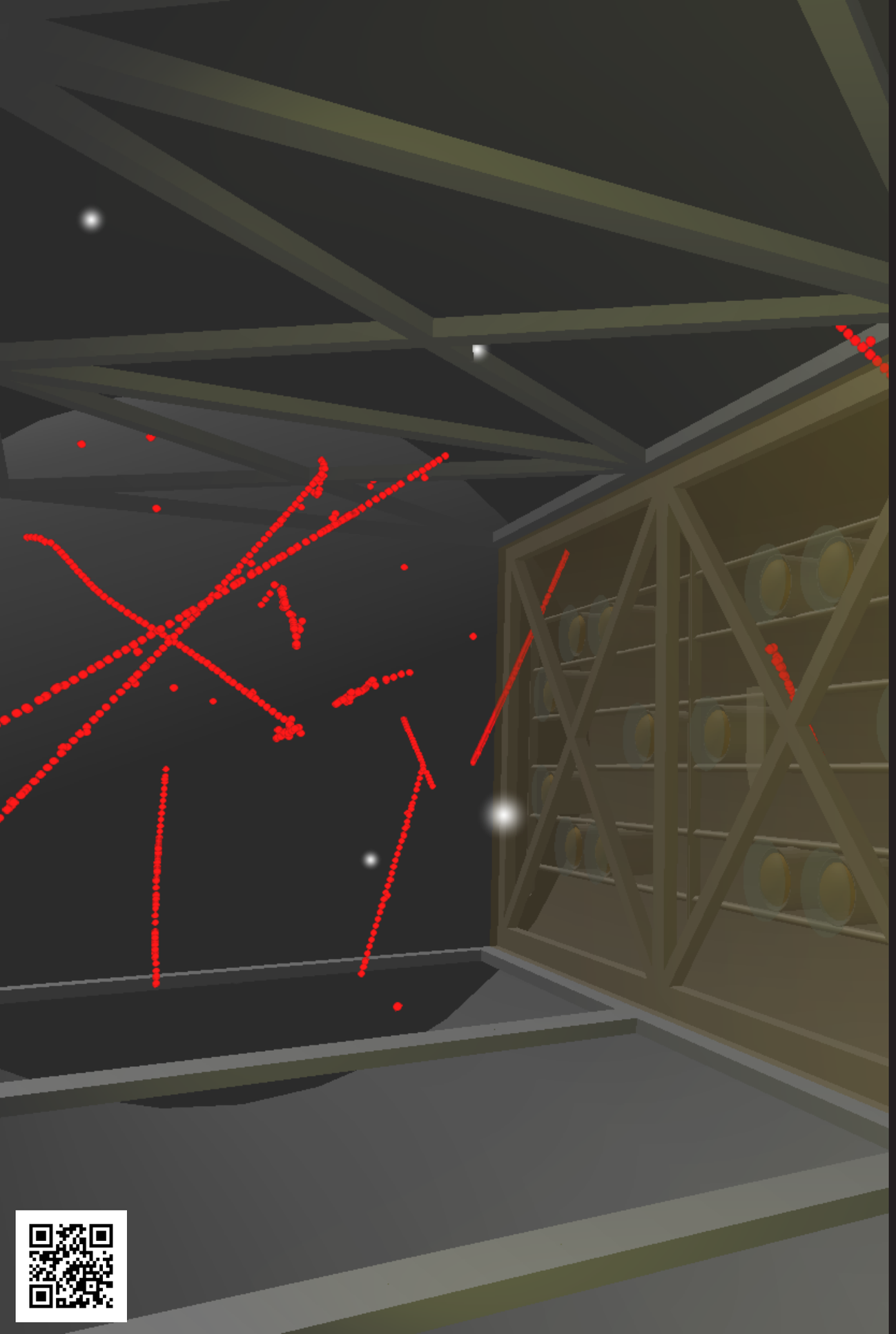


UNIVERSITY OF OXFORD

μBooNE

Cross Section Prospects for MicroBooNE

Marco Del Tutto

representing the MicroBooNE collaboration

NUFACT2017

26th September 2017

Introduction

PAST

1970-1990's

Using deuterium-filled bubble chambers:

- to test the V-A nature of the weak interactions
- to measure the axial vector form factor of the nucleon

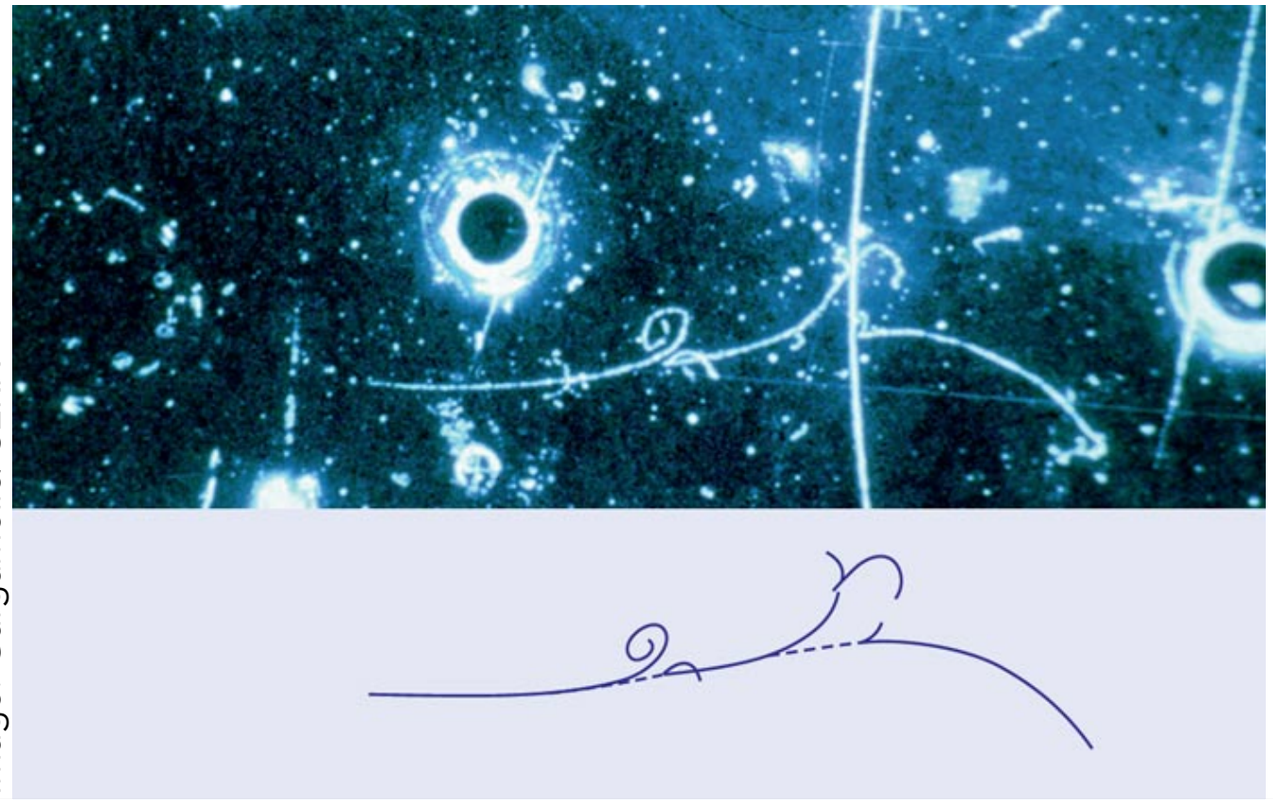


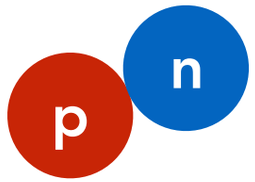
Image: Gargamelle/CERN

Introduction

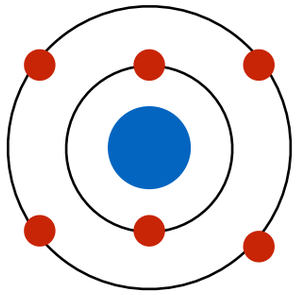
TODAY

Modern experiments no longer include deuterium but use complex nuclei as their neutrino targets

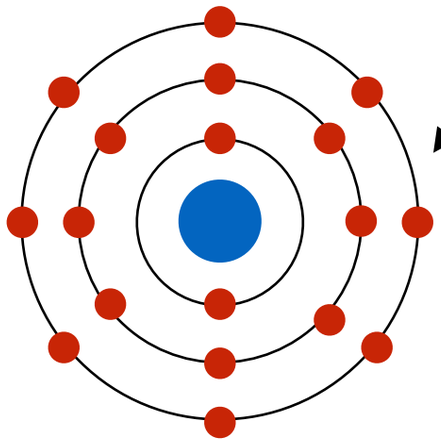
For heavy elements nuclear effects are not understood -> more data is needed



Deuterium



Carbon



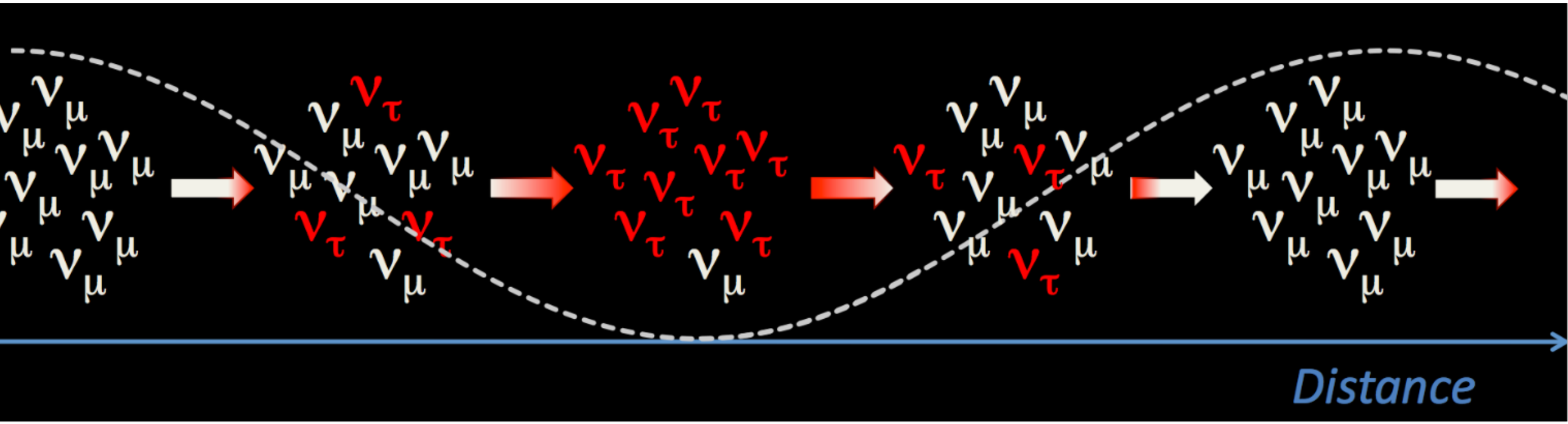
Argon

Introduction

TODAY

Modern experiment are trying to make precision measurements of neutrino oscillation parameters, requiring precise and accurate cross section measurements

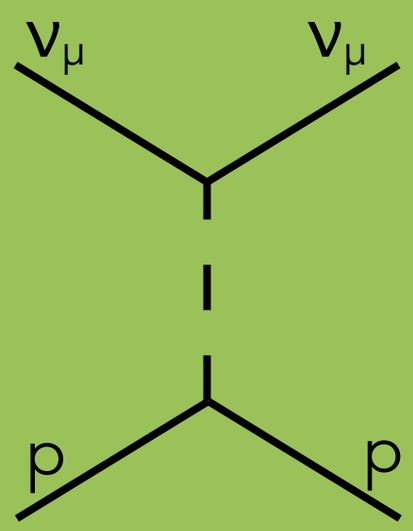
MicroBooNE also has an oscillation programme:
see talk by Xiao Luo in the WG1+WG2 session today



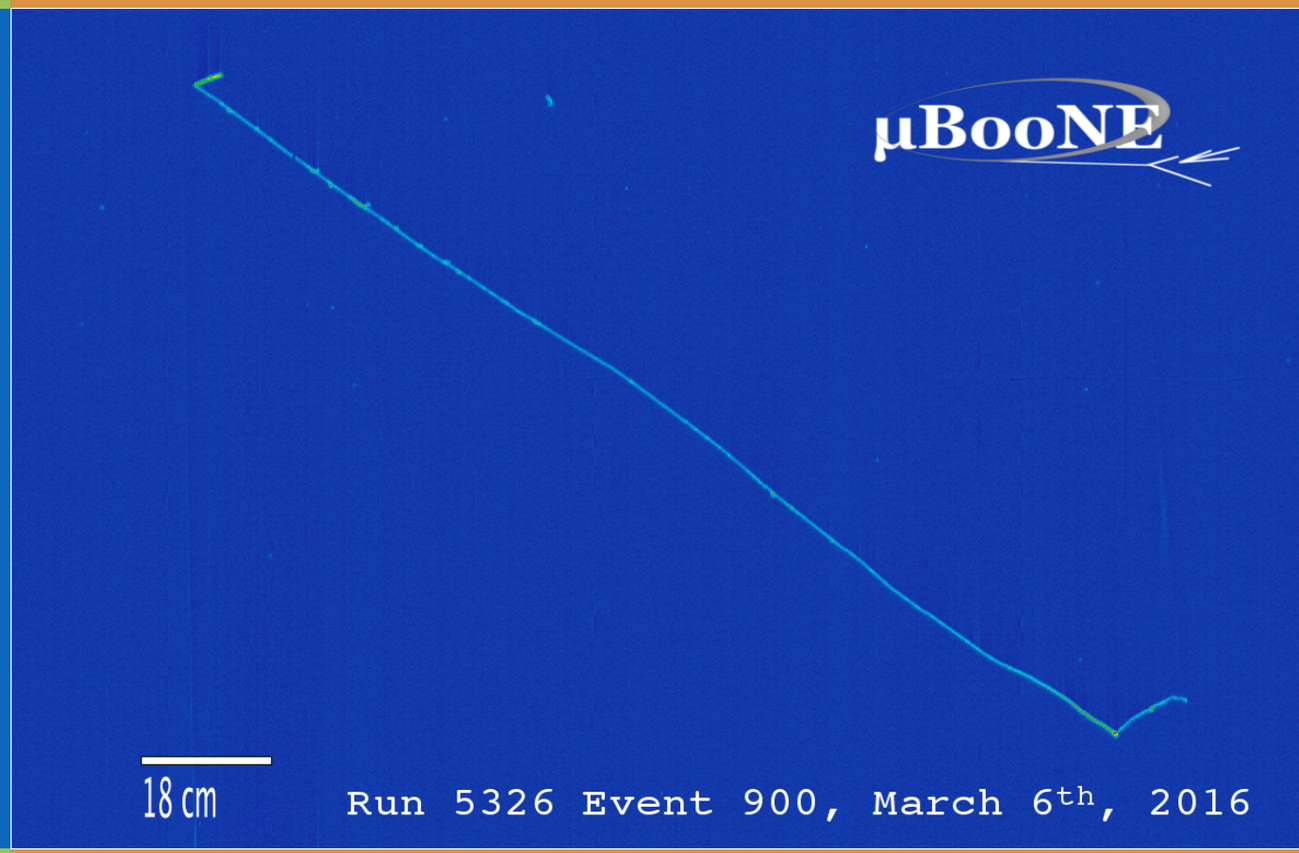
Outline

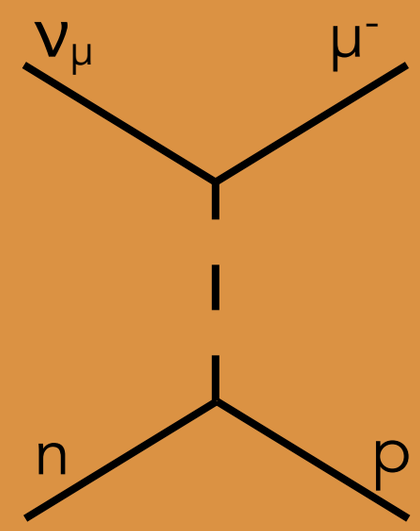
- **CC0π events**
  - a quick look at results from other experiments
- **LArTPC/MicroBooNE**
  - how it works
  - event reconstruction
  - how it compares to other experiments
- **MicroBooNE CC Inclusive Analysis**
- **Particle Multiplicity and Proton Identification**
  - ArgoNeuT results
  - MicroBooNE analyses

Neutral Current

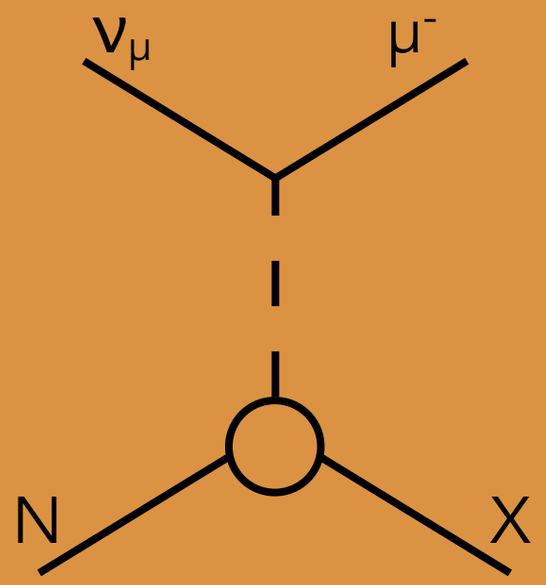


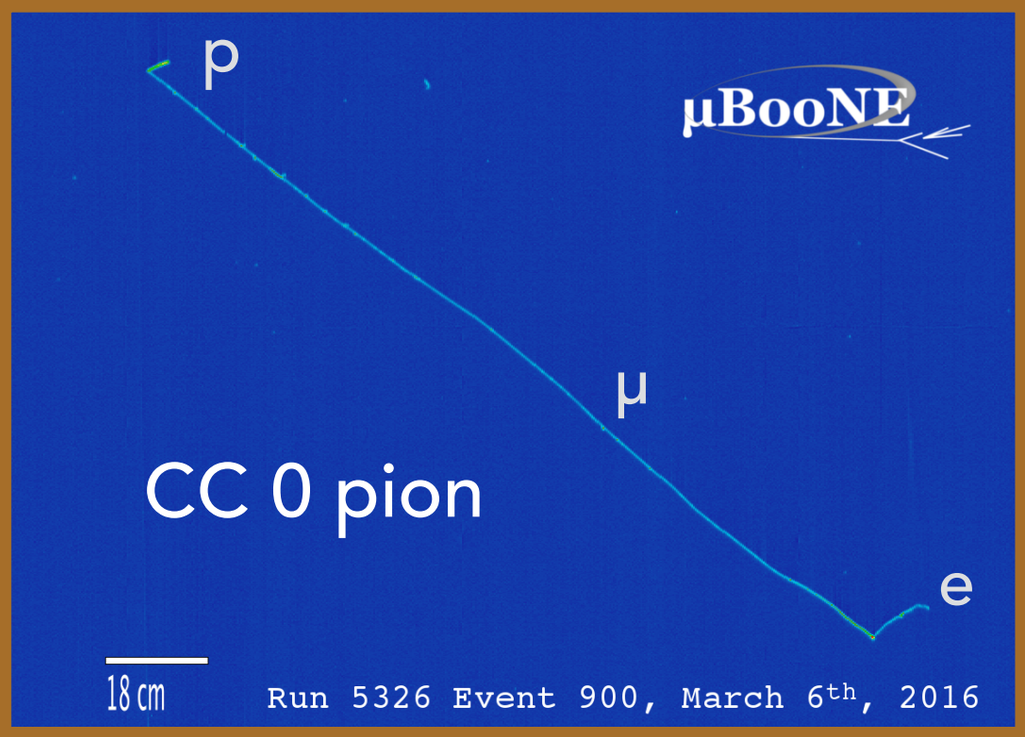
Charged Current

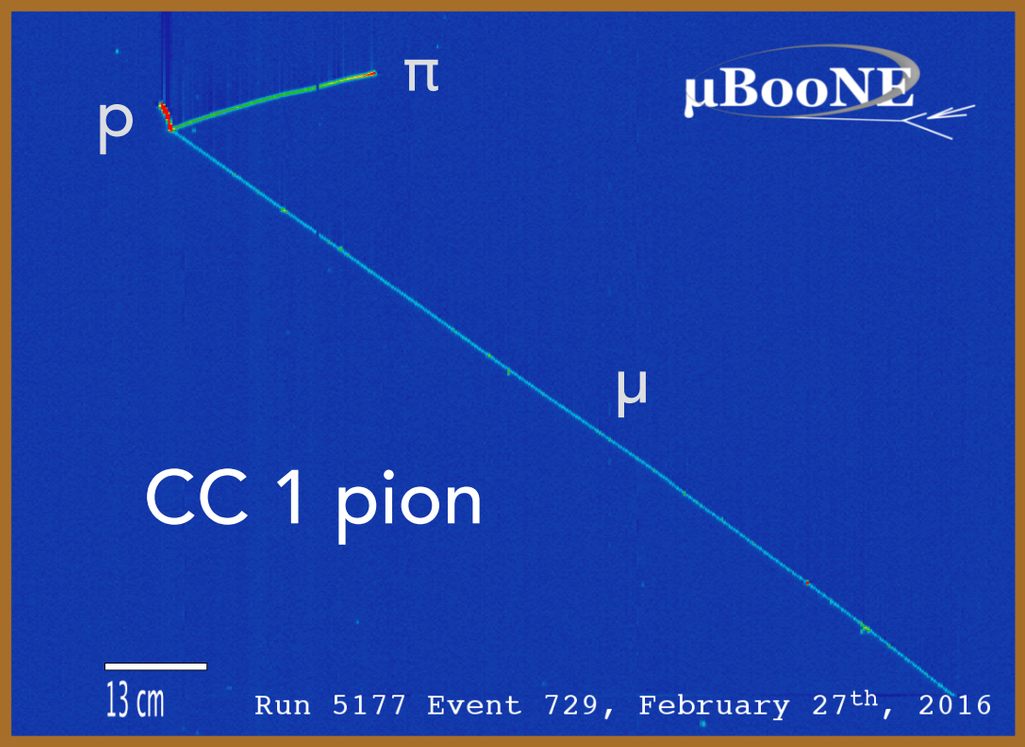




Charged Current

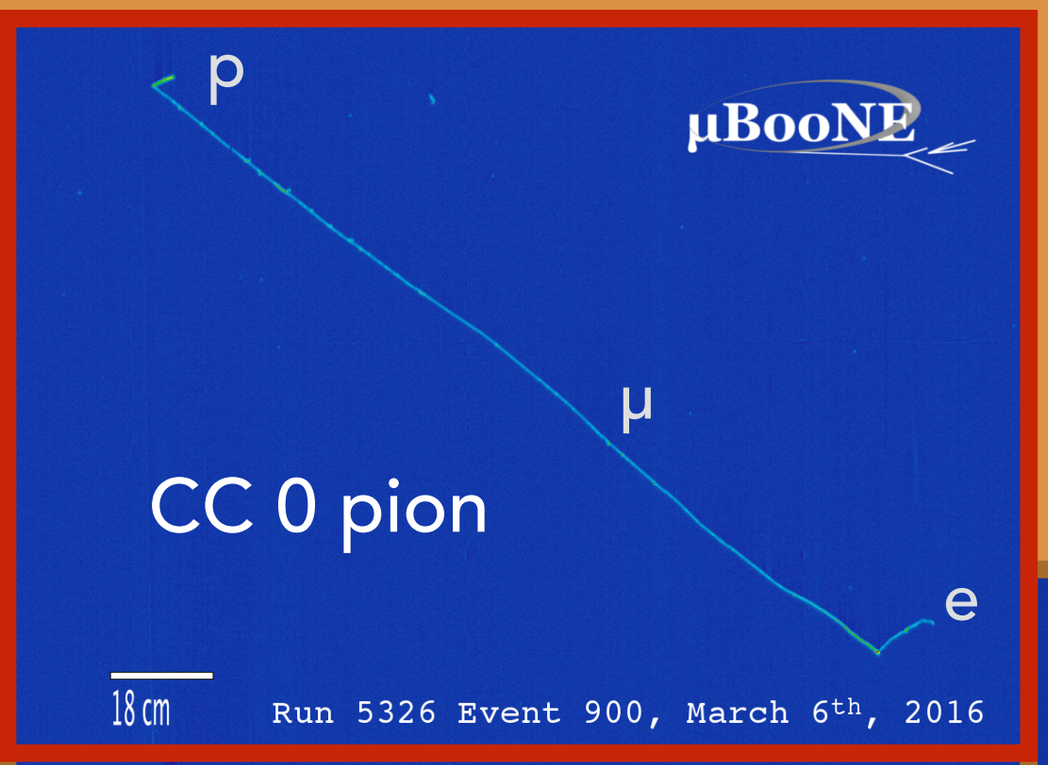


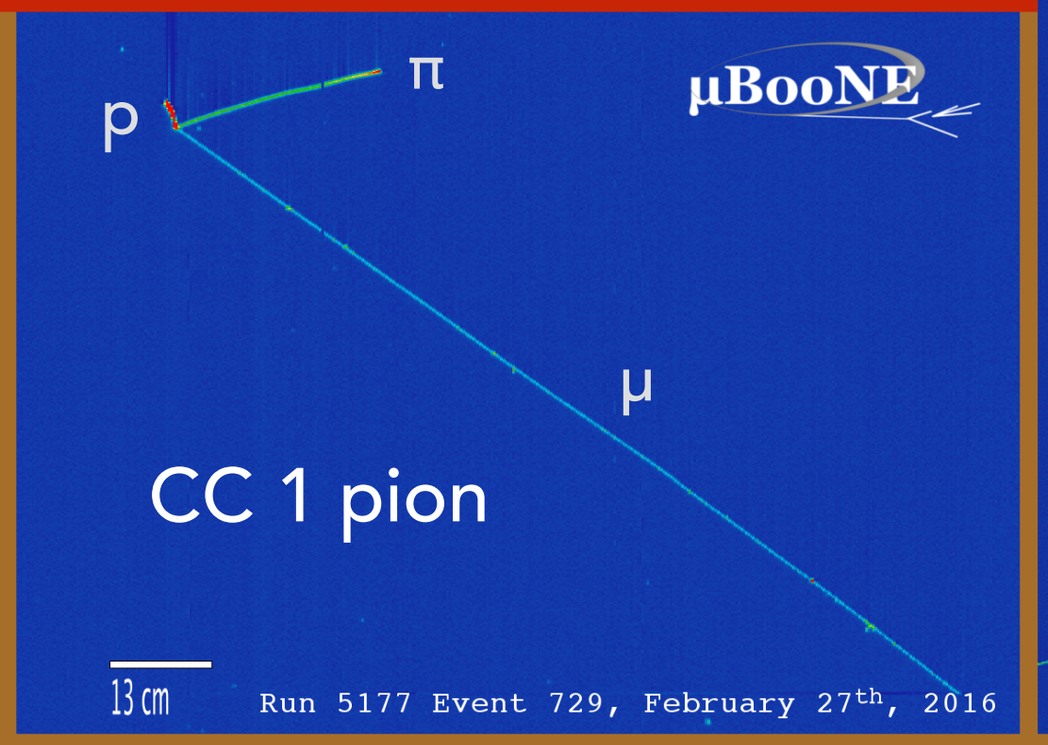


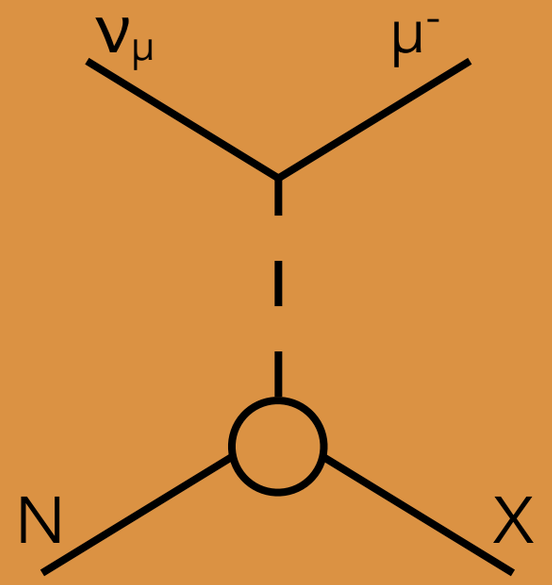


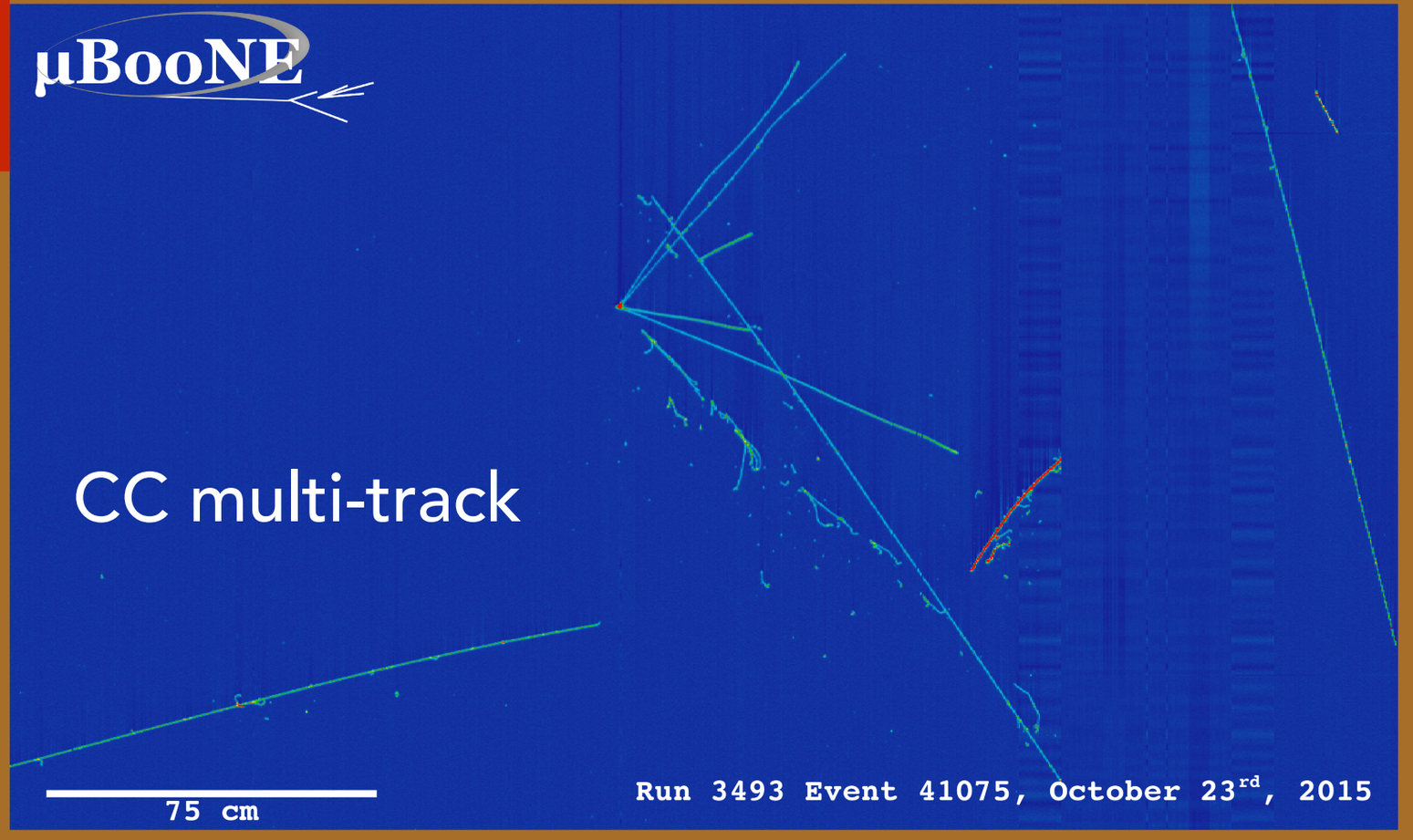
Now Focusing on CC0π

Charged Current

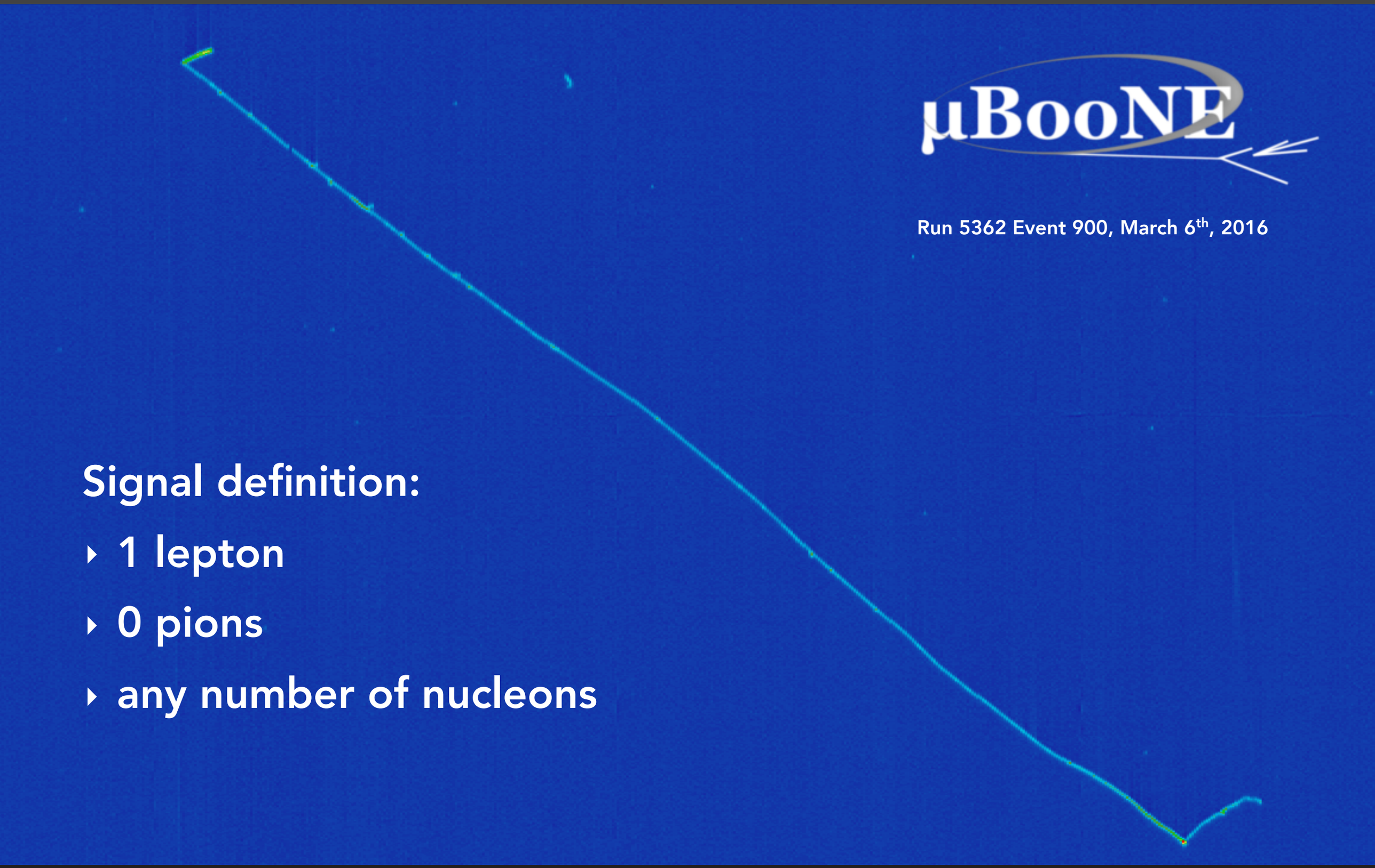








CC0π Interactions

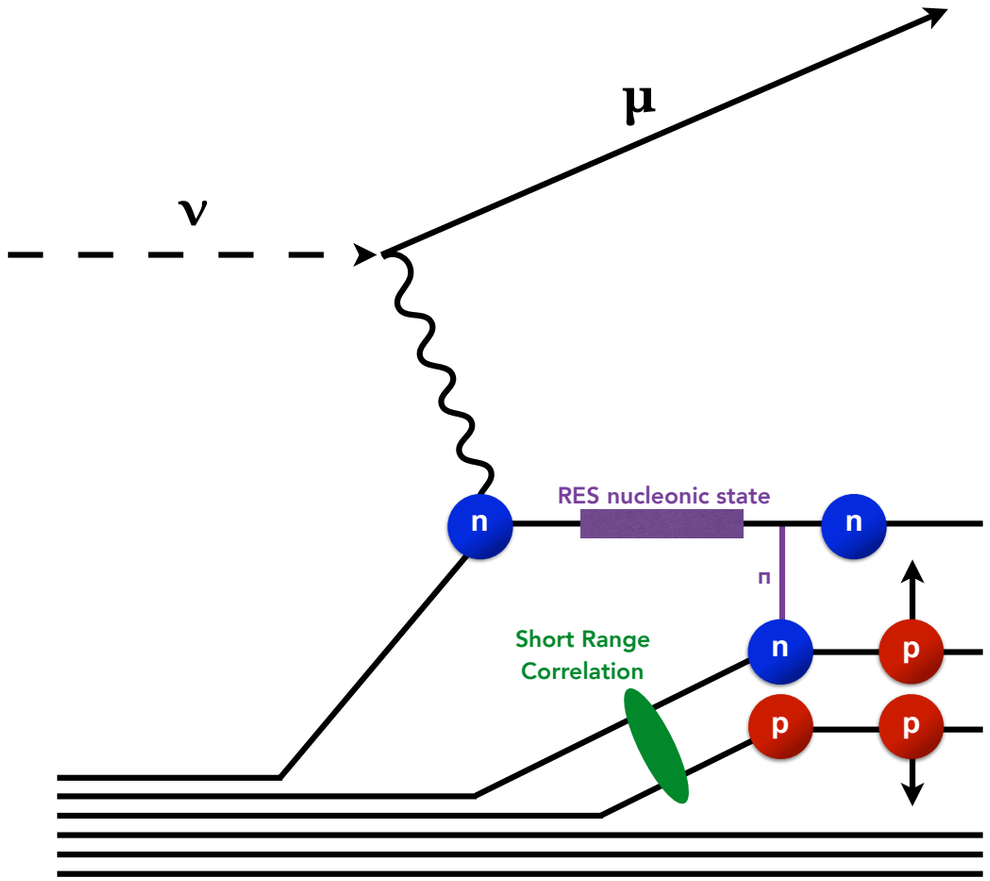


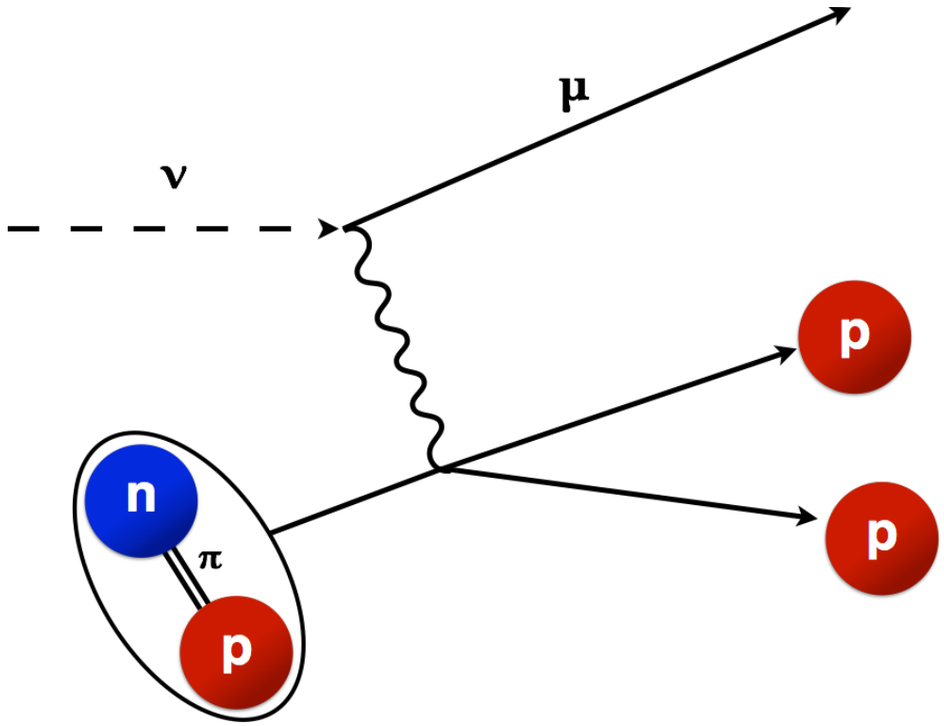
Signal definition:

- 1 lepton
- 0 pions
- any number of nucleons

CC0π Interactions

Nuclear Effects





- Final state is different from the “traditional quasi-elastic final state” with 1μ1p
- Need a detector that can resolve hadrons: can be done in LAr

CC0π - Recent Experimental Results

MiniBooNE

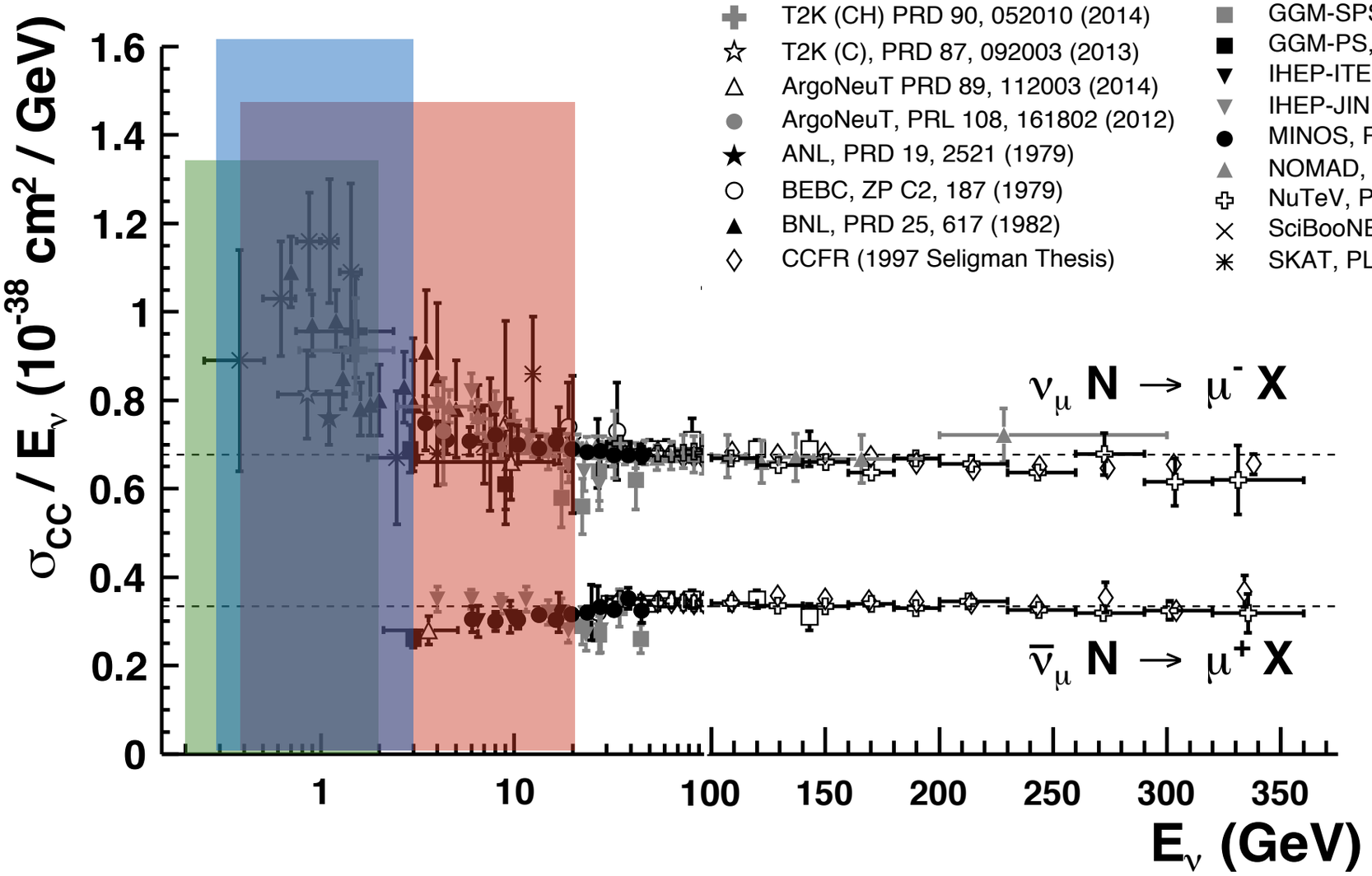
CH_2

MINERvA

CH

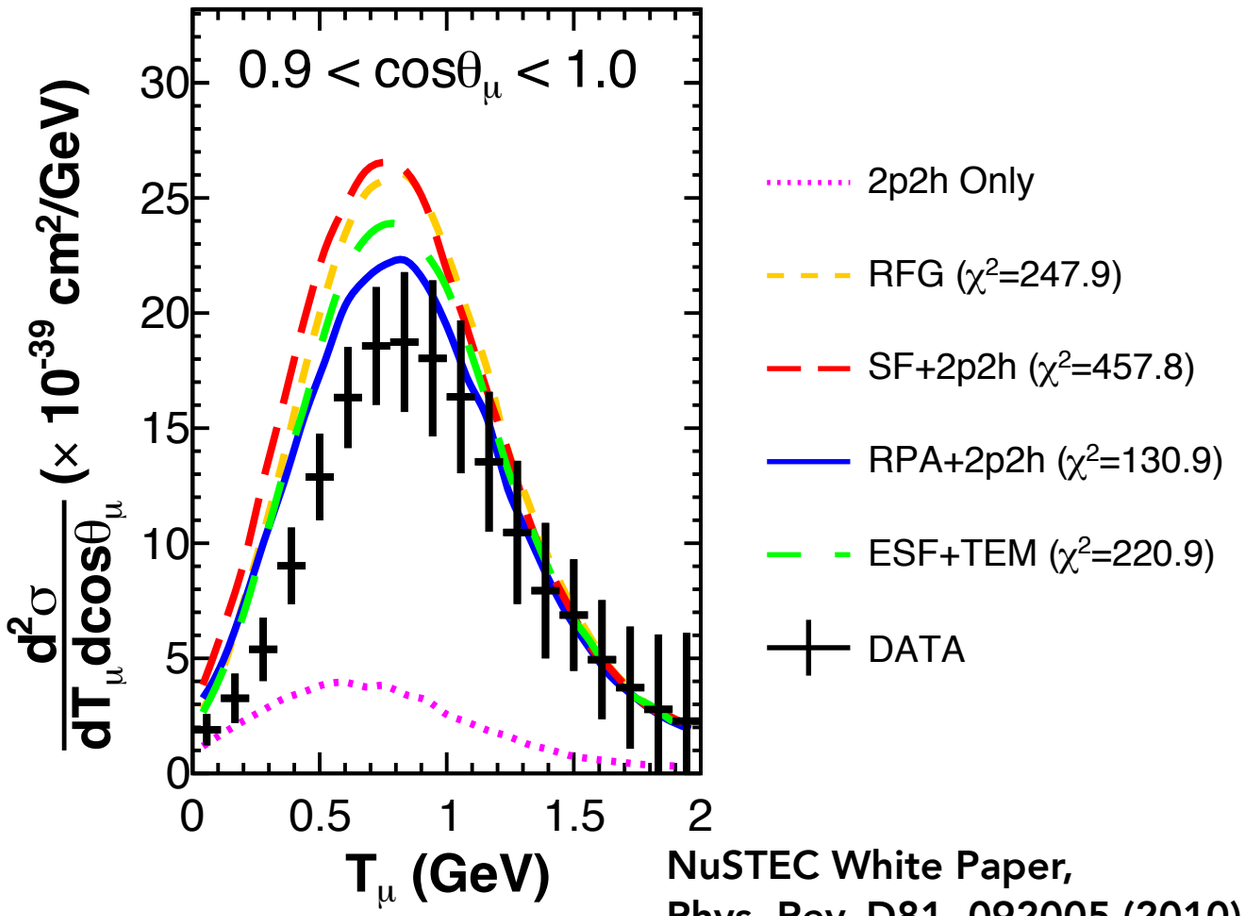
T2K

CH



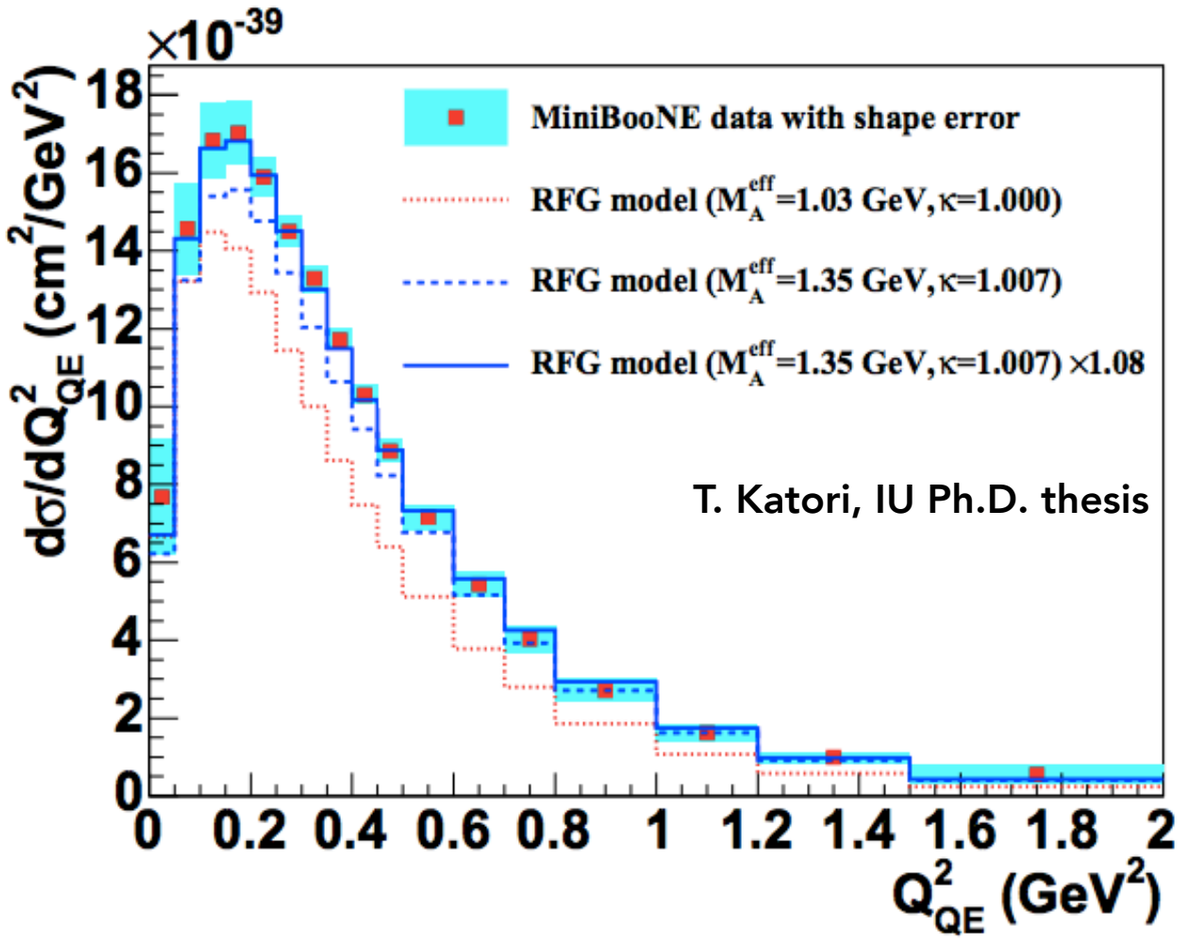
CC0π - Recent Experimental Results

MiniBooNE



NuSTEC White Paper,
Phys. Rev. D81, 092005 (2010)

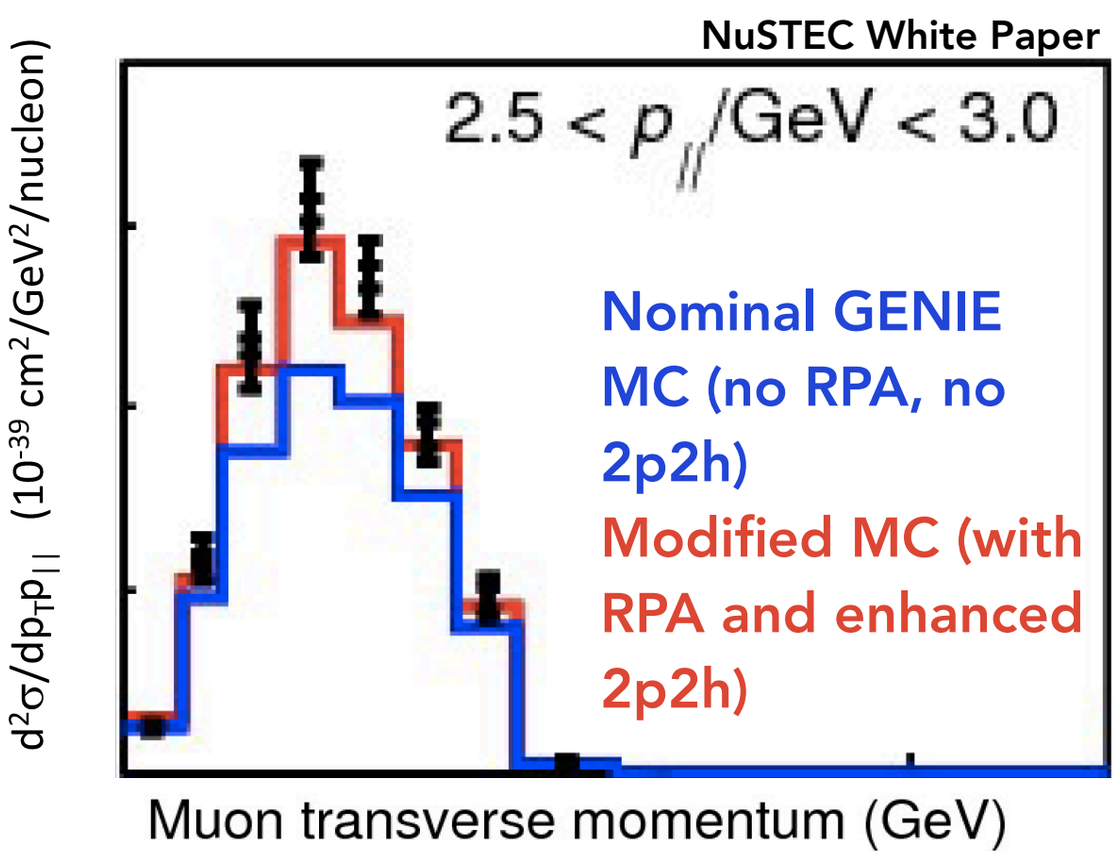
MiniBooNE data agree well with predictions that include both 2p2h and RPA



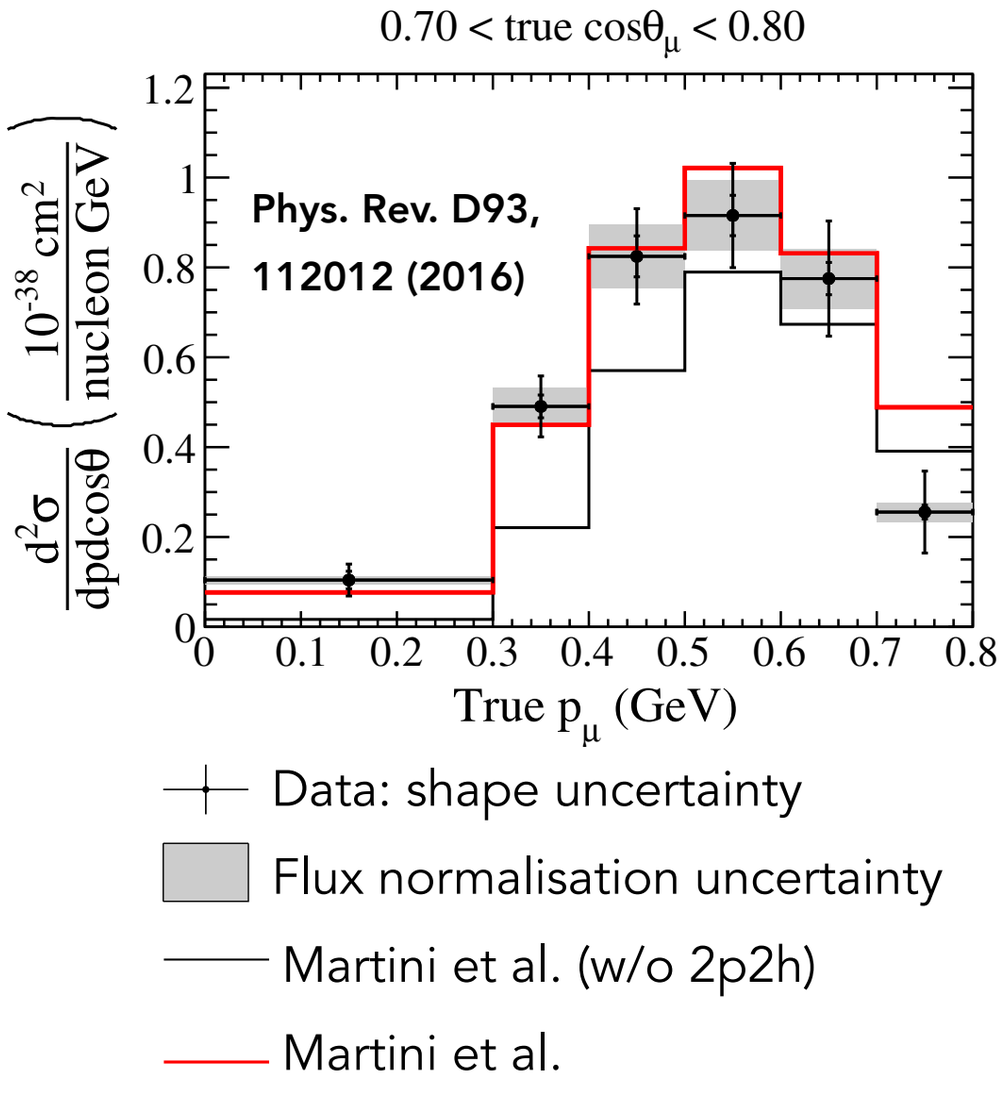
MiniBooNE data agree with an effective value of M_A = 1.35 GeV

CC0π - Experimental Results

MINERvA



T2K

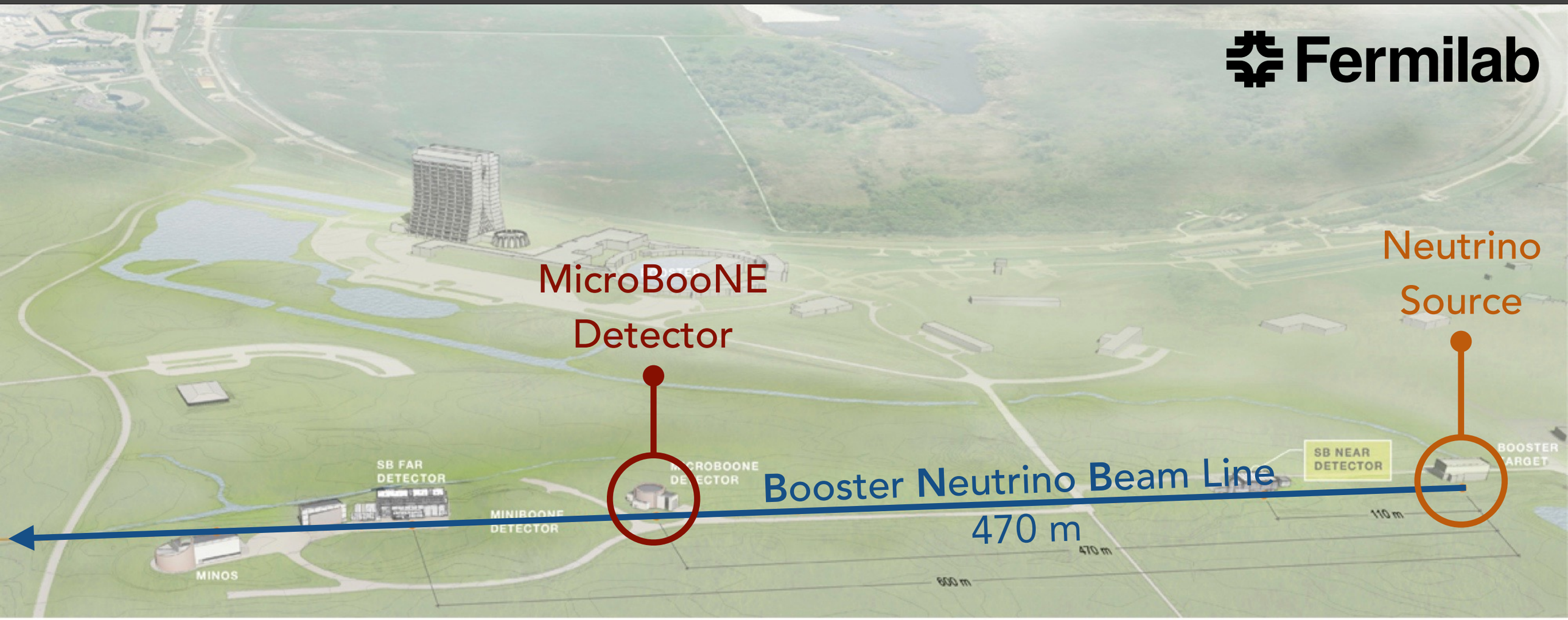


MINERvA and T2K data agree with simulations that include multinuclear processes

What Next?

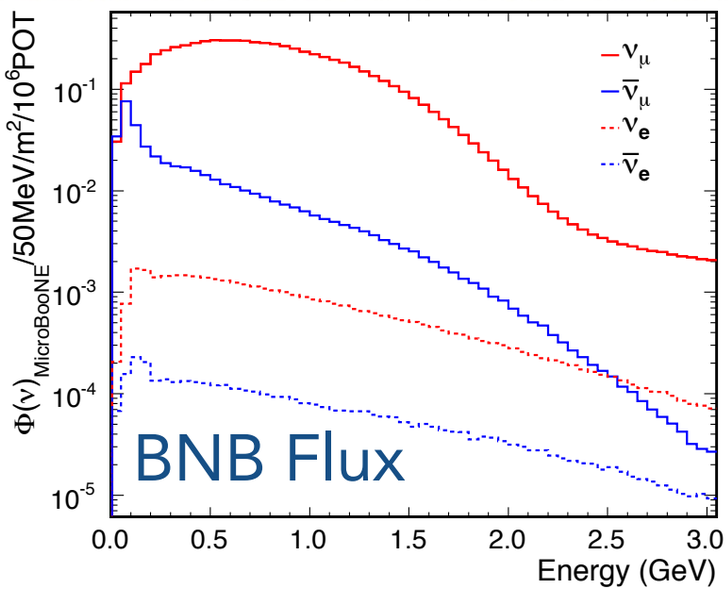
- How do we further tune theory models?
- How is the situation going to look like for argon?
- Can MicroBooNE tell us more about final states and nuclear effects?

The MicroBooNE Experiment



Goals of the **S**hort **B**aseline **N**eutrino program:

- low-energy excess observed by MiniBooNE
- sterile neutrinos
- cross section measurements
- R&D for future LArTPC experiments

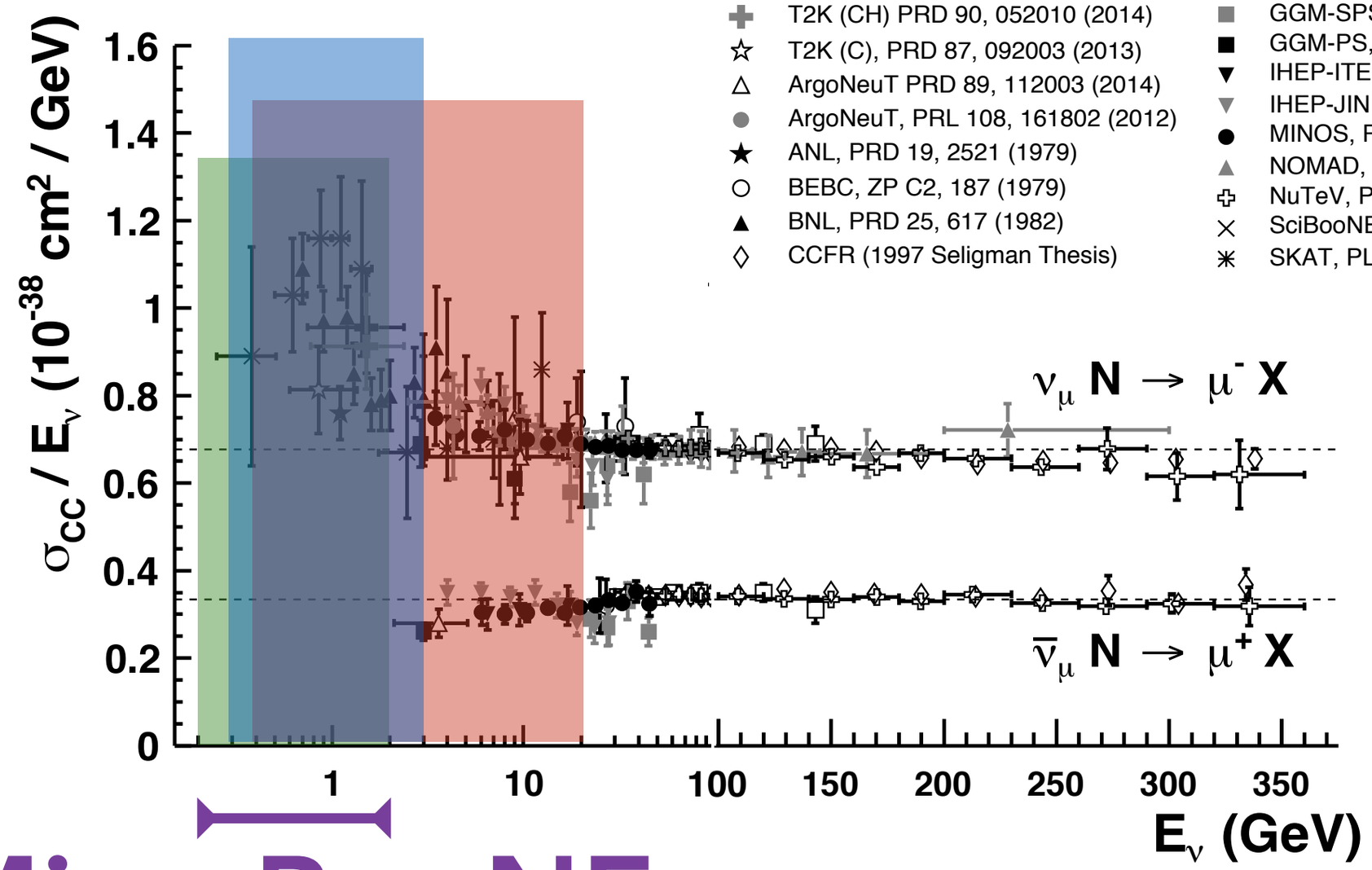


The MicroBooNE Experiment

MiniBooNE

MINERvA

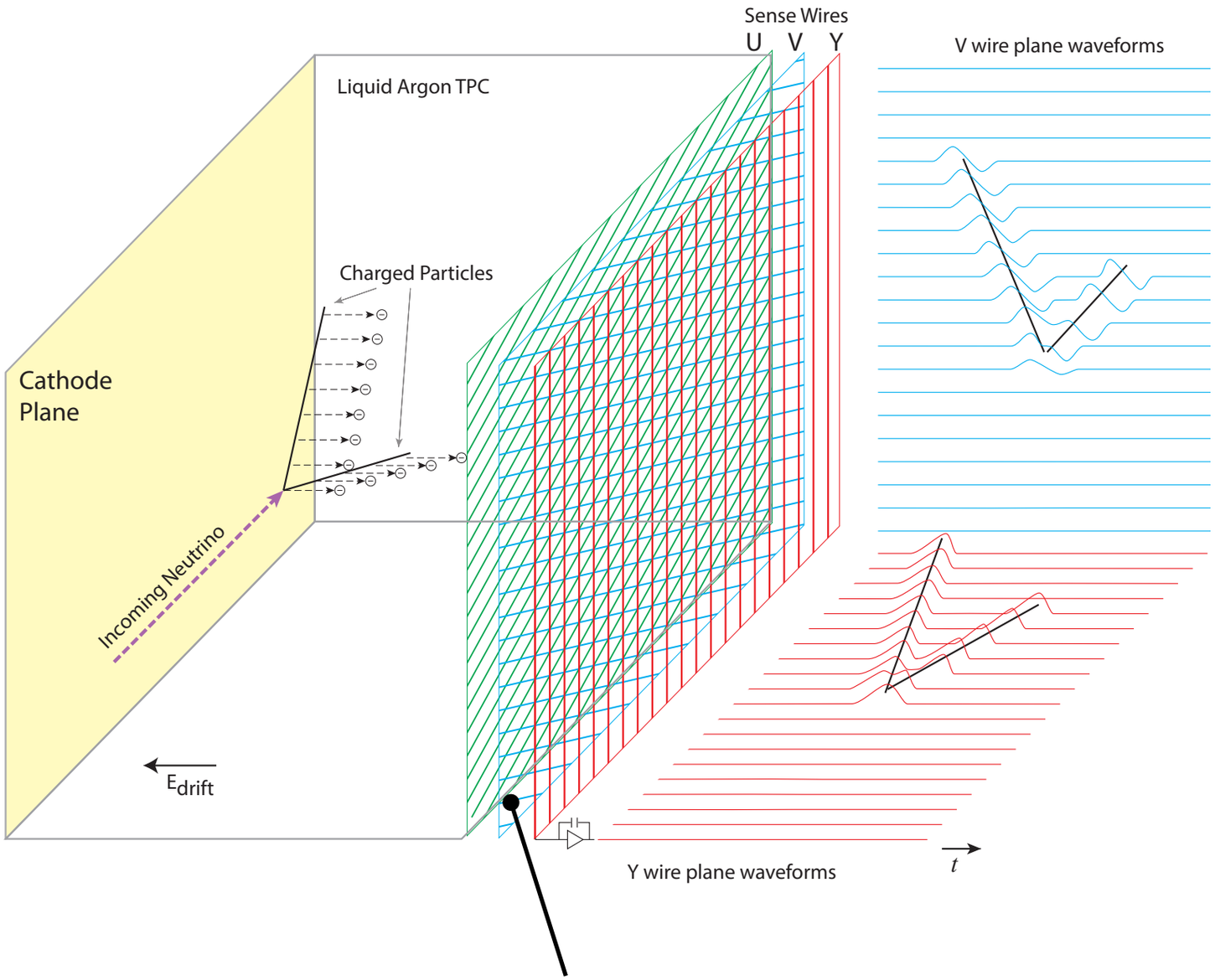
T2K

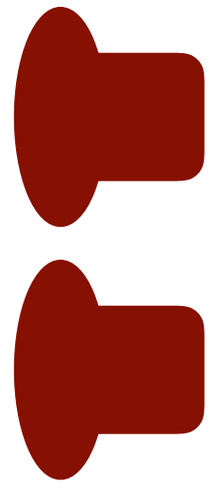


MicroBooNE

The MicroBooNE Detector

A liquid argon time projection chamber



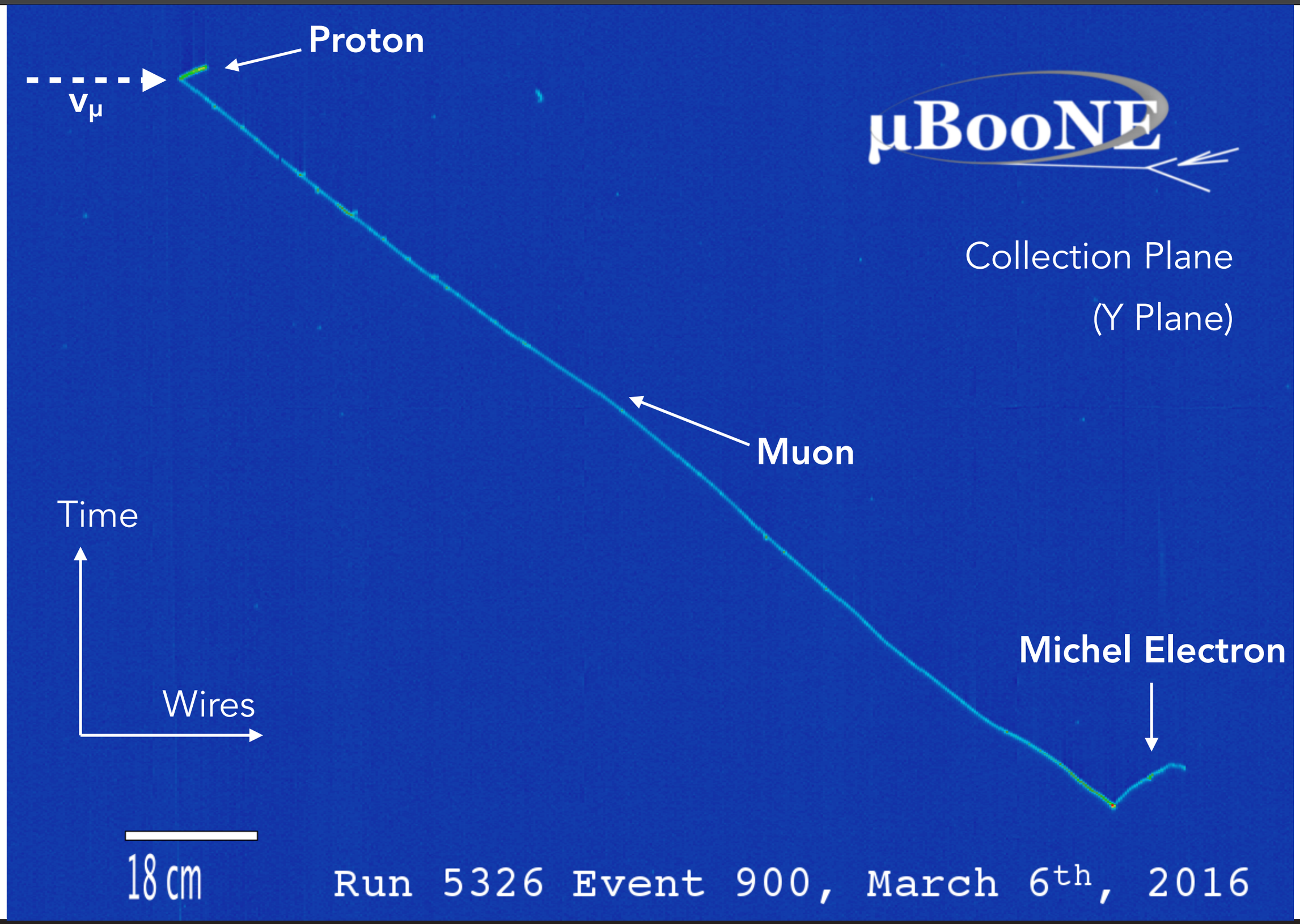


32 8″ Cryogenic PMTs

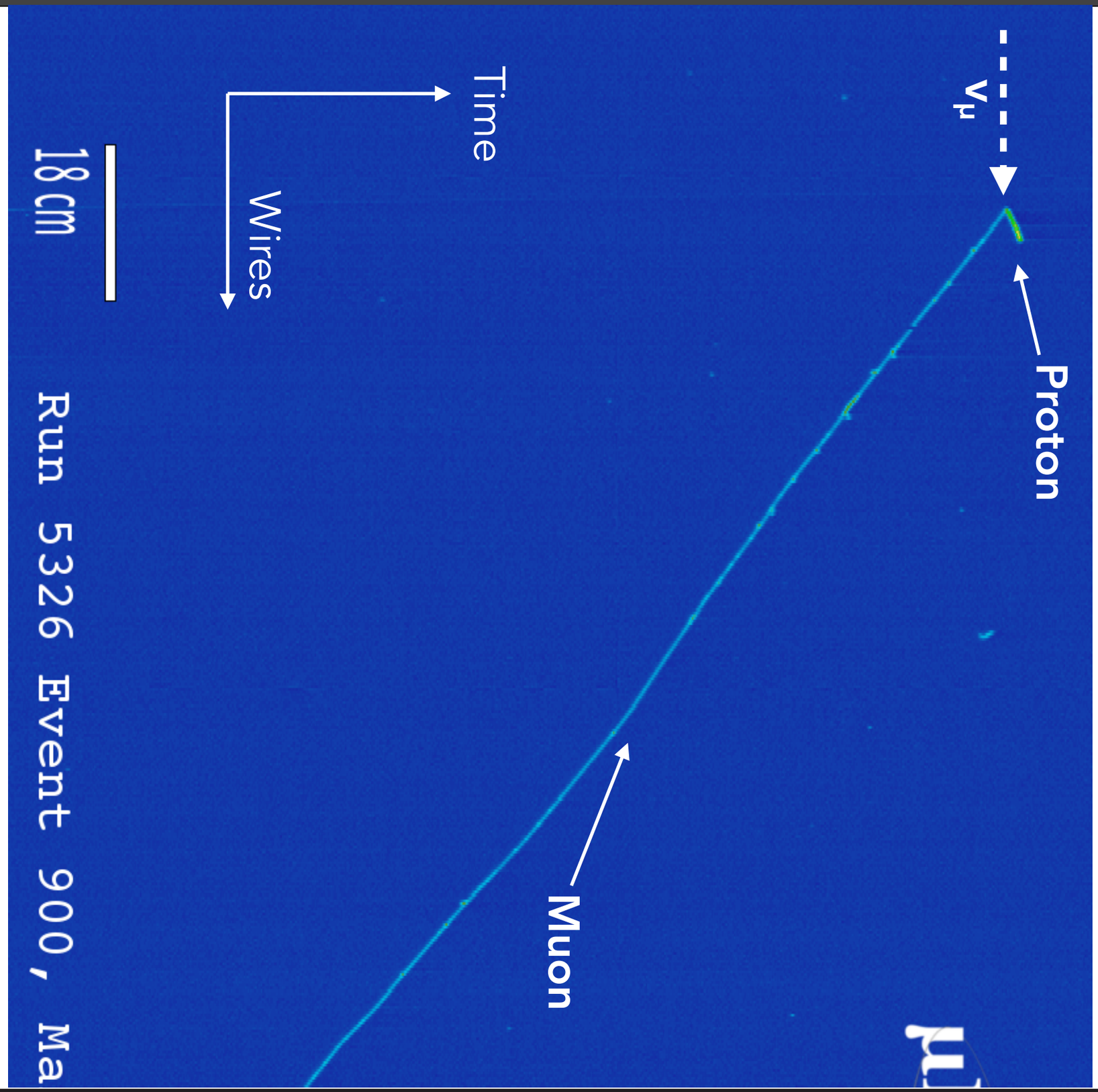
8192 wires (3 mm pitch)

170 ton LArTPC (total mass)

A MicroBooNE Event Display

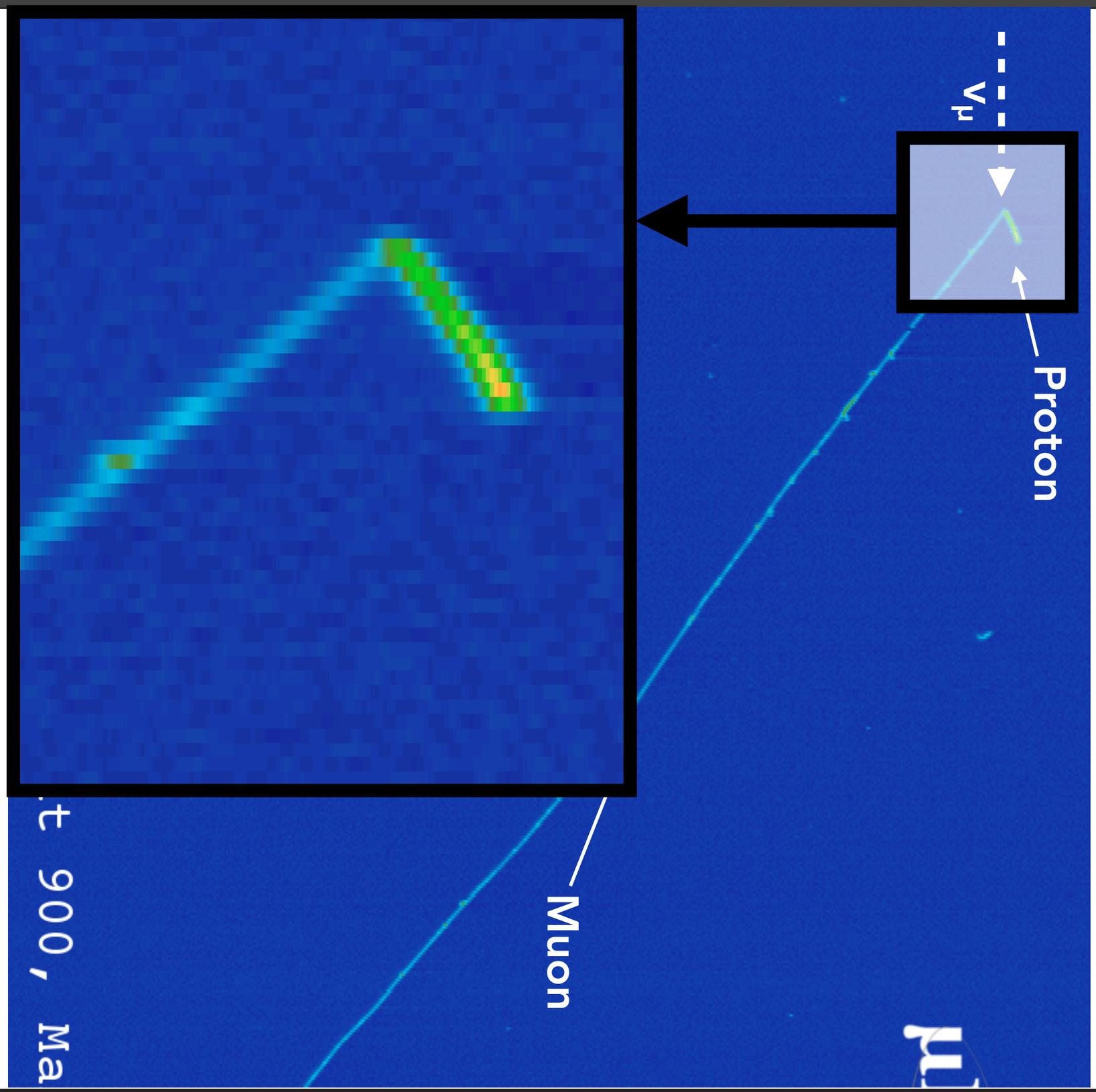


MicroBooNE Event Reconstruction



Same image, rotated by 90°

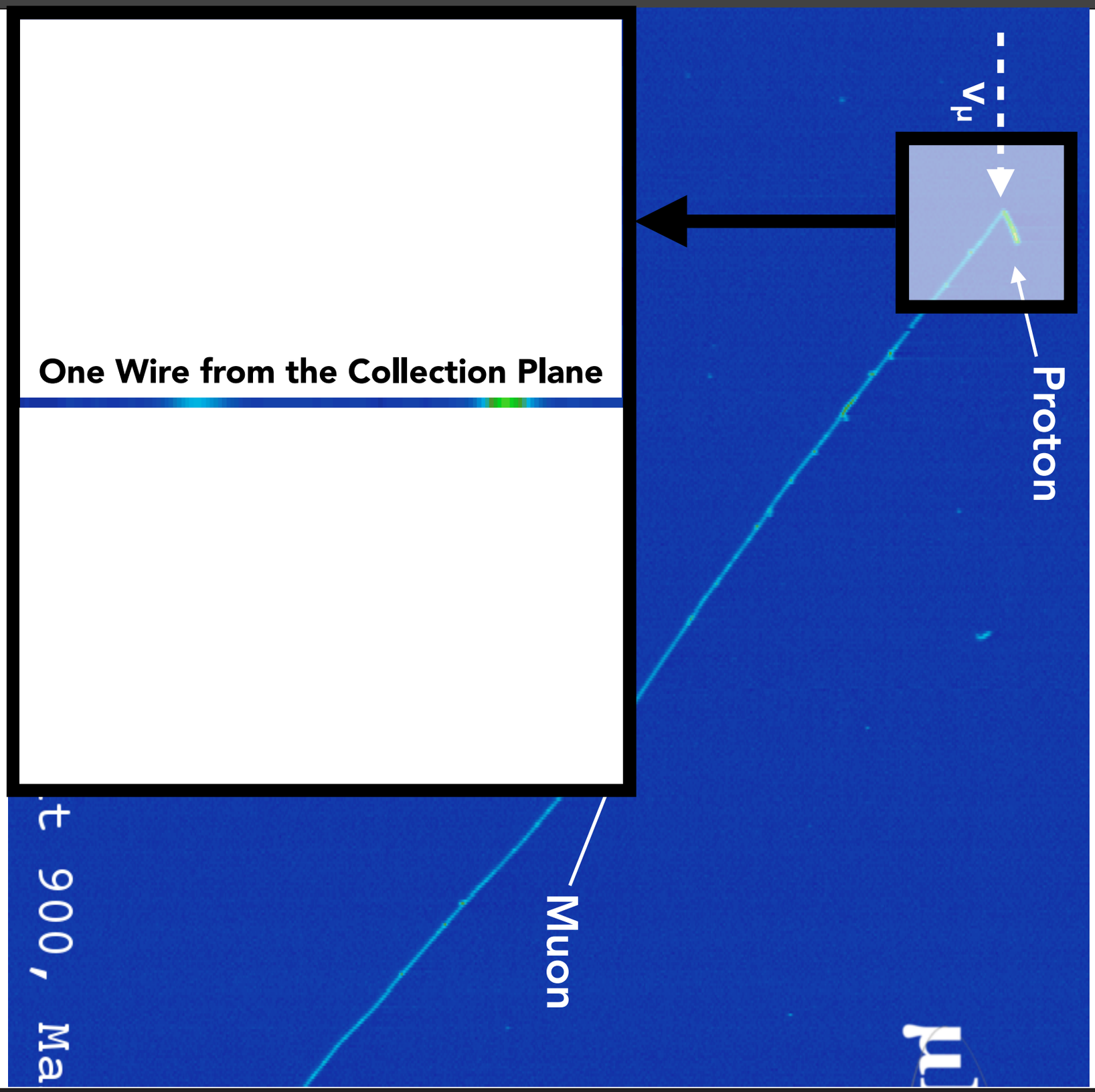
MicroBooNE Event Reconstruction



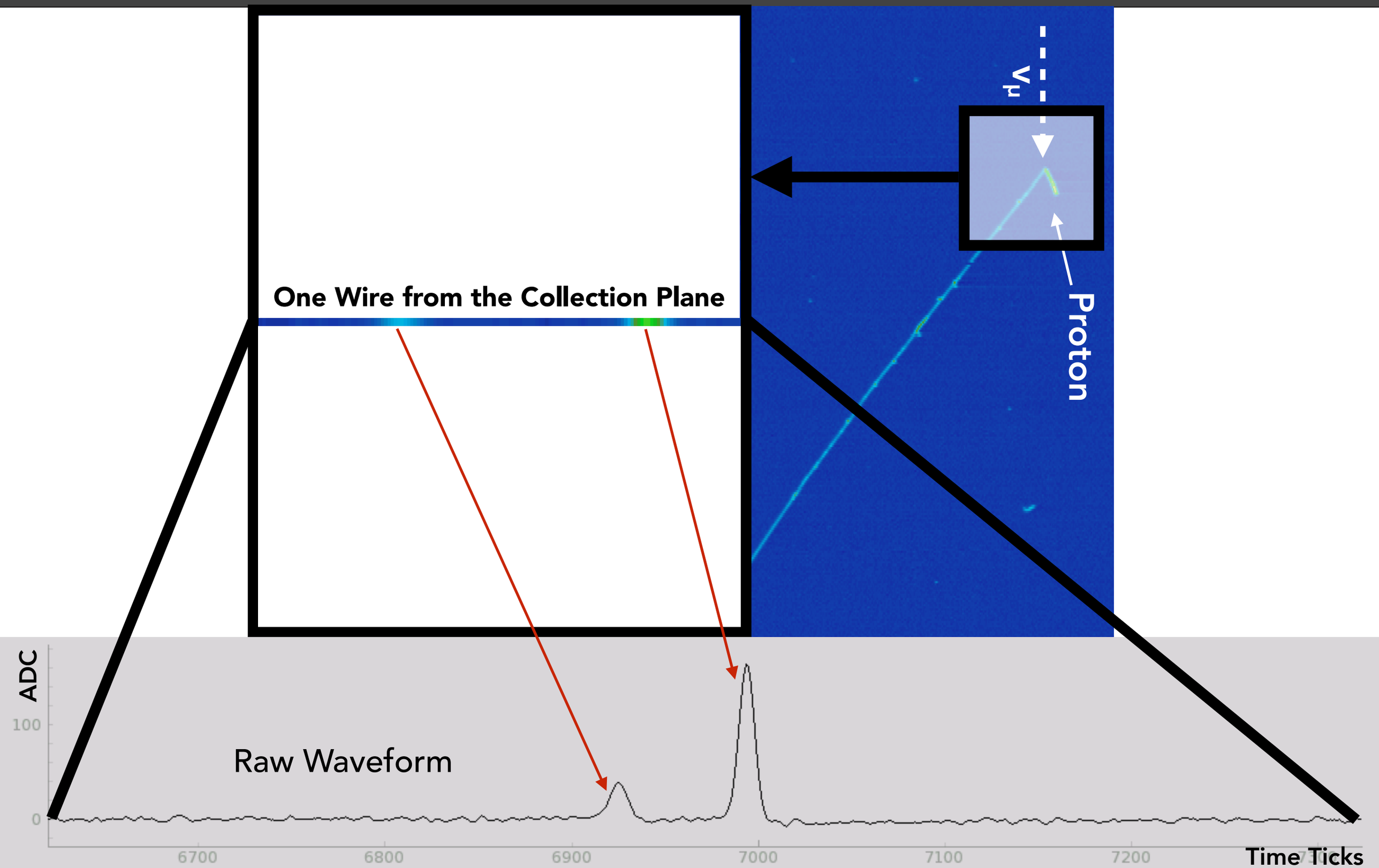
Zoom in

Colour shows amount of deposited charge

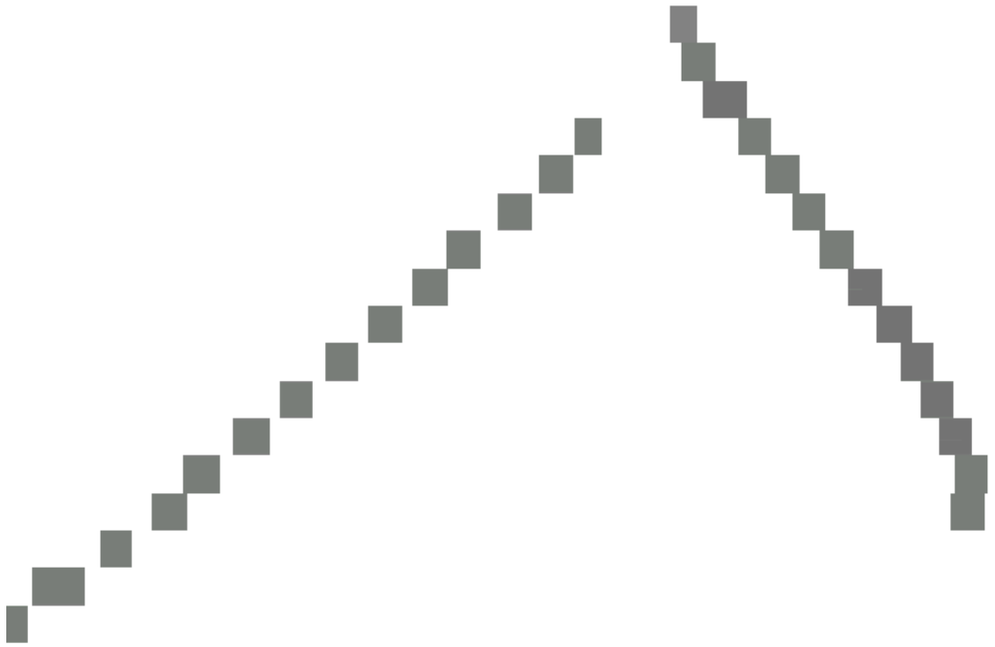
MicroBooNE Event Reconstruction



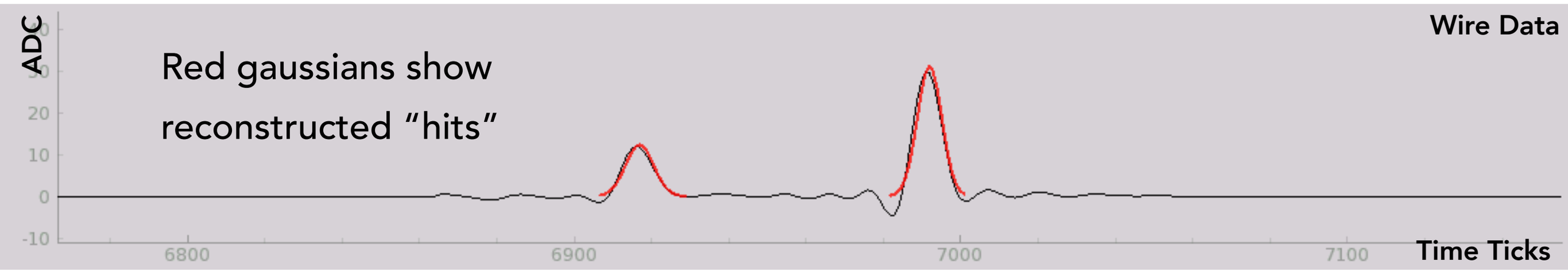
MicroBooNE Event Reconstruction



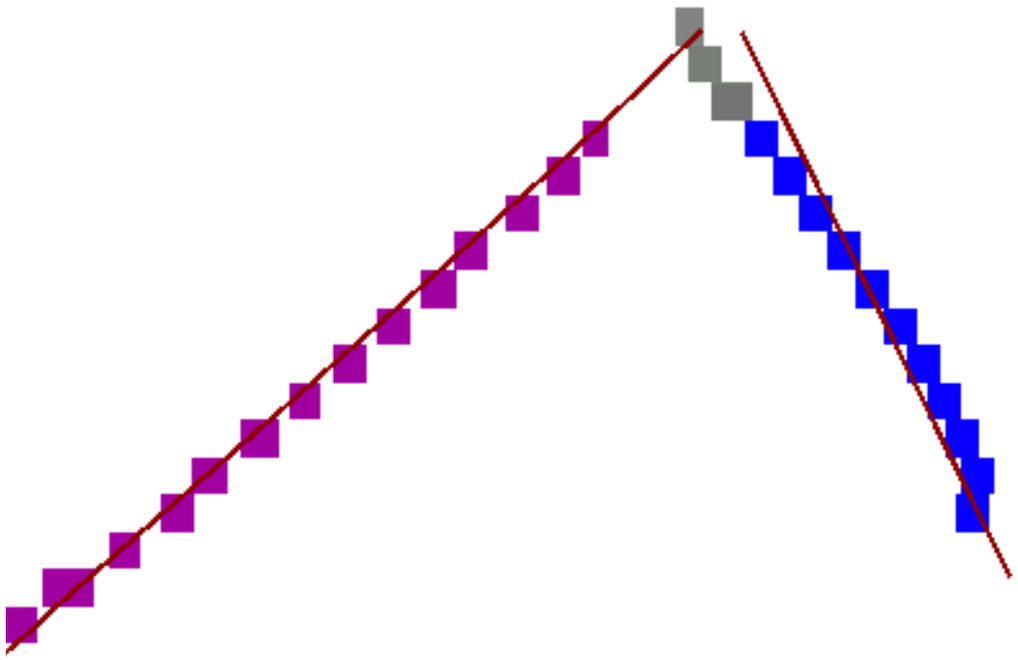
MicroBooNE Event Reconstruction



Each **hit** correspond to a wire, and has a specific time.
The area below the gaussian is proportional to the **deposited charge**, and from this we can derive the particle **dE/dx**.

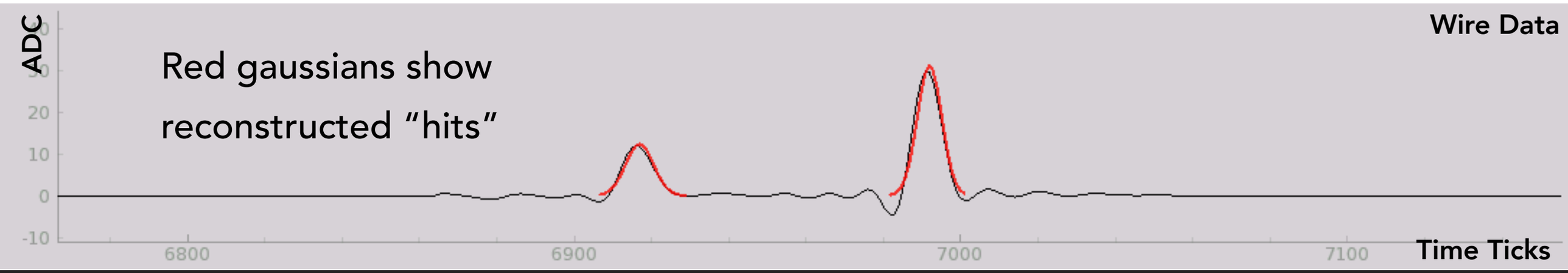


MicroBooNE Event Reconstruction

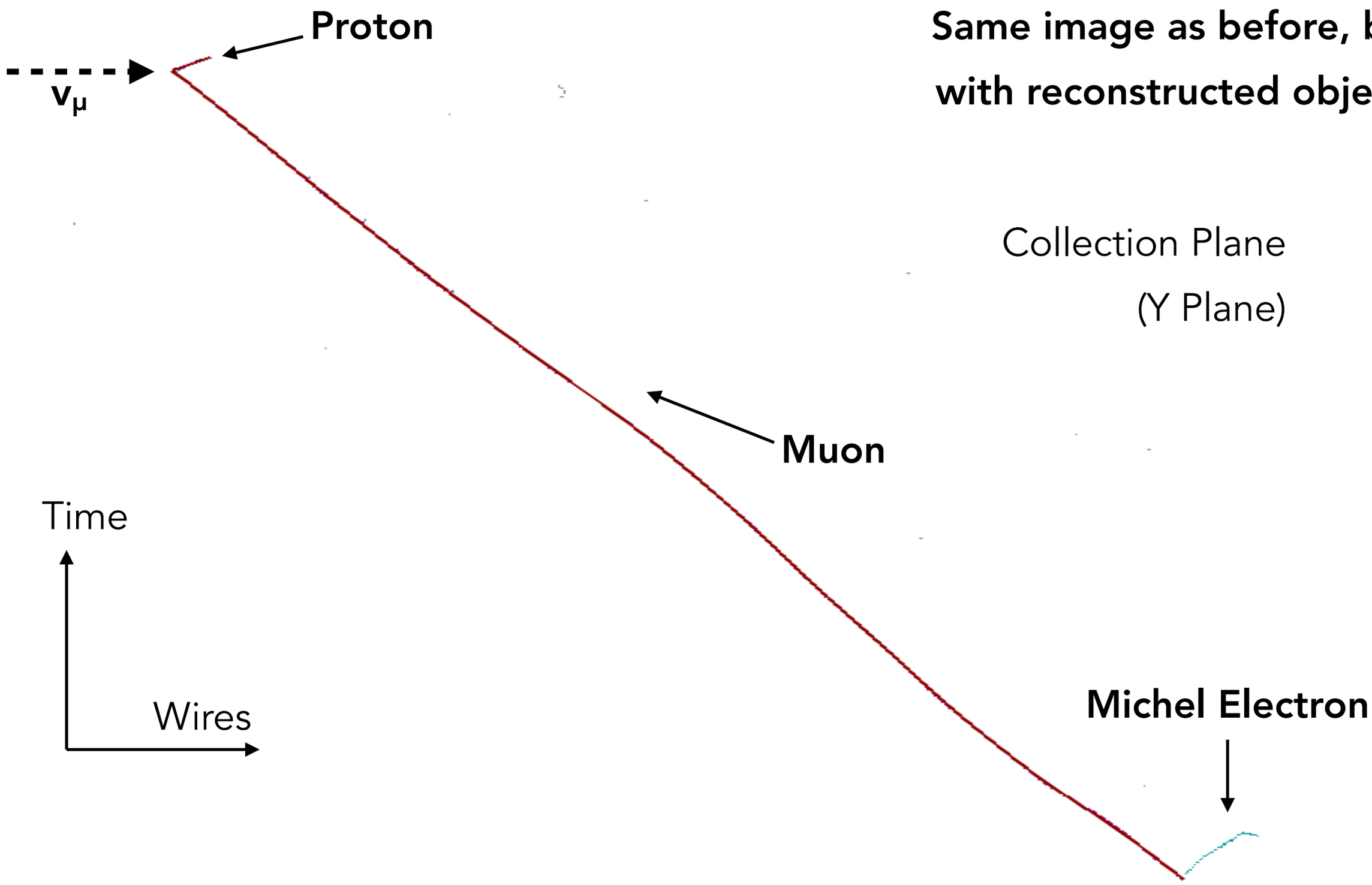


Hit Clustering and

Track Fitting



MicroBooNE Event Reconstruction



Same image as before, but with reconstructed objects

Collection Plane

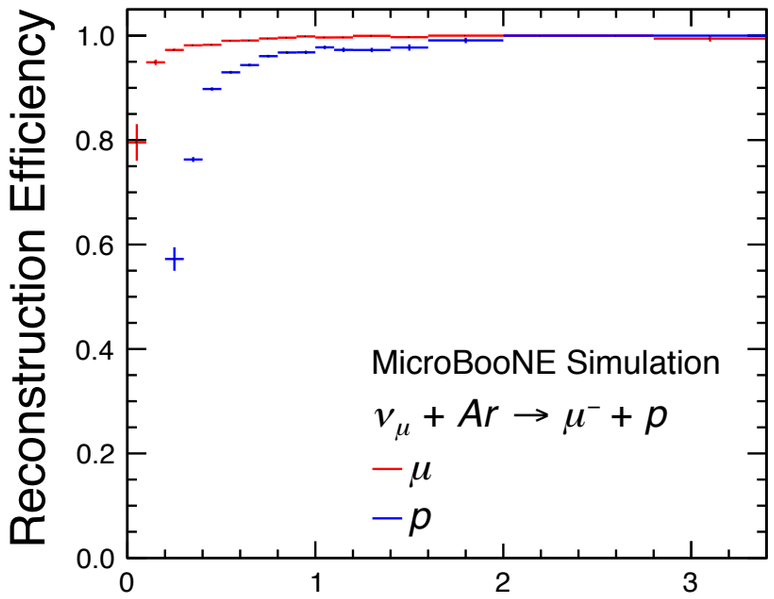
(Y Plane)

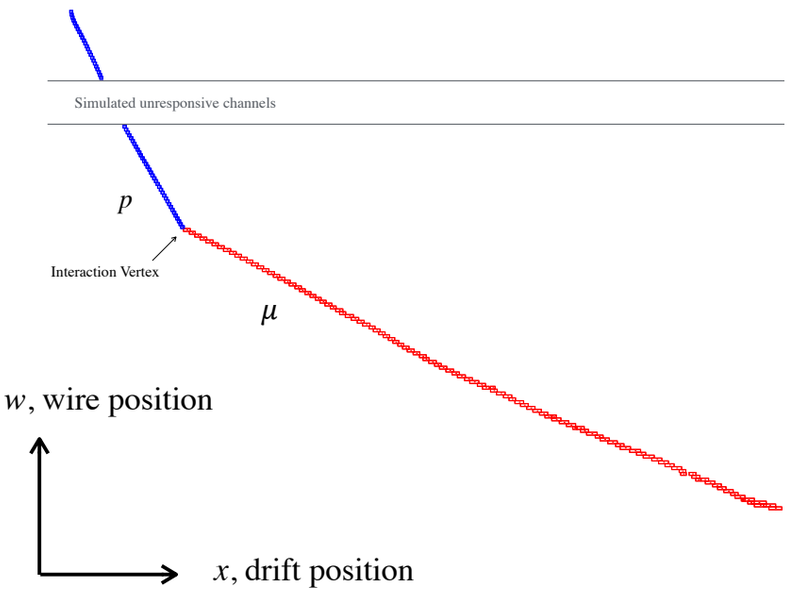
MicroBooNE Event Reconstruction

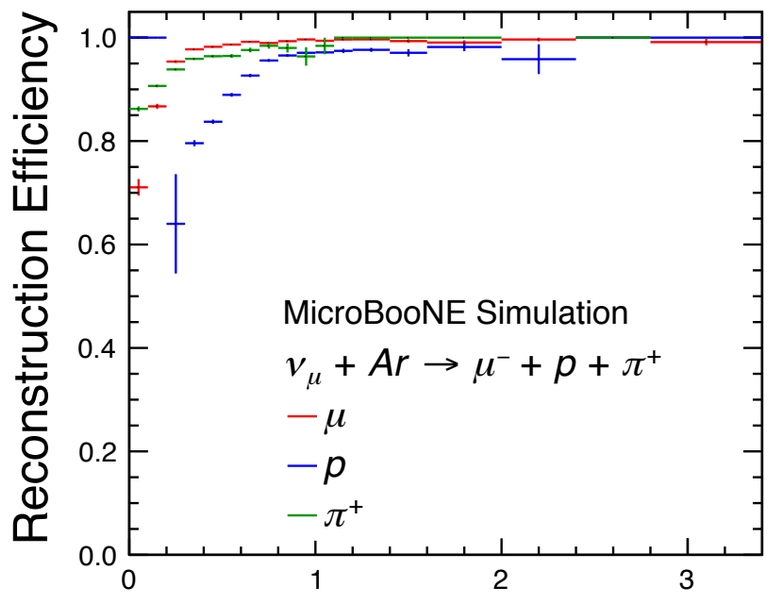
Pandora: automated pattern recognition

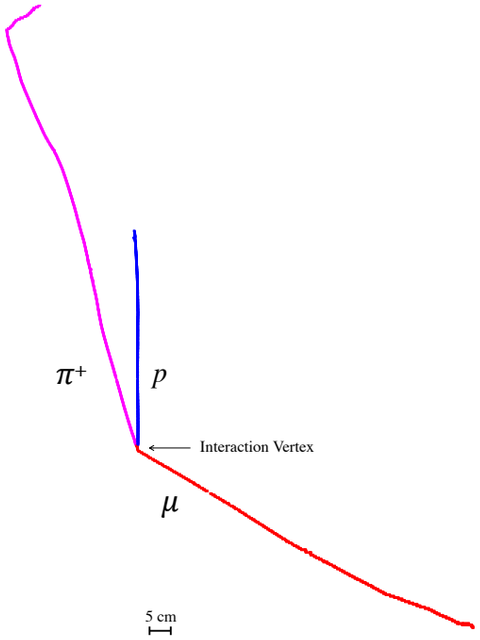
arXiv:1708.03135

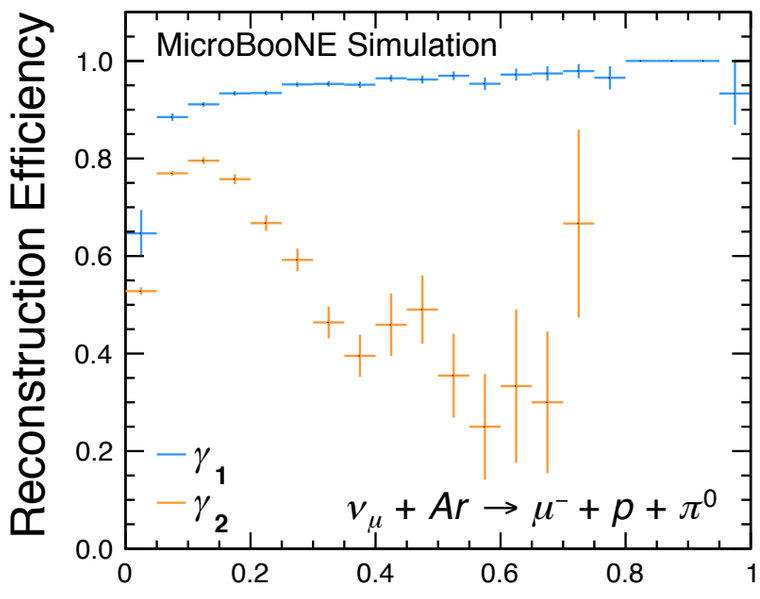
MicroBooNE uses Pandora to perform automated pattern recognition of cosmic-ray muon and neutrino events

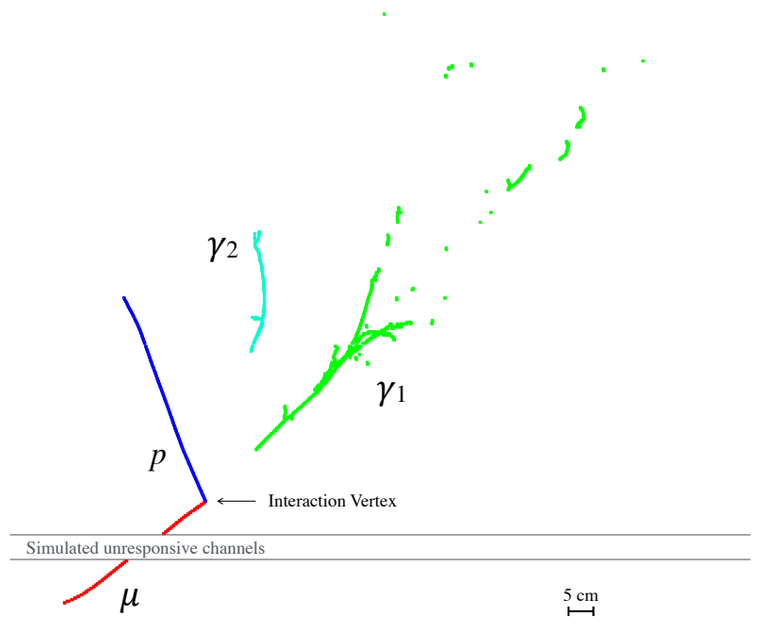




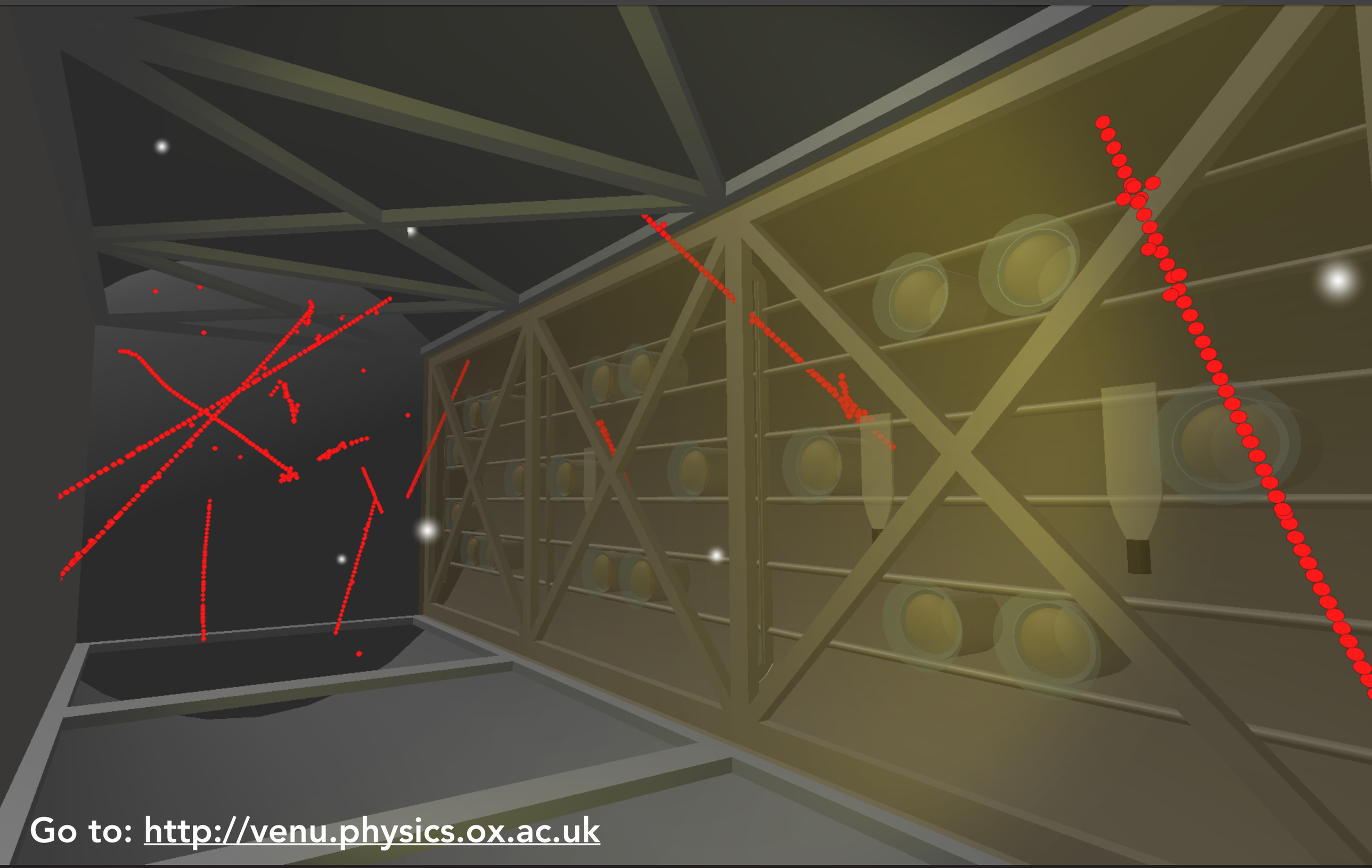








The MicroBooNE LArTPC

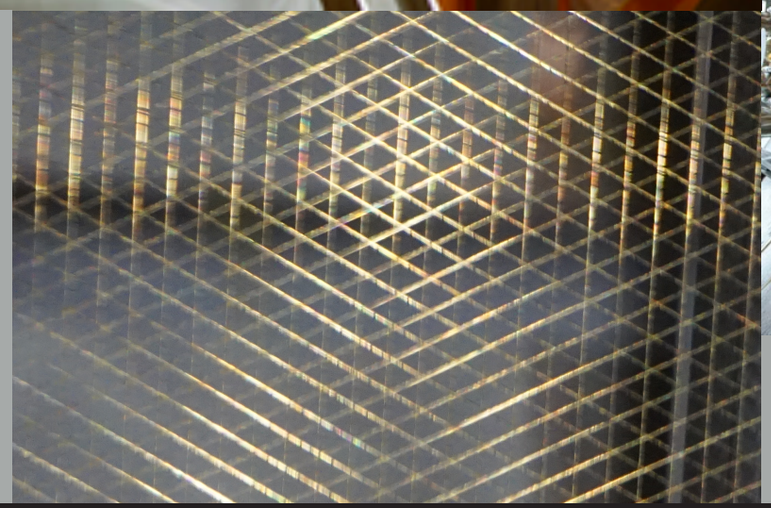


Go to: http://venu.physics.ox.ac.uk

The MicroBooNE Detector

Stainless steel wires
with gold coating

3 wire planes
8192 wires total

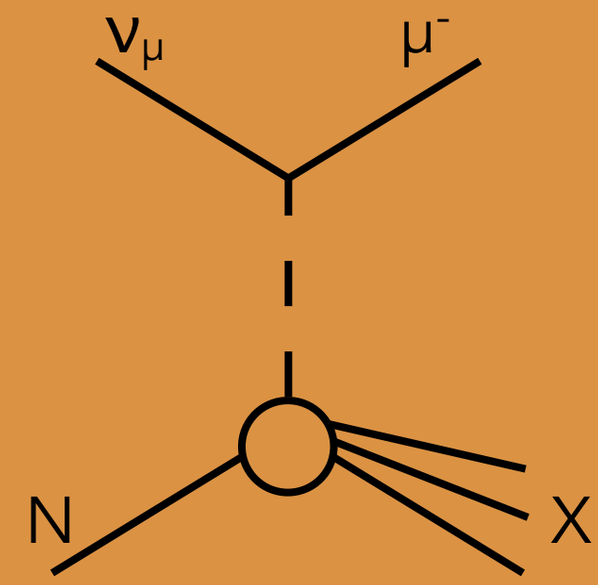


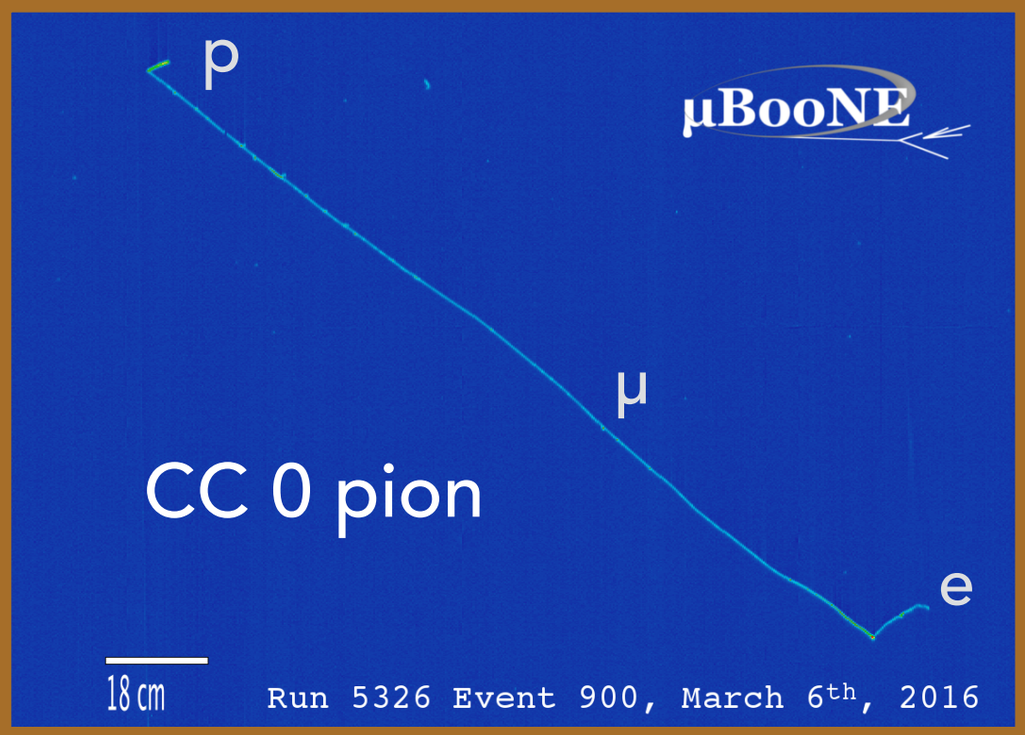
MicroBooNE cryostat lowered into the pit

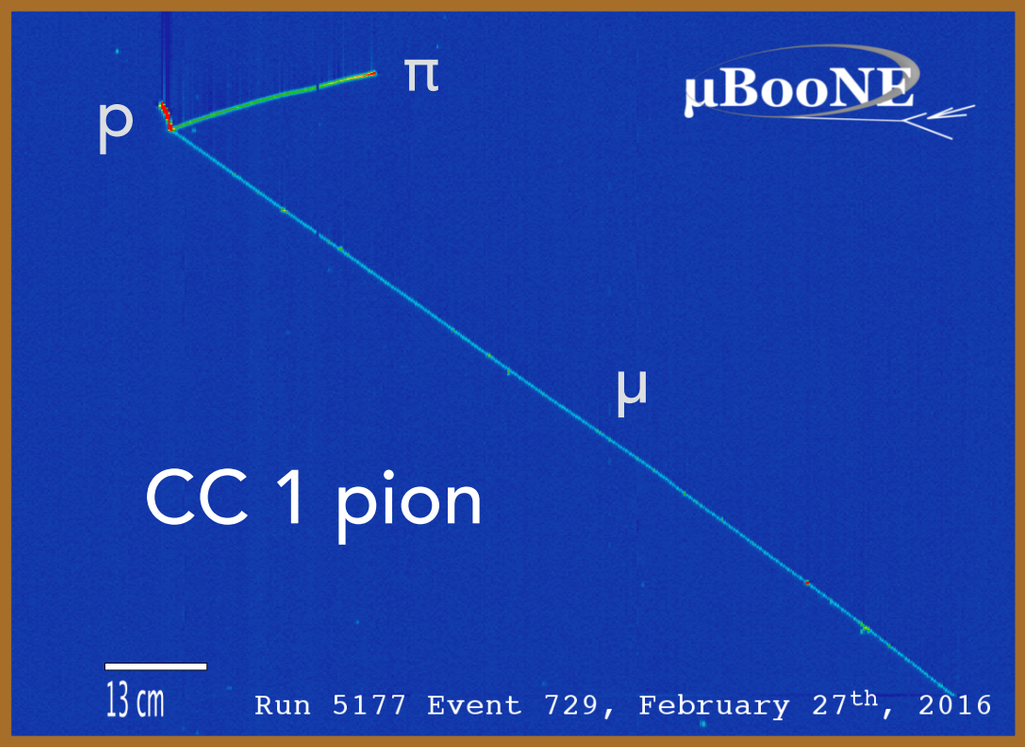
Inside the detector: PMT system

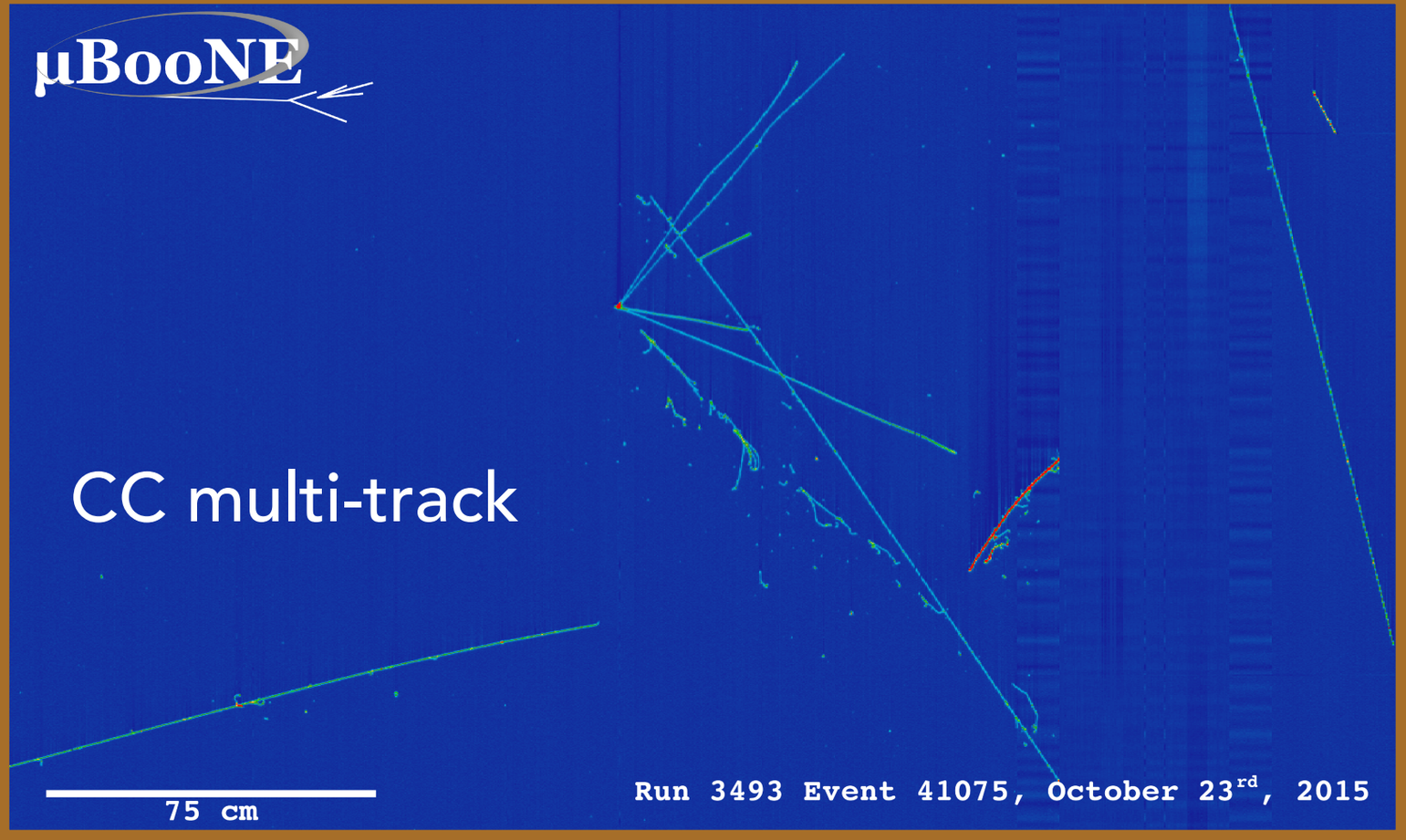
How Do These Interactions Look Like in MicroBooNE?

Charged Current



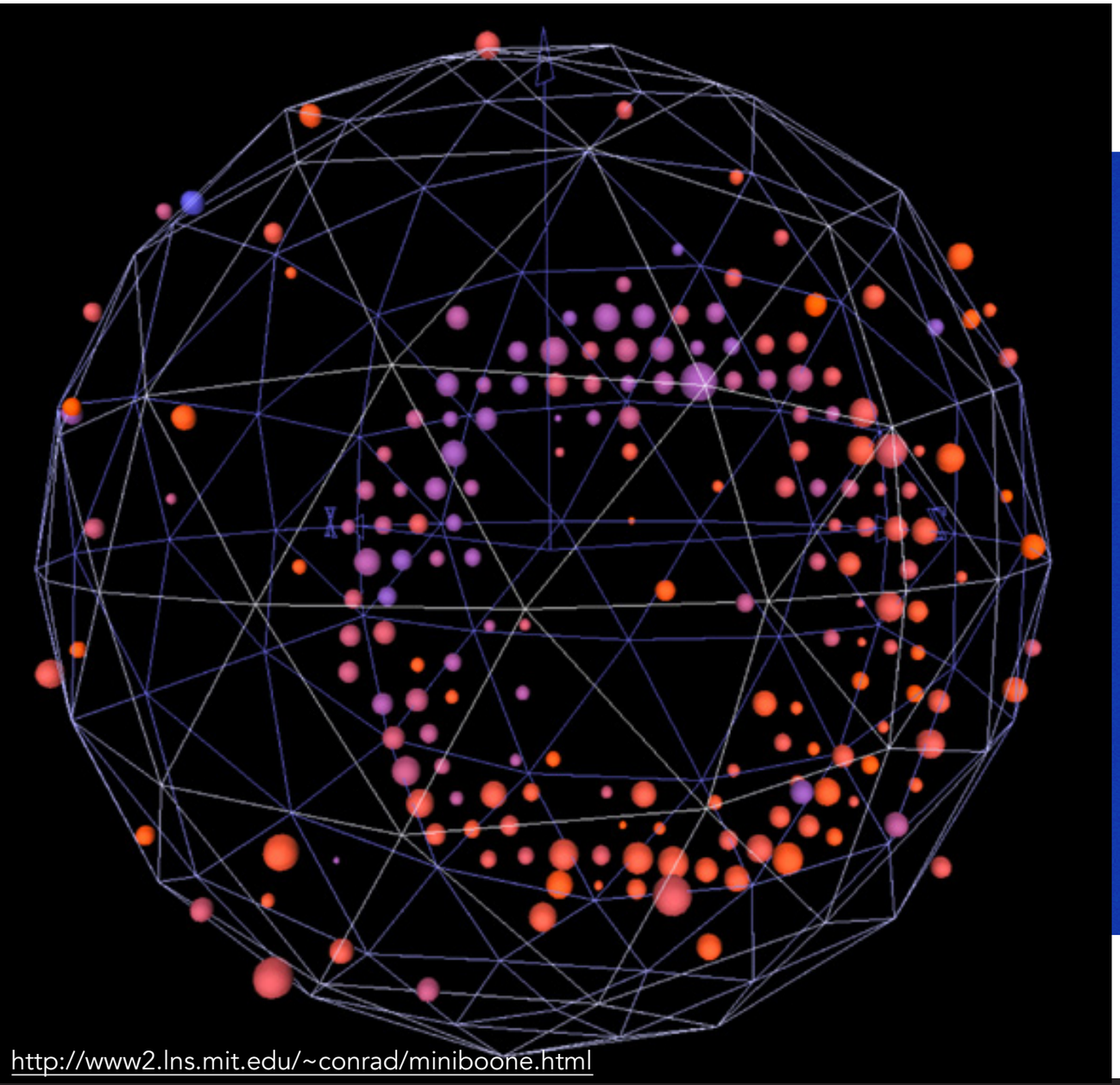






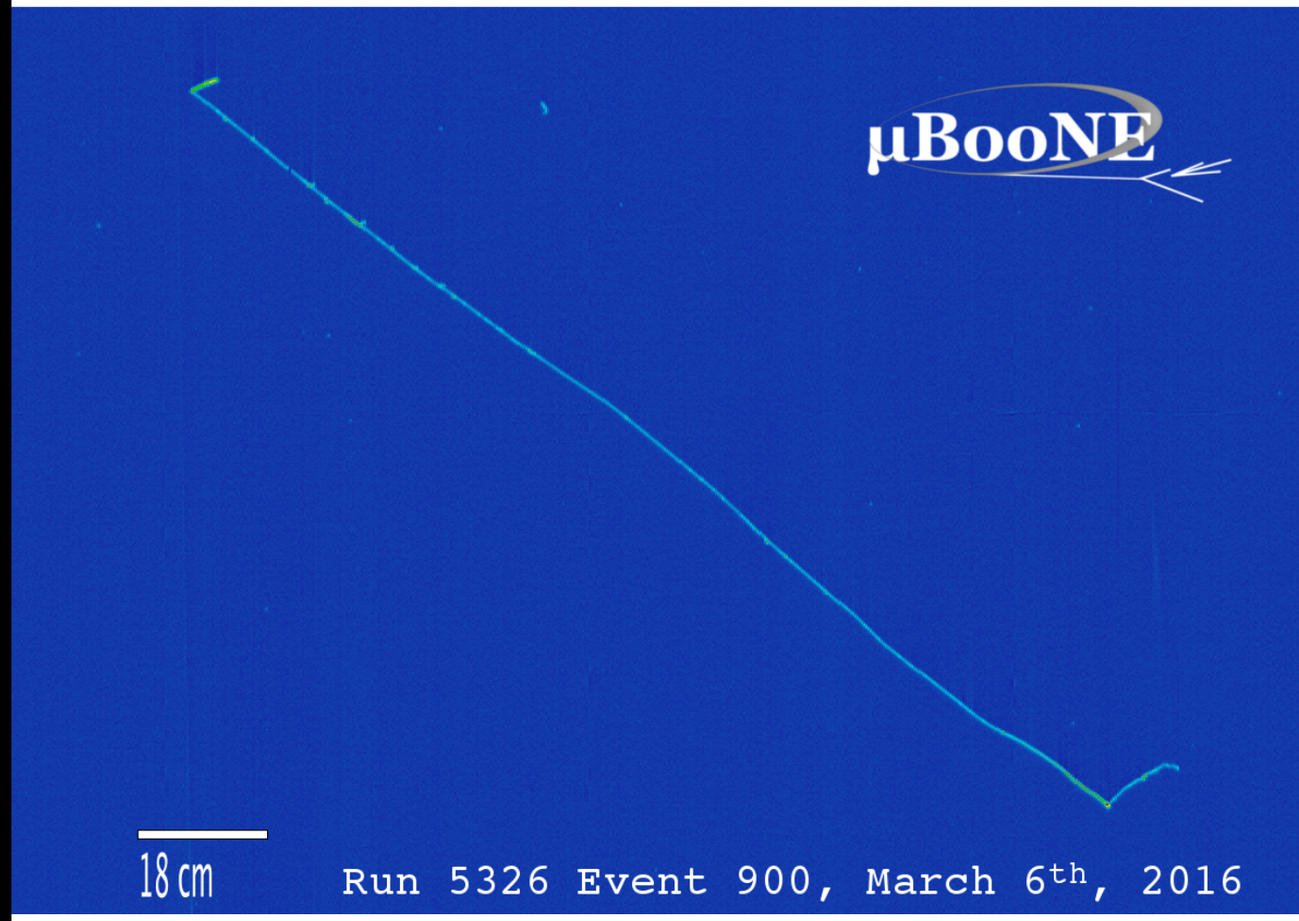
CC0π - Event Topology

MiniBooNE



http://www2.lns.mit.edu/~conrad/miniboone.html

MicroBooNE



CC0π - Event Topology

Electron, Photon

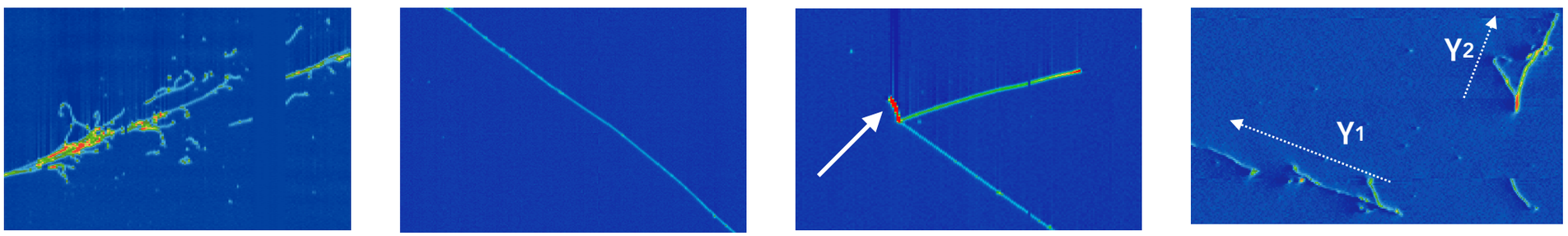
Muon

Proton

$\pi^0 \rightarrow \gamma\gamma$

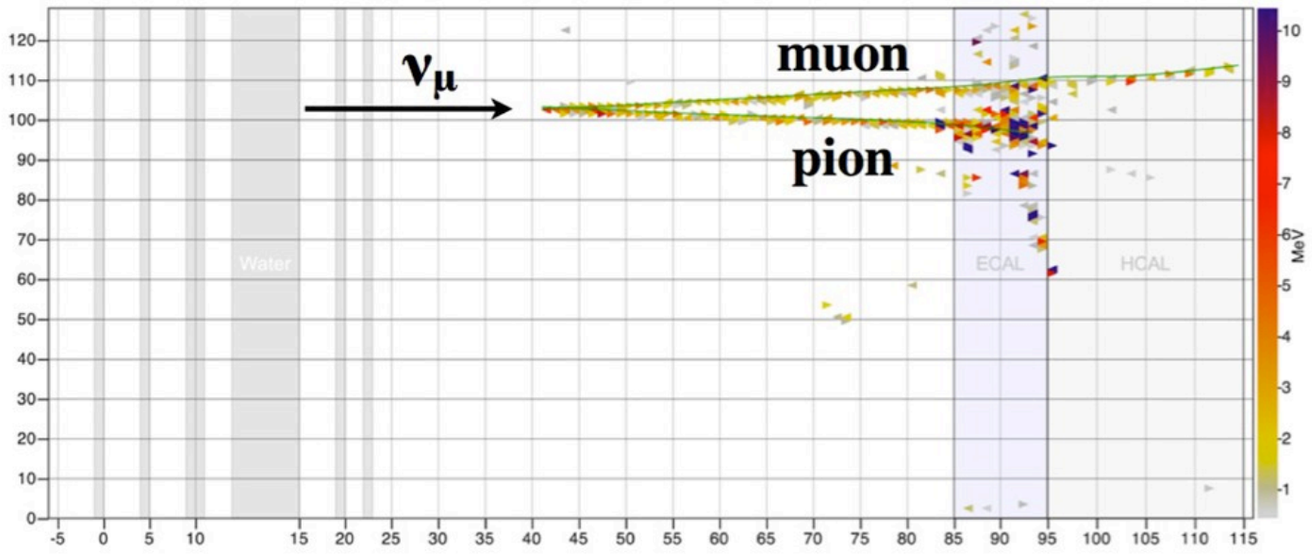
Cherenkov (MiniBooNE)

LArTPC (MicroBooNE)



CC1π - Event Topology

MINERvA

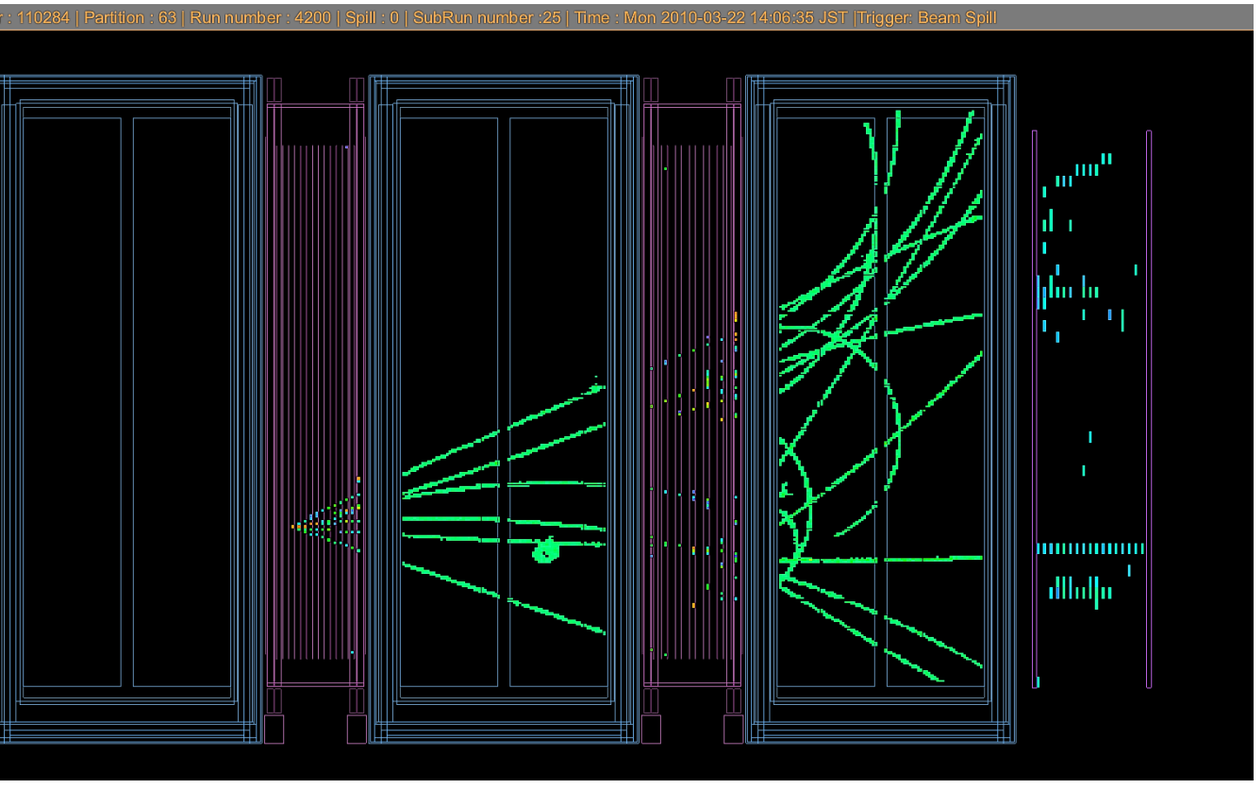


https://sciencesprings.wordpress.com/tag/fnal-minerva/

MicroBooNE

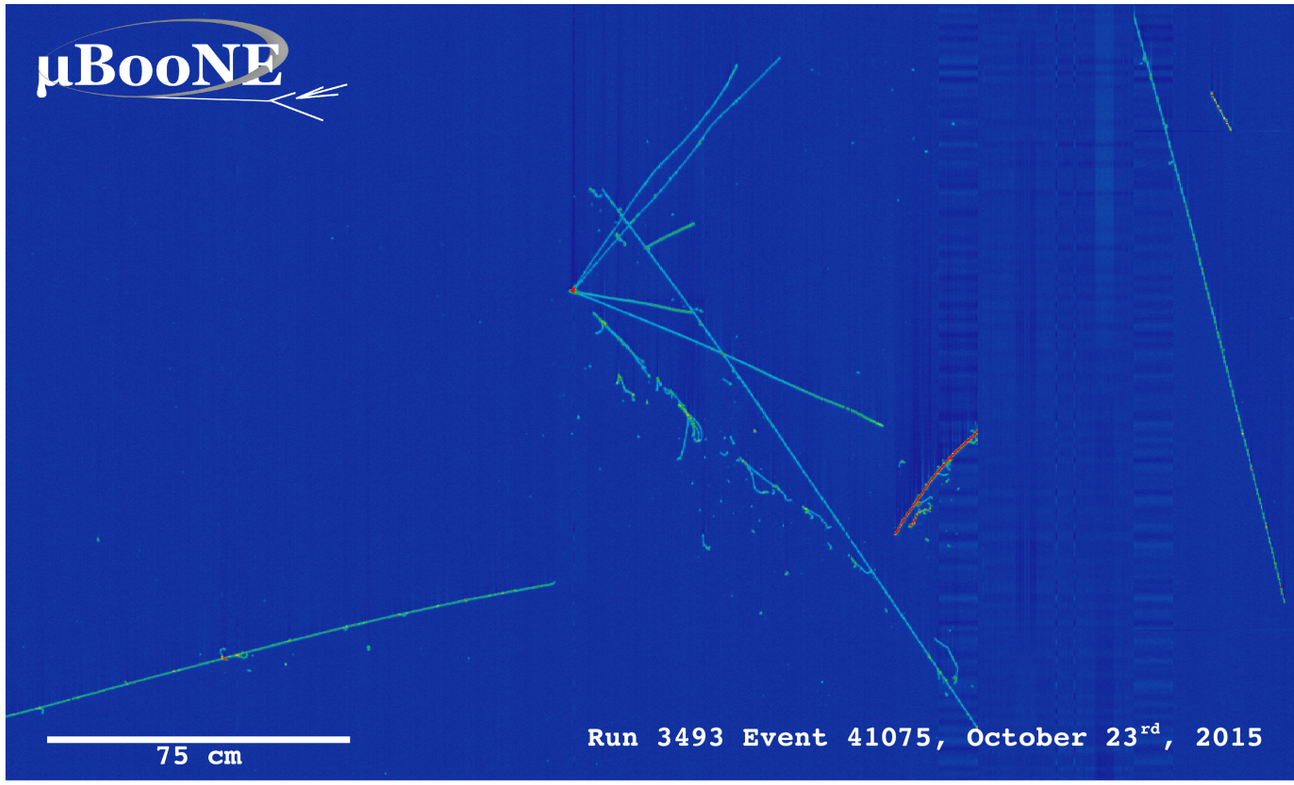
CC Multi Track - Event Topology

T2K



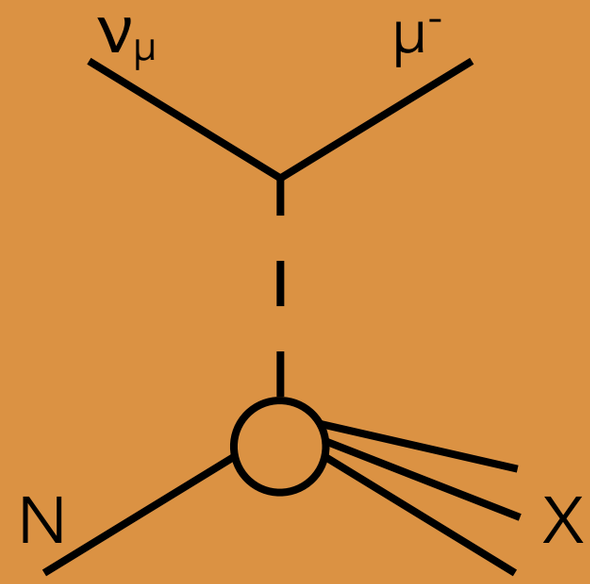
http://www.uvic.ca/science/physics/vispa/research/projects/neutrino/

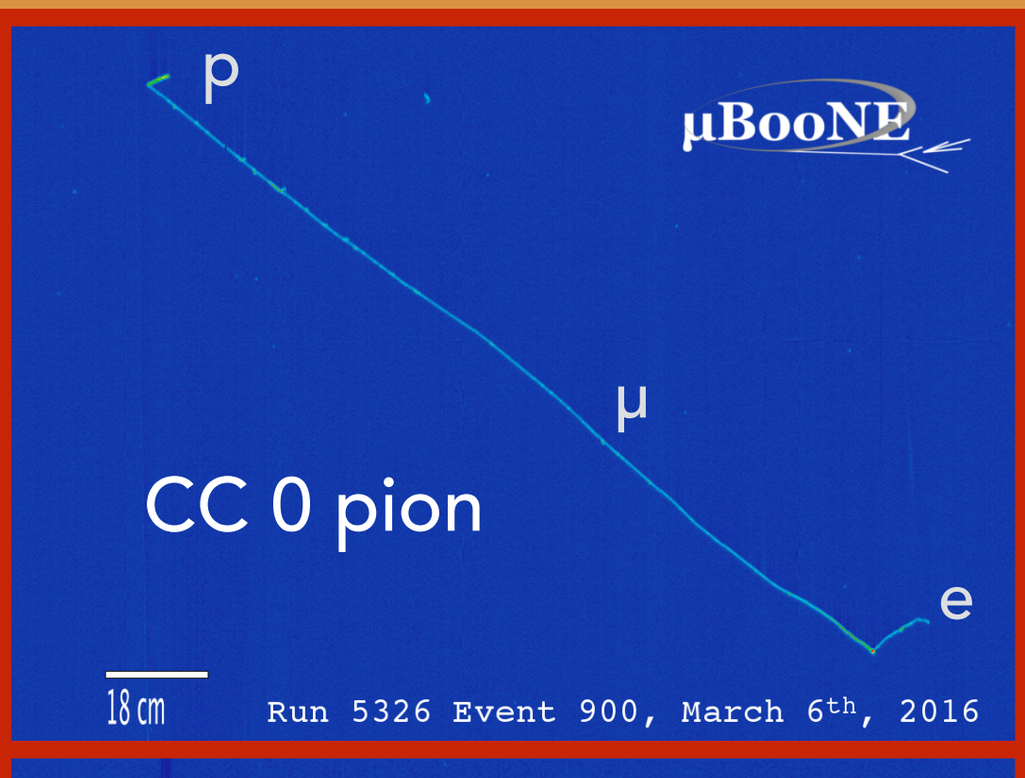
MicroBooNE

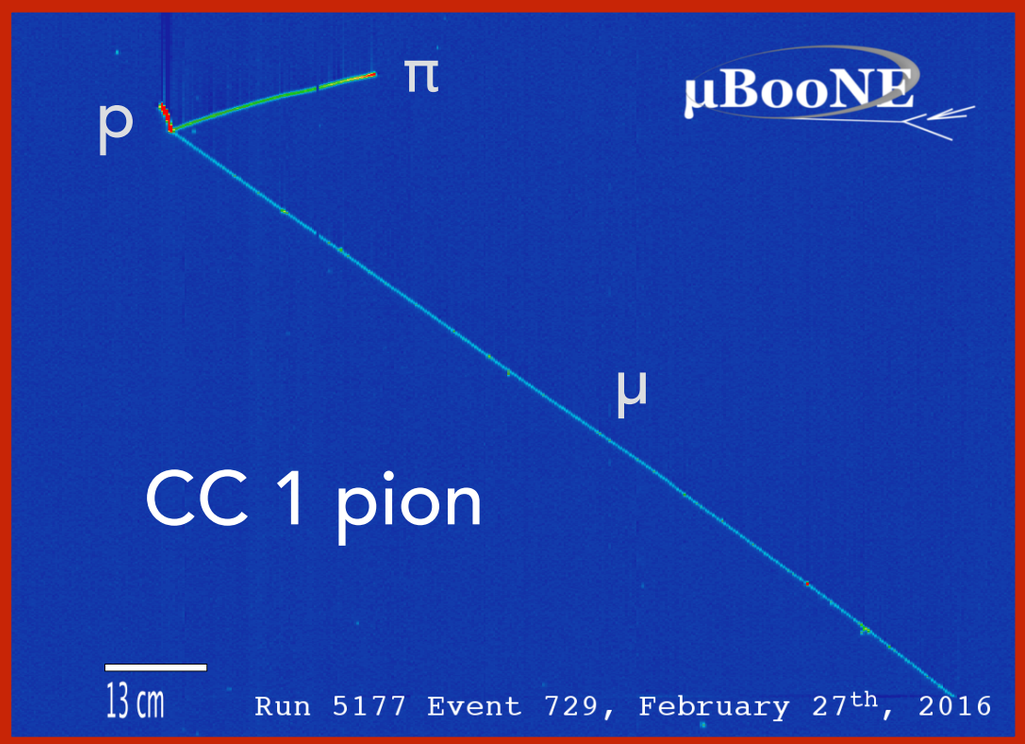


Now Focusing on CC-Inclusive

Charged Current

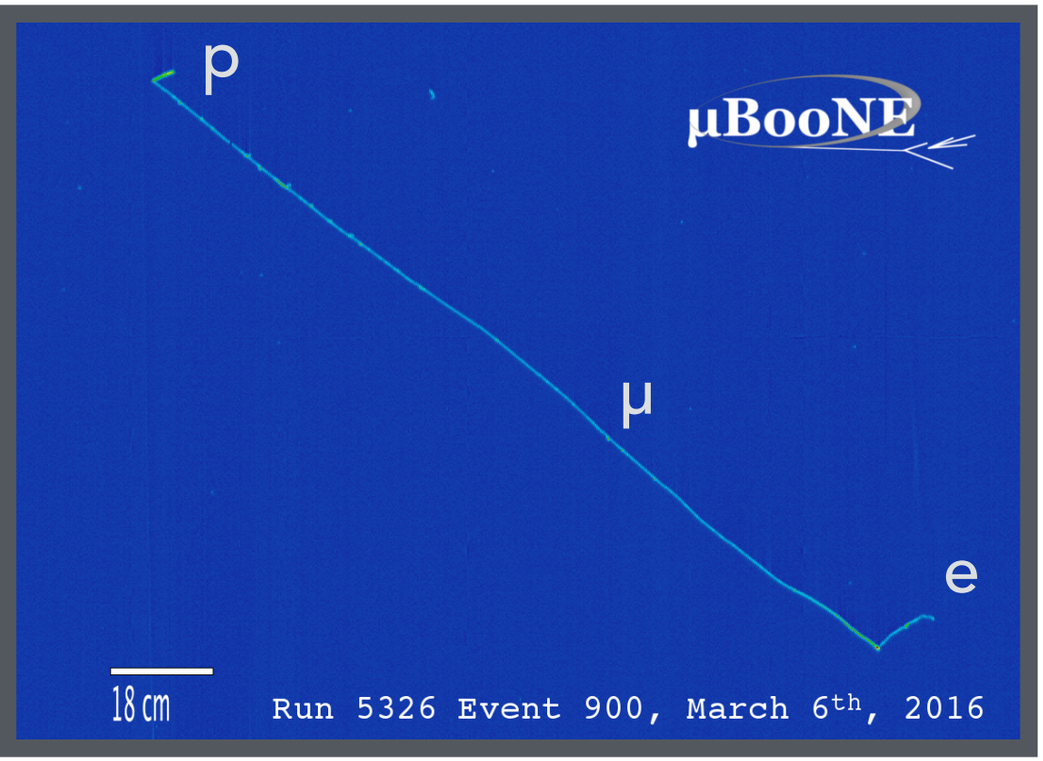






CC Interactions @ MicroBooNE

ν_μ CC-Inclusive Analysis



- First channel that will be addressed by the MicroBooNE cross-section program
- Simple: looking for a long muon track
- We have an automated reconstruction and event selection

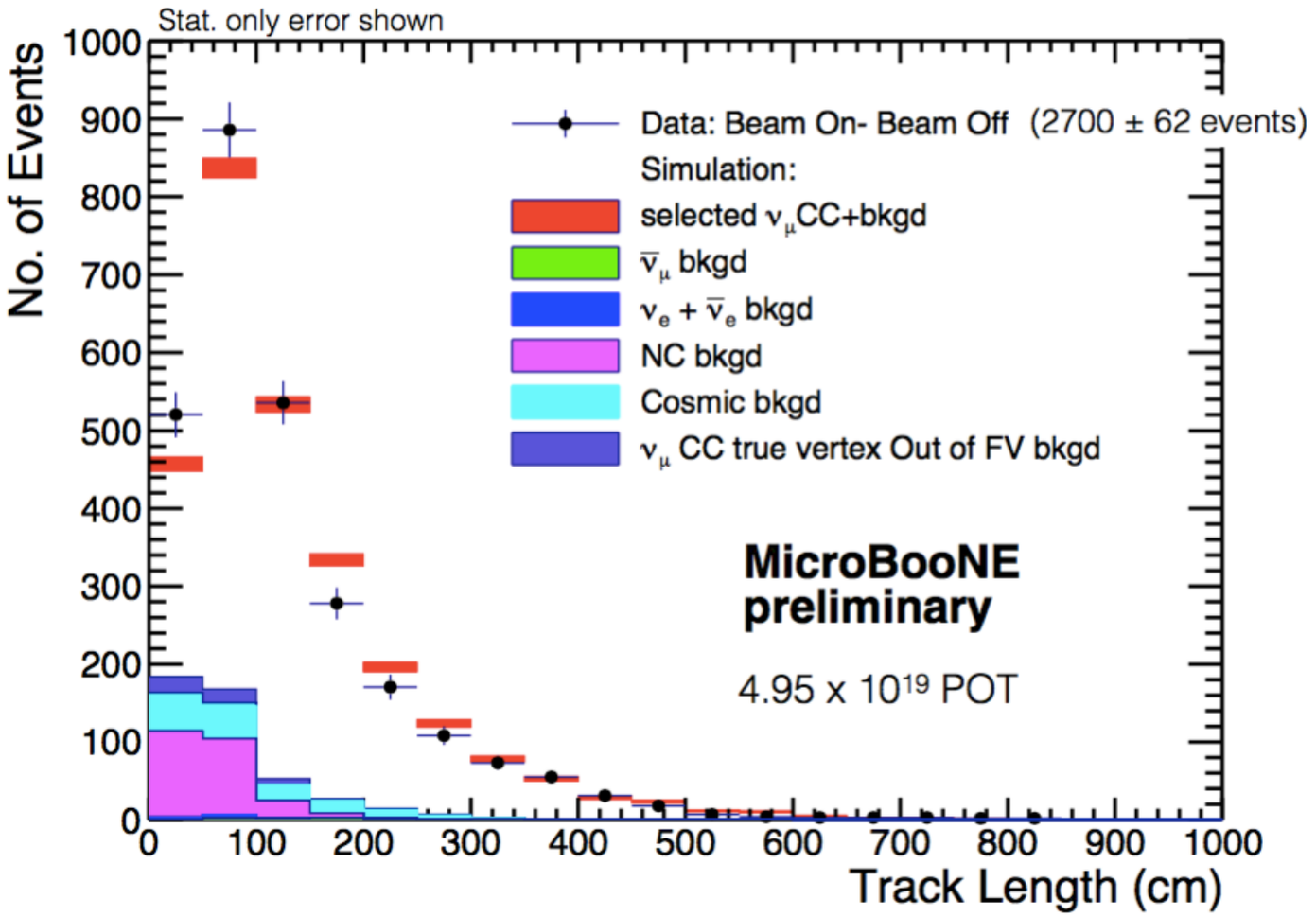
Motivations

- Interesting physics measurement on argon, provides input for theory
- Will constrain the ν_e rate in MicroBooNE and other backgrounds
- Will provide a sample to study other specific channels (π^0, proton kinematics, …)

CC Interactions @ MicroBooNE

CC-inclusive event distributions

MICROBOONE-NOTE-1010-PUB



Data

(Beam On – Beam Off)

corresponds to 4.95x10^{19} POT

(3 months of data taking), about

2700 ν_μ-CC candidate events

MC

Neutrino interaction (GENIE 2.8.6),

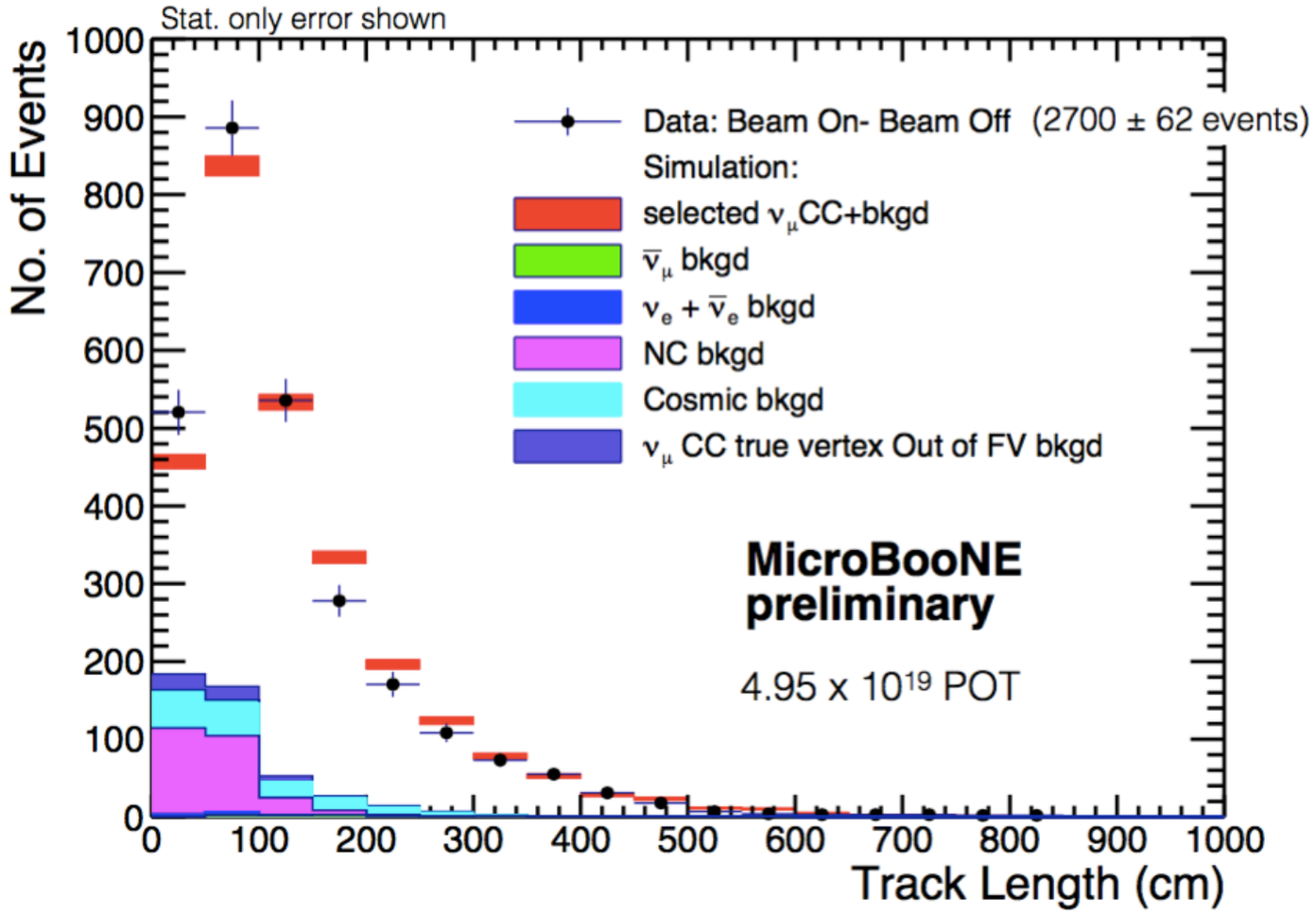
cosmic (CORSIKA v7.4003).

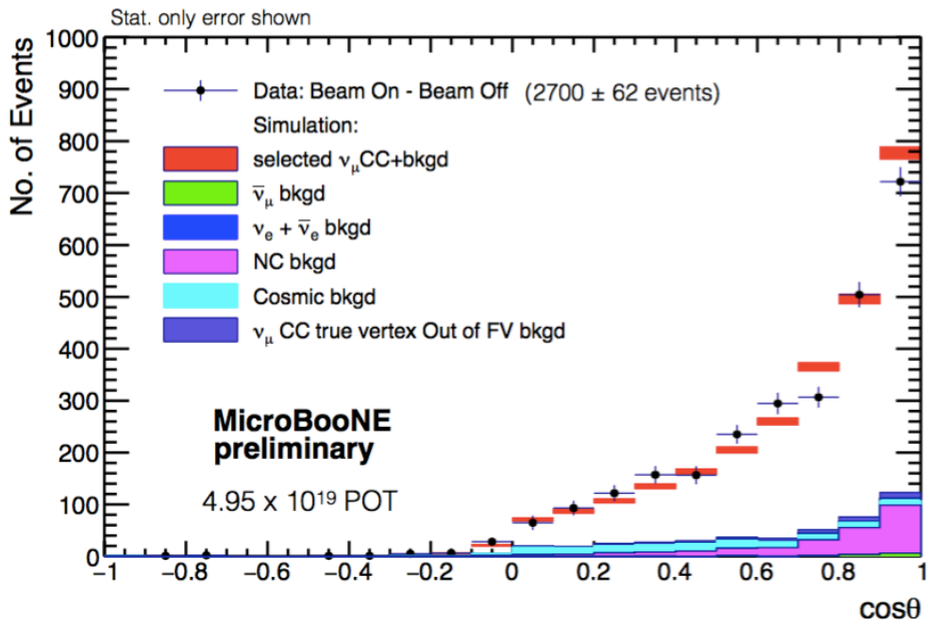
- Simulation scaled to same number of events as data
- Cosmic background subtracted

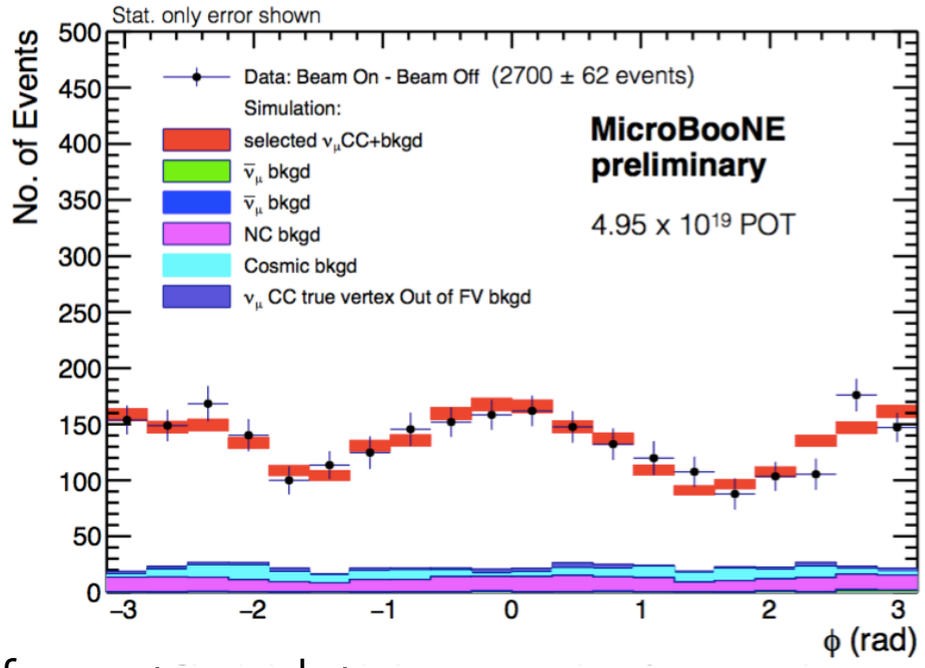
CC Interactions @ MicroBooNE

CC-inclusive event distributions

MICROBOONE-NOTE-1010-PUB





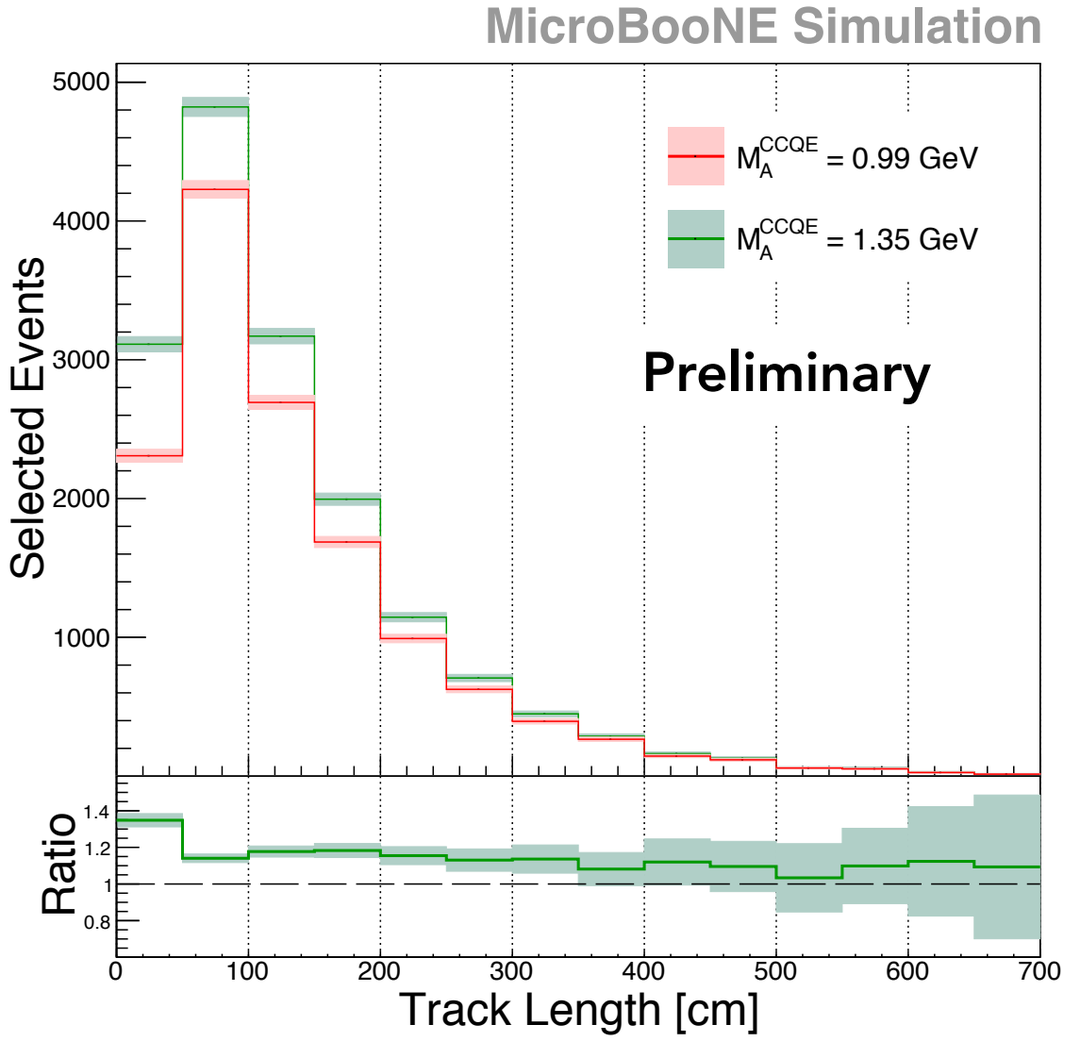


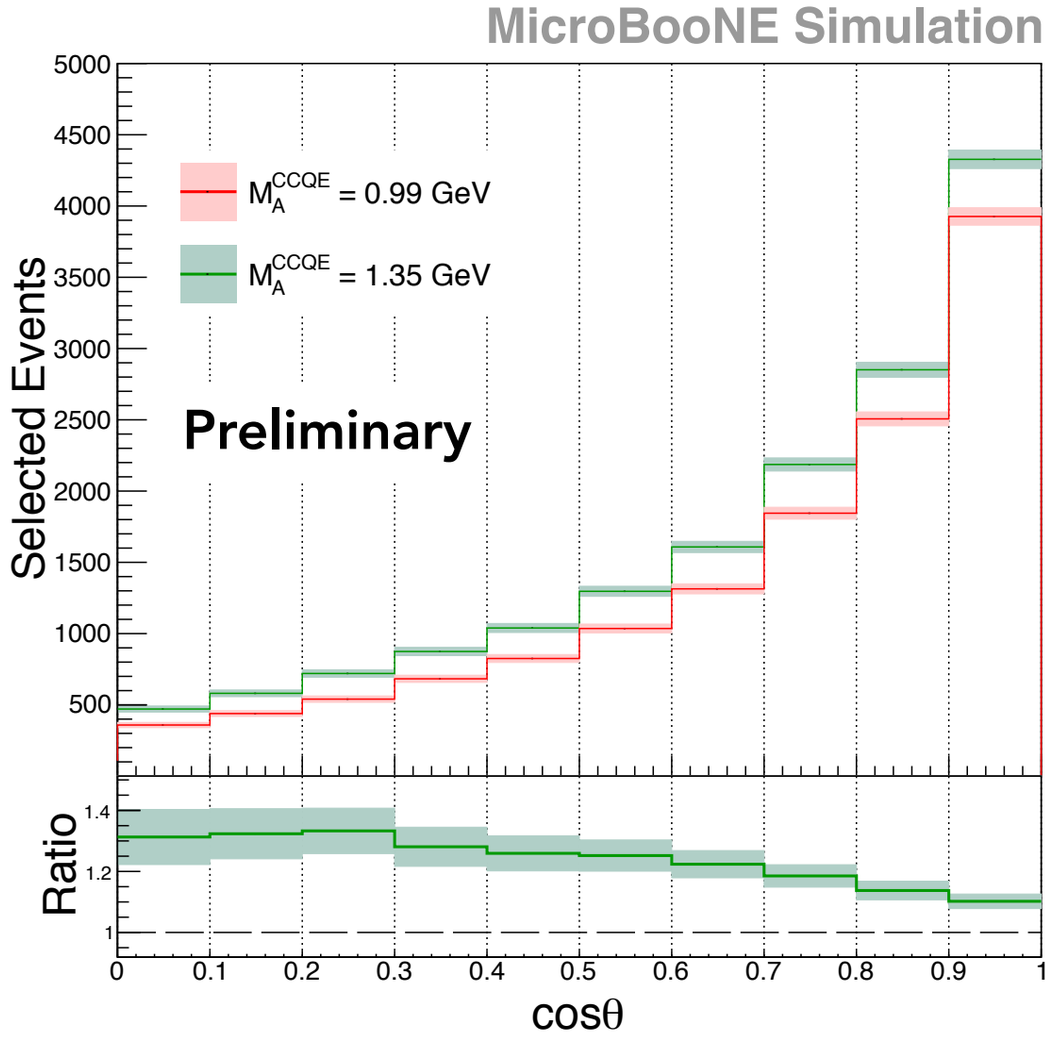
- Simulation scaled to same number of events as data
- Cosmic background subtracted

CC Interactions @ MicroBooNE

Simulated Observable Muon Kinematic Distributions

MICROBOONE-NOTE-1010-PUB





Statistical error only
No background subtraction

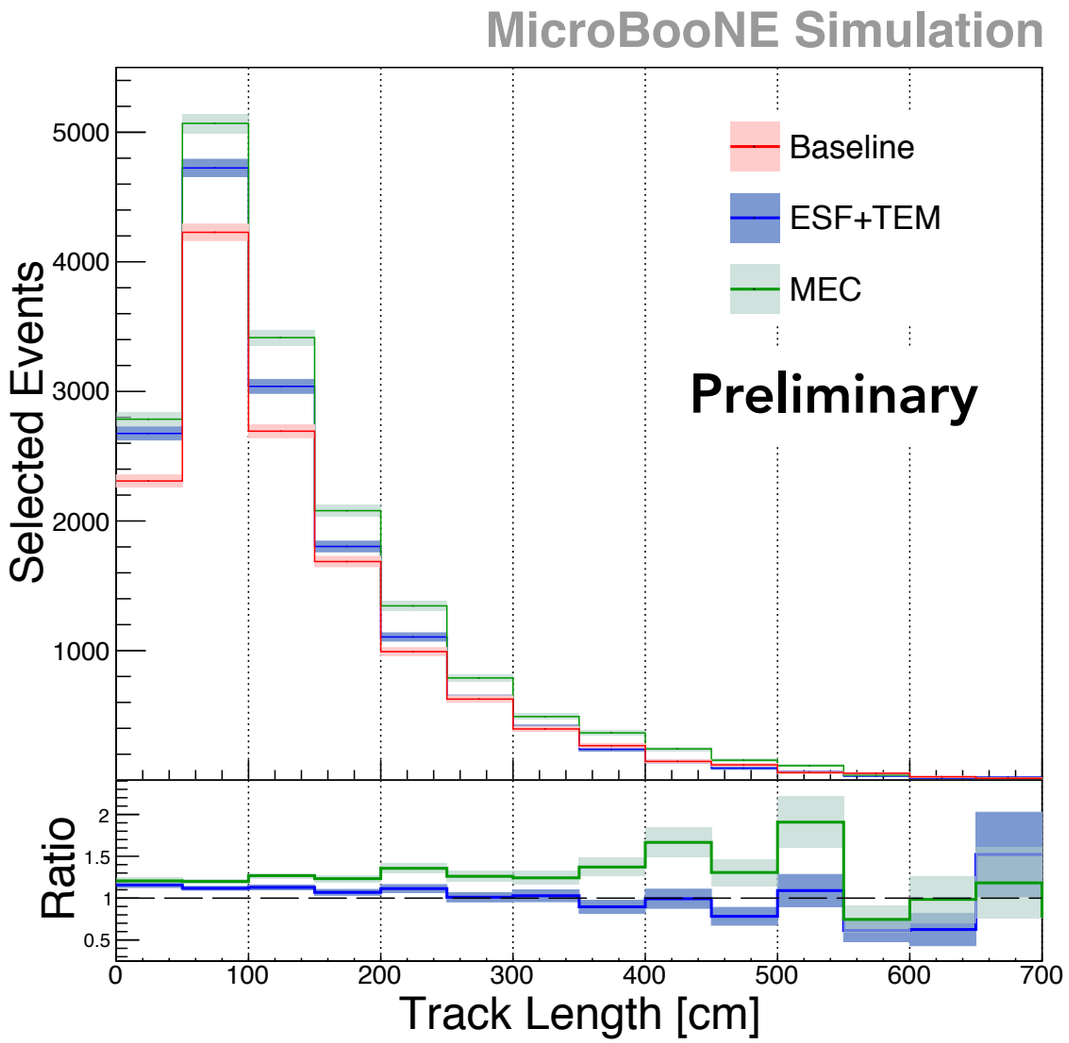
Started looking at how the event distributions look like if using a different value for M_A

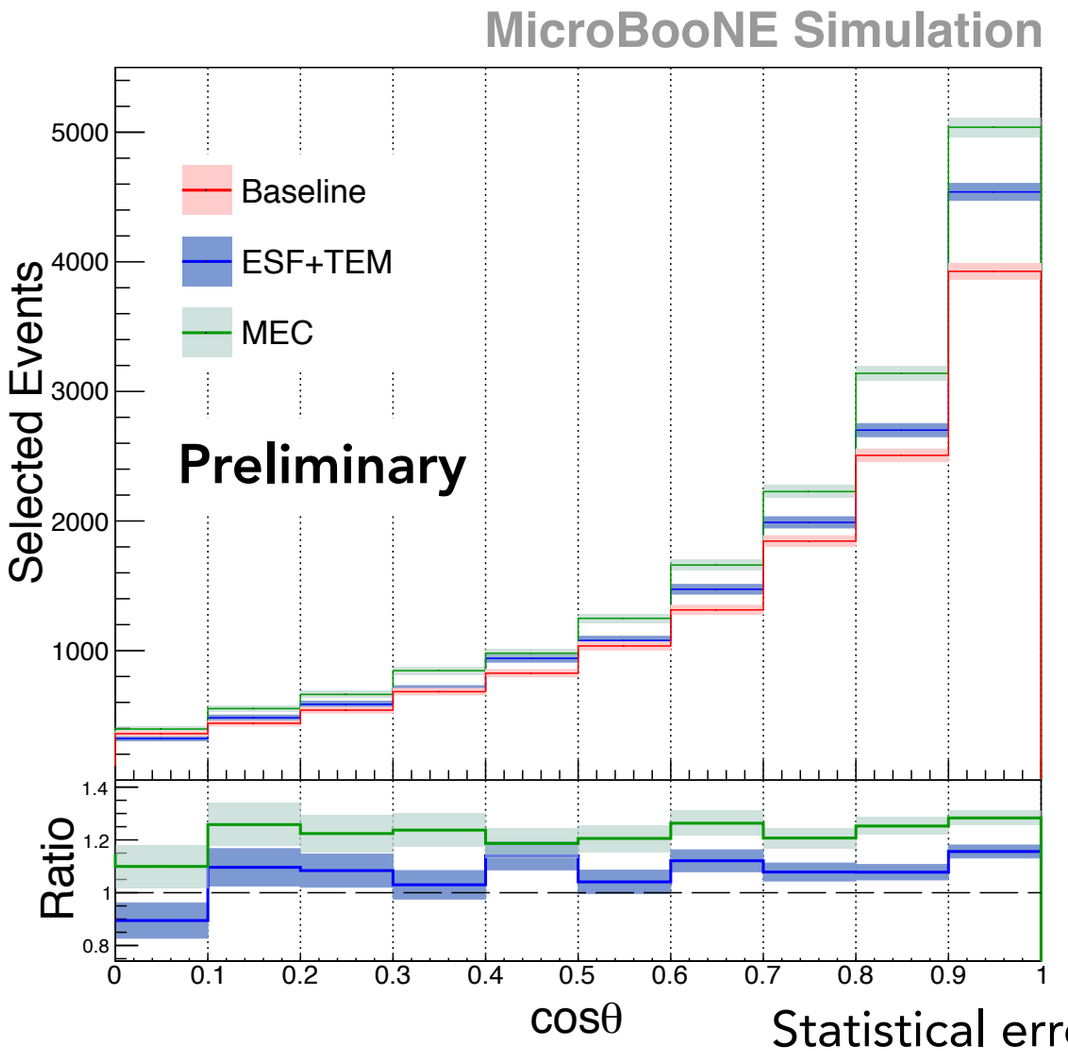
Increase in normalisation of the order of 24%

CC Interactions @ MicroBooNE

Simulated Observable Muon Kinematic Distributions

MICROBOONE-NOTE-1010-PUB





Statistical error only
No background subtraction

Baseline: GENIE default 2.10.6

ESF+TEM: Effective Spectral Function + Transverse Enhancement Model

A. Bodek et al., EPJ C, 71(9):1726 (2011),
A. Bodek et al., EPJ C, 74(10):1–17, (2014) (13%)

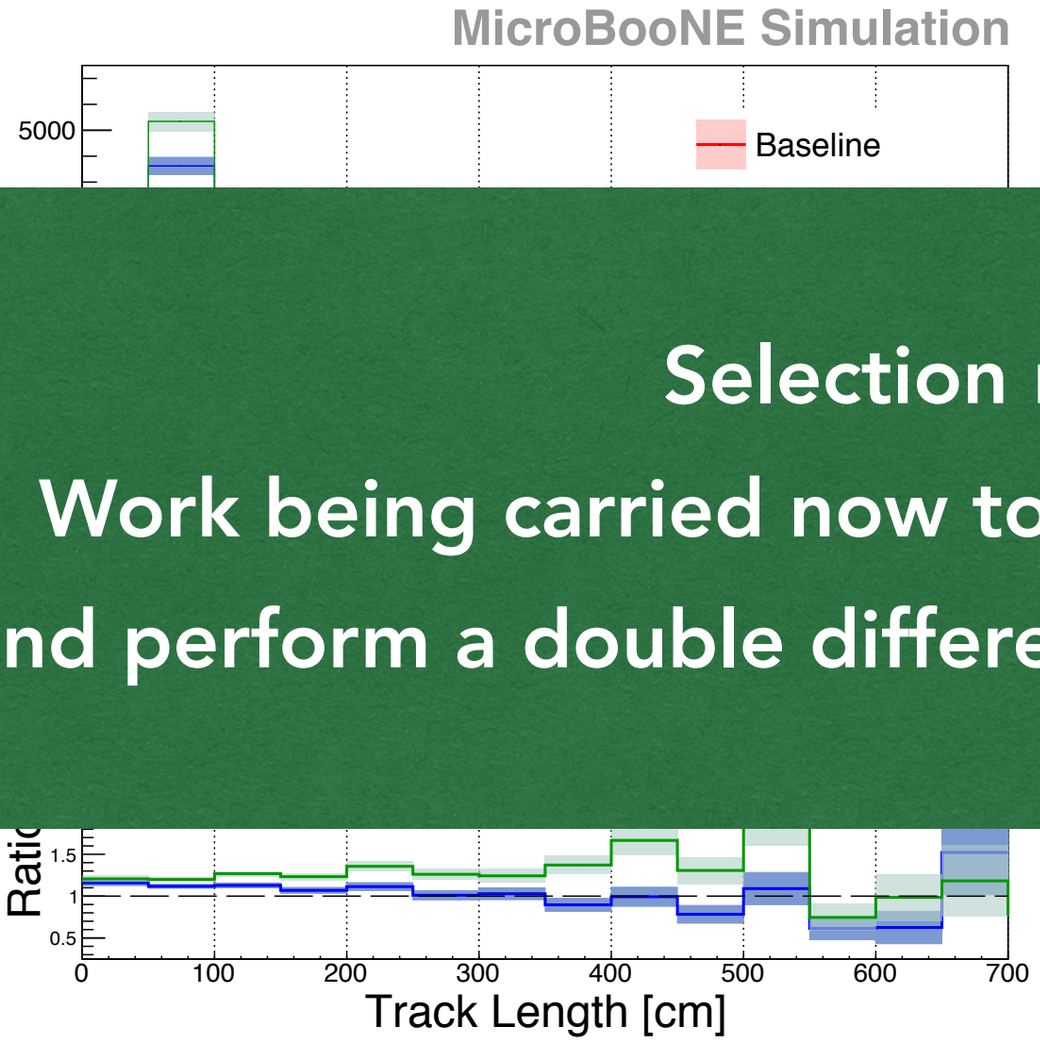
MEC: Addition of Meson Exchange Current

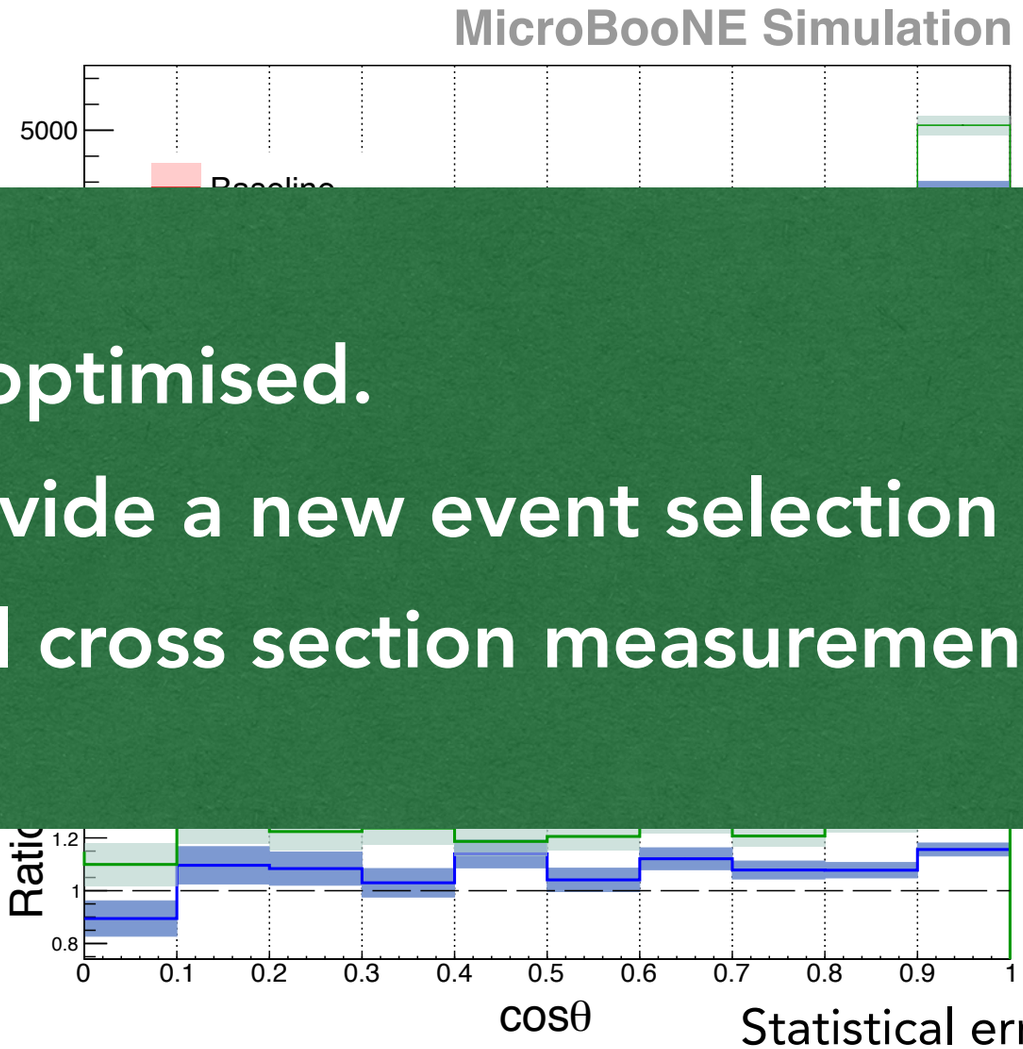
J. Nieves et al., Phys. Rev. C, 83:045501 (2011)] (24%)

CC Interactions @ MicroBooNE

Simulated Observable Muon Kinematic Distributions

MICROBOONE-NOTE-1010-PUB





Selection not optimised.

Work being carried now to provide a new event selection and perform a double differential cross section measurement.

Statistical error only
No background subtraction

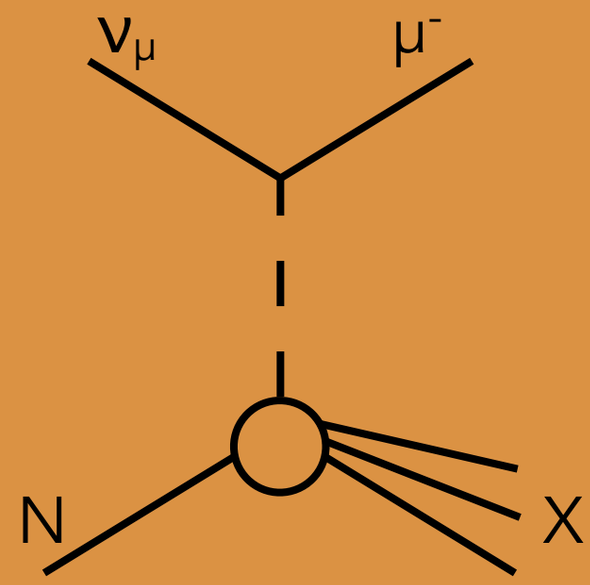
Baseline: GENIE default 2.10.6

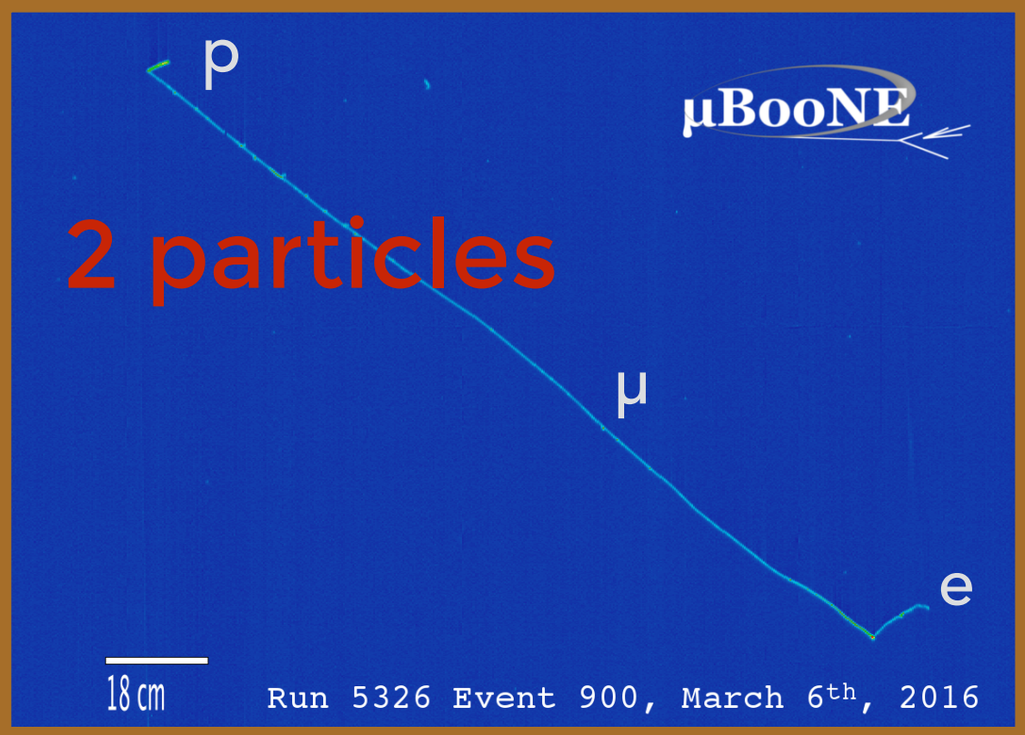
ESF+TEM: Effective Spectral Function + Transverse Enhancement Model — A. Bodek et al., EPJ C, 71(9):1726 (2011), A. Bodek et al., EPJ C, 74(10):1–17, (2014) (13%)

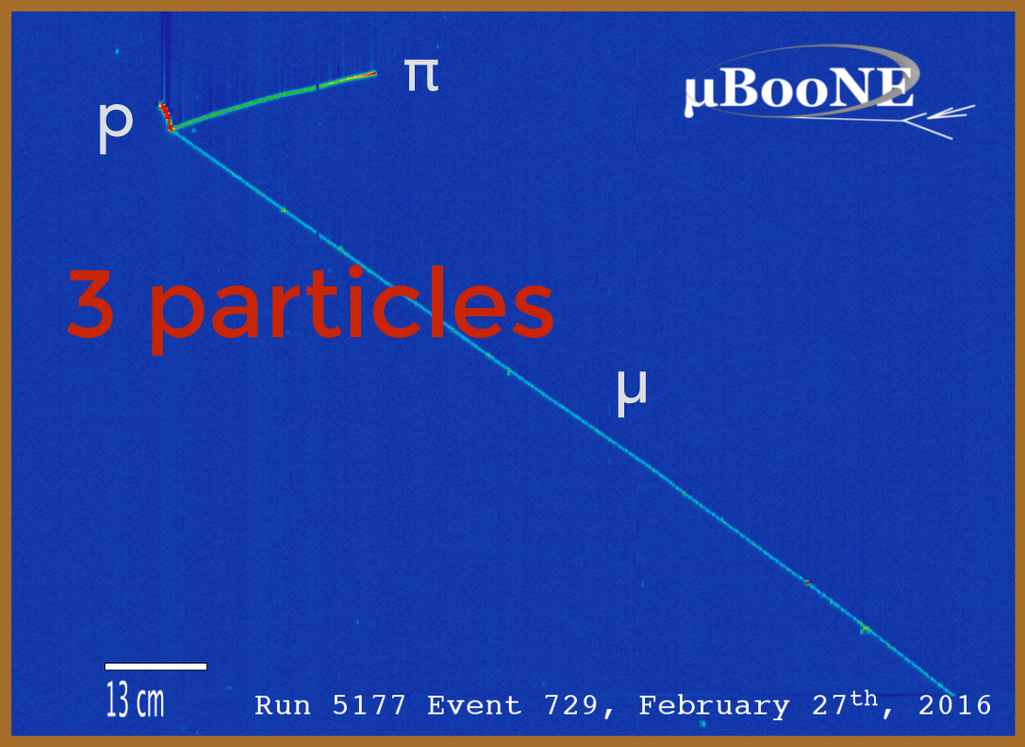
MEC: Addition of Meson Exchange Current — J. Nieves et al., Phys. Rev. C, 83:045501 (2011)] (24%)

Now Focusing on Particle Multiplicity

Charged Current

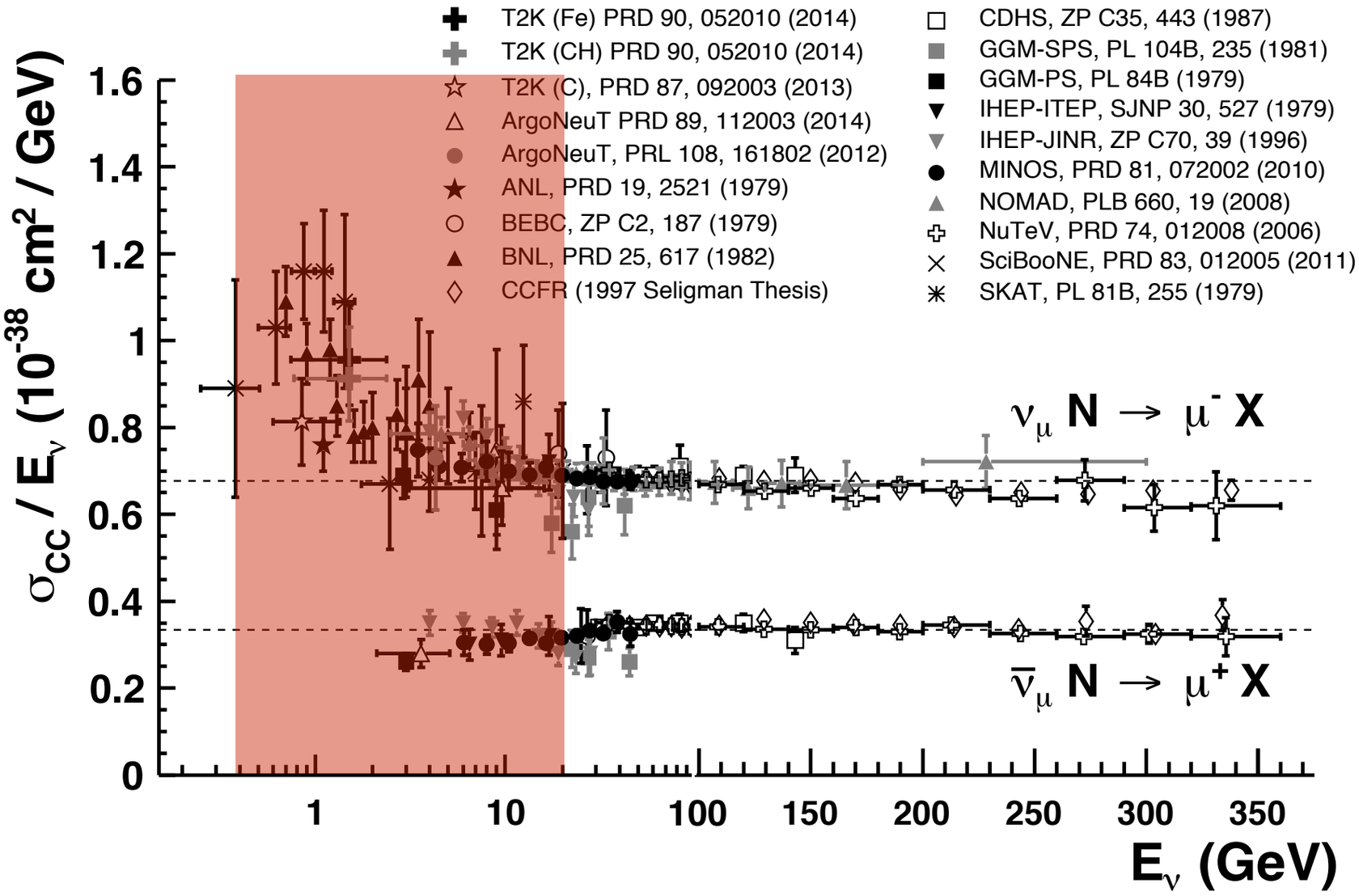






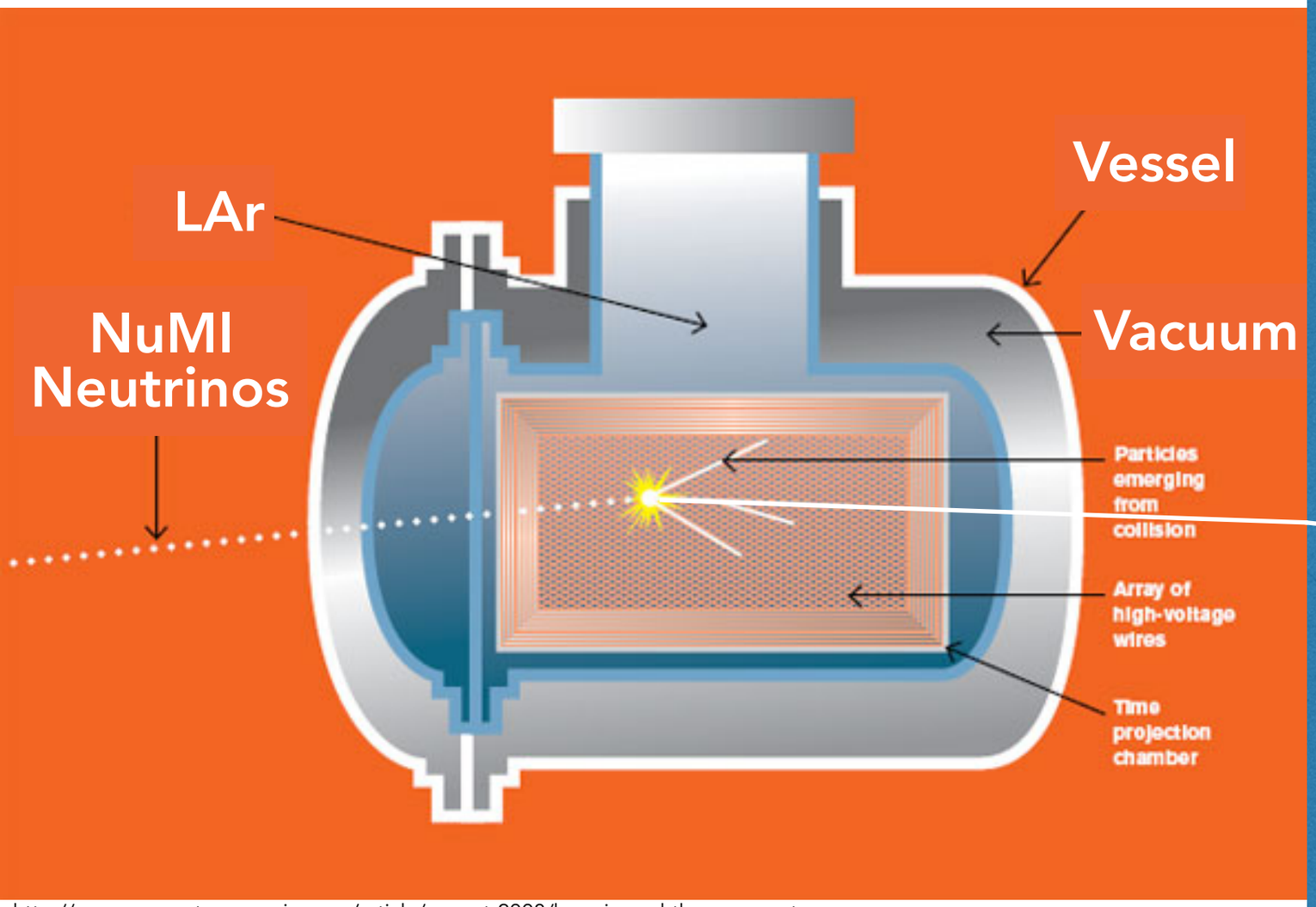
The ArgoNeuT Experiment

ArgoNeuT



The ArgoNeuT Experiment

The Detector



http://www.symmetrymagazine.org/article/august-2008/bonnie-and-the-argoneuts

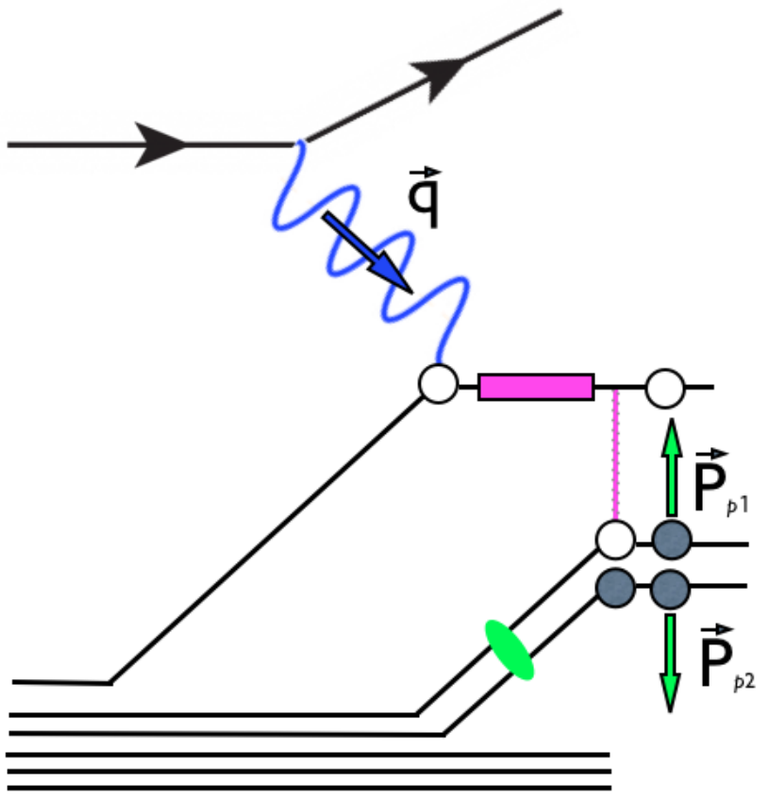
Magnetised MINOS Near Detector

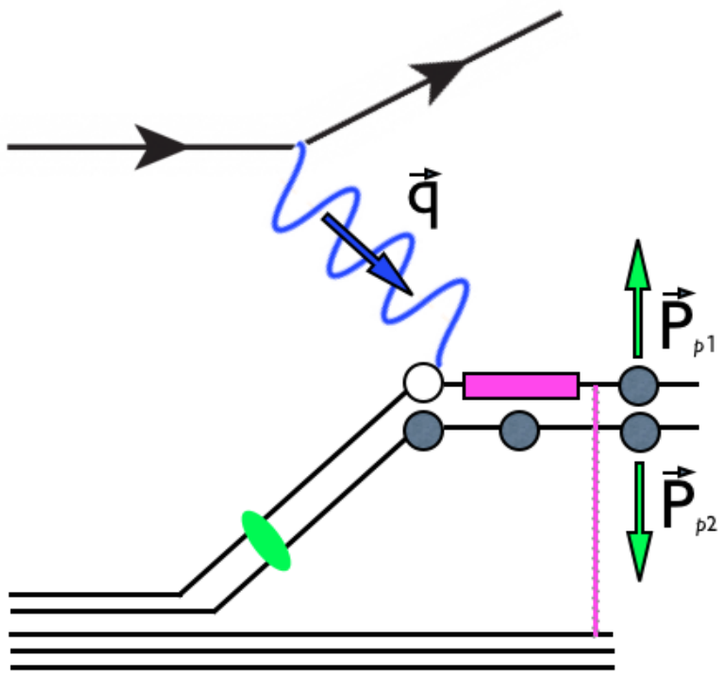
μ

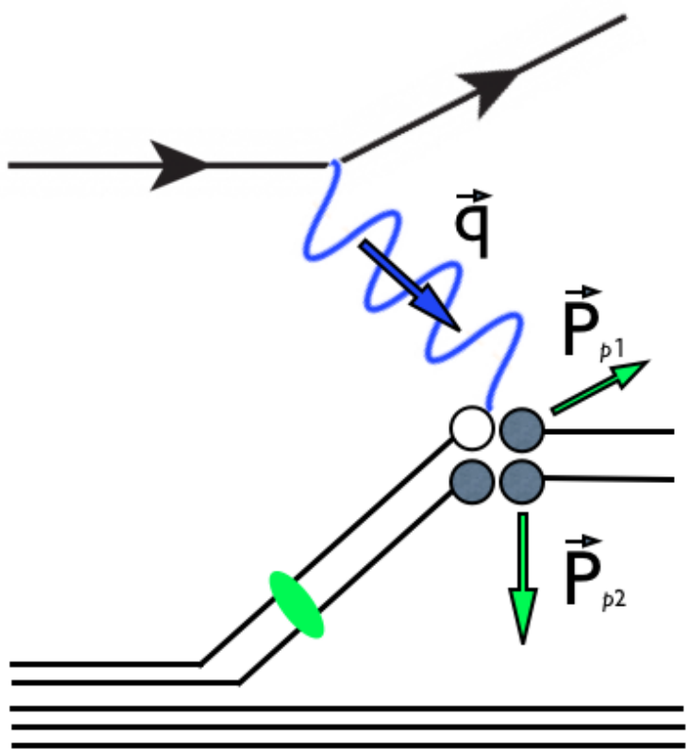
The ArgoNeuT Experiment

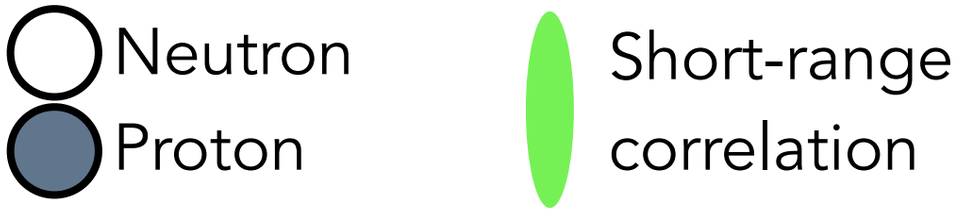
Results - Back-to-back protons

Phys. Rev. D90, 012008 (2014)









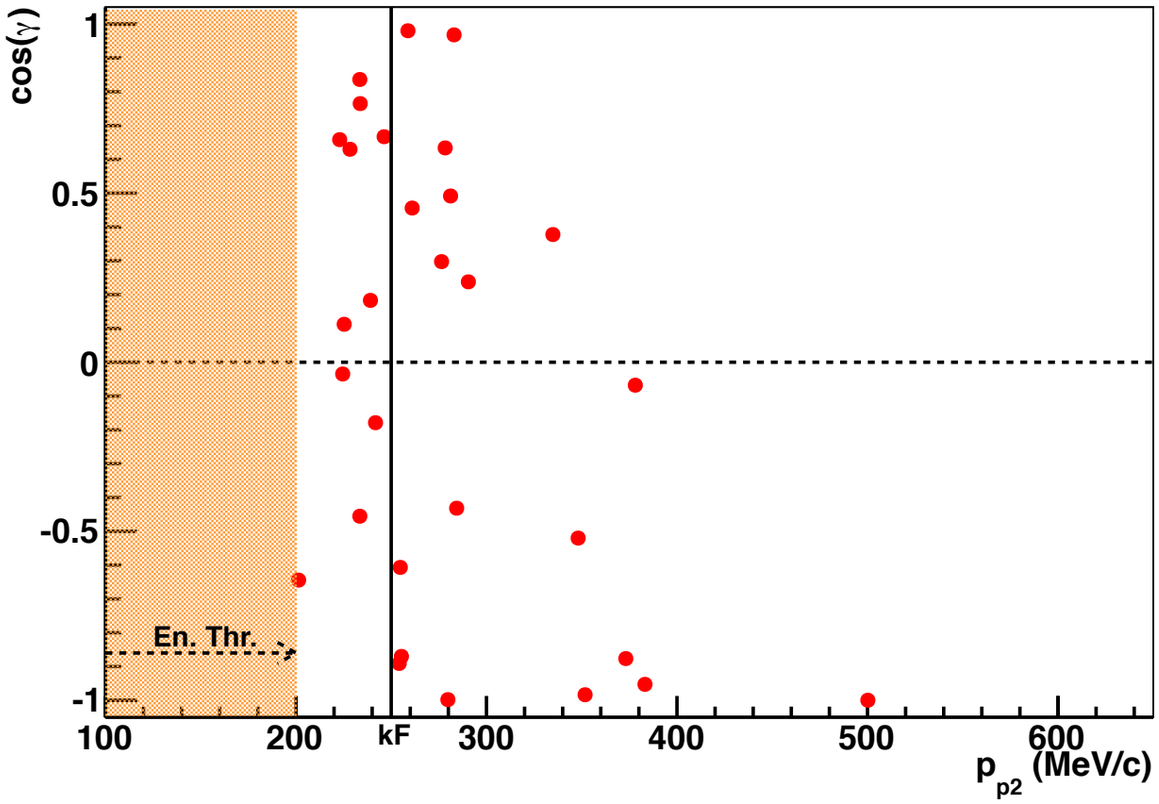
ArgoNeuT investigated other processes other than two-nucleon currents: short-range nucleon-nucleon correlations (NN SRC)

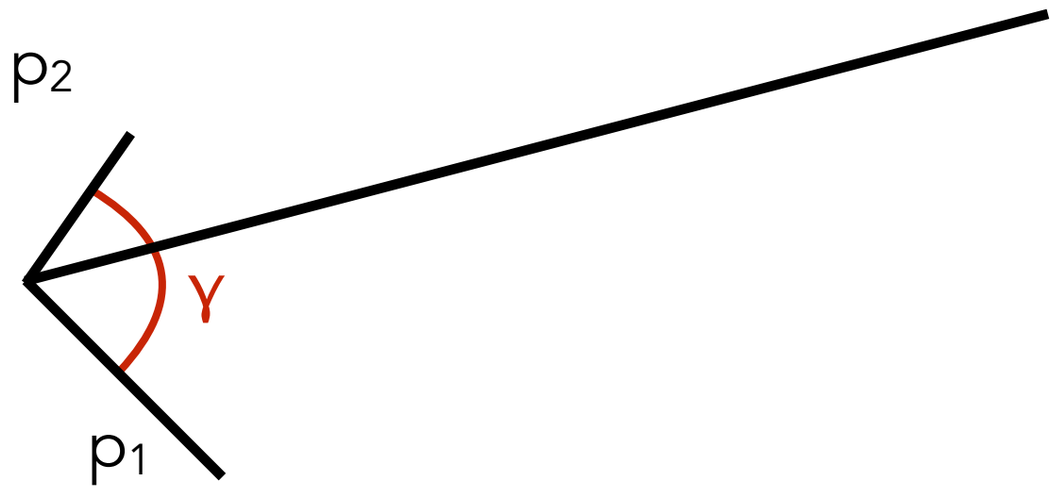
The ArgoNeuT Experiment

Results - Back-to-back protons

Phys. Rev. D90, 012008 (2014)

Selection: ν_μ CC0π with 2 protons in the final state



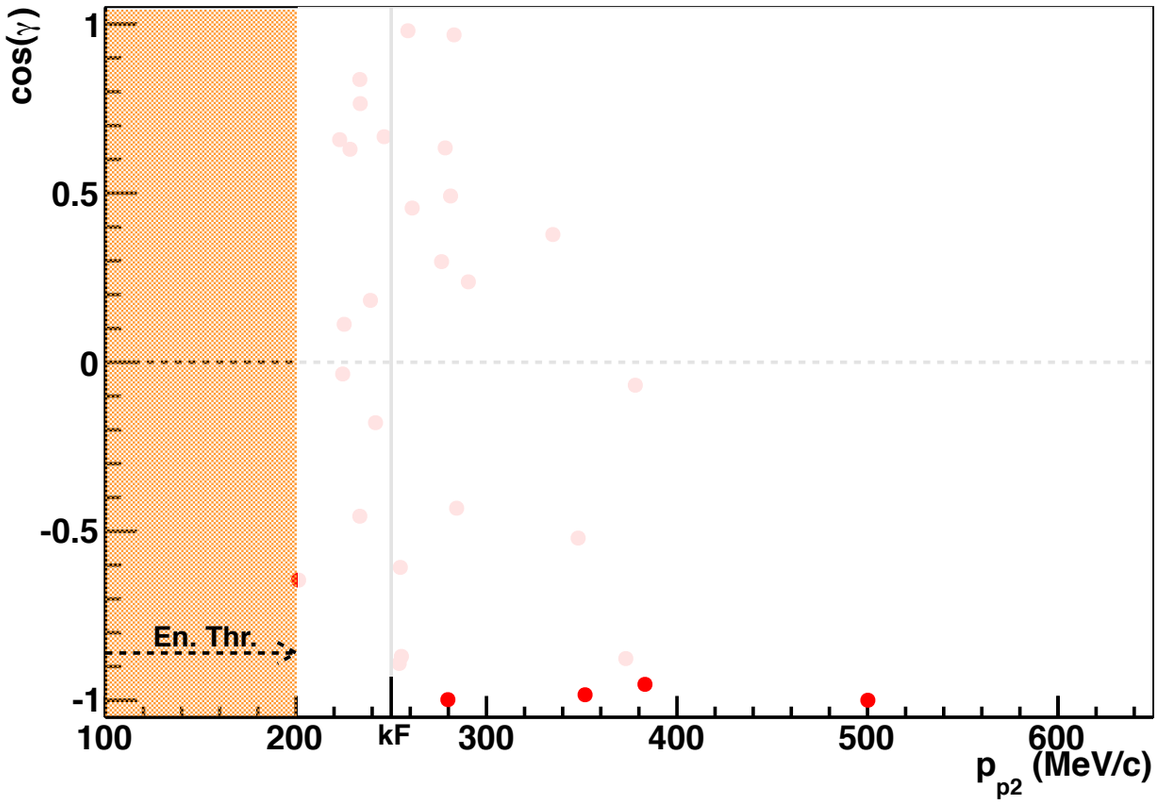


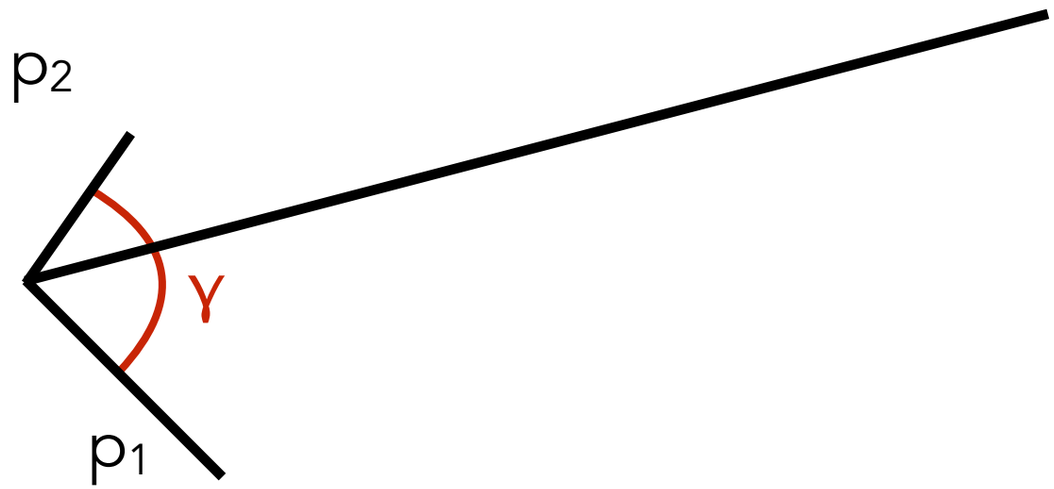
The ArgoNeuT Experiment

Results - Back-to-back protons

Phys. Rev. D90, 012008 (2014)

Selection: ν_μ CC0π with 2 protons in the final state





30 fully reconstructed events

19 have protons above Fermi momentum of Ar

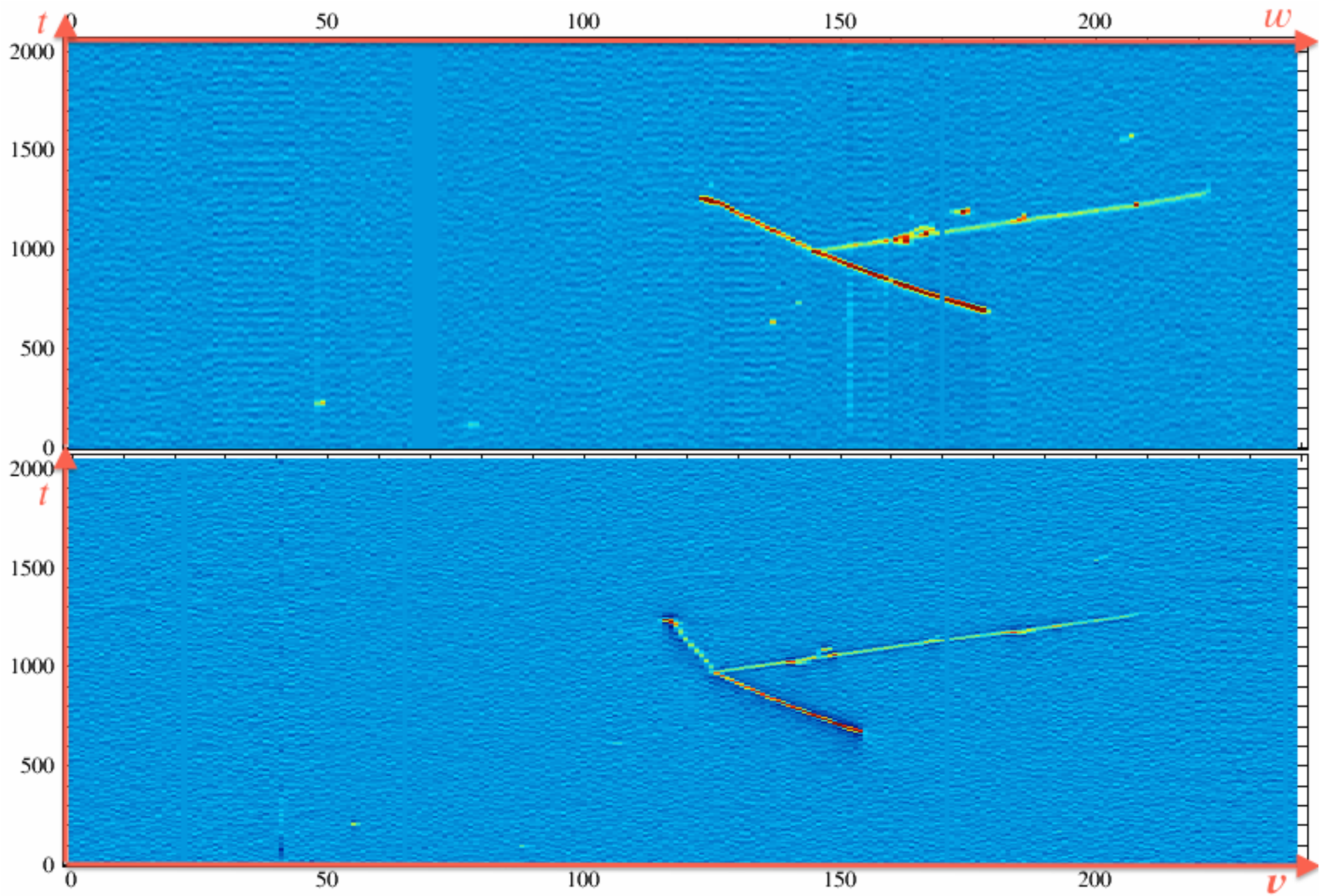
4 events have back-to-back protons

The ArgoNeuT Experiment

Results - Back-to-back protons

Phys. Rev. D90, 012008 (2014)

A candidate back-to-back proton pairs

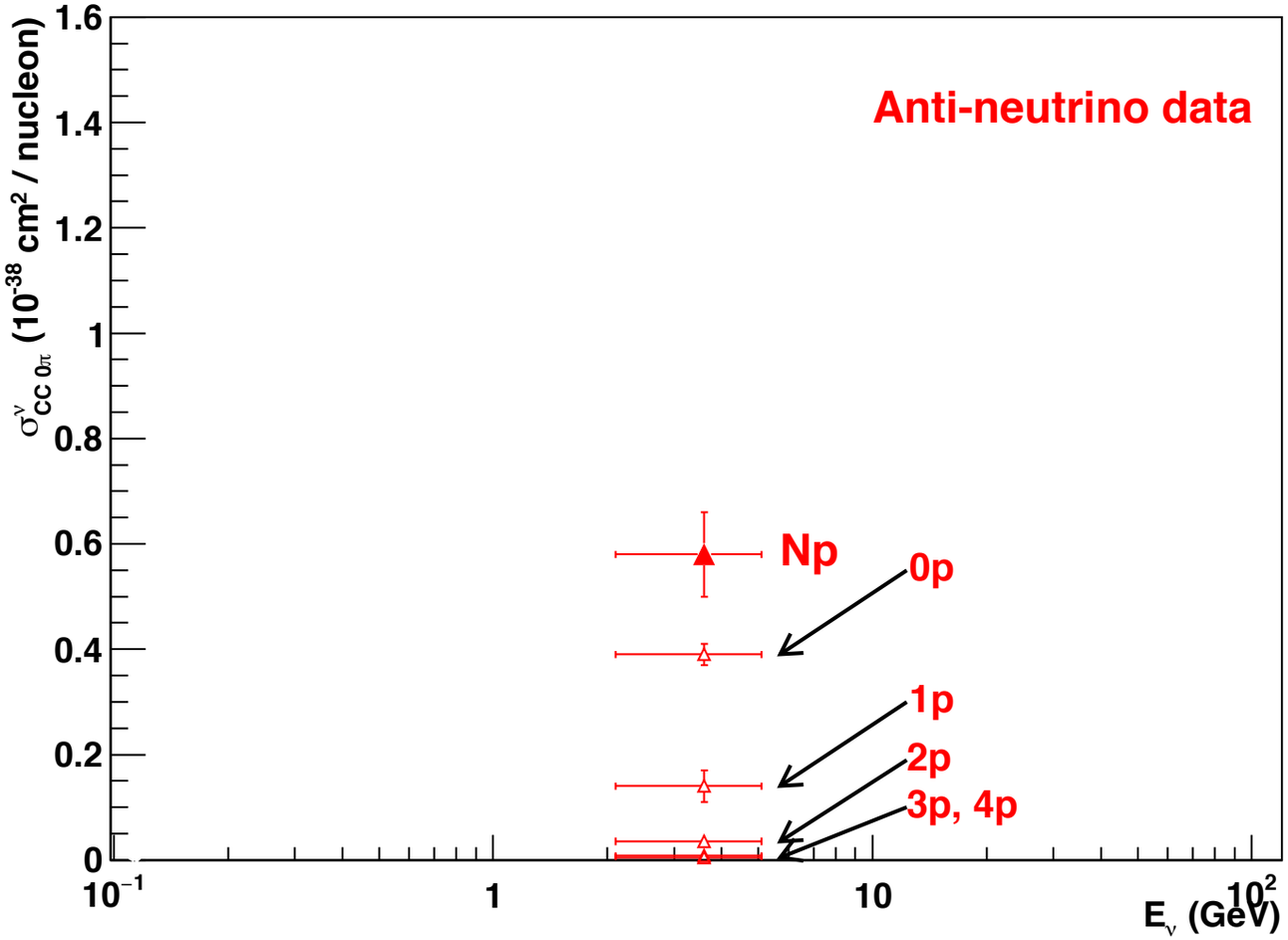


The ArgoNeuT Experiment

Results - Proton multiplicity

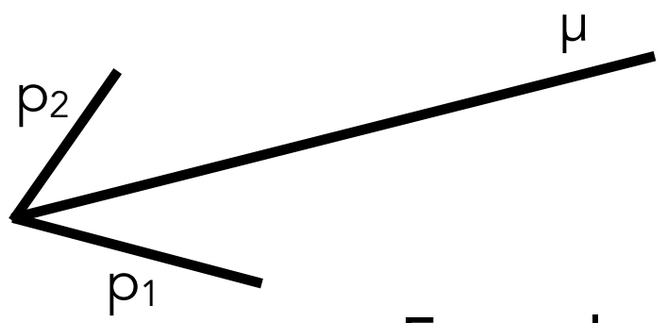
JPS Conf. Proc. 12, 010017 (2016)

ArgoNeuT performed an exclusive (anti-)ν_μ CC0π cross section measurement

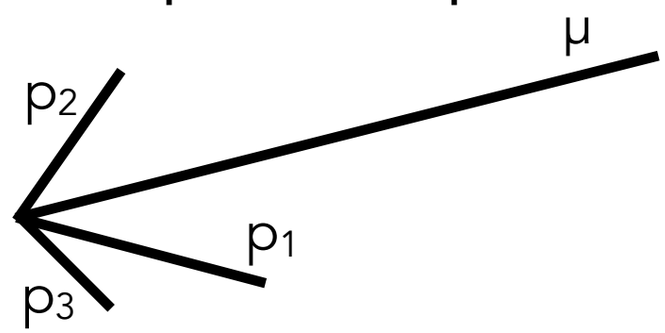


They looked at the number of protons coming out from the interaction

Example with 2 protons



Example with 3 protons

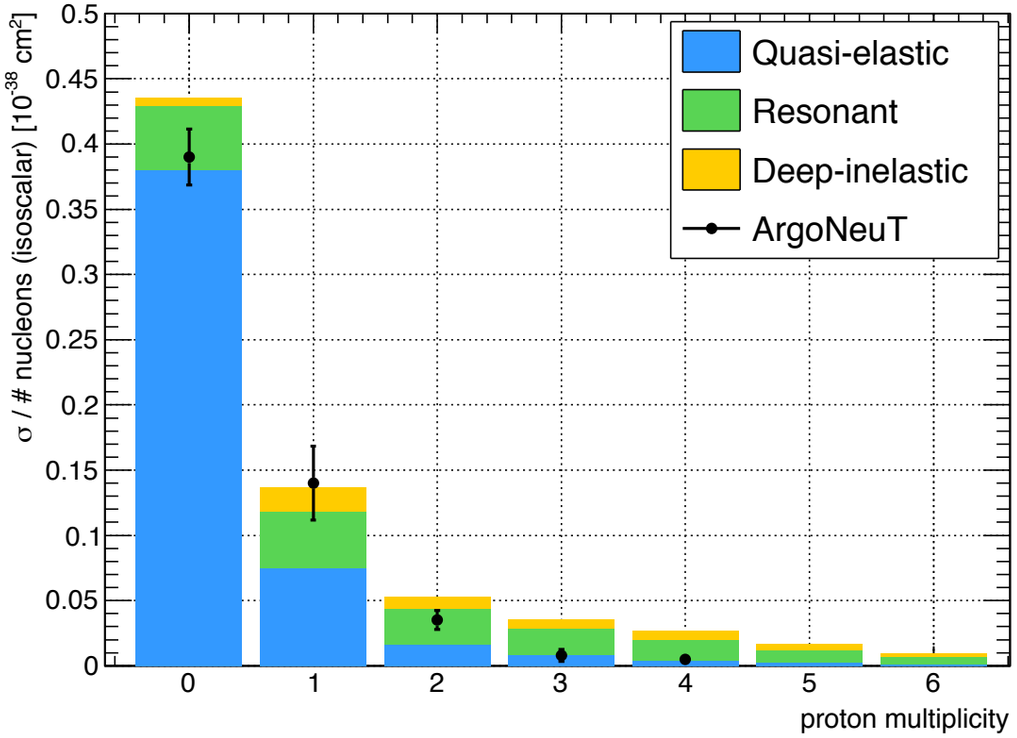


The ArgoNeuT Experiment

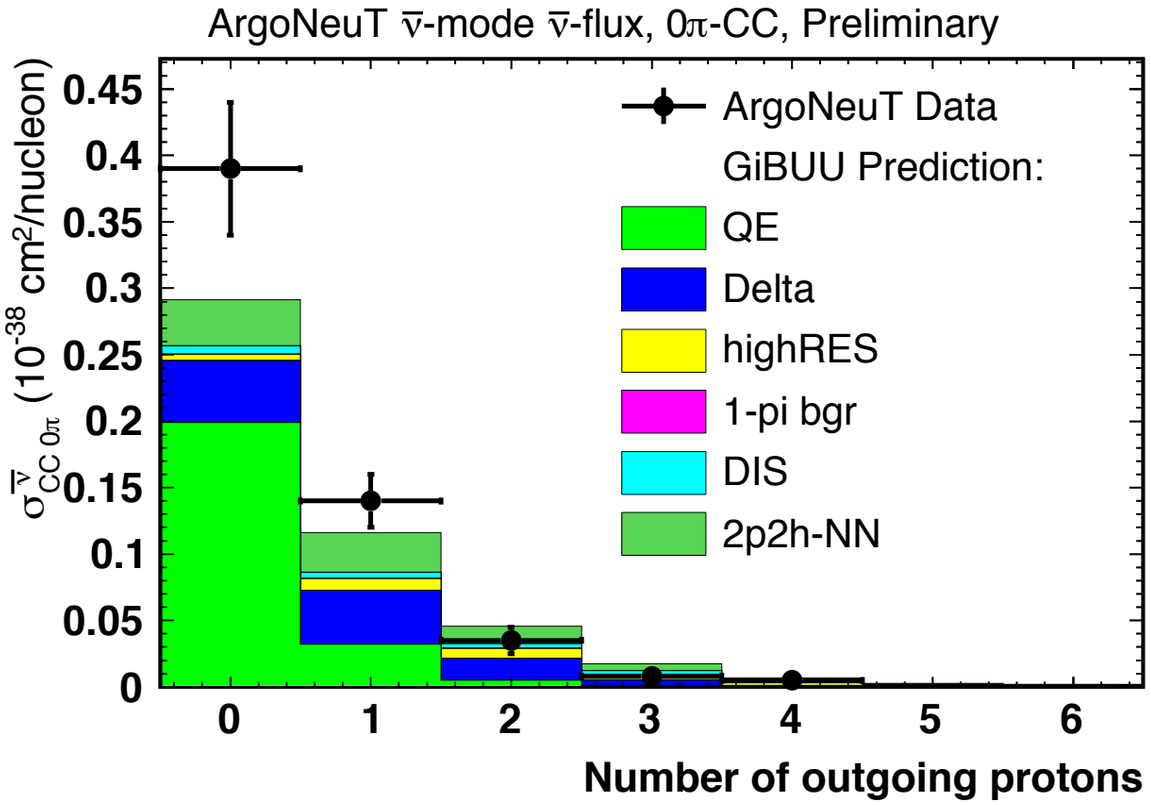
Results - Proton multiplicity

JPS Conf. Proc. 12, 010017 (2016)

Anti-ν_μ CC0π cross section measurement



GENIE prediction is 22% higher than ArgoNeuT data

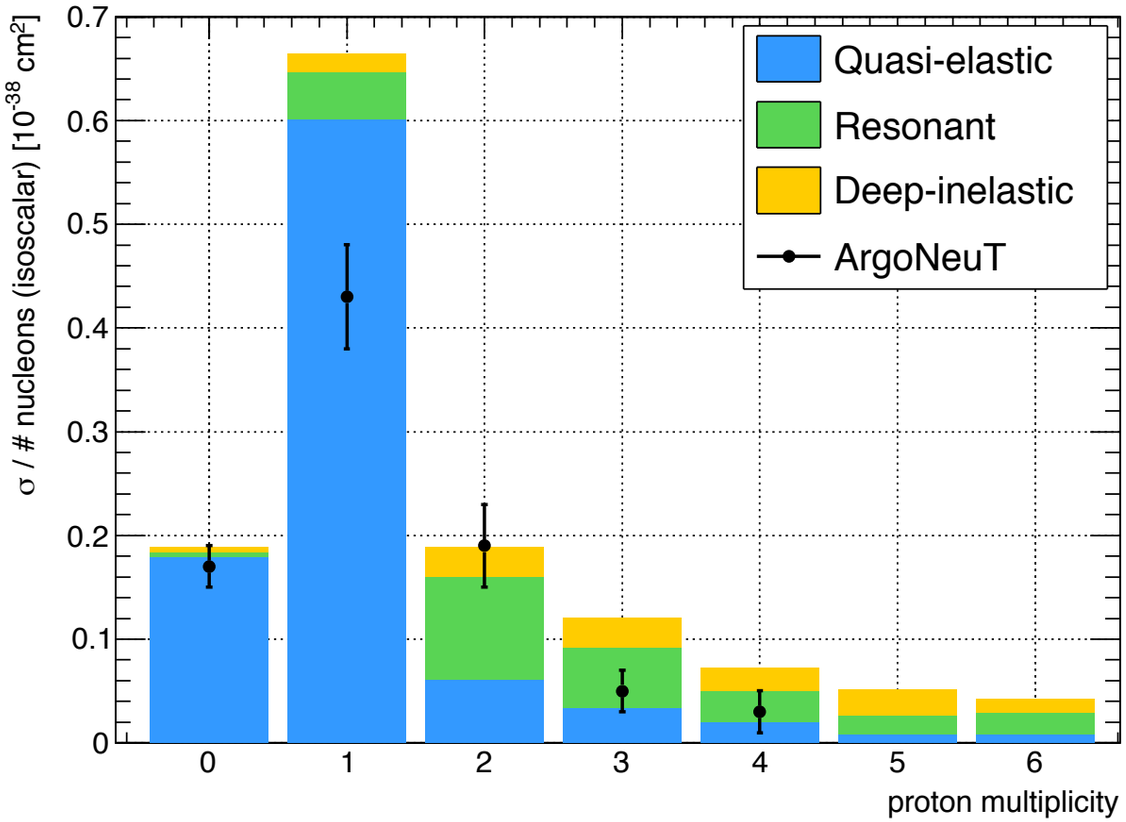


GiBUU prediction is 17% lower than ArgoNeuT data

Results - Proton multiplicity

JPS Conf. Proc. 12, 010017 (2016)

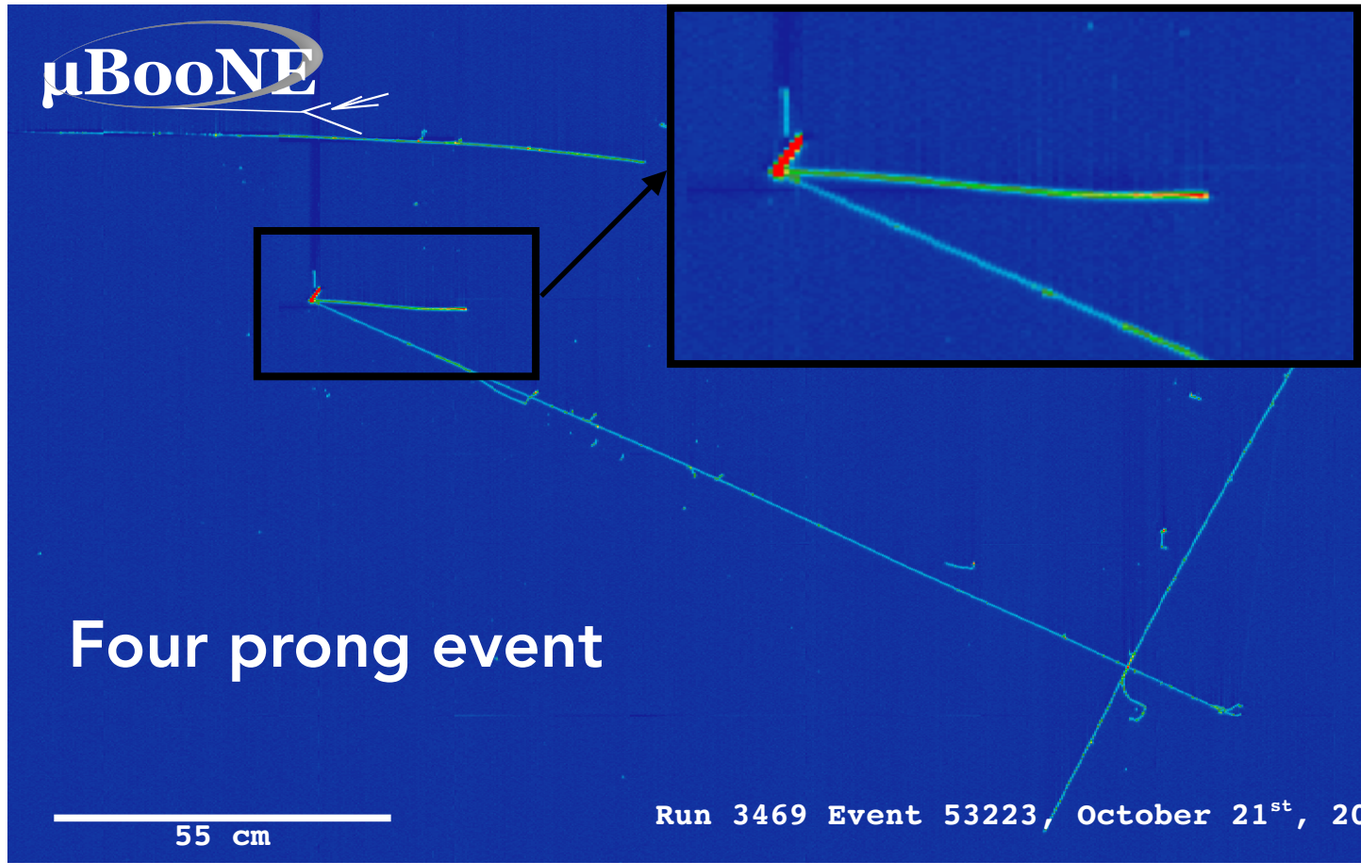
ν_μ CC0π cross section measurement



GENIE prediction is 64% higher than ArgoNeuT data

MicroBooNE Current Efforts

Particle multiplicity



MicroBooNE Current Efforts

Particle multiplicity

MICROBOONE-NOTE-1024-PUB

ν_μ CC Inclusive Filter

↓

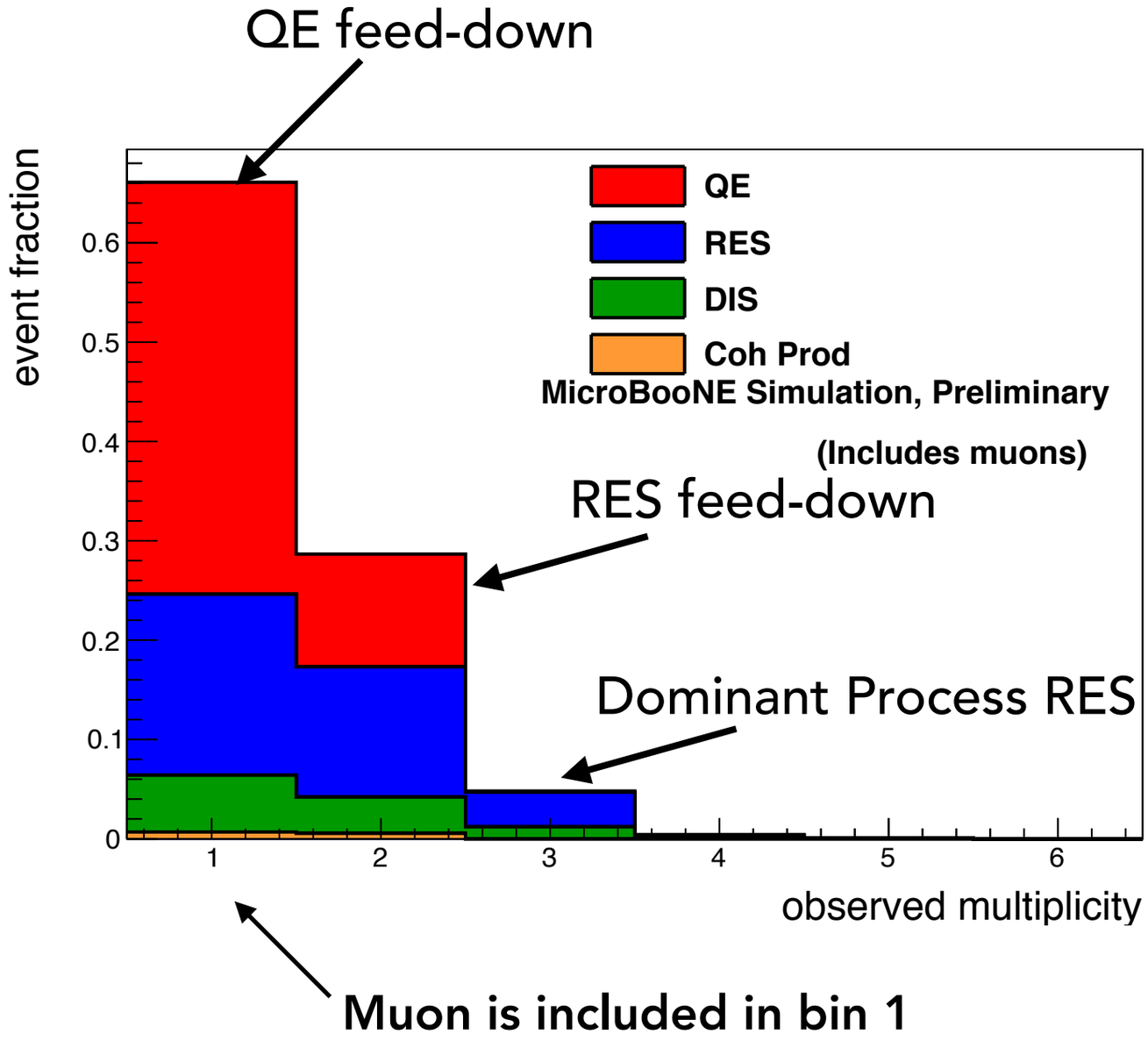
Muon Quality Filter

↓

Muon Directionality Classifier

↓

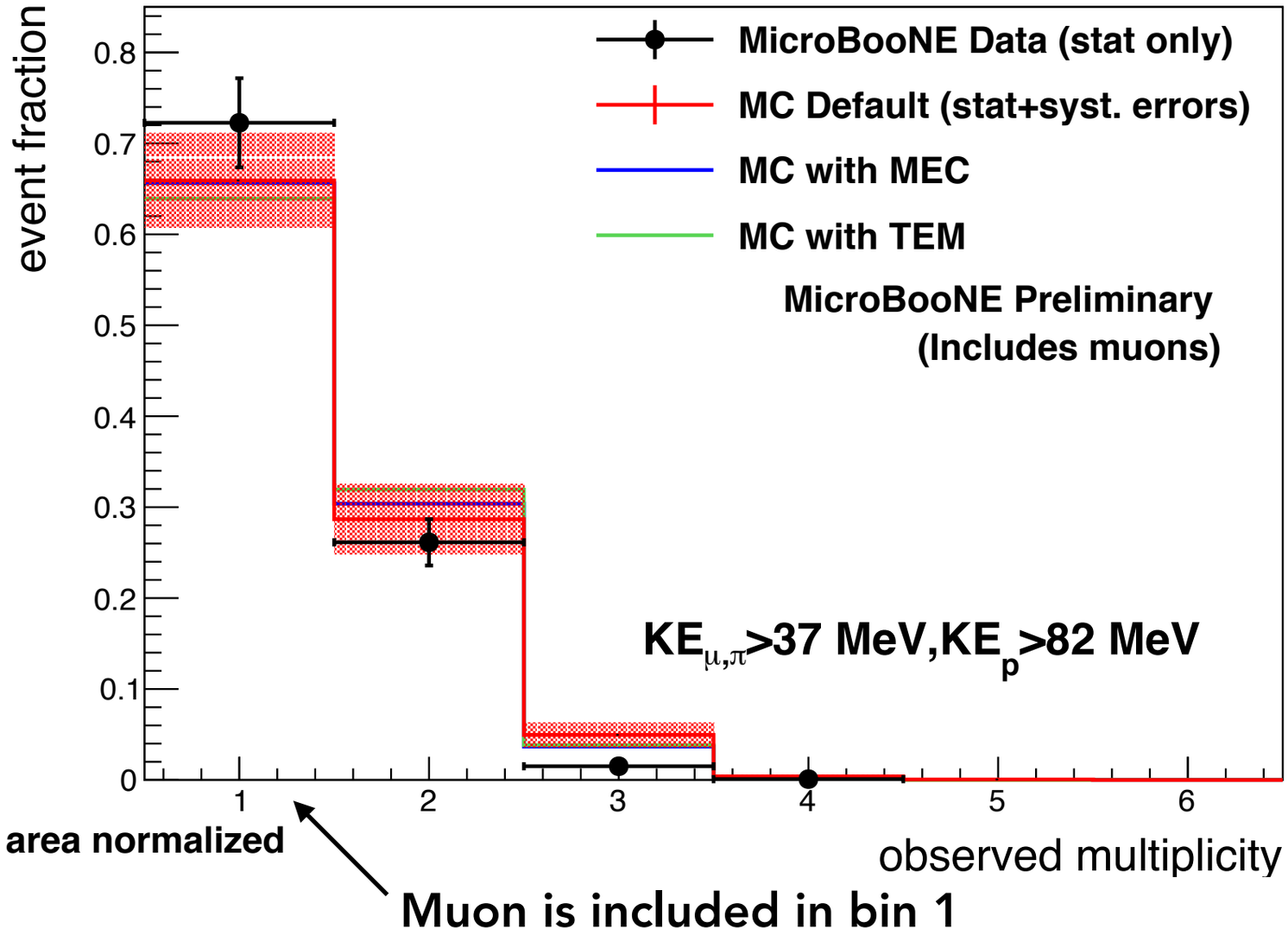
Get Particle Multiplicity (muons included)



MicroBooNE Current Efforts

Particle multiplicity

MICROBOONE-NOTE-1024-PUB

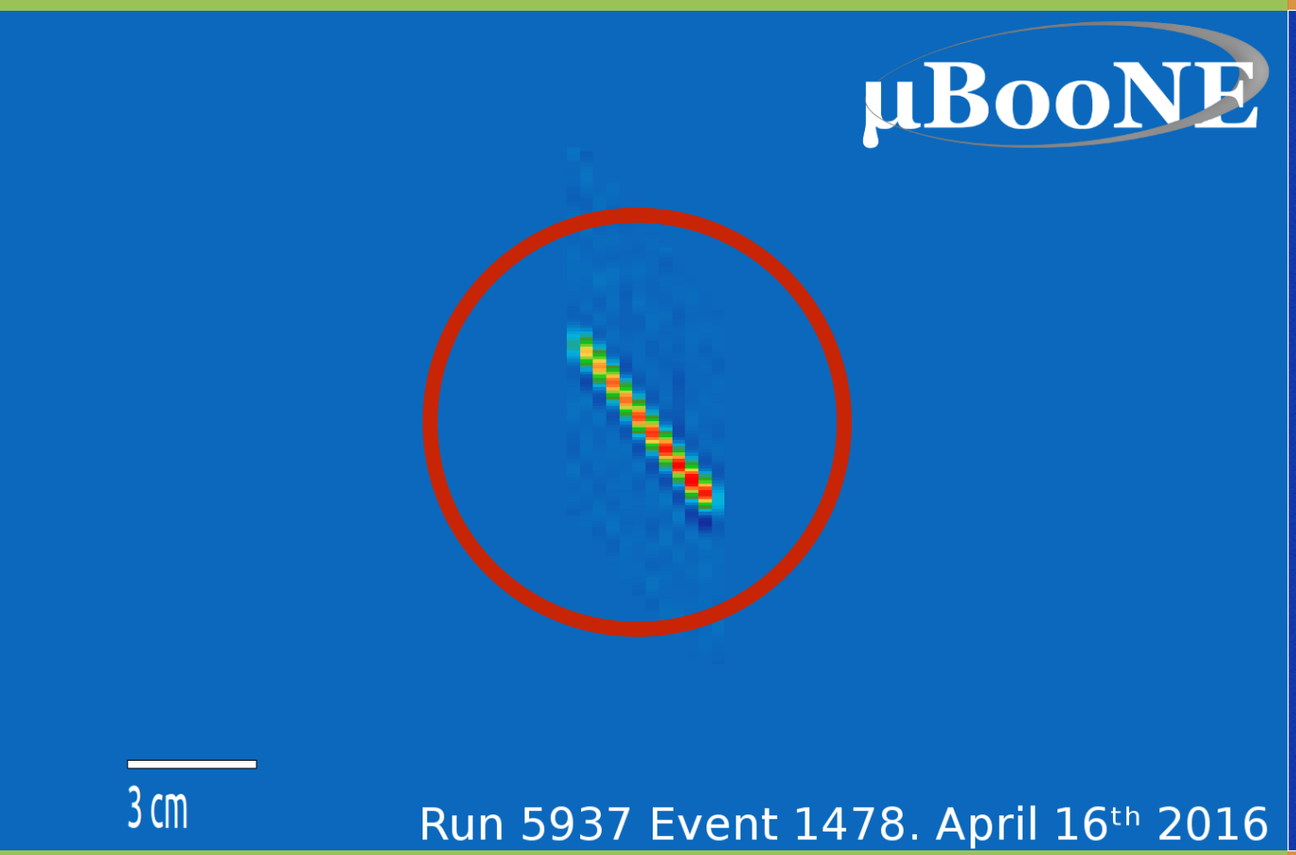


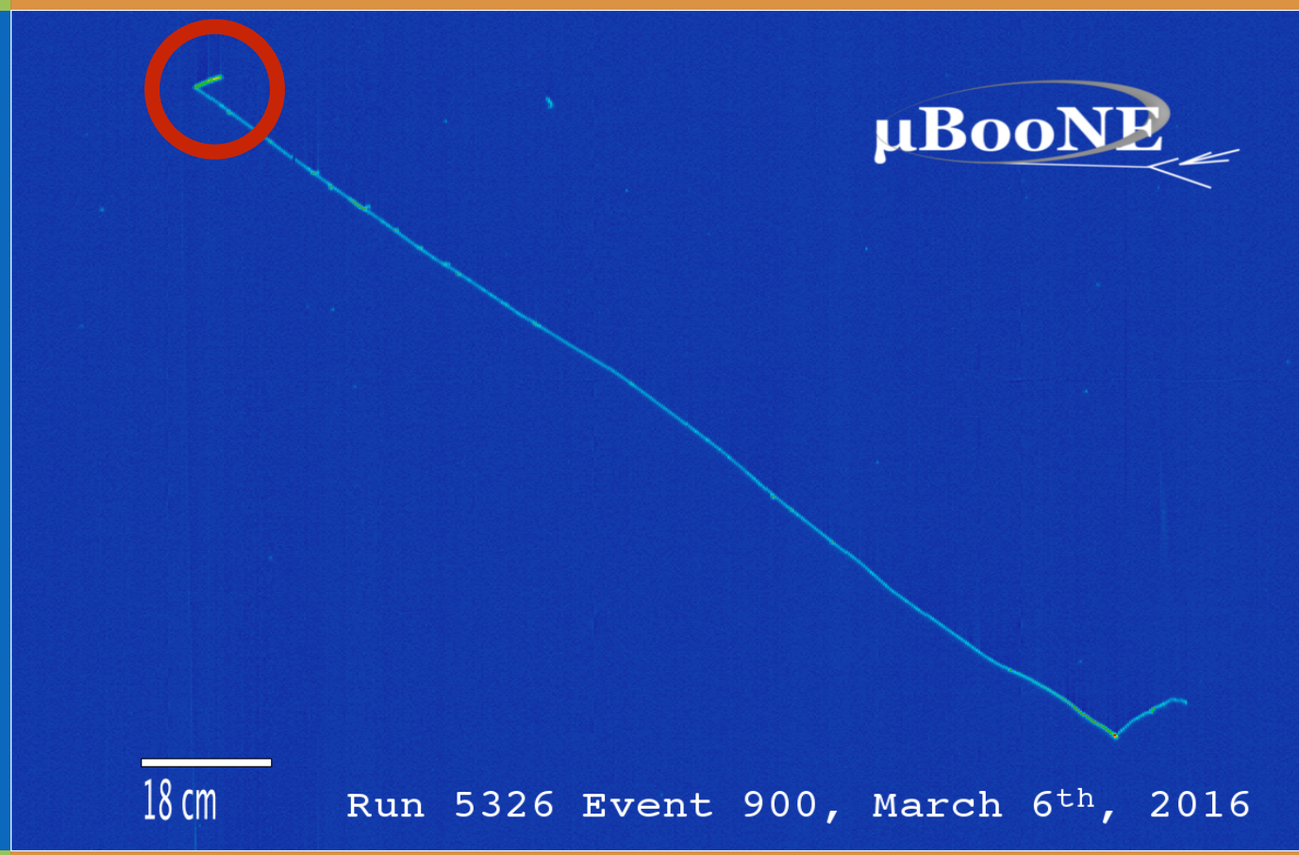
Observed multiplicity after event selection, no efficiency correction

Future: improve statistics and lower threshold per particle type

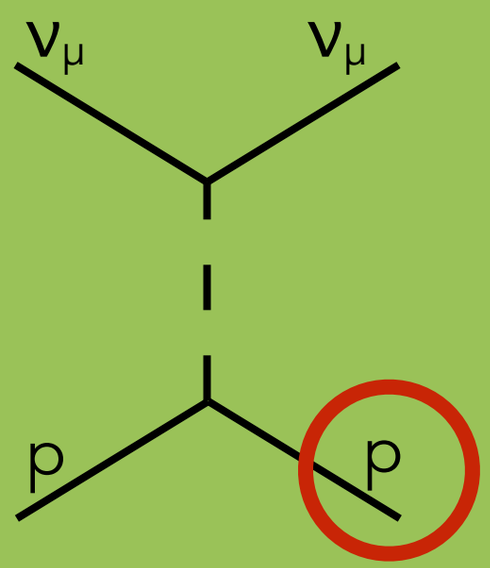
Neutral Current

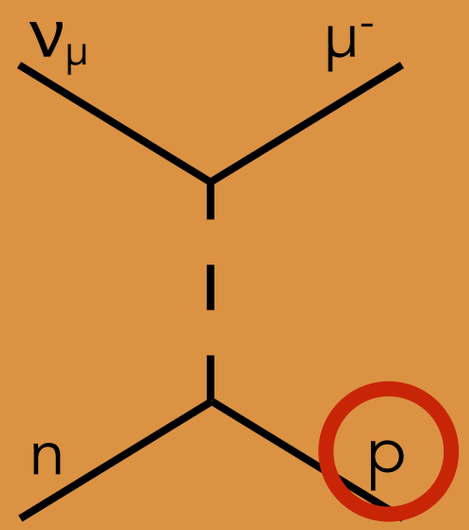
Charged Current





Now Focusing on Proton Identification

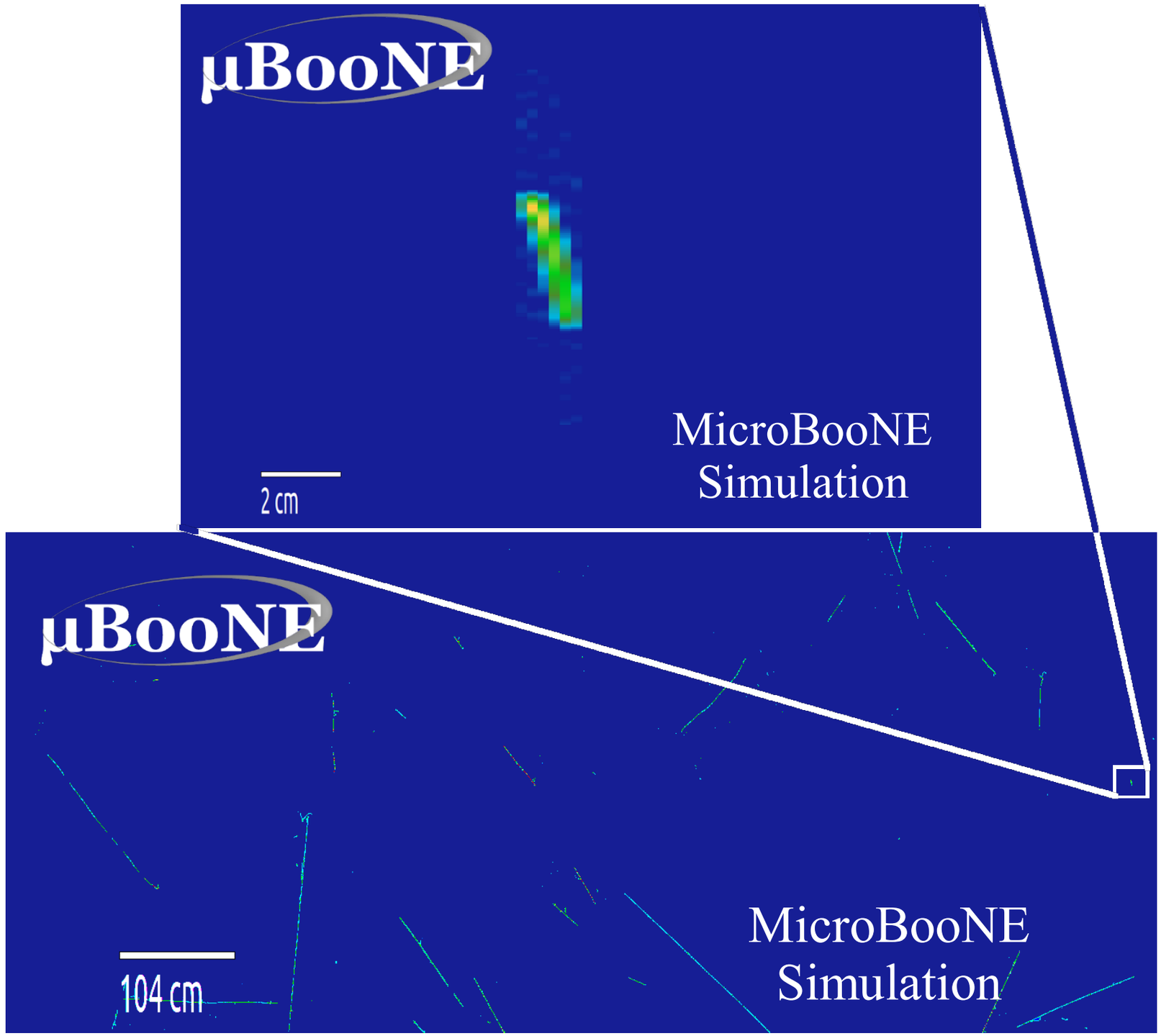




MicroBooNE Current Efforts

Proton Identification

MICROBOONE-NOTE-1025-PUB



MicroBooNE Current Efforts

Proton Identification

- We are able to detect protons that traverse as few as five wires (1.5 cm)
- We expect 10,000 NC elastic proton events during MicroBooNE's three year run
- Makes up ~5% of neutrino interactions in MicroBooNE

Large cosmic background:

- Need automated reconstruction and selection!
- **Hasn't been done before in a LArTPC!**

MicroBooNE Current Efforts

Proton Identification

K. Woodruff,
ACAT2017

Wire Waveform

↓

Hit Reconstruction

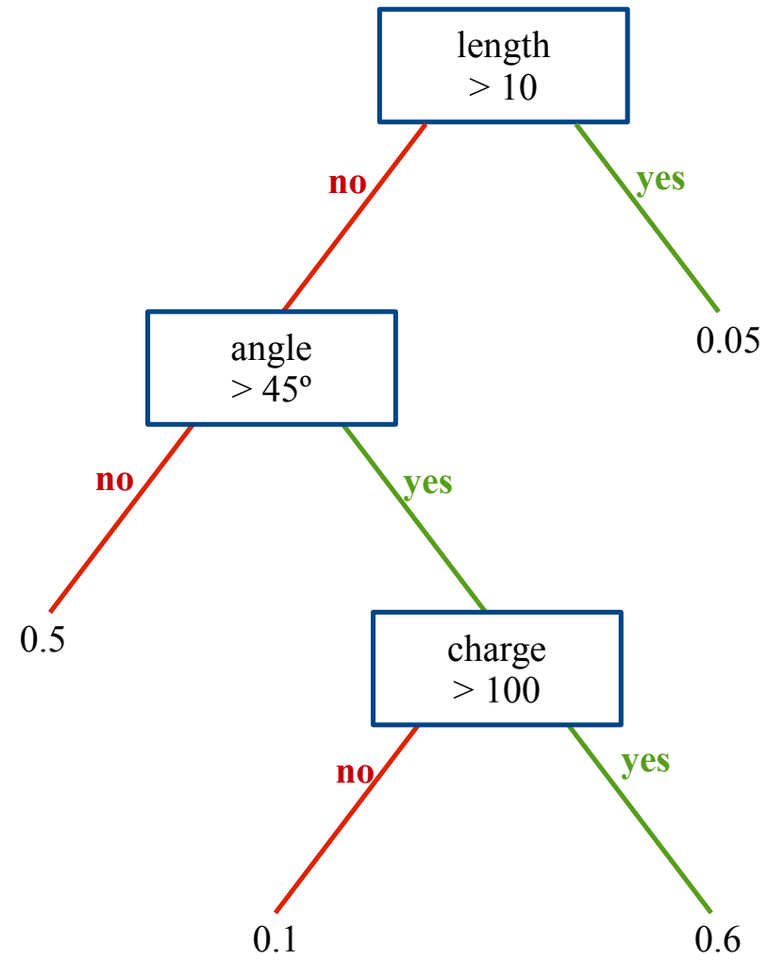
↓

Track Finding

↓

Track Features:
Position
Angle
Shape
Charge

→ **Boosted Decision Tree**

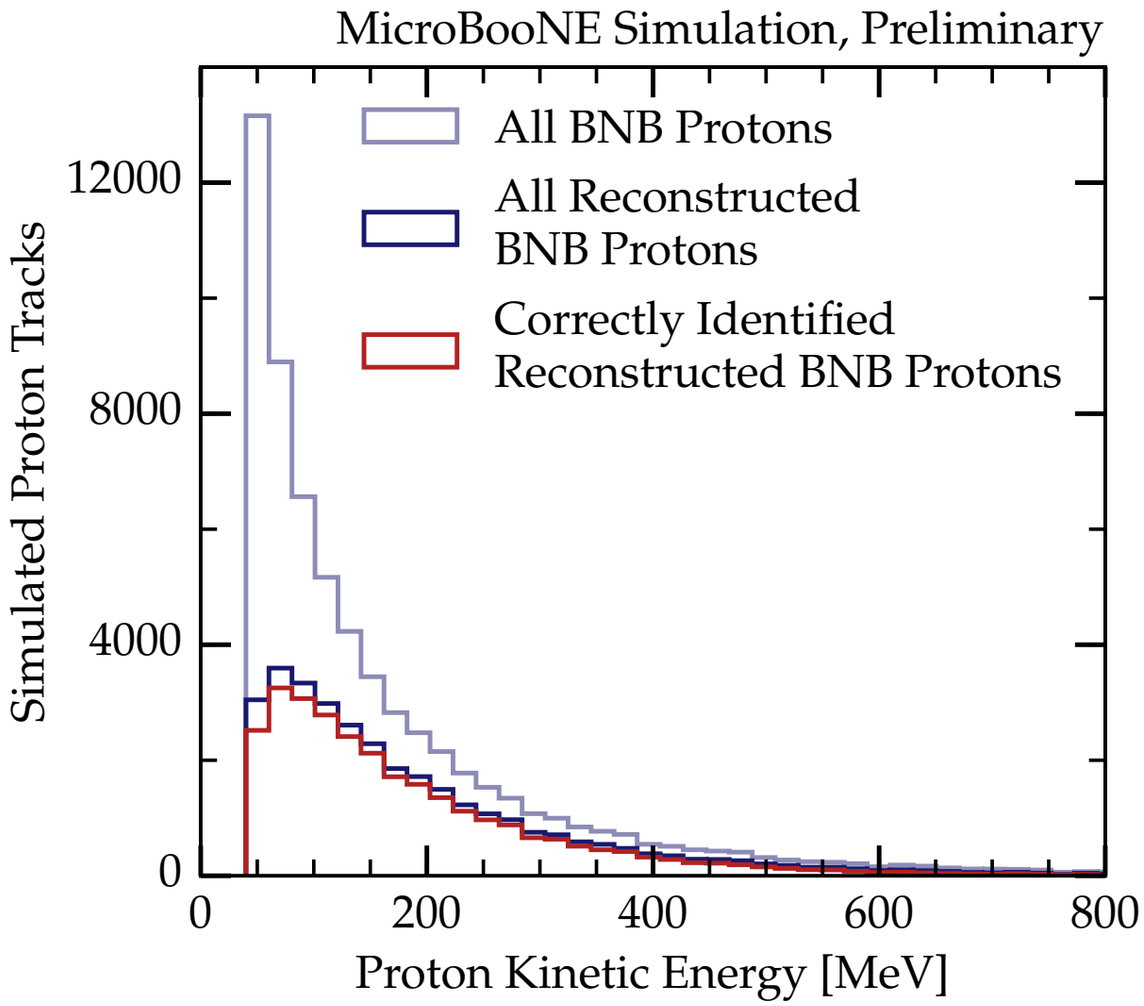


MicroBooNE Current Efforts

Proton Identification

MICROBOONE-NOTE-1025-PUB

Showing the number of simulated neutrino-induced ("BNB") protons **generated**, **reconstructed**, and **classified correctly**

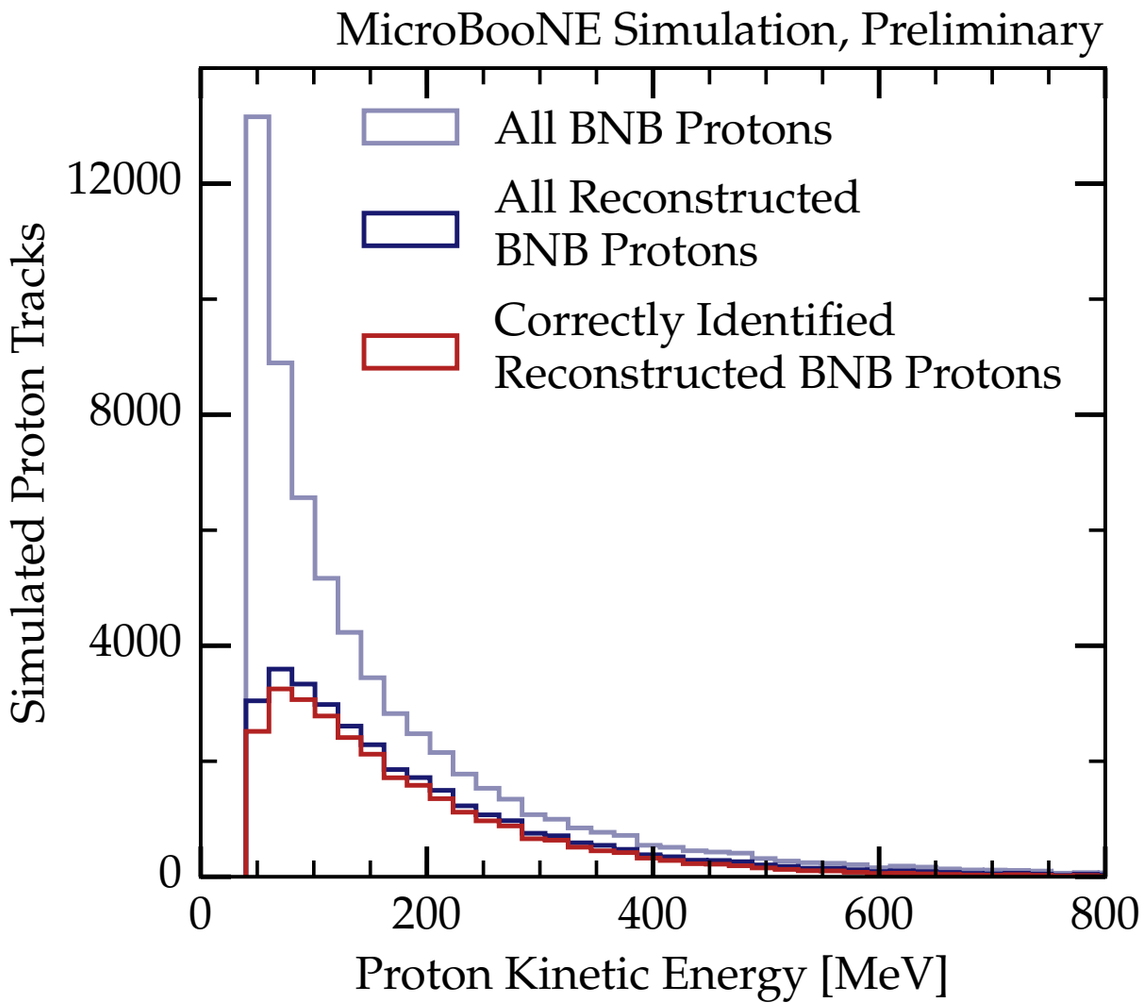


MicroBooNE Current Efforts

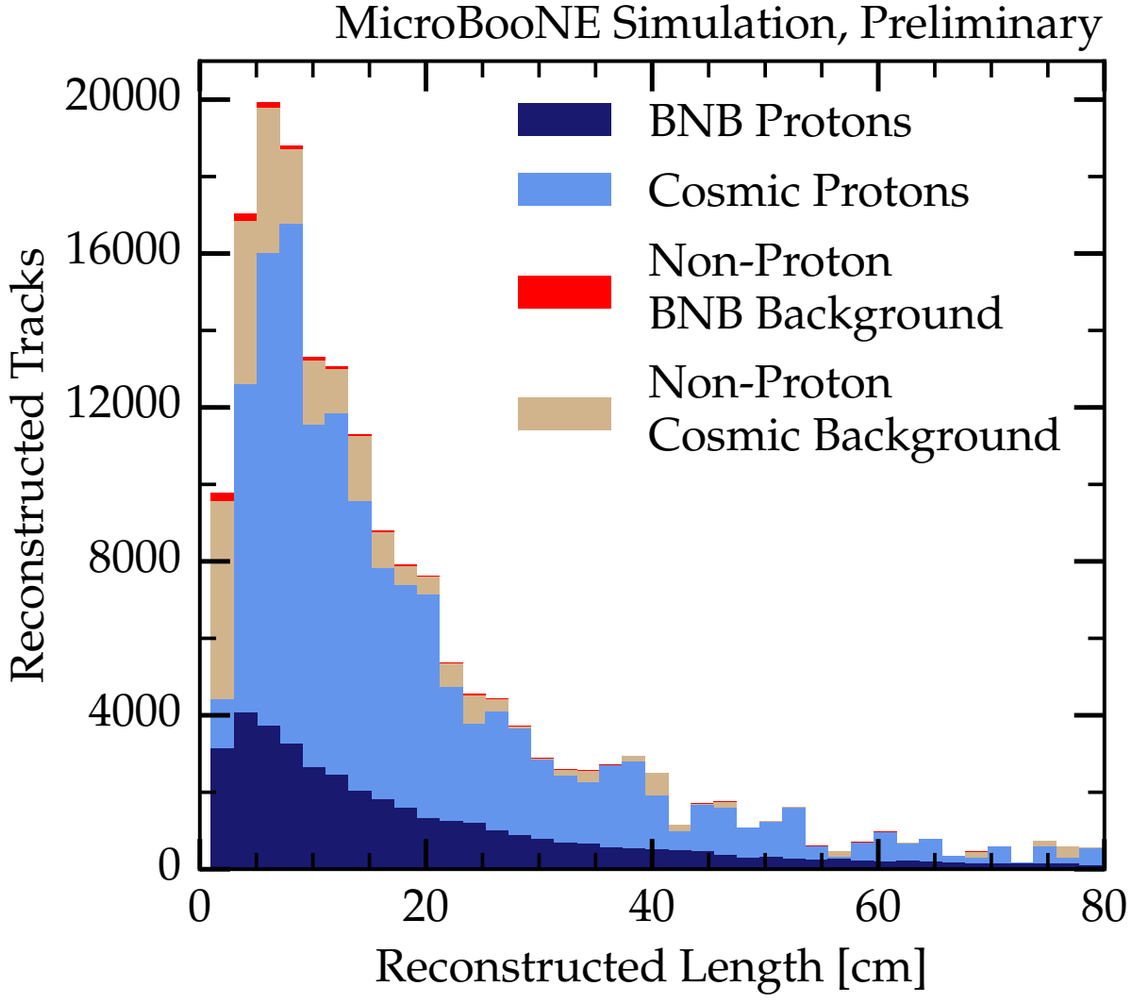
Proton Identification

MICROBOONE-NOTE-1025-PUB

Showing the number of simulated neutrino-induced ("BNB") protons **generated**, **reconstructed**, and **classified correctly**



Showing the different simulated track types classified as protons



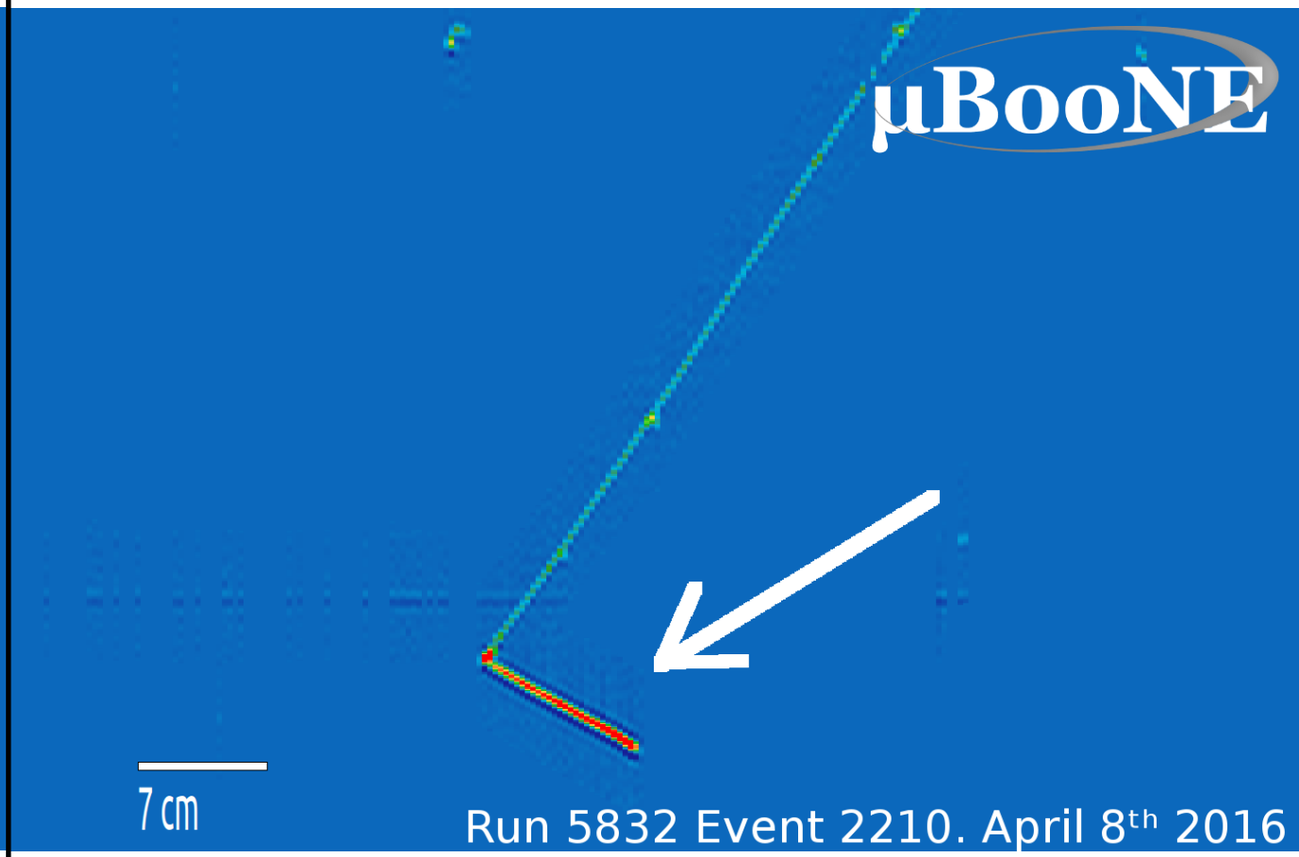
MicroBooNE Current Efforts

Proton Identification

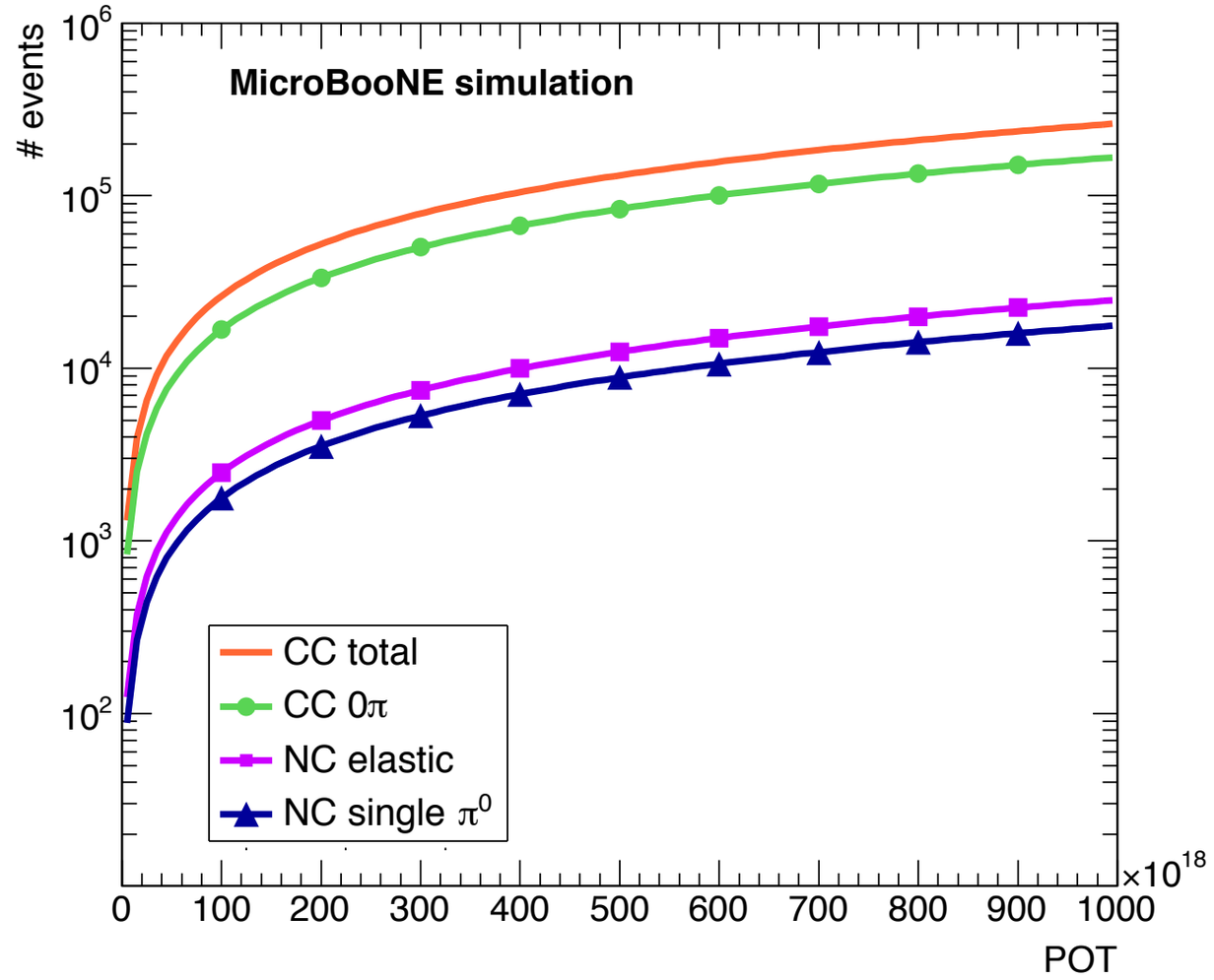
MICROBOONE-NOTE-1025-PUB

NC Candidate

CC Candidate



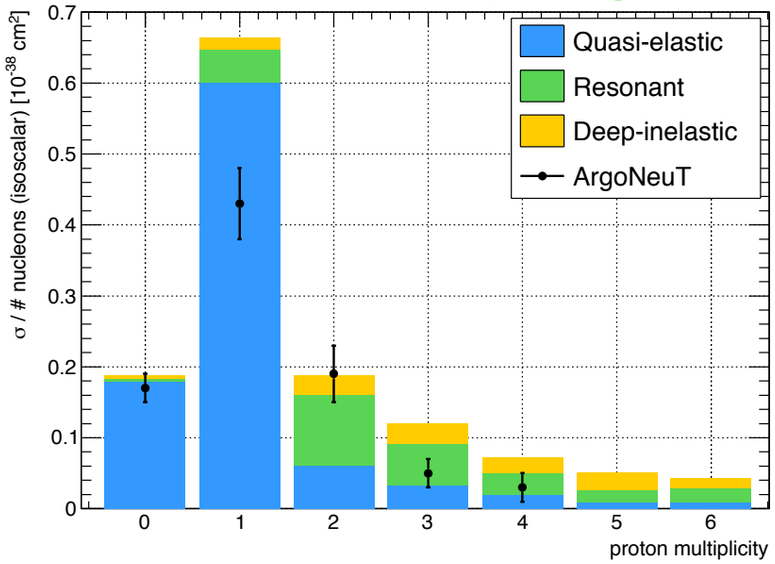
MicroBooNE in the Future



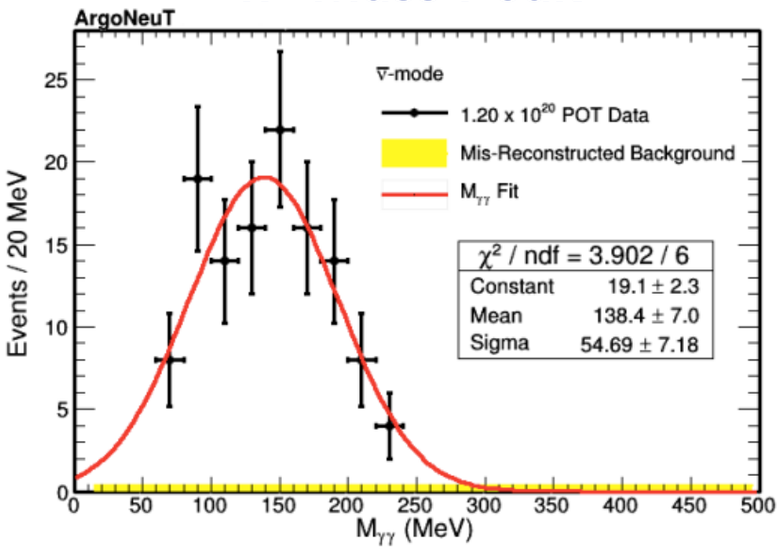
Slide Courtesy: A. Schukraft

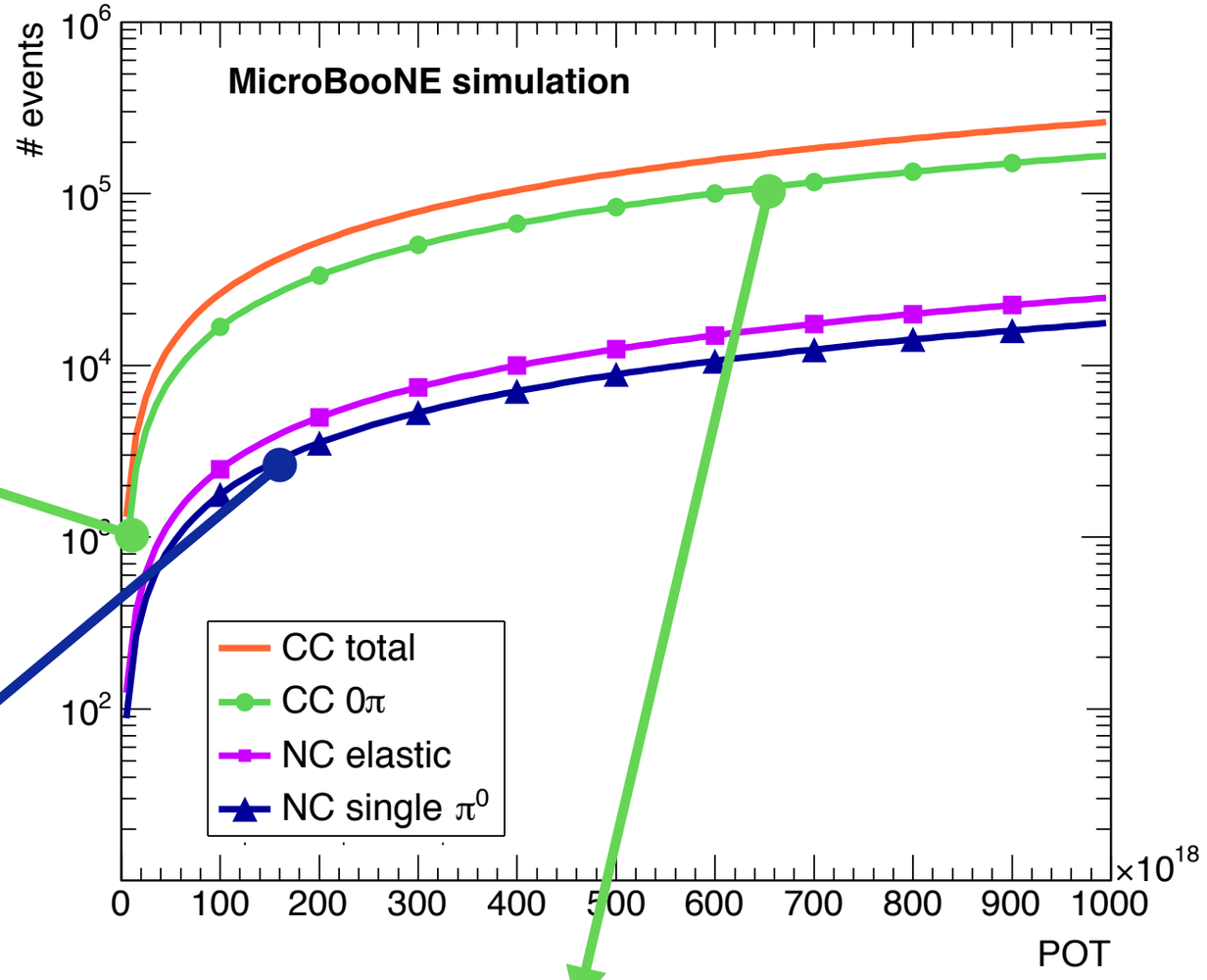
MicroBooNE in the Future

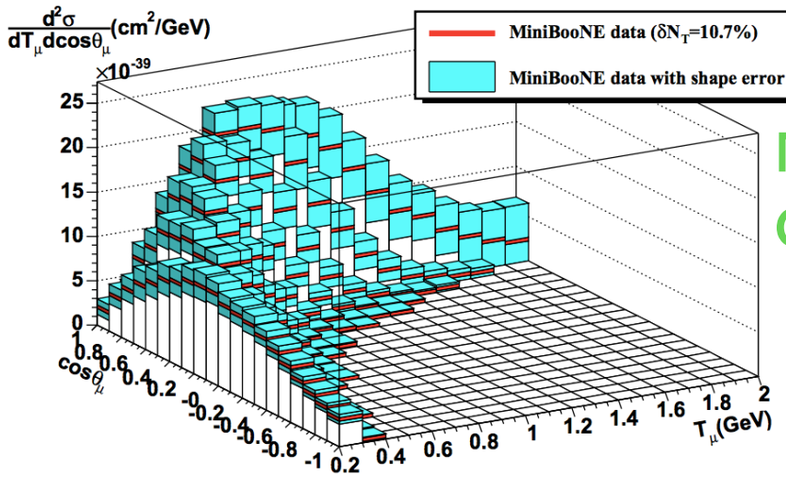
ArgoNeuT
Proton Multiplicity



ArgoNeuT
π^0 Mass Peak





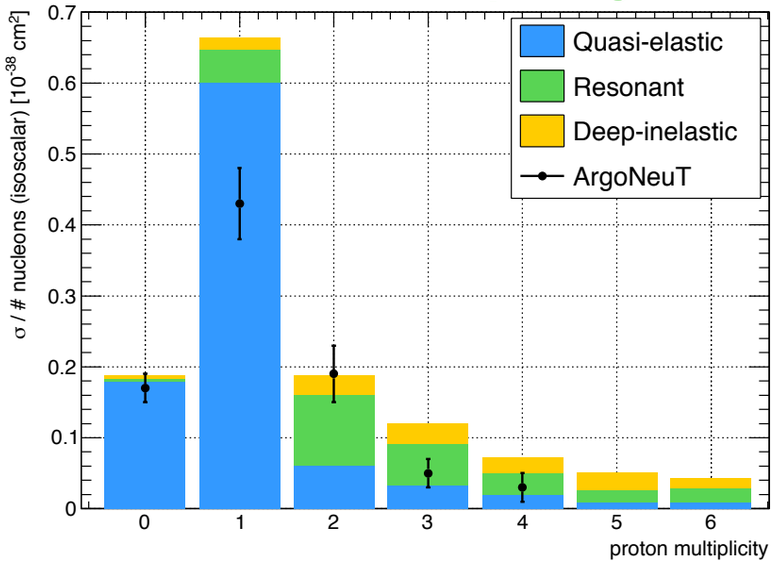


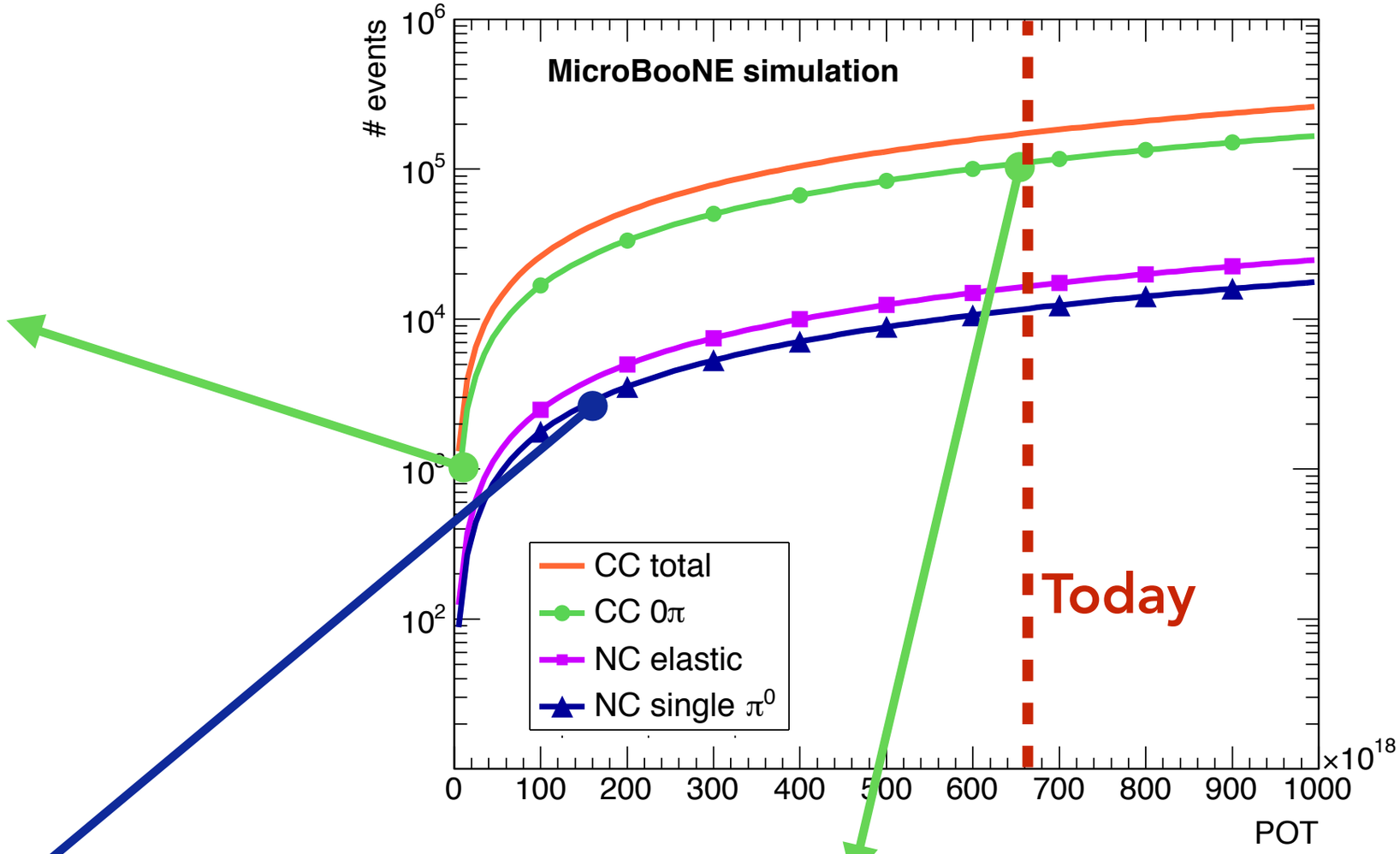
MiniBooNE
CCQE Cross Section

Slide Courtesy: A. Schukraft

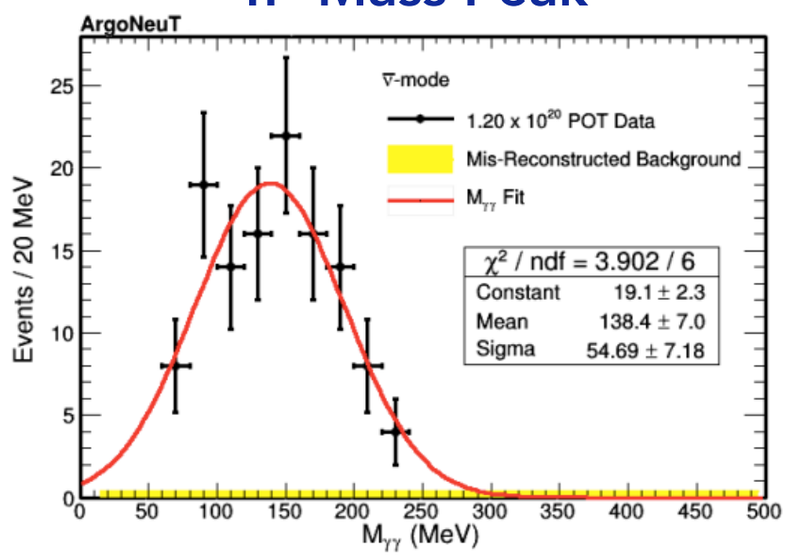
MicroBooNE in the Future

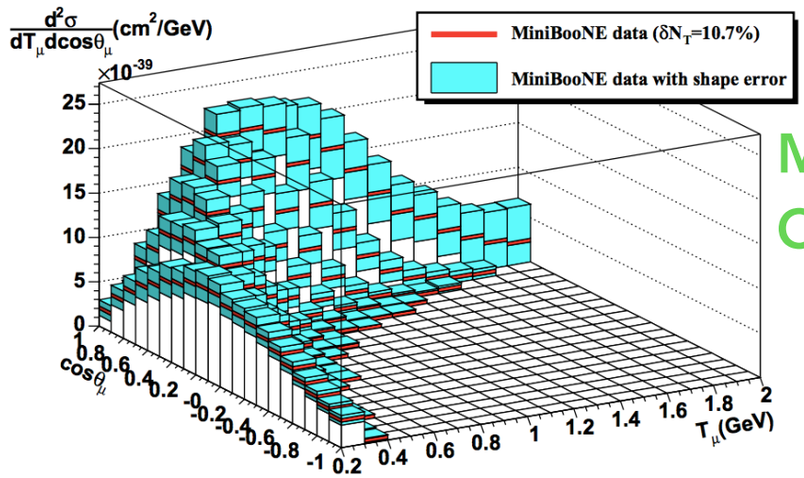
ArgoNeuT
Proton Multiplicity





ArgoNeuT
π⁰ Mass Peak



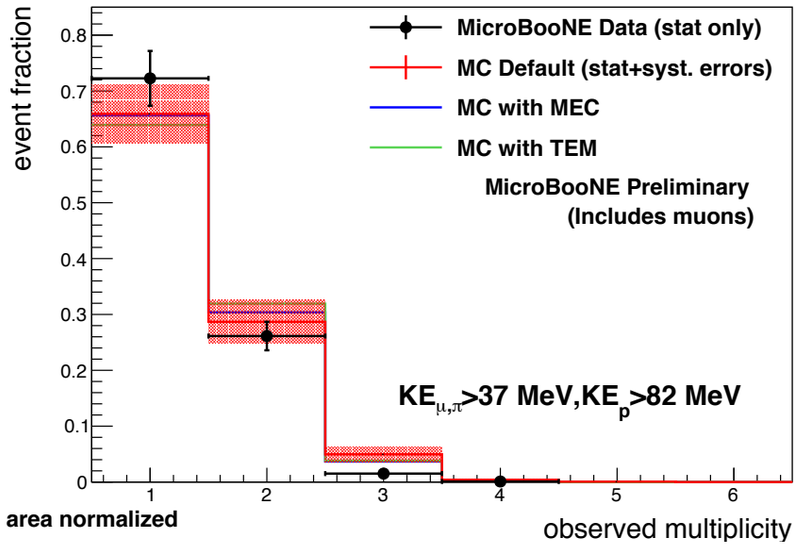


MiniBooNE
CCQE Cross Section

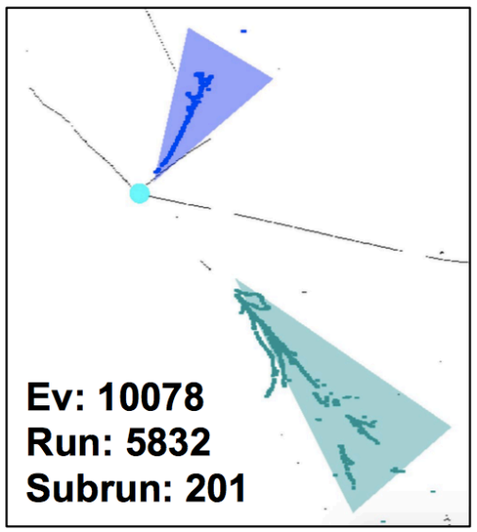
Slide Courtesy: A. Schukraft

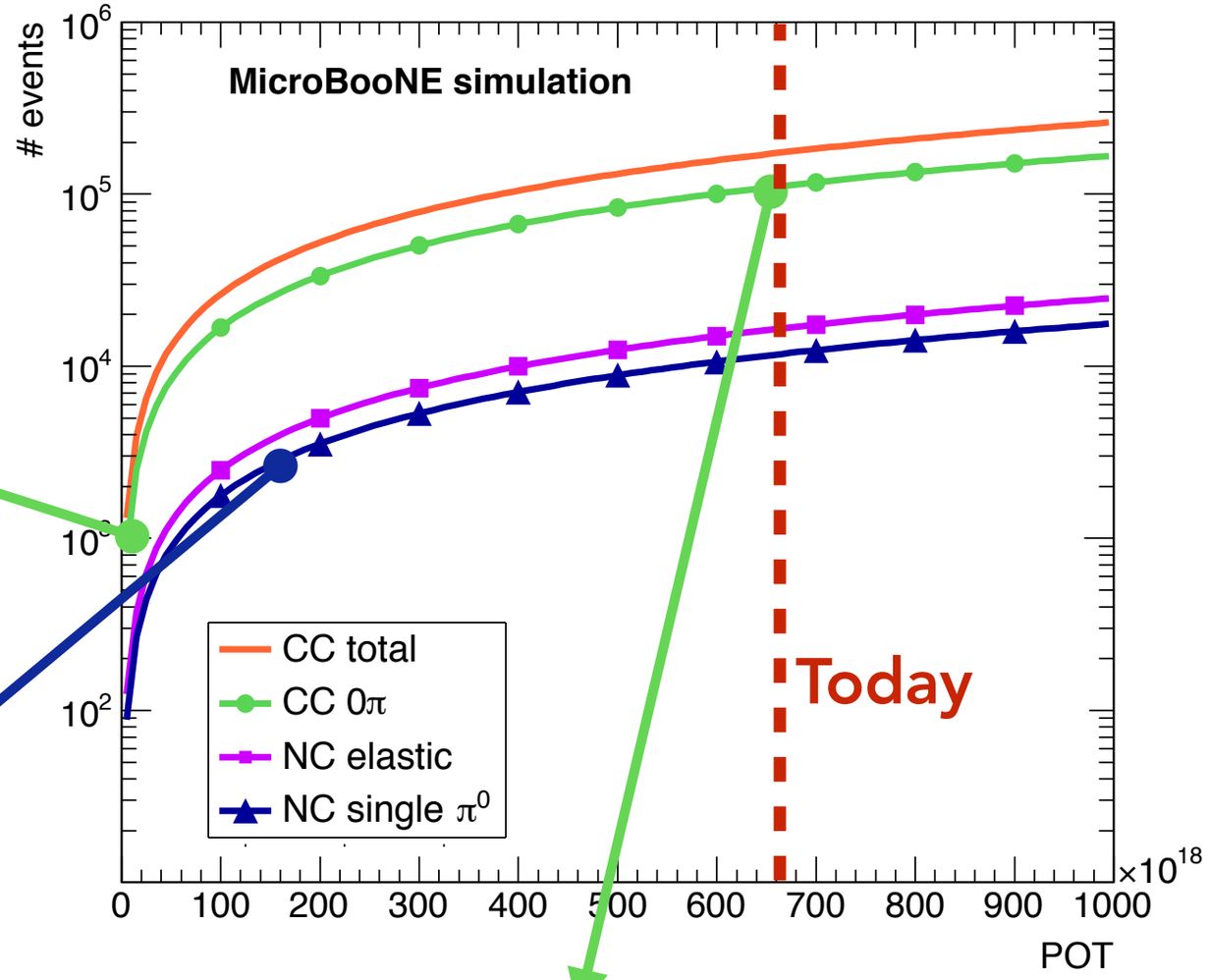
MicroBooNE in the Future

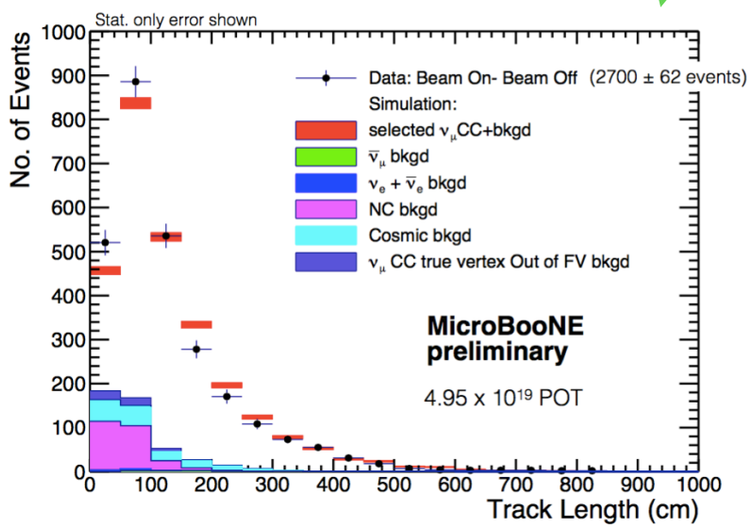
MicroBooNE Particle Multiplicity



MicroBooNE Towards a π^0 Mass Peak



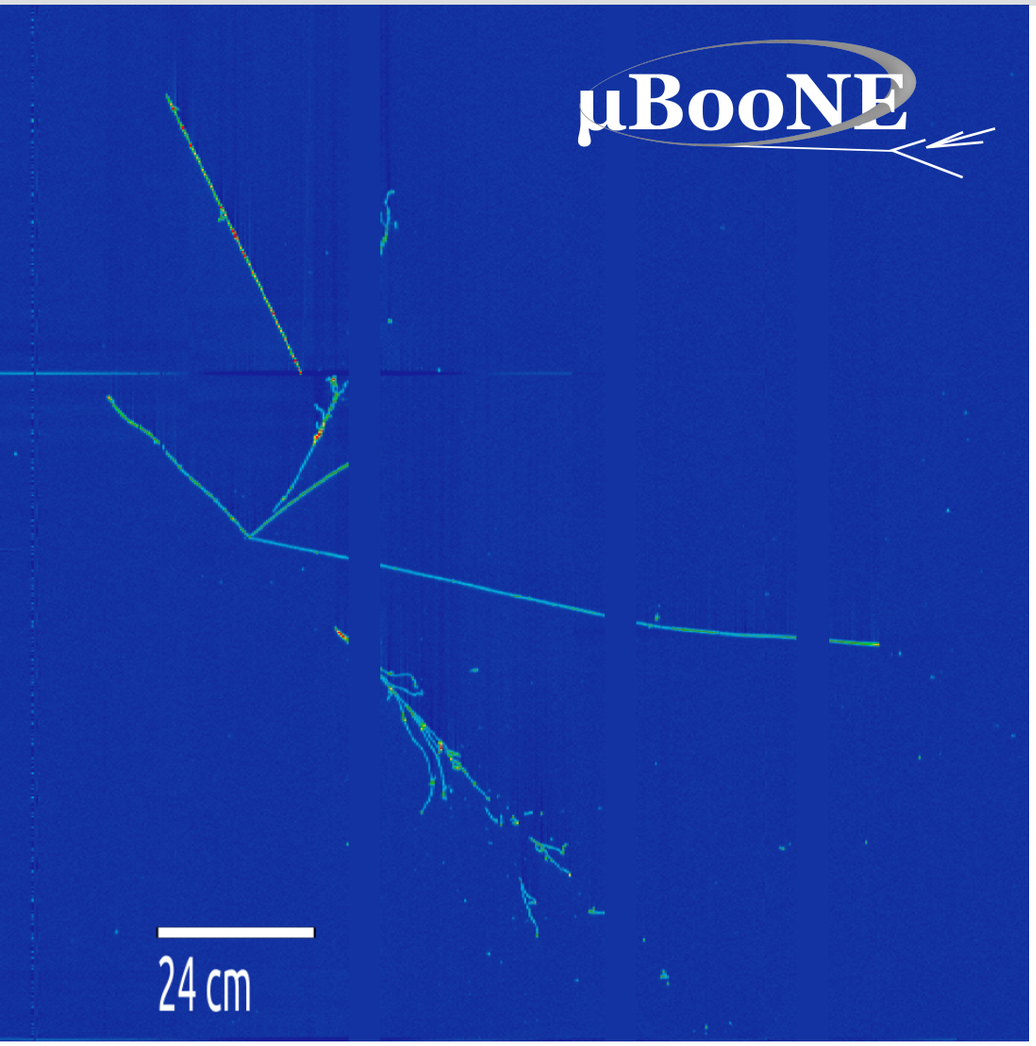




MicroBooNE Event Distribution towards a Cross Section Measurement

MicroBooNE Current Efforts

CCπ^0 Channel



Use CC Muon filter to select CC + π^0 events

- Enables data-based electromagnetic shower reconstruction.
- Characterise background for electron neutrino search.
- π^0 energy reconstruction is excellent validation of detector calibration.
- Pion production is an interesting cross section measurement for LArTPCs.

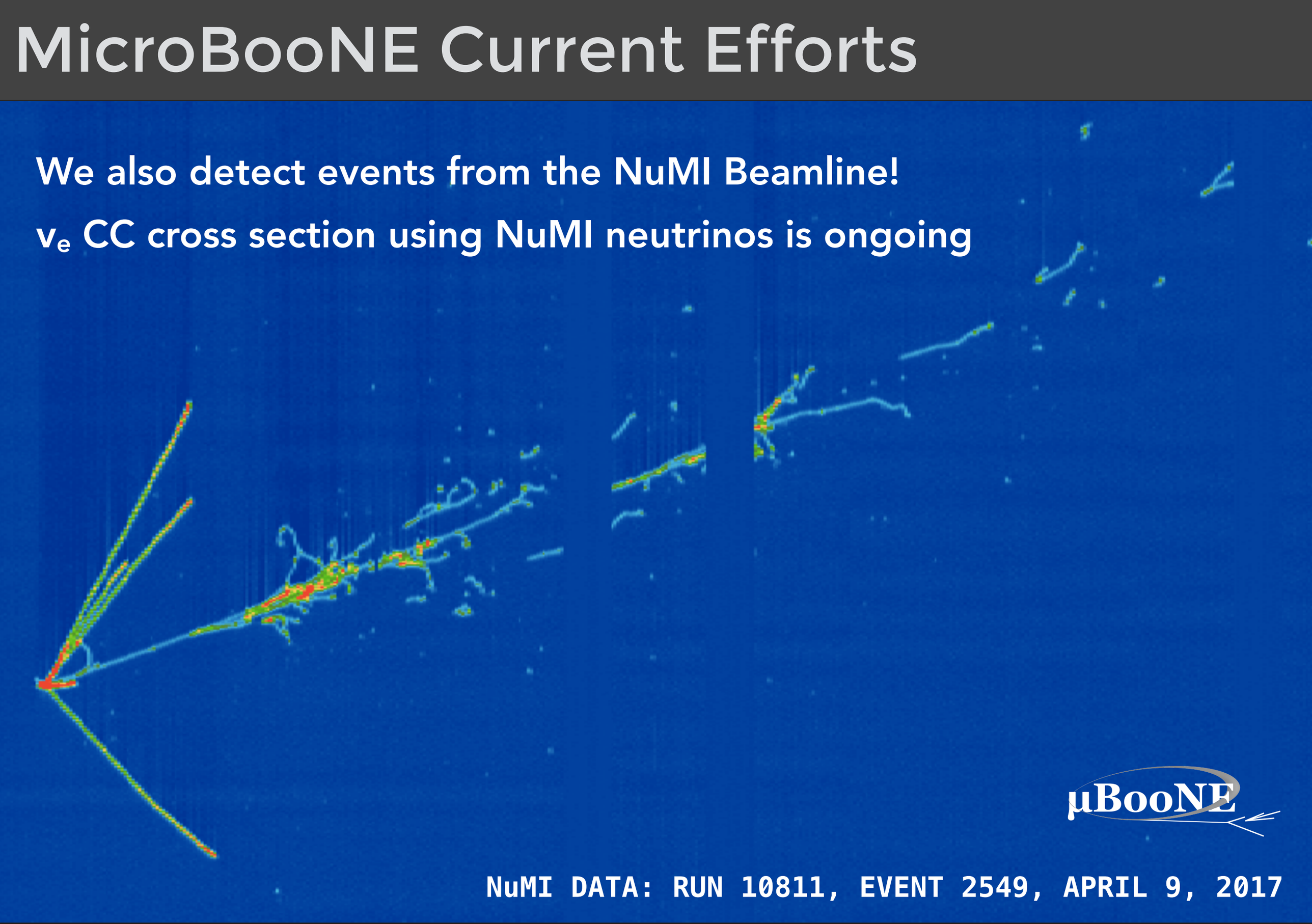
Very challenging analysis - electromagnetic shower reconstruction is hard due to the difficulty of automatic clustering and pattern recognition.

Slide Courtesy: C. Adams

MicroBooNE Current Efforts

We also detect events from the NuMI Beamline!

ν_e CC cross section using NuMI neutrinos is ongoing



Next Plans for Cross Section Measurements

ν_μ CC inclusive

First selections shown at NEUTRINO2016

ν_μ CC 0π inclusive

Proton multiplicity

1μ + 1p

1μ + 2p

Track multiplicity

CC π^0

CC $\pi^{+/-}$

NuMI ν_μ CC inclusive

NuMI ν_e CC inclusive

NC elastic

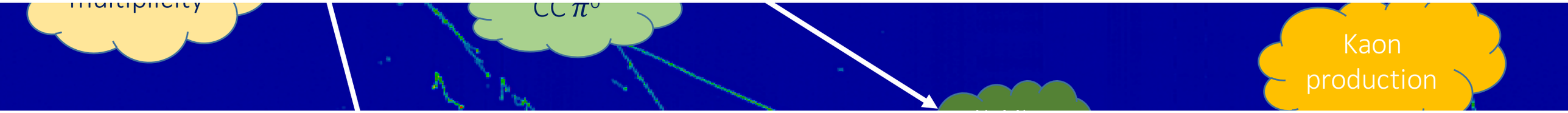
NC π^0

Kaon production

Slide Courtesy: A. Schukraft

Next Plans for Cross Section Measurements

- MicroBooNE has a wide cross section program
- Many analysis are currently ongoing
- Stay tuned for future results!



Check out our public notes:

http://www-microboone.fnal.gov/publications/publicnotes/

Slide Courtesy: A. Schukraft

Back up

CC0π Interactions

Quasi elastic scattering

$$\nu_\mu(k_1) + n(p_1) \rightarrow \mu^-(k_2) + p(p_2)$$

Need to calculate the matrix element:

$$\langle p(p_2)|\, J_\mu \,|n(p_1)\rangle = \cos\theta_C\, \bar{u}(p_2)\Gamma_\mu u(p_1)$$

Using Lorentz-invariant form factors:

$$\Gamma_\mu = \gamma_\mu F_V^1(q^2) + \frac{i\sigma_{\mu\nu}\xi F_V^2(q^2)}{2M} + \frac{q_\mu F_V^3(q^2)}{M} + \gamma_\mu\gamma_5 F_A(q^2) + \frac{q_\mu\gamma_5 F_P(q^2)}{M} + \frac{\gamma_5(p_1+p_2)_\mu F_A^3(q^2)}{M}$$

Violate G parity

Can be related via CVC to electromagnetic form factors

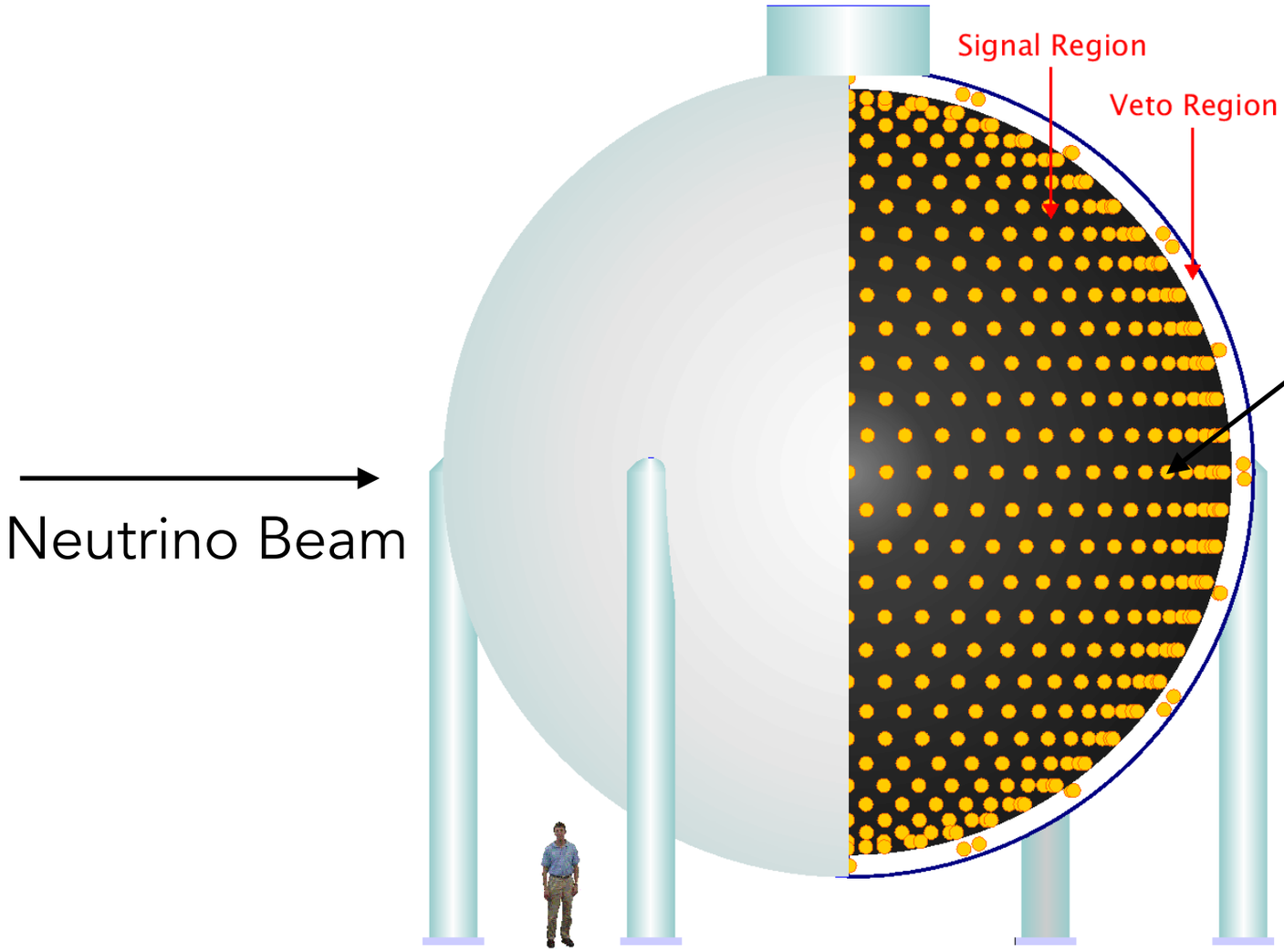
Assumed to have the form suggested by the partially conserved axial current (PCAC) hypothesis

Usually a dipole form is assumed for the axial vector form factor

$$F_A(q^2) = \left[1 - \frac{q^2}{\left(M_A^{CCQE}\right)^2}\right]^{-2}$$

CC0π - Experimental Results

MiniBooNE Experiment - Detector



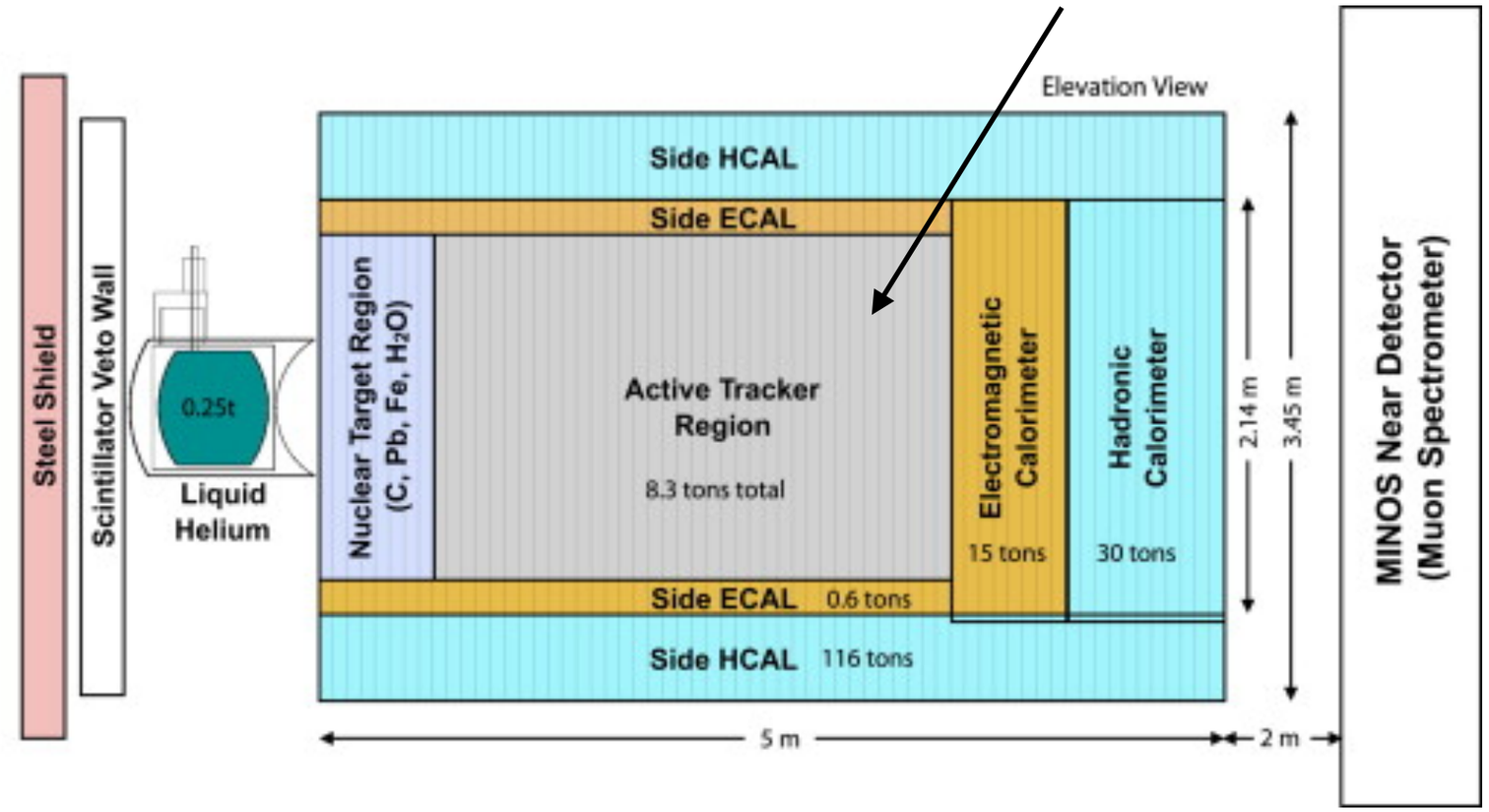
Analysis used neutrino interactions occurring in the inner region

Fiducial Volume: CH_2

CC0π - Experimental Results

MINERvA Experiment - Detector

Analysis used neutrino interactions occurring in the tracker



Neutrino Beam

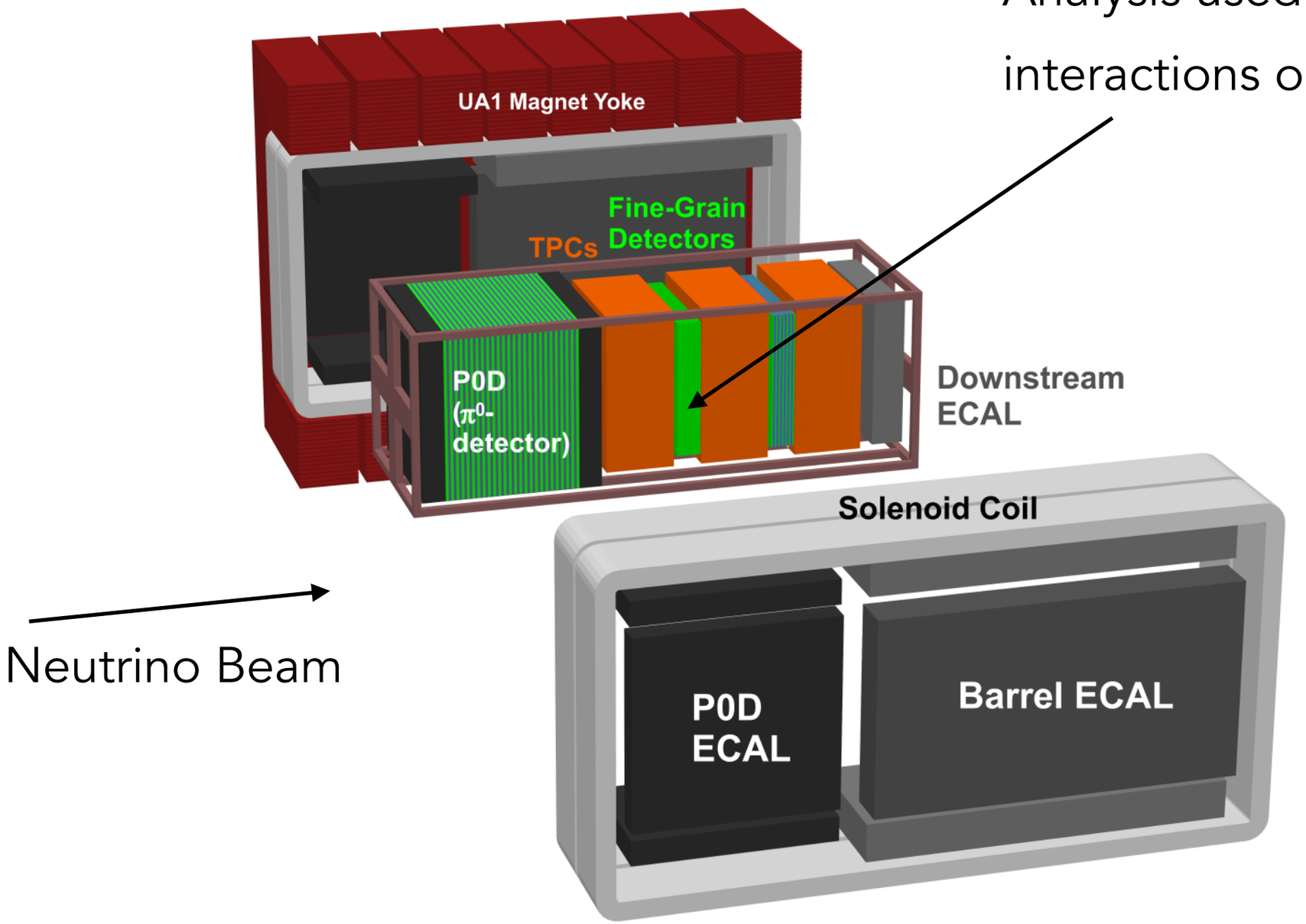
Fiducial Volume

- 88% carbon
- 7.5% hydrogen
- 3.2% oxygen

CC0π - Experimental Results

T2K Experiment - Detector

Phys. Rev. D93, 112012 (2016)



Analysis used neutrino interactions occurring in FGD1:

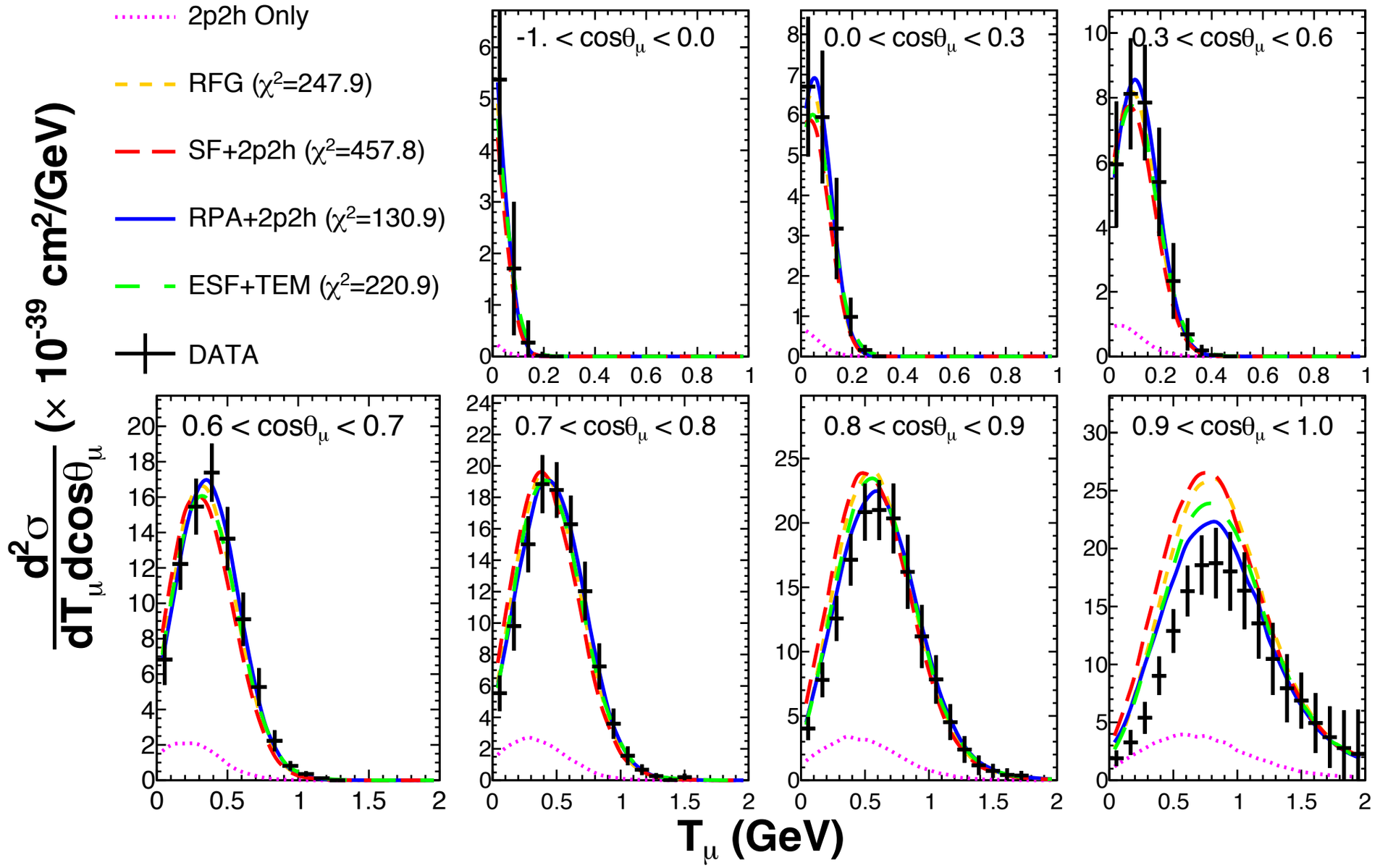
Fiducial Volume:

- 86.1% carbon
- 7.35% hydrogen
- 3.70% oxygen
- Ti, Si, N

CC0π - Experimental Results

MiniBooNE Experiment - Results

NuSTEC White Paper,
Phys. Rev. D81, 092005 (2010)



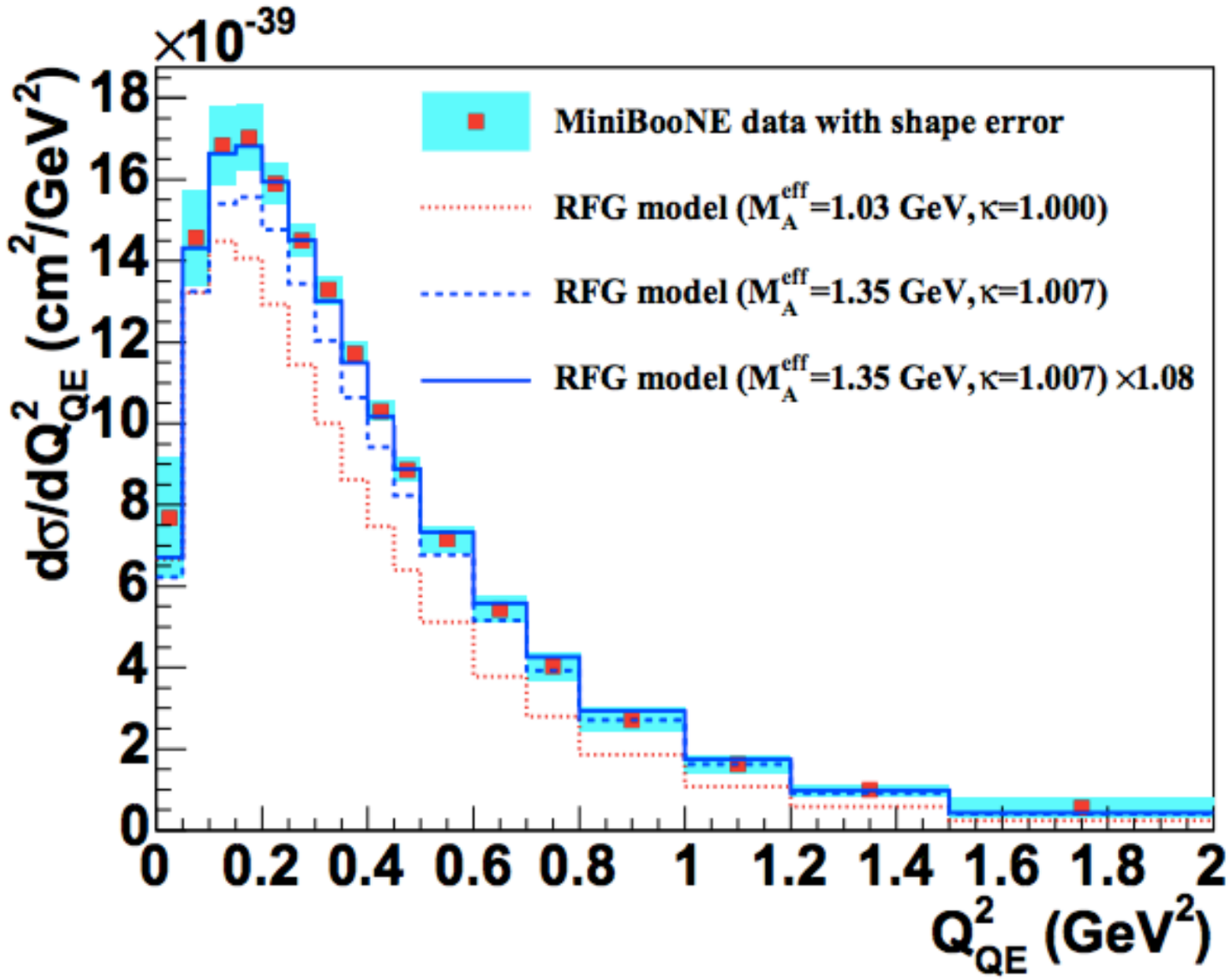
$M_A = 1.01$ GeV/c^2

MiniBooNE data agrees well with predictions that include both 2p2h and RPA

CC0π - Experimental Results

MiniBooNE Experiment - Results

NuSTEC White Paper,
Phys. Rev. D81, 092005 (2010)

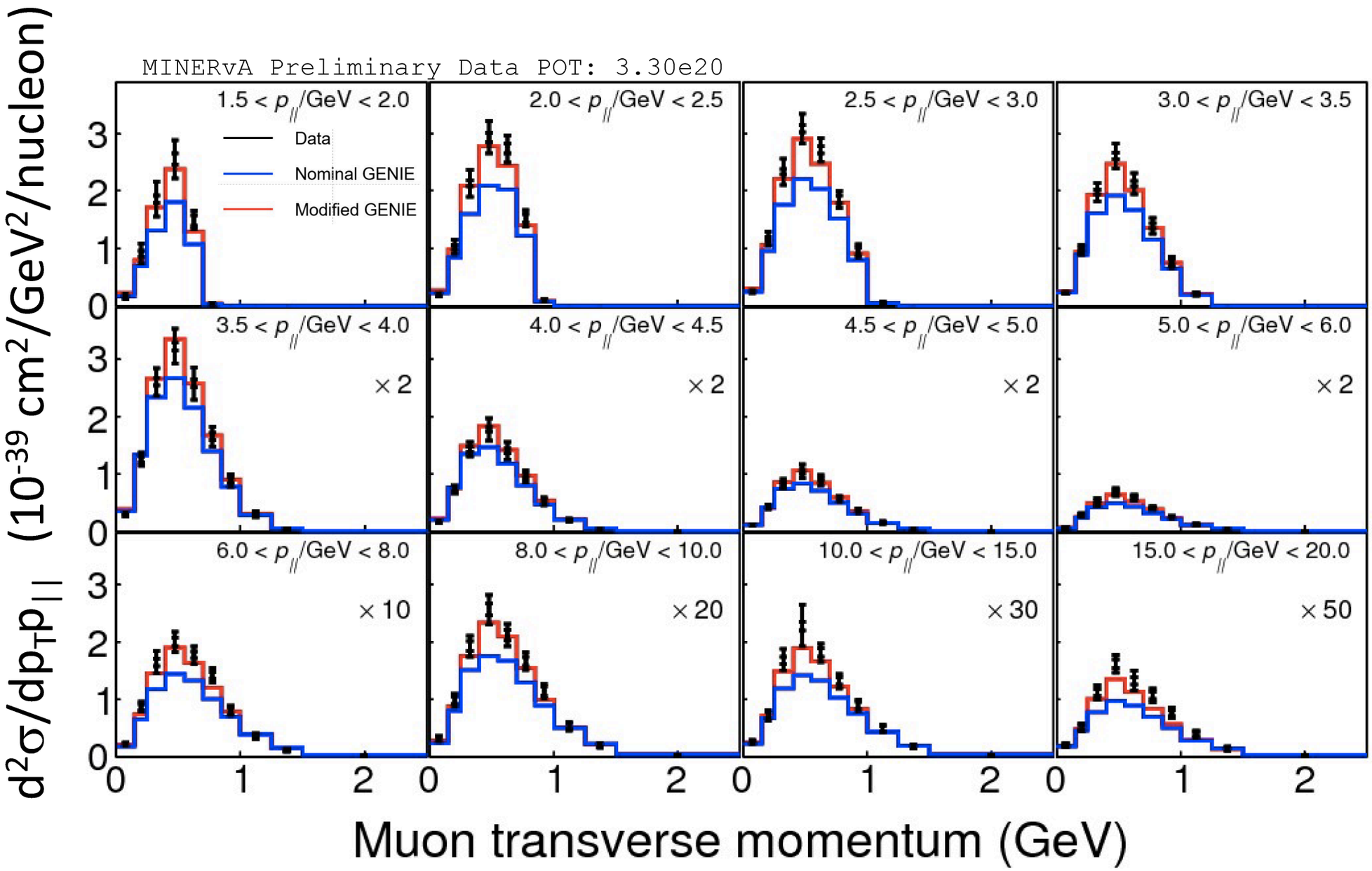


MiniBooNE data agrees with an effective value of M_A = 1.35 GeV

CC0π - Experimental Results

MINERvA Experiment - Results

NuSTEC White Paper



Nominal GENIE MC (no RPA, no 2p2h)

Modified MC (with RPA and enhanced 2p2h)

MINERvA data agrees with with simulations that include multinuclear processes

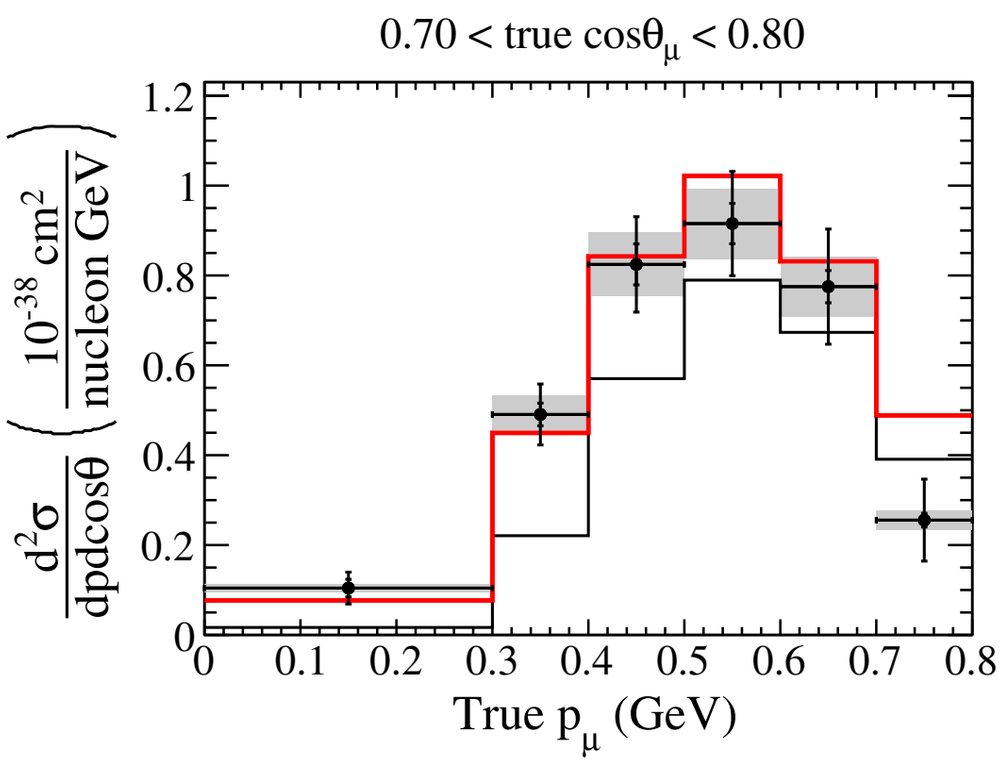
CC0π - Experimental Results

T2K Experiment - Results

Phys. Rev. D93, 112012 (2016)

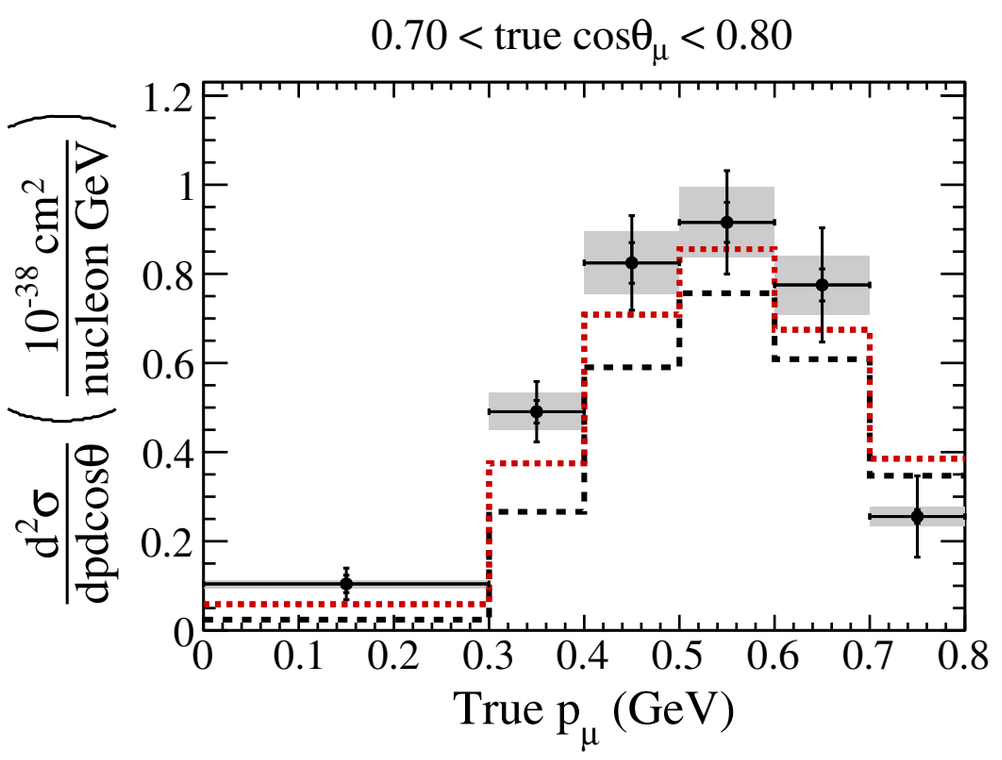
Data: shape uncertainty

Flux normalisation uncertainty



Martini et al. (w/o 2p2h)

Martini et al.



Nieves et al. (w/o 2p2h)

Nieves et al.

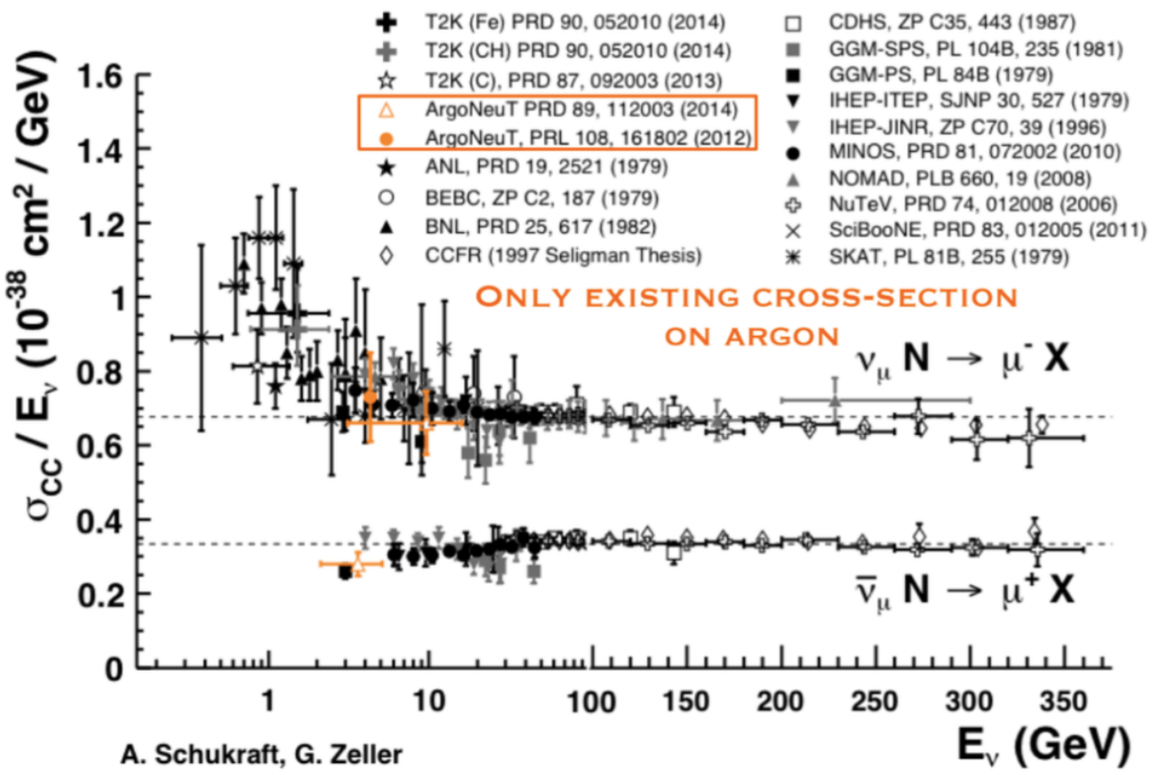
T2K data agrees with with simulations that include multinuclear processes

Motivations

- Neutrino oscillation goals require precise measurements of neutrino (and antineutrino) cross sections (e.g. DUNE experiment).

- MicroBooNE can probe different theories of nuclear effects in ν-Ar scattering

- ν-Ar is important as there are only limited measurements and the future short and long baseline neutrino programs will both use argon for their neutrino detectors

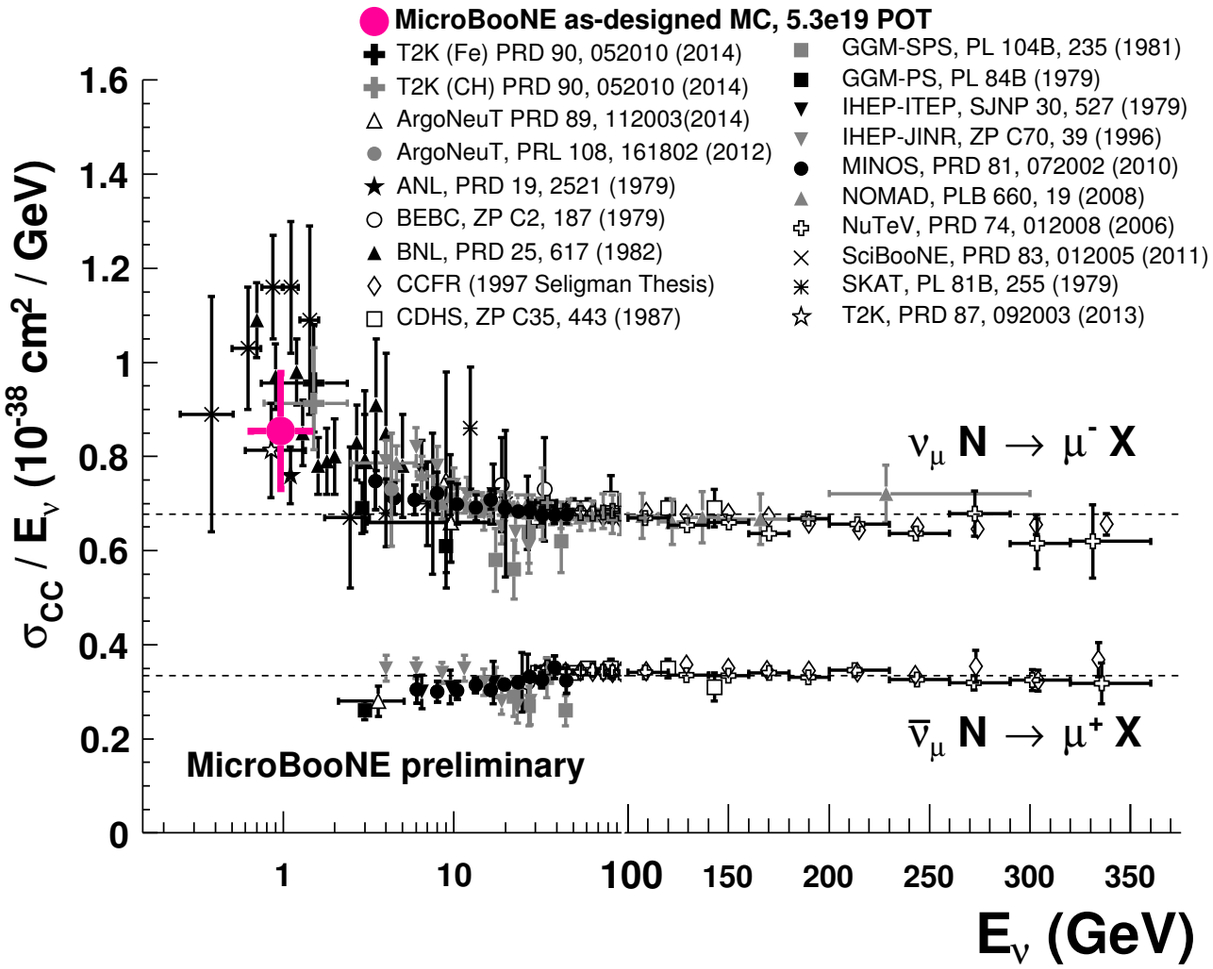


MicroBooNE

CC Interactions @ MicroBooNE

CC-inclusive event selection performances

MICROBOONE-NOTE-1004-PUB



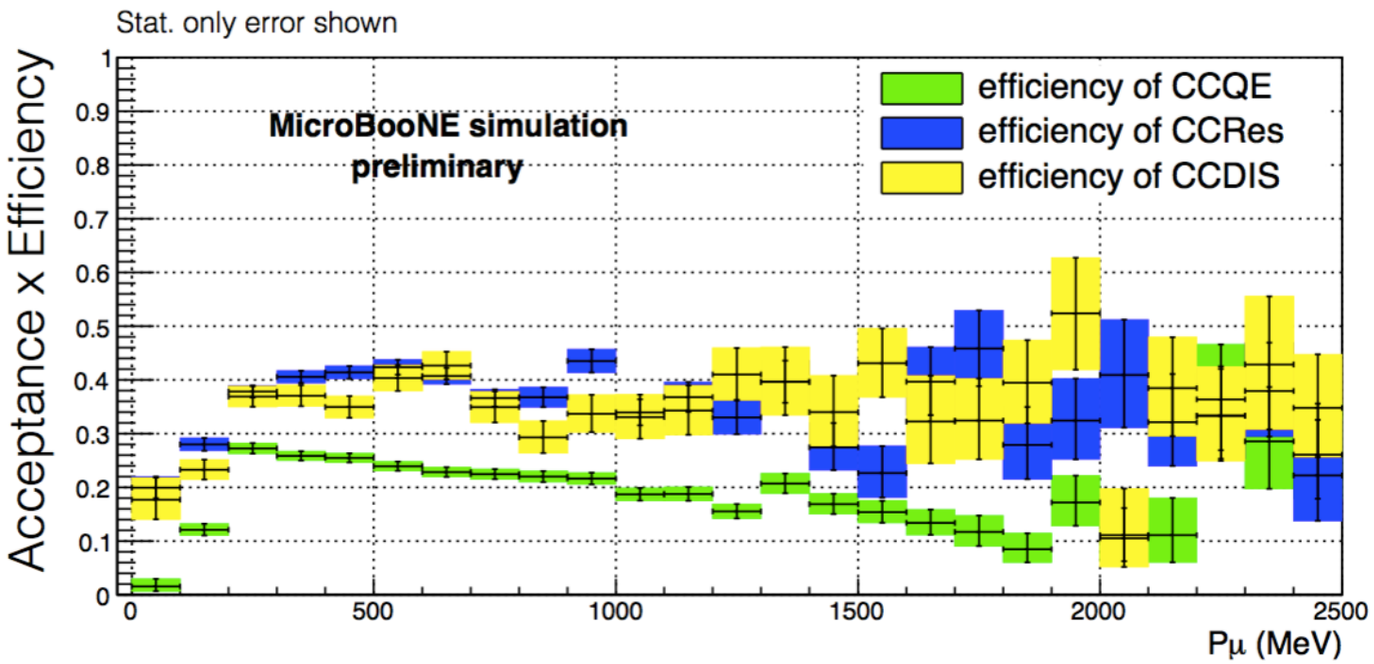
- Working on way to improve the current event selection
- New results will come out in a few months
- Recently finished installation of the Cosmic Ray Tagger, that will help us in tagging and removing cosmic rays.

CC Interactions @ MicroBooNE

CC-inclusive event selection performances

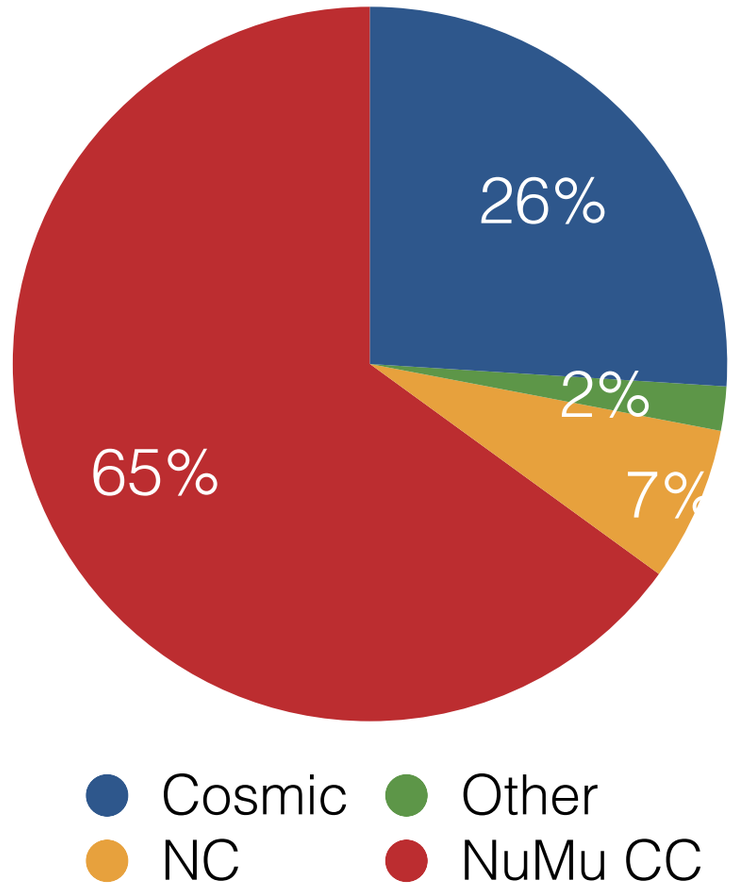
MICROBOONE-NOTE-1010-PUB

Efficiency



Acceptance x Efficiency: 30%

Purity



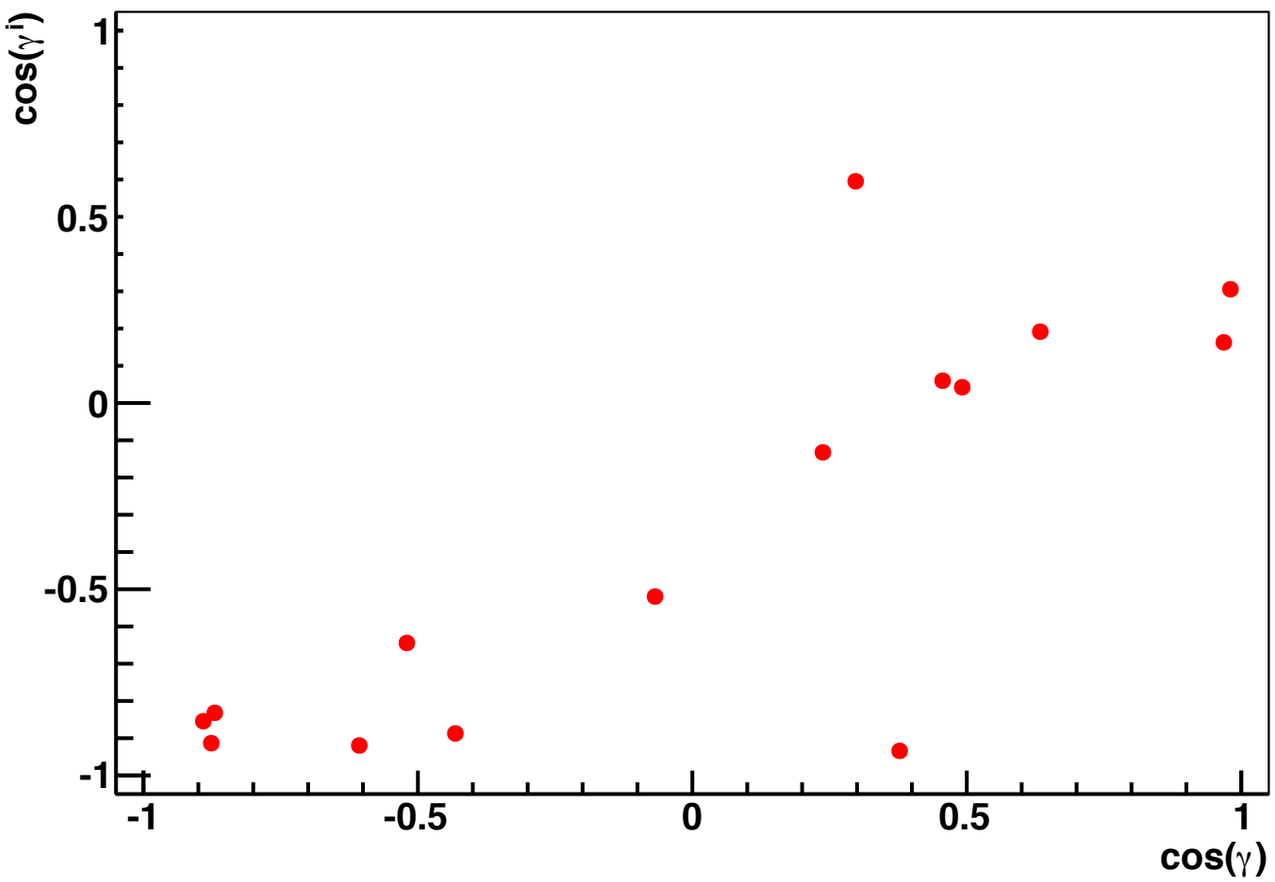
Purity: 65%

The ArgoNeuT Experiment

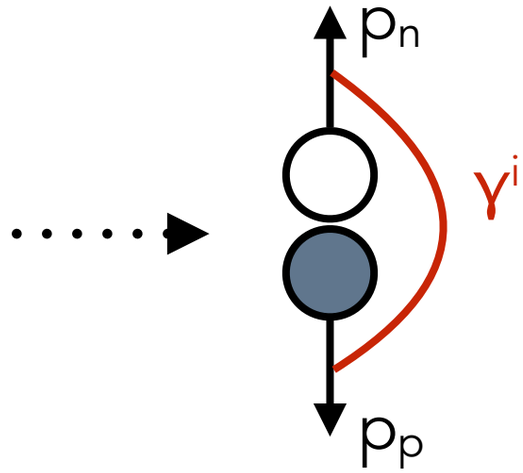
Results - Back-to-back protons

Phys. Rev. D90, 012008 (2014)

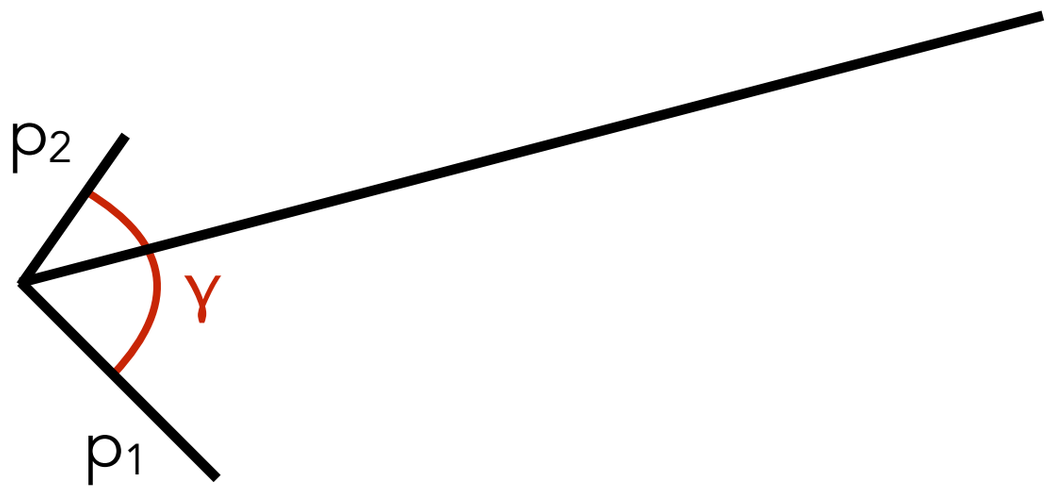
Selection: ν_μ CC0π with 2 protons in the final state



Initial State



Final State

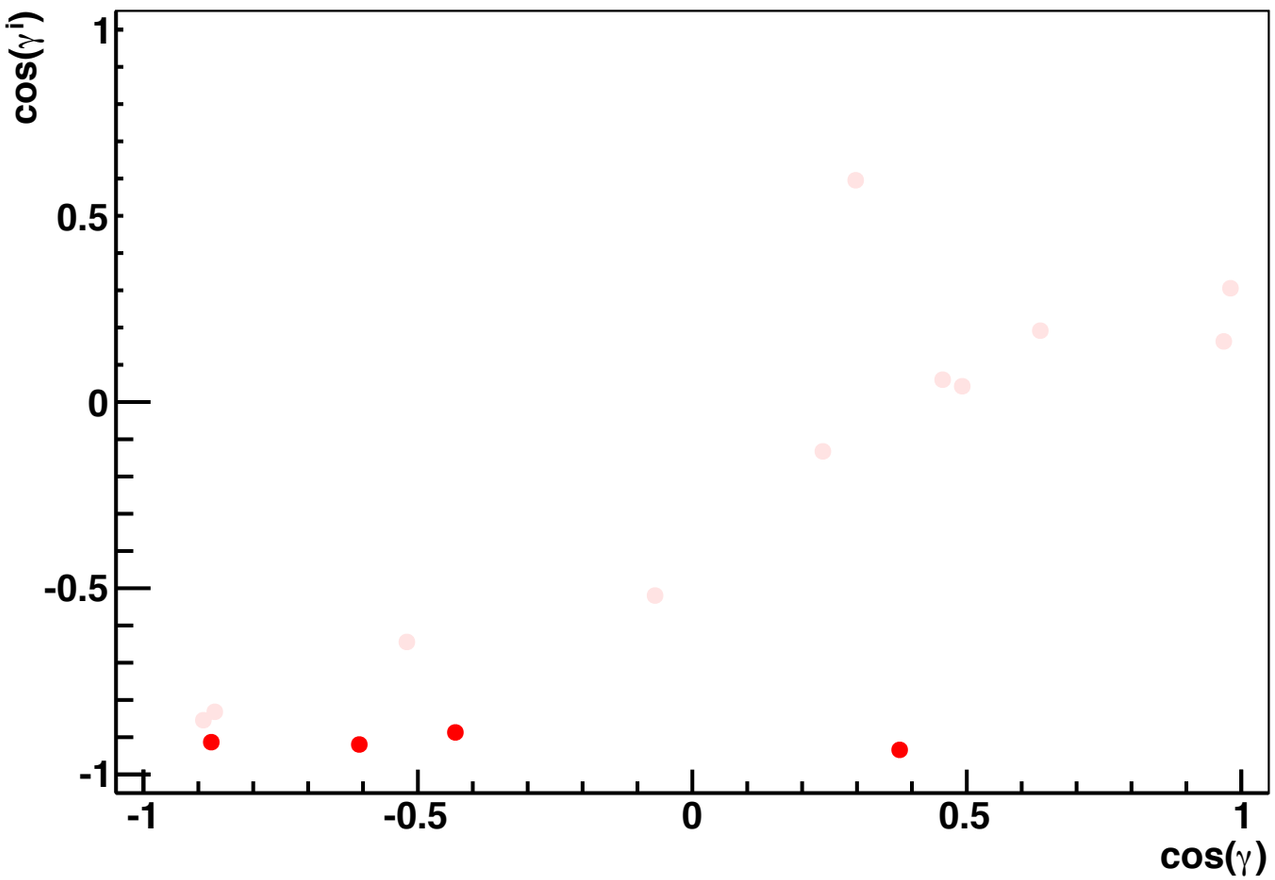


The ArgoNeuT Experiment

Results - Back-to-back protons

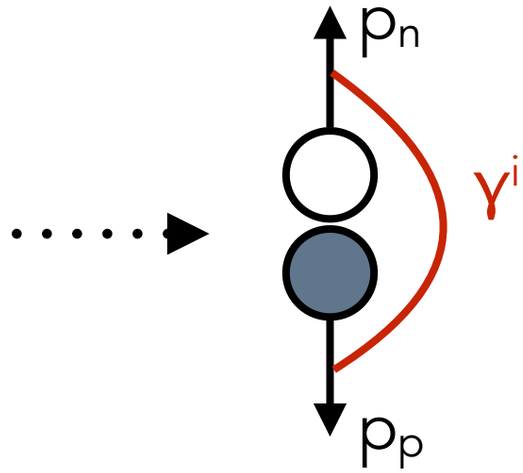
Phys. Rev. D90, 012008 (2014)

Selection: ν_μ CC0π with 2 protons in the final state

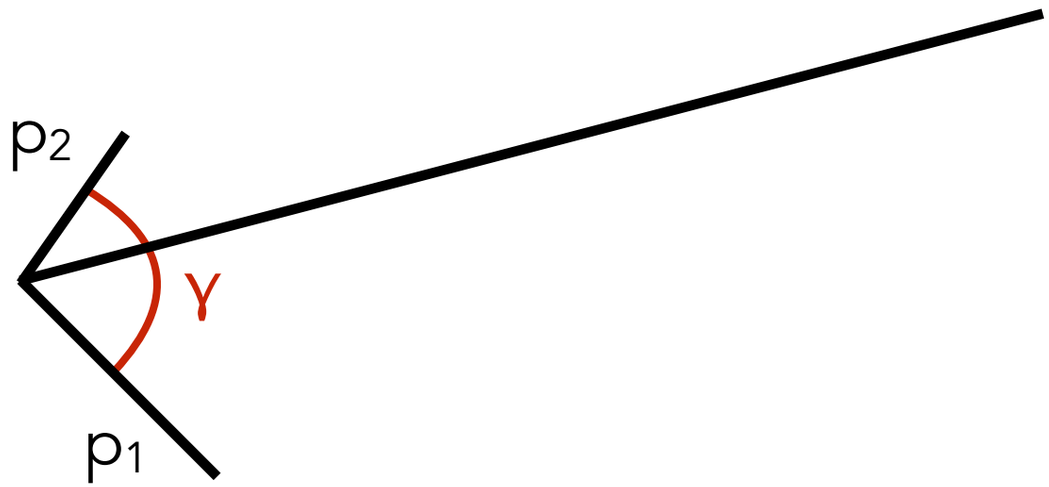


Other 4 events are compatible with a reconstructed back-to-back configuration of a np pair in the initial state inside the nucleus

Initial State

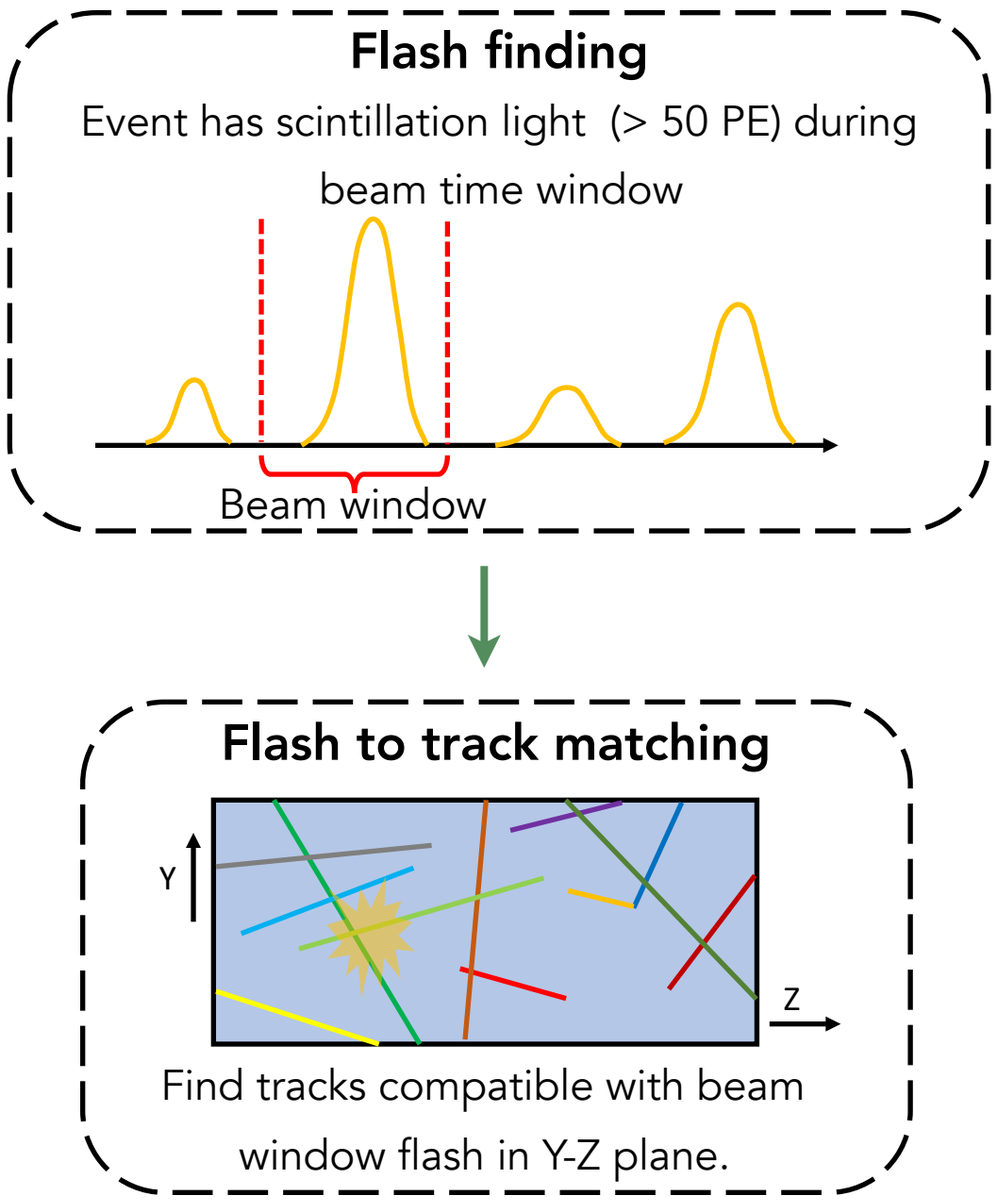


Final State



Charged Current Interactions

CC-inclusive event selection



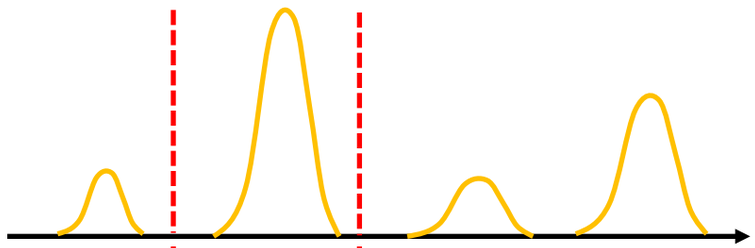
Thanks to A. Schukraft

Charged Current Interactions

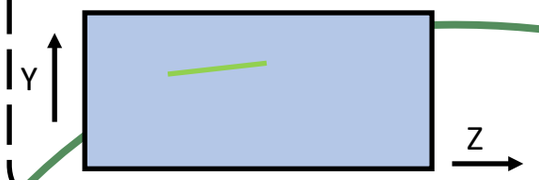
CC-inclusive event selection

Flash finding

Event has scintillation light (> 50 PE) during beam time window



Containment



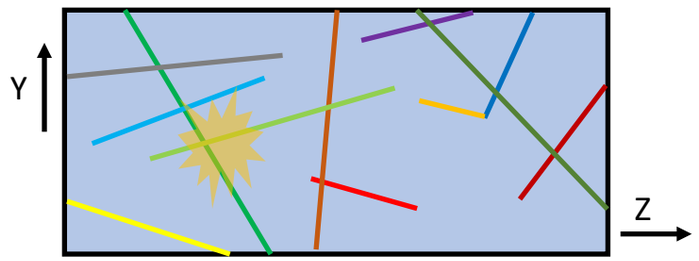
Minimum length

Direction

Bragg peak at higher end

1 track

Flash to track matching



Find tracks compatible with beam window flash in Y-Z plane.

Selected

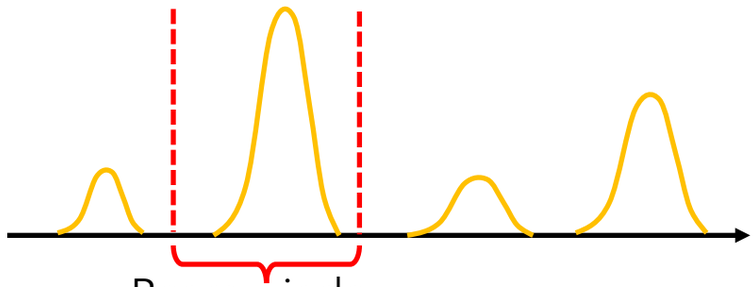
Thanks to A. Schukraft

Charged Current Interactions

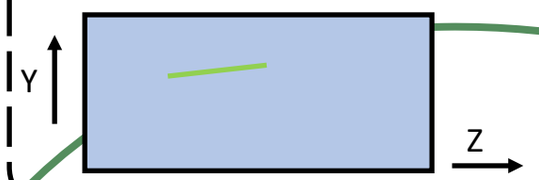
CC-inclusive event selection

Flash finding

Event has scintillation light (> 50 PE) during beam time window



Containment



Minimum length

Direction

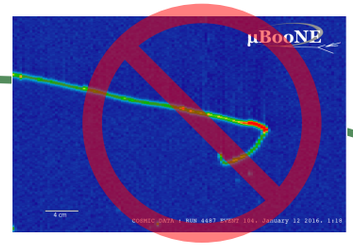
Bragg peak at higher end

1 track

2 tracks

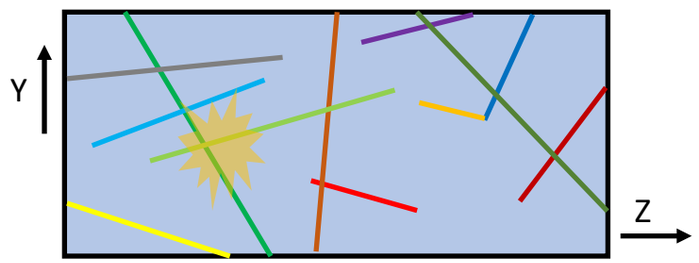
>2 tracks

Michel removal



Broken track removal

Flash to track matching

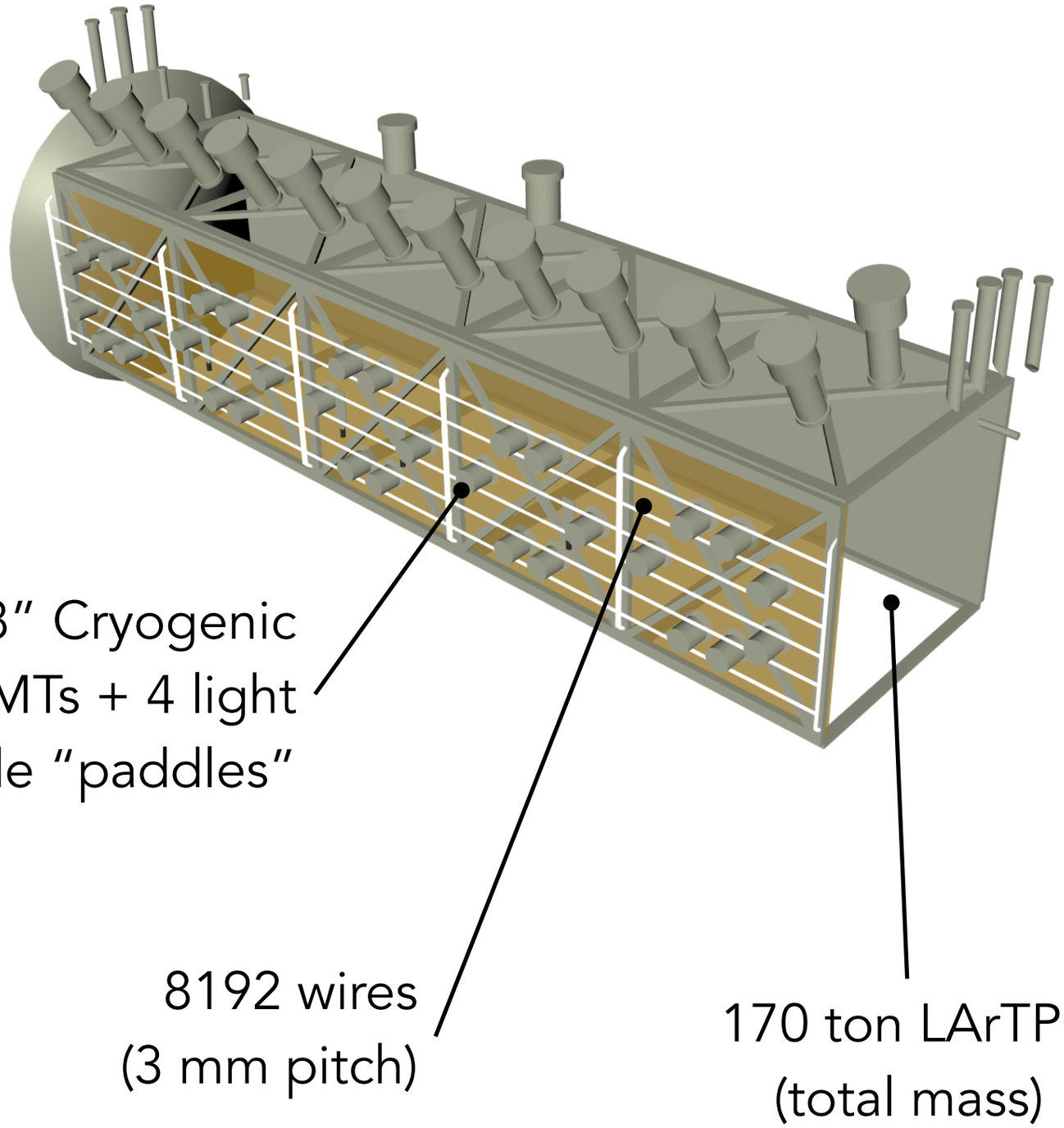


Find tracks compatible with beam window flash in Y-Z plane.

Selected

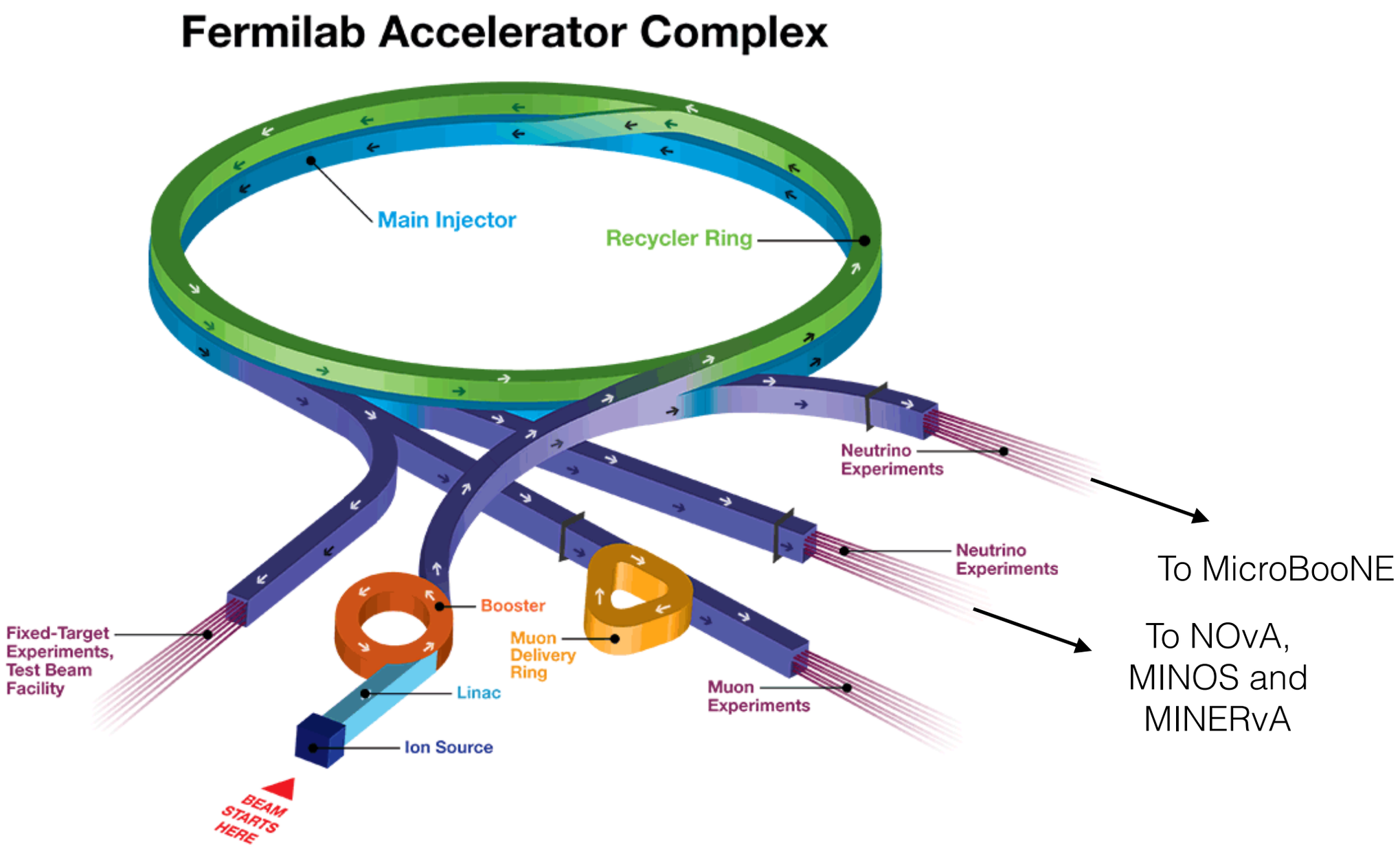
Thanks to A. Schukraft

The MicroBooNE Detector



MicroBooNE cryostat lowered into the pit

Inside the detector: PMT system


Fermilab Accelerator Complex
Main Injector
Recycler Ring
Neutrino Experiments
To MicroBooNE
Neutrino Experiments
To NOvA, MINOS and MINERvA
Booster
Muon Delivery Ring
Fixed-Target Experiments, Test Beam Facility
Linac
Muon Experiments
Ion Source
BEAM STARTS HERE

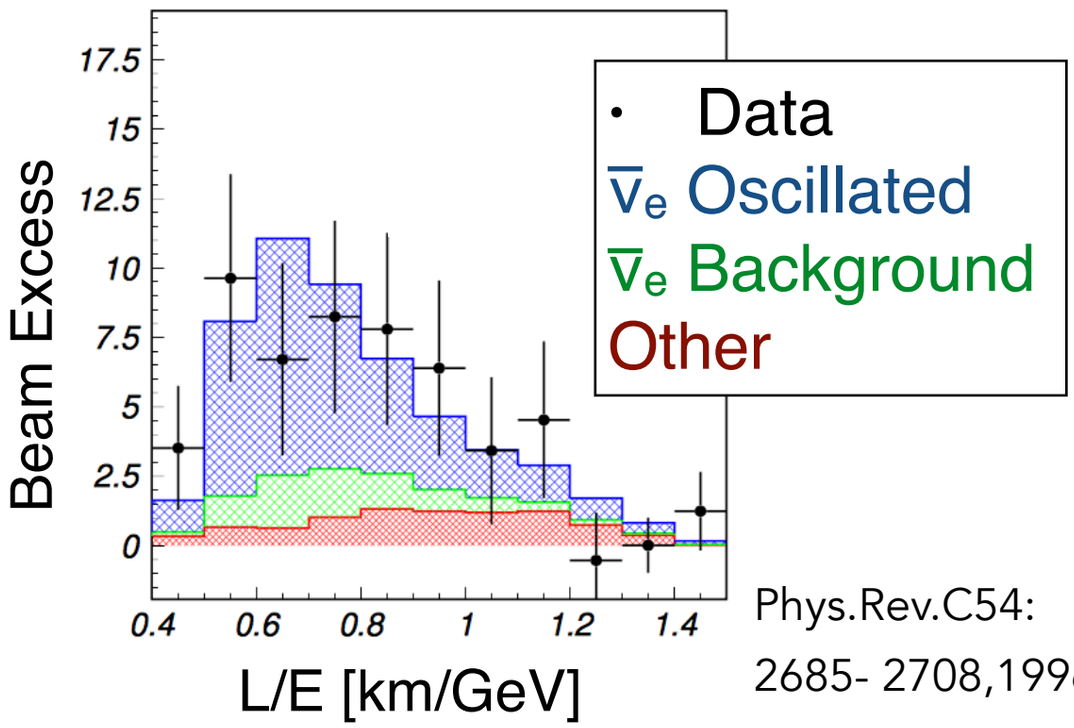
Motivations for MicroBooNE

LSND

Muon anti-neutrino beam

Excess of electron anti-neutrino events

Could be explained by oscillations
L/E ~ 1 km/GeV



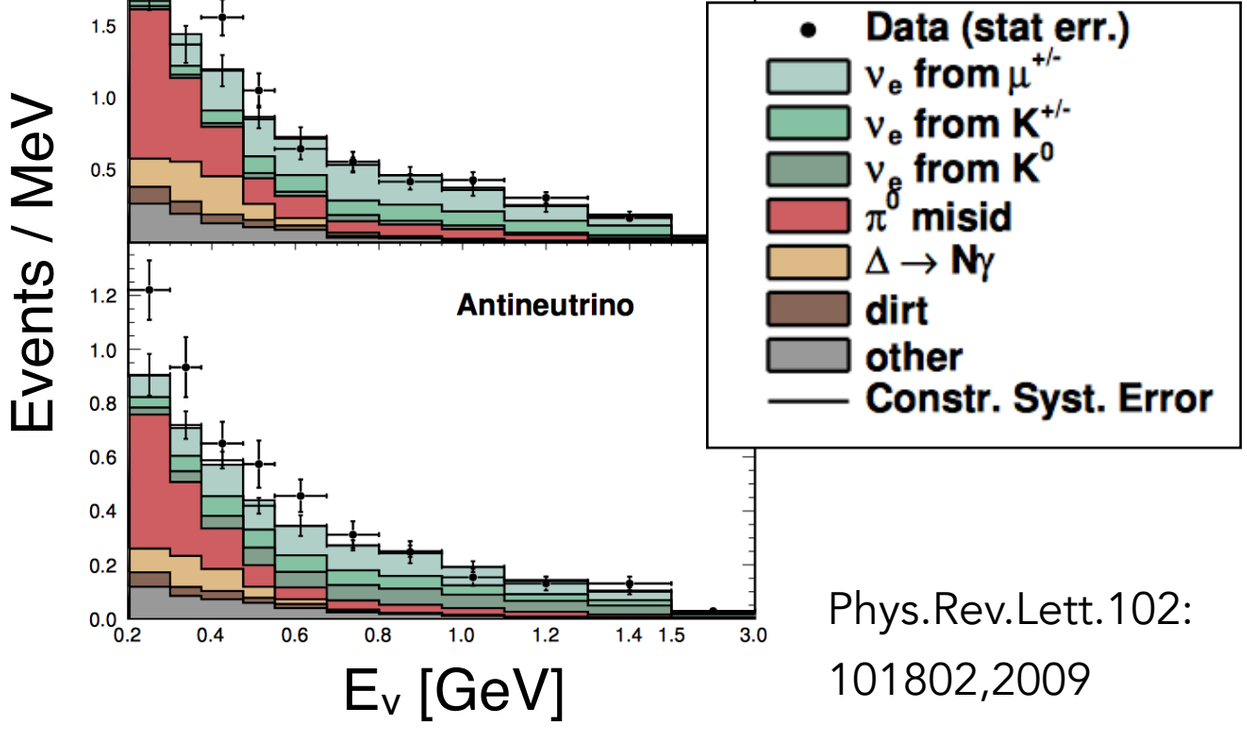
Phys.Rev.C54: 2685- 2708,1996

MiniBooNE

Designed to study the LSND anomaly

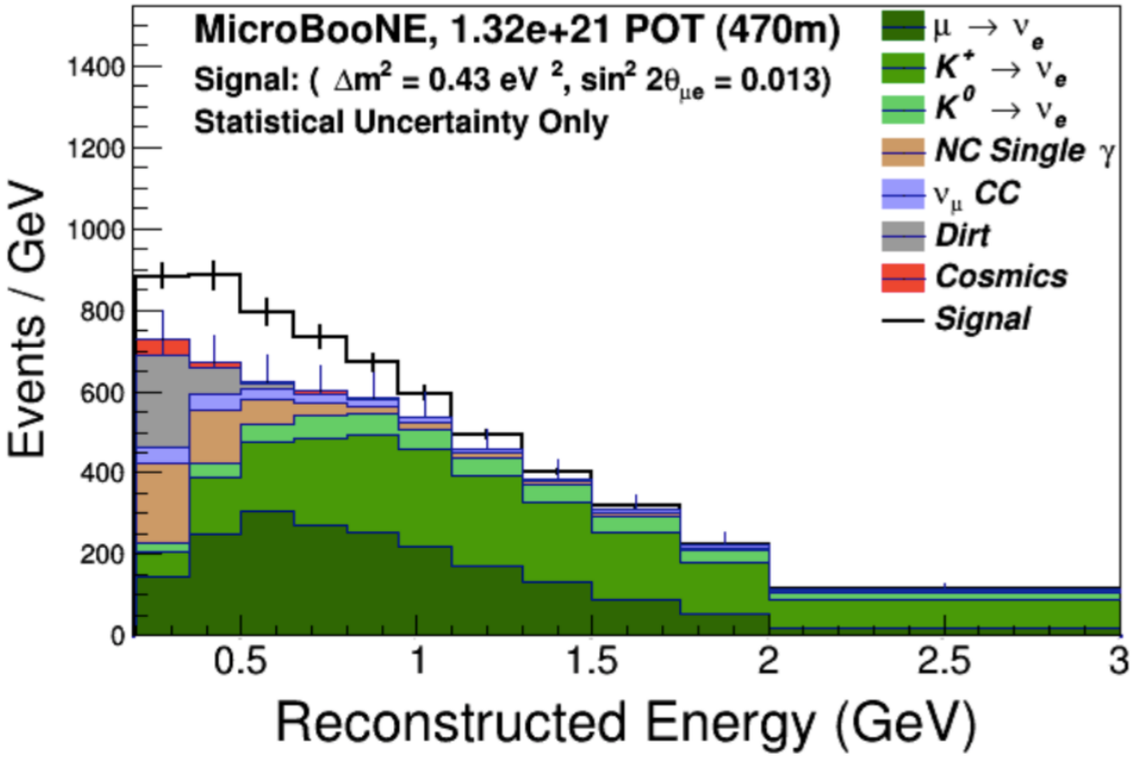
Different baseline and energy but same L/E

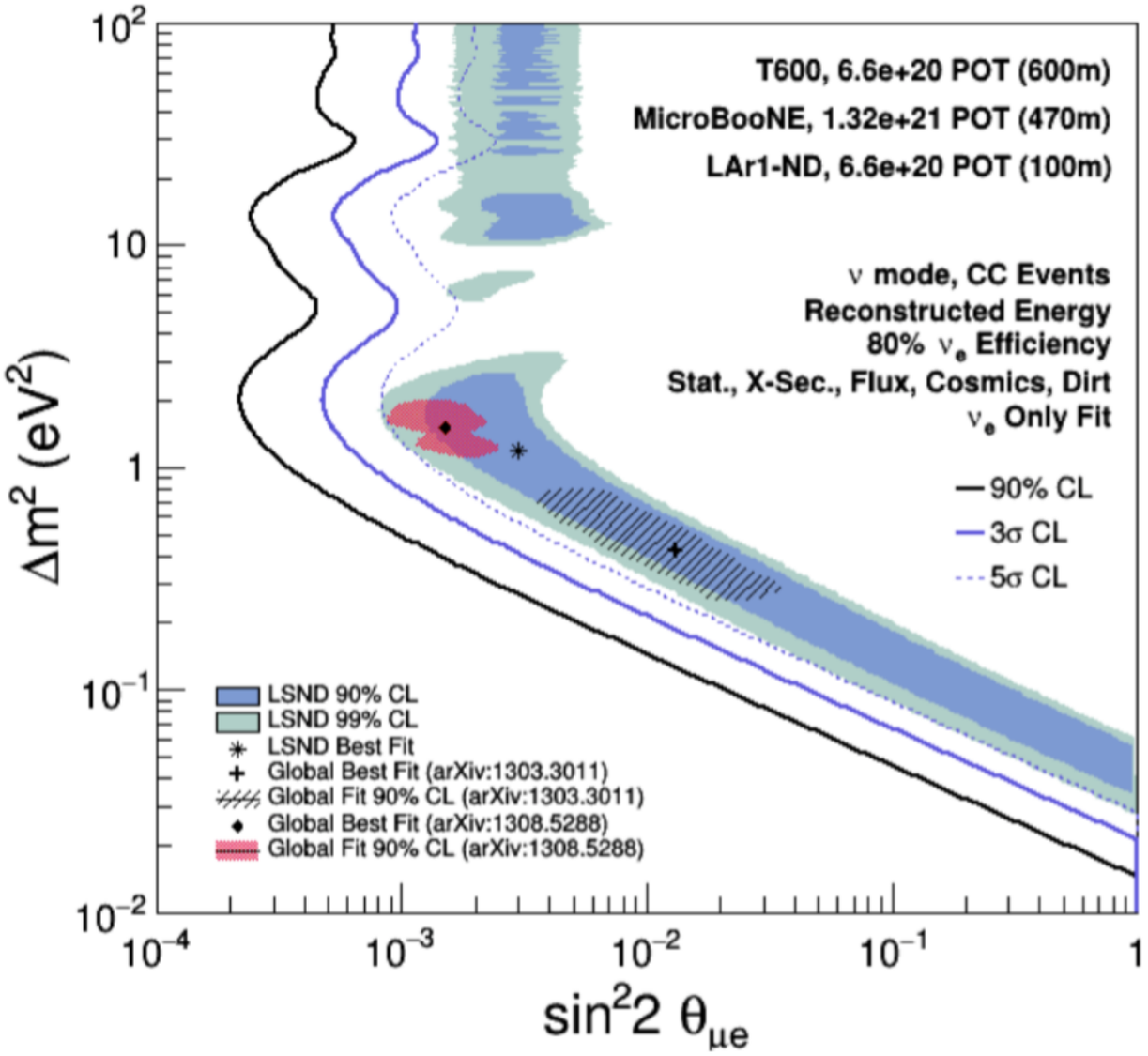
Found excess in both neutrino and anti-neutrino data



Phys.Rev.Lett.102: 101802,2009

SBN - Neutrino oscillation





"A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam", arXiv:1503.01520v1