MicroBooNE Cross Section Measurements

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Lederman Fellow

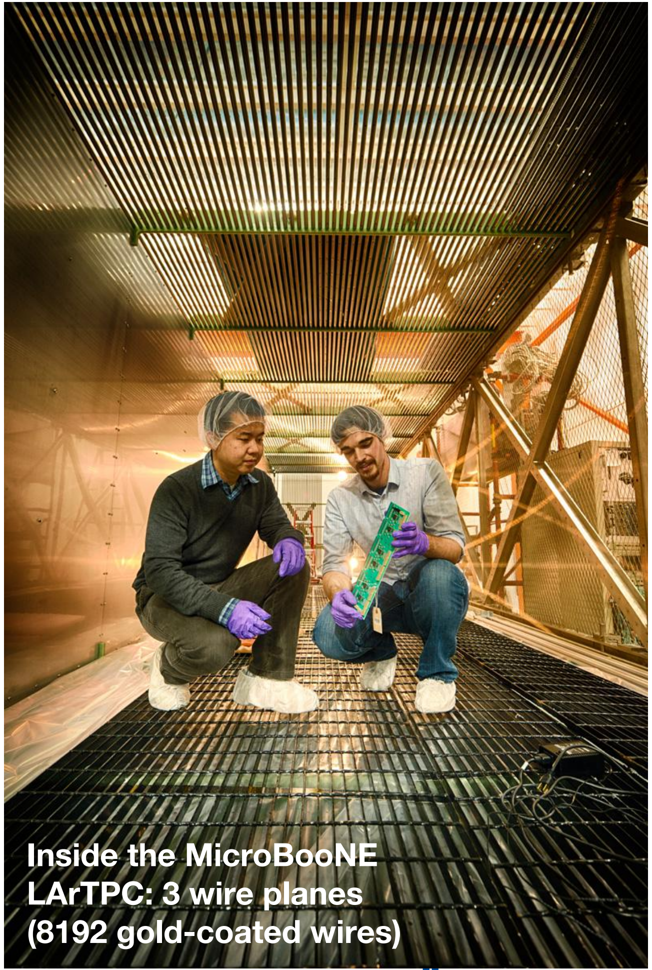
August 5th, 54th Annual Users Meeting

MicroBooNE at a glance

MicroBooNE is the longest running **Liquid Argon Time Projection Chamber** at FNAL. With 85 ton active volume, MicroBooNE collects neutrinos on-axis from the BNB and highly off-axis from NuMI.

Completed 5 years physics runs: 2015-2021.
Largest neutrino-argon dataset available to date.

Just started exciting R&D program!



MicroBooNE at a glance

MicroBooNE
Chamber at
neutrinos on-

Completed 5
Largest neutr

Just started e

Thanks FNAL!!!
for all the support during construction, commissioning and data-taking!!!

MicroBooNE Publications

MicroBooNE has a large body of published work:
33 papers,
56 public notes

Sharing findings with LAr community…

2017 Design and Construction of the MicroBooNE Detector
Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber
Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering
Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC
Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC
Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter

2018 The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector
Ionization Electron Signal Processing in Single Phase LArTPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation
Ionization Electron Signal Processing in Single Phase LArTPCs II: Data/Simulation Comparison and Performance in MicroBooNE

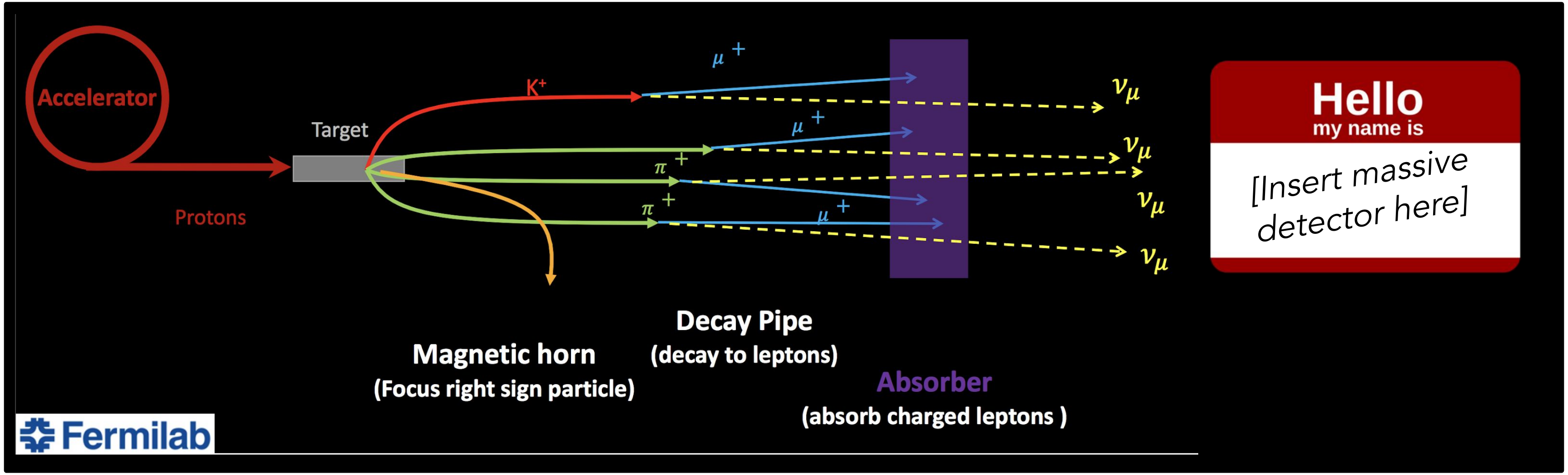
2019 Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions
A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE detector
Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector
Design and Construction of the MicroBooNE Cosmic Ray Tagger System
First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Enu ~0.8 GeV with the MicroBooNE Detector

2020 Calibration of the Charge and Energy Response of the MicroBooNE Liquid Argon Time Projection Chamber Using Muons and Protons
A Method to Determine the Electric Field of Liquid Argon Time Projection Chambers Using a UV Laser System and its Application in MicroBooNE
Reconstruction and Measurement of O(100) MeV Electromagnetic Activity from Neutral Pion to Gamma Gamma Decays in the MicroBooNE LArTPC
Search for heavy neutral leptons decaying into muon-pion pairs in the MicroBooNE detector
First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector
Measurement of Space Charge Effects in the MicroBooNE LAr TPC Using Cosmic Muons
Measurement of Differential Cross Sections for Muon Neutrino CC Interactions on Argon with Protons and No Pions in the Final State

2021 Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector
The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos
A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
Neutrino Event Selection in the MicroBooNE LAr TPC using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching
High-performance Generic Neutrino Detection in a LAr TPC near the Earth's Surface with the MicroBooNE Detector
Semantic Segmentation with a Sparse Convolutional Neural Network for Event Reconstruction in MicroBooNE
Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC
Measurement of the Flux-Averaged Inclusive CC ve and Anti-ve Cross Section on Argon using the NuMI Beam in MicroBooNE
Cosmic Ray Background Rejection with Wire-Cell LAr TPC Event Reconstruction in the MicroBooNE Detector
Measurement of the Longitudinal Diffusion of Ionization Electrons in the Detector
Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector

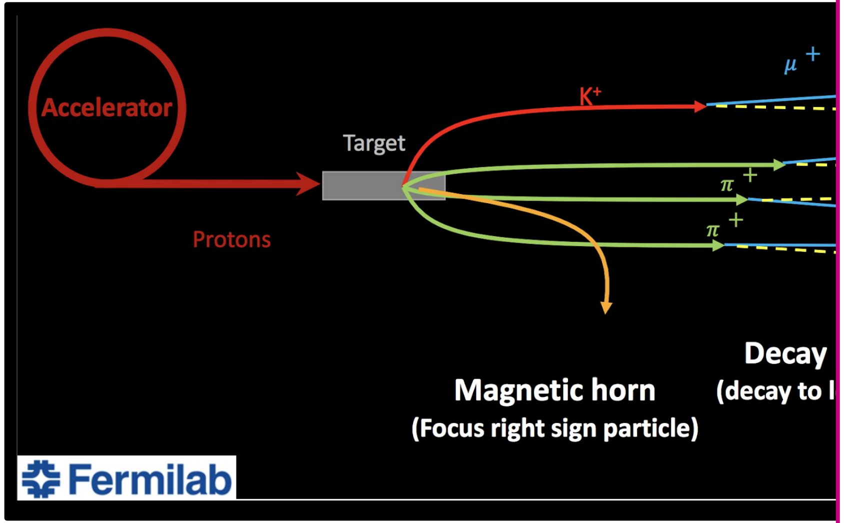
…to boost SBN and DUNE's success
See Denver Whittington's talk

Ingredients for a successful on-beam neutrino experiment



1. Know your neutrino flux

Ingredients for a successful on-b



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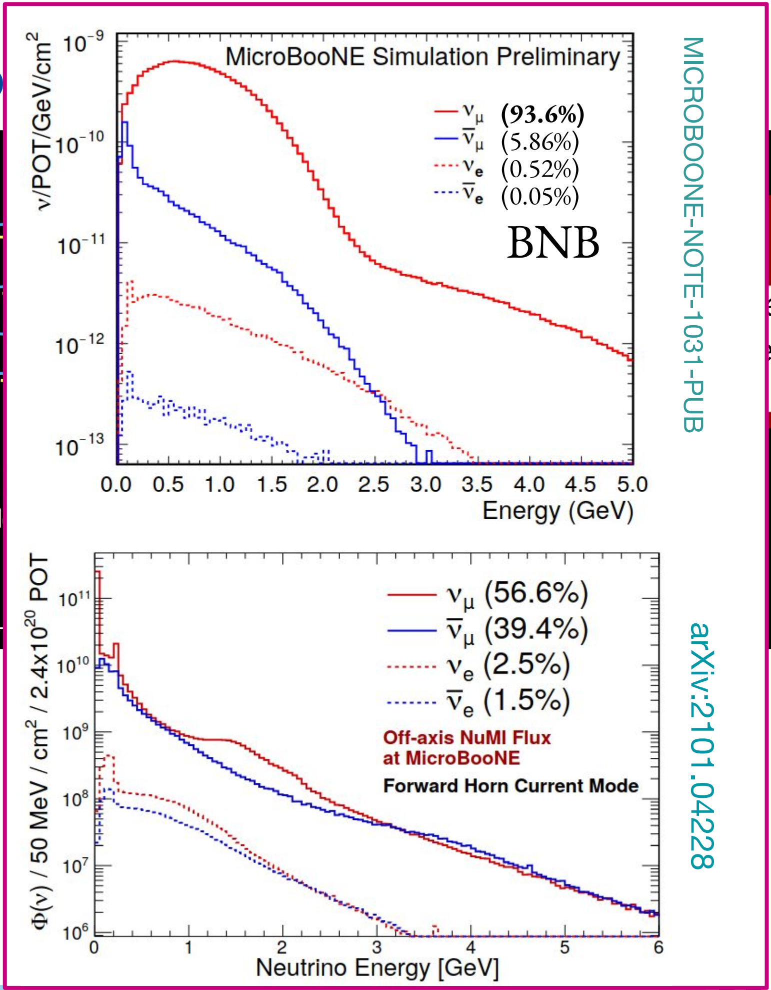

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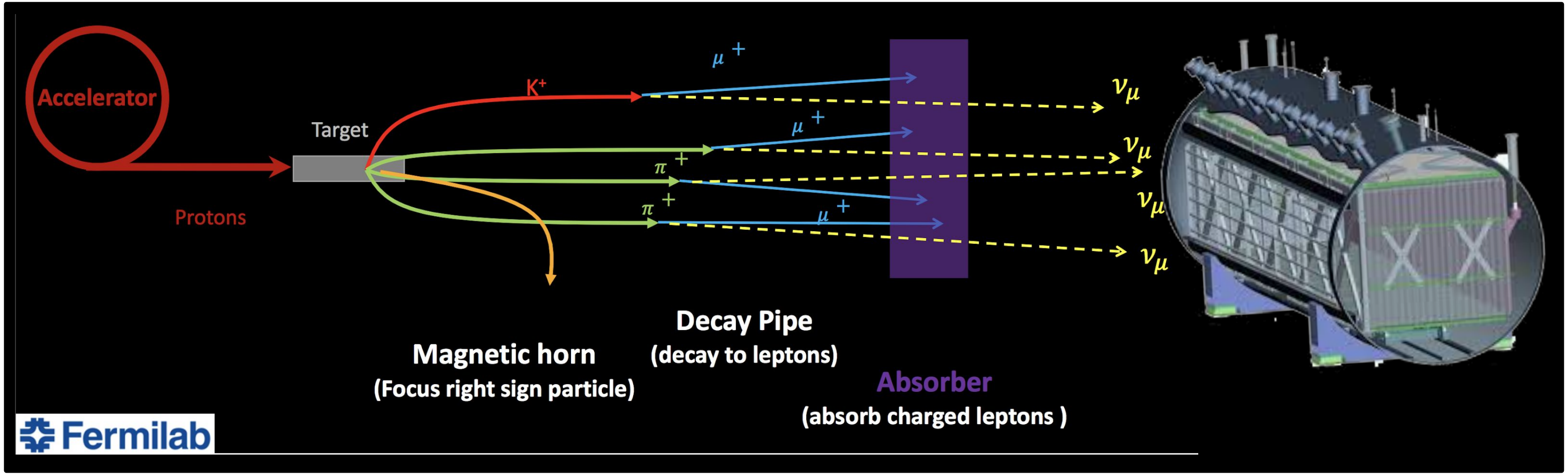
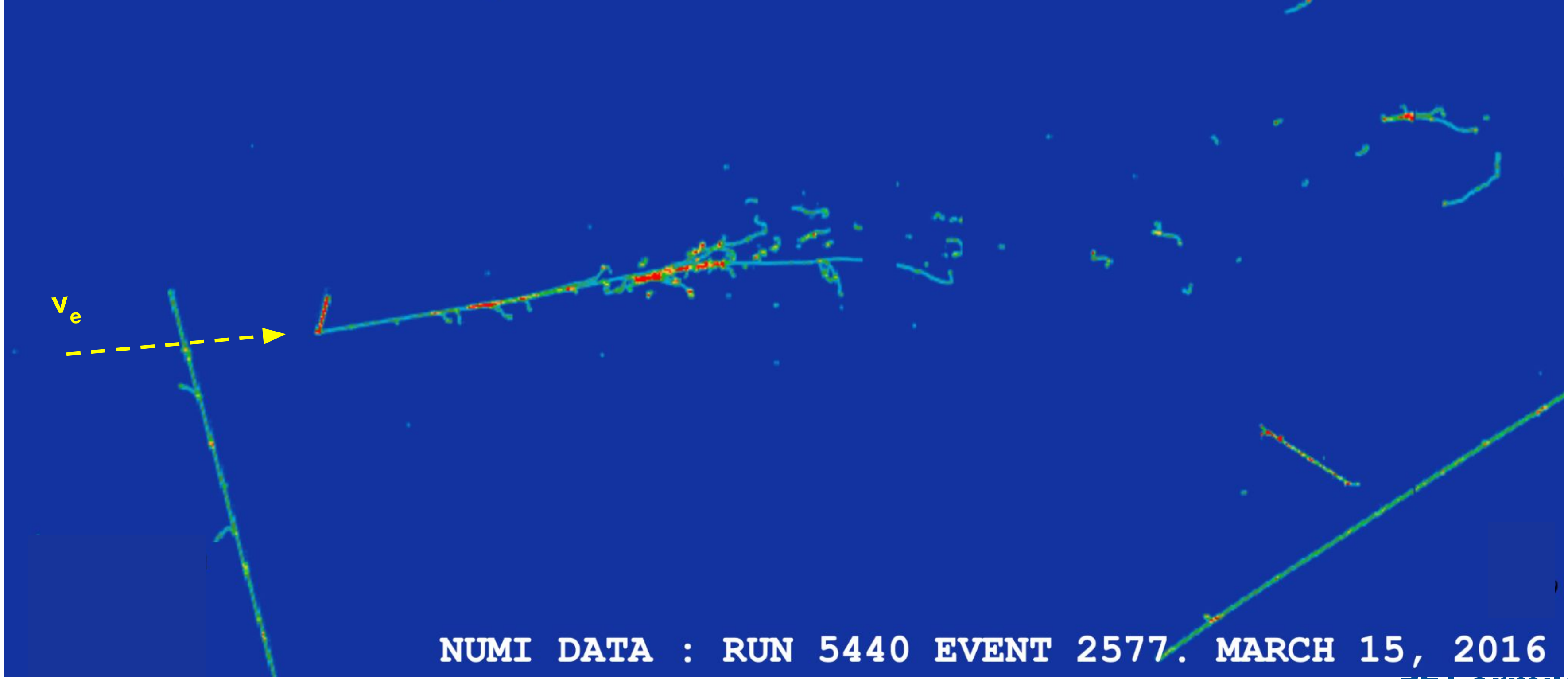


1. Know your neutrino flux → MICROBOONE-NOTE-1031-PUB
2. Know your detector → JINST 15, P03022 (2020) (and many more)

LArTPC in action

Extremely detailed 3D images + calorimetry + PID:

unprecedented tool for neutrino interaction & BSM physics



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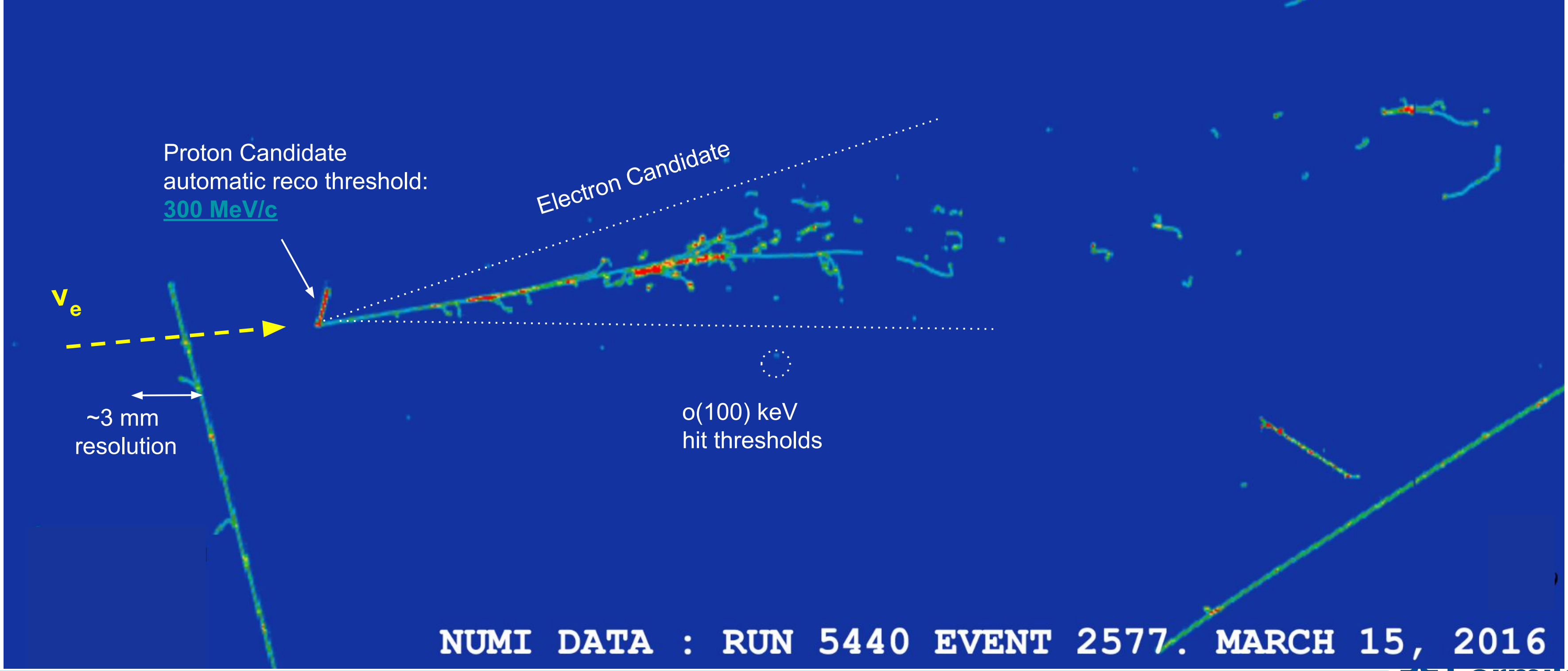

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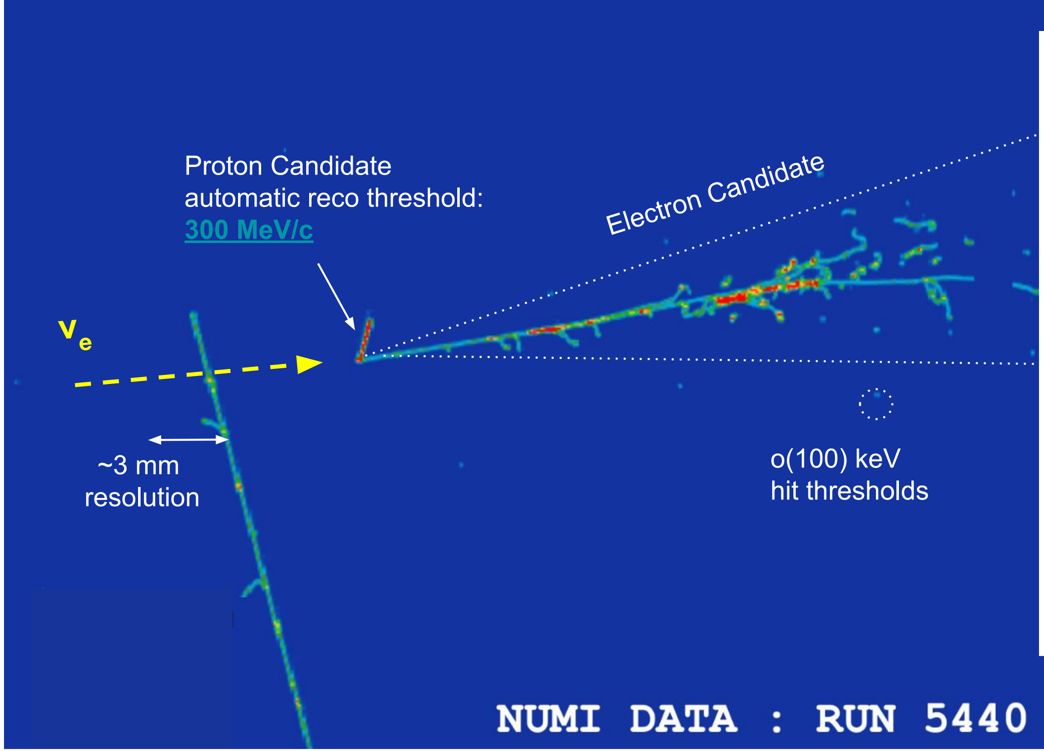
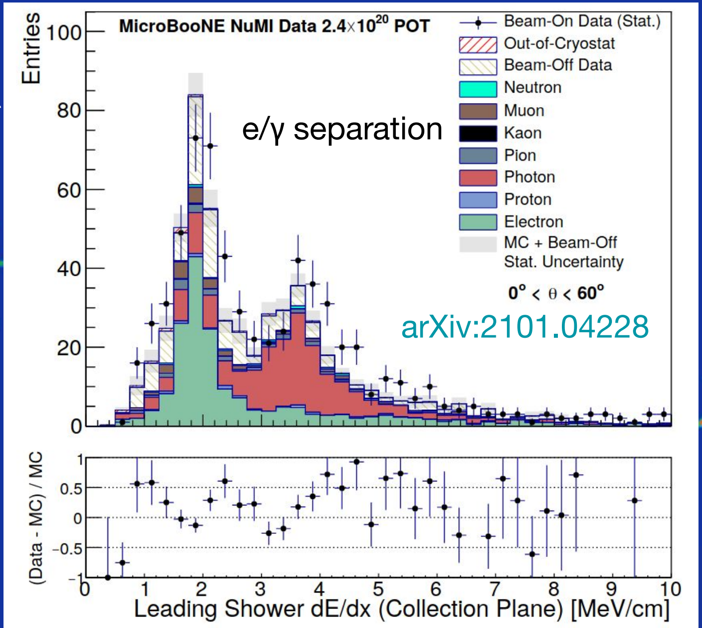
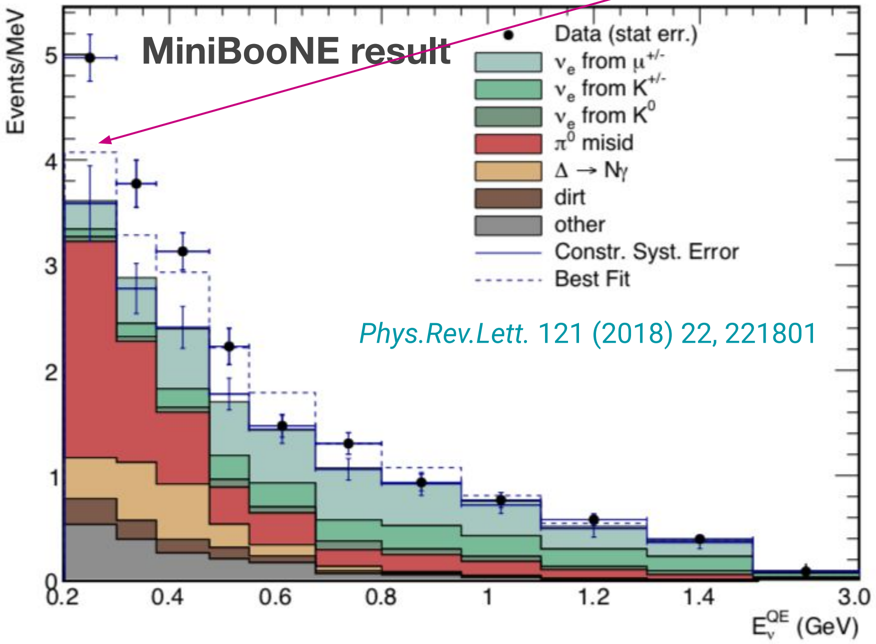




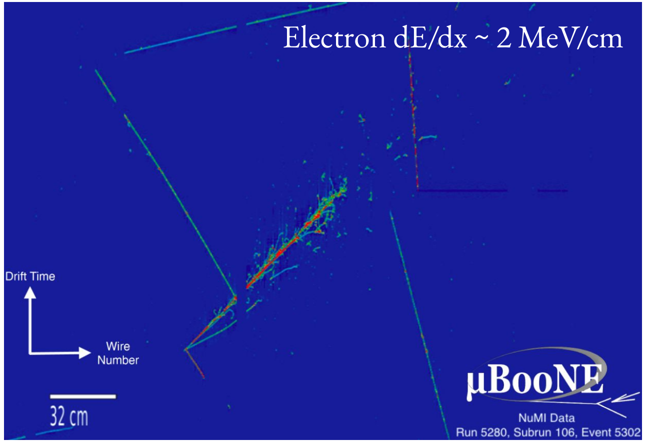
To e⁻ or not to e⁻? Why is e/γ separation a big deal?

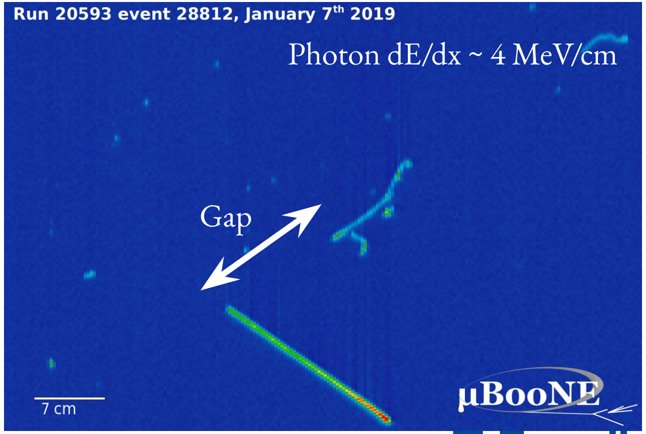
Primary physics goal:

Investigate the nature of the MiniBooNE excess of low energy electromagnetic events. **Is it electrons? Is it photons?**



Phys.Rev.Lett. 121 (2018) 22, 221801





Exploring the MiniBooNE LEE

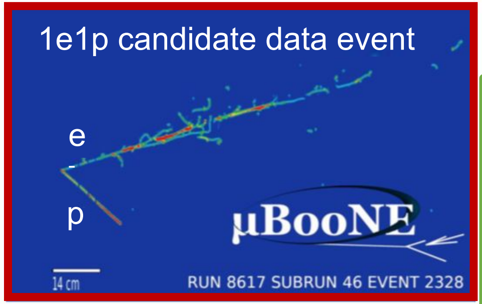
ν_e analyses:

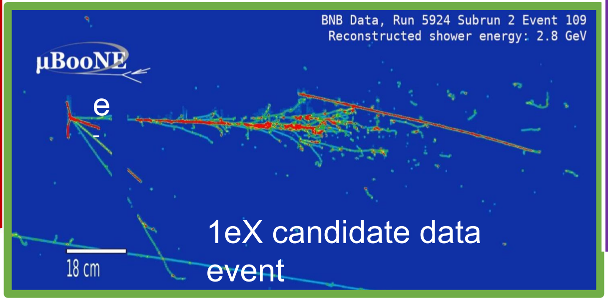
→ MiniBooNE-like final state (Pandora, 1eNp, 1e0p)
→ restricting to quasi-elastic kinematics (Deep Learning , 1e1p)
→ all ν_e final states (Wire-Cell, 1eX)

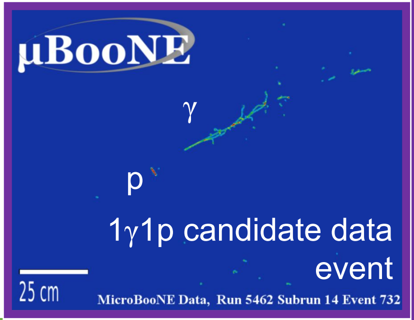
single photon analysis:

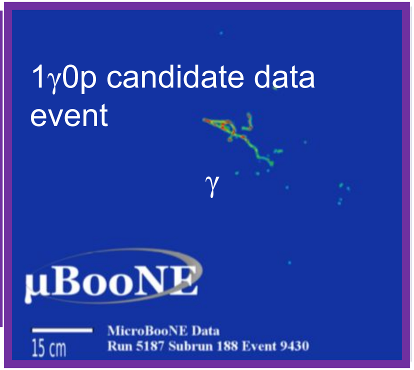
→ targeting Delta radiative decay hypothesis (Pandora, 1γ1p, 1γ0p)

3 reconstruction paradigms, 6 complementary channels

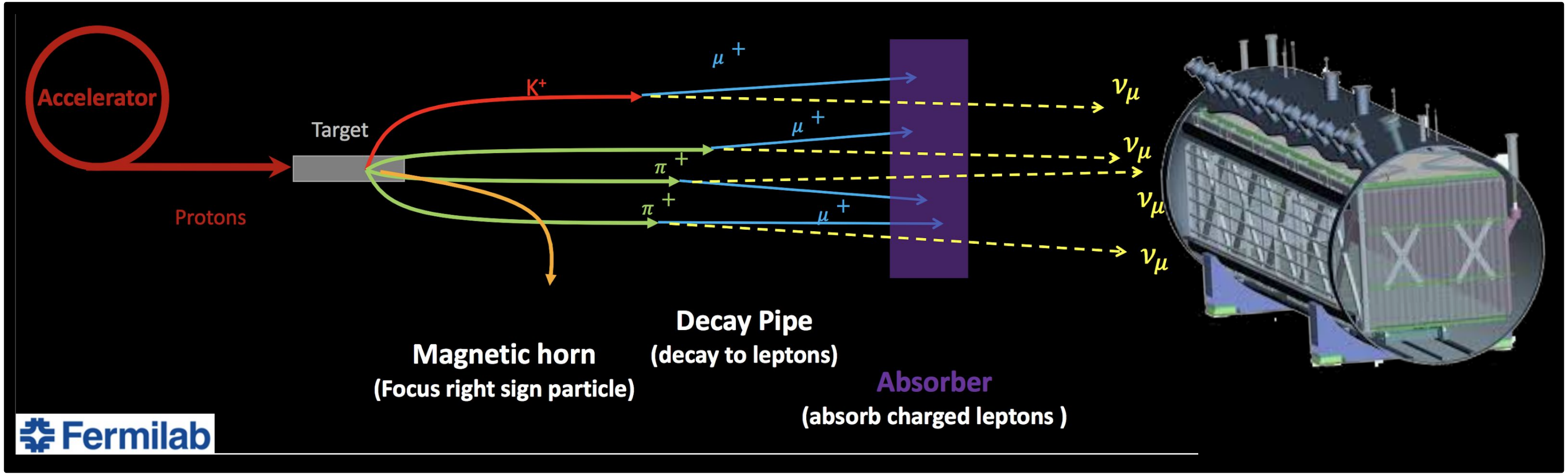








Ingredients for a successful on-beam neutrino experiment



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2. Know your detector → JINST 15, P03022 (2020) (and many more)

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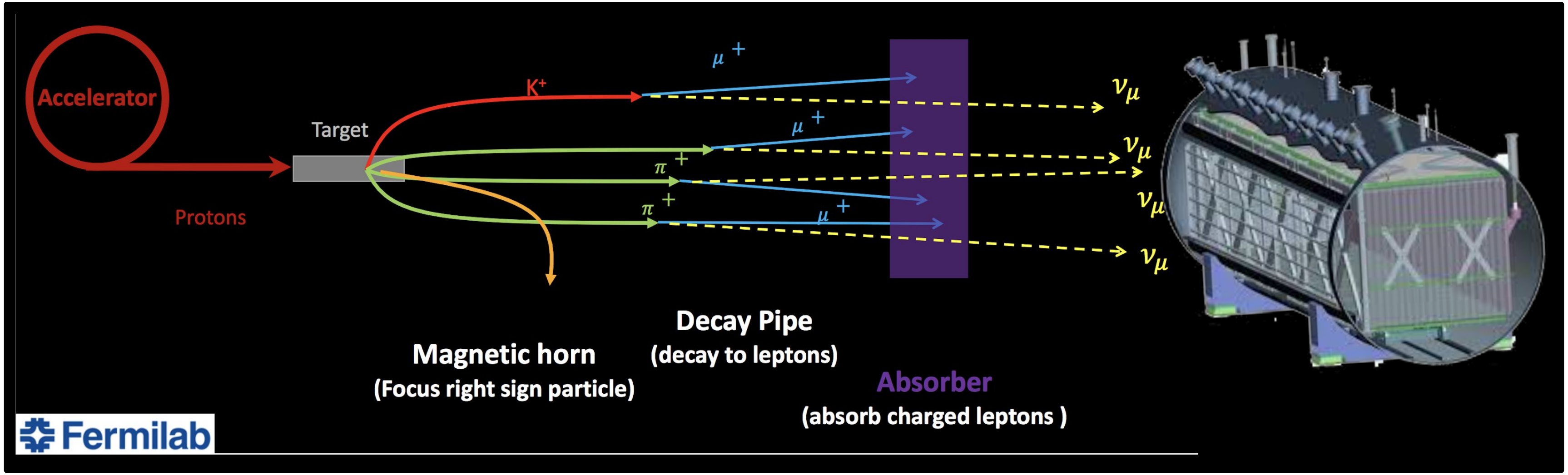

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3. Know how neutrinos interact

Fermilab

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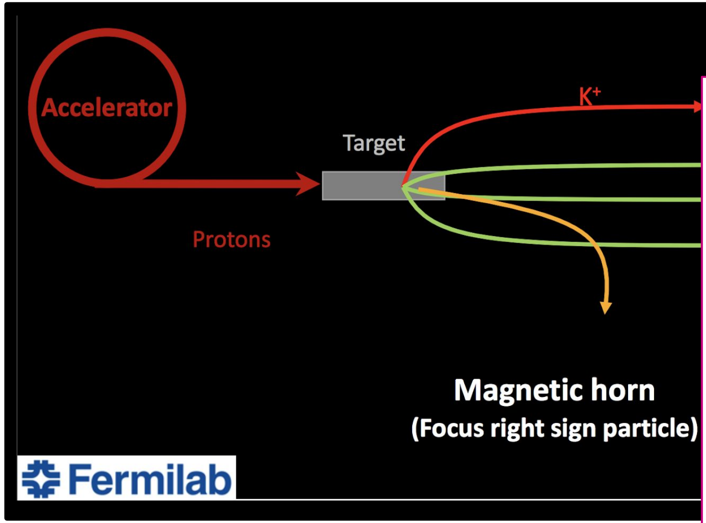
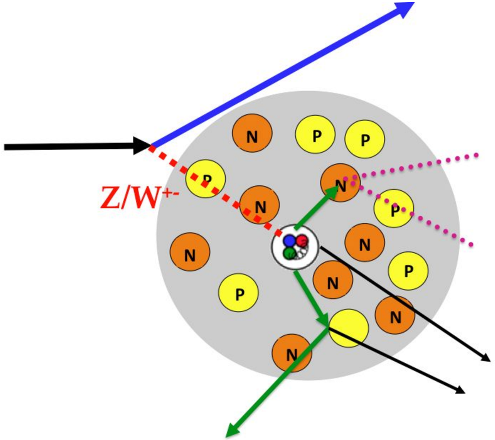


1. Know your neutrino flux
2. Know your detector
3. Know how neutrinos interact

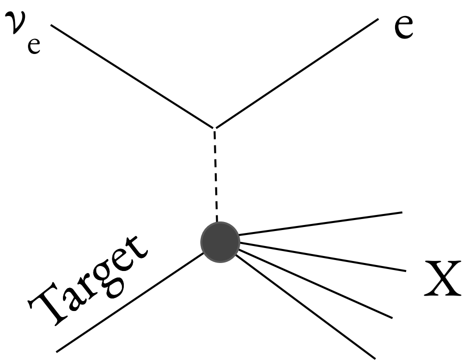
Experiments need good interaction modeling: **predict final states** on a **wide range of energies** with **high precision**.

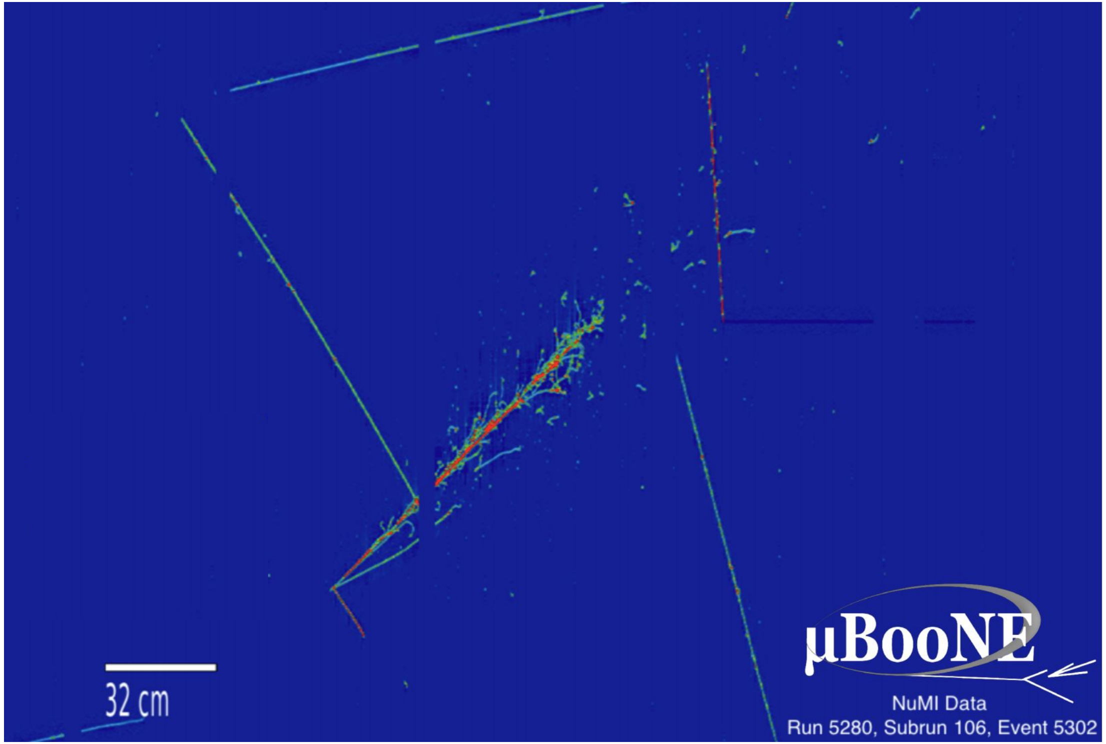
Theory is **complex**: several interaction processes + nuclear effects (FSI, MEC)

Cross section measurements essential to benchmark theory and help improve it!



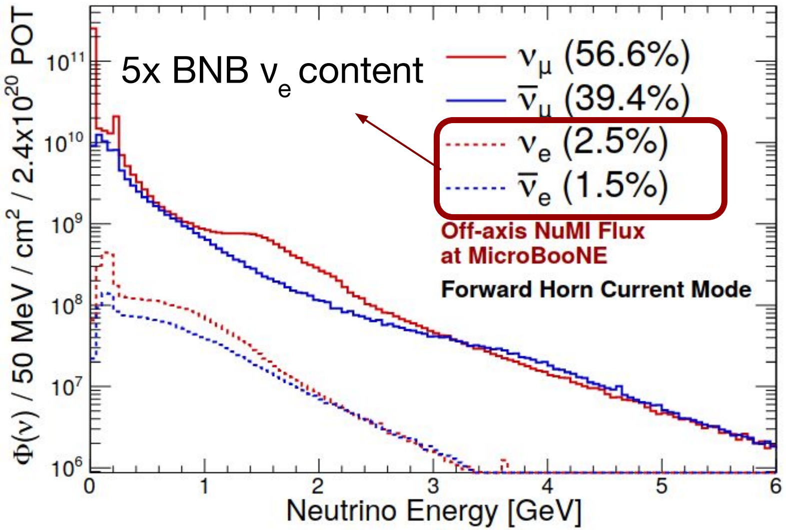
$\nu_e + \bar{\nu}_e$ Bar CC Inclusive @ NuMI



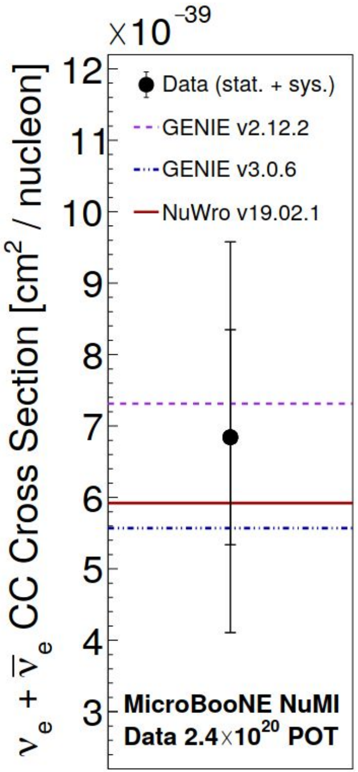


$\nu_e + \bar{\nu}_e$ Bar CC Inclusive @ NuMI

Flux averaged total cross section.
Largest ever sample of ν_e-Ar interactions with > 200 events
Selection main requirement: at least one shower compatible with electron hypothesis: Purity ~40%, Efficiency ~10%.
In good agreement with models



Systematic Source	Relative Uncertainty [%]
Interaction	10
Detector Response	23
Beam Flux	22
POT Counting	2
Cosmic Simulation	4
Out-of-Cryostat Simulation	6
Total	34



arXiv:2101.04228 (PRD accepted)

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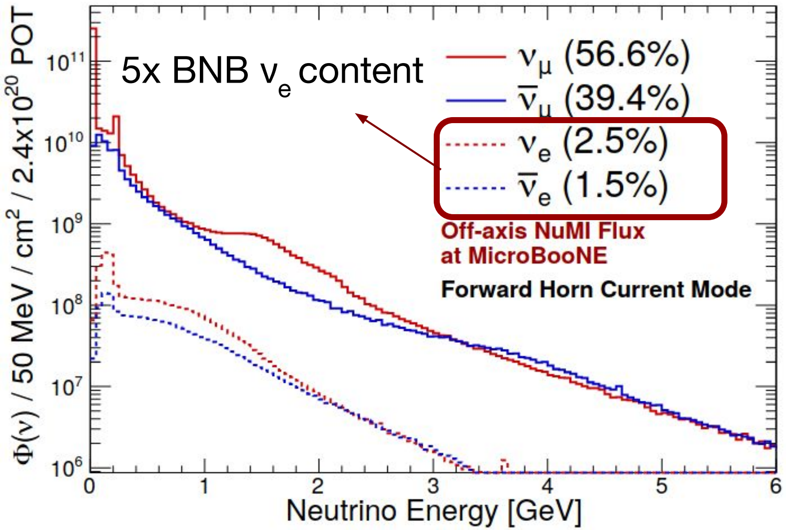

Systemati
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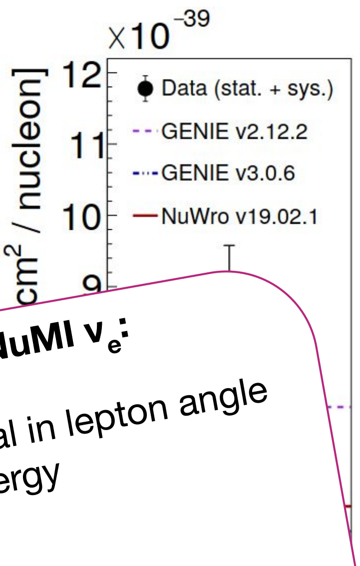


In the works from NuMI ν_e:

→ ν_e CC inclusive differential in lepton angle and energy, neutrino energy

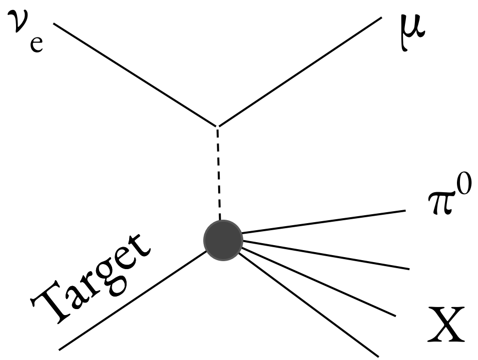
→ ν_e CC 1eNp exclusive

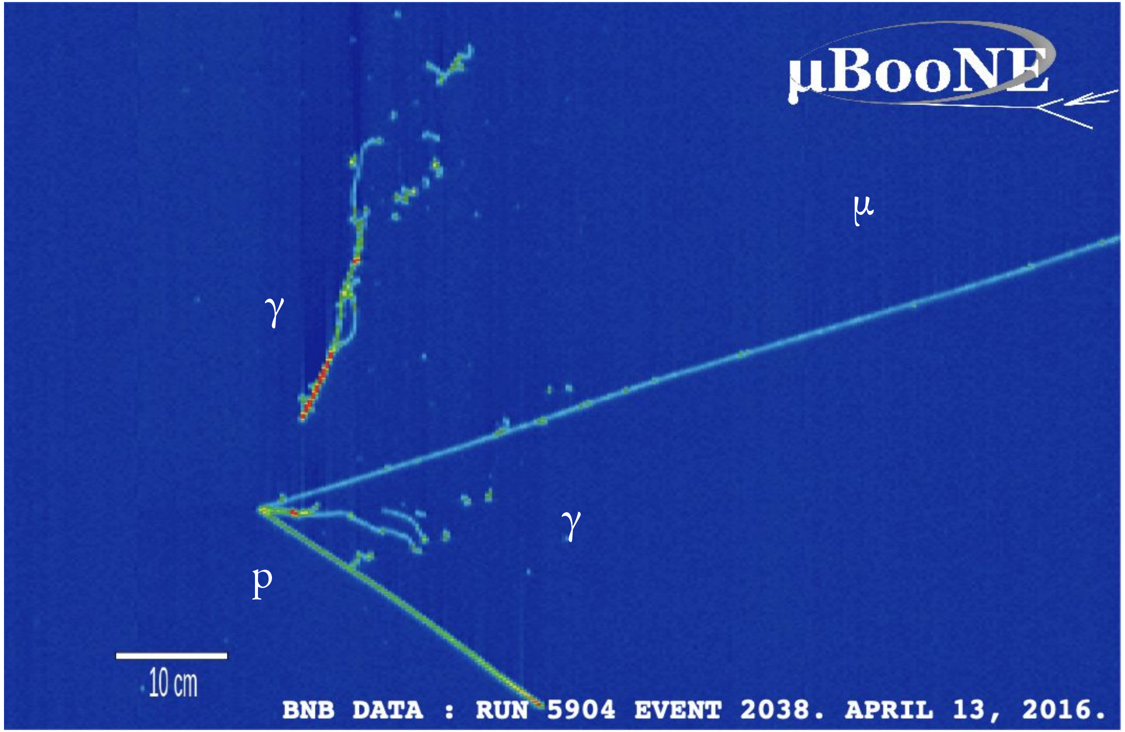
→ ν_e/ν_μ ratios

→ Anti ν_e inclusive

accepted)

Production of neutral pions





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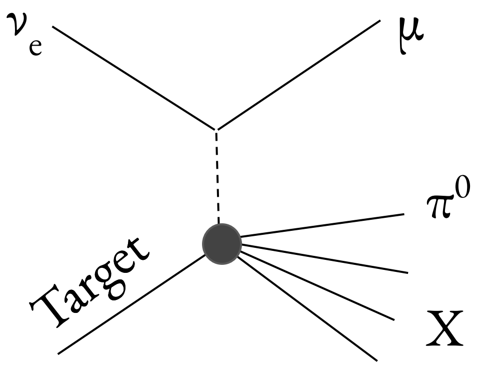
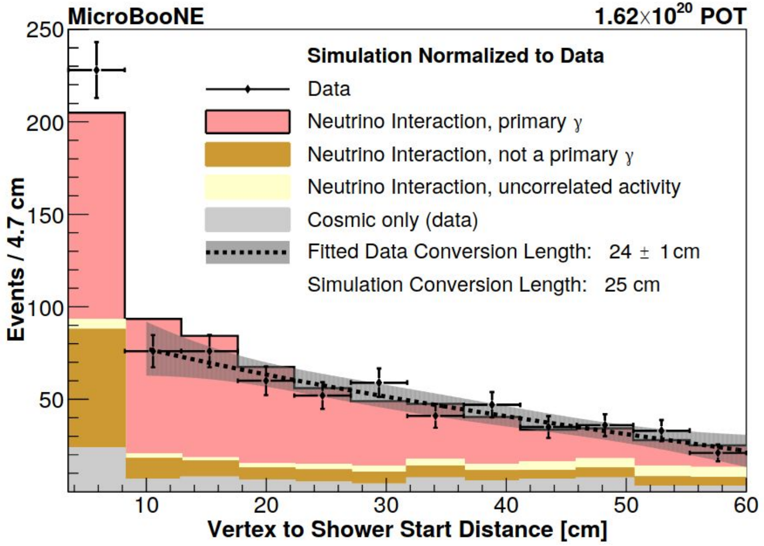
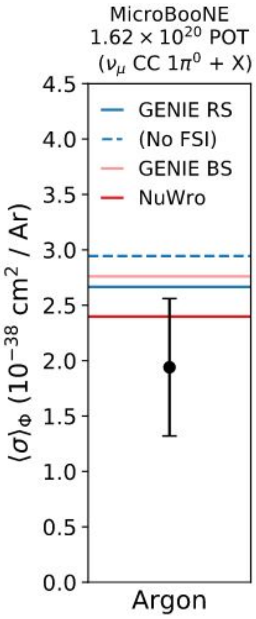
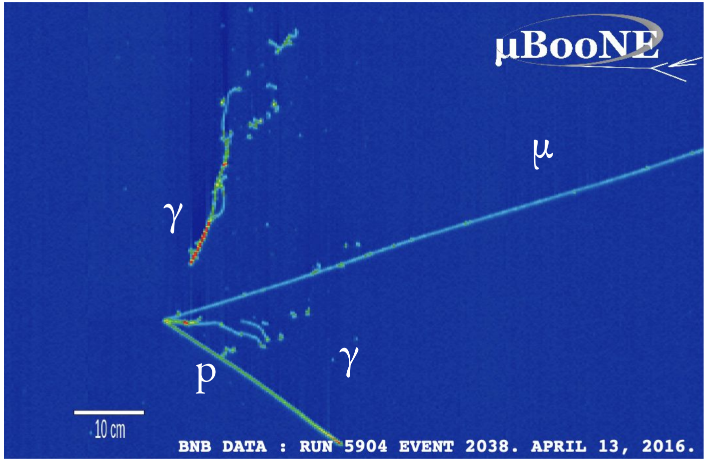


Fundamental background to the LEE search
First measurement of flux averaged ν_μ-Ar CCπ^0 cross section
Phys. Rev. D99, 091102(R) (2019)







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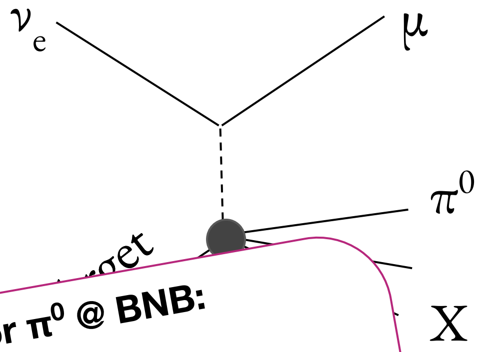

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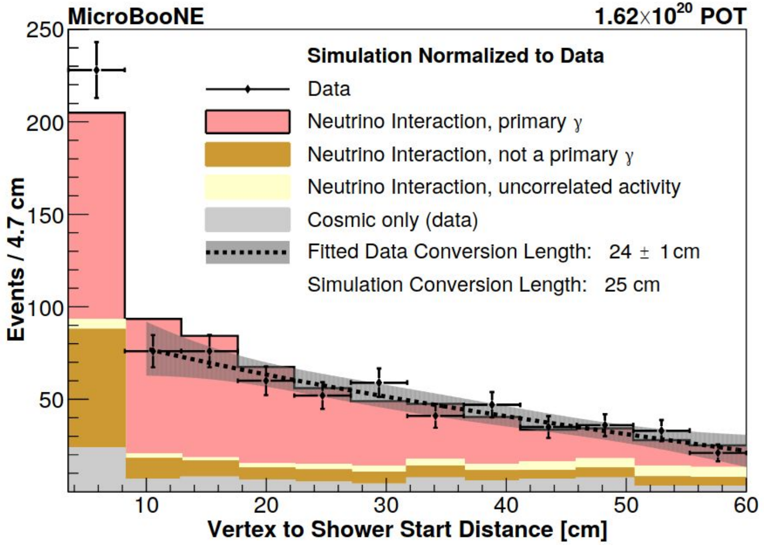
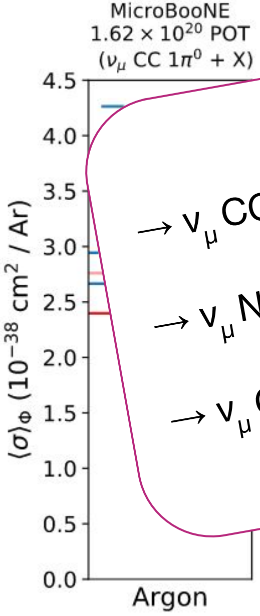
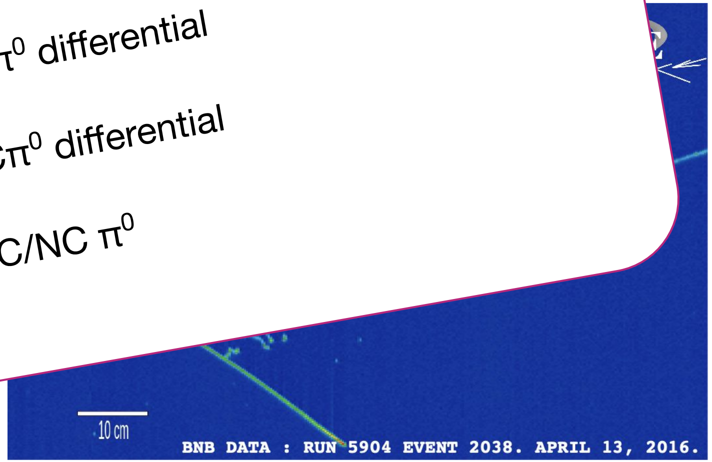






In the works for π^0 @ BNB:

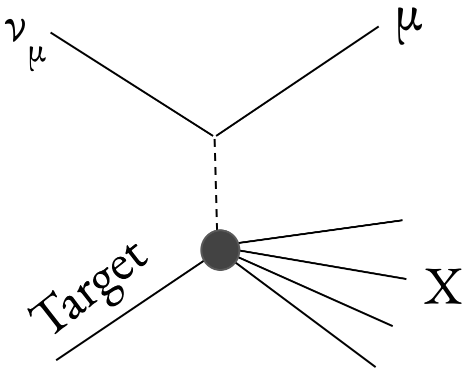
→ ν_μ CCπ^0 differential

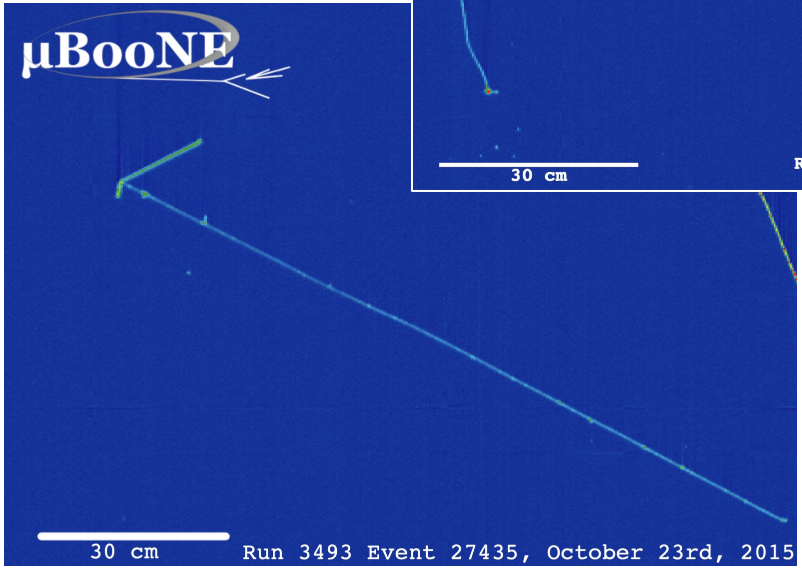
→ ν_μ NCπ^0 differential

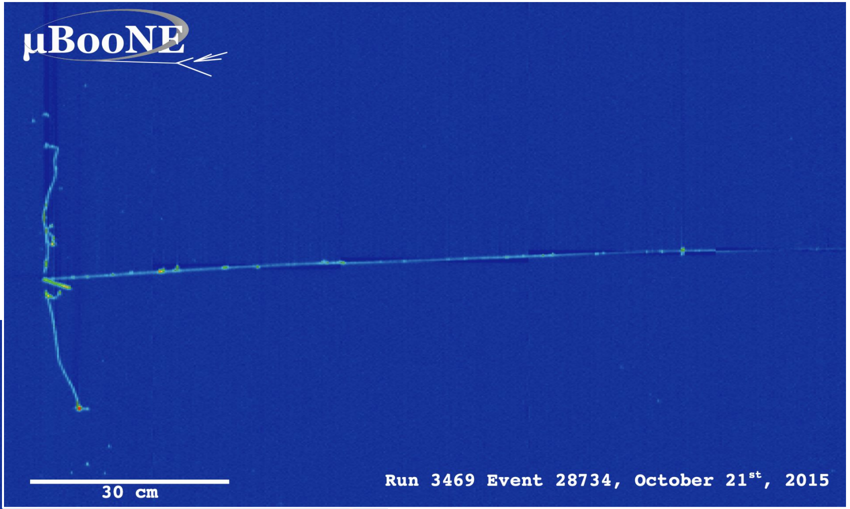
→ ν_μ CC/NC π^0

Fermilab

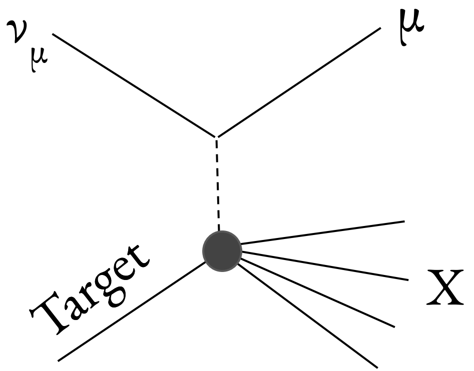
ν_μ CC Inclusive @ BNB



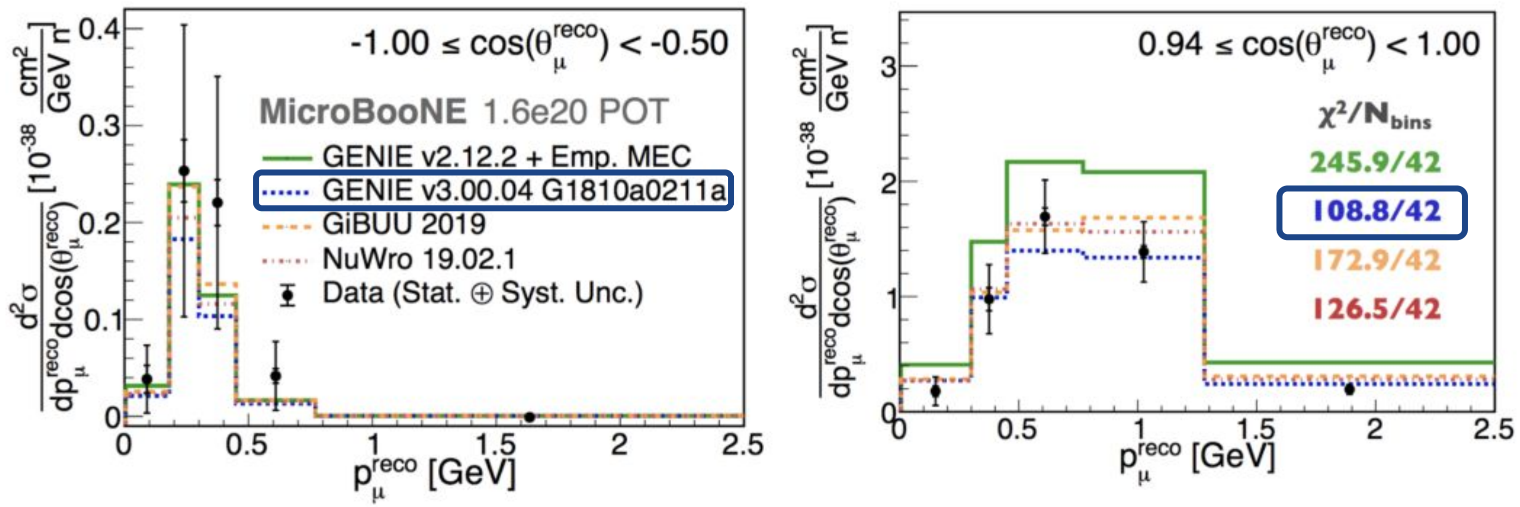




ν_μ CC Inclusive @ BNB



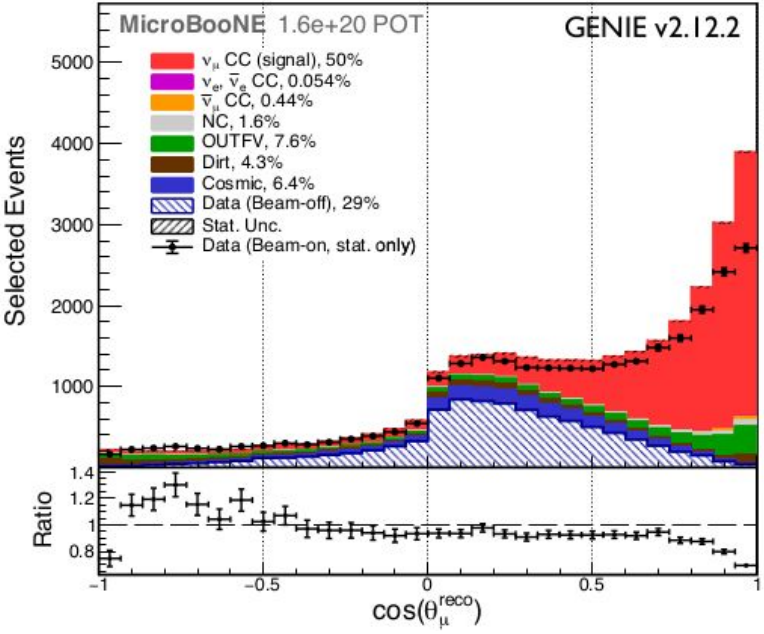
In single detector measurements, muon neutrinos are used to constrain uncertainties on electron neutrinos flux and interaction model.
First double differential measurement on Argon
→ Overall good agreement with theory (Phys. Rev. Lett. 123, 131801 (2019)).
More recent models achieve better agreement at forward scattering angles.



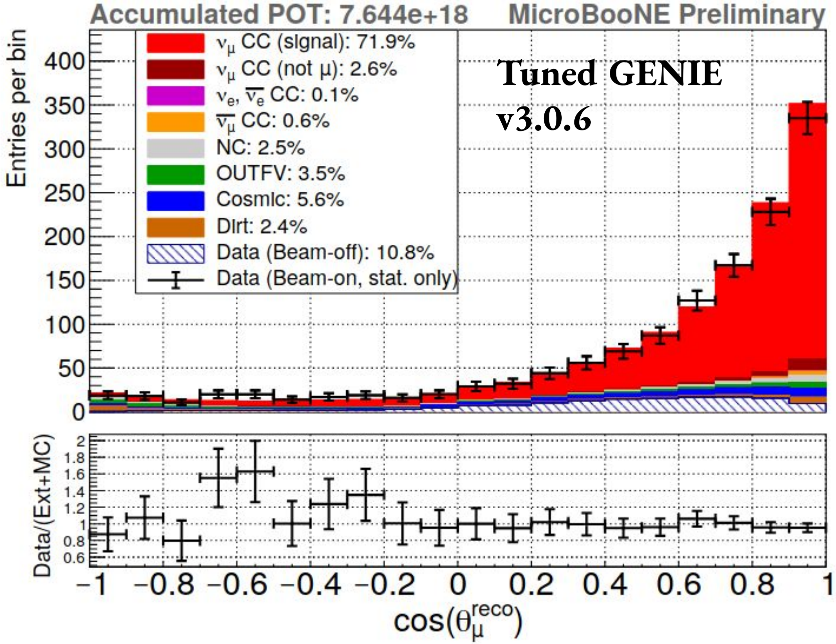
Fermilab

ν_μ CC Inclusive @ BNB: a Sneak Peek at Next Gen Analyses

Improved detector simulation and tuned nuclear modelling



Previously published measurement
Phys. Rev. Lett. 123, 131801 (2019)



Current measurement
MICROBOONE-NOTE-1069-PUB

ν_μ CC Inclusive @ BNB: a Sneak Peek at Next Gen Analyses

Improved detector simulation and tuned nuclear modelling

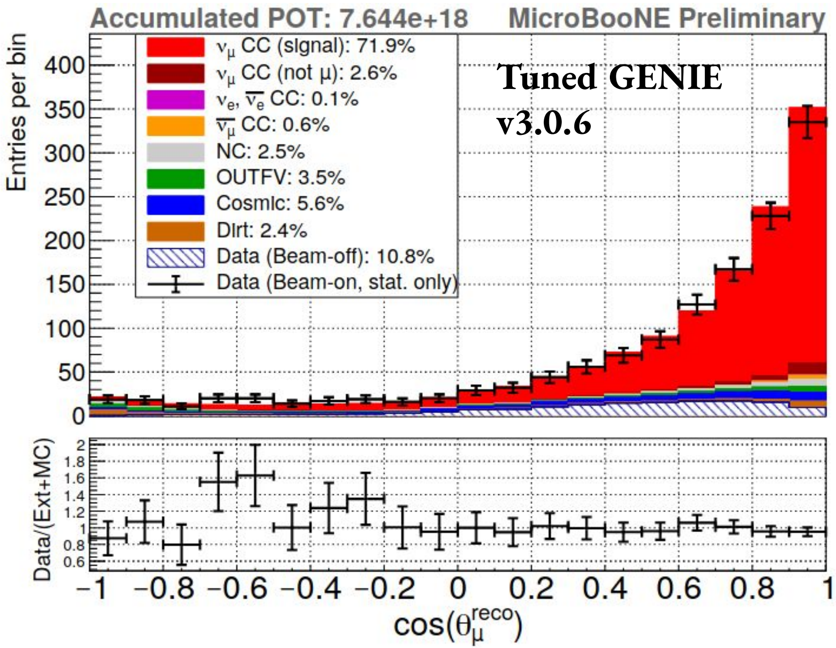
→ Purity: from 50% to 71.9%
→ 3x Reduction of cosmic contamination
→ Detector uncertainties from 16.2 % to 3.3 %

Better detector understanding: signal processing from all planes & improved calorimetry
JINST 13, P07006 (2018), JINST 13, P07007 (2018)

Reduced systematic uncertainties via a data driven method
MICROBOONE-NOTE-1075-PUB

Improved neutrino interaction model
MICROBOONE-NOTE-1074-PUB

Cosmic Ray Tagger use, JINST 14, P04004 (2019)



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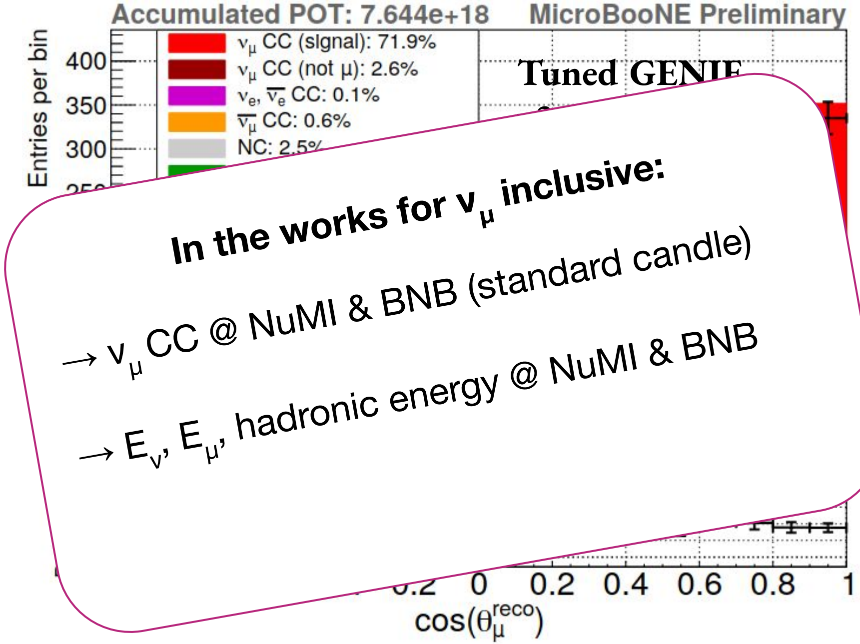


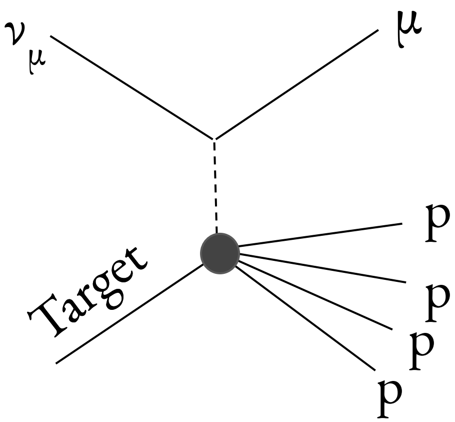
In the works for ν_μ inclusive:

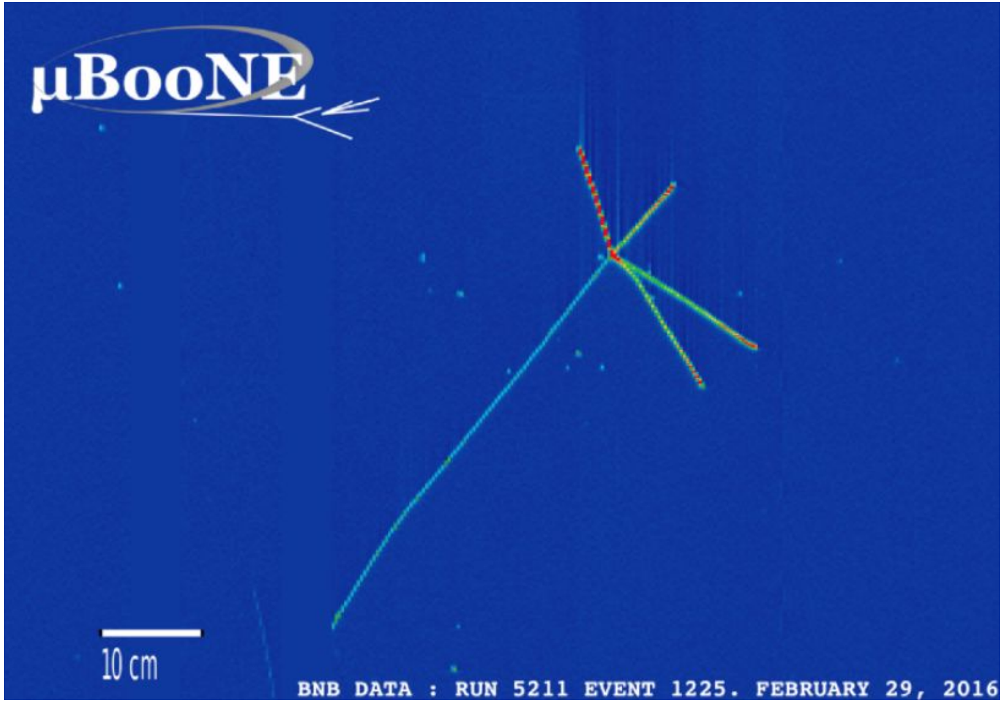
→ ν_μ CC @ NuMI & BNB (standard candle)

→ E_ν, E_μ, hadronic energy @ NuMI & BNB

Current measurement
MICROBOONE-NOTE-1069-PUB

ν_μ CC exclusive topologies: ν_μ CC0πNp with N ≥ 1





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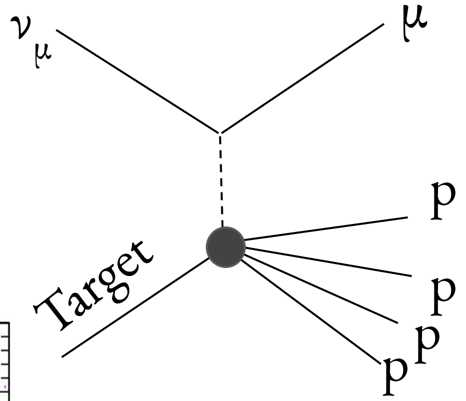
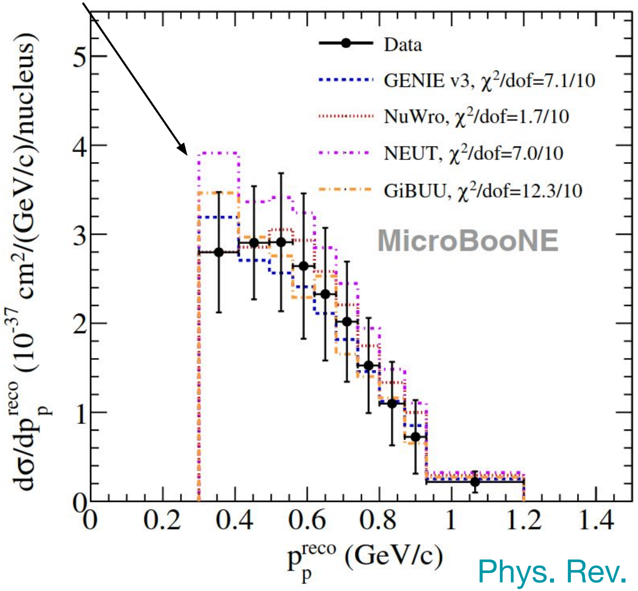
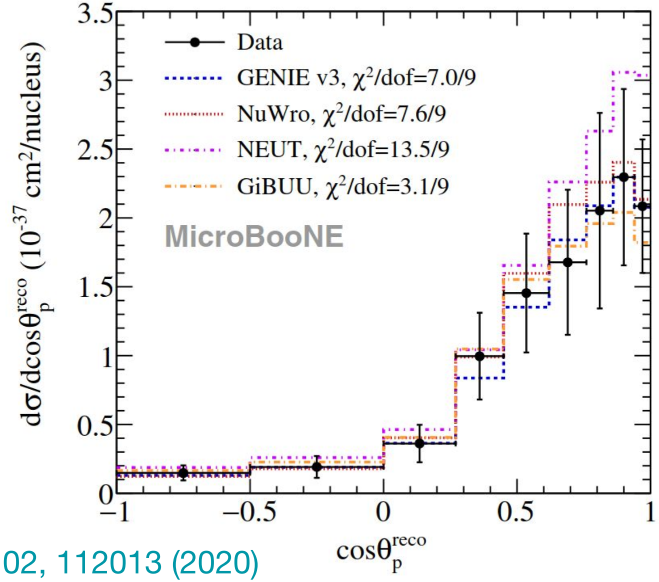


Event selection: P_μ > 100 MeV/c, 300 < P_p < 1200 MeV/c , 0π

Purity ~70% & efficiency ~30%, overall agreement in proton kinematics

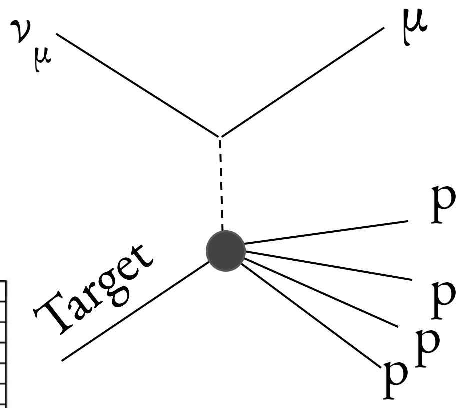
Lowest momentum bin (close to detection threshold) most sensitive to model differences



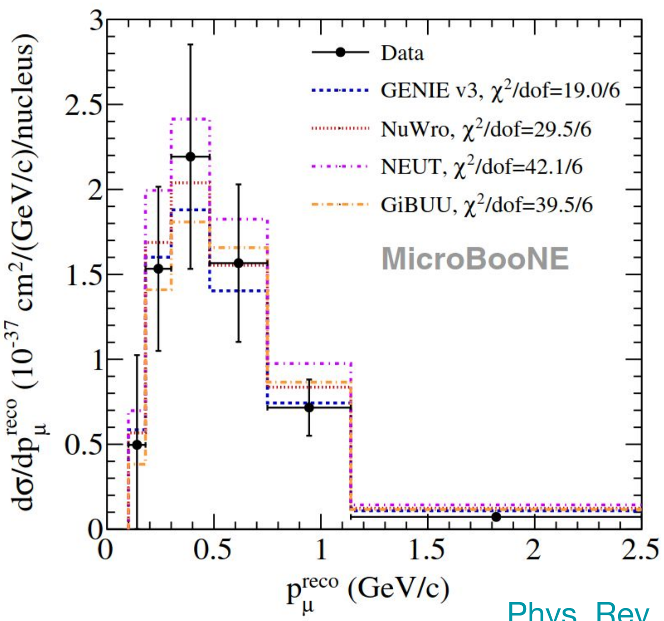


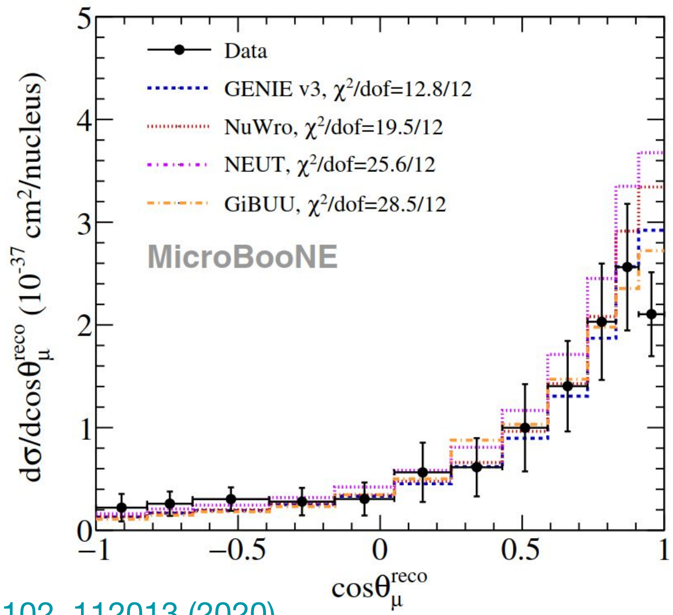
Phys. Rev. D102, 112013 (2020)

ν_μ CC exclusive topologies: ν_μ CC0πNp with N ≥ 1



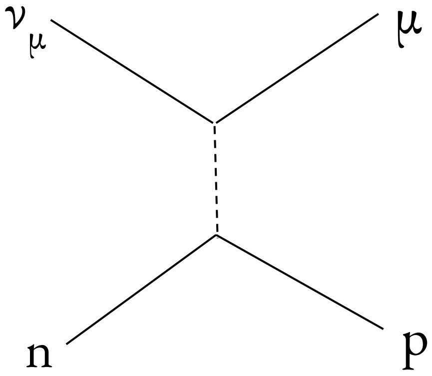
Disagreement in muon kinematics at forward scattering angles

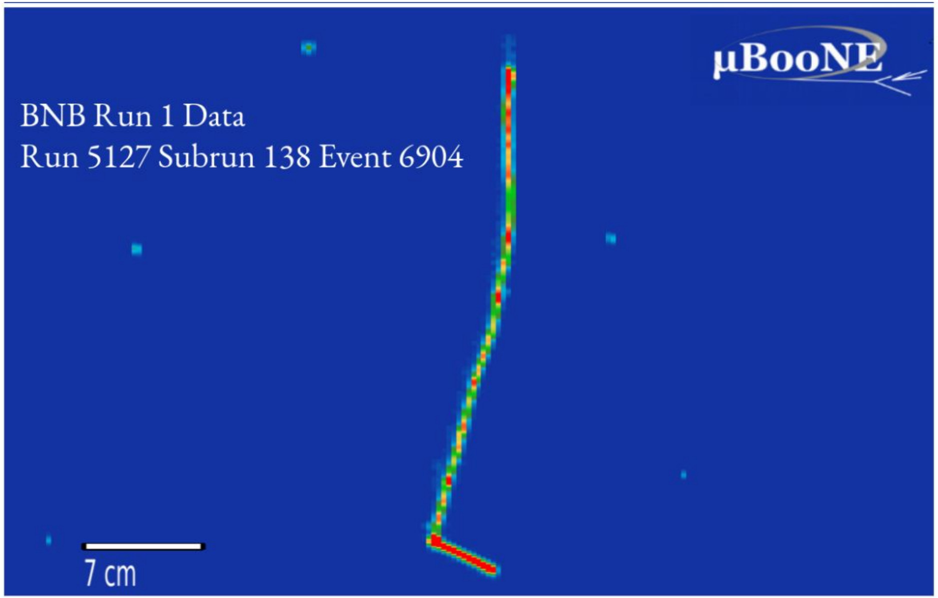




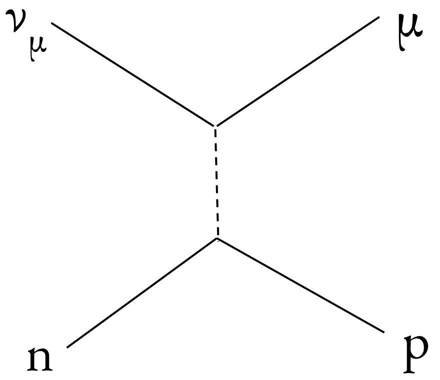
Phys. Rev. D102, 112013 (2020)

ν_μ CC exclusive topologies: ν_μ CCQE-like





ν_μ CC exclusive topologies: ν_μ CCQE-like



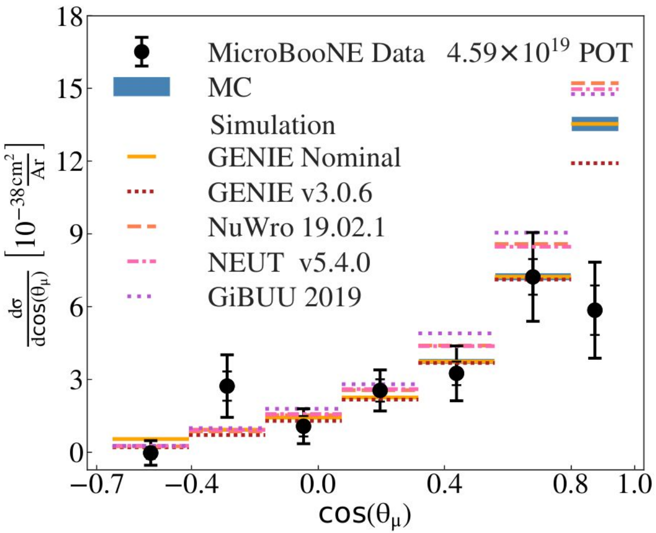
Simple topology dominant at energies relevant for SBN

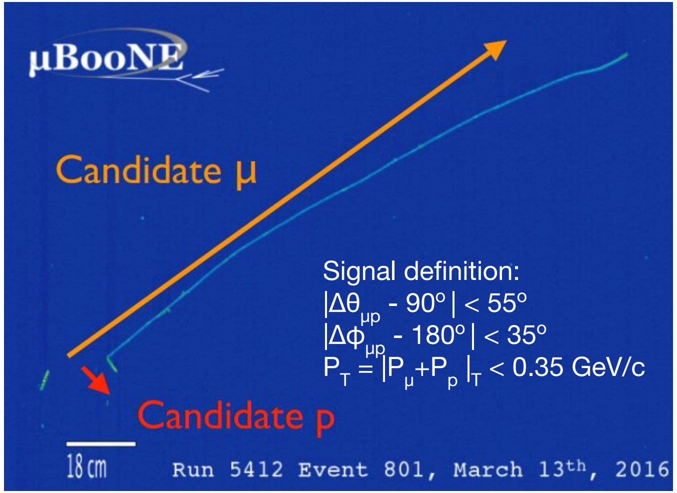
CCQE-like in restricted phase space boosts CCQE predicted purity: ~80%

Event selection: P_μ > 100 MeV/c, single proton P_p > 300 MeV/c

Good agreement with models, except at very forward muon scattering angles.

Phys. Rev. Lett. 125, 201803 (2020)

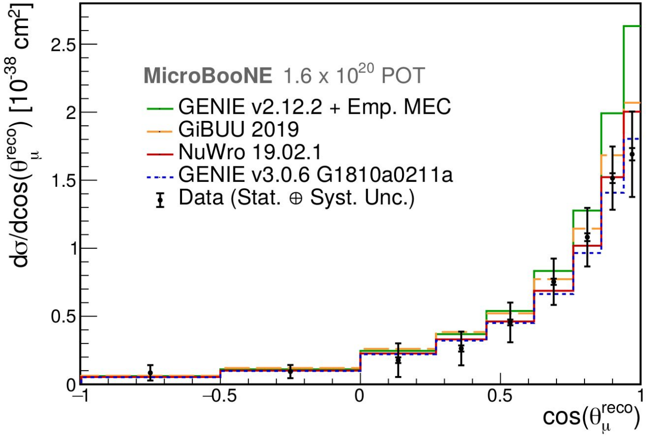




Fermilab

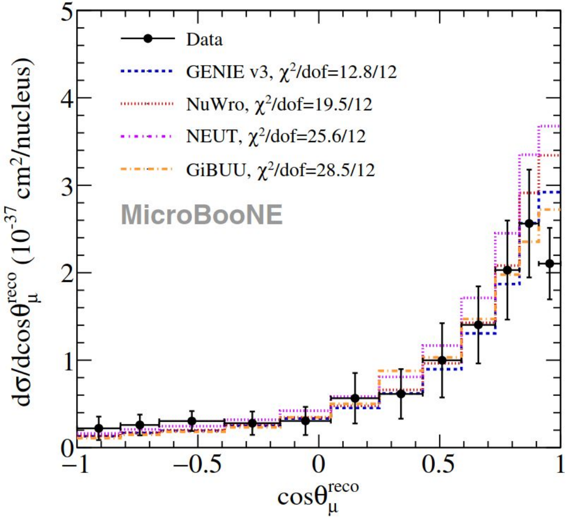
Consistent Picture for ν_μ CC

ν_μ CC Inclusive
MC excess in forward bin



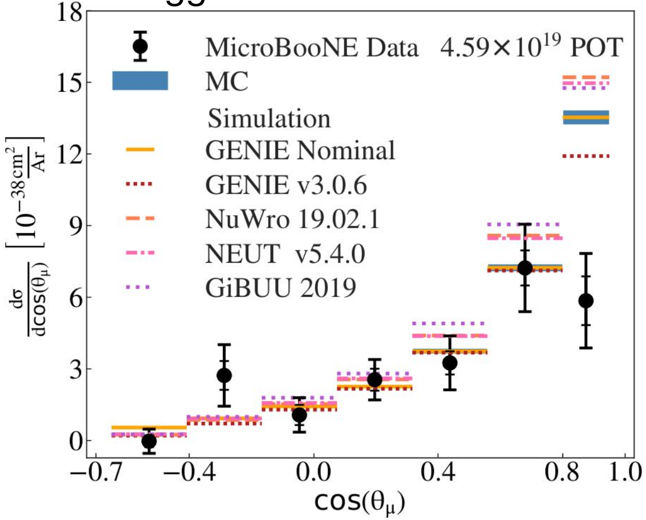
Phys. Rev. Lett. 123, 131801 (2019)

ν_μ CCNp
Data turnover in forward bin



Phys. Rev. D102, 112013 (2020)

ν_μ CCQE-like
Biggest deficit in forward bin

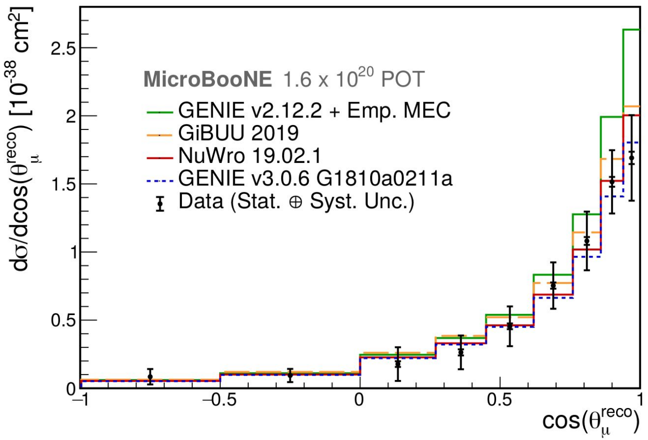


Phys. Rev. Lett. 125, 201803 (2020)

Forward region is very sensitive to nuclear physics: more modern generators show promise.
Investigation with using exclusive channels will shed light on the matter.

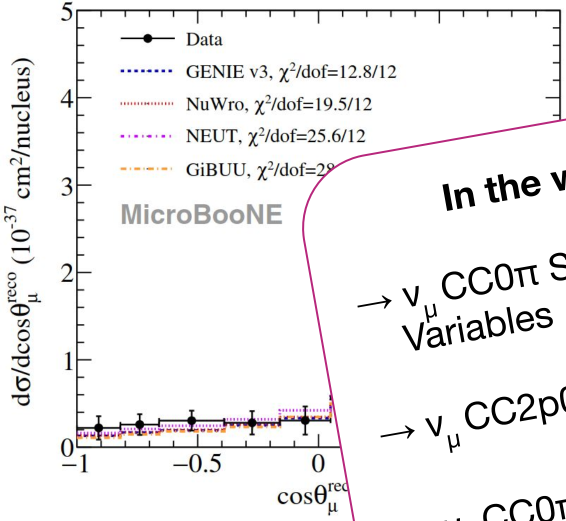
Consistent Picture for ν_μ CC

ν_μ CC Inclusive
MC excess in forward bin



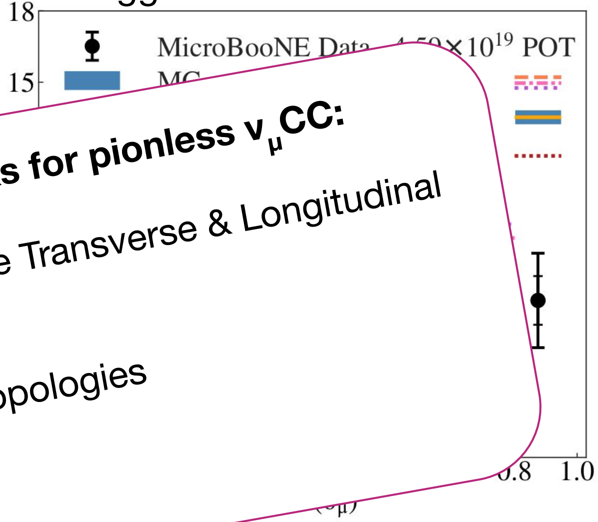
Phys. Rev. Lett. 123, 131801 (2019)

ν_μ CCNp
Data turnover in forward bin



Phys. Rev. D102, 11

ν_μ CCQE-like
Biggest deficit in forward bin



Phys. Rev. Lett. 125, 201803 (2020)

In the works for pionless ν_μCC:

→ ν_μ CC0π Single Transverse & Longitudinal Variables

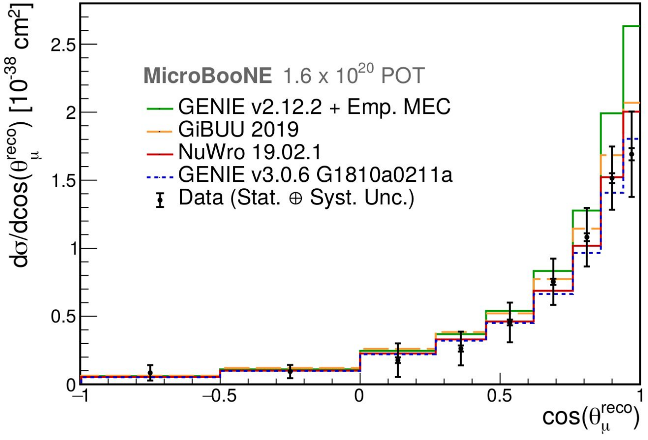
→ ν_μ CC2p0π topologies

→ ν_μ CC0π0p

Forward region is very sensitive to nuclear physics: more modern generators show promise.
Investigation with using exclusive channels will shed light on the matter.

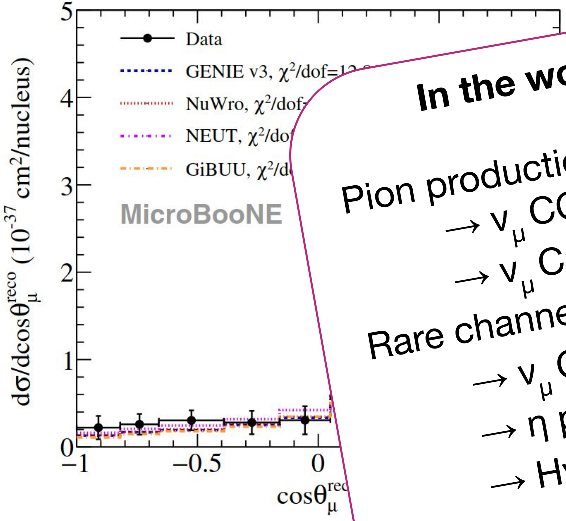
Consistent Picture for ν_μ CC

ν_μ CC Inclusive
MC excess in forward bin



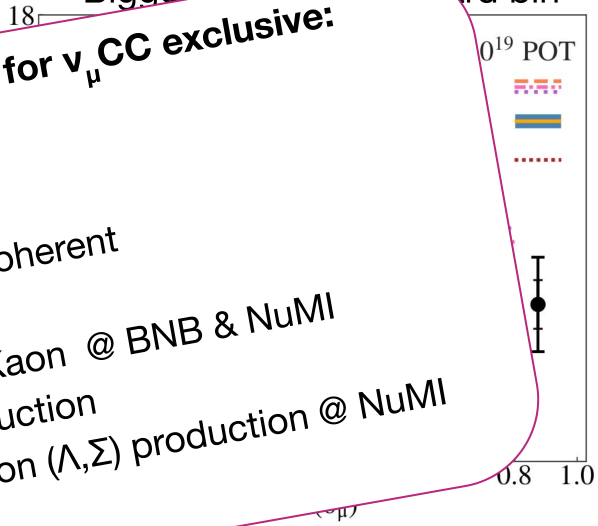
Phys. Rev. Lett. 123, 131801 (2019)

ν_μ CCNp
Data turnover in forward bin



Phys. Rev. D102, 11

ν_μ CCQE-like
Biggest d… …ard bin



…ys. Rev. Lett. 125, 201803 (2020)

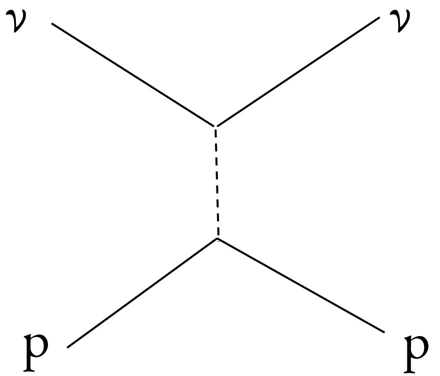
In the works for ν_μCC exclusive:

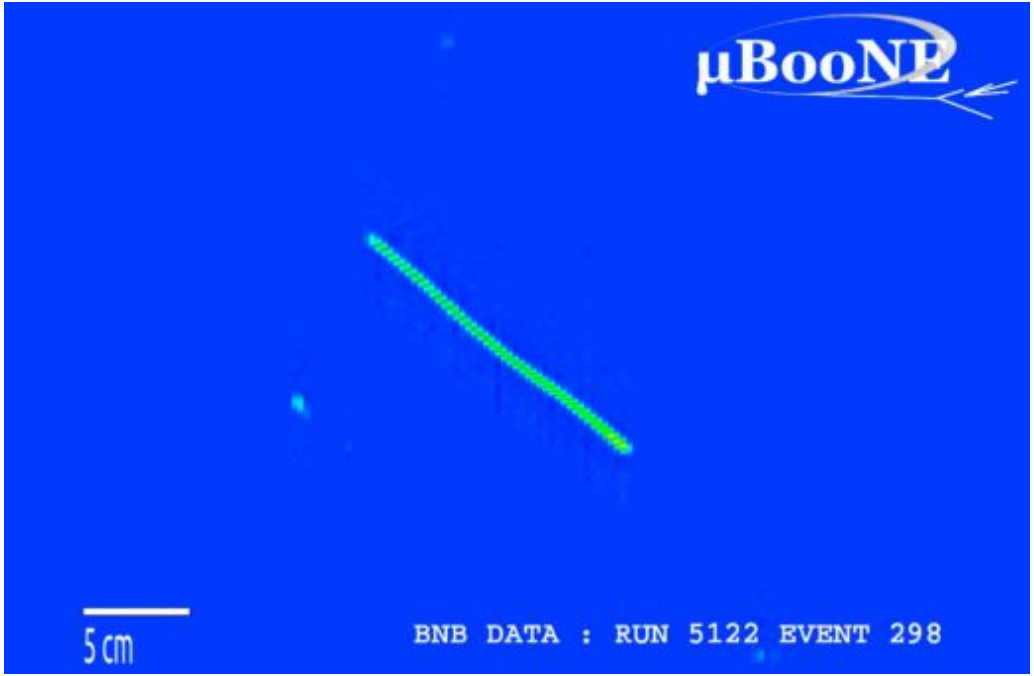
Pion production:
→ ν_μ CC1π^+
→ ν_μ CC-Coherent

Rare channels
→ ν_μ CC Kaon @ BNB & NuMI
→ η production
→ Hyperon (Λ,Σ) production @ NuMI

Forward region is very sensitive to nuclear physics: more modern generators show promise.
Investigation with using exclusive channels will shed light on the matter.

Challenging topologies: NC1p





Fermilab

Challenging topologies: NC1p

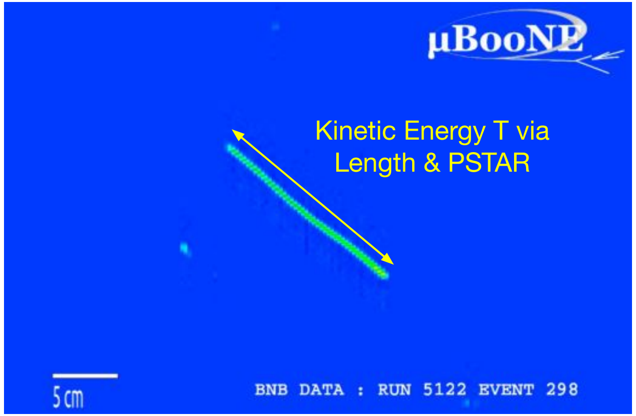
Neutral current interactions w/ single proton:

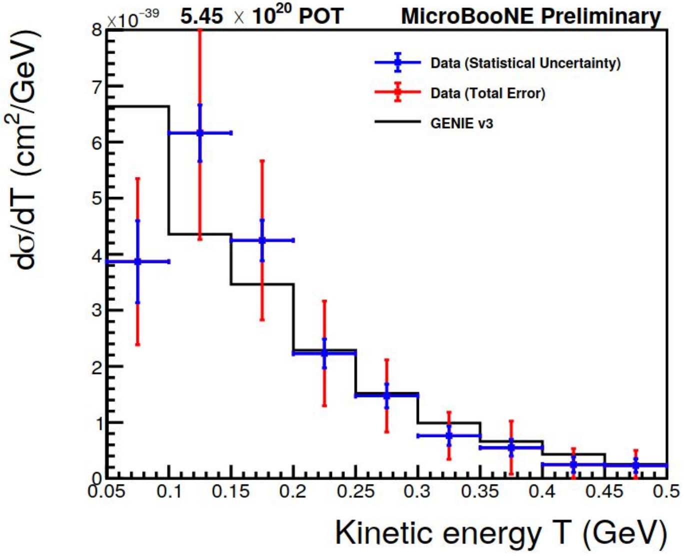
1 proton track with 1.2 < length < 200 cm

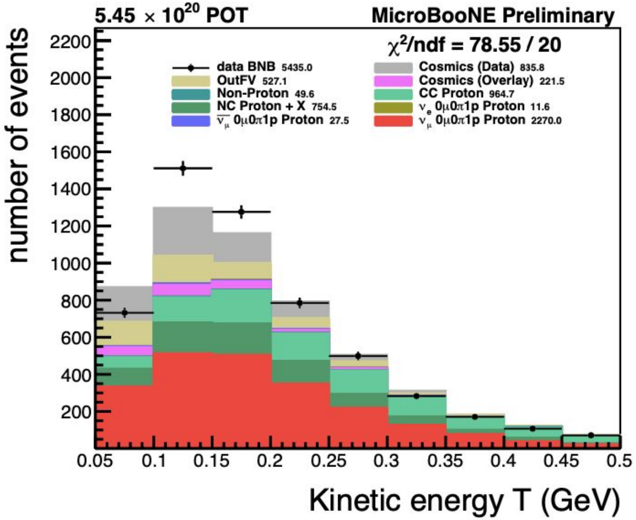
Lowest Q^2 NC1p analysis to date (0.1 GeV^2)

Purity ~40% & efficiency ~30%

Sensitive to strange component of neutral-current axial form factor





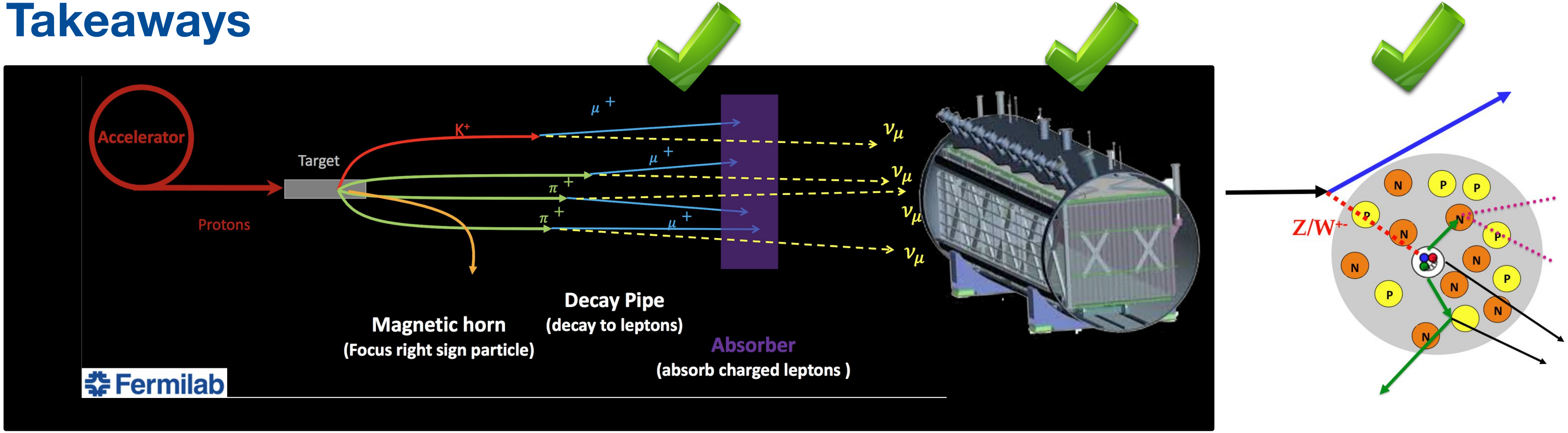


No previous data for NCE with T < 225 MeV

MICROBOONE-NOTE: 1067-PUB

Fermilab

Takeaways



MicroBooNE has collected the **largest sample** of **neutrino-argon** interactions available to date and has **completed our first era of detector studies and cross section analyses.**
→ Stepping stone measurements for many more to come! Much more data to analyze!

Measuring neutrino cross sections on argon with high precision **opens a new window in the exploration of the nucleus** and it is **foundational for BSM work** in LArTPCs:
we are setting solid basis for **a series of first results** on the MiniBooNE low energy excess (coming soon).

Exciting times ahead!!! Stay tuned!

Backup

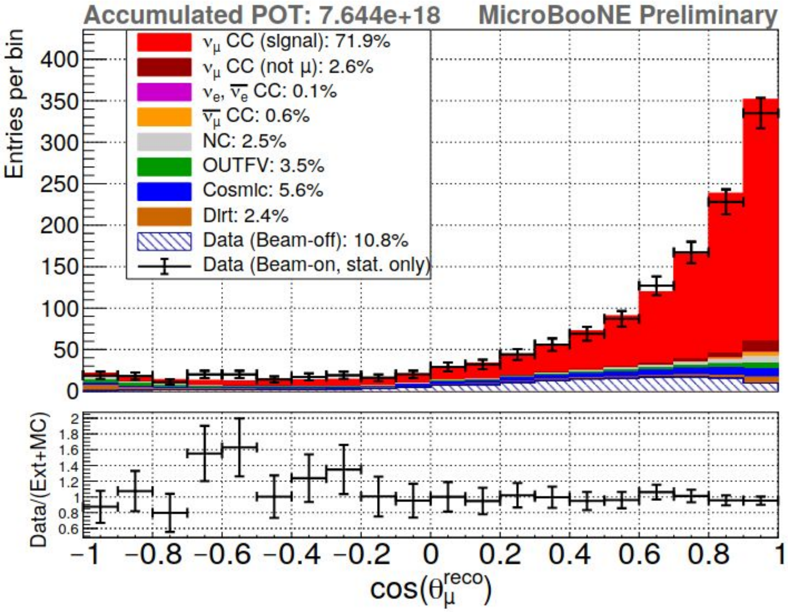
Improved Interaction Model: GENIE Tune

GENIE v2.12.2 → GENIE v3.0.6

Tuned CCQE and CCMEC models
to T2K ν_μ CC0π data

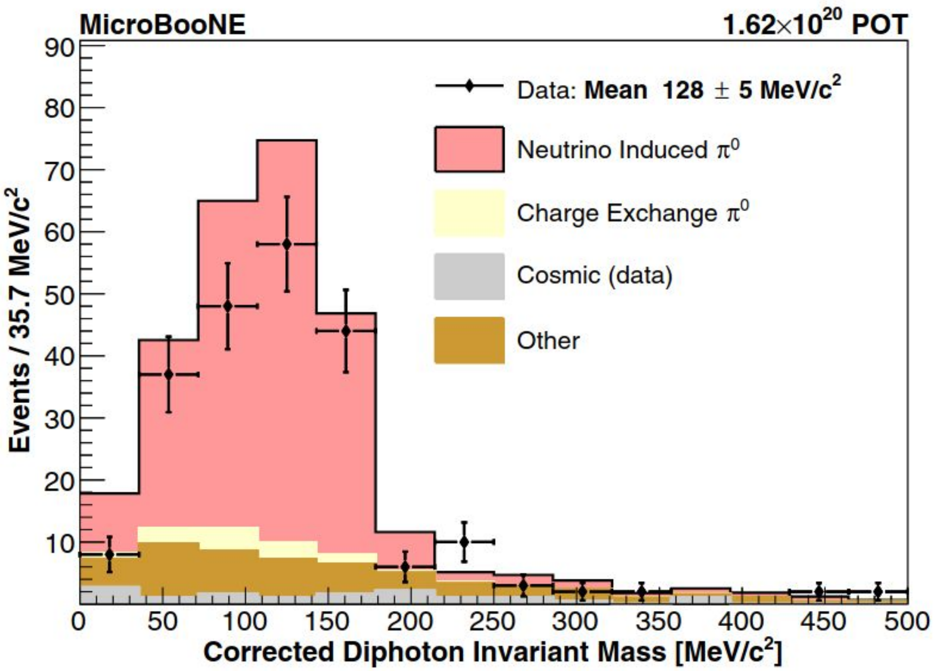
T2K data is on a carbon target
→ Tuning seems to give good agreement with MicroBooNE's argon-target data

MICROBOONE-NOTE-1074-PUB

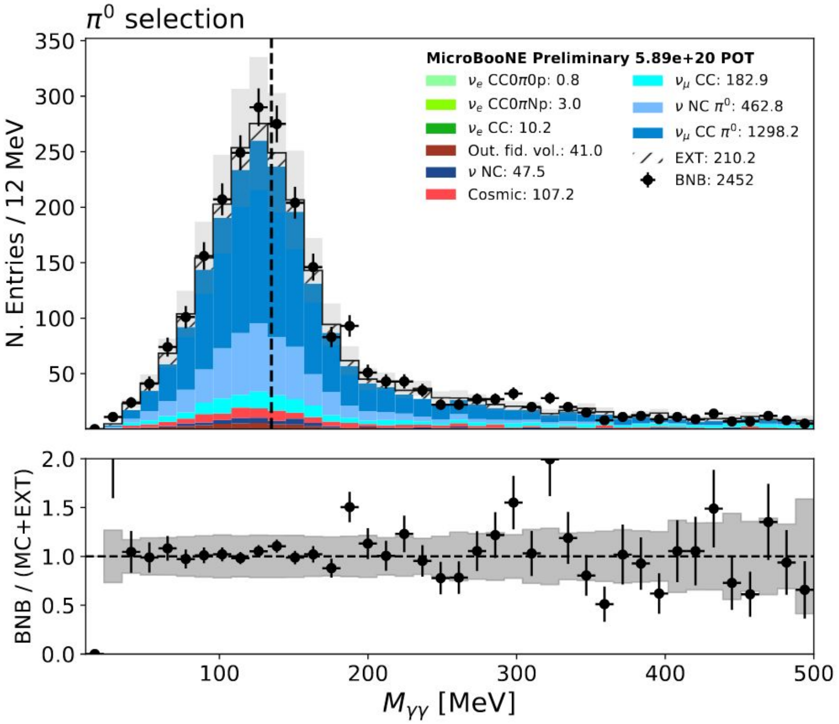


GENIE v3.0.6 models used:
QE/MEC → **J. Nieves, J.E. Amaro, M. Valverde** Phys. Rev. C 70, 055503 (2004) and **R. Gran, J. Nieves, F. Sanchez. M. Vicente-Vacas** Phys. Rev. D 88, 113007 (2013)
RES/COH → **C. Berger, L. Sehgal** Phys. Rev. D 76, 113004 (2007), Phys. Rev. D 79, 053003 (2009)
FSI → work by **L. Salcedo, E. Oset, M. Vicente-Vacas, C. Garcia-Recio** Nucl. Phys. A 484, 557-592 (1988) and **V. Pandharipande, S.C. Pieper** Phys. Rev. C 45, 791-798 (1992)

More on Neutral Pions



Phys. Rev. D99, 091102(R) (2019)



MICROBOONE-NOTE-1085-PUB

MicroBooNE: current R&D

Brief R&D parenthesis

Noise source in MicroBooNE: MicroBooNE noise characterization paper: JINST 12, P08003 (2017)

Single photo-electron rates as a function of drift HV and with reverse cathode polarity.

HV studies: 70 kV → 128 kV

Impact of UV laser grounding schemes for DUNE?

Real-time triggering solutions that can get physics faster in SBND, DUNE ND

Argon doping

NuMI

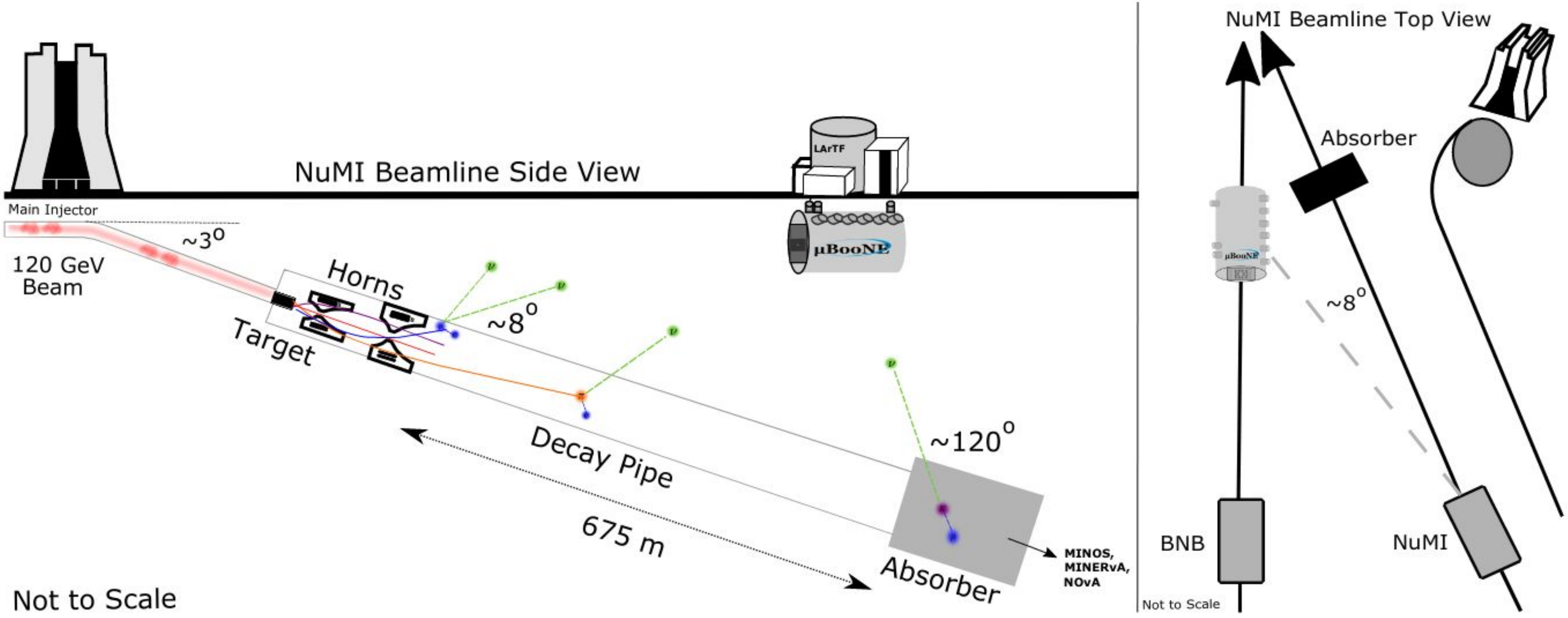


FIG. 3. The position of the MicroBooNE detector relative to the NuMI neutrino beam target with views projected to the side and above. The NuMI beamline is angled 3° downwards and the distance of the NuMI target to MicroBooNE is approximately 679 m. The flux of neutrinos at MicroBooNE covers angles ranging from 8° to 120° relative to the NuMI beamline direction.

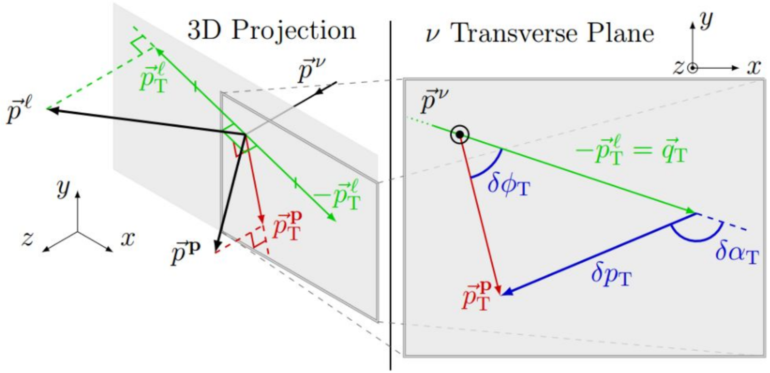
Single Transverse Variables

Transverse direction characterized by magnitude & 2 angles

$$\delta\vec{p}_T = \vec{p}_T^{\,\ell} + \vec{p}_T^{\,p},$$

$$\delta\phi_T = \arccos\frac{-\vec{p}_T^{\,\ell}\cdot\vec{p}_T^{\,N}}{p_T^{\ell}p_T^{N}},$$

$$\delta\alpha_T = \arccos\frac{-\vec{p}_T^{\,\ell}\cdot\delta\vec{p}_T}{p_T^{\ell}\delta p_T}.$$



Longitudinal Variables

Introduced by the Minerva collaboration to remove dependence on E_ν while assuming ground state remnant nucleus. Phys. Rev. Lett. 121, 022504 (2018), Phys.Rev. D 101, 092001 (2020), Phys. Rev. C 95, 065501 (2017)

$$R = m_A + p_L^{\mu} + p_L^{p} - E^{\mu} - E^{p}$$

$$\delta p_L = \frac{1}{2}R - \frac{m_{A-1}^2 + \delta p_T^2}{2R}$$

$$p_{n,proxy} = \sqrt{\delta p_L^2 + \delta p_T^2}$$

Struck nucleon momentum

$$\delta p_{Tx} = (\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_T^{\mu}) \cdot \delta\mathbf{p}_T$$

$$\delta p_{Ty} = -\hat{\mathbf{p}}_T^{\mu} \cdot \delta\mathbf{p}_T$$

Sensitivity to nuclear effects

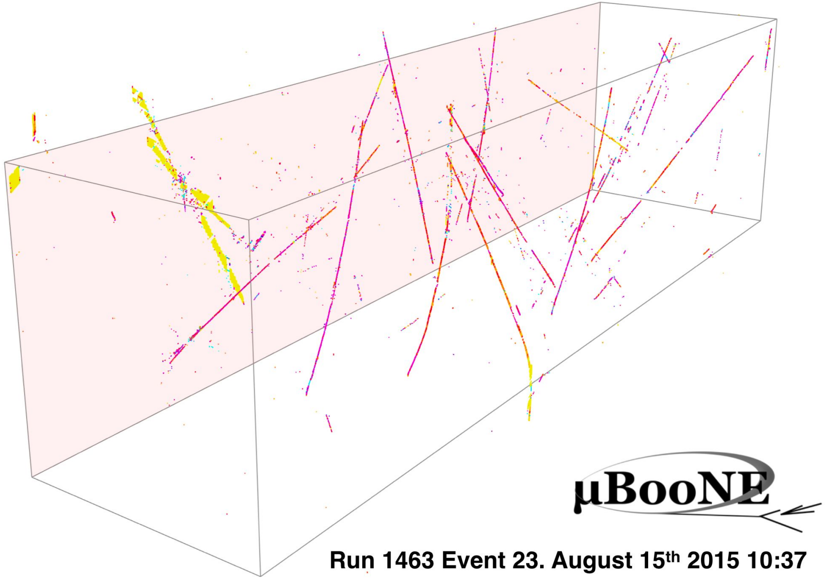
MicroBooNE: event reconstruction

3D Event reconstruction is crucial in LArTPC.
Multiple avenues:

→ "The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector", Eur. Phys. J. C78, 1, 82 (2018)

→ "Neutrino Event Selection in the MicroBooNE Liquid Argon Time Projection Chamber using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching", JINST 16, P06043 (2021)

→ "A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber", Phys. Rev. D103, 092003 (2021)



Run 1463 Event 23. August 15th 2015 10:37

Cosmic contamination plays a big role on the surface:
Cosmic Ray Tagger installed in 2018 JINST 14, P04004 (2019),
Cosmic data as background to simulation (pioneered the "overlay" technique in LAr).

ν_μ CC exclusive topologies: protons

Low thresholds probe more detailed interaction channels and nuclear effects

→ ArgoNeuT: 200 MeV/c
Phys. Rev. D 90, 012008

→ T2K: 500 MeV/c
Phys. Rev. D 98, 032003

→ MINERvA: 450 MeV/c
Phys. Rev. D 99, 012004

→ MicroBooNE: **300 MeV/c**
Phys. Rev. D102, 112013

Protons identified by Bragg peak in last 30 cm of track
MICROBOONE-NOTE-1056-PUB