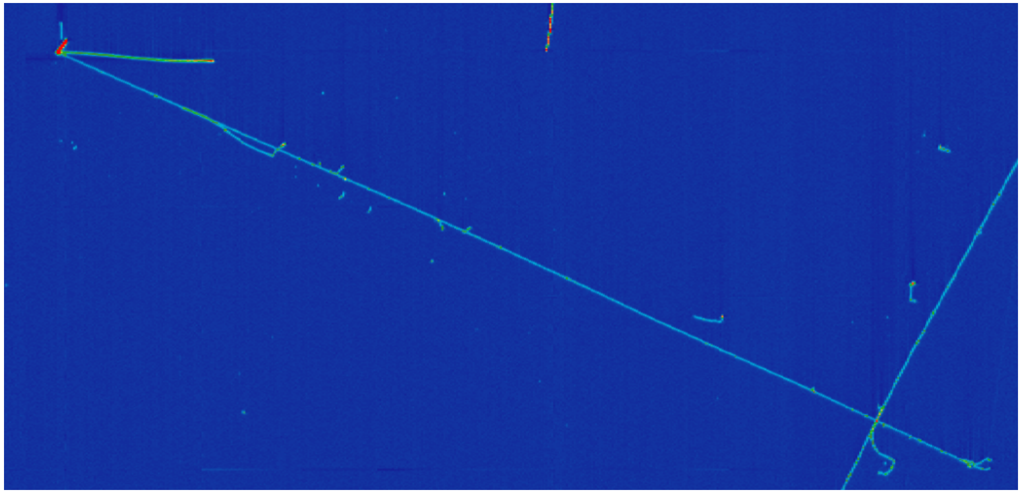
CC0πNp cross section measurement at MicroBooNE



Andrew Furmanski, for the MicroBooNE collaboration

NuSTEC CEWG, 3rd December 2020

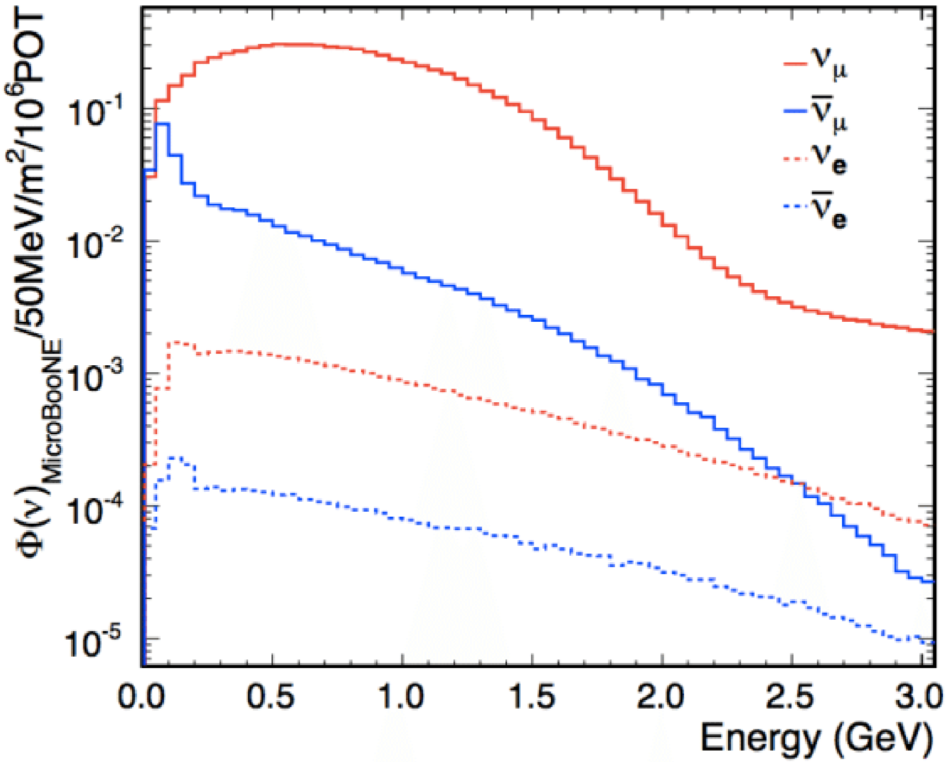
Introduction

- I'm assuming that I am speaking to people who understand:
  - Why we care about measuring cross sections
  - Why we want to measure final state protons
  - What nuclear effects are
- This talk will be a "deep dive" into a specific cross section measurement
  - What we **try** to measure
  - What our detector lets us measure
  - Finally, what the data tells us

What is the measurement

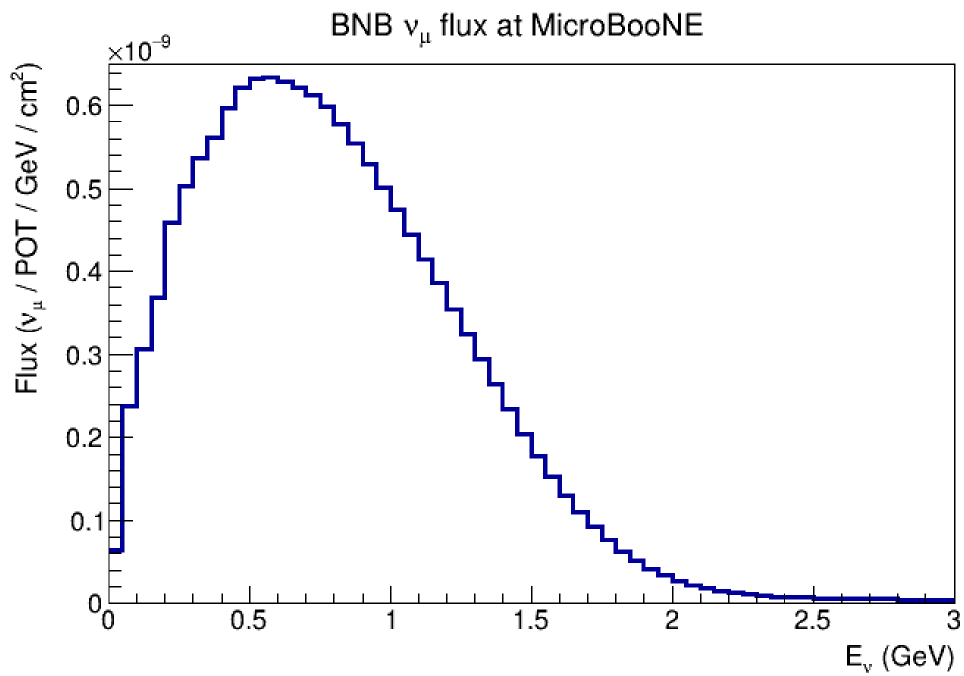
- CC0πNp
  - That is, one muon, zero pions, some number of protons
  - Specific details coming later
- ~50% CCQE, with MEC+RES forming the remainder
  - According to GENIE v2.12.2
- Measuring "simple" detector-level variables with well-understood efficiency and smearing
  - i.e. no transverse kinematics etc
  - Not measuring proton multiplicity, focus on "leading" proton

Booster Neutrino Beam

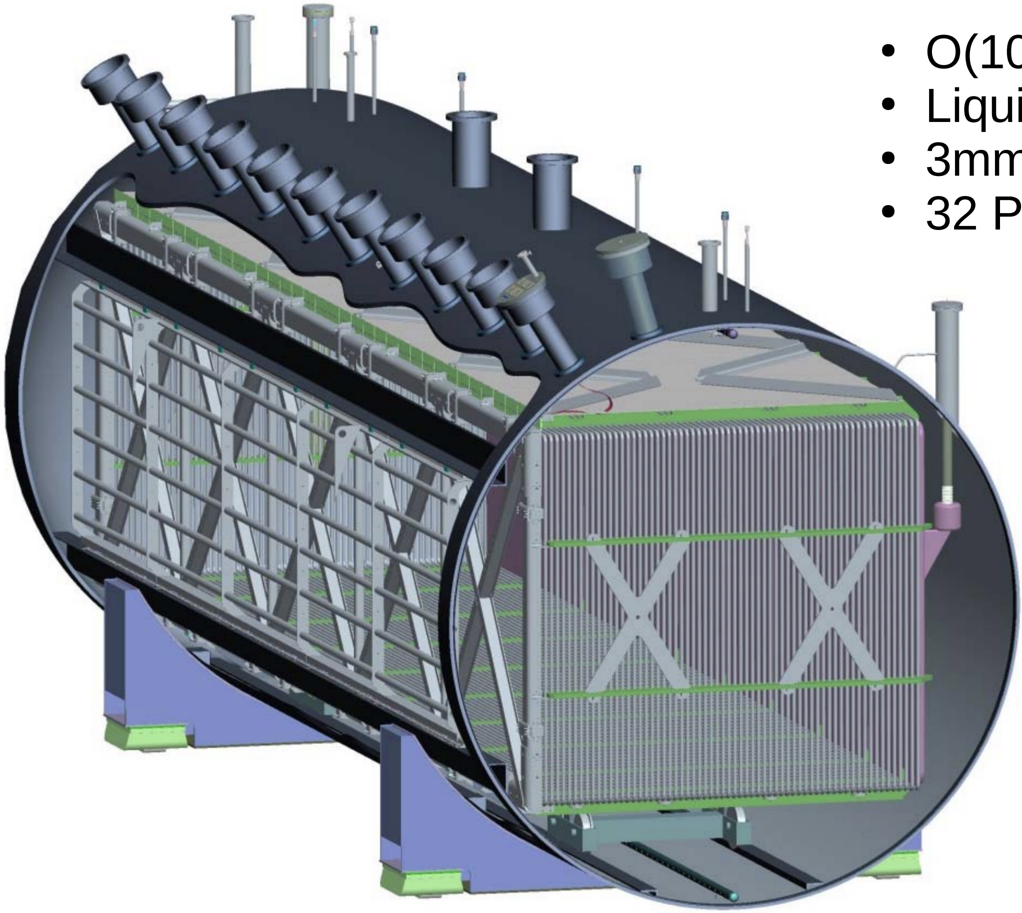


Low energy, and wide spectrum

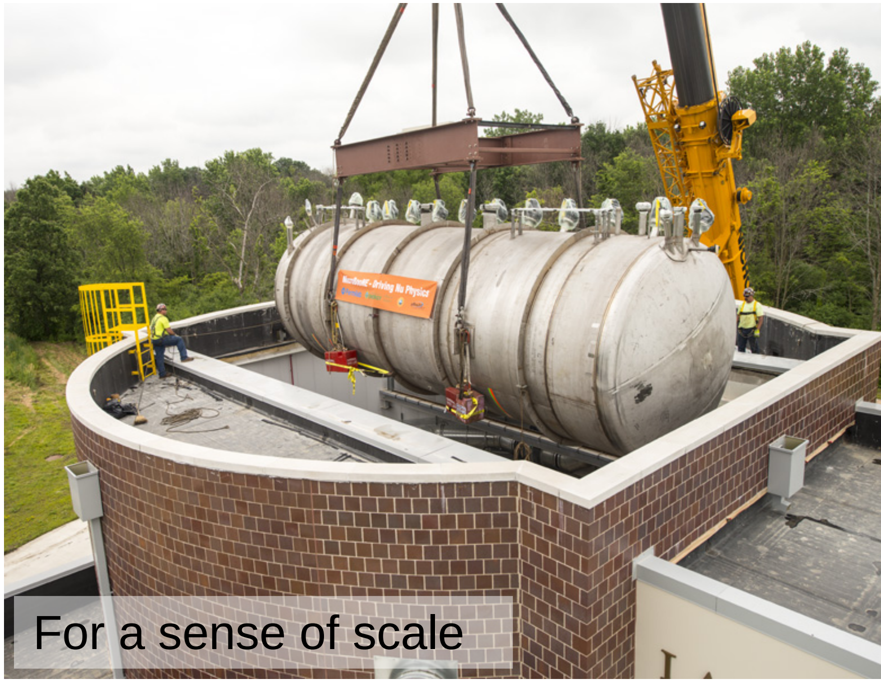
Minimal high-energy tail (8 GeV proton beam)



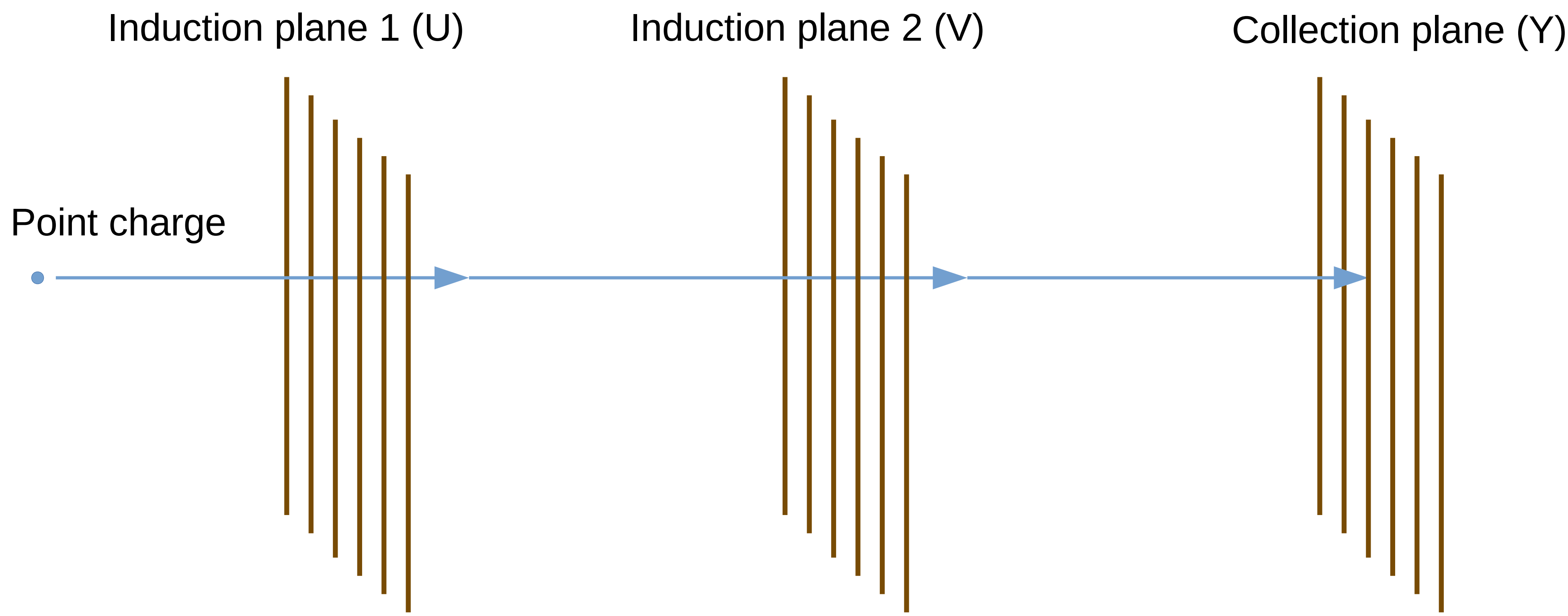
MicroBooNE detector



- O(100) tons (fiducial mass closer to 50)
- Liquid argon time-projection chamber
- 3mm wire spacing, 3 planes (0°, ±60°)
- 32 PMTs (all behind wire plane)



LArTPC signals



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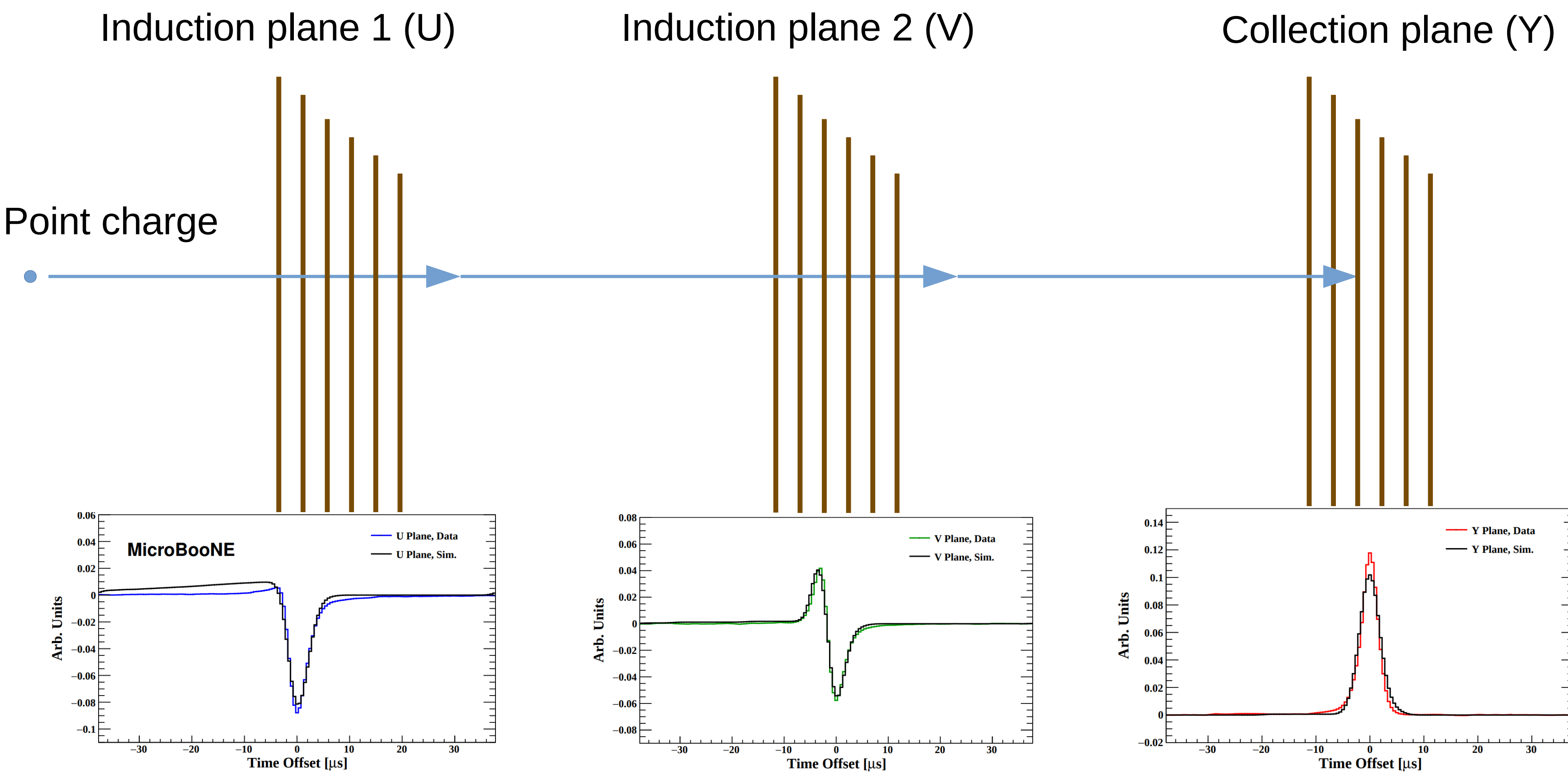
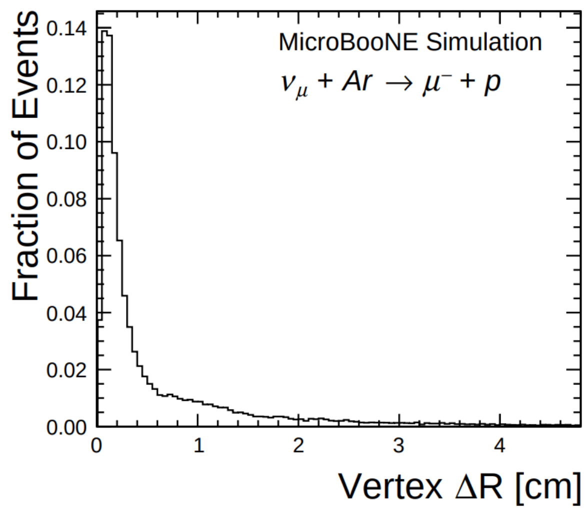
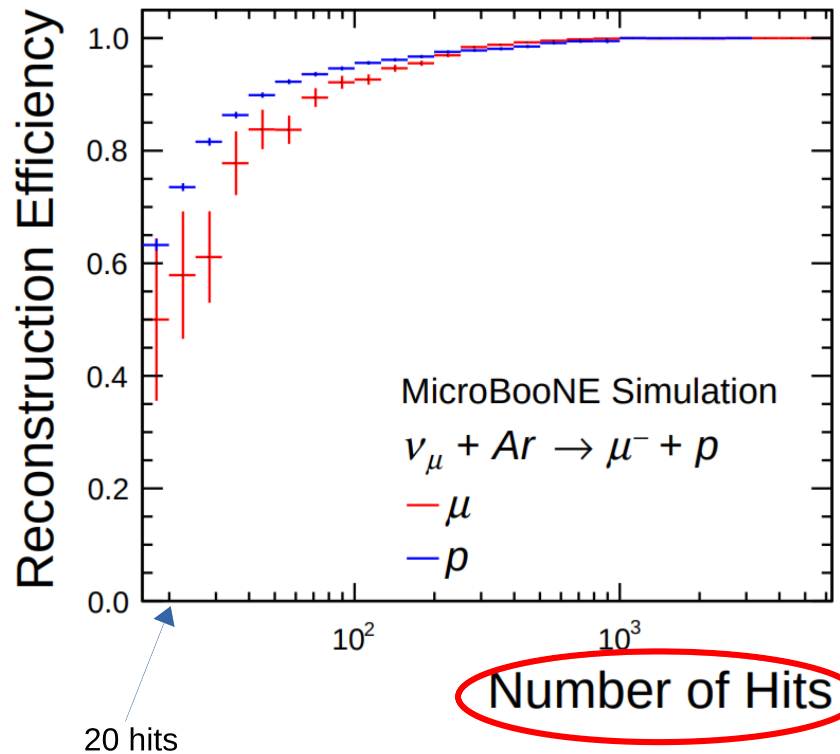


Track Reconstruction

Pandora’s box

- This analysis uses the **Pandora** “multi-algorithm approach to automated pattern recognition”
- Highly configurable suite of algorithms
- Very good efficiency and accuracy
- Reconstructs tracks with just a handful of hits
- Vertex resolution, track length resolution, etc ~1cm



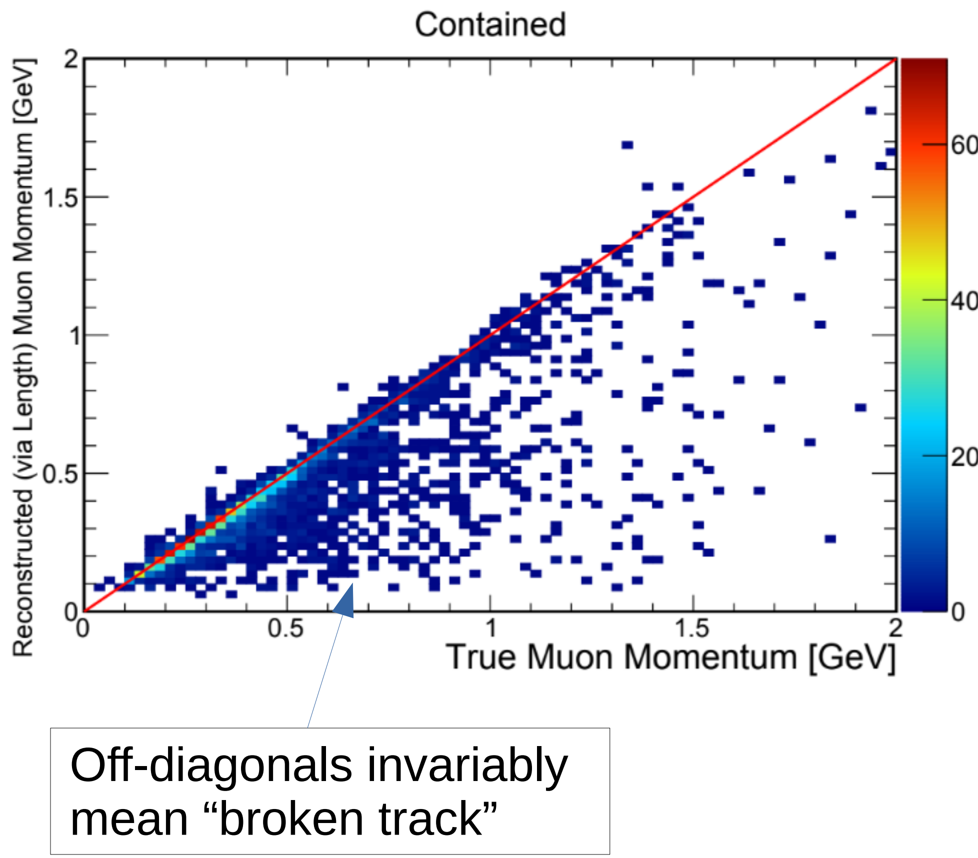


Plots from:
Eur. Phys. J. C **78**, 82 (2018)
ArXiv:1708:03135

Momentum Reconstruction

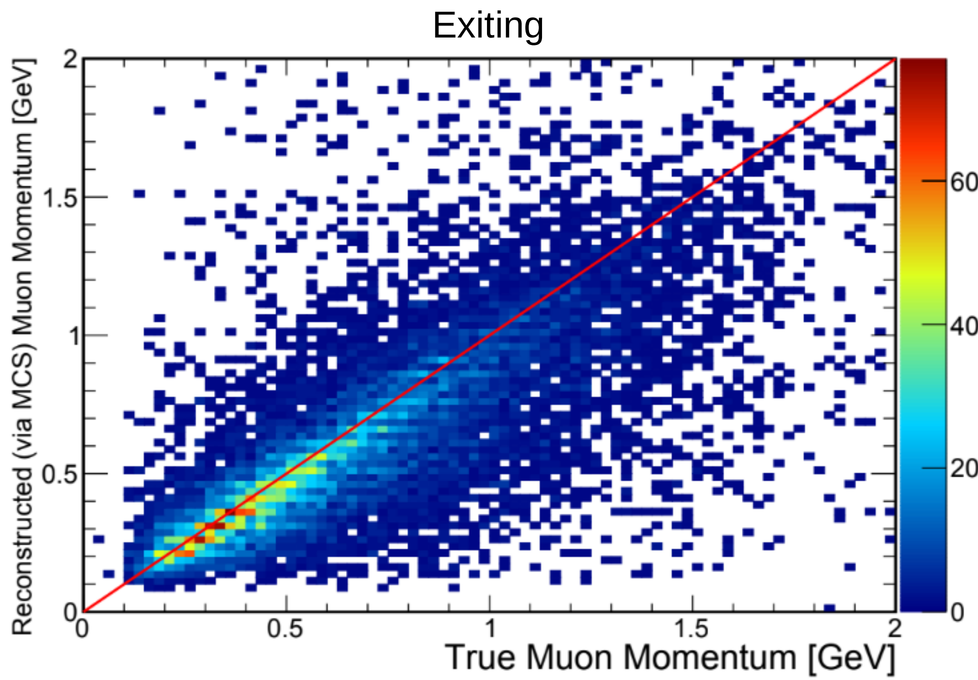
Contained Tracks

- For contained tracks, we use range-based momentum
- Requires a particle hypothesis
- Simple look-up table
- Resolution is excellent



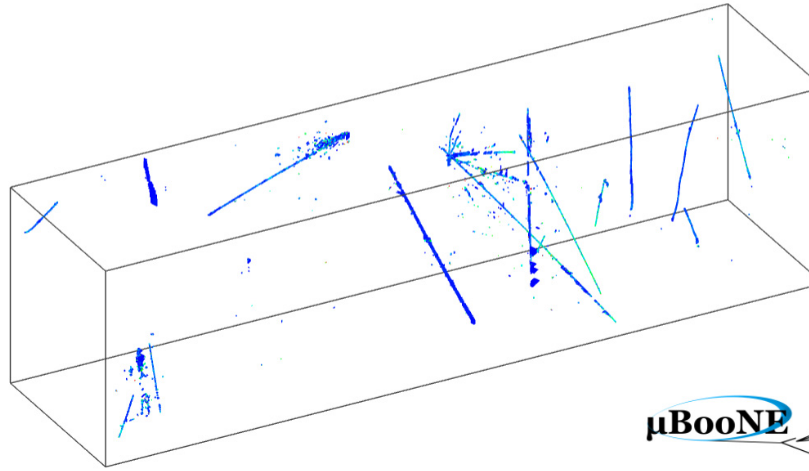
Exiting Tracks

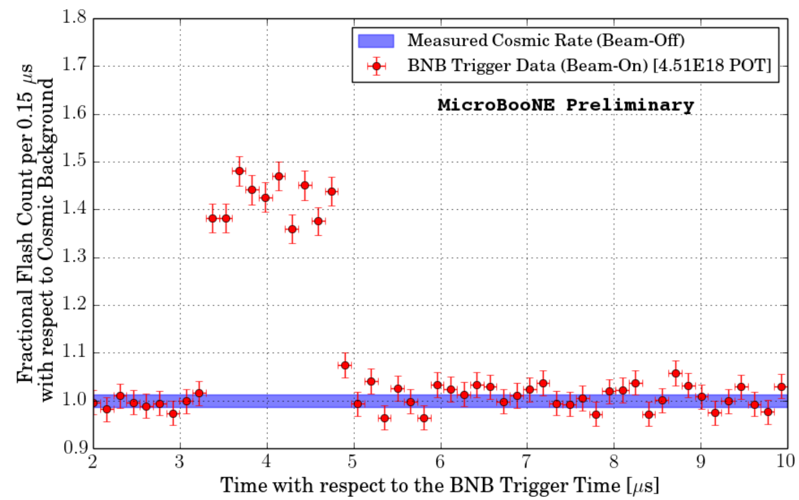
- For tracks that exit, we use a fit to the amount of scatter
- “Multiple Coulomb Scattering” (MCS)
- Resolution is still reasonable (10-20%)
- But ~50% of neutrino-induced muons exit the TPC



Cosmic rejection in MicroBooNE

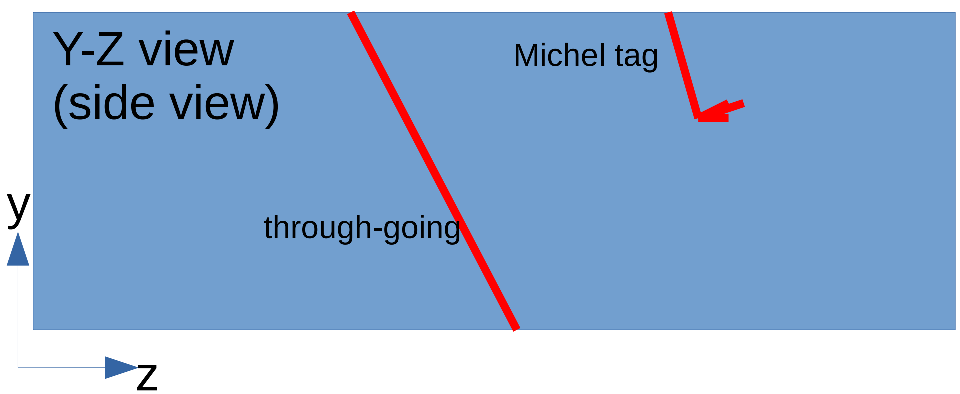
- MicroBooNE is on the surface
- Drift time is ~2ms
- Every event readout contains ~10 cosmic muons
- 99.9% of signal events produce light in time with the beam spill
- In 1% of spills, a cosmic produces light in time with the beam spill
  - Still 10:1 after optical trigger

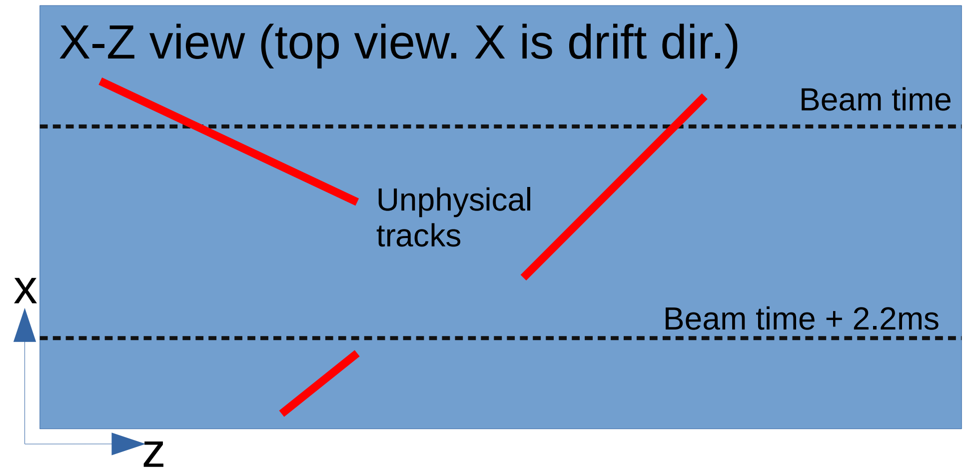




Geometrical Tagging

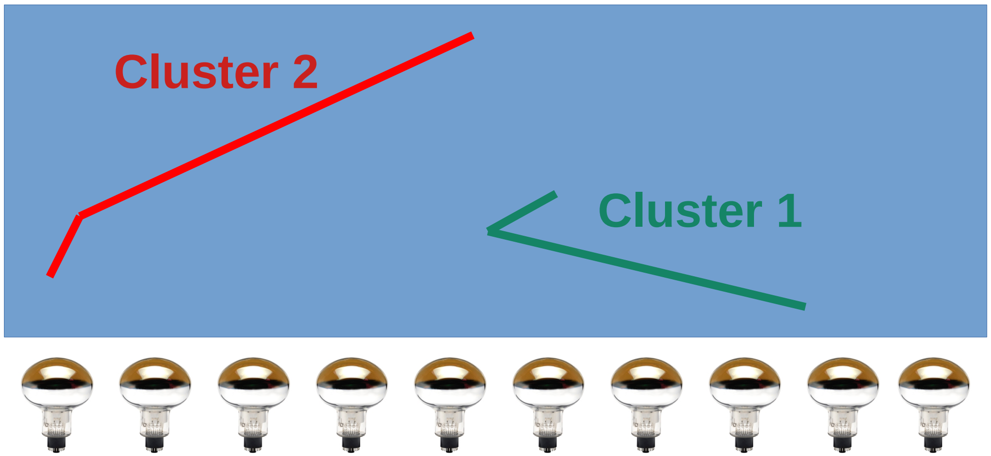
- Reject as cosmic-like:
  - Top-bottom through-going tracks
  - Tracks that have “unphysical” x-positions
  - Tracks that enter through the top, stop, and produce a michel

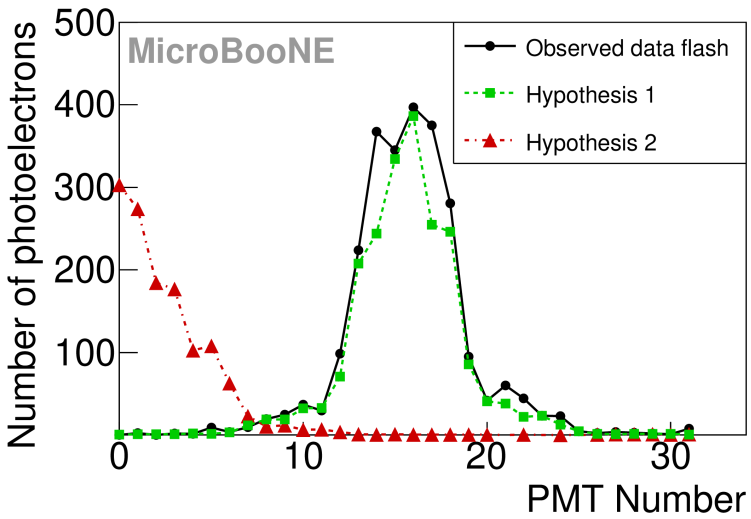




PMT Matching

- Using a cluster of TPC charge, predict light intensity on each PMT
- If that matches the in-spill observation, the TPC cluster is the neutrino!
  - Note, we are also developing “many-to-many” matching, which does perform better





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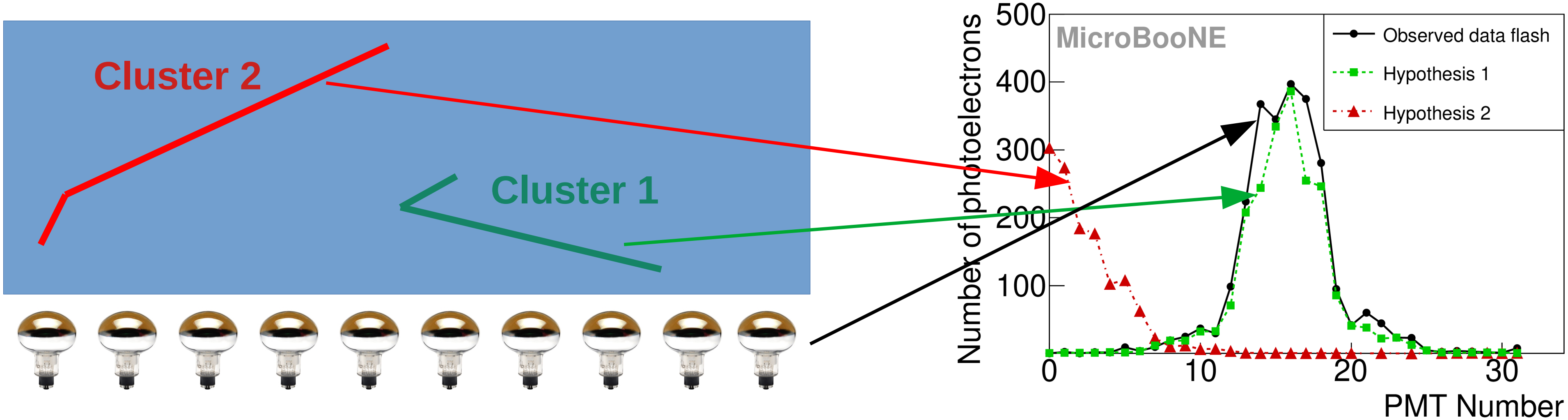


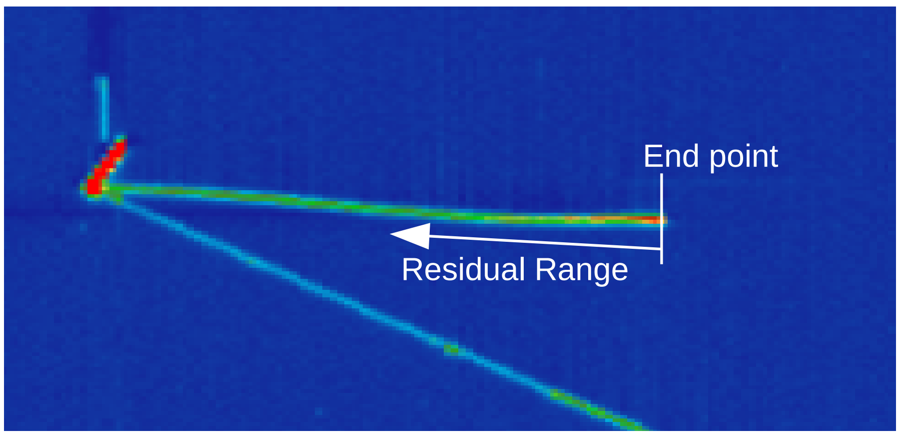
PID in MicroBooNE

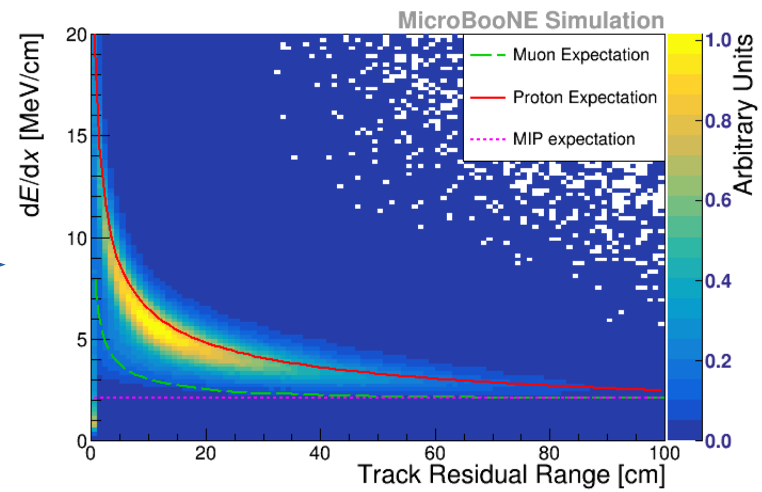
PID in MicroBooNE

- In general, for track-like particles, we rely on the Bragg peak
  - Requires particles come to a stop in the detector
  - PID all based off **dE/dx** vs **Residual Range**
  - Pions and muons are functionally indistinguishable
  - So PID is basically – is it a proton or not?

N.B. We only use the collection plane for PID at this time.

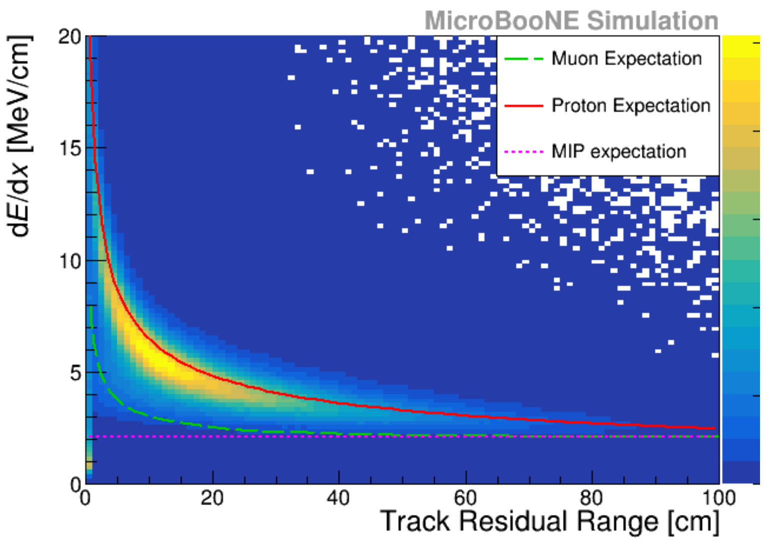
Collection plane has the highest S/N and best understood response.

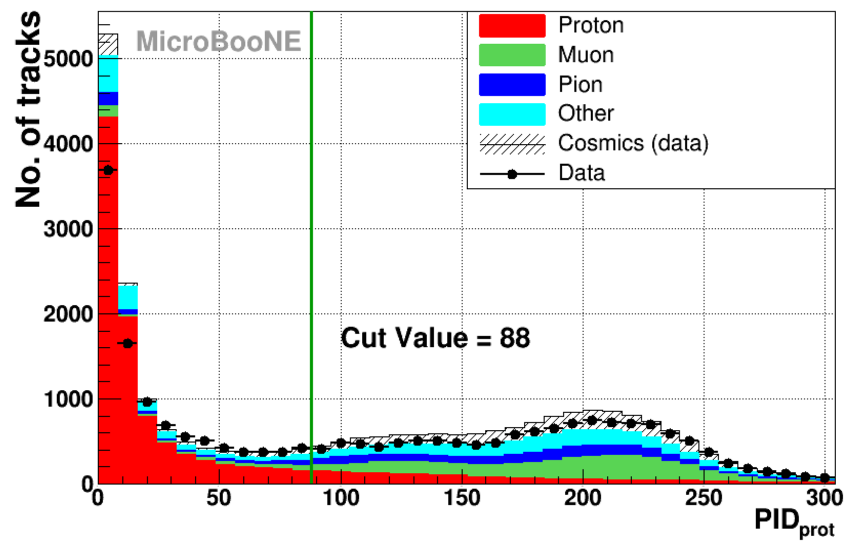




PID method used

- We convert the dE/dx vs residual range into a single number
  - Essentially a summed average distance from proton expectation
  - Built like a χ^2, but don't interpret the value as one
  - Low is proton-like, high is not proton-like





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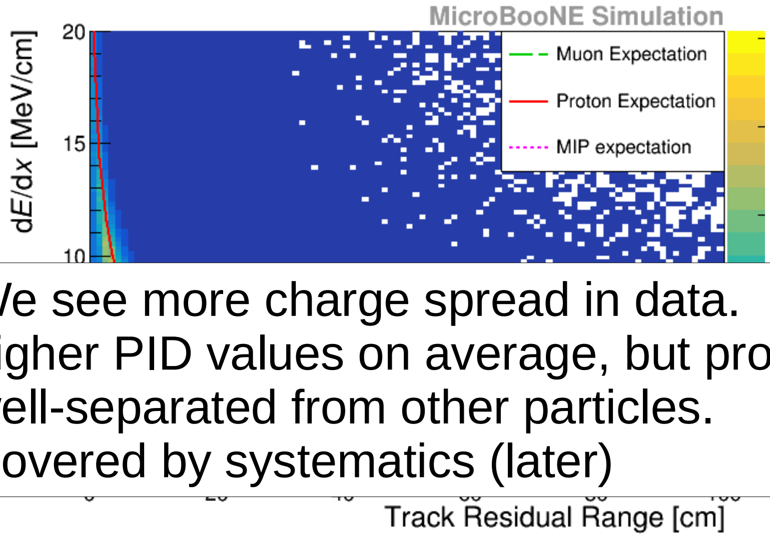
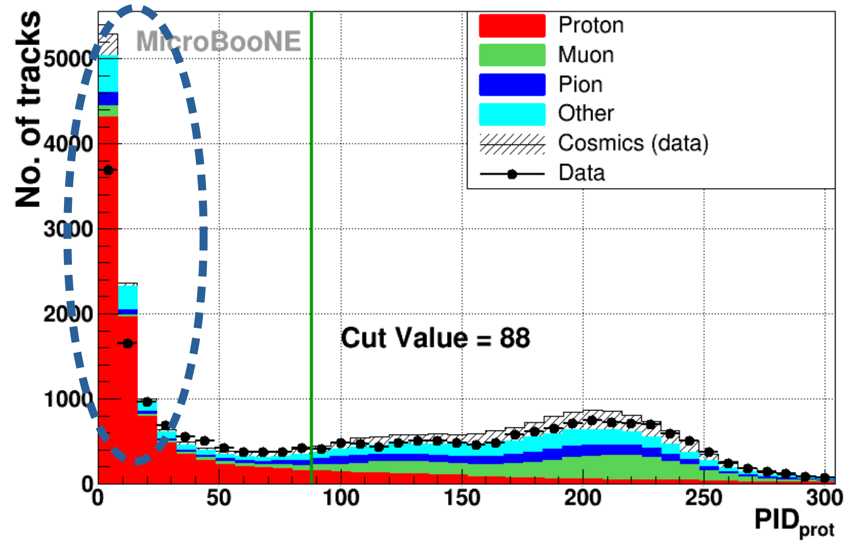
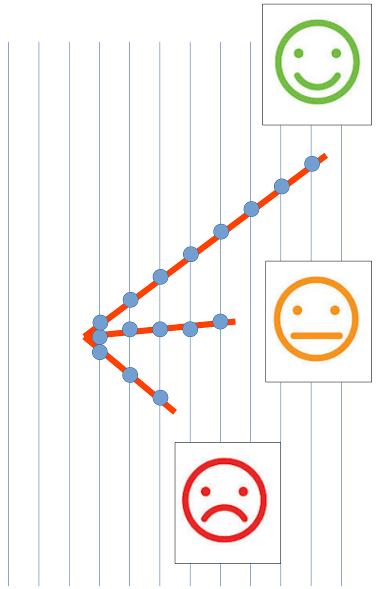


We see more charge spread in data. Leads to higher PID values on average, but protons still well-separated from other particles.
Covered by systematics (later)



PID and number of hits

- Due to dQ/dx fluctuations, we require **at least 5 hits to achieve good PID accuracy**
- This is going to introduce a natural threshold
- Remember, wires are 3 mm apart, so 5 hits is at least 1.5 cm



Ok, the measurement?

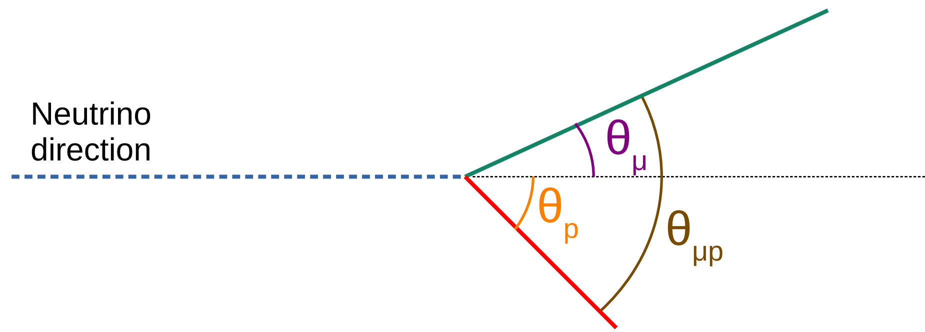
Signal definition

- Muon neutrino charged current interaction, producing:
  - **One muon**
  - **Zero pions** (charged or neutral)
  - **Any number of protons**
  - Any number of neutrons
- With some **phase space limitations**:
  - Highest momentum (leading) proton must be between 300 MeV/c and 1200 MeV/c
  - Muon must be above 100 MeV/c

We'll come back to these later

Variables

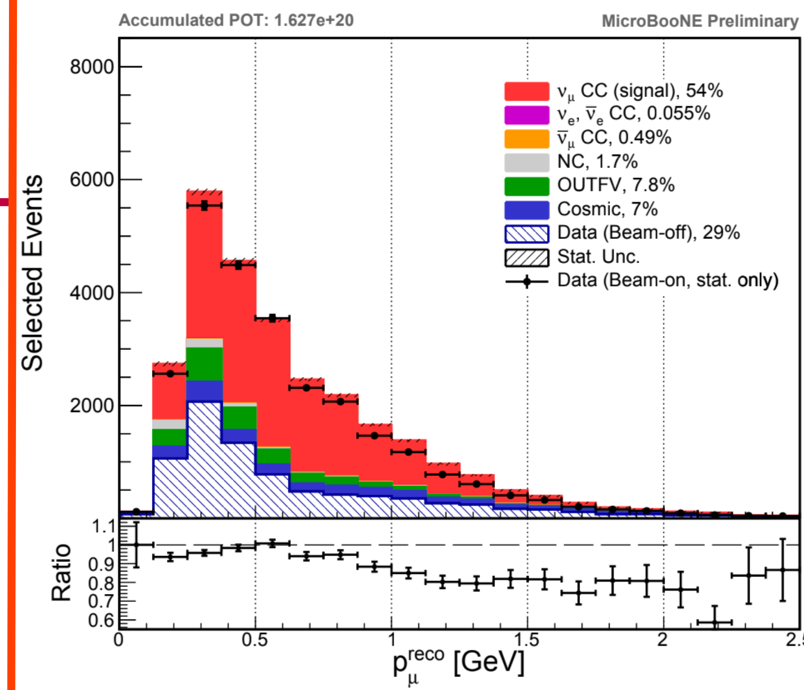
- For the first analyses, we focused on “simple” detector variables:
  - **Muon Momentum**
  - **Proton Momentum**
  - **Muon Angle**
  - **Proton Angle**
  - **Muon-Proton opening angle**

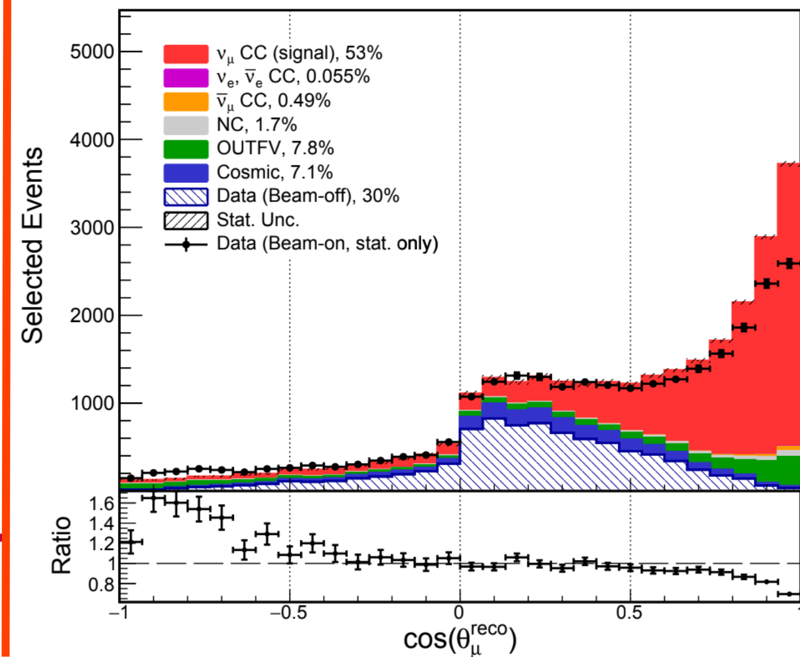


- We only ever measure the **leading** proton
  - Sub-leading protons are interesting for follow-up analyses

CC pre-selection

- Charged-current inclusive selection used as a pre-filter
  - Phys. Rev. Lett. 123, 131801 (2019)
  - (or arXiv:1905.09694)
- Applies a number of cosmic rejection methods to identify the best neutrino candidate
- **Longest track in interaction selected as muon candidate**
- Muon candidate required to be muon-like (i.e. not proton-like)
- Cosmic backgrounds down from 10:1 to 0.3:1





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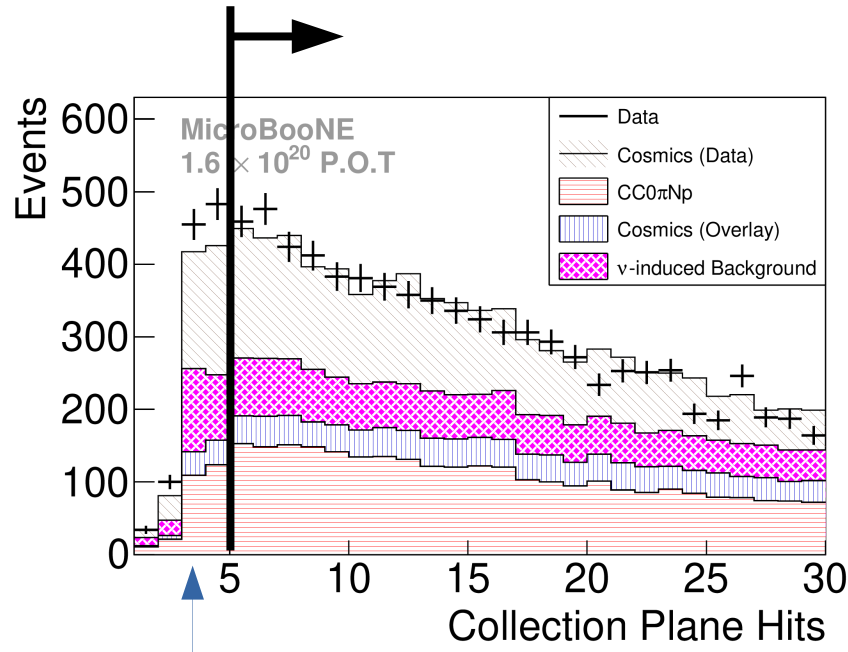
University of Minnesota

Leading proton selection

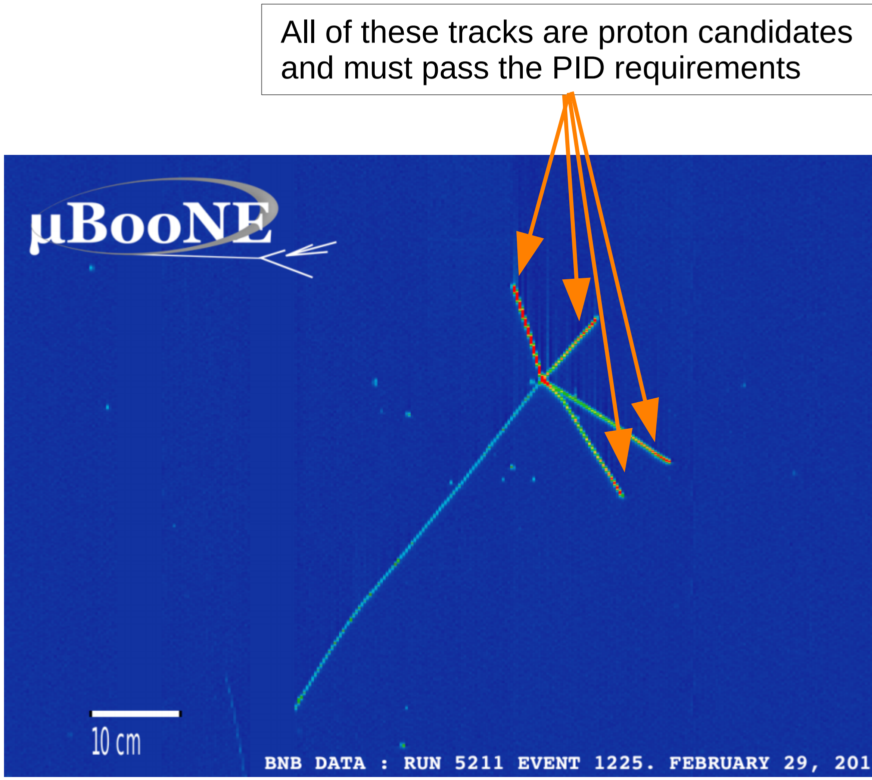
- Everything that is not the muon candidate is a proton candidate
- The **longest** proton candidate is the **leading** proton candidate
  - This one **must have at least 5 collection plane hits**
  - And a PID value below 88 (proton-like)



Clearly we can reconstruct tracks with < 5 hits, but we can't PID them right now

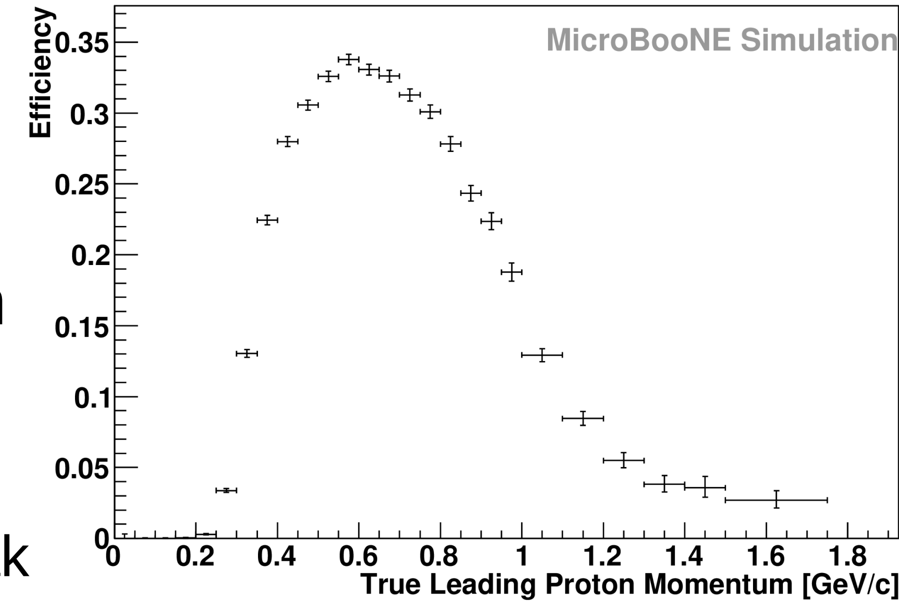
Secondary Proton Candidates

- 30% of our selected events have more than one proton candidate
- We require all the remaining proton candidates to have PID < 88
- **Unless** they have 5 hits or fewer
  - In that case, the PID is inaccurate, so we apply “bayesian” PID:
  - **P(proton|short) = 0.75 ≈ 1**
  - If it has 5 hits or fewer, it’s a proton
- This applies to all proton candidates, however many there may be



Phase space limits

- Efficiency very low for event with leading protons below 300 MeV/c (~2 cm, 47 MeV KE)
  - As expected, from the 5-hit requirement
- Also see a drop off at high proton momentum
  - Proton exits → no bragg peak
  - Proton re-interacts → no bragg peak



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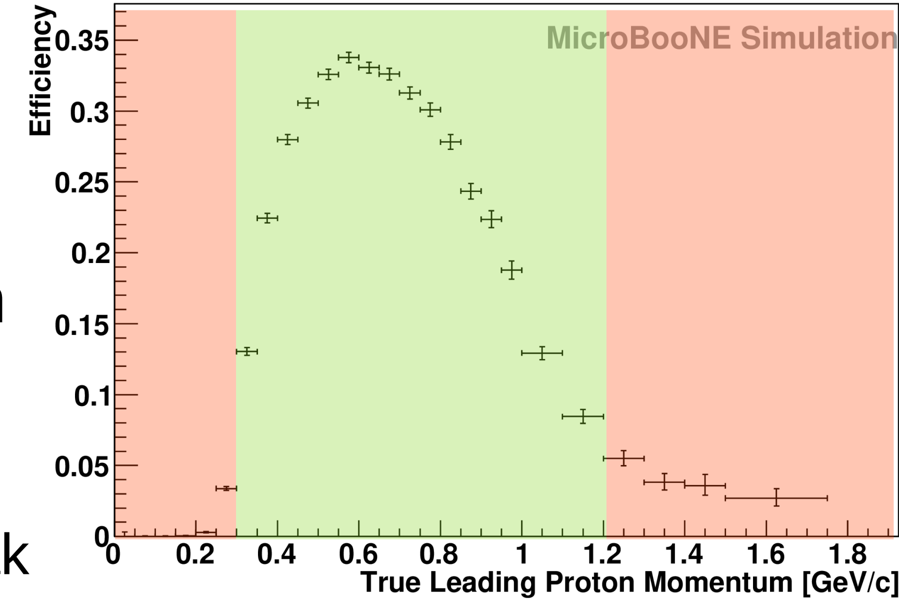
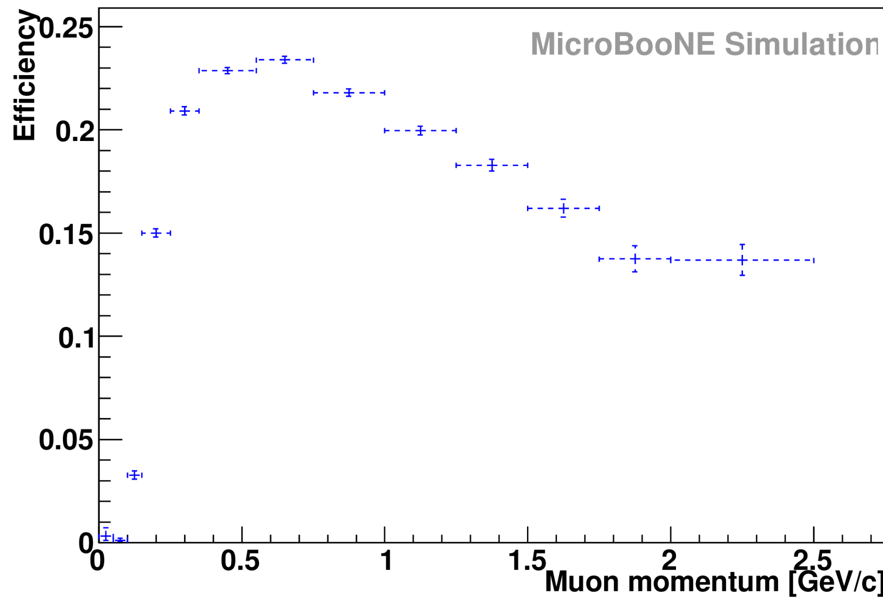
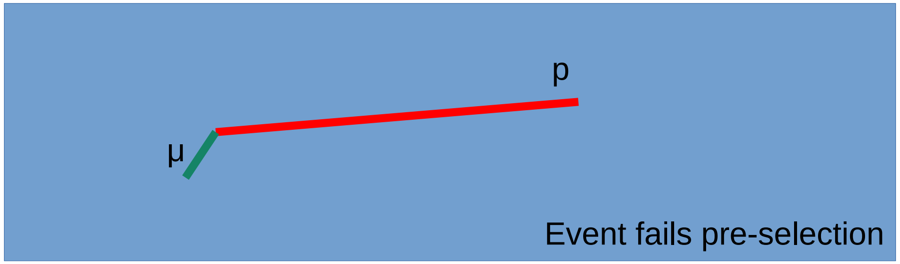
Leading proton must be in the green range
Secondary protons have no requirements



More phase space limits

- Efficiency also low at muon momentum < 100 MeV/c
- So, we also cut this
- Generally paired with a high-momentum proton
- Commonly the proton is tagged as muon candidate and it fails the CC-inclusive pre-selection





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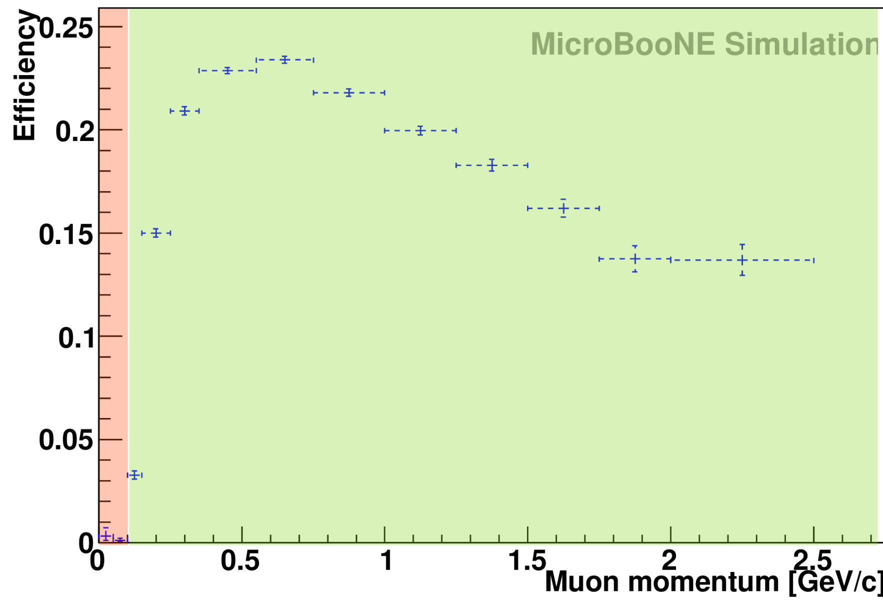
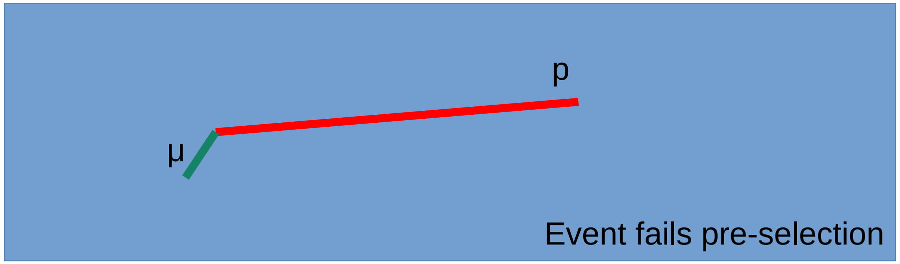
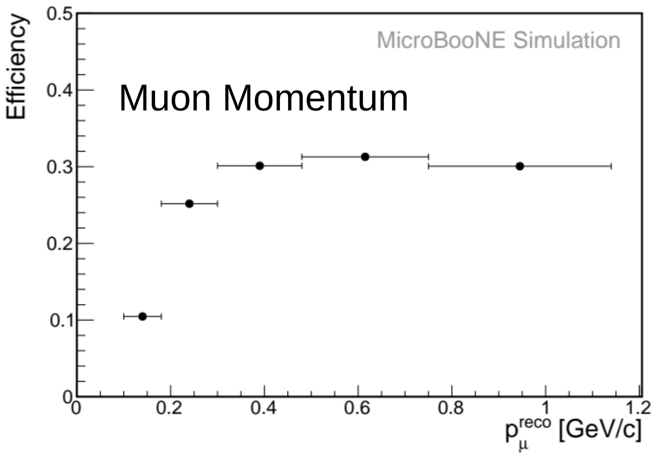
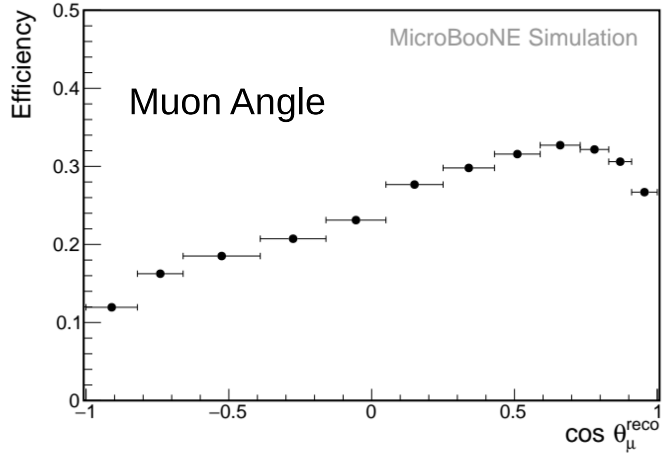




Event Selection Performance

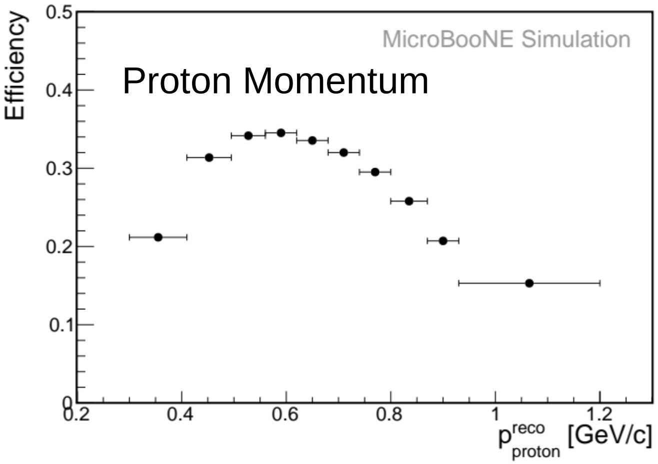
Efficiencies

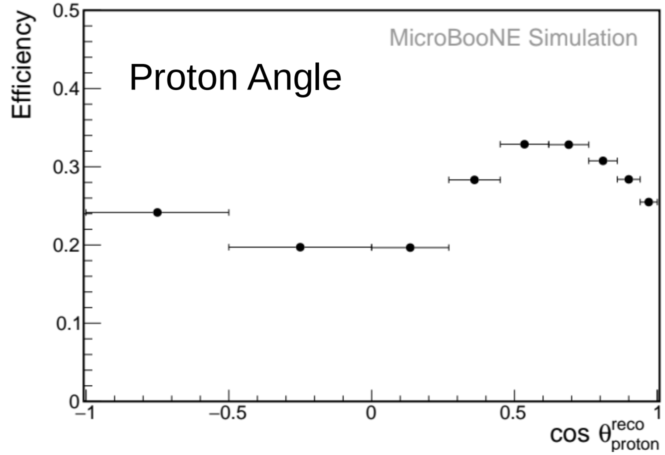


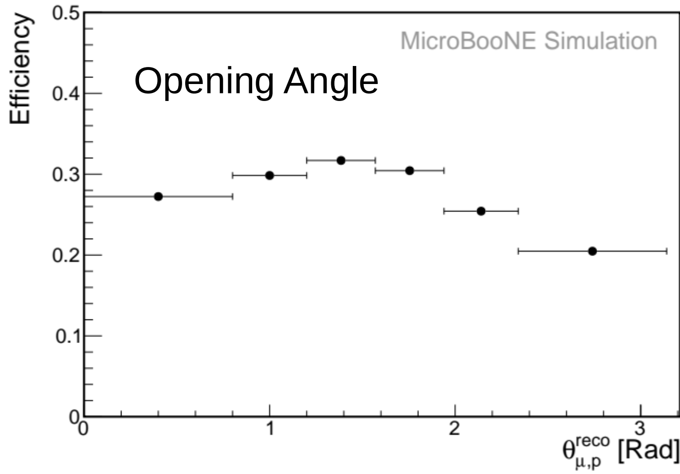


Total efficiency = 29%
Purity = 71%

Peak efficiency ~ 35%



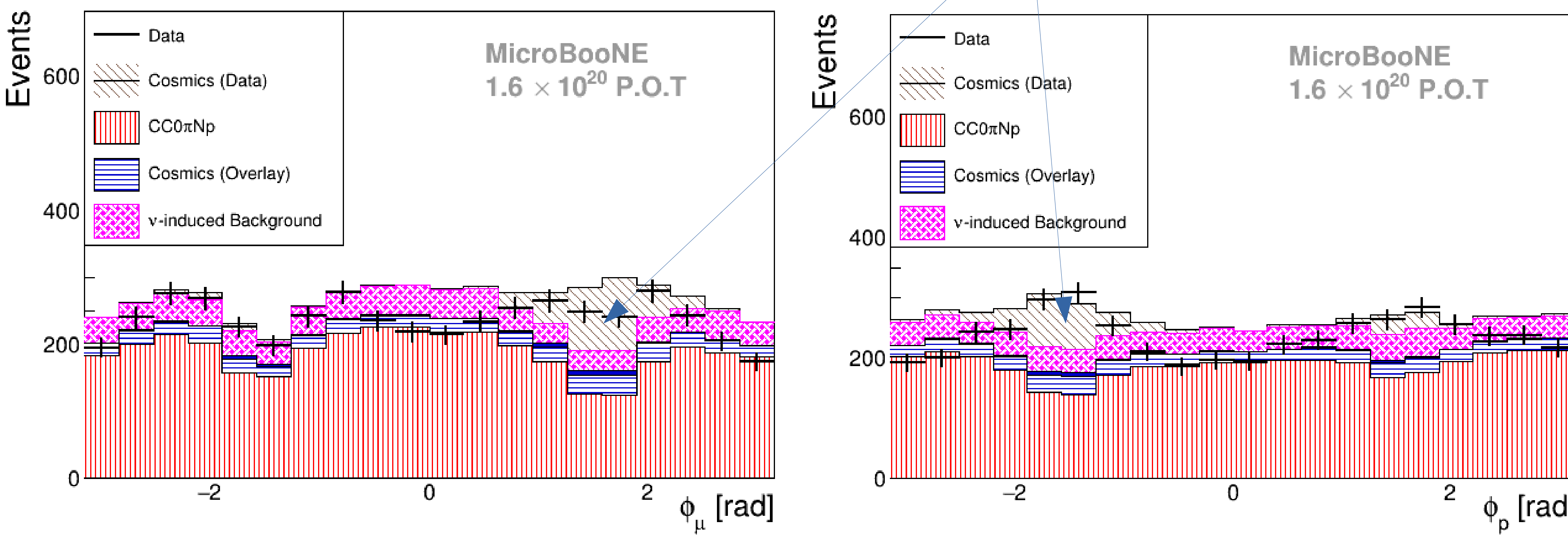




Azimuthal distributions

π/2 = upwards-going
-π/2 = downwards-going

Remaining cosmic backgrounds now below 10%



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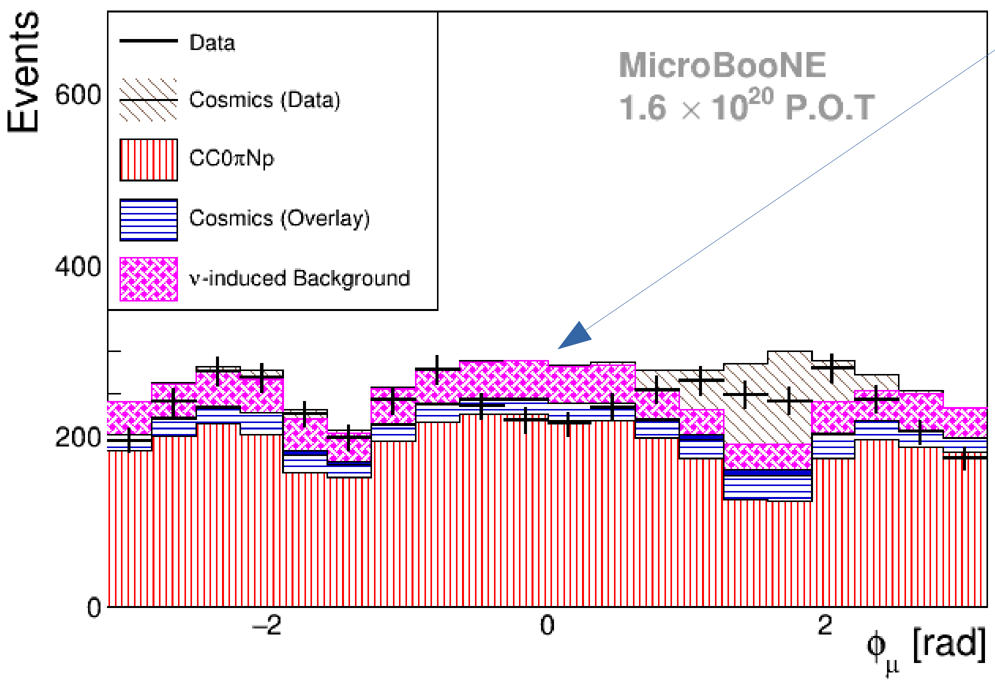
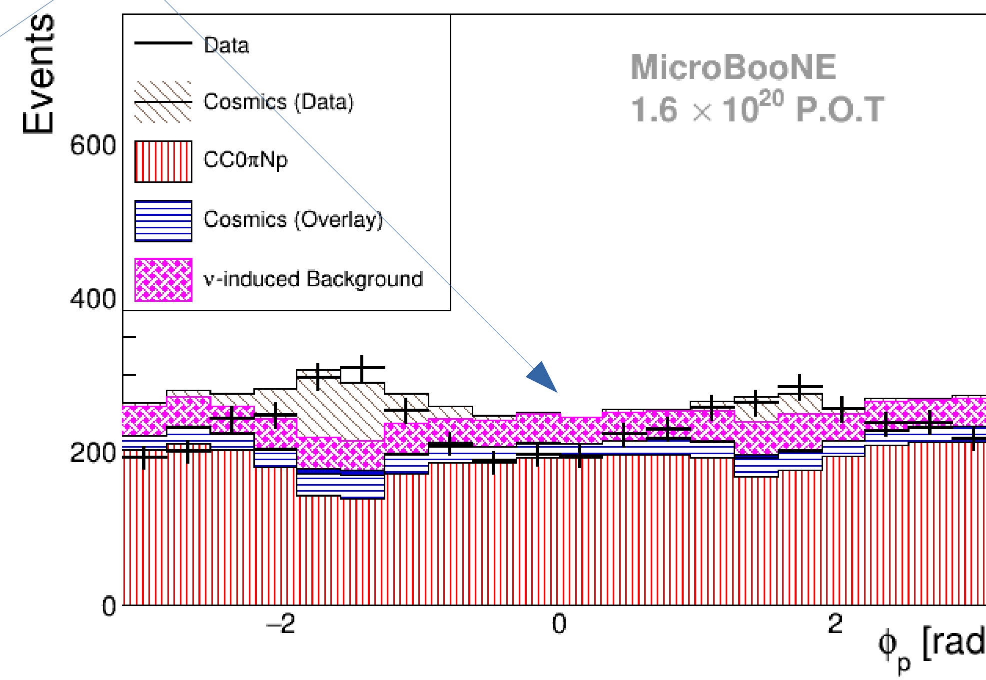
Azimuthal distributions

0 = towards cathode
±π = towards wires

This defect is understood, and covered by systematics

Will discuss more shortly





Detector smearing

Forward-folding method

- Chosen to present results in reconstructed variables
- Smearing matrices published with data
- However, to encapsulate uncertainties, we apply a "reco efficiency correction":

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

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

"normalised smearing matrix"

Folding method – good?

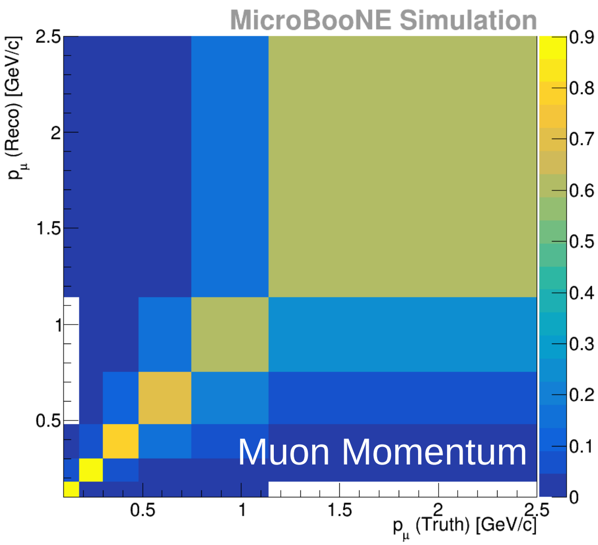
- No regularisation to worry about
- No unfolding biases to worry about
- Reduced model dependency (hopefully)
- Comparisons remain simple:
  - Produce true prediction
  - Fold prediction with smearing matrix
  - Compare to reco data (includes full cov. mat.)

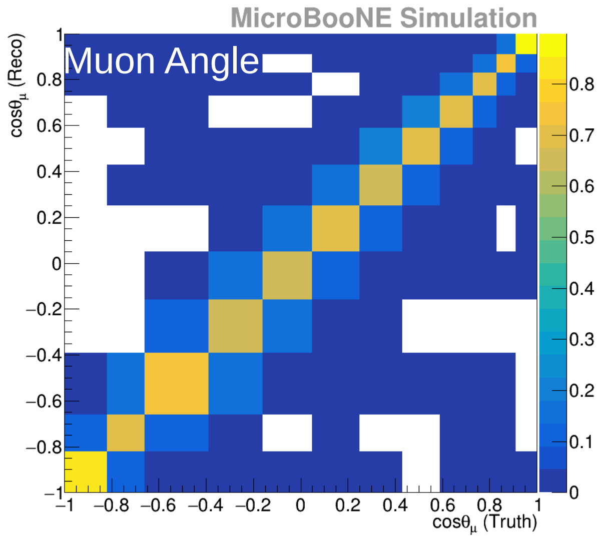
Folding method – bad?

- Smearing uncertainties only partially propagated to final results

- Fortunately, our smearing:
  - Has no interdependency (muon momentum doesn't depend on proton angle, etc)
  - Is not model-dependent (fake data studies verified this)
  - Has a small uncertainty
- Our biggest uncertainties come from the efficiency itself
  - And those uncertainties are taken care of just fine, we believe

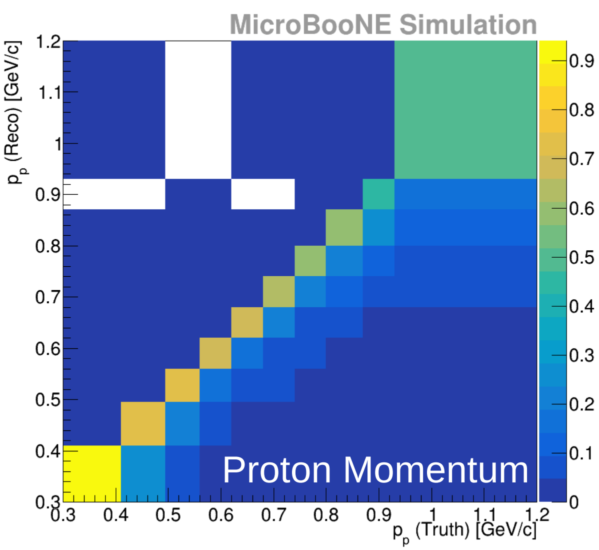
Smearing matrices

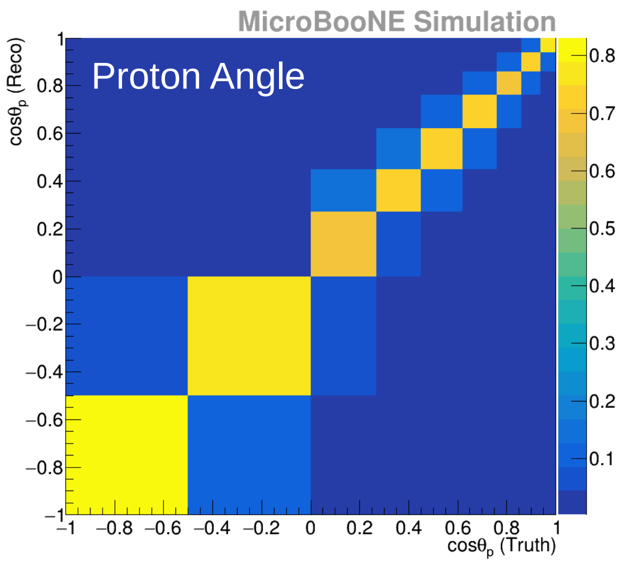


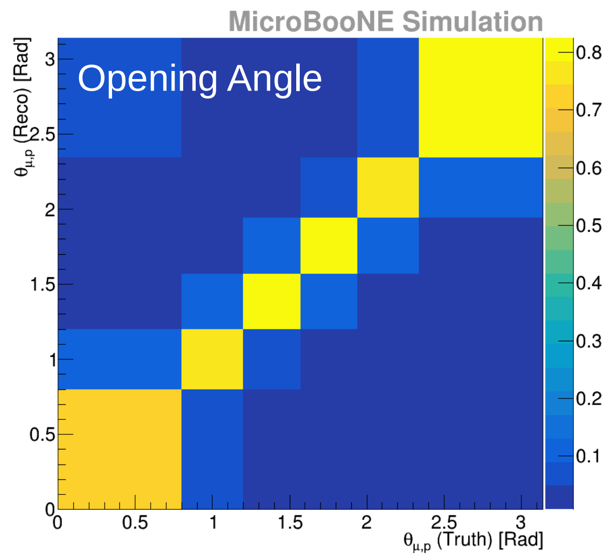


Angles generally very diagonal

Proton momentum has some down-smearing







Systematic Uncertainties

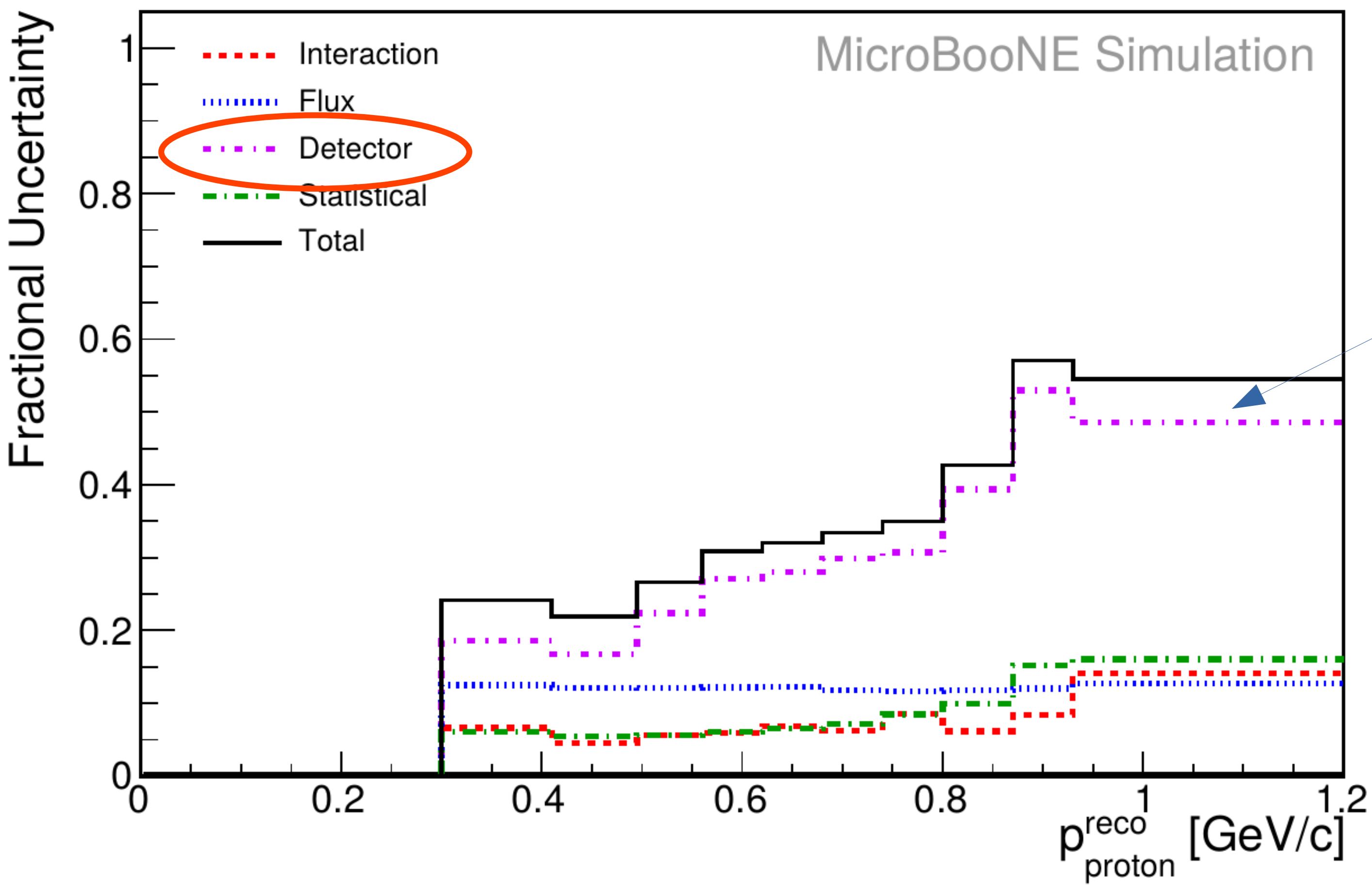
Sub-dominant Uncertainties

- Flux model:
  - 15% (11% normalisation)
- GENIE uncertainties:
  - 4-10%
  - below 2% efficiency uncertainty
- Extra CCQE/CCMEC uncertainty:
  - Switch both to Nieves model
  - Minimal efficiency impact. Backgrounds change though
- Secondary interactions:
  - < 2% on average
  - 7% at highest proton momentum

Interestingly, our biggest interaction uncertainties are due to background CCQE and MEC events!

Overlaid cosmics and OOFV events all scale with the total neutrino event rate...

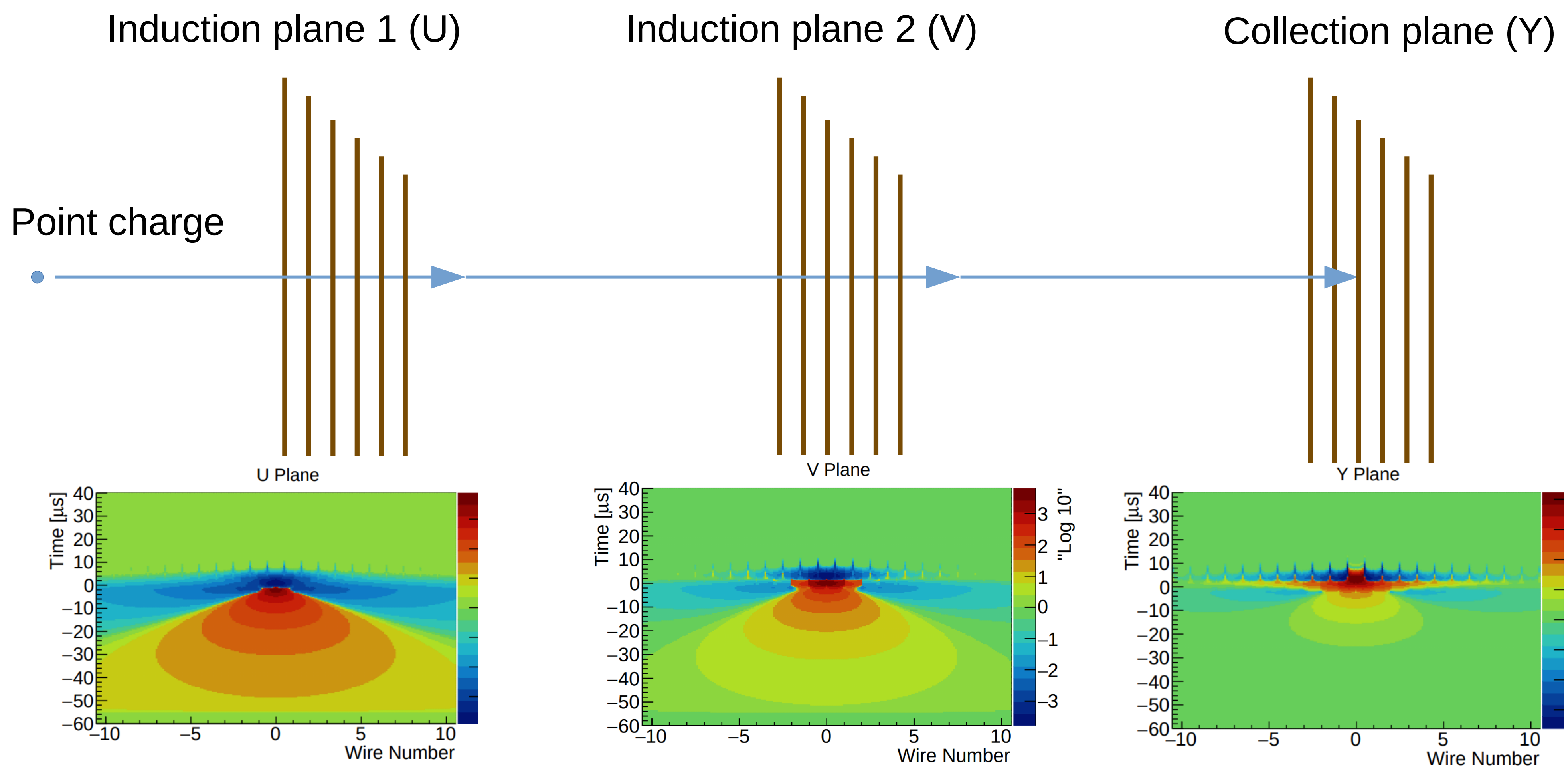
The detector



Detector uncertainty always dominates, reaching 50% or more.

Primarily induced charge effects

Those LArTPC signals again



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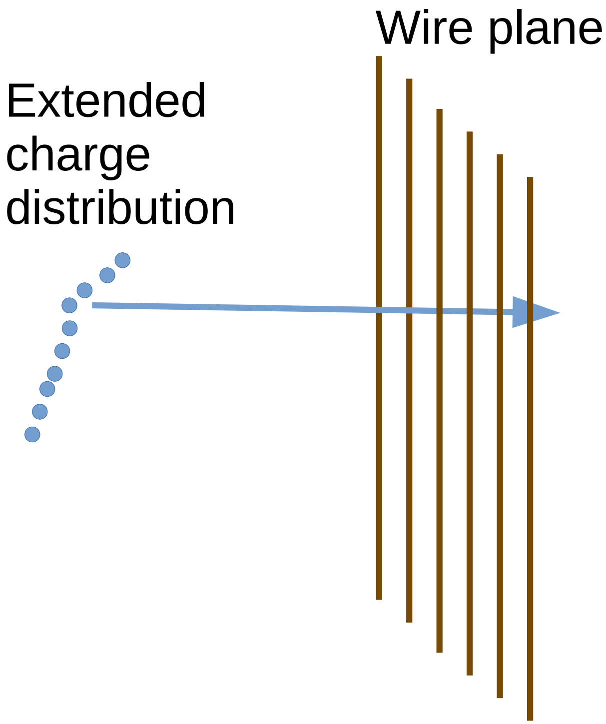
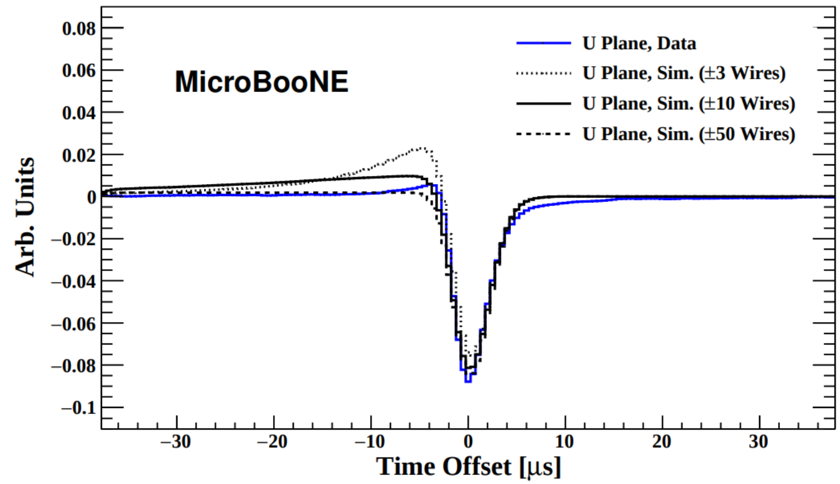
University of Minnesota

LArTPC signals for tracks



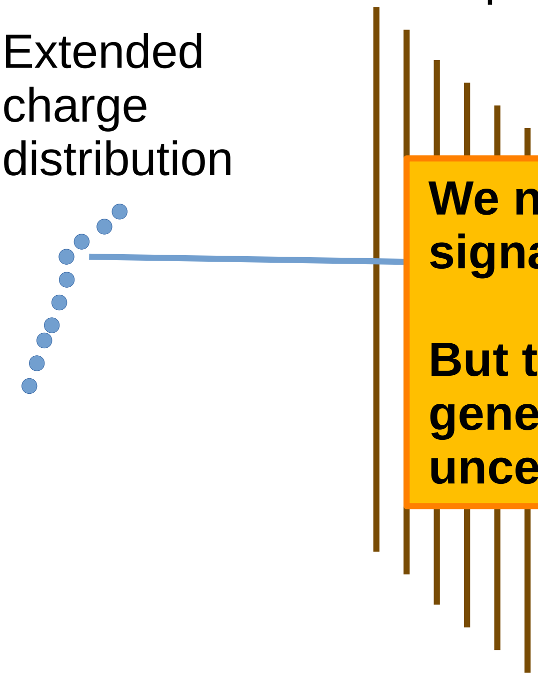


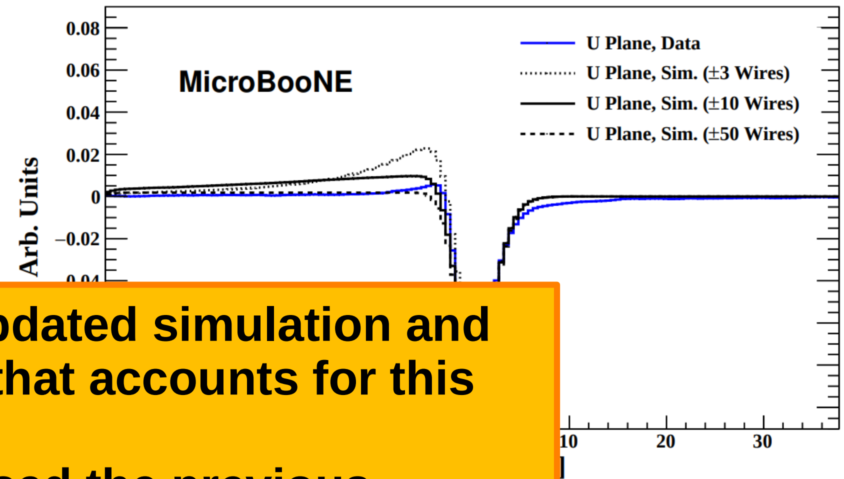
- All wires will see induced signals for each point-like charge
- Different points in the charge distribution give signals at different times
- **Correct** simulation needs to sum all the contributions of all signals with time offsets
- Leads to an angular dependence to the signal shapes

LArTPC signals for tracks

Extended charge distribution

Wire plane





We now have an updated simulation and signal processing that accounts for this

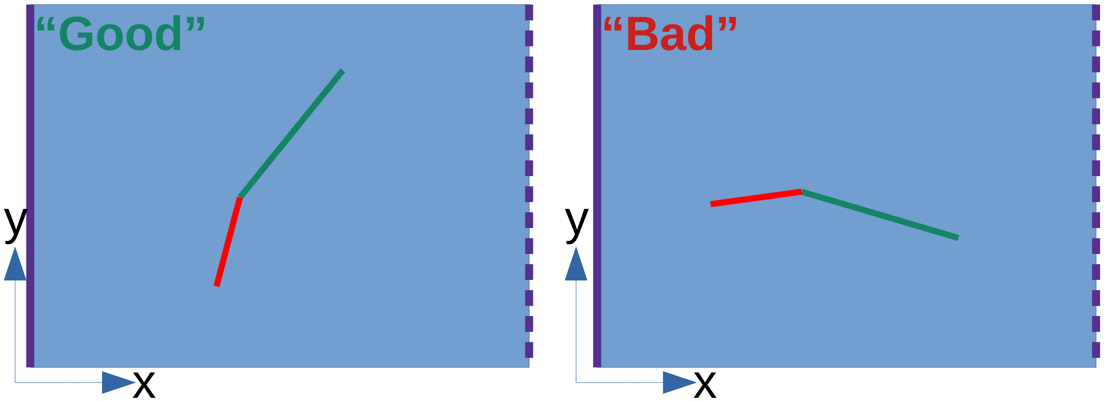
But this analysis used the previous generation, and we include a systematic uncertainty that covers the effect

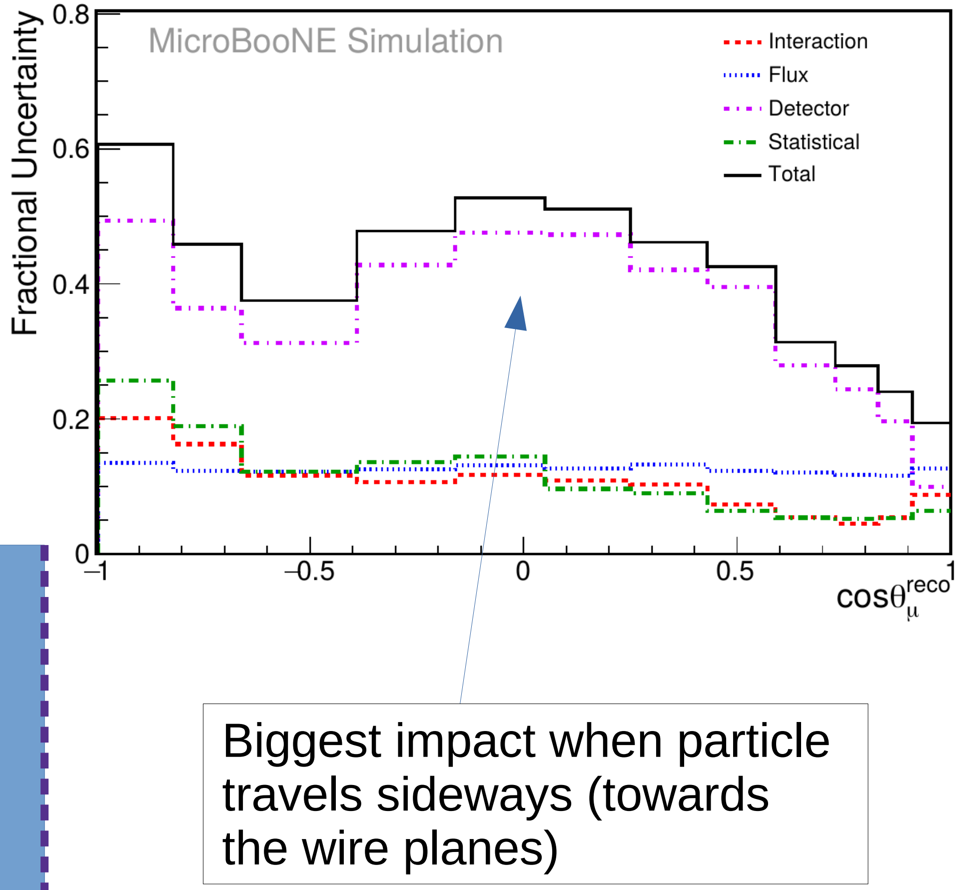
each point-like charge

- Different points in the charge distribution give signals at different times
- **Correct** simulation needs to sum all the contributions of all signals with time offsets
- Leads to an angular dependence to the signal shapes

Induced charge uncertainty

- Induced charge effects reduce the efficiency at certain angles
- Those angles are symmetric
- Momentum conservation means muon and proton tend to get "hit" at the same time
- Additionally, a few percent impact to PID efficiency due to charge smearing





The results

Does this slide have enough acronymns?

- We modified NUISANCE to include our data and smearing routines
- Used this to make comparisons to several generators
  - GENIE v2.12.2
  - GENIE v3.0.6 (G18_10a_02_11a)
  - NuWro v19.02.1
  - NEUT v5.4.0.1
  - GiBUU 2019

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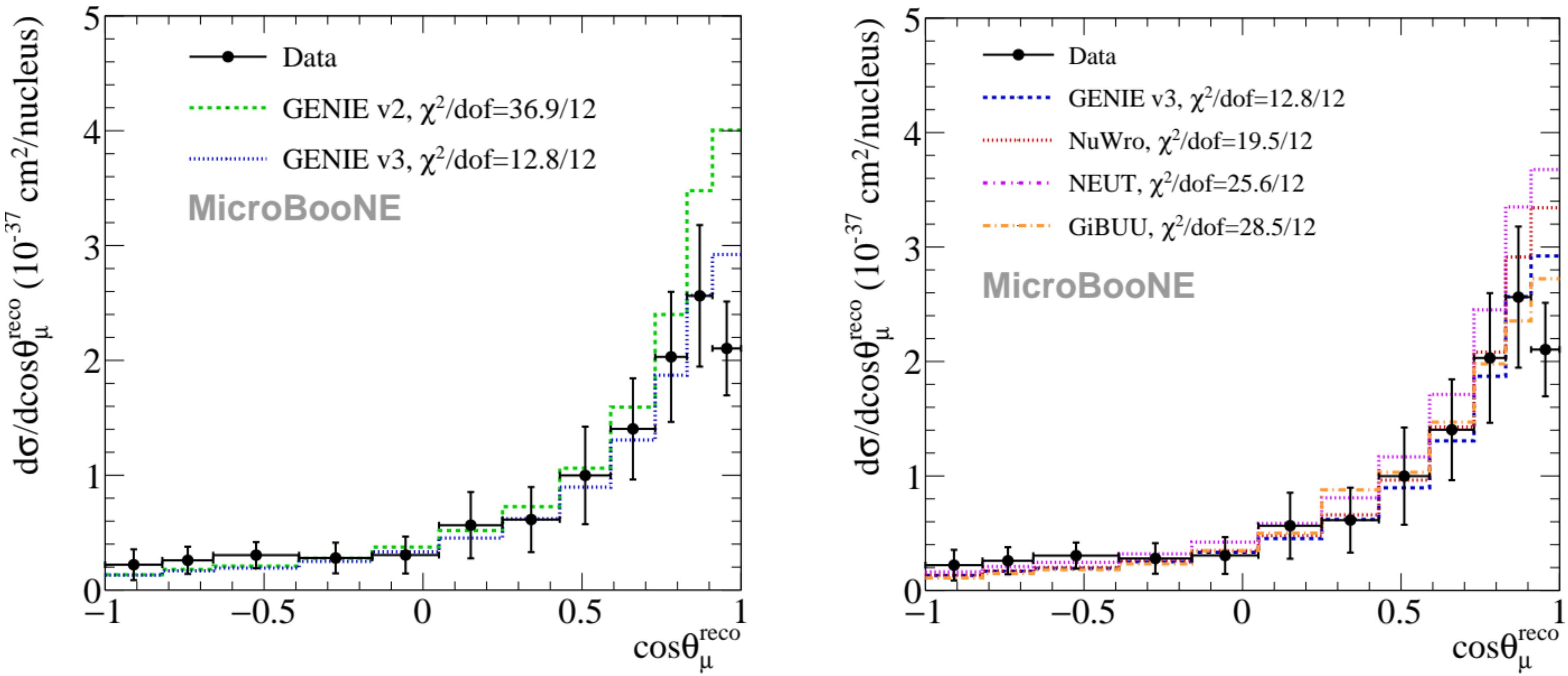
GENIE version used for MC in this analysis

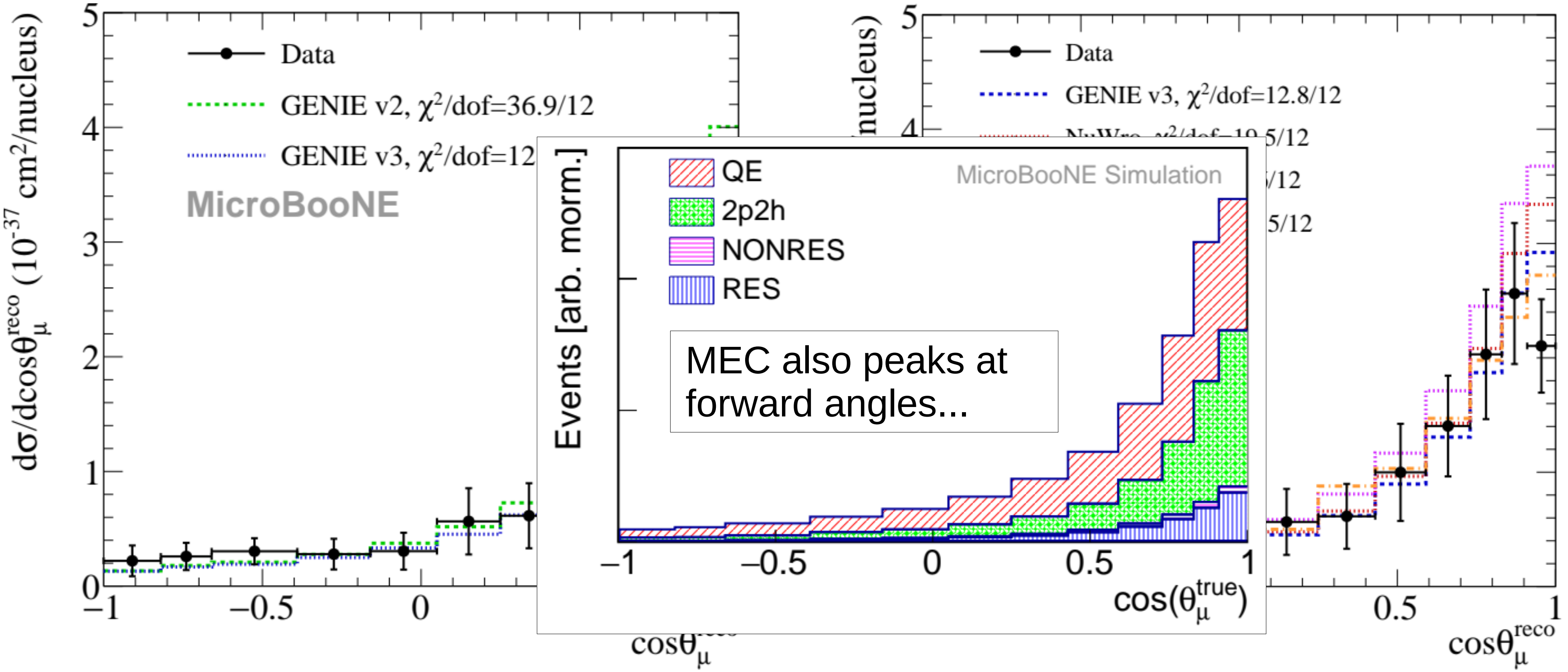
MicroBooNE now basing MC off this “tune”

Muon Angle



- BIG over-prediction at forward angles
- Models with RPA do much better, but not quite there

Muon Angle



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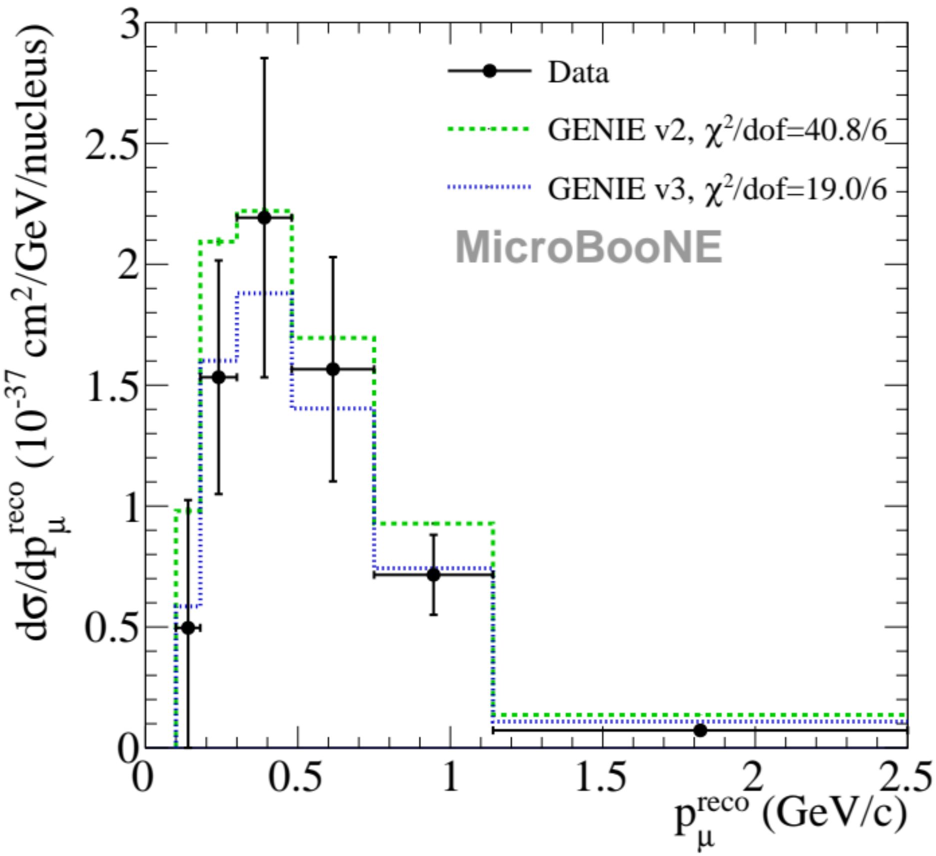
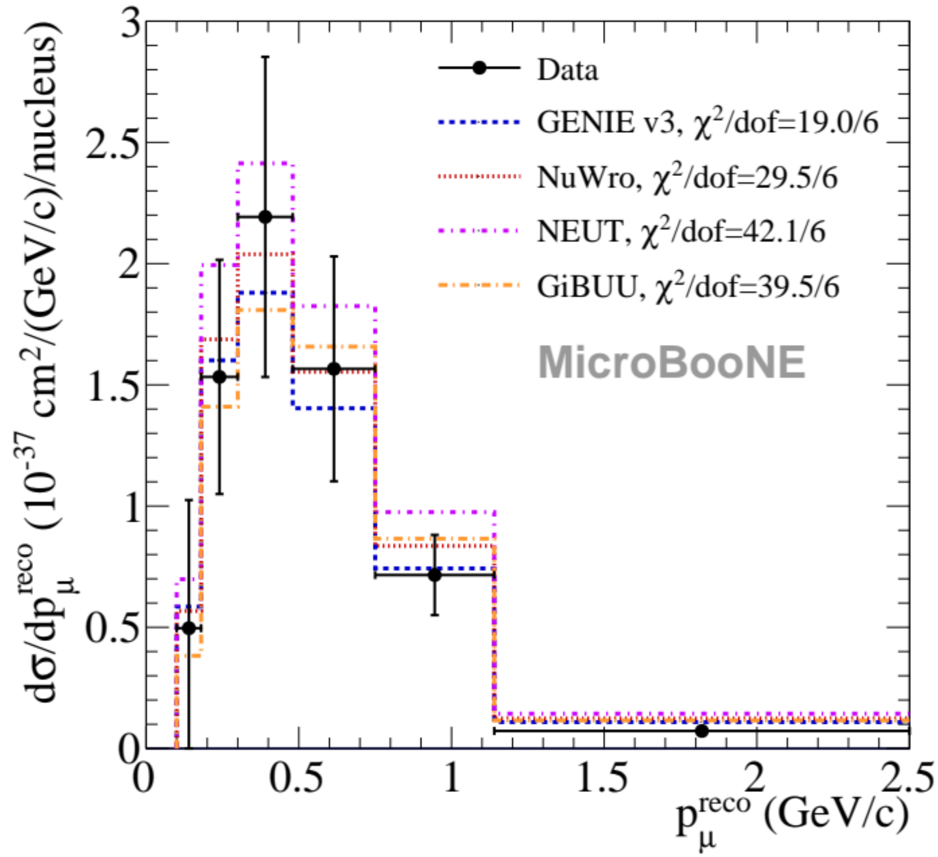
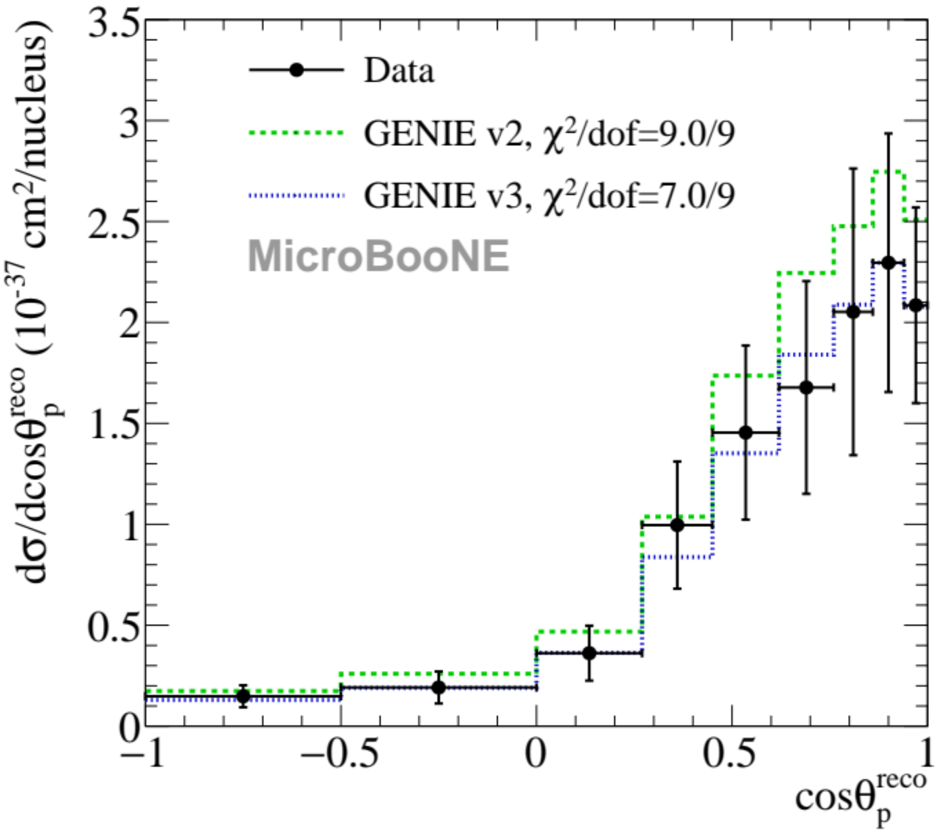
Muon Momentum

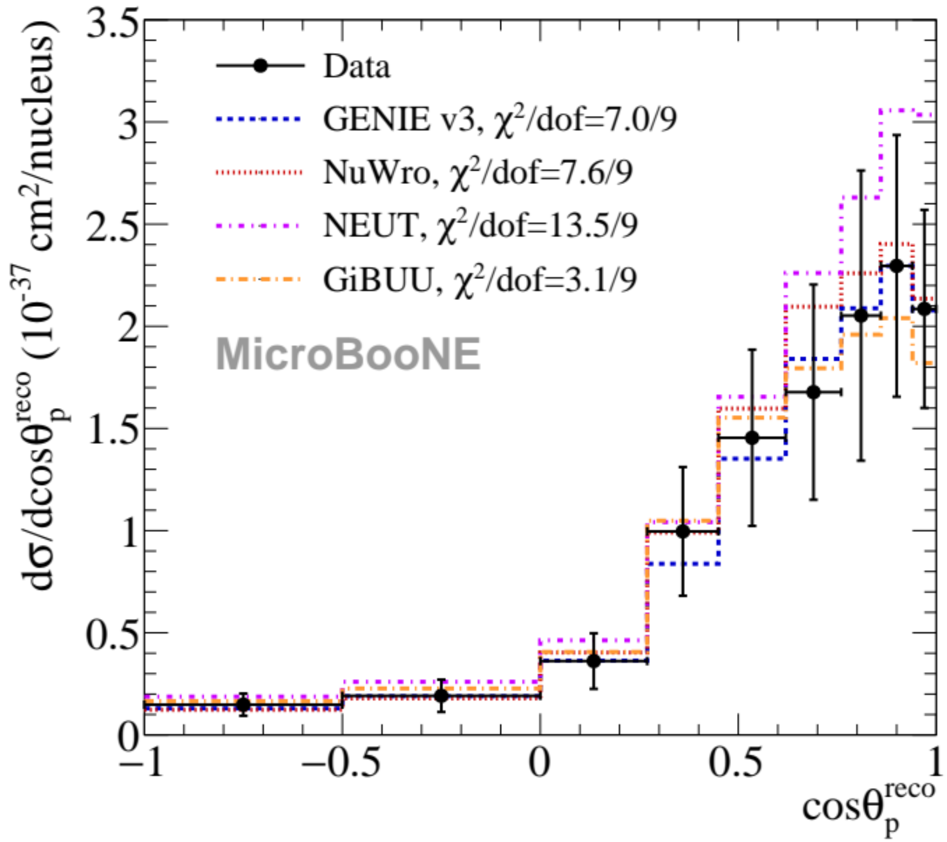




- Error bars look big but correlations constrain shape
- Large χ^2 values driven by highest-momentum bin

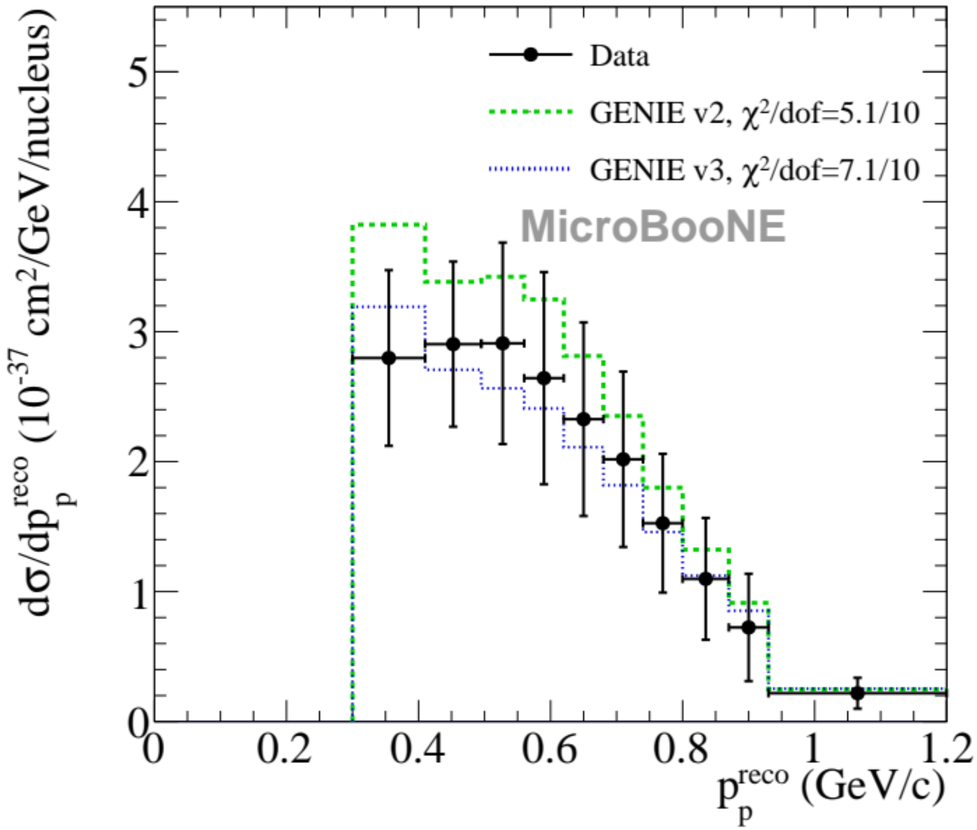
Proton Angle

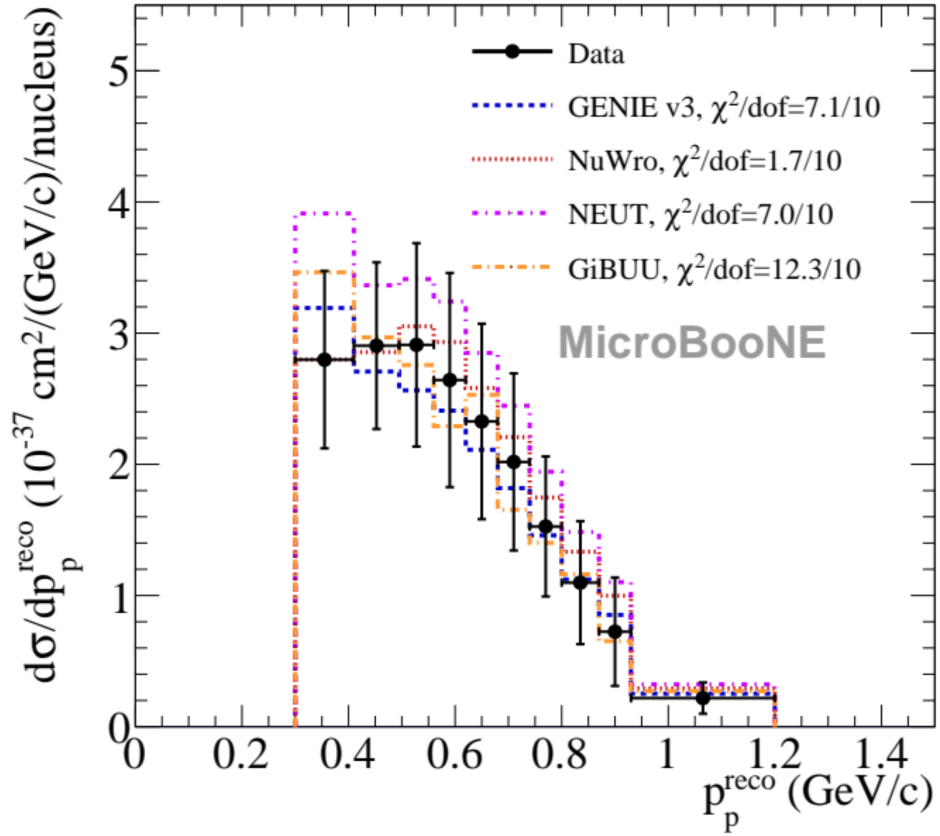




- Agreement is remarkably good for all generators!
- Again, error bars contain large normalisation component

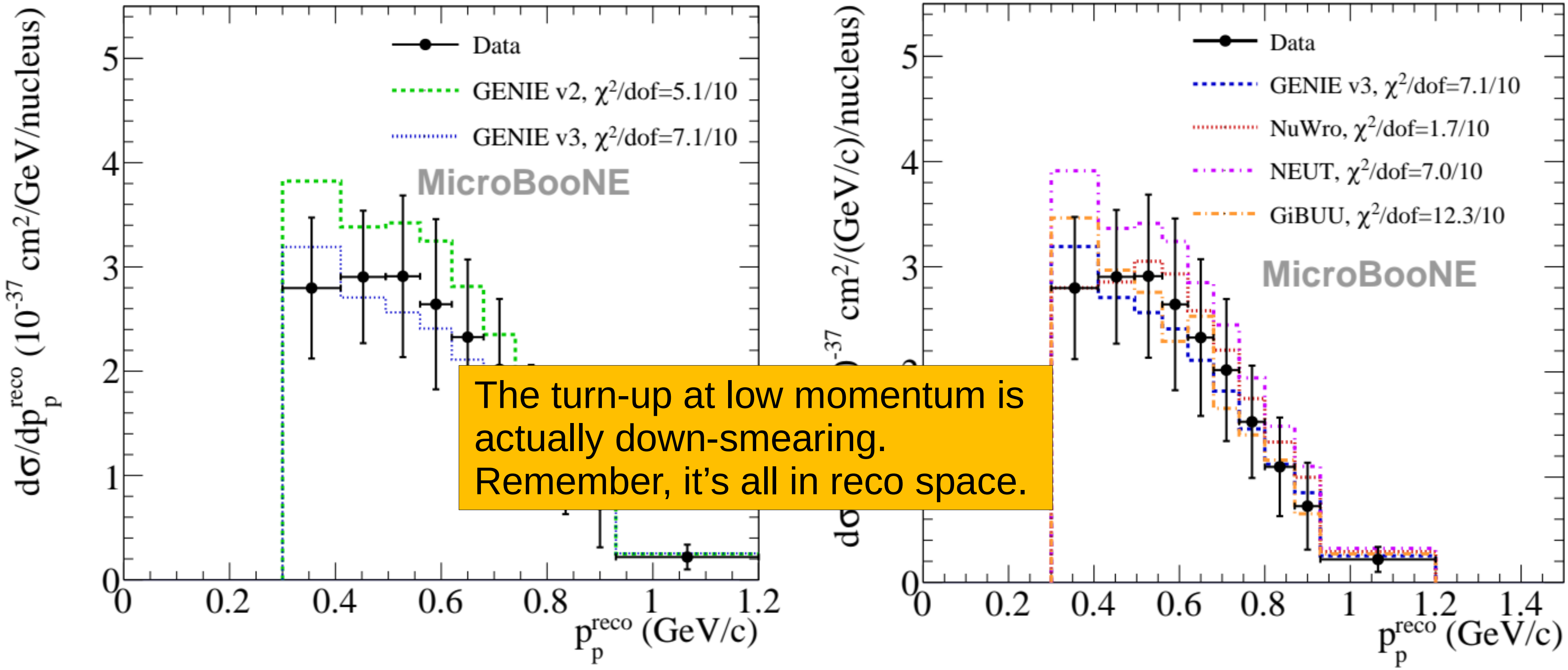
Proton Momentum





- Low momentum bin is **new** – starting to become sensitive to FSI differences
- NuWro is MVP for proton momentum!

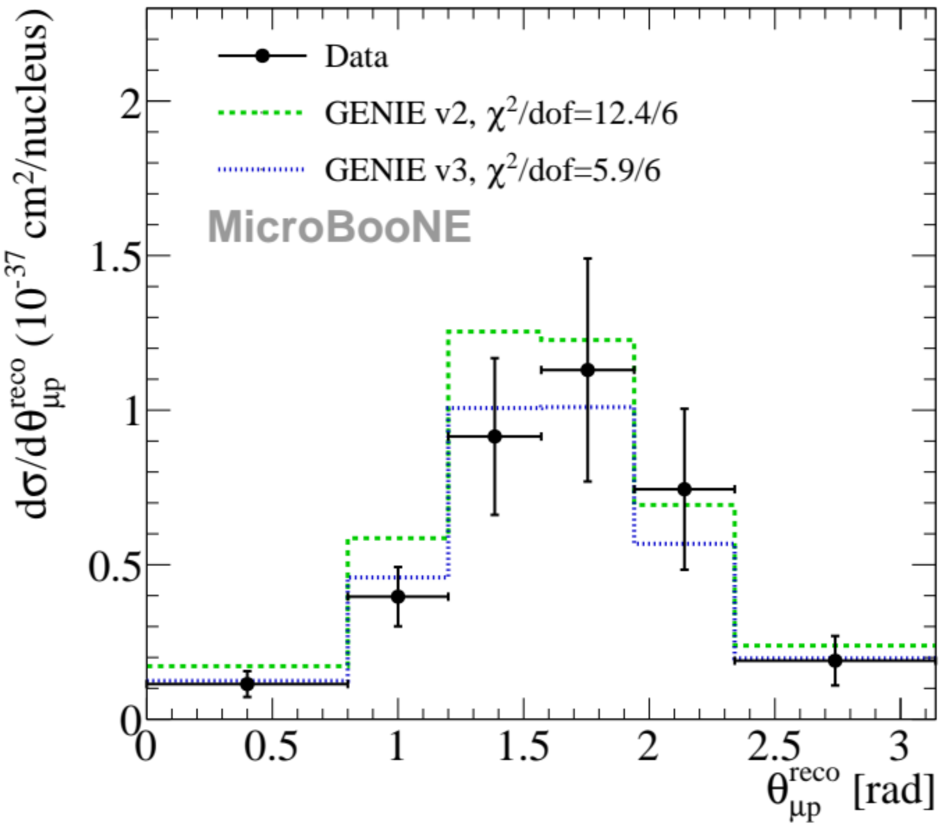
Proton Momentum

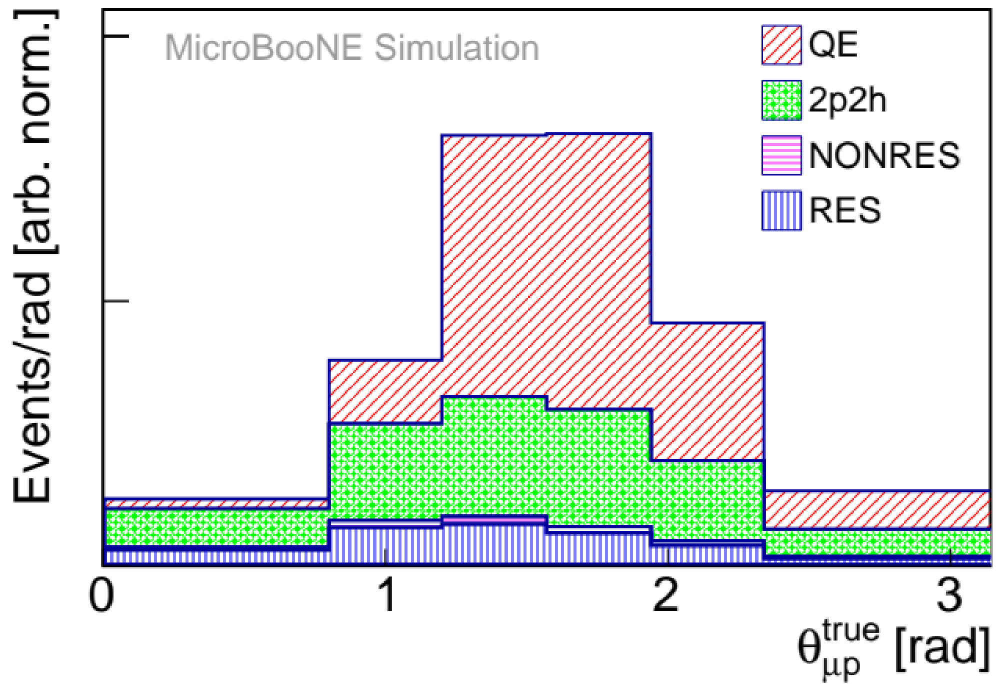


The turn-up at low momentum is actually down-smearing. Remember, it's all in reco space.

- Low momentum bin is **new** – starting to become sensitive to FSI differences
- NuWro is MVP for proton momentum!

Opening Angle

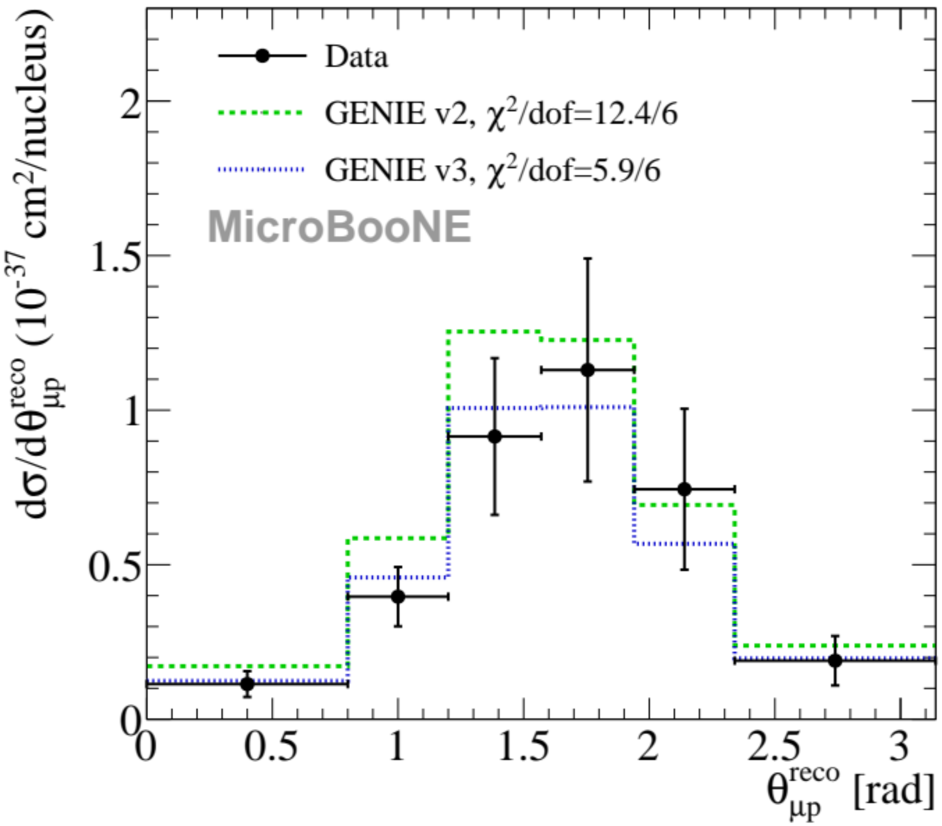


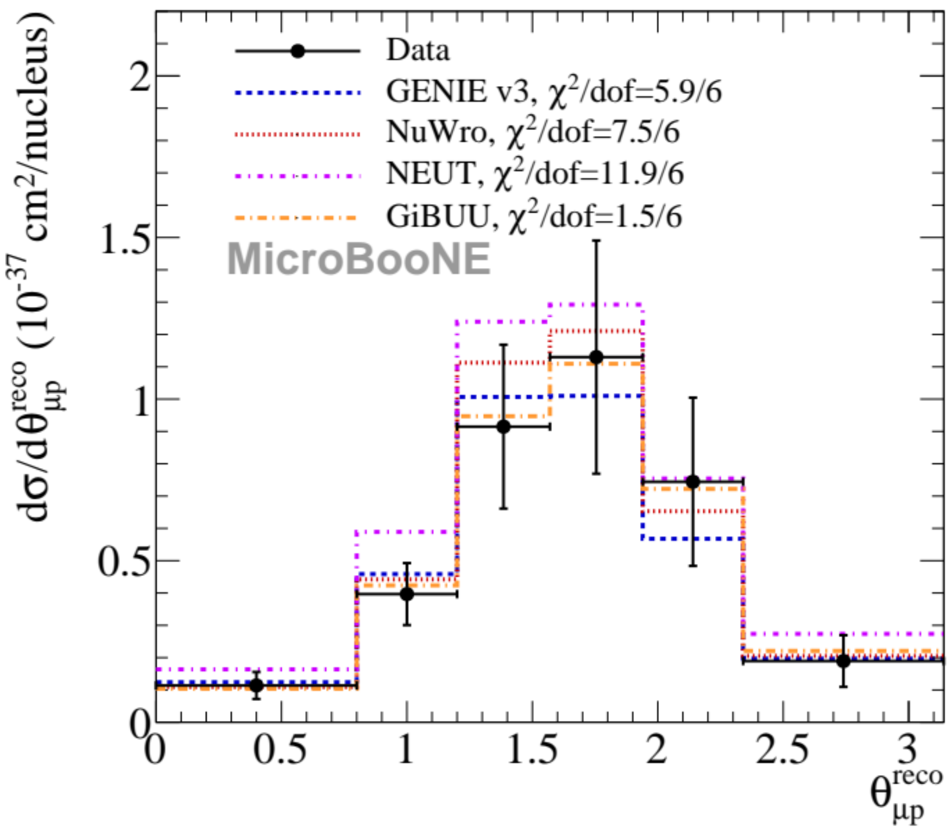


Variable very good at distinguishing QE from other components

Clearly the QE/MEC ratio isn't *too* far off

Opening Angle





- Data shows a shift in the peak position to slightly higher opening angles
- GiBUU, NEUT, and NuWro all predict the same shift

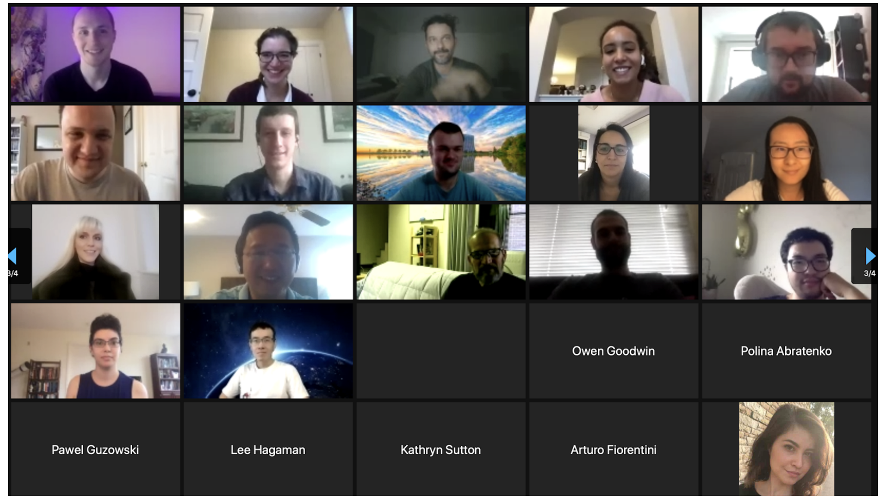
Data Summary

- First ever measurement of CC0πNp on argon
- **Low proton threshold** achieved
  - Generators still holding up down there!
- **Large phase space** measured
  - Future analysis may be able to increase slightly
- Data sensitive to QE/non-QE ratio, FSI, RPA
- No stand-out winner generator
  - Multi-dimensional analyses will reveal more
  - Modern generators tailored to carbon data work reasonably well for argon

Future Prospects

- 10x as much data ready to analyse
  - Did someone say *double differential?*
- New simulation, new signal processing
- 3-plane PID
  - **Better angular efficiency**, better cosmic rejection, **lower threshold?**
- Completely re-vamped detector uncertainties
  - **Significantly** reduced in preliminary analyses
- Working on various derived variables
  - Transverse kinematics – interesting comparisons with carbon data
  - 2-proton final states, etc

Thank you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Polina Abratenko
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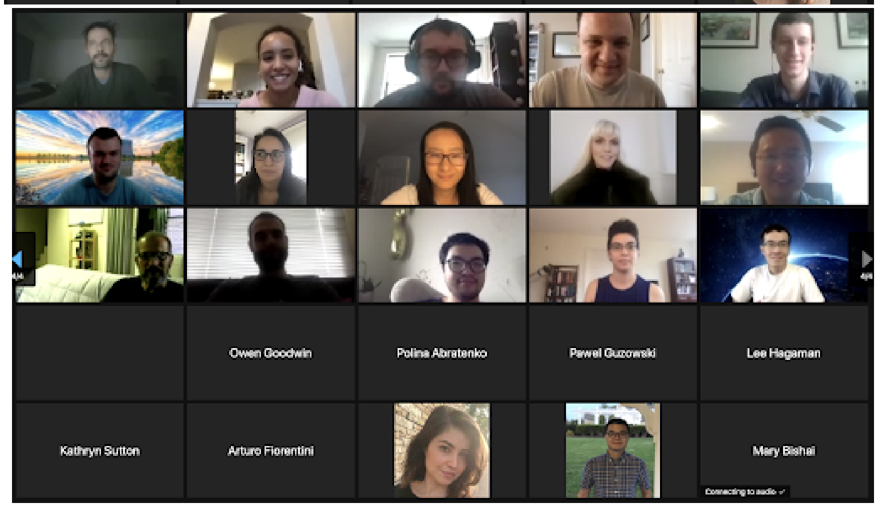
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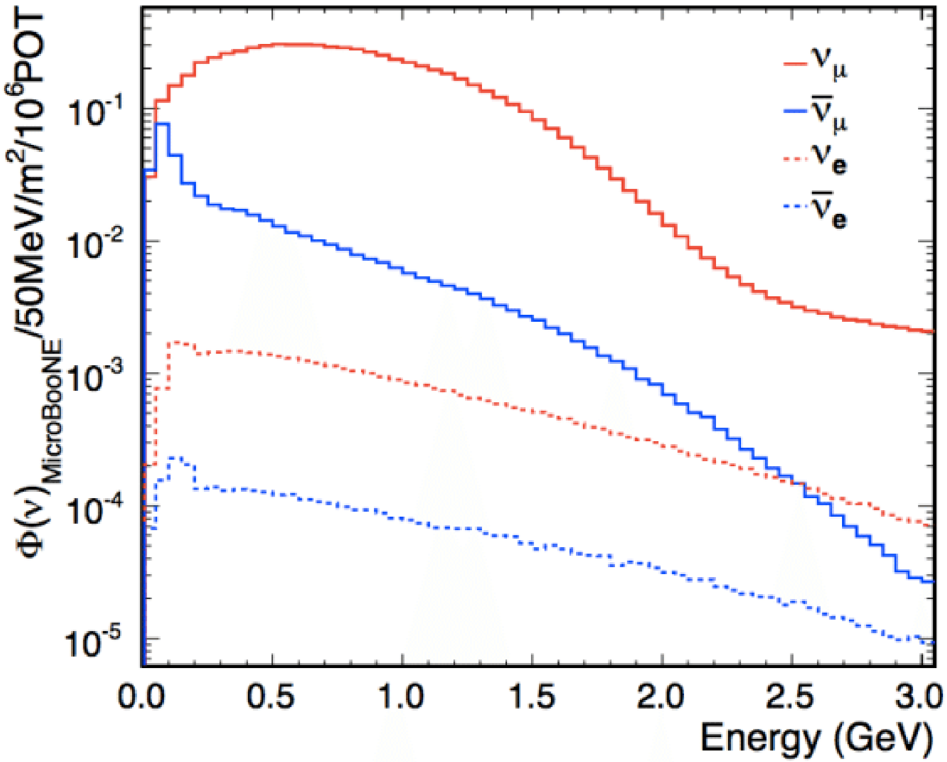
Kathryn Sutton
Arturo Fiorentini
Mary Bishai

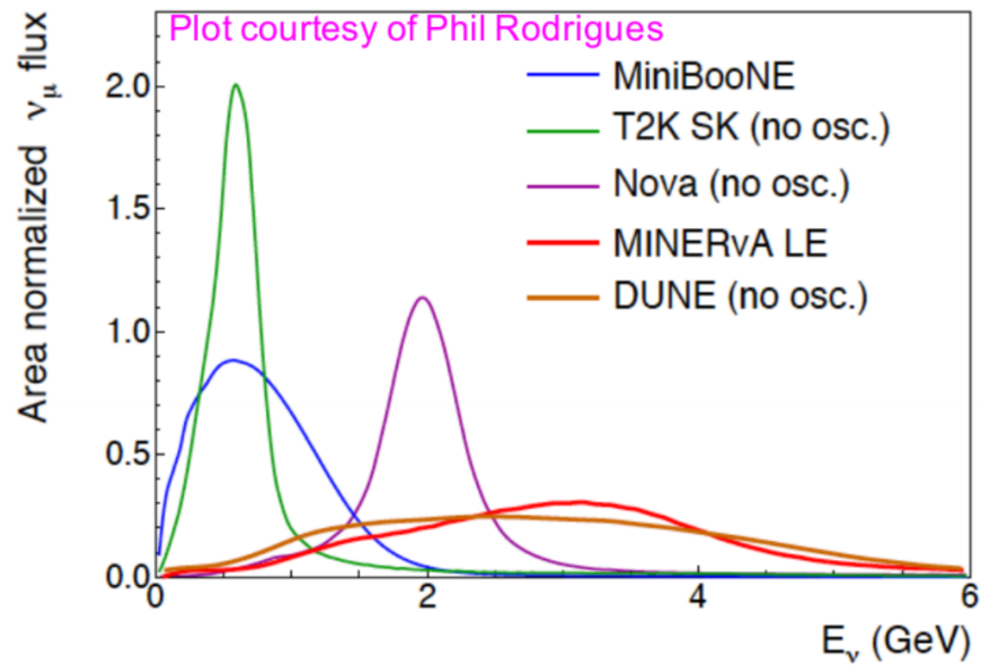
Backup Slides

Booster Neutrino Beam



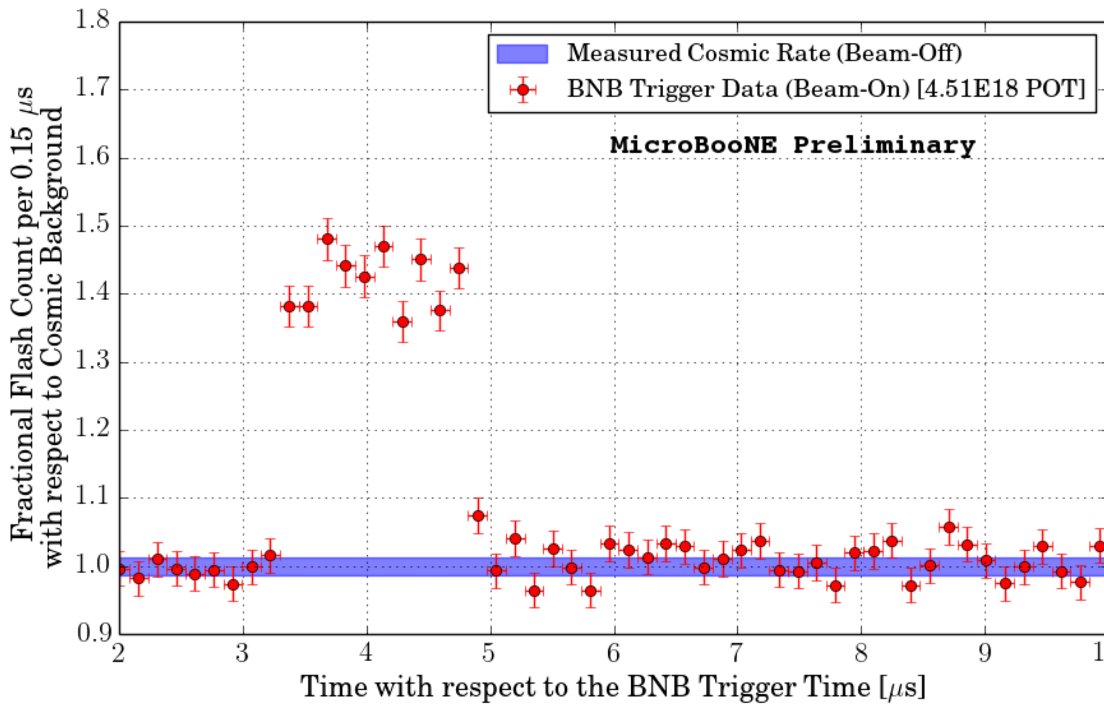
Low energy, and wide spectrum

Minimal high-energy tail (8 GeV proton beam)



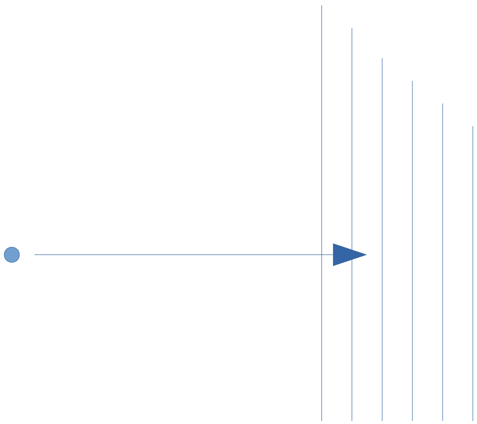
Beam timing

- Beam only lasts for 1.6μs
- Drift time is up to 2.2ms
- 99.9% of signal events produce light in time with the beam spill
- 1% of cosmics produce light in time with the beam spill

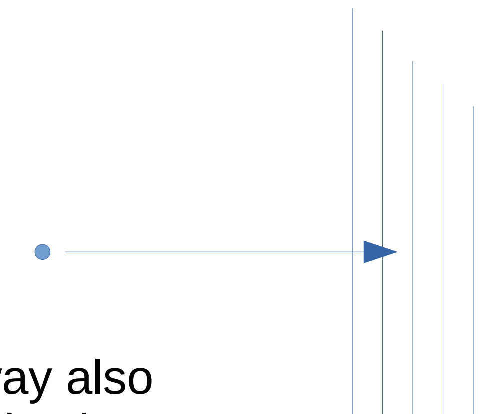


LArTPC signals

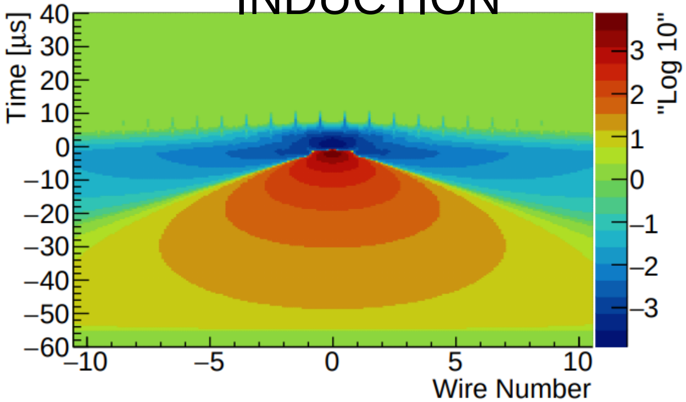
Induction plane



Collection plane

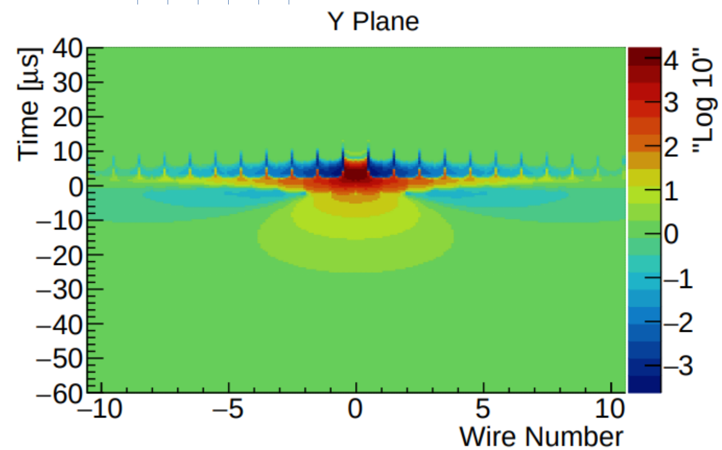


INDUCTION



Wires further away also see a weaker induction signal

Even on the collection plane



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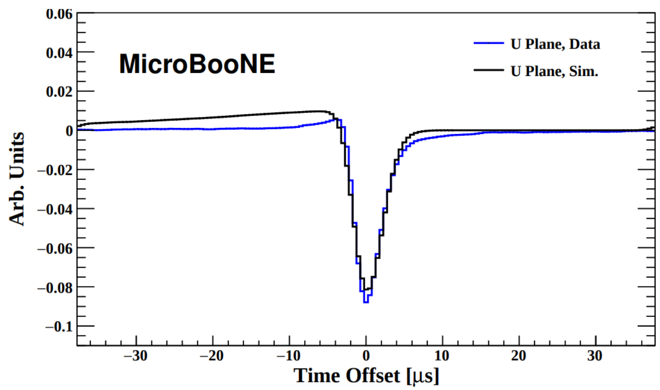
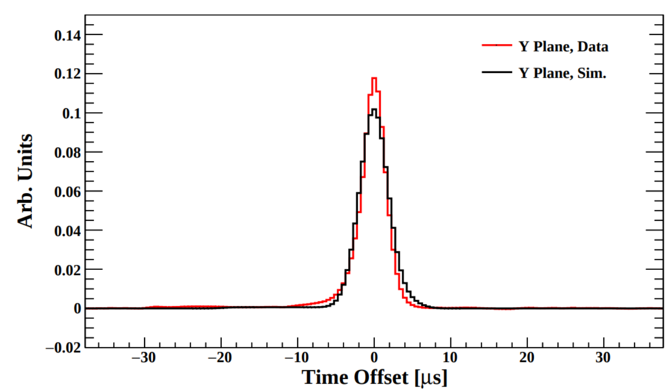
University of Minnesota

Those TPC signals again

- Collection plane **collects** charge – the area is proportional to the charge
- Induction planes don't collect charge – the peak height is proportional to the charge
- **Collection plane has better signal-to-noise** (50:1 vs 10:1)
  - Additionally, due to our use of nearest-neighbour induction signals, the response on the induction planes is not modelled well (improvements coming though!)
- **For this analysis, we only use the collection plane**



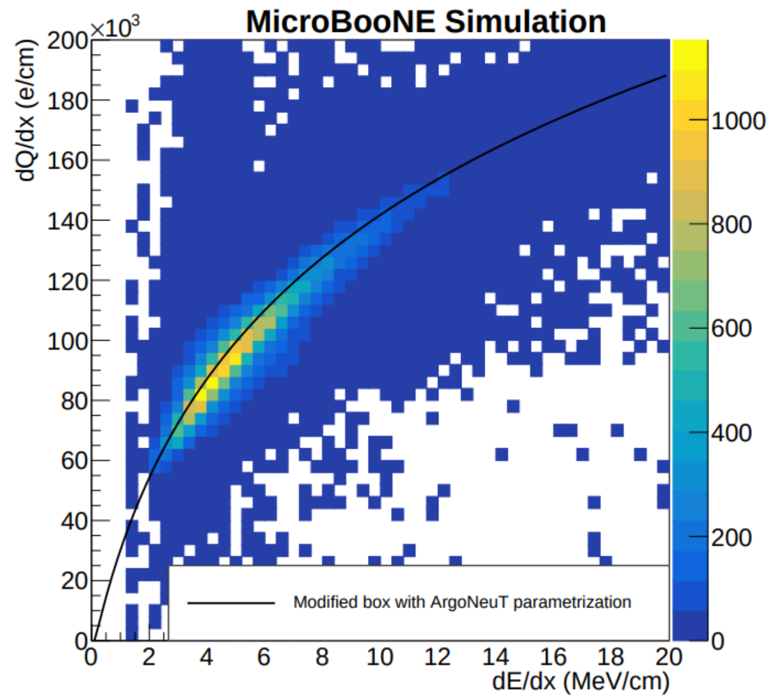


What was used in this analysis

- Our understanding of LArTPC signals has improved greatly in the last 2-3 years
- We have now updated our simulation and signal processing based on this
- But, **for this analysis** we are still using the "simple" nearest-wire treatment
- In-progress analyses are being developed with better signal simulation

Recombination

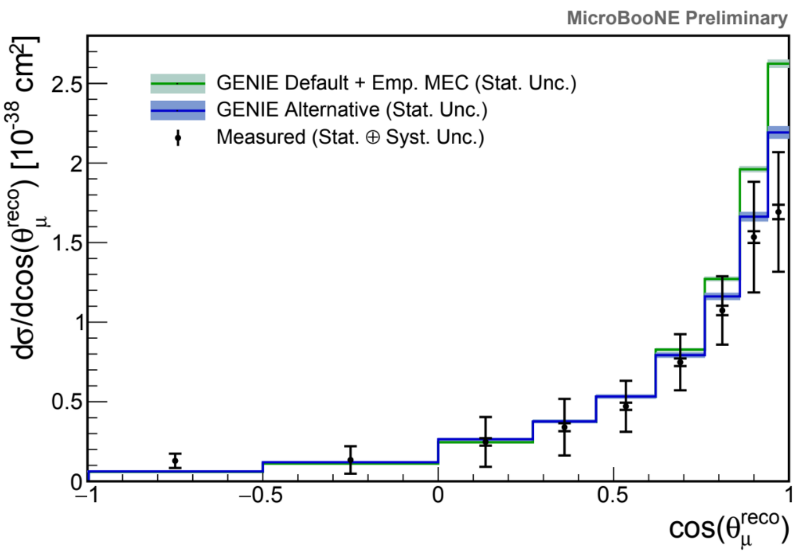
- Ionisation electrons can “recombine” with argon ions
- The rate at which they do this depends on the local density of argon ions
- Non-trivial conversion from observed charge → deposited energy



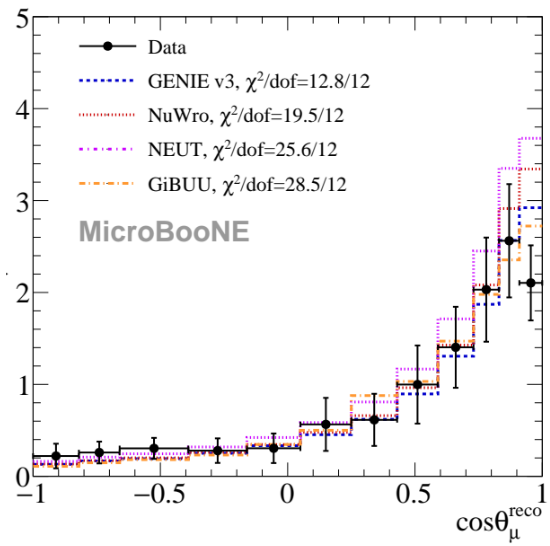
Cos theta comparions

- Defect at forward angles grows as QE content increases
- We interpret this as an *indication* that the QE-RPA suppression needs to be increased further

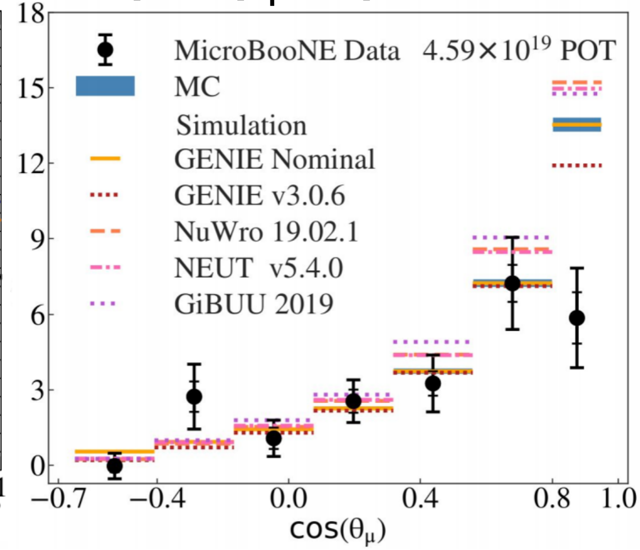
CC-inclusive



CC-Np



CC-1p QE-like (low p_T etc)



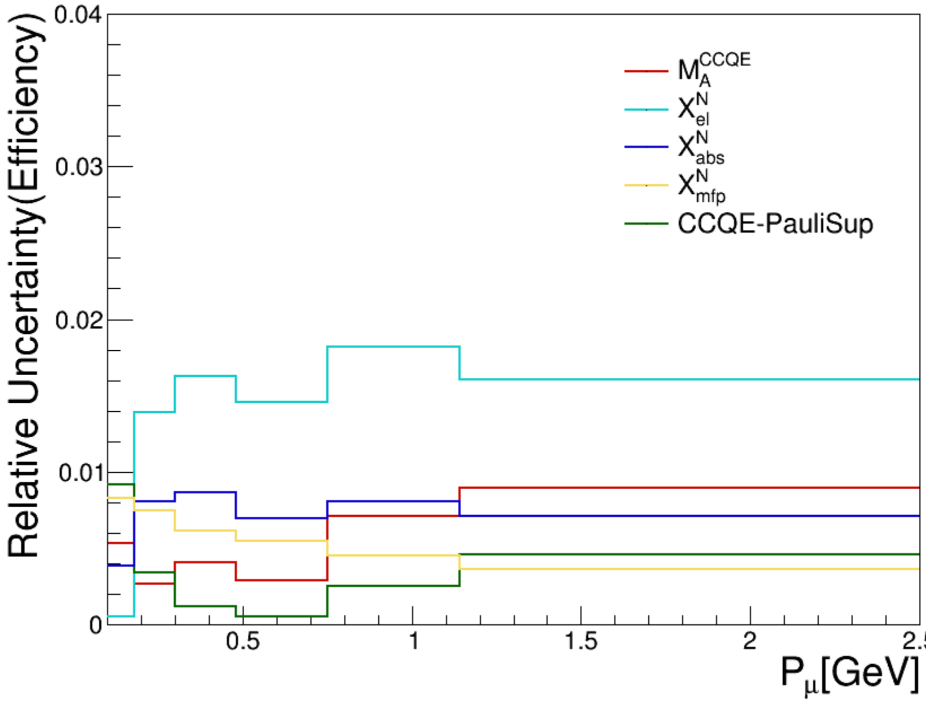
Fake Data studies

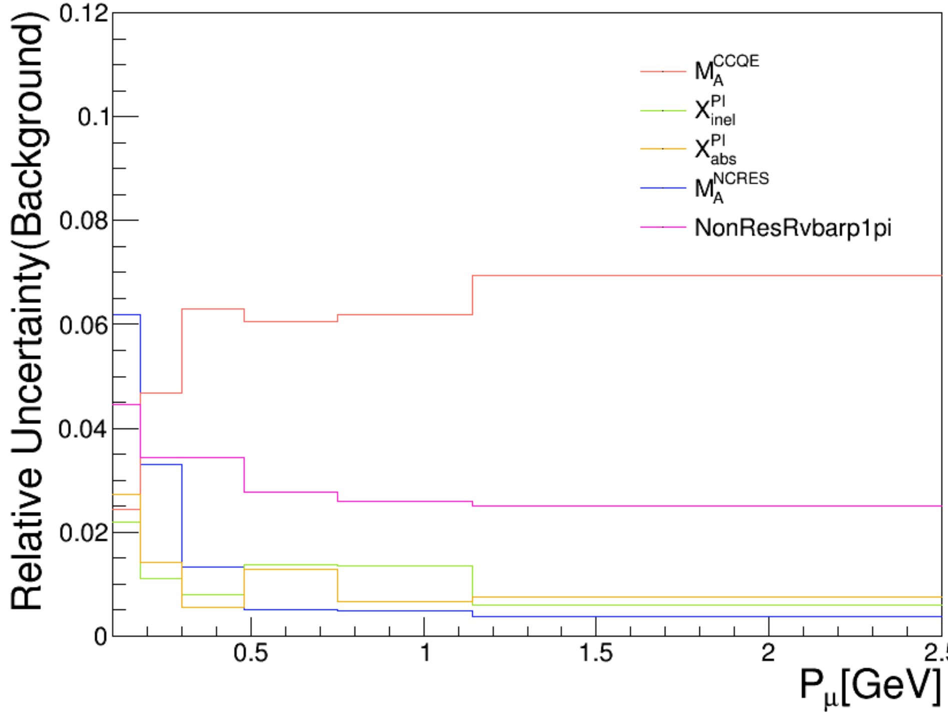
- Primary fake data study:
  - Alternative GENIE model set “treated as data”
  - Still uses GENIE v2.12.X, but ran with non-standard configuration
  - Nieves QE/MEC
  - Berger-Sehgal for RES
  - hN instead of hA for FSI
  - Produces substantially different distributions to nominal MC (and closer to data)
- Results: extracted cross sections from fake data in agreement with the true xsec input
  - Within GENIE uncertainties

GENIE uncertainties

- Uncertainty on the **efficiency** from GENIE parameters < 2% (usually < 1%)
- FSI parameters (change proton angle/mom) most important

- Uncertainty on the **background** from GENIE parameters up to 5%
- Largest is M_A^{QE} – most backgrounds are cosmic-overlay and OOFV, which scale with total neutrino event rate





Reason to efficiency-correct

- Intention is to provide “theorists” with a single smearing matrix
- Encapsulating smearing and efficiency uncertainties on the data simplifies the data release
- Theorists don’t need to worry about the smearing uncertainty – that’s already on the data for them
- The limit… It’s only approximately the right answer

Forward-folding "problem"

- Reco-space efficiency defined as:

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

- Issue – if the efficiency is flat, then $N^{sel} = N^{gen}$ and the smearing matrix cancels
  - Uncertainties on the smearing matrix don't show up in the final measurement

Checks performed

1) Is the efficiency 100%?
   - No…
2) Is the efficiency flat and constant?
   - Also no
3) Is the smearing uncertainty large?
   - No, the smearing matrices are driven by well-understood physics and reconstruction effects
   - Muon momentum driven by multiple scattering
   - Angles driven by wire spacing etc
   - Proton momentum driven by vertex/end-point resolution
   - Smearing matrix changes by significantly less than the efficiency