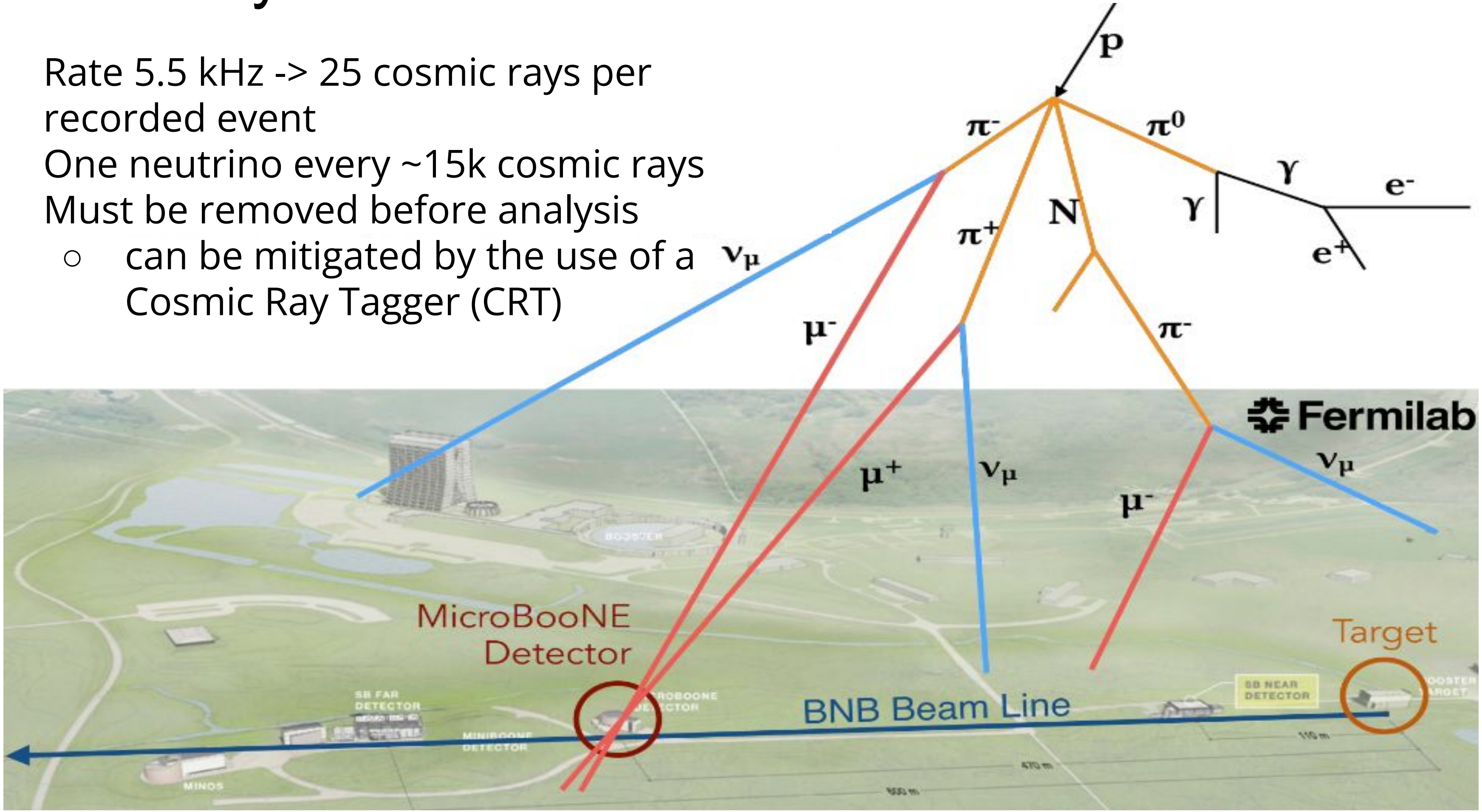
Background events, efficiency and smearing matrix change in every universe

The covariance matrix is calculated as:

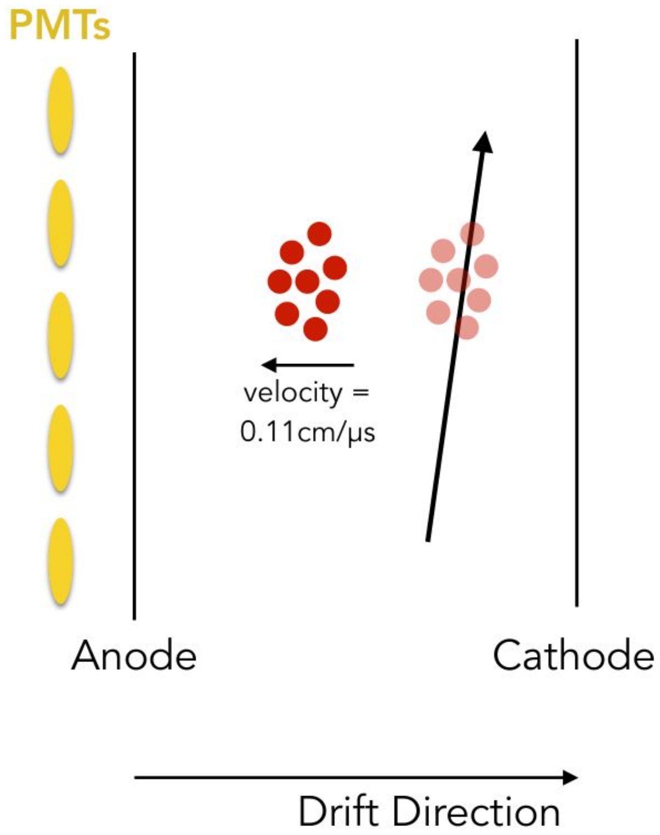
$$E_{ij} = \frac{1}{N_s} \sum_{s=0}^{N_s} \left(\left\langle \frac{d\sigma^{s}}{dx_\mu} \right\rangle_i - \left\langle \frac{d\sigma^{cv}}{dx_\mu} \right\rangle_i \right) \left(\left\langle \frac{d\sigma^{s}}{dx_\mu} \right\rangle_j - \left\langle \frac{d\sigma^{cv}}{dx_\mu} \right\rangle_j \right)$$

Cosmic Rays

- Rate 5.5 kHz -> 25 cosmic rays per recorded event
- One neutrino every ~15k cosmic rays
- Must be removed before analysis
  - can be mitigated by the use of a Cosmic Ray Tagger (CRT)



Drift Time and Interaction Time t_0



- Ionized electrons drift toward the anode at a velocity of 0.11**cm/μs**
- From cathode to anode it takes 2.3**ms**
- The scintillation is prompt (O(ns)) - provides accurate timing
- Accelerator signals provide interaction time

Cross Section Measurement

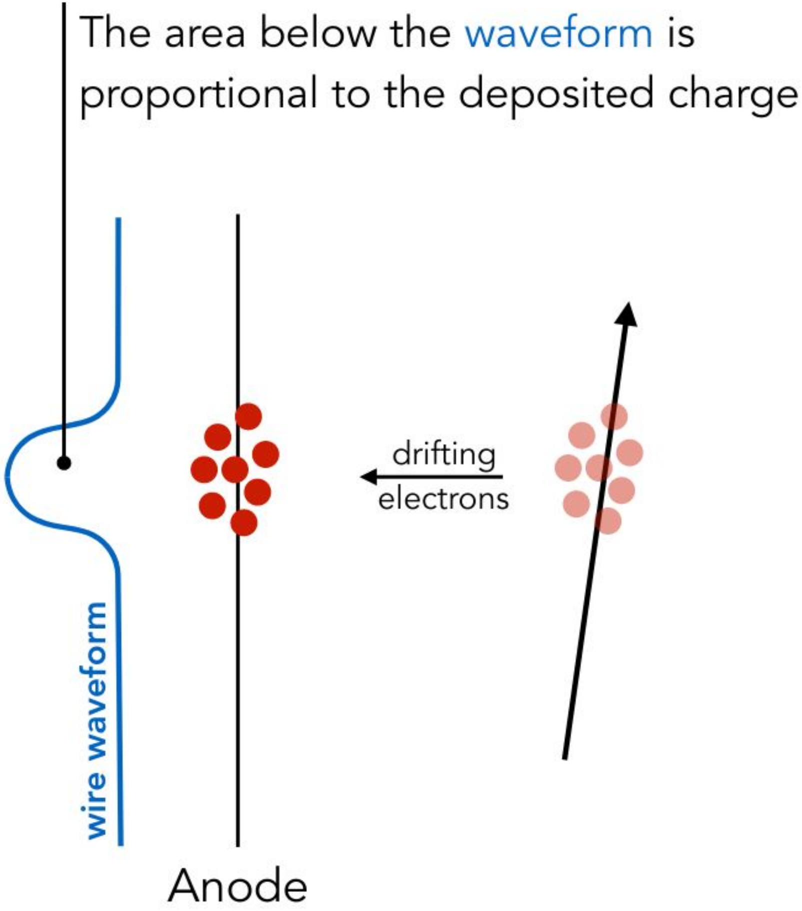
Single-differential cross sections:

$$\left\langle \frac{d\sigma}{dp_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{target} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu)_i} \qquad \left\langle \frac{d\sigma}{d\cos\theta_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{target} \cdot \Phi_{\nu_\mu} \cdot (\Delta \cos\theta_\mu)_i}$$

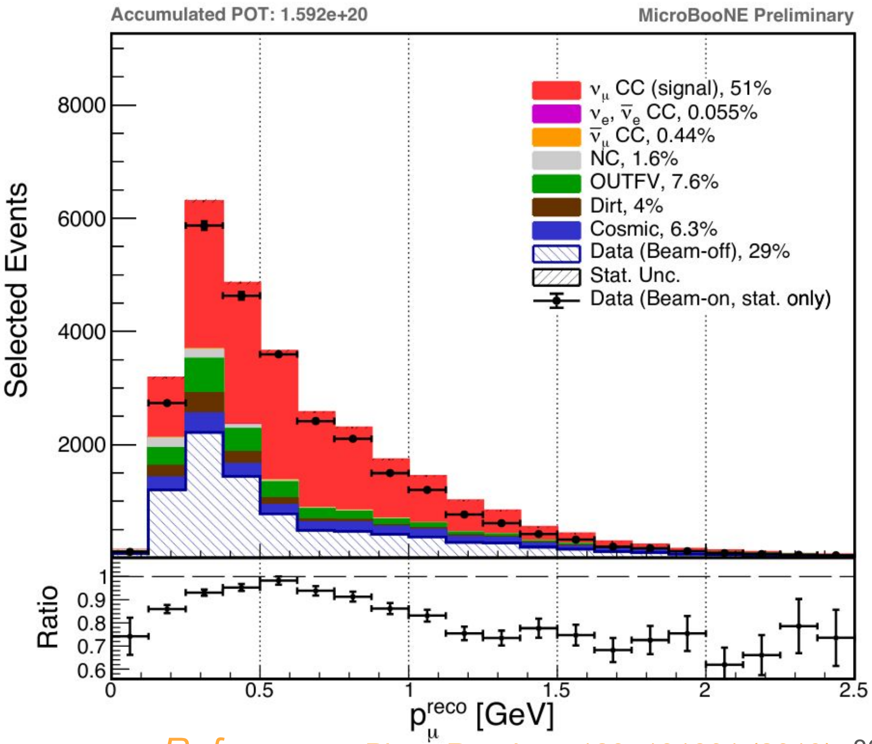
N_i	number of selected events in reconstructed bin i (data)
B_i	number of background events in reconstructed bin i (MC and cosmic data)
$\tilde{\varepsilon}_i$	overall efficiency (selection eff. x acceptance) in reconstructed bin i (MC)
N_{target}	number of target nucleons
Φ	muon neutrino flux (integrated over all energies)

- Measured differential cross sections as a function of muon momentum (**p_μ**), muon angle (**$\cos\theta_\mu$**), proton momentum (**p_p**), proton angle (**$\cos\theta_p$**) and open angle between muon candidate and leading proton candidate (**$\theta_{\mu p}$**)

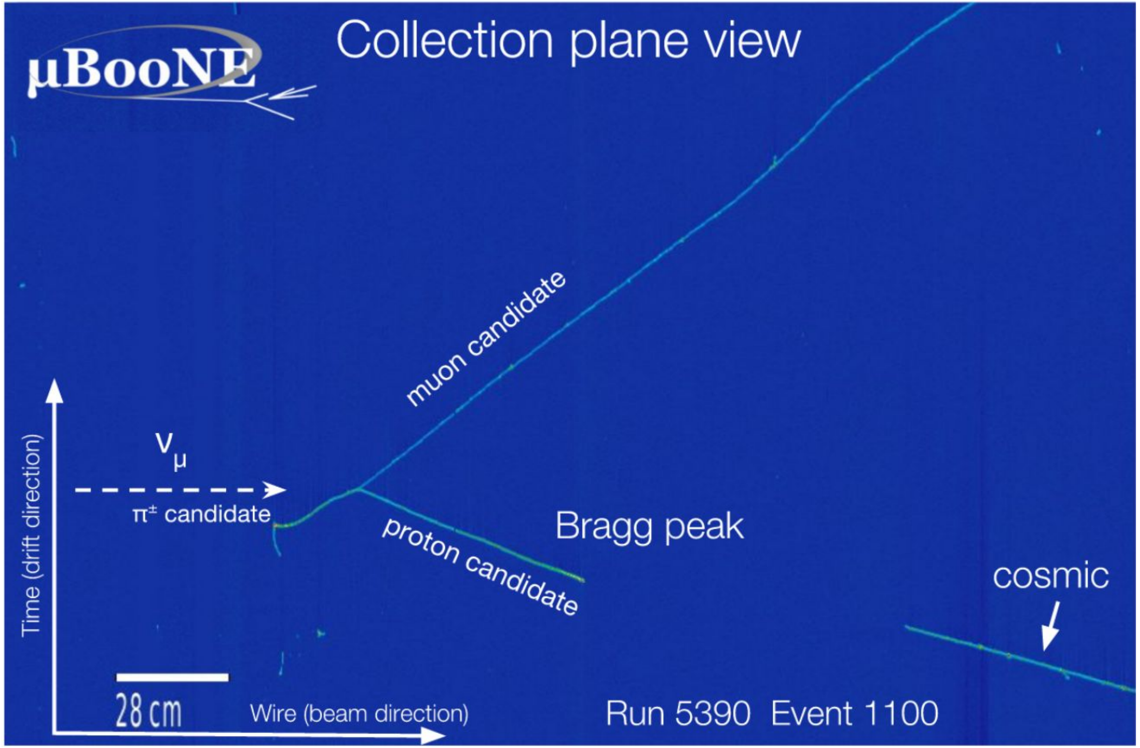
Muon Identification



- Muon selection based on **truncated dQdx vs residual range** is used for a Minimum Ionizing Particle MIP consistency check



Reference: Phys. Rev. Lett. 123, 131801 (2019)


μBooNE
Collection plane view
muon candidate
ν_μ
$\pi^\pm$ candidate
proton candidate
Bragg peak
cosmic
Time (drift direction)
28 cm
Wire (beam direction)
Run 5390 Event 1100

Neutrino Oscillations

$$N_{FD}(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \varepsilon \times P(\nu_\alpha \rightarrow \nu_\beta)$$

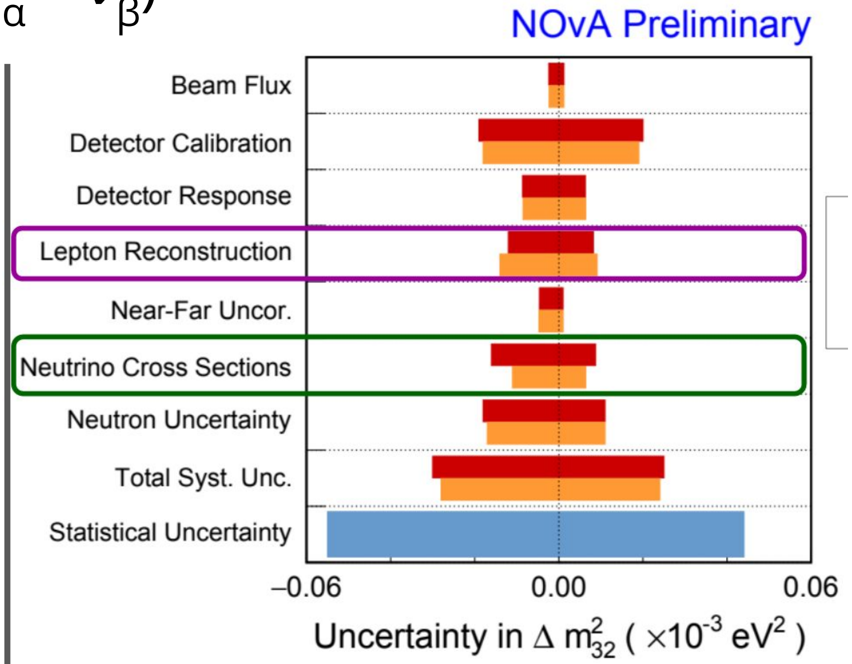
Neutrino Flux

- A sophisticated strategy for neutrino flux constraint has been developed in many neutrino experiments
  - T2K has near detector, and flux constrain from hadronic production experiment at CERN (NA61)
  - MicroBooNE benefits from MiniBooNE flux development and cross checks

Cross Sections

- Can be measured through neutrino interactions
- Consistently one of the major systematic uncertainty sources

Efficiency: determined with MC model of detectors/physics

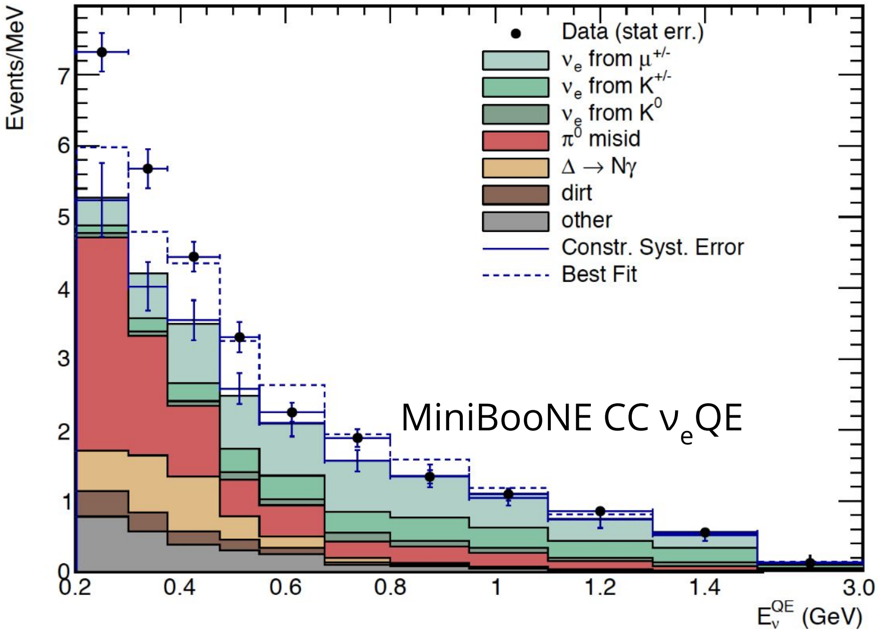


Credit: NOvA Collaboration, neutrino 2020

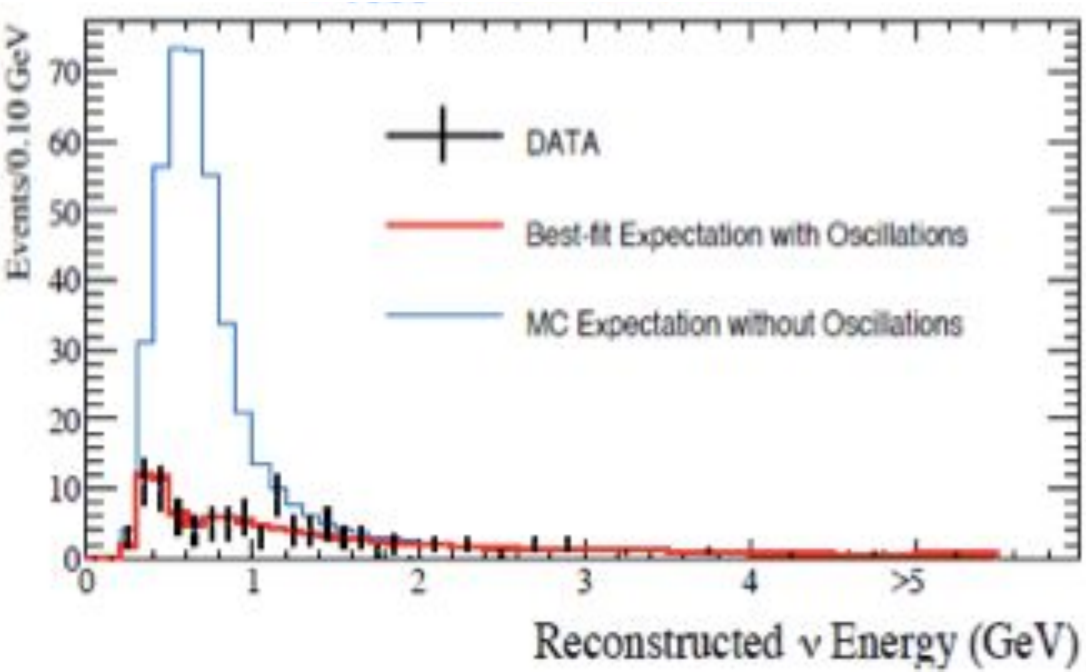
Neutrino Oscillations

Low energy excess (LEE) observed in MiniBooNE

- Figure on the right side shows the reconstructed electron neutrino energy distributions under QE assumption
  - Full MiniBooNE dataset
- LEE observed in both neutrino and antineutrino mode in MiniBooNE analysis
- CC ν_eQE event excess with 4.7 σ is observed in the energy range between 200 and 1,250 MeV (shown in figure on the right side)
- Excess due to electrons or gammas
  - Require a new detector capable of distinguish between electrons and gammas (e.g. LArTPC)
- Recent Icecube result (*Phys.Rev.Lett.* 125 (2020)) has tighter limits for sterile neutrinos

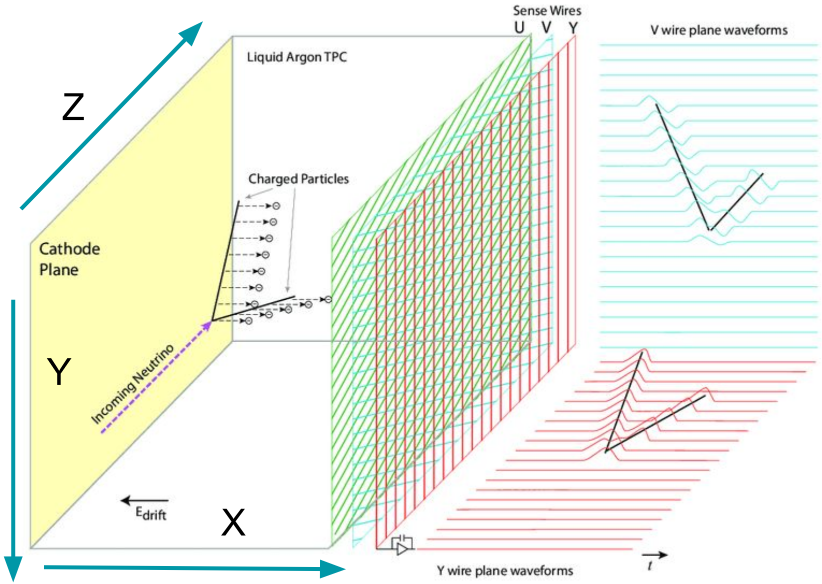


Reference : arXiv:1805.12028, Phys. Rev. Lett. 121, (2018) No. 22 221801

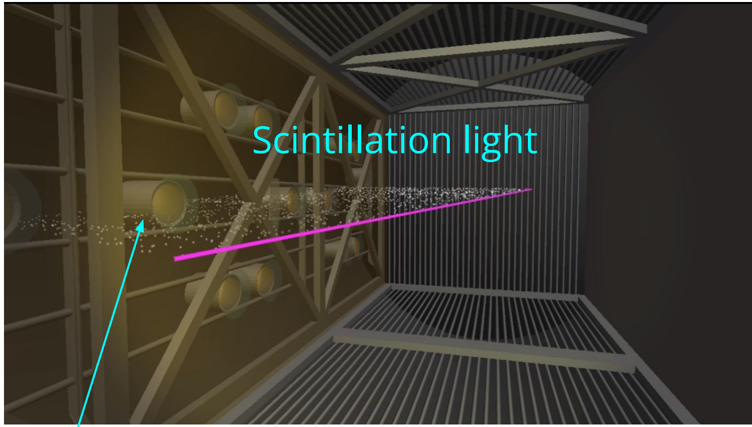


Events/0.10 GeV
70
60
50
40
30
20
10
0
0
1
2
3
4
>5
DATA
Best-fit Expectation with Oscillations
MC Expectation without Oscillations
Reconstructed ν Energy (GeV)

The Liquid Argon Time Projection Chamber



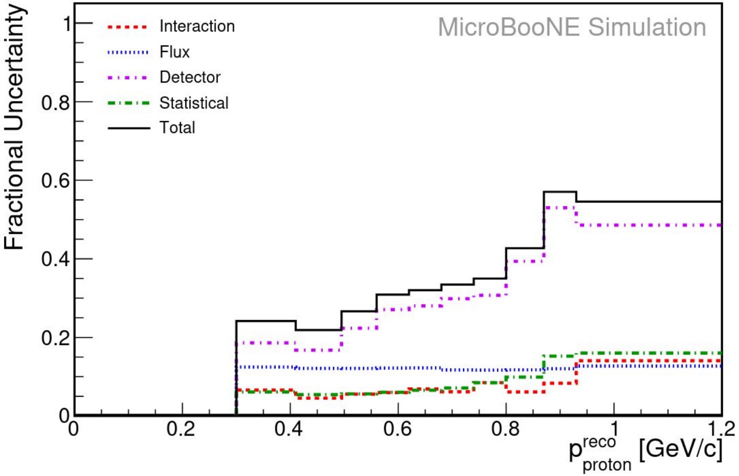
10.36m L×2.56m W×2.36m H

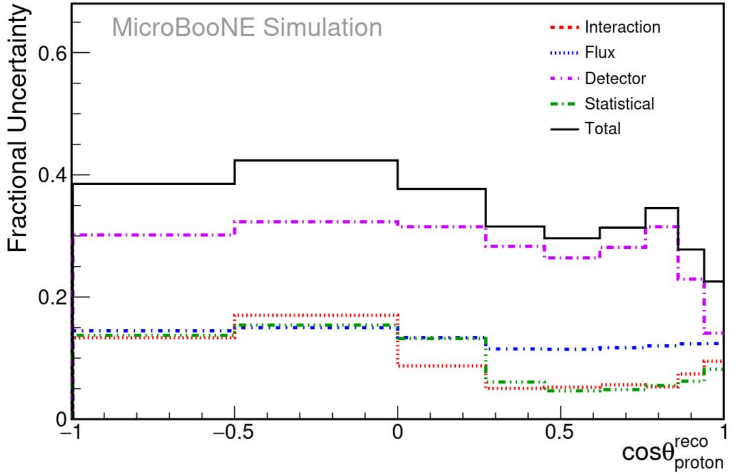


32 PMTs collect light from a flash at time of interaction

- Charged particles lose energy through Ar atom excitation (scintillation light) and ionization (drift electrons travel toward anode)
- The area below **waveform** is proportional to **deposit charge**
- 2 induction planes (+/-60 degrees with respect to Y axis) and 1 collection plane -> **3D reconstruction** from drift time (X) and Wire-plane matching (Y-Z)

Systematic Uncertainty



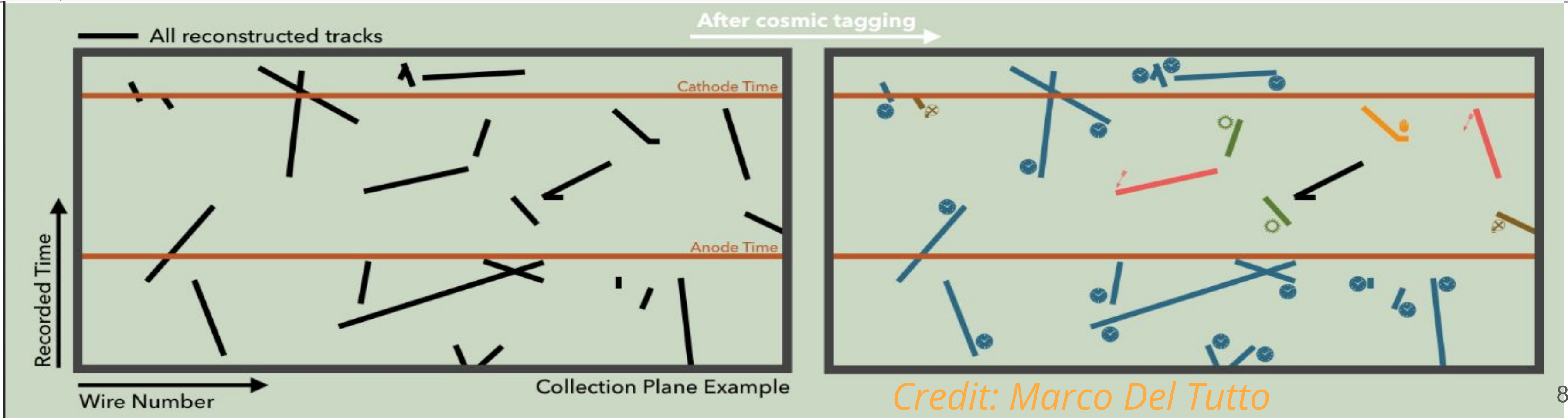


- The systematic uncertainties are dominated by systematics from Detector Response (~18% in the highest statistical bin).
    - conservatively take the variation that leads to the largest uncertainty as a 1σ uncertainty when vary parameters.
    - The various detector modeling uncertainties are added in quadrature to determine the total detector uncertainty.
    - Many improvements of the detector response in most recent MicroBooNE simulation not here.
- The second dominant uncertainties are from flux estimation.
    - More investigation to flux constraint needed?
- Uncertainties from interaction systematics and statistics are close to each other.

Tagging of Cosmic Rays

	It crosses through the entire detector
	not compatible with the neutrino beam window
	not compatible with the flash in the neutrino beam spill (spatial position and intensity)
	crossing the anode or cathode plane (LAr can not reconstruct t_0 by itself)
	entering and stopping (Bragg peak or Michel electron)

99.9% Cosmic Rejection



Credit: Marco Del Tutto

Neutrino Oscillations

Neutrino Event Rate:

$$N_{FD}(\mathbf{E_\nu}) = \Phi(\mathbf{E_\nu}) \times \sigma(\mathbf{E_\nu}) \times \varepsilon \times \mathbf{P(\nu_\alpha \rightarrow \nu_\beta)}$$

- $\Phi(\mathbf{E_\nu})$: Flux, $\sigma(\mathbf{E_\nu})$: Cross section
  ε: detector efficiency
- Cross sections always one of the major contributors
- More for T2K(E_ν~0.7GeV) than NOvA(E_ν~2.4GeV)
- DUNE will detect pions, protons, neutrons, etc. with enough accuracy to get neutrino energy accuracy of a few %

T2K: Systematic uncertainties on far detector event yields

Source [%]	ν_μ	ν_e	$\nu_e\pi^+$	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	2.4	7.8	4.1	1.7	4.8
Flux & ND280-constrained cross sec.	3.3	3.2	4.1	2.7	2.9
SK detector systematics	2.4	2.9	13.3	2.0	3.8
Hadronic re-interactions	2.2	3.0	11.5	2.0	2.3
Total	5.1	8.8	18.4	4.3	7.1

PRL 121, 171802 (2018)

T2K and NOvA use targets like Carbon and Oxygen for which a lot of existing data and measurements are available. DUNE will use Argon as neutrino target, not a lot of existing data is available on Argon.

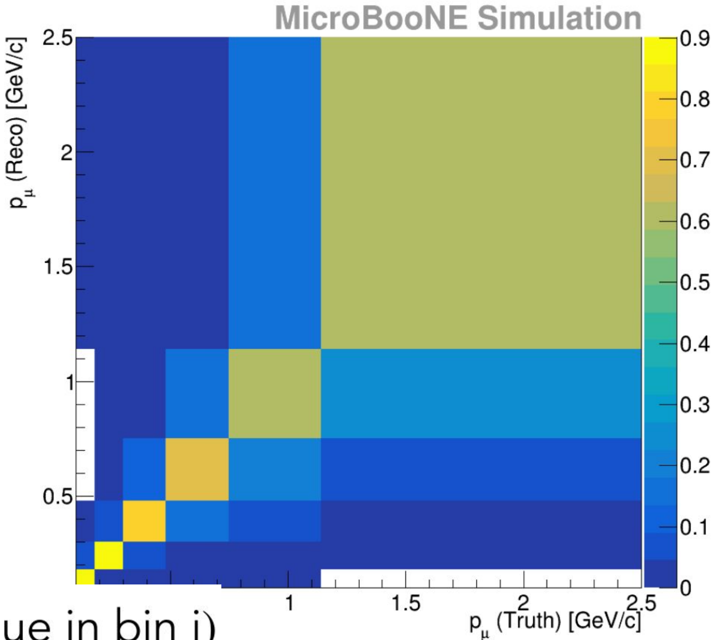
Cross Section Measurement

$$\left(\frac{d\sigma}{dp_\mu}\right)_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu)_i}$$

Smearing Matrix (normalized)

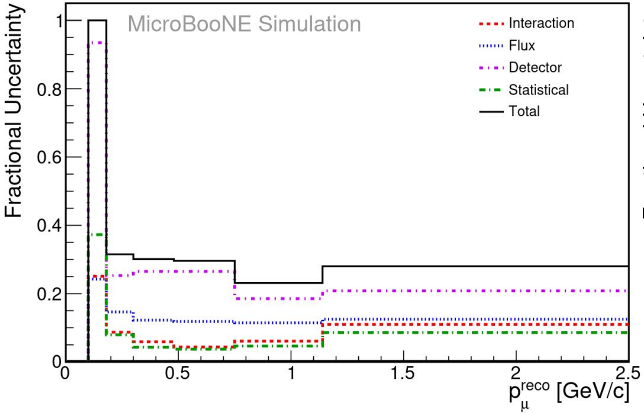
$$S_{ij} = N_{ij}^{\text{sel}} / N_j^{\text{sel}}$$

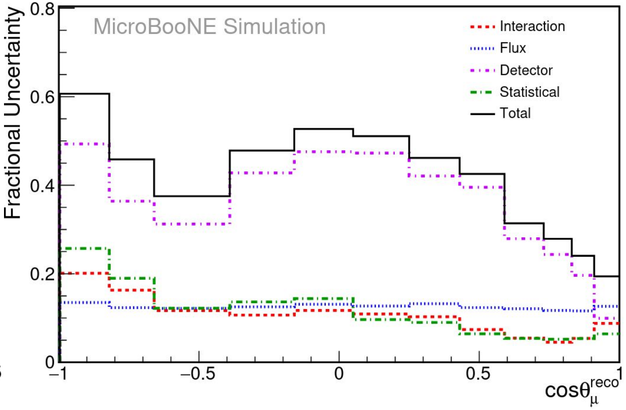
where N_{ij}^{sel} is the number of selected events in reconstructed bin i, which come from true bin j, and N_j^{sel} is the total number of selected events from true bin j.

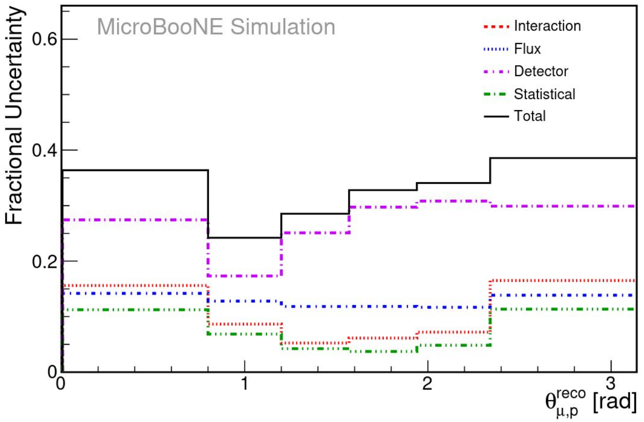


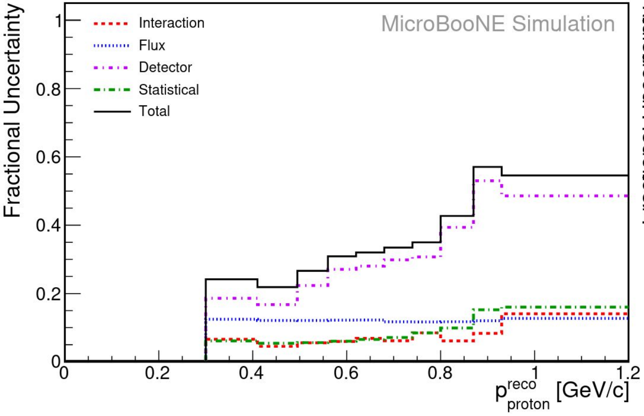
$$N_i^{\text{reco}} = \sum_j S_{ij} N_j^{\text{true}}$$ $$S_{ij} = P(\text{observed in bin i} \mid \text{true value in bin j})$$

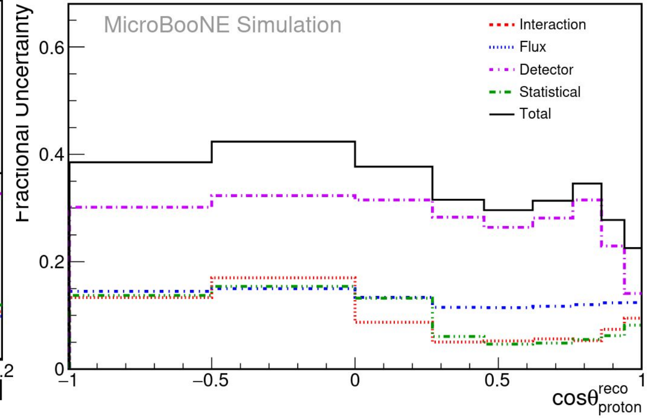
Systematic Uncertainty











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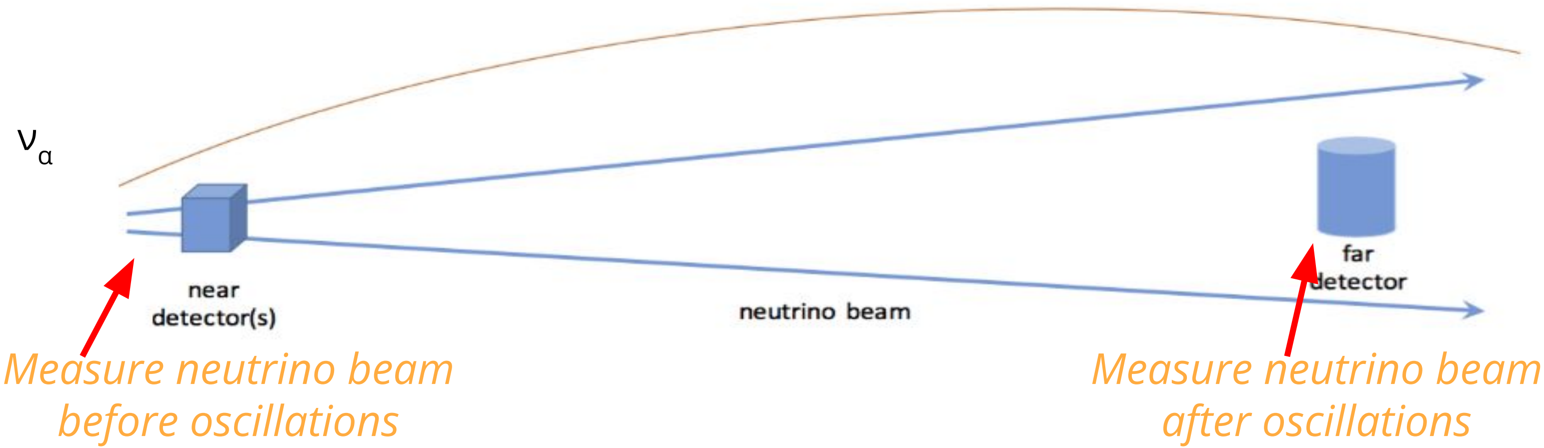
 (proton momentum+proton angle)

Neutrino Oscillation Experiments



Signature of Neutrino Oscillation

- Neutrino Spectrum Distortions

Near to Far extrapolation

- Provides data-driven estimate of un-oscillated event rate at the Far detector.
- Neutrino spectrum distortions calculated from the ratio of neutrino spectrum at far detector to un-oscillated predicted event rate at far detector
- Influenced by uncertainties in the knowledge of flux and cross sections.

Neutrino Oscillation Measurement

The event rate at Near detector and Far detector is given by

$$N_{\nu_\mu;Far}(E_\nu) \propto \epsilon_{\nu_\mu;Far}(E_\nu) \times \Phi_{\nu_\mu;Far}(E_\nu) \times \sigma_{\nu_\mu}(E_\nu, A) \times P_{\nu_\mu \to \nu_\mu}(E_\nu)$$

$$N_{\nu_\mu;Near}(E_\nu) \propto \epsilon_{\nu_\mu;Near}(E_\nu) \times \Phi_{\nu_\mu;Near}(E_\nu) \times \sigma_{\nu_\mu}(E_\nu, A)$$

For functionally identical detector (same atomic mass)

$$\epsilon_{\nu_\mu;Far}(E_\nu) \approx \epsilon_{\nu_\mu;Near}(E_\nu)$$

Detector efficiency and cross section errors are cancelled, only un-correlated far/near detectors play in a role.

$$N_{\nu_\mu;Far}(E_\nu) \propto N_{\nu_\mu;Near}(E_\nu) \times \frac{\Phi_{Far}(E_\nu)}{\Phi_{Near}(E_\nu)} \times P_{\nu_\mu \to \nu_\mu}(E_\nu)$$