μBooNE Pushing the Limits for Improved Cross Section Results with LArTPC Technology

New Directions in Neutrino-Nucleus Scattering
NuSTEC workshop 3/15/21

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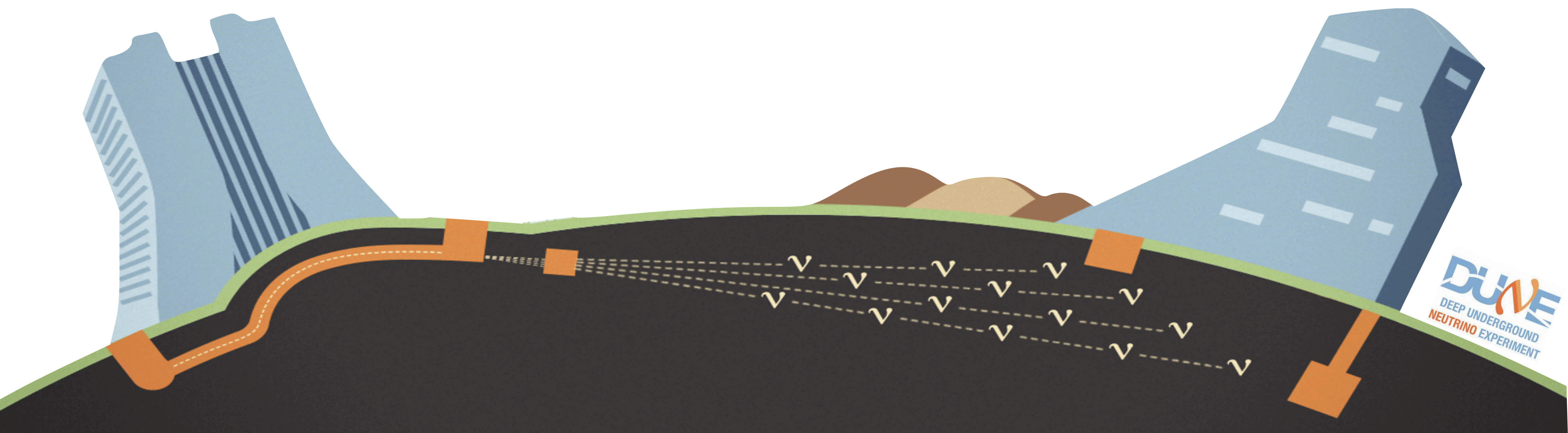
Introduction

Already now, MicroBooNE offers a series of cross section measurements

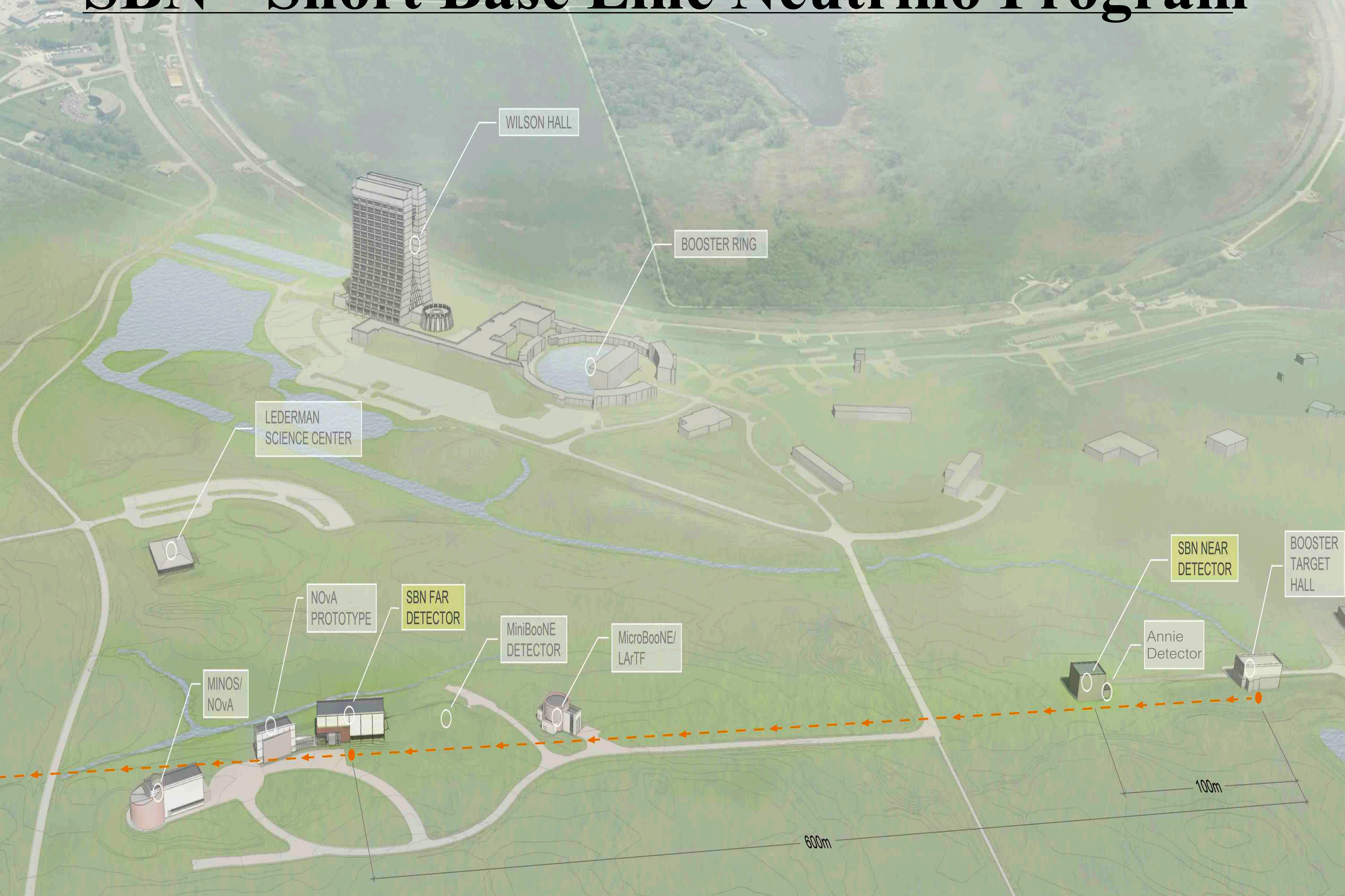
Available cross section on Argon is vital for SBN and DUNE

A LArTPC detector has low detection threshold & 4π acceptance

Better understanding of LArTPC, energy reconstruction and improvements of models.



SBN - Short Base Line Neutrino Program



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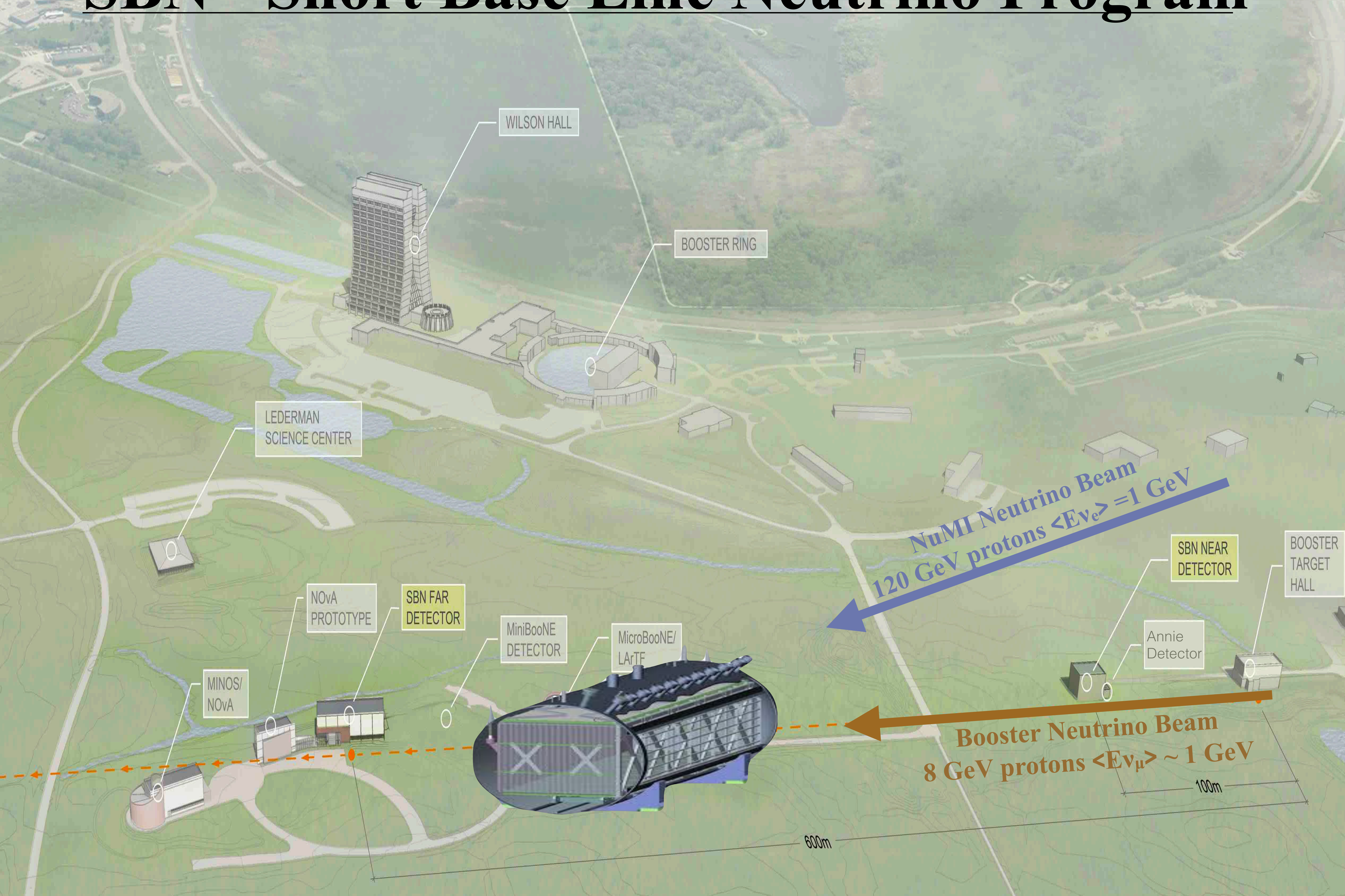
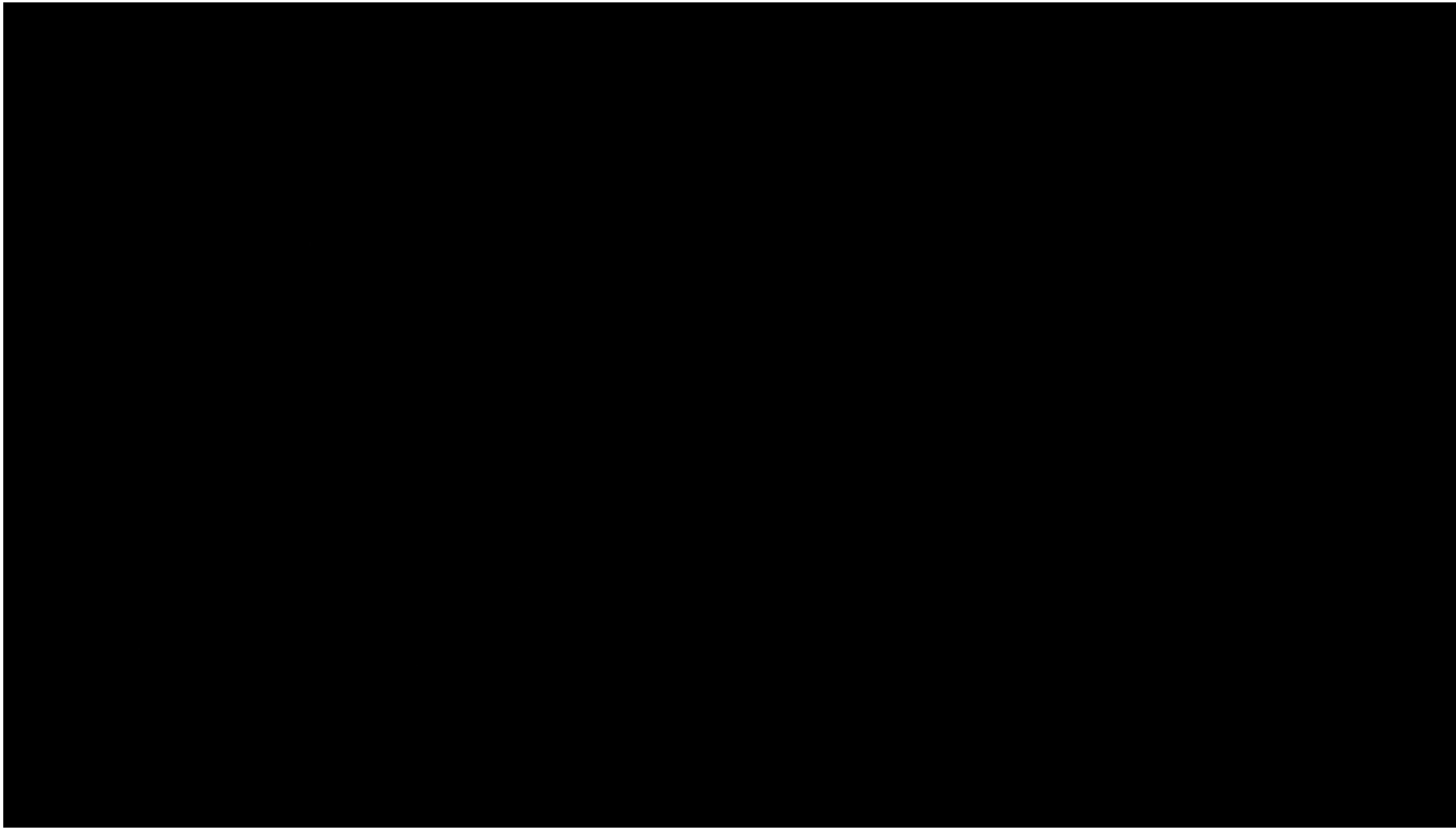
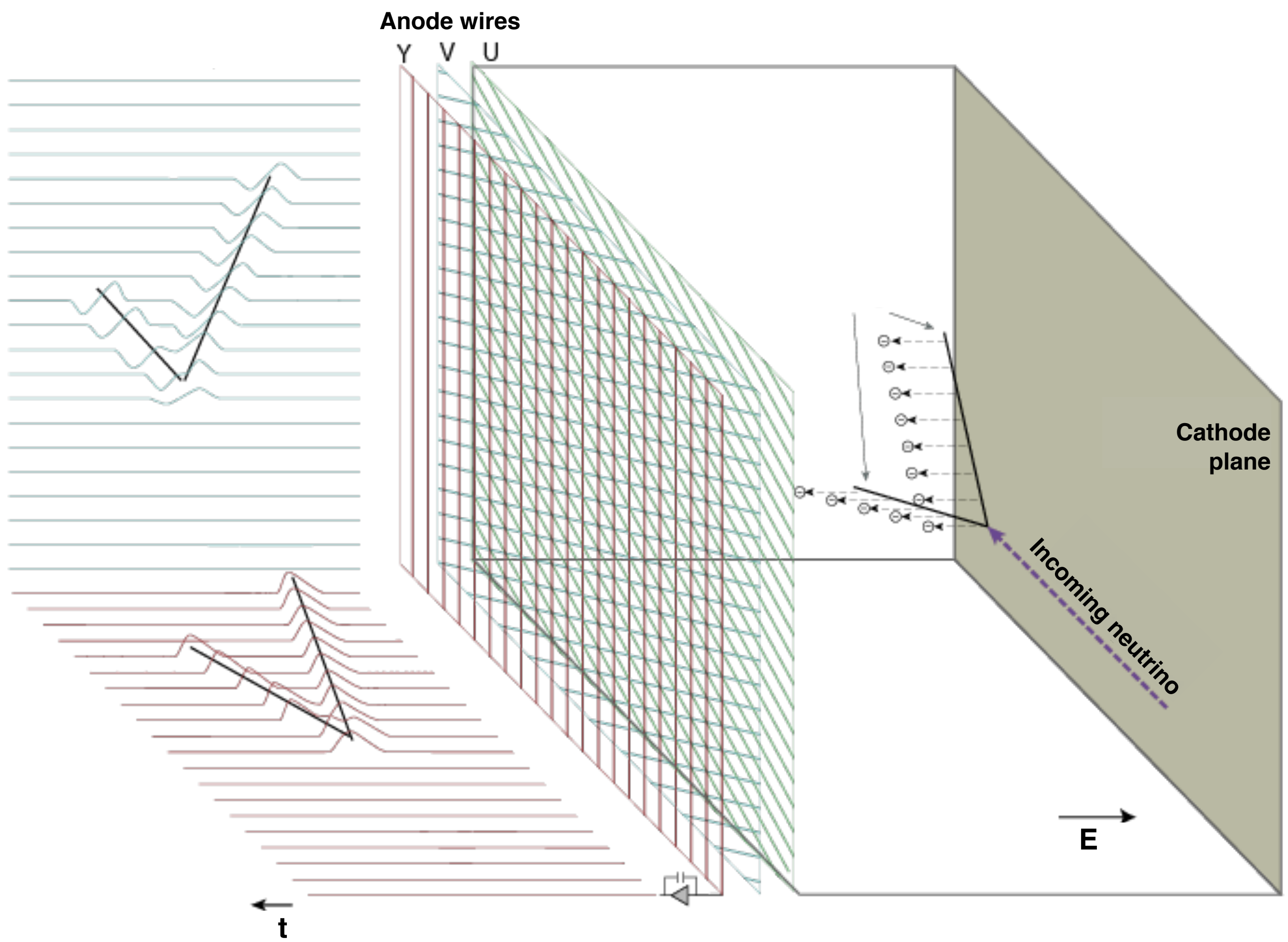


LAr TPC - MicroBooNE



For more see here

LAr TPC - MicroBooNE



Near surface LArTPC detector

Active mass: 85 tons

Fiducial Volume: 2.5 x 2.2 x 10 m

Triggered by 32 PMTs

Anode: 3 wire planes

Stable detector operation since 2015

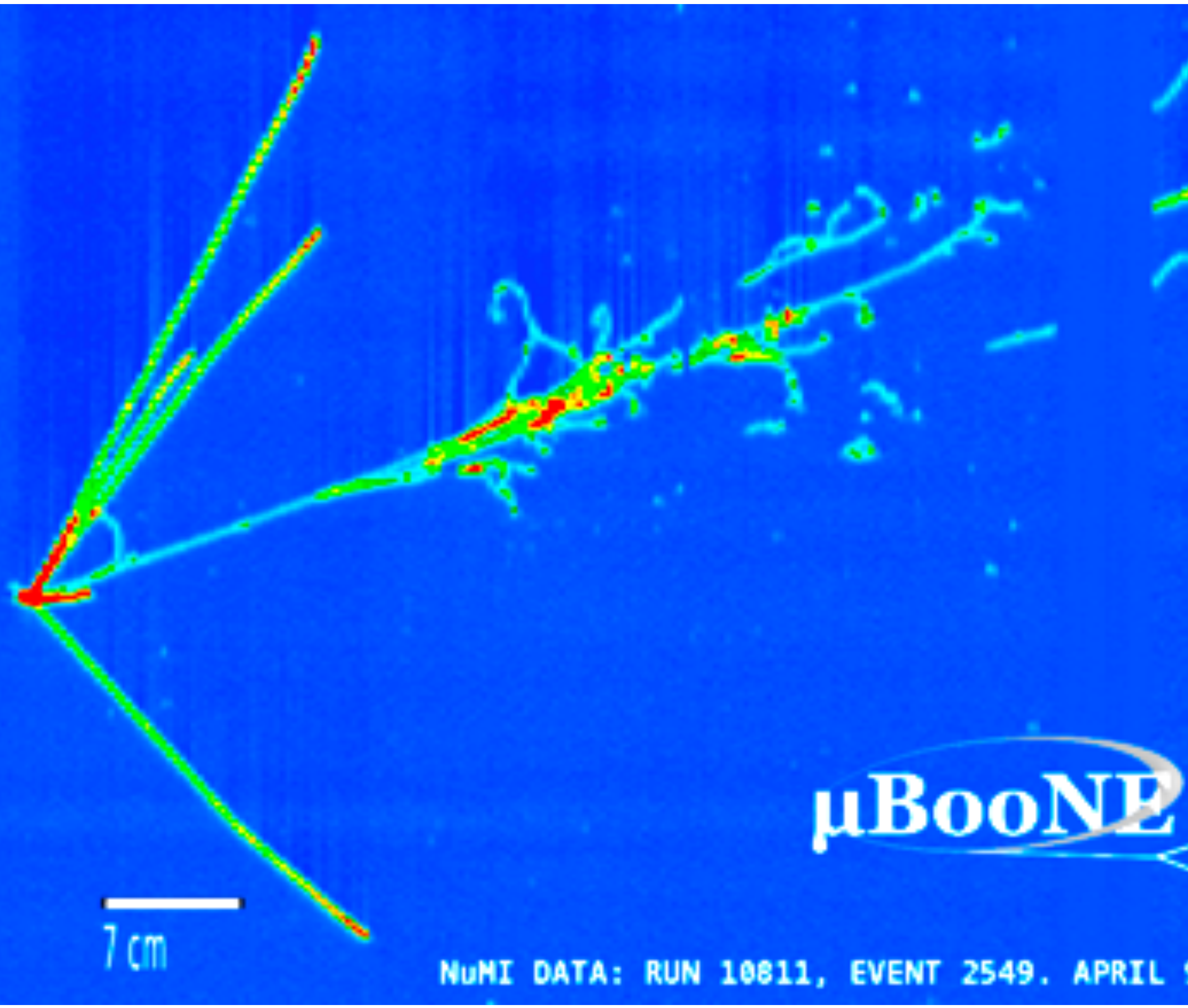
1.52E21 POT collected

Analysis of the initial subset of the data shown today

Cosmic Ray Tagger (CRT) help rejecting background since 2018

LAr TPC - MicroBooNE

- Low tracking threshold
- Charge collection supply calorimetry
- High statistics
- Latest results with improved detector understanding and reduced systematics uncertainties



LArTPC MicroBooNE's improvements

Improved signal processing

Cosmic Rejection

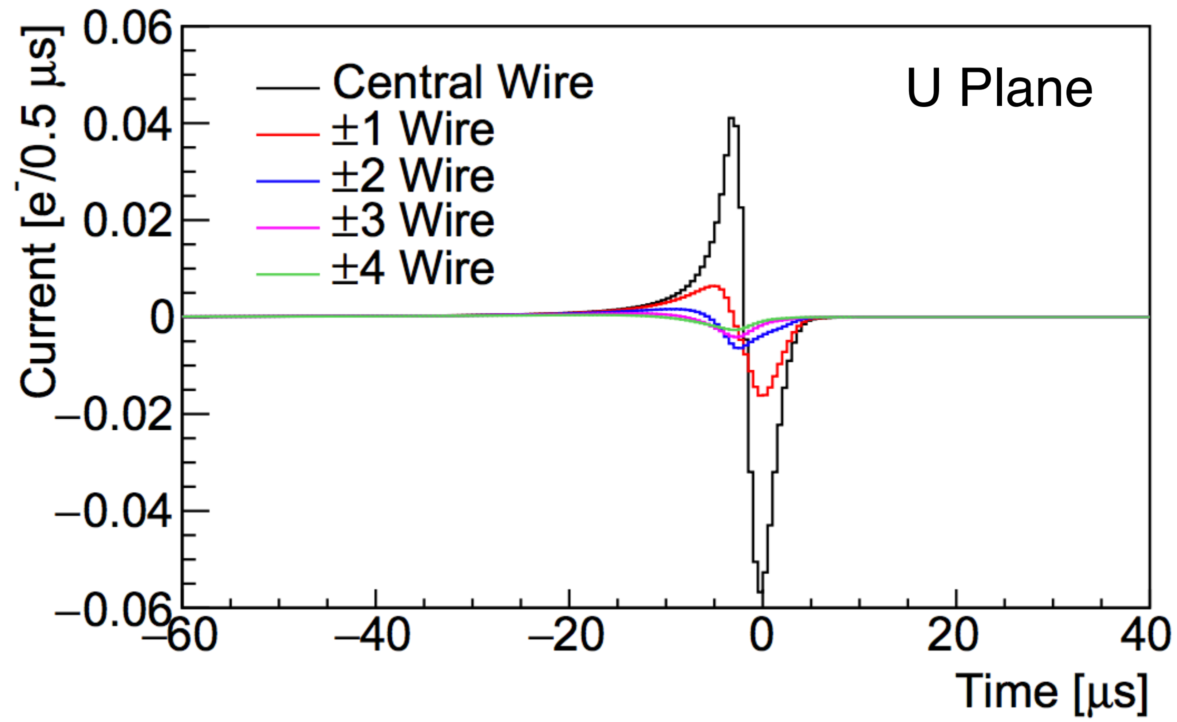
Flash Matching

Data driven based detector uncertainties

LArTPC MicroBooNE's improvements

Improved signal processing

- Accounting for signals from different wires in all 3 planes
- Better calorimetry in all phase space
- Better efficiency
- Reduced detector systematics



For more see: JINST 13 P07006, JINST 13 P07007

Flash Matching

Data driven based detector uncertainties

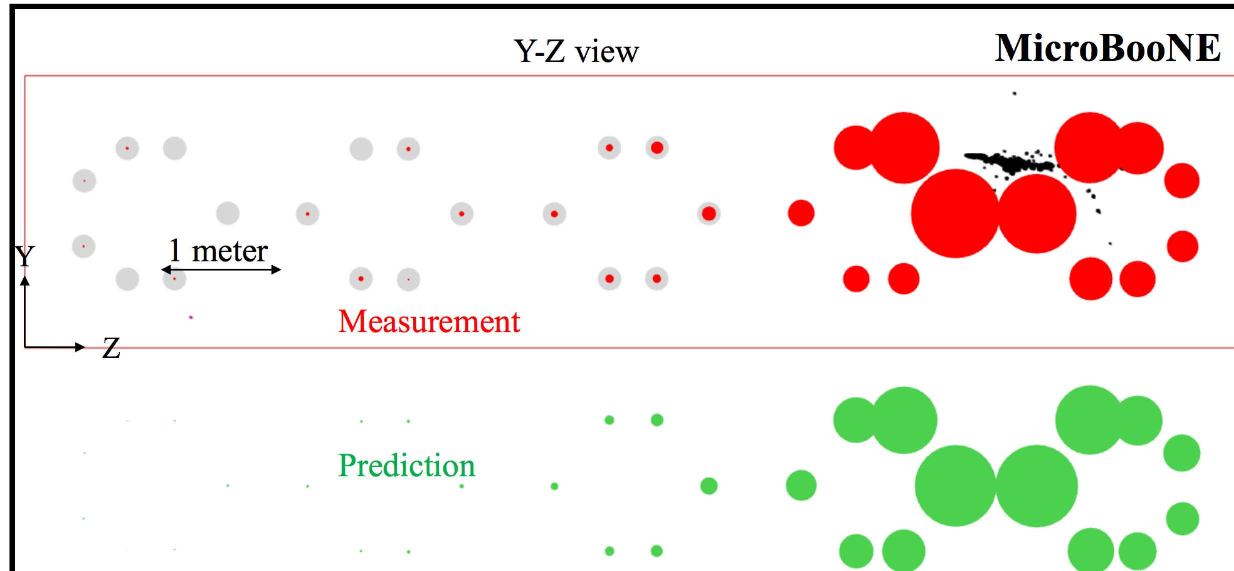
LArTPC MicroBooNE’s improvements

Improved signal processing

Cosmic Rejection

Flash Matching

- New methods for TPC/PMT matching
- Predicting light distribution of a cluster and comparing to light measurement.



For more see: [arXiv:2012.07928[hep-ex]]

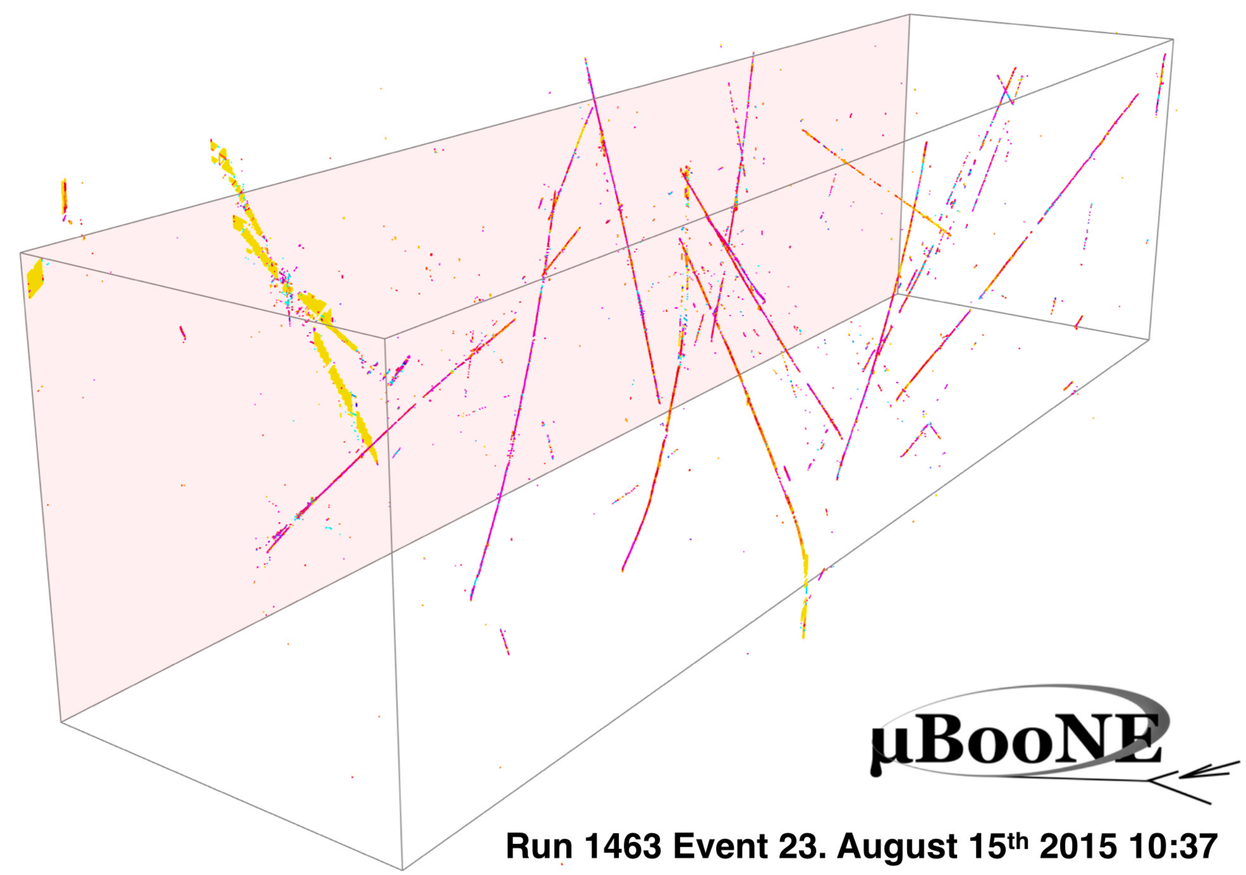
LArTPC MicroBooNE's improvements

Improved signal processing

Cosmic Rejection

- Using off beam data as background to simulation
- CRT since 2018 helps exclude crossing penetrating tracks

Flash Matching



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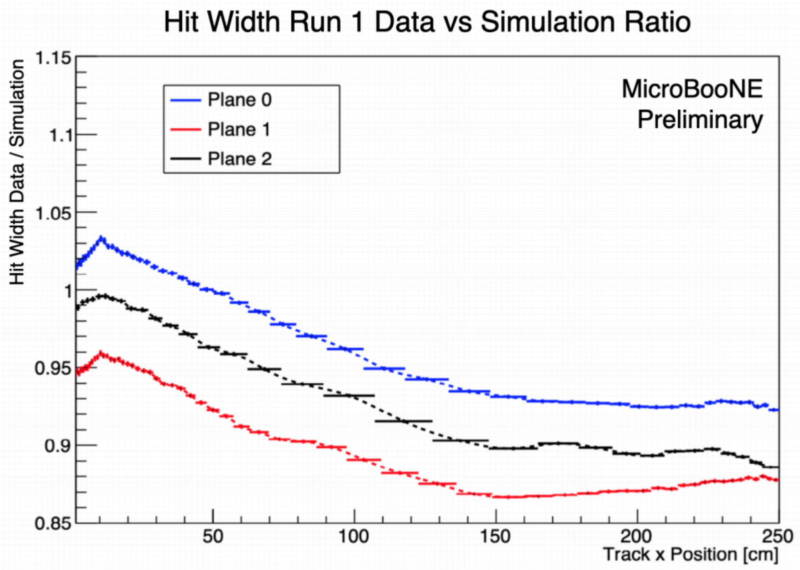
Data driven detector uncertainties



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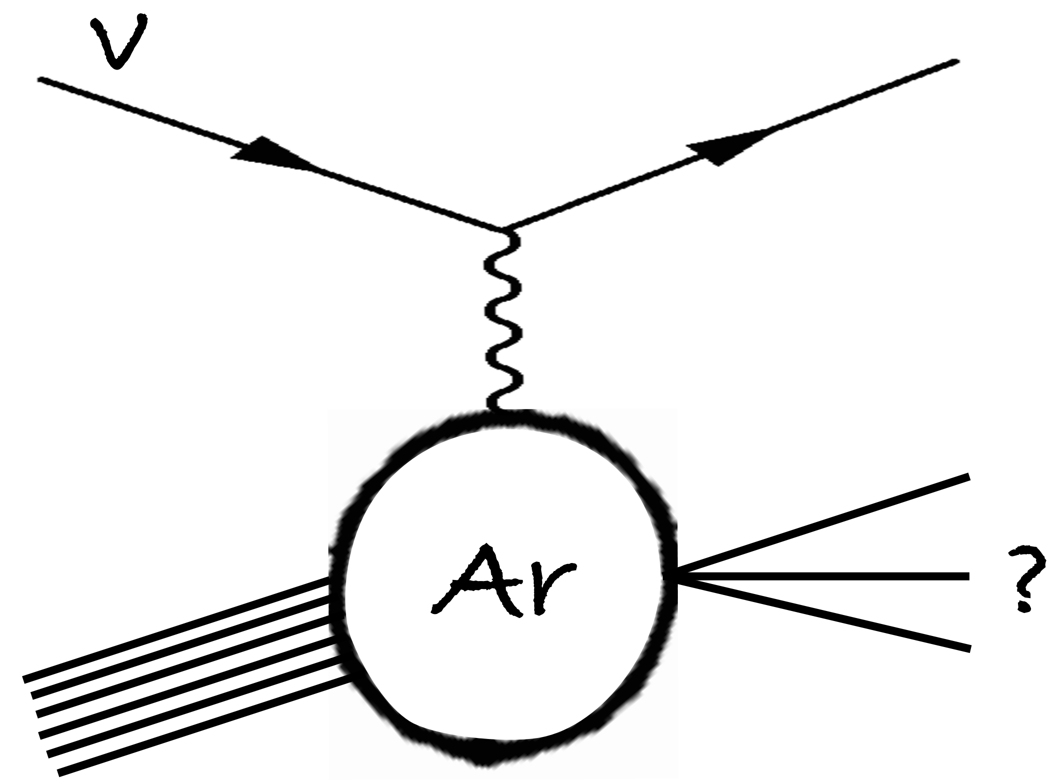
Parameterising the hits charge and width with respect to location and orientation

Cross section results

MicroBooNE is shifting gears to precision measurements.

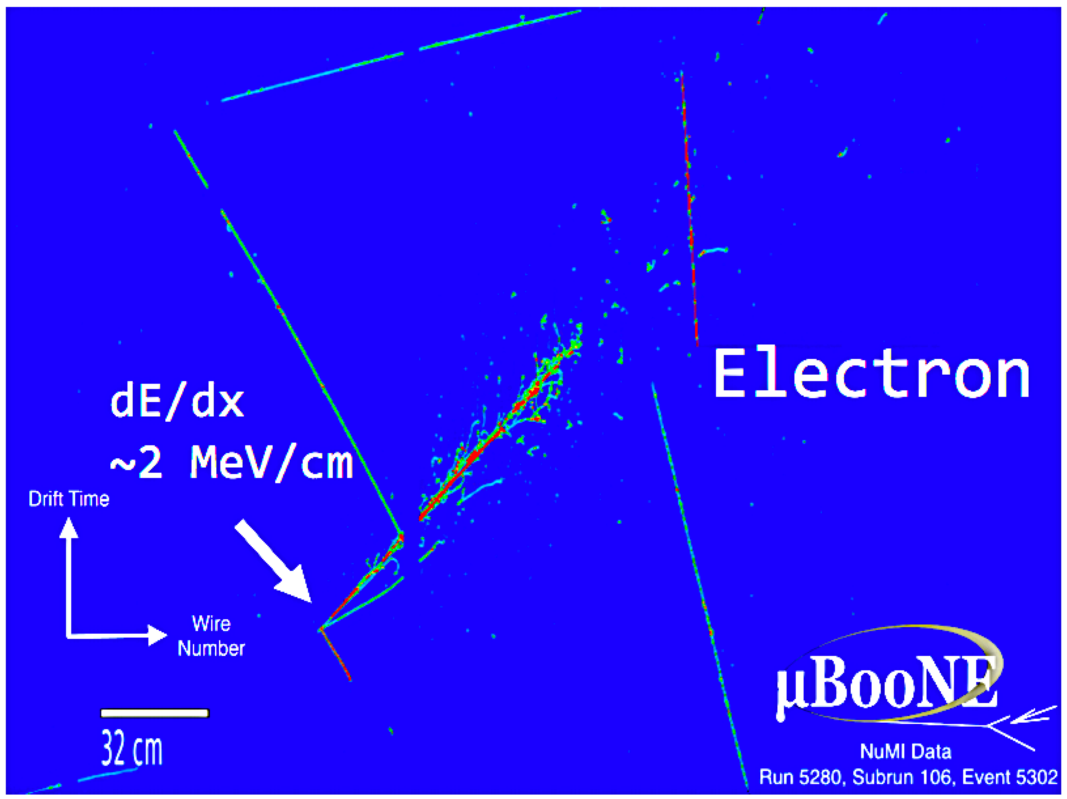
MicroBooNE inclusive results stands in good agreement with many event generator’s prediction. Specifically, GENIE v3.0.6

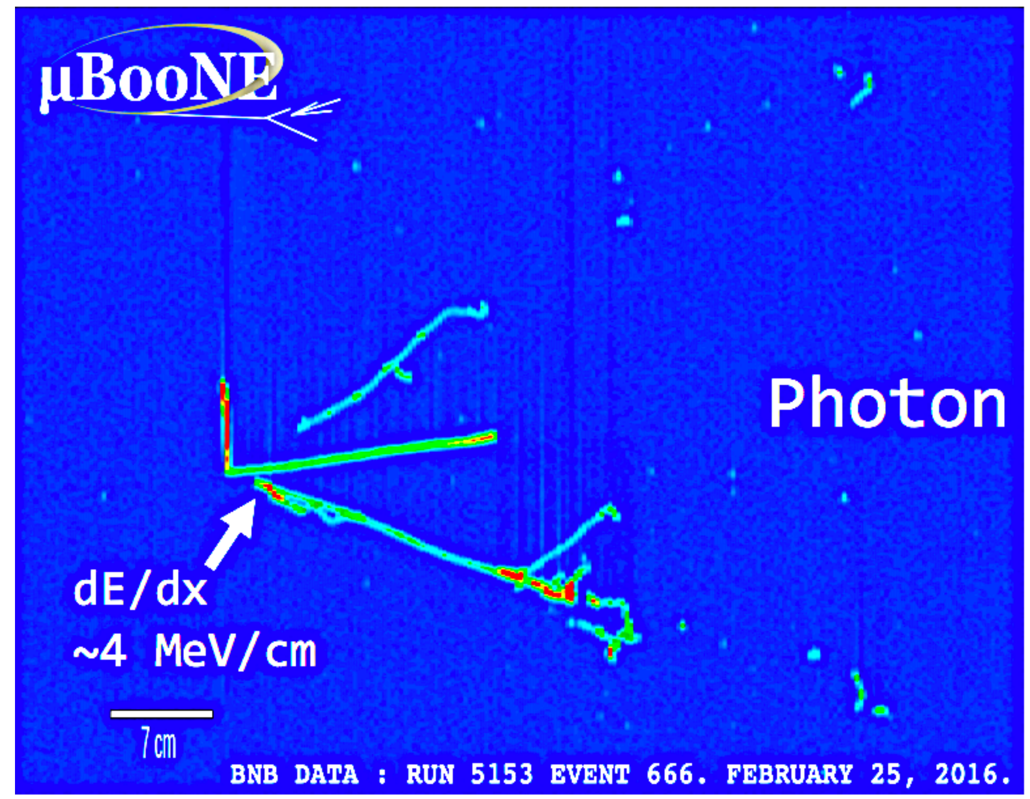
Exclusive results show differences at specific regions of phase-space



$\nu_e + \nu_e$ CC inclusive with Numi

One of MicroBooNE's greatest ability: Distinguish between photons and electrons





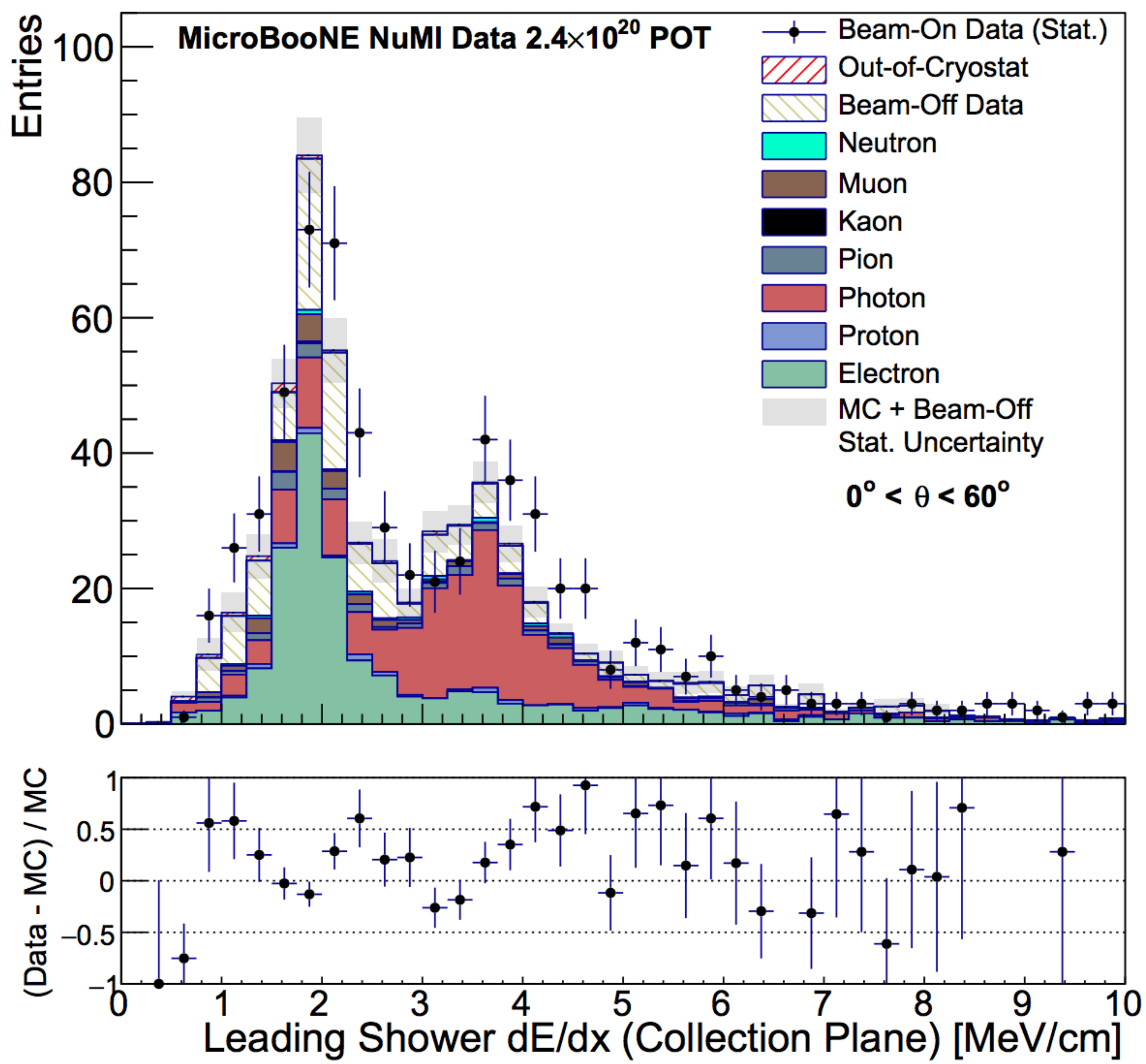
dE/dx at the beginning of an electron induced shower is of MIP ~2 MeV/c

dE/dx at the beginning of a photon induced shower, producing e^+e^- pair is twice MIP ~ 4 MeV/c

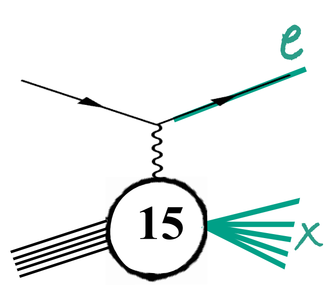
π^0 background will result with a distance between vertex and beginning of shower

$\nu_e + \bar{\nu}_e$ CC inclusive with Numi

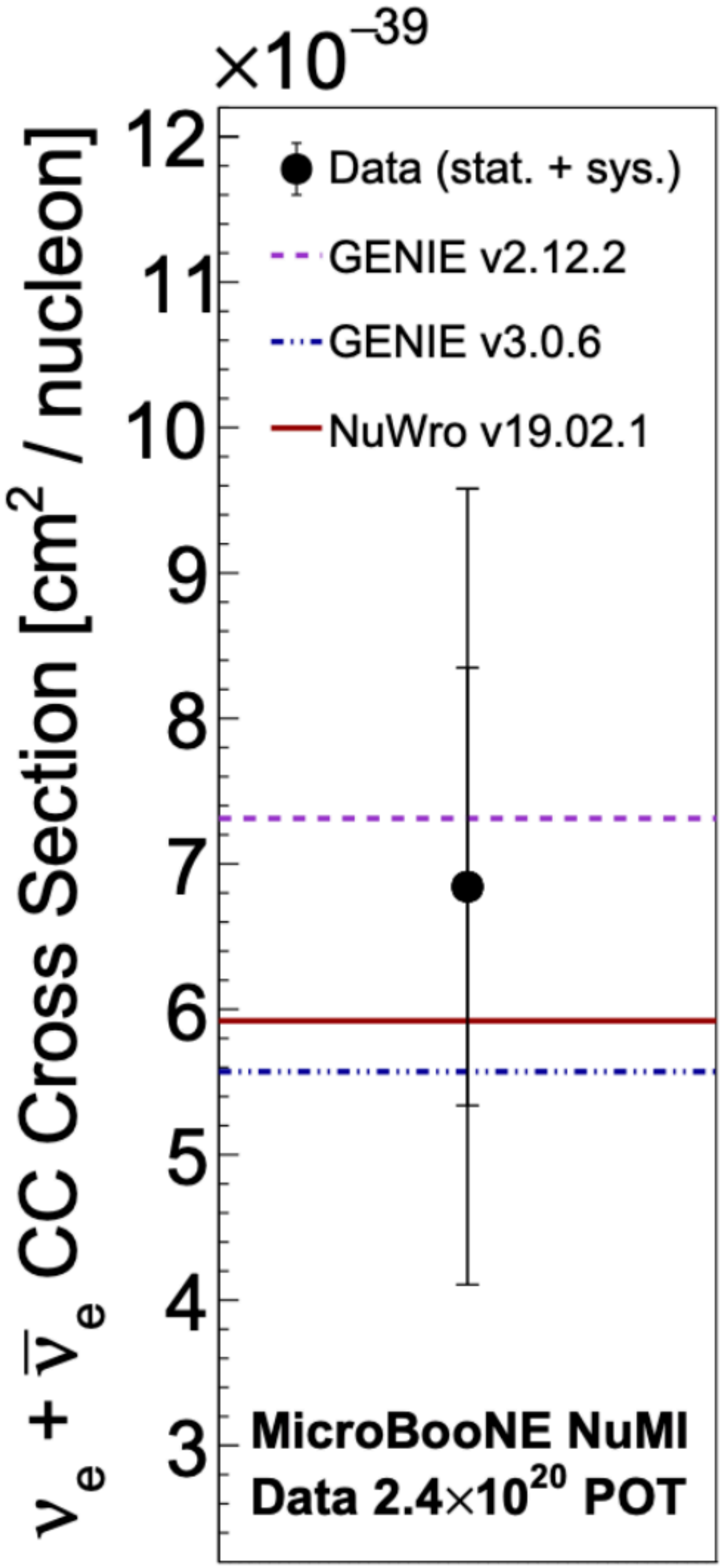
One of MicroBooNE's greatest achievements: Distinguish between photons and electrons



arXiv:2101.04228v1 [hep-ex]



$\nu_e + \bar{\nu}_e$ CC inclusive with Numi



arXiv:2101.04228v1 [hep-ex]

While searching for ν_e excess in BNB, measuring the flux averaged cross section in NuMI

First demonstration of electron neutrino reconstruction in a surface LArTPC in the presence of cosmic ray backgrounds. Largest sample to data > 200 events

Final selection: purity of 39% and efficiency 9%

Good agreement with models

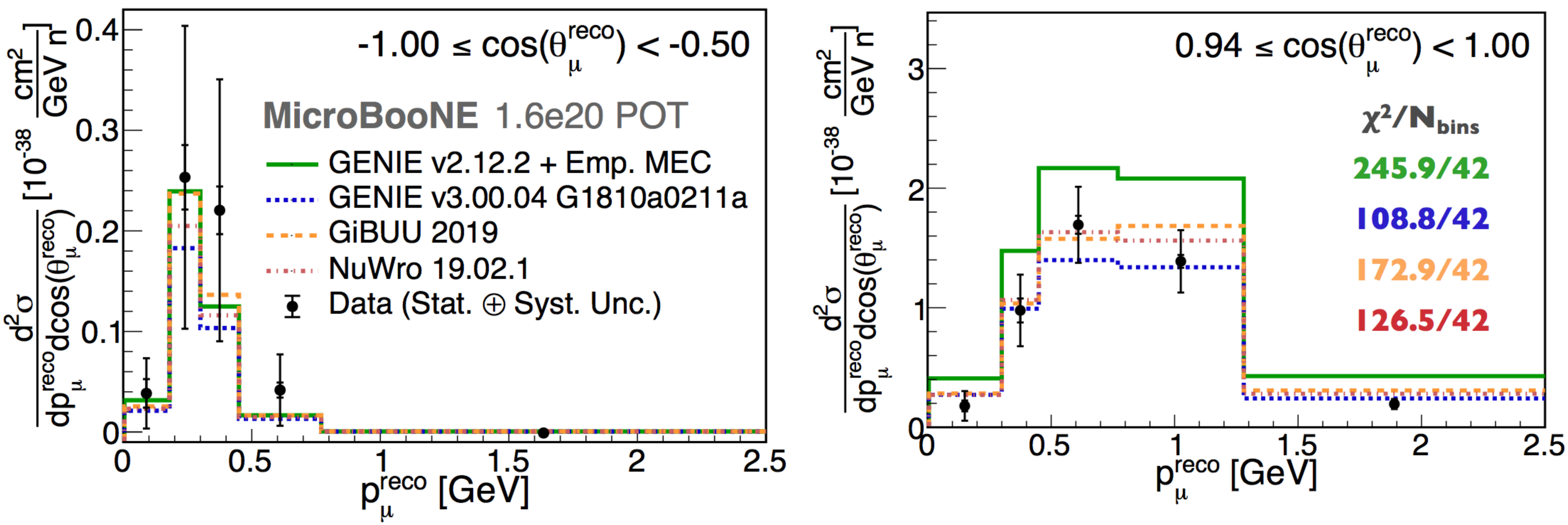
Stay tuned for the next round of this analysis: differential cross section, with reduced cosmic background and uncertainties

ν_μCC inclusive with BNB

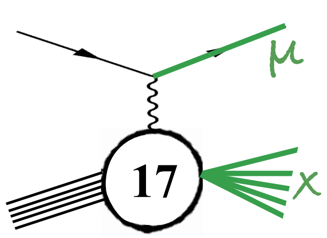
First ever double differential cross section measurement on Argon

Overall good agreement with prediction. GENIE v3 best describe data

Disagreement observed in forward scattering angle at high momentum



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

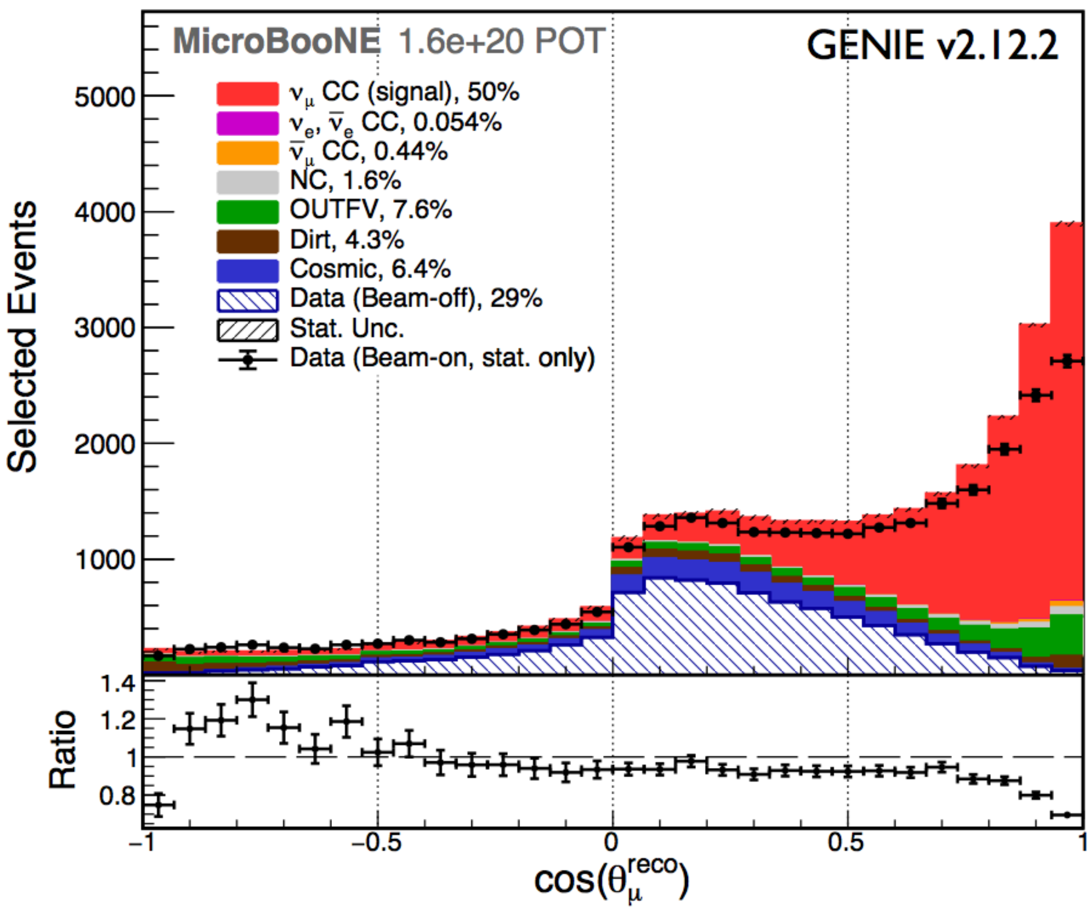


ν_μCC inclusive - Looking to the Future

Improved detector understanding and cosmic rejection, improves the results

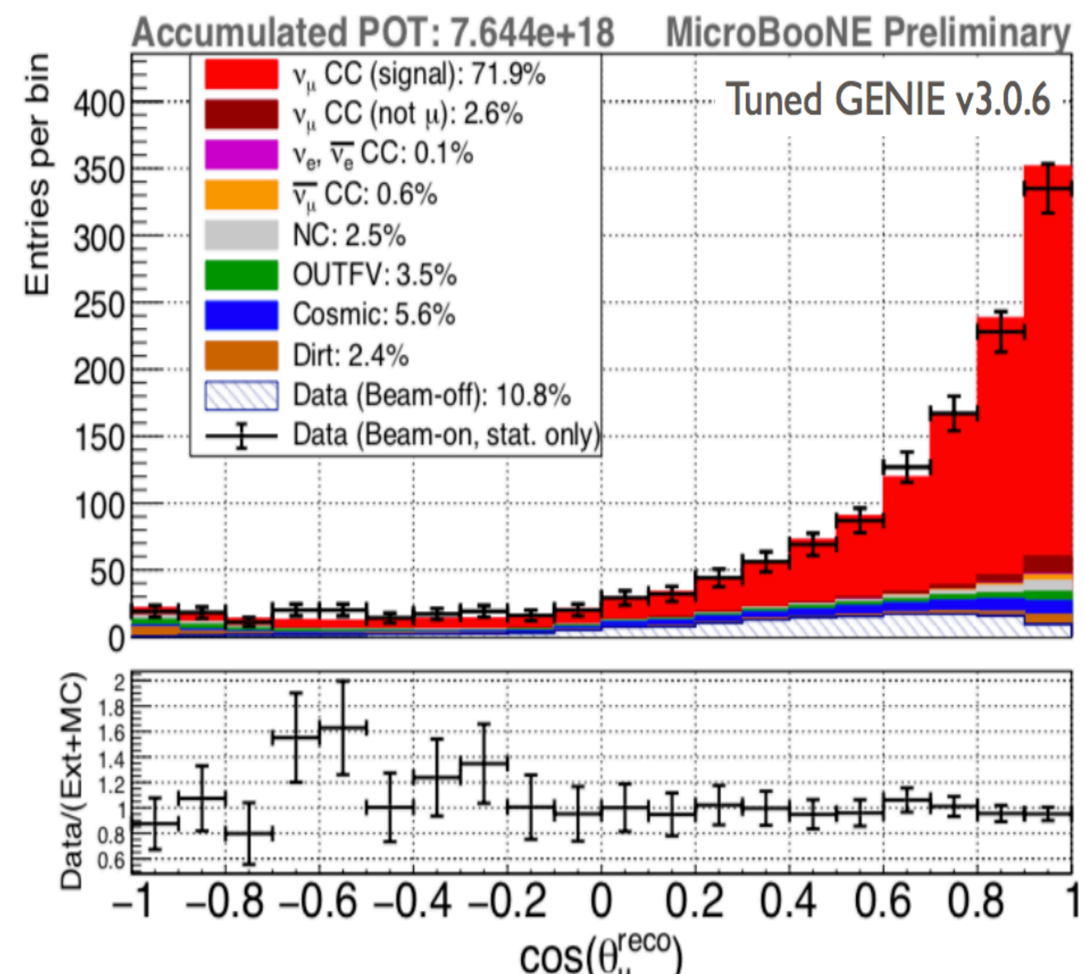
The purity: From 50% to 71.9%

Detector uncertainties: From 16.2% to 3.3%



Previous published measurement

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



Current measurement

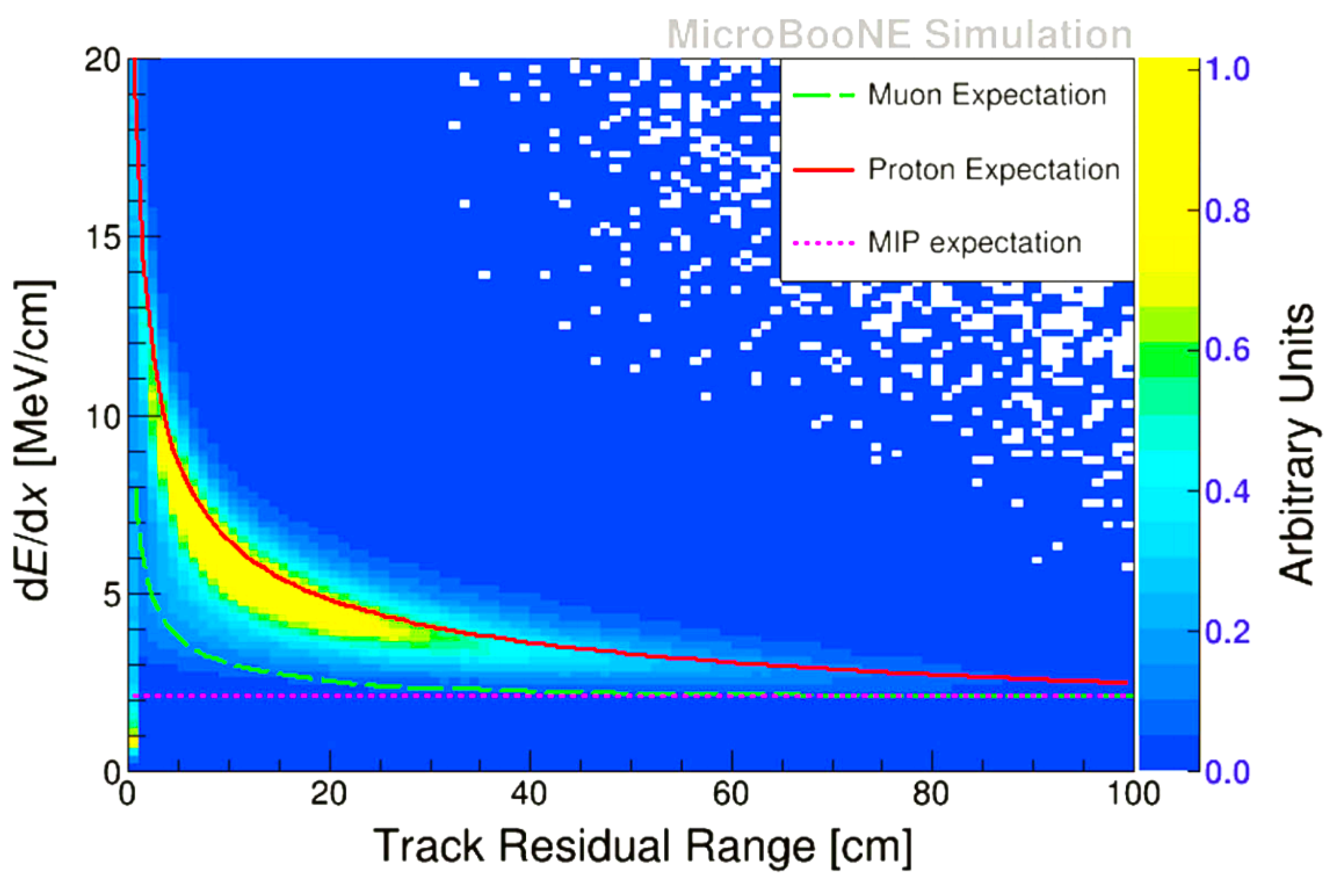
[MICROBOONE-NOTE-1069-PUB]

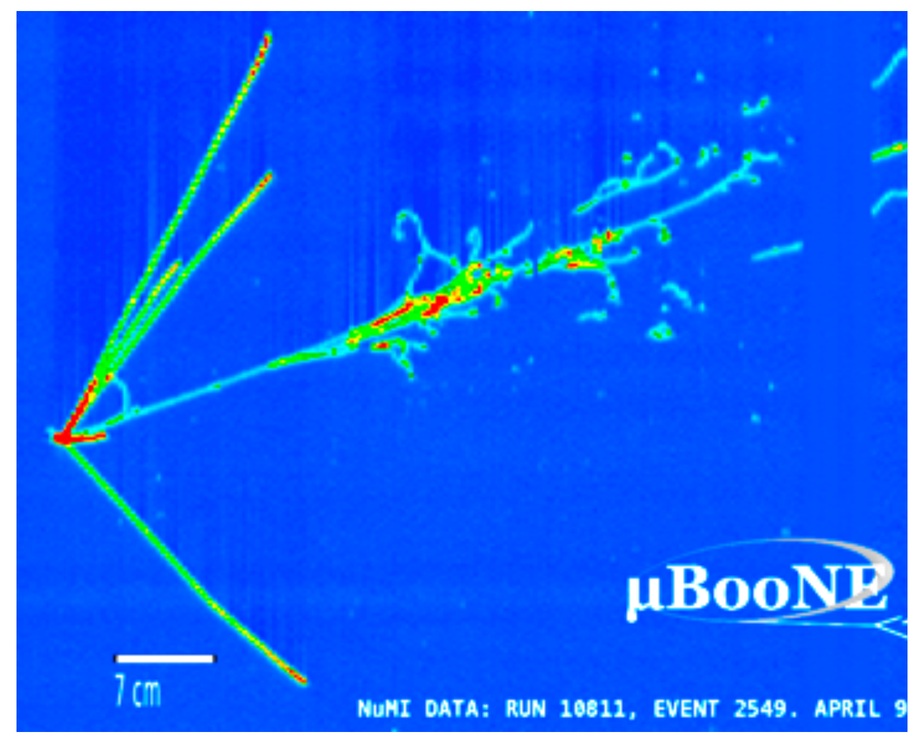
Protons in LArTPC

LArTPC supply the lowest threshold particle detection

MicroBooNE's proton detection threshold 300 MeV/c

Identified using dE/dx and the Bragg peak at end of track





For more see: [JINST 15, P03022 (2020)]

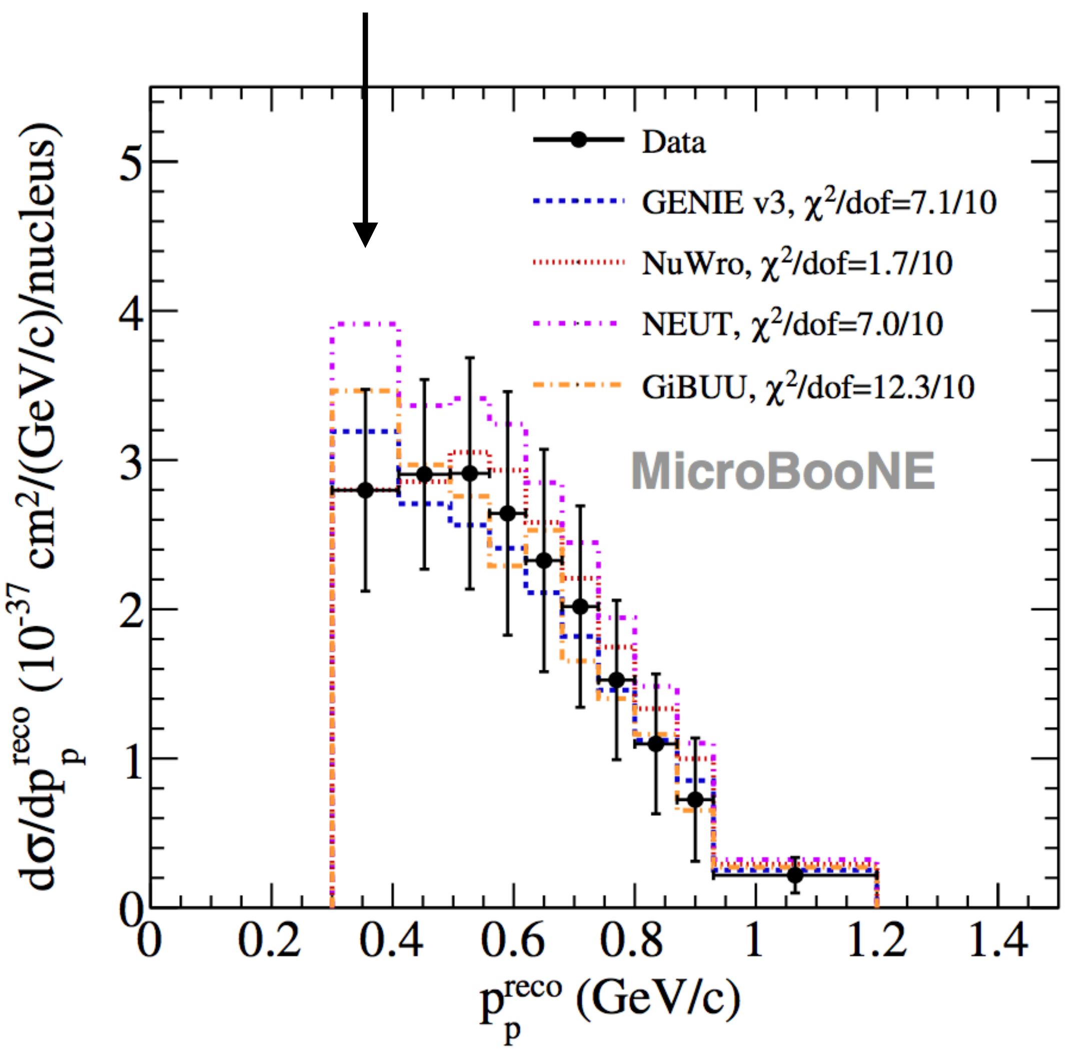
CC0πNP N ⩾ 1

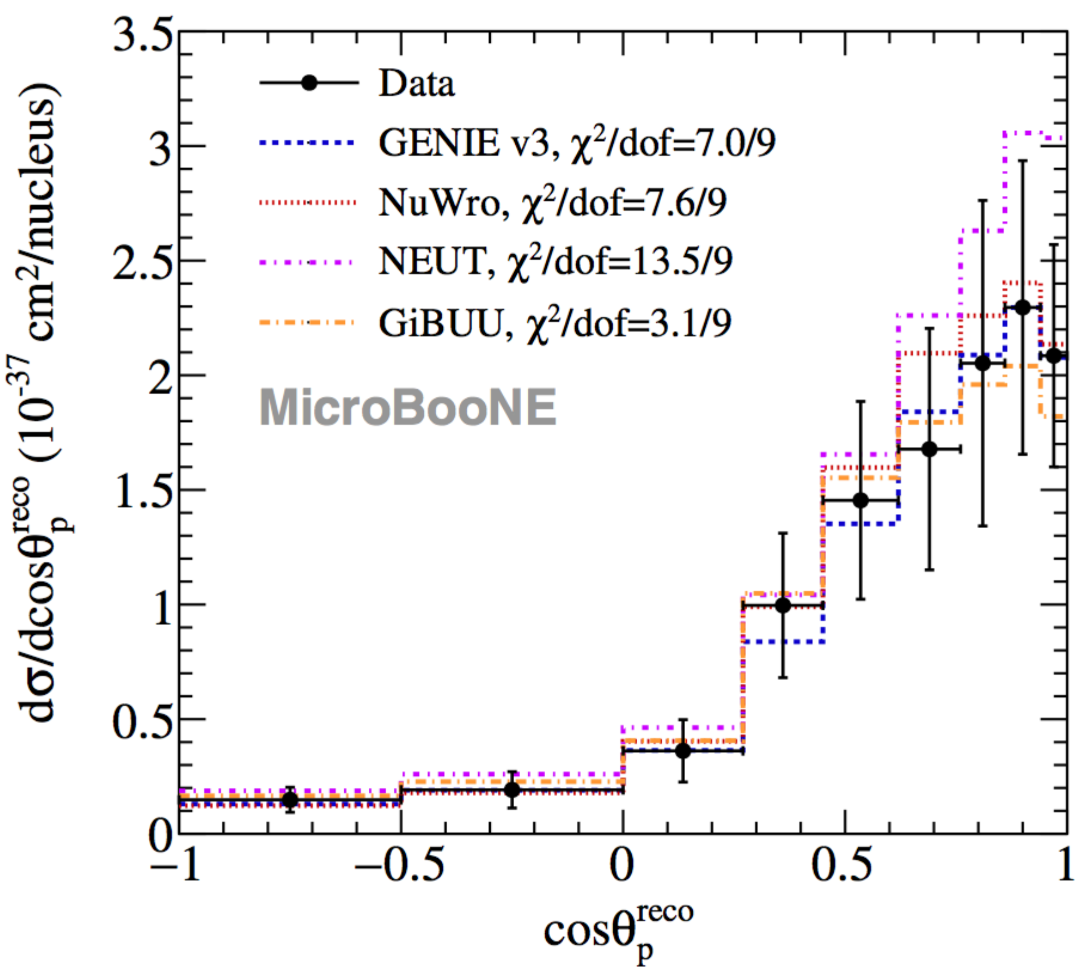
Event selection: 1μ (**Pμ > 100 MeV/c**) 1p (**300 MeV/C < Pp < 1200 MeV/c**), 0π

71% purity, 29% efficiency

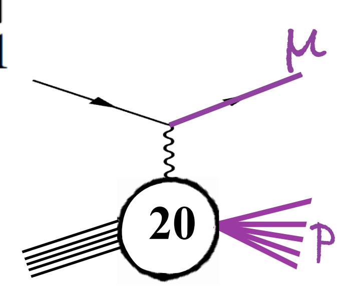
Overall agreement in proton kinematic

Notice low bin allowed by detection threshold,
also most sensitive to differences between models



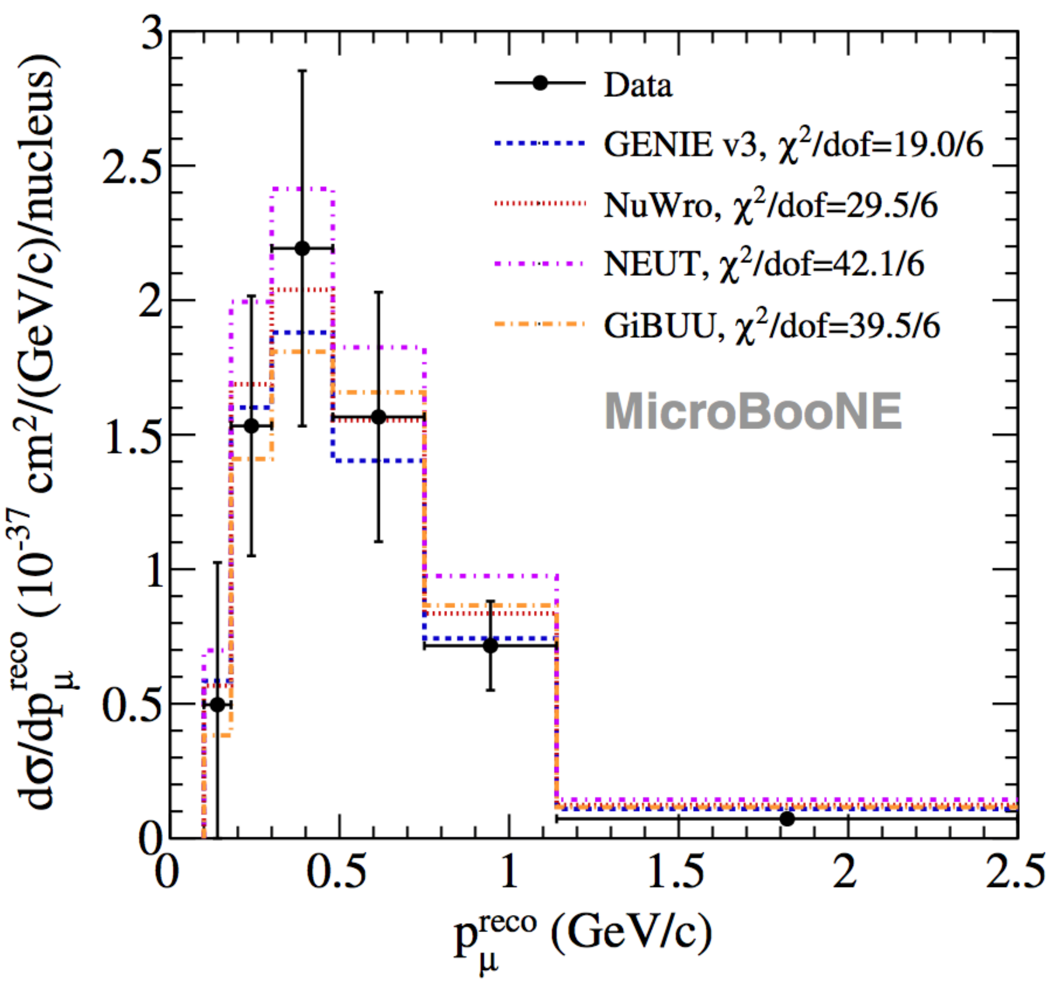


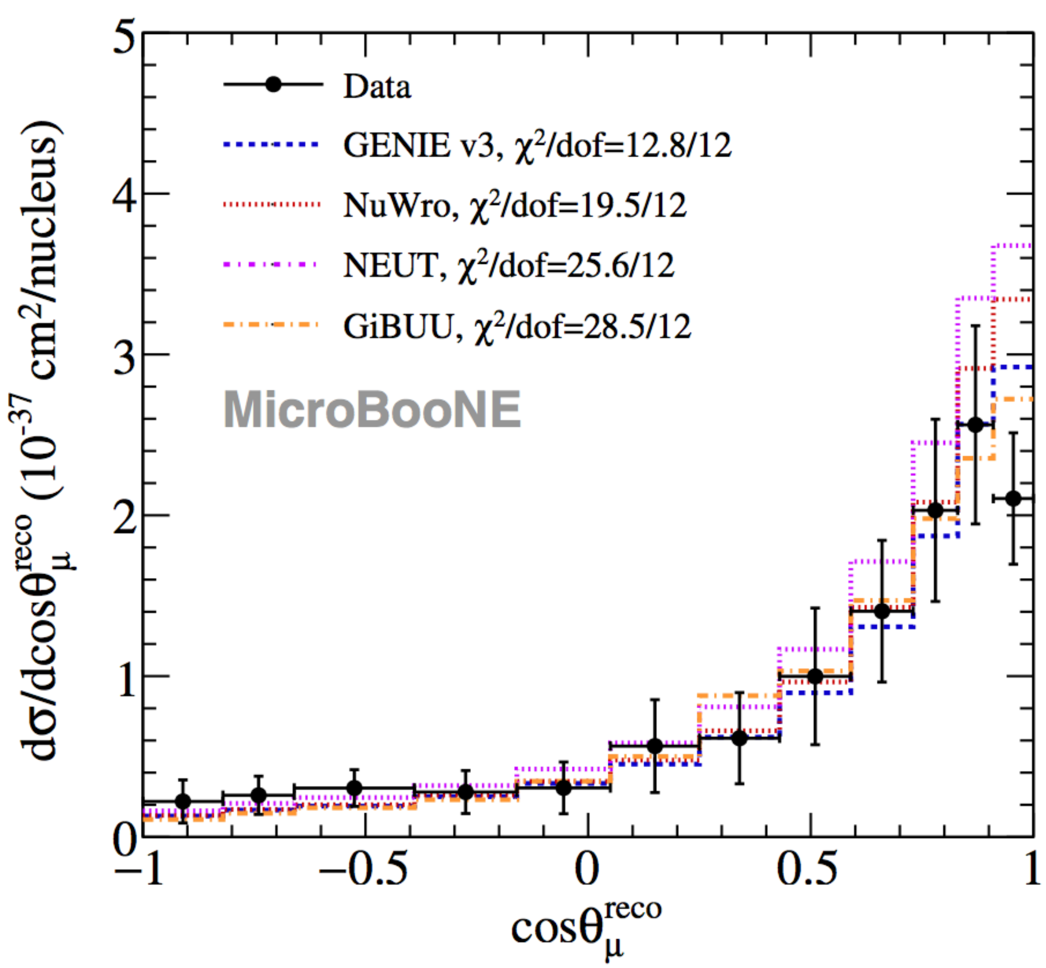
[Phys Rev. D 102, 112013 (2020)](https://doi.org/10.1103/PhysRevD.102.112013)



CC0πNP N ⩾ 1

This semi-exclusive measurement shows interesting disagreement in muon kinematics at very forward scattering angles





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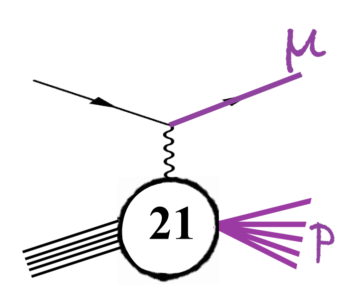


CC0π1P or CCQE-like events

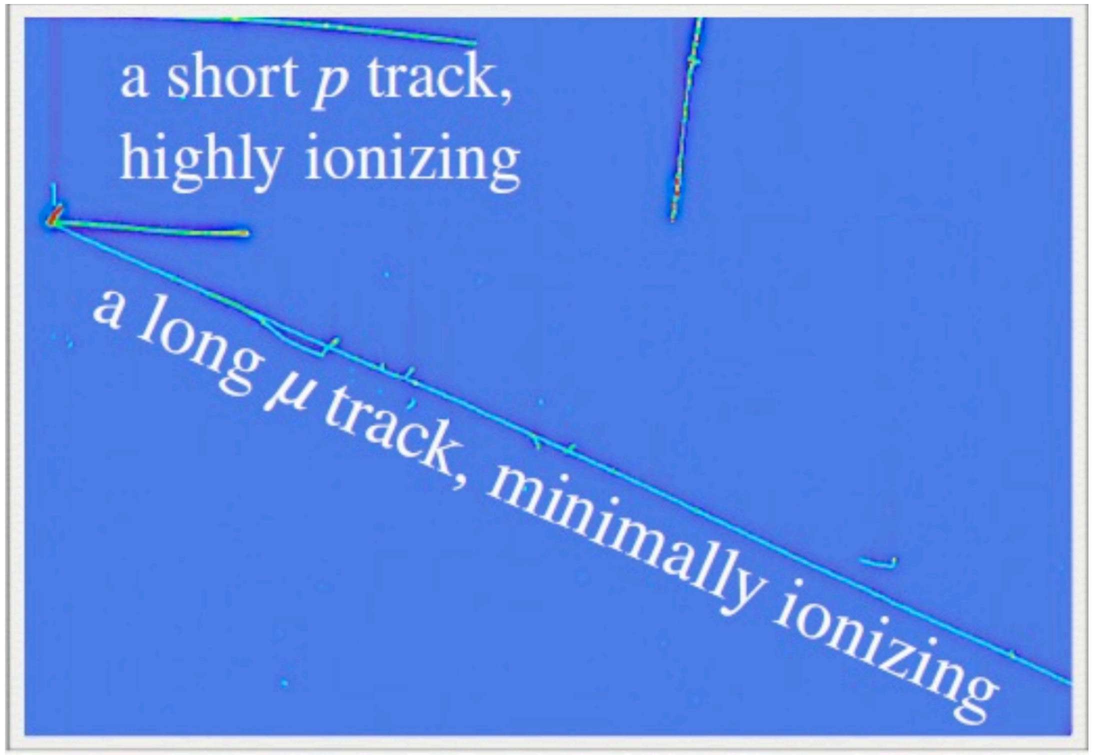
Vertex of 2 semi-contained tracks

(start within the fiducial volume)

one muon (**Pμ > 100 MeV/c**)

one proton (**Pp > 300 MeV/c**)

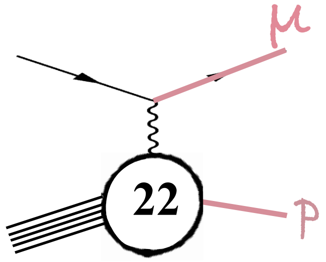
no π0 , no charged π (≥ 70 MeV/c)



Additional cuts on:

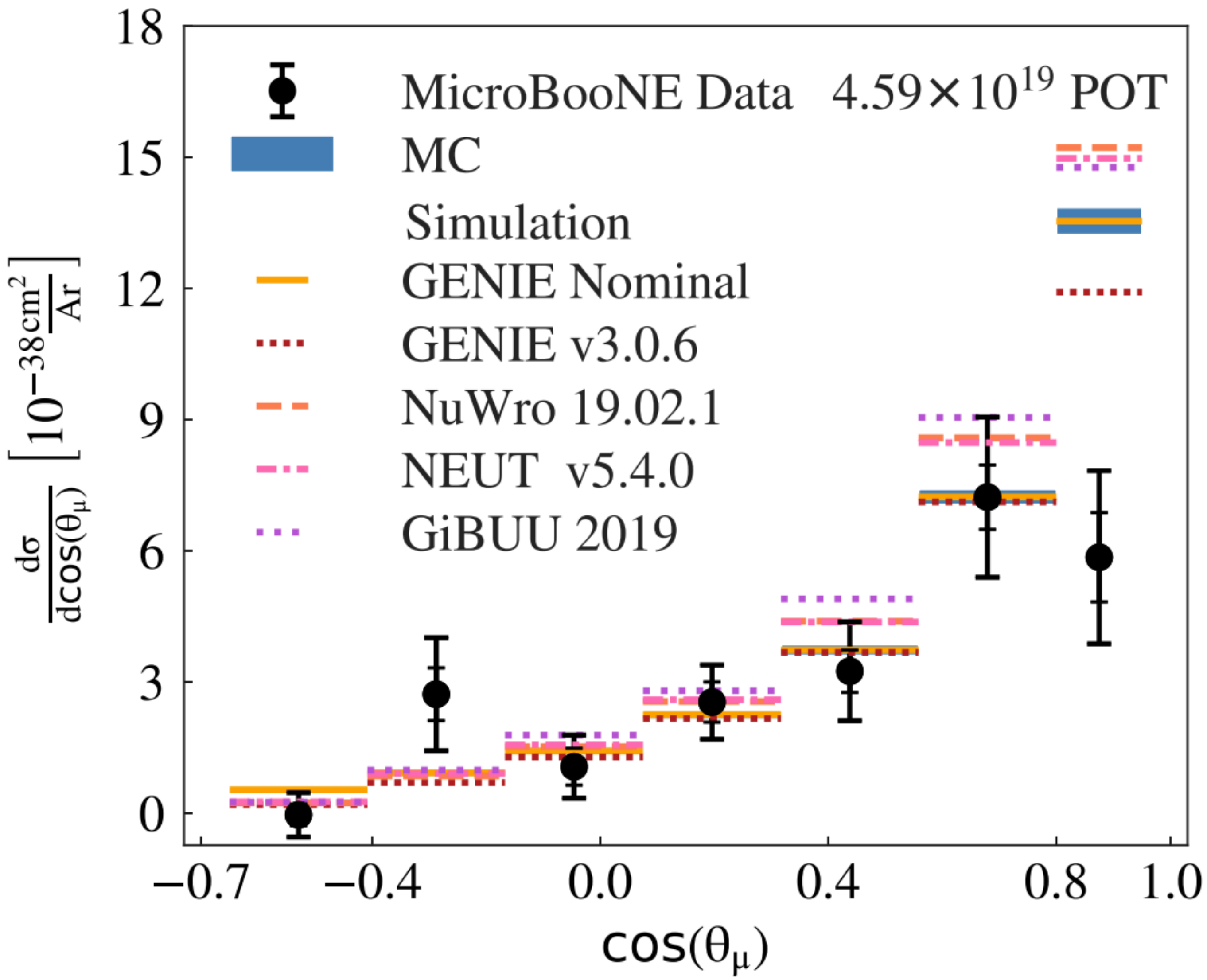
- To reduce cosmic contamination
  - $|\Delta\theta_{\mu p} - 90^{o}| < 55^{o}$
- To enhance QE contribution
  - $|\Delta\varphi_{\mu p} - 180^{o}| < 55^{o}$
  - $p_T = |\vec{p}_{T,\mu} + \vec{p}_{T,p}| < 350$ **MeV/c**

~84% CC1p0π (~81% CCQE) purity, 20% efficiency

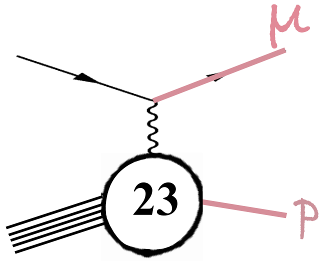


CC0π1P - CCQE-like events

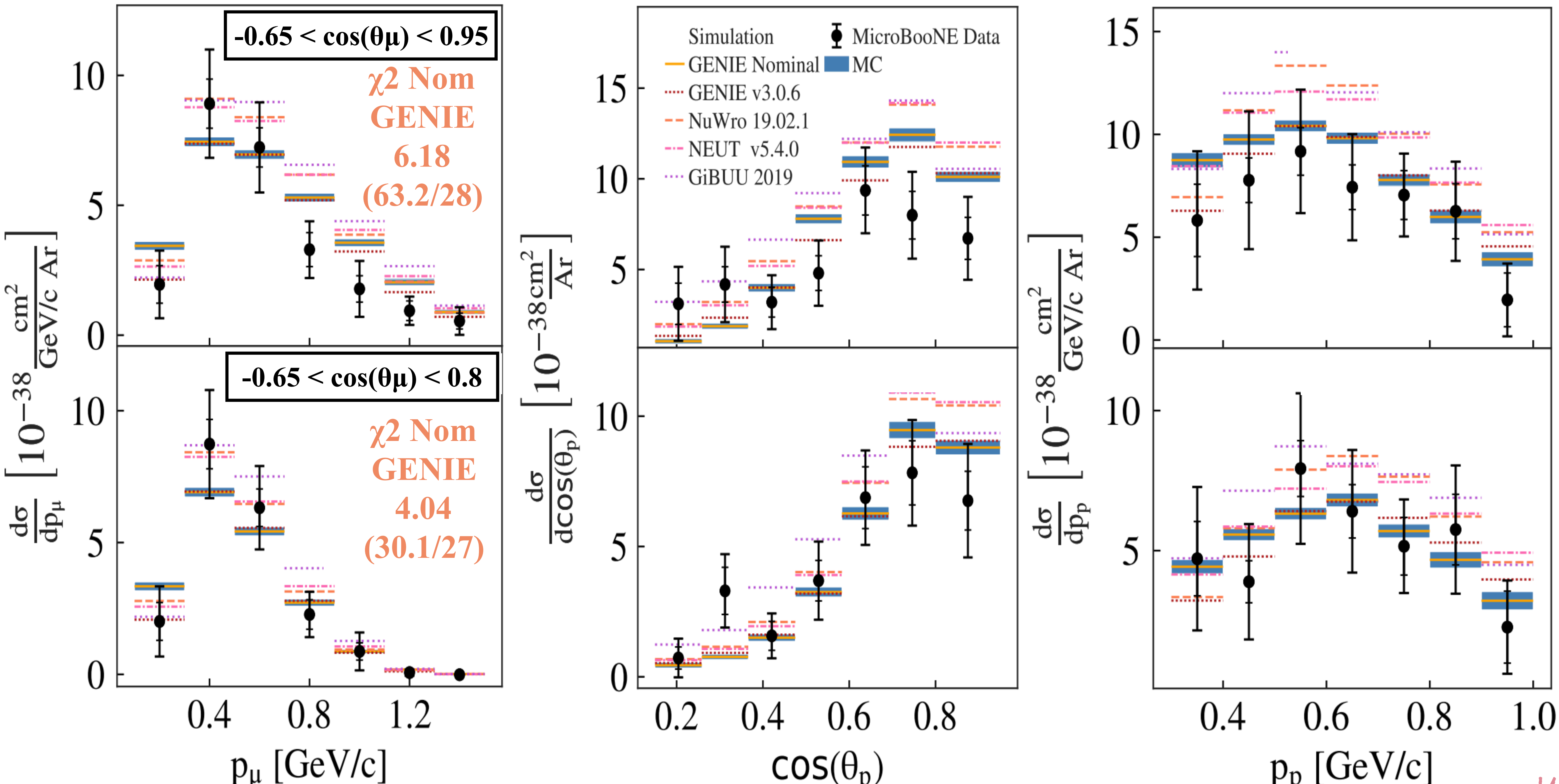
Overall agreement except for forward muon scattering angle



[Phys Rev Lett. 125, 201803 (2020)](https://doi.org/10.1103/PhysRevLett.125.201803)

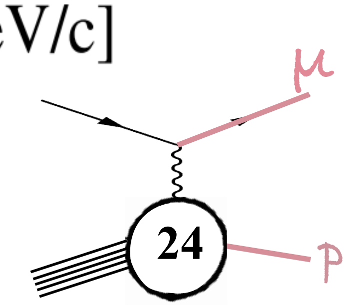


CC0π1P - CCQE-like events



Significantly better agreement when excluding events with forward going muon

Phys Rev Lett. 125, 201803 (2020)



Going more exclusive with protons

CC inclusive

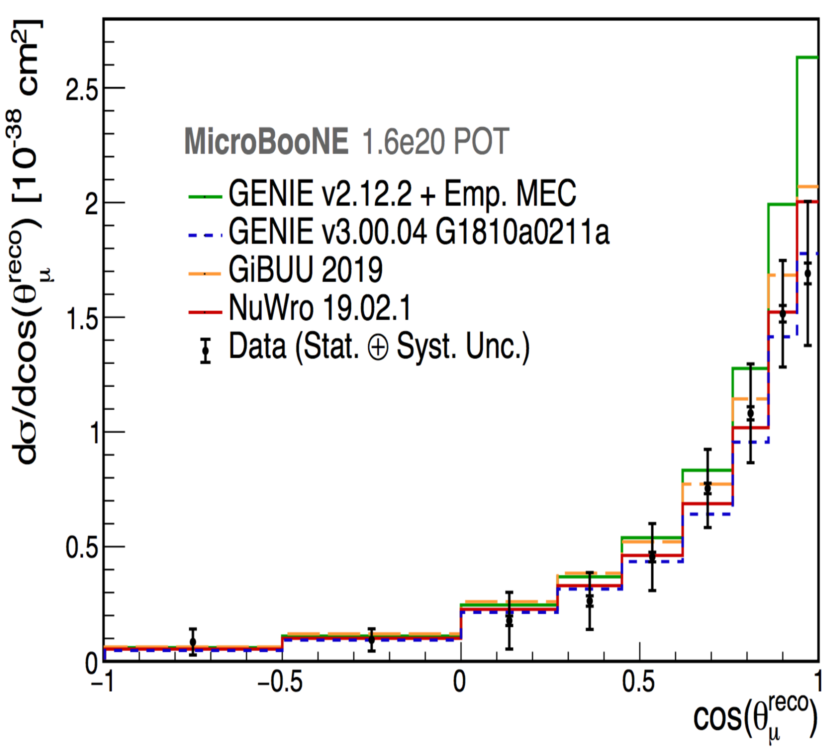
Overall agreement small deficit in forward bin

CCNP

Semi exclusive notice turn over in data

CC1P

Exclusive Biggest deficit in data



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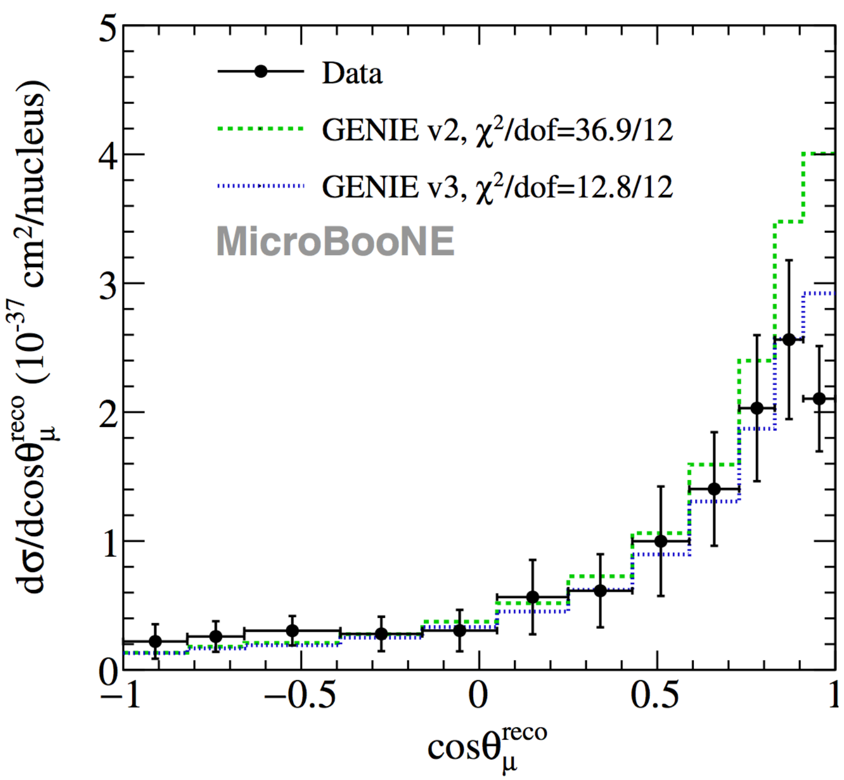

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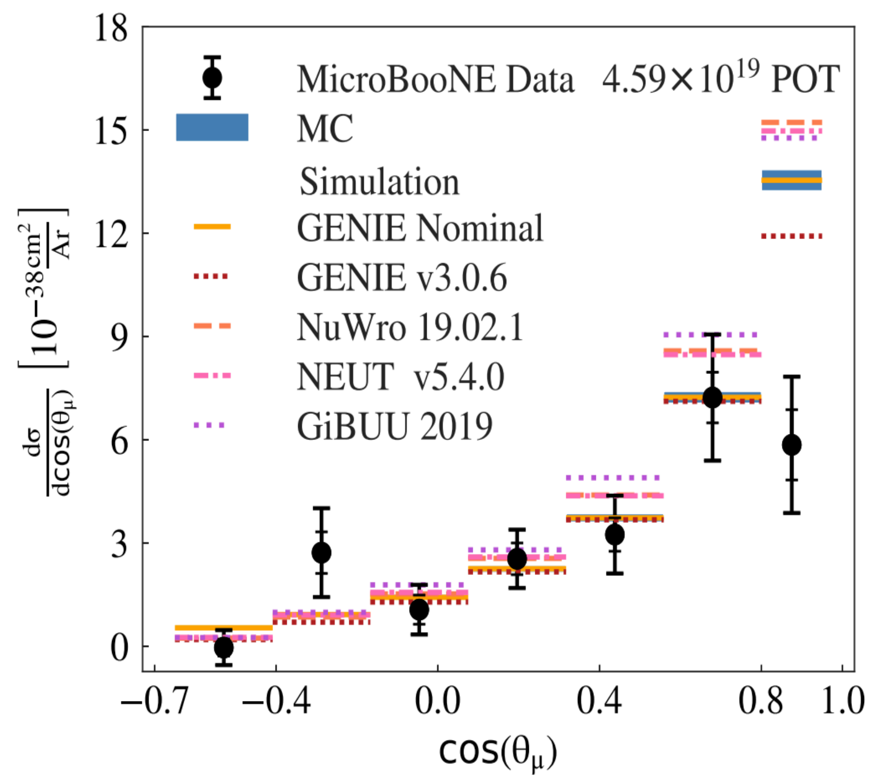
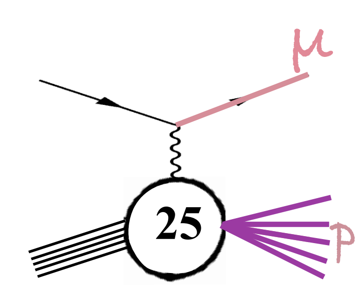


[Phys Rev Lett. 125, 201803 (2020)]

Stay tuned to new results with better detector understanding and differential cross section from off axis NuMI



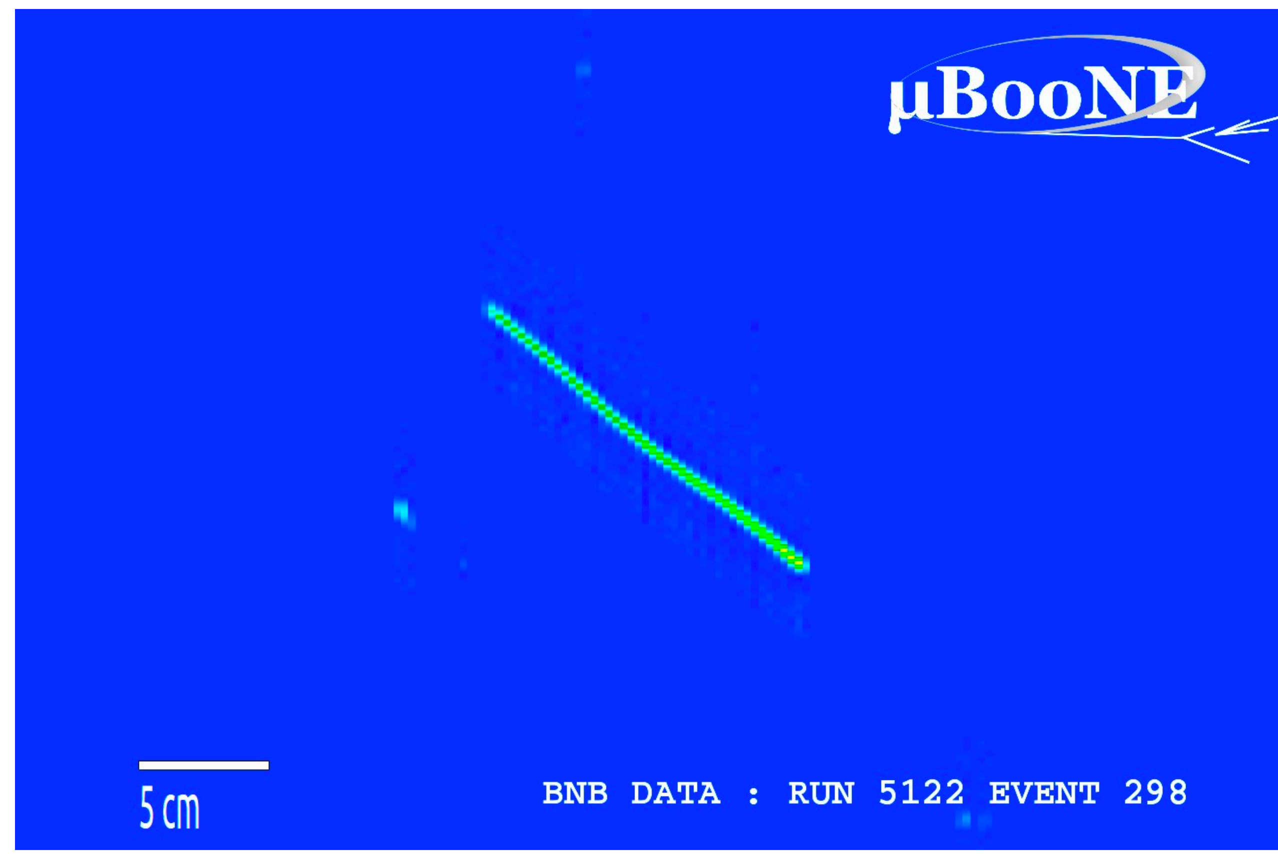
NC1P

Challenging signal: 1 proton track (**1.2 < L < 200 cm**) no additional tracks / showers

Lowest Q^2 NC1P analysis to date (0.1 GeV^2)

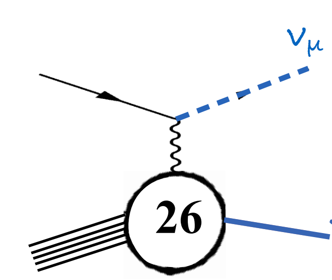
Using BDT based on 13 track variables (exp. dE/dx, length, direction)

Efficiency 29.8% purity 42.1%



Using:

- off beam data background
- Data driven based detector uncertainties
- Comparing to MicroBooNE tune



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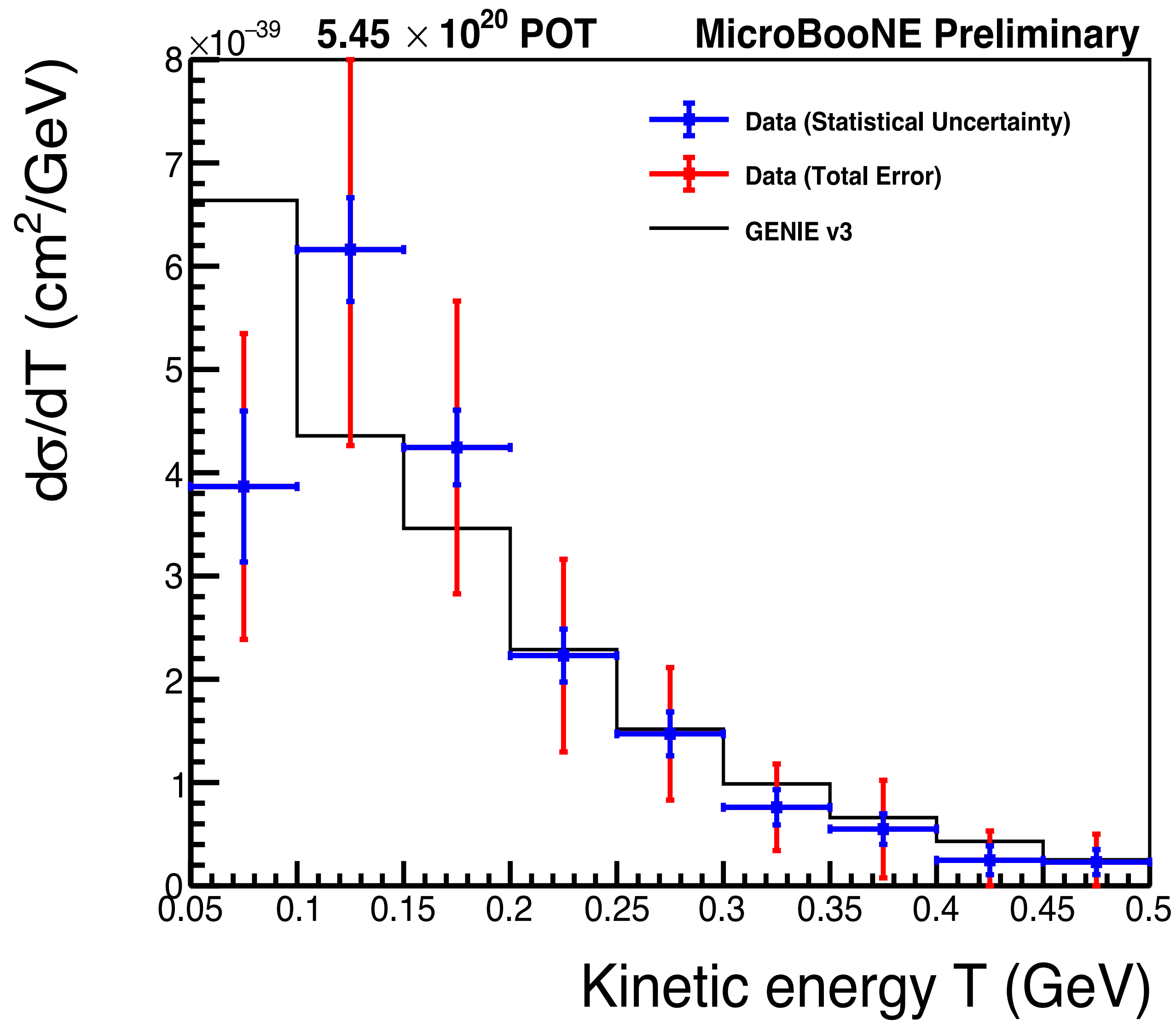

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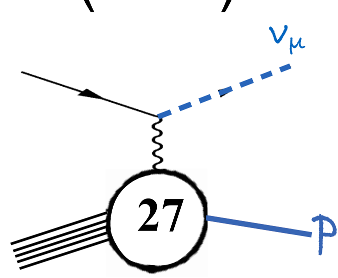


New Directions

This is only the beginning!

MicroBooNE holds 10 times more data than analysed

MicroBooNE is also working on a specific tune GENIE v3.06 based on T2K data.
Initial studies show for the first time a good agreement between data on Argon and a tune based on Carbon!

Given MicroBooNE's achievements in detector understanding and improvements:

Improved signal processing Cosmic Rejection

Flash Matching Data driven detector uncertainties

We excited for the coming future

New Directions

Improved ν_μCC inclusive - see talk by London Cooper-Troendle

Next step with protons:
- Double differential cross sections with 1p
- Extracting differential cross section wrt standard transverse variables
- Studying 2p

Given recalibration of showers, and improved π^0 resolution:
- π, μ kinematics, and studies for CC/NC ratio

First analyses with charged pions
- π, μ kinematic, proton multiplicity
- Coherent π^+

New Directions with Numi

Improved ν_eCC inclusive see talk by Krishan Mistry

ν_eCC0πNp

ν_μ kaon analysis (for better statistics)

and more…

Summary

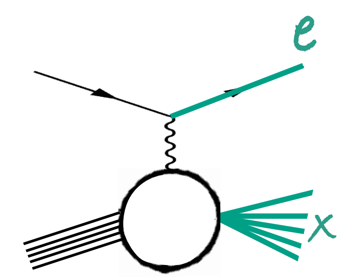
Presenting a series of νAr cross section results from MicroBooNE

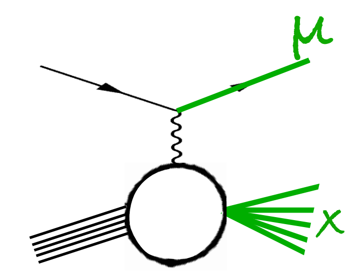
Nice data simulation agreement in inclusive results

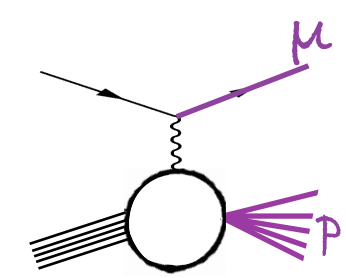
Hints for disagreement in:

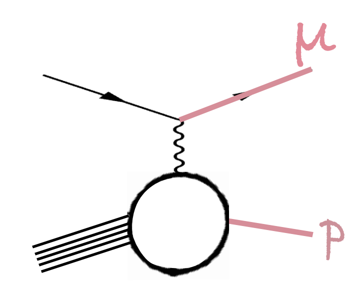
- forward going muons
- low momentum protons

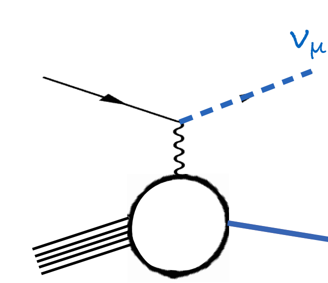
Looking forward to explore new directions

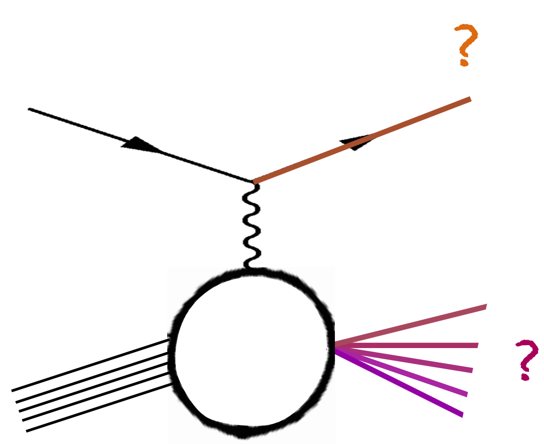












Thank you for your attention

μBooNE Cross section Publications

ν_μ CC inclusive

double differential Phys. Rev. Lett. 123, 131801

single differential MICROBOONE-NOTE-1069-PUB

ν_μ exclusive

particle multiplicity Eur Physical Journal C volume 79

CCQE-like 1μ1p Phys. Rev. Lett. 125, 201803, Eur. Phys. J. C 79

CCNp 1μNp Phys. Rev. D 102, 112013

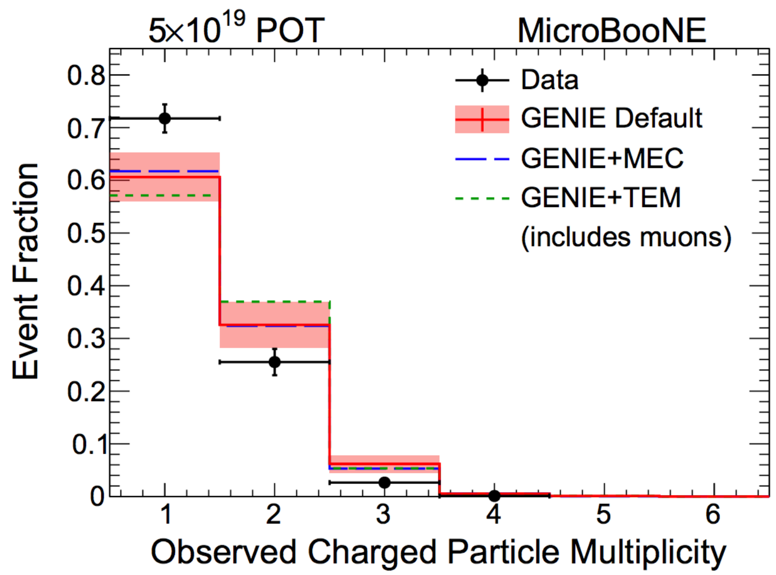
CCπ^0 pion production Phys. Rev. D 99, 091102

kaon production MICROBOONE-NOTE-1071-PUB

NC MICROBOONE-NOTE-1067-PUB

ν_e inclusive arXiv:2101.04228 [hep-ex]

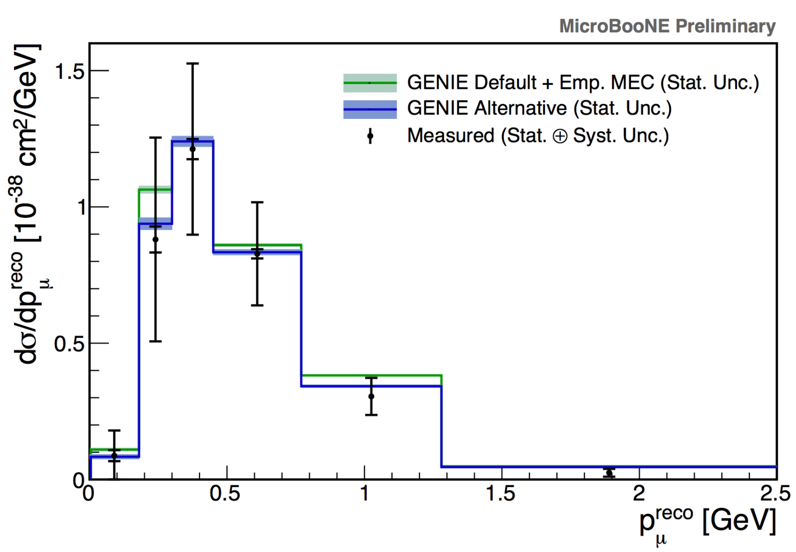
MicroBooNE First Results



Charged particle Multiplicity

First detailed measurement testing GENIE models on Argon nuclei

arXiv:1805.06887 (submitted to PRD)



CC inclusive

good cosmic rejection

model dependencies are negligible

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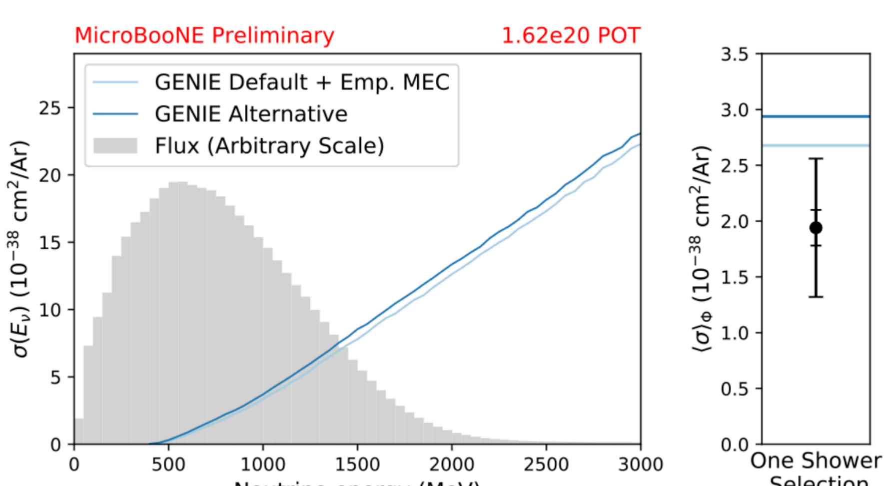


CC π^0

Low statistics, lower cosmic background

Model dependent

MicroBooNE–Note–1032–PUB

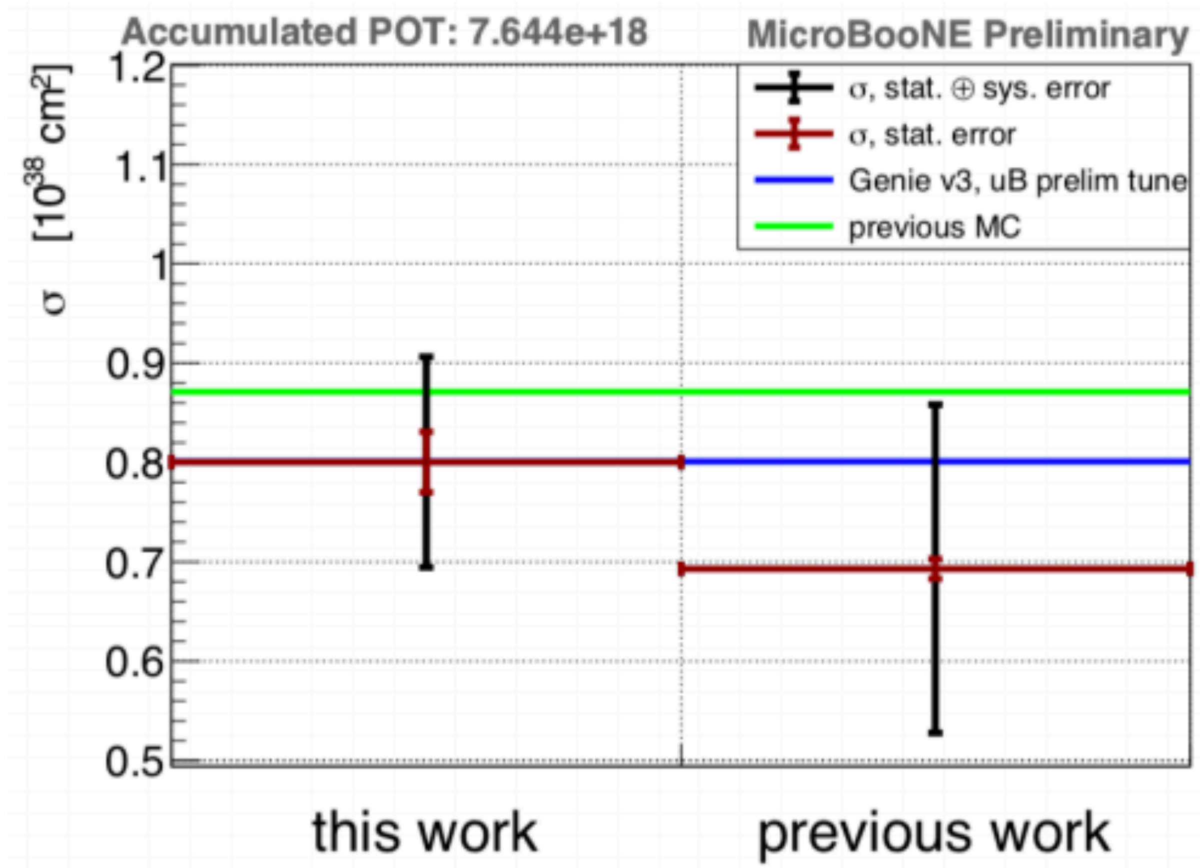
Protons analyses selection

CCQE-like analysis: An event is CC1p0pi “signal” if...	CCNp analysis: An event is CC0pi “signal” if...
True charged-current numu interaction	**True charged-current numu interaction**
Exactly one muon, that passes the following requirments	**Exactly one muon, that passes the following requirements**
$p_\mu > 0.1$ GeV/c	
$p_\mu < 1.5$ GeV/c	-
$-0.65 < \cos\theta_\mu < 0.95$	-
Exactly one proton, that passes the following requirements	**At least one proton, that passes the following requirements**
$p_p > 0.3$ GeV/c	
$p_p < 1.0$ GeV/c	$p_p < 1.2$ GeV/c
$\cos\theta_p > 0.15$	-
Non-collinearity: $\lvert\Delta\theta_{\mu p} - 90°\rvert < 55°$	-
Coplanarity: $\lvert\Delta\phi_{\mu p} - 180°\rvert < 35°$	-
Small missing transverse momentum: $p_T = \lvert p_T^\mu + p_T^p\rvert < 350$ MeV/c	-
Any number of protons with $p_p < 300$ MeV/c	**Any number of protons**
No charged pions with momentum > 70 MeV/c	**No charged pions with any momentum**
Any number of neutrons	
Any number of neutral pions	**No neutral pions**
Any number of electrons or photons	

NC models

Model	Parameter	Description
Nuclear model	LFG	Local Fermi Gas model
Final State Interaction Model	hA2018	Hadron-nucleus interaction model
NC Elastic model	$M_A = 0.96$ GeV	Axial mass in Ahrens model
	$\eta = 0.12$	Strange quark contribution in Ahrens model
NC Resonance model	$M_A = 1.120$ GeV	Axial mass of Berger-Sehgal model
	$M_V = 0.840$ GeV	Vector mass of Berger-Sehgal model
NC Meson Exchange Current model	-	Empirical Dytman model

Improved systematics CCν_μ Inclusive



Source	Uncertainty	
	Previous Analysis	This Analysis
Detector response	16.2%	3.3%
Cross section	3.9%	2.7%
Flux	12.4%	10.5%
Dirt background	10.9%	3.3%
Cosmic ray background	4.2%	N/A
POT counting	2.0%	2.0%
CRT	N/A	1.7%
Total Sys. Error	23.8%	12.1%
Statistics	1.4%	3.8%
Total (Quadratic Sum)	**23.8%**	**12.7%**

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