MicroBooNE, Introduction and Latest Results

Joseph Zennamo,
Fermilab,
On behalf of MicroBooNE Collaboration

Weak Interactions and Neutrinos 2019
June 5th, 2019

Fermilab

Anomalies at Small-Baselines

There have been hints of short-baseline neutrino oscillation in experiments dating to the 1990s when LSND release their results

These results span a wide variety of experiments including searches at reactors, nuclear sources, and accelerators and point to a new (large) mass splitting

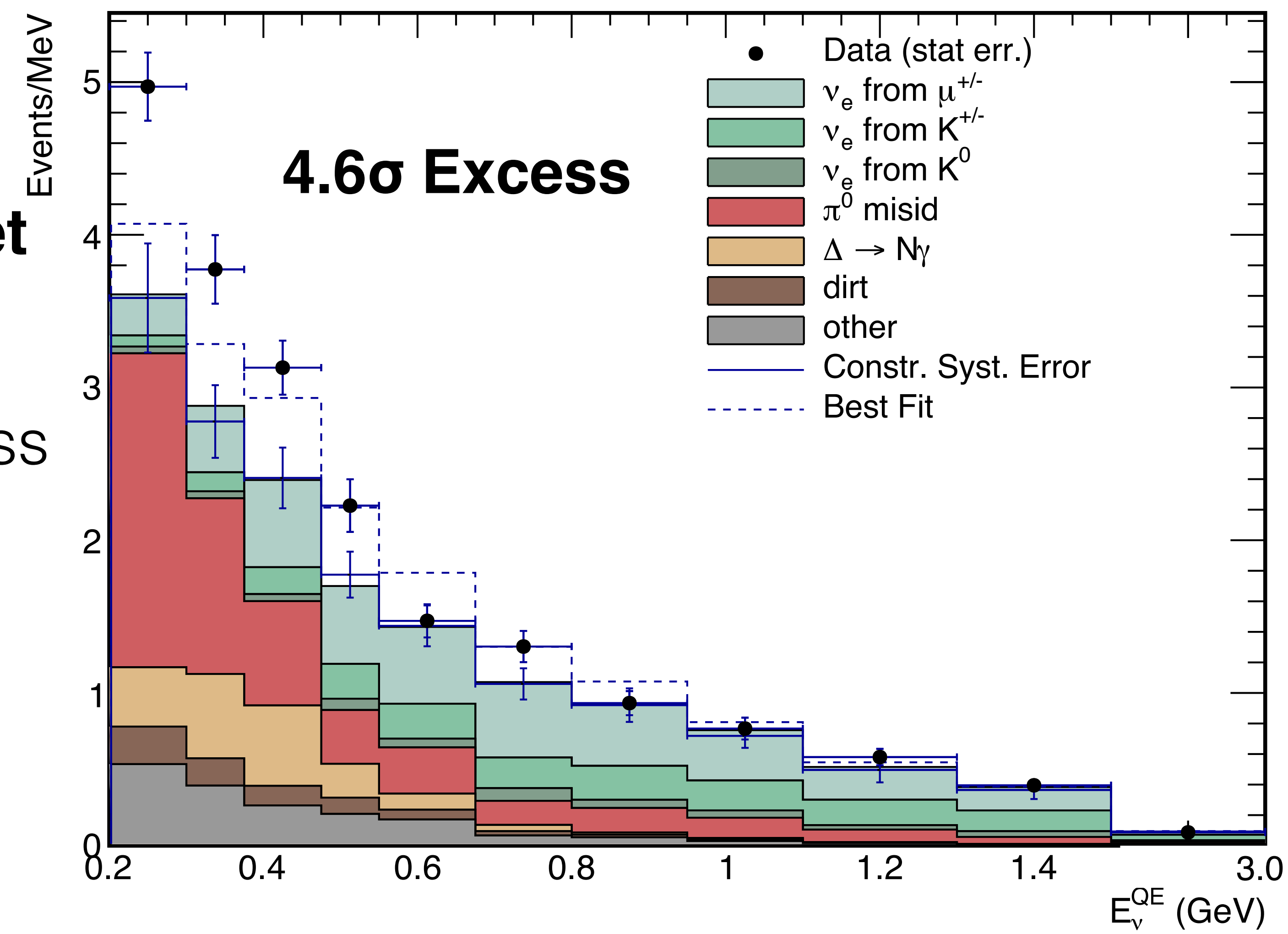
There are also number of negative searches which complicate the picture

One experiment with positive results, MiniBooNE, recently released updated results doubling their neutrino data-set

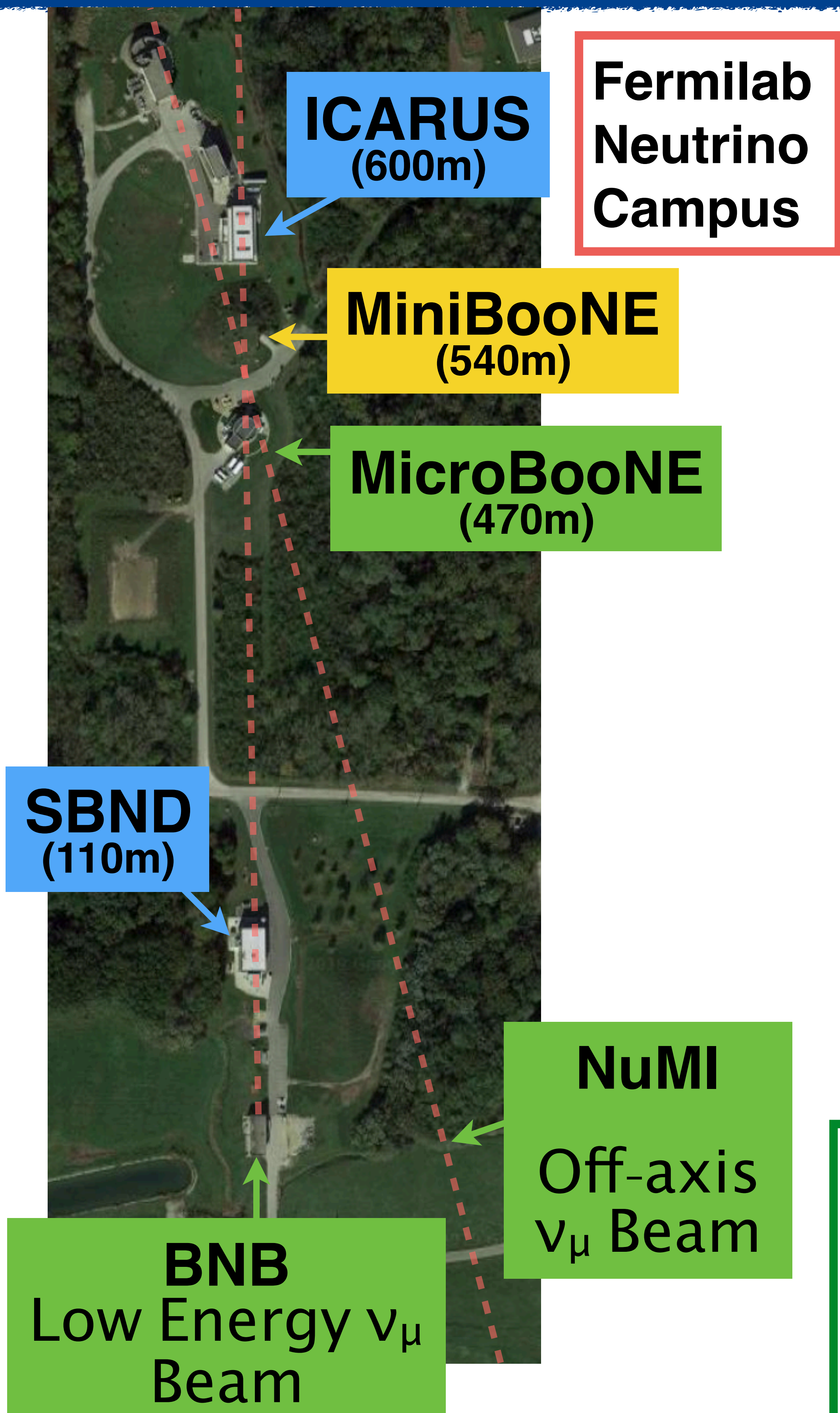
These new results increased the significance of their neutrino-mode excess

When these results were combined with their anti-neutrino data and the LSND results it yielded a high significance picture consistent with oscillations

PRL 121, 221801 (2018)



MicroBooNE



Past: MiniBooNE

Present: MicroBooNE

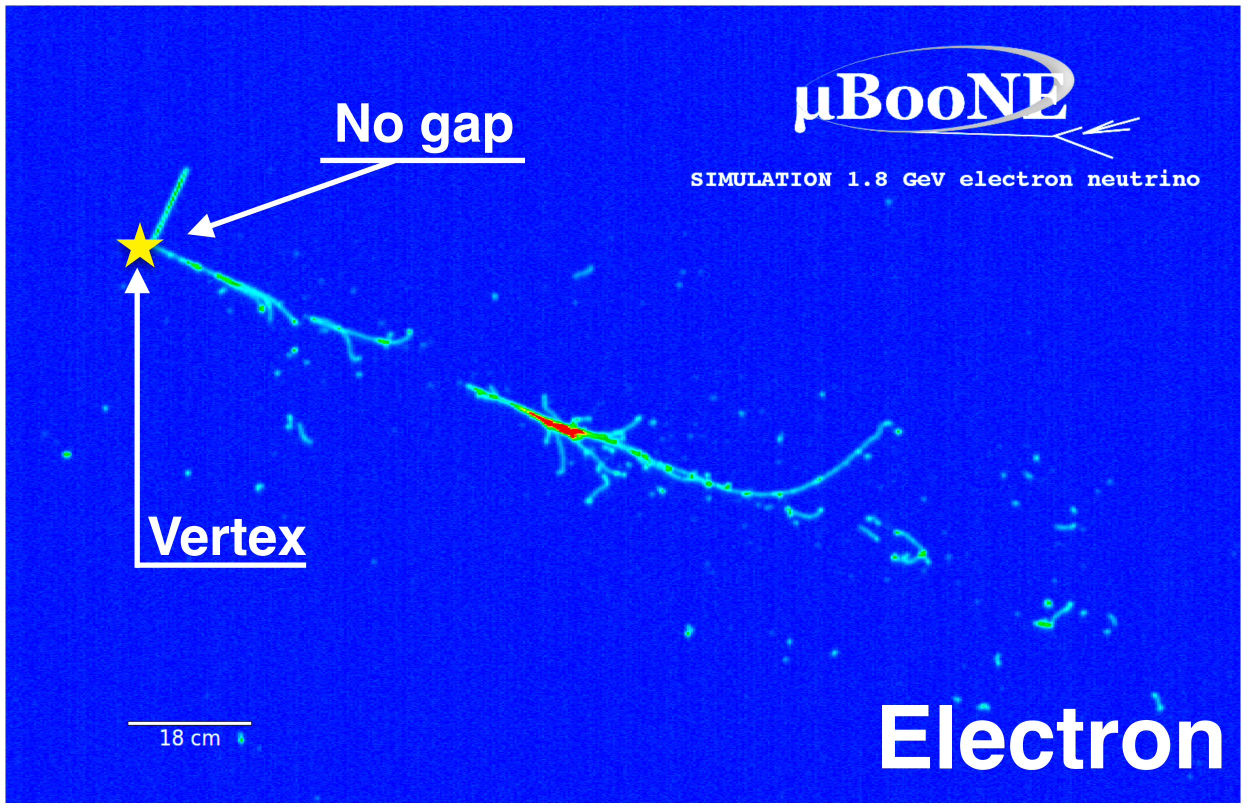
Using a different detector technology and sitting close to MiniBooNE determine the composition of events in the excess

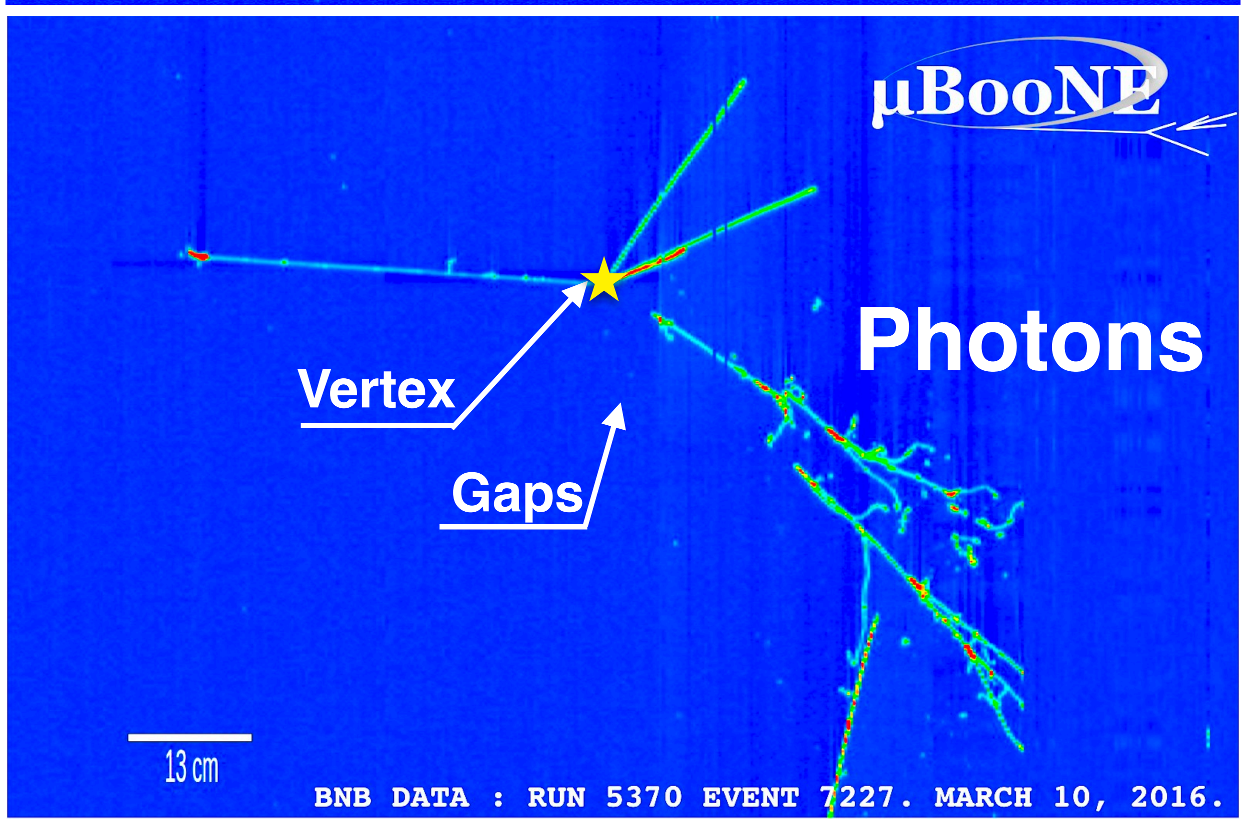
Future: SBN Program

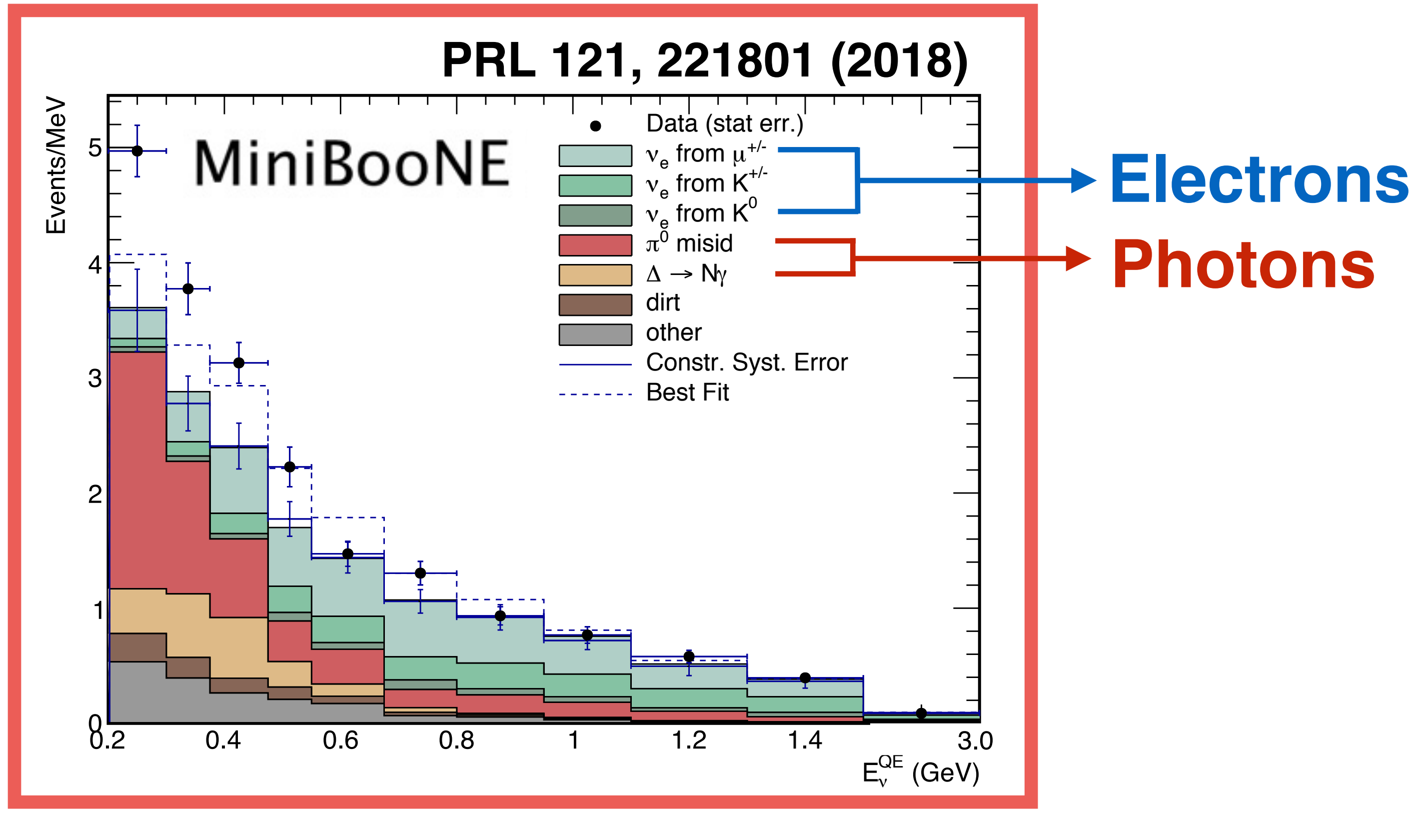
Adding two additional detectors to definitively explore the phase-space allowed by LSND at 5σ

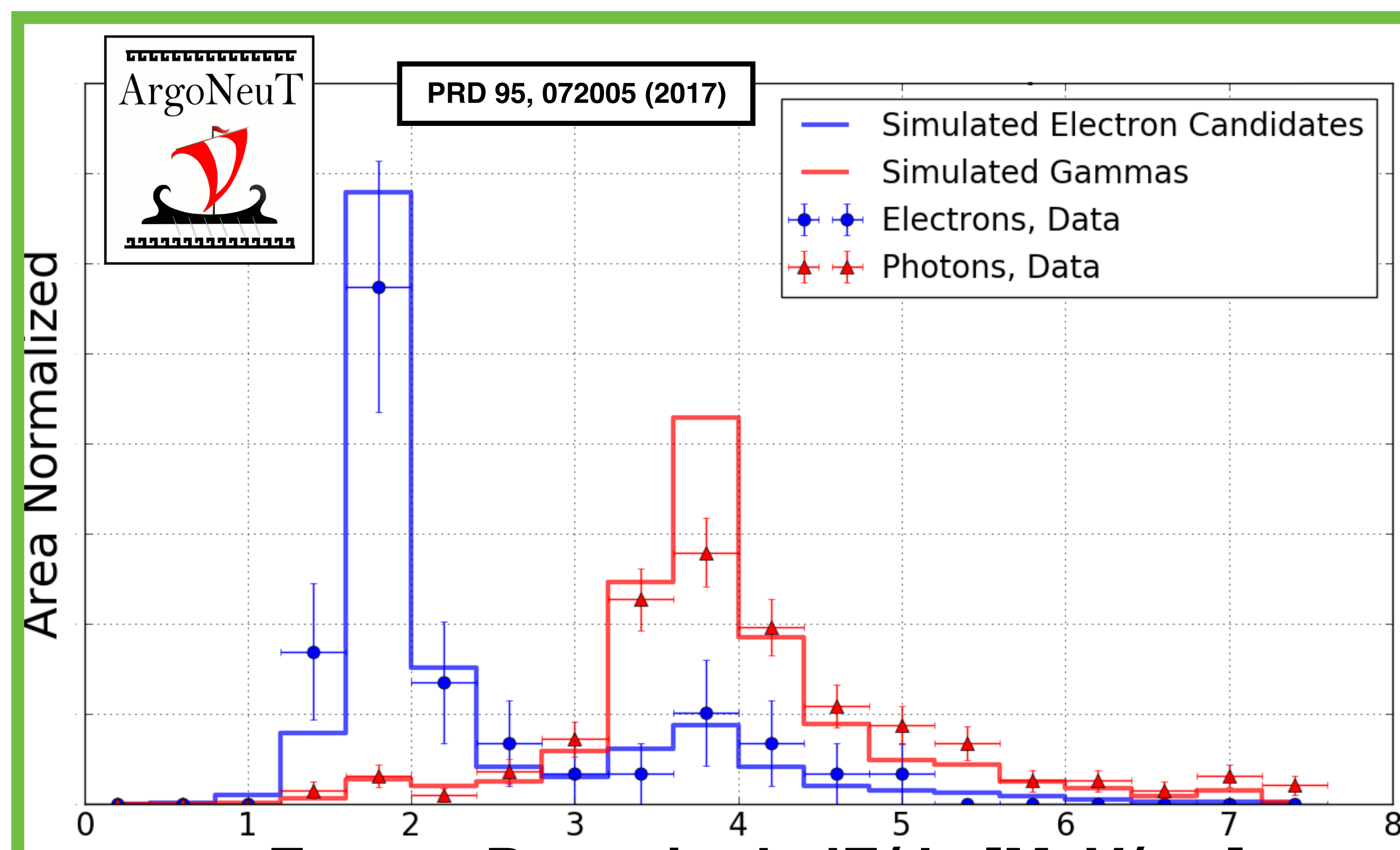
Last year MicroBooNE became the longest running LArTPC
Having collected ~700k ν-Ar interactions

Liquid Argon TPCs









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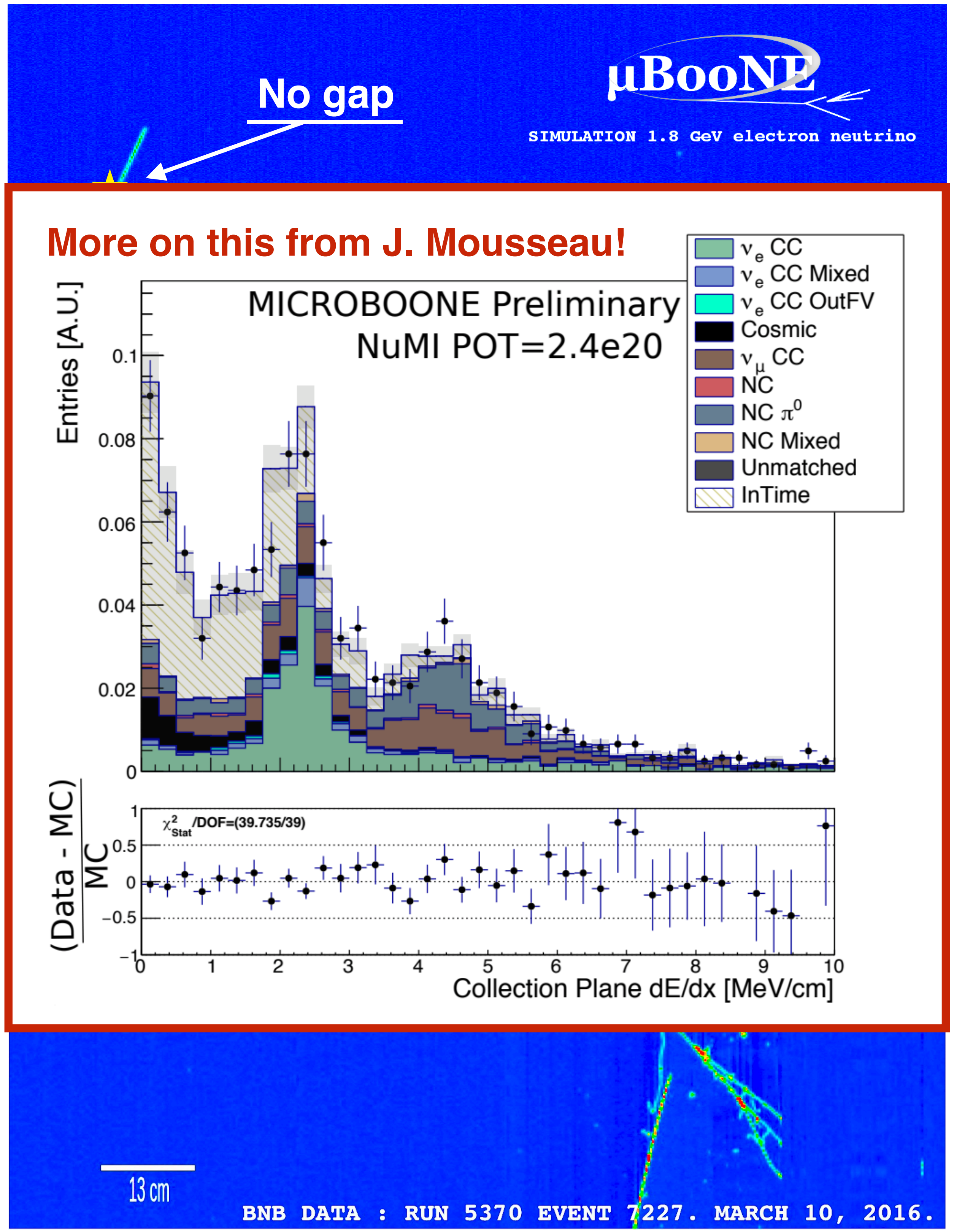

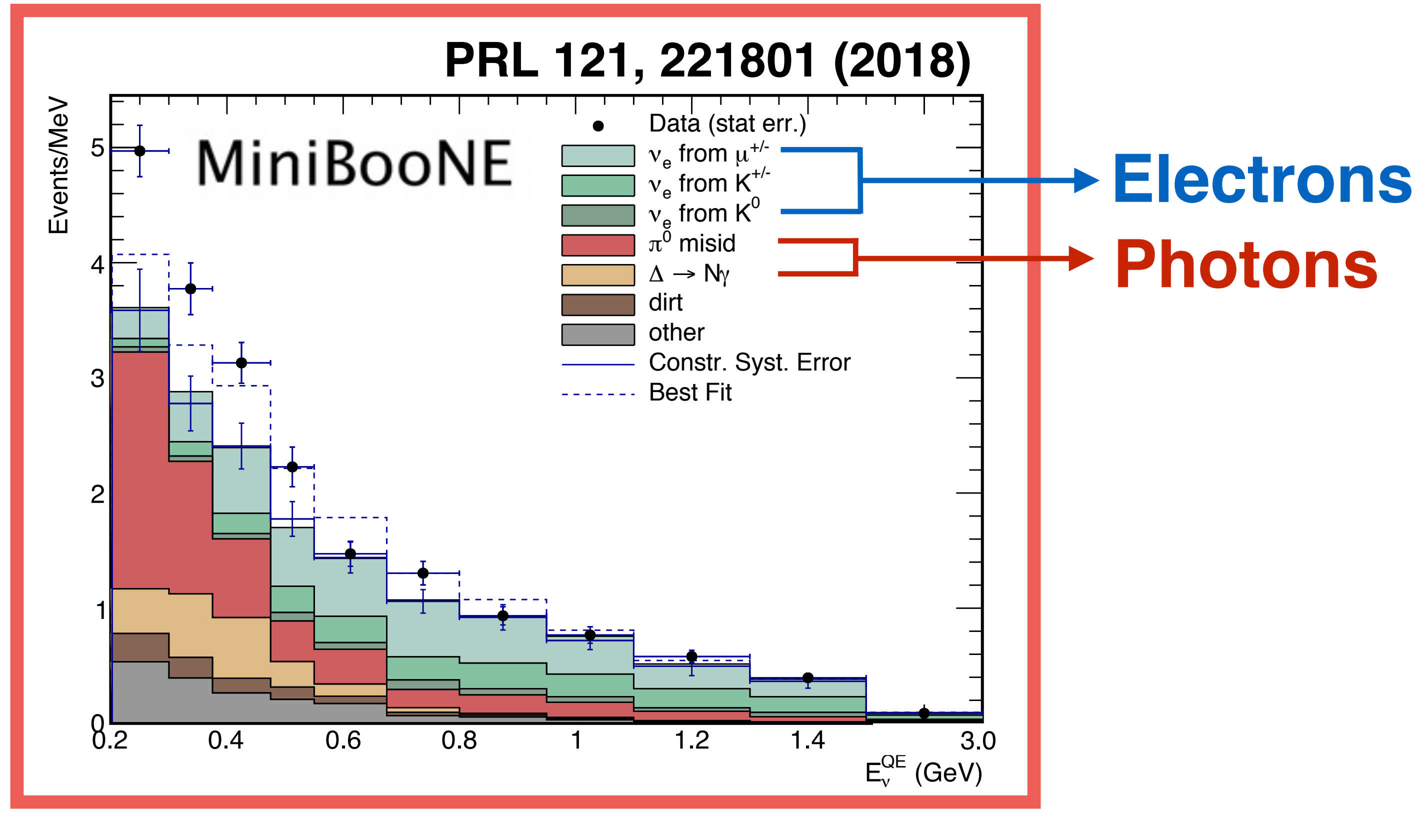

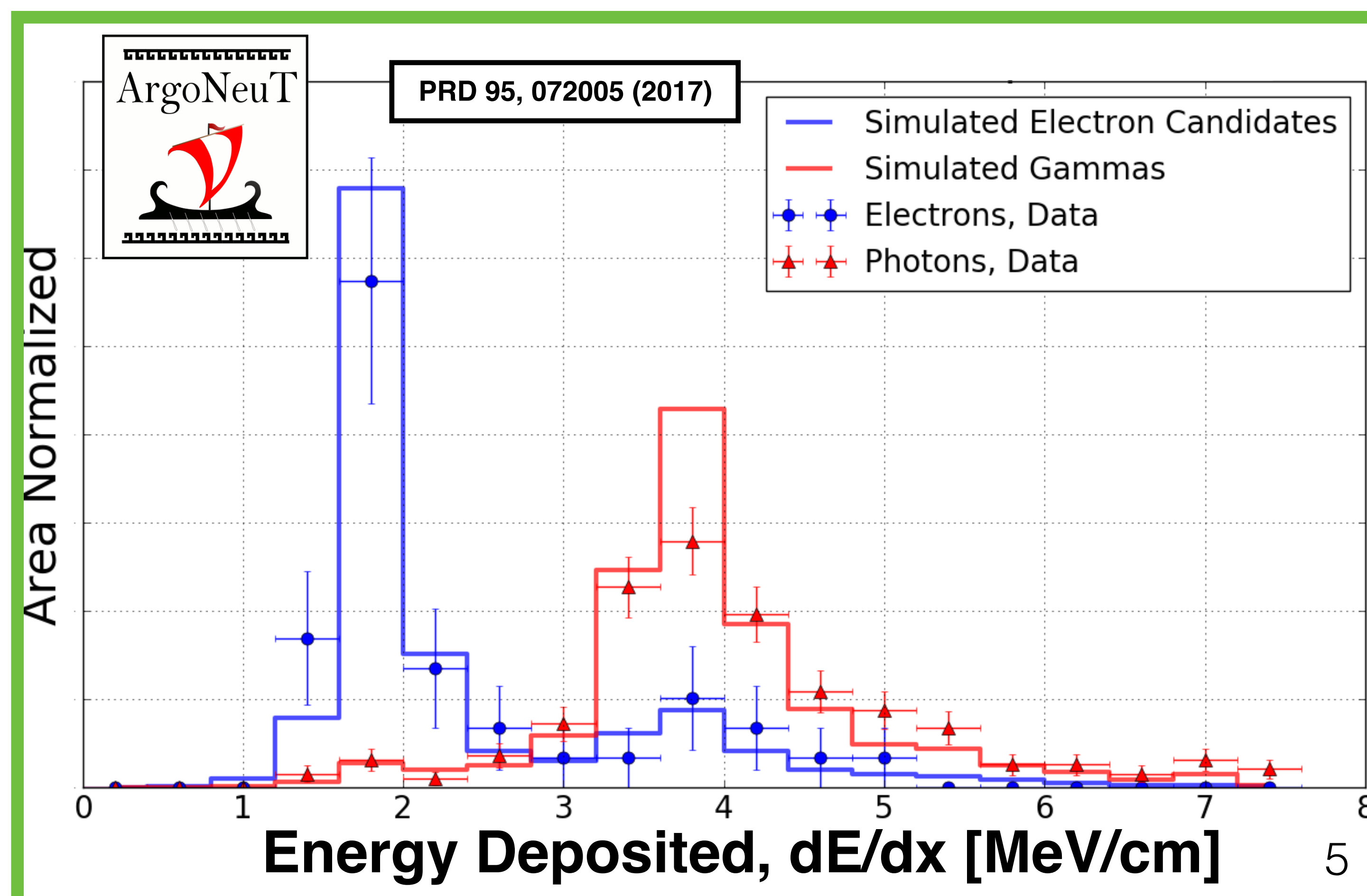

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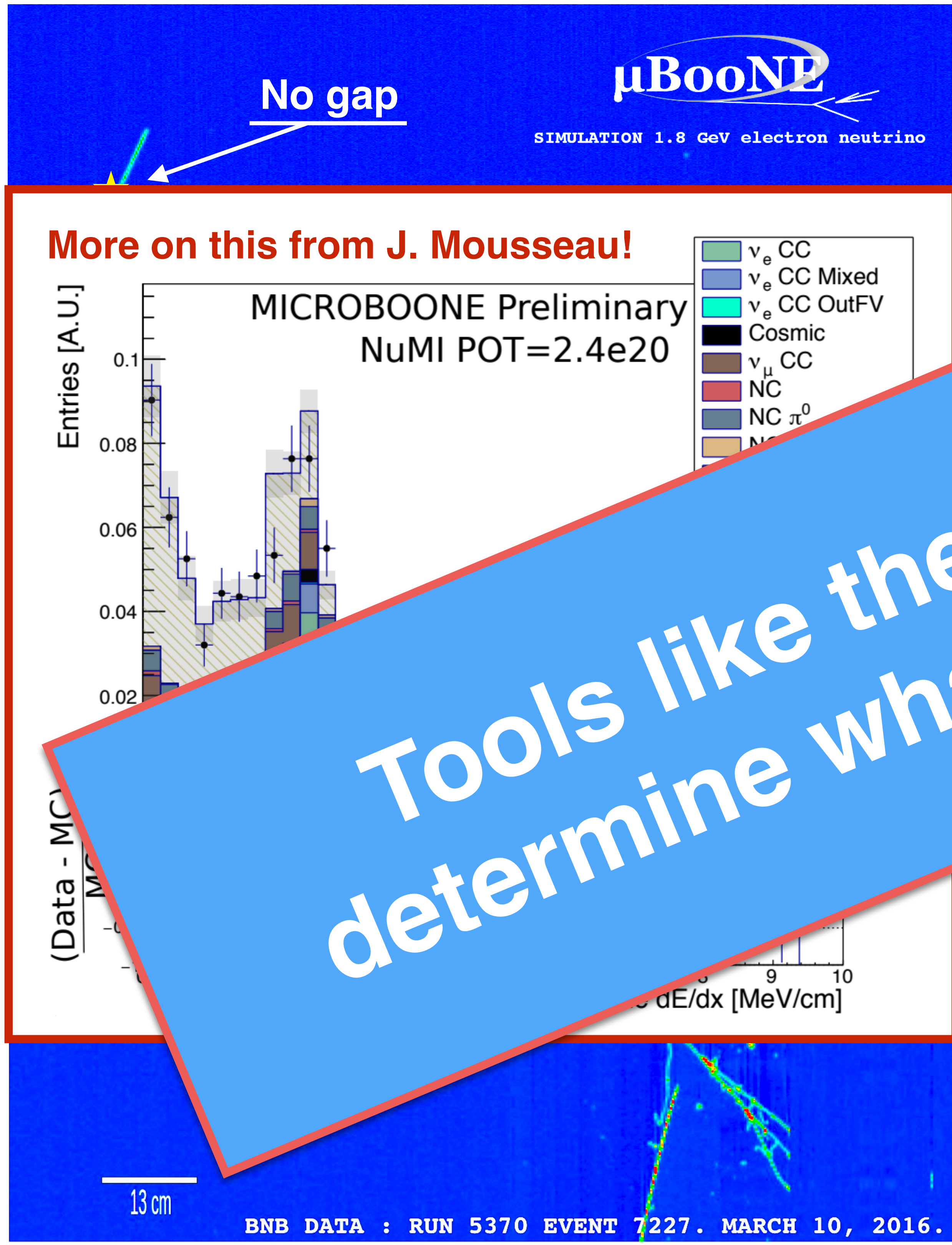
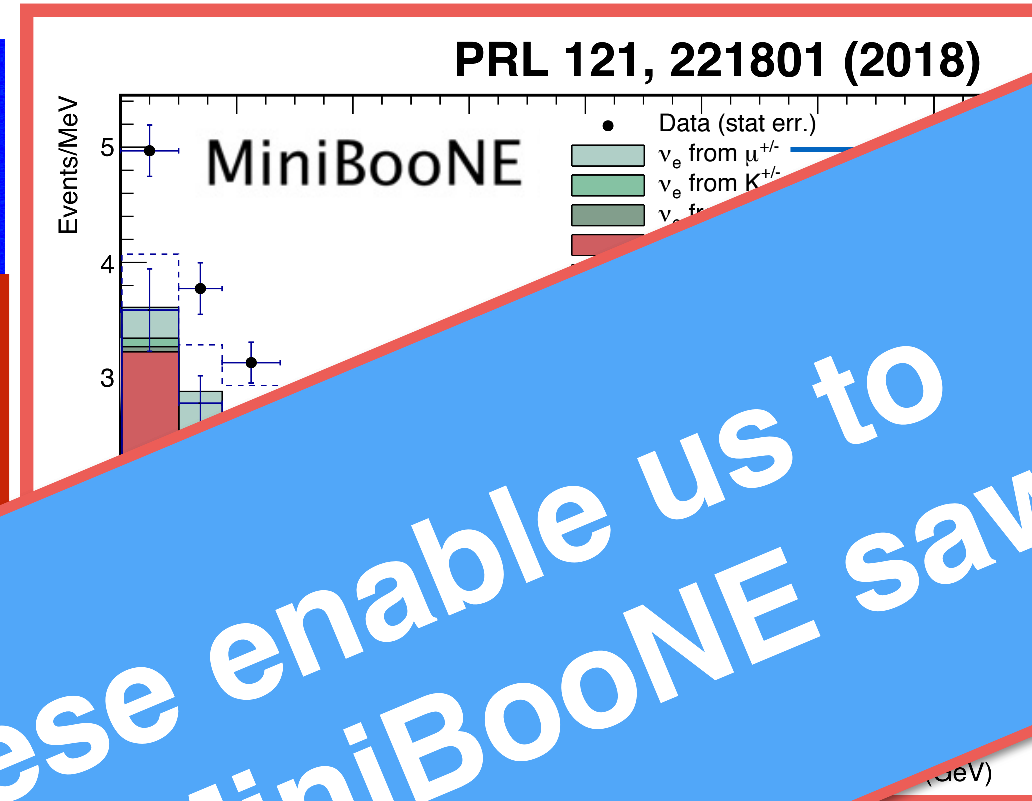
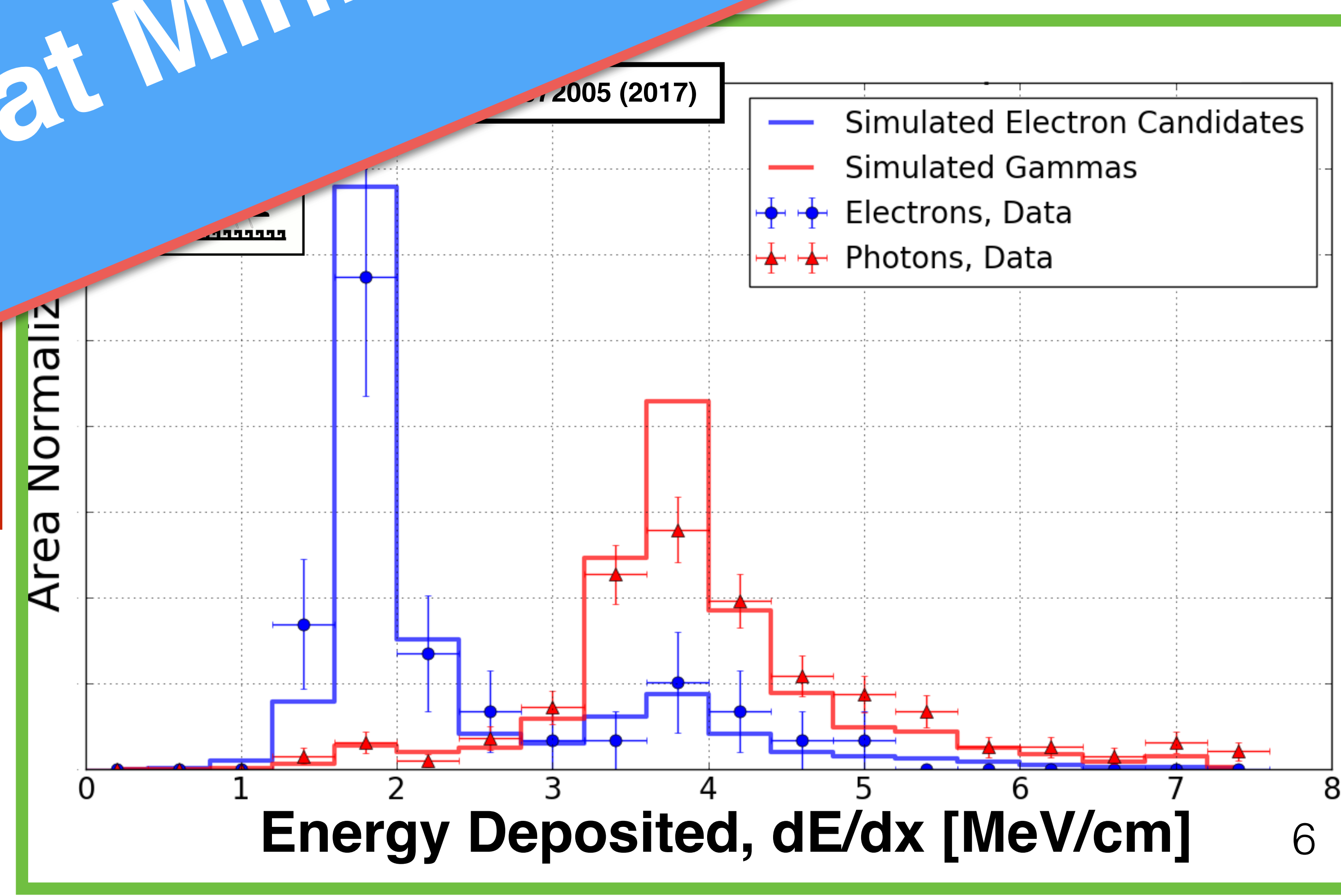




Tools like these enable us to determine what MiniBooNE saw!



Path Towards Understanding an Anomaly

1. Understanding Detector

Model detector effects and calibrate detector's response

2. Study ν-Ar Interactions

Explore low energy ν-Ar scattering and test models

3. Constraining Systematics

Using side-band and direct measurements constrain the shape and normalization of intrinsic neutrino backgrounds

4. Search for Excess

Define channel, develop selection, and perform a <u>blinded</u> search for an anomolous excess of events

All aspects of our analysis chain are following data-driven approaches!

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Understanding Our Detector

We are sensitive to many detector effects and are using our data to perform direct calibrations of each:

1. Localized electric field distortions
   MICROBOONE-NOTE-1055-PUB
2. Detector response functions
   JINST 13, P07007 (2018)
3. Readout uniformity
   MICROBOONE-NOTE-1048-PUB
4. Electro-negative contamination
   MICROBOONE-NOTE-1026-PUB
5. Induced charge responses
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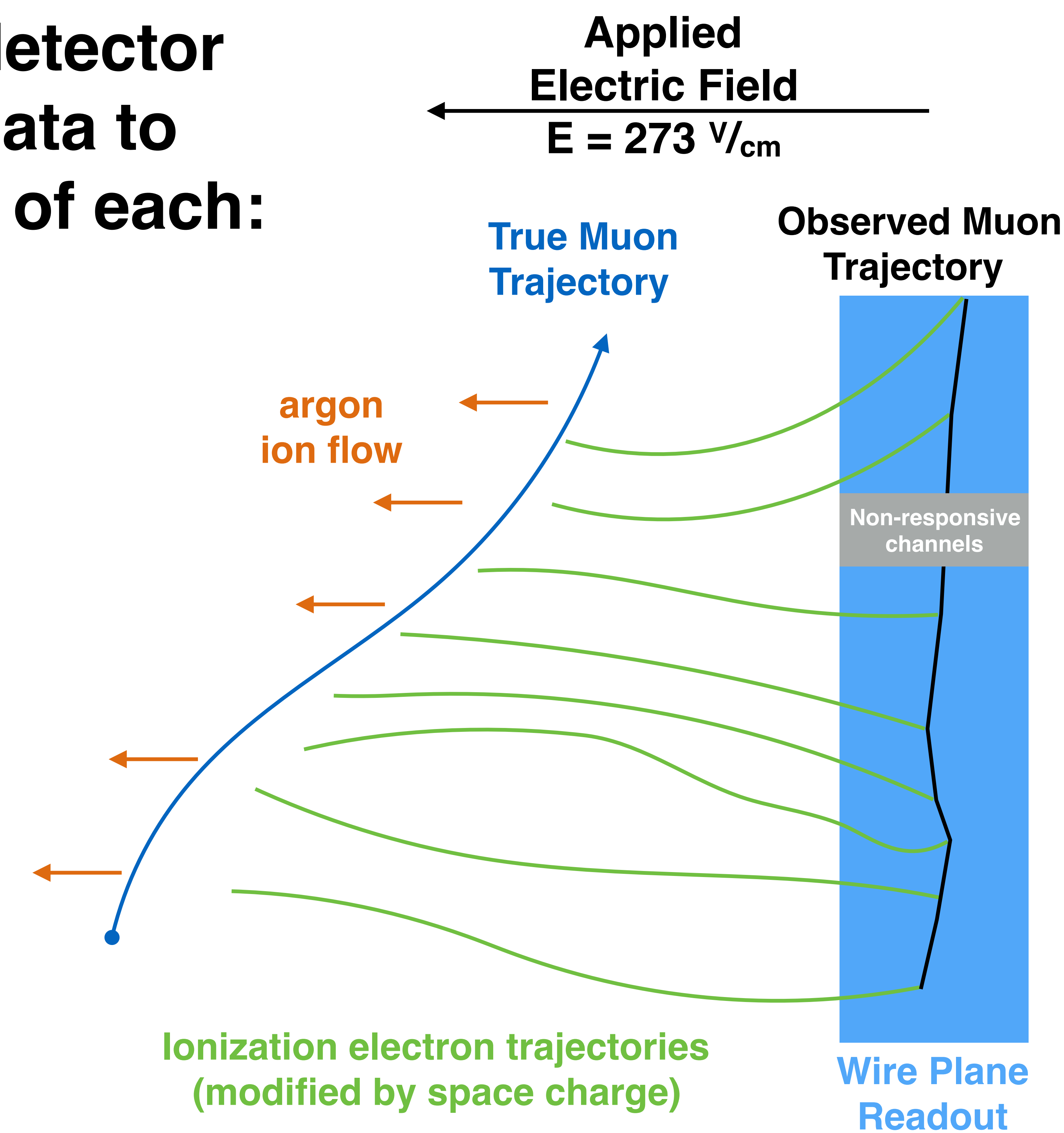
7. Electronics noise mitigation
   JINST 12, P08003 (2017)
8. PMT Responses

More publications are on their way!



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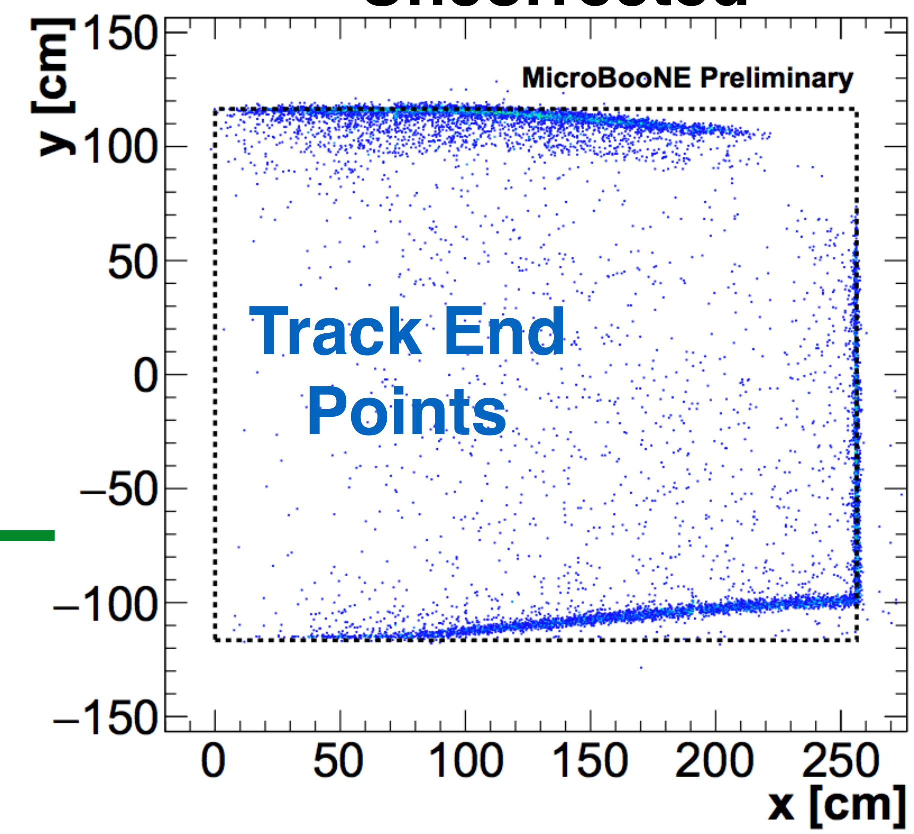
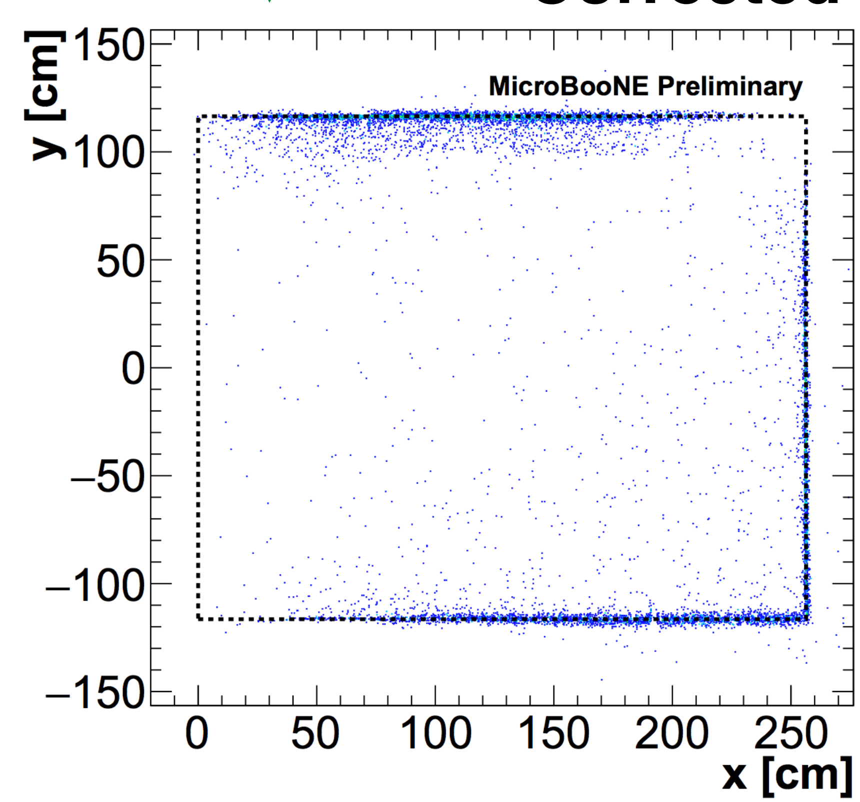
Uncorrected



Corrected



MICROBOONE-NOTE-1018-PUB

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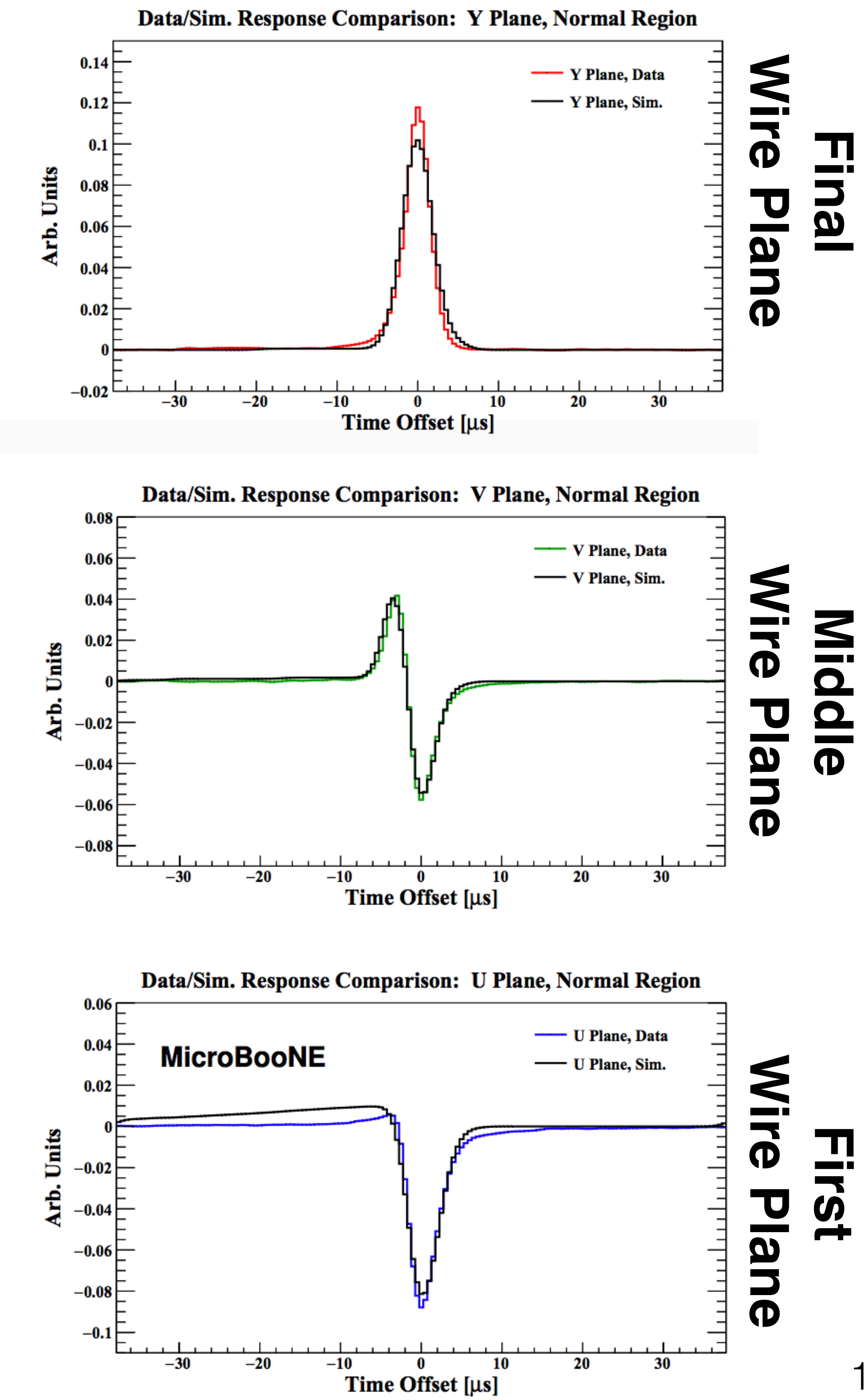

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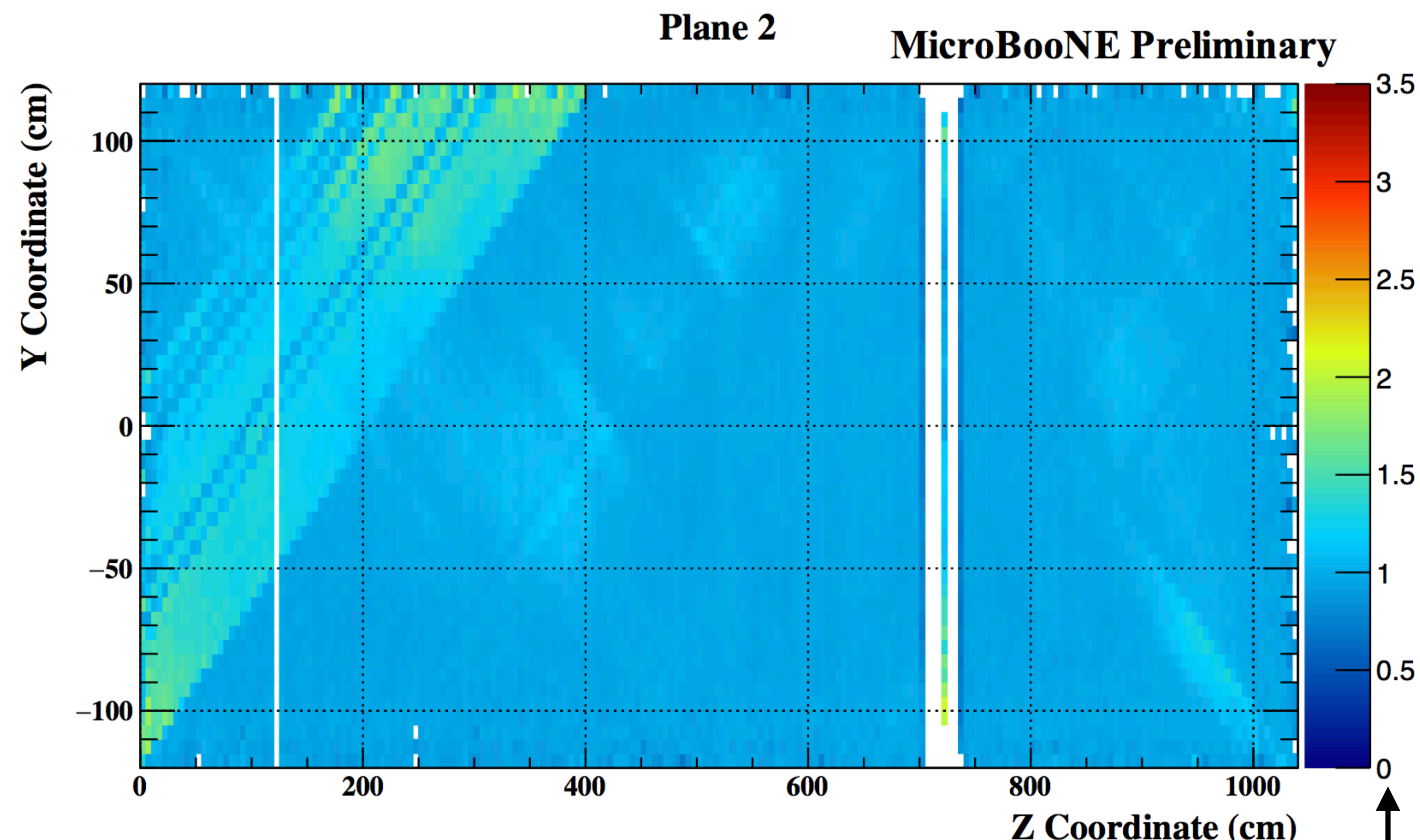

Variation in energy deposits from through-going muons

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DOE HEP Science Highlight (05/21/19)

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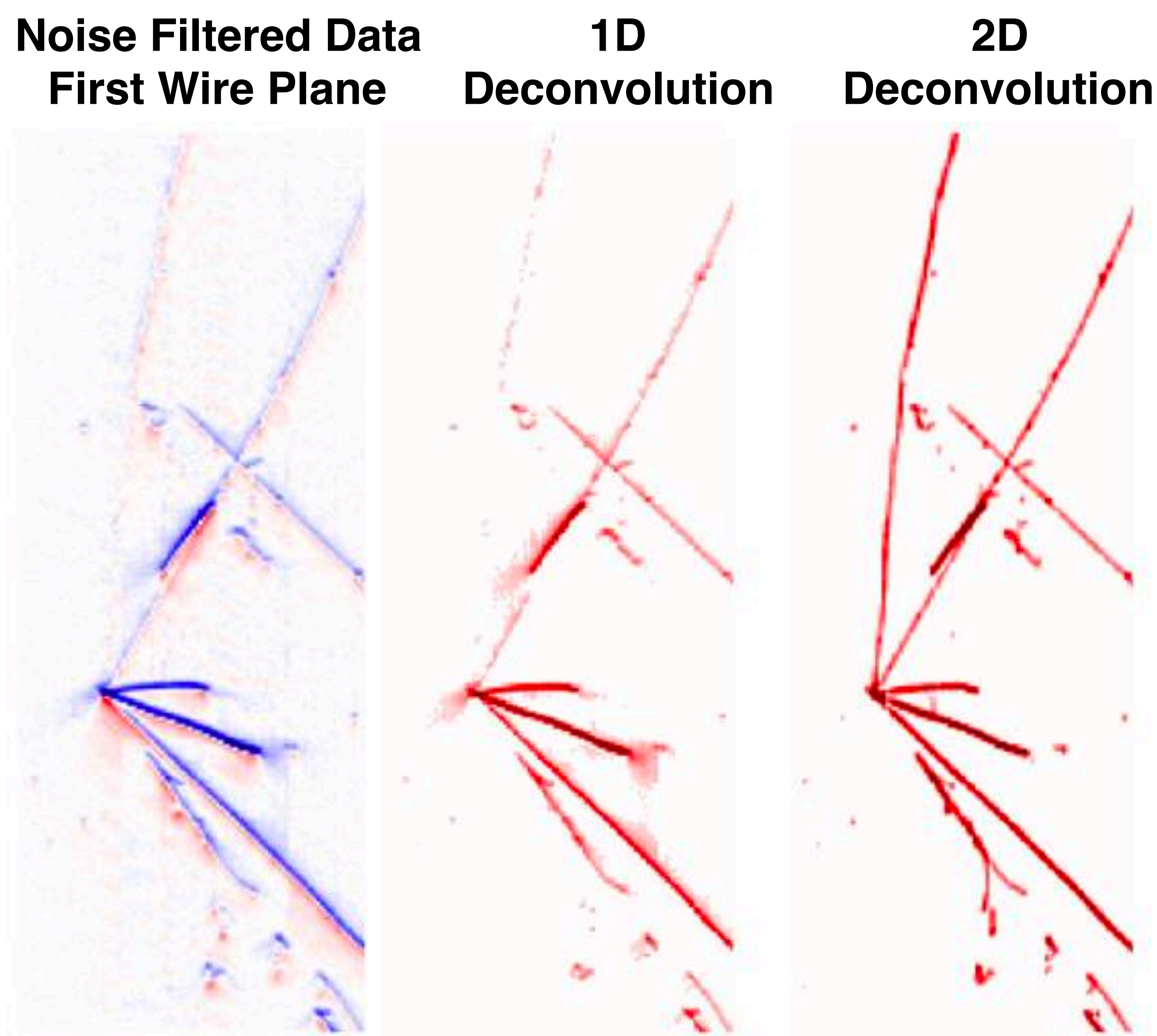

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J. Zennamo, Fermilab

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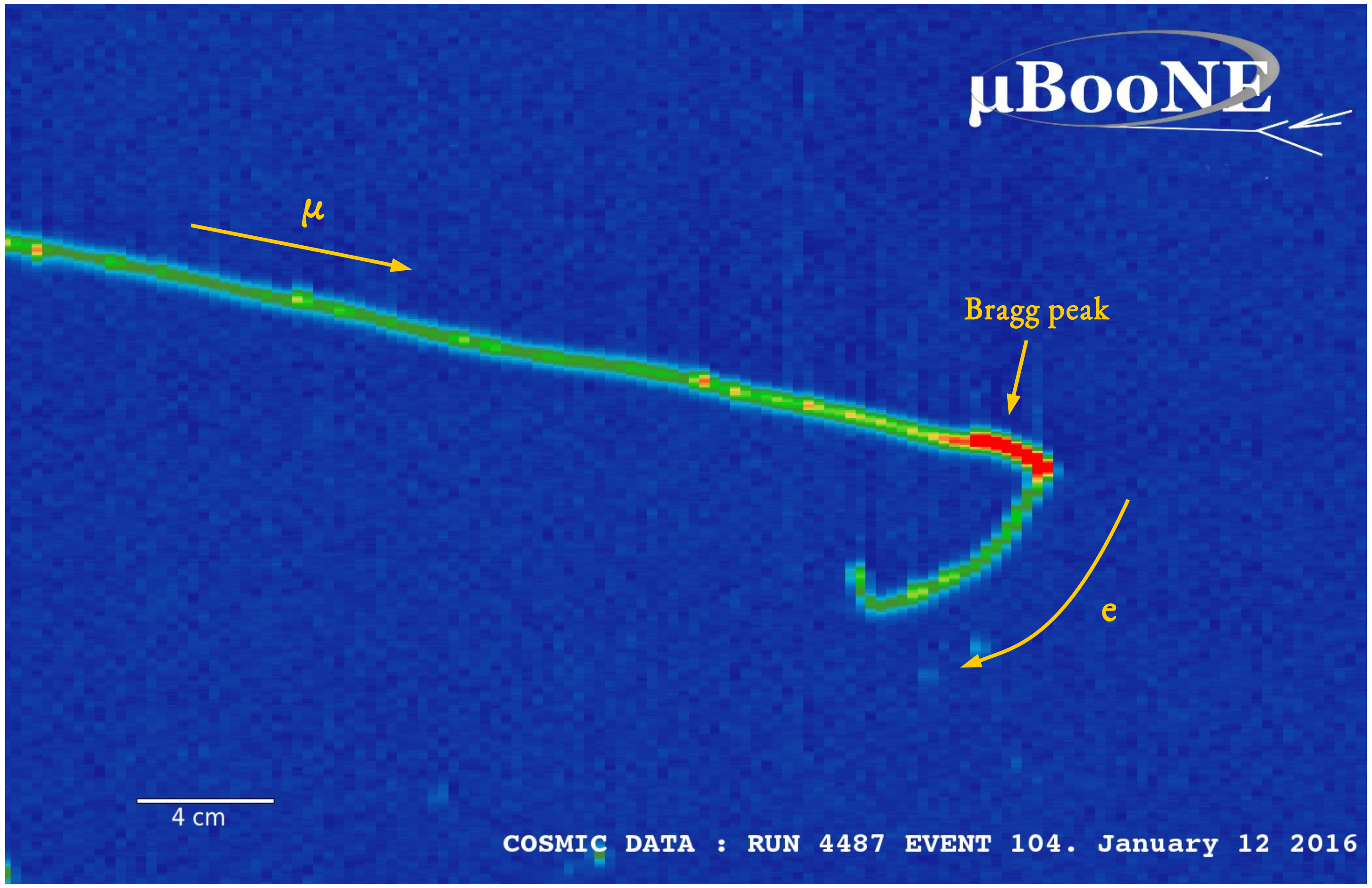
These measurements have allowed us to develop the next generation LArTPC detector simulation!

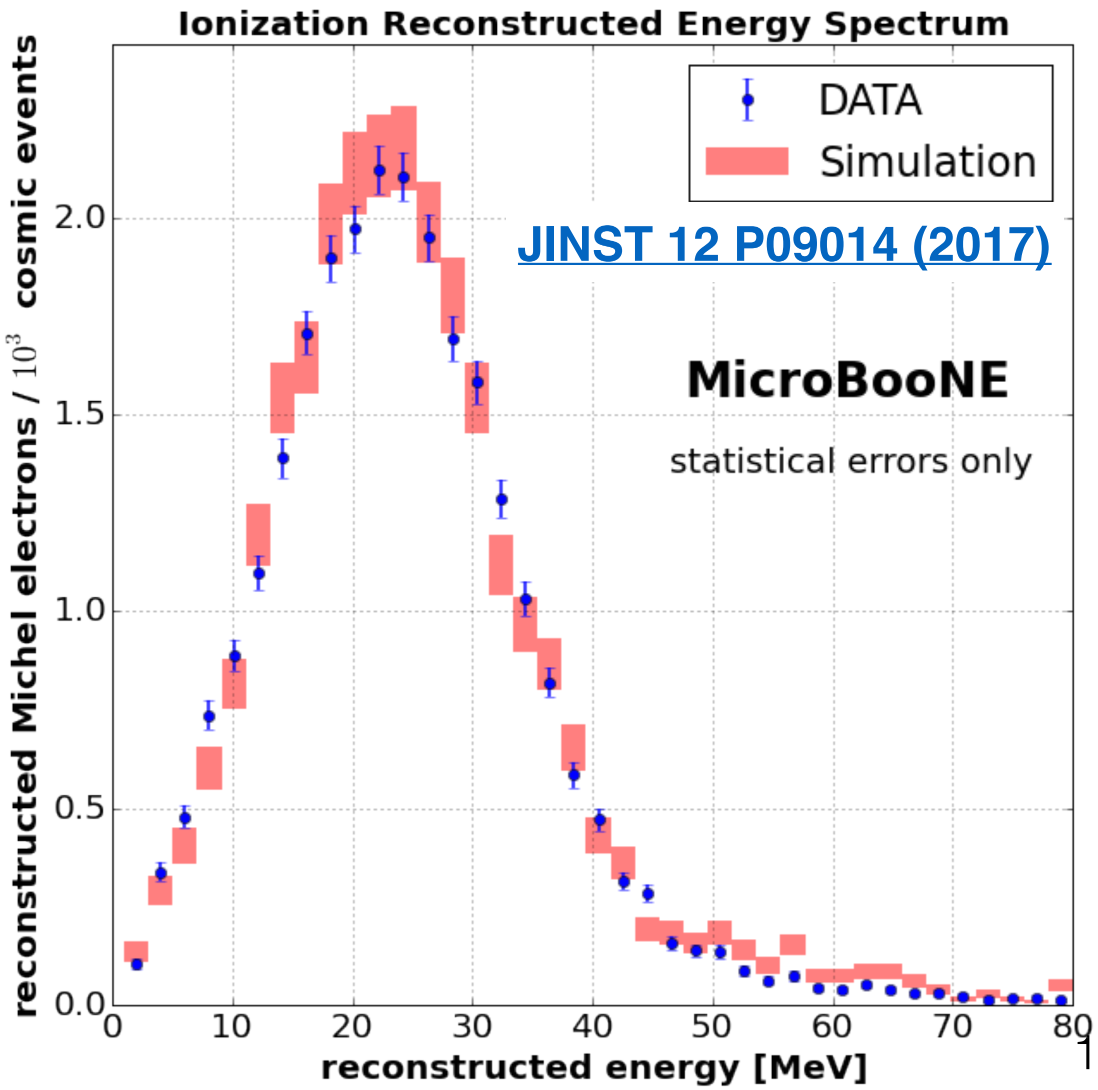
More publications are on their way!

Validating Detector Response Modeling

Once calibrations are integrated it is necessary to verify our simulation well describes our data

Study aspects of how our particles interact in our detector using things like the energy profiles of stopping particles compared to multiple coulomb scattering, the Michel electron spectrum, and charged-current produced neutral pion mass





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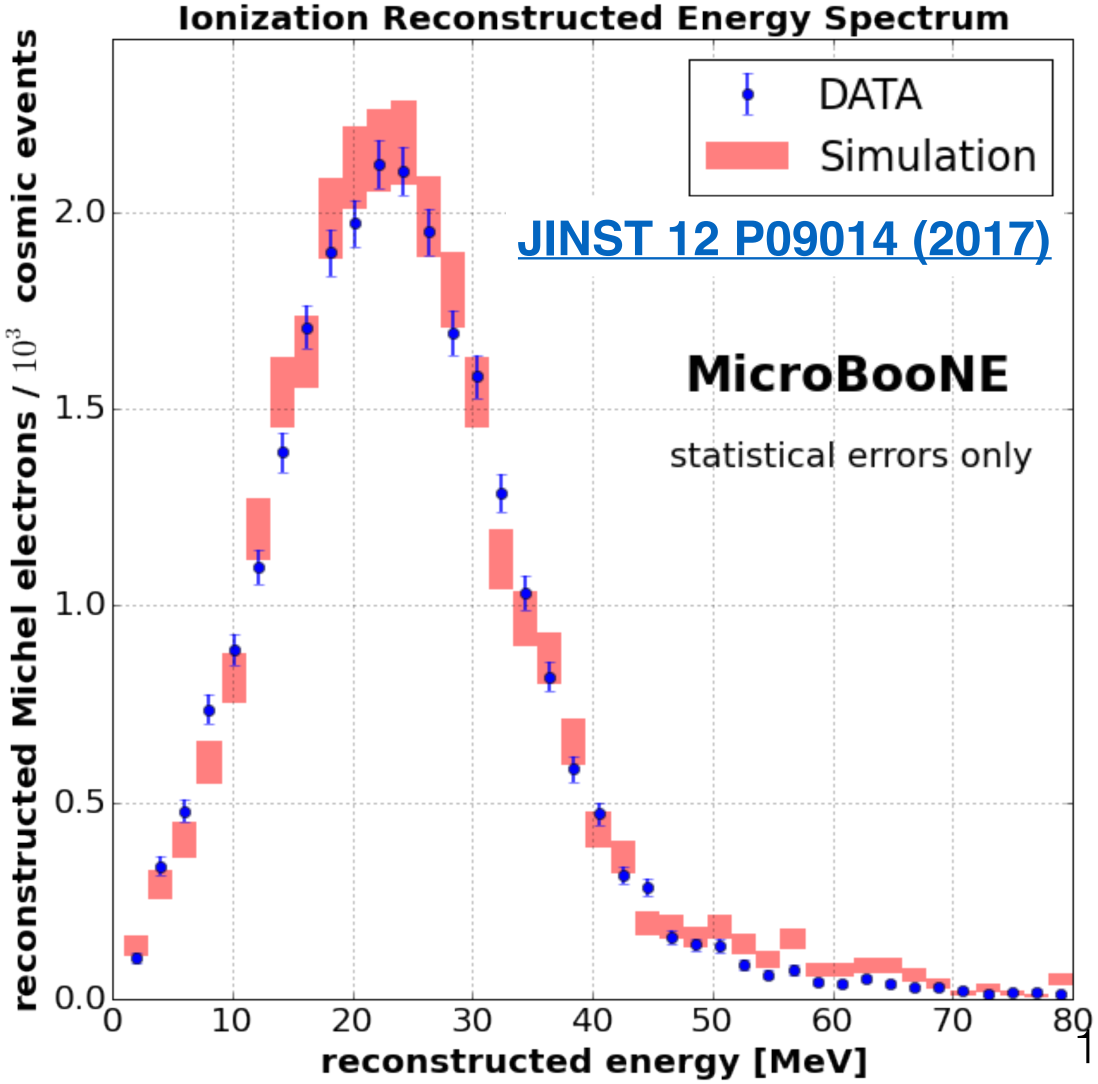
As part of this we've analyzed the **largest sample of Michel electrons** in a LArTPC, created the **first tuning of MCS parameters for LAr**, and performed the **first analysis of ν_μ CC π^0 production**



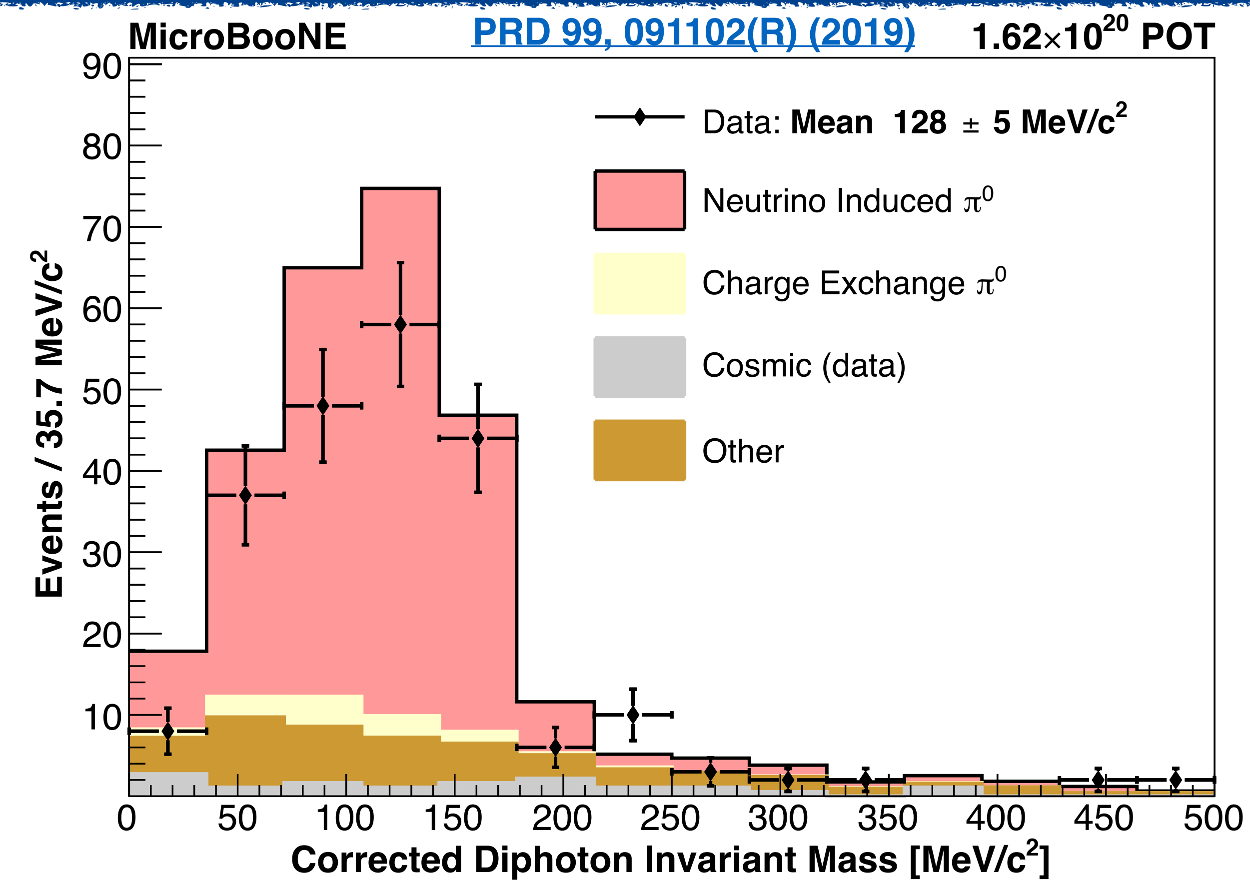
Neutral Pion Mass Validation

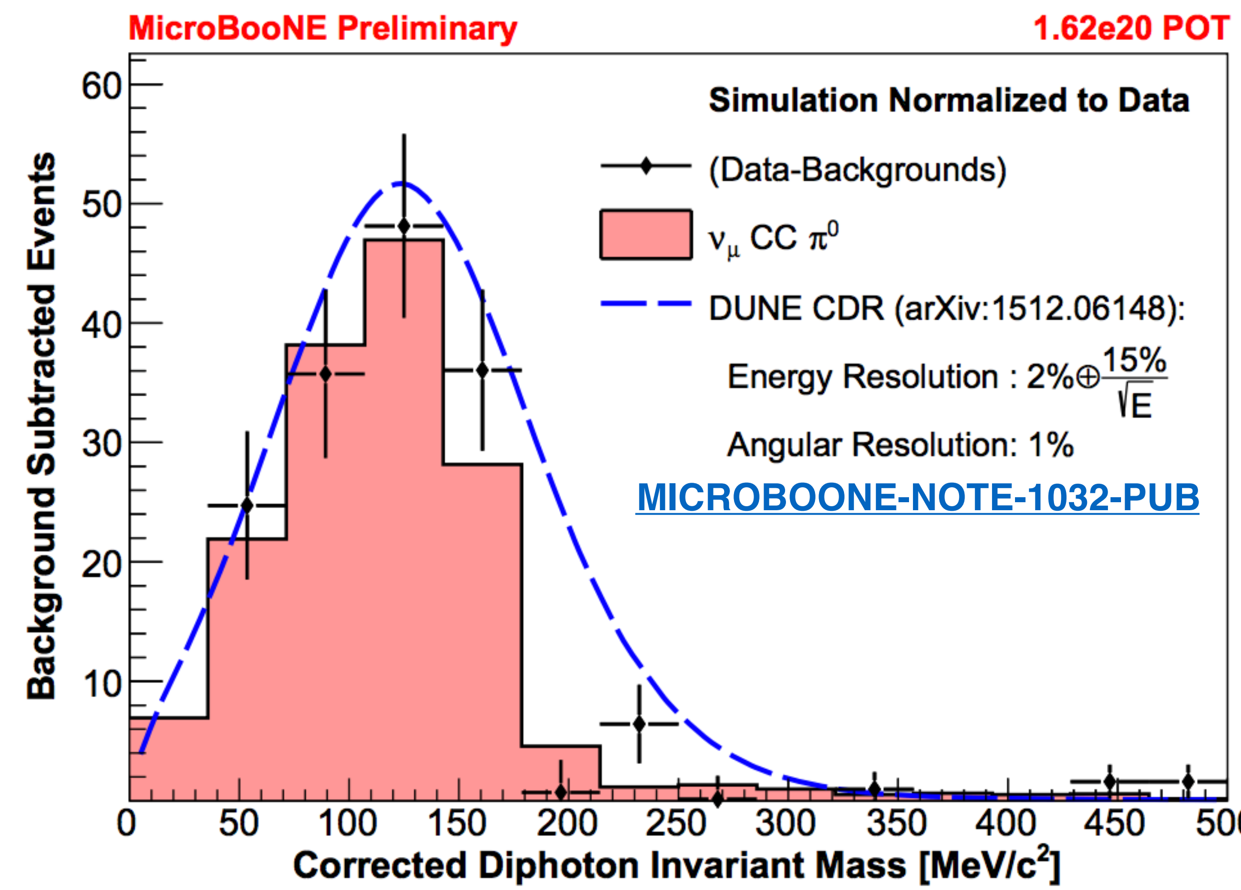
A challenge in our detector is verifying our calibrations are applicable to EM showers

Charged-current neutral-pion enables us to test this thanks to its powerful topology

Thanks to the clearly defined vertex from the muon starting point we can accurately track the opening angle between the showers

Using a very pure selection we find good data-MC **shape agreement** in the diphoton invariant mass





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MicroBooNE Cross Section Program

Booster Neutrino Beam

ν_μ CC inclusive
arXiv:1905.09694, submitted to PRL

meson production

proton final states

ν_μ CC π^0
PRD 99, 091102(R) (2019)

ν_μ CC $1\pi^+$

ν_μ CC Coh. π

ν_μ CC $K^\pm$

ν_μ CC 0π

ν_μ CC Np
MICROBOONE-NOTE-1056-PUB

ν_μ CC 1p

ν_μ CC 2p
MICROBOONE-NOTE-1056-PUB

NC elastic
MICROBOONE-NOTE-1053-PUB

NC π^0

Track Multiplicity
EPJC 79, 248 (2019)

NuMI Neutrino Beam

ν_e CC inclusive
MICROBOONE-NOTE-1054-PUB

ν_e CC 0π

ν_μ CC inclusive (KDAR)

There is limited data to help us constrain our models, we're relying on a dedicated program of measurements to help

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019)

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ν_e CC 0π

ν_μ CC inclusive (KDAR)

These measurements will be covered later in the next session by J. Mousseau

There limited data to help us constrain our models, we're relying on a dedicated program of measurements to help

Exploring Neutrino Interaction Modeling

We need to be confident in our neutrino interaction modeling

With limited ν-Ar data we're using our measurements as a guide

A dedicated series of measurements are being performed to help us move towards the best model set

Our recent νμ CC double differential measurement finds that GENIEv3 theory models best describes our data

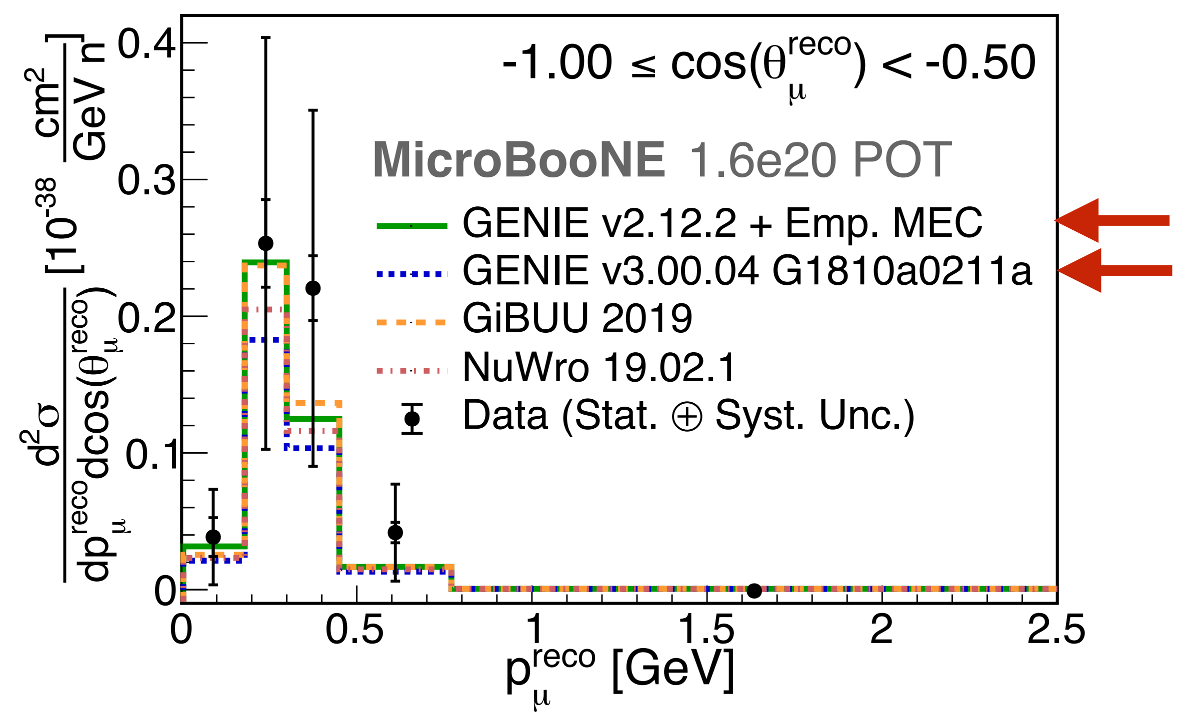
Based on this we've adopted GENIEv3

ν_μ CC Inclusive Double Differential

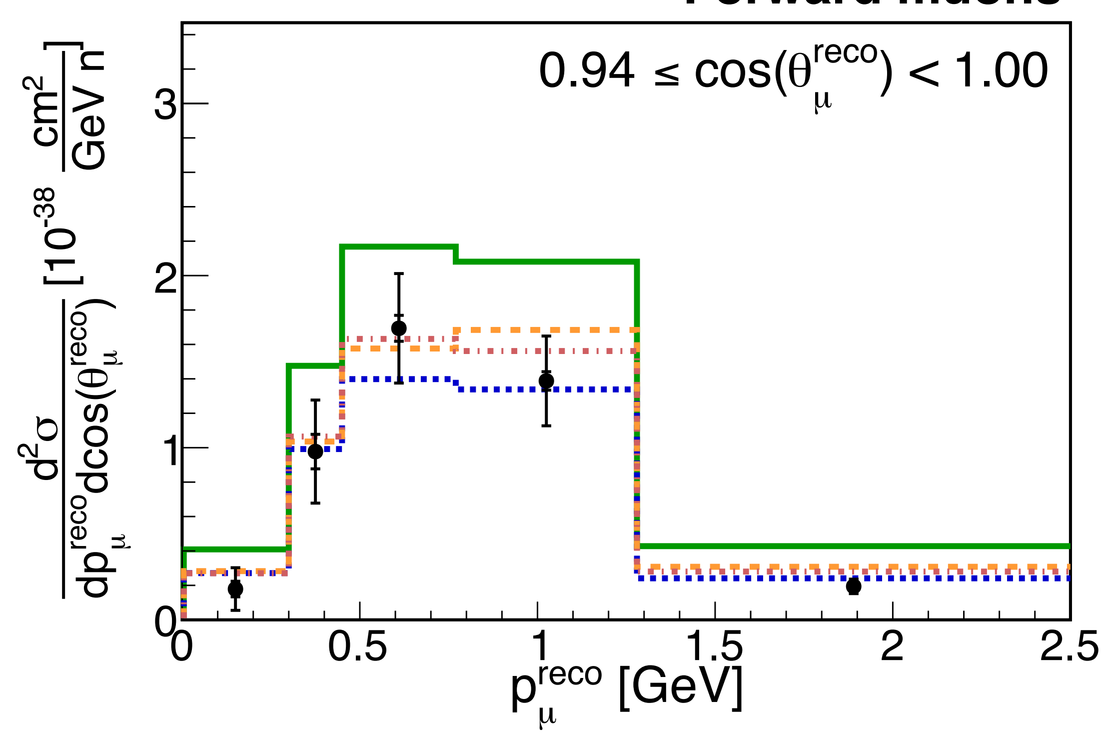
arXiv:1905.09694, submitted to PRL

(Only showing 10 of our 42 bins!)

Backward muons



Forward muons



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Going to go out of order to add context to our systematics

What Makes an Anomaly?

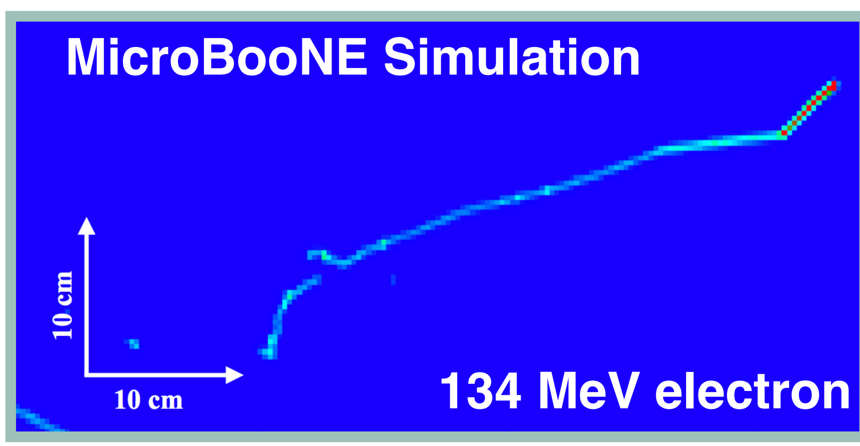
Historically there have been two scenarios floated to describe the MiniBooNE excess of events

1. Electron neutrino interactions
2. Neutral-current production of Δ which then decay radiatively

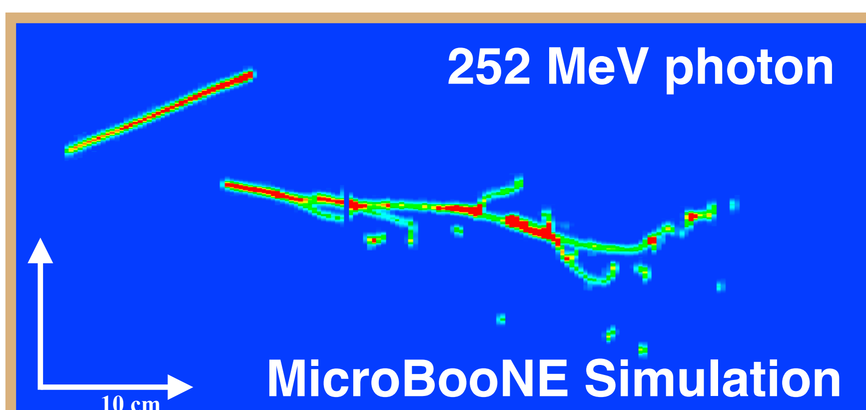
Ingredients:

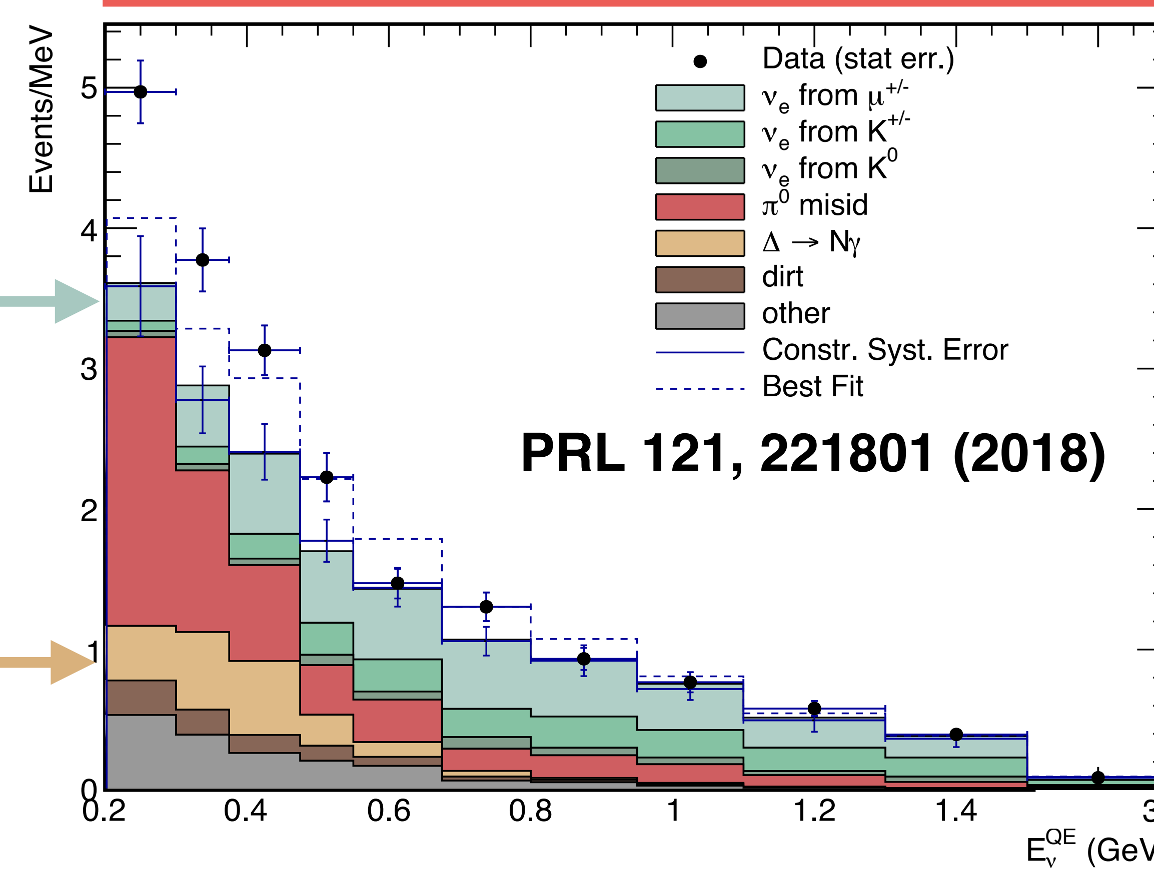
1. Reconstructing low energy EM showers
2. Rejecting backgrounds
3. Determining particle species associated with excess
4. Controlling systematics
5. Constraining backgrounds with data

Charged-current Electron neutrino (electron + X)



Neutral-current Δ radiative decay (photon + X)





Complementary Independent Analyses

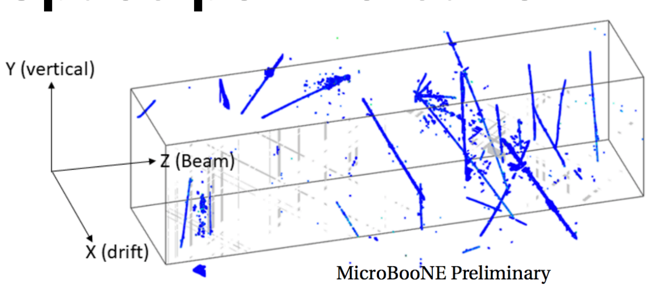
Electron-like Low Energy Excess Searches | **Photon-like Low Energy Excess Search**

WireCell Reconstruction

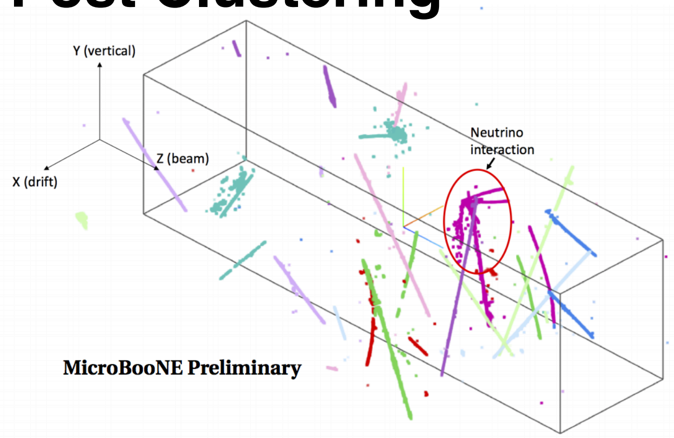
JINST 13, P05032 (2018)
MICROBOONE-NOTE-1040-PUB

Tomographic reco. creates 3D space points and clusters in 3D

Space point creation



Post Clustering

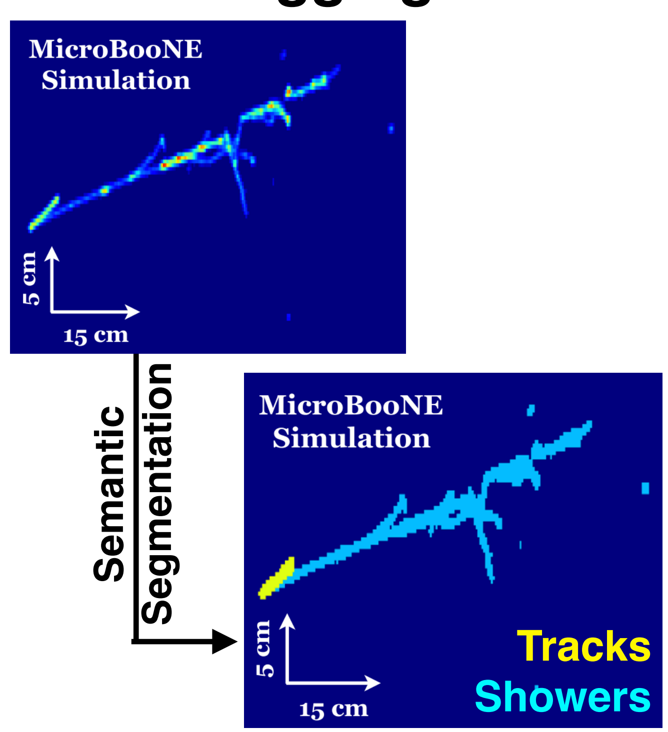


Deep Learning Reconstruction

JINST 12, P03011 (2017)
PRD 99, 092001 (2019)

Using the latest in CNN technology; provides pixel tagging and neutrino event finding

Pixel tagging demo



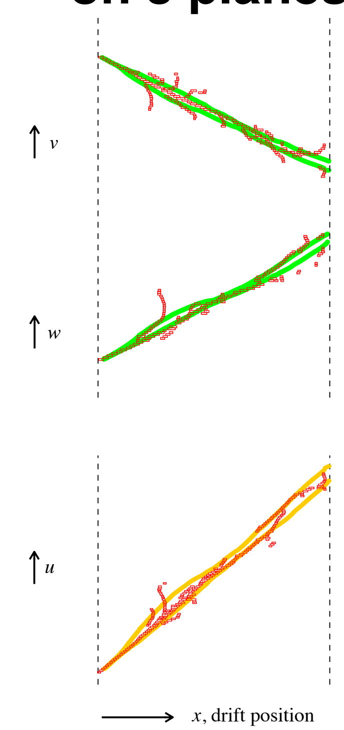
Pandora Multi-algorithm Toolkit Reconstruction

EPJC 78, 1, 82 (2018)

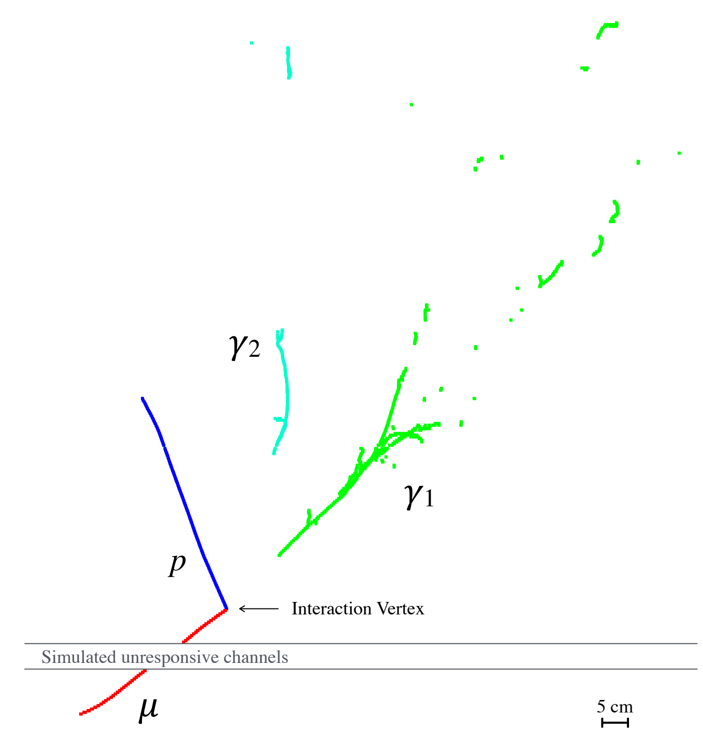
Clustering charge independently on each wire-plane before matching across planes to make a 3D reconstructed object

Cross section program largely uses this reconstruction paradigm

Simultaneous fitting on 3 planes



3D reco of ν_μ CC π^0 event



Electron Neutrino Excess Searches Strategies

We have adopted a complementary analysis strategy for our searches

1. Exclusive final state selections (1 lepton, 1 proton)

Pros:

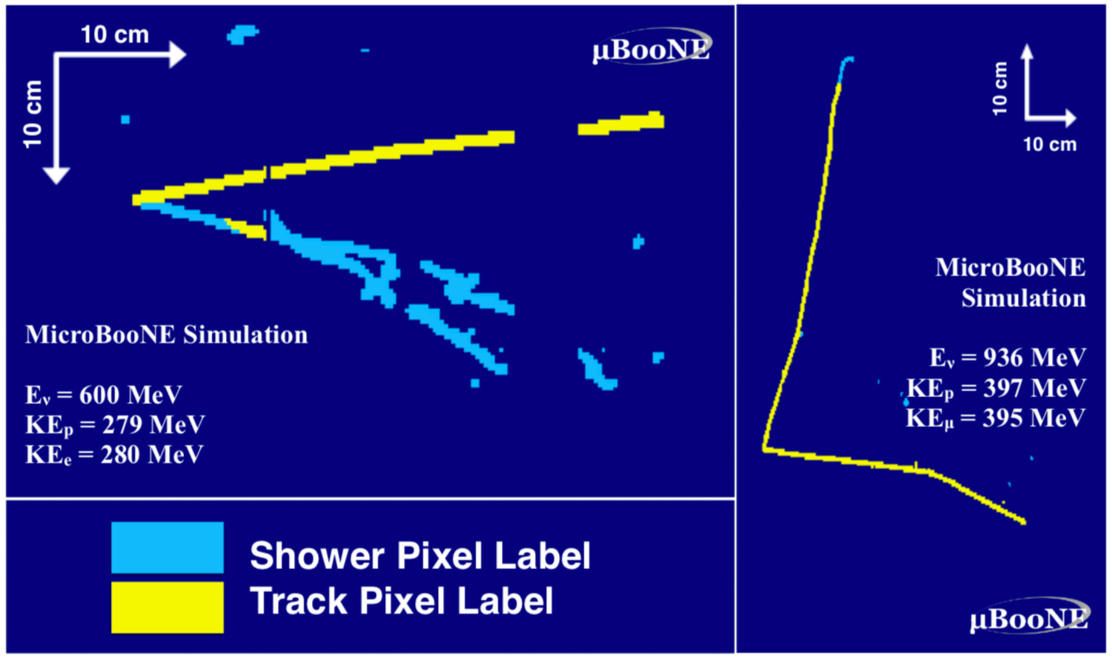
Higher purity,
Better neutrino energy determination,
Reconstruction can focus on final state

2. More inclusive final state selections (1 lepton, N proton)

Pros:

Higher statistics,
More like what MiniBooNE measured

Exclusive Search Topology



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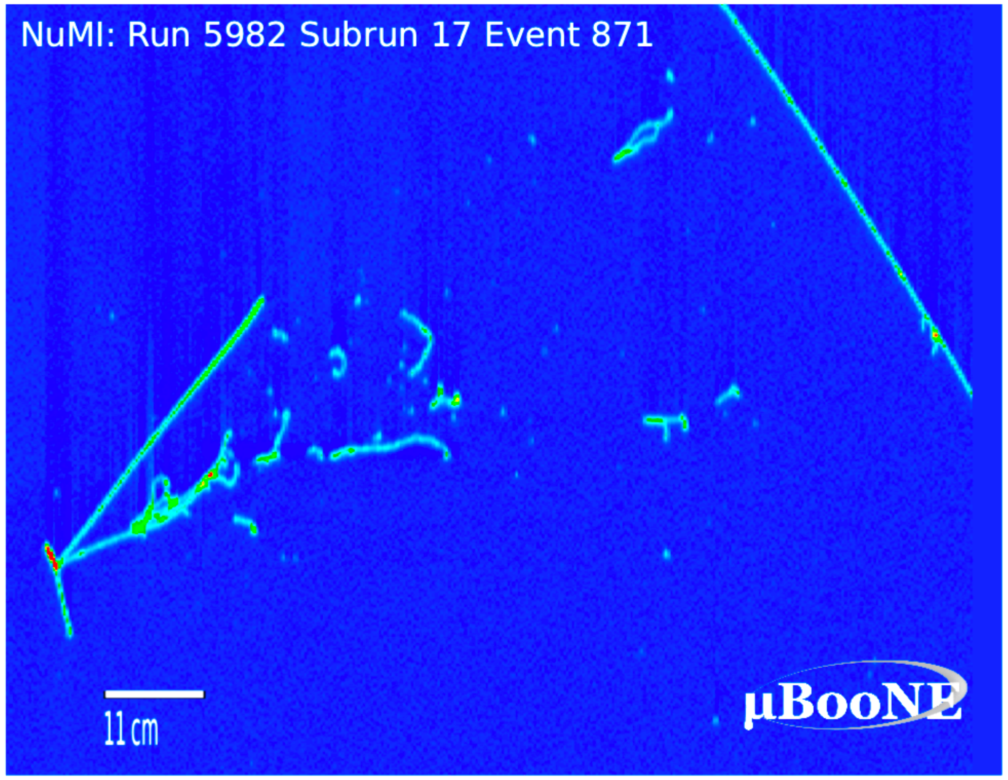

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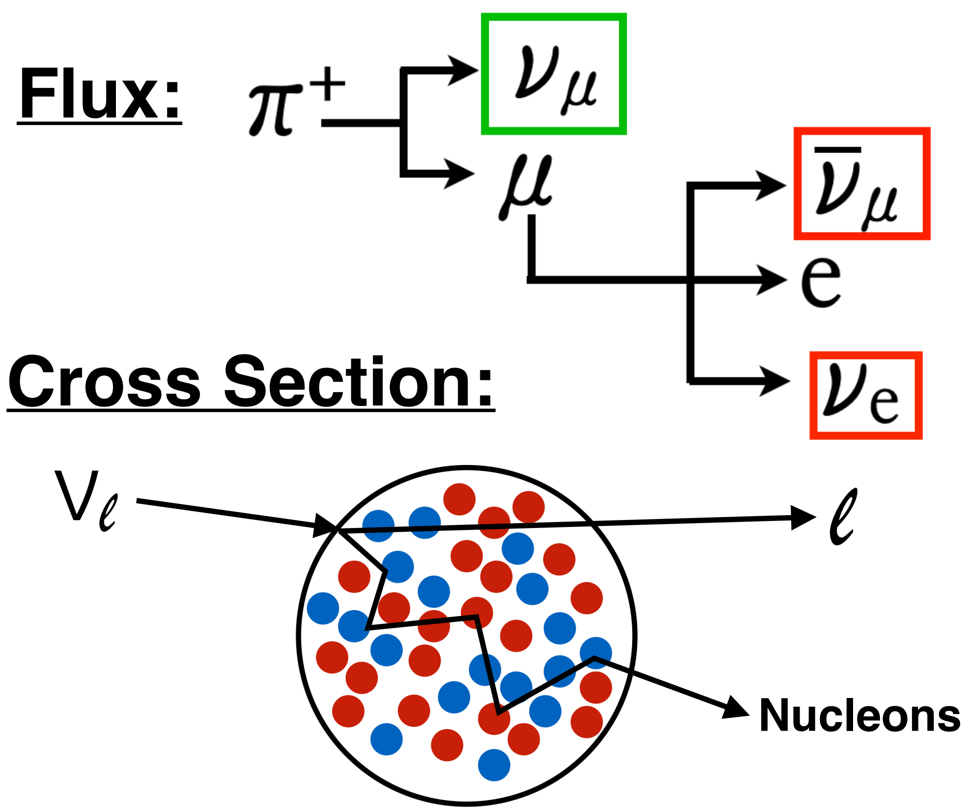
Now we can go back and discuss how we are constraining the various backgrounds in the analysis

A major challenge will be constraining systematics associated with neutrino-induced backgrounds

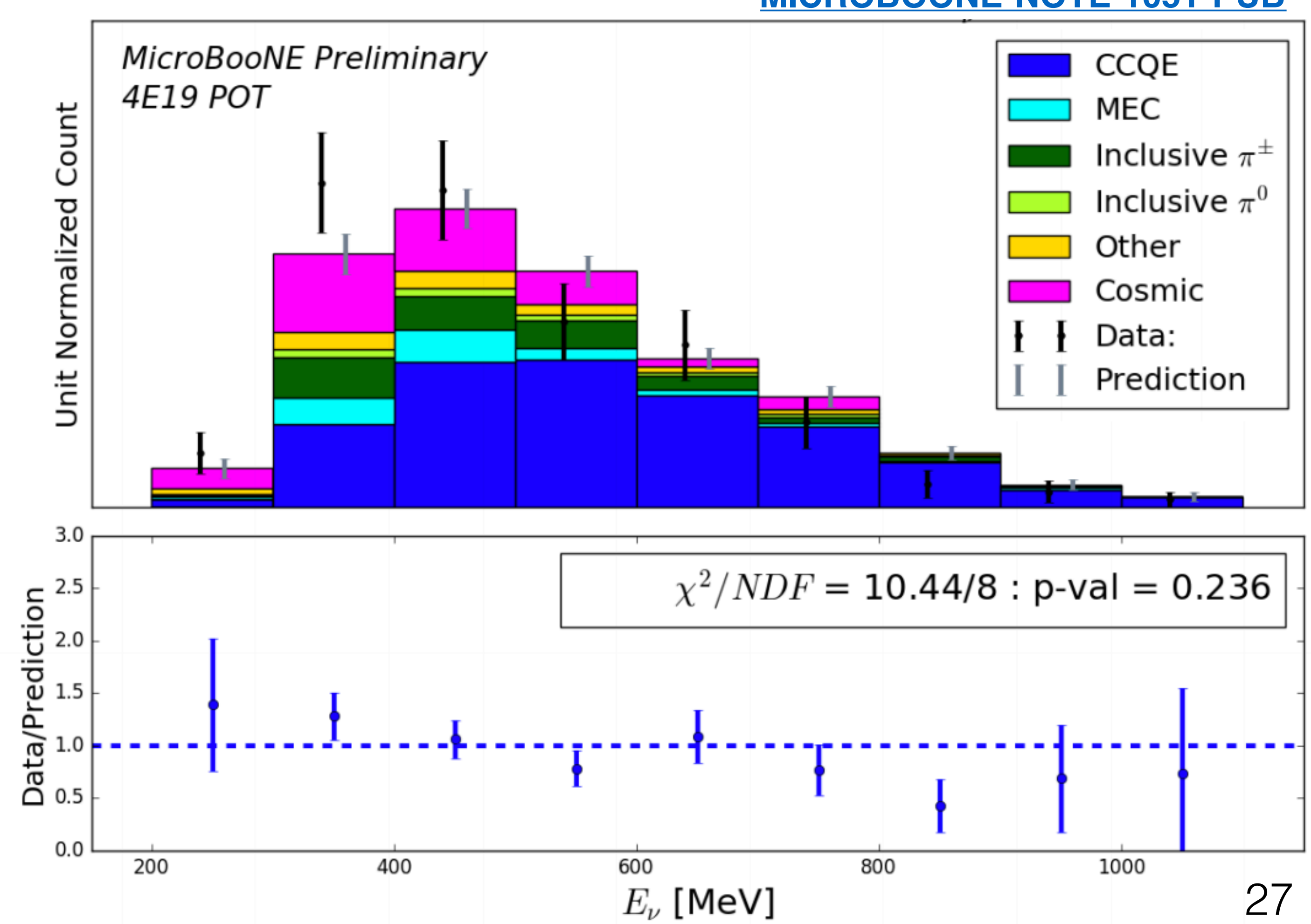
Intrinsic ν_e flux and cross section uncertainties are 20-30%

Without a near-detector, ν_μ measurement will be used to constrain these uncertainties through correlations



ν_μ Selection for exclusive analysis

MICROBOONE-NOTE-1051-PUB



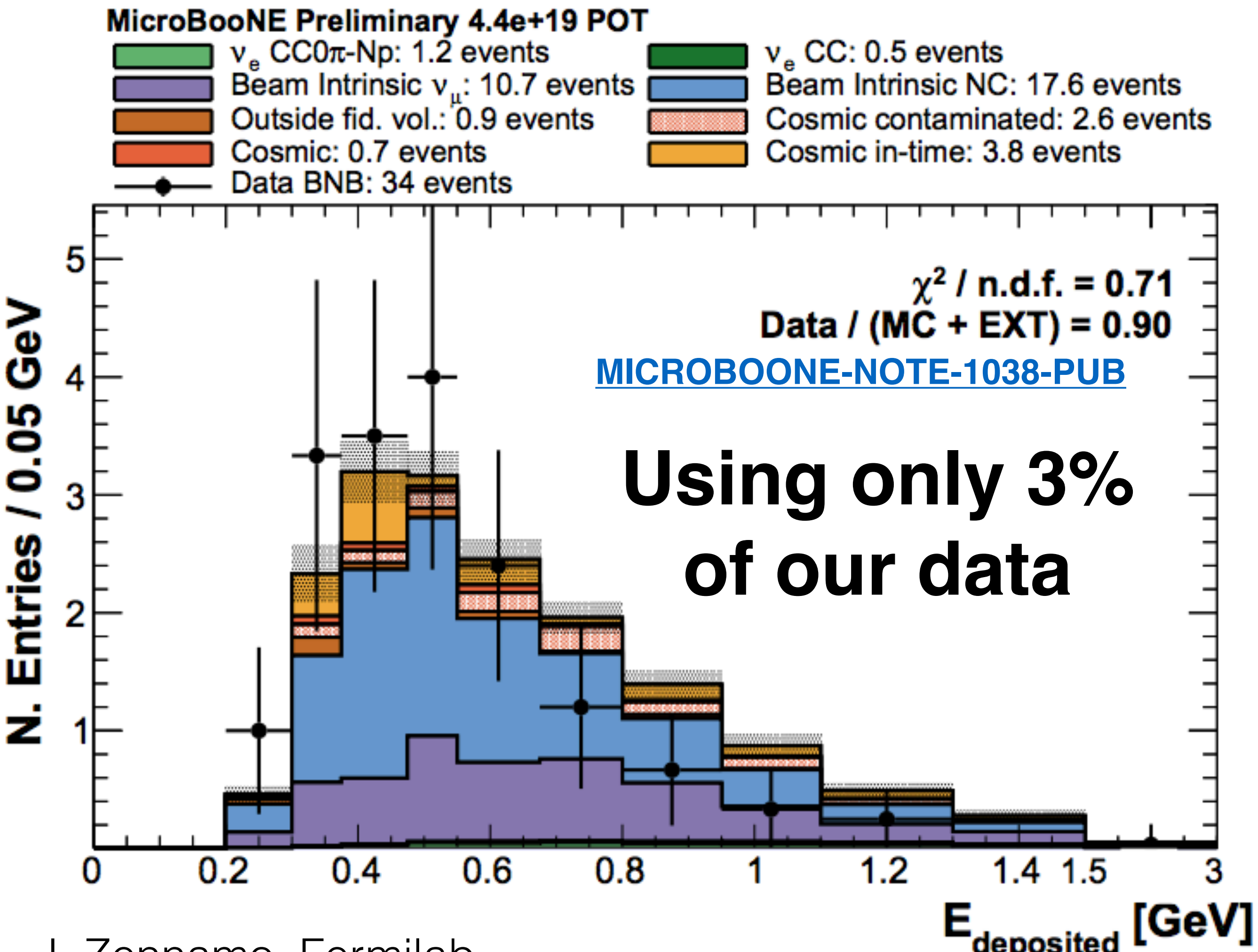
With these constraints and studies we're aiming to achieve systematic uncertainties in the sub-10% range

Electron Neutrino Excess Systematic Constraints

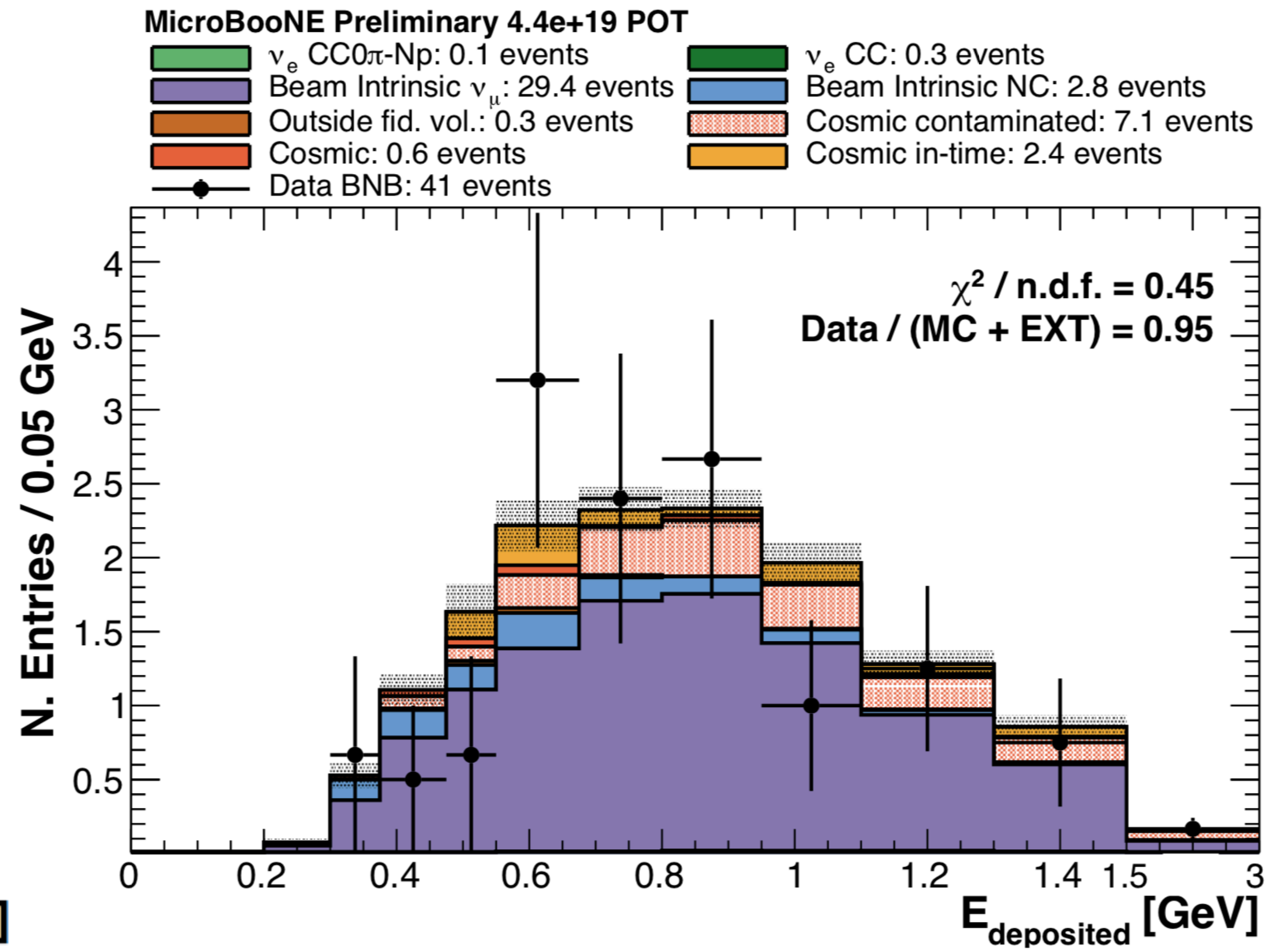
When performing more inclusive searches a wider variety of backgrounds feed into the analysis, these likewise need to be constrained in a data-driven way

Reversing our various purifying cuts allows us to create samples that are enhanced in different backgrounds to verify their modeling against our data

Photon-sideband for inclusive analysis



ν_μ-sideband for inclusive analysis



NC Radiative Delta Decay Excess Searches

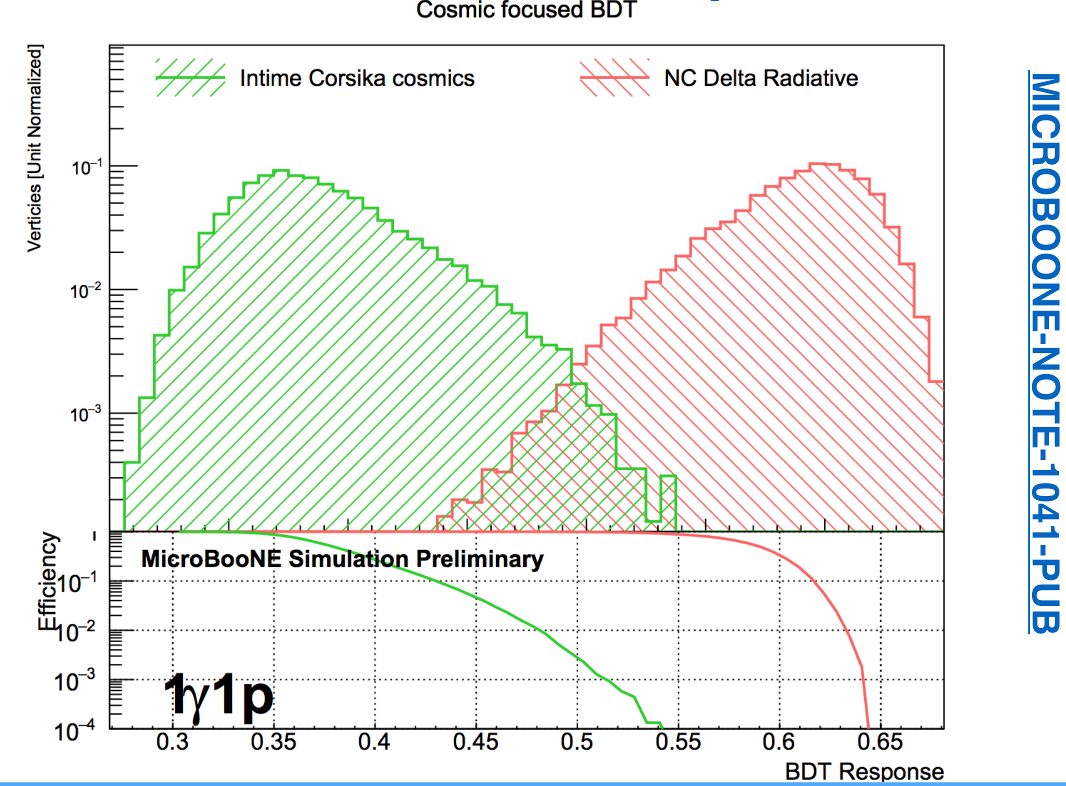
To put our searching for an excess of NC Δ→(p/n)+γ into context this is a process that hasn't been measured in a neutrino experiment

Using measurements of the NC π^0 production one can directly constrain the expected rate of radiative decays

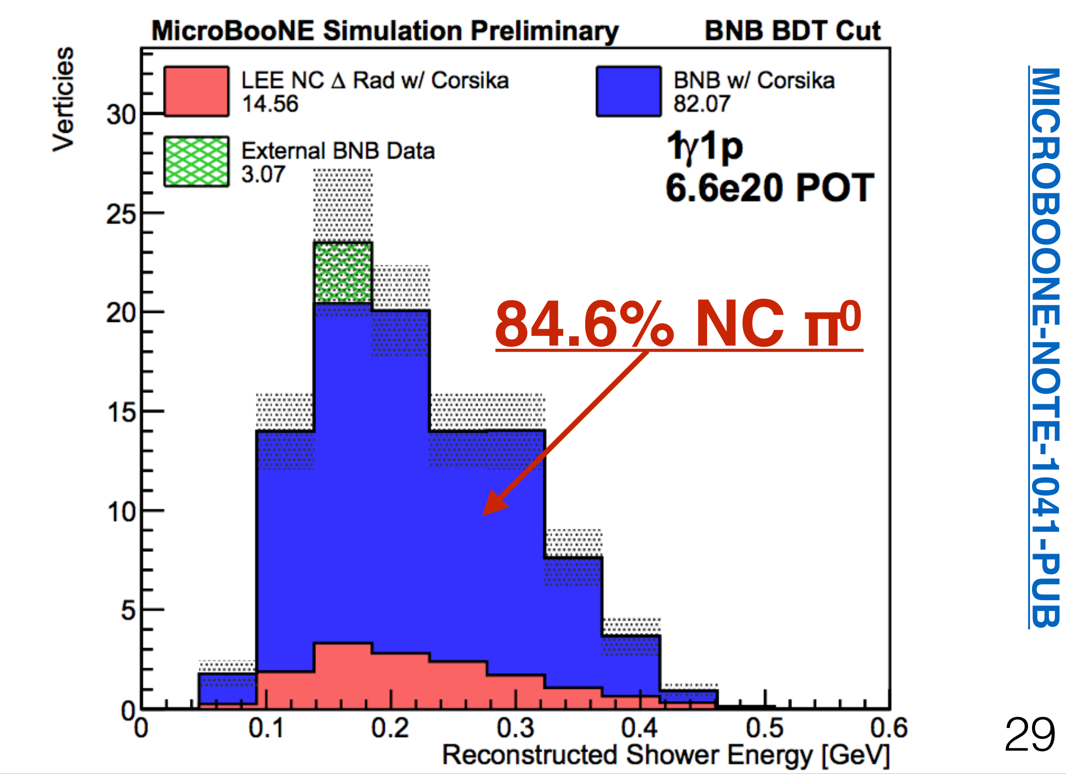
Using a powerful BDT we can distinguish our signal from that coming from cosmics; **a major challenge in a liquid argon TPC**

The next great challenge laying ahead for this analysis is the mitigation of the large NC π^0 background, many techniques to tag the low energy showers are being explored **(including using our deep learning tools)**

Cosmic Removal BDT response



Post-selection Shower Energy Distribution



Path Towards Understanding an Anomaly

Looking forward:

We have recently updated our complete simulation chain

Search for Excess

Define channel, develop selection, and perform a blinded search for an anomolous excess of events

Integrating our calibrations into a new detector simulation, implemented a more complete signal processing, and the latest version of the GENIE event generator

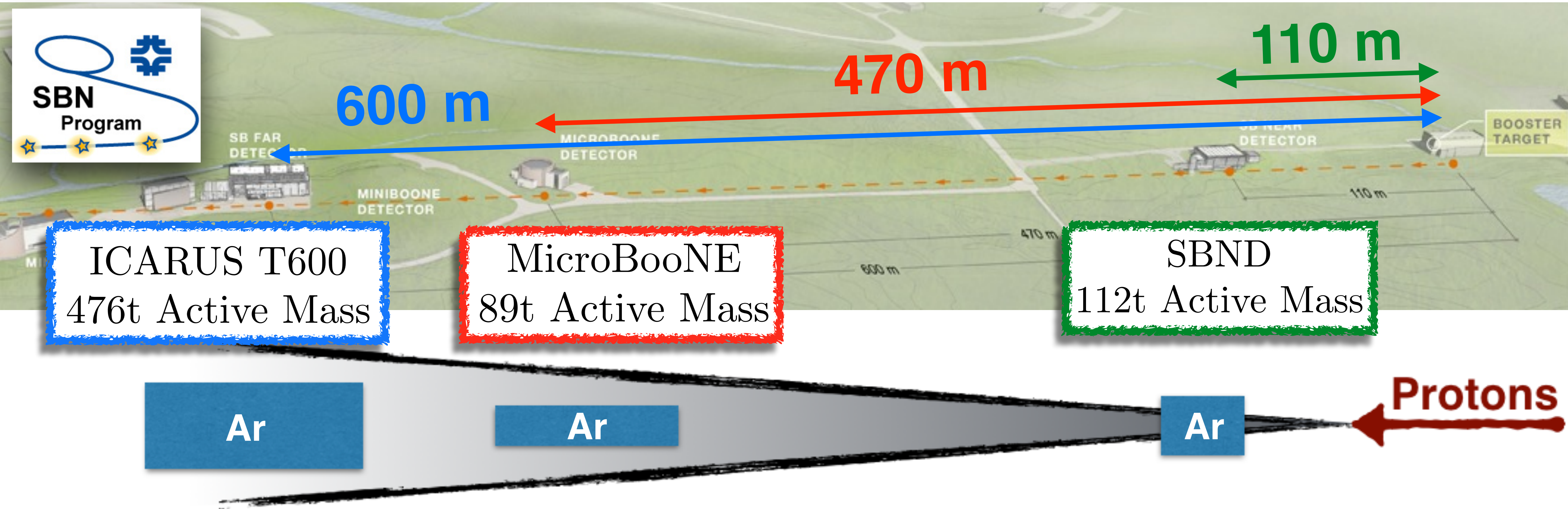
These are now being integrated into our searches

Short-Baseline Neutrino Program

Over the next couple of years two additional detectors, ICARUS and SBND, will come online joining MicroBooNE

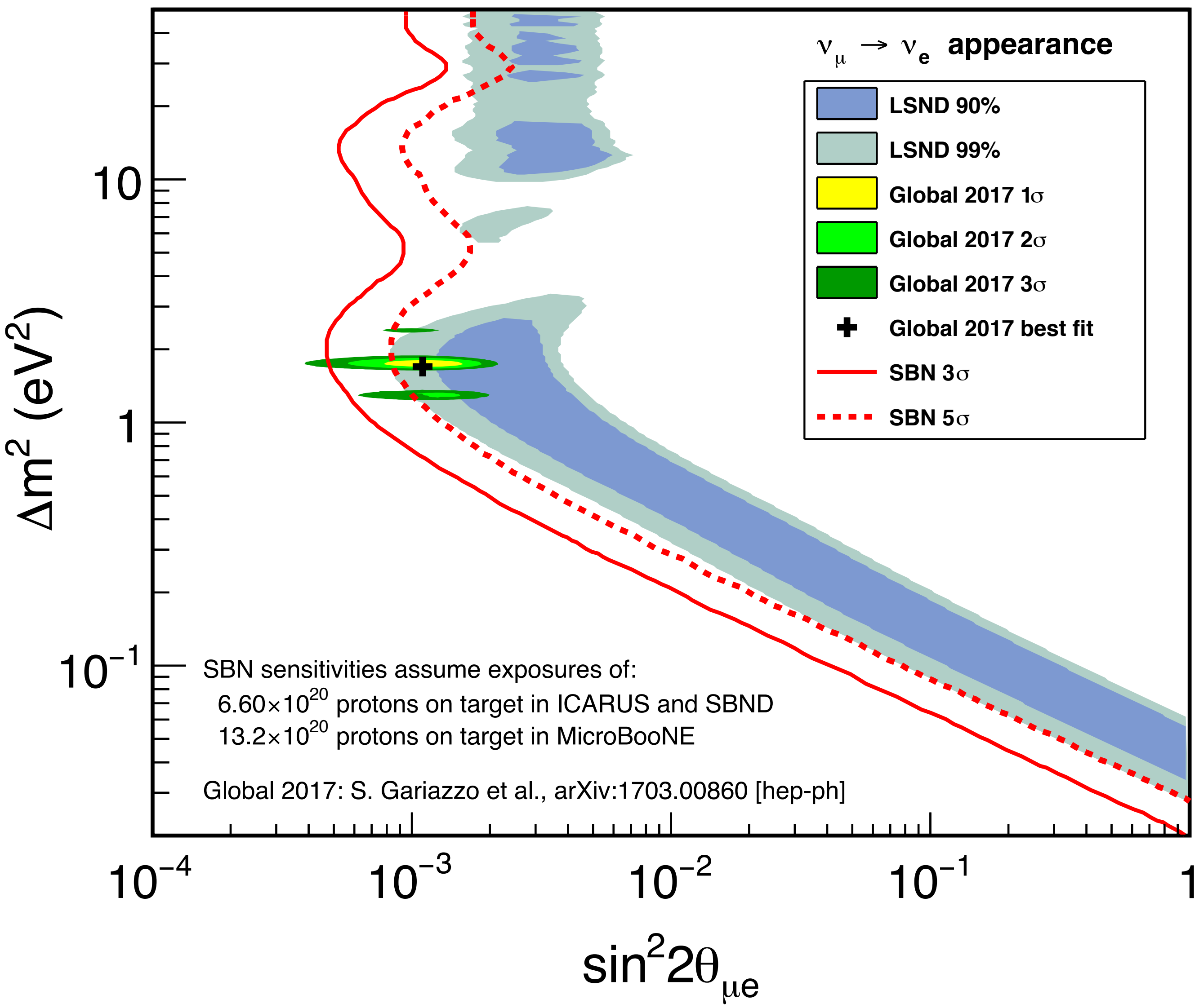
By using three detectors exposed to the same neutrino beam, using same target, and using functionally identical detectors we can use correlations across the detectors to constrain the uncertainties

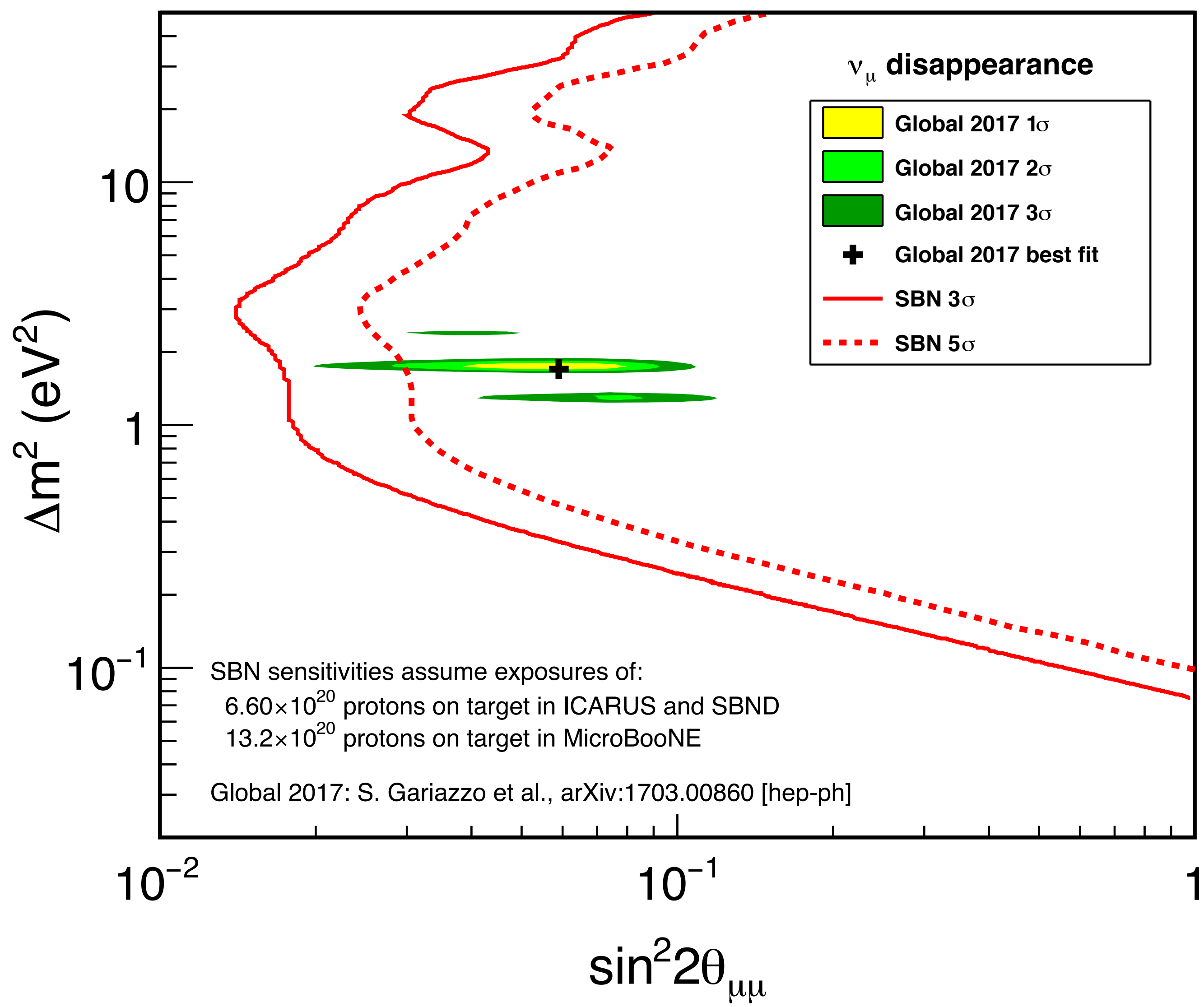
The goal of this program is to definitively test (a 5σ) the LSND allowed space



Short-Baseline Neutrino Program

The SBN Program can simultaneously probe globally allowed sterile neutrino phase-space in both appearance and disappearance channels with high confidence





Conclusions

MicroBooNE has begun publishing our first neutrino cross section measurements

(More on this later from J. Mousseau!)

These measurements are enabling us to take in-depth look at the neutrino interaction modeling and how this impacts our searches for an event excess

Using our data we have significantly advanced the state-of-the-art in LArTPC detector simulation over the past year

Calibrations are now integrated into our detector simulation enabling us to directly reduce of our largest systematics

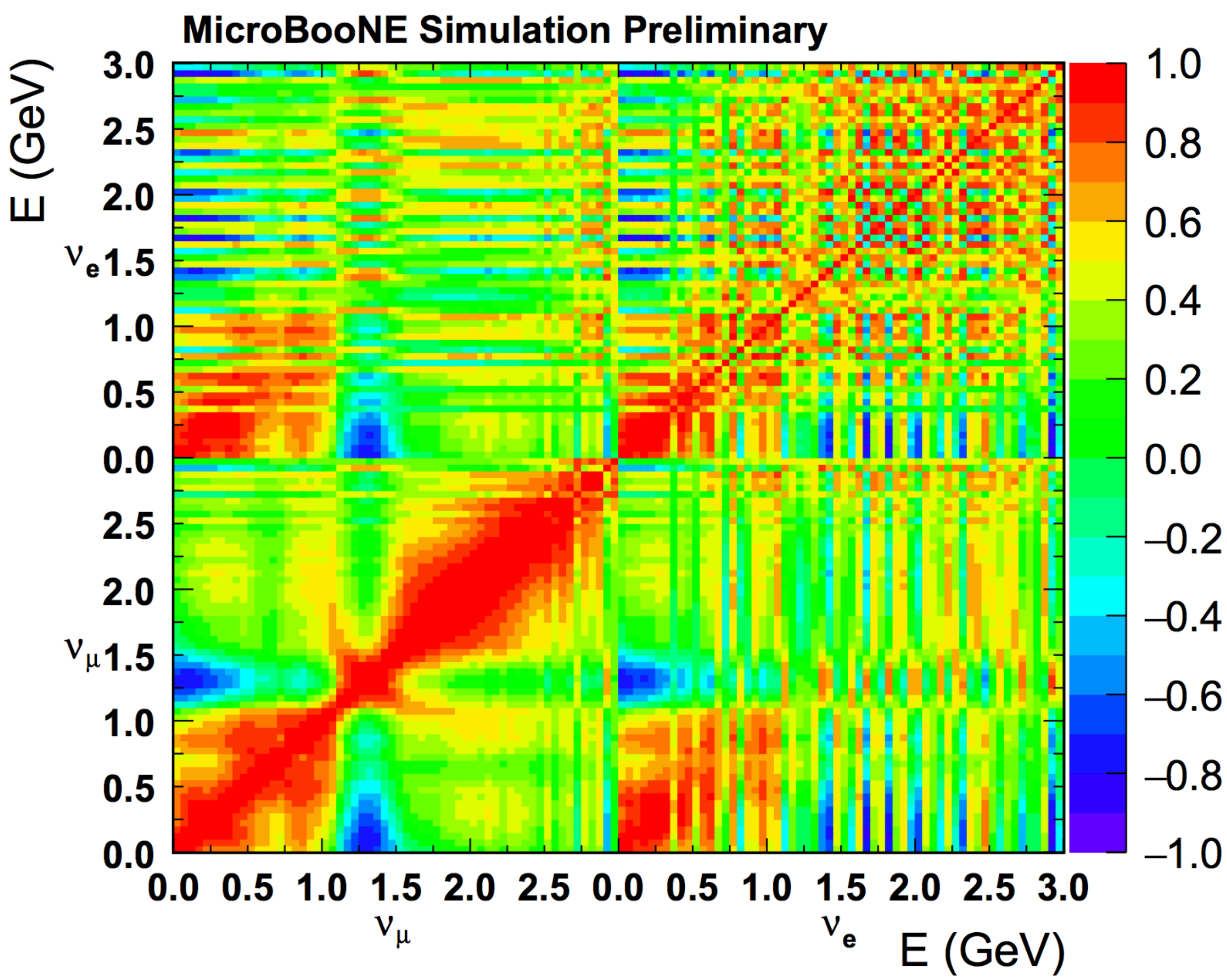
The next year is going to be an exciting time for MicroBooNE as our analyses begin to directly benefit from these efforts

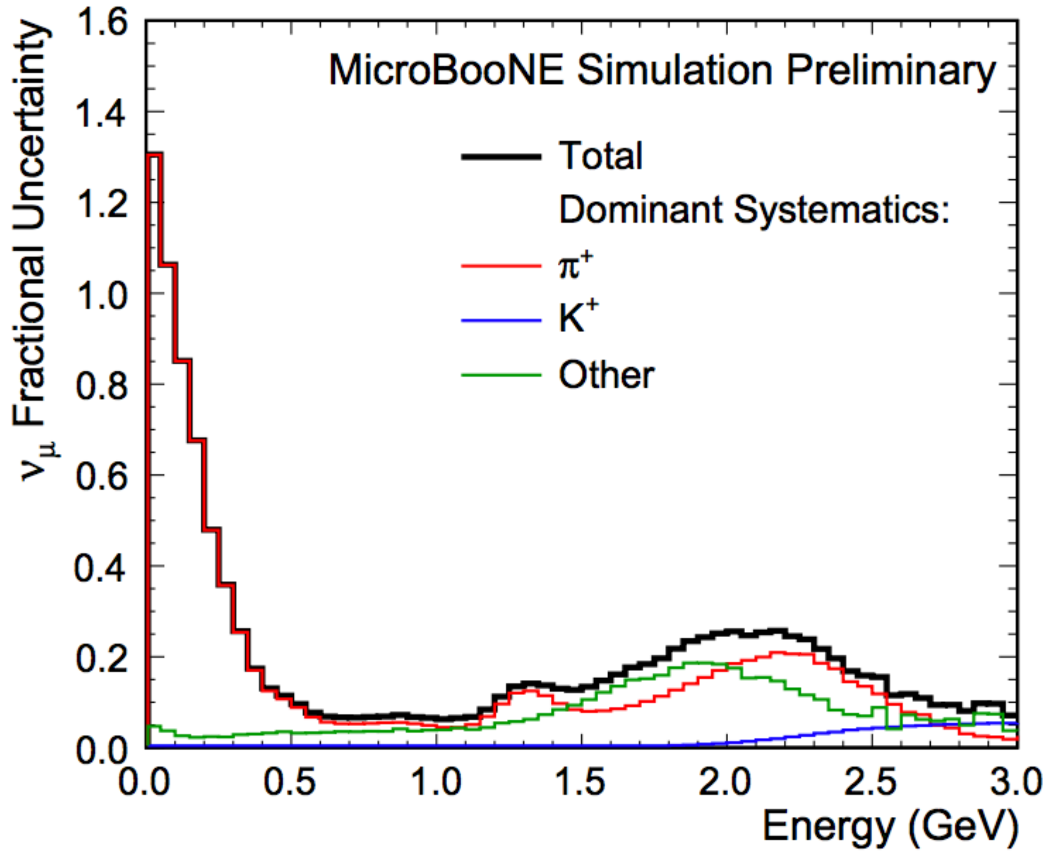
Stay tuned!

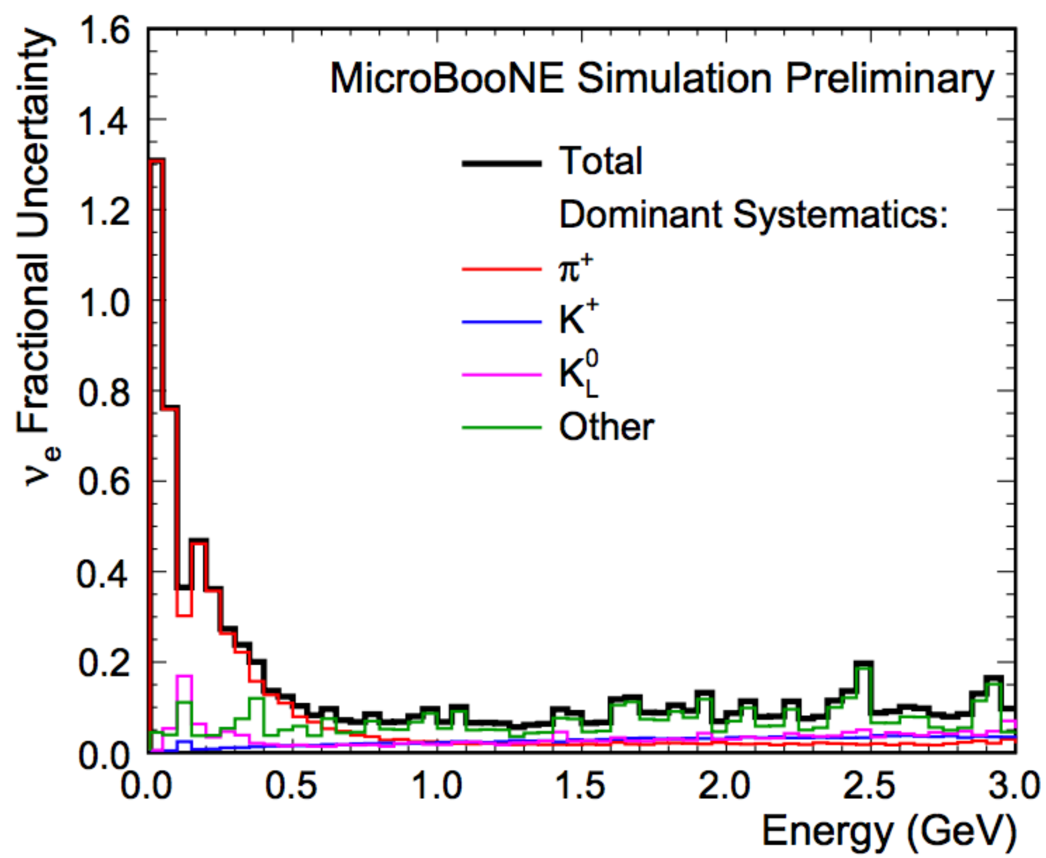
Backup Slides

Flux Uncertainties and Correlations

Flux Correlation Matrix







Double Differential ν_μ-Ar Cross Section

arXiv:1905.09694, submitted to PRL

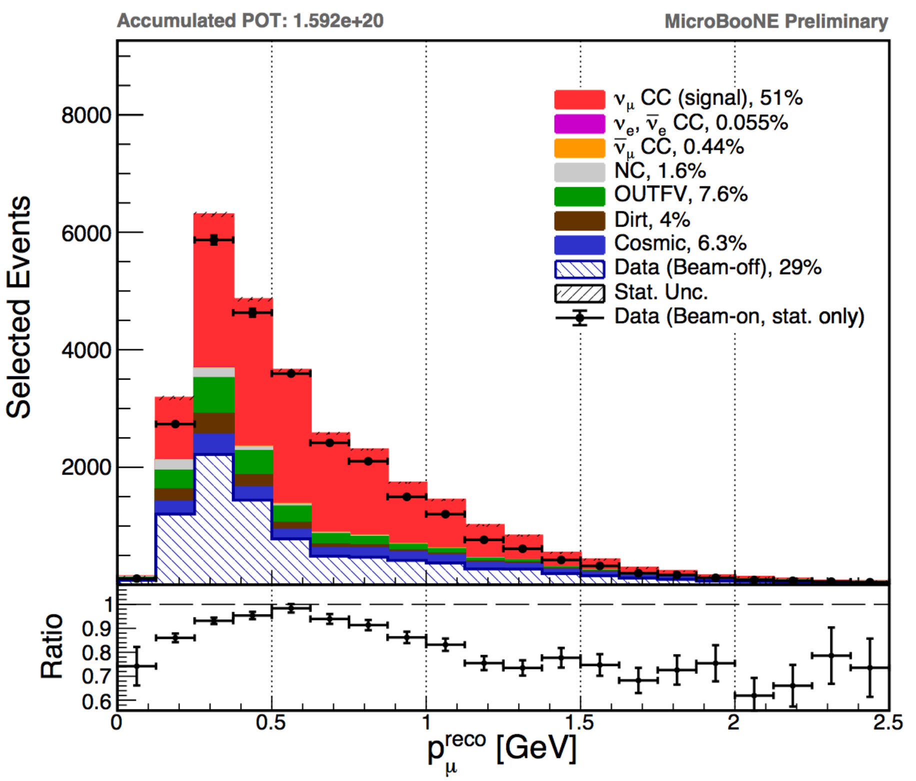
Challenging due to cosmic contamination from surface operation

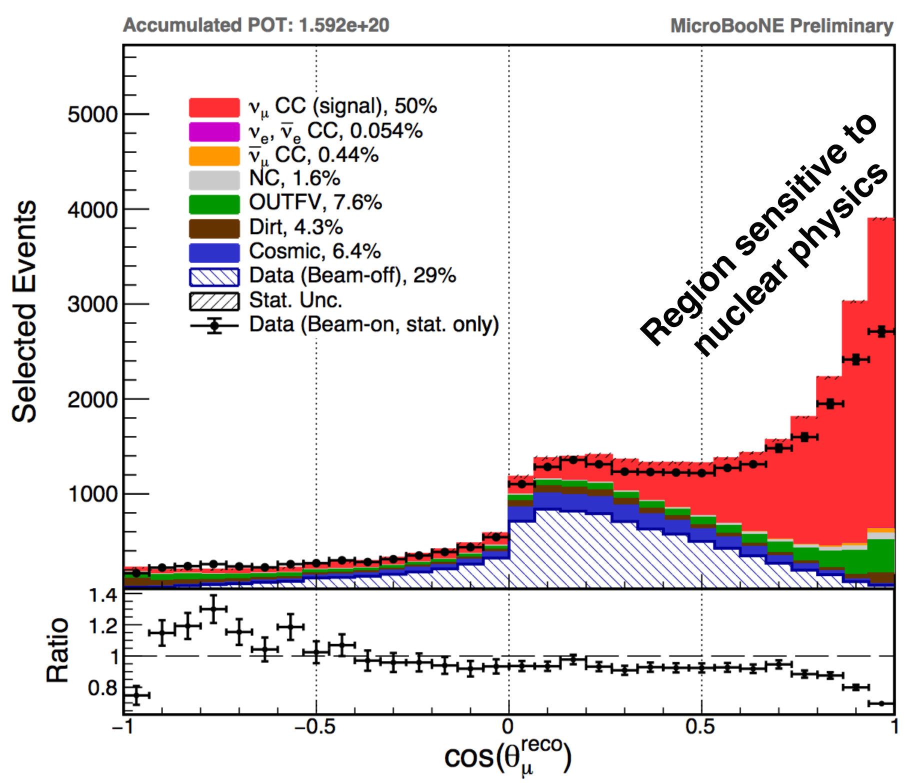
Analysis introduced many LArTPC firsts currently being ported to other LArTPC experiments

1. Use of multiple coulomb scattering for measuring muon momentum JINST 12 P10010 (2017)
2. Application of TPC-PMT charge-to-light matching to reject cosmic backgrounds
3. Full angular coverage

The cross section is measured as a function of the muons reconstructed momentum and angle with respect to the neutrino's direction

The largest background comes from beam-coincident cosmic muons that we constrain with data

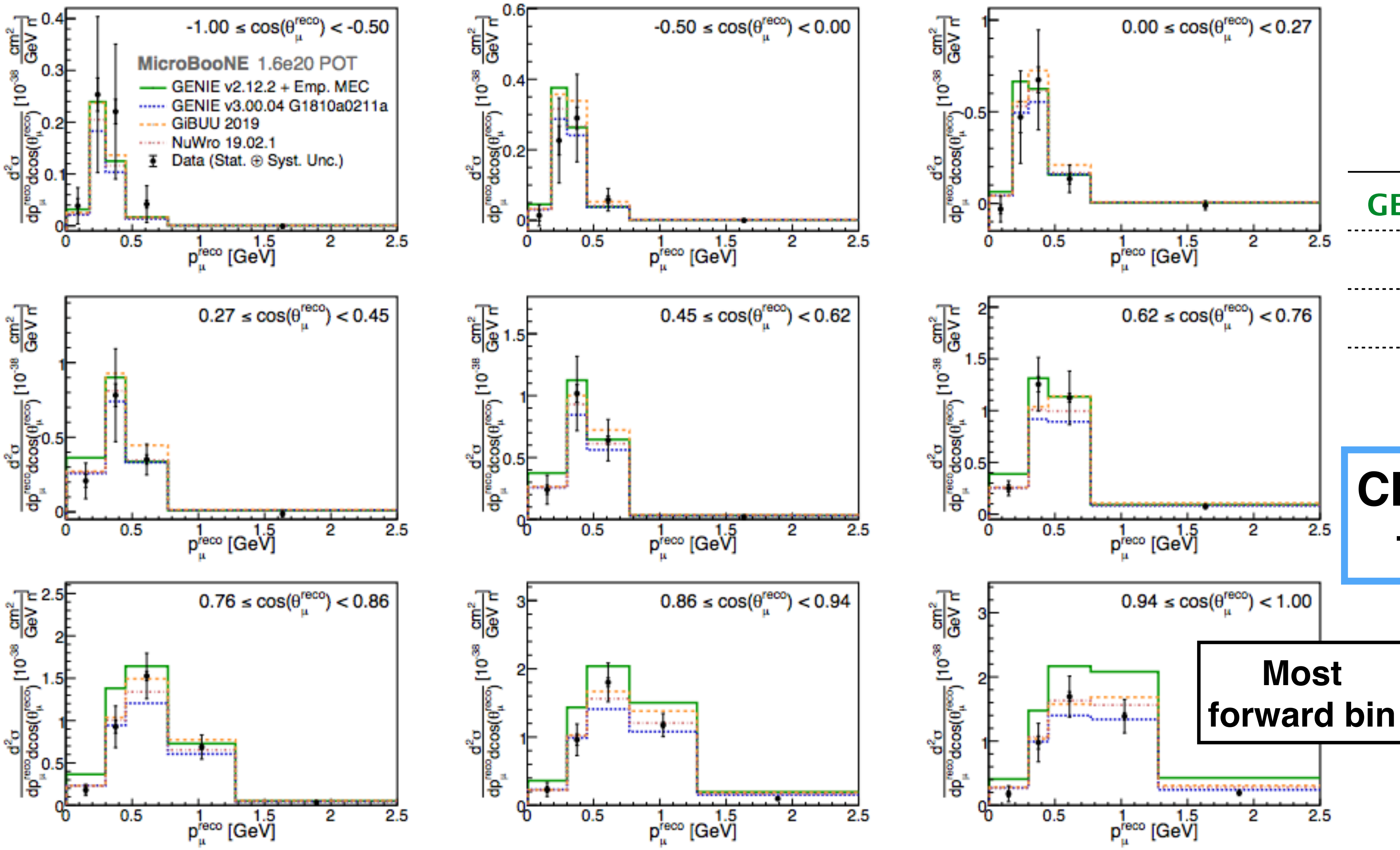




Double Differential ν_μ-Ar Cross Section

Measured in 42 bins of $\cos(\theta_\mu)$-p_μ includes covariance matrix

First double differential ν_μ-Ar cross section, measurement clearly favors the latest nuclear models found in the newest version of GENIEv3, specifically in the G1810a0211a tune



Model	χ^2
GENIEv2+MEC	245.9
GENIEv3	108.8
NuWro	172.9
GiBUU	126.5

Clear preference for GENIEv3!

arXiv:1905.09694, submitted to PRL

Double Differential ν_μ-Ar Cross Section

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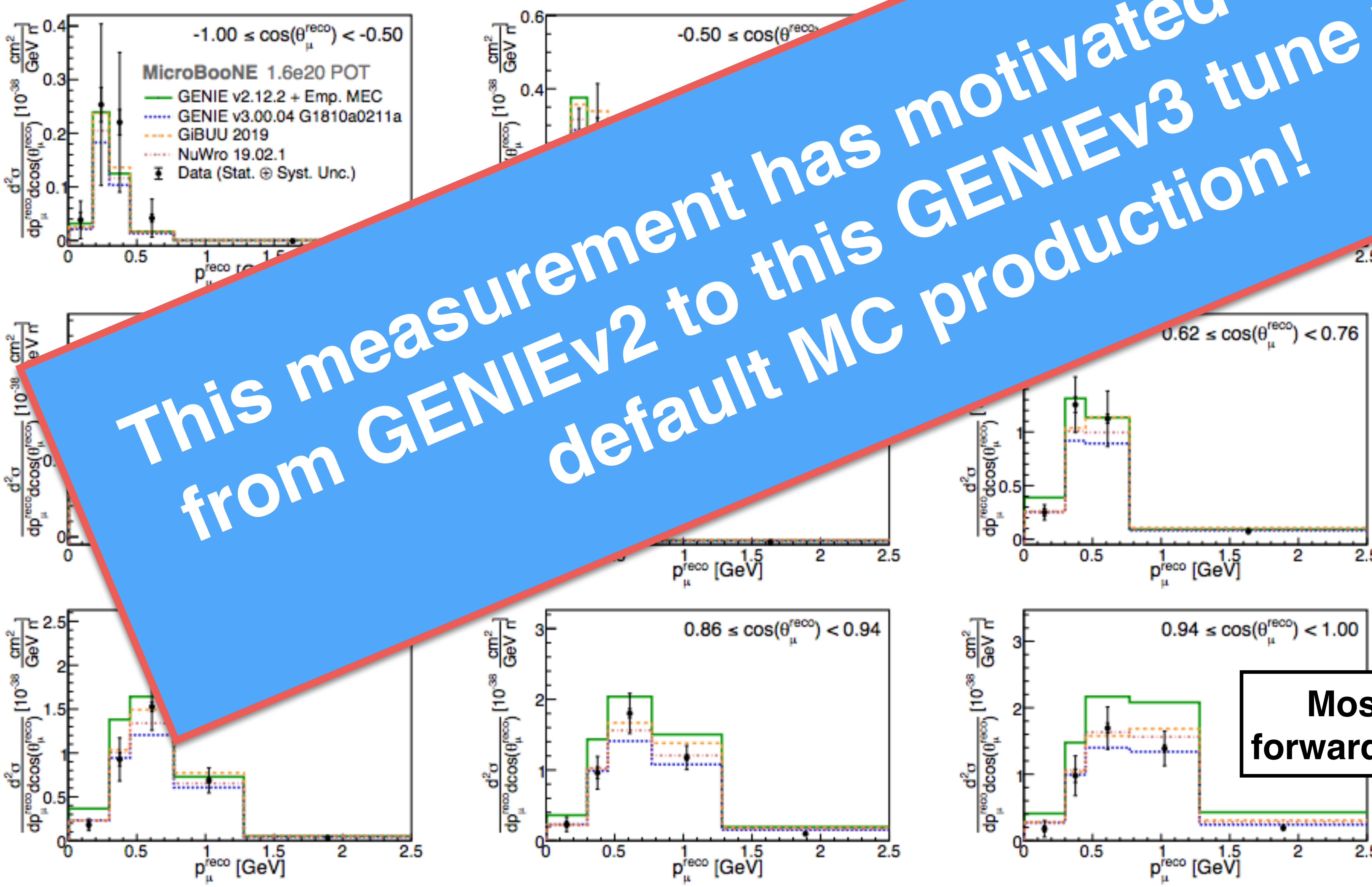
First double differential ν_μ-Ar cross section, measurement cl... uclear models found in the newest version of GENIEv3, spec... e



This measurement has motivated us moving from GENIEv2 to this GENIEv3 tune for our default MC production!

	χ^2
GENIEv2+MEC	245.9
GENIEv3	108.8
NuWro	172.9
GiBUU	126.5

Clear preference for GENIEv3!

arXiv:1905.09694, submitted to PRL

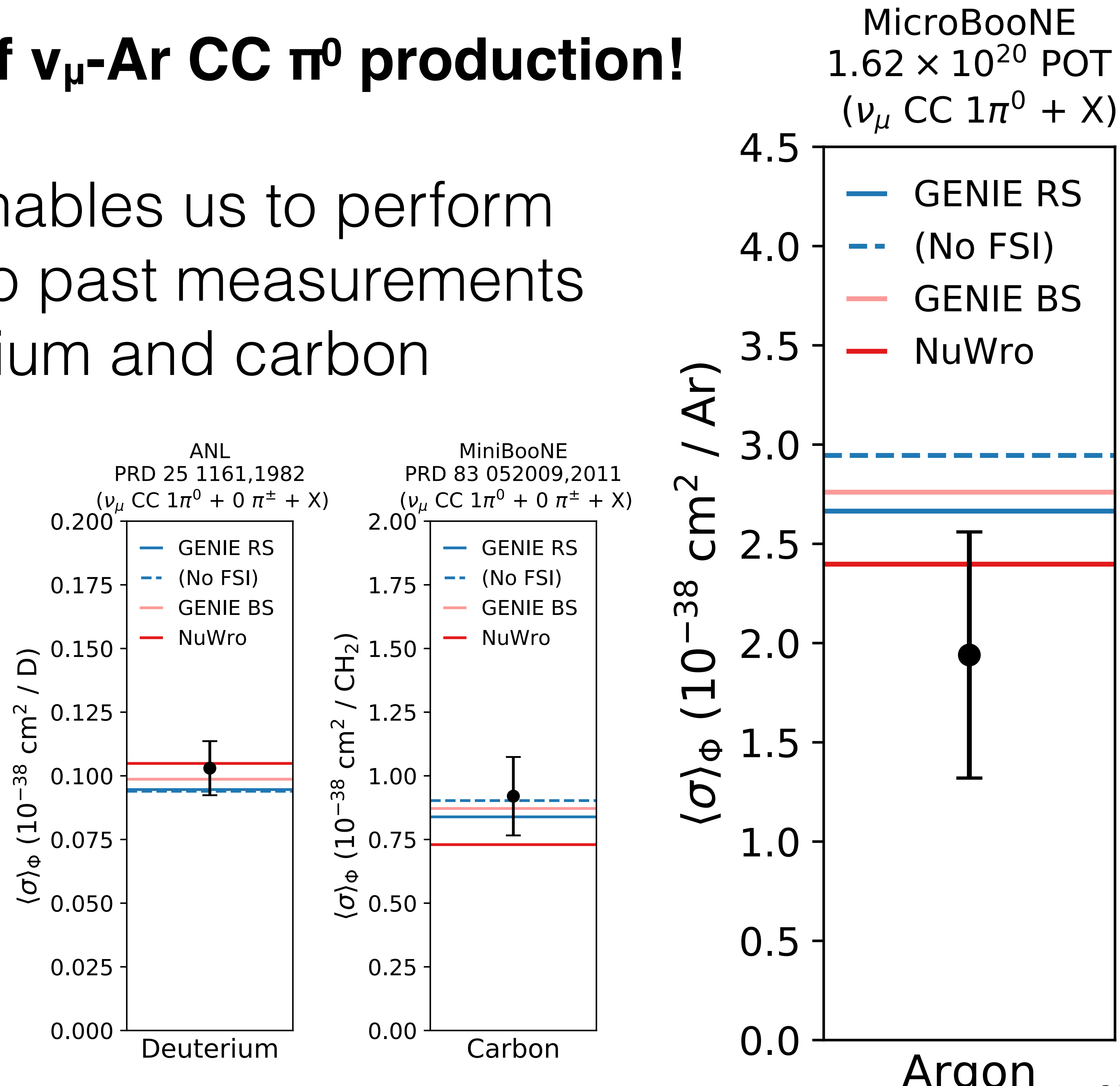
Charged Current Neutral Pion Production

First measurement of ν_μ-Ar CC π^0 production!

This measurement enables us to perform direct comparisons to past measurements performed on deuterium and carbon

We verify that the scaling used in models for larger nuclei is consistent with our data

Note the increased strength of final-state interactions for heavier nuclei



PRD 99, 091102(R) (2019)

Charged Current Neutral Pion Production

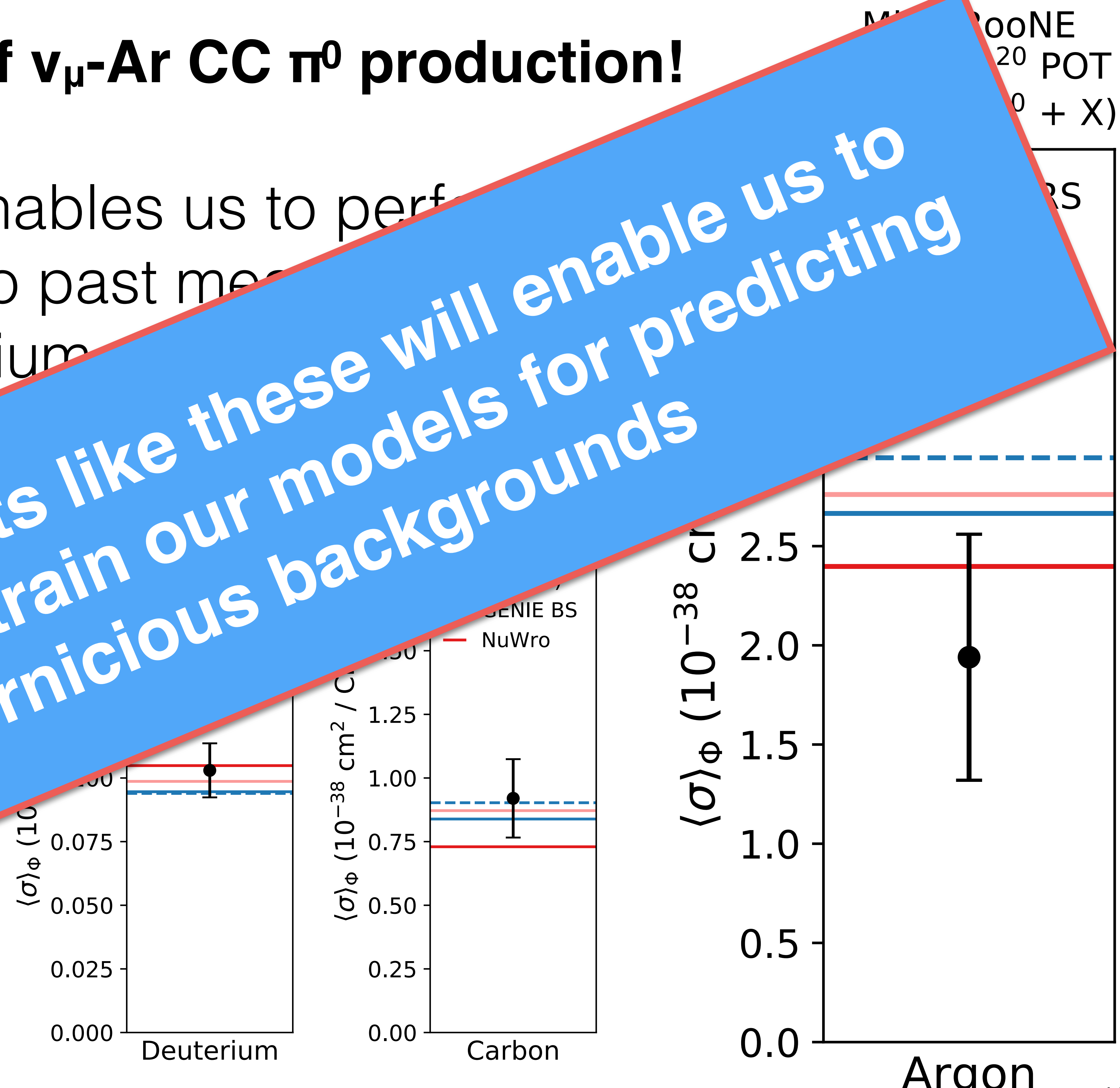
First measurement of ν_μ-Ar CC π^0 production!

This measurement enables us to perf… direct comparisons to past me… performed on deuterium…

We verify that th… scaling … for… c…

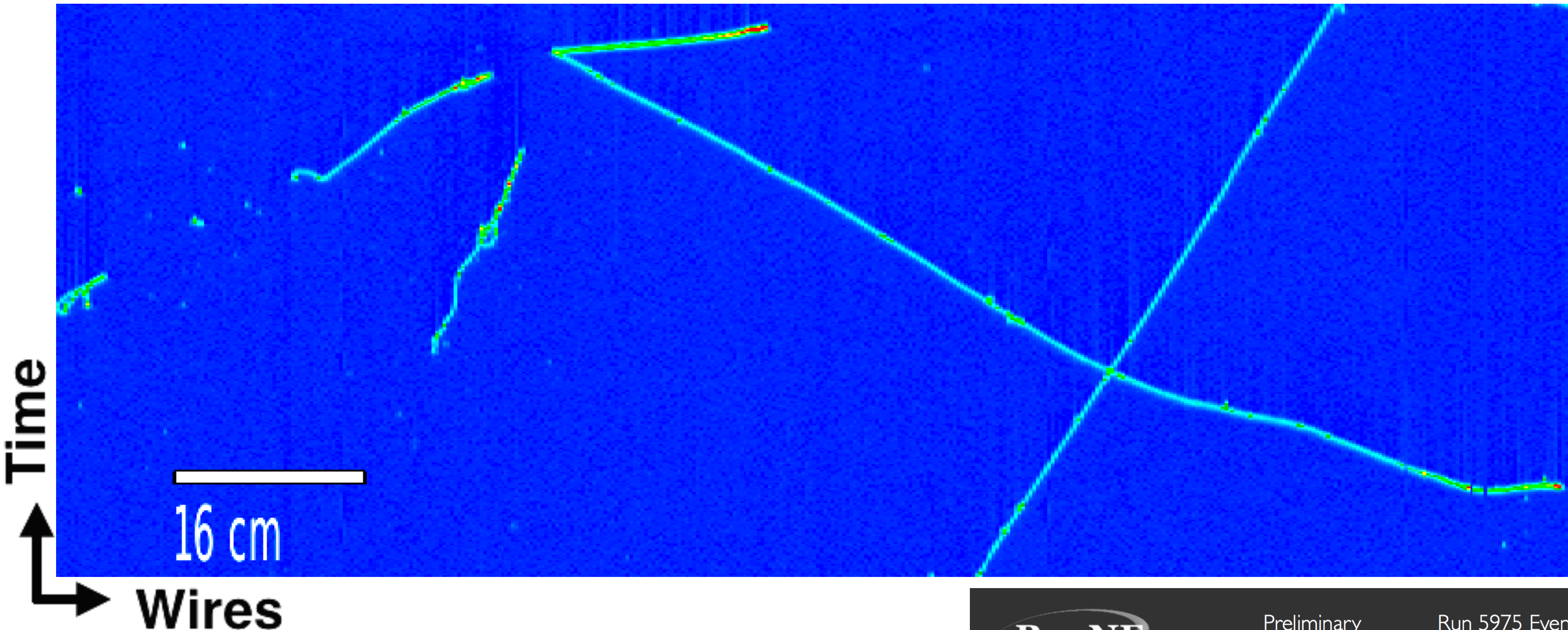
Not… stren… state intera… s for heavier nuclei

Measurements like these will enable us to further constrain our models for predicting pernicious backgrounds

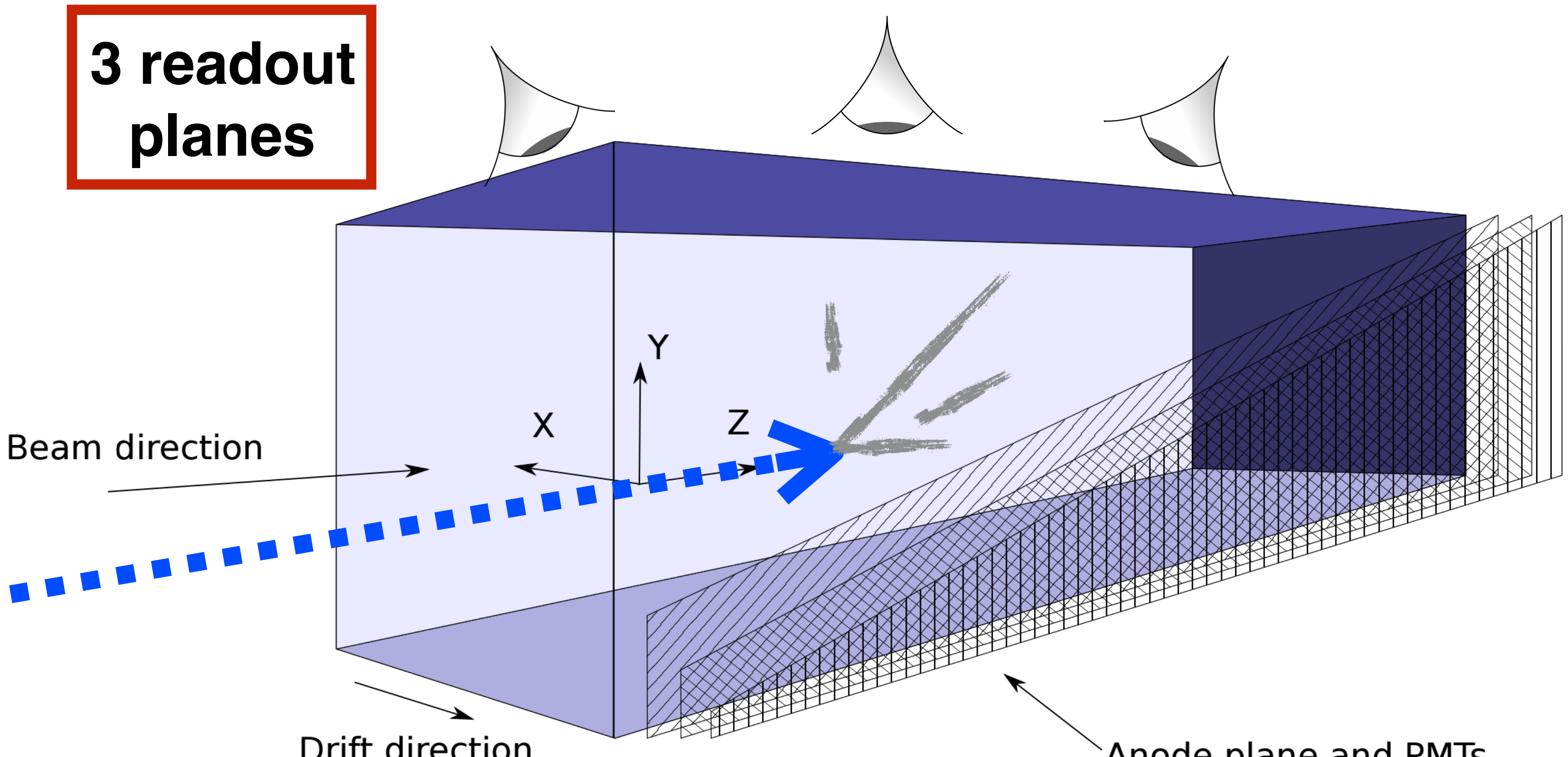


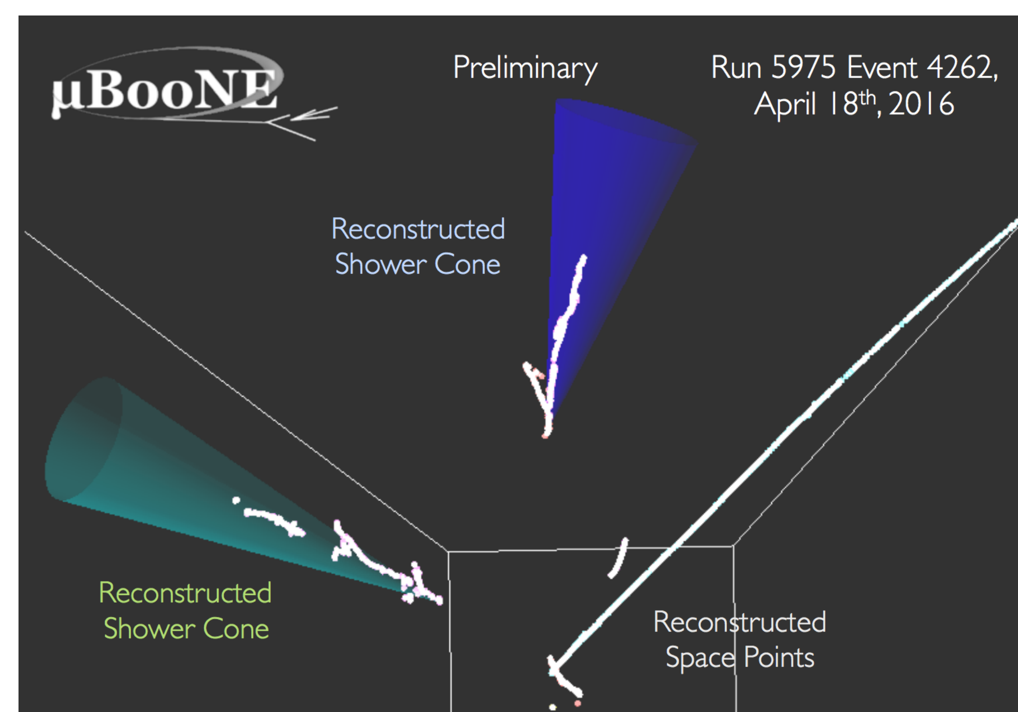
PRD 99, 091102(R) (2019)

Liquid Argon TPCs



3 readout planes





Multiple views allow for 3D reconstruction

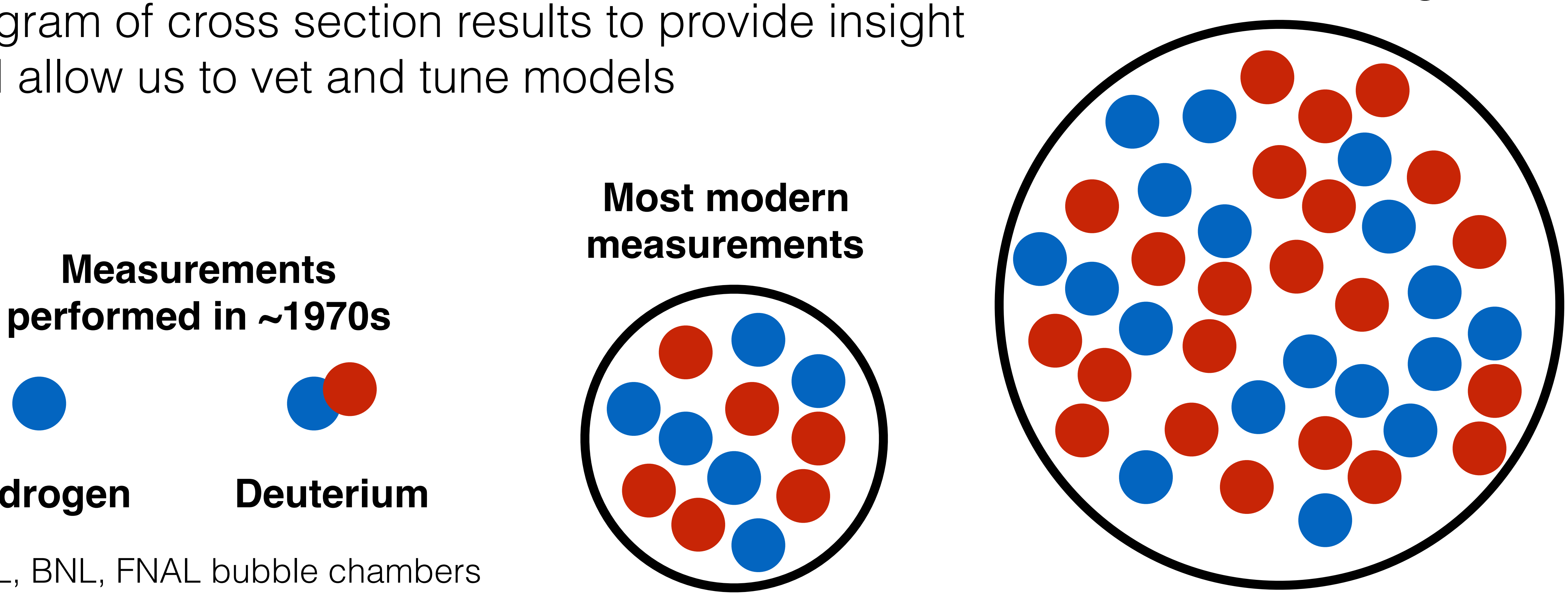
Neutrino Interactions on Argon

To resolve an anomaly we'll need precise a understanding of how neutrinos interact with argon

Currently there is limited ν-Ar cross section data available

A majority of modern neutrino scattering data is on carbon and the scaling cross sections and observed nuclear effect to argon is highly uncertain

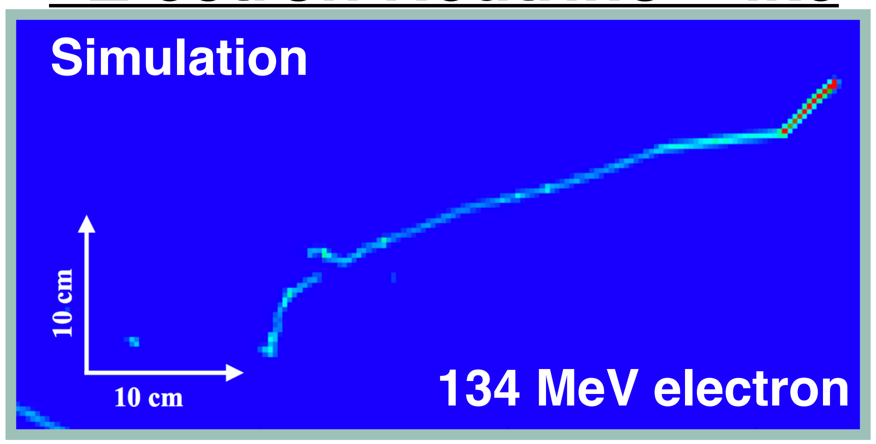
This has greatly elevated our need for a robust program of cross section results to provide insight and allow us to vet and tune models



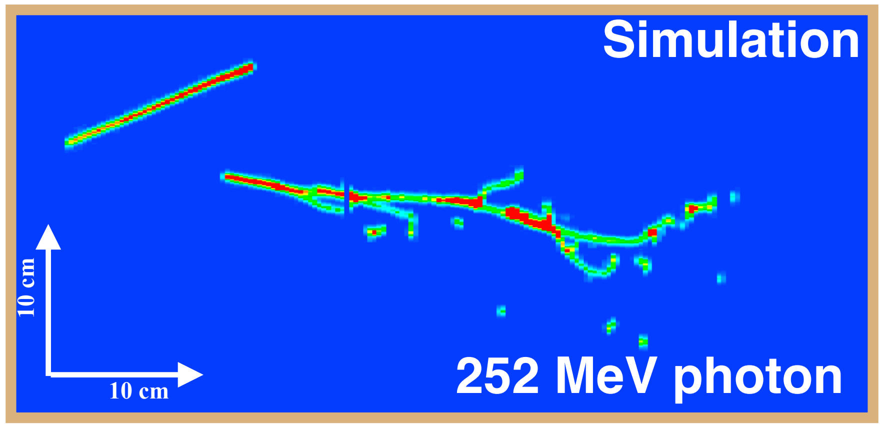
What Makes a Signal?

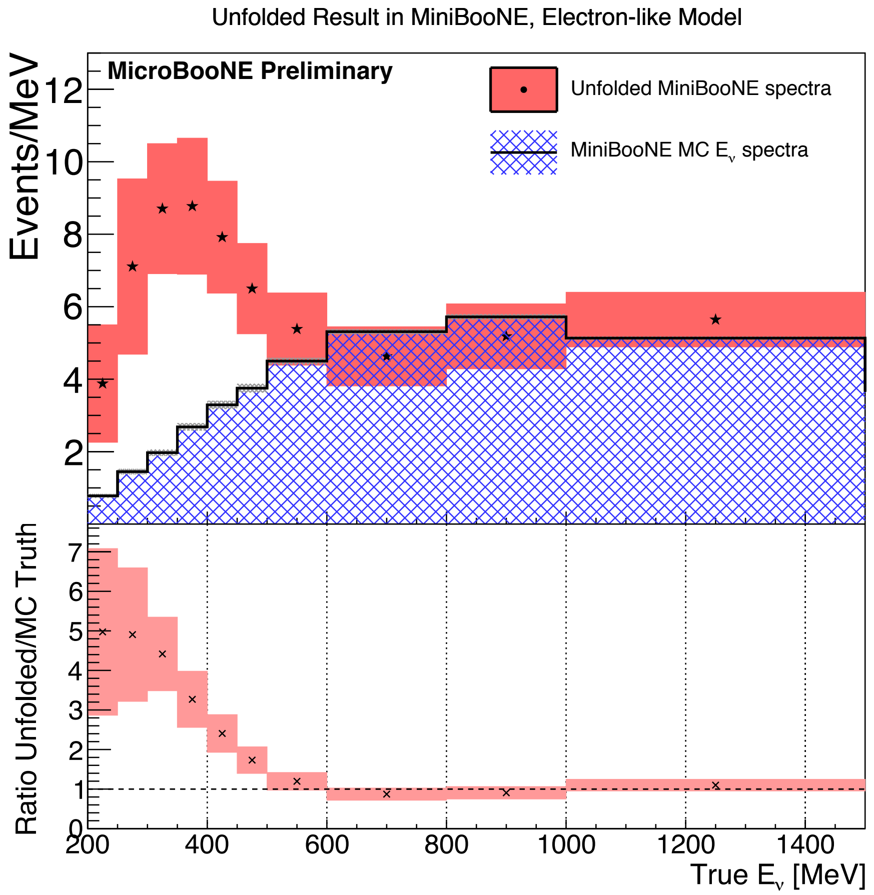
Unfolded MiniBooNE's results into signals we expect to observe under both hypotheses

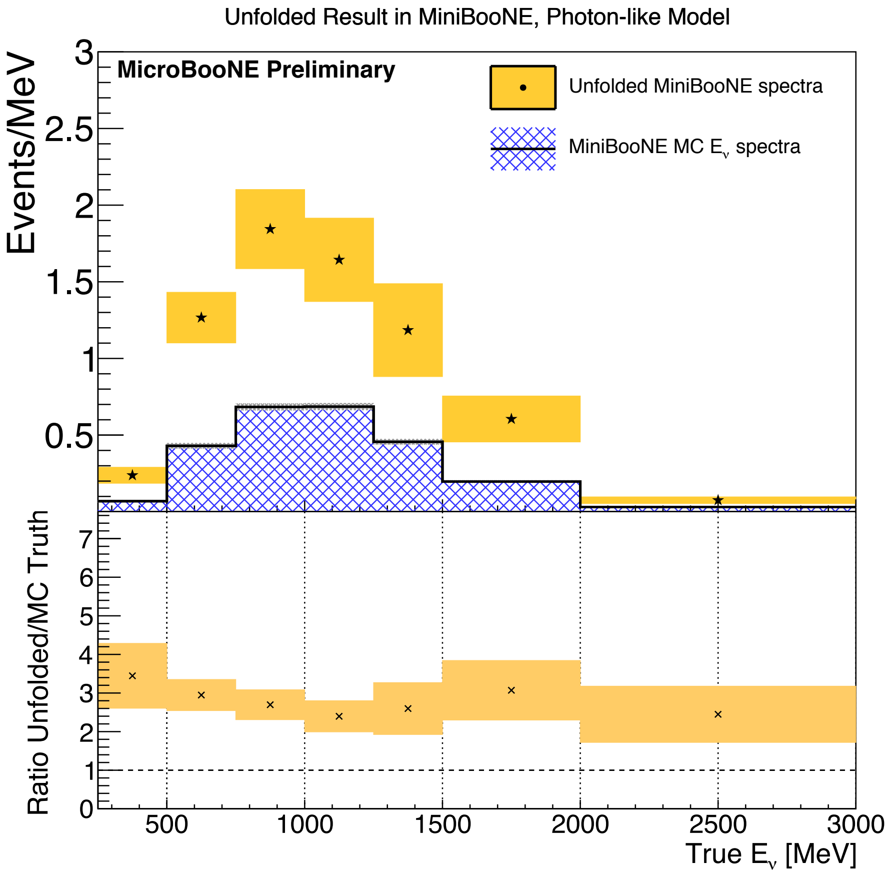
"Electron Neutrino"-like



"NC Delta Radiative"-like







Challenges:

1. Reconstructing low energy EM showers
2. Rejecting backgrounds
3. Determining particle species associated with excess
4. Controlling systematics
5. Building confidence in our results

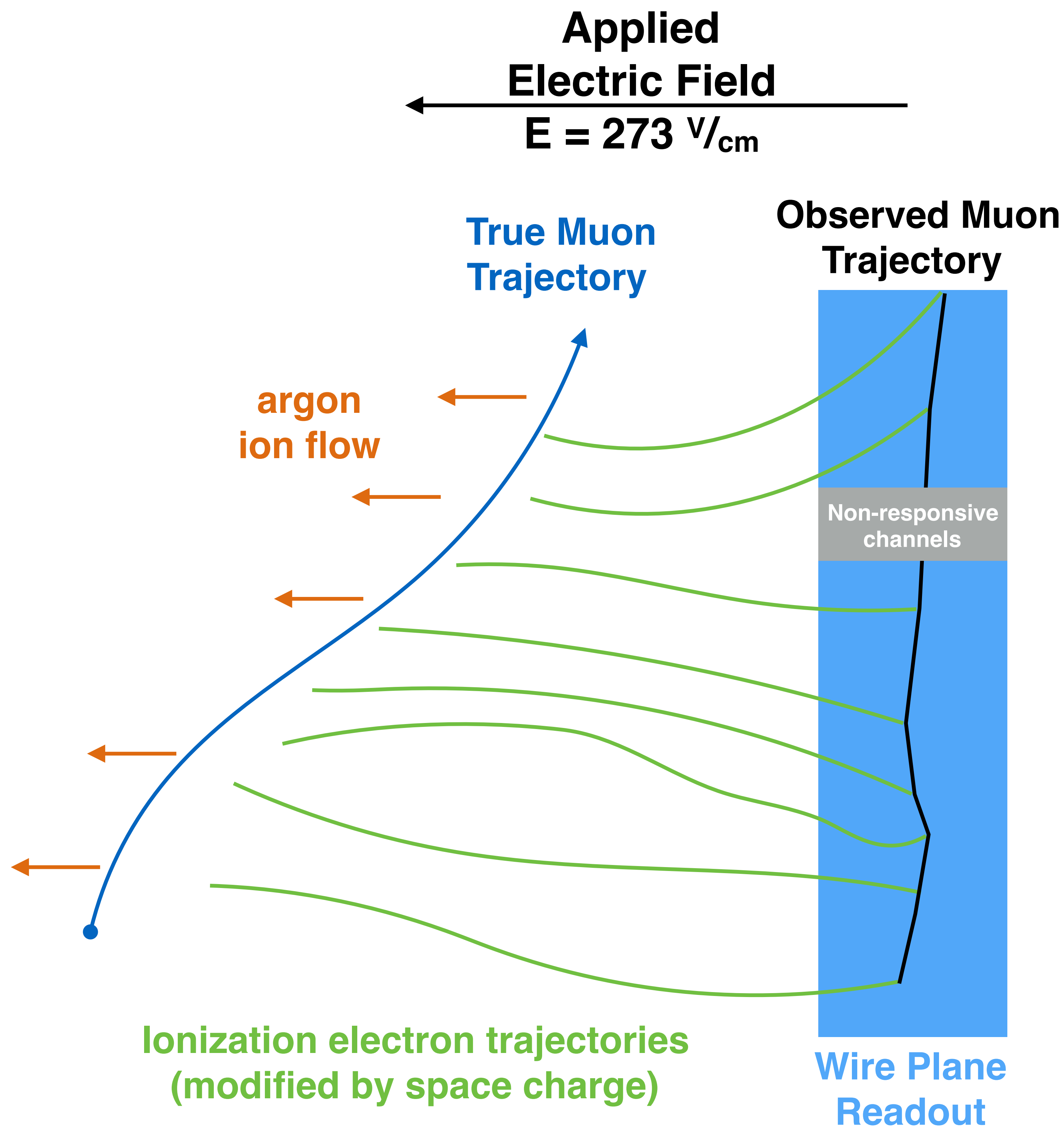
Unfolding described here:

MICROBOONE-NOTE-1043-PUB

Looking Forward

- Much of the work that has been shown did not fully integrate our cosmic tagging system which is available in 65% of our data
  - **Enables us to loosen our cosmic veto cuts and recover efficiency**
- The theoretical community has been exploring many possibilities for the MiniBooNE excess and are we are developing searches for many of these complex final states
  - **Dark photon decays, e^+e^- final states, fully inclusive ν_e searches, etc.**

Electron Drifting in LArTPC



Impact of 3D simulation