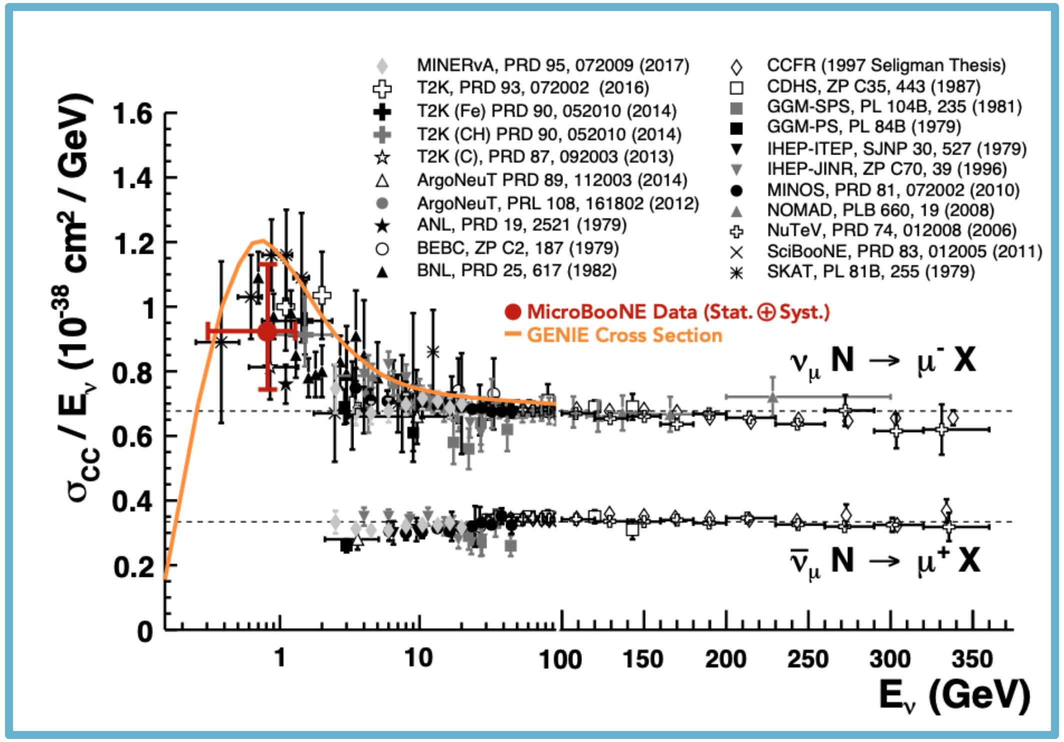
NEUTRINO-INDUCED PROTON KNOCKOUT IN MICROBOONE

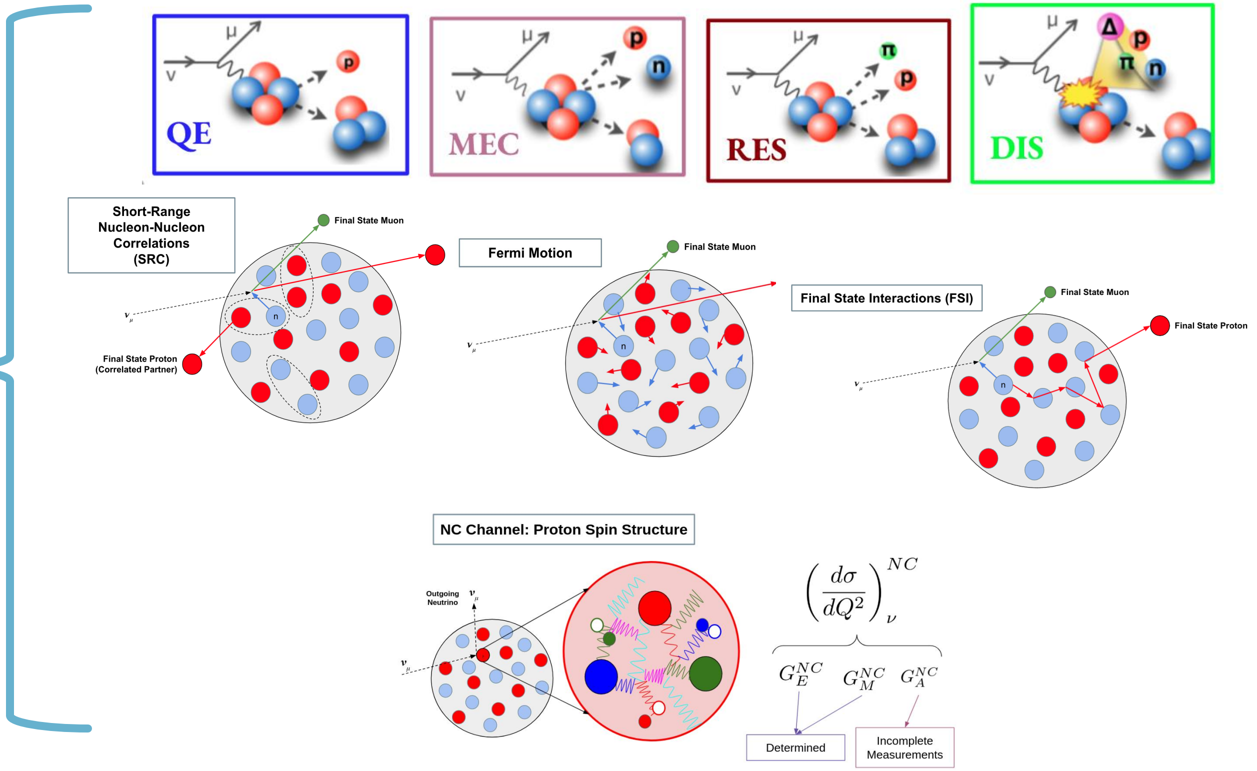
SAMANTHA SWORD-FEHLBERG
ON BEHALF OF MICROBOONE

NUFACT 2021

SEPTEMBER 8TH, 2021



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

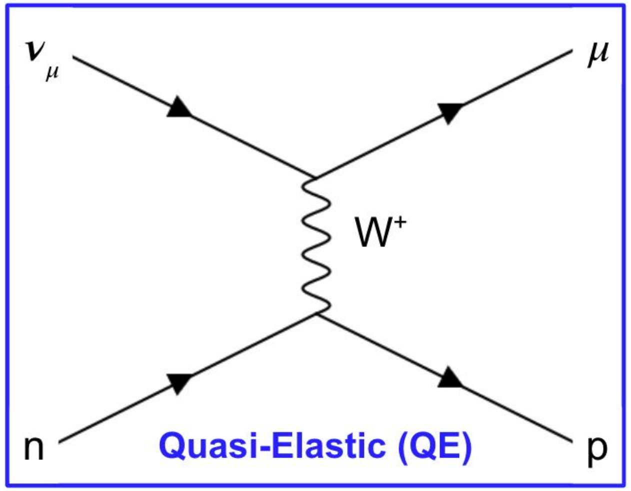


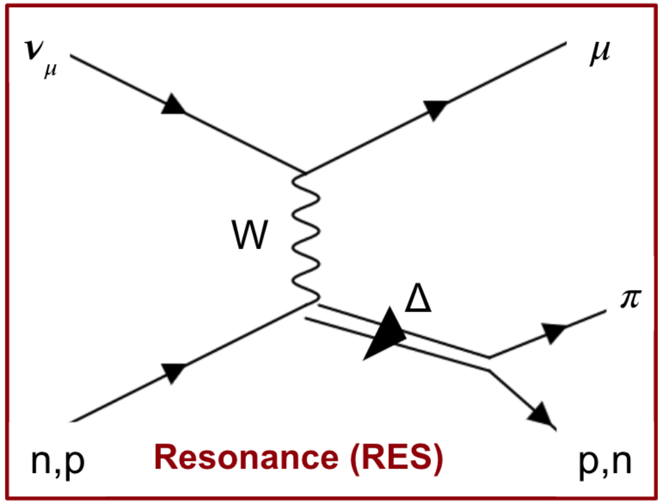
THE PHYSICS OF CROSS-SECTIONS

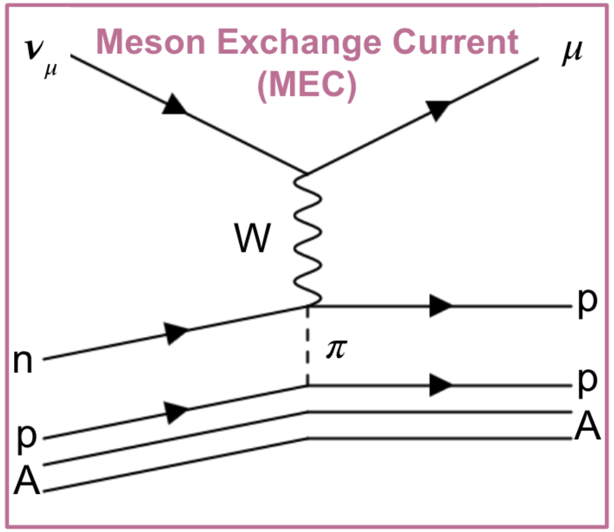
- Neutrino Cross-Sections can probe physics related to:
  - Neutrino Interaction Channels
  - Nuclear Properties of the Target Nucleus
  - Properties of Individual Nucleons

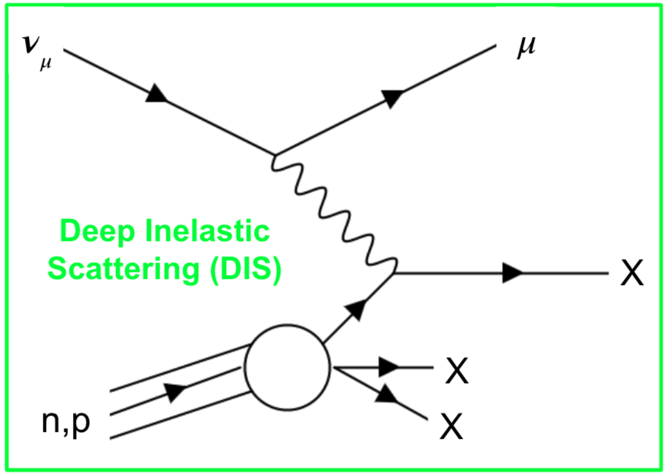
HOW CAN WE PROBE ALL THIS PHYSICS?

- All of this physics can be probed by looking at mesonless final states with any number of protons
- Selecting a specific number of protons allows us to probe specific neutrino interactions and nuclear physics
  - N Protons:
    - Probe all the neutrino interaction channels



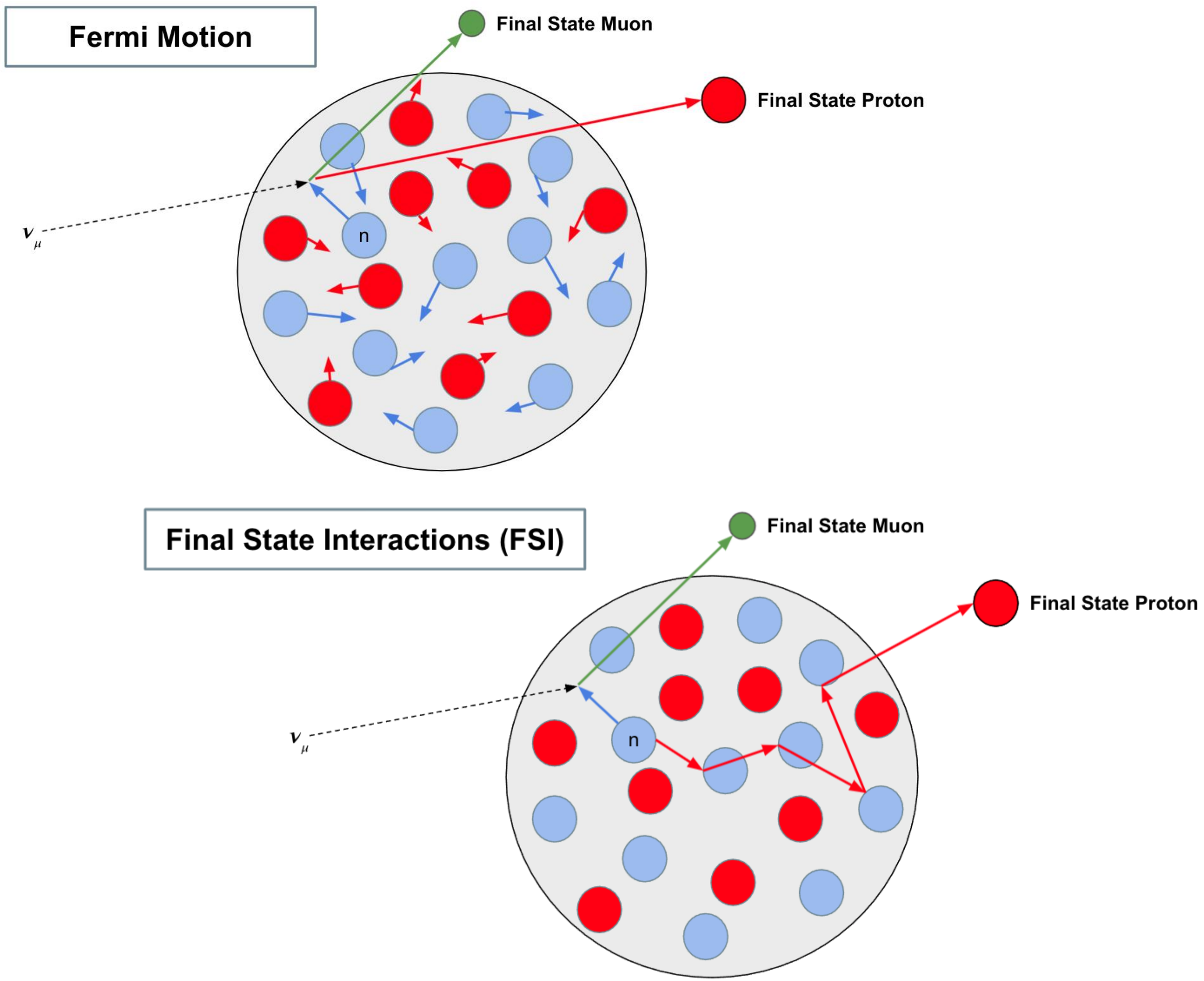






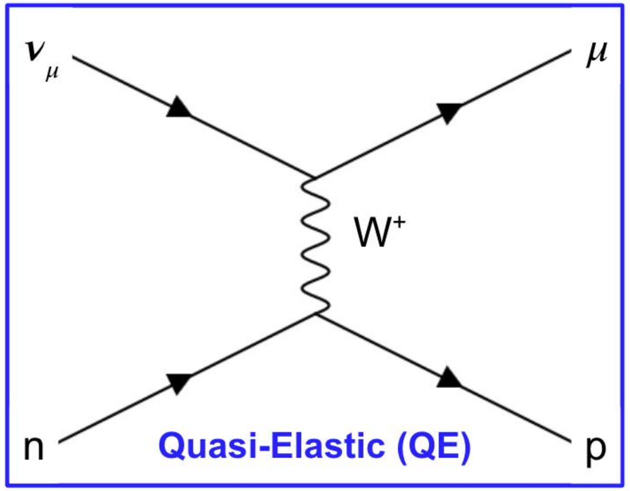
HOW CAN WE PROBE ALL THIS PHYSICS?

- All of this physics can be probed by looking at mesonless final states with any number of protons
- Selecting a specific number of protons allows us to probe specific neutrino interactions and nuclear physics
  - N Protons:
    - Probe Fermi Motion
    - Probe FSIs



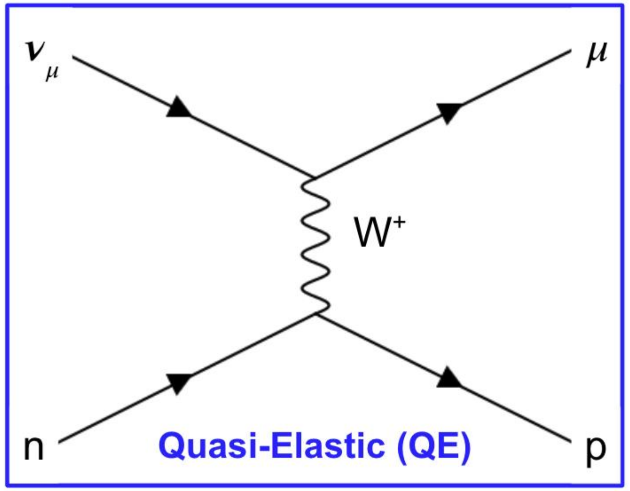
HOW CAN WE PROBE ALL THIS PHYSICS?

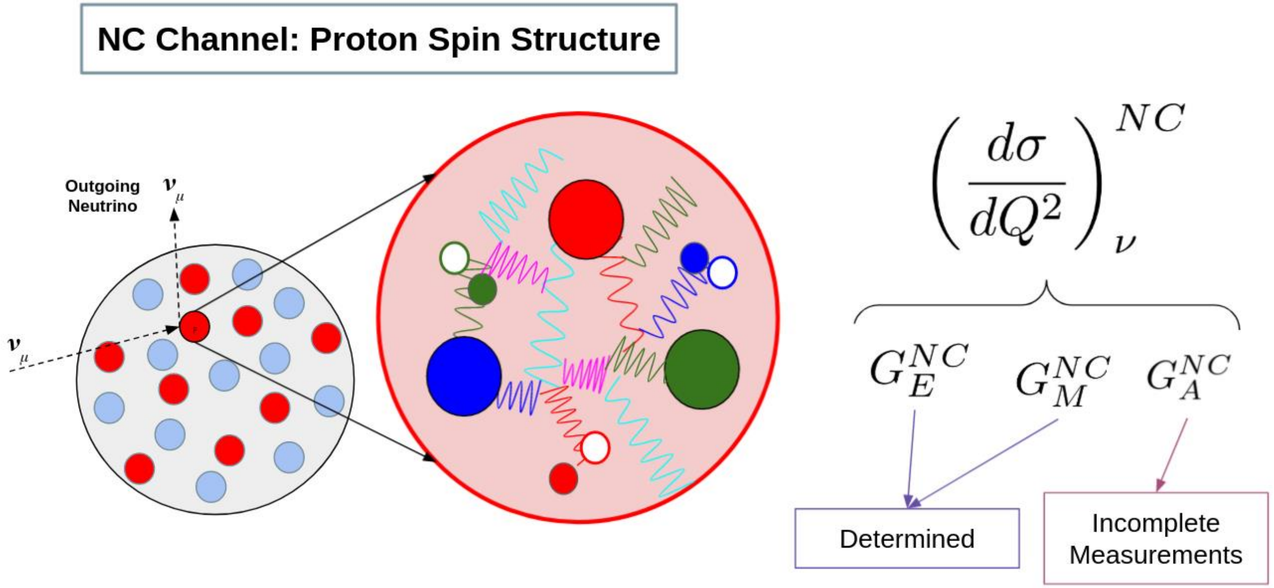
- All of this physics can be probed by looking at mesonless final states with any number of protons
  - 1 Proton:
    - QE Channel



HOW CAN WE PROBE ALL THIS PHYSICS?

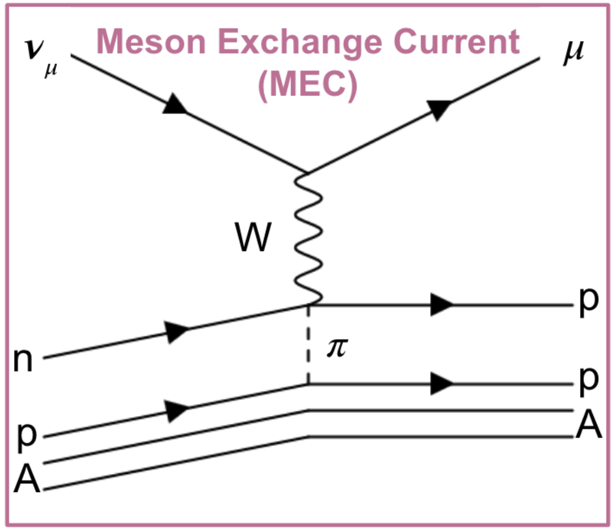
- All of this physics can be probed by looking at mesonless final states with any number of protons
  - 1 Proton:
    - QE Channel
    - Single Proton Spin Structure





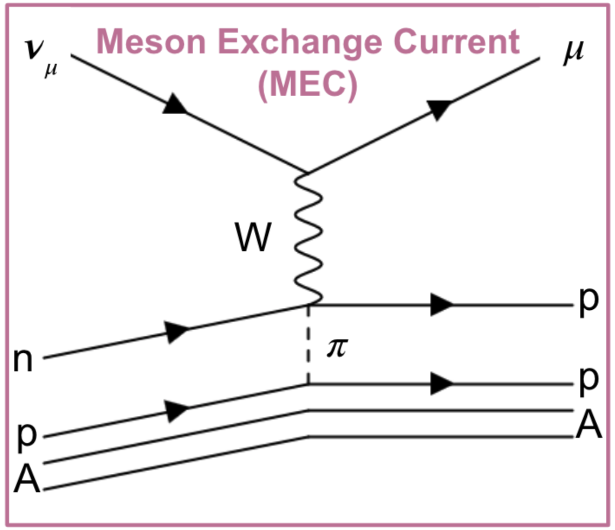
NEUTRINO INTERACTIONS + NUCLEAR EFFECTS

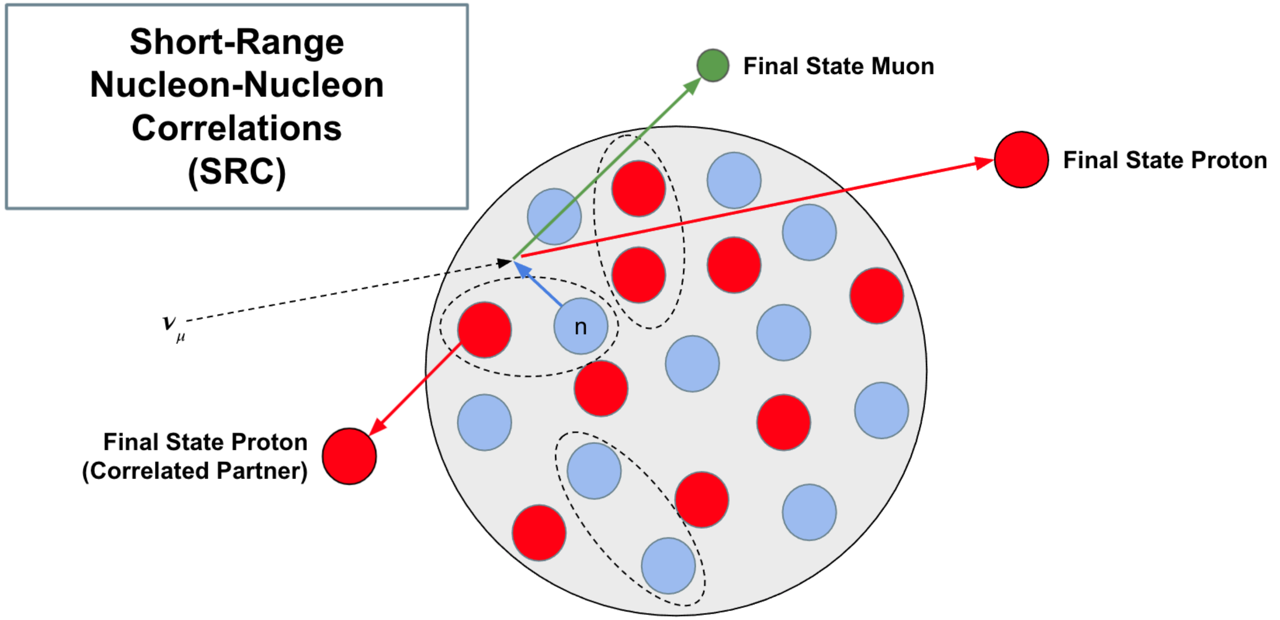
- All of this physics can be probed by looking at mesonless final states with any number of protons
  - 2 Protons:
    - MEC Channel



NEUTRINO INTERACTIONS + NUCLEAR EFFECTS

- All of this physics can be probed by looking at mesonless final states with any number of protons
  - 2 Protons:
    - MEC Channel
    - Short-Range Nucleon-Nucleon Correlations (SRCs)

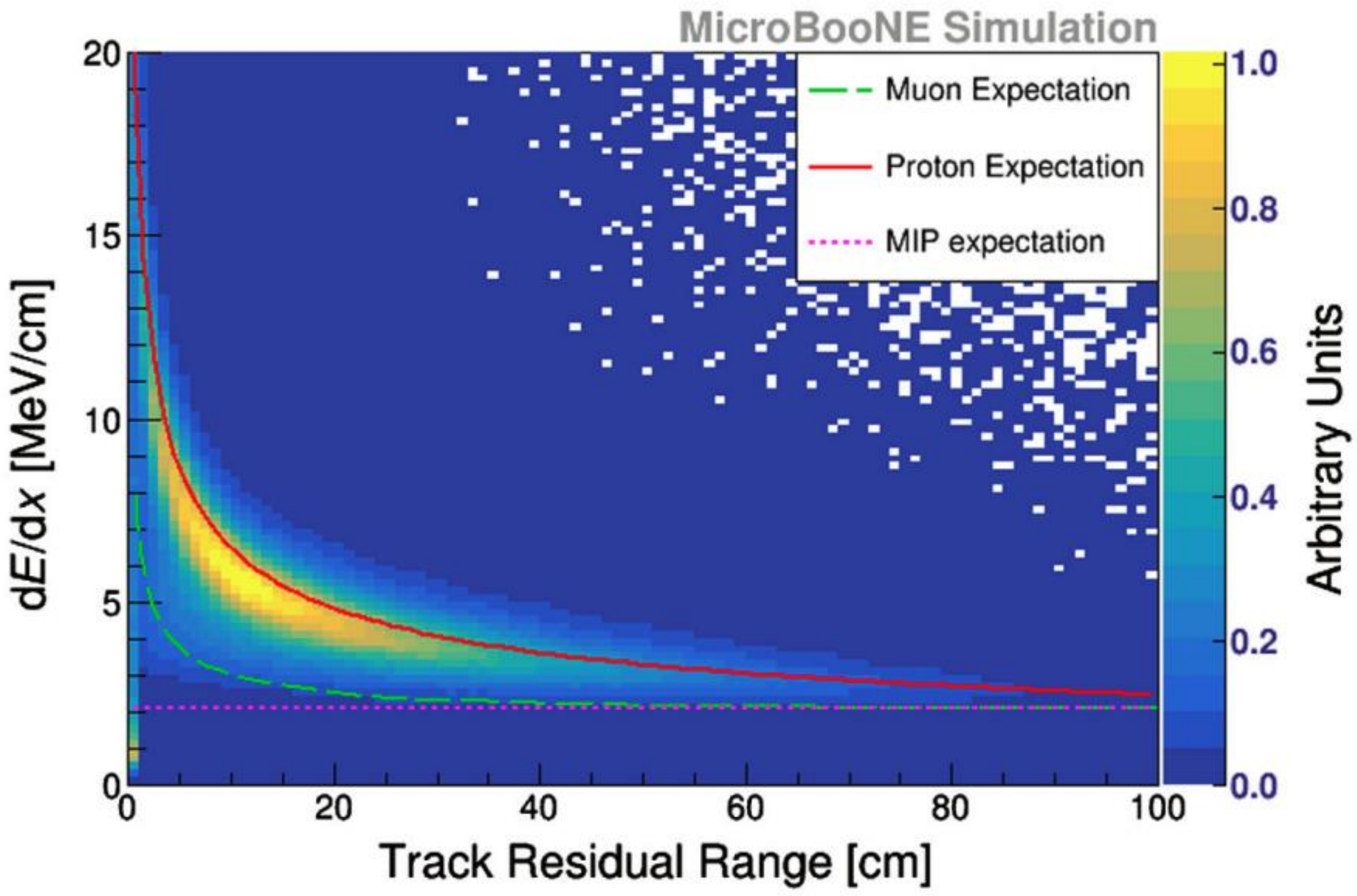




HOW IS MICROBOONE POISED TO DO THIS?

- LArTPCs are well poised to study protons because of their great calorimetric reconstruction

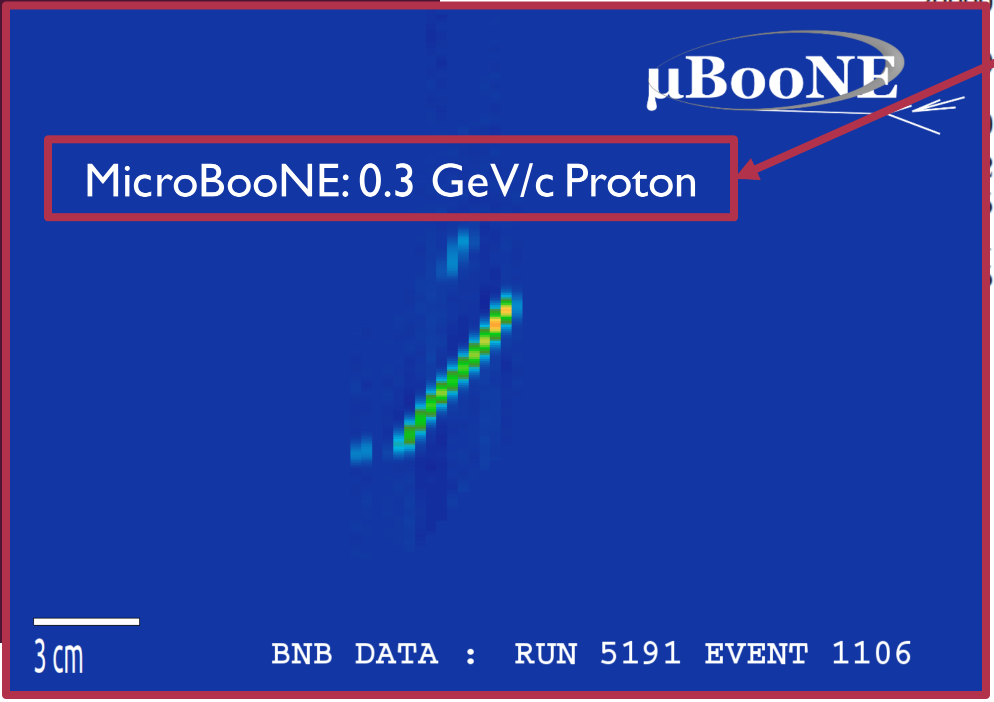
MICRBOONE-NOTE-1056-PUB

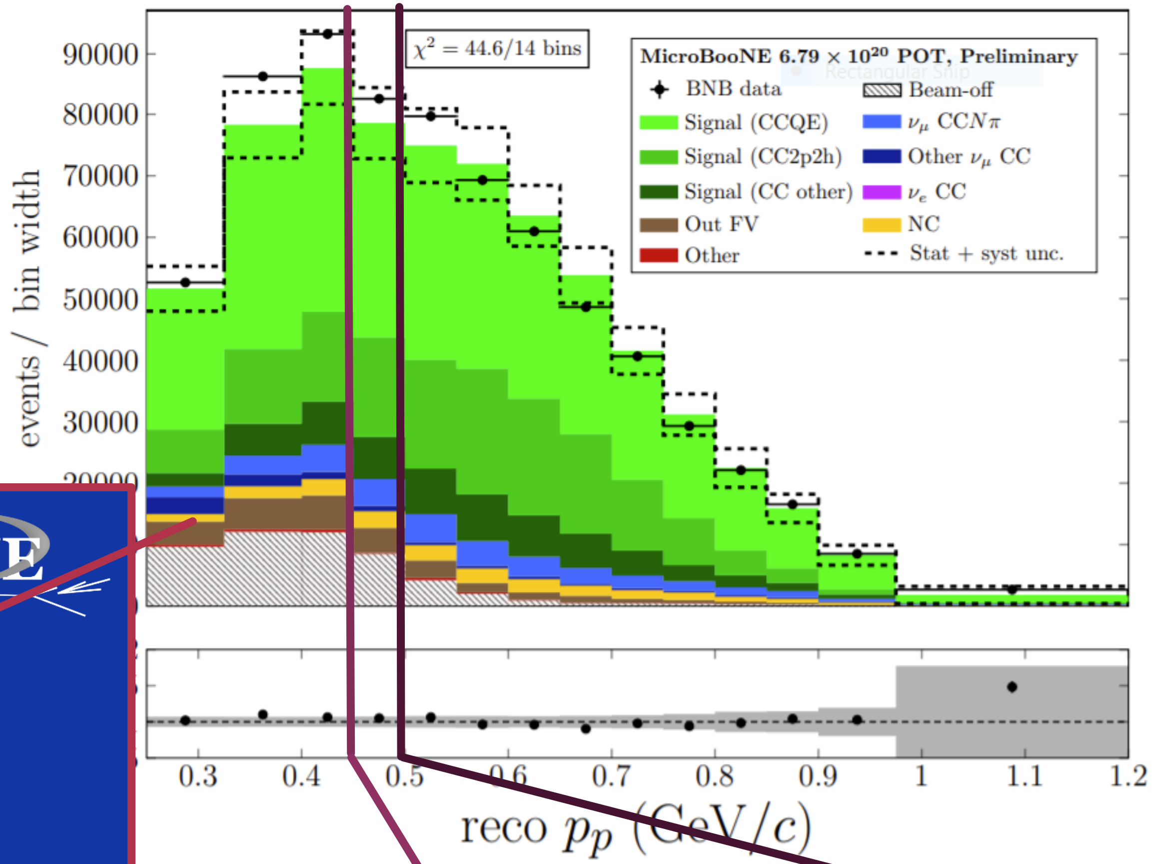


HOW IS MICROBOONE POISED TO DO THIS?

- LArTPC technology pushes the envelope of proton momentum reconstruction to record lows

MICROBOONE-NOTE-1099-PUB





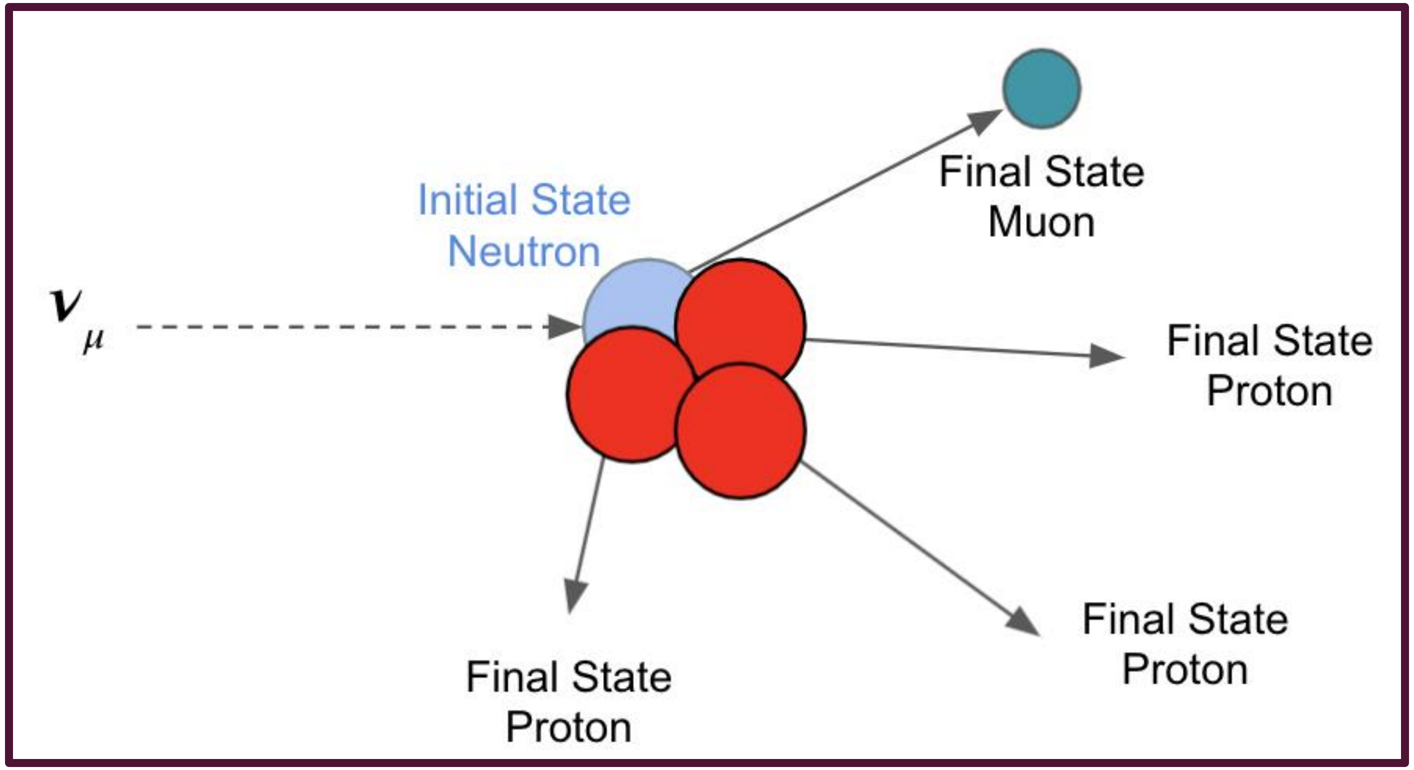
MINERvA: 0.45 GeV/c
Phys. Rev. D 99, 012004

T2K: 0.5 GeV/c
Phys. Rev. D 98, 032003

TODAY'S TALK

Provide a **BRIEF** Introduction to the Proton Knockout Analyses of MicroBooNE:

- **Charged-Current N Proton (CCNP):** MICROBOONE-NOTE-1099-PUB
- **Charged-Current Quasi-Elastic Like (CCQE-Like):** Phys. Rev. Lett. 125, 201803 (2020)
- **Charged-Current 2 Proton (CC2p):** MICROBOONE-NOTE-1096-PUB
- **Neutral-Current Elastic (NCE):** MICROBOONE-NOTE-1101-PUB



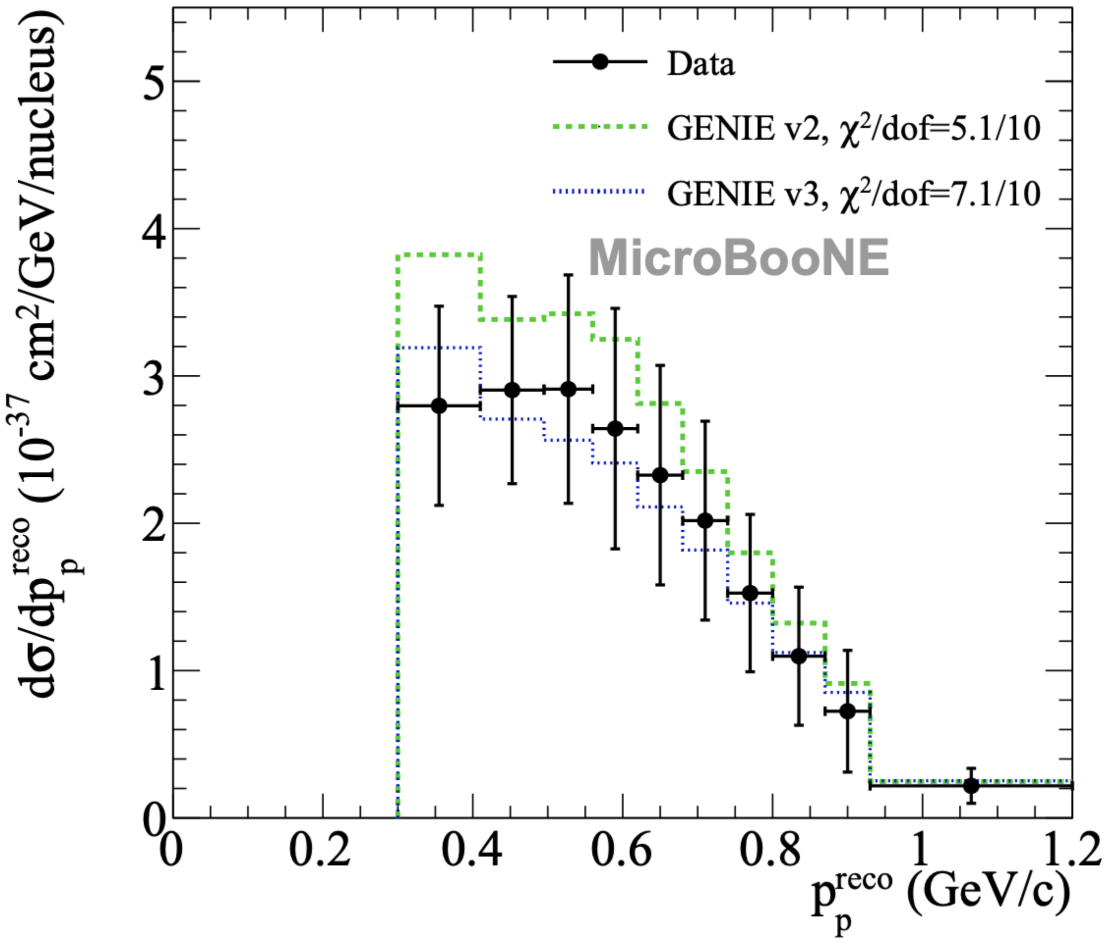
CHARGED-CURRENT N PROTONS (CCNP)

MICROBOONE-NOTE-1099-PUB

CCNP

MICROBOONE-NOTE-1099-PUB

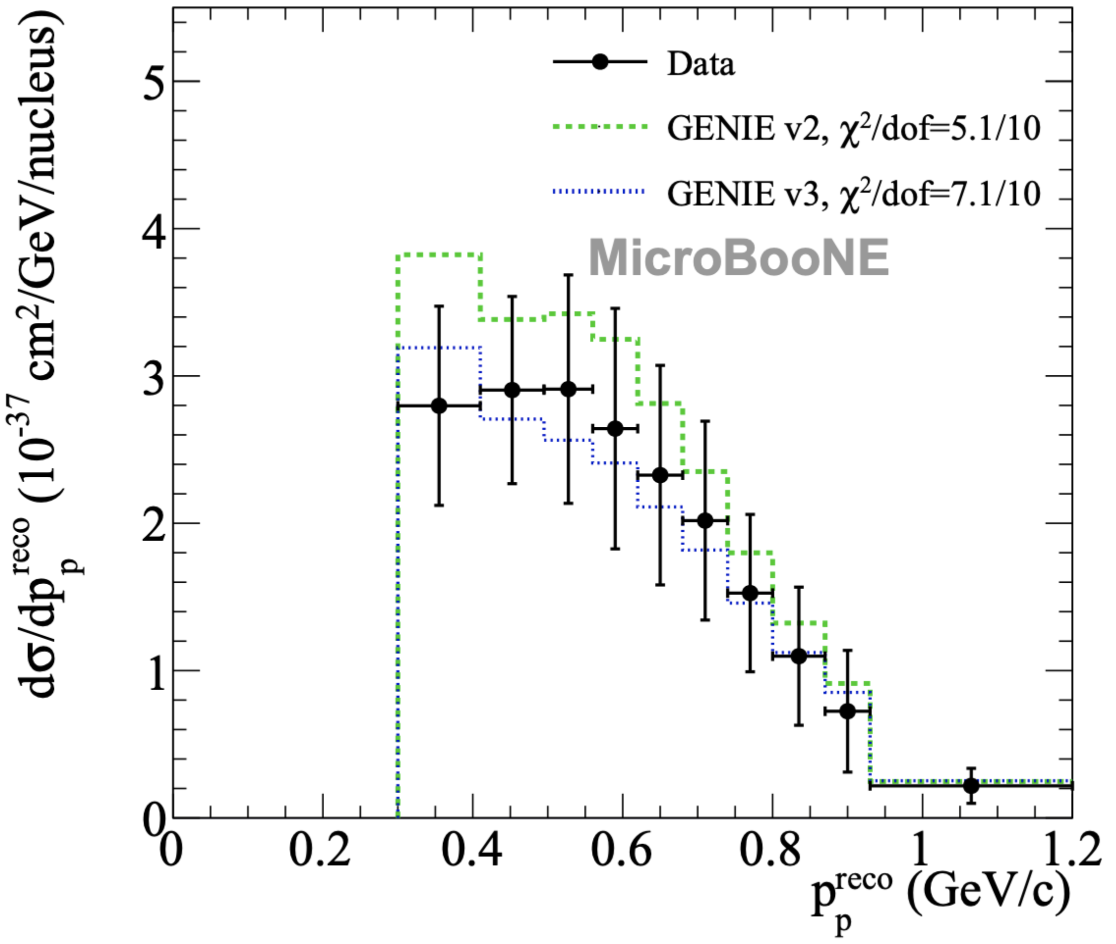
- CCNP is sensitive to all the neutrino interaction processes and variety of nuclear processes
- MicroBooNE has an existing CCNP measurement of proton and muon kinematics: Phys. Rev. D102, 112013 (2020)



CCNP

MICROBOONE-NOTE-1099-PUB

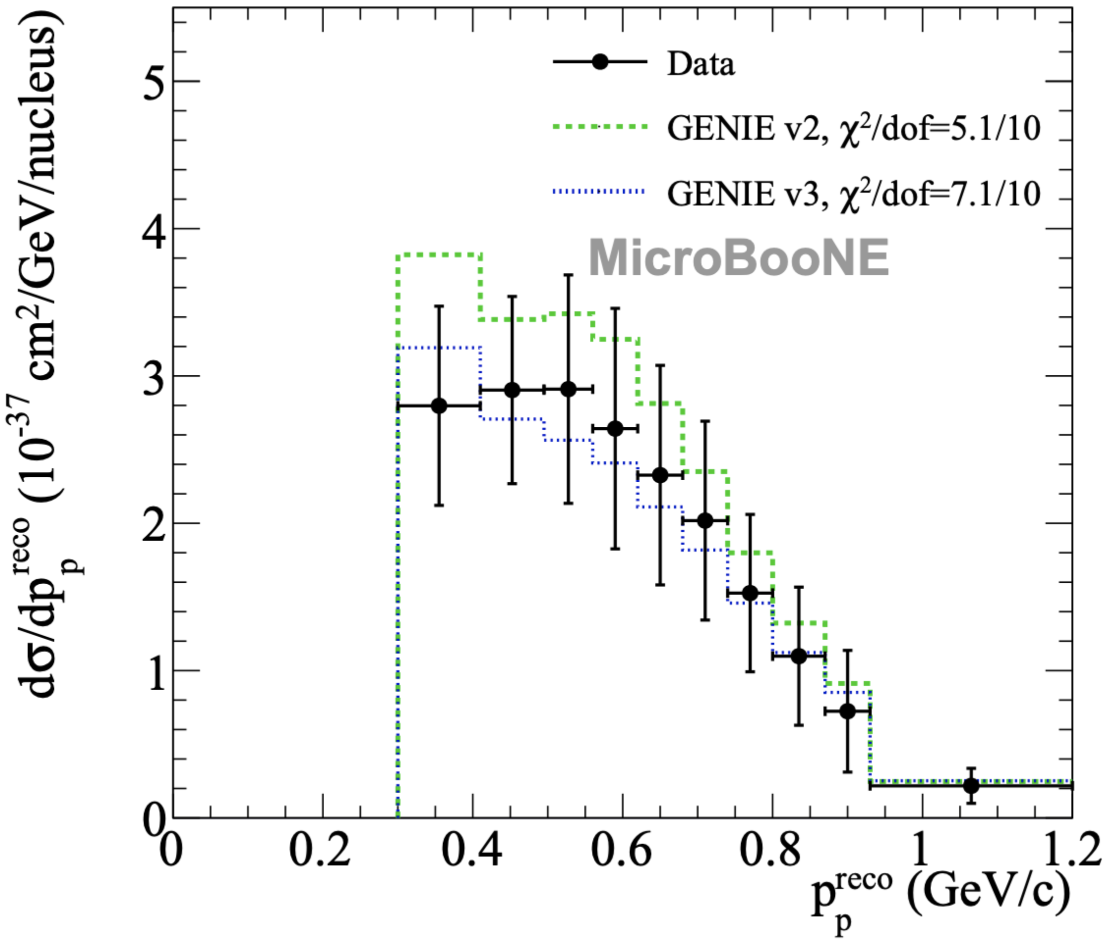
- MicroBooNE has made significant updates since previous measurement:
  - MC simulation
  - Event reconstruction algorithms
  - Updated procedure for calculating systematic uncertainties
- ~4.2x more POT open to be utilized



CCNP

MICROBOONE-NOTE-1099-PUB

- Goal of the new analysis is to extract the double differential cross-section as a function of proton and muon kinematics utilizing all of the new updates and more statistics



CCNP: SIGNAL DEFINITION

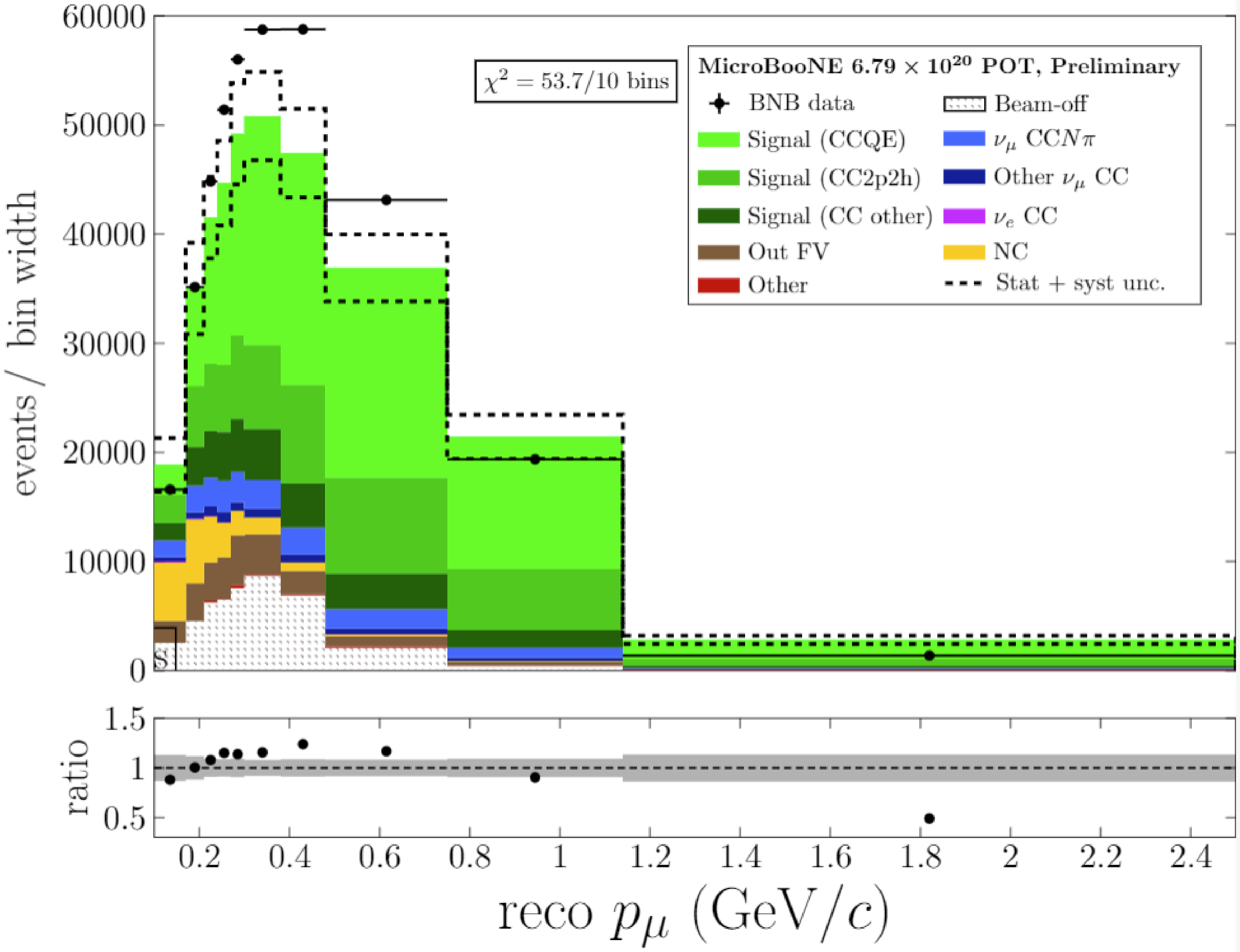
MICROBOONE-NOTE-1099-PUB

- 1 Muon
  - 0.1 GeV/c < P_μ
- N Proton
  - 0.25 < P_p < 1.2 GeV/c
- 0 (anti) mesons

CCNP: EVENT SELECTION

MICROBOONE-NOTE-1099-PUB

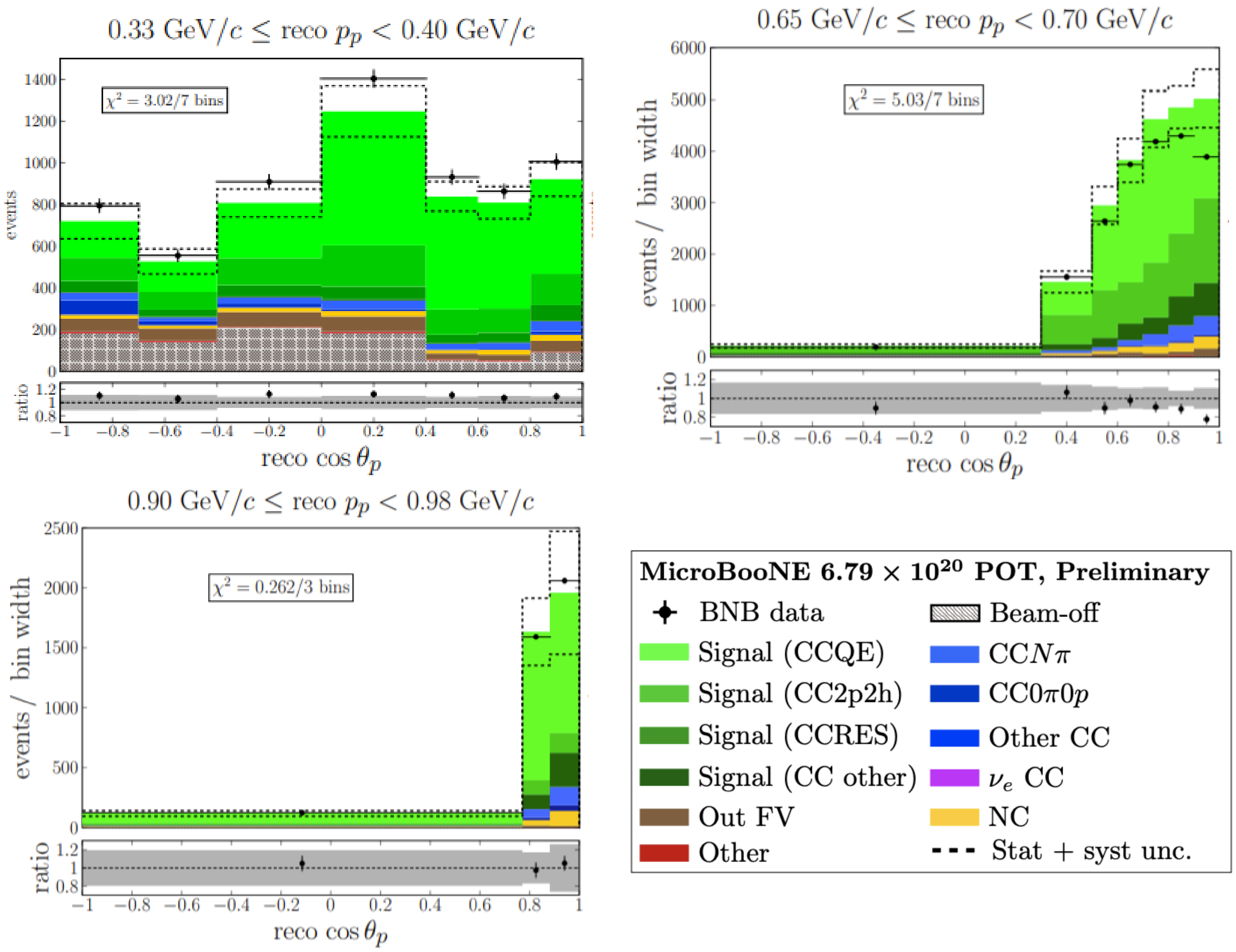
- 6.79×10^{20} POT
  - From MicroBooNE's first 3 years of running
- Efficiency: 36.6%
- Purity: 77.4%



CCNP: COS(θ_P)

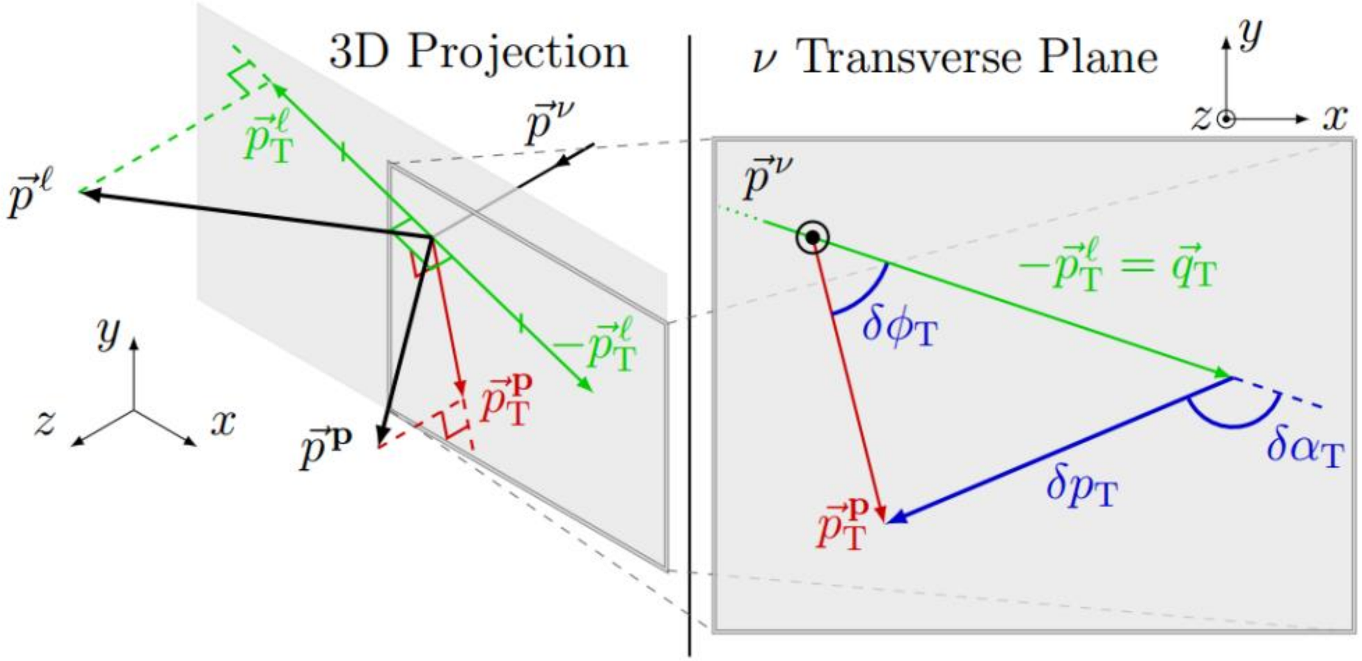
MICROBOONE-NOTE-1099-PUB

- Can measure the momentum and angle with respect to the beam direction of the lead proton candidate
- Plots show reconstructed proton angle in different bins of reconstructed proton momentum
  - See tension between data and MicroBooNE MC predictions



CCNP: FUTURE WORK
MICROBOONE-NOTE-1099-PUB

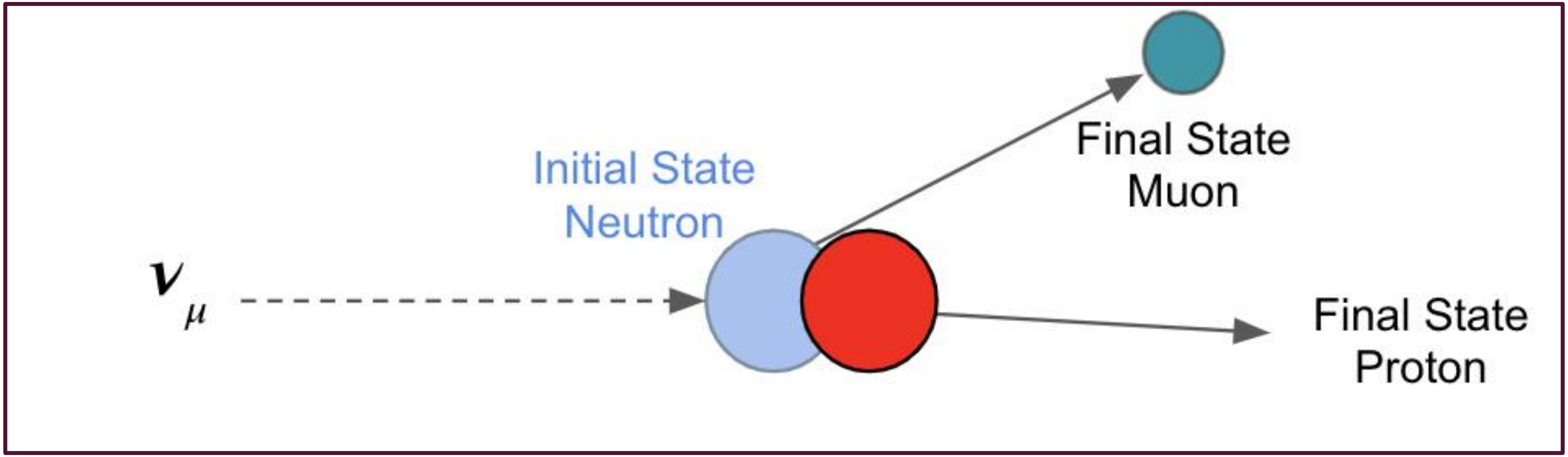
- Extraction of the double-differential cross-sections to benchmark theoretical calculations
- Investigation of Single Transverse Variables (STVs) to characterize various nuclear effects Phys. Rev. D **103**, 112009



$$\delta p_T = |\vec{p_T}^{\,l} + \vec{p_T}^{\,p}|$$

$$\delta \alpha_T = \arccos\left(\frac{-\vec{p_T}^{\,l} \cdot \delta\vec{p_T}}{p_T^l \cdot \delta p_T}\right)$$

$$\delta \phi_T = \arccos\left(\frac{-\vec{p_T}^{\,l} \cdot \vec{p_T}^{\,p}}{p_T^l \cdot p_T^p}\right)$$



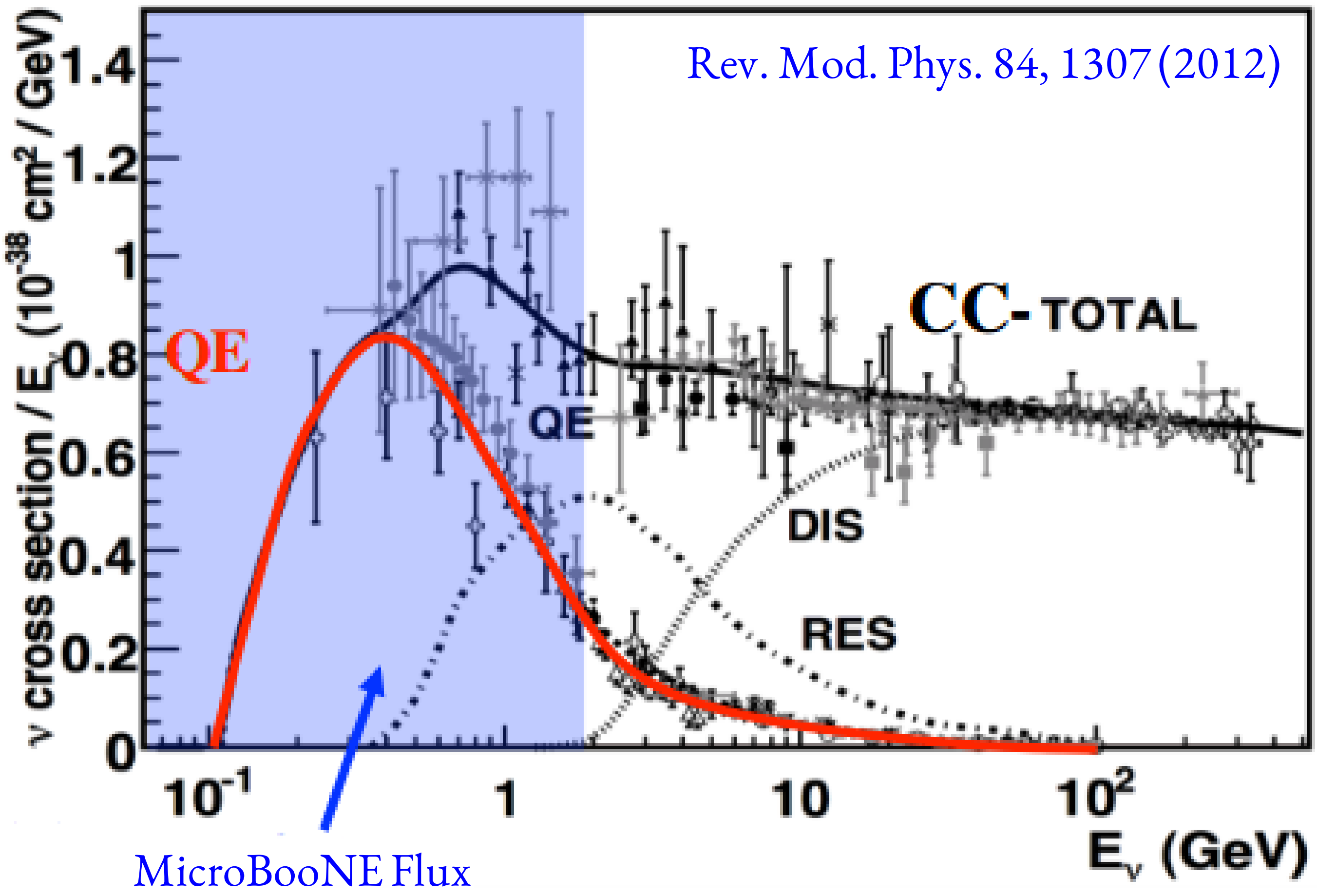
CHARGED-CURRENT QUASI-ELASTIC LIKE (CCQE-LIKE)

PHYS. REV. LETT. 125, 201803 (2020)

CCQE-LIKE

PHYS. REV. LETT. 125, 201803 (2020)

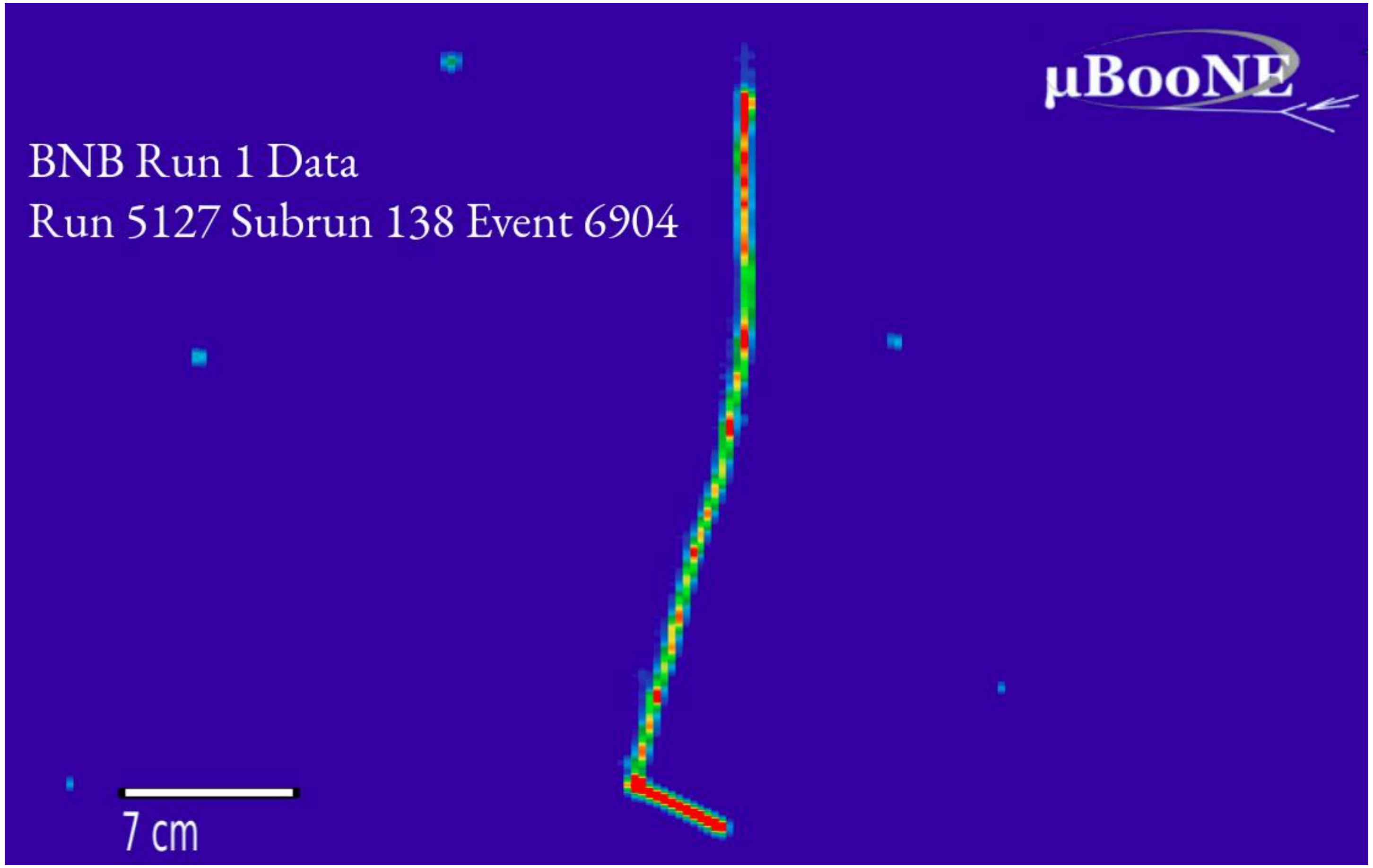
- The dominant topology in the MicroBooNE data stream
- Goal of this analysis is to extract the differential cross-section as function of muon and proton kinematics



CCQE-LIKE: SIGNAL DEFINITION

PHYS. REV. LETT. 125, 201803 (2020)

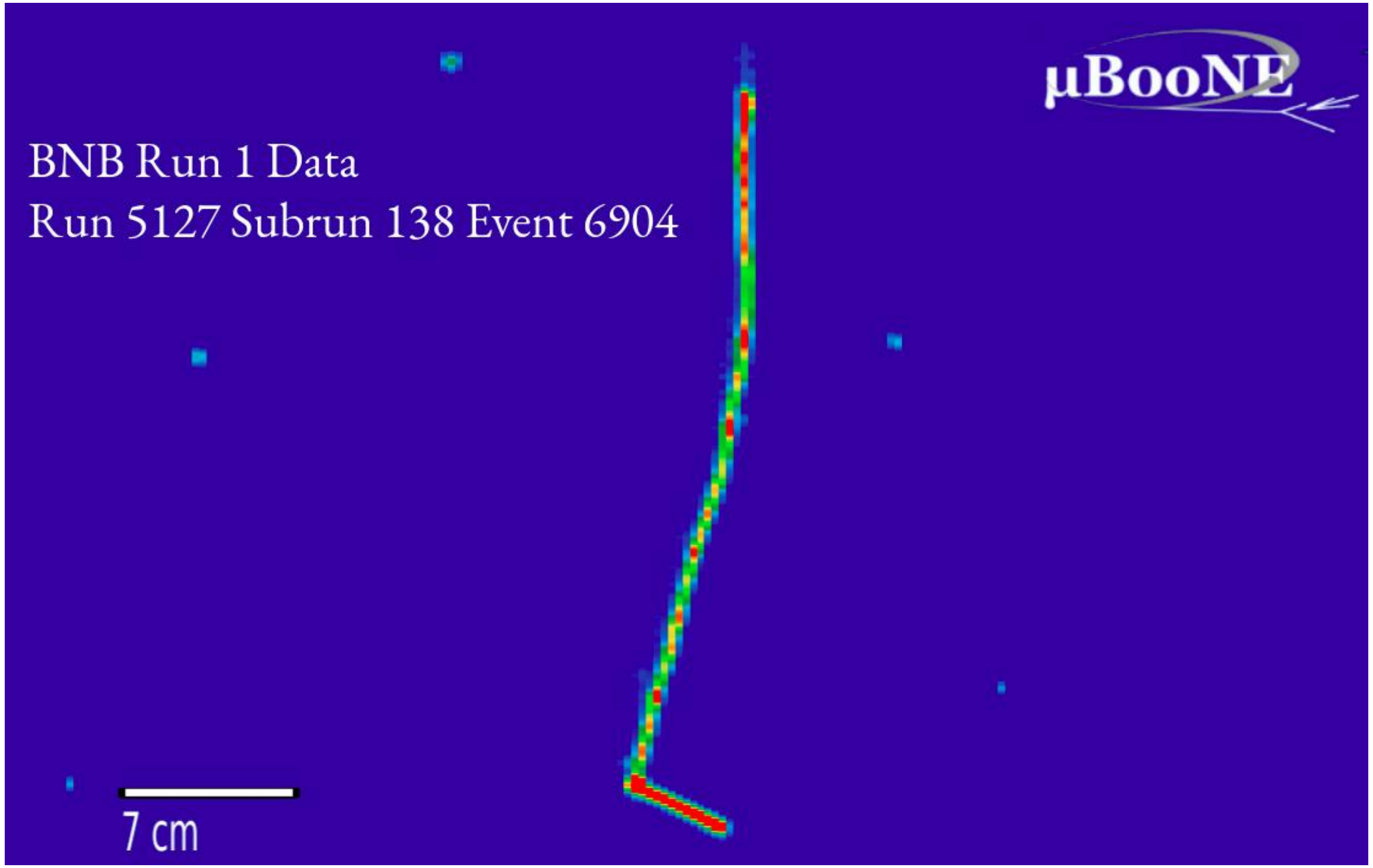
- 1 Muon
  - 0.1 GeV/c $< P_\mu$
- 1 Proton
  - 0.3 GeV/c $< P_p$
- $0\ \pi^\pm$
  - 0.07 GeV/c $< P_{\pi\pm}$



CCQE-LIKE: ENHANCEMENT CUTS

PHYS. REV. LETT. 125, 201803 (2020)

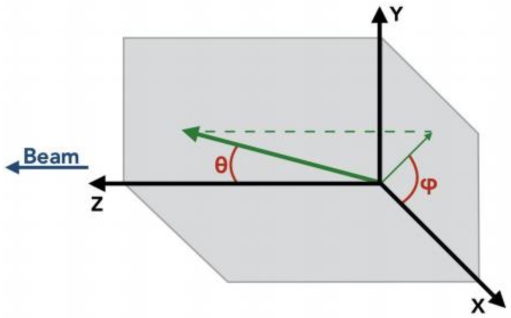
- Non-collinearity requirement
  - $|\Delta\theta_{\mu,p} - 90°| < 55°$
- Muon and proton must be coplanar relative to beam axis
  - $|\Delta\phi_{\mu,p} - 180°| < 35°$
- Small missing transverse momentum:
  - $P_T = |P_T^{\mu} + P_T^{p}| < 0.35$ GeV/c

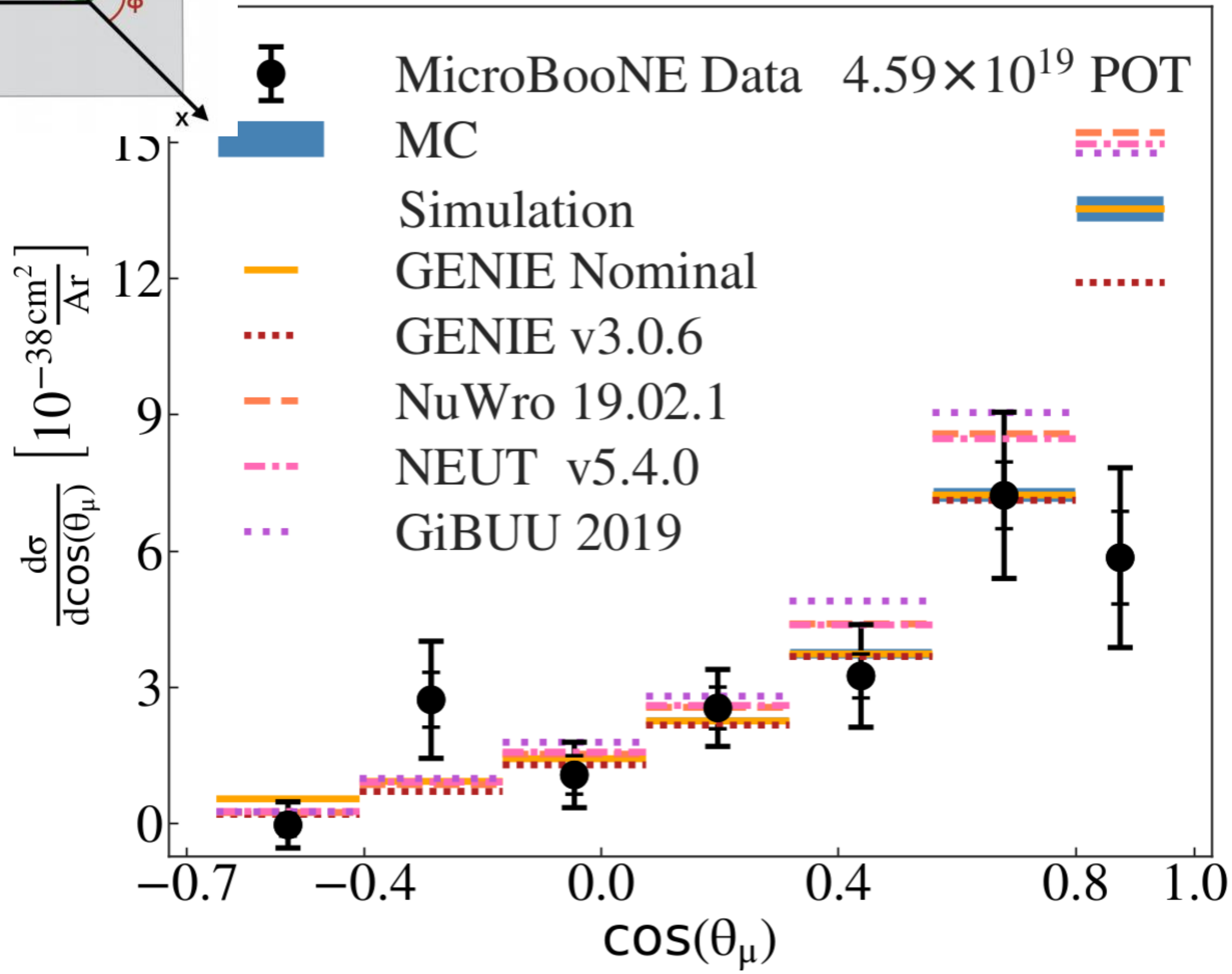


CCQE-LIKE: INITIAL CROSS-SECTIONS

PHYS. REV. LETT. 125, 201803 (2020)

- Utilizes 4.59 x 10^{19} POT
  - From MicroBooNE's first year of running
- Efficiency: 19.6%
- Purity: 84.0%
- Improved modeling of forward going muons is needed





CCQE-LIKE: IMPROVED CROSS-SECTIONS

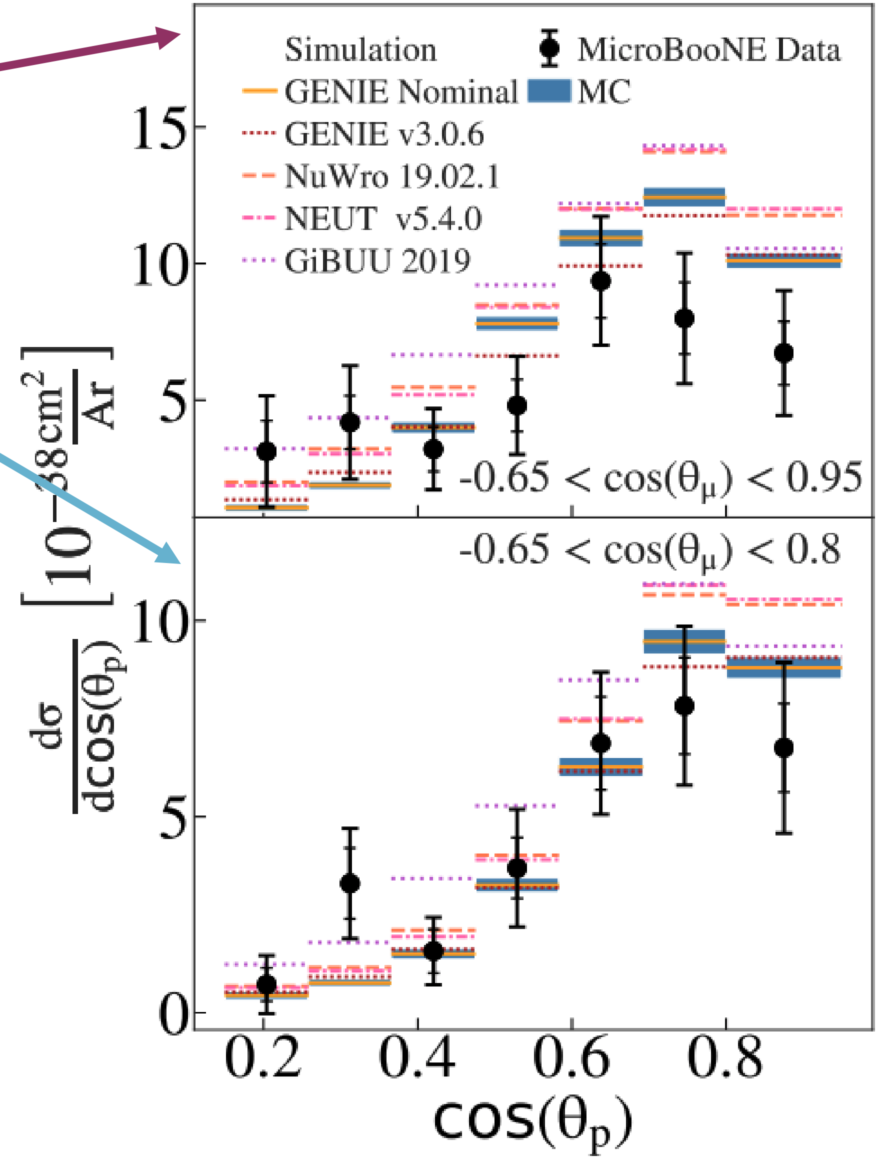
PHYS. REV. LETT. 125, 201803 (2020)

- Restrict ourselves to $-0.65 < \cos(\theta_\mu) < 0.8$
- See better agreement between data and MC.

Full Phase space

$-0.65 < \cos(\theta_\mu) < 0.8$

	Integrated Cross Section $[10^{-38}\mathrm{cm}^2]$ (Differential Cross Section χ^2/d.o.f)	
	$-0.65 < \cos(\theta_\mu) < 0.95$	$-0.65 < \cos(\theta_\mu) < 0.8$
Data CC1p0π Integrated	4.93 ± 1.55	4.05 ± 1.40
Generators: GENIE Nominal	6.18 (63.2/28)	4.04 (30.1/27)
GENIE v3.0.6	5.45 (34.6/28)	3.66 (21.4/27)
NuWro 19.02.1	6.67 (76.7/28)	4.39 (29.9/27)
NEUT v5.4.0	6.64 (78.5/28)	4.39 (32.2/27)
GiBUU 2019	7.00 (82.2./28)	4.78 (40.0/27)



CCQE-LIKE:
THE FUTURE IS CC1P0π

PHYS. REV. LETT. 125, 201803 (2020)

- The CCQE-Like analysis has concluded, but CC1p0π analysis is ongoing
- CC1p0π utilizes:
  - More statistics
  - Improved MC models
  - Updated event reconstruction tools
  - Updated systematics procedure

		Integrated Cross Section [10^{-38}cm^2] (Differential Cross Section χ^2/d.o.f)	
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CC1P0π : FUTURE WORK

[PHYS. REV. LETT. 125, 201803 (2020)](#)

- Goals of CC1p0π:
  - To extract double differential cross-sections
  - Also investigating the STVs

		Integrated Cross Section $[10^{-38}\mathrm{cm}^2]$ (Differential Cross Section $\chi^2/\mathrm{d.o.f}$)	
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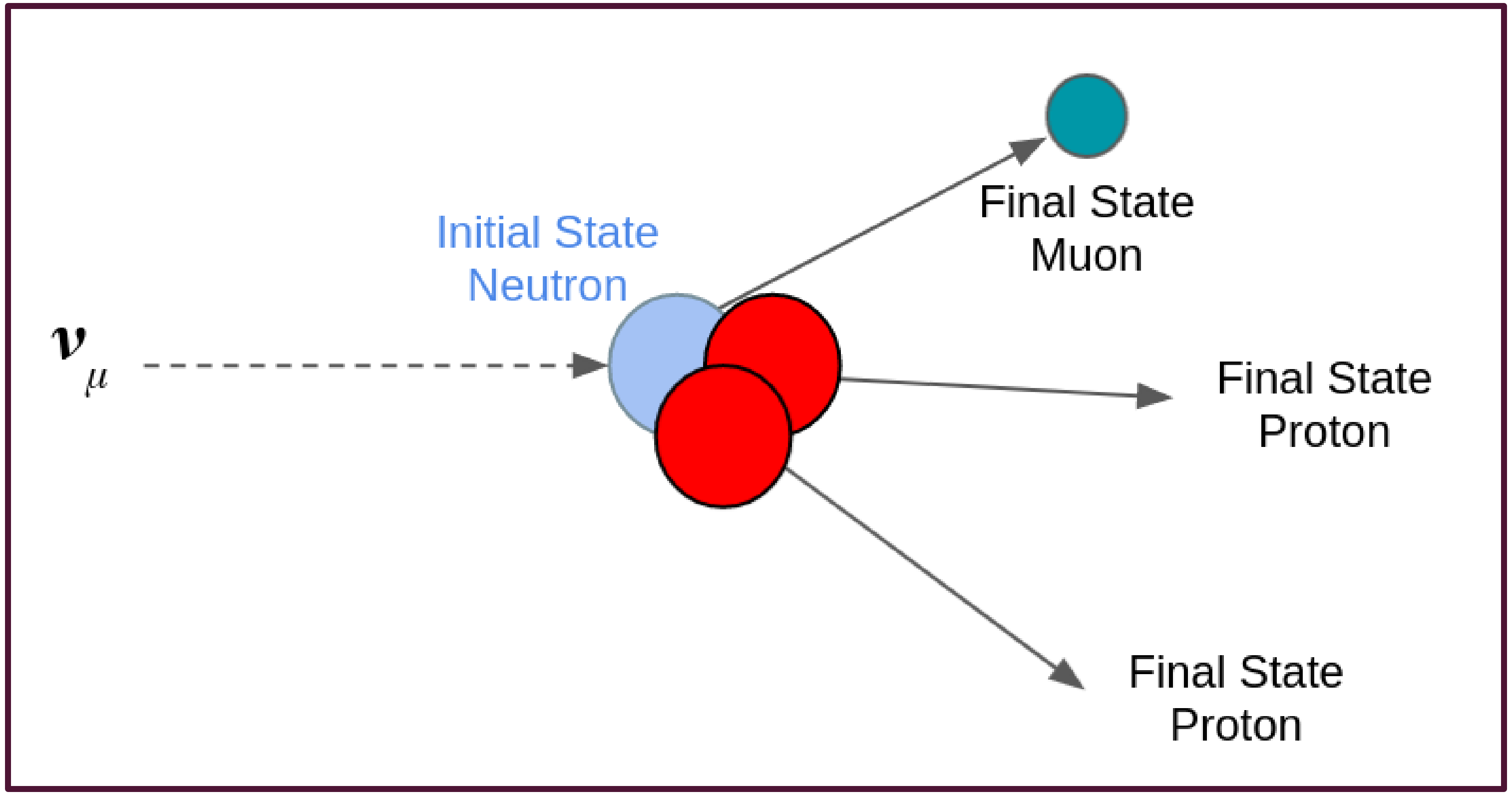


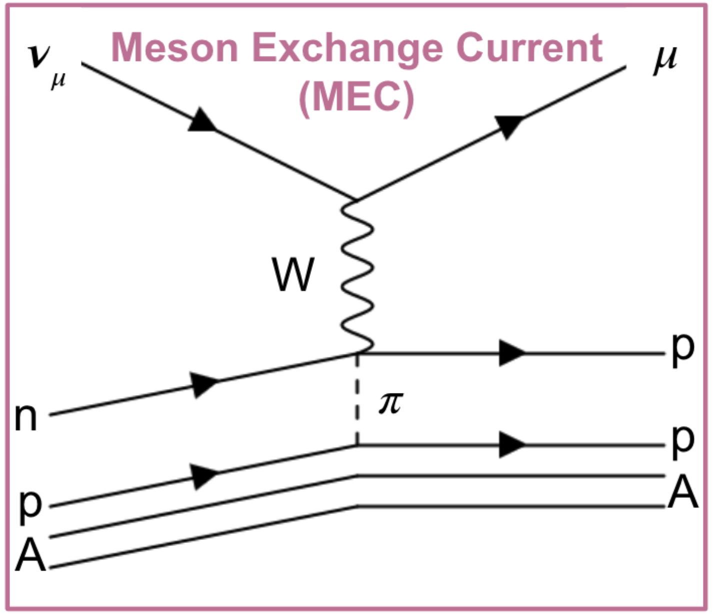
CHARGED-CURRENT 2 PROTON (CC2P)

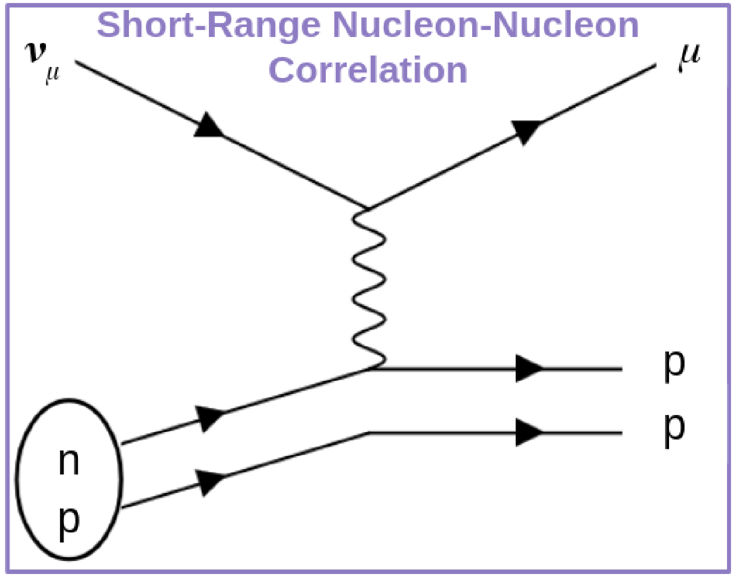
MICROBOONE-NOTE-1096-PUB

CC2P

MICROBOONE-NOTE-1096-PUB

- Sensitive to 2p2h Processes: MECs and SRCs

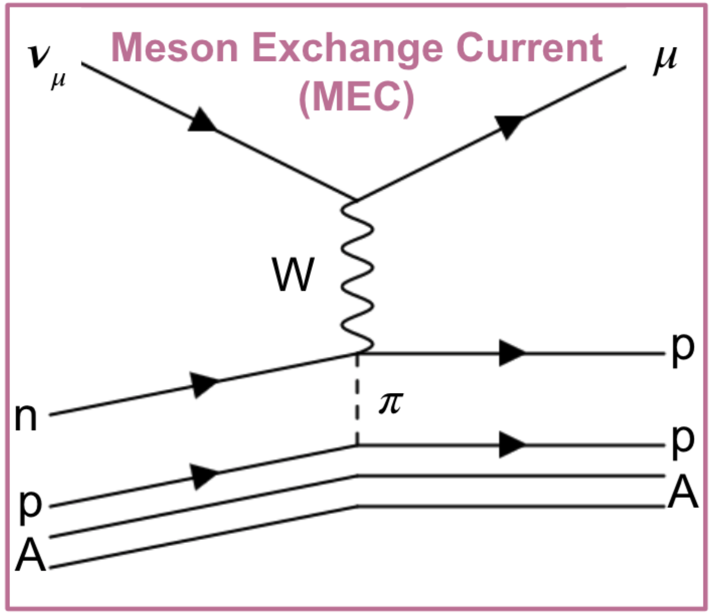


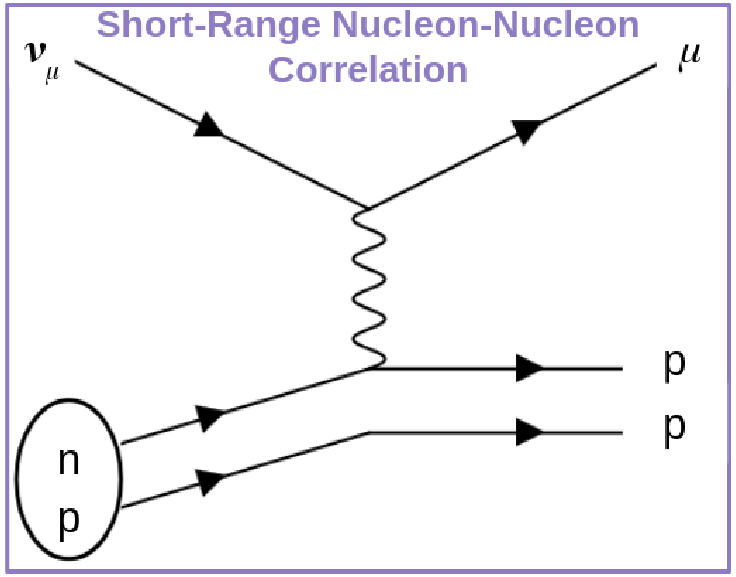


CC2P

MICROBOONE-NOTE-1096-PUB

- Sensitive to 2p2h Processes: MECs and SRCs
  - Many different models exist for MEC

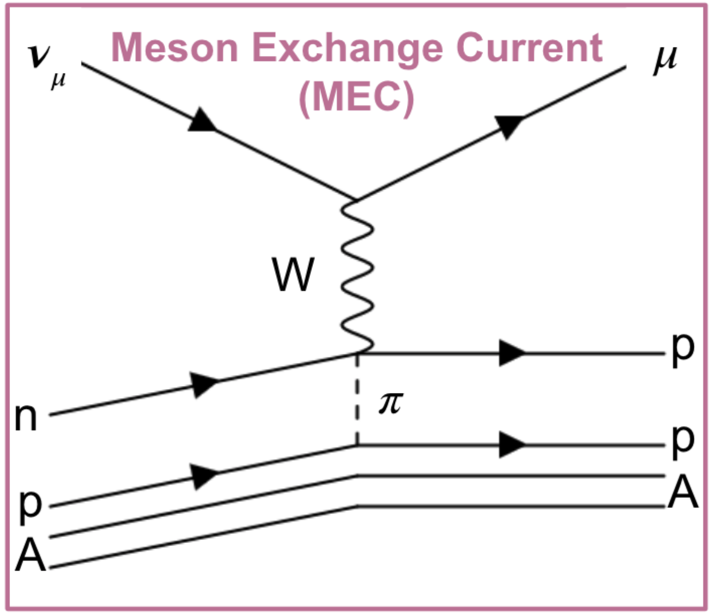


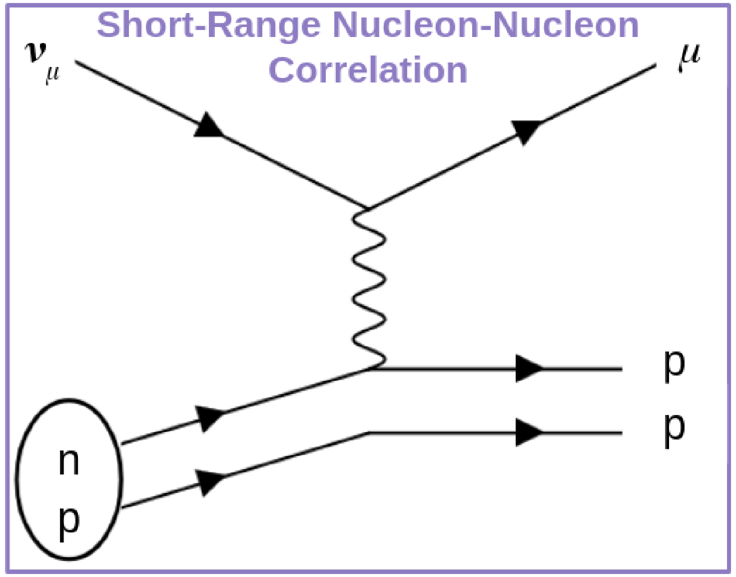


CC2P

MICROBOONE-NOTE-1096-PUB

- Sensitive to 2p2h Processes: MECs and SRCs
  - Many different models exist for MEC
  - Many event generators do not take contributions from SRCs into account





CC2P

MICROBOONE-NOTE-1096-PUB

- Two other measurements of CC2p events on argon exist, but both were statistically limited

CC2P

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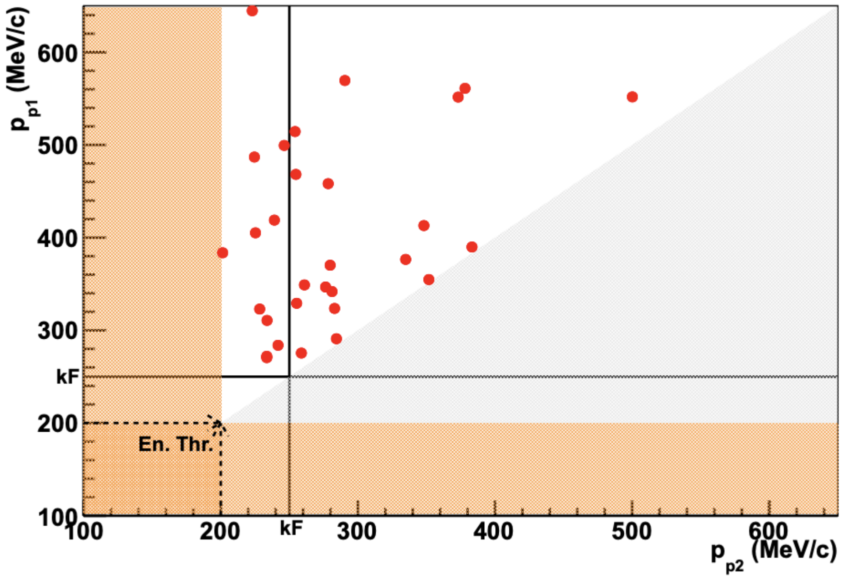
  - ArgoNeuT: 30 CC2p Events

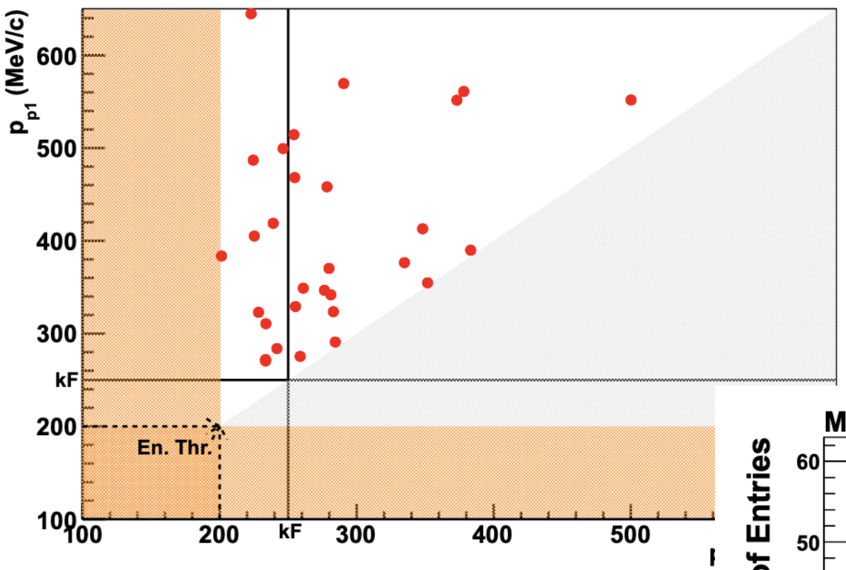


Phys. Rev.D 90 (2014) 1, 012008 (2014)

CC2P

MICROBOONE-NOTE-1096-PUB

- Two other measurements of CC2p events on argon exist, but both were statistically limited
  - ArgoNeuT: 30 CC2p Events
  - MicroBooNE: 119 CC2p Events



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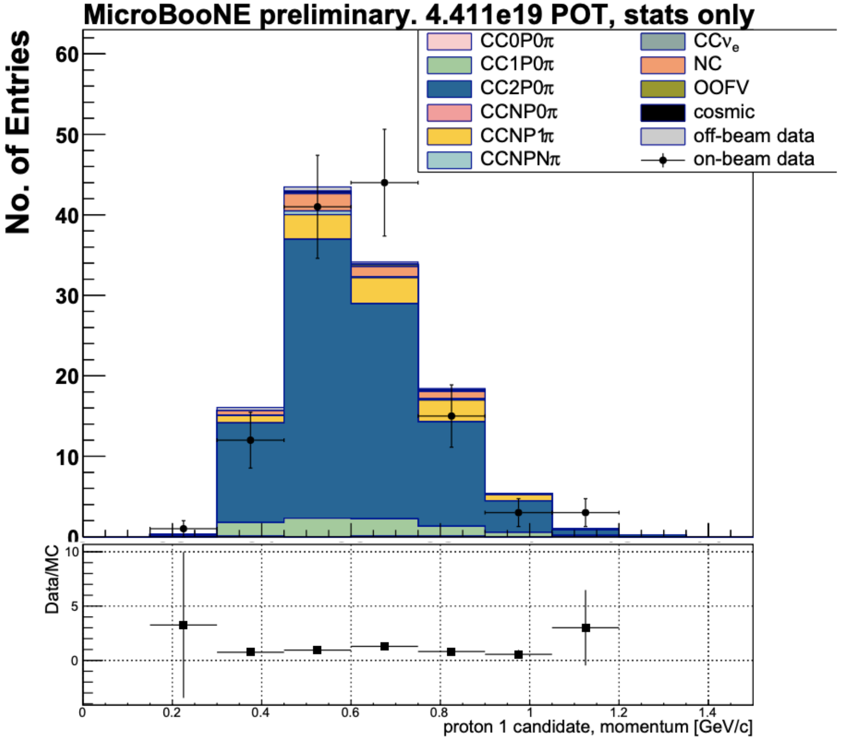
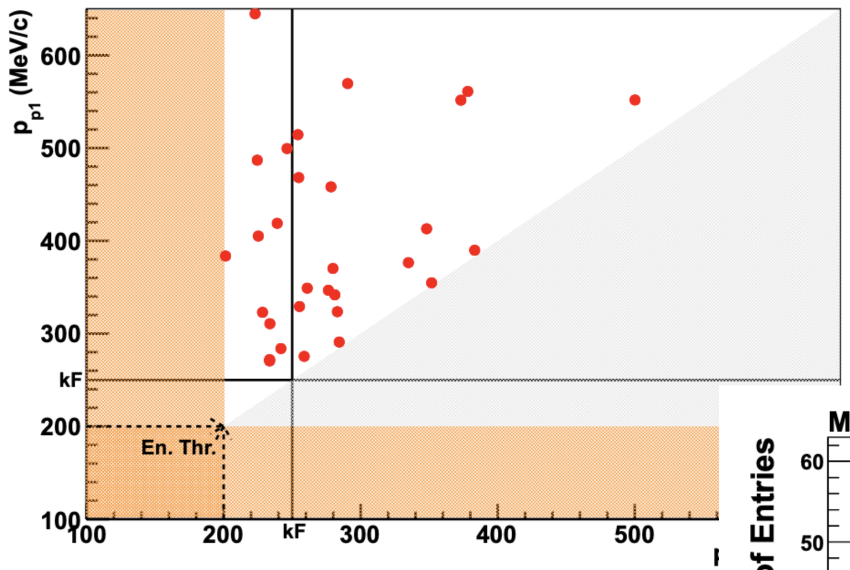
MICRBOONE-NOTE-1056-PUB



CC2P

MICROBOONE-NOTE-1096-PUB

- Analysis has Two Goals:
  - Determine variables sensitive to differences between MEC models
  - Extract the differential cross-section as function of these variables with higher statistics



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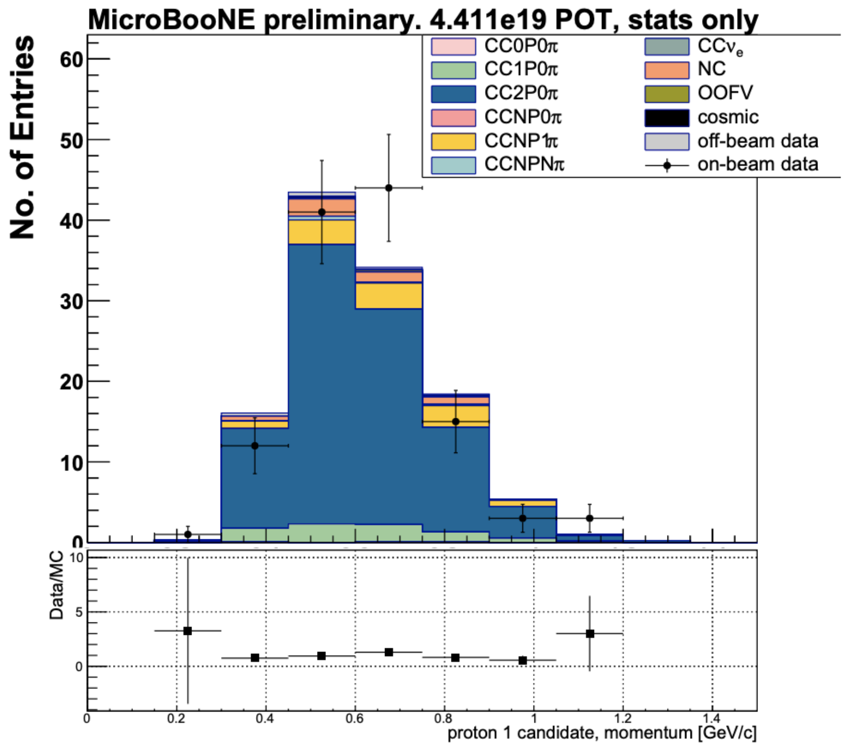
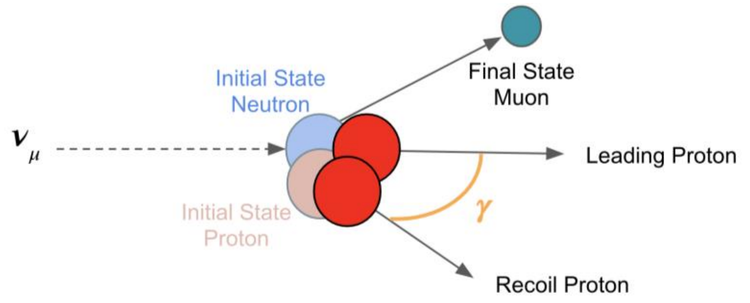
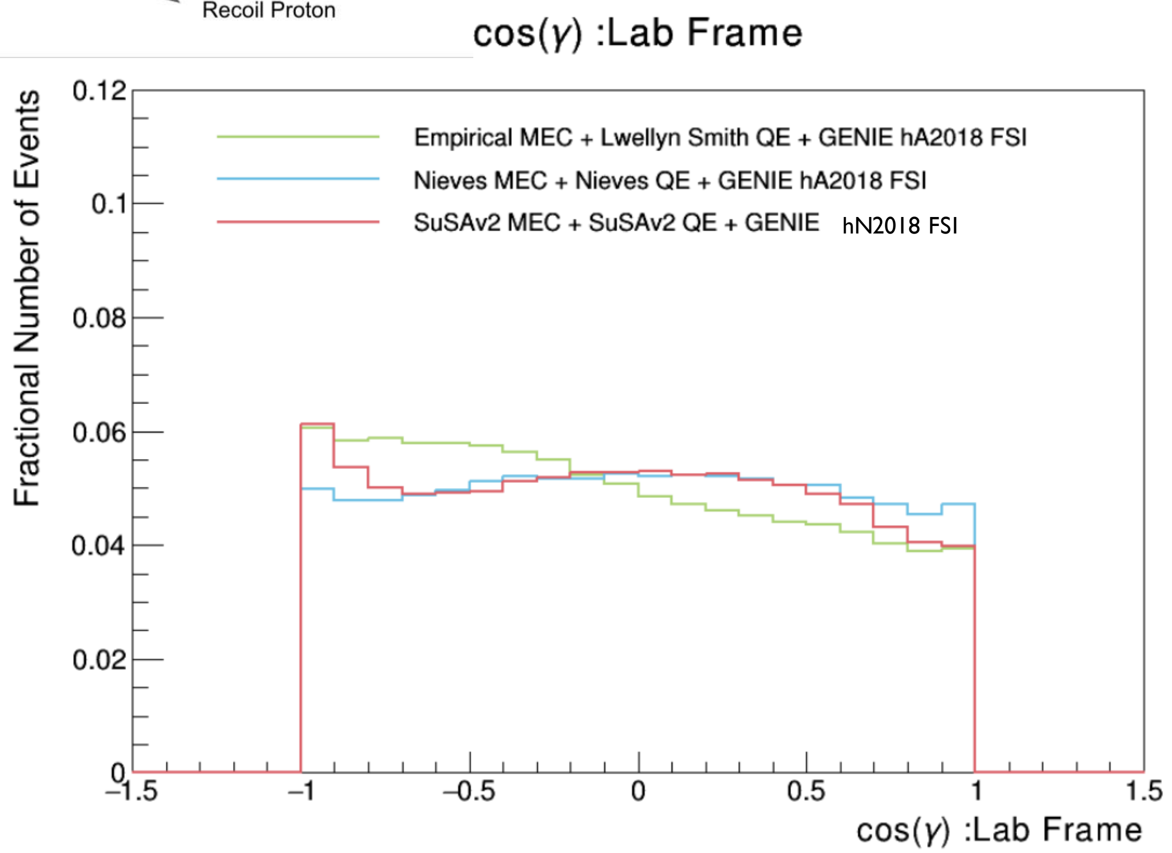


CC2P: MEC STUDIES

MICROBOONE-NOTE-1096-PUB

- Studied Events from 3 MEC Model Sets to find variables sensitive to differences between the models:
  - Empirical MEC + Lwellyn Smith QE + GENIE hA2018 FSI
  - Nieves (QE + MEC) + GENIE hA2018
  - SuSAv2 (QE+MEC) + GENIE hN2018
- Opening angle between the protons in the lab frame (γ_{Lab})

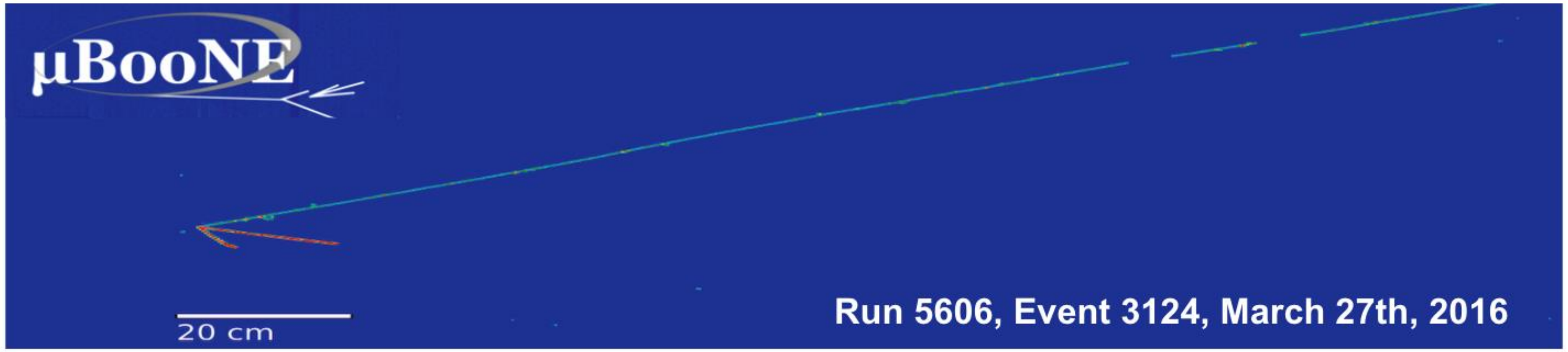




CC2P: SIGNAL DEFINITION

MICROBOONE-NOTE-1096-PUB

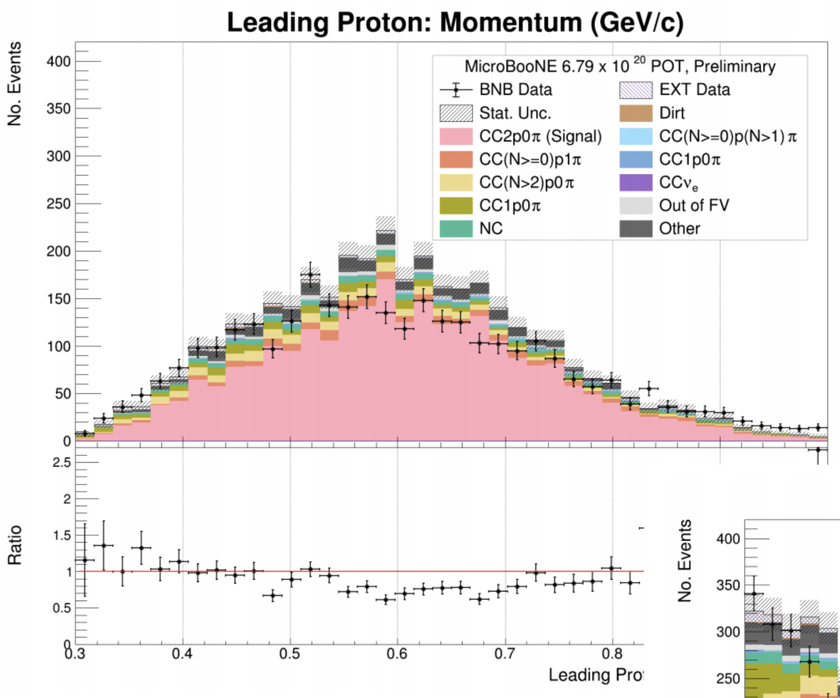
- 1 Muon
  - $0.1 < P_{\mu} < 1.2$ GeV/c
- 2 Protons
  - $0.3 < P_{p} < 1.0$ GeV/c
- $0\ \pi^{\pm}$
  - 0.065 GeV/c $< P_{\pi\pm}$
- No π^{0}



CC2P: EVENT SELECTION

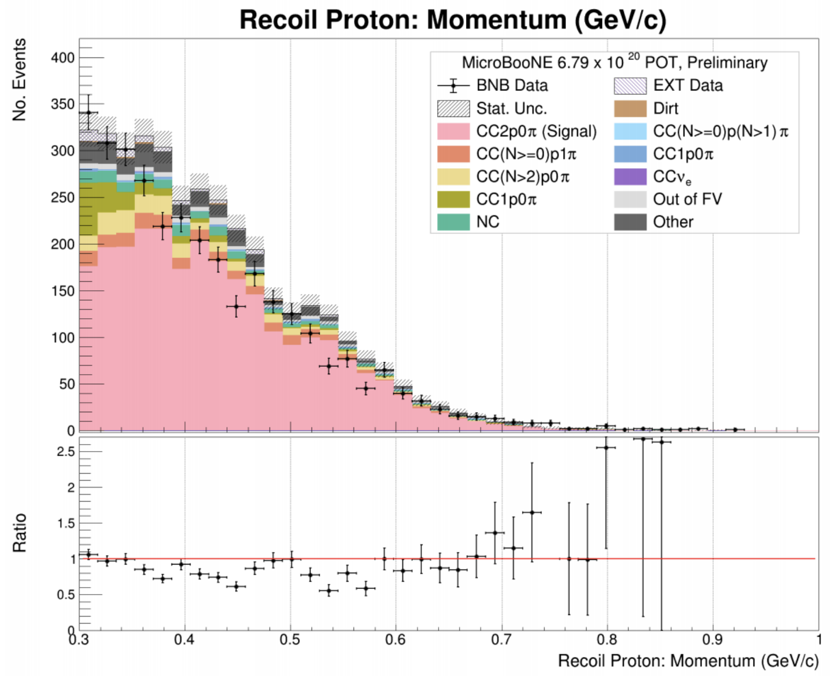
MICROBOONE-NOTE-1096-PUB

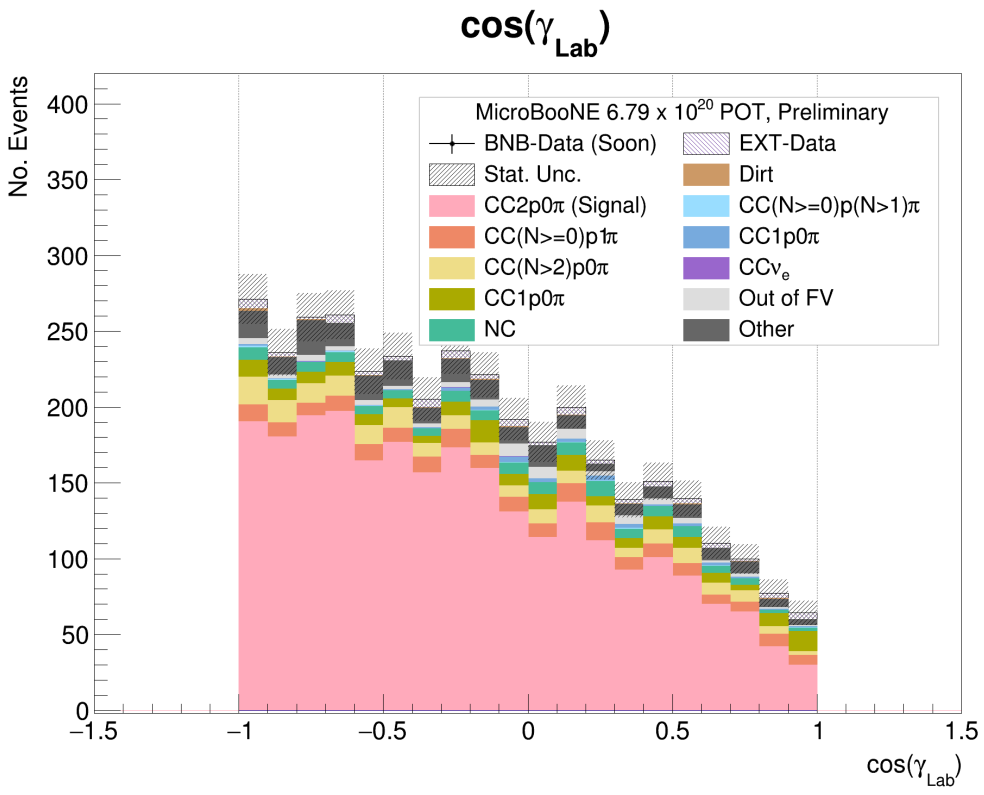
- 6.79×10^{20} POT
  - From MicroBooNE's first 3 years of running
- Statistical uncertainties only
- Efficiency: 13%
- Purity: 65.4%

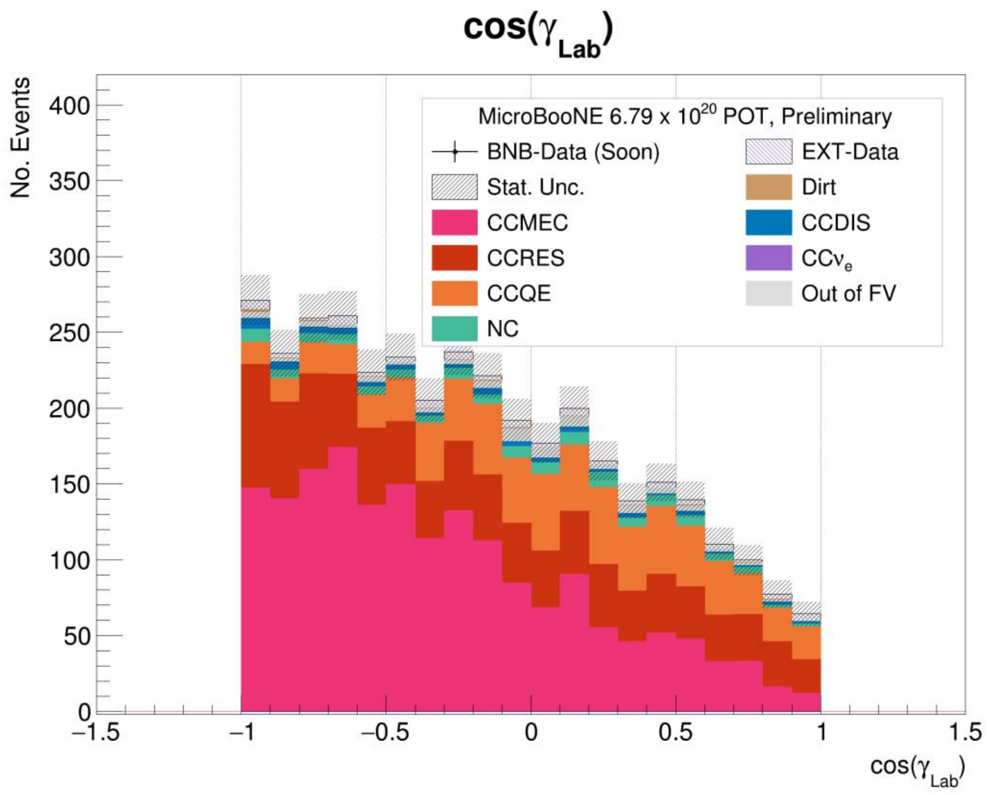


Leading = Proton with most momentum

Recoil = Proton with least momentum



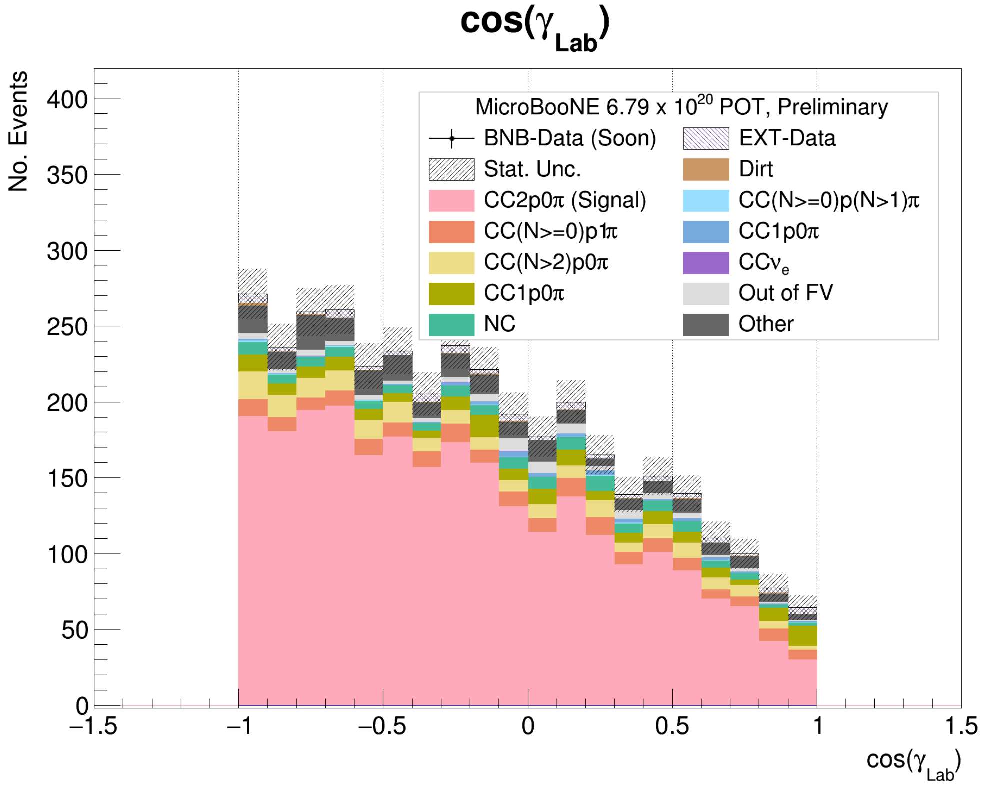


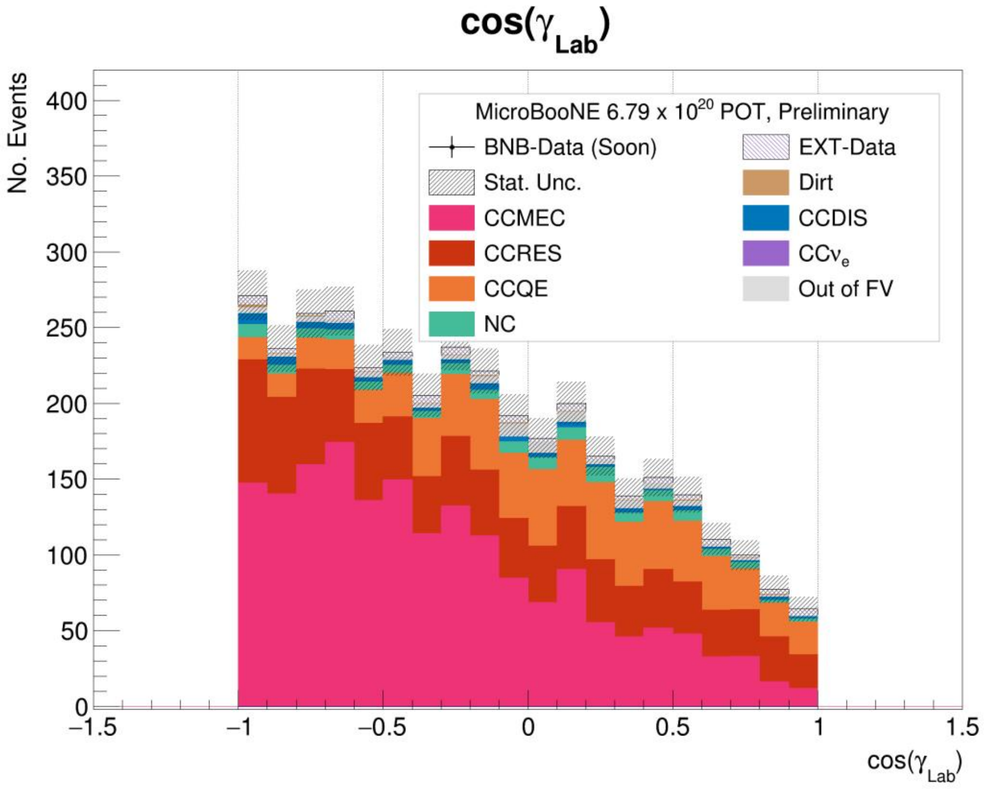


CC2P: COS(γ_{LAB})

MICROBOONE-NOTE-1096-PUB

- Data not displayed as systematic uncertainties yet to be evaluated
- CC2p (left, pink) and CCMEC (right, magenta) show slight preference of back-back protons

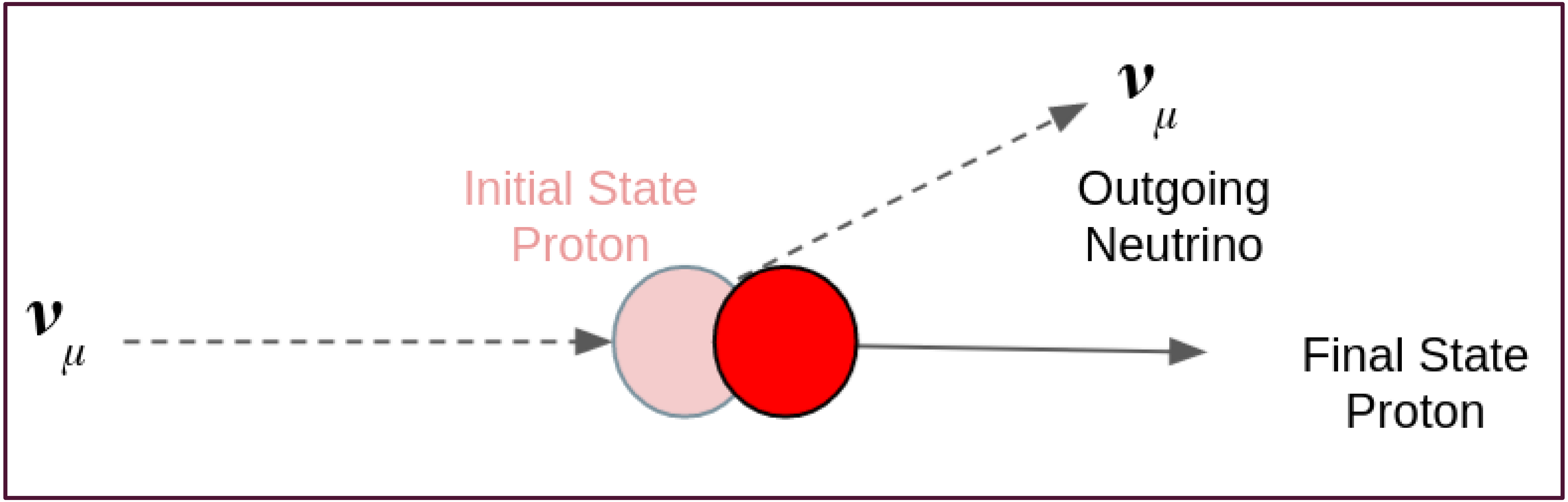




CC2P: FUTURE WORK

MICROBOONE-NOTE-1096-PUB

- Investigation of STVs (see backup slides)
- Evaluation of systematic uncertainties
- Extraction of the differential cross-sections
- Development of model set in which contributions of SRCs are considered under Generalized Contact Formalism (GCF) Phys. Lett.B 780 211-215 (2018)



NEUTRAL-CURRENT ELASTIC (NCE)

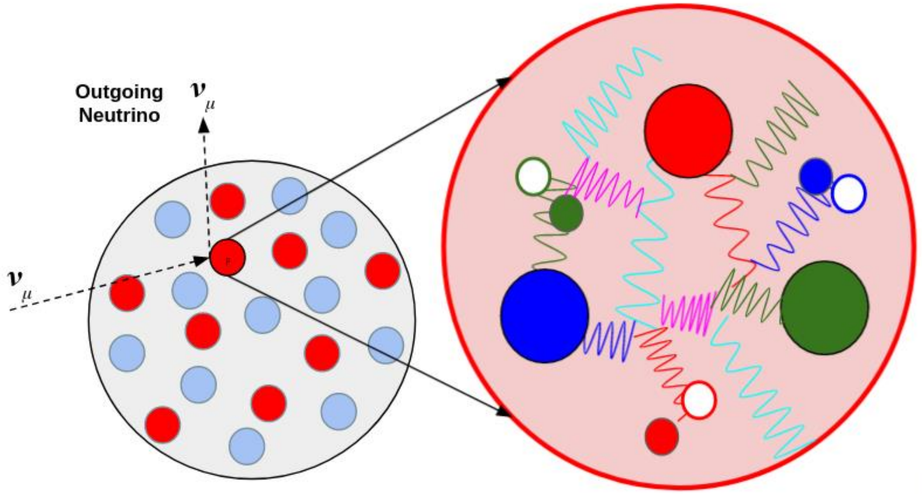
MICROBOONE-NOTE-1101-PUB

NCE

MICROBOONE-NOTE-1101-PUB

- The NC axial form factor of the proton , G_A^{NC} , has yet to be fully measured
- When $Q^2 = 0$, G_A^{NC} depends on g_A and Δs
- Conflicting measurements of Δs
  - BNL E734: -0.15 ± 0.09
  - MiniBooNE $-0.196 \pm 0.127 \pm 0.041$

NC Channel: Proton Spin Structure



$$\left(\frac{d\sigma}{dQ^2}\right)_\nu^{NC}$$

G_E^{NC} G_M^{NC} $\boxed{G_A^{NC}}$

Determined

Incomplete Measurements

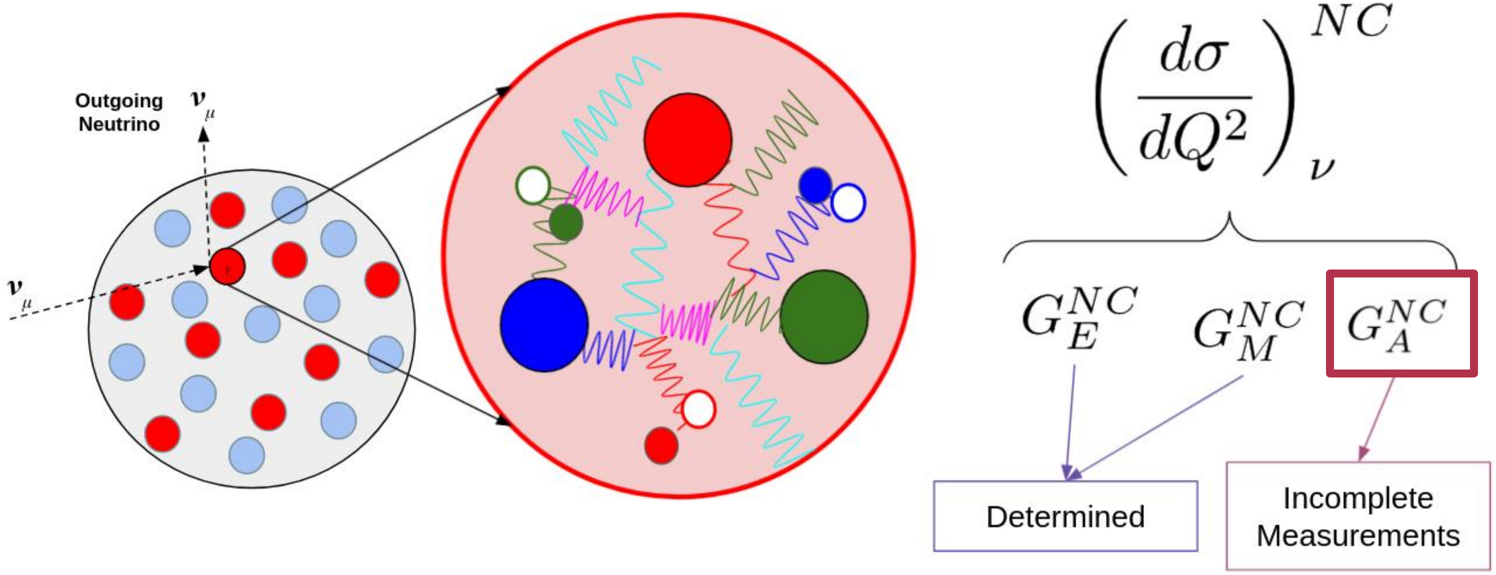
$$\boxed{G_A^{NC}(Q^2=0) = \frac{1}{2}g_A - \frac{1}{2}\boxed{\Delta s}}$$

NCE

MICROBOONE-NOTE-1101-PUB

- Since MicroBooNE can reconstruct 300 MeV/c protons, we can get to $Q^2 = 0.1$ GeV^2
  - Provides opportunity to measure Δs at lowest values of Q^2 to date

NC Channel: Proton Spin Structure



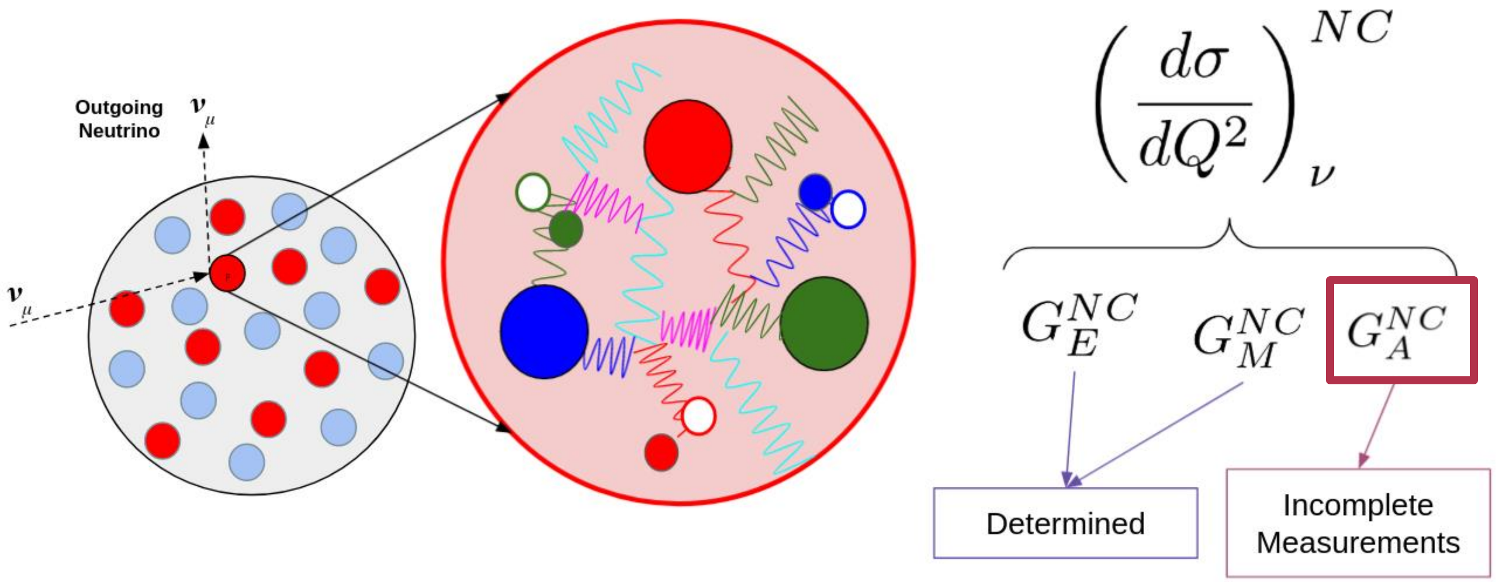
$$G_A^{NC}(Q^2 = 0) = \frac{1}{2}g_A - \frac{1}{2}\boxed{\Delta s}$$

NCE

MICROBOONE-NOTE-1101-PUB

- This analysis aims to extract the differential cross-section as function of Q^2 to determine Δs

NC Channel: Proton Spin Structure

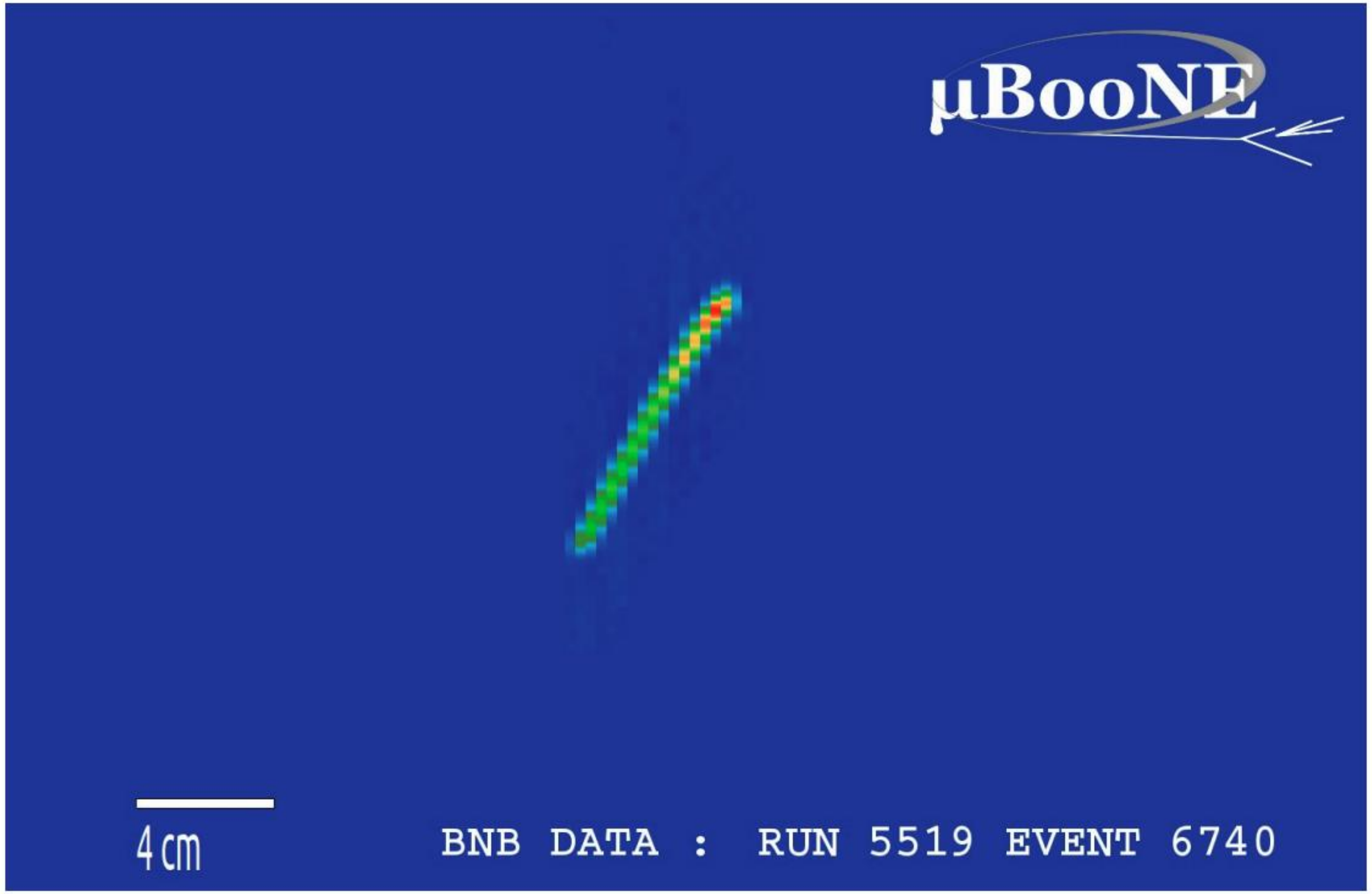


$$G_A^{NC}(Q^2=0) = \frac{1}{2}g_A - \frac{1}{2}\boxed{\Delta s}$$

NCE:
SIGNAL DEFINITION

MICROBOONE-NOTE-1101-PUB

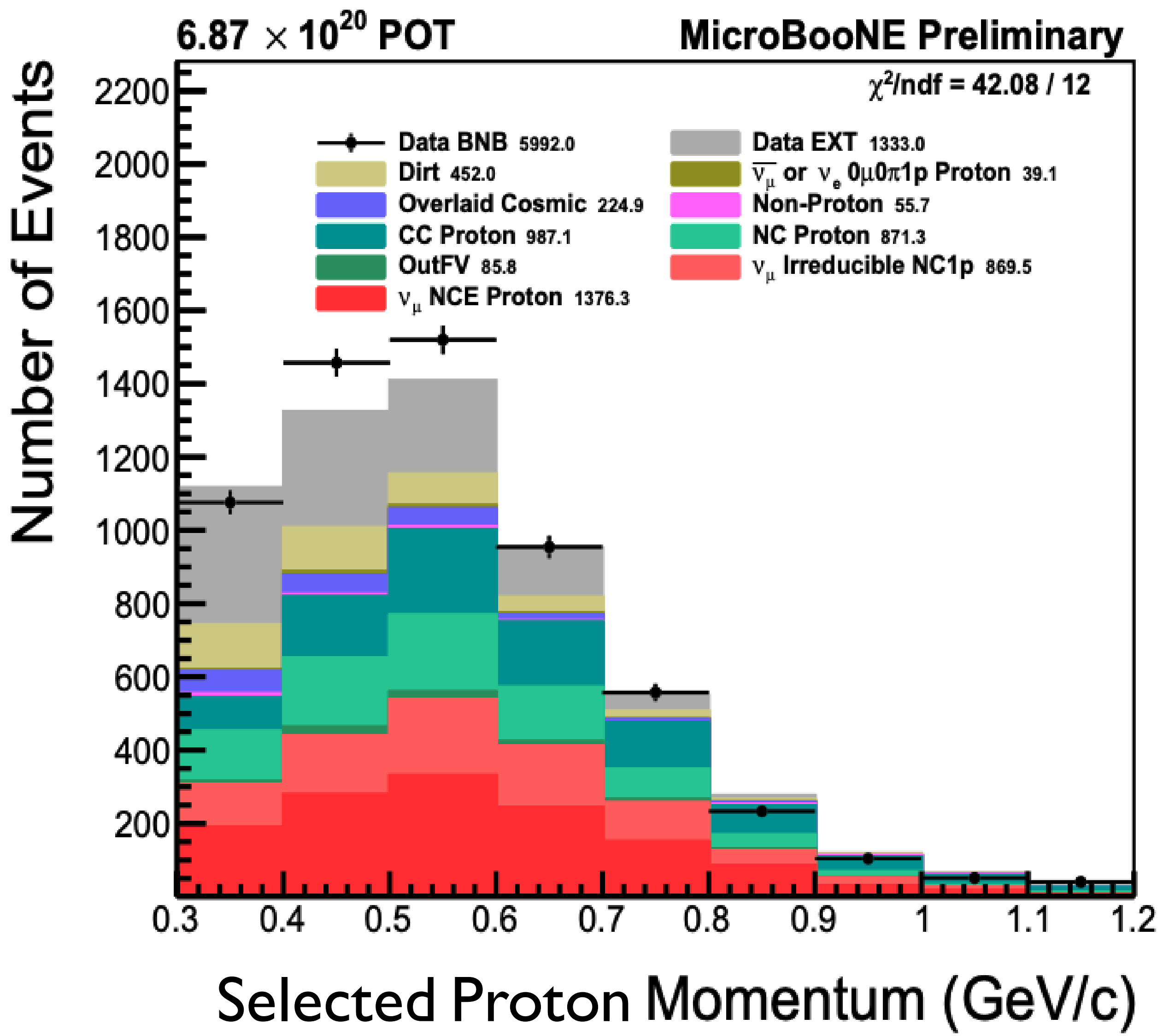
- 1 Proton 0.3 GeV/c < P_P
- 0 Muons 0.1 GeV/c < P_μ
- 0 pions 0.065 GeV/c < $P_{\pi(\pm,0)}$
- Any number of neutrons
- True NCE
  - Determined from MC-Truth
- Struck nucleon is a proton
  - Determined from MC-Truth



NCE: EVENT SELECTION

MICROBOONE-NOTE-1101-PUB

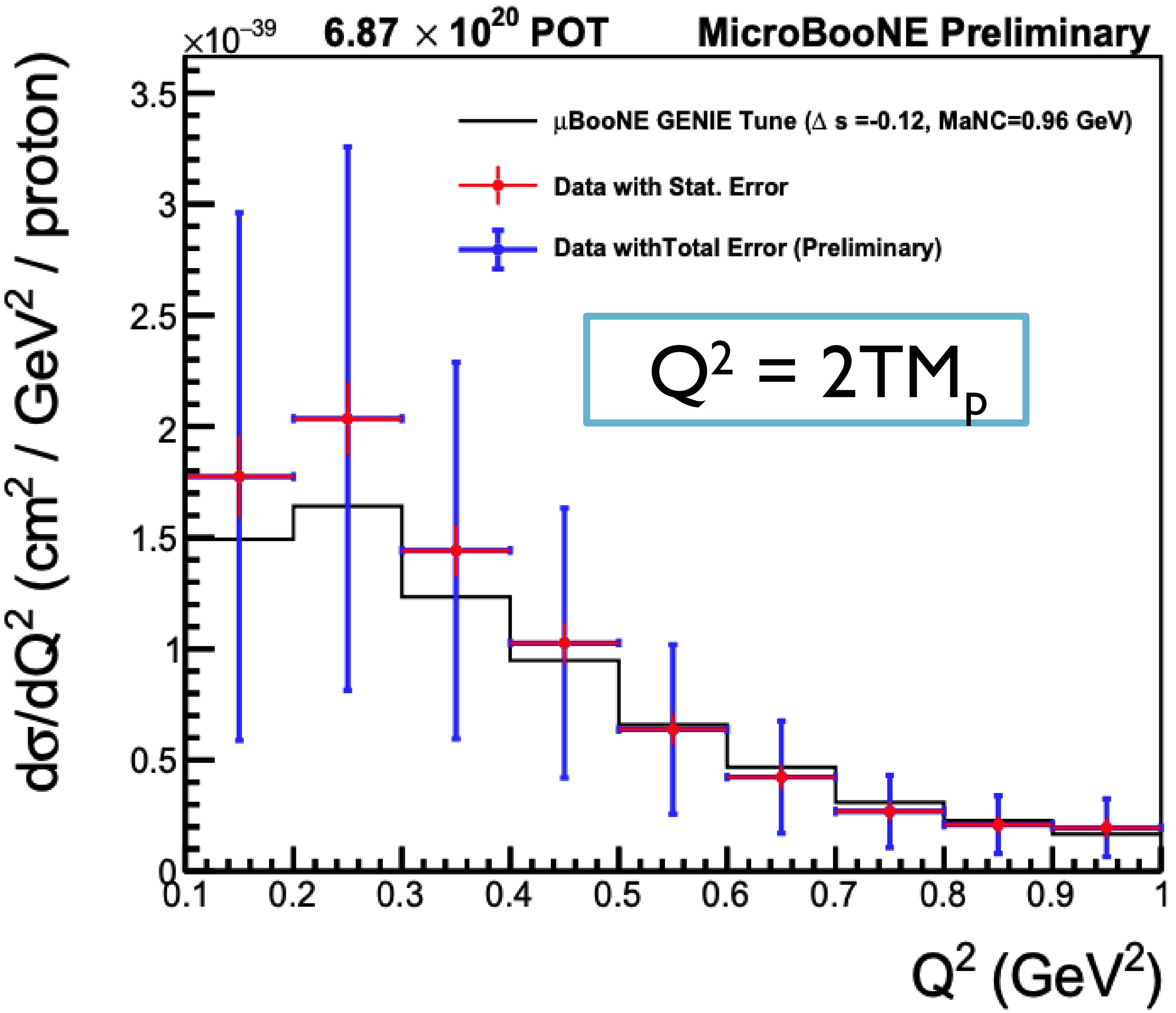
- 6.87×10^{20} POT
  - From MicroBooNE's first 3 years of running
- Purity: 22.7%
- Efficiency: 37.7%



NCE: Q^2

MICROBOONE-NOTE-1101-PUB

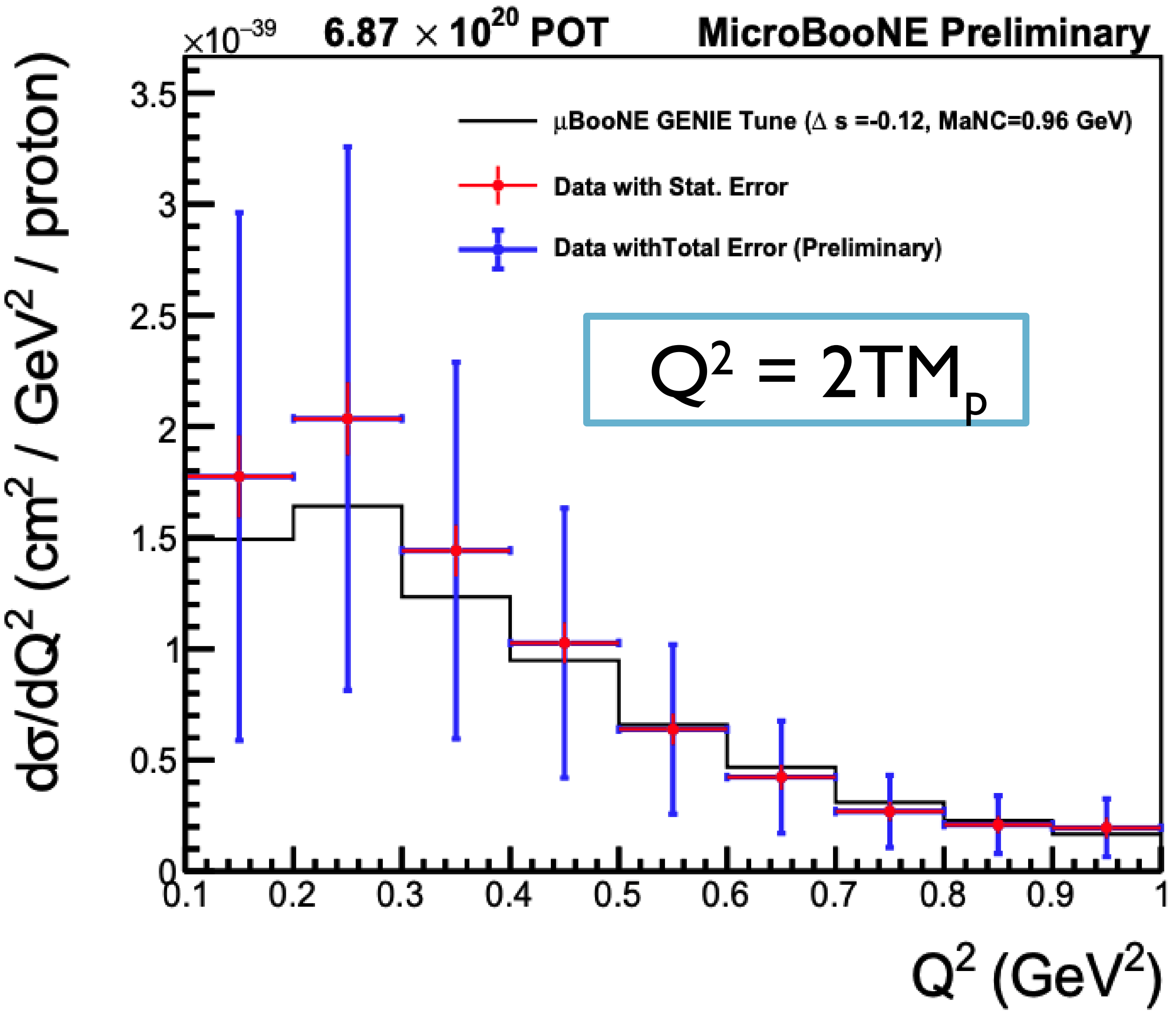
- Q^2 is calculated from proton kinetic energy
- See good data-MC agreement across the range of Q^2
- Minimum $Q^2 = 0.1\ GeV^2$
  - Significantly lower than other measurements in neutrino scattering experiments



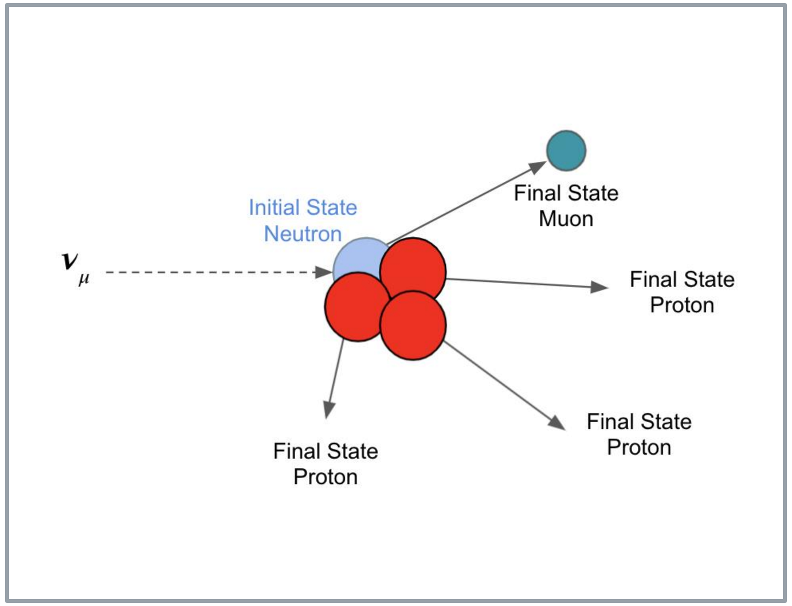
NCE: FUTURE WORK

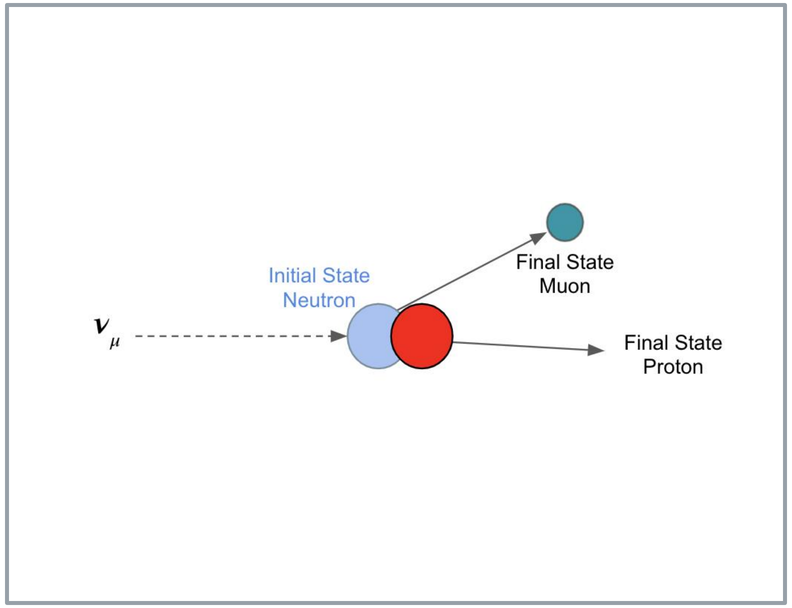
MICROBOONE-NOTE-1101-PUB

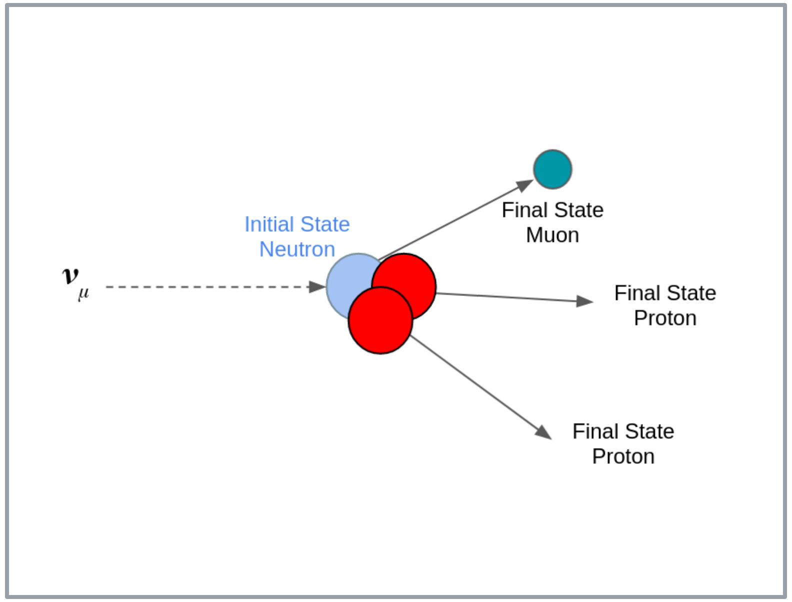
- Future Work Will Include:
  - Updates to binning to reduce error caused by bins with low statistics
  - Improving purity by reducing backgrounds
  - Finalization of systematic uncertainties

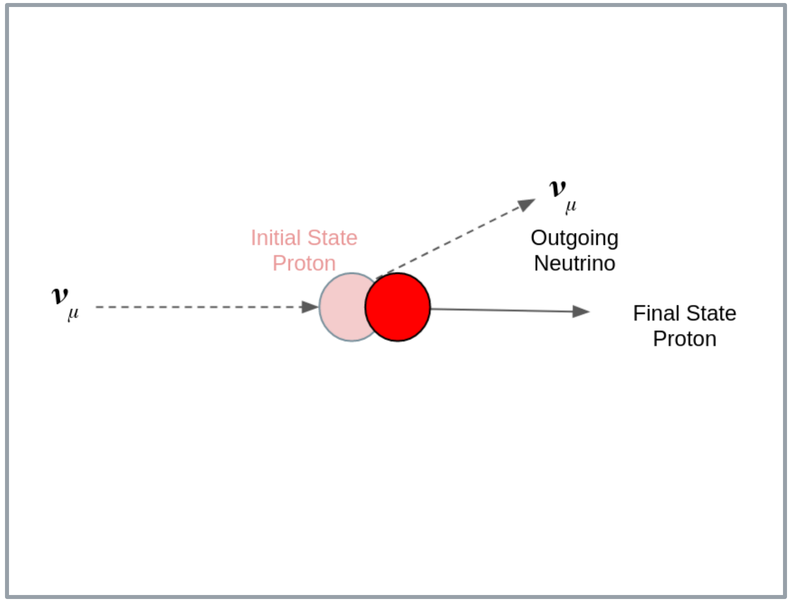


SUMMARY


Initial State
Neutron
ν_μ
Final State
Muon
Final State
Proton
Final State
Proton
Final State
Proton

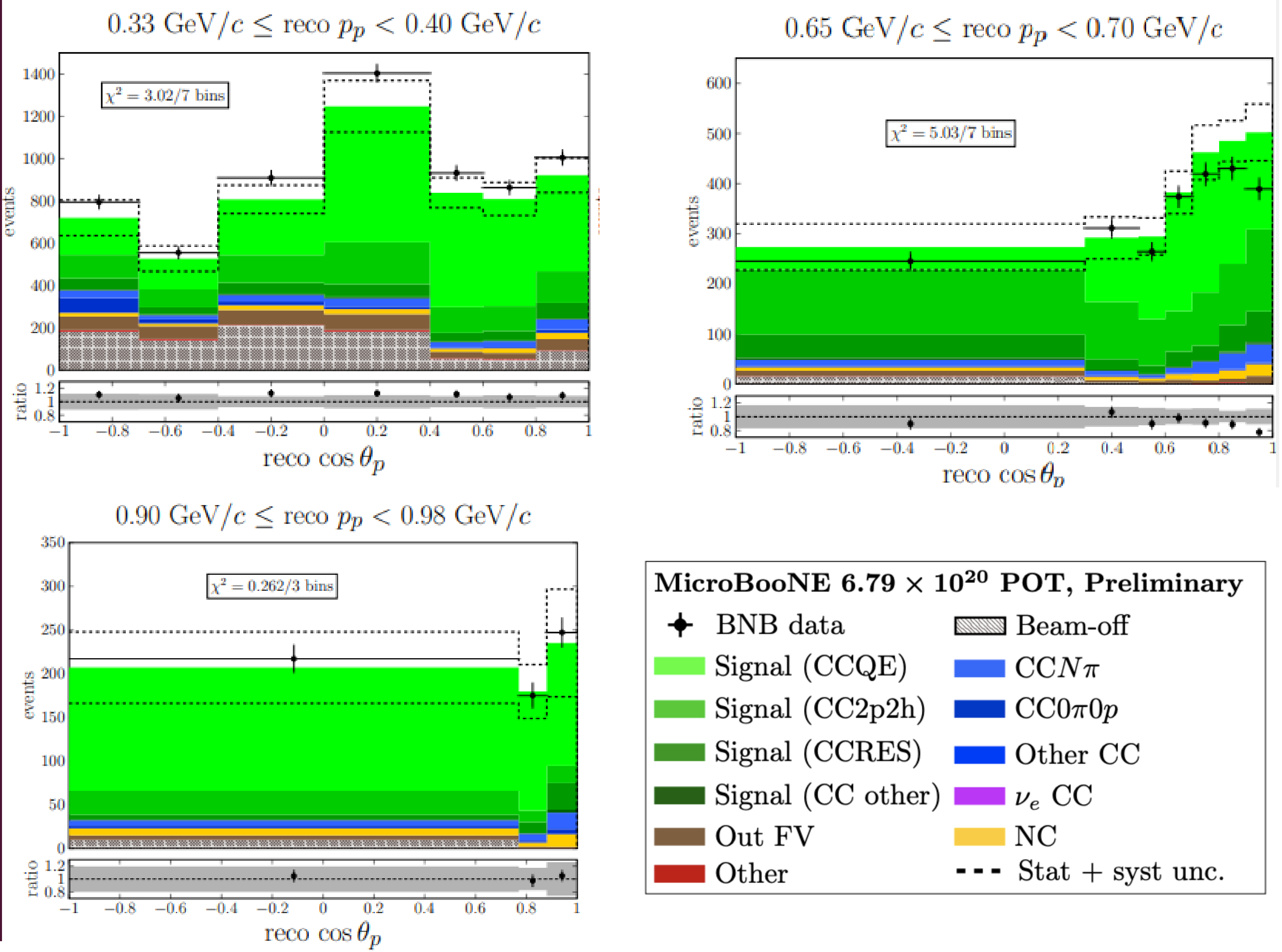

Initial State
Neutron
ν_μ
Final State
Muon
Final State
Proton


Initial State
Neutron
ν_μ
Final State
Muon
Final State
Proton
Final State
Proton


Initial State
Proton
ν_μ
ν_μ
Outgoing
Neutrino
Final State
Proton

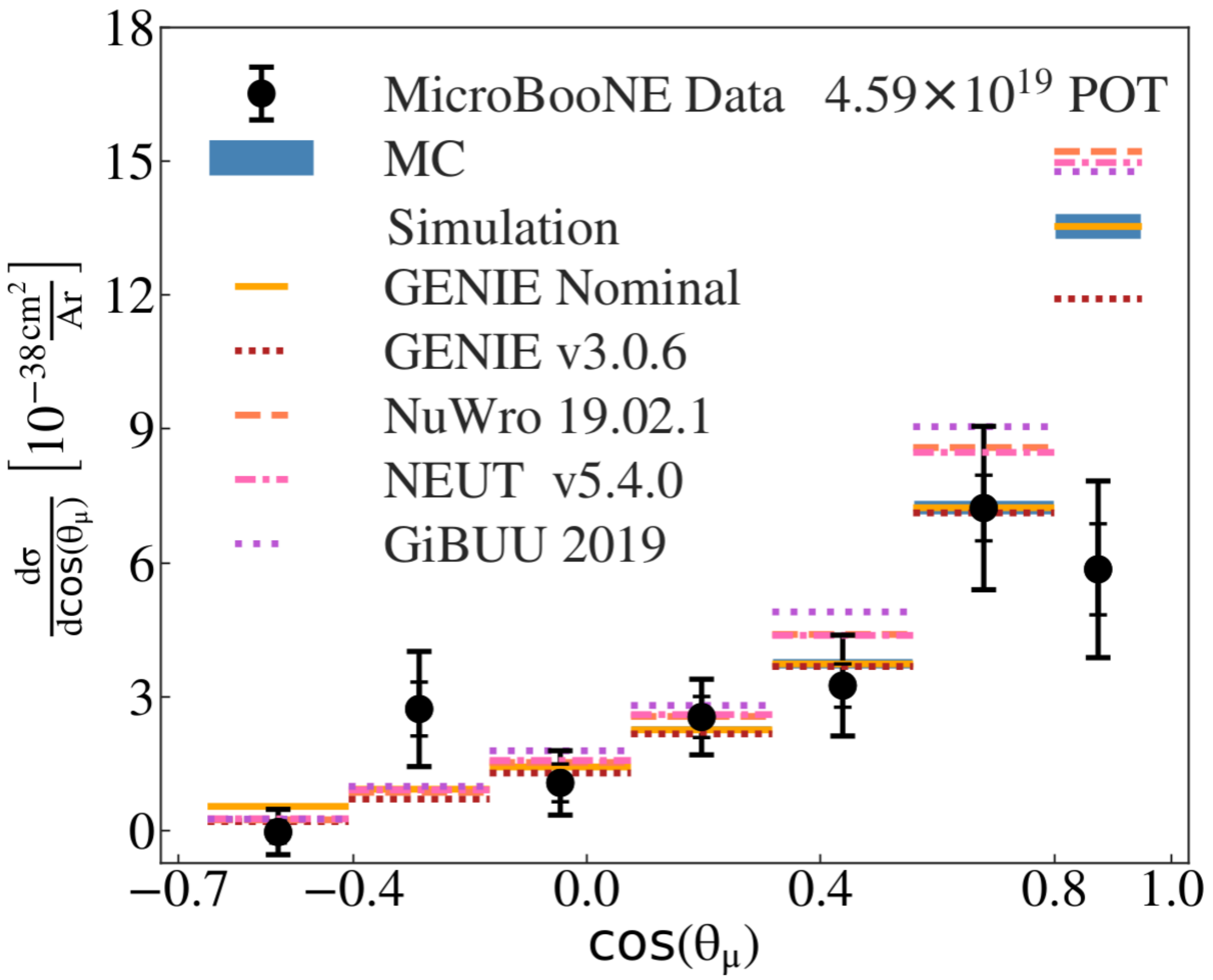
PRESENTED 4 MICROBOONE PROTON ANALYSES

- **Charged-Current N Proton (CCNP):** MICROBOONE-NOTE-1099-PUB



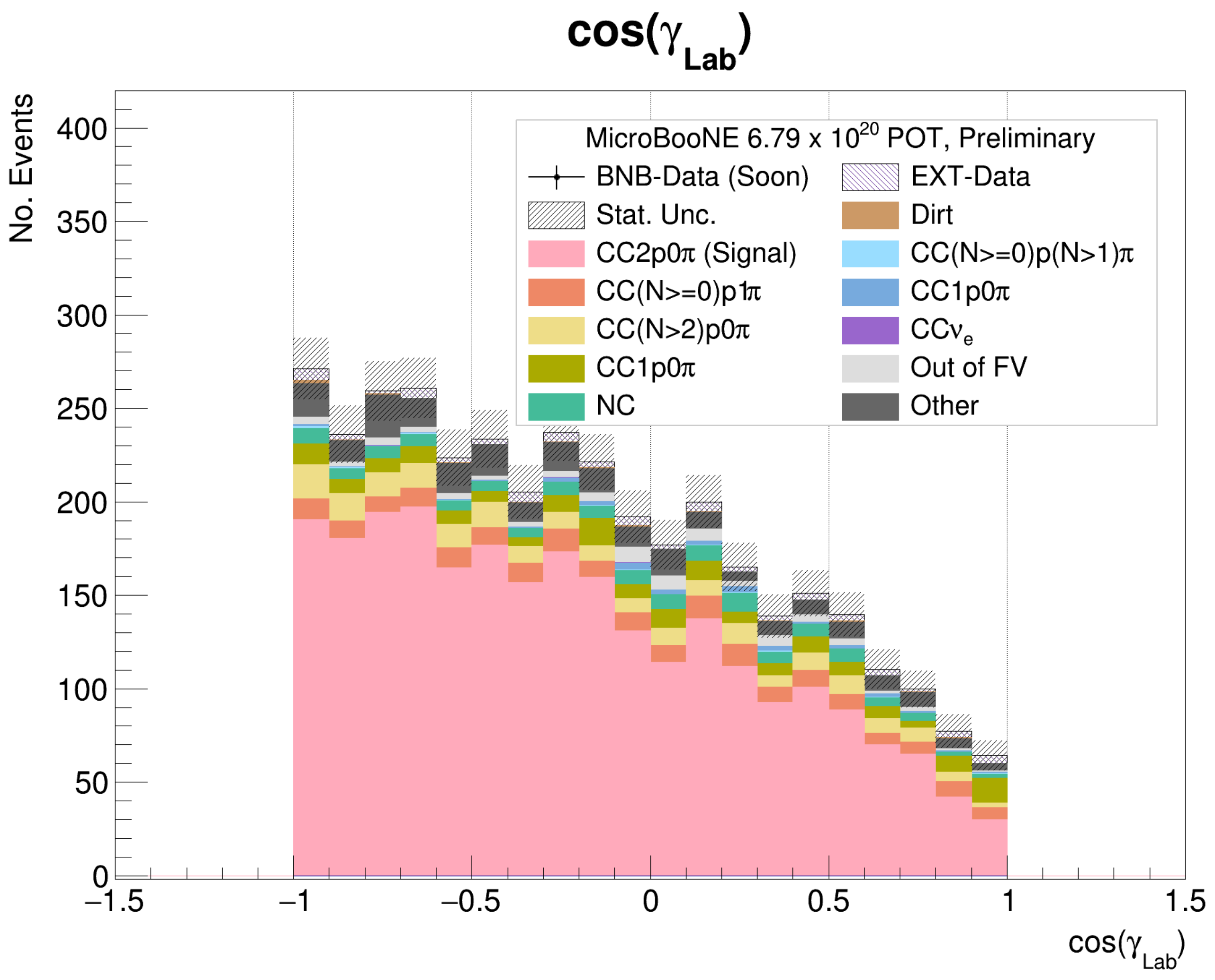
PRESENTED 4 MICROBOONE PROTON ANALYSES

- **Charged-Current N Proton (CCNP):** MICROBOONE-NOTE-1099-PUB
- **Charged-Current Quasi-Elastic Like (CCQE-Like):** Phys. Rev. Lett. 125, 201803 (2020)



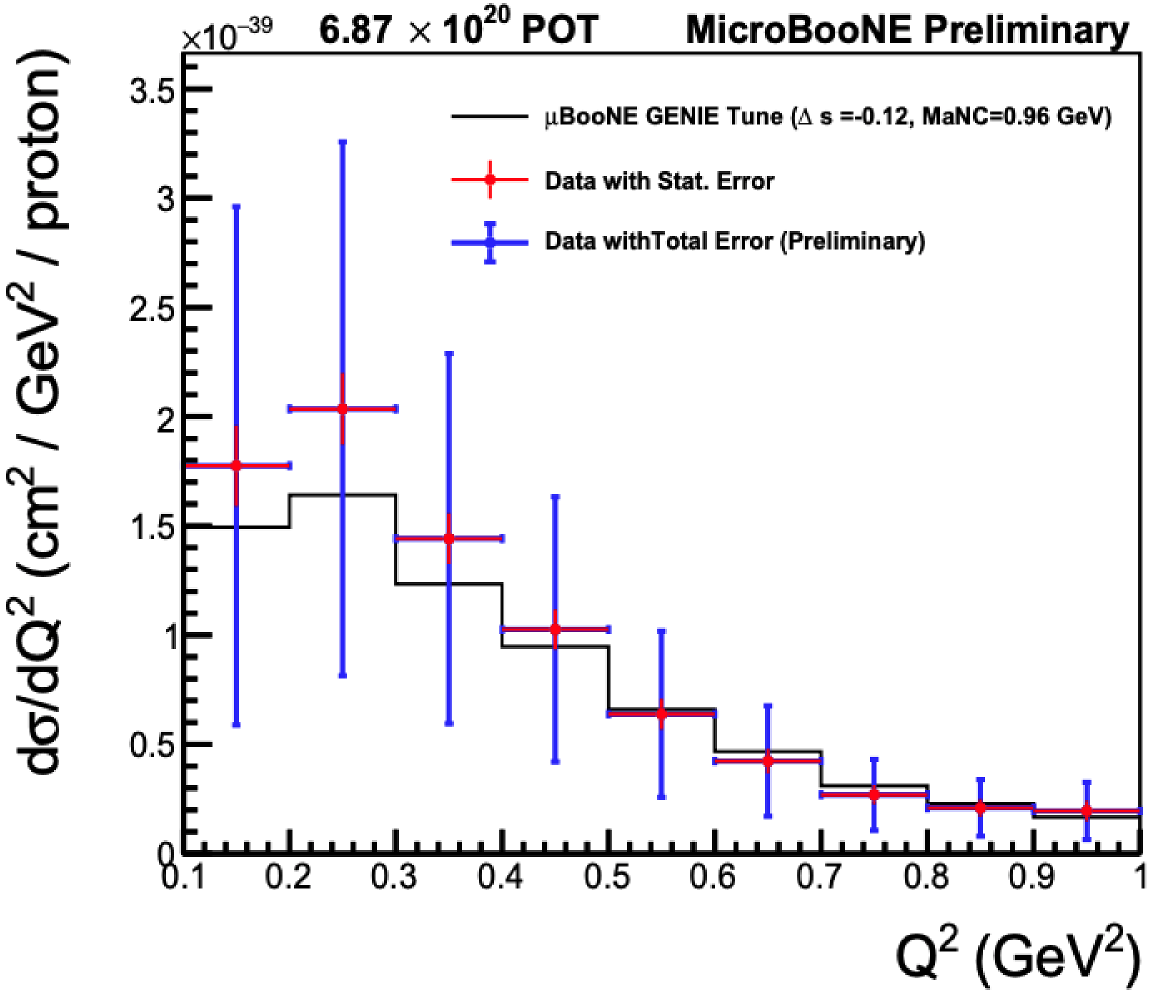
PRESENTED 4 MICROBOONE PROTON ANALYSES

- **Charged-Current N Proton (CCNP):** MICROBOONE-NOTE-1099-PUB
- **Charged-Current Quasi-Elastic Like (CCQE-Like):** Phys. Rev. Lett. 125, 201803 (2020)
- **Charged-Current 2 Proton (CC2p):** MICROBOONE-NOTE-1096-PUB



PRESENTED 4 MICROBOONE PROTON ANALYSES

- **Charged-Current N Proton (CCNP):** MICROBOONE-NOTE-1099-PUB
- **Charged-Current Quasi-Elastic Like (CCQE-Like):** Phys. Rev. Lett. 125, 201803 (2020)
- **Charged-Current 2 Proton (CC2p):** MICROBOONE-NOTE-1096-PUB
- **Neutral-Current Elastic (NCE):** MICROBOONE-NOTE-1101-PUB



SOME WORLD FIRSTS

- **Charged-Current N Proton (CCNP):** MICROBOONE-NOTE-1099-PUB
- **Charged-Current Quasi-Elastic Like (CCQE-Like):** Phys. Rev. Lett. 125, 201803 (2020)
- **Charged-Current 2 Proton (CC2p):** MICROBOONE-NOTE-1096-PUB
- **Neutral-Current Elastic (NCE):** MICROBOONE-NOTE-1101-PUB

- First double differential distributions of CCNP events on argon

- First single differential cross-section of CCQE-Like on argon

- First look at MEC models in argon
- First event distributions of CC2p with large statistics on argon

- First single differential cross-section of NCE on argon
- Lowest Q^2 of any experiment to date!

BUT WAIT...THERE IS MORE!

- **Charged-Current N Proton (CCNP):** MICROBOONE-NOTE-1099-PUB
- **Charged-Current Quasi-Elastic Like (CCQE-Like):** Phys. Rev. Lett. 125, 201803 (2020)
- **Charged-Current 2 Proton (CC2p):** MICROBOONE-NOTE-1096-PUB
- **Neutral-Current Elastic (NCE):** MICROBOONE-NOTE-1101-PUB

- First double-differential cross-section of CCNP on argon
- First look at STVs for CCNP

- First single differential cross-section of CC1p
- First look at STVs for CC1p

- First single differential cross-section of CC2p on argon
- First look at GCF generated events
- First look at STVs for CC2p

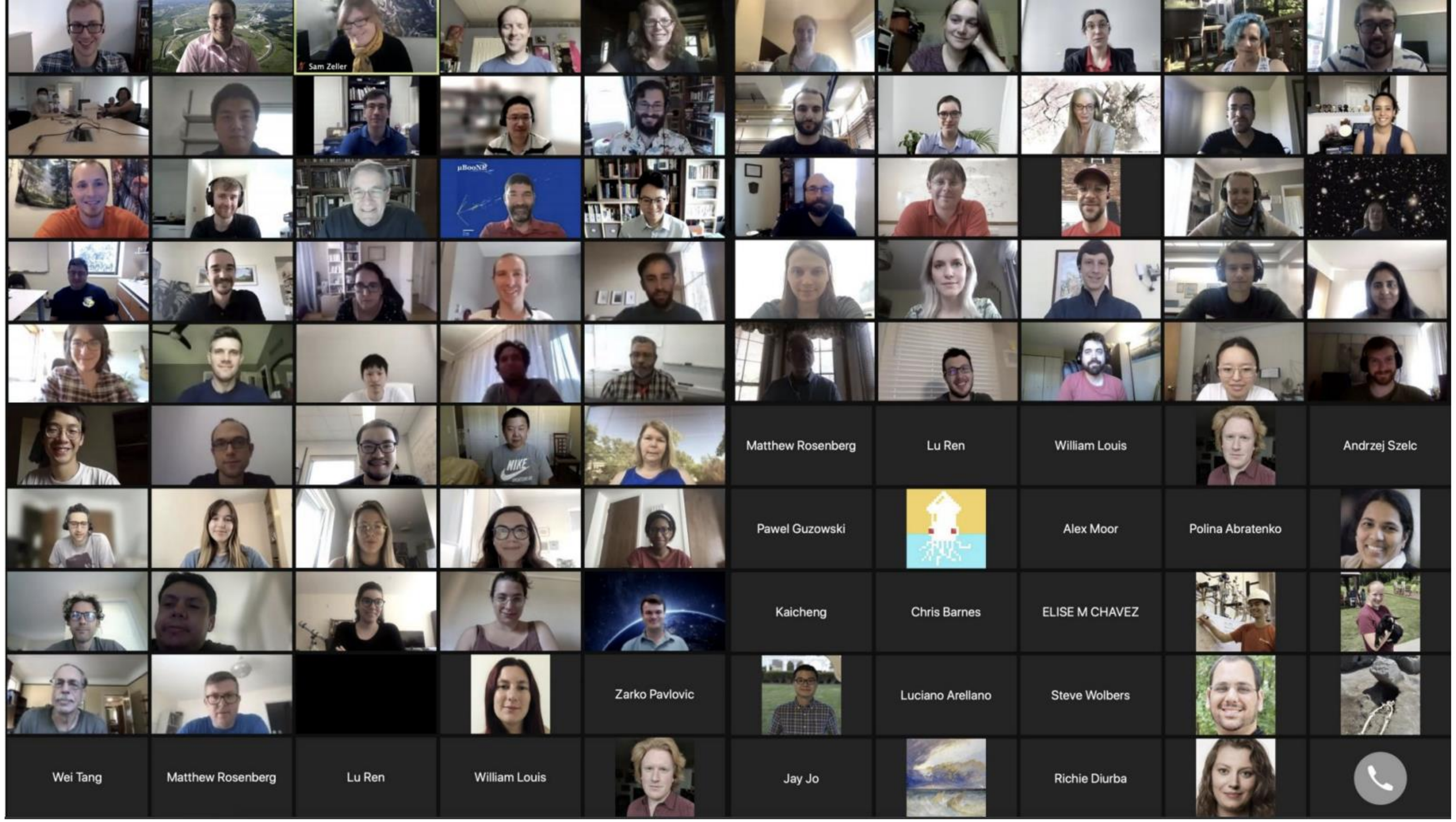
- Extraction of Δs from lowest Q^2 of any experiment yet

BUT WAIT...THERE IS MORE!

- **Charged-Current N Proton (CCNP):** MICROBOONE-NOTE-1099-PUB
- **Charged-Current Quasi-Elastic Like (CCQE-Like):** Phys. Rev. Lett. 125, 201803 (2020)
- **Charged-Current 2 Proton (CC2p):** MICROBOONE-NOTE-1096-PUB
- **Neutral-Current Elastic (NCE):** MICROBOONE-NOTE-1101-PUB

- First double-differential cross-

These exciting results coming to a paper near you soon!



THANK YOU!

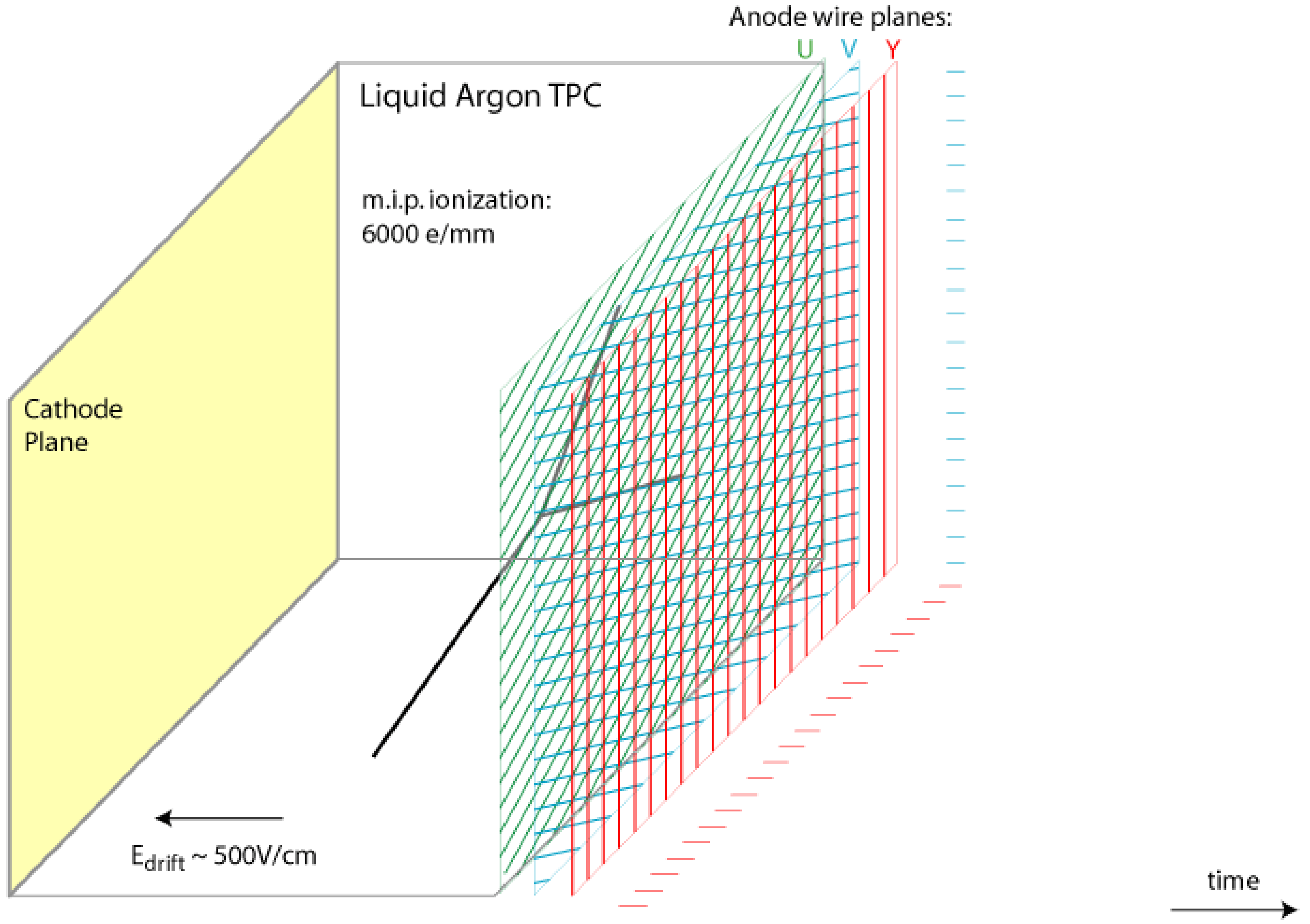
EMAIL: FEHLBERG@NMSU.EDU SLACK: @SAMANTHA SWORD-FEHLBERG

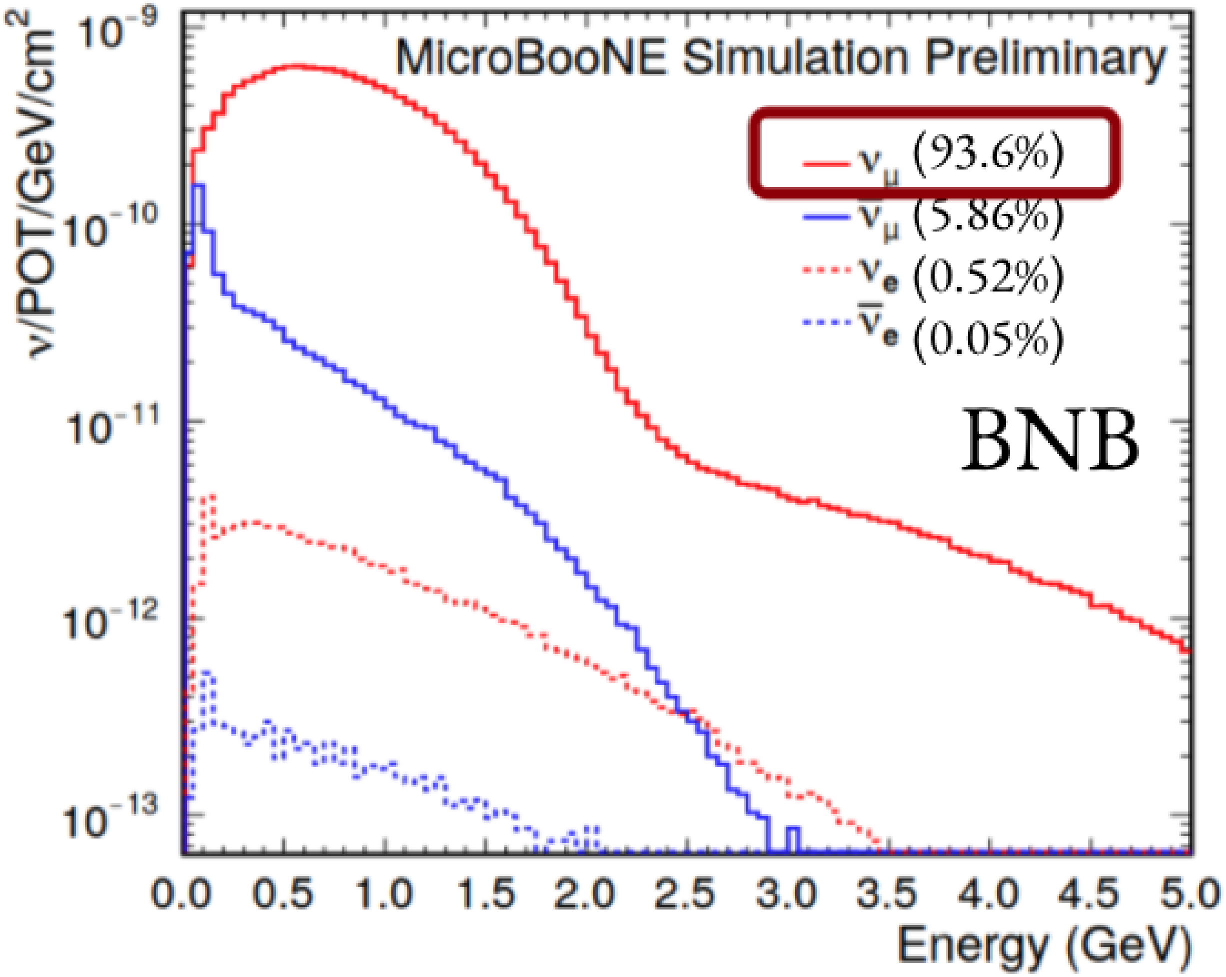
Fermilab | U.S. DEPARTMENT OF ENERGY Office of Science | NSF | FNSNF SWISS NATIONAL SCIENCE FOUNDATION | Science & Technology Facilities Council | THE ROYAL SOCIETY

BACKUP SLIDES

MICROBOONE

- Liquid Argon Time Projection Chamber (LAr TPC) at Fermilab
- Primary beam is BNB:
  - $<E_{\upsilon}> = 0.8$ GeV
- 170 Tons of LAr (85 Active Tons)
- 179 Collaborators
  - 34 Institutions (8 non-U.S)
  - 45 Postdocs
  - 55 Graduate Students
- First neutrino event October 2015

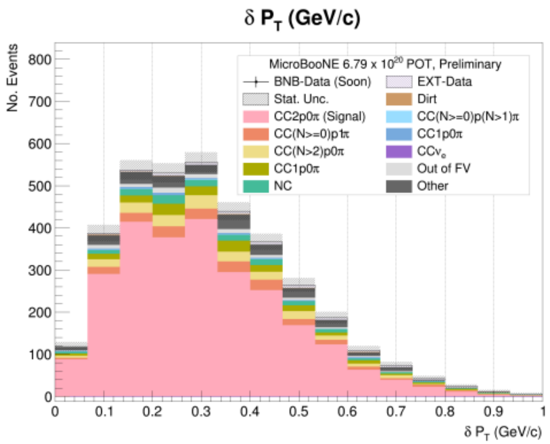


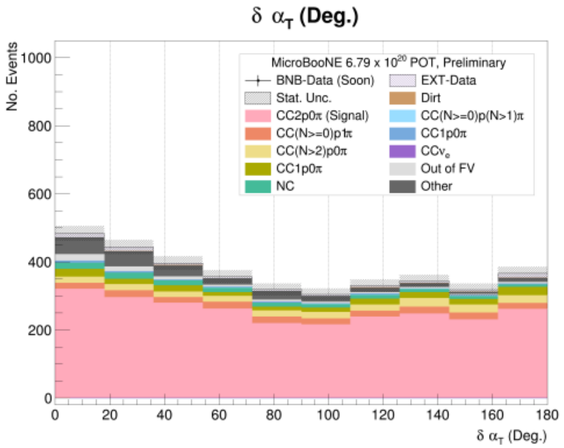


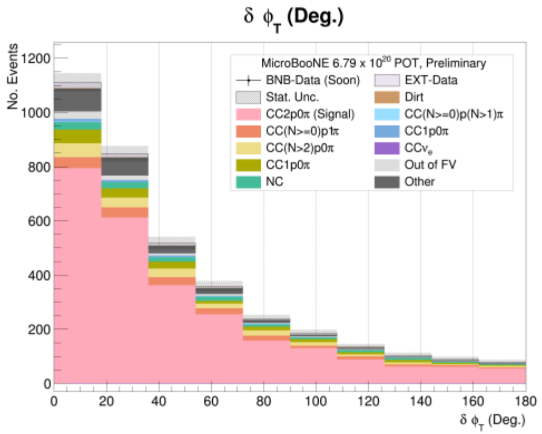
MICROBOONE SIMULATED FLUX

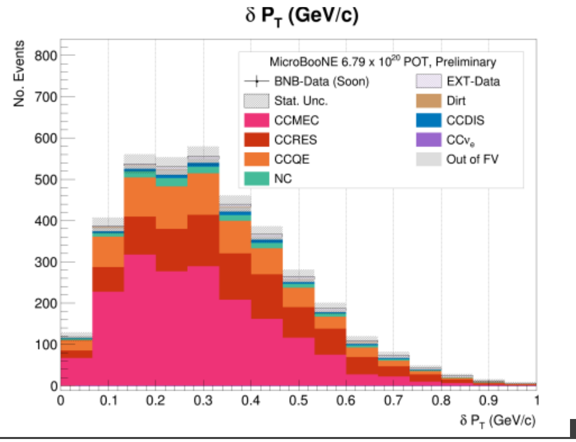
CC2P MEC STUDIES: GENIE TAGS

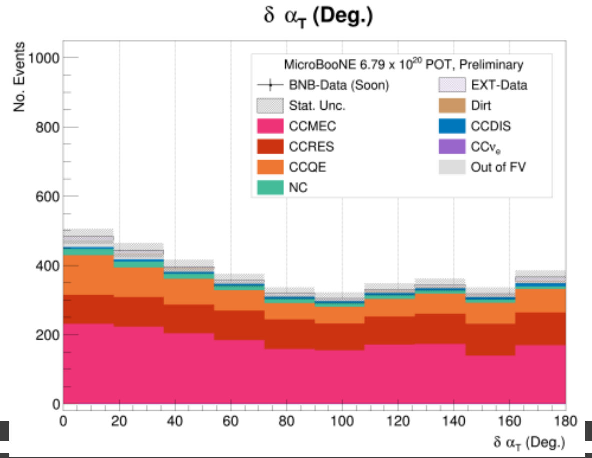
- Empirical MEC + Lwellyn Smith QE + GENIE hA2018 FSI
  - G18_02a_00_000
- Nieves (QE + MEC) + GENIE hA2018
  - G18_10a_02_11a
- SuSAv2 (QE+MEC) + GENIE hN2018
  - G21_11b_00_000

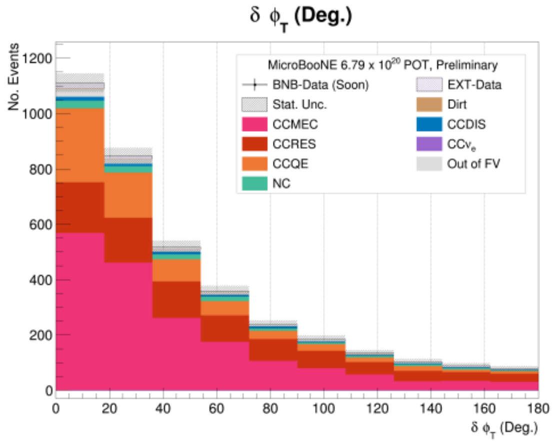












CC2P: STVS

MICROBOONE-NOTE-1096-PUB

Note: Leading and Recoil Proton Momentum added together