Recent MicroBooNE Cross-section Results: Neutrino-Induced Baryon Production

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On behalf of the μBooNE collaboration

NuFACT 2022

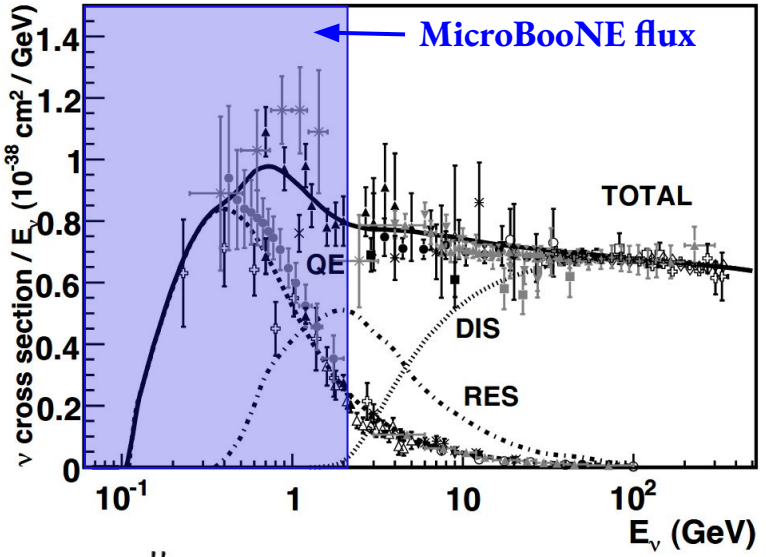
Argonne NATIONAL LABORATORY

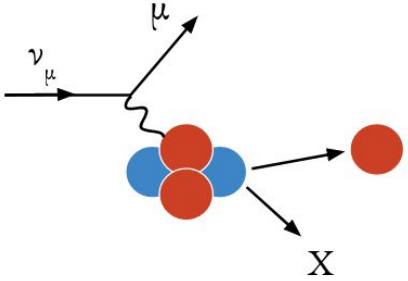
Need for Accurate Understanding of Neutrino Interactions

- Broad neutrino spectra
- Various complex interaction mechanisms

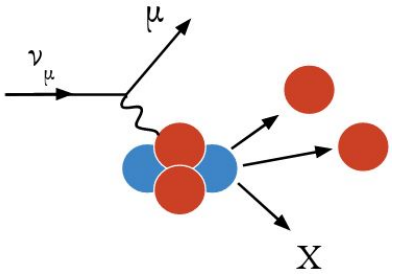
- Mismodeling can limit experimental sensitivity

Rev. Mod. Phys. 84, 1307 (2012)

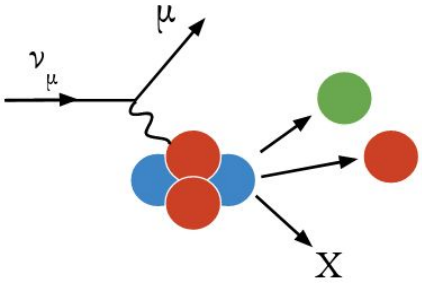




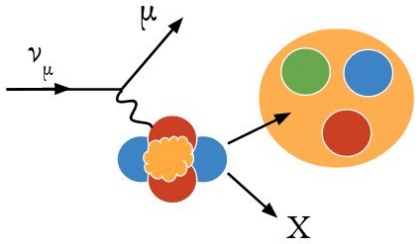
Quasi-elastic (QE)



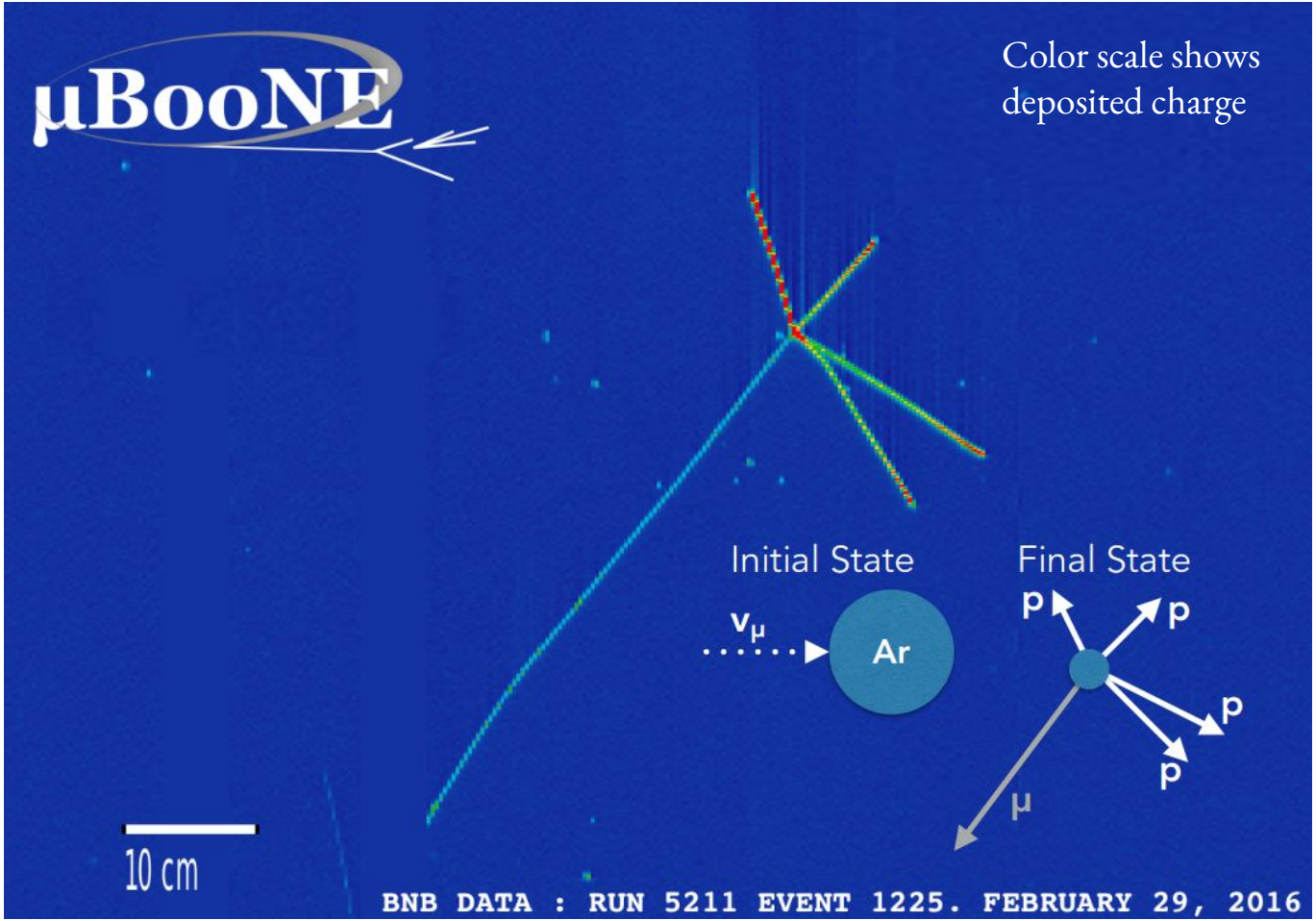
Meson Exchange Current (MEC)



Resonance (RES)

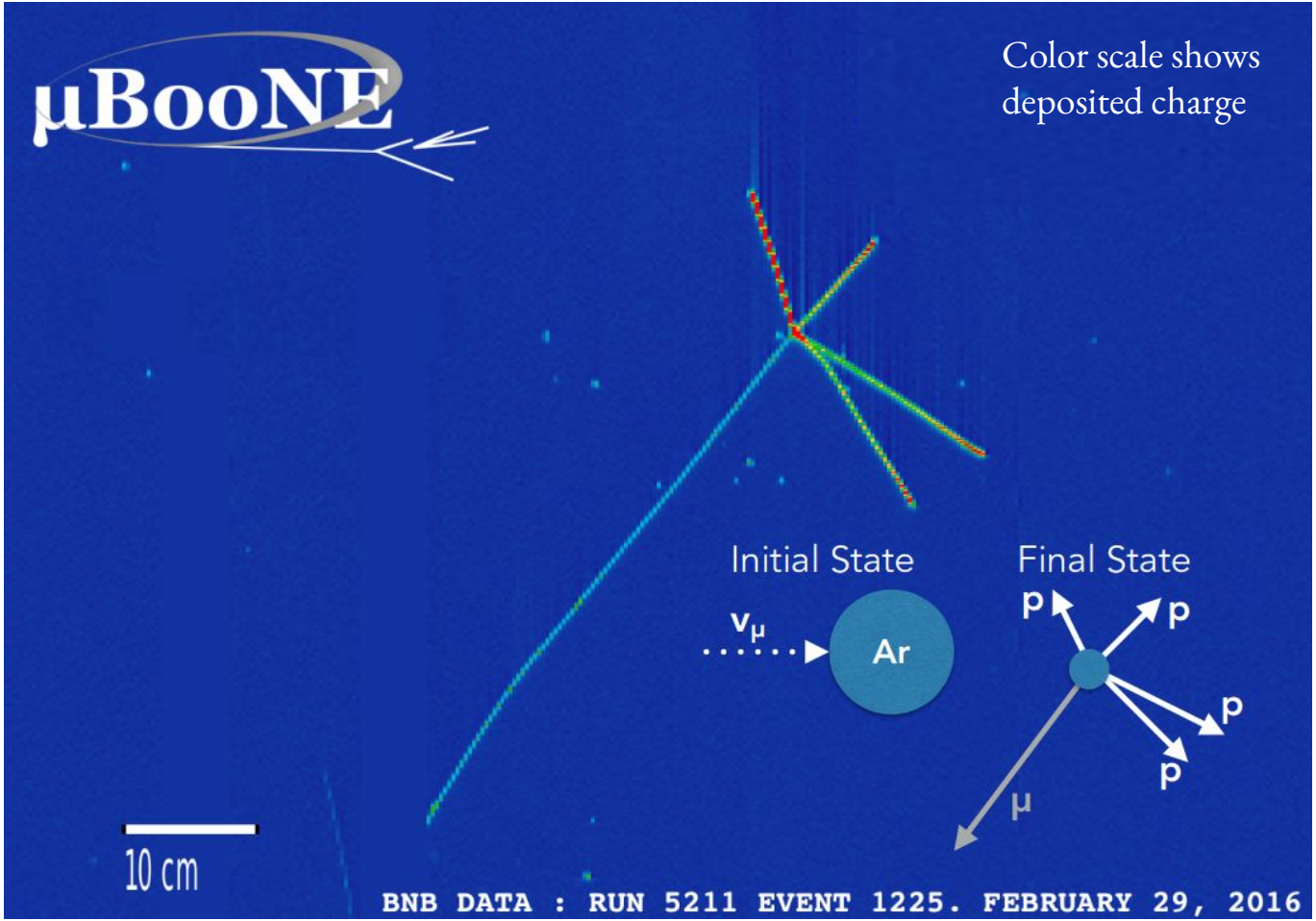


Deep Inelastic Scattering (DIS)



- Liquid argon time projection chamber (LArTPC) like SBN & DUNE
- Low detection thresholds
- Precise calorimetric information

Also see talks by S.Gollapinni & M.Ross-Lonergan



- Largest available neutrino-argon data set with ~500k recorded neutrino interactions

Also see talks by X.Ji, E.Gramellini & K.Sutton

- ~35 active MicroBooNE cross-section analyses
- Many focus on topologies with detected hadrons

Hadronic Energy Modeling Is Crucial for Neutrino Calorimetry

- Oscillation measurements require understanding of energy-dependent event rates

"Easy" "Hard"

$$E_\nu = E_\ell + \omega$$

- $E_{Cal} \simeq E_\nu$: add up everything & correct for missing energy

$$\omega = E_{had} + E_{miss}$$

- E_{miss} can be a large fraction of the total

Hadronic Energy Modeling Is Crucial for Neutrino Calorimetry

- Oscillation measurements require understanding of energy-dependent event rates

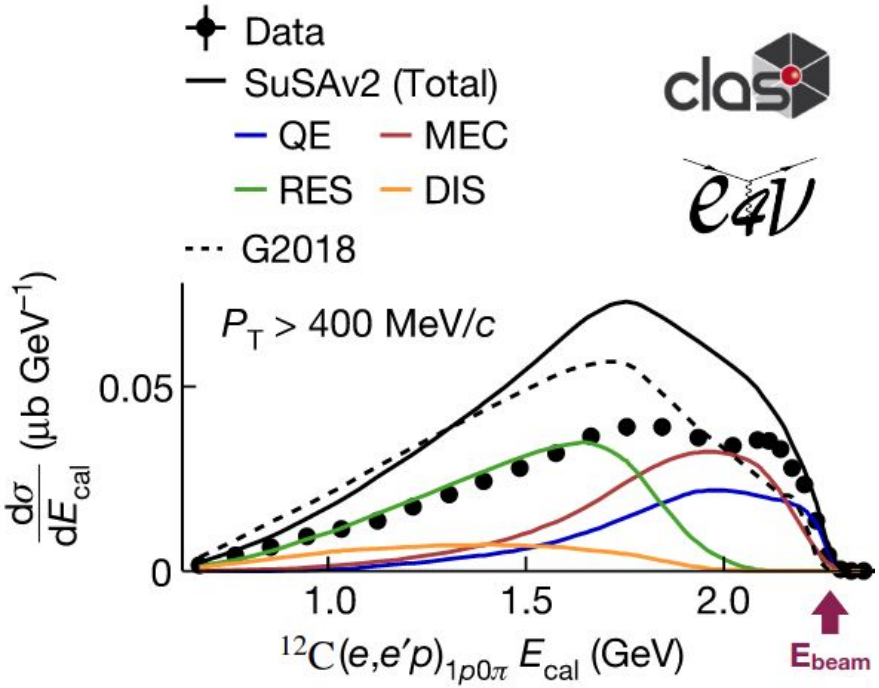
"Easy" "Hard"

$$E_\nu = E_\ell + \omega$$

- $E_{Cal} \simeq E_\nu$: add up everything & correct for missing energy

- Current simulations do not describe the bias well
- Benchmarked with electron beam data (monoenergetic, high-statistics)

Nature 599, 565–570 (2021)

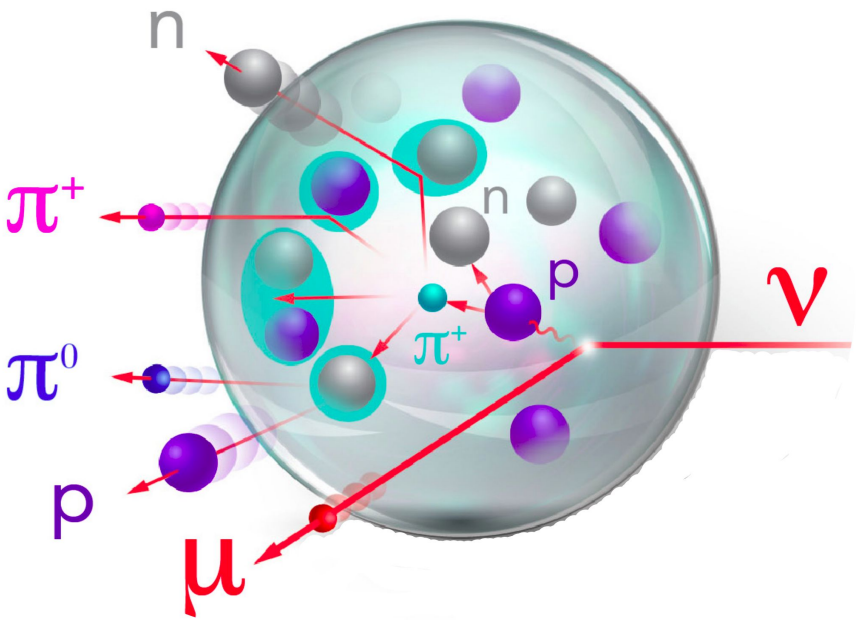


Also see talks by N.Rocco, S.Gardiner, V.Pandey, W.Ketchum & A.Papadopoulou

Answering Key Hadronic Modeling Questions With MicroBooNE

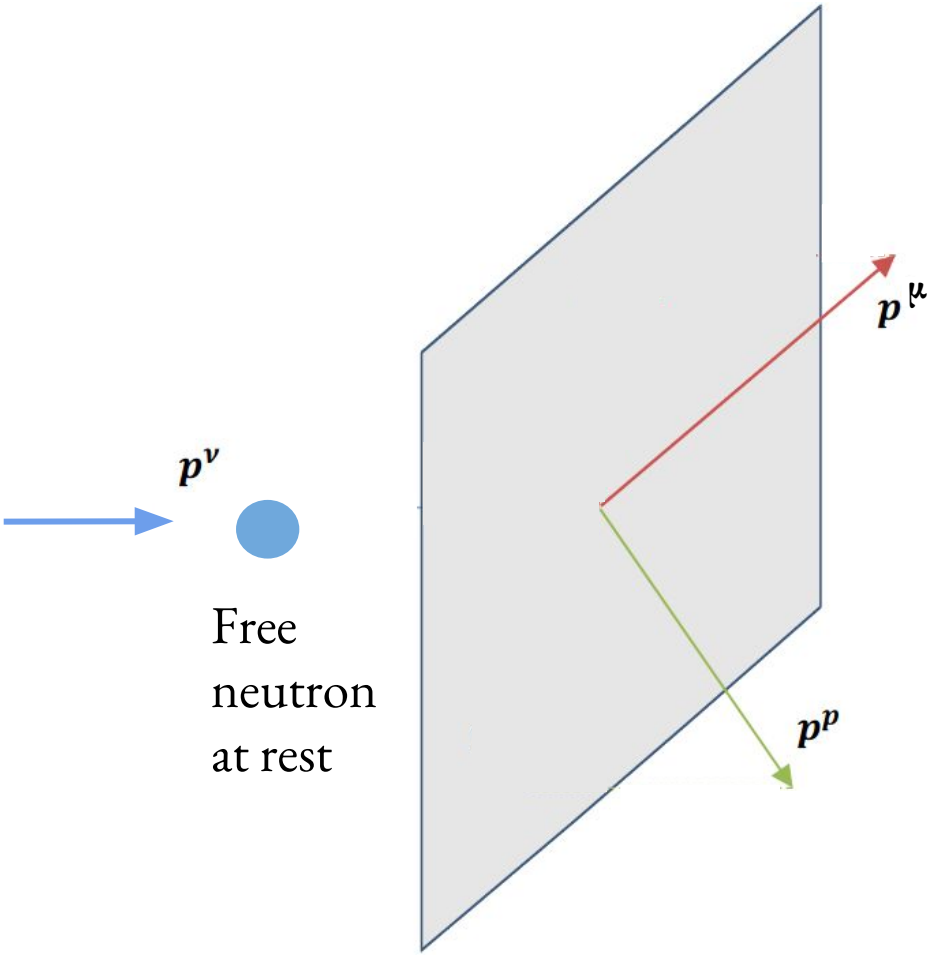
Four examples with baryons in this talk

- Transverse kinematic imbalance
- Two-proton final states
- Lambda-baryon production
- Exclusive electron neutrino measurement



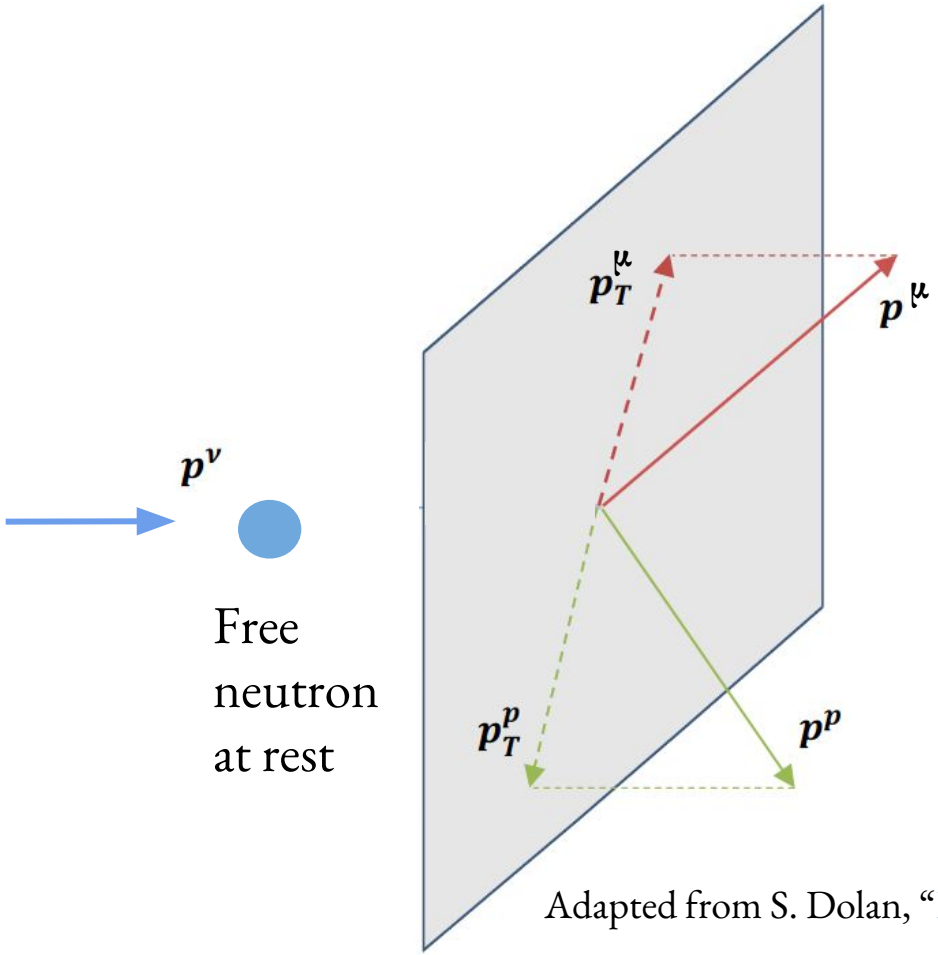
Nature 599, 565–570 (2021)

Transverse Kinematic Imbalance (TKI)



Free
neutron
at rest

Transverse Kinematic Imbalance (TKI)



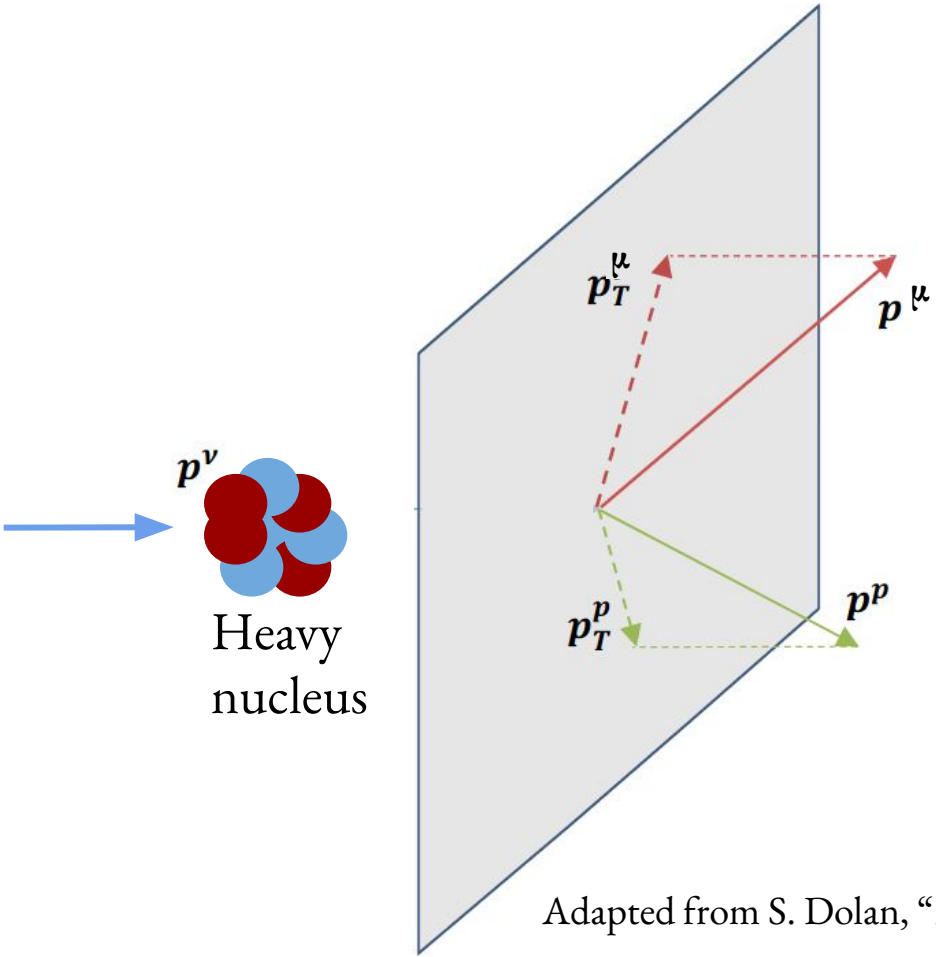
Free neutron at rest

- $\delta p_T = | \mathbf{p_T}^{\mu} + \mathbf{p_T}^{p} | = 0$

Transverse projections equal and opposite due to momentum conservation

Adapted from S. Dolan, "Exploring nuclear effects with transverse imbalances"

Transverse Kinematic Imbalance (TKI)

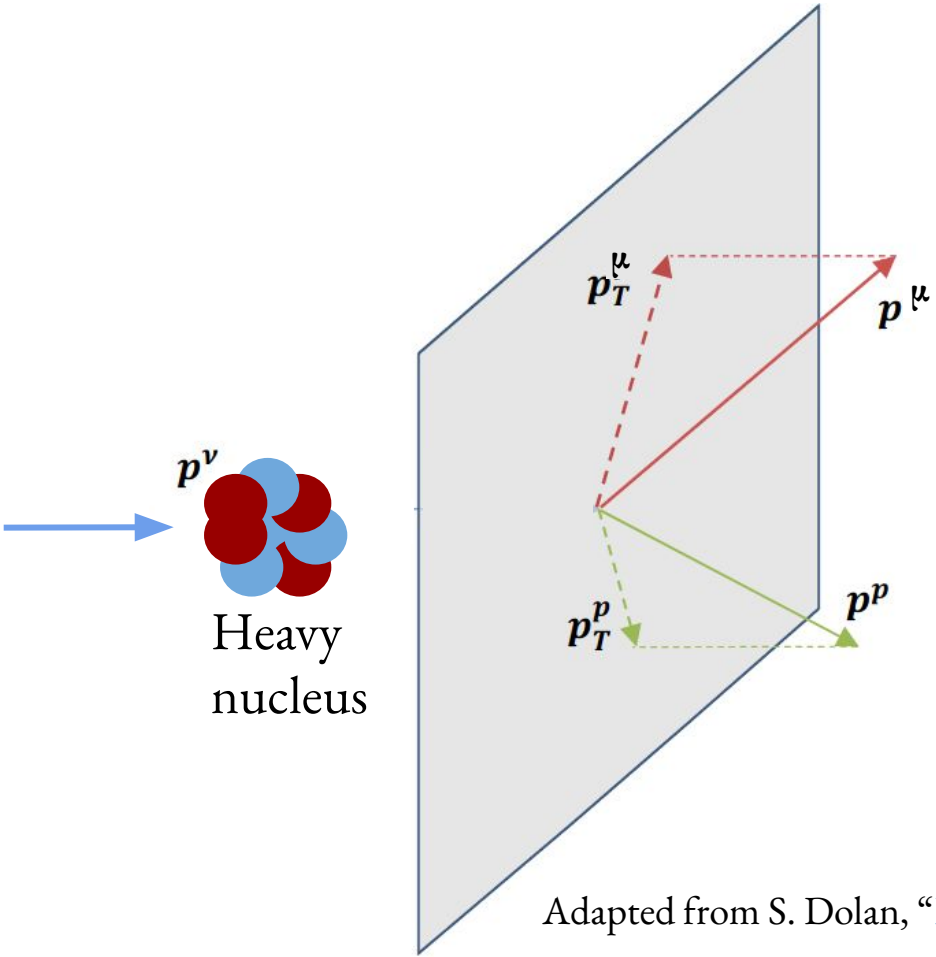


- $\delta p_T = | \mathbf{p_T}^{\mu} + \mathbf{p_T}^{p} | > 0$

Imbalance due to initial nucleon motion and other nuclear effects

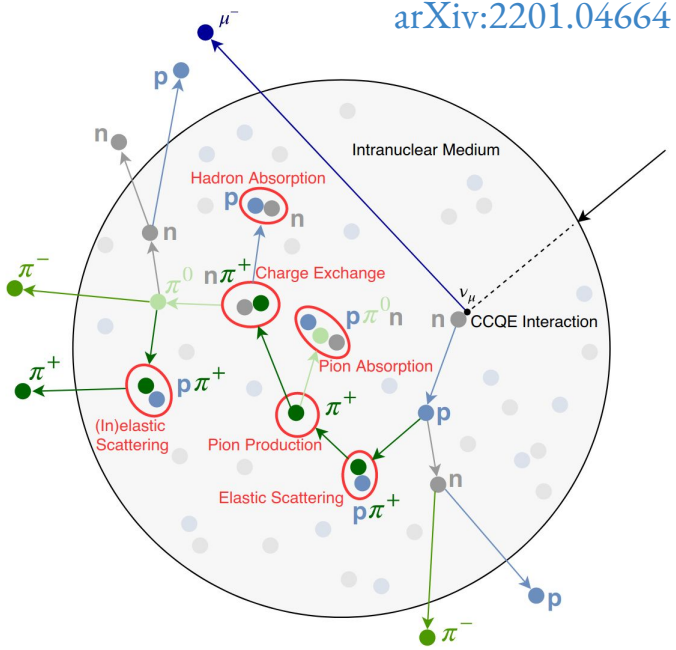
Adapted from S. Dolan, "Exploring nuclear effects with transverse imbalances"

Transverse Kinematic Imbalance (TKI)



Hadronic final-state interactions (FSI)

arXiv:2201.04664



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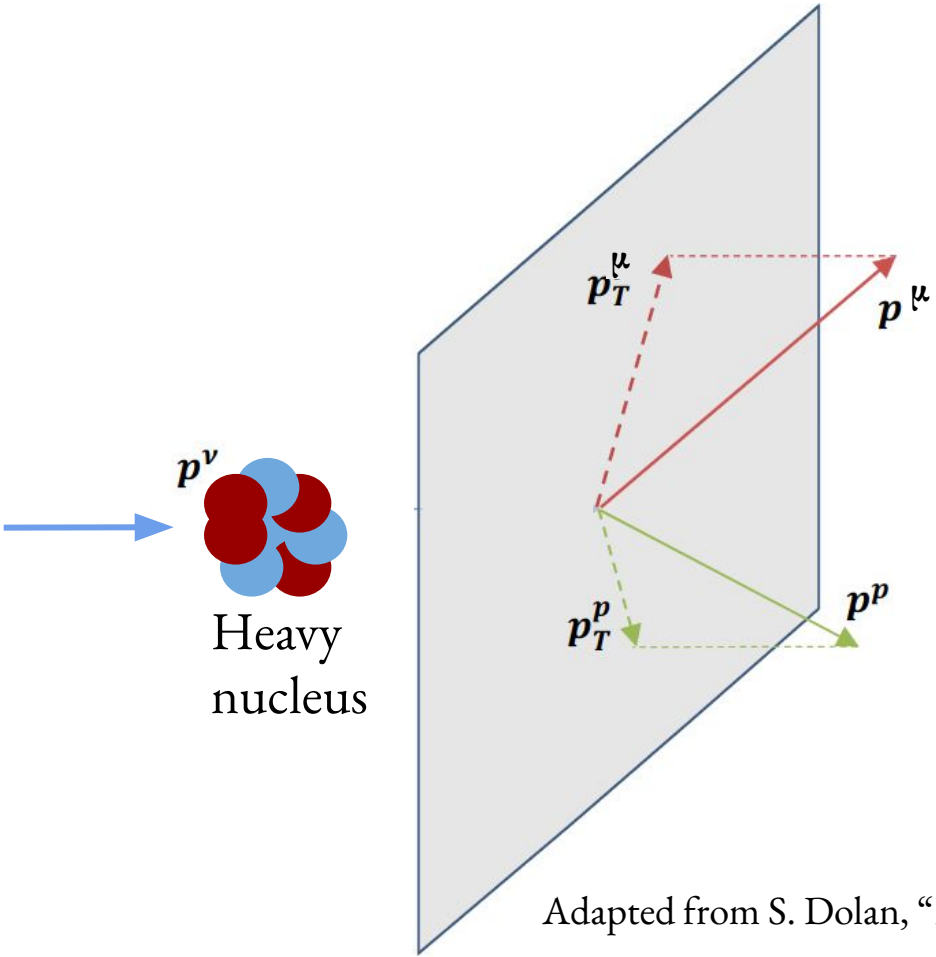
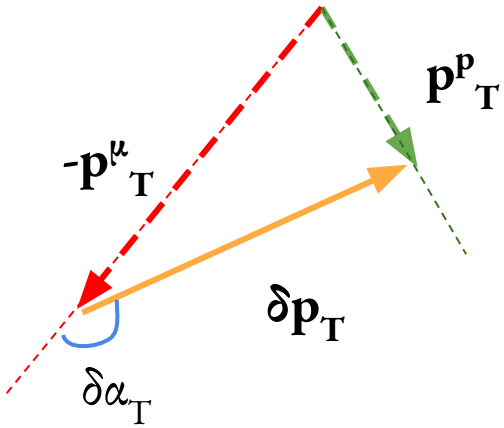


Orientation of the imbalance ($\delta\alpha_T$) also meaningful



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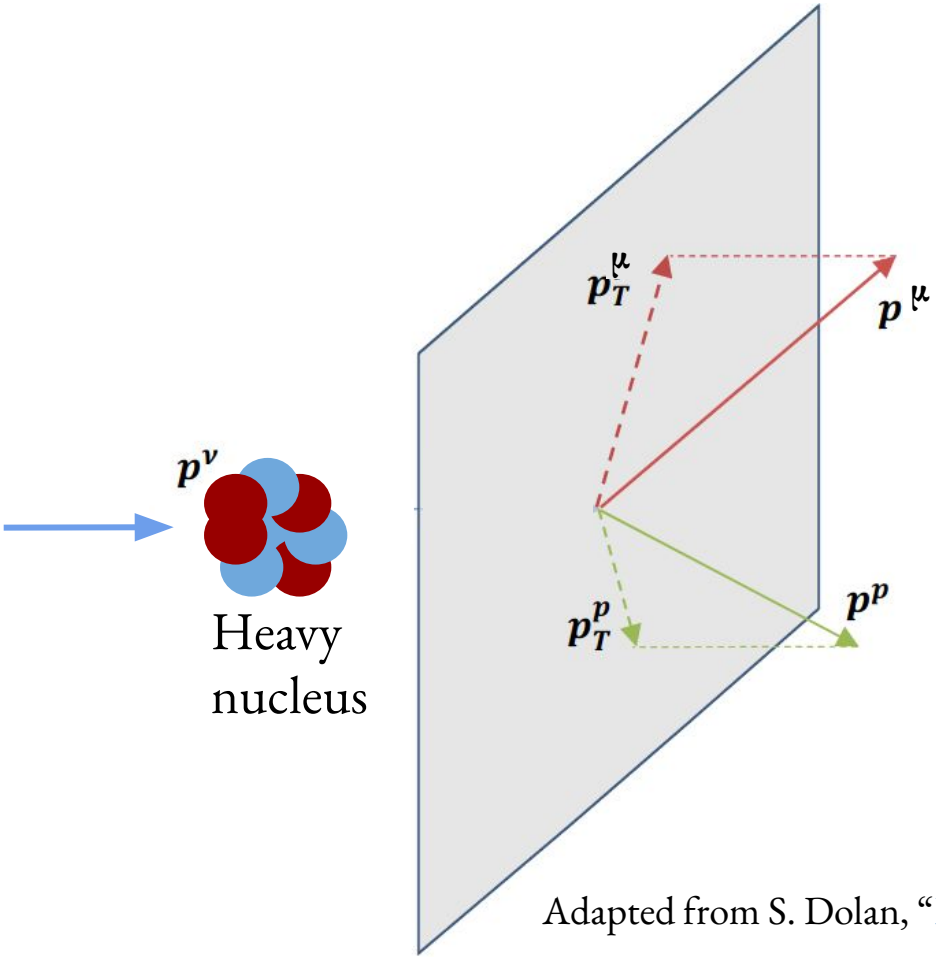
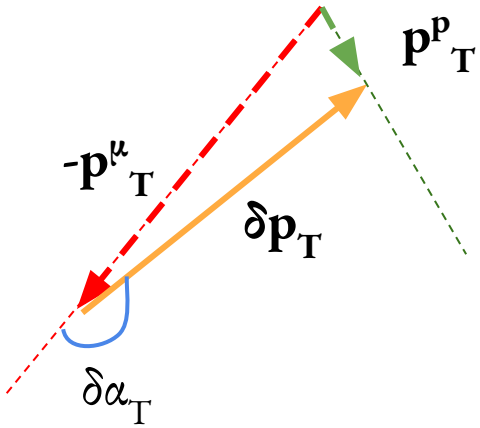


High $\delta\alpha_T$ values correspond to proton deceleration due to FSI



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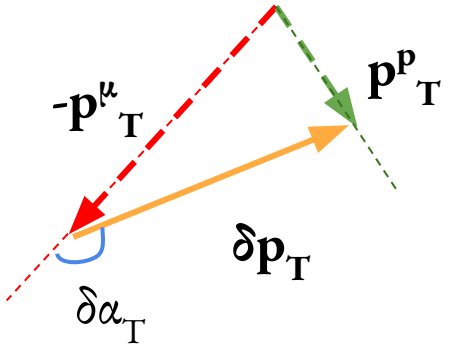
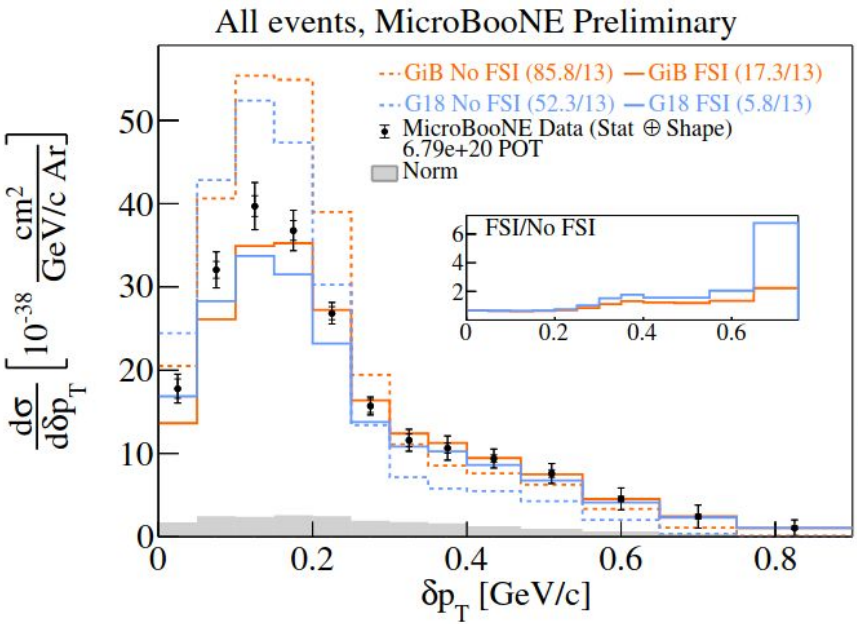
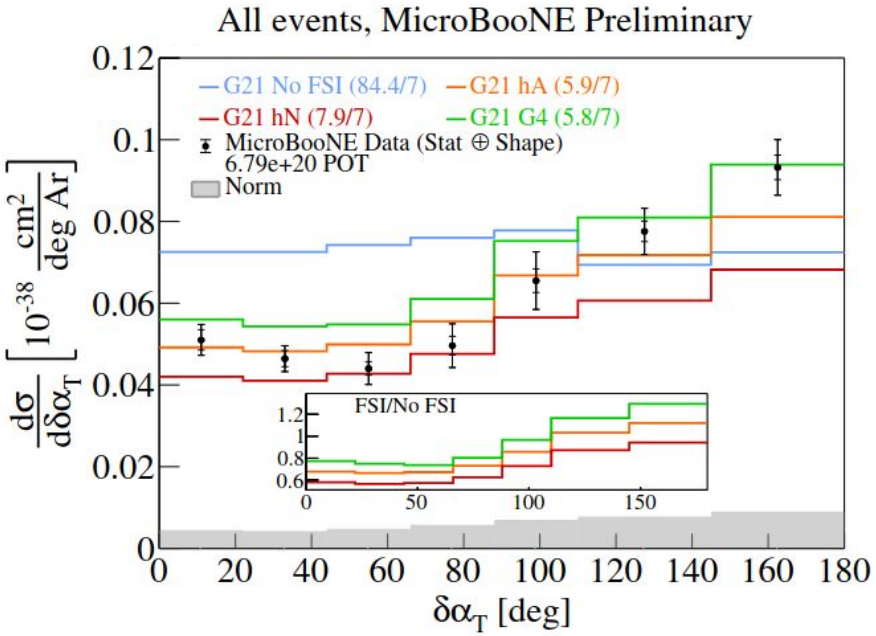
ν_μ CC1p0π TKI



- First neutrino-argon differential cross section in TKI variables
- Sensitive to initial nucleon motion & proton FSI modeling

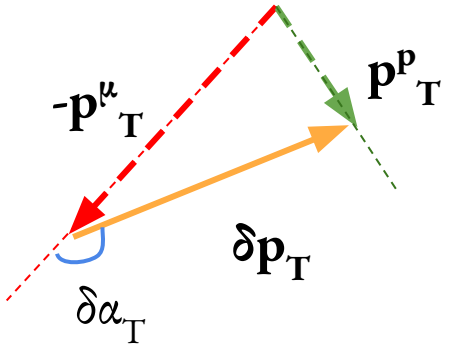


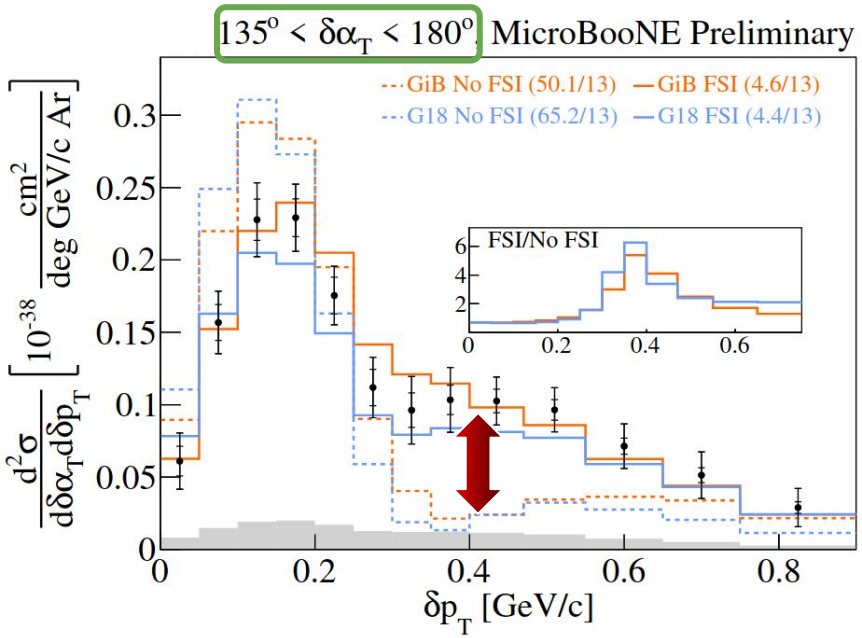


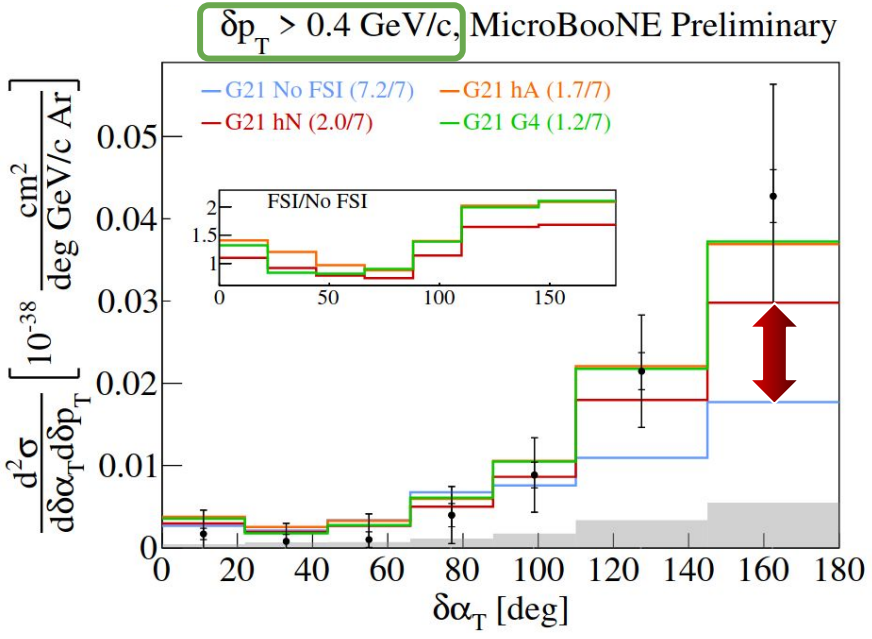
MICROBOONE-NOTE-1108-PUB Also see poster by J.Book (award winner)

ν_μ CC1p0π TKI

- Extension to 2D for the first time on any neutrino target
- Probe regions with greater model discrimination power







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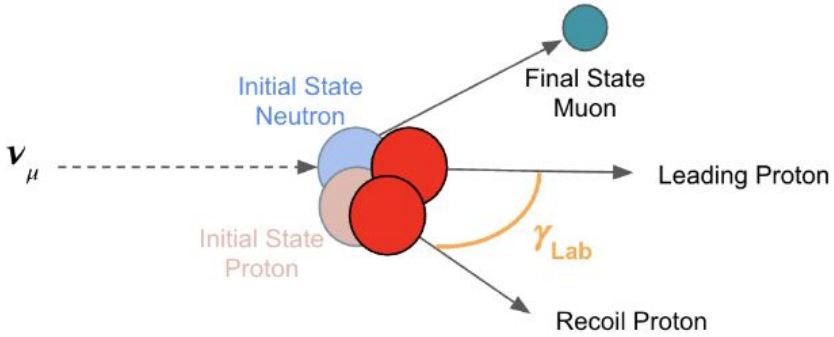
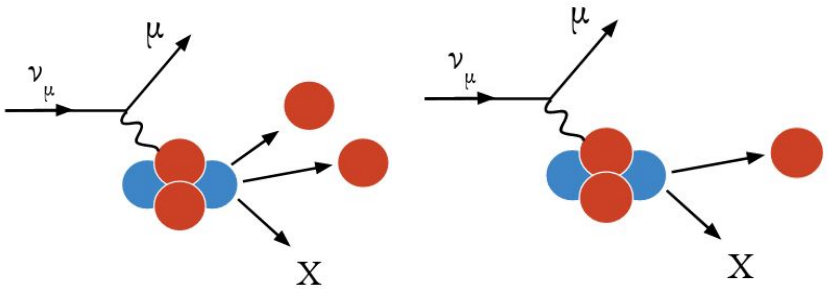
ν_μ CC2p0π



- First neutrino-argon cross sections for an exclusive 2p final state
  - Various observables studied

- γ_{Lab}: angle between the two protons
  - Sensitive to modeling choices for MEC and QE

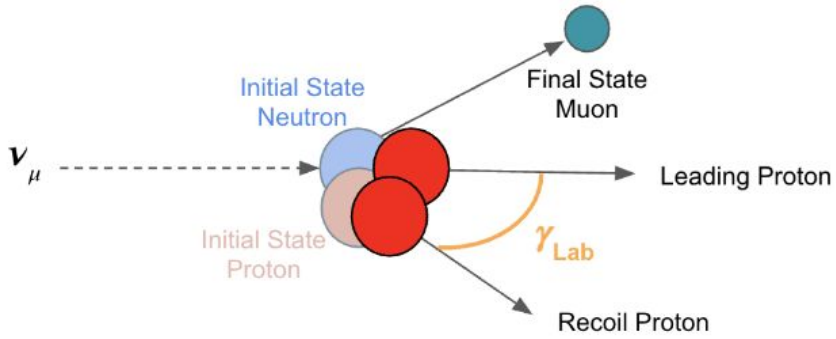


Meson Exchange Current (MEC)

Quasi-elastic (QE)

MICROBOONE-NOTE-1117-PUB

ν_μ CC2p0π



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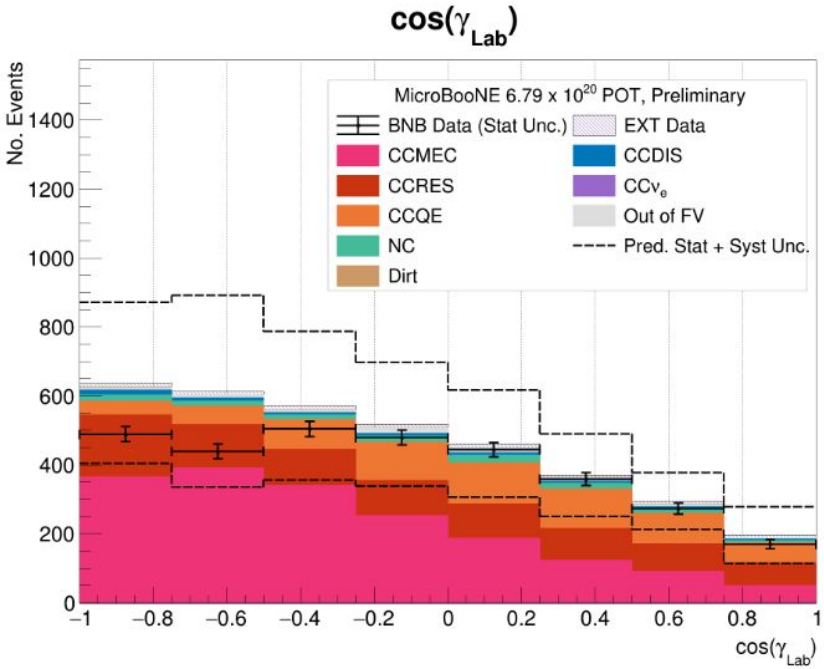
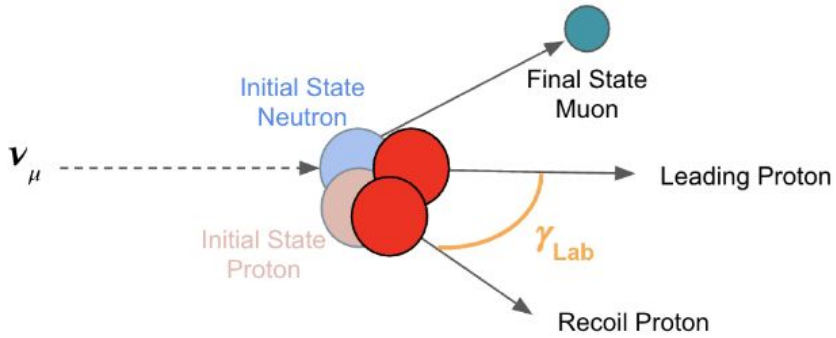
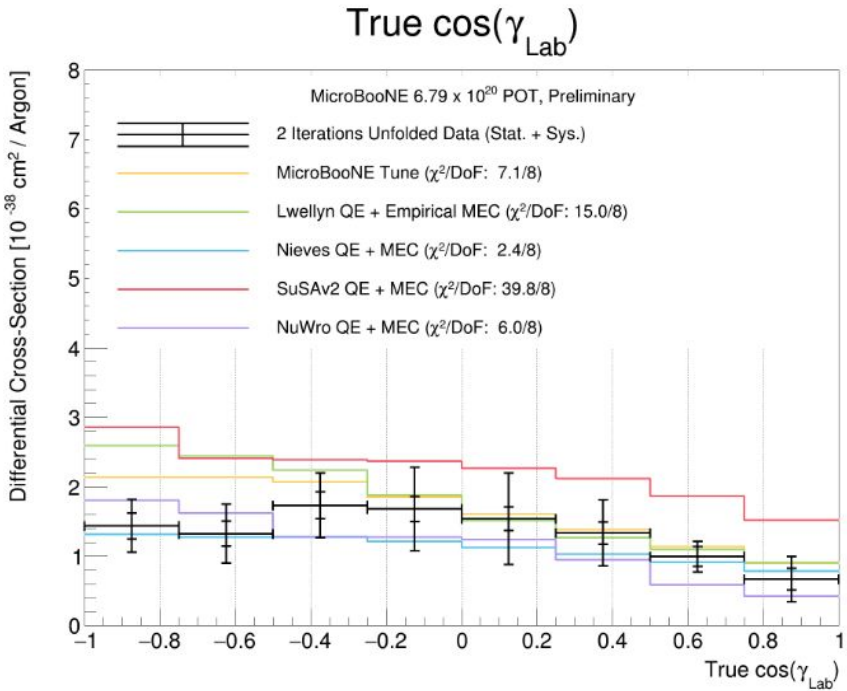


MICROBOONE-NOTE-1117-PUB

ν_μ CC2p0π



- First neutrino-argon cross sections for an exclusive 2p final state
  - Various observables studied
- γ_{Lab}: angle between the two protons
  - Sensitive to modeling choices for MEC and QE
- Data-MC shape & normalization differences identified

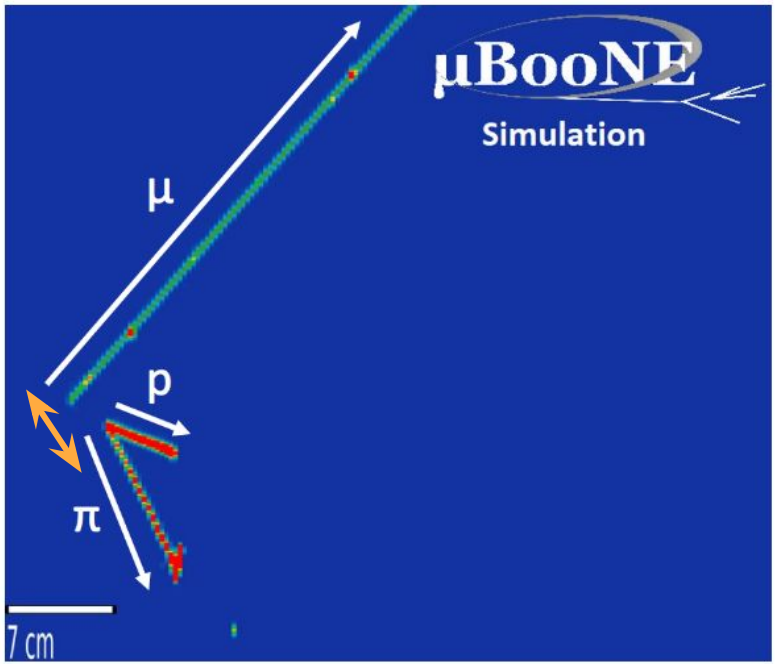


MICROBOONE-NOTE-1117-PUB

$\bar{\nu}_\mu$ Λ Production

- Cabibbo suppressed reaction
- Sensitivity to cross section modeling and final state interaction parameters
- Very distinct “track + V shape” topology
- Challenging analysis!
- Expect ~40 interactions in ~2M triggers before any selection

$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda + X$$



Also see poster by C.Thorpe

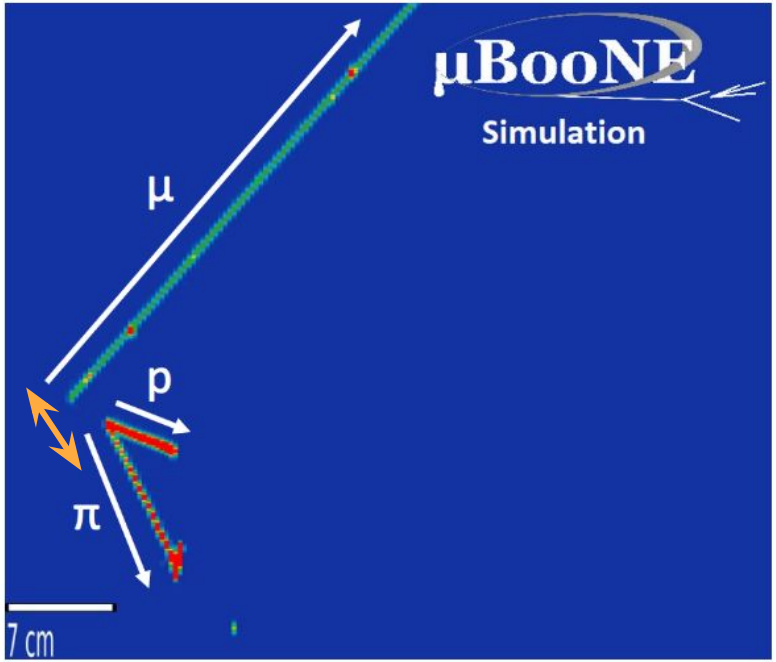
MICROBOONE-NOTE-1097-PUB

$\bar{\nu}_\mu$ Λ Production

Event Selection

- Selection identifies a muon candidate and a proton-pion candidate pair
- Proton-pion "island" activity separated from muon candidate
- Proton-pion kinematics consistency with Λ baryon decay

$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda + X$$



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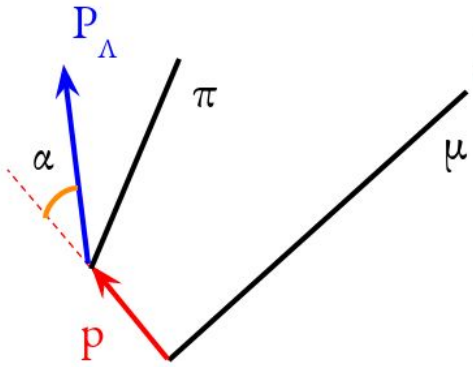
MICROBOONE-NOTE-1097-PUB

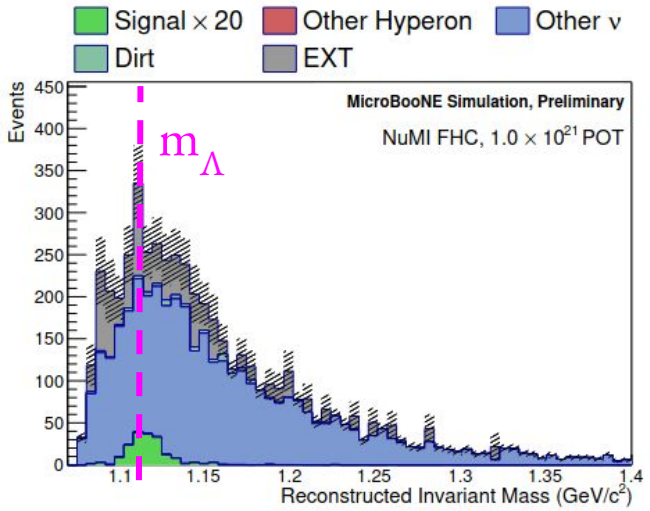
$\bar{\nu}_\mu$ Λ Production

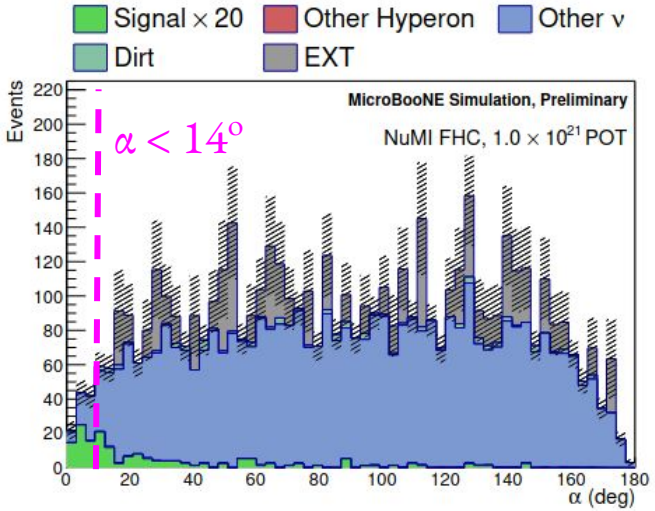
Λ baryon decay consistency

- Keeping events with
  1.09 < invariant mass W < 1.14 GeV/c^2
  and angular deviation α < 14°

- After selection
  Signal = 2.5 events
  Bkg = 2.8 events
  when initially
  Signal = ~40 events
  Bkg = ~2M events







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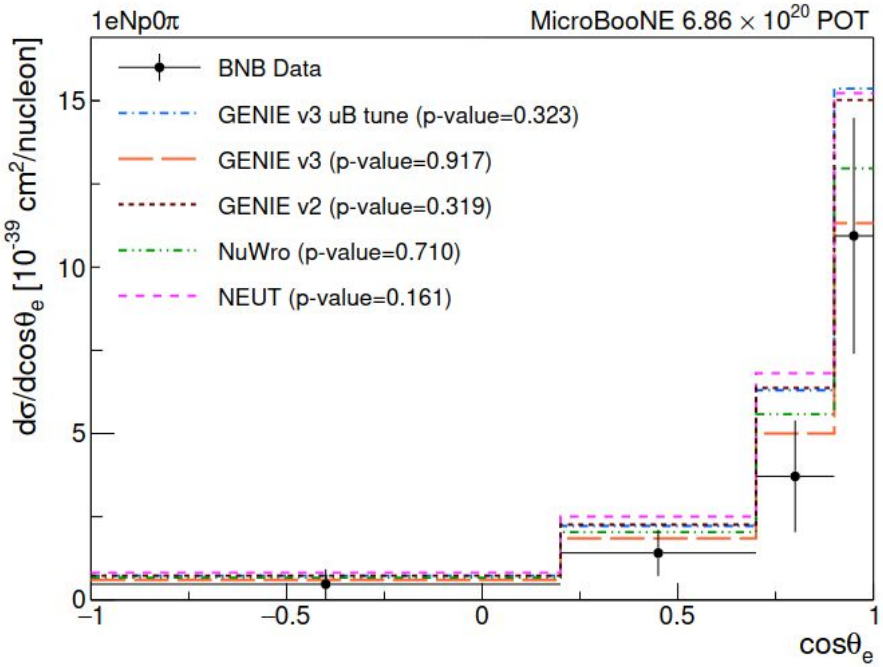
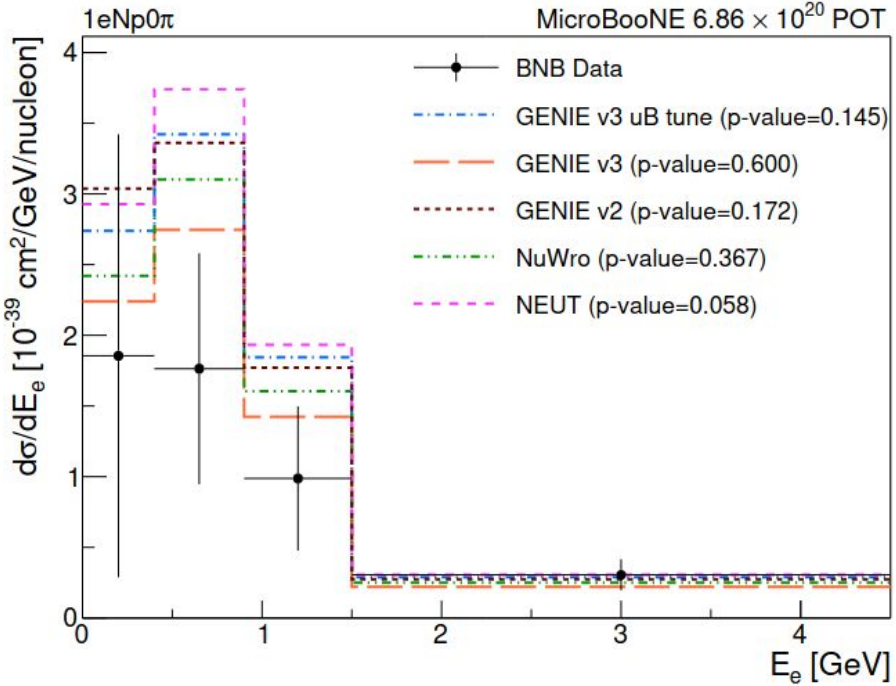
MICROBOONE-NOTE-1097-PUB

ν_e CCNp0π

- First differential measurement in lepton and leading proton kinematics
- Data shows best agreement with the generators that predict a lower overall cross section (GENIE v3, NuWro)

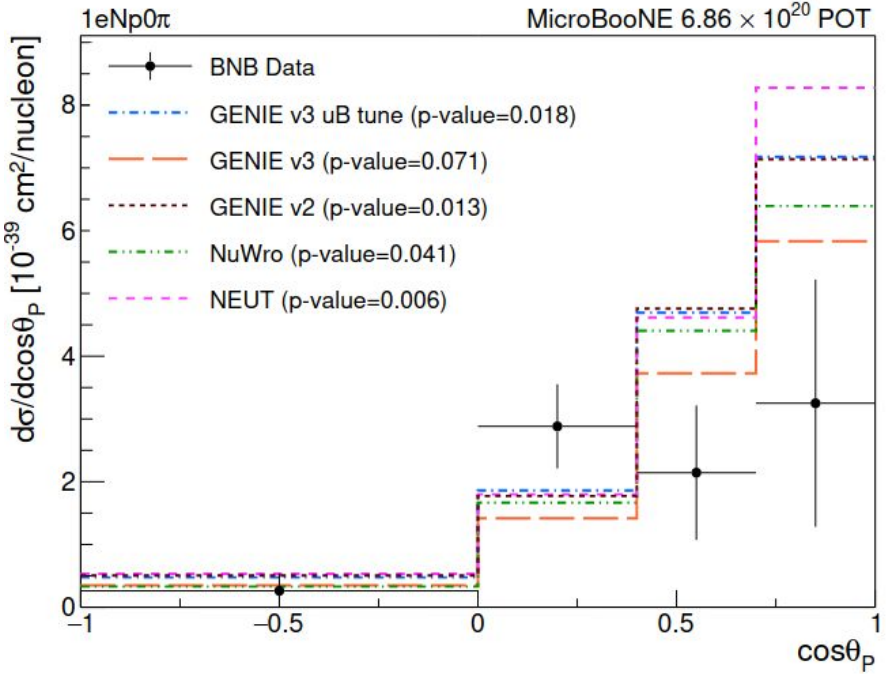


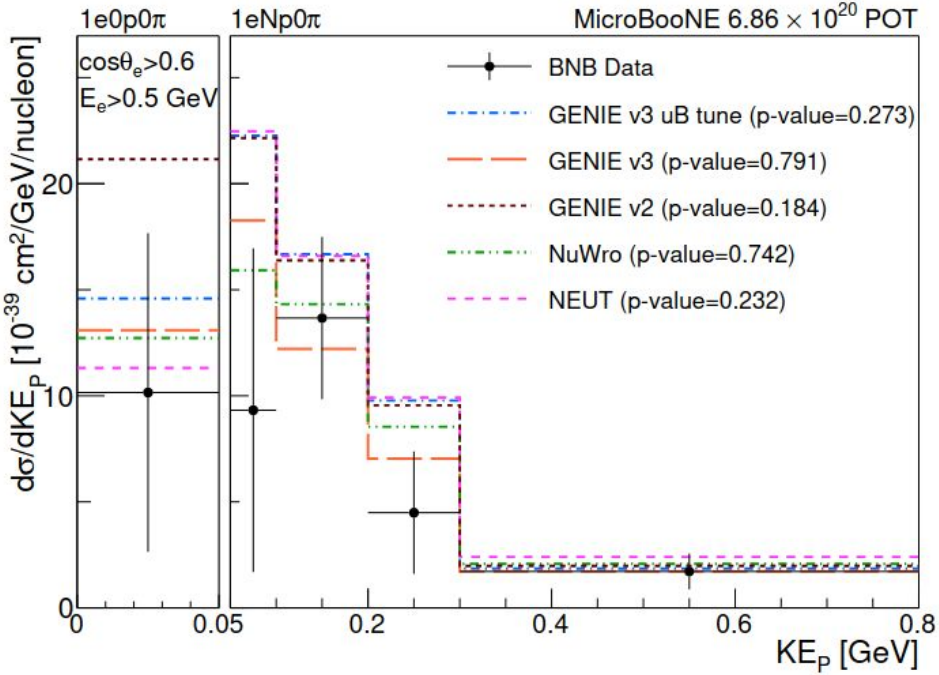


arXiv:2208.02348 (50th paper!)

ν_e CCNp0π

- First measurement to characterize proton production across the visibility threshold on argon

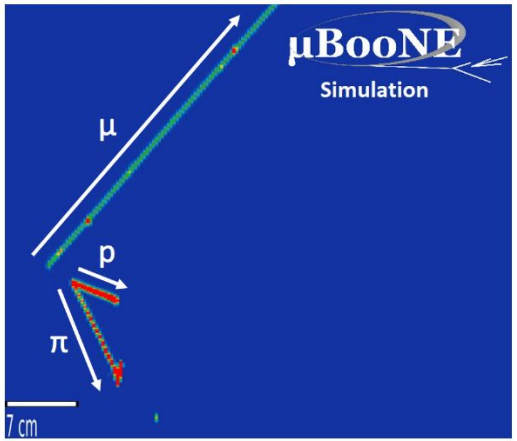


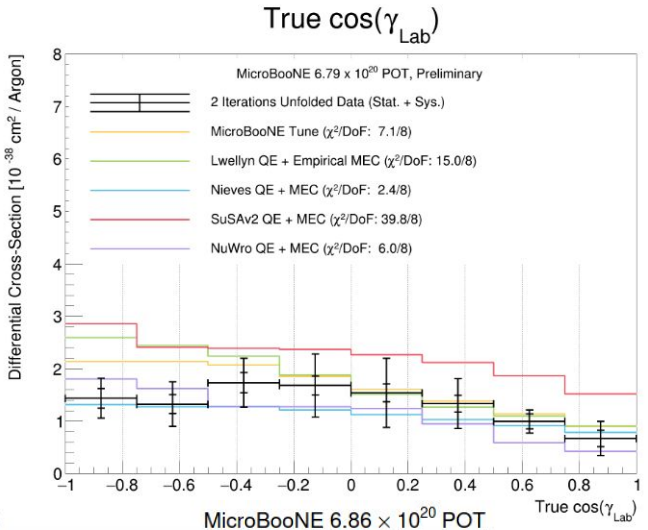


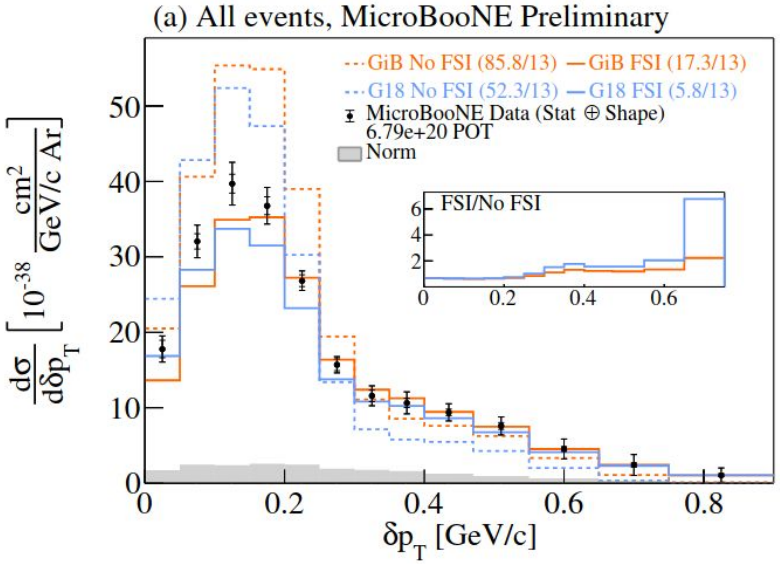
arXiv:2208.02348 (50th paper!)

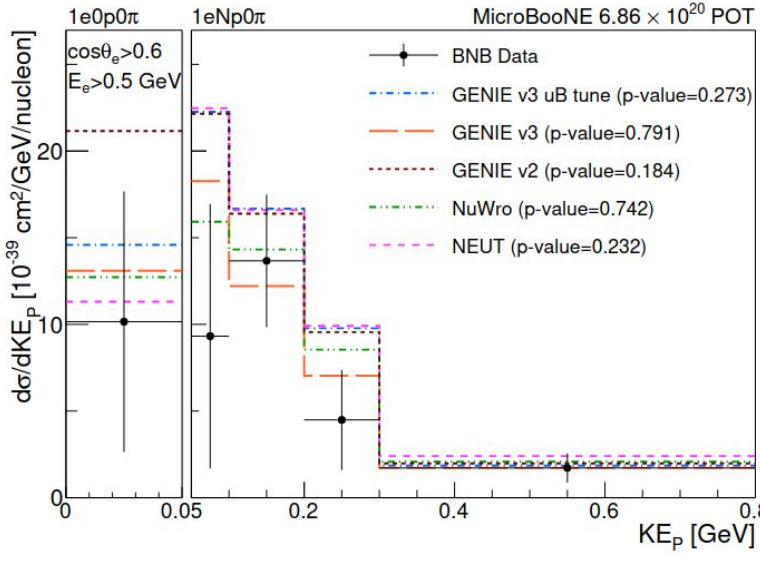
Summary

- MicroBooNE is paving the path towards high precision modeling with baryons









μBooNE

Thank you!

Backup Slides

Neutrino Experiments

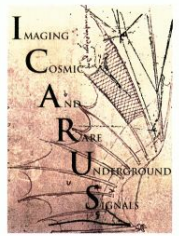
Goal: Oscillation parameter extraction with few-percent level uncertainties

Need: precise neutrino-nucleus cross-section modeling

Start: Short-Baseline Neutrino Program

Status: ~500k ν scattering events with MicroBooNE

Completed data collection

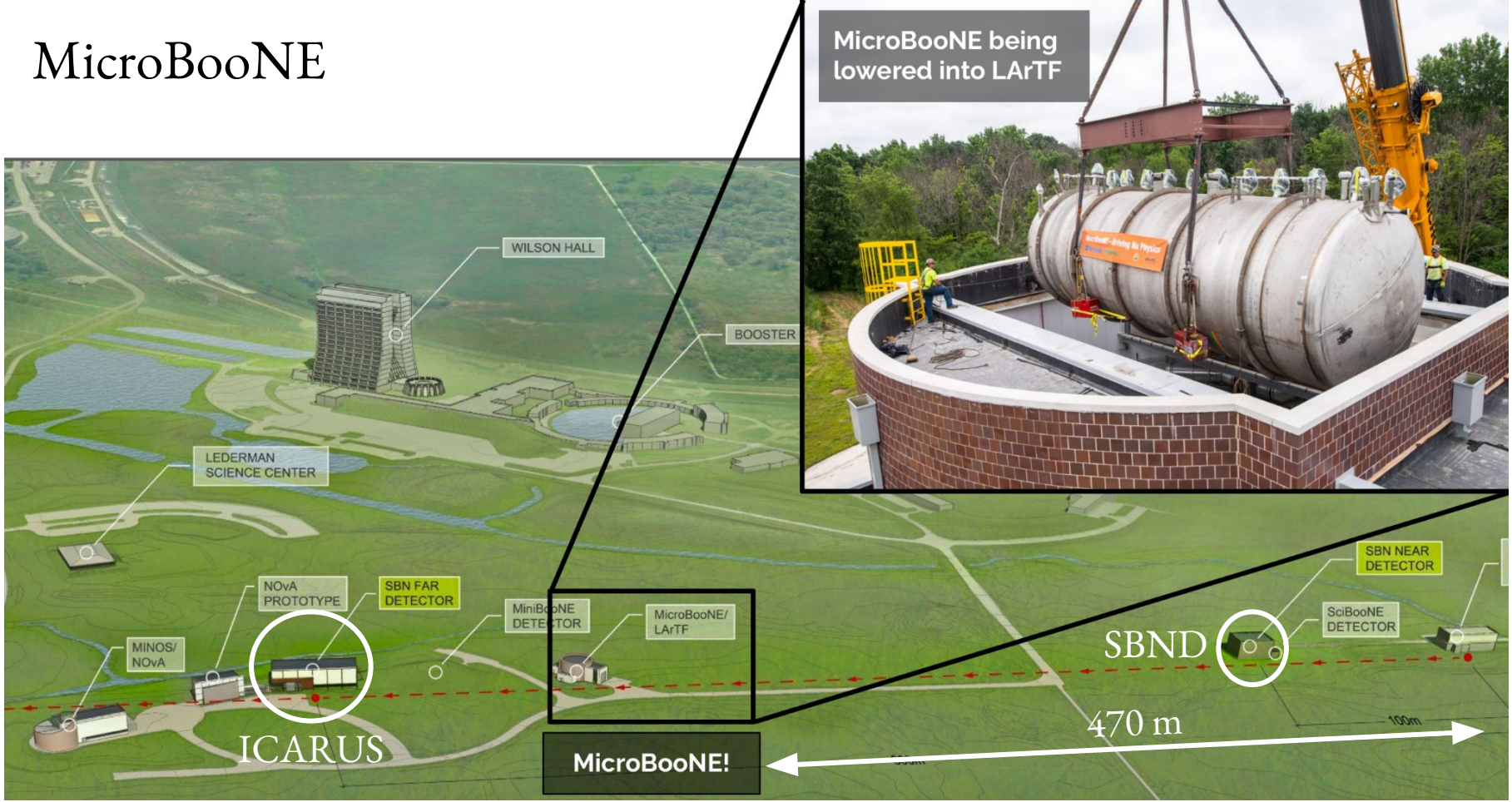


Collecting data

Data collection starts in 2023

Data collection starts in ~2030

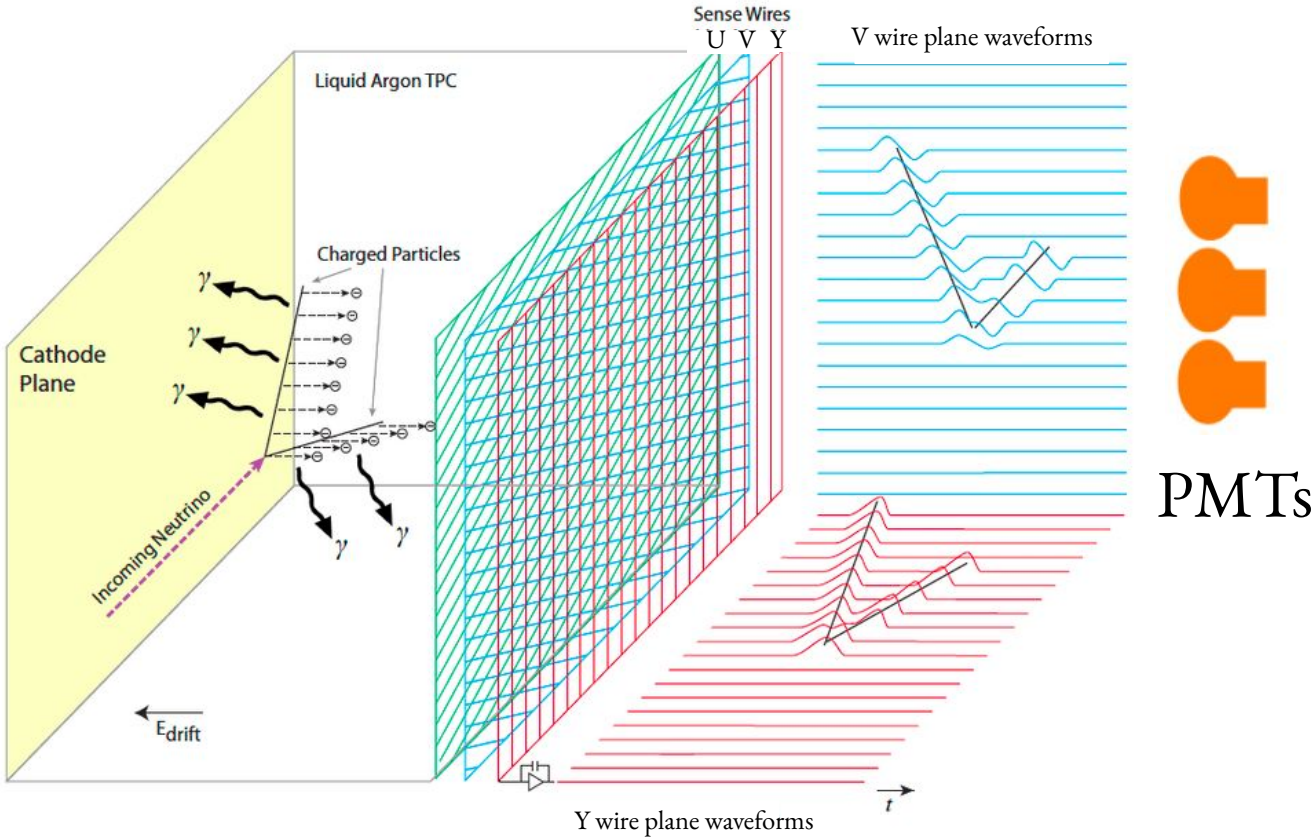
MicroBooNE



85 ton Liquid Argon Time Projection Chamber (LArTPC)

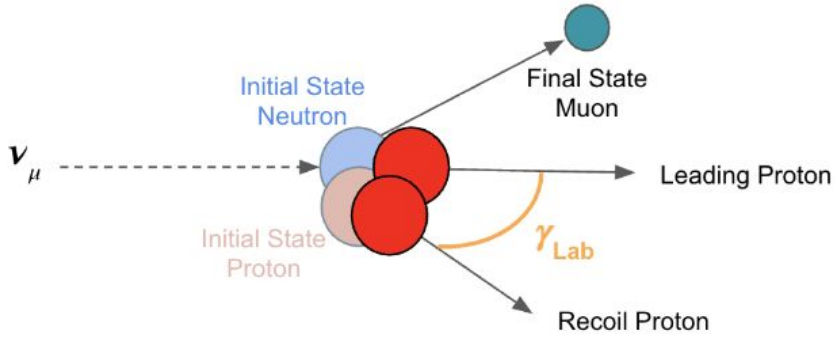
JINST 12, P02017 (2017)

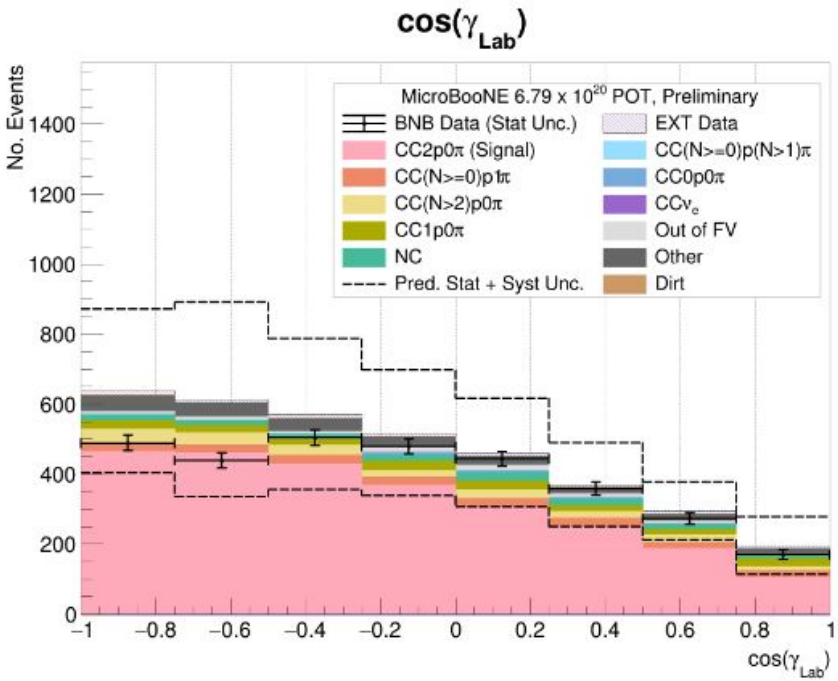
Time Projection Chambers

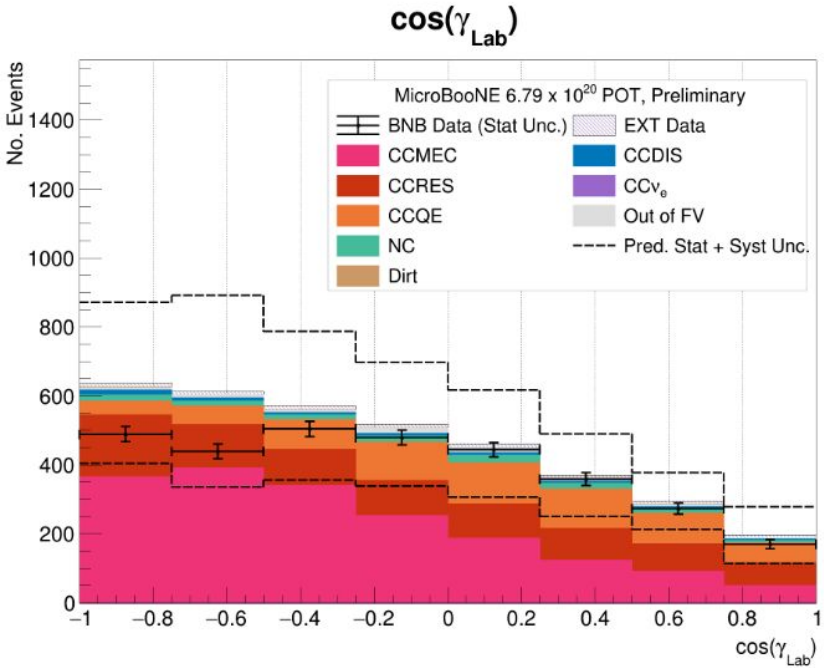


ν_μ CC2p0π

- 65% purity & 13% efficiency
- 3157 selected data events



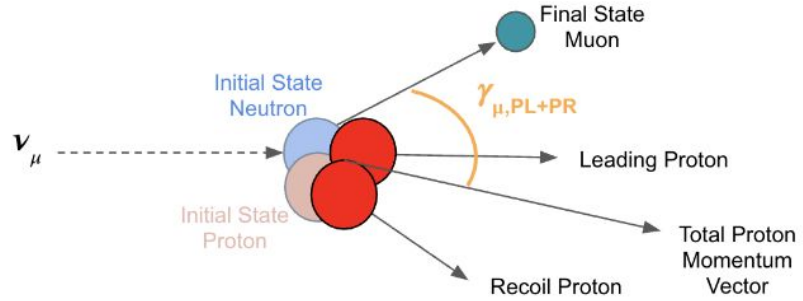


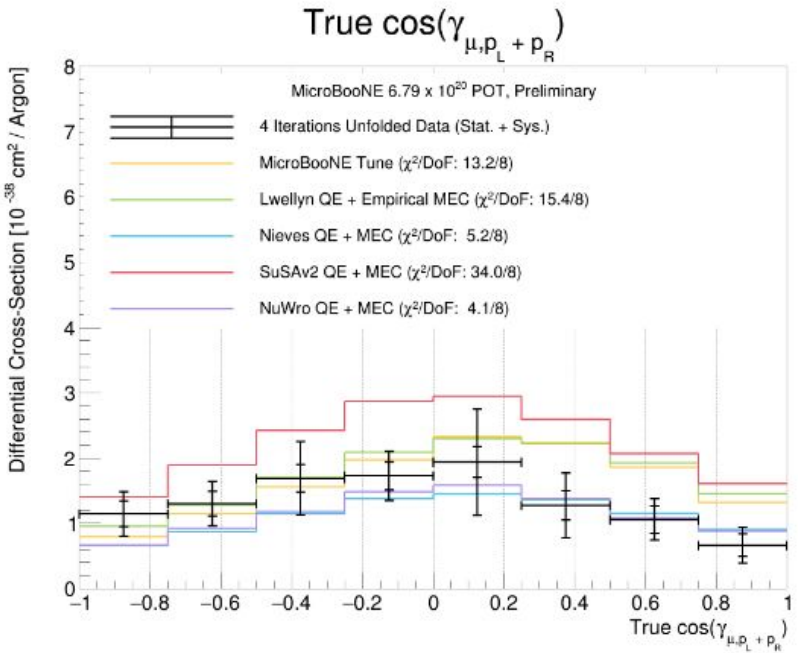


MICROBOONE-NOTE-1117-PUB

ν_μ CC2p0π

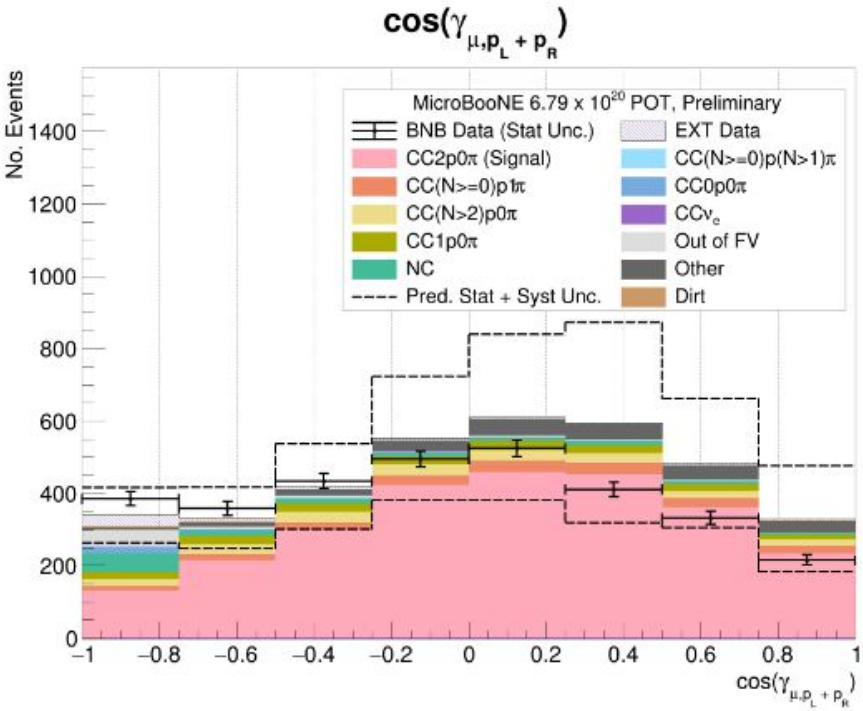
- $\gamma_{\mu,\,PL\,+\,PR}$: angle between the muon and the vector sum of the two protons
  - Sensitive to modeling choices for MEC and QE

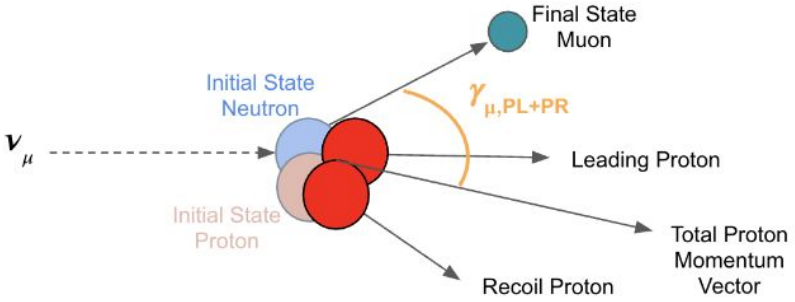


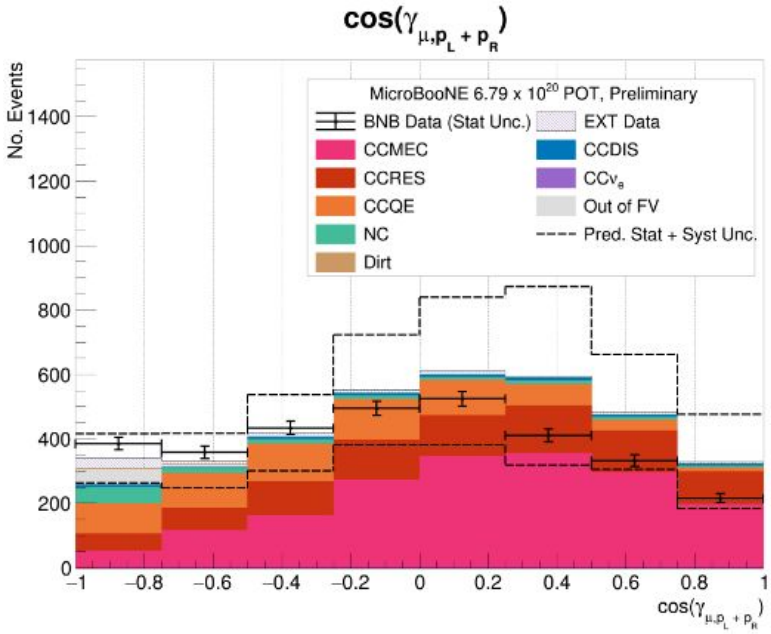


MICROBOONE-NOTE-1117-PUB

ν_μ CC2p0π

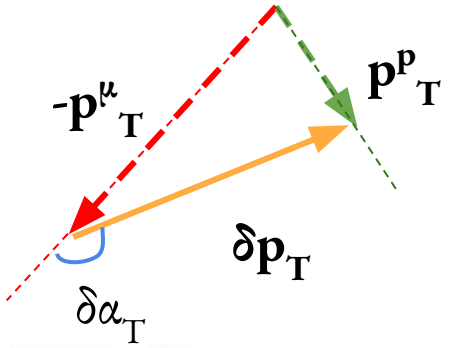


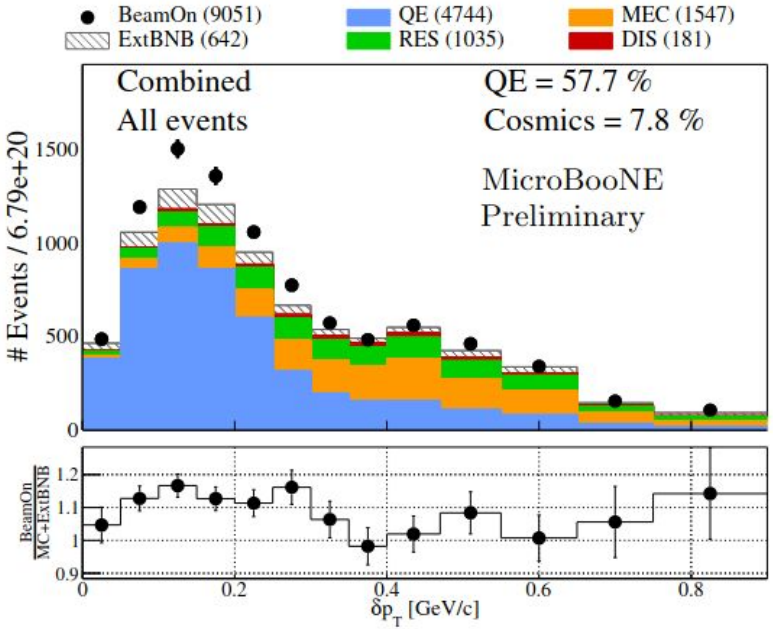


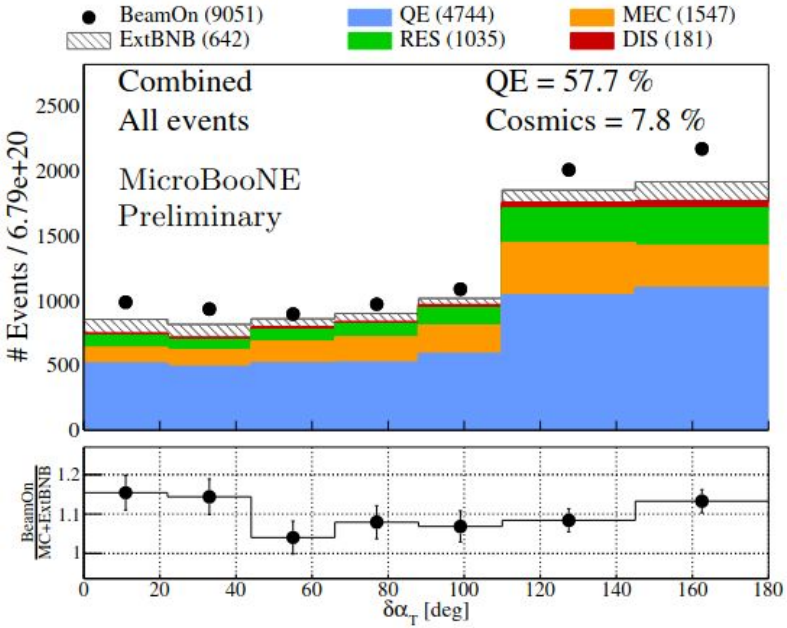


MICROBOONE-NOTE-1117-PUB

Transverse Kinematic Imbalance (TKI)

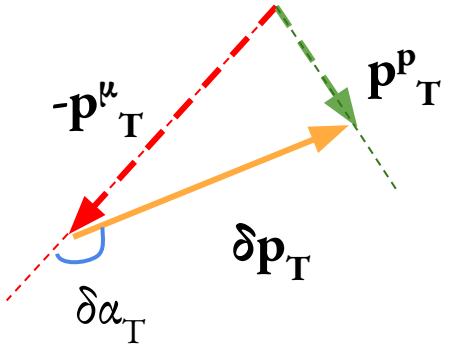


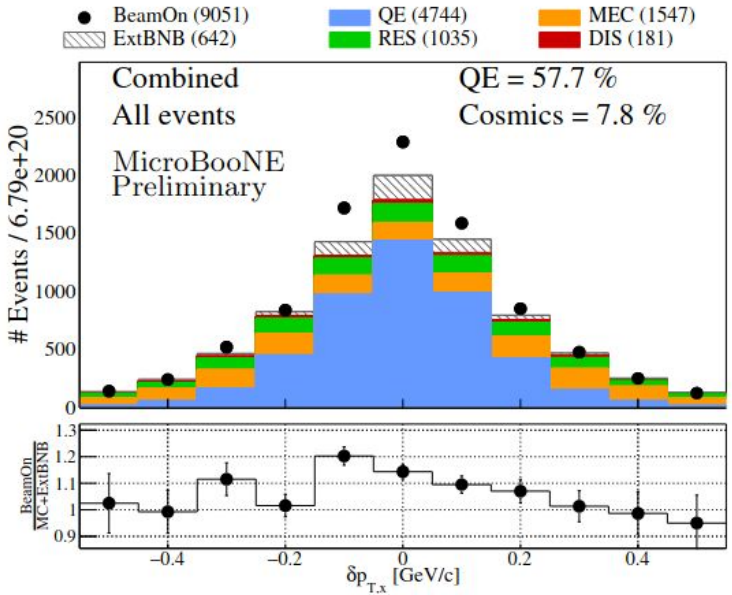


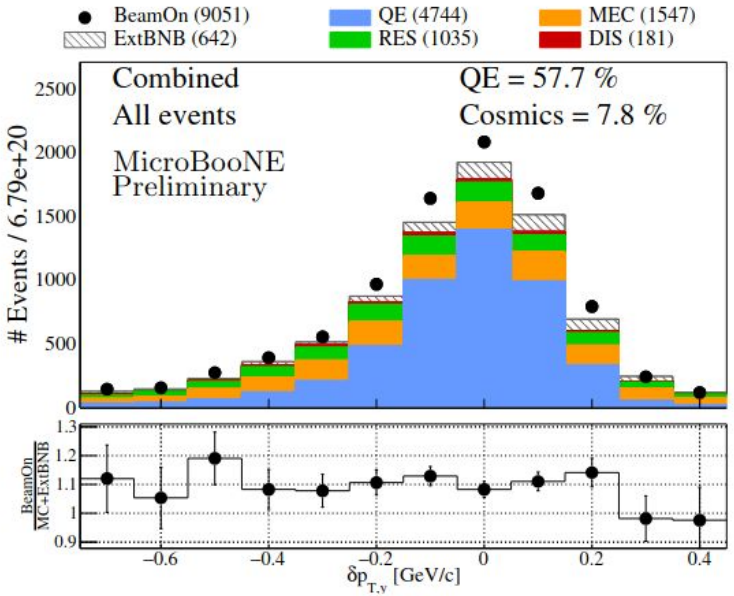


MICROBOONE-NOTE-1108-PUB

Transverse Kinematic Imbalance (TKI)

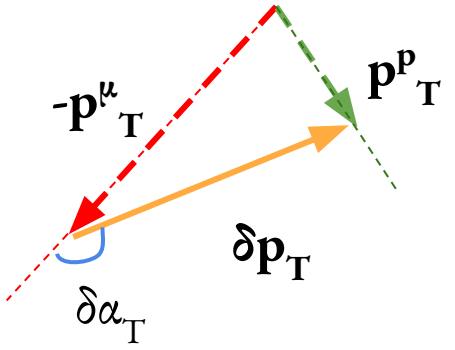


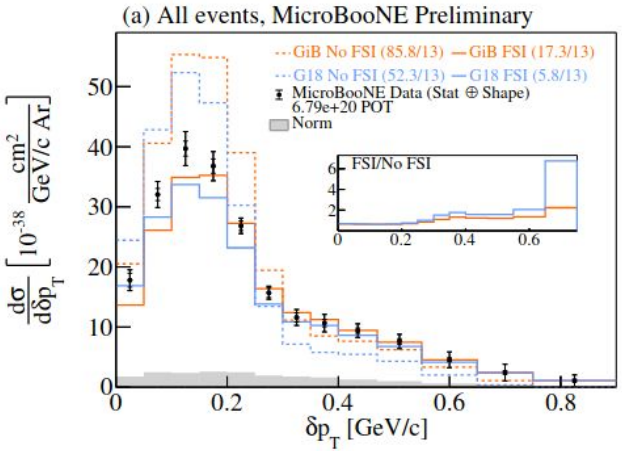


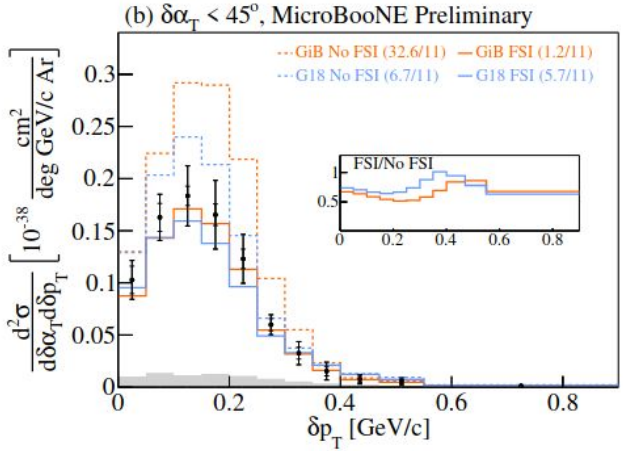


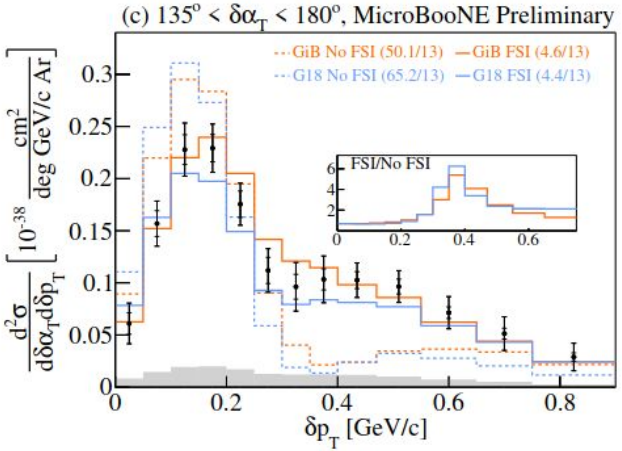
MICROBOONE-NOTE-1108-PUB

Transverse Kinematic Imbalance (TKI)



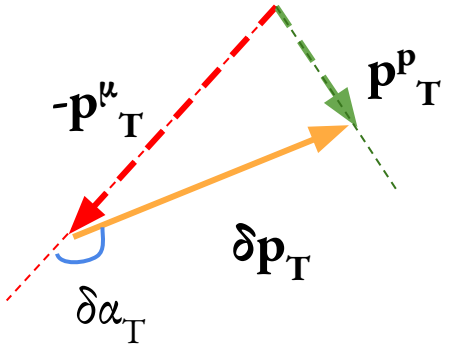


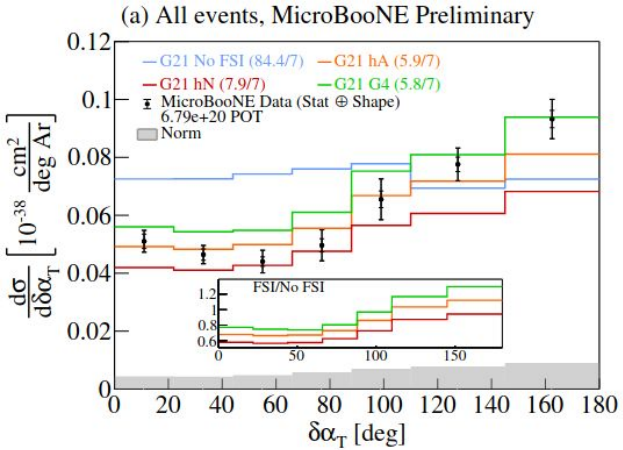


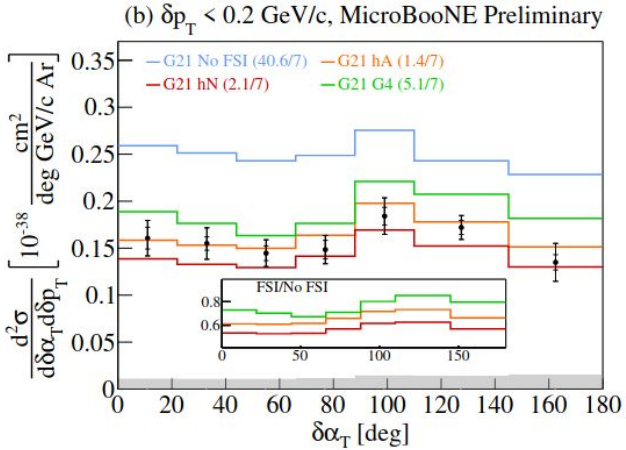


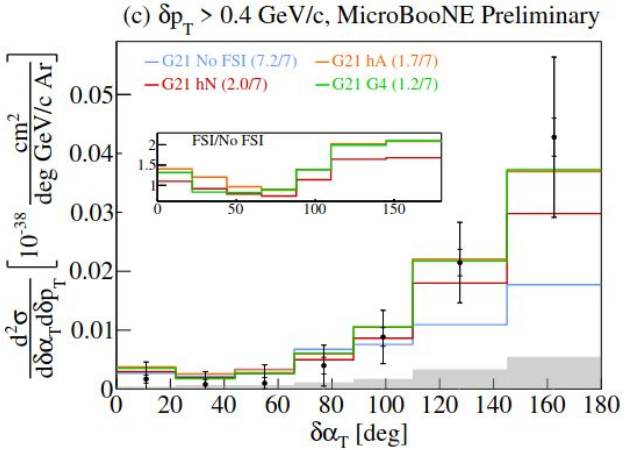
MICROBOONE-NOTE-1108-PUB

Transverse Kinematic Imbalance (TKI)



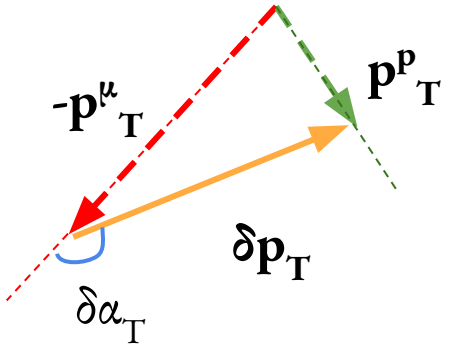


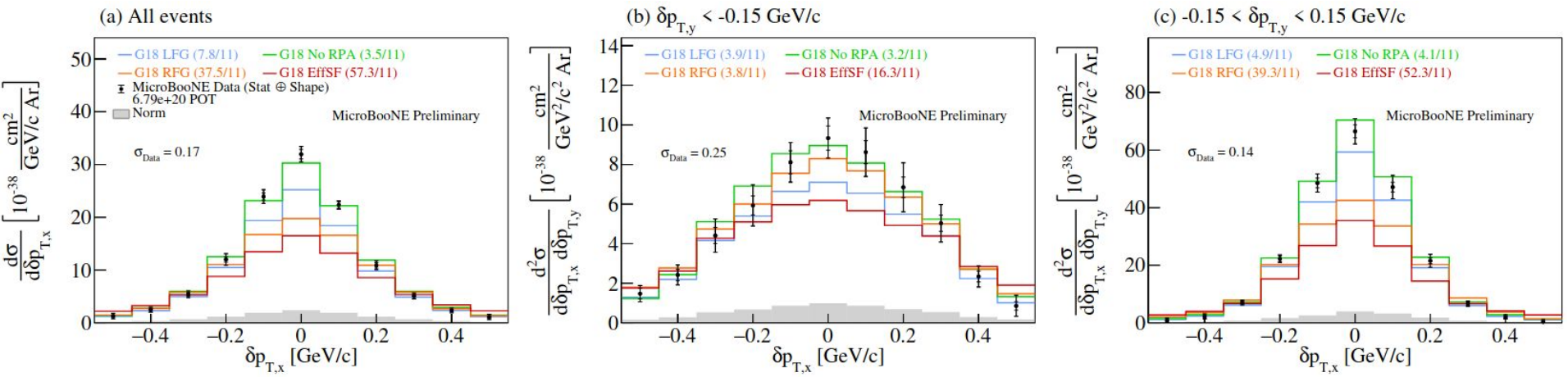




MICROBOONE-NOTE-1108-PUB

Transverse Kinematic Imbalance (TKI)





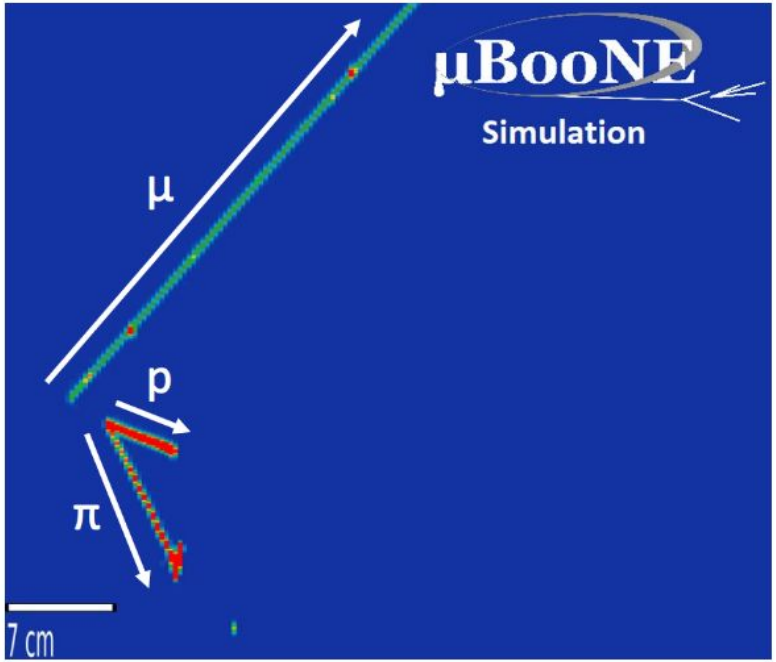
MICROBOONE-NOTE-1108-PUB

ν_μ Λ Production

- Uses NuMI flux
- 7% efficiency
- 99.9% background rejection

- Monte Carlo simulation predicts
  9.0 ± 0.8 (MC stat.) signal and
  3.1 ± 1.4 background events
- Combining 1.0×10^{21} protons on target of neutrino mode flux and 1.3×10^{21} protons on target of anti-neutrino mode flux
- Significance of 2.6 σ

$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda + X$$



MICROBOONE-NOTE-1097-PUB

ν_μ Λ Production

α Parameter

- Angle between the direction of the Λ's momentum vector and the line connecting the primary vertex to the decay vertex.

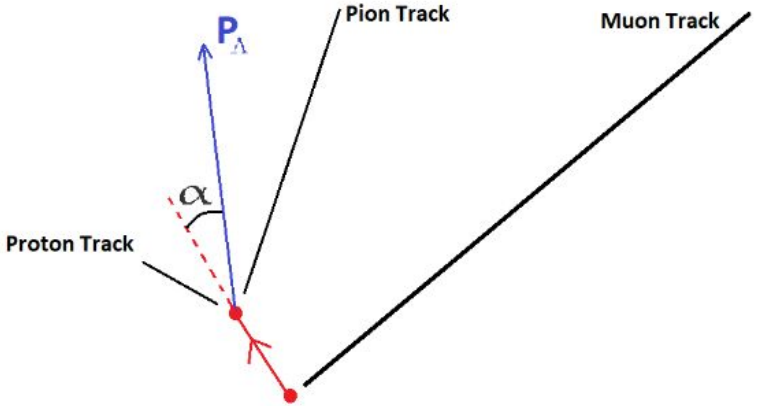


Figure: α angle calculation.

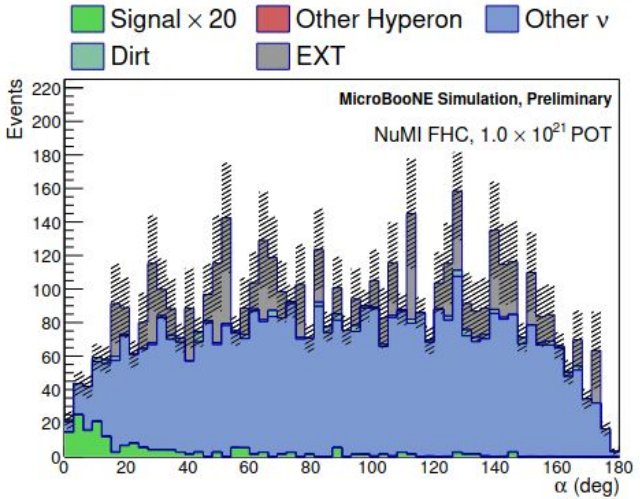
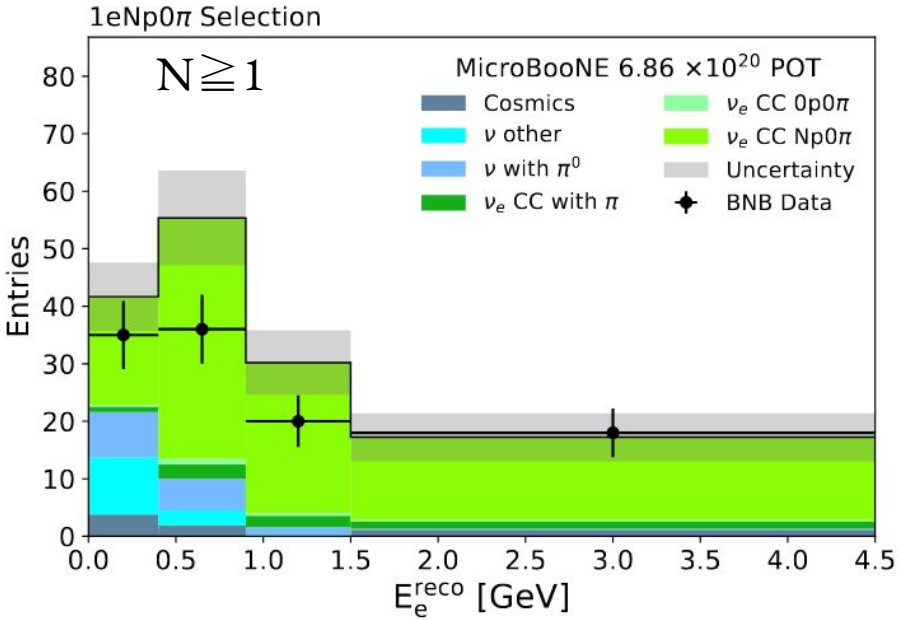


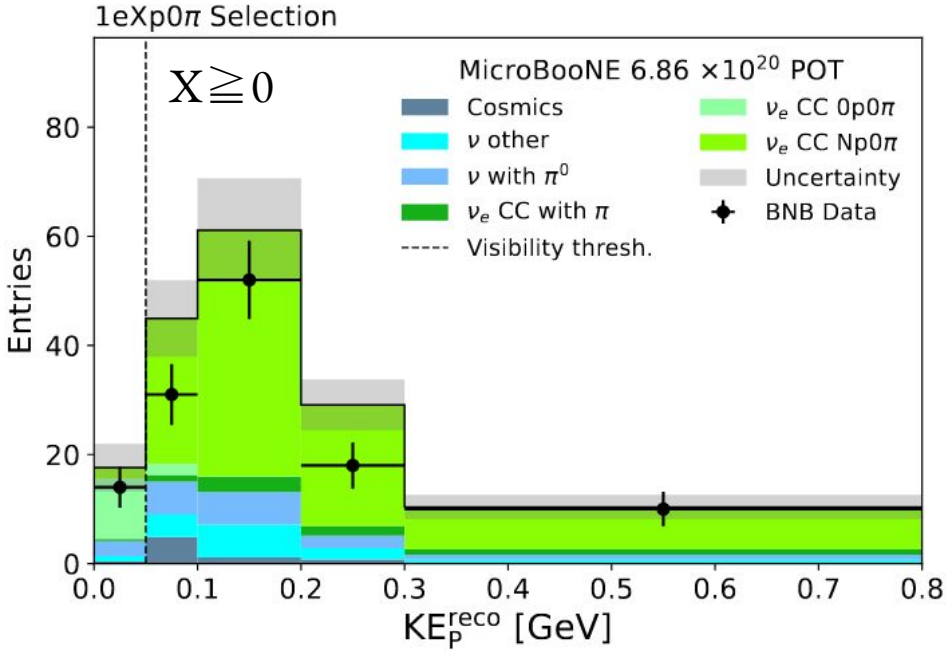
Figure: Values for signal and BG.

MICROBOONE-NOTE-1097-PUB

ν_e CCNp0π

- First energy and angle measurements for outgoing electron and leading proton on argon





MICROBOONE-NOTE-1109-PUB