Recent Cross-section Measurements from MicroBooNE

Lorena Escudero
University of Cambridge
on behalf of the MicroBooNE collaboration

μBooNE

EPS-HEP, Ghent, Belgium
13th July 2019

Disclaimer

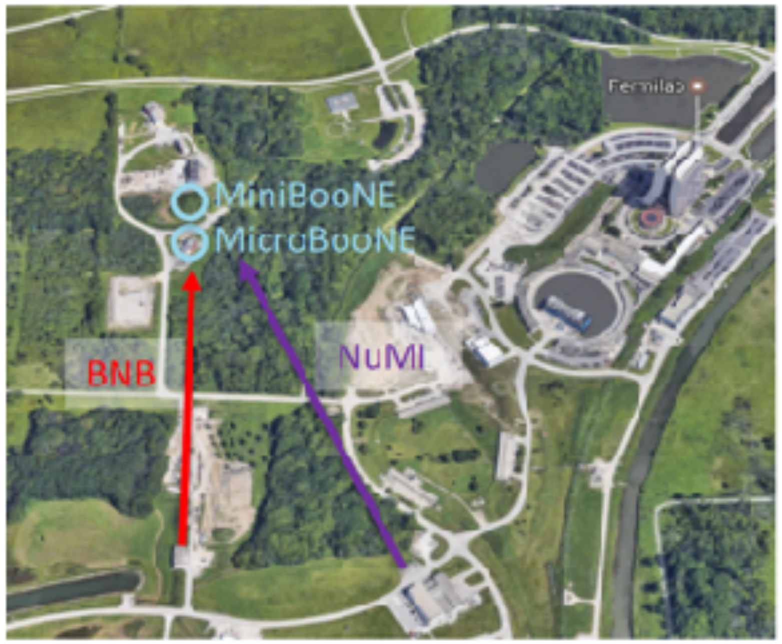
This talk is trying to cover in ~15 minutes more than 2 hours worth of material on new results from MicroBooNE!

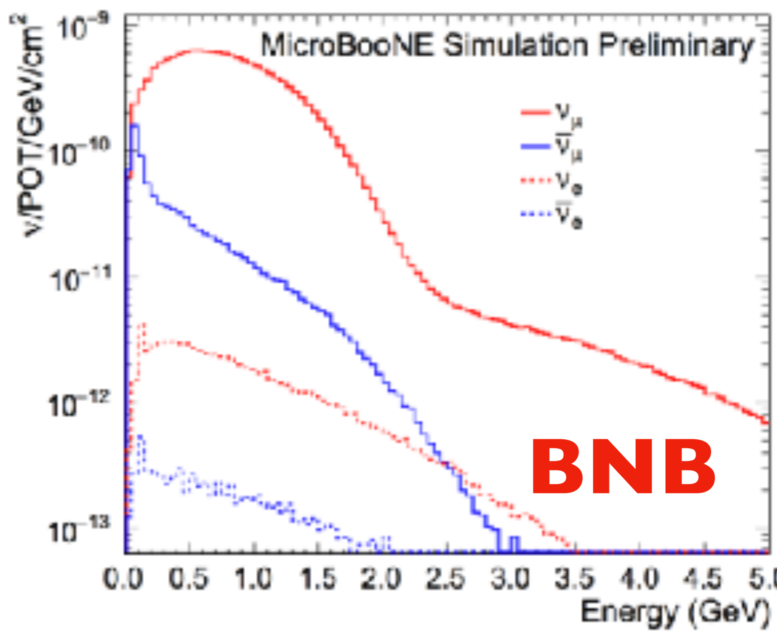
NuINT 2018

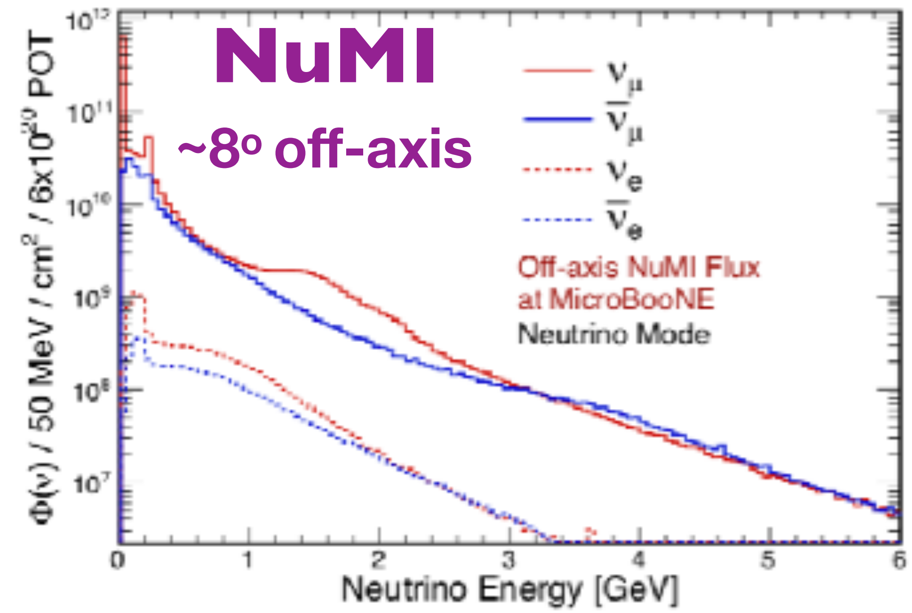
	MicroBooNE detector, modelling and performance *Gran Sasso Science Institute (GSSI)*	*Anne Schukraft* 16:30 - 17:00	Simulation and calibration Fully automated reconstruction
17:00	MicroBooNE charged-current inclusive cross section measurement *Gran Sasso Science Institute (GSSI)*	*Marco Del Tutto* 17:00 - 17:25	Track reconstruction
	MicroBooNE charged-current neutral pion cross section measurement *Gran Sasso Science Institute (GSSI)*	*Joel Mousseau* 17:25 - 17:50	Shower reconstruction
18:00	MicroBooNE electron neutrino inclusive cross section *Gran Sasso Science Institute (GSSI)*	*Colton Hill* 17:50 - 18:15	e/γ separation
	MicroBooNE charged-current analyses with final state protons *Gran Sasso Science Institute (GSSI)*	*Raquel Castillo Fernandez* 18:15 - 18:40	Calorimetric reconstruction

There is no way I can make justice to those analyses in this short time, so apologies in advance to MicroBooNE analysers!

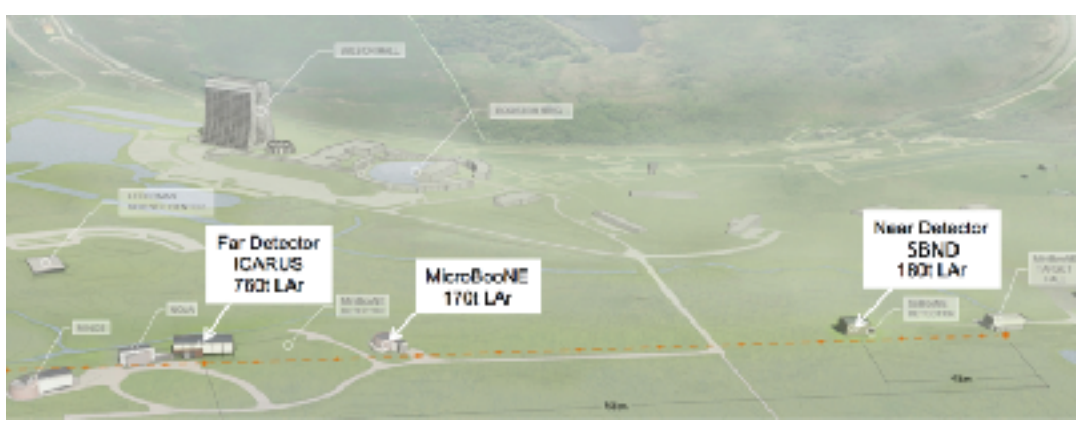
Short Baseline Accelerator Neutrino Experiment

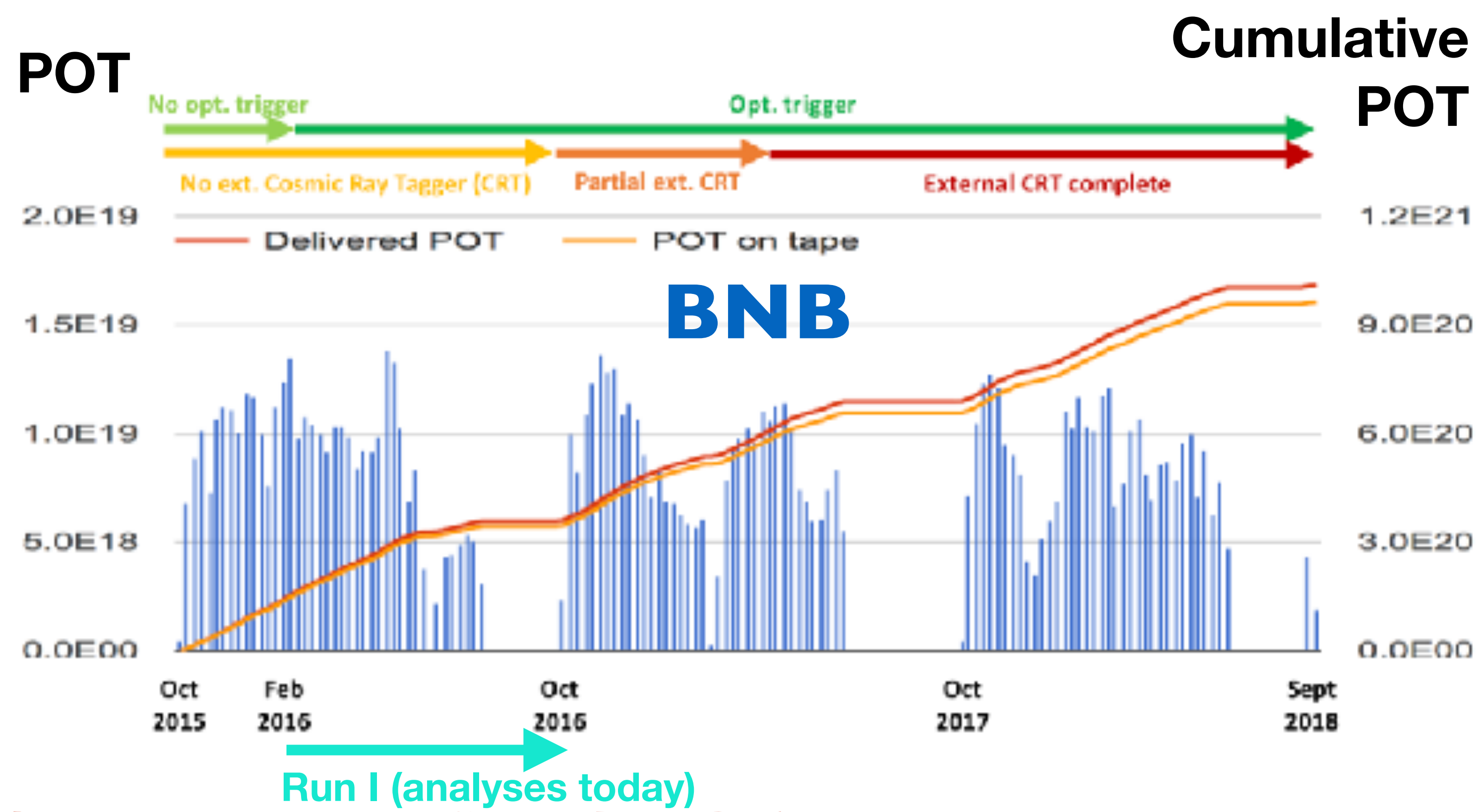






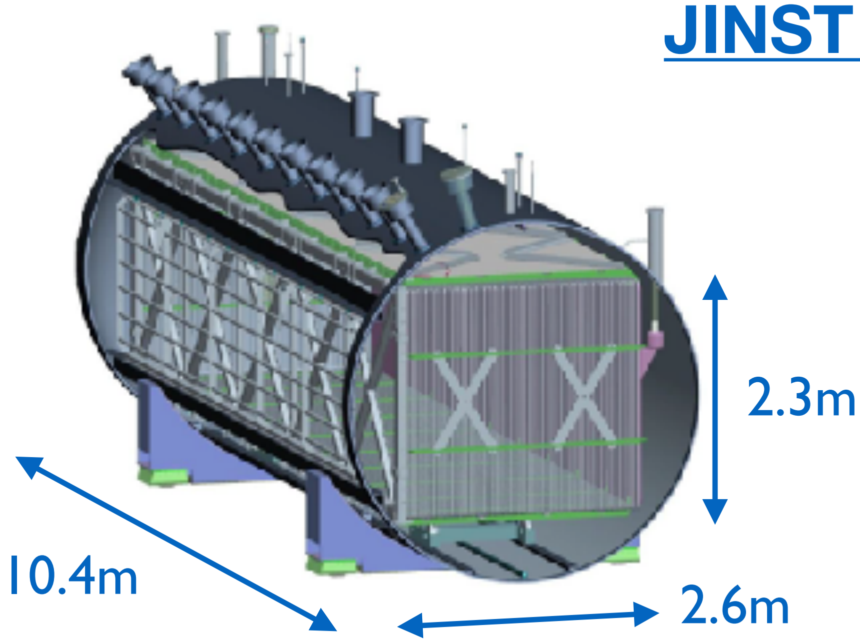
Part of the SBN program to resolve anomalies seen by LSND/MiniBooNE





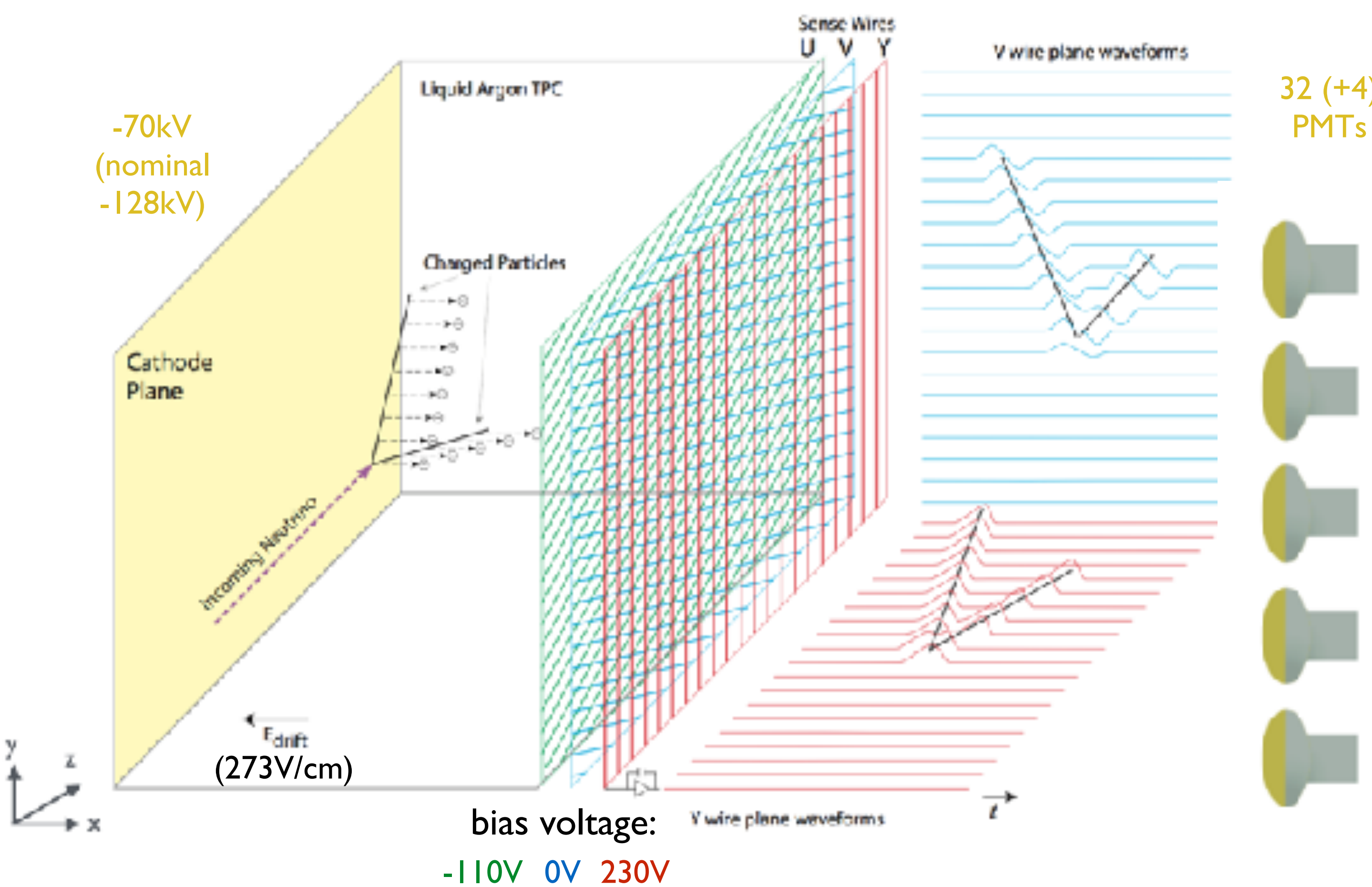
MicroBooNE

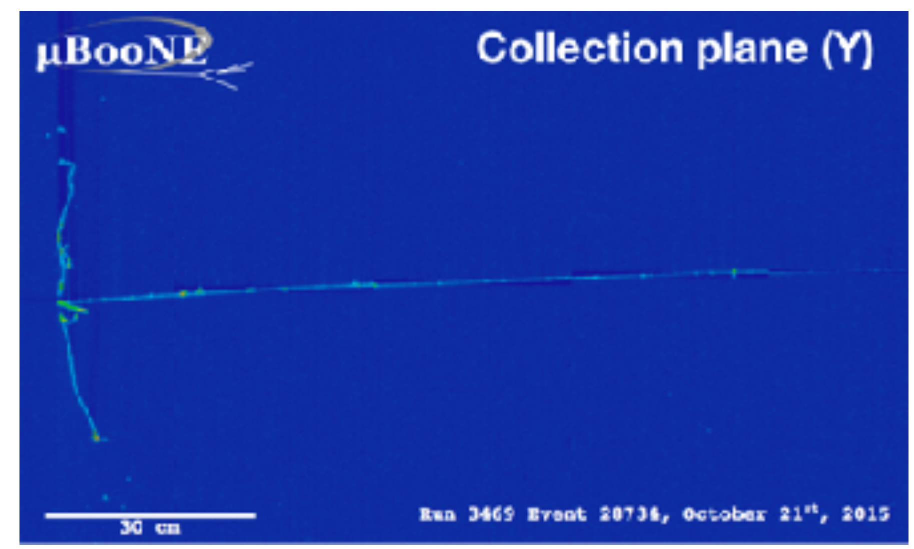
[JINST 12, P02017 (2017)](#)

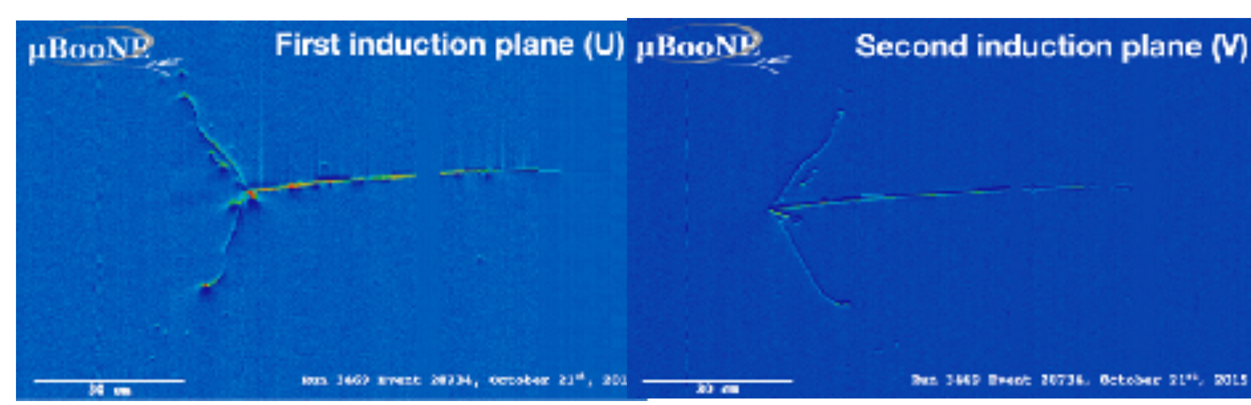


- ~90 tonnes mass Liquid Argon TPC (LArTPC)
- 3 planes of sensing wires (0º,+/-60º)
- System of 8-inch PMTs

MicroBooNE is the first LArTPC measuring and accounting for effects such as Space Charge Effects and Dynamic Induced Charge, effects previously unknown but now understood & implemented in others (e.g. ProtoDUNE-SP)

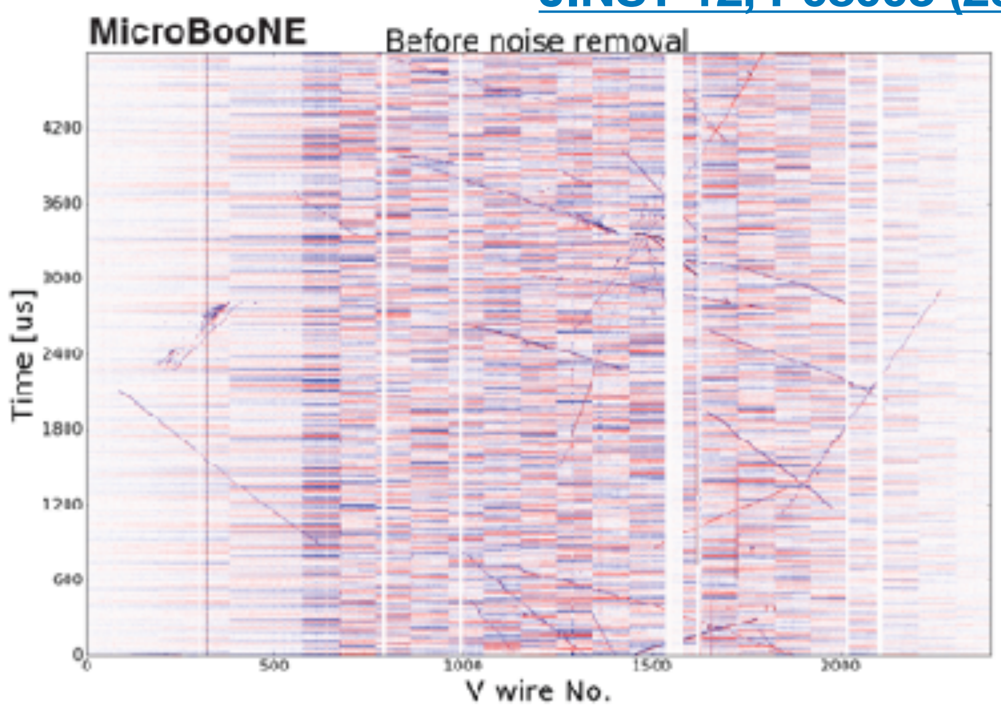


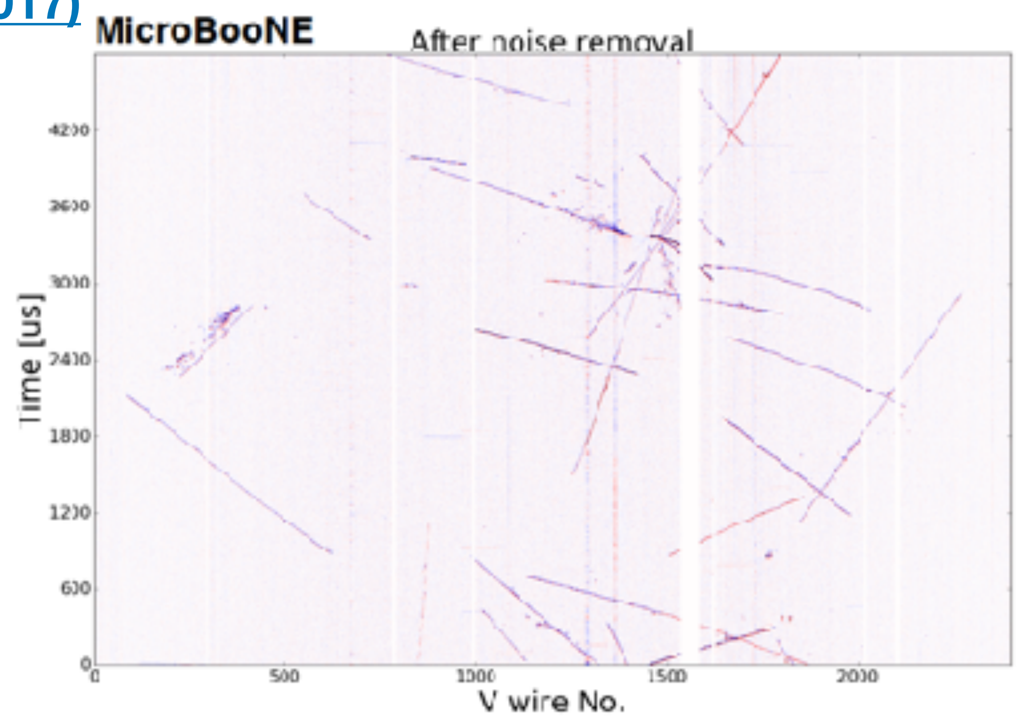


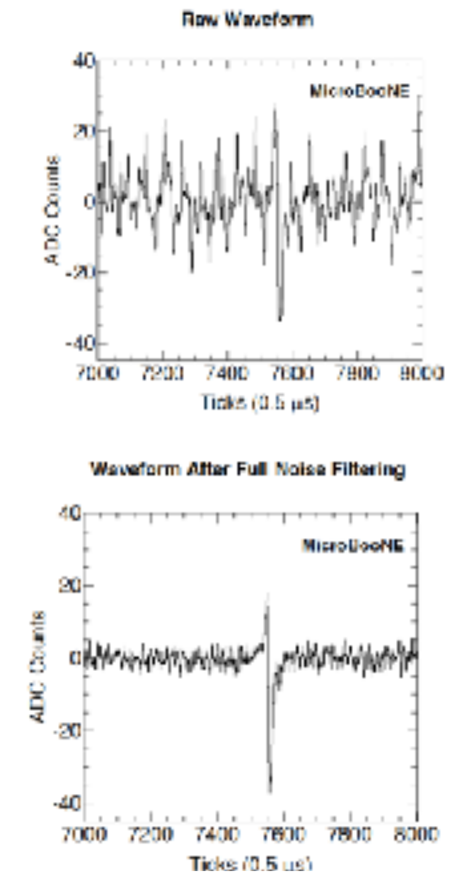


Important Noise Filtering Developments

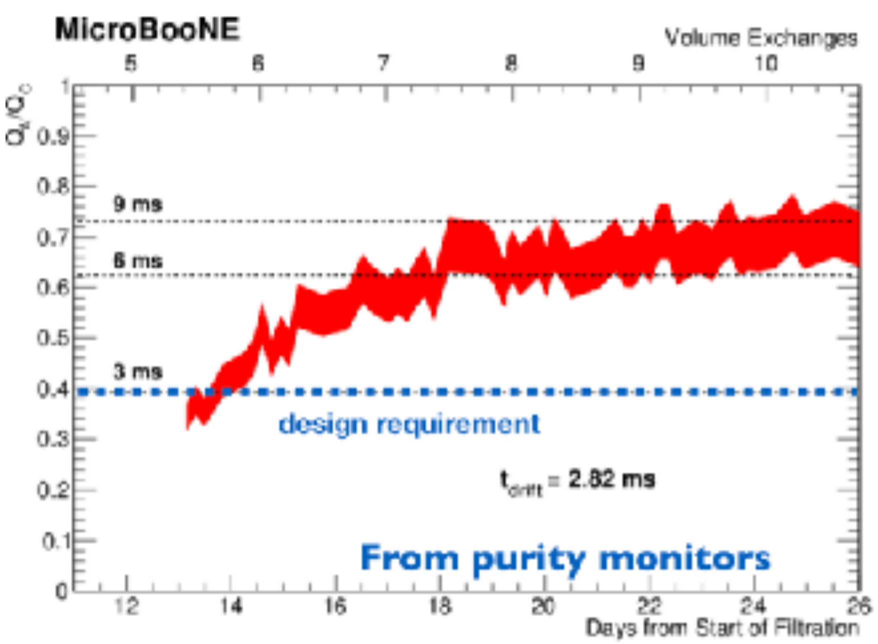
JINST 12, P08003 (2017)



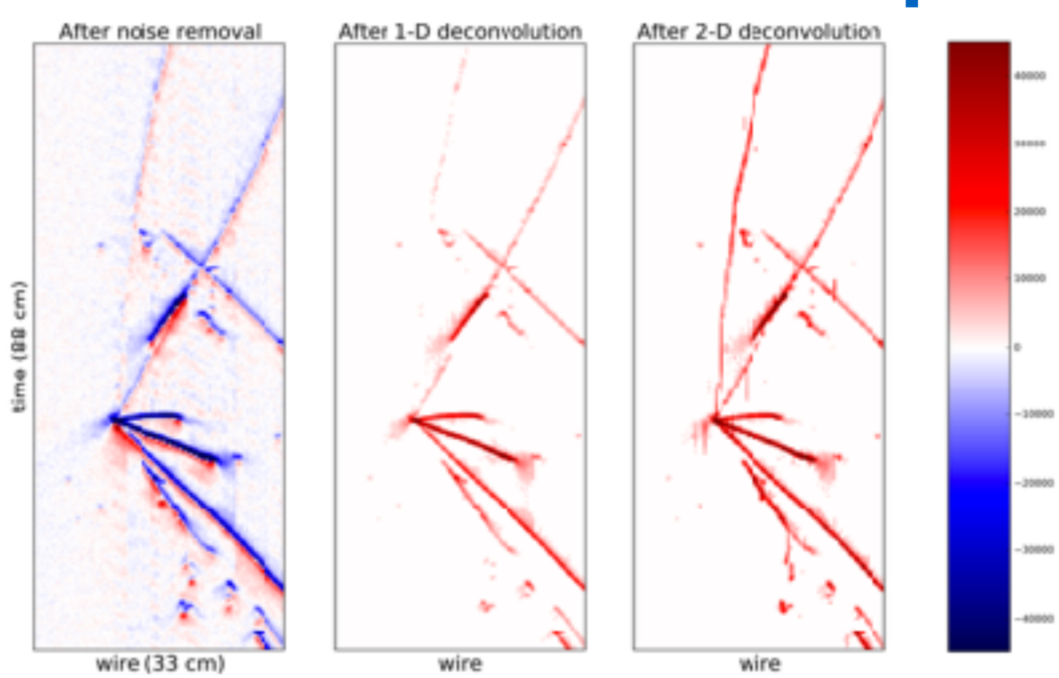


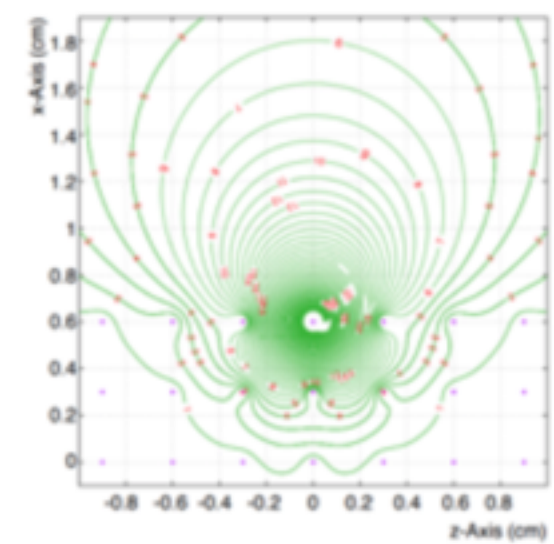


Excellent Purity



Novel *Deconvolution* techniques & induced charge



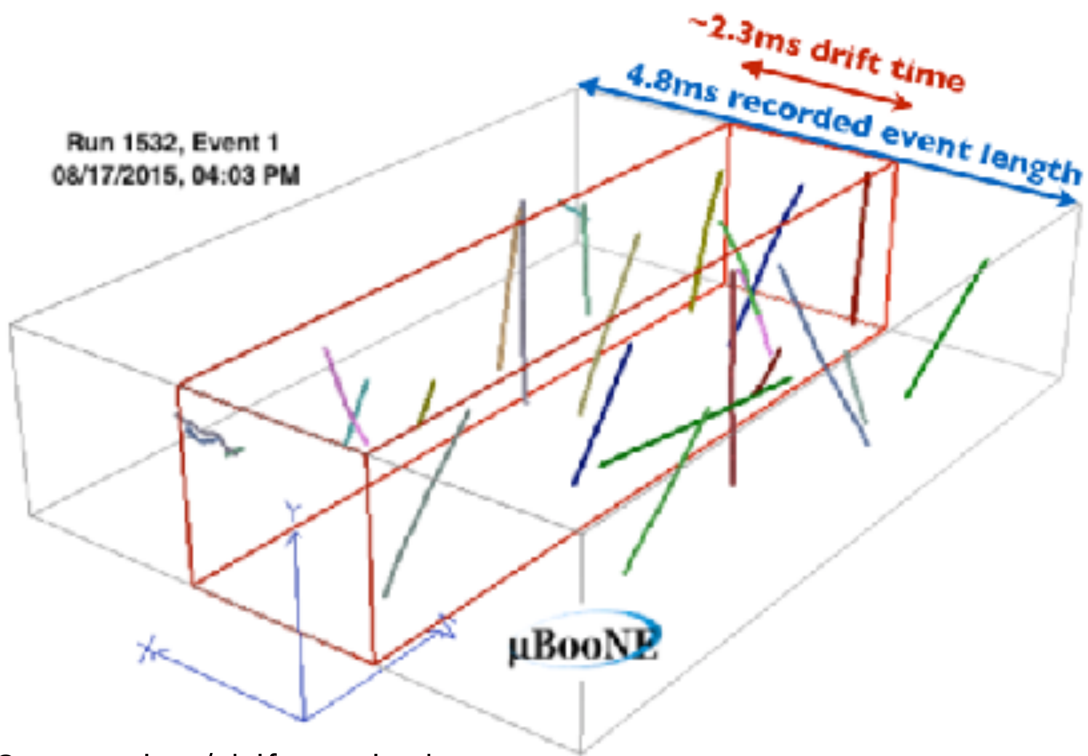


(b) Weighting potential on a U wire.

JINST 13, P07006 & P07007 (2018)

Cosmics in MicroBooNE

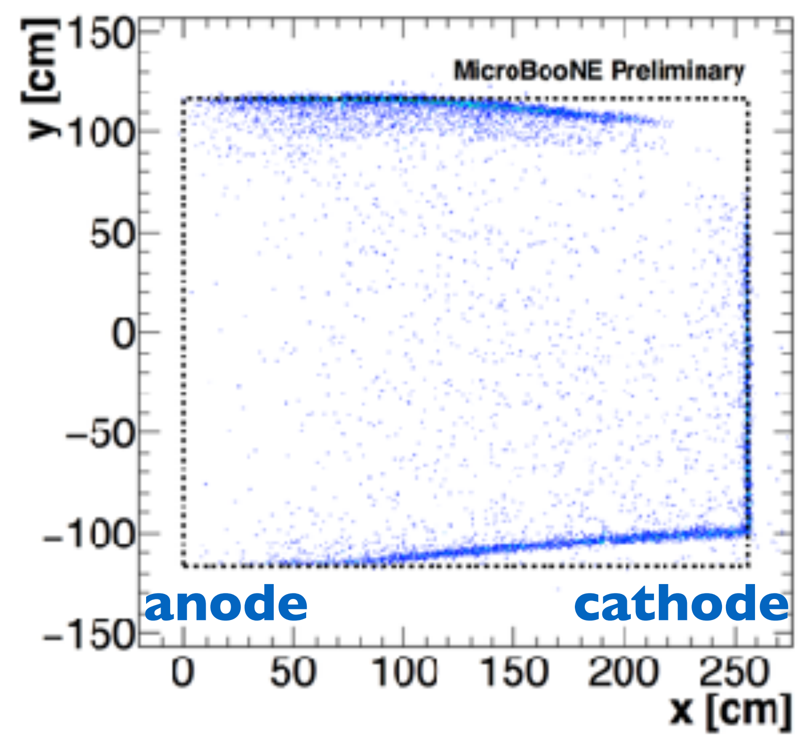
Cosmic rays: the challenge of a surface detector



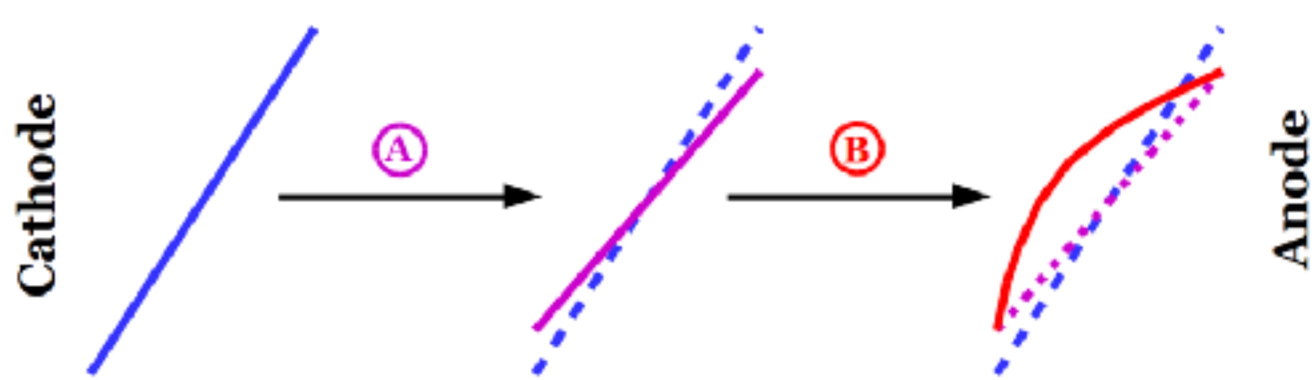
~10 cosmics/drift period

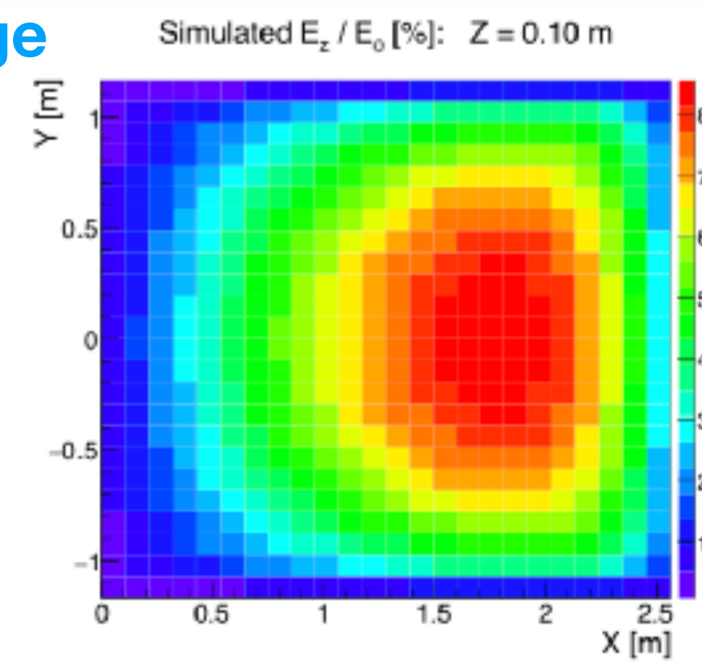
They are one of the main backgrounds in analyses, but also an important source for calibrations (SCE, calorimetry, etc)

Space Charge Effect simulation/measurement



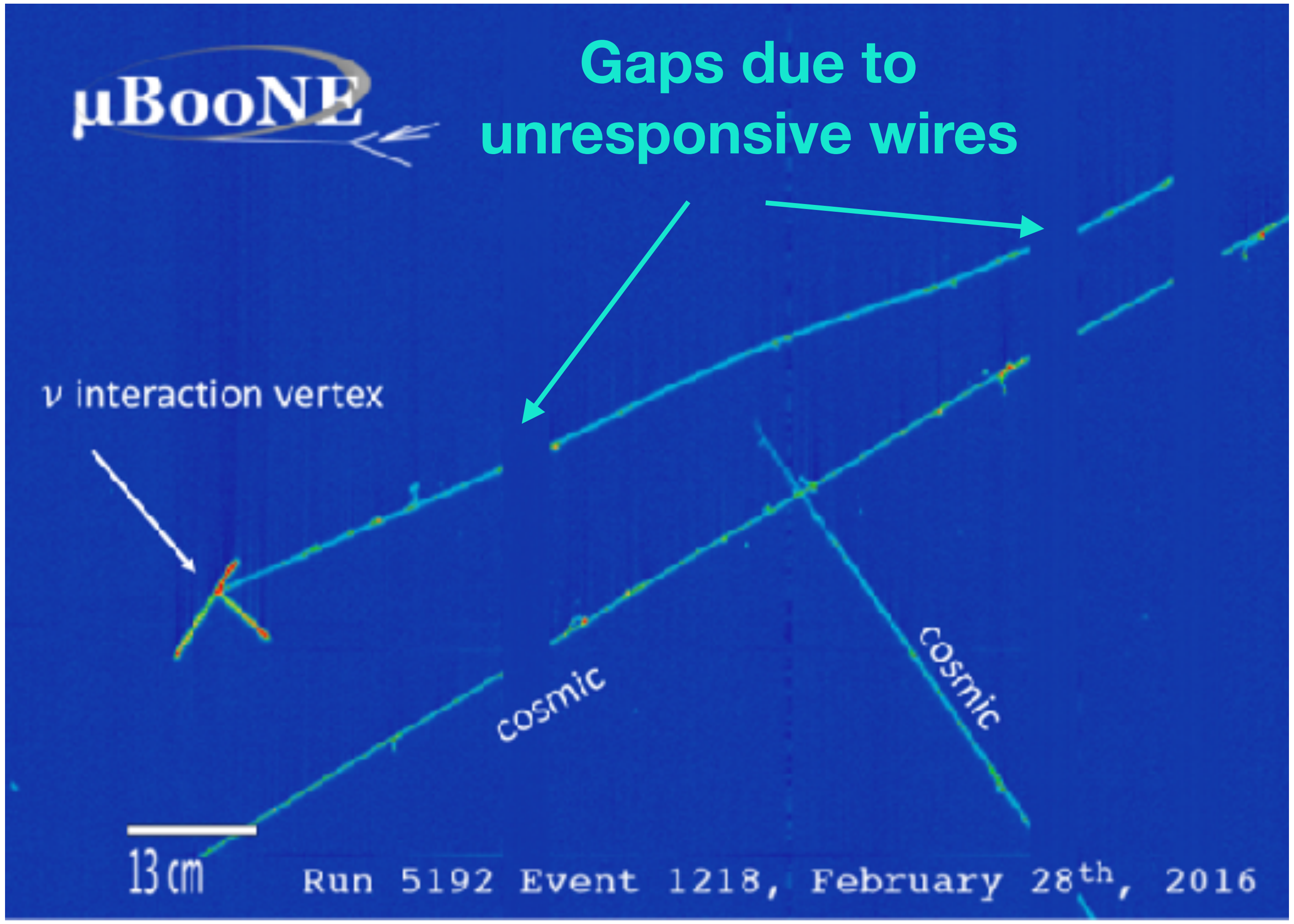
Space Charge Effect distortion of drift electric field due to charge build-up of slow moving Ar ions. Produces spatial distortion of tracks. Effect now simulated and corrected (measured maps)





[MicroBooNE public note 1018]

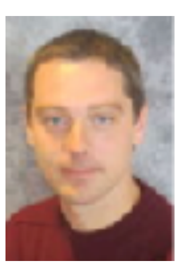
*Color scale indicates amount of deposited charge



First fully automated reconstruction in a LArTPC

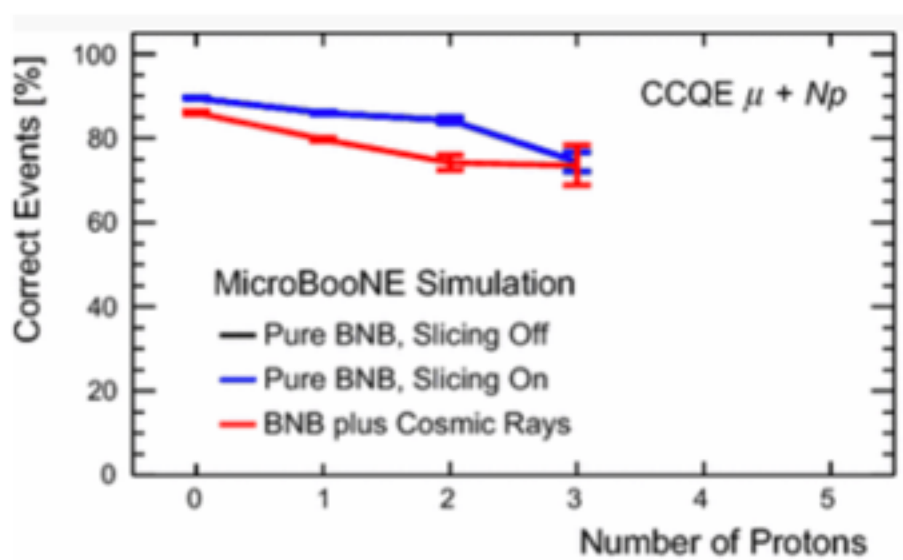
- Pandora (in these slides)
- Deep Learning
- Wire cell
- Others (3D)

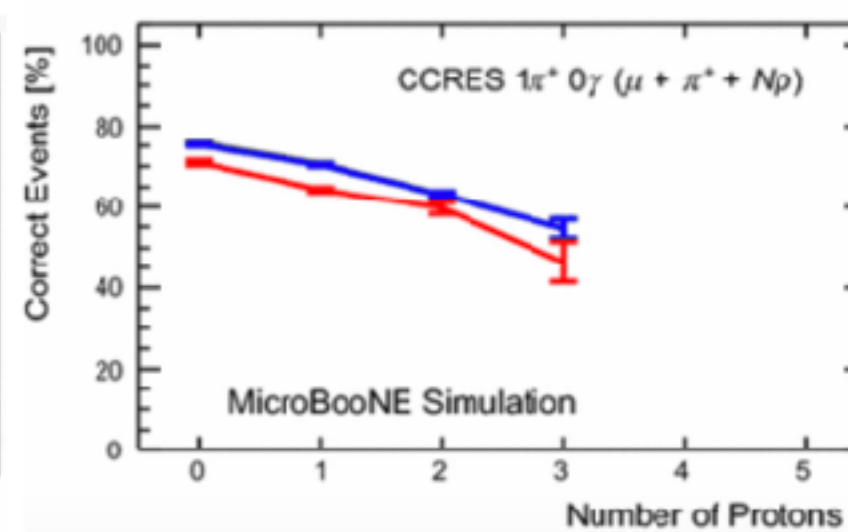
This shows "*perfect*" event fractions



Despite cosmic rays contamination, noise, unresponsive regions, we achieve a good reconstruction performance

Eur. Phys. J. C78, 1, 82 (2018)

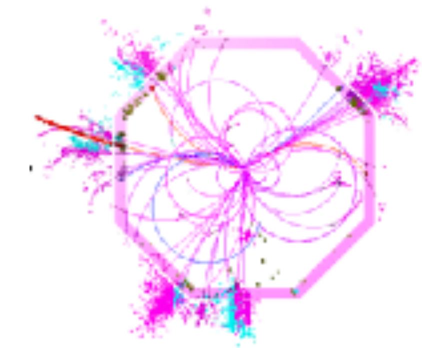




Pandora Pattern Recognition

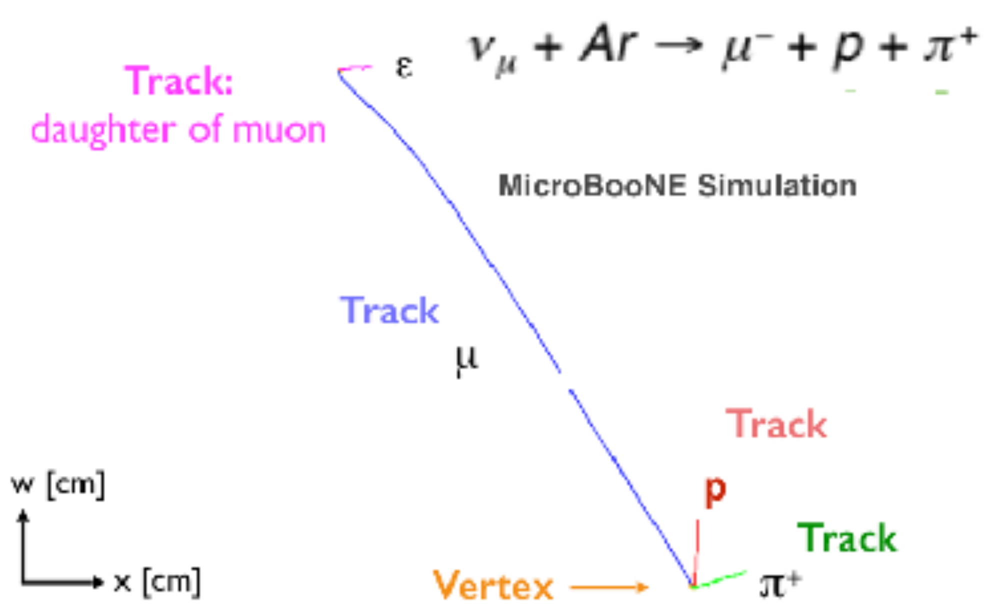
Pandora is a novel method of pattern recognition, which uses an advanced multi-algorithm approach (with hundred of algorithms) for the reconstruction of cosmic ray muons and neutrino interactions

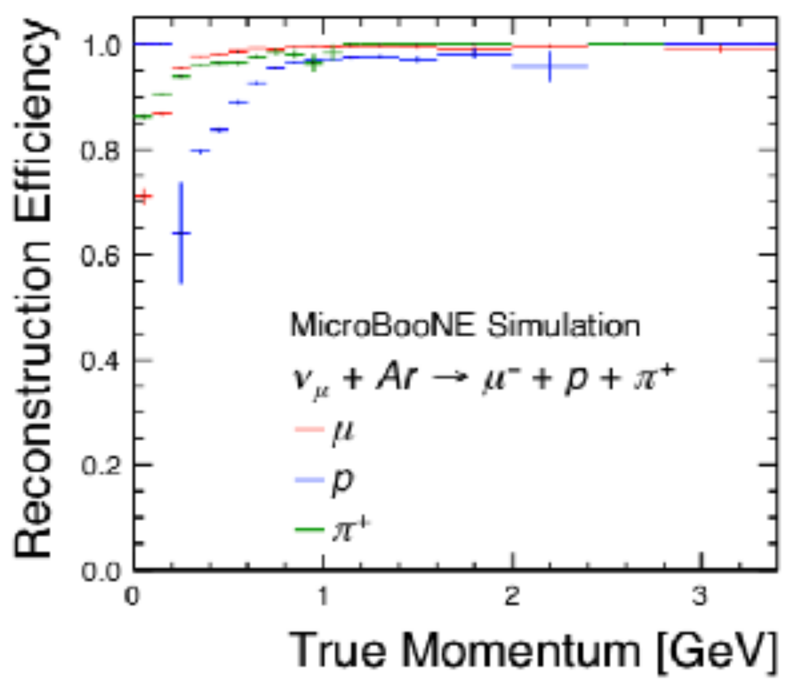
Started in ILC and LHC, used for LArTPCs in MicroBooNE for the first time, now established in other detectors (ProtoDUNE, DUNE FD)

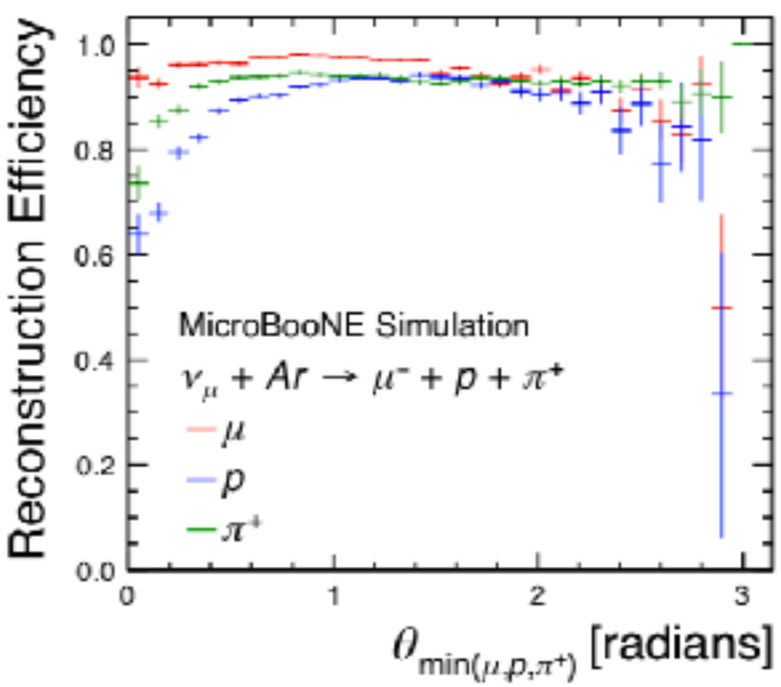


https://github.com/PandoraPFA

Example reconstruction in MicroBooNE







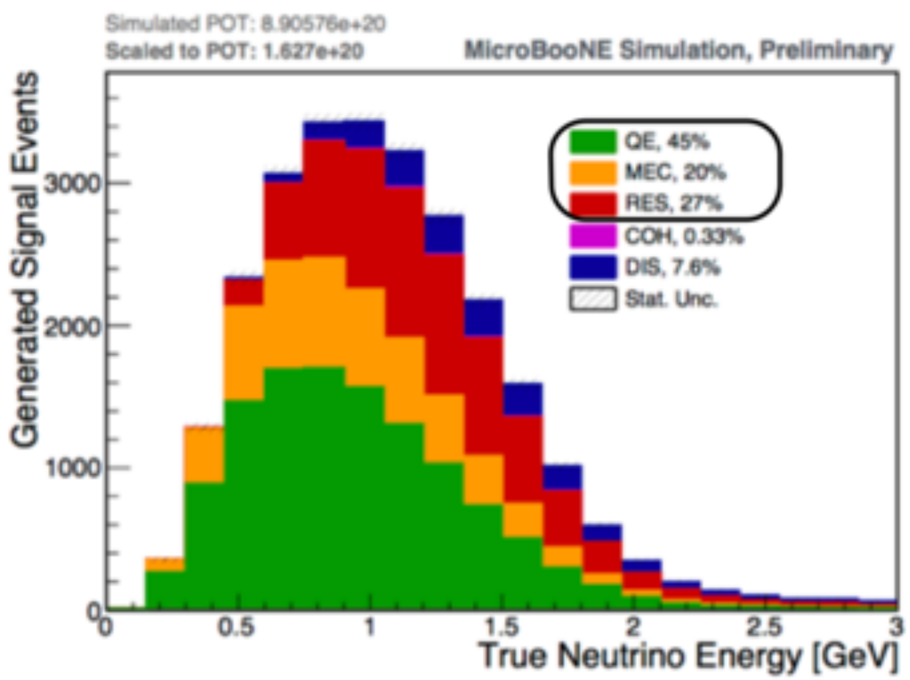
It is also the first time we use this *sophisticated* output of particle hierarchies (flow) in a LArTPC experiment

Used in the analyses and calibrations in following pages

Eur. Phys. J. C78, 1, 82 (2018) & Eur. Phys. J. C 2015, 75, 439 (2015)

ν_μ CC interactions

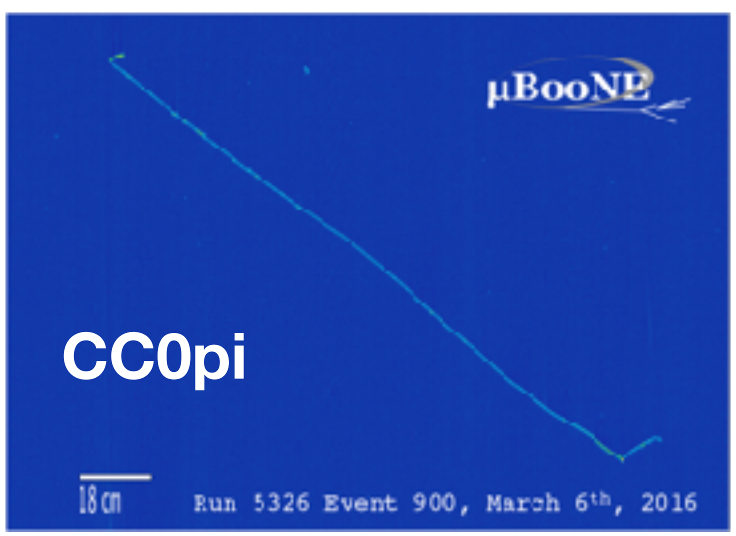
Simulated ν_μ CC events



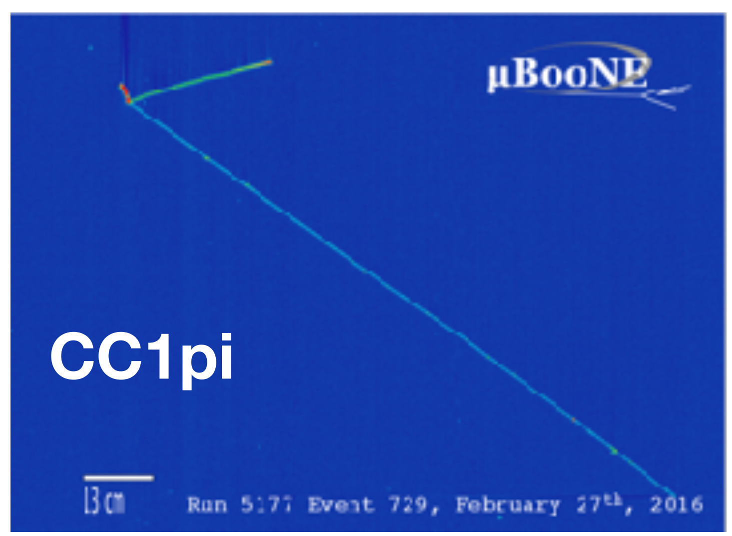
Cross section measurements are crucial for oscillation analyses (currently the dominant systematic error e.g. T2K, NOvA)

Moving towards LArTPC detectors (SBN, DUNE) but not many ν-Ar measurements (only ArgoNeuT, high energy)

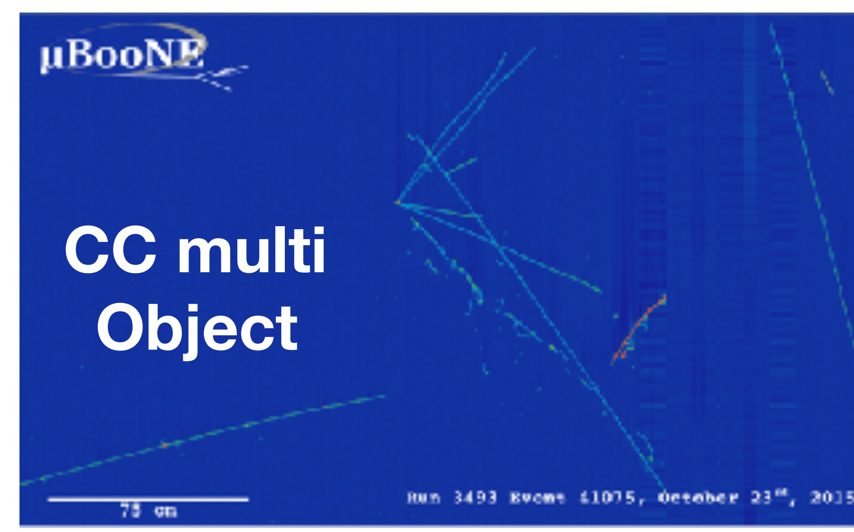
MicroBooNE detector is fully-active and high-resolution, providing full acceptance in angle and momentum (4π coverage)



&



&



e.g. CC inclusive:

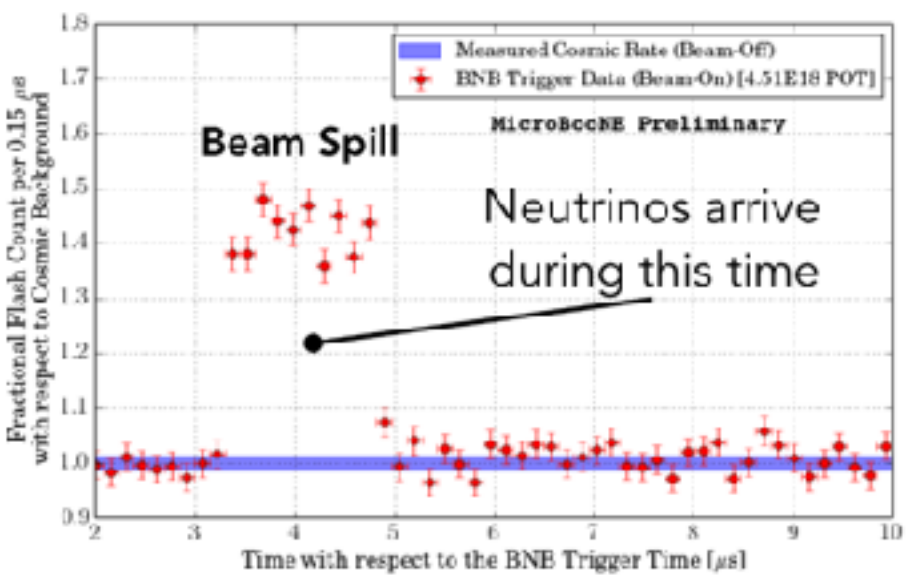
Pro: high stats (anything with a muon)

Con: cosmic ray contamination

ν_μ CC inclusive cross section

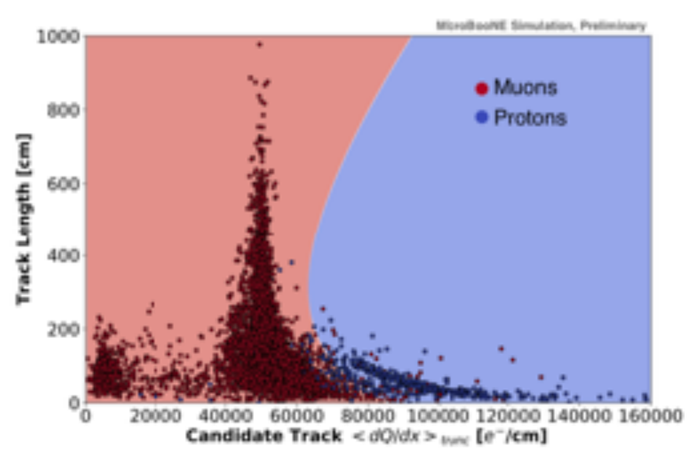
Event selection

Impressive effort to remove (99.9%!) cosmics using a combination of TPC information and optical activity (PMTs), matching the flash in beam spill with TPC reconstructed hierarchies



Selection eff: 57.2% pur: 50.4%

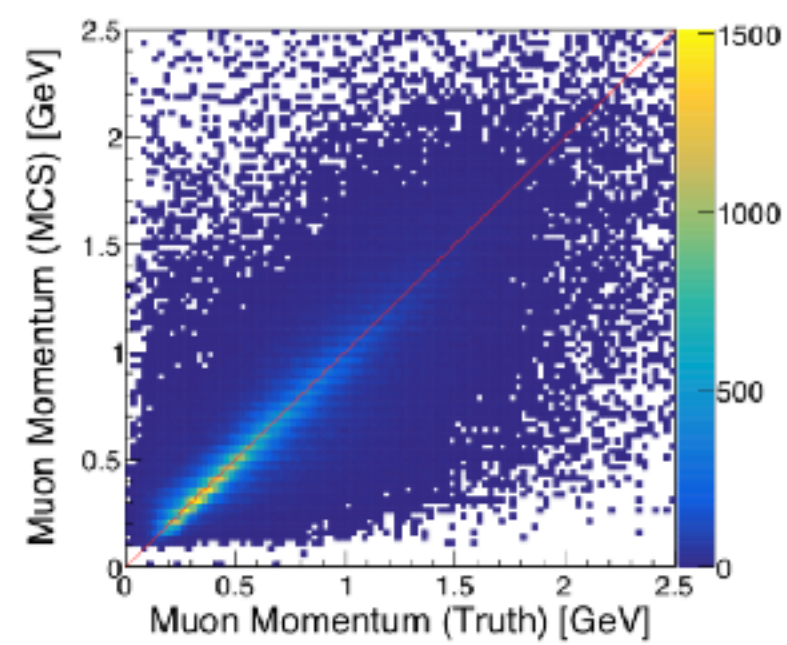
Using MCS for momentum estimation and (truncated mean) dQdx vs length for MIP separation



Forward folding approach

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

Rather than unfolding measurements to true muon momentum and angle, final results are presented in terms of reco quantities. Efficiency is forward folded as a function of reconstructed variables using a smearing matrix S:

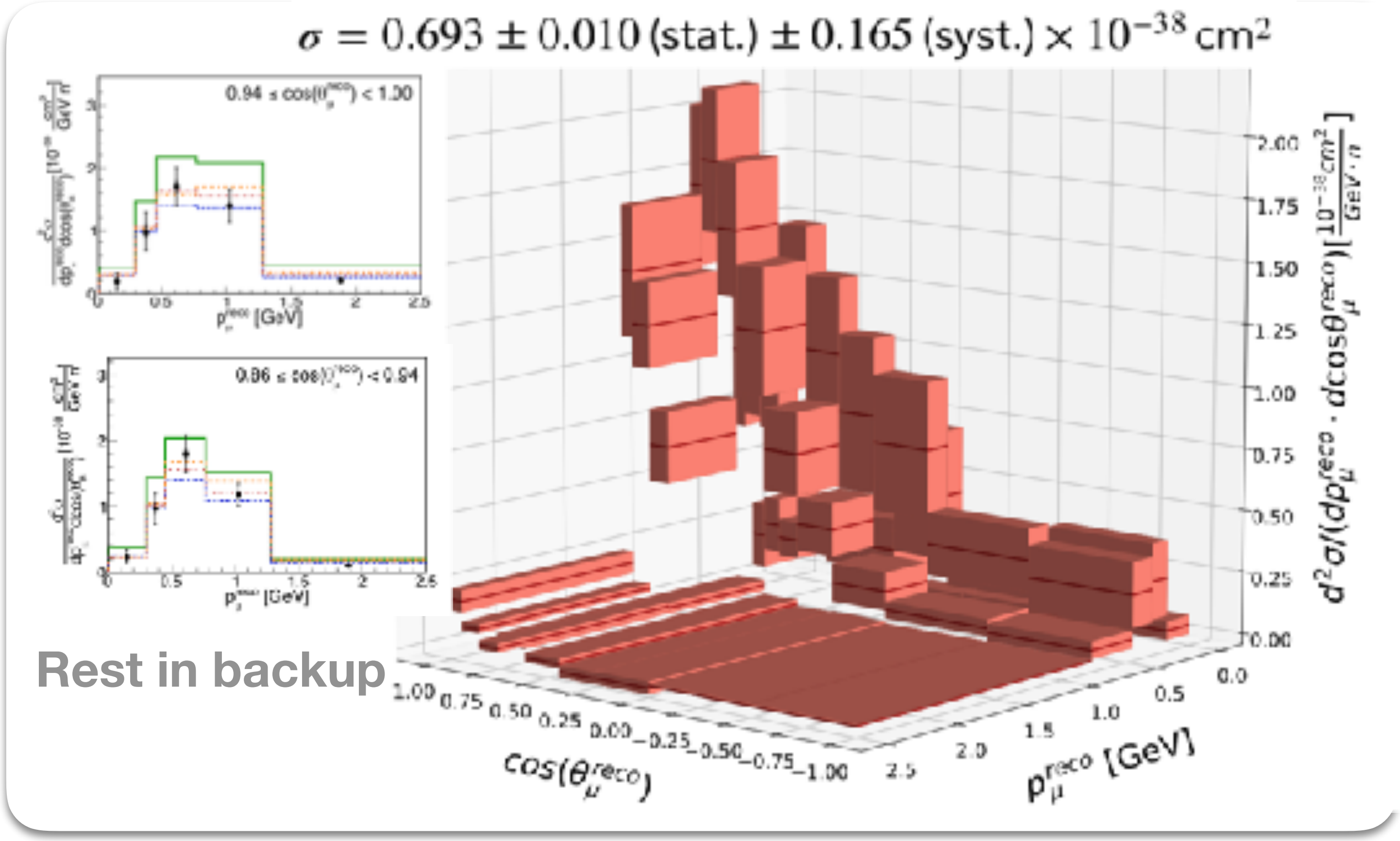


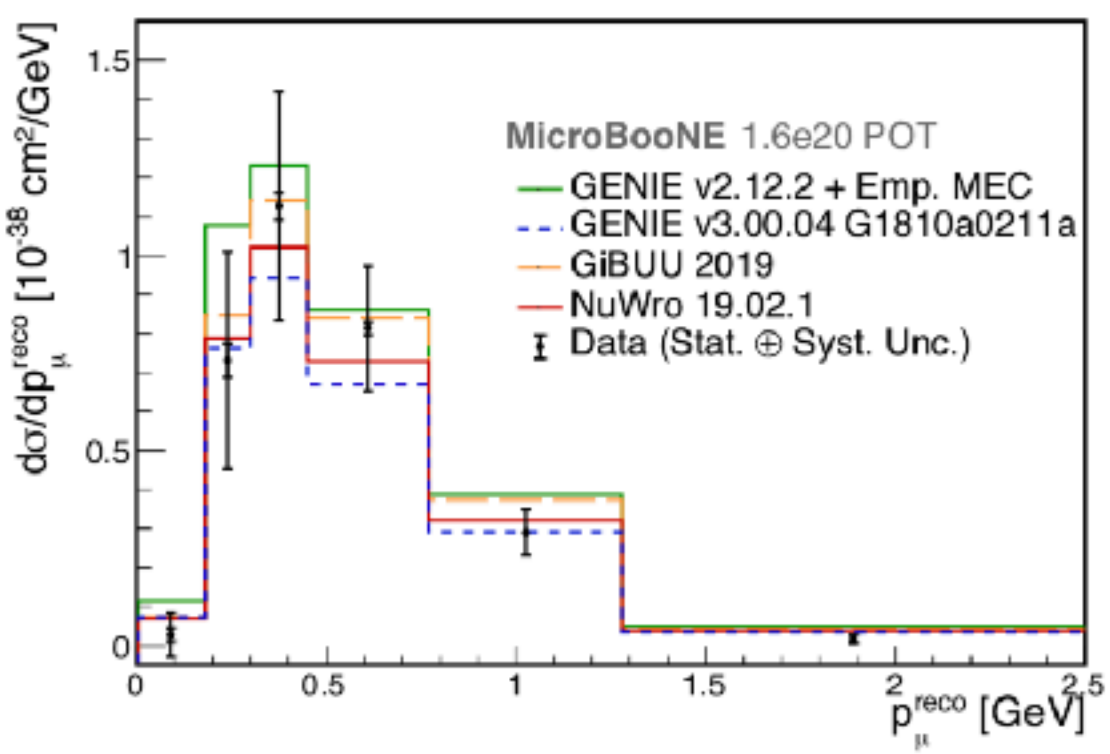
See CC inclusive paper here and MCS paper JINST 12 P10010 (2017)

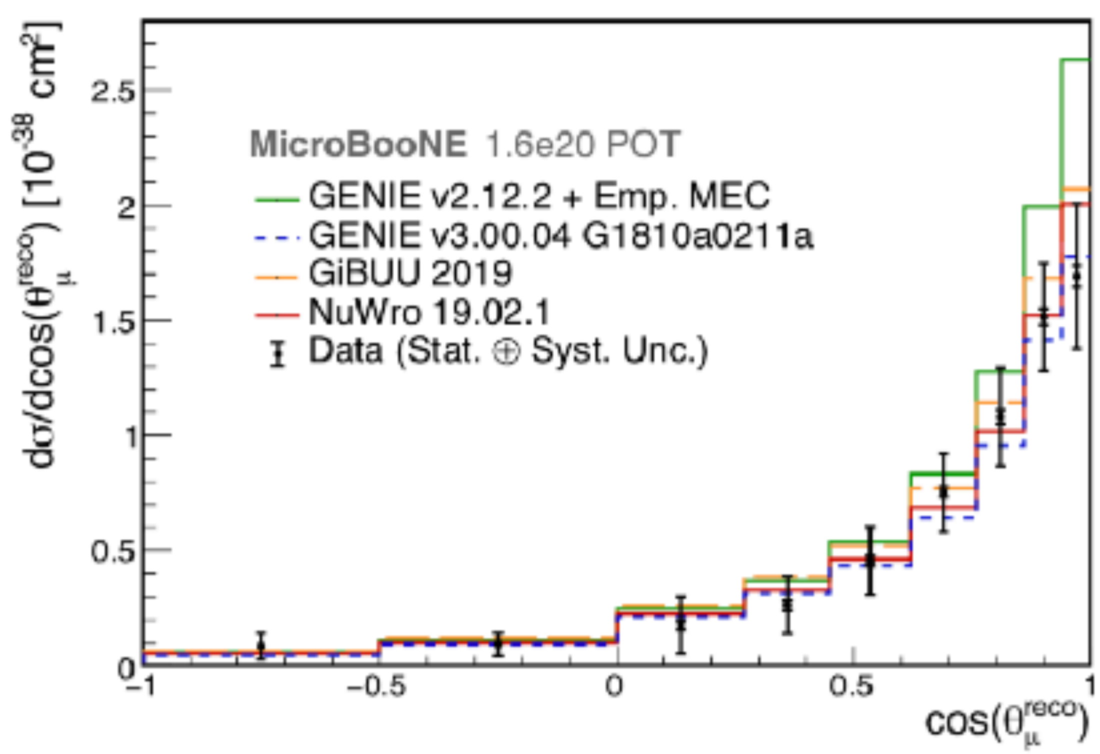
ν_μ CC inclusive cross section

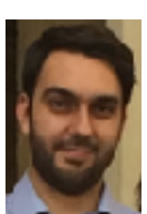
Single differential (bottom) and for the first time double differential in Ar (right and backup) cross section measurements.

Tested with different neutrino event generators (see details in backup) showing discriminating power: tension at high momentum & most forward-going angle



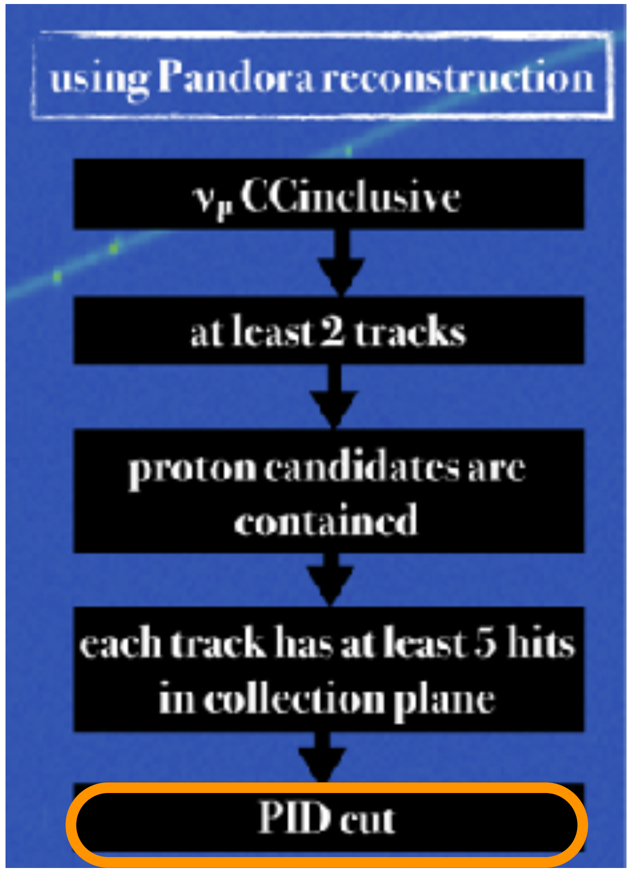




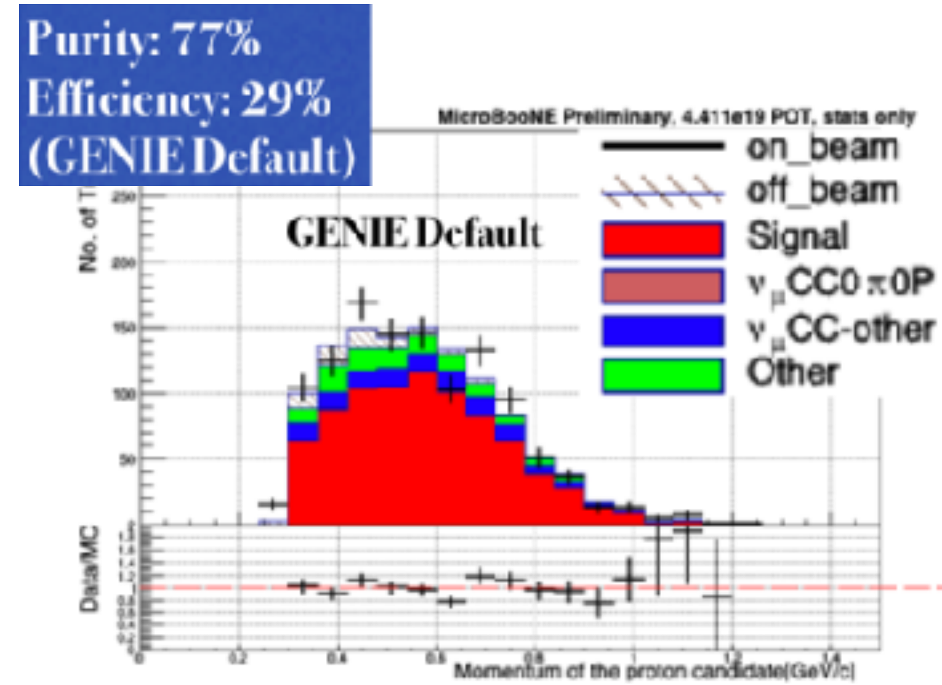


See paper here and Marco del Tutto's Fermilab Wine and Cheese Seminar here

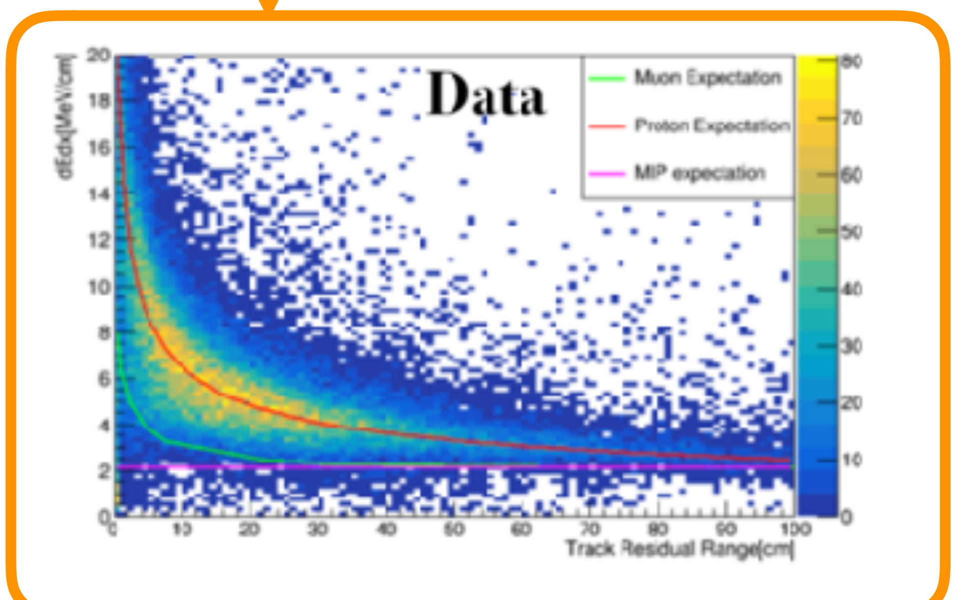
ν_μ CC Np and 2p



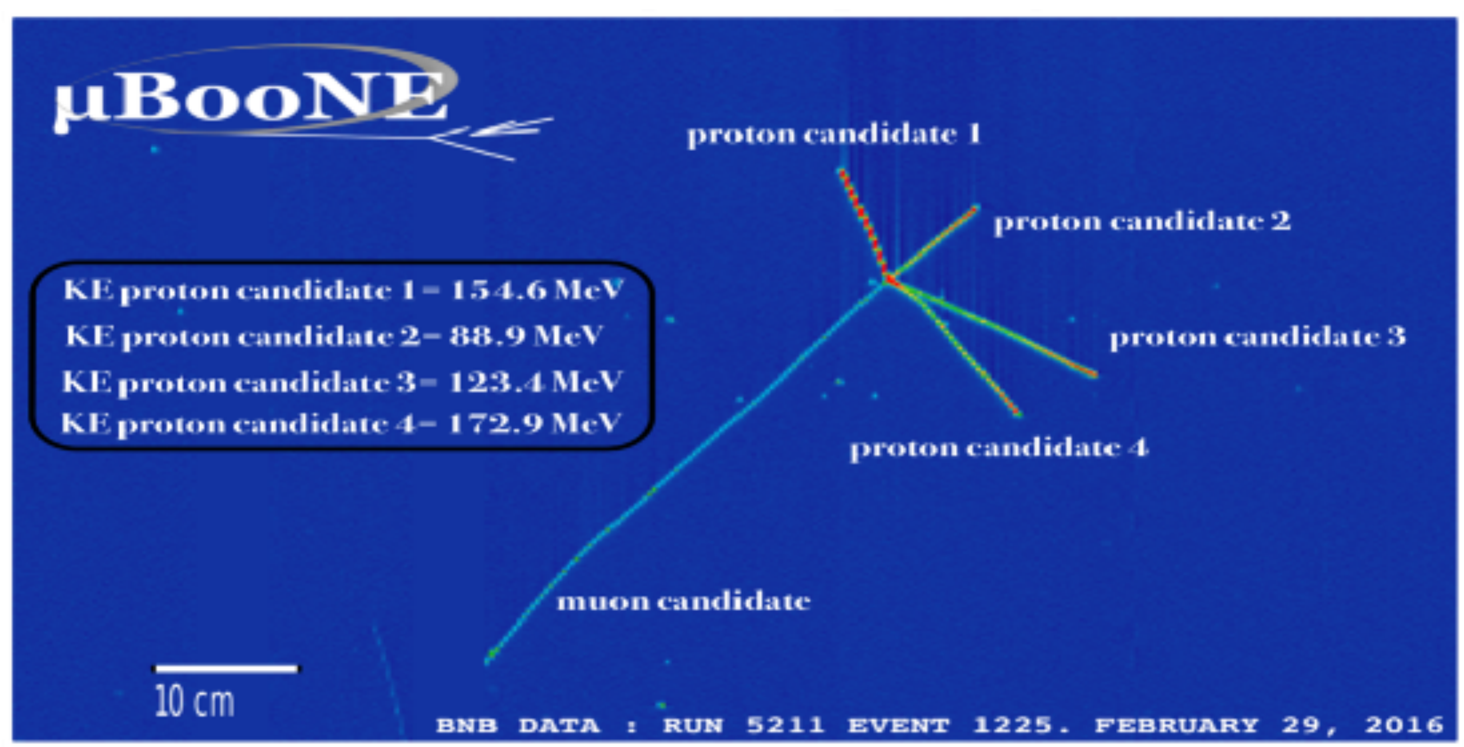
Identification of low E protons ~47 MeV KE!
(not due to detector but method, being updated)
Important for E reco

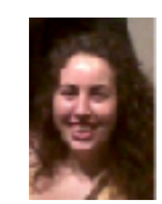


Using full calibration and recombination studies (paper this summer)



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

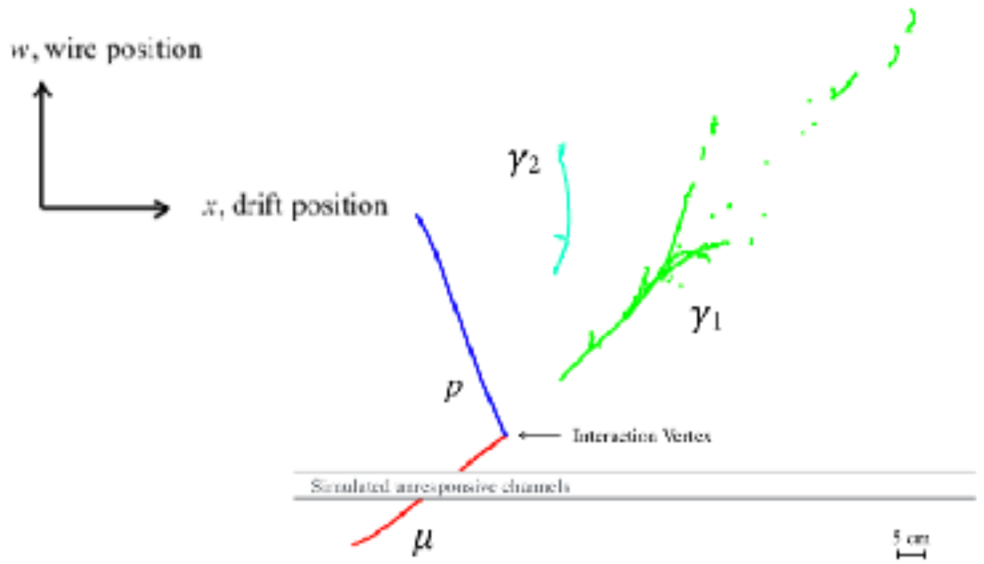


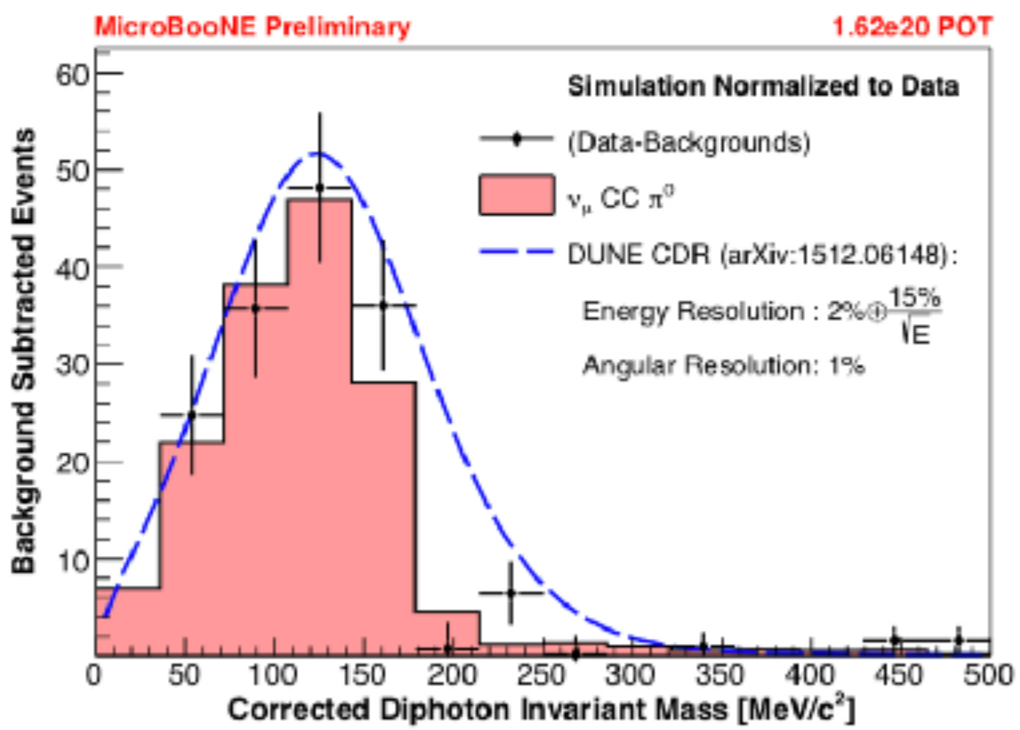


See talk at NuINT 2018 by Raquel Castillo here

ν_μ CC π^0

Important proof of shower reconstruction and calibration and EM energy scale

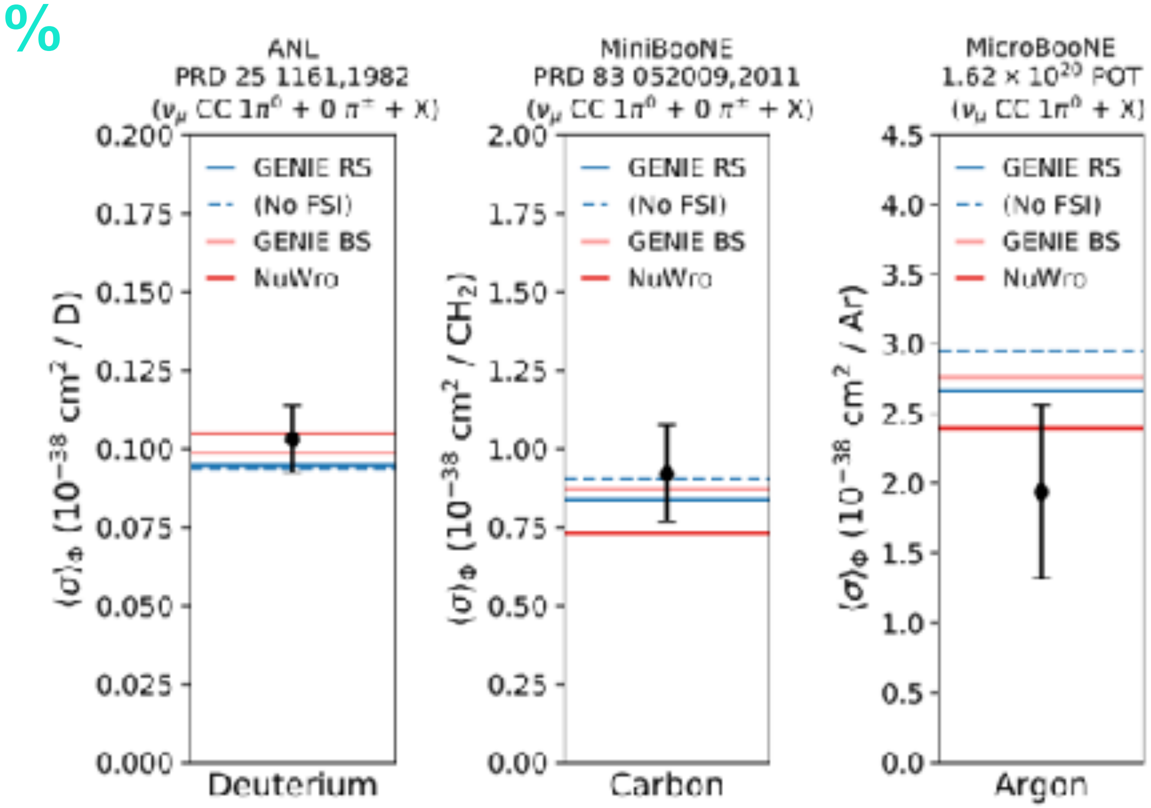




Selection eff: 16% pur: 56%

At least one photon

$$\langle\sigma\rangle_\Phi = 1.9 \pm 0.2(\text{stat}) \pm 0.6(\text{syst}) \times 10^{-38}\ \frac{\text{cm}^2}{\text{Ar}}$$



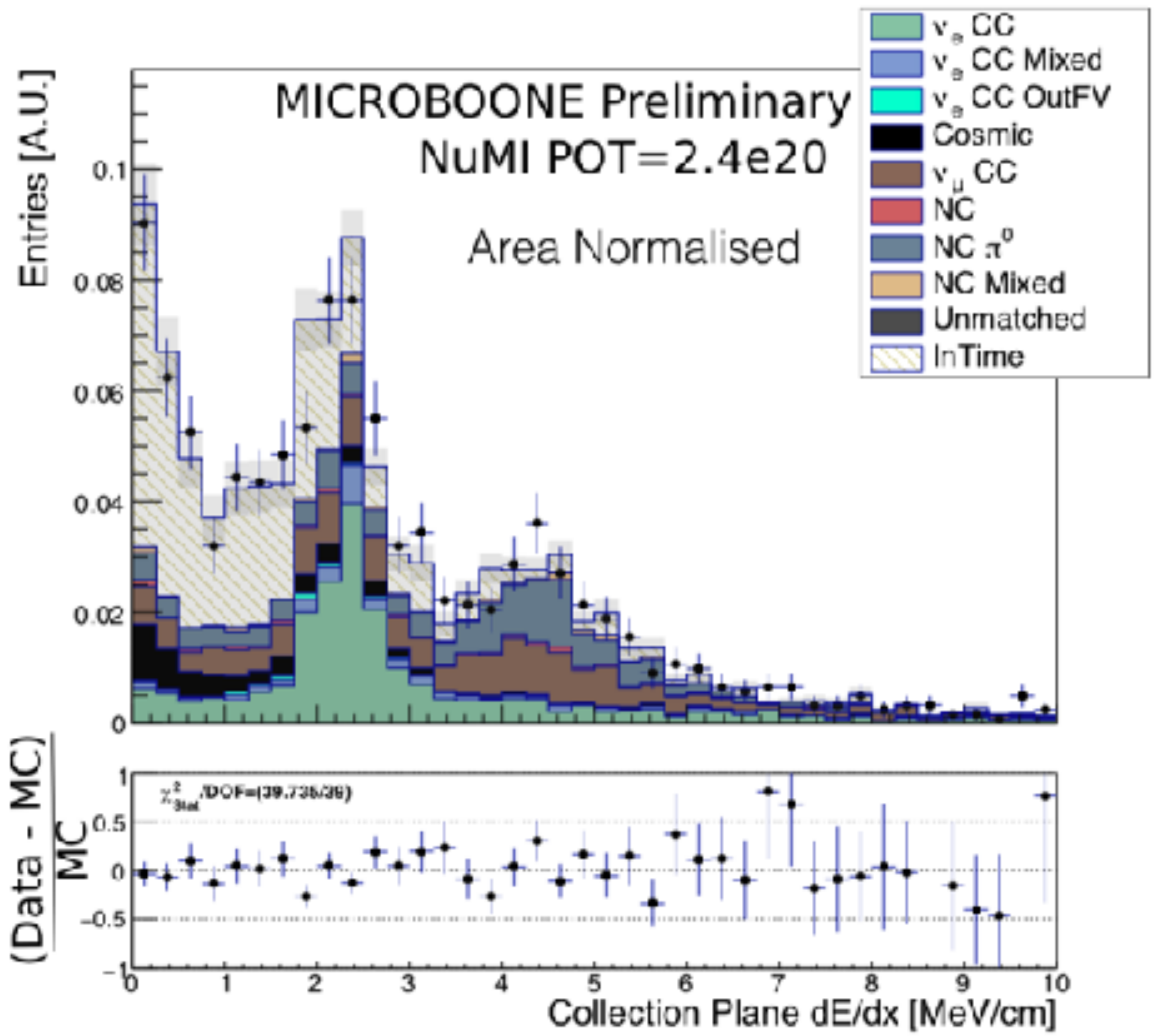
Identifying pi0 gammas, important background for ν_e. Differential measurement is underway

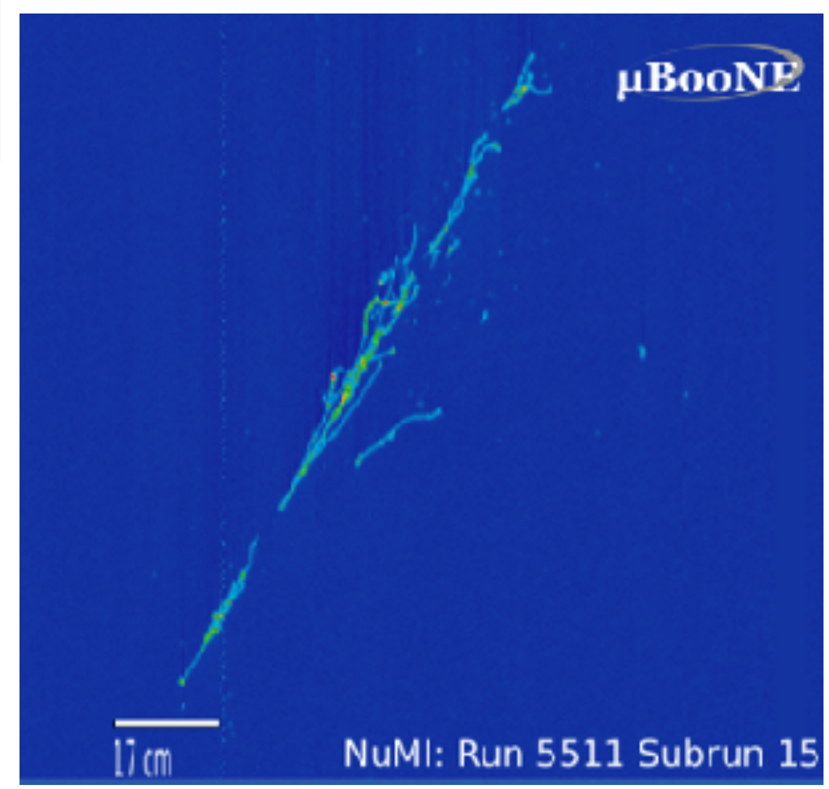
See paper Phys Rev D99 091102 (2019) and talks: NuINT 2018 here and W&C seminar here

ν_e from NuMI

Fully-automated reconstruction (also Pandora) and selection of data ve CC events from the NuMI beam in MicroBooNE.

Electron/gamma separation, extremely important for oscillation analysis





See talk at NuINT 2018 by Colton Hill here

Summary and Forwards

MicroBooNE has been successfully operating for over 3 years, and has built the expertise now exported to other LArTPCs in many aspects:

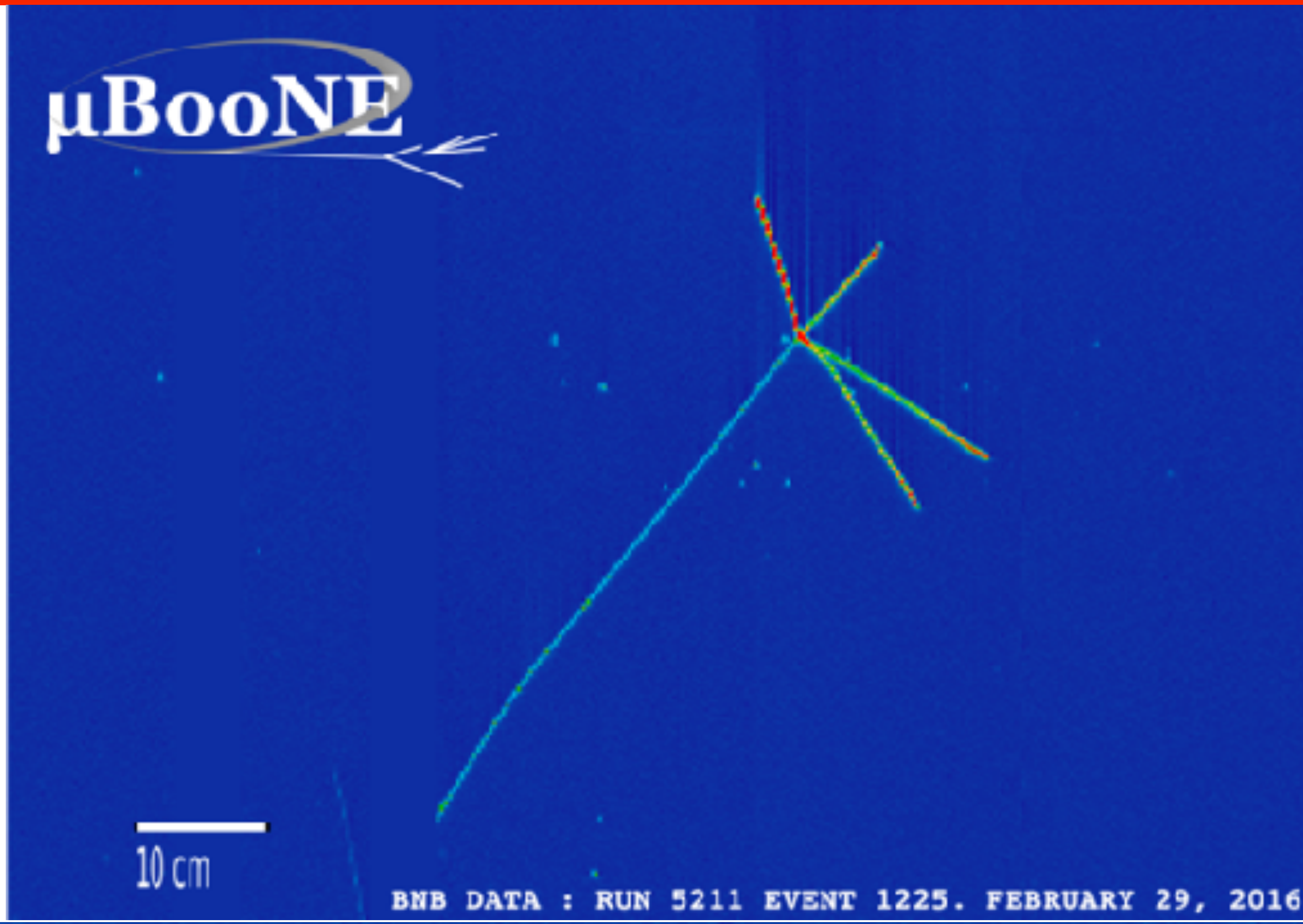
- **Noise filtering**
- **Cosmic background and space charge effects**
- **Dynamic induced charge and signal processing**
- **Fully-automated pattern recognition and reconstruction**
- **Calibration and recombination studies**

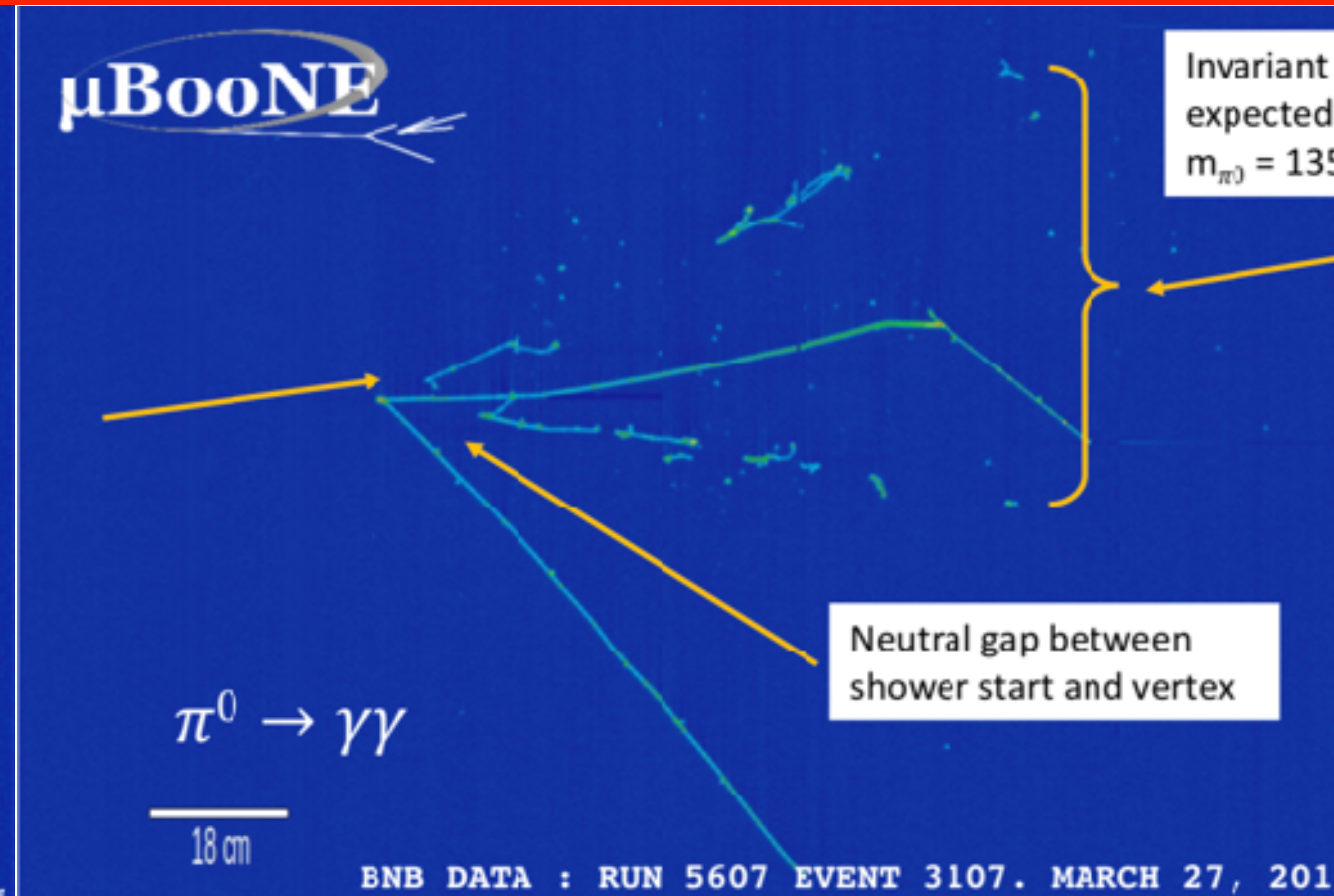
MicroBooNE has successfully produced first cross section measurements and many other studies are ongoing:

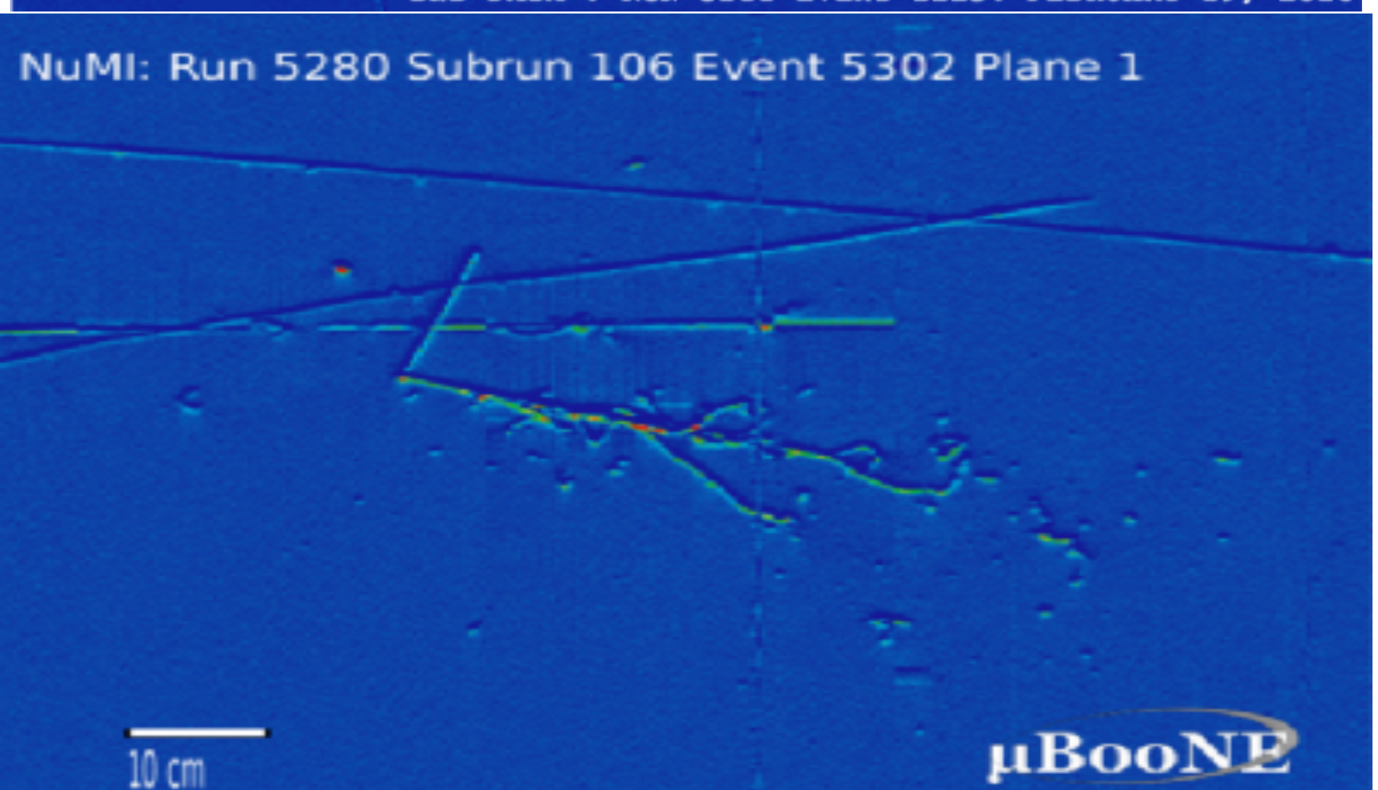
- **ν_μ CC inclusive + ν_μ CC π^0**
- **ν_μ CC 0pi Np (and 2p), others**
- **And low energy excess**

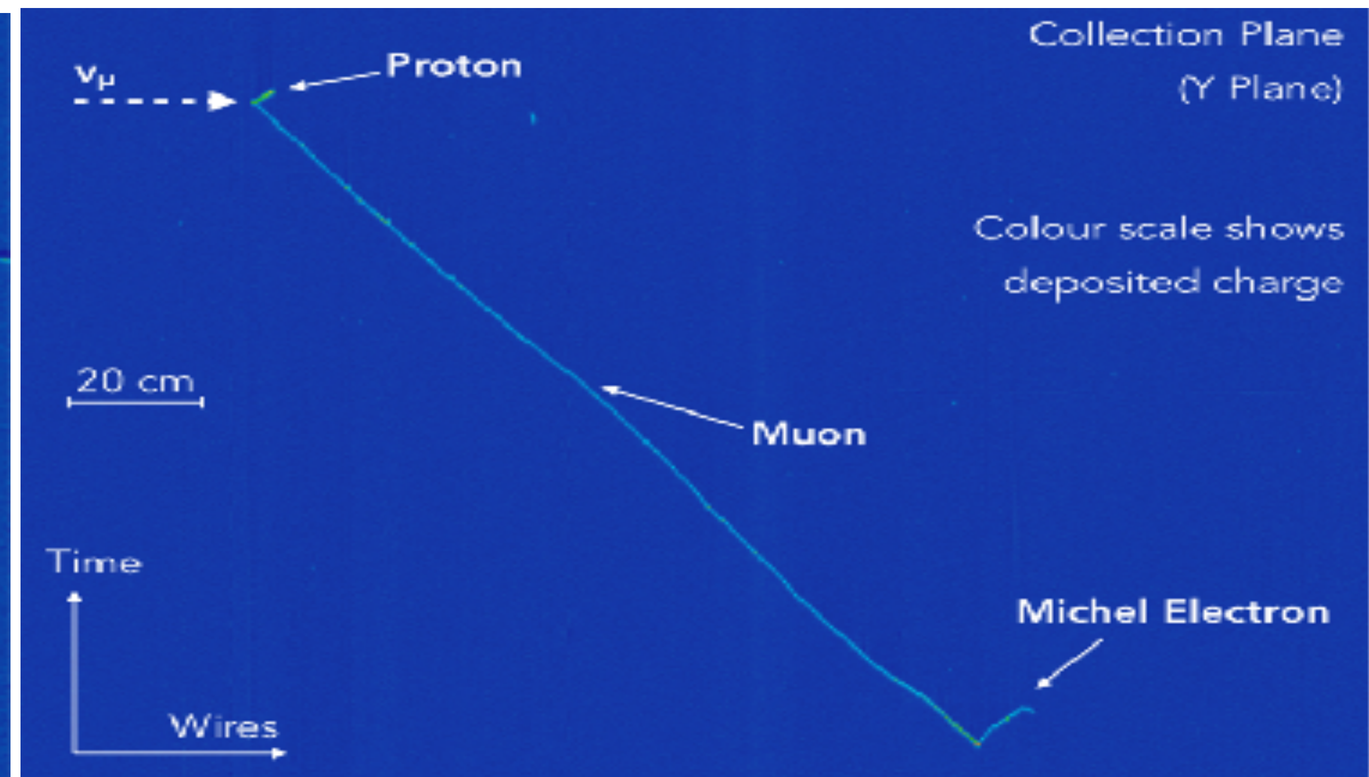
Also analysis and simulation improvements are underway to reduce uncertainties - so stay tuned!

Thanks


µBooNE
10 cm
BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016


µBooNE
Invariant
expected
m_{π^0} = 135
Neutral gap between shower start and vertex
$\pi^0 \rightarrow \gamma\gamma$
18 cm
BNB DATA : RUN 5607 EVENT 3107. MARCH 27, 201

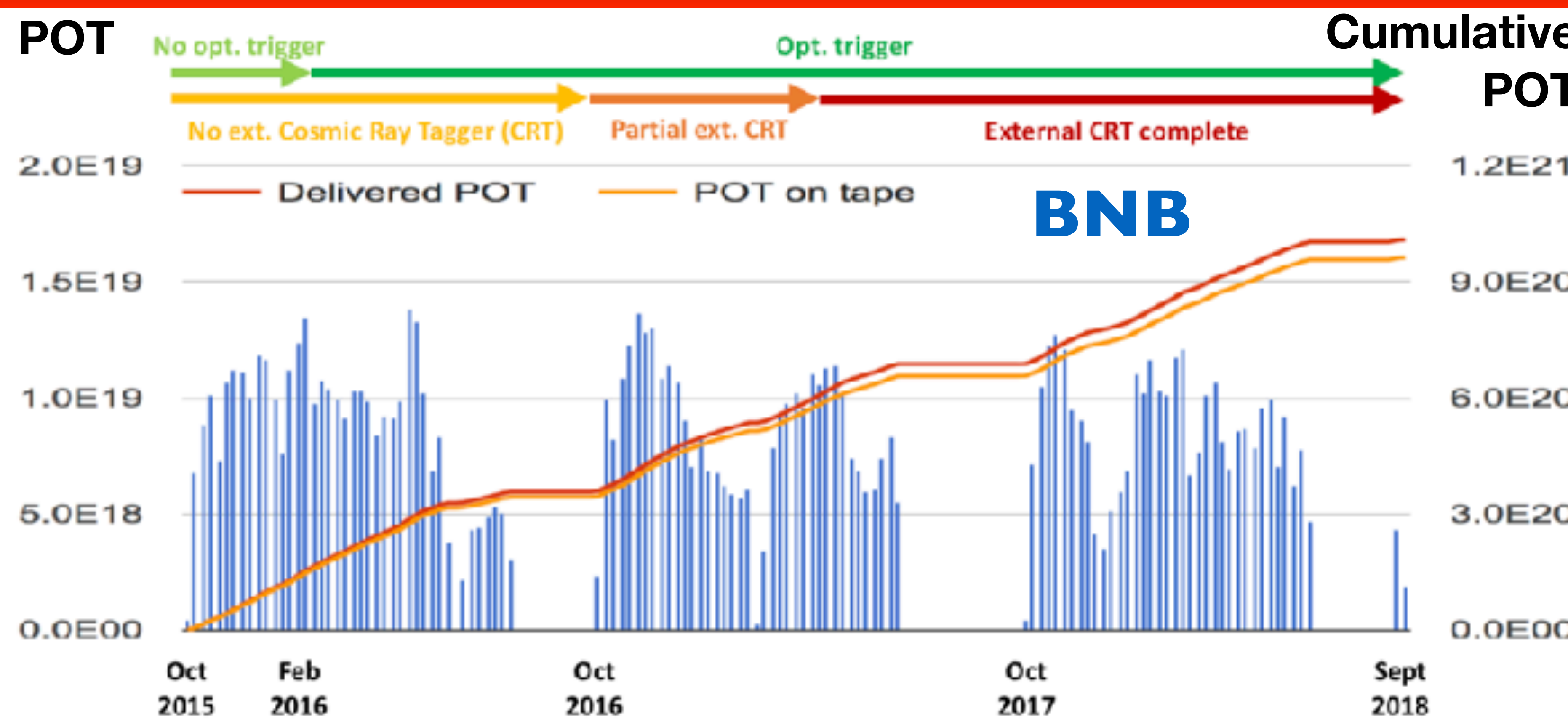

NuMI: Run 5280 Subrun 106 Event 5302 Plane 1
10 cm
µBooNE

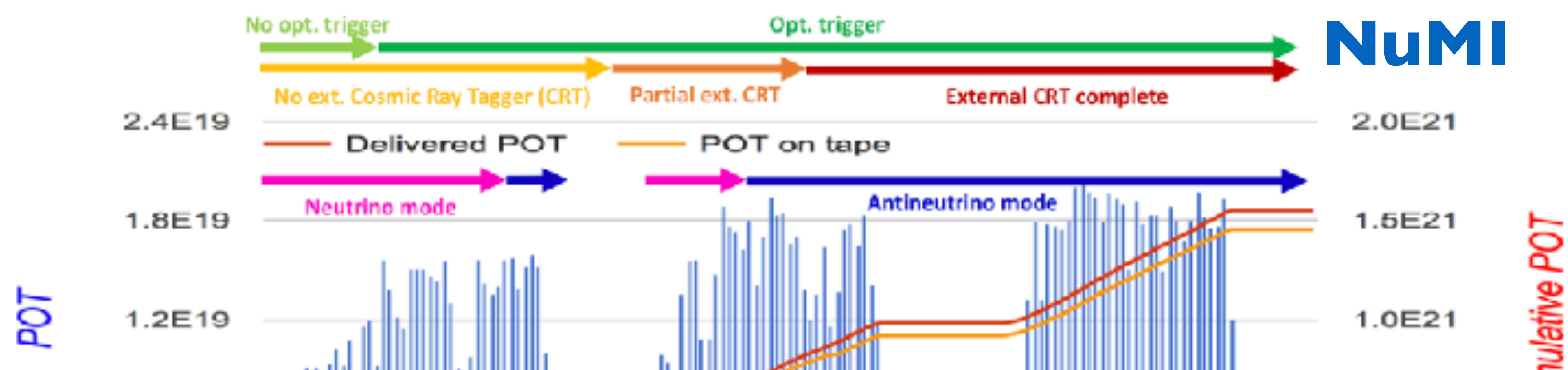

ν_μ
Proton
Collection Plane
(Y Plane)
Colour scale shows deposited charge
20 cm
Muon
Time
Michel Electron
Wires

BACKUP

Data taking

μBooNE





Expected interaction numbers per 2.4 x 10^{20} POT

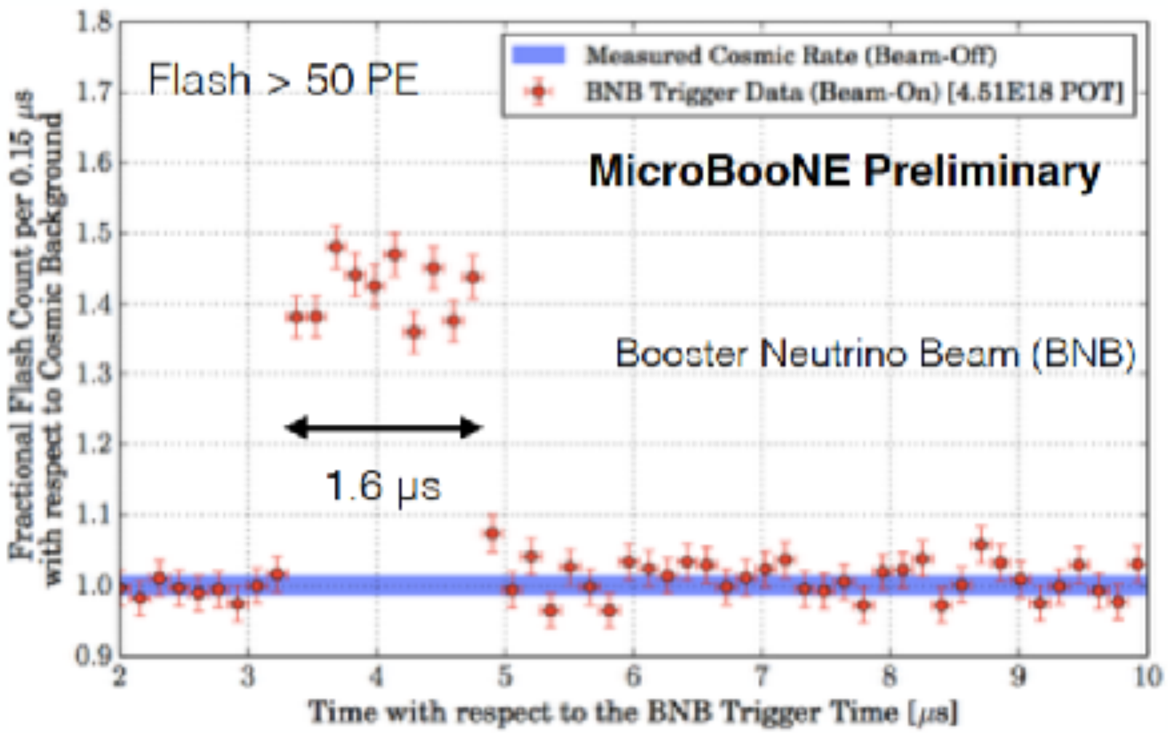
$\nu_e + \bar{\nu}_e$ CC inclusive: ~3000

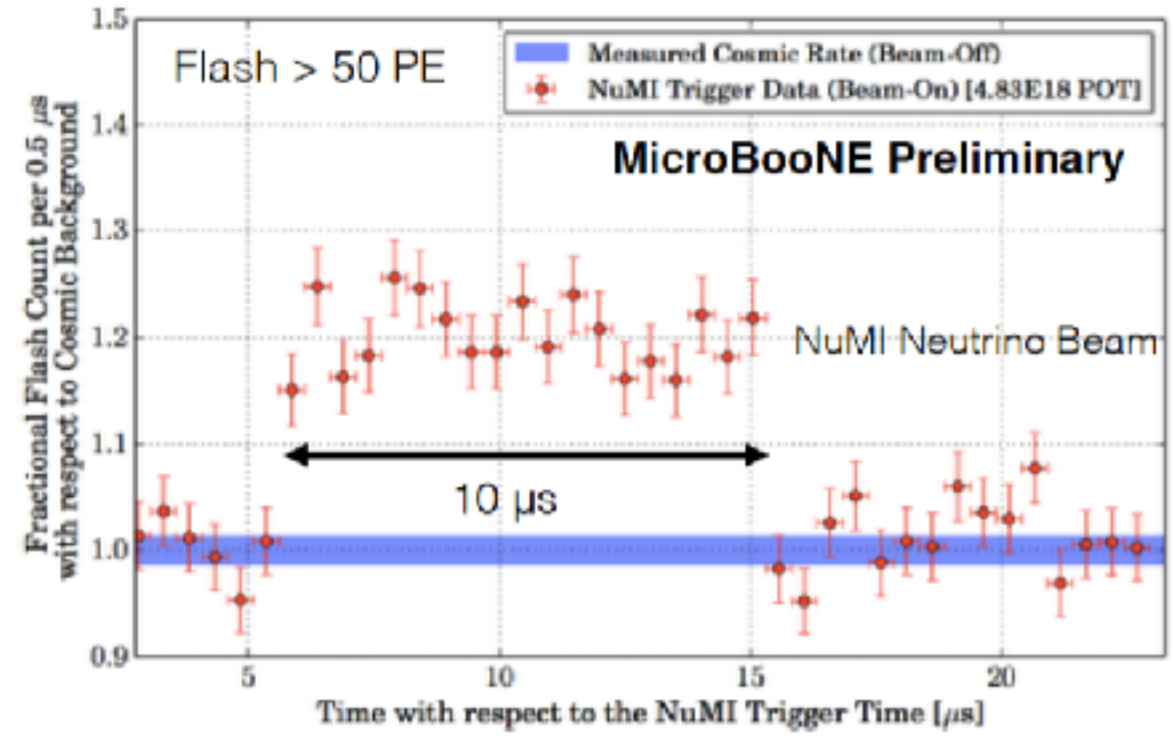
Run I neutrino mode analyses: 2.4 x 10^{20} POT

ν_e CC (NuMI)

All analyses presented today are pre-external Cosmic Tagger era

Recording neutrino interactions

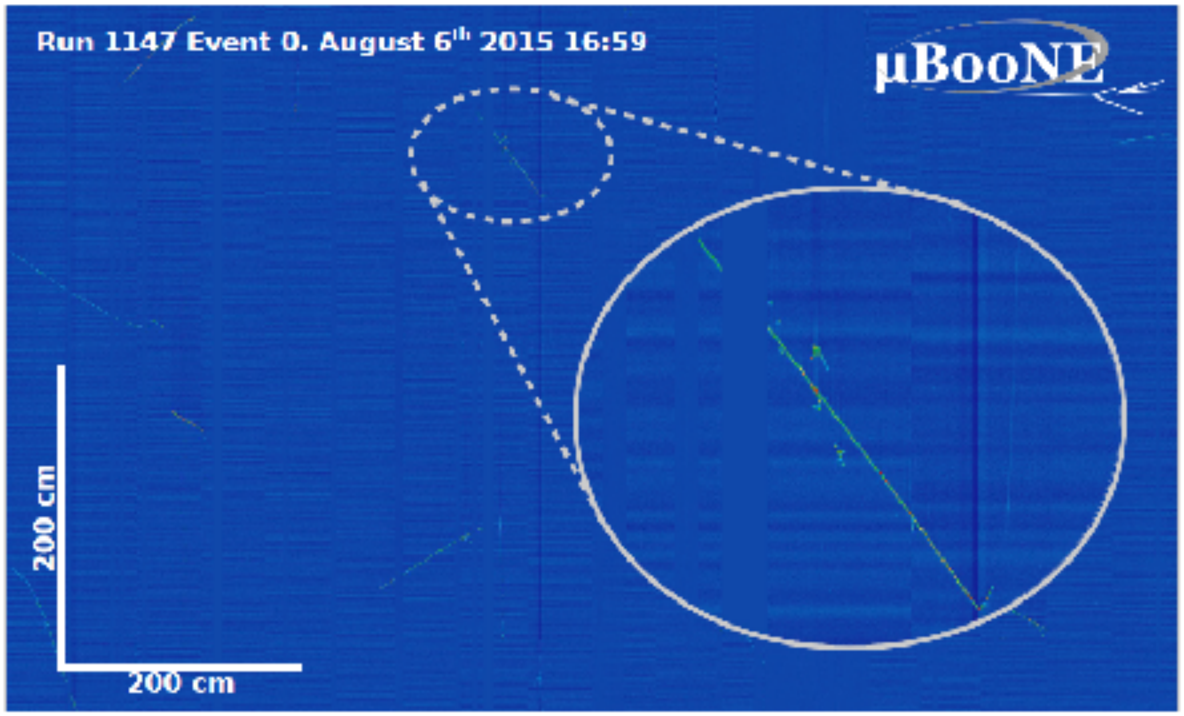




multi-PMT coincidences ("flashes")

- Prompt scintillation light detected by the optical system and used as trigger to determine the beam spill period
- The duration of the beam spills is only a fraction of the e- drift time (~2.3ms) and additional activity is recorded during drift time window due to cosmic rays

[MicroBooNE public note 1002]



Electron drift and purity

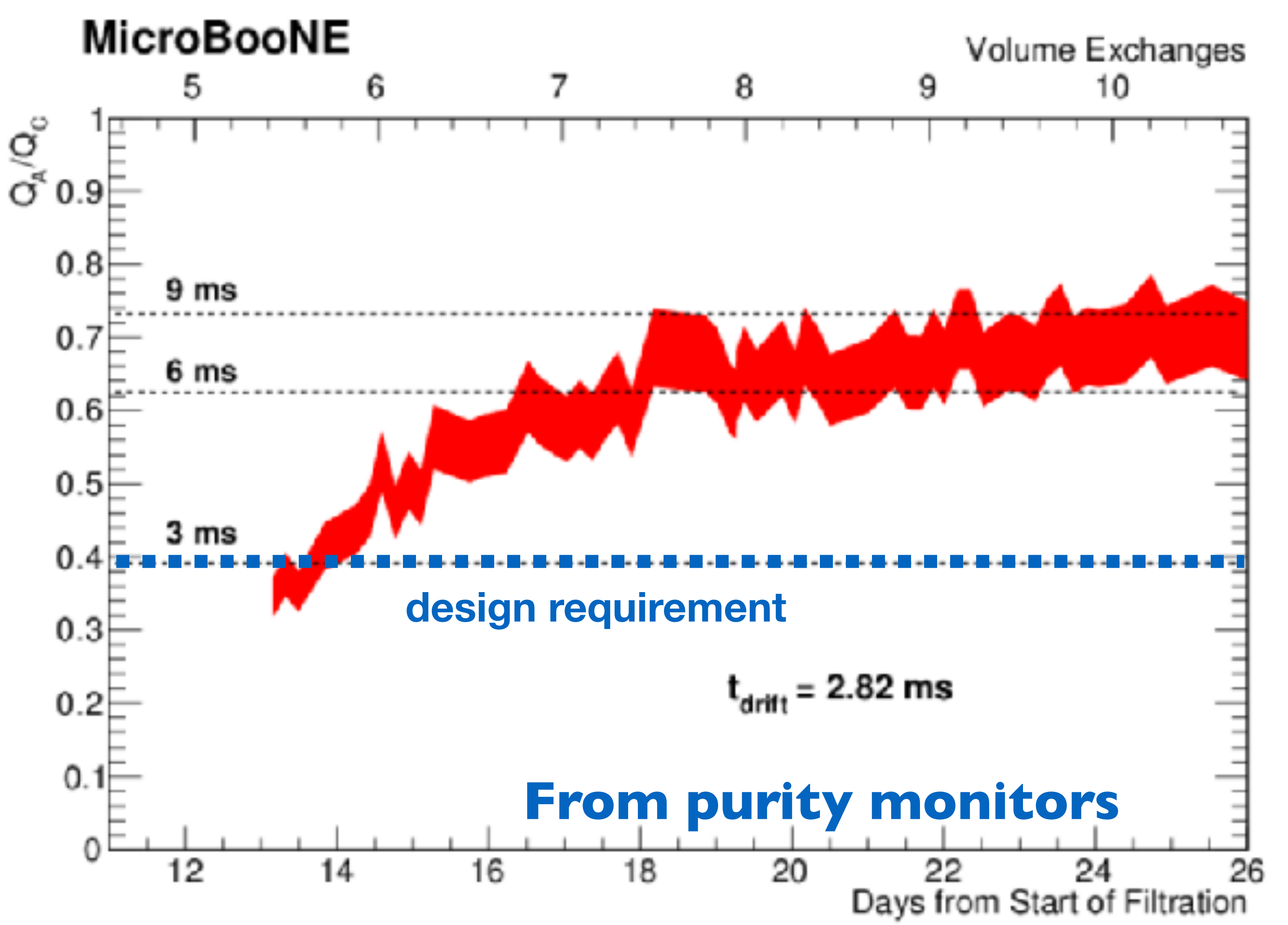
- Long time for electrons to drift from cathode to anode (~2.3 ms)
- High-purity LAr is essential for a LArTPC operation

Main electronegative contaminants: O_2 & H_2O

- Removed:
  - Gasesous purge (April 2015)
  - LAr purification (July 2015)
- Monitored:
  - Gas analyzers
  - Purity monitors (measuring drift time of e^- between their cathodes and anodes)

Within 3 weeks from start of filtration, surpassed design expectation and achieved >= 6ms e^- drift lifetime, maintained since then

MicroBooNE public note 1003



Noise

Front-end ASIC inherent noise reduced with operation in cold

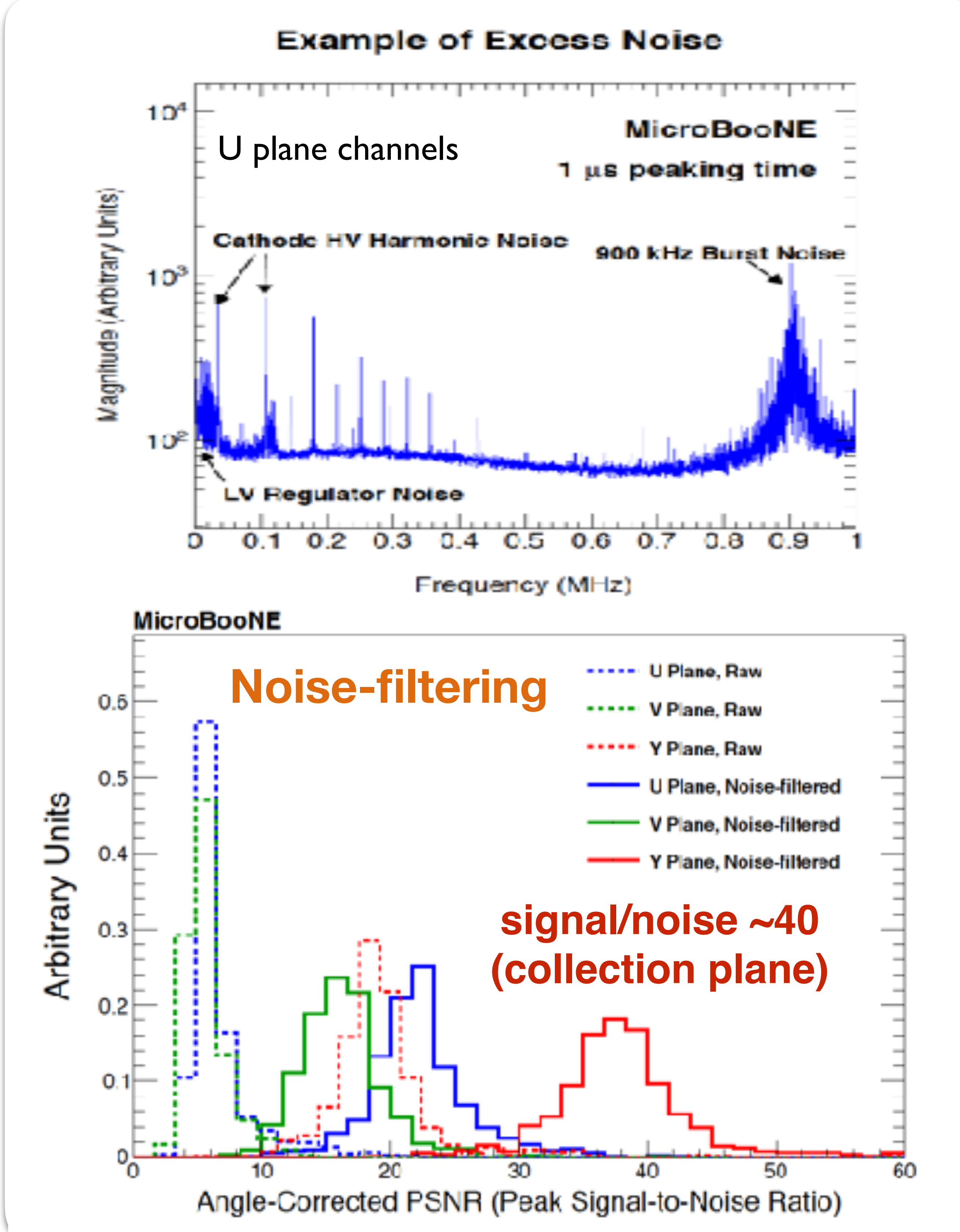
TPC excess noise

- Coherent noise: induced by the low-voltage regulators
- Harmonic noise: induced by the cathode high-voltage power supply (appearing at odd harmonics of its ripple frequency 36kHz)
- Burst noise at 900kHz, source not confirmed yet (suspected PMT HV supply or interlock system power supply)

With hardware upgrades in summer 2016 (for coherent and harmonic noise) and noise-filtering, greatly improved ratio signal/noise

Important LAr R&D results!

arxiv:hep-ex/1705.07341 (submitted to JINST)

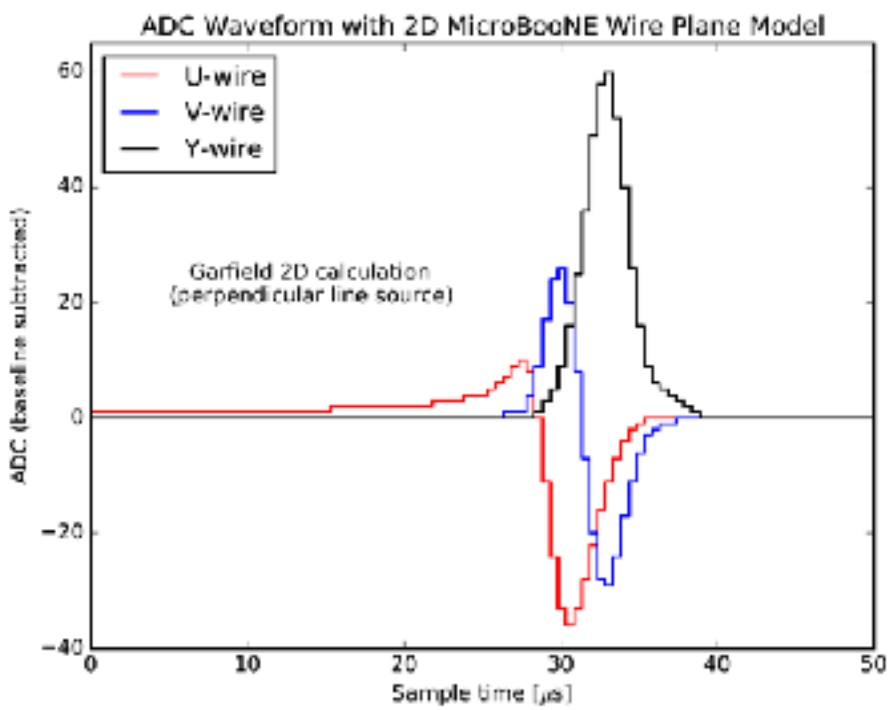


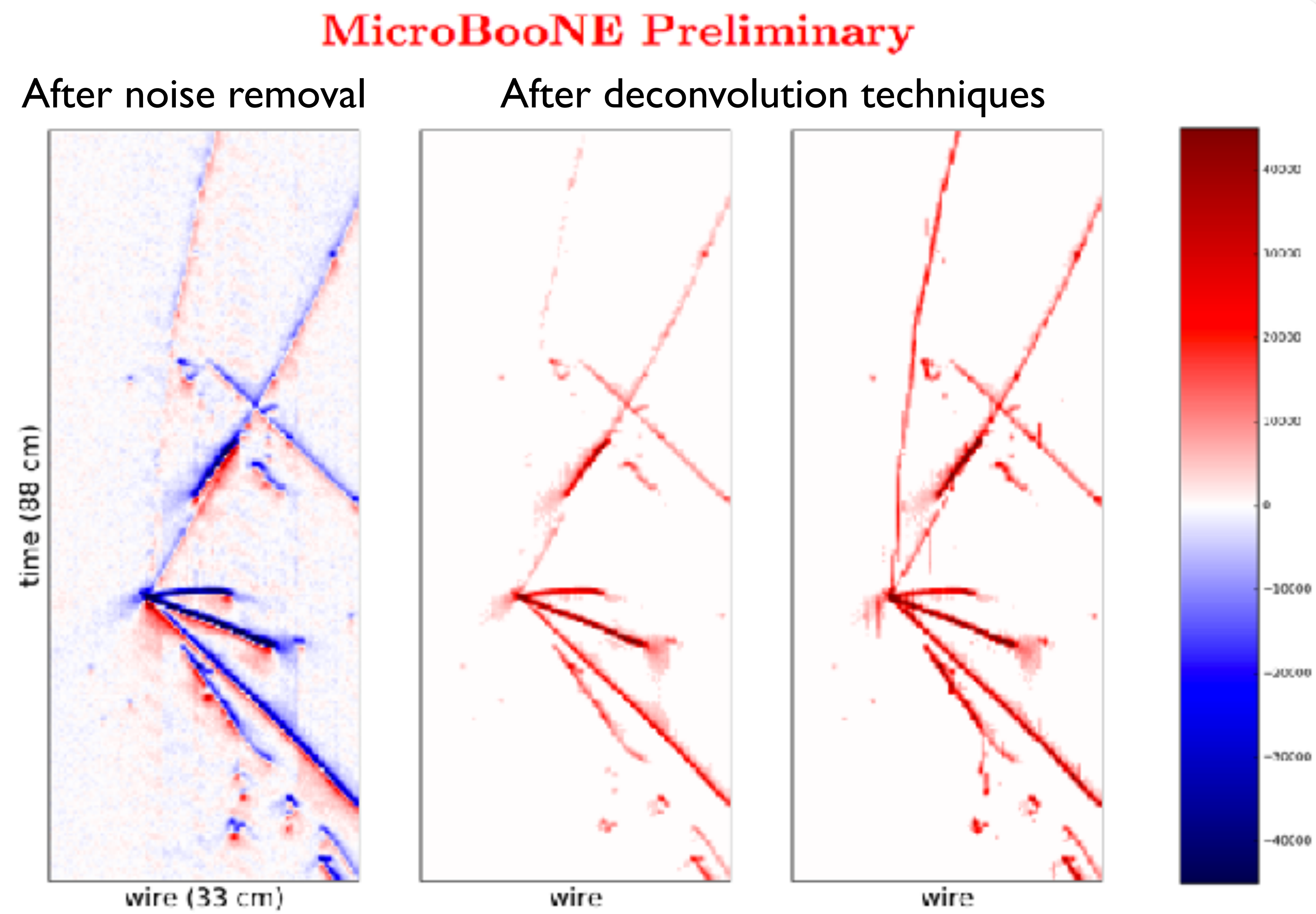
Signal processing and hit reconstruction

µBooNE

[MicroBooNE public note 1017]

After noise filtering, we want to convert the raw digitized TPC waveform to the number of ionized electrons





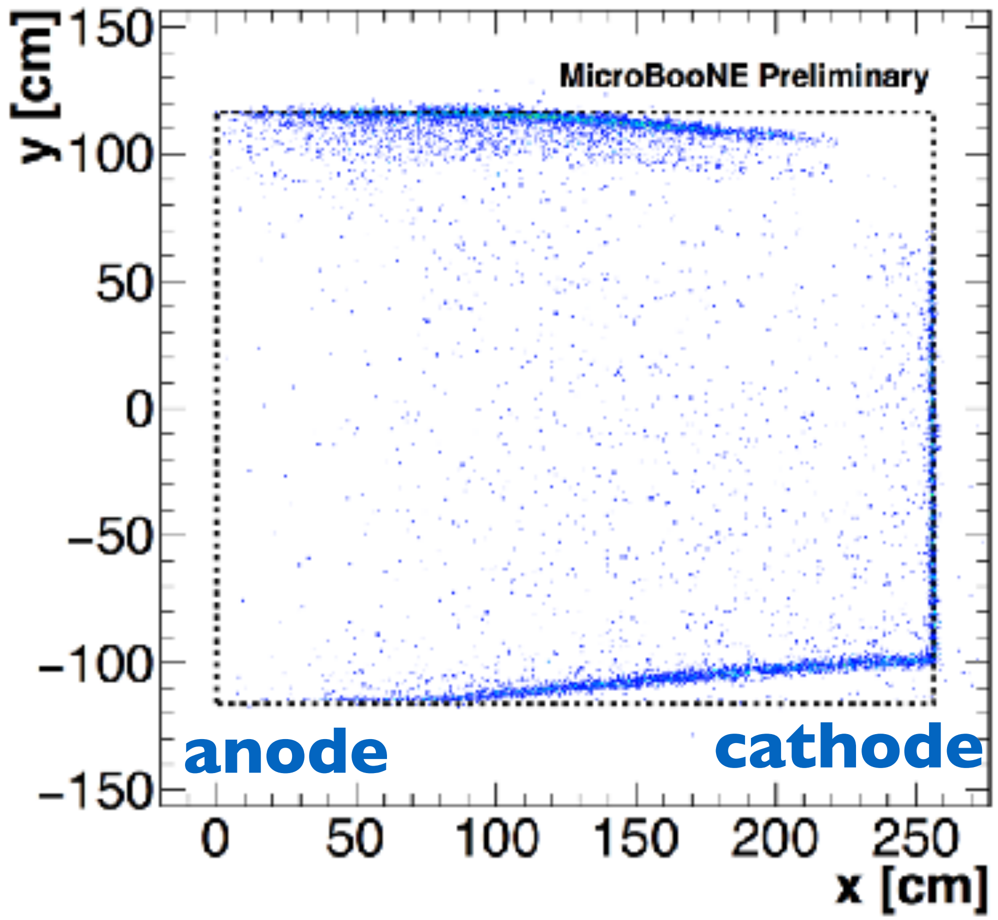
Example event in first induction plane

***Deconvolution* techniques to remove the impact of field and electronics response**

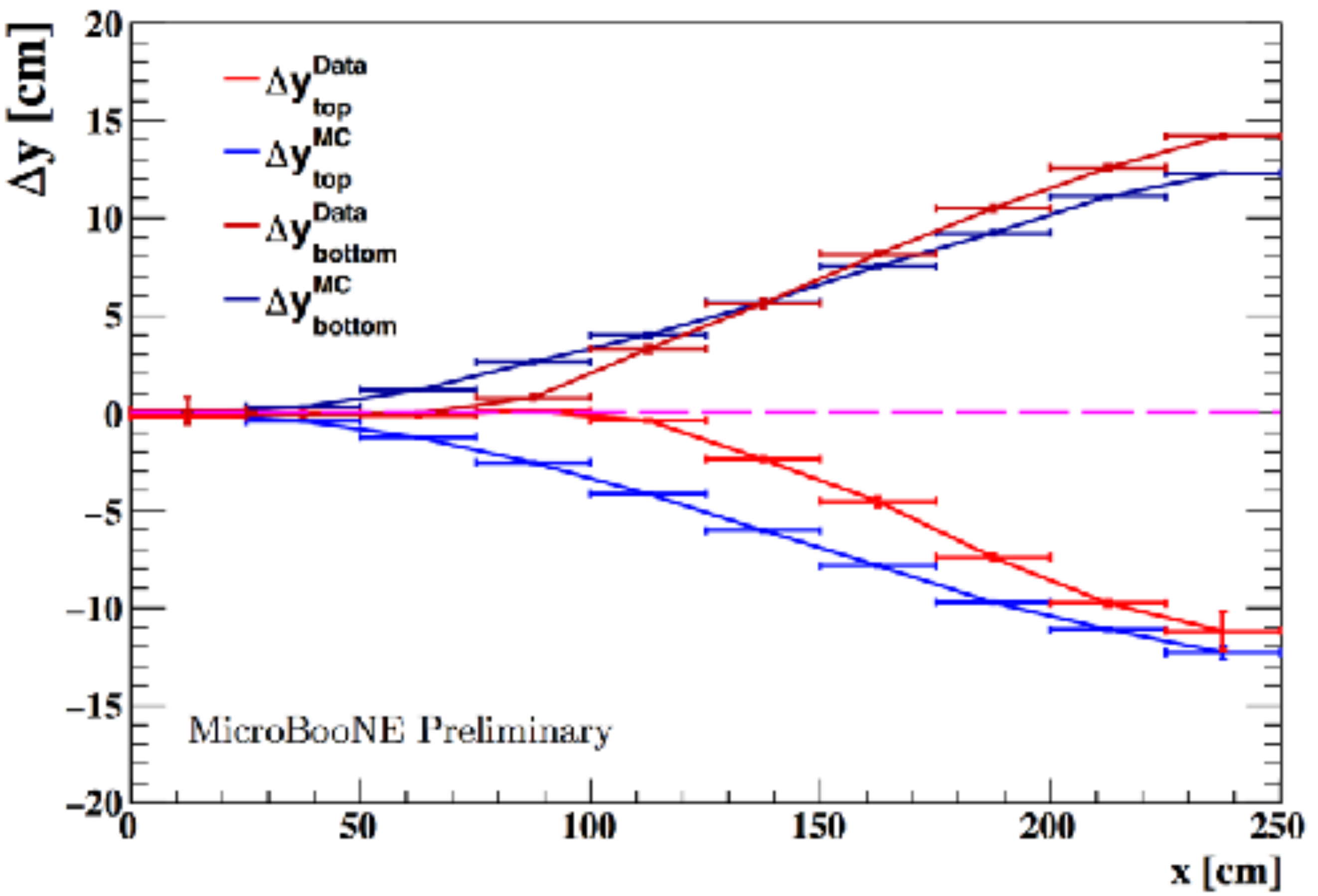
Hit finding: find regions with a wire waveform above a threshold at a definite drift time, calculate deposited charge corresponding to the hits found, and input them to the pattern recognition

Space charge effects

[MicroBooNE public note 1018]



Predicted/measured SCE spatial distortions



Space charge effect

- due to build-up of positive Ar ions (slow-moving)
- can impact the drift electric field
- and lead to spatial variations of the amount of recombination
- thus distorting tracks

Measuring it with

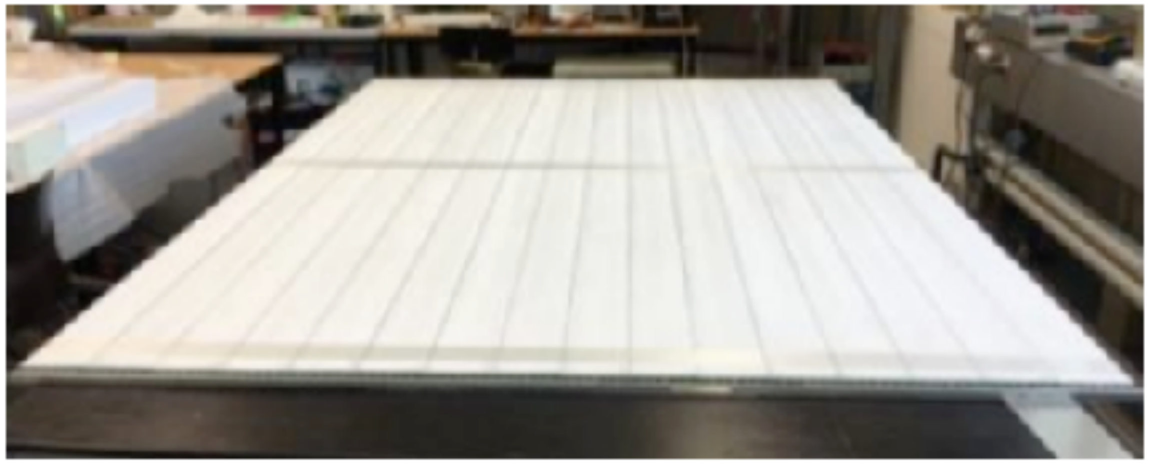
- Start/end point of reconstructed tracks in the TPC for MIPs (cosmics) tagged by the Muon Cosmic Stack in off-beam data
- Laser calibration system (UV laser) can produce a useful sample as well
- Detailed calibration is on its way!

Cosmic Ray Tagger

New Cosmic Ray Tagger providing external cosmic ray tagging system to MicrobooNE installed and fully operational since March 2017

Composed of 73 individual modules, proving 85% coverage

- Plastic scintillator strips readout by 2 WLS fibres and SiPMs (2 xy layers)
- Custom designed electronics for digitization and triggering (now licensed to CAEN) with ~ns timing precision



Made in-house at Bern University

MDPI paper (Instruments 2017, 1, 2.)

Momentum reconstruction

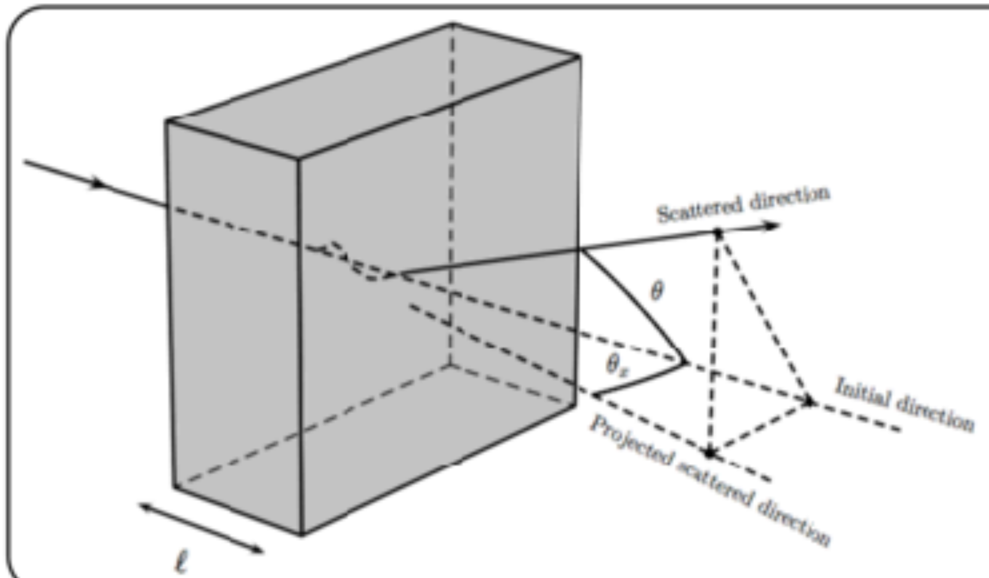
Methods of momentum reconstruction in MicroBooNE

For contained muons:
- Range-based
- Calorimetric

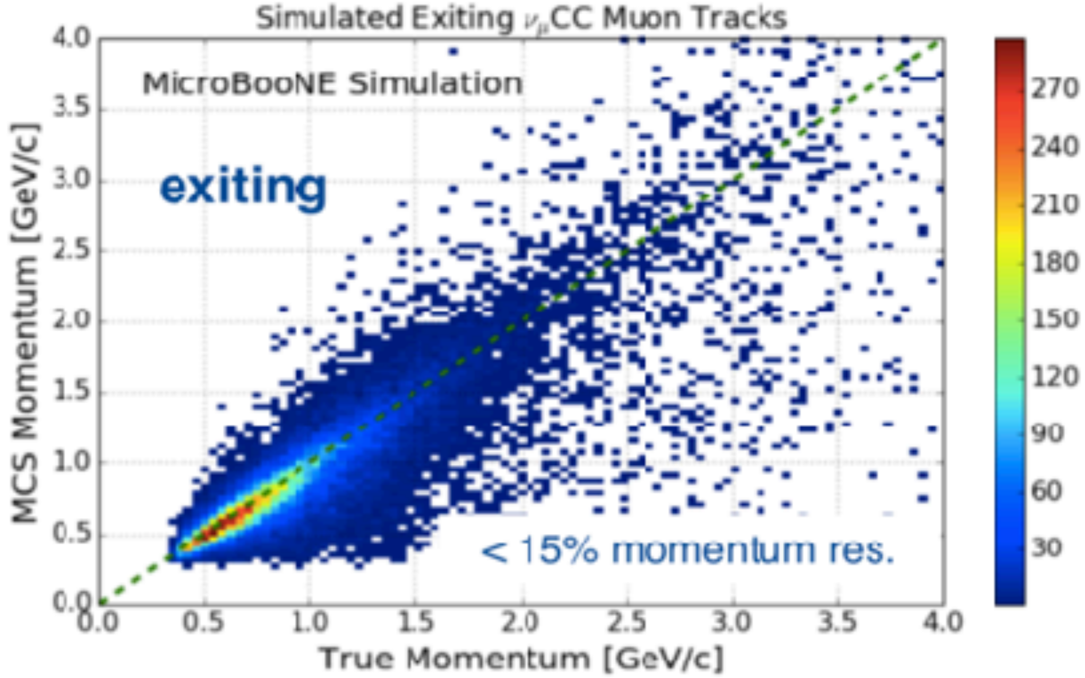
JINST 12 (2017) no.10, P10010
https://arxiv.org/abs/1703.06187

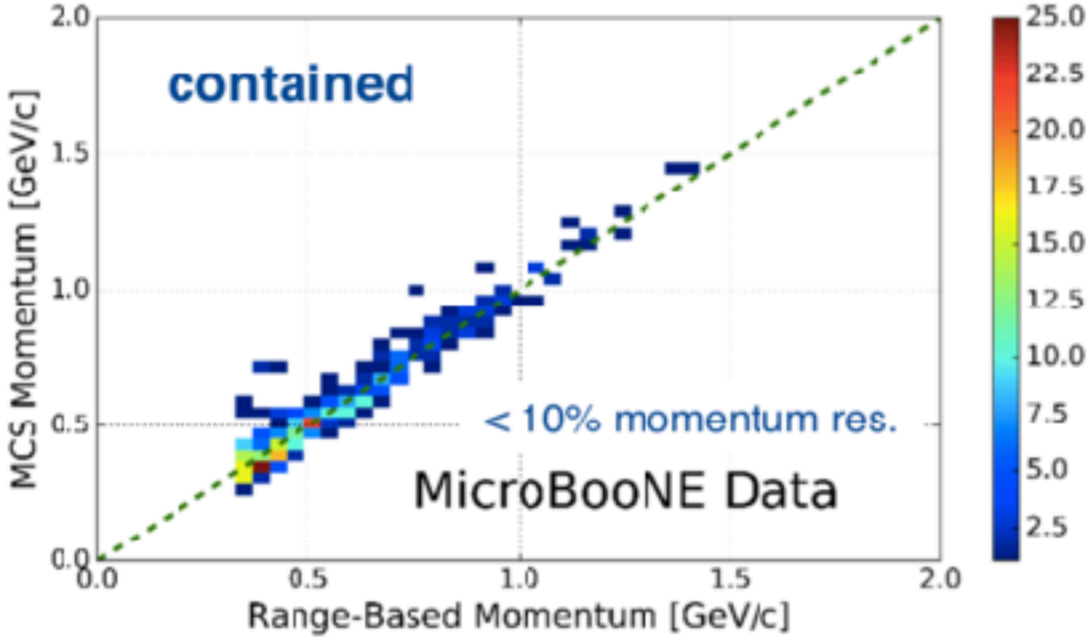
For contained and exiting muons
- Multiple Coulomb scattering

The majority of BNB muons in MicroBooNE is exiting!

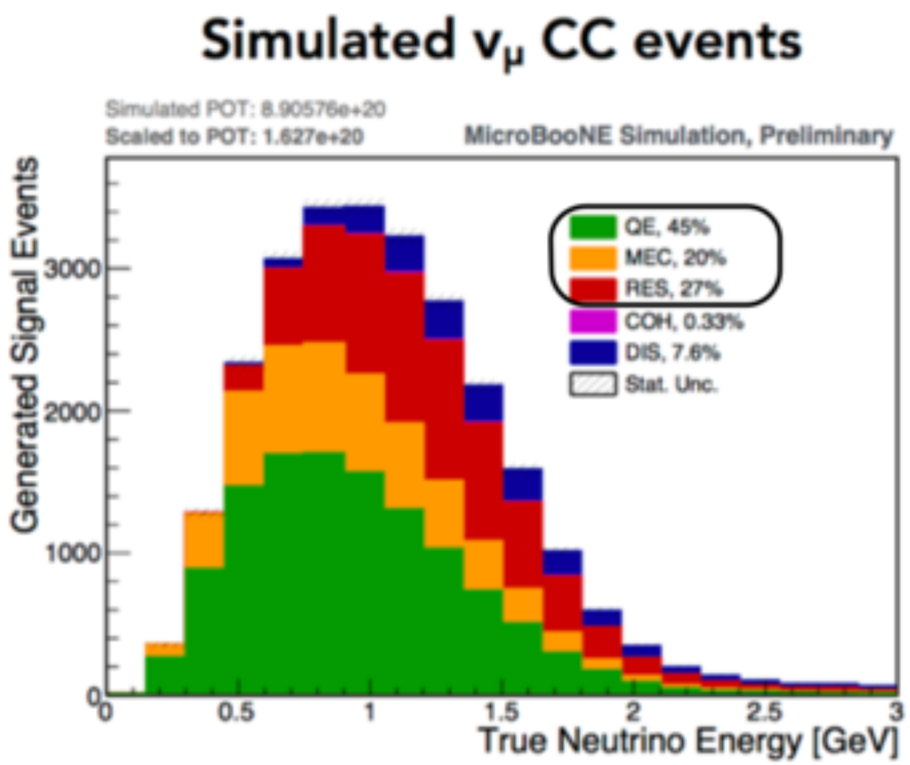


The spread of deflection angles along a track depends on the particle's momentum





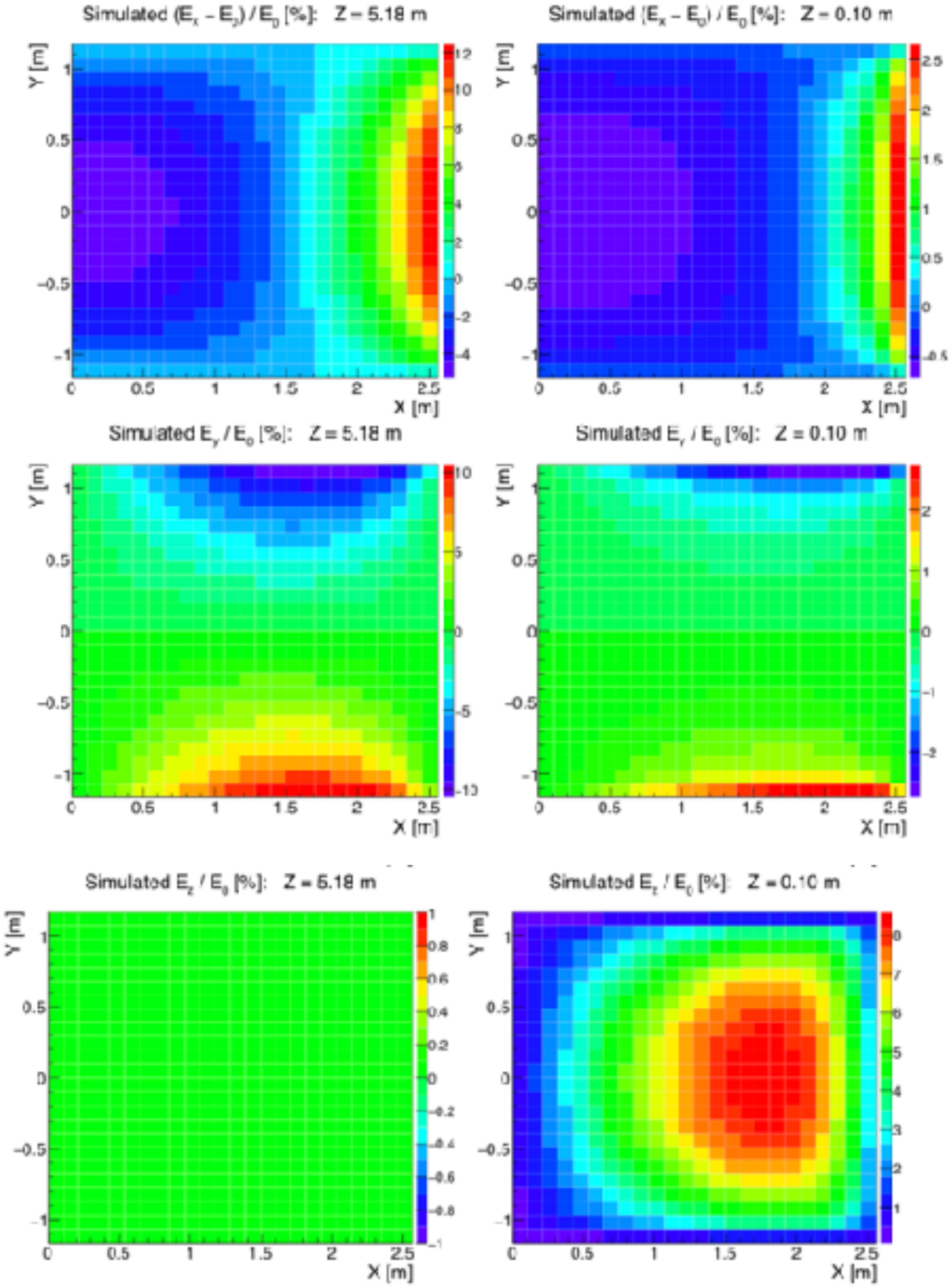
ν_μ CC interactions



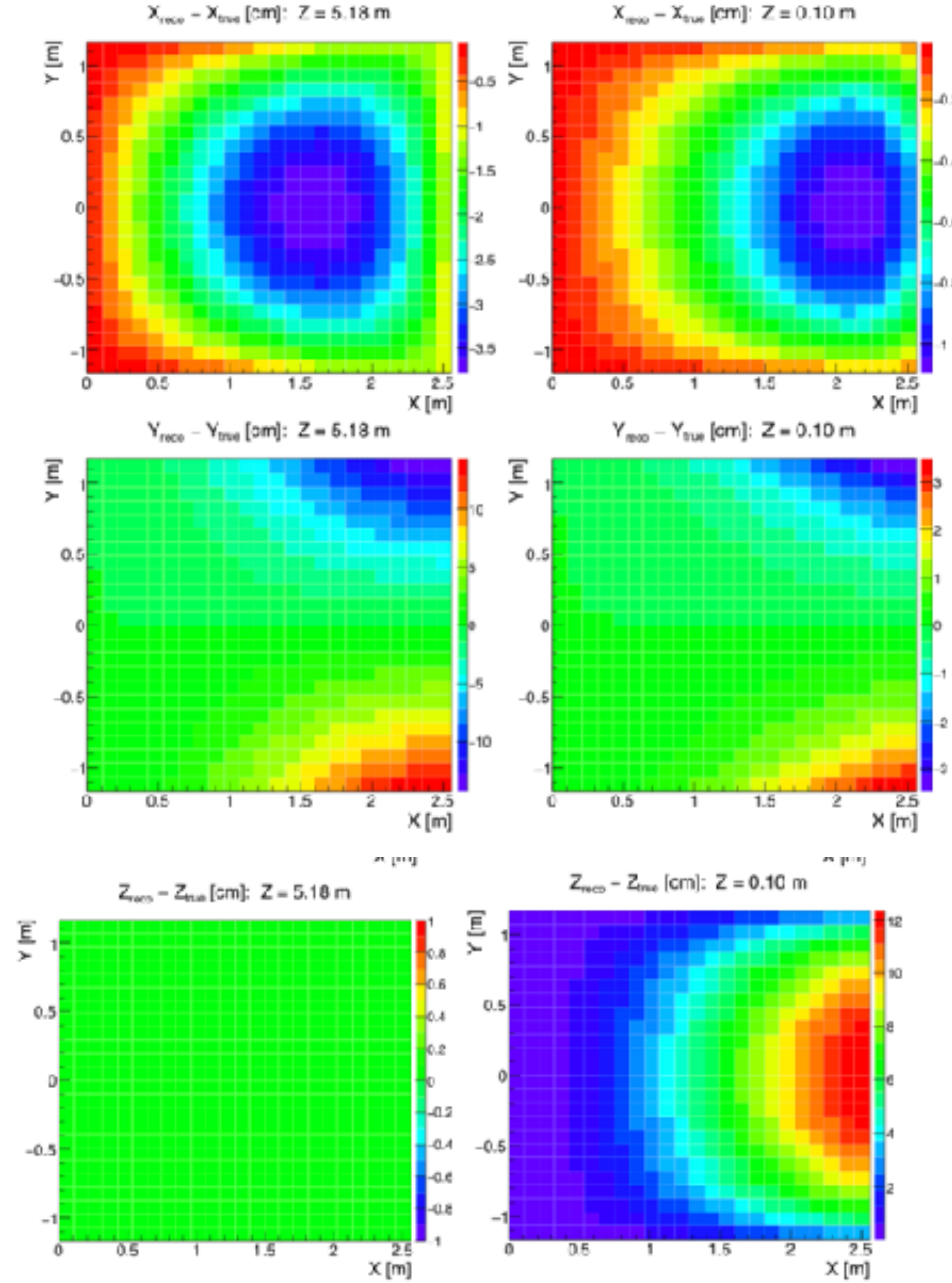
Cross section measurements are crucial for oscillation analyses (currently the dominant systematic error e.g. T2K, NOvA)

Moving towards LArTPC detectors (SBN, DUNE) but not many ν-Ar measurements (only ArgoNeuT, high energy)

CC inclusive	CC Np & CC 2p
Simple signal definition, minimal model dependency	Provides test of different models (MEC, RES, but also FSI and short range correlations)
Relatively insensitive to hadronic final states	Shows reliable particle ID and calorimetric reconstruction
Pro: high stats (anything with a muon) Con: cosmic ray contamination	Pro: very little cosmic contamination Con: few stats



igure 4: Illustration of the simulated effects of space charge on the drift electric field in the MicroBooNE TPC, as described in Sec. 3. Results are shown for the effect in x (top row), y (middle row), and z (bottom row). The electric field distortions are normalized to the nominal drift electric field magnitude (E_0) of 273 V/cm and are plotted as a function of the true position in the TPC. Simulation results are shown both for a central slice in z (left column) and for a slice in z closer to the end of the TPC, z = 10 cm (right column).



: 5: Illustration of the simulated effects of space charge on the distortions in reconstructed ionization electron cluster position in the MicroBooNE TPC, as described in Sec. 3. Results are shown for the effect in x (top row), y (middle row), and z (bottom row). The distortions in reconstructed ionization electron cluster position are shown in units of cm and are plotted as a function of the true position in the TPC. Simulation results are shown both for a central slice in z (left column) and for a slice in z closer to the end of the TPC, z = 10 cm (right column).

Detector Systematics

We generated MC samples for each one of these detector parameters and recalculated the cross section for each: σ^m.

The uncertainty has then been evaluated as:

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

Systematic Sample	Relative Uncertainty [%]
Induced Charge Effect	13.0
Light Yield Model	4.7
Channel Saturation	4.3
Space Charge Effect	3.7
TPC Visibility	3.7
Electron Lifetime	2.9
Misconfigured Channels	1.8
Longitudinal Diffusion	1.7
Transverse Diffusion	1.6
PE Noise	0.4
Wire Response	0.2
Wire Noise	0.1
Electron Recombination	0.1

Detector Response Relative Uncertainty on Total Cross Section: 16%

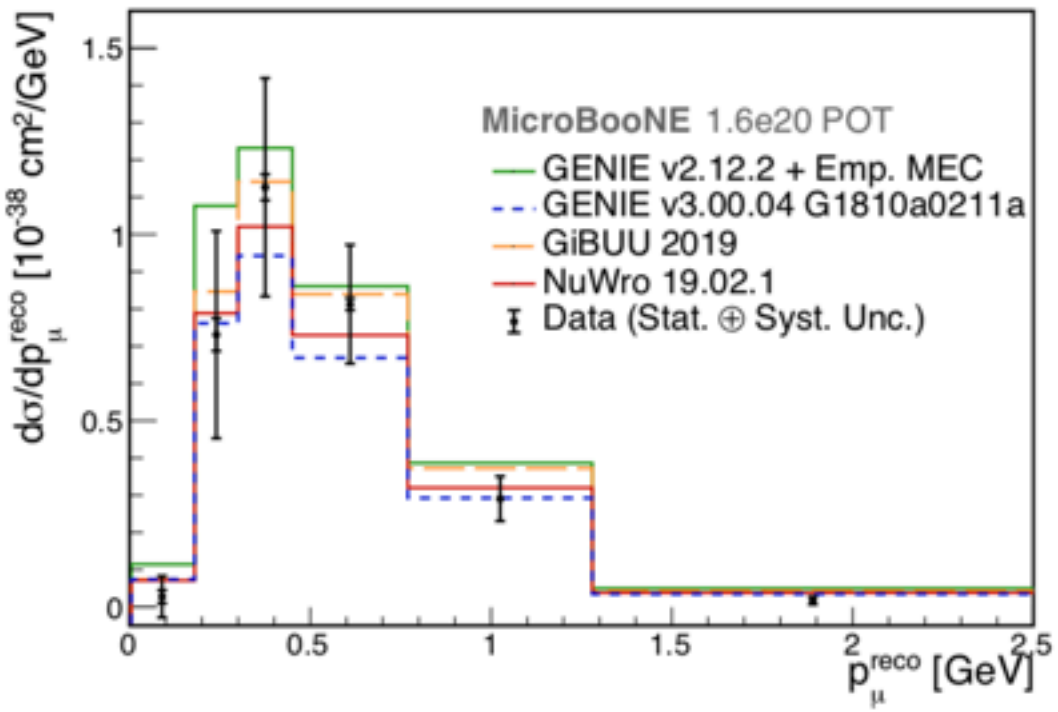
Summary of Systematics

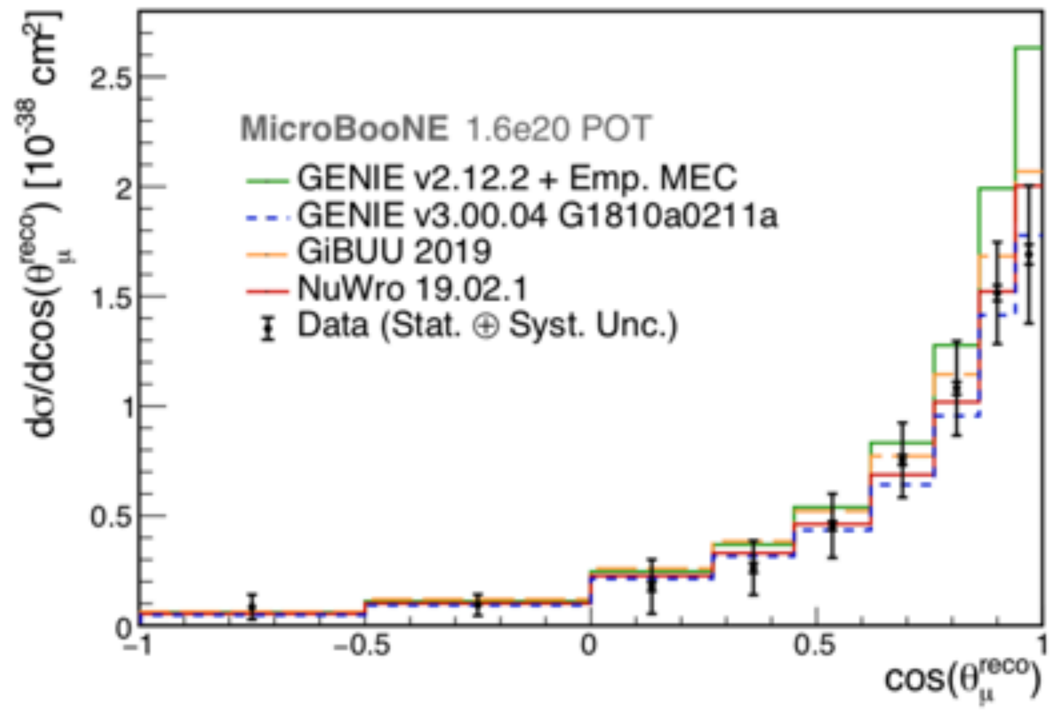
- ◆ Described previously
- ◆ Improved reconstruction and cosmic ray tagger will mitigate this background
- ◆ It will be reduced when we switch to a neutrino simulation with cosmic data overlaid

Source of Uncertainty	Relative Uncertainty	
Beam Flux	12.2	◆
Cross Section Modelling(*)	3.9	◆
Detector Response	16.2	◆
POT Counting	2.0	
Dirt Background	10.9	◆
Cosmics (Corsika)	4.1	◆
Cosmic (data)	0.7	
MC Statistics	0.2	
Stat	1.4	
Total	23.8	

(*) Includes an additional uncertainty on MEC interactions (1.5%)

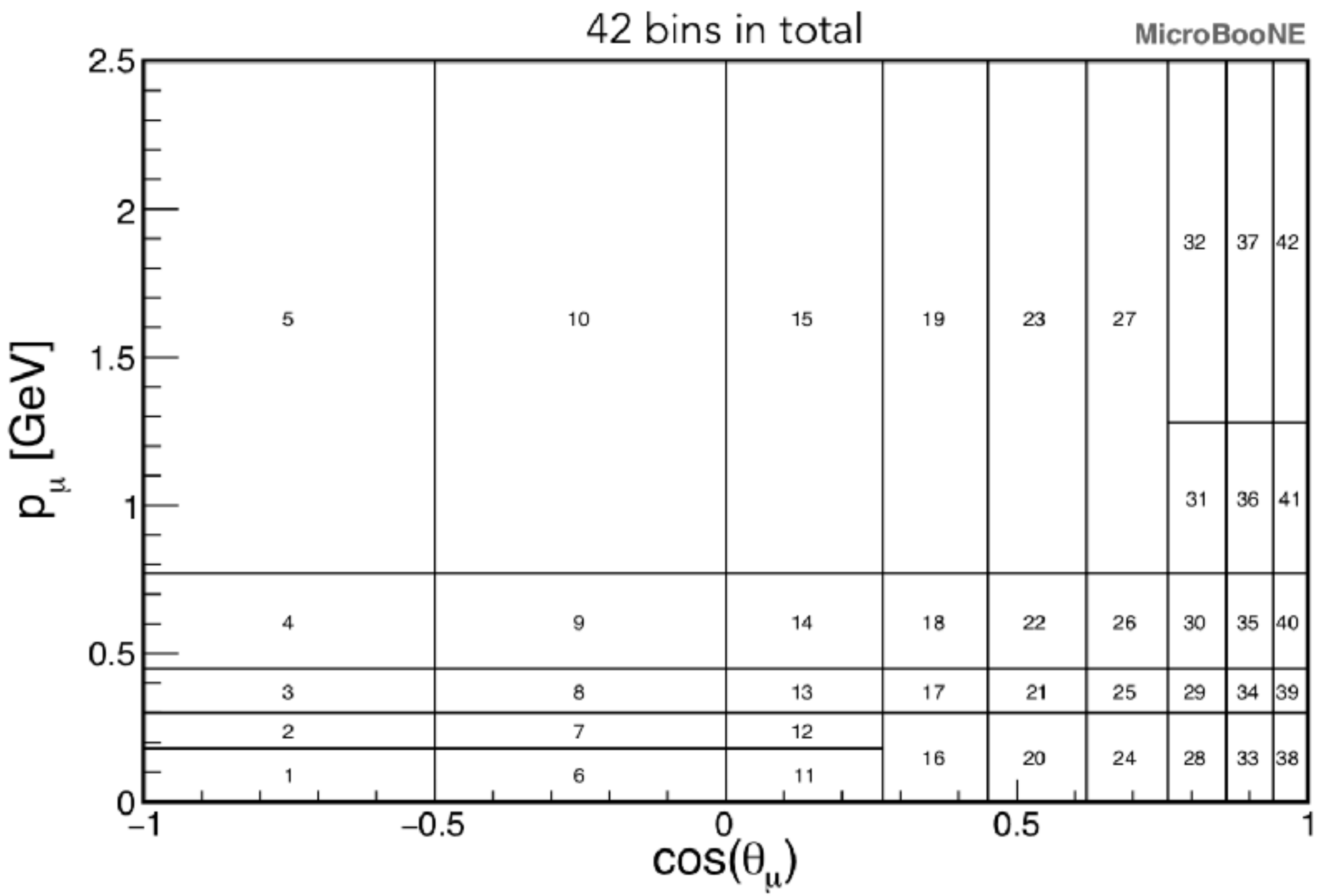
Cross Section Measurement



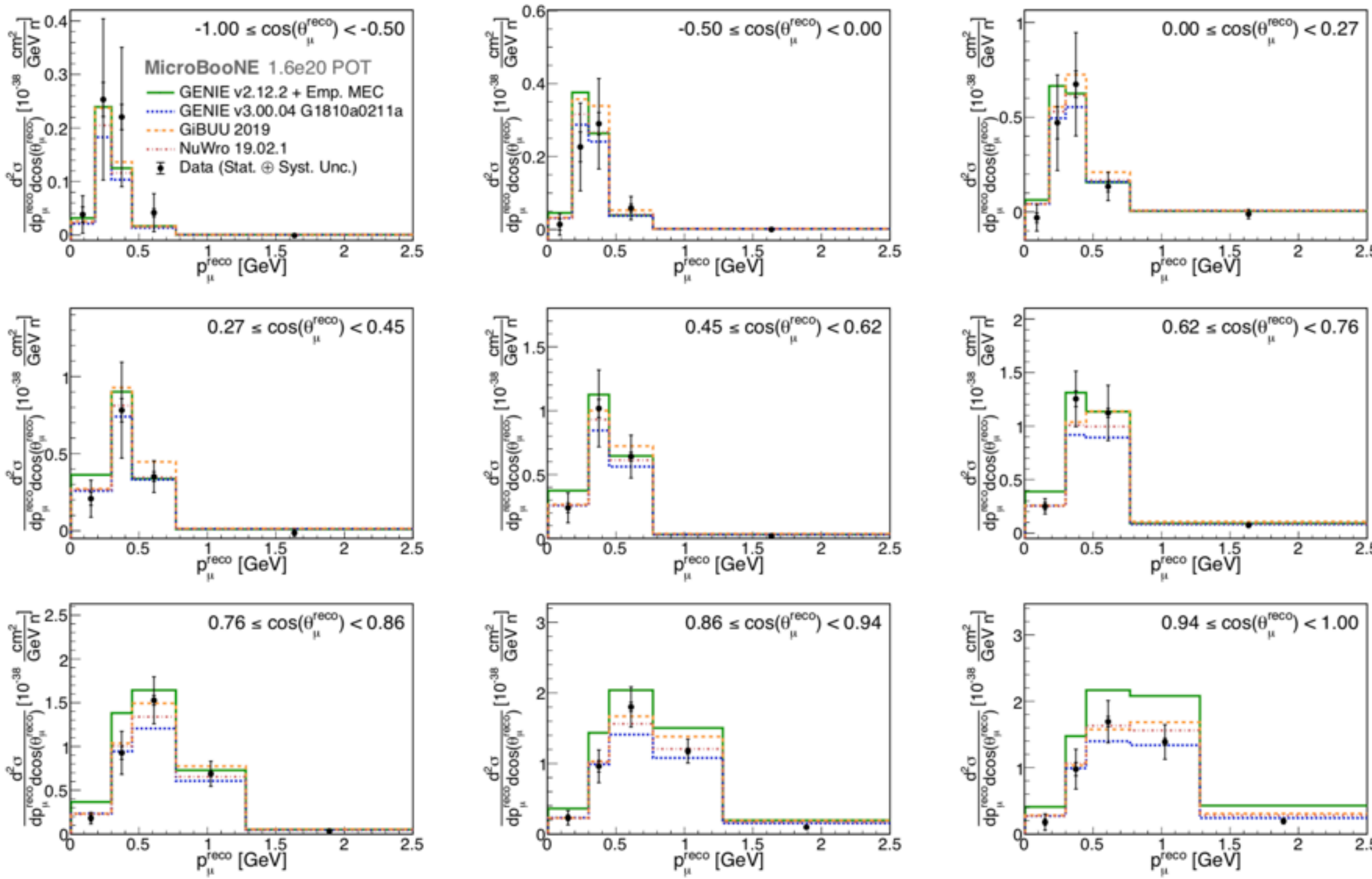


Model Element	GENIE v2 + MEC (v2.12.2)	GENIE v3 (v3.00.04 G1810a0211a)	NuWro (19.02.1)	GiBUU (2019)
Nuclear Model	Bodek-Ritchie Fermi Gas [1]	Local Fermi Gas [2, 3]	Local Fermi Gas [2, 3]	Consistent nuclear medium corrections throughout. Also uses a LFG model for nucleon momenta, a separate MEC model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

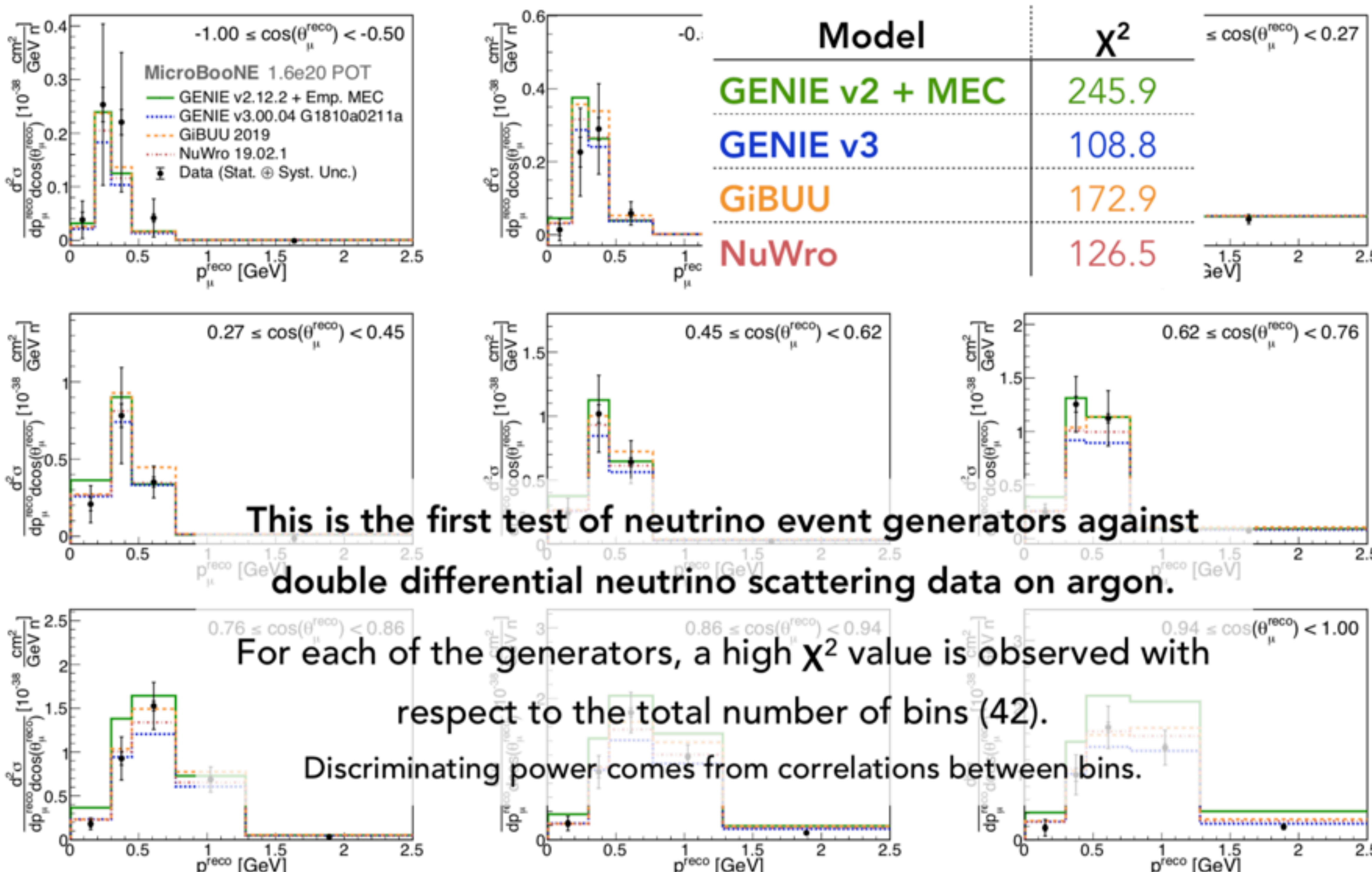
Binning for the double-differential cross section measurement:



Cross Section Measurement



Cross Section Measurement



Model	χ^2
GENIE v2 + MEC	245.9
GENIE v3	108.8
GiBUU	172.9
NuWro	126.5

This is the first test of neutrino event generators against double differential neutrino scattering data on argon.

For each of the generators, a high χ^2 value is observed with respect to the total number of bins (42).

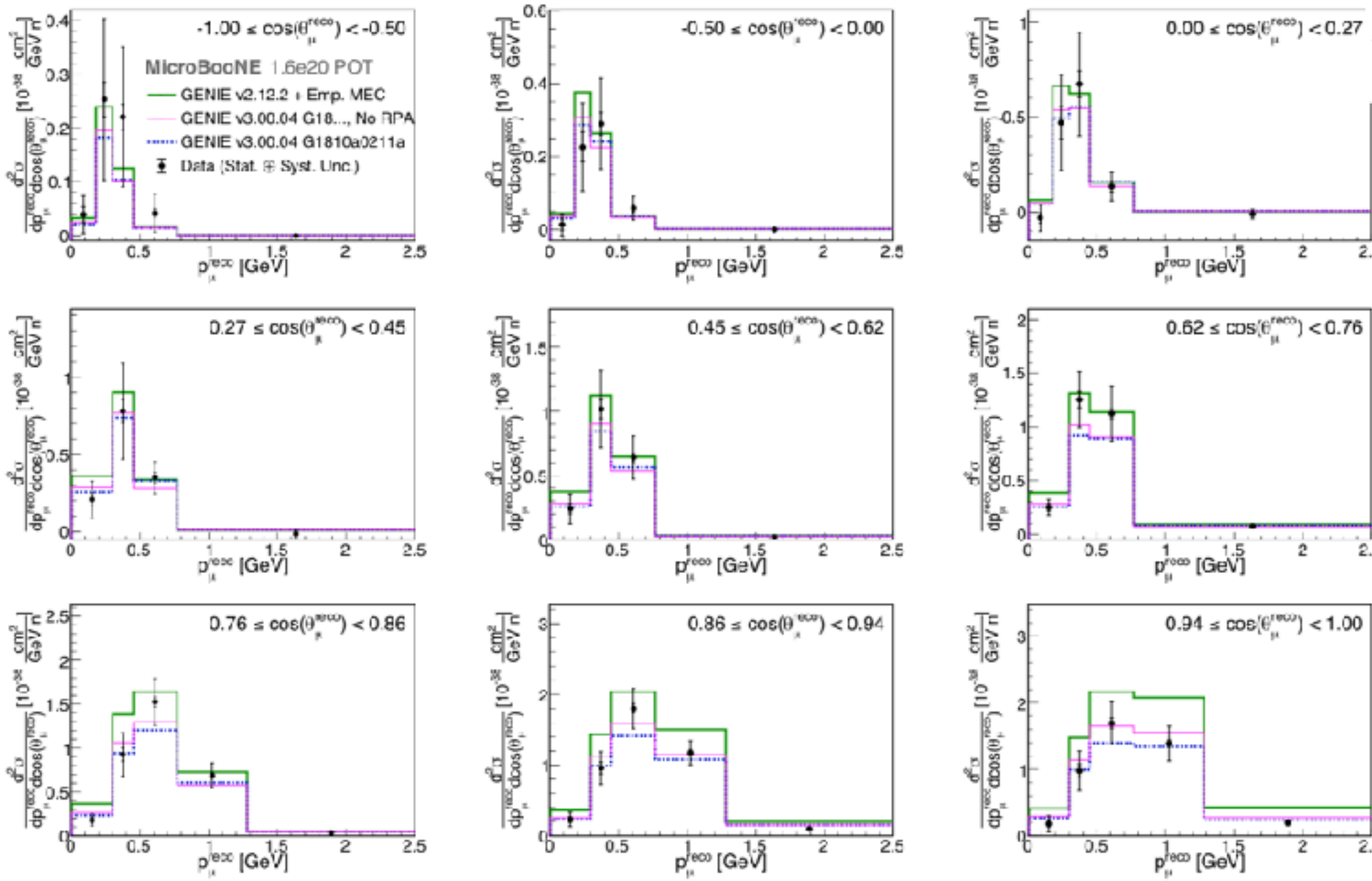
Discriminating power comes from correlations between bins.

The large χ^2 is mostly driven by the high-momentum bins in the most forward-going muon angular bins of $0.94 \leq \cos(\theta) \leq 1$ and $0.86 \leq \cos\theta < 0.94$.

The tension is reduced for GENIE v3, NuWro and GiBUU.

Cross Section Measurement

Model	χ^2
GENIE v2 + MEC	245.9
GENIE v3 No RPA	121.6
GENIE v3 (contains RPA)	108.8

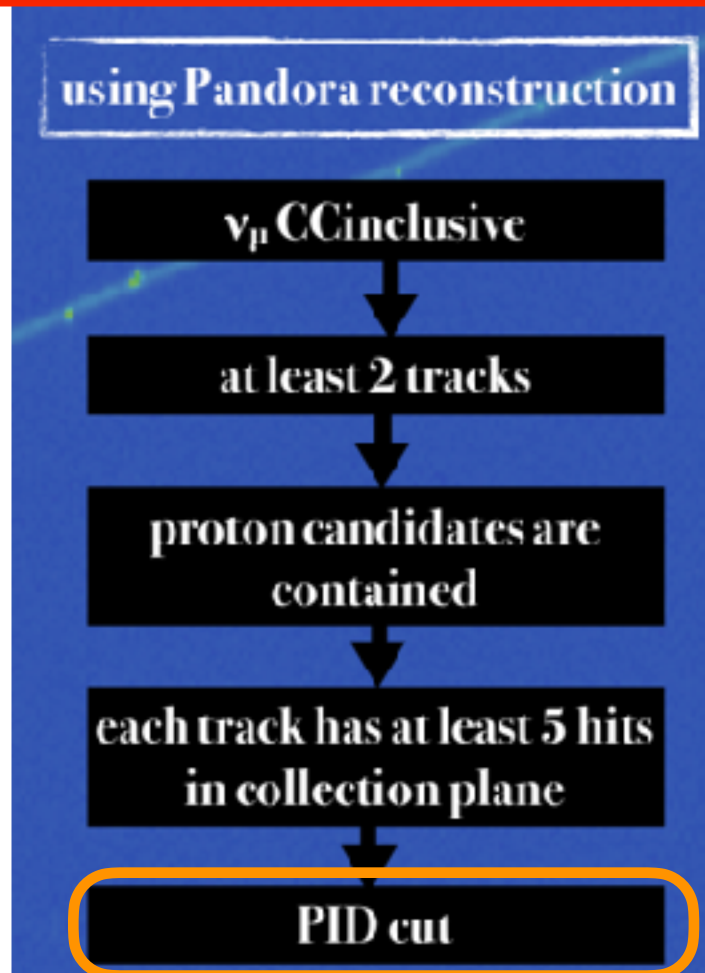


The reduced tension originates from the overall reduced cross section in the forward region when adopting the Local Fermi Gas nuclear initial state.

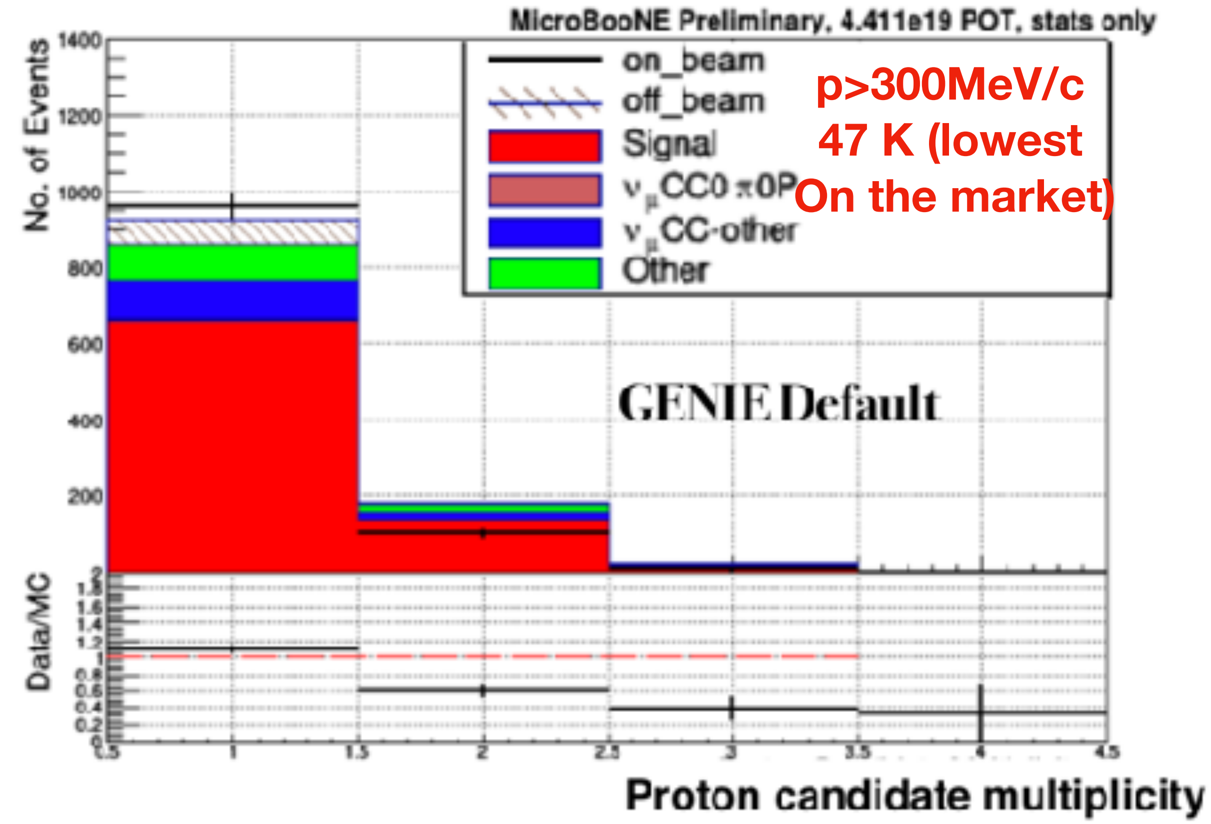
To a lesser extent also from the RPA correction as included in the Genie v3 and NuWro predictions.

ν_μ CC Np and 2p

*Notes: analysis done with 5x10[19] POT.
Using collection plane only for now.
Proton candidates are required to be contained.
Proton momentum threshold due to method (at least 5 hits)

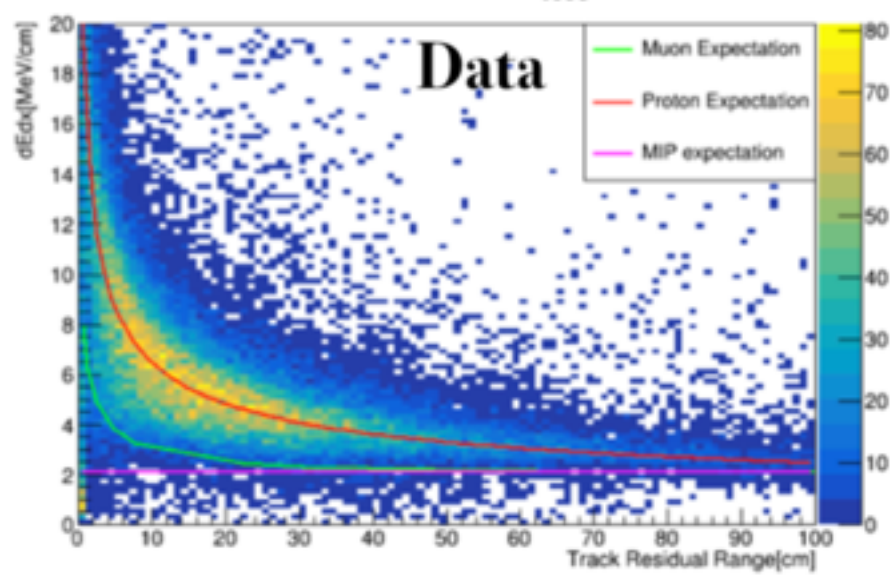


See talk at NuINT 2018 by Raquel Castillo here



Proof of the important work performed on (fully) calibration and recombination studies (paper coming this summer)

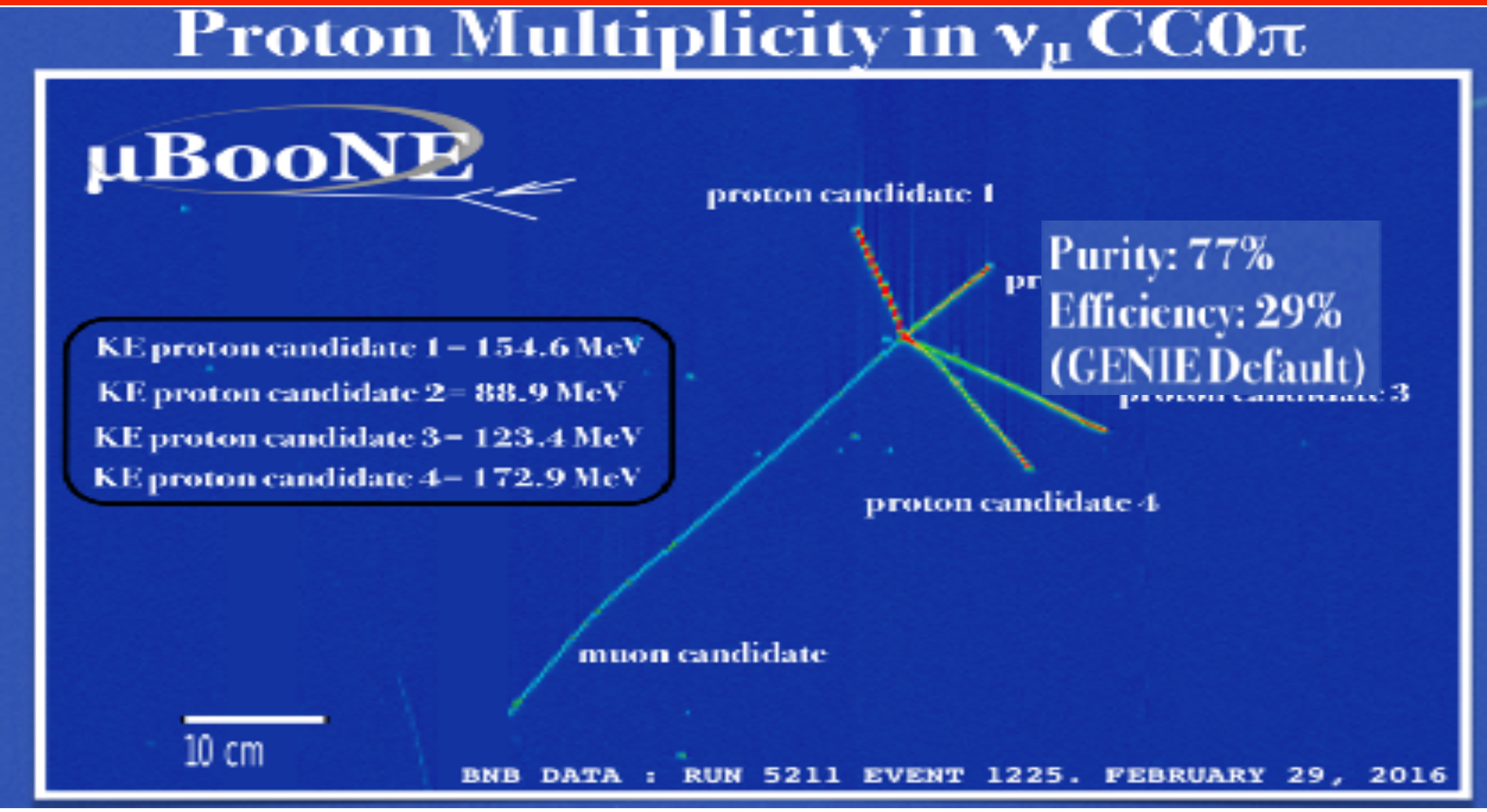
$$PID = \chi^2_{proton}/ndof = \sum_{hit} \left(\frac{(dE/dx_{measured} - dE/dx_{theory})}{\sigma_{dE/dx}}\right)^2/ndof$$



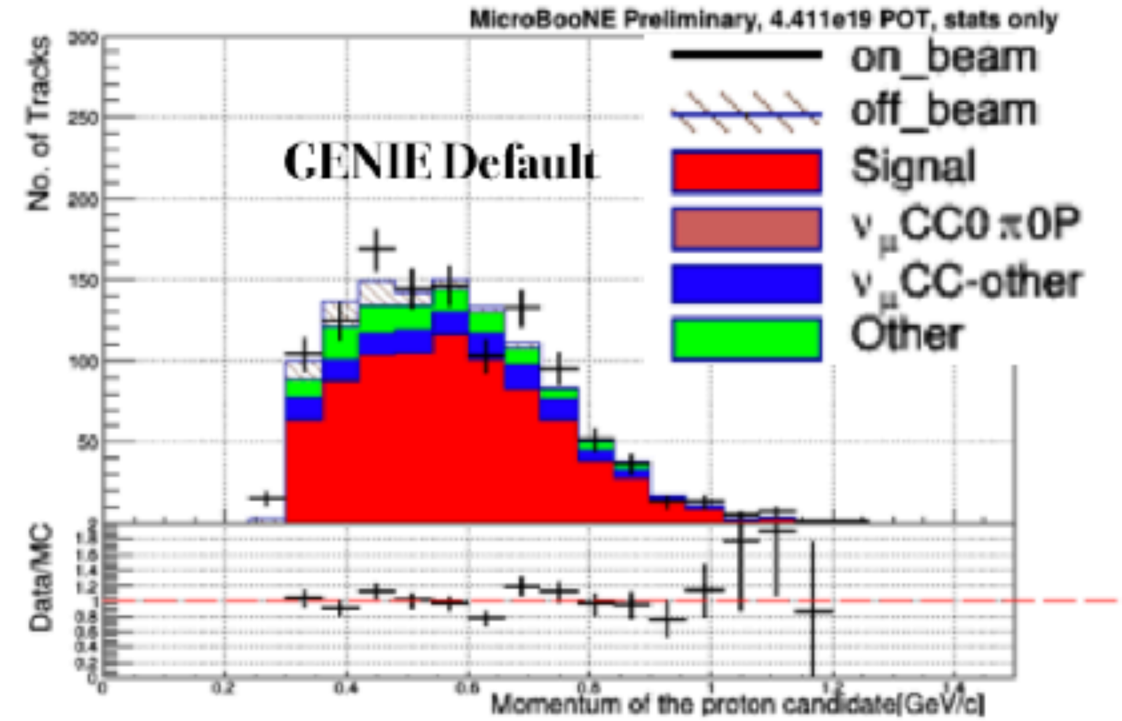
Selected protons in ν_μ CC sample

Proton enhanced sample	Before PID requirement	After PID
true μ	18.7%	2.0%
true proton	64.5%	92.6%
other	16.8%	5.4%

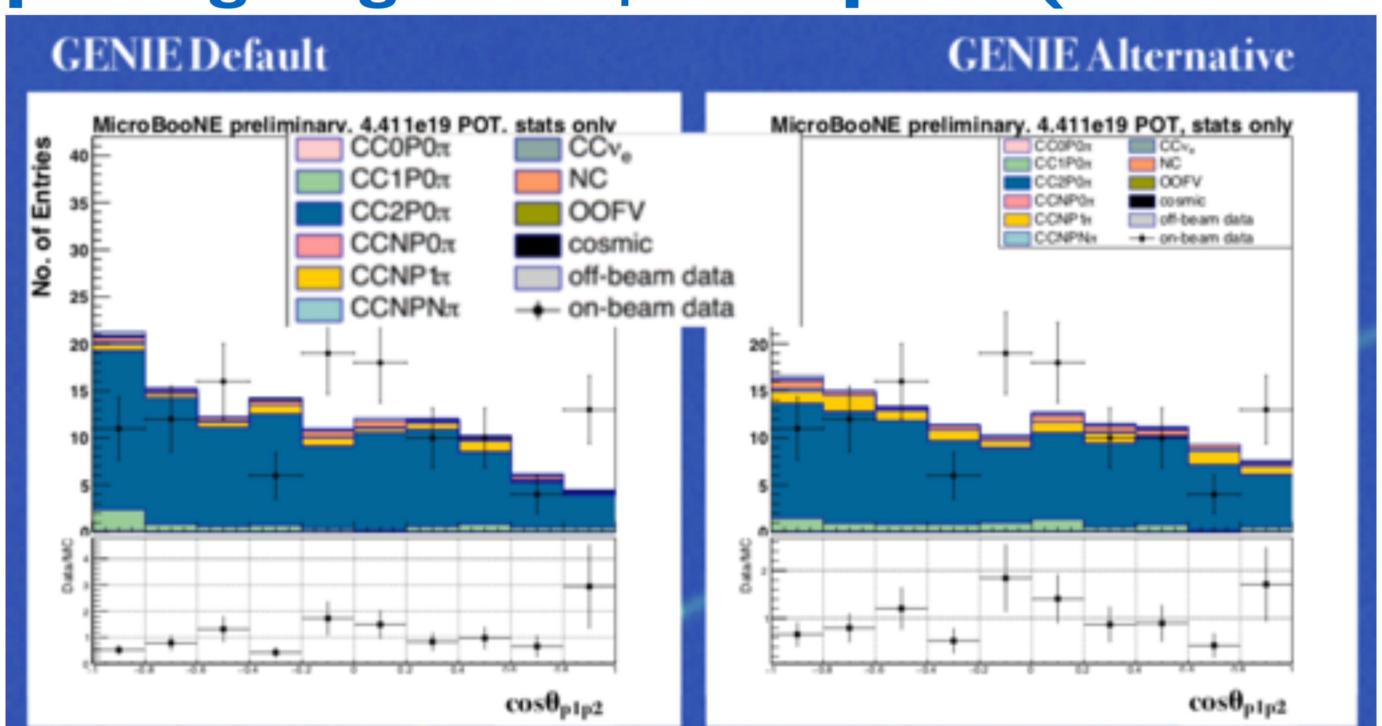
ν_μ CC Np and 2p

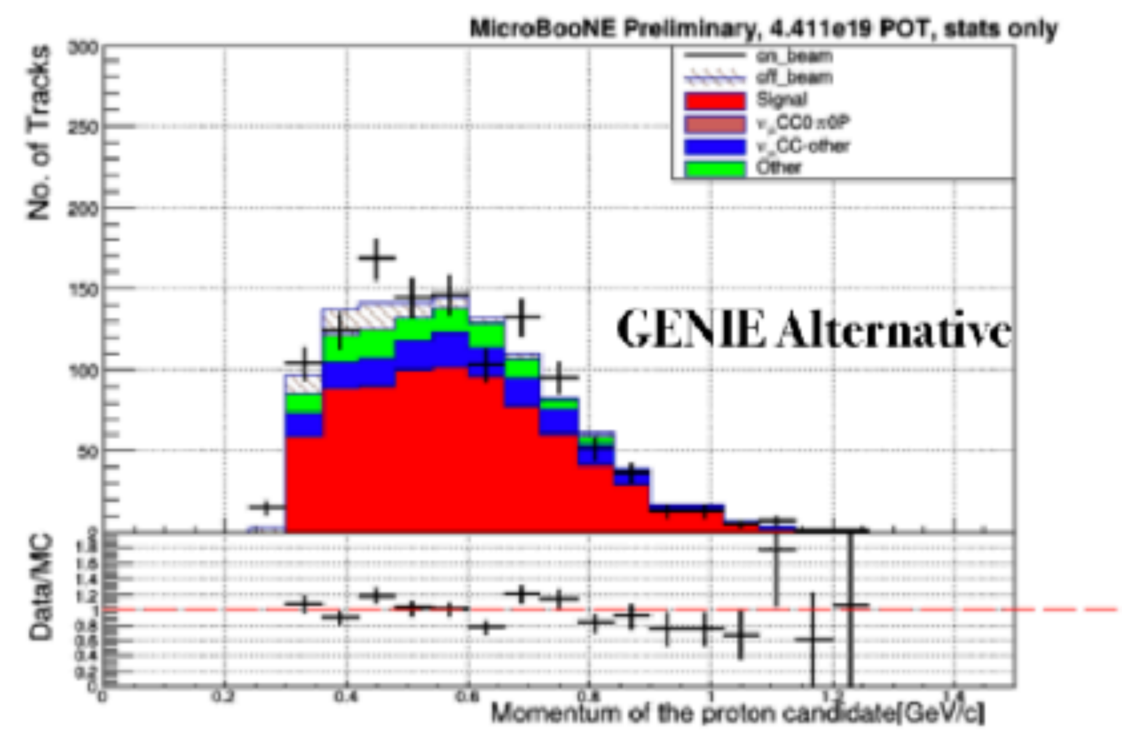


Leading proton momenta in ν_μ CC Np 0π



Opening angle in ν_μ CC 2p 0π (lab frame)



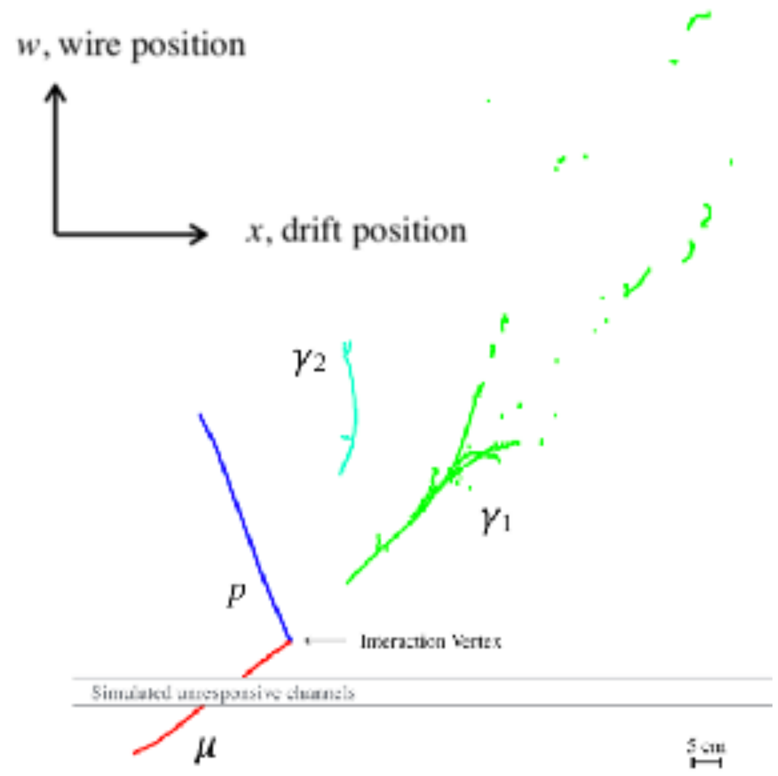


See talk at NuINT 2018 by Raquel Castillo here

Distinguishing between electrons and photons is extremely important for MicroBooNE to achieve its physics goals and investigate the MiniBooNE low energy excess

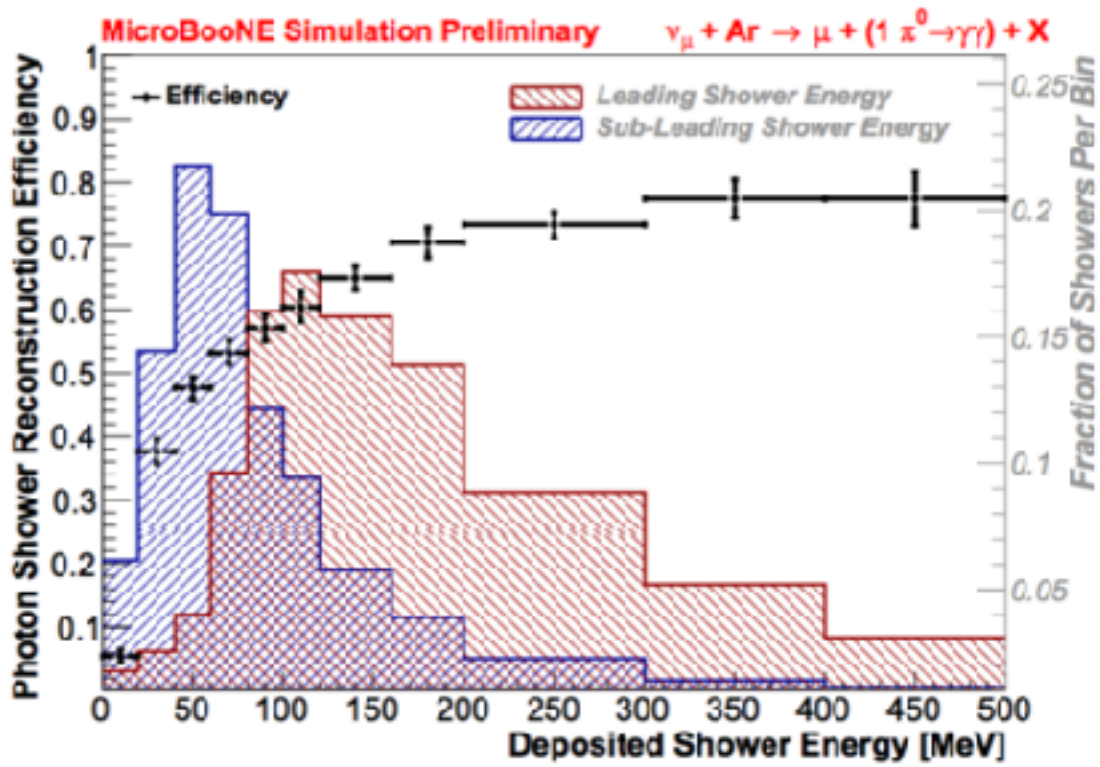
CC pi0 cross section:

- Provides measurement/ analysis tools to identify pi0 gammas, background for ν_e
- Pi0 invariant mass to cross check EM energy scale
- Measurement sensitive to pion absorption in Ar



This analysis uses a combination of geometric, PMT and containment cuts to eliminate cosmic contamination.

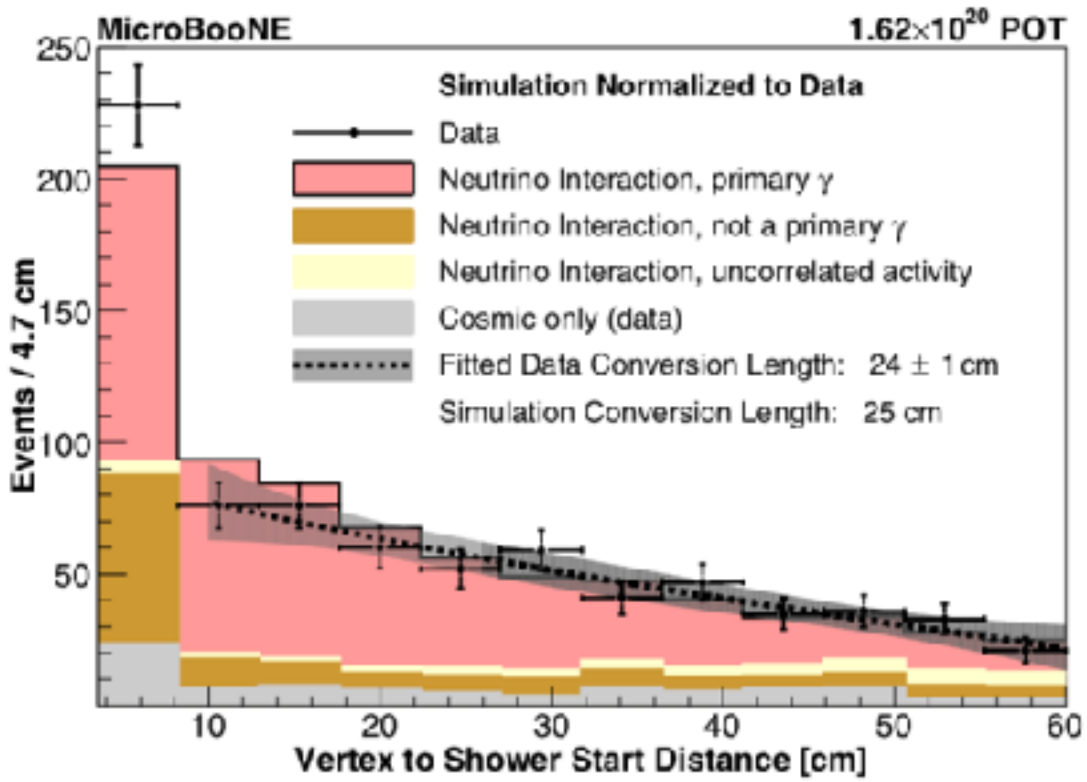
The reconstruction uses Pandora output, then OpenCV for reclustering of shower-like hits in the event



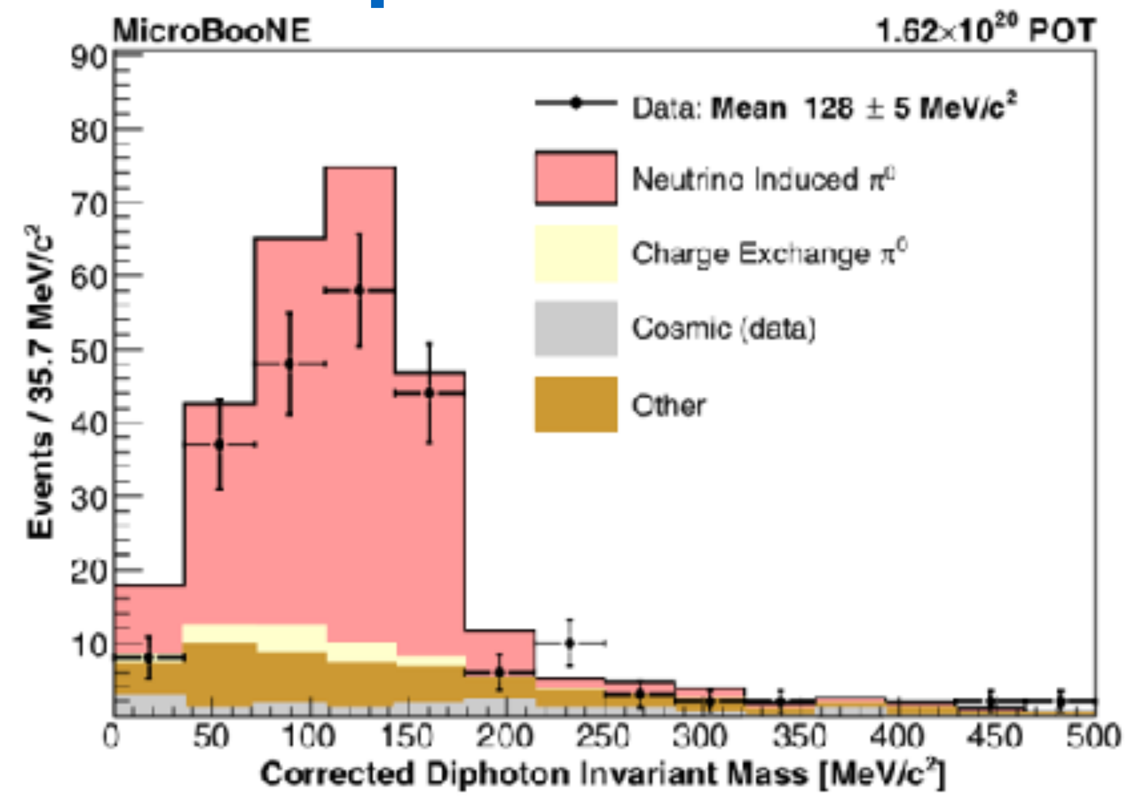
See talk at NuINT 2018 by Joel Mousseau here

ν_μ CC π^0

Single photon selection

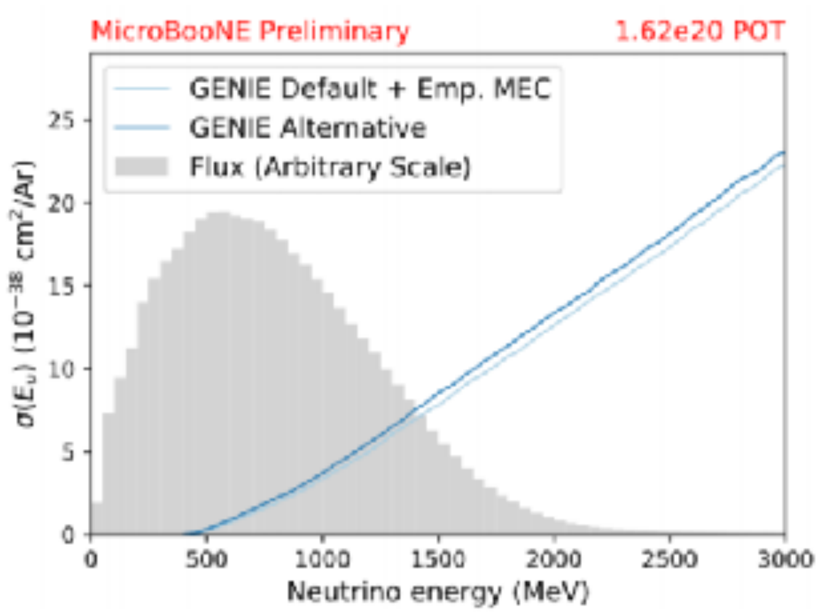


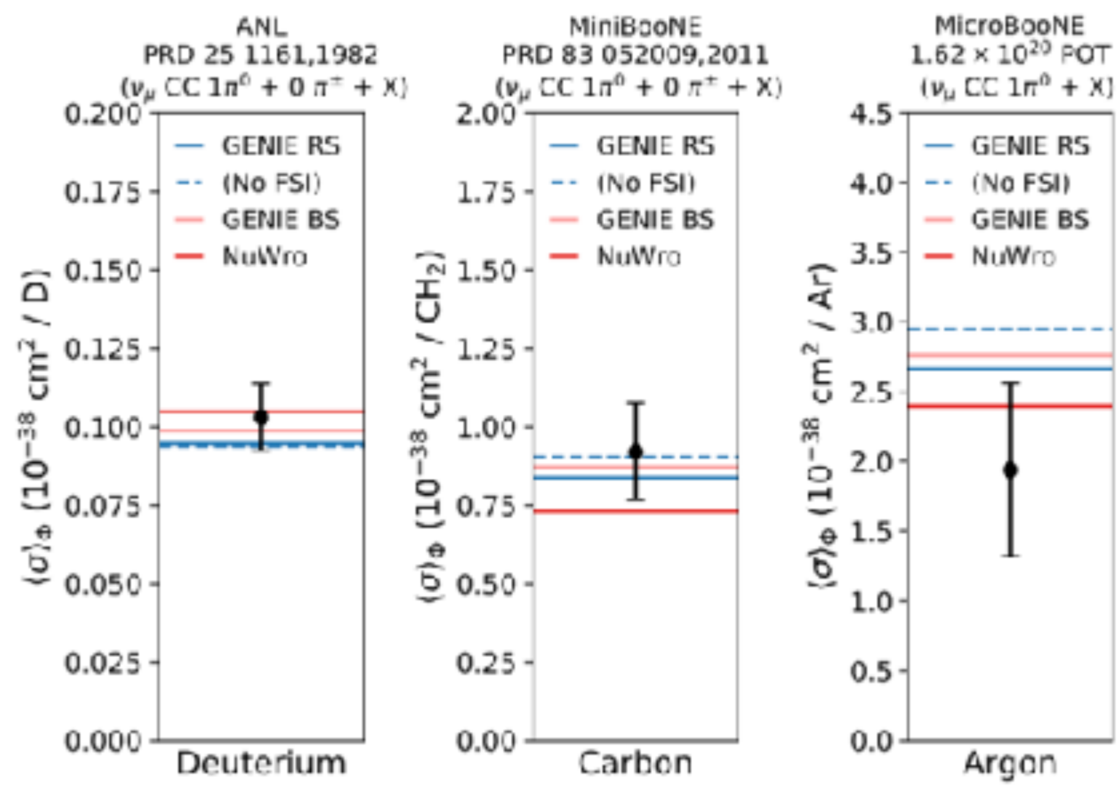
Two photon selection



At least one photon

$$\langle\sigma\rangle_\Phi = 1.9 \pm 0.2(\text{stat}) \pm 0.6(\text{syst}) \times 10^{-38}\ \frac{\text{cm}^2}{\text{Ar}}$$





Pandora Pattern Recognition

Pandora is an open project and new contributors would be extremely welcome.
We'd love to hear from you and we will always try to answer your questions.

Pandora SDK Development	John Marshall (John.Marshall@warwick.ac.uk) Mark Thomson (thomson@hep.phy.cam.ac.uk)
LAr TPC algorithm development	John Marshall (John.Marshall@warwick.ac.uk) Andy Blake (a.blake@lancaster.ac.uk)
DUNE FD Integration	Lorena Escudero (escudero@hep.phy.cam.ac.uk)
ProtoDUNE Integration	Steven Green (sg568@hep.phy.cam.ac.uk)
MicroBooNE Integration	Andy Smith (asmith@hep.phy.cam.ac.uk)
Other team members	MicroBooNE: Joris Jan de Vries, Jack Anthony ProtoDUNE: Stefano Vergani

https://github.com/PandoraPFA

https://pandorapfa.slack.com

UNIVERSITY OF CAMBRIDGE

Lancaster University

WARWICK
THE UNIVERSITY OF WARWICK