Recent Physics Results on ν-Ar Scattering from MicroBooNE

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for the MicroBooNE collaboration

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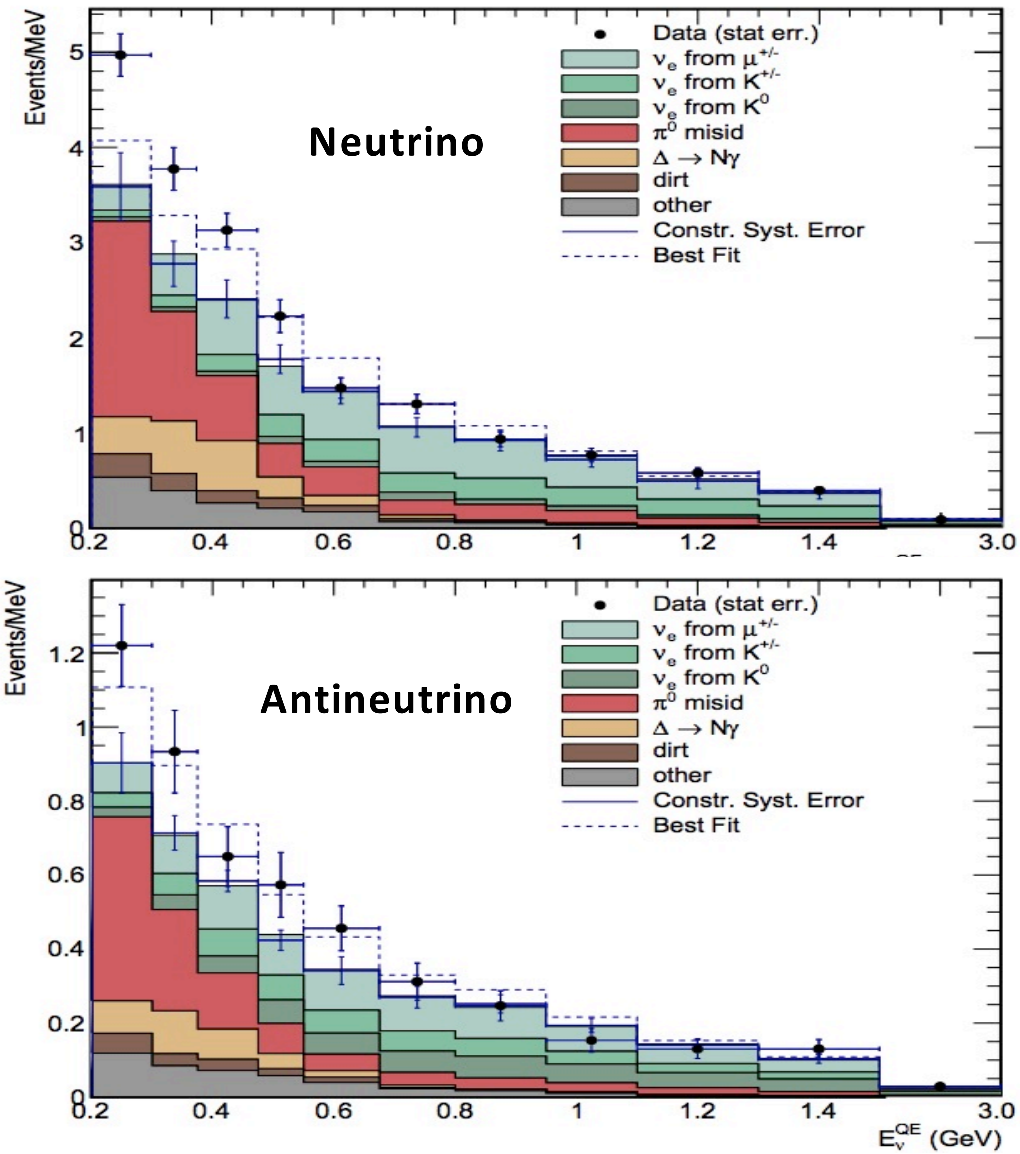
MiniBooNE Low Energy Excess Anomaly

- **MicroBooNE goal:** Confirm or rule out "low energy excess of electron-like events" observed by MiniBooNE
- MicroBooNE's LArTPC is able to distinguish electrons from photons
- **Oscillation studies require good knowledge of neutrino scattering at these energies**



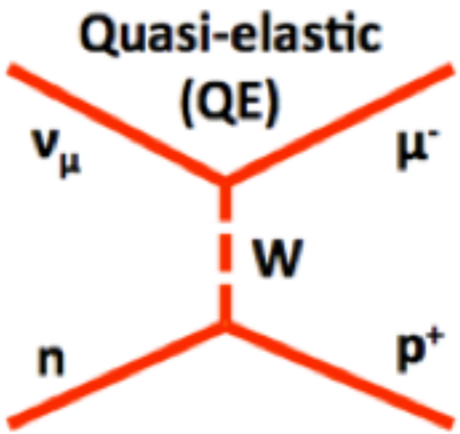
Neutrino Scattering from Ar

- Limited data is available on ν-Ar scattering
  - ArgoNeuT is the only other LArTPC to produce cross section results with higher E_ν
- We need to understand ν-Ar interactions for MicroBooNE physics analyses and future LArTPC experiments (like DUNE and SBN)
- Should test neutrino event generators for future LArTPC experiments
  - MicroBooNE presents the most comprehensive tests of GENIE* with ν_μ-Ar data

*GENIE: Neutrino event generator: https://genie.hepforge.org/

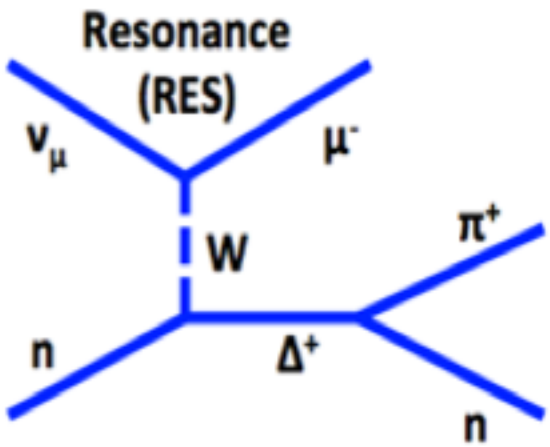
Charged Current Interactions

Two charged particles



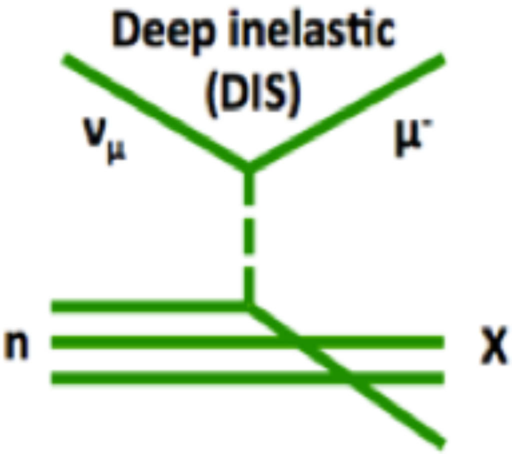
Scattering from Independent nucleon

Two/three charged particles



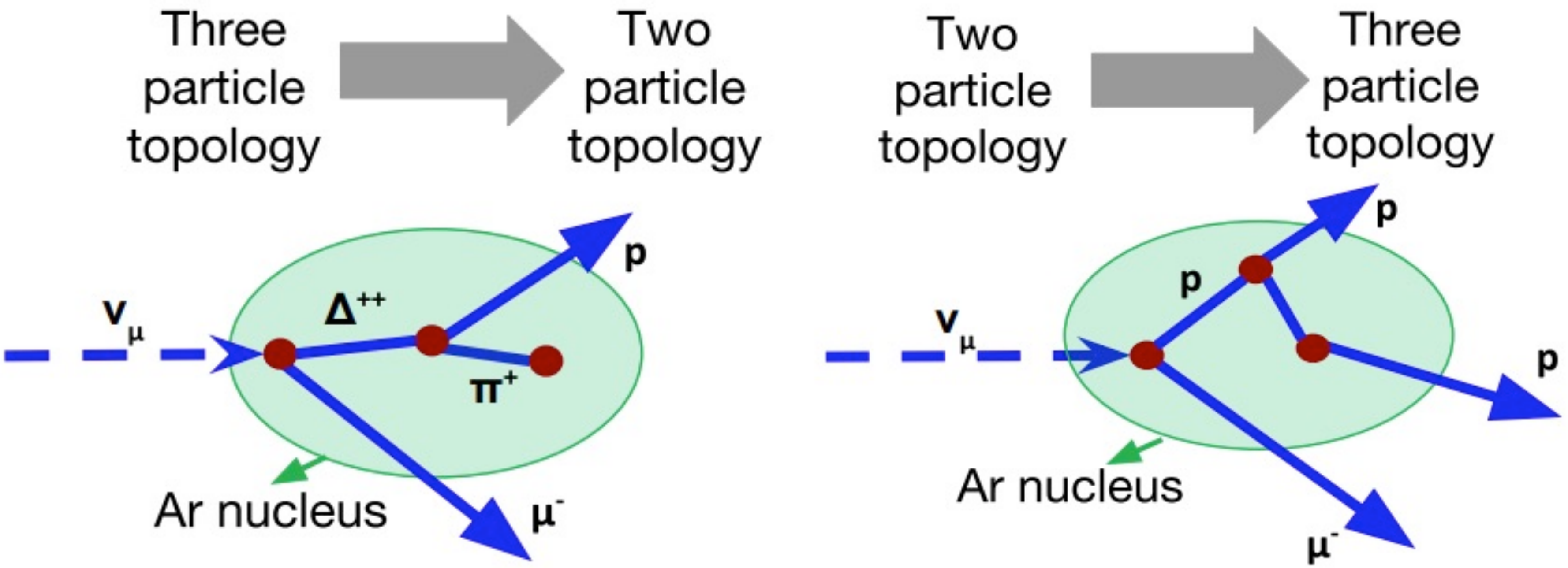
Inelastic scattering:
Excites the nucleon

Many charged particles

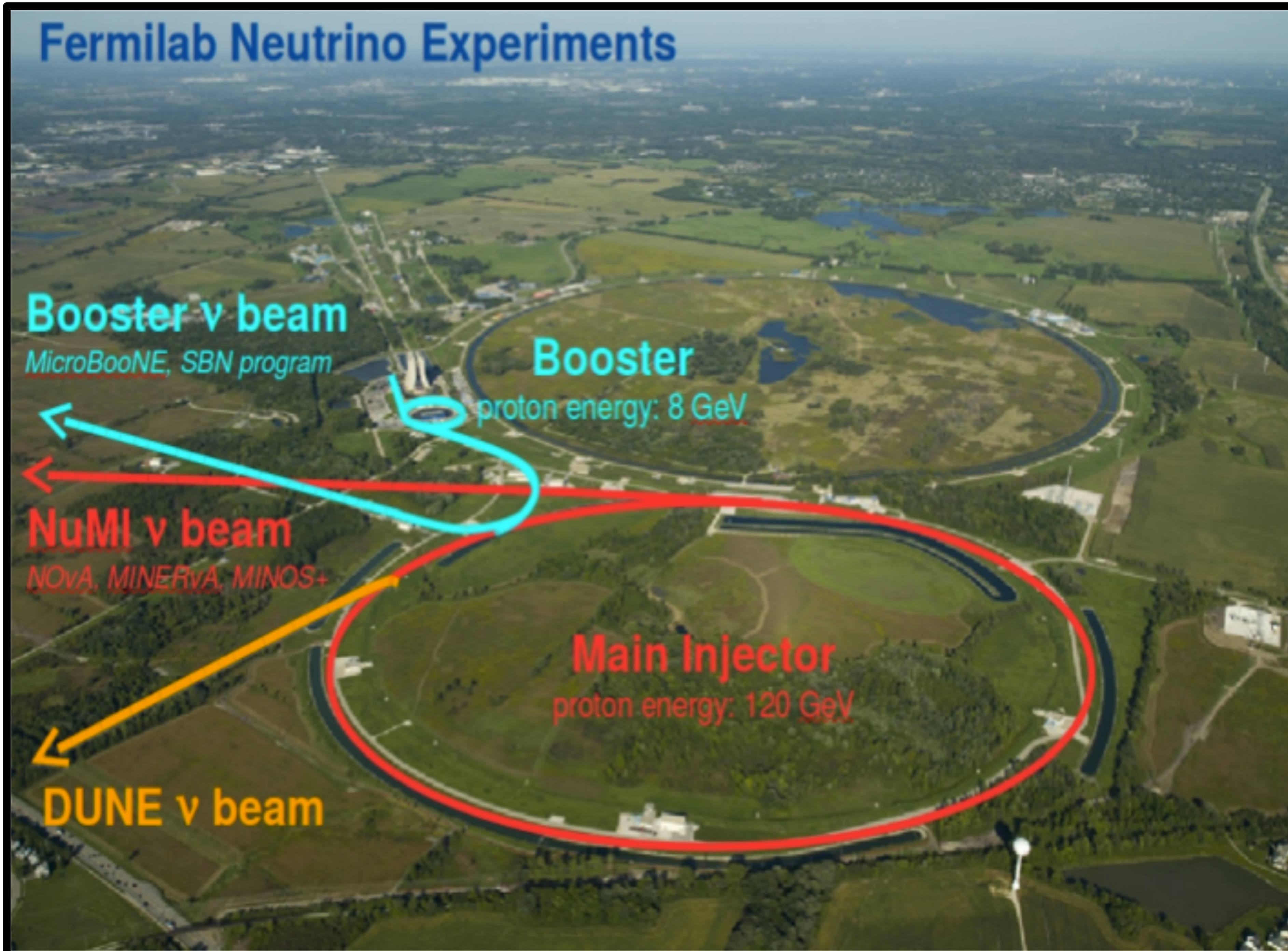


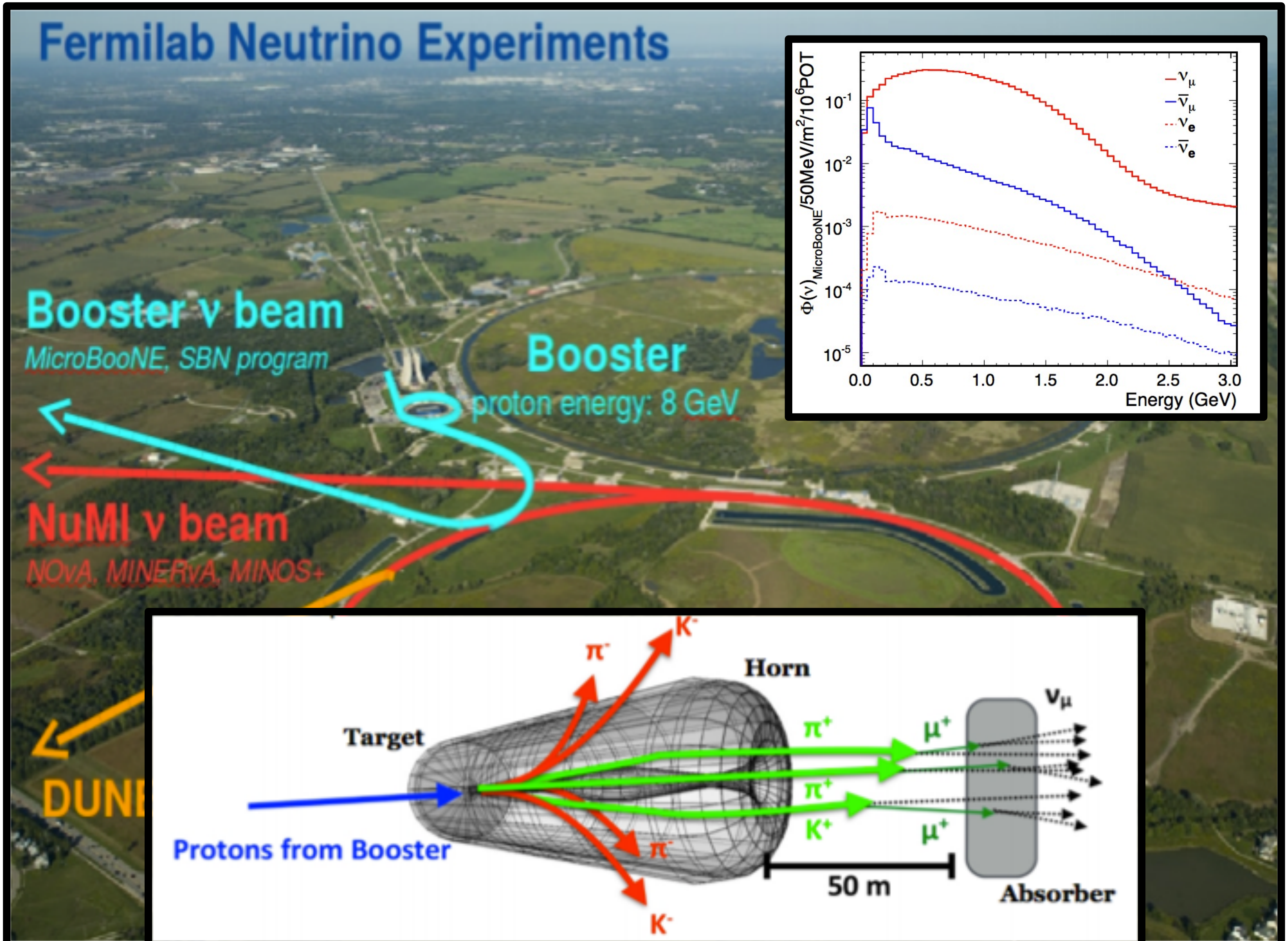
Scattering through quarks:
Nucleon breaks up

Nuclear Effects



Argon is a heavy nucleus in which final state interactions can change the final state topology of the interaction


Fermilab Neutrino Experiments
Booster ν beam
MicroBooNE, SBN program
Booster
proton energy: 8 GeV
NuMI ν beam
NOvA, MINERvA, MINOS+
Main Injector
proton energy: 120 GeV
DUNE ν beam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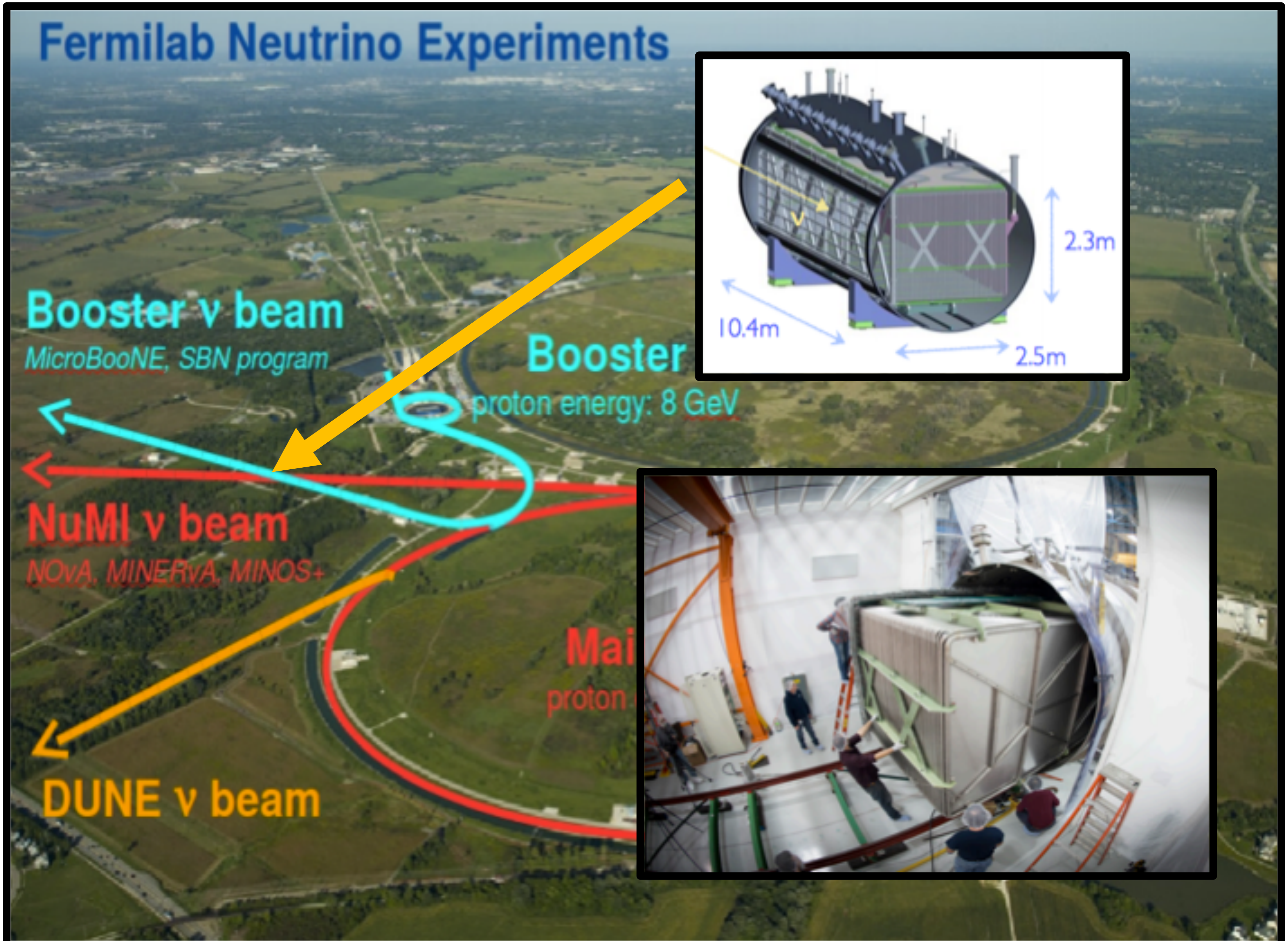
$\Phi(\nu)_{MicroBooNE}$/50MeV/m^2/10^{6}POT
Energy (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
Target
Horn
Absorber
Protons from Booster
50 m
π^-
K^-
π^+
K^+
μ^+
ν_μ


Fermilab Neutrino Experiments
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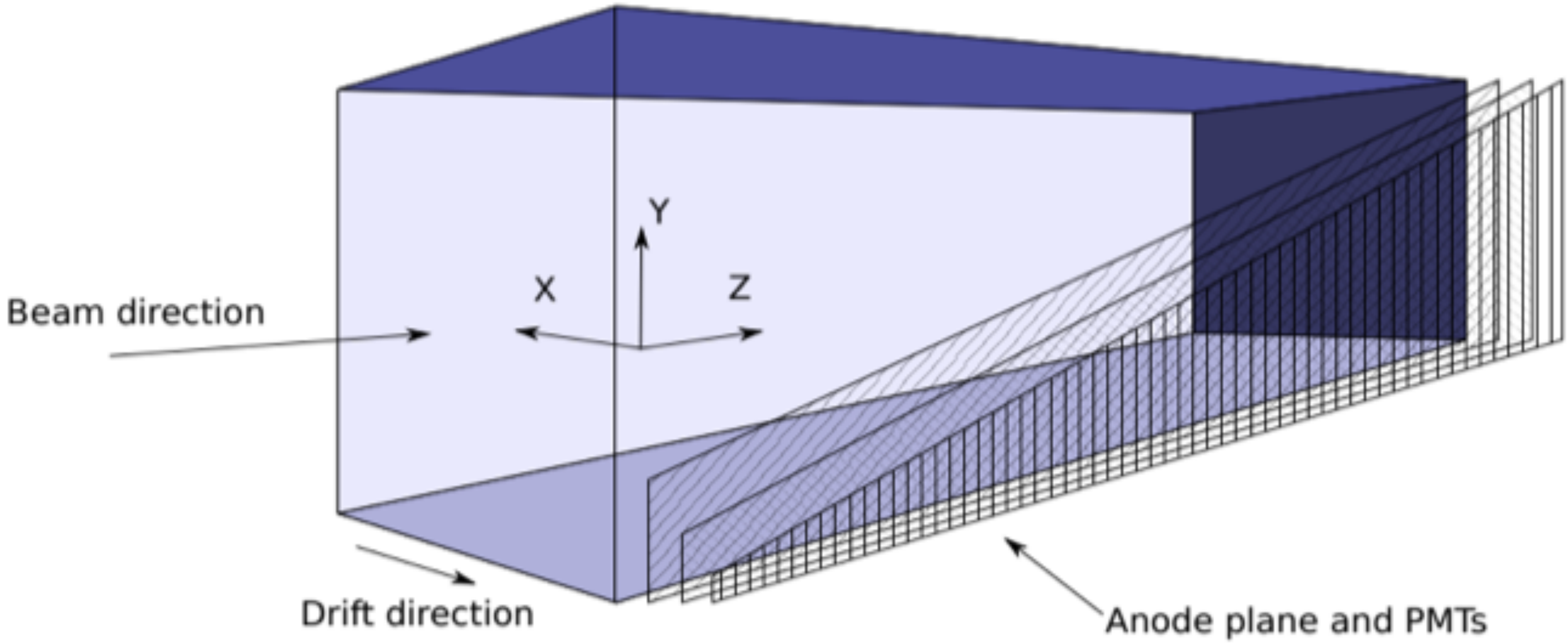
DUNE ν beam
2.3m
10.4m
2.5m

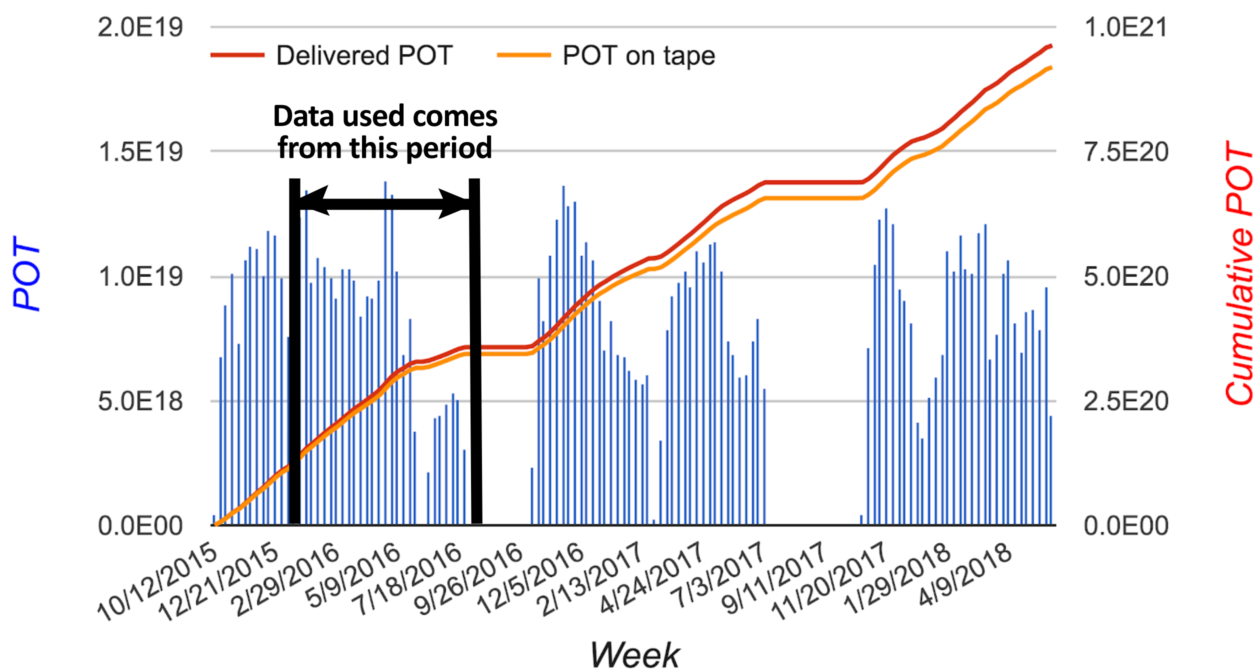
MicroBooNE LArTPC



- 85 tonne active mass
- Has three wire planes:
  - 3mm wire spacing gives us impeccable spatial resolution
  - Final plane collects charge to give calorimetric measurements
- Triggered by an array of PMTs

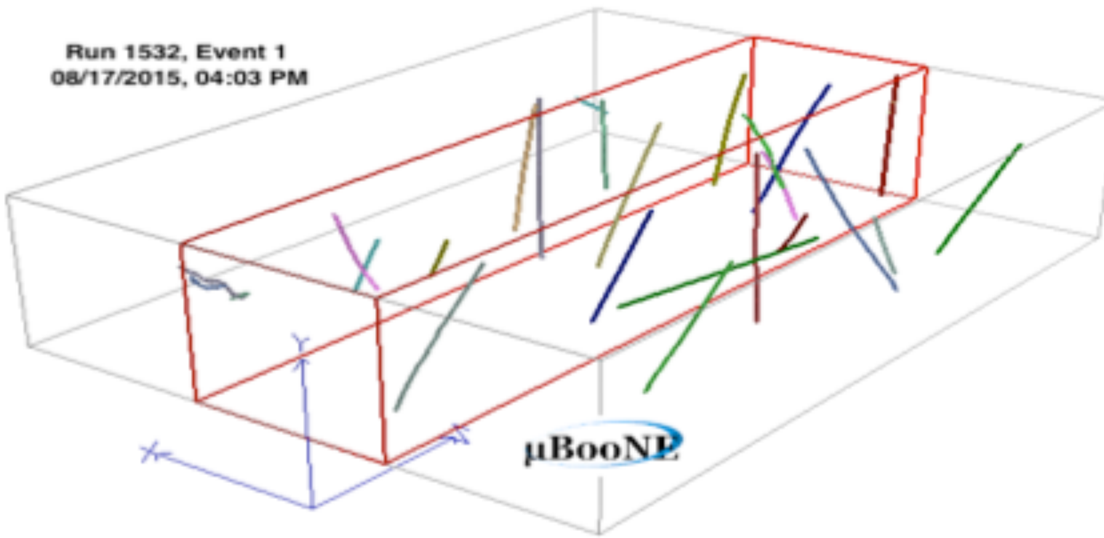
MicroBooNE Status

- Cosmic data collection started: August 2015
- Neutrino data collection started: October 2015
- Running stably since then
- Collected almost 10^{21} protons on target
- Results presenting today use ~10% of the collected data



Cosmics in MicroBooNE

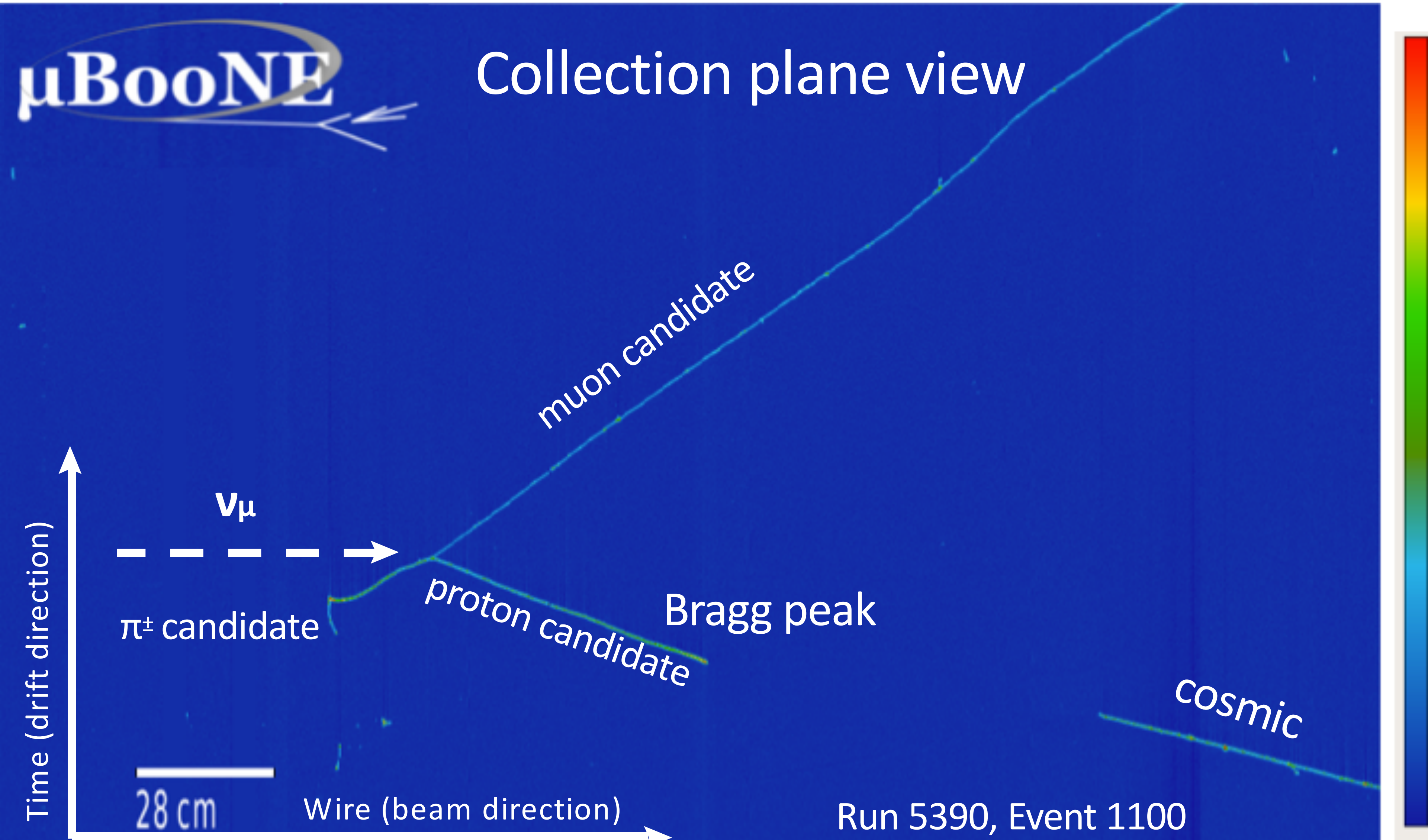
- Cosmic backgrounds come from:
  - Near surface location
  - 2.3 ms drift time



Challenge for MicroBooNE analyses:

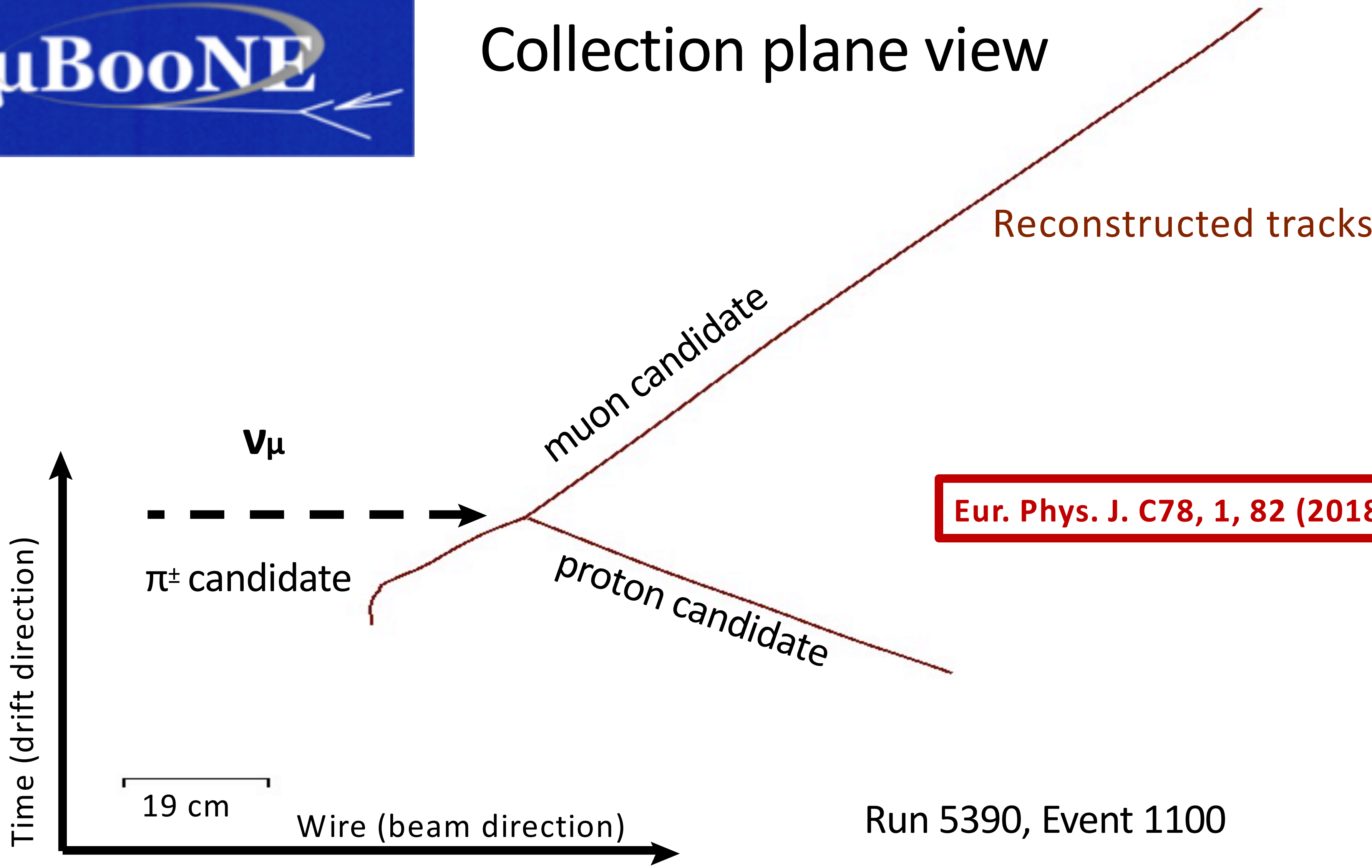
- 97% of the triggered events have cosmic-only data events
- Remaining 3% events have both cosmics and neutrinos in same event (~20 cosmics and 1 neutrino)

Candidate Neutrino Event Display



Fully Automatic Track Reconstruction

Collection plane view



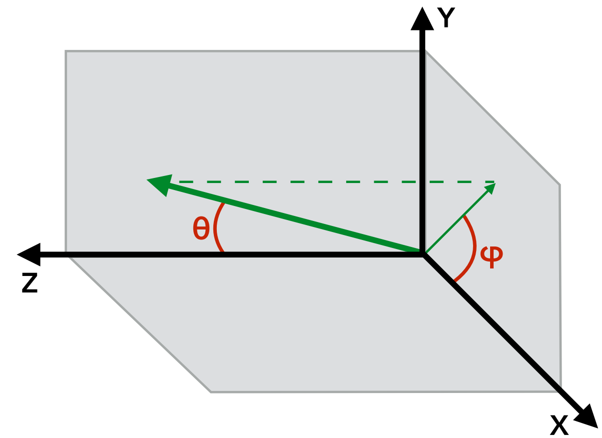
Eur. Phys. J. C78, 1, 82 (2018)

Run 5390, Event 1100

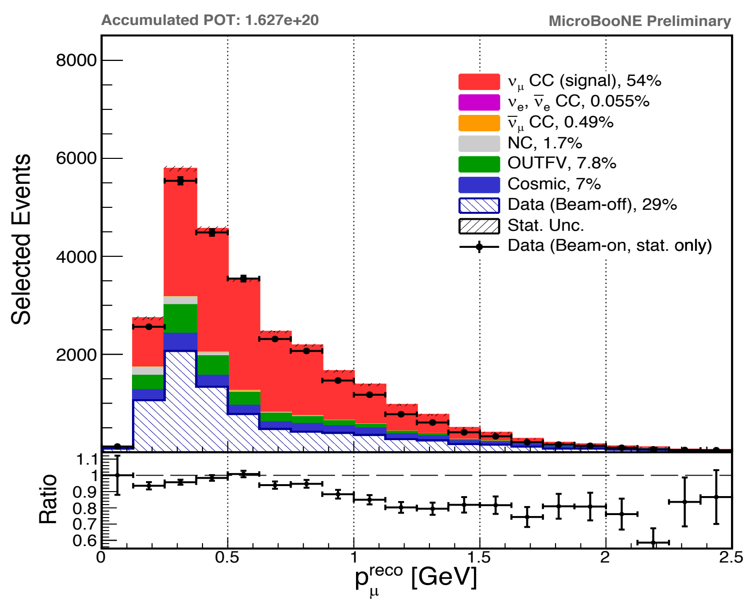
Recent Results from MicroBooNE

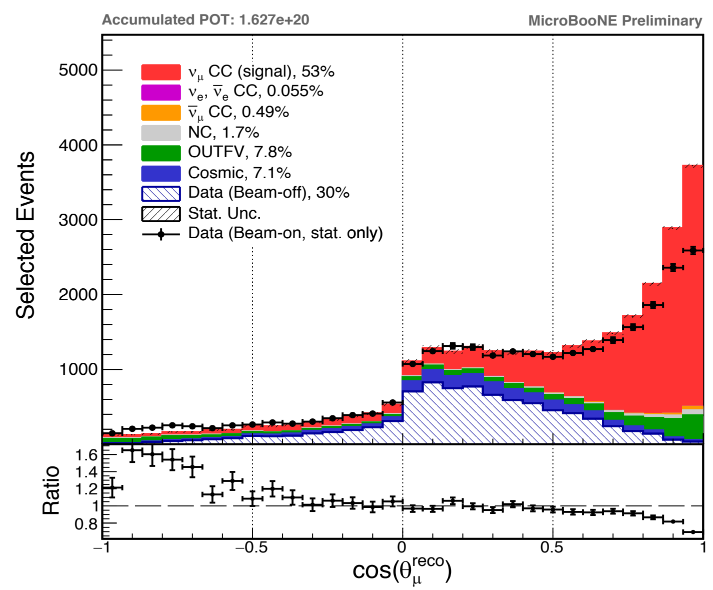
ν_μ CC Inclusive Cross Section Measurement

- First inclusive cross section measurement from MicroBooNE
- Single differential measurement as function of reconstructed muon kinematics



Muon kinematic distributions

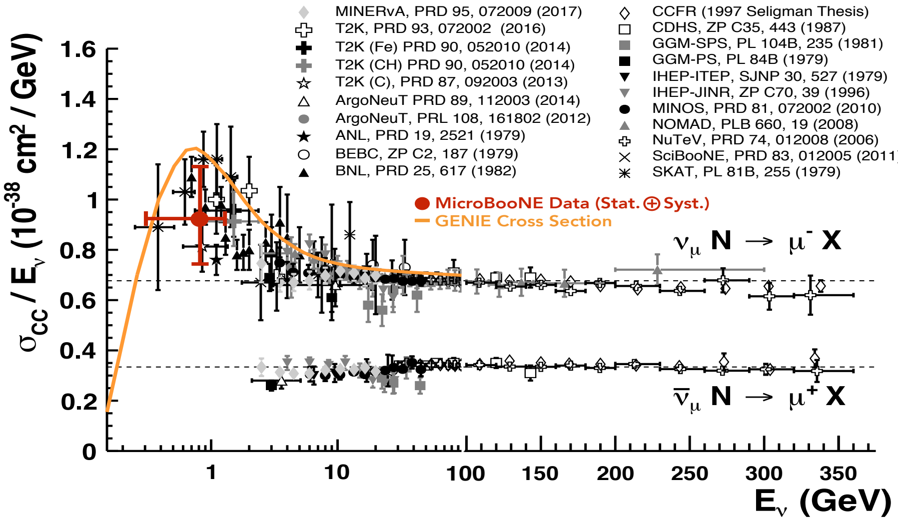


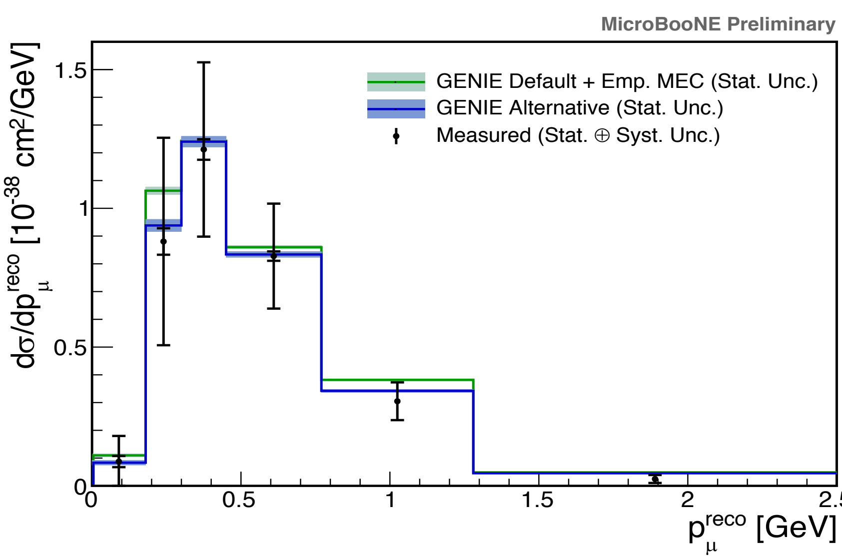


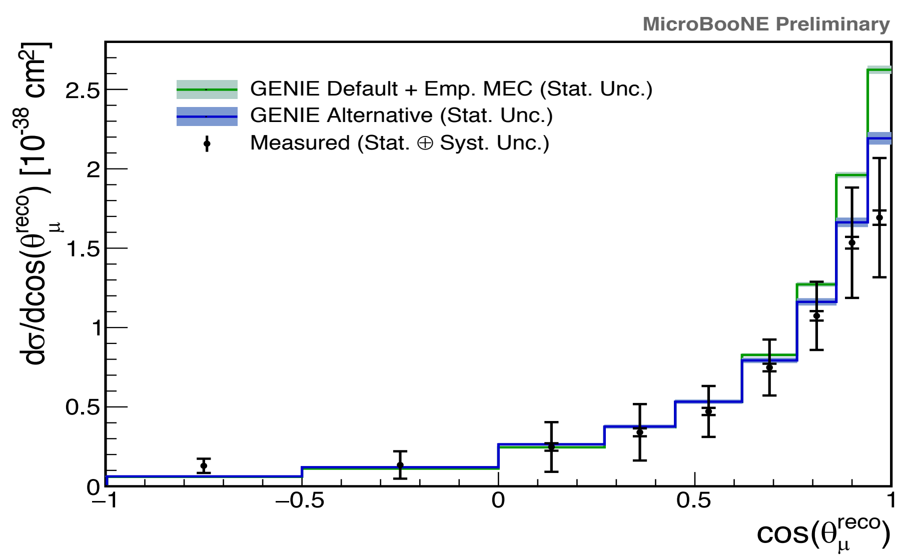
"First Muon-Neutrino Charged-Current Inclusive Differential Cross Section Measurement for MicroBooNE Run 1 Data" MICROBOONE-NOTE-1045-PUB (2018)

ν_μ CC Inclusive Cross Section Measurement

- Used two different sets of GENIE models
- Systematic uncertainties dominate currently
  - Studies are underway



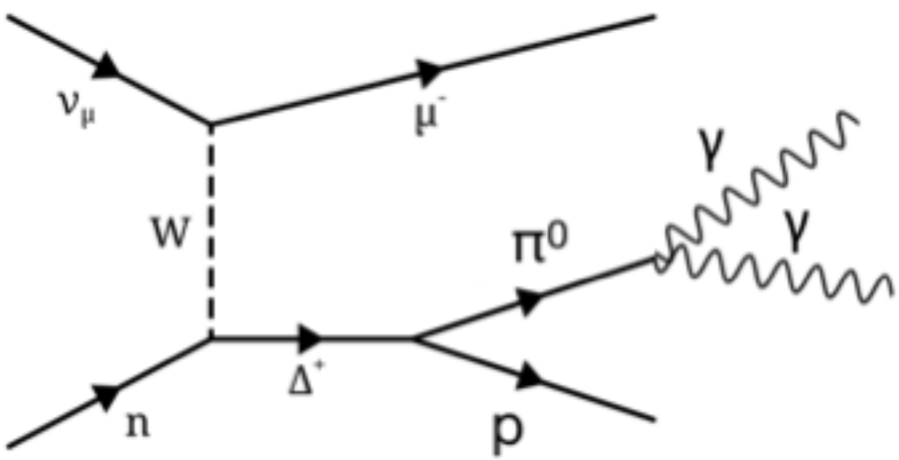


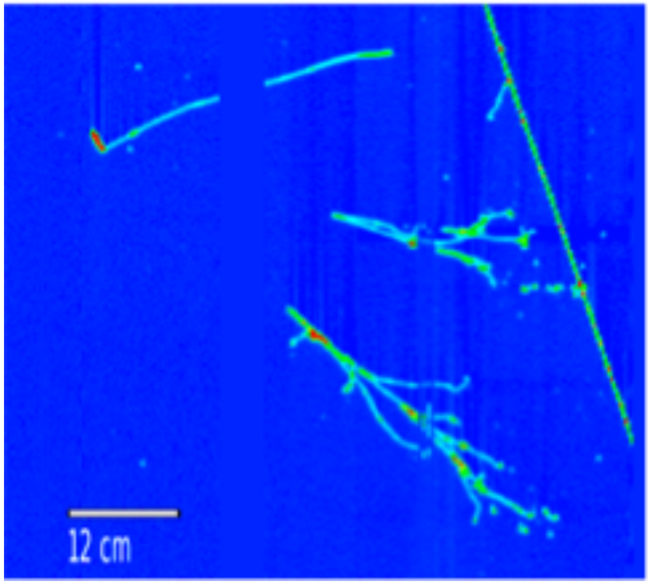


"First Muon-Neutrino Charged-Current Inclusive Differential Cross Section Measurement for MicroBooNE Run 1 Data" MICROBOONE-NOTE-1045-PUB (2018)

CC π^0 Cross Section Measurement

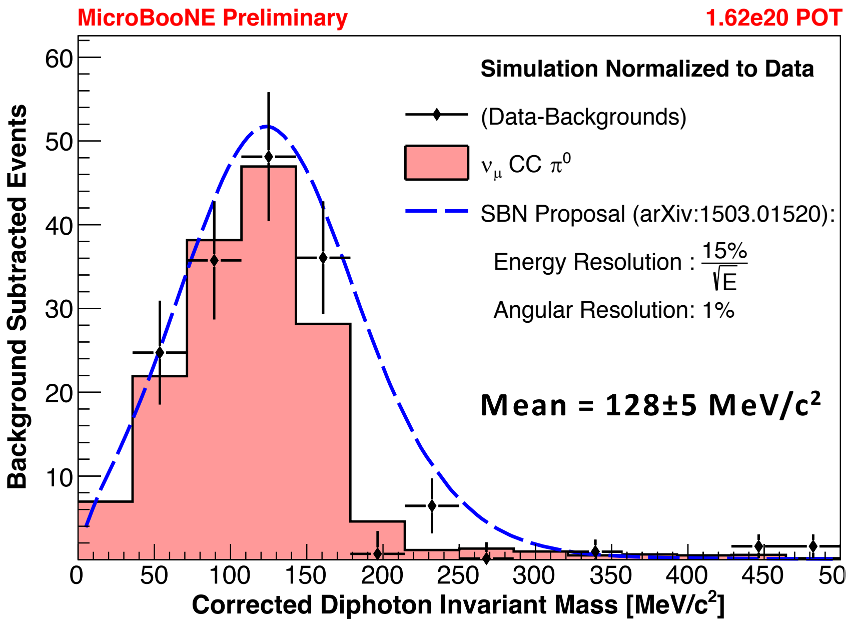
- The first measurement of total flux-integrated cross section for CC single π^0 production on argon
- Allows the study of shower reconstruction performance
  - NC π^0 production is a background for $\nu_\mu \rightarrow \nu_e$ oscillation searches

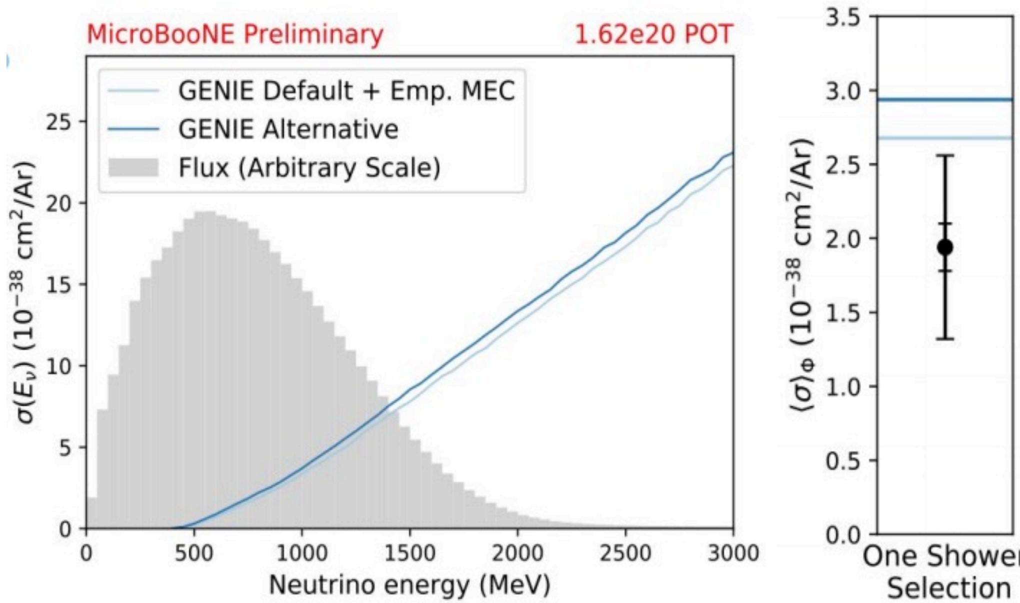




"First Measurement of Muon Neutrino Charged Current Single Neutral Pion Production on Argon with the MicroBooNE LArTPC" MICROBOONE-NOTE-1032-PUB (2018)

CC π^0 Cross Section Measurement





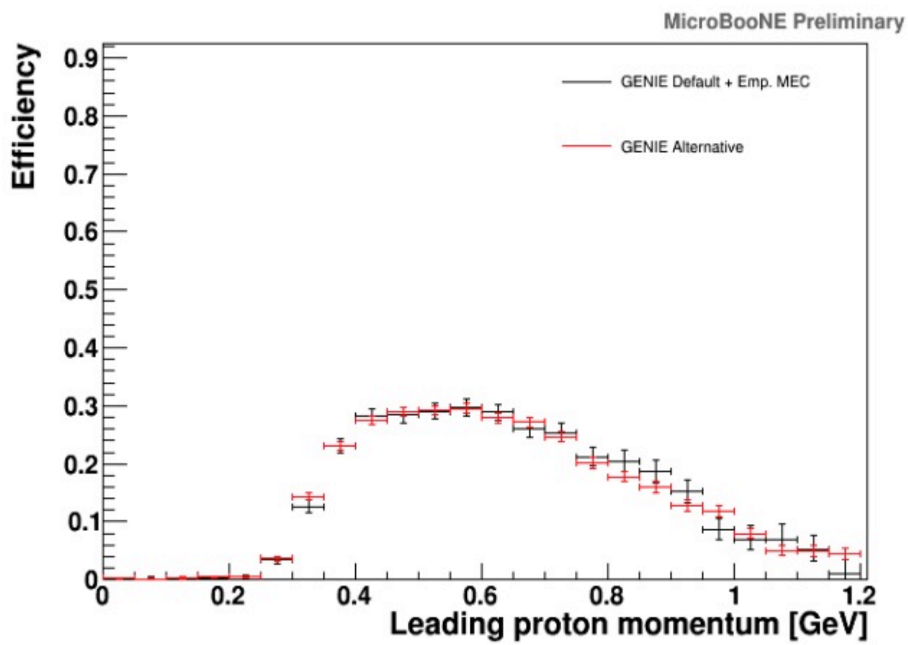
- Measured diphoton mass peak is consistent with π^0 mass
- Compared the measurement with two sets of GENIE models
  - Measurement is consistent within 1.6σ, with predictions from both model sets

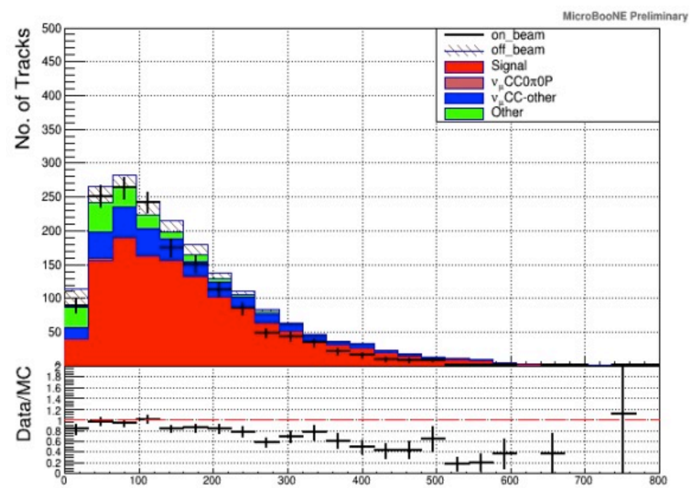
$$\left\langle \sigma^{\nu_\mu \mathbf{CC}\pi^0} \right\rangle_\Phi = (1.94 \pm 0.16\ [\mathrm{stat.}] \pm 0.60\ [\mathrm{syst.}]) \times 10^{-38}\ \frac{\mathrm{cm}^2}{\mathrm{Ar}}$$

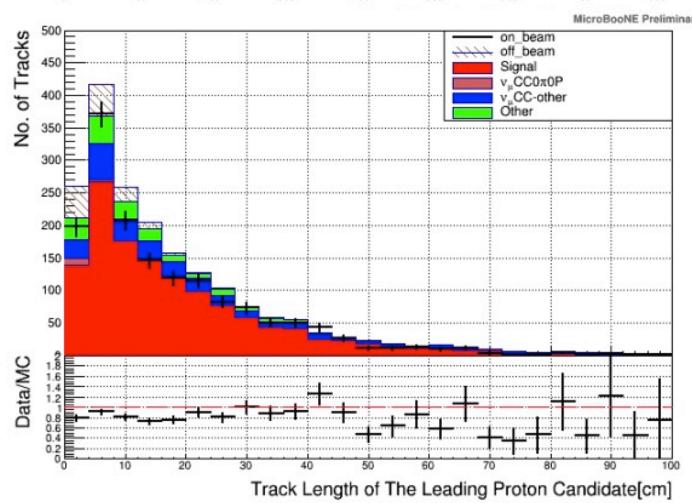
"First Measurement of Muon Neutrino Charged Current Single Neutral Pion Production on Argon with the MicroBooNE LArTPC" MICROBOONE-NOTE-1032-PUB (2018)

ν_μ CC Np0π Selection (N>0)

- Important for studies of nuclear effects
- Lower KE threshold for protons → more phase space
  - 46 MeV (~300 MeV/c momentum)
- Useful for oscillation searches





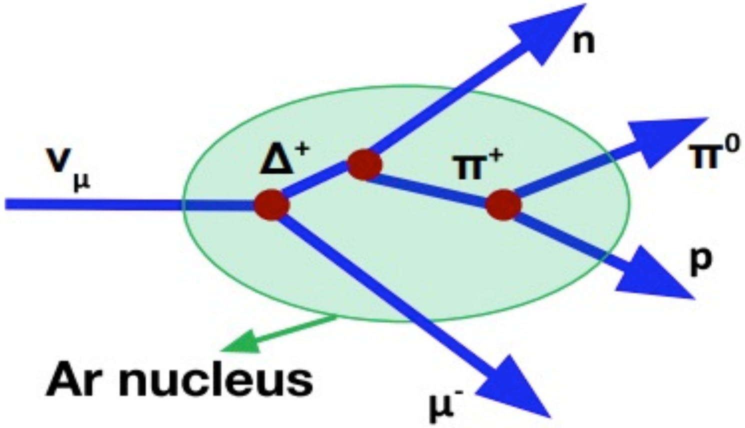


"Towards measurements of nuclear effects in MicroBooNE", MICROBOONE-NOTE-1046-PUB, (2018)

Charged Particle Multiplicity (CPM)

- **<u>Analysis Goal</u>:** Count the number of reconstructed charged particles exiting the target nuclei at the interaction point
  - We tag $\mu^{\pm}$, $\pi^{\pm}$, and *p*; but π^{0} and *n* are not included
  - Kinetic energy thresholds: 69 MeV for *p* and 31 MeV for $\mu^{\pm}/\ \pi^{\pm}$
- Gives knowledge of ν_{μ}-Ar interactions in form of directly observable quantity
- First measurement of charged track multiplicity in ν_{μ} CC interactions in argon

Resonance Interaction



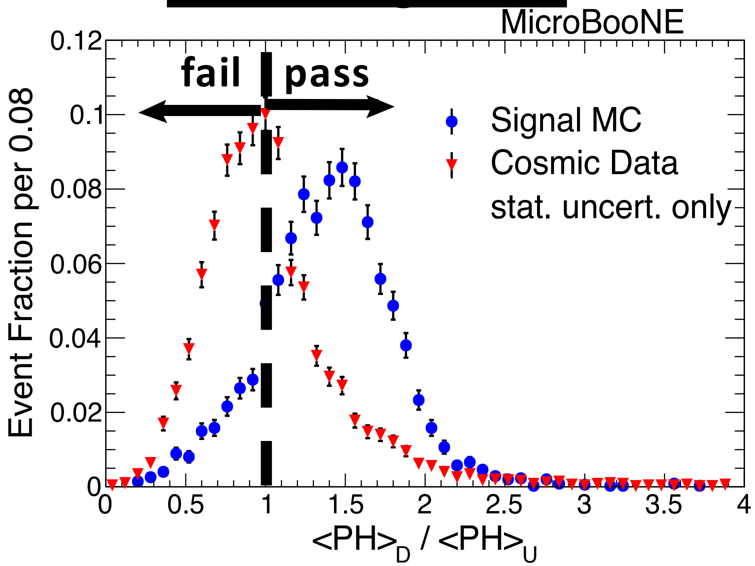
CPM = 2

"Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions", arXiv:1805.06887, submitted to PRD (2018)

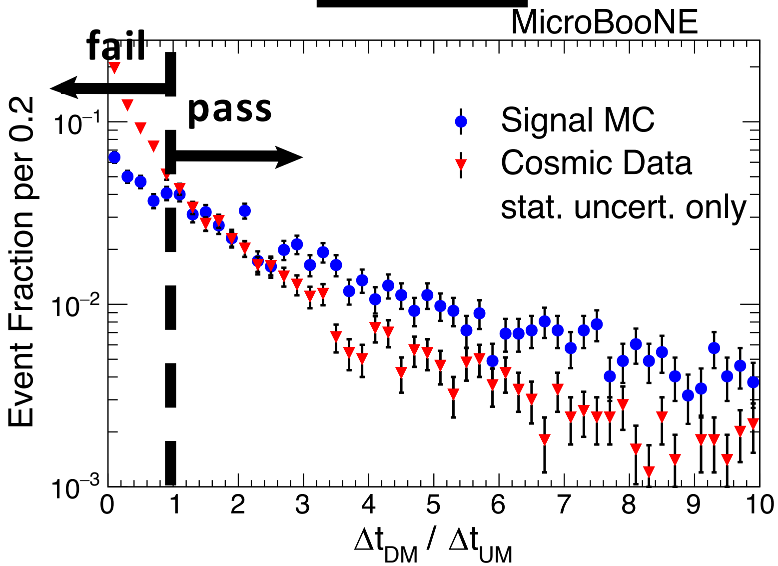
Cosmic Rejection Technique

- Perform two tests
  - Look for Bragg peak (Pulse Height test)
  - Look for pronounced muon scattering towards the end of the track (MCS test)

Pulse Height test



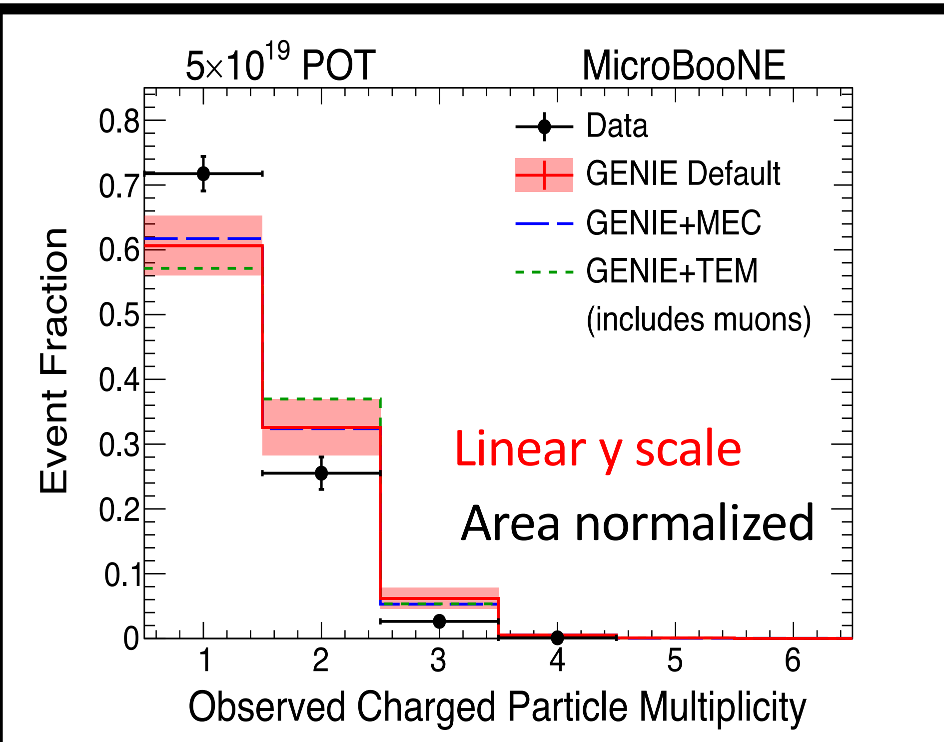
MCS test

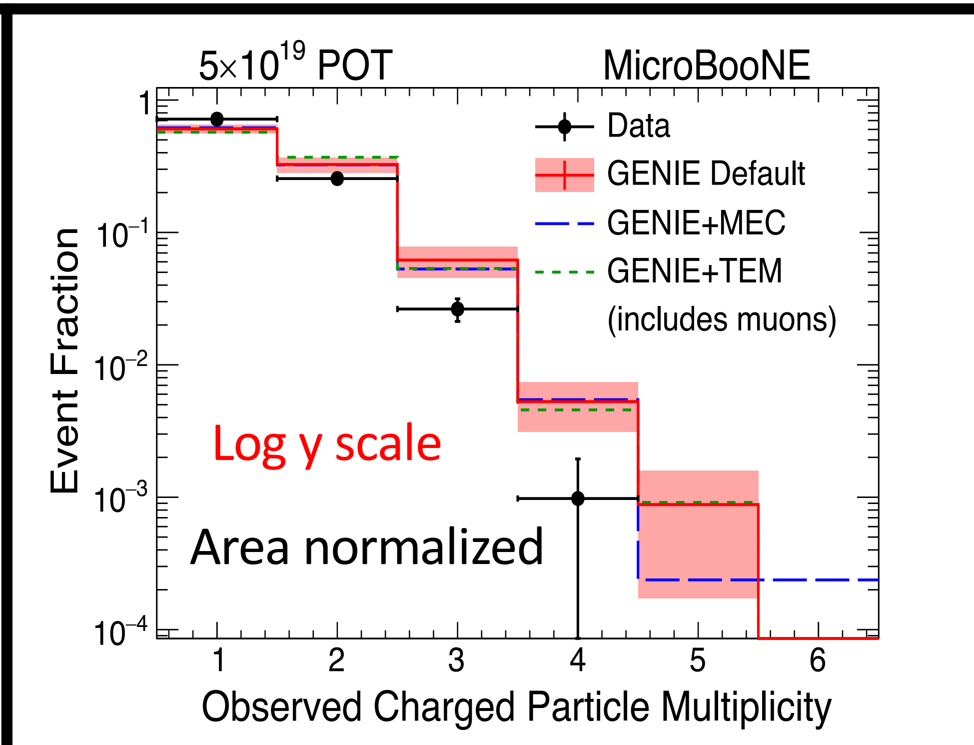


Perform likelihood fit to extract the number of neutrino events from a cosmic ray background dominated sample

"Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions", arXiv:1805.06887, submitted to PRD (2018)

First CPM Distribution from ν_μ-Ar Data





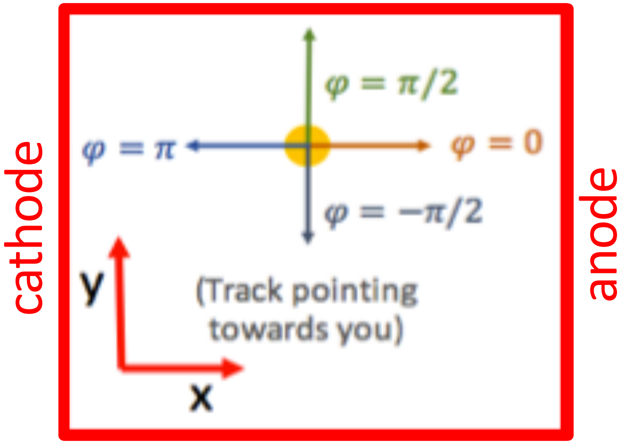
- Data favors lower multiplicity compared to all three simulations
- Simulation agrees with data at the 2σ level

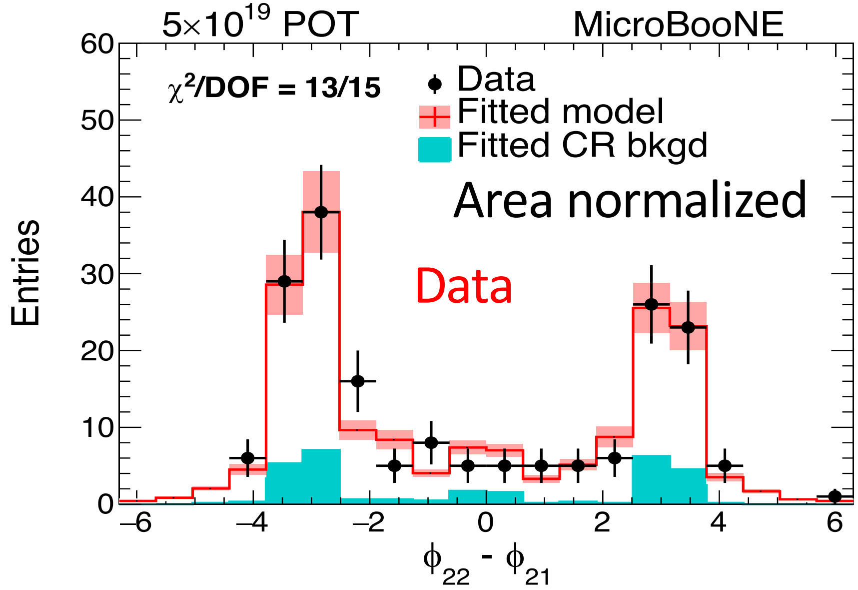
"Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions", arXiv:1805.06887, submitted to PRD (2018)

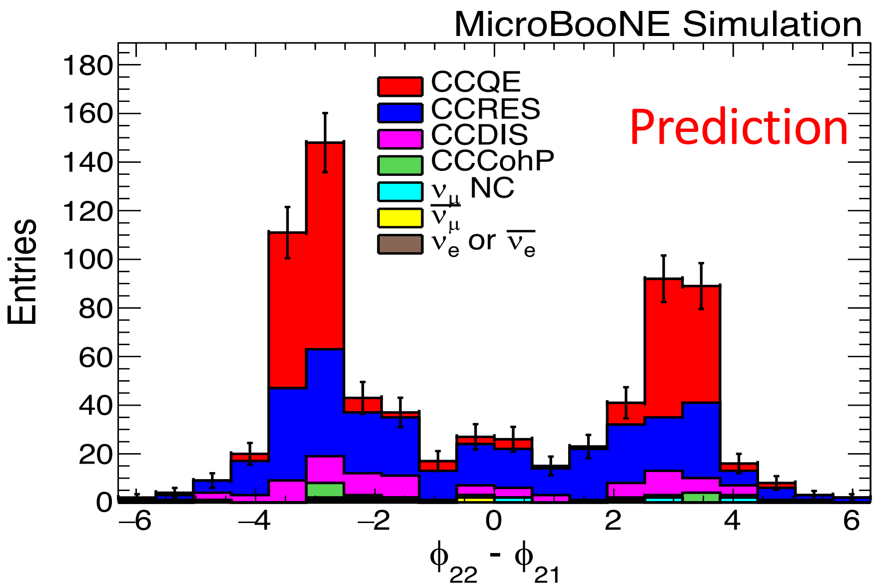
Azimuthal angle difference distribution

$\Phi_{short} - \Phi_{long}$
(multiplicity = 2)

- Good shape agreement
- Can distinguish QE and RES contributions







"Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions", arXiv:1805.06887, submitted to PRD (2018)

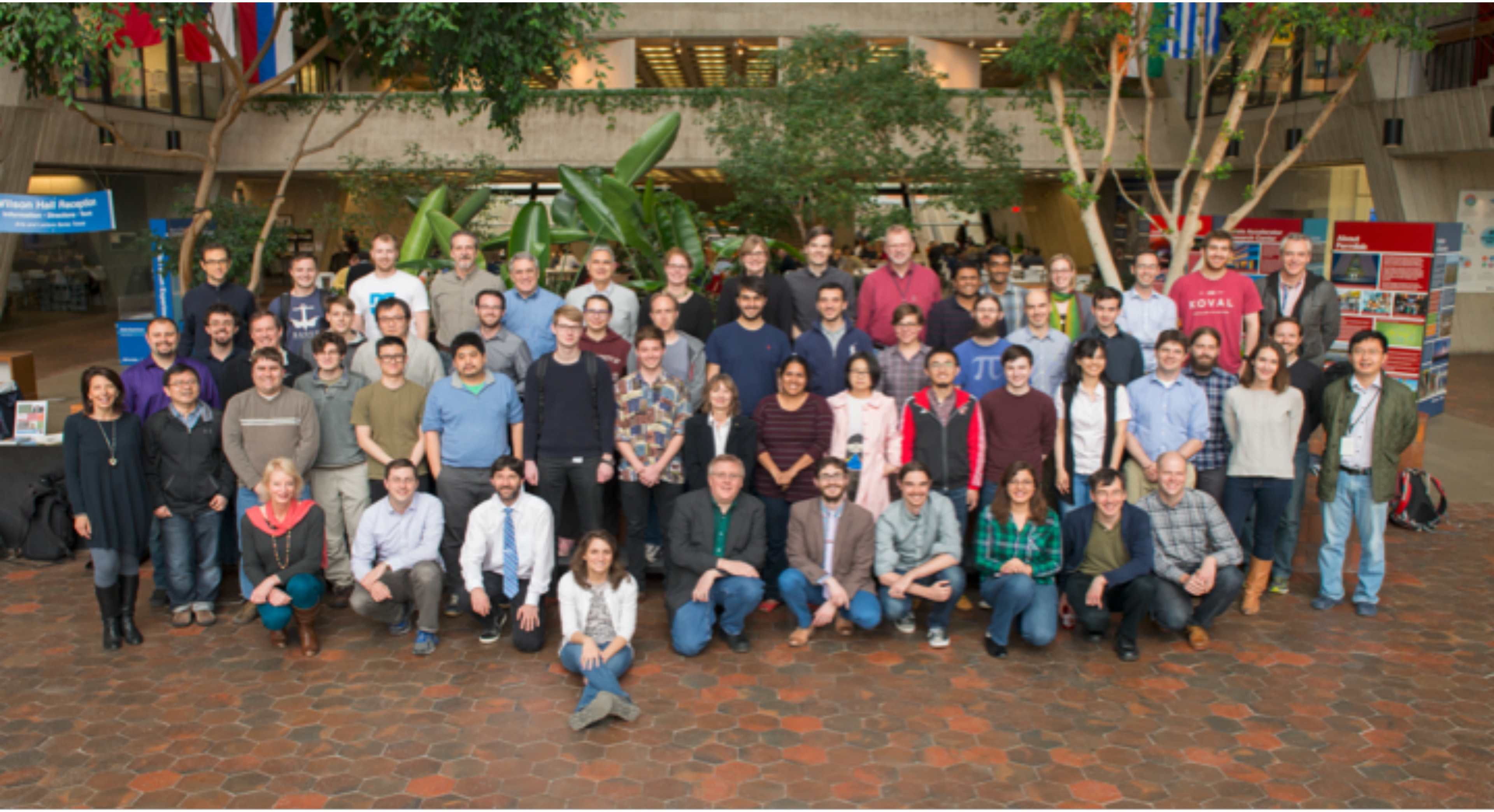
Future Prospects

- Many more cross section analyses are in the pipeline
  - CC Np0π
  - CC 2p0π
  - NC elastic cross section
- Will use advanced reconstruction algorithms
  - Pandora (**Eur. Phys. J. C78, 1, 82 (2018)**)
  - WireCell (**arXiv:1804.02583** and **arXiv:1802.08709**)
  - Convolutional Neural Network (**JINST 12, P0311 (2017)**)
- Utilize full statistics of the experiment
- Utilize more sophisticated systematics evaluation
- Will test more neutrino generators in the near future
  - NuWro, GiBUU, NEUT etc

Summary

- MicroBooNE has been collecting neutrino data stably for almost three years
- MicroBooNE is developing successful tools for LArTPCs
    - Automatic reconstruction
    - Calorimetry
    - Particle identification
- Many technical and physics results have been produced
- First ν–Ar cross section results have been presented at Neutrino this year
- Implementing and testing different neutrino generators for Ar is a near term goal

Thank you from MicroBooNE

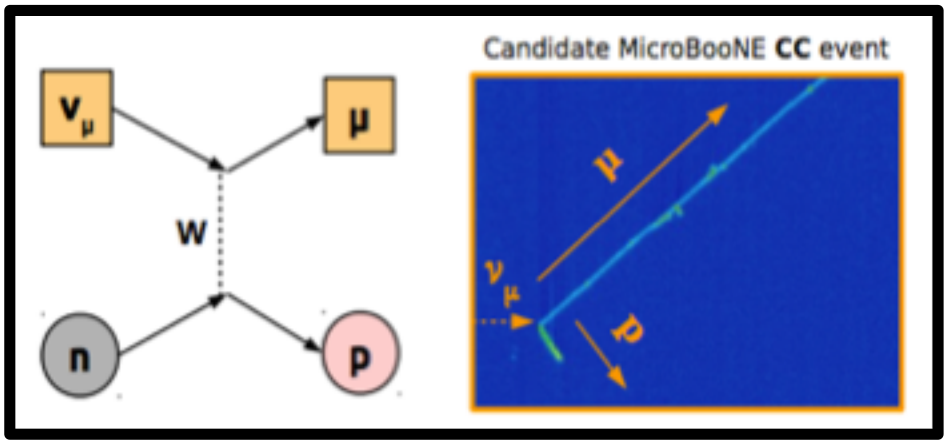


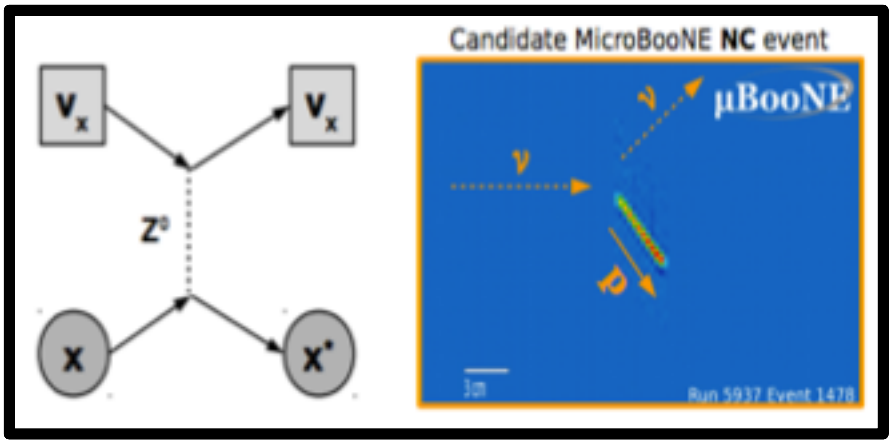
Backup Slides

Neutrino interactions

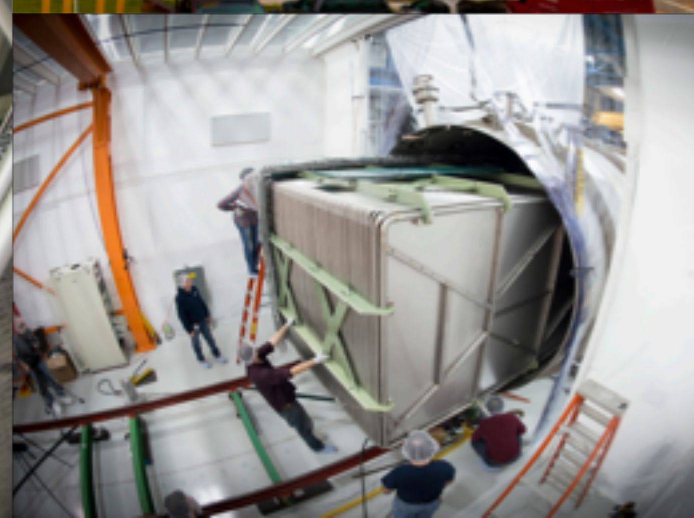
Charged Current Interactions:
1- via W^+, W^- bosons
2- Outgoing lepton flavor → incoming ν flavor
3- Outgoing lepton charge → incoming ν nature (ν, anti ν)

Neutral Current Interactions:
1- via Z boson
2- No information of neutrino flavor
3- No information of incoming ν nature (ν, anti ν)





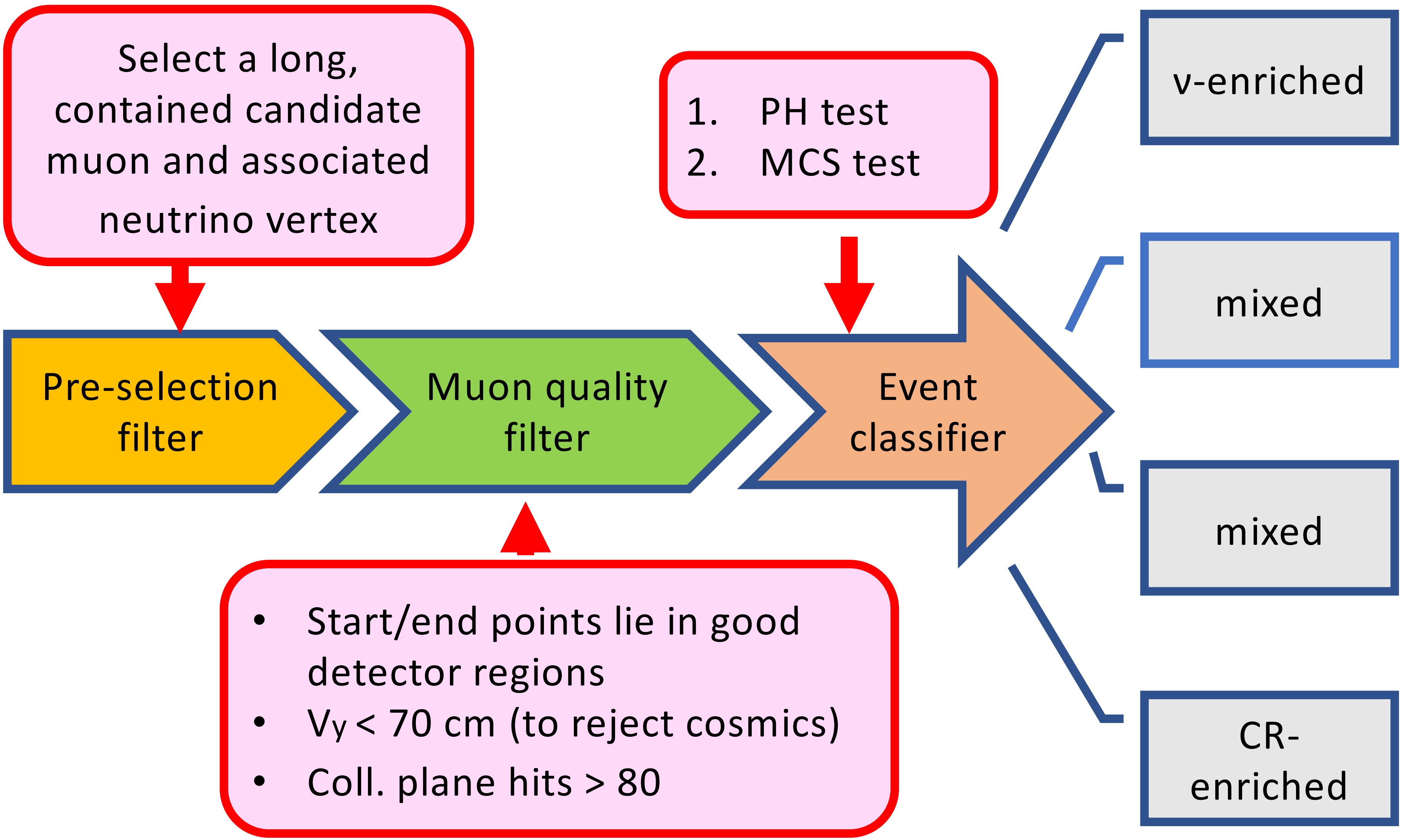
MicroBooNE Installation & Commissioning



GENIE Model Sets

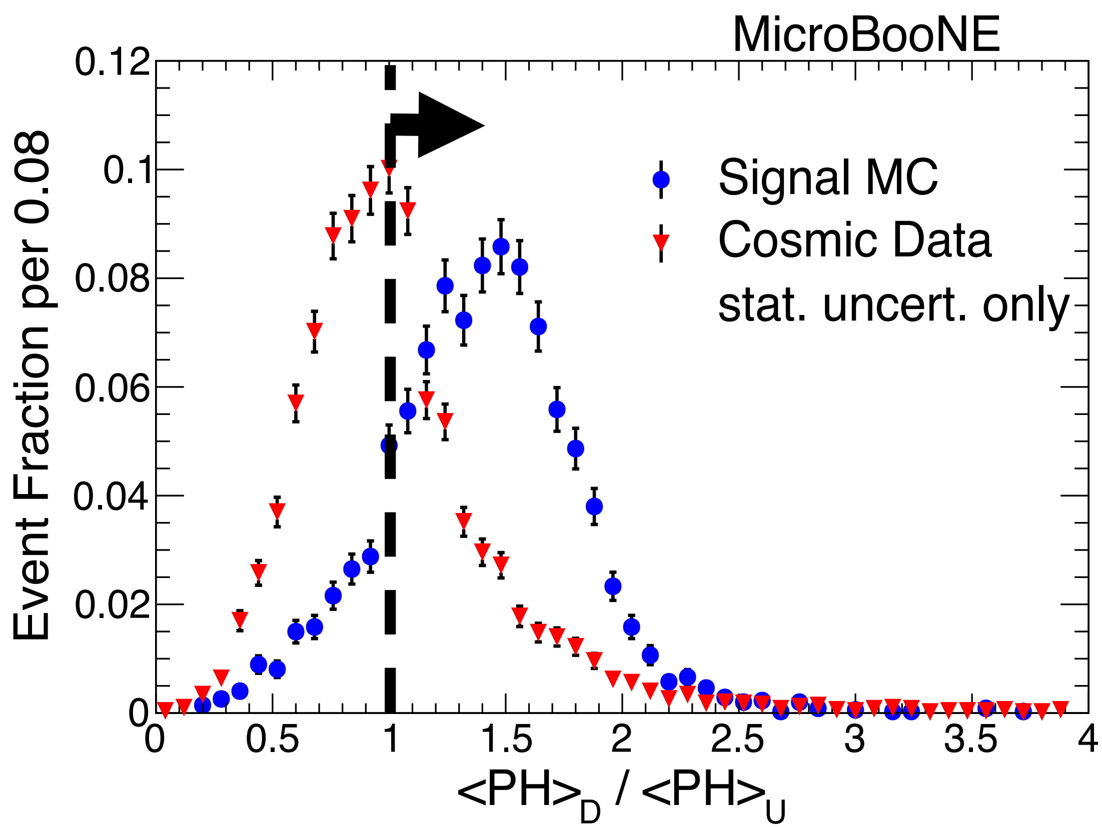
MC	Tune1	Tune3
nuclear momentum	Relativistic Fermi Gas	Local Fermi Gas
QE model	Llewellyn-Smith	Nieves
MEC model	Empirical	Valencia
resonance model	Rein-Sehgal	Berger-Sehgal
final state interactions	hA	hA2014

Analysis Chain



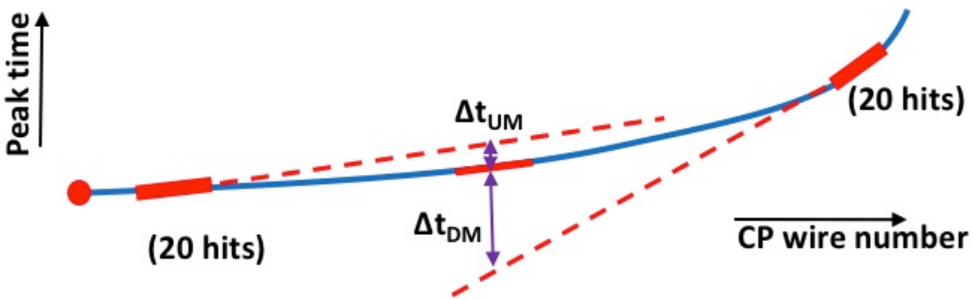
Pulse height (PH) test

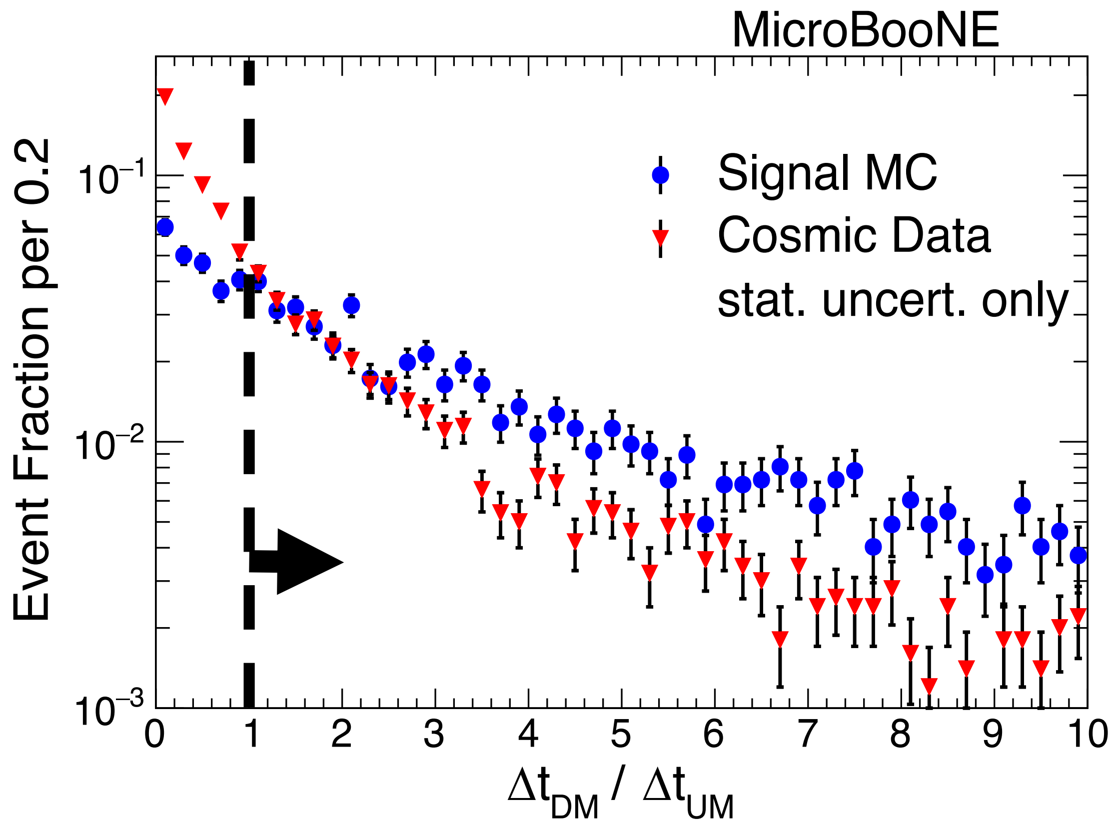
Rate of energy loss increases along the track from upstream to downstream end



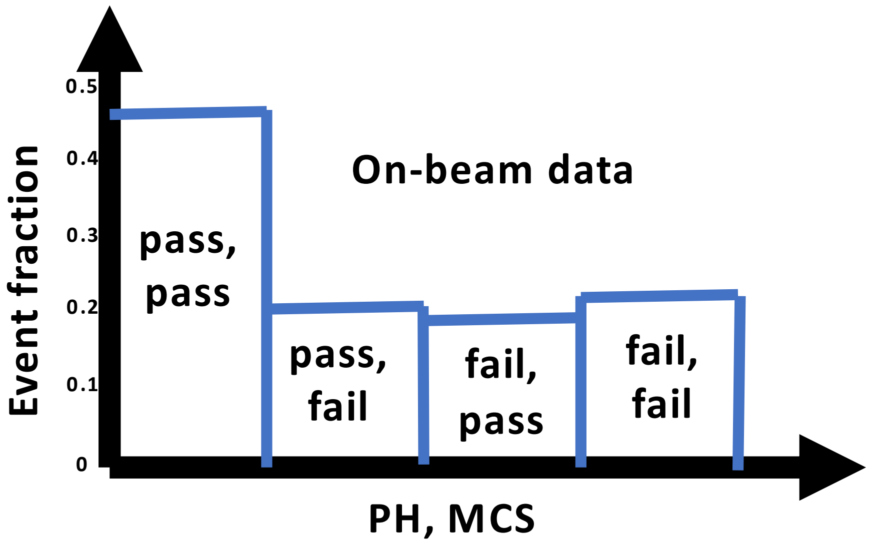
Multiple Coulomb scattering (MCS) test

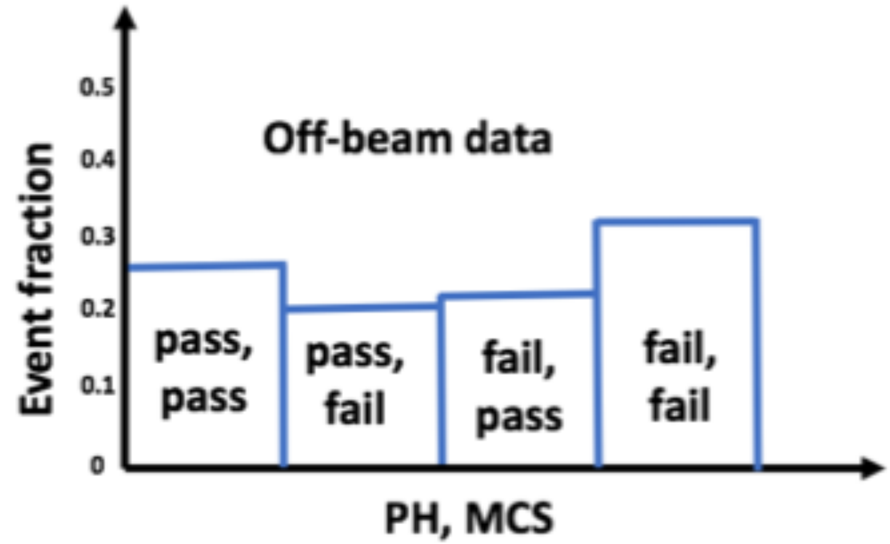
Scattering is more pronounced along the downstream end of the track as the momentum decreases.





Signal extraction model





Relate number of events in each of 8 subsamples to:

- Number of on-beam neutrinos
- Number of on-beam cosmics
- Number of off-beam cosmics
- Probability that a neutrino or cosmic passes the PH or MCS tests

Final likelihood function:

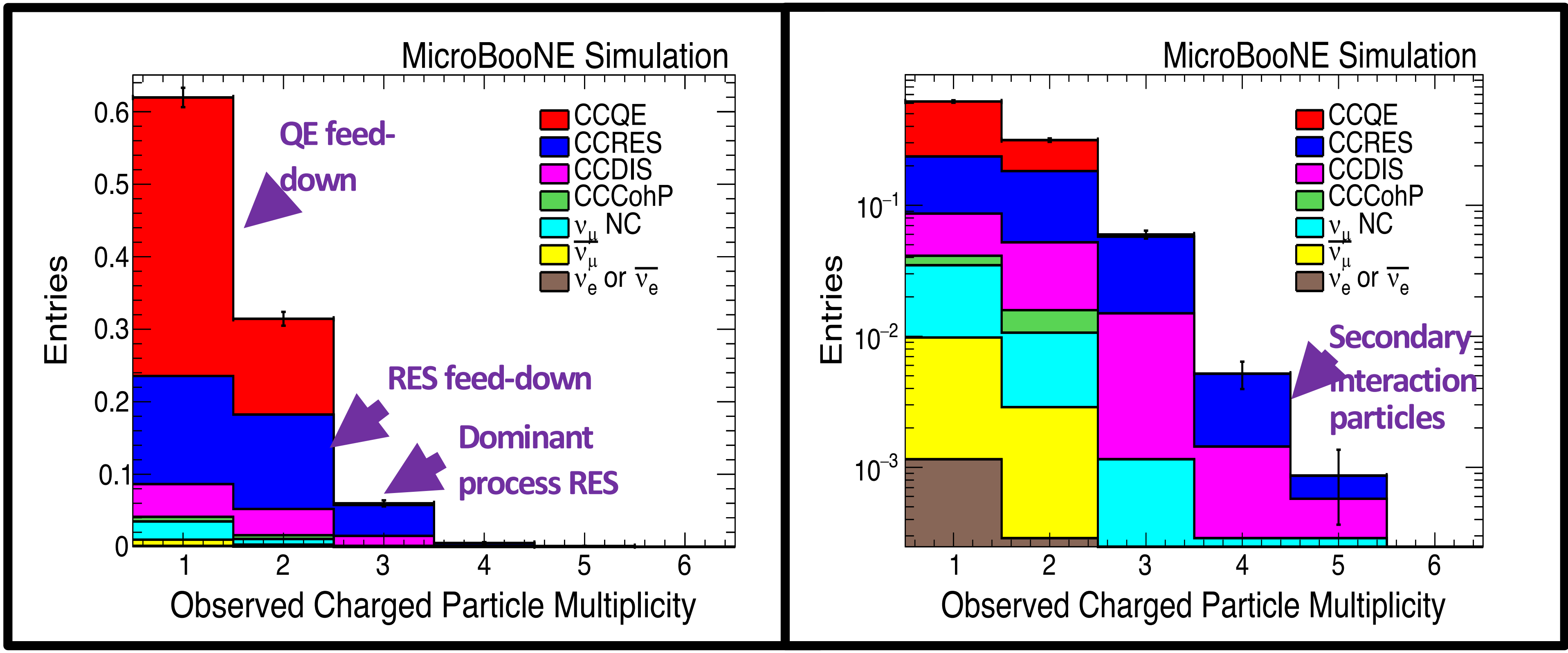
$$
\begin{aligned}
L_{TOT} = {} & M\left(N_{\nu\nu}, N_{CR\nu}, N_{\nu CR}, N_{CRCR}; \frac{\hat{N}_{\nu\nu}}{\hat{N}}, \frac{\hat{N}_{CR\nu}}{\hat{N}}, \frac{\hat{N}_{\nu CR}}{\hat{N}}, \frac{\hat{N}_{CRCR}}{\hat{N}}\right) \\
& \times M\left(N'_{\nu\nu}, N'_{CR\nu}, N'_{\nu CR}, N'_{CRCR}; \frac{\hat{N}'_{\nu\nu}}{\hat{N}'}, \frac{\hat{N}'_{CR\nu}}{\hat{N}'}, \frac{\hat{N}'_{\nu CR}}{\hat{N}'}, \frac{N'_{CRCR}}{\hat{N}'}\right) \\
& \times \frac{\hat{N}^{N}}{N!} e^{-\hat{N}} \times \frac{\hat{N}'^{N'}}{N'!} e^{-\hat{N}'}.
\end{aligned}
$$

No dependence on off-beam to on-beam normalization

Nearly model independent

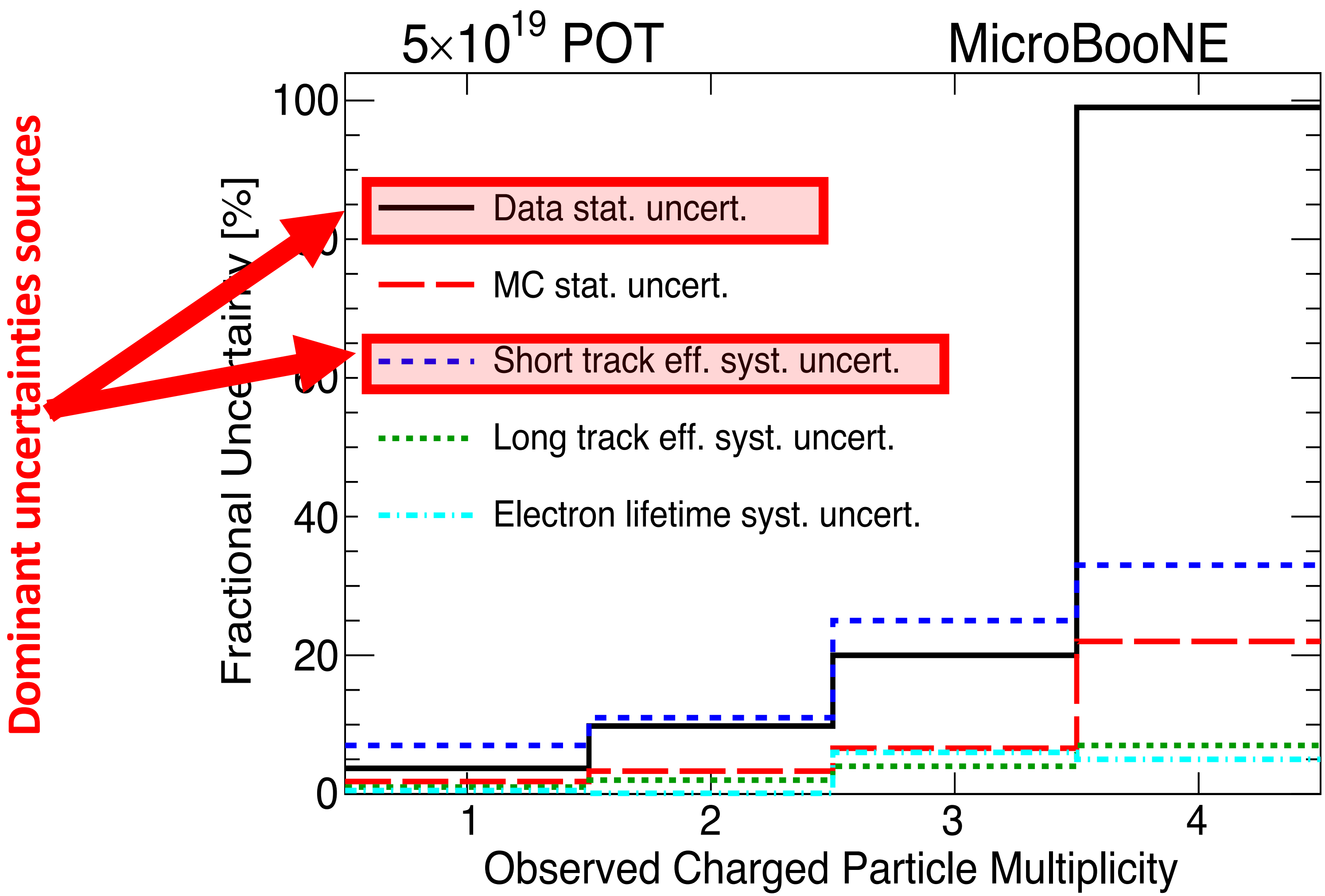
Expectations for observed charged particle multiplicity distribution

No Unfolding

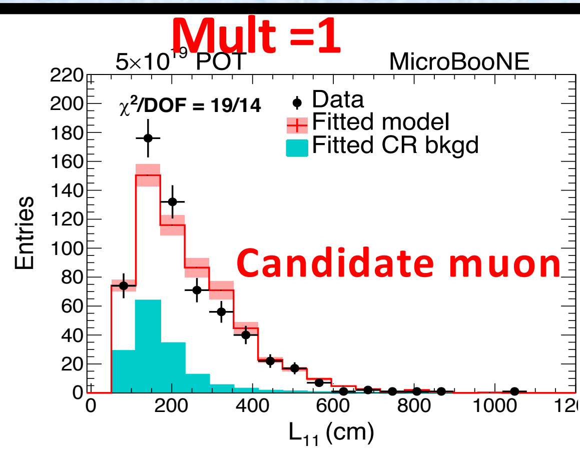


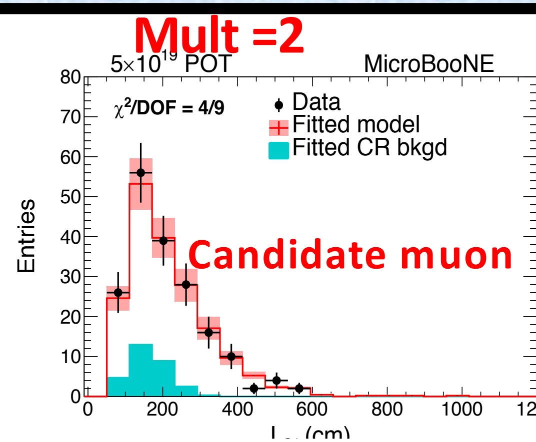
Common feed-down occurrence is due to efficiency*acceptance effects.

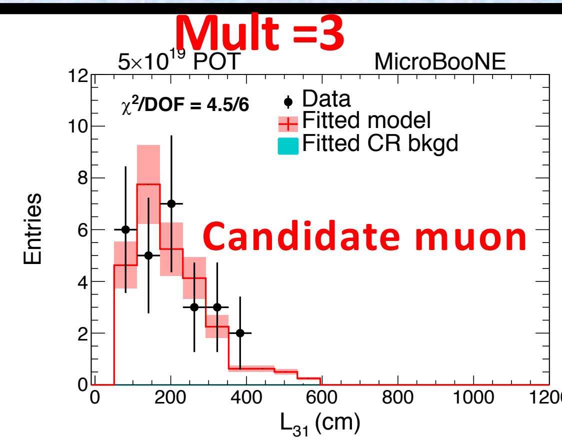
Uncertainty estimates

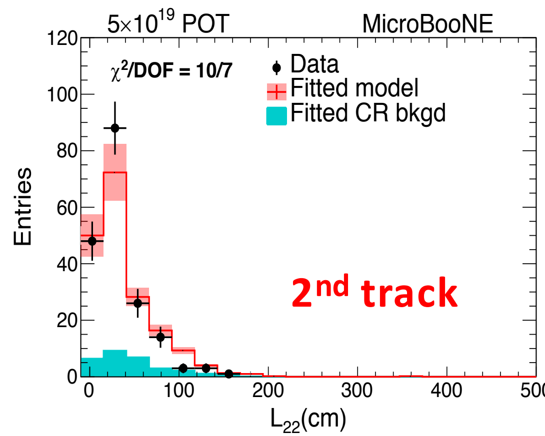


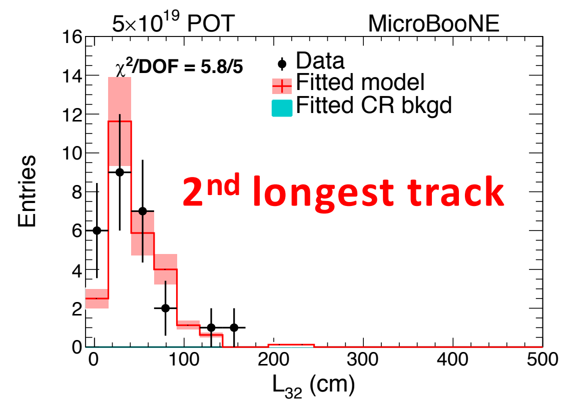
Track length distribution





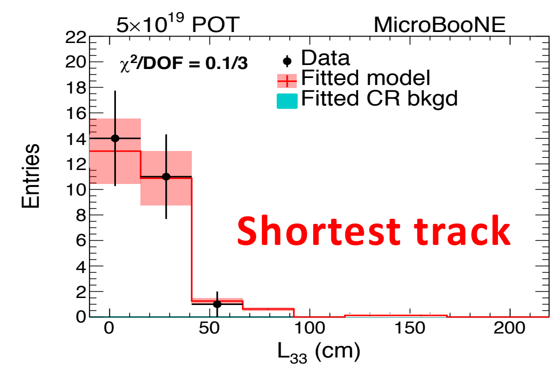






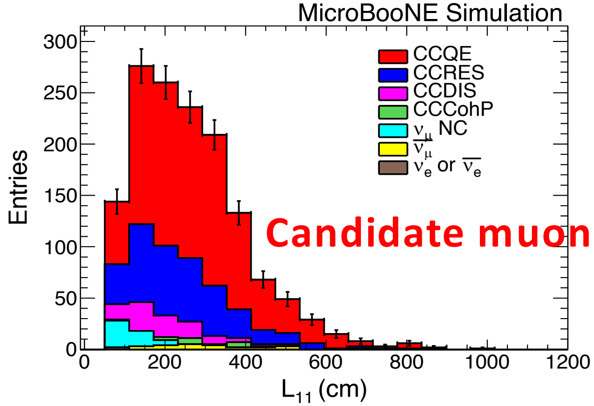
Track length distribution

Track Length: 3D distance between start and end points

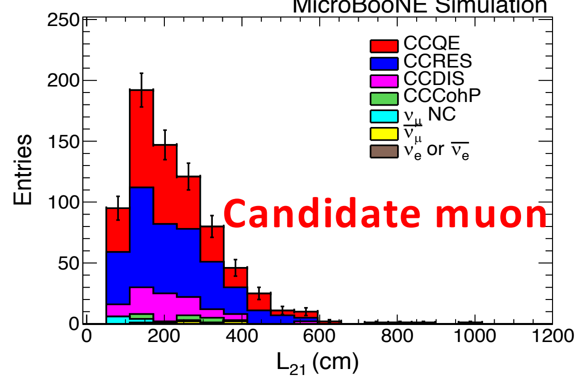


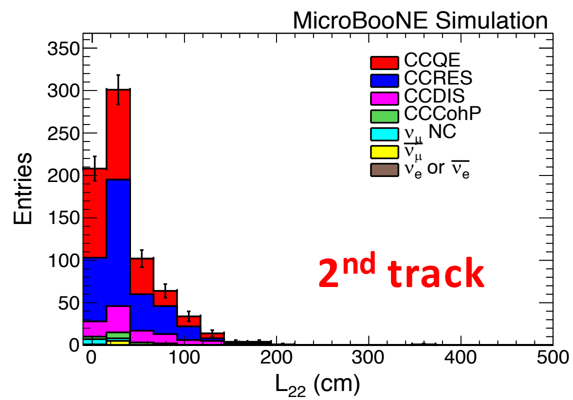
Track length distribution (GENIE prediction)

Mult =1

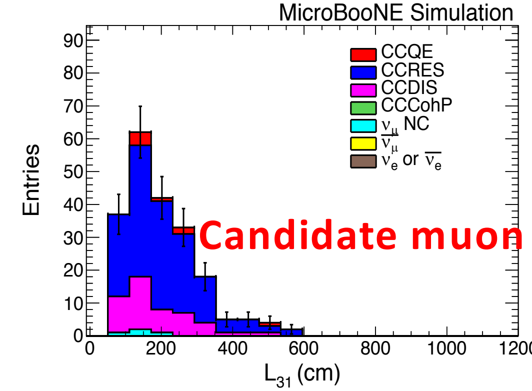


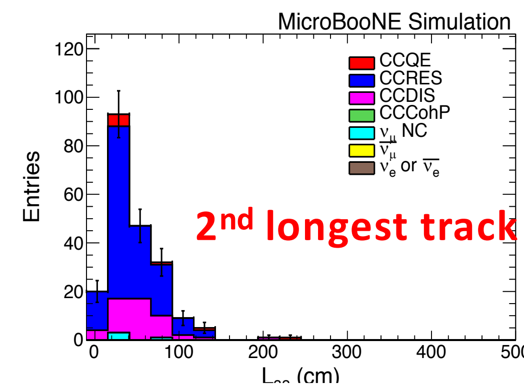
Mult =2

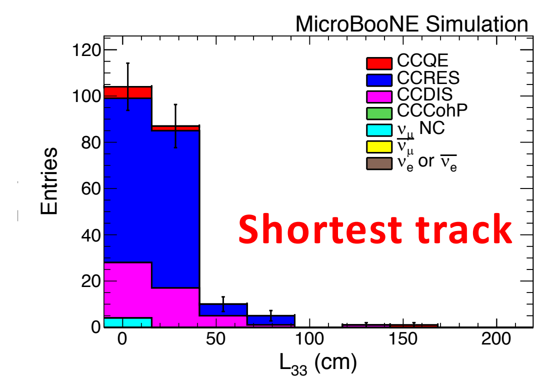




Mult =3







Track length distribution

Track Length: 3D distance between start and end points