Mesonless $\overline{\nu}_\mu$CC Cross Section @ ProtoDUNE-ND

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ND Prototypes Analysis Workshop
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THE UNIVERSITY OF CHICAGO
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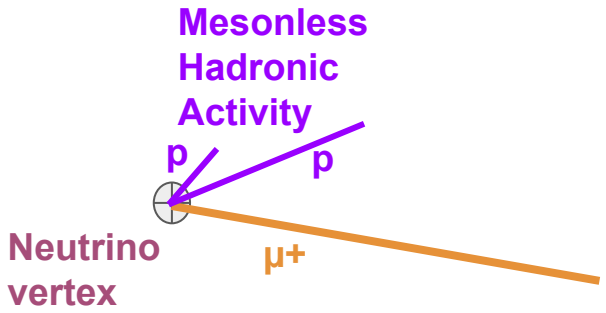
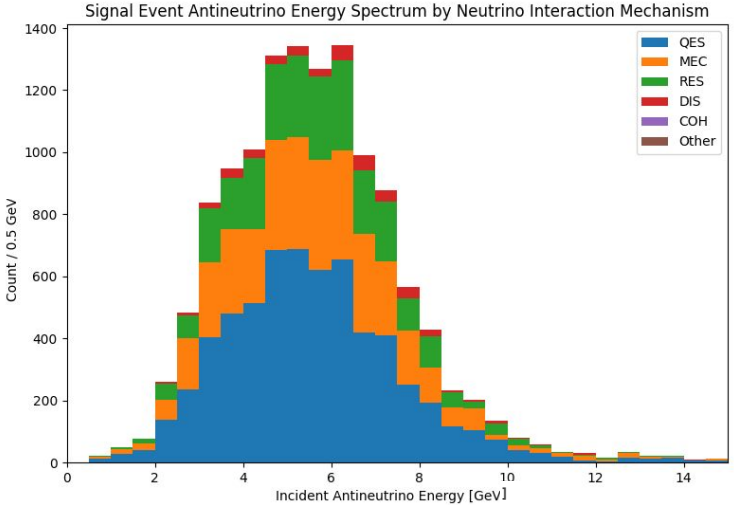
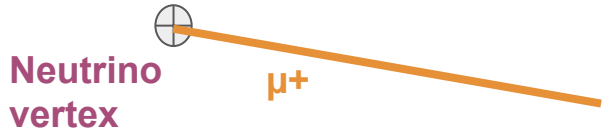
Mesonless $\overline{\nu}_\mu$ CC Cross Section: Physics Motivation



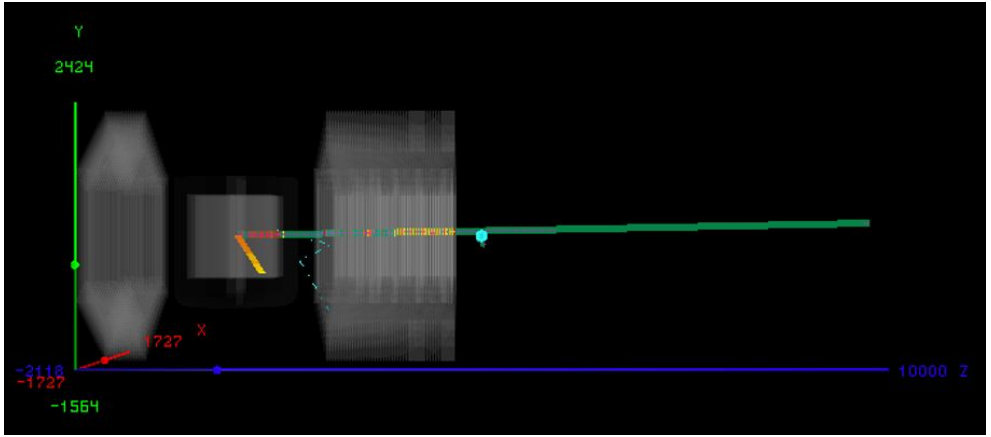


- Neutrino interaction mis-modeling acts as a major source of systematic uncertainty in neutrino energy reconstruction for DUNE oscillation analyses
- Signal topology does not align with only one physics process
  - Includes QE events, but also 2p2h (MEC), pion production and reabsorption, etc.
  - **Measurements from data are essential to reconcile differences in energy spectra from neutrino interaction mechanisms vs. those from event topologies**
- This channel has not been measured before for $\overline{\nu}_\mu$ on Ar
  - However, events in our topology are included in ArgoNEUT's $\overline{\nu}_\mu$ CC inclusive cross section measurement



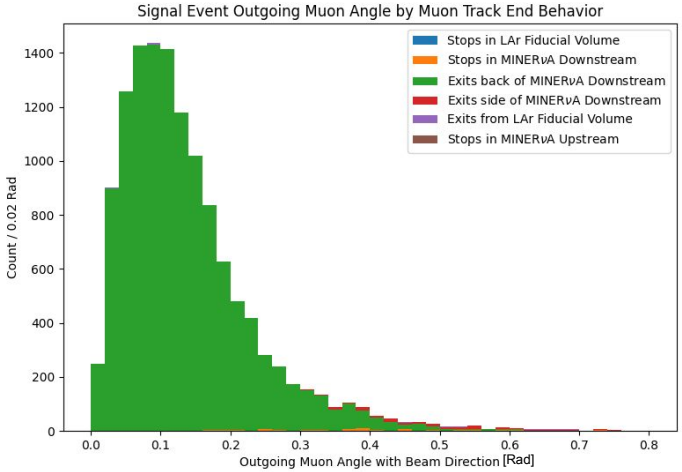
Mesonless $\overline{\nu}_\mu$ CC Cross Section: Why at ProtoDUNE-ND?

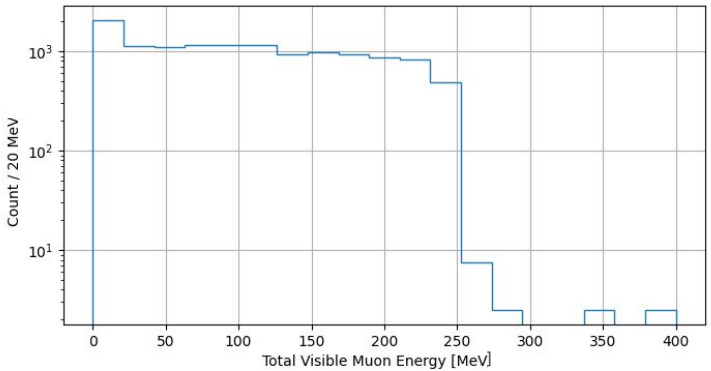
- Very simple topology
  - Signature = single muon with hadronic activity in 2x2 LAr fiducial volume
  - First antineutrino-Ar measurement of this topology
- MINERνA can be used for muon tagging
  - Track length possibly used as discriminant to mitigate backgrounds
- NuMI beam energy spectrum is higher and more broad than the BNB energy spectrum
  - Closer to what will be seen in DUNE



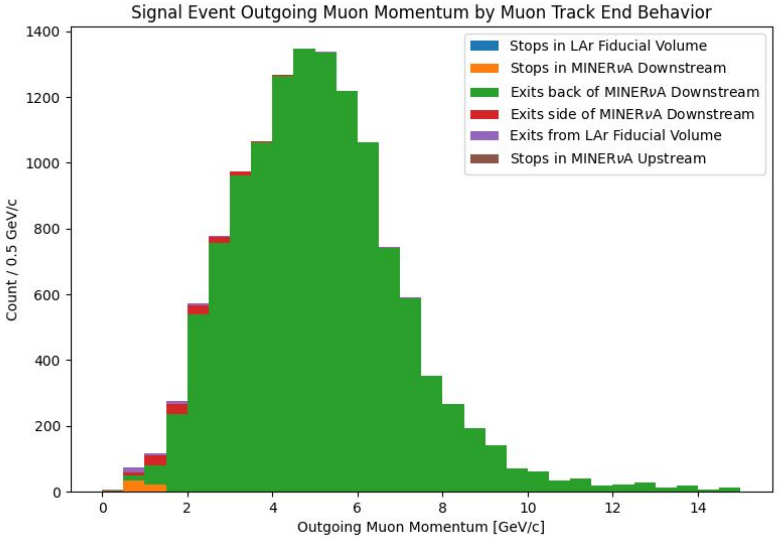
Exercise ND-LAr design capabilities:
- *3D reconstruction of ν signals*
- *Track-matching with external trackers*
- *Charge-light signal correlations across modules*

Signal Muon Kinematics



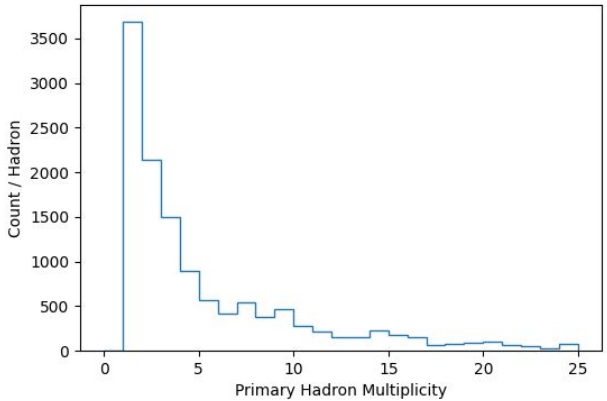


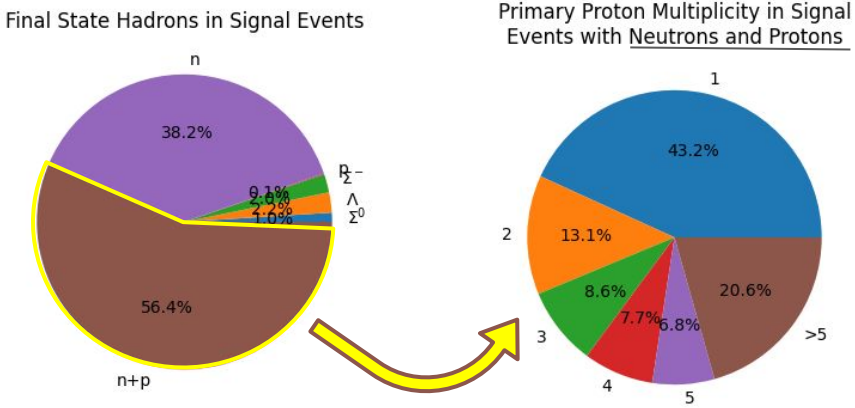
- ***Signal definition***
  - ν vertex inside LAr FV
  - Visible μ^+
    - TBD: Cut on μ^+ containment and/or punching through MINERνA?
  - Hadronic activity in LAr FV
  - Zero mesons detected
- *Expect **12788** events for 2.5 E19 POT*

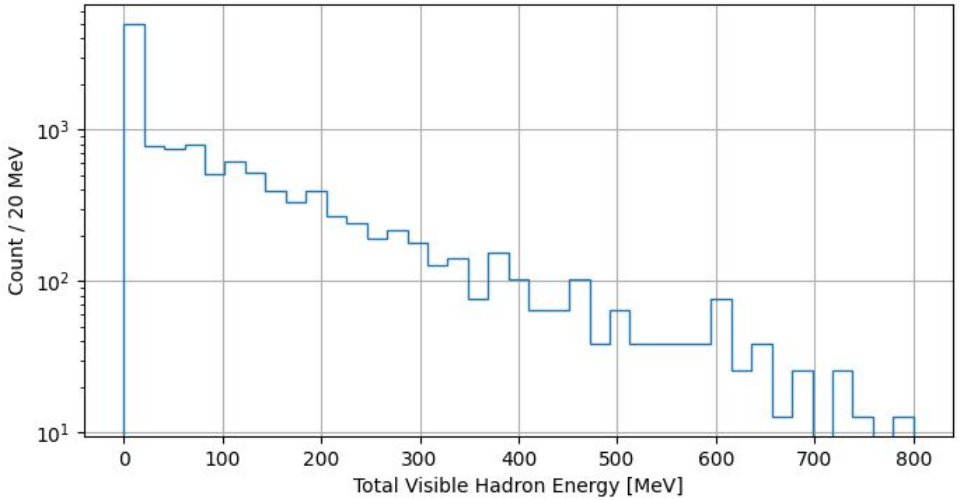


Signal Hadron Kinematics

- ***Signal definition***
  - ν vertex inside LAr FV
  - Visible μ^+
    - TBD: Cut on μ^+ containment and/or punching through MINERνA?
  - Hadronic activity in LAr FV
  - Zero mesons detected
- *Expect **12788** events for 2.5 E19 POT*

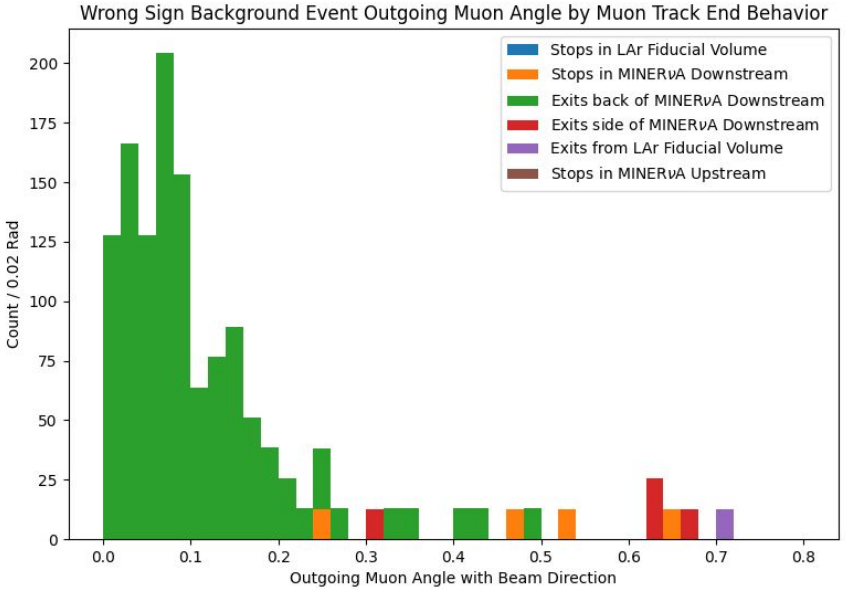


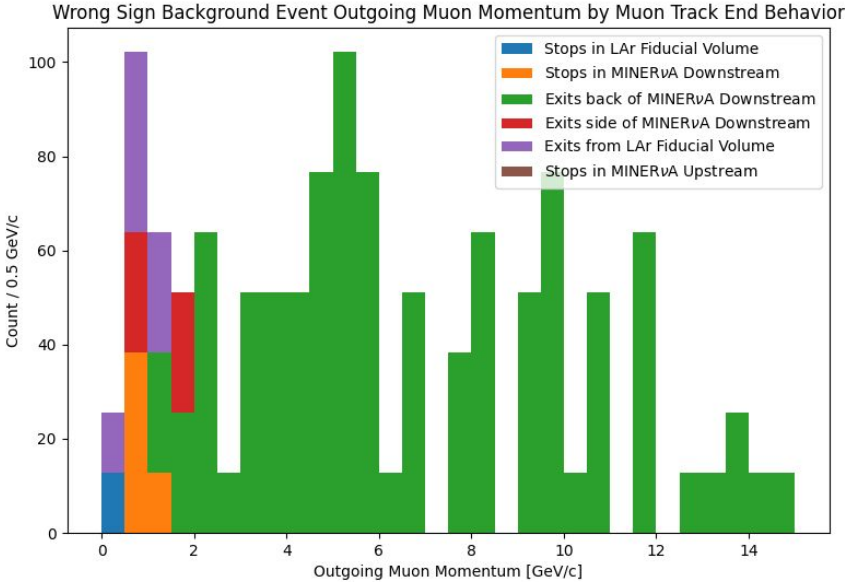




Wrong Sign Neutrino Backgrounds

- *Wrong sign neutrino background definition*
  - ν vertex inside LAr FV
  - Visible μ^-
  - Hadronic activity in LAr FV
  - Zero mesons detected
  - Irreducible background
- *Expected **1483** events for 2.5 E19 POT*

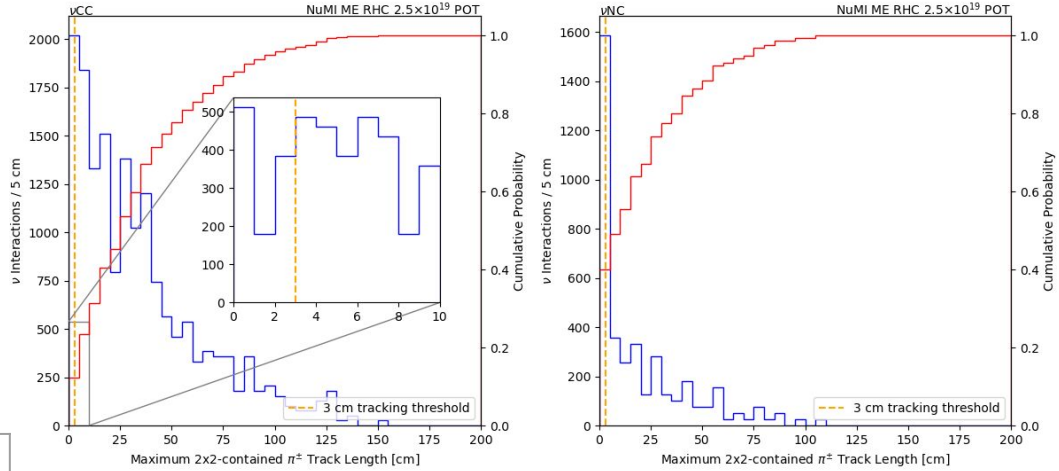




Neutrino Beam Induced Backgrounds – ν vertex in active volume

- *Threshold backgrounds* - fail to detect mesons in ν CC events
  - Charged mesons:
    - Longest track below tracking threshold
  - Neutral mesons - *contribution to be quantified*
    - Non-fiducial gamma
    - Collinear gammas
    - Unbalanced gamma children
- *PID backgrounds* - mistake non-muon for primary muon in ν NC events
  - single MIP above tracking threshold
- *Inactive volume backgrounds* - meson particle trajectories reside between modules

Background Category	Event Count
Threshold*	1074
PID	2558
Inactive volume	TBD



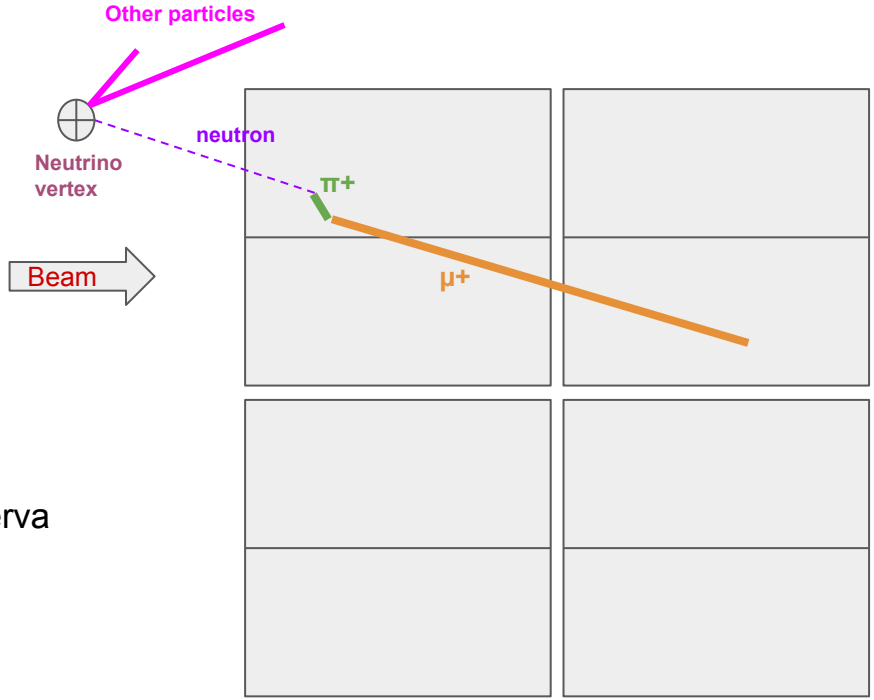
3 cm (~7 pixels) tracking threshold assumed

Track matching to MINERνA required to mitigate NC backgrounds

*Background contribution from neutral mesons not yet quantified

“Dirt” Induced Backgrounds – ν vertex external to active volume

- *Dirt background definition*
  - ν vertex out of FV
  - -> Neutron entering FV
  - -> very short charged meson < 3 cm
  - -> μ that looks like starting from a ν vertex

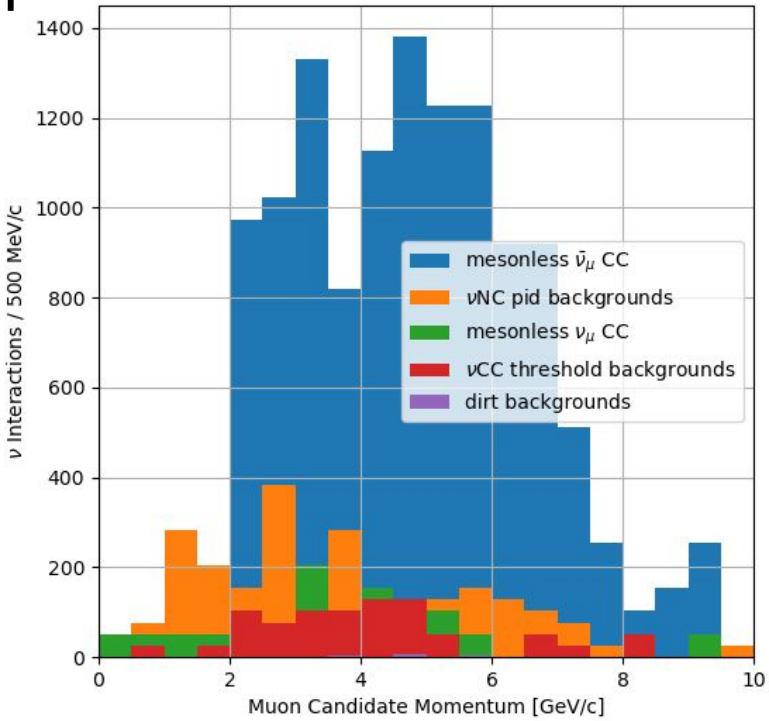


- *Expected **13 events** for 2.5E19 POT*
  - Typical μ length of 50-60 cm
  - Can remove them by requiring μ exiting Minerva

Preliminary Truth-based Selection

- Signal kinematics constraints under study
  - Secondary, tertiary hadrons TBD
  - Muon kinematic requirements (momentum, angle) TBD
- Further study needed on discrimination power using MINERvA
- Additional backgrounds under investigation (e.g. neutral mesons, inactive volume)

Category	**Event Count**
Mesonless $\overline{\nu}_{\mu}$CC	12,788
νNC PID	2558
Mesonless ν_{μ}CC	1483
νCC Threshold	1074
Dirt	13



4.3:1 signal:background

Initial Expectations on Leading Systematics: Detector

Systematic	Preliminary Proposed Evaluation Method
Proton versus MIP separation	MIP confidence score in CAFs
Track versus shower separation	Track confidence score in CAFs
Tracking threshold	Randomly remove pixels from active list
Recombination	Bern module cosmic data E-field scans
Beam pileup	Single- versus multi-ν simulation

Initial Expectations on Leading Systematics: Cross Section

Systematic	**Preliminary Proposed Evaluation Method**
“Dirt” modeling	n-p inelastic scatter rate (data control sample)
FSI model	Vary generator input to Geant4
Hadron re-interactions	Geant4 re-weight

Initial Expectations on Leading Systematics: Flux

Systematic	**Preliminary Proposed Evaluation Method**
Hadron production rates	Evaluate variations across simulated PPFX universes
Horn focusing	TBD

Near-term Analysis Group Focus

- Study bias due to limited acceptance
- Study additional signal considerations and constraints
  - Secondary, tertiary hadrons TBD
  - Muon kinematic requirements (momentum, angle) TBD
- Incidence of dead volume passing backgrounds
- Re-evaluate MC signal, background kinematic distributions with production reconstruction
- Systematic control sample studies
- Systematic calibration studies
- Initiate interfacing with NIUWG/DIRT2 working group on cross section systematics

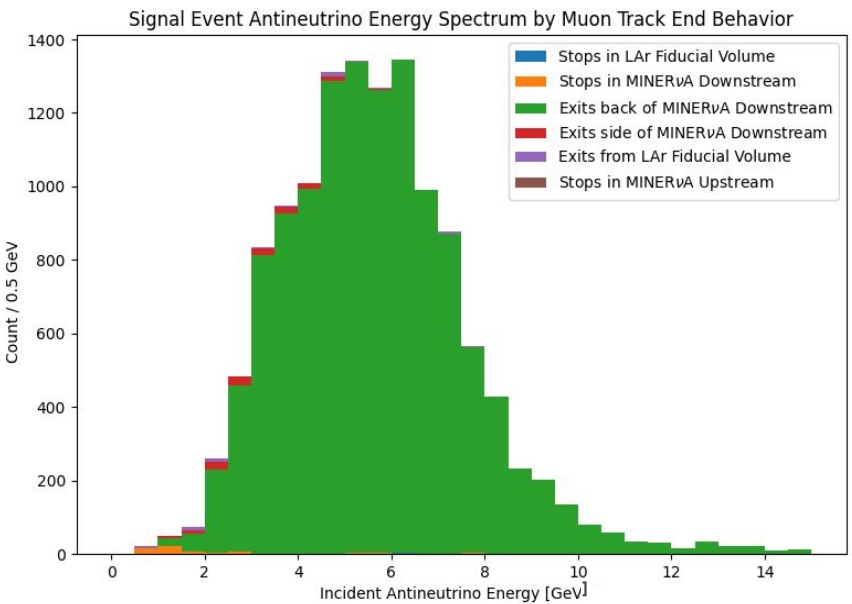
Additional analyzers welcome to join the team! Informal analysis meetings held weekly over zoom

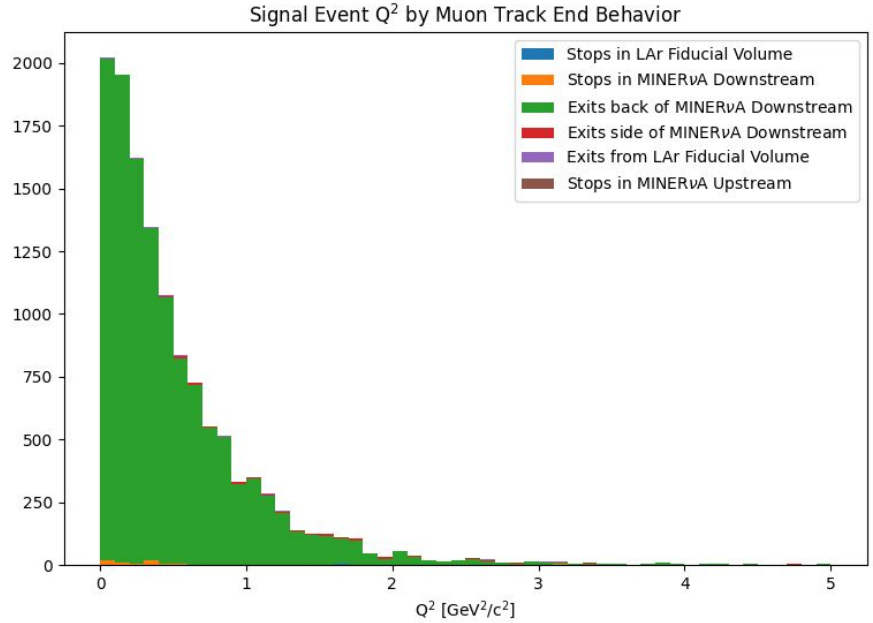
Summary

- Measurements from data are essential to reconcile differences in energy spectra from neutrino interaction mechanisms vs. those from event topologies, and the mesonless $\overline{\nu}_\mu$ CC cross section has not yet been measured on argon.
- A differential cross section measurement as a function of muon momentum is unlikely, but measuring differential cross sections in terms of other variables may be possible.
- Mesonless $\overline{\nu}_\mu$ CC has a simple signal topology, while still exercising ND-LAr design aspects critical to FDR.
- The plan for systematics evaluation in progress, focusing on control sample/calibration independent constraints.

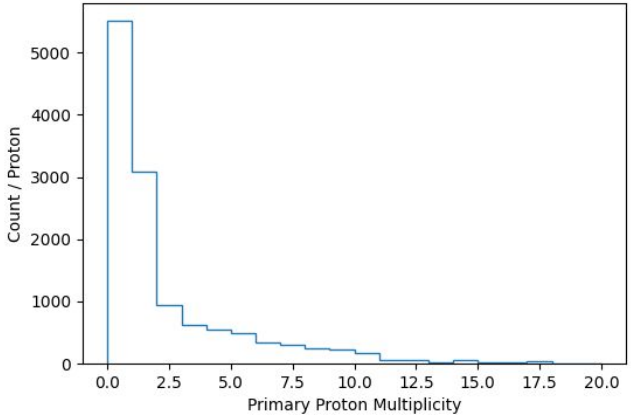
Backup Slides

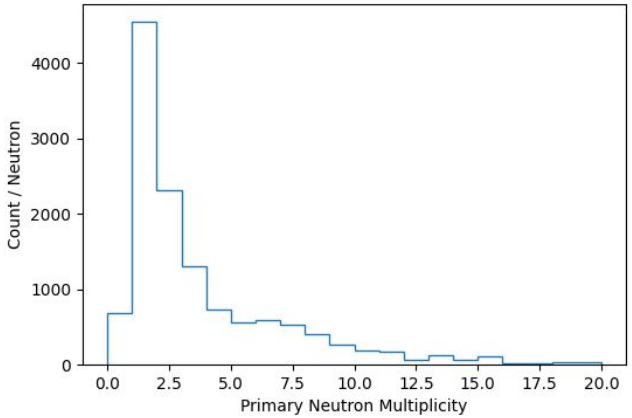
Signal Kinematics: Antineutrino Energy & Q^2

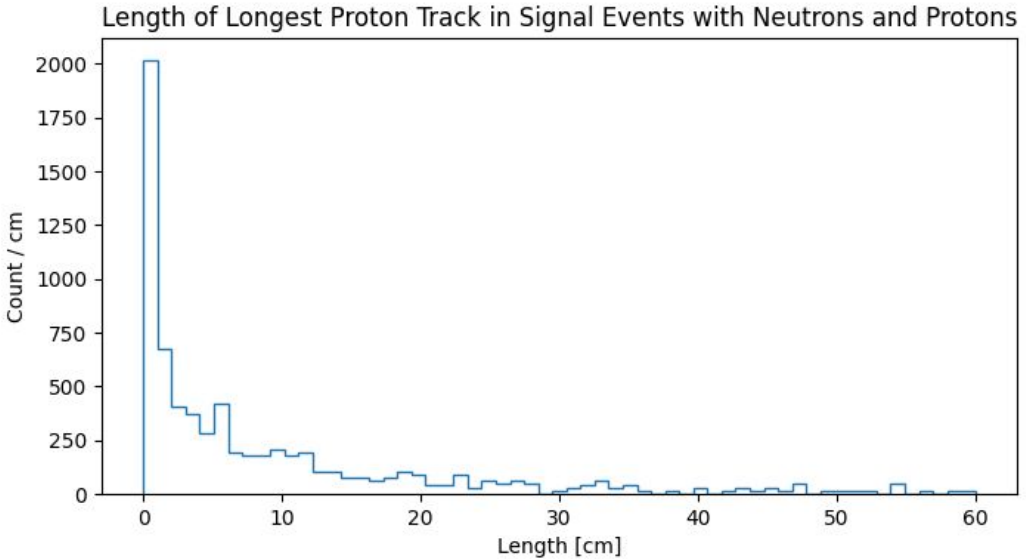




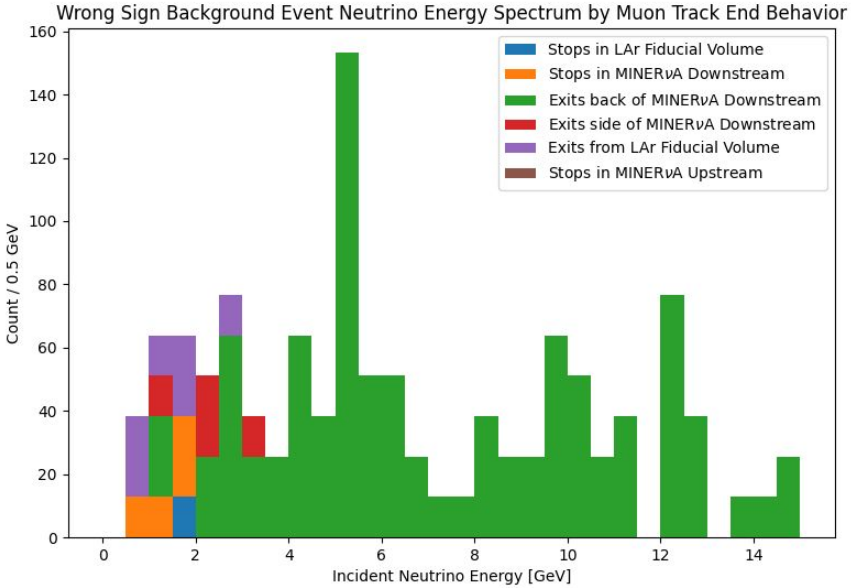
Signal Event (Primary) Hadron Characterization

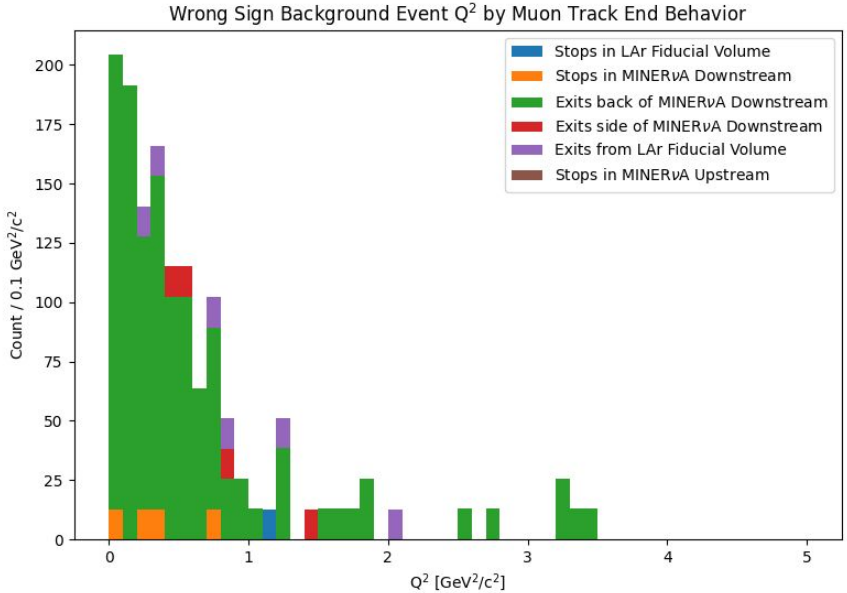




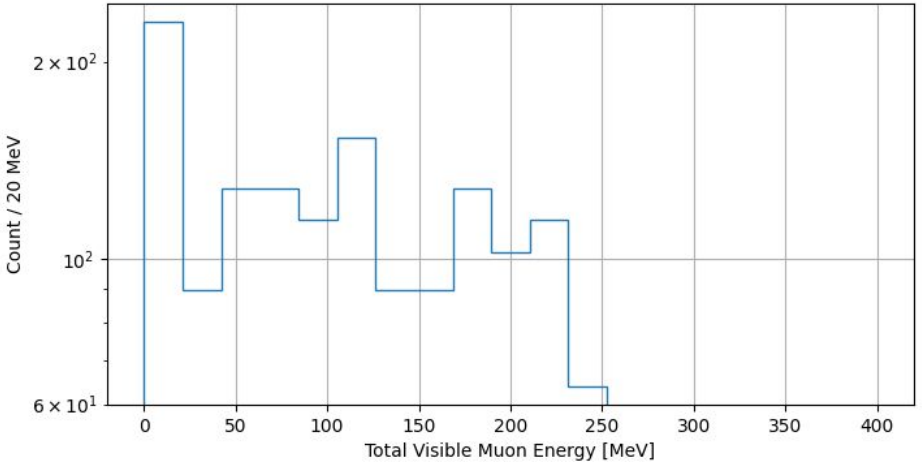


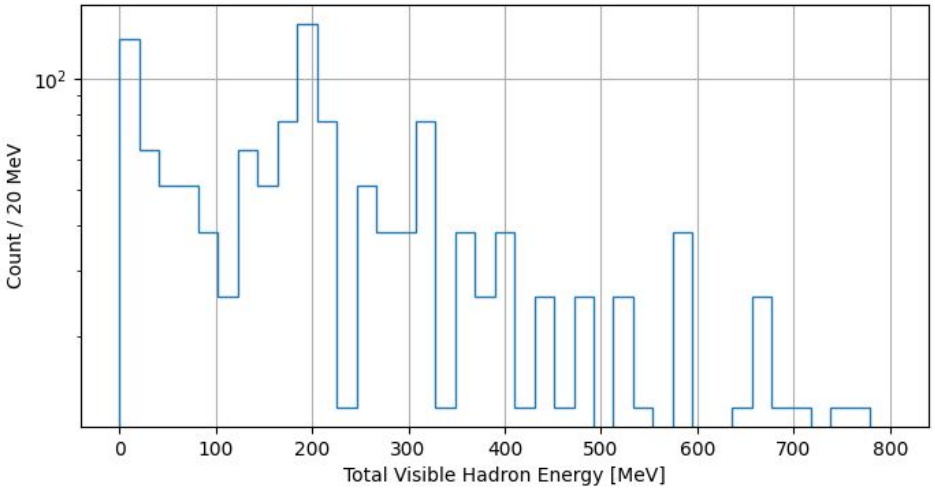
Wrong Sign Background: Antineutrino Energy & Q^2



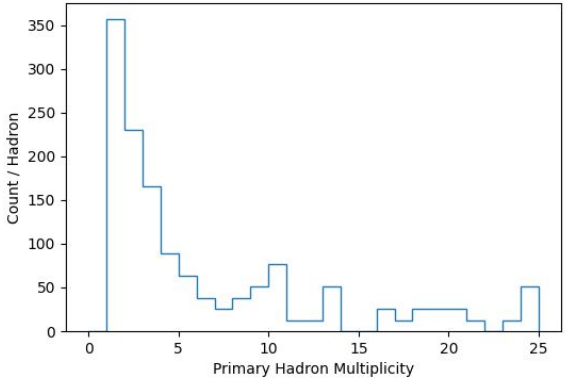


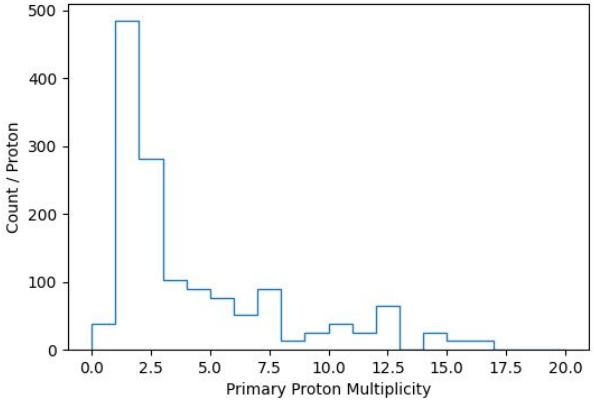
Wrong Sign Neutrino Backgrounds: Visible Energy

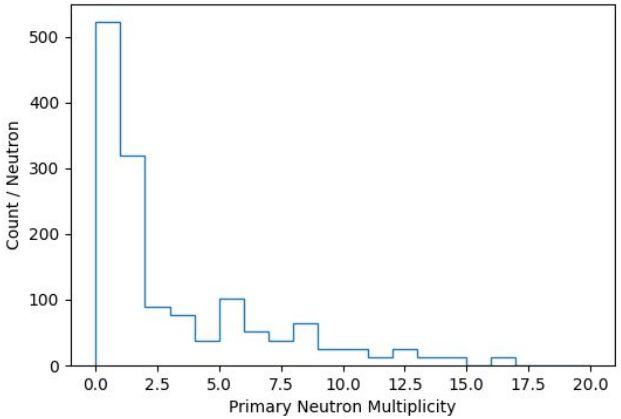




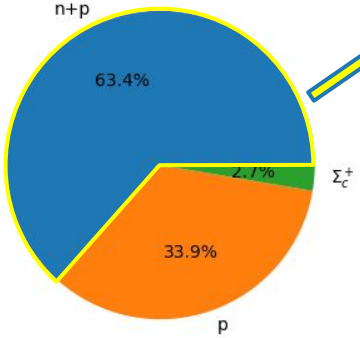
Wrong Sign Background Primary Hadron Characterization



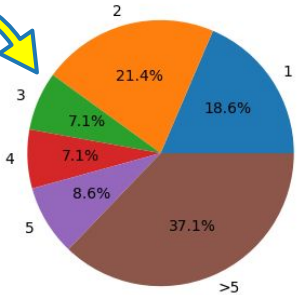




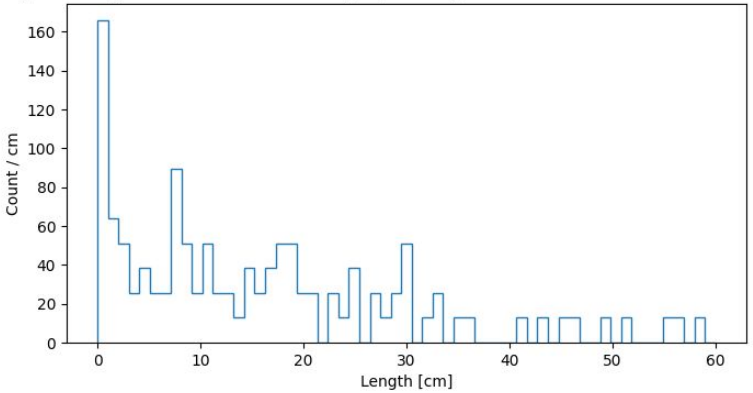
Final State Hadrons in Wrong Sign Background Events

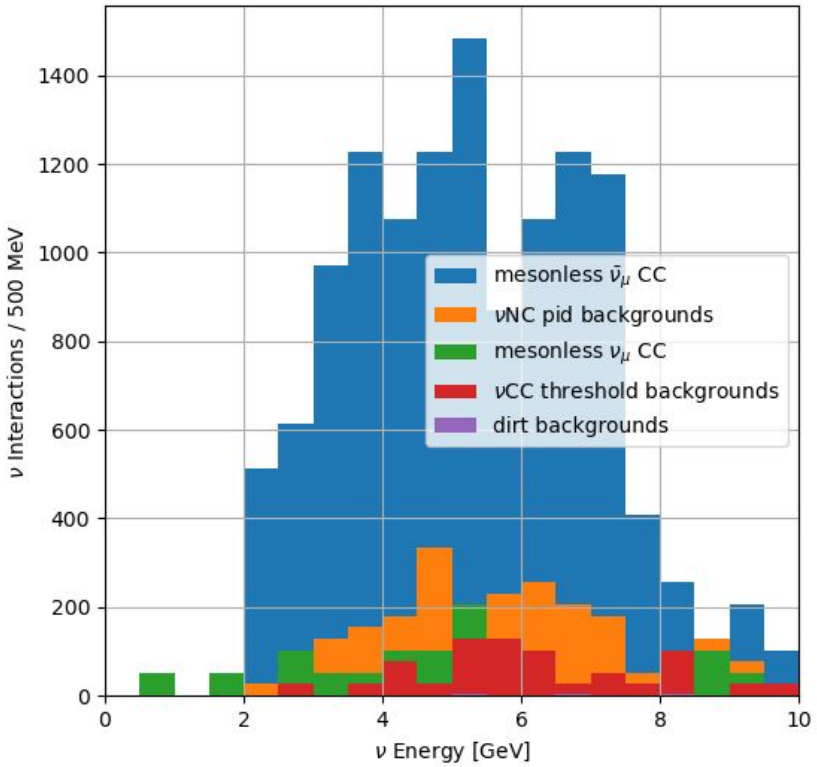


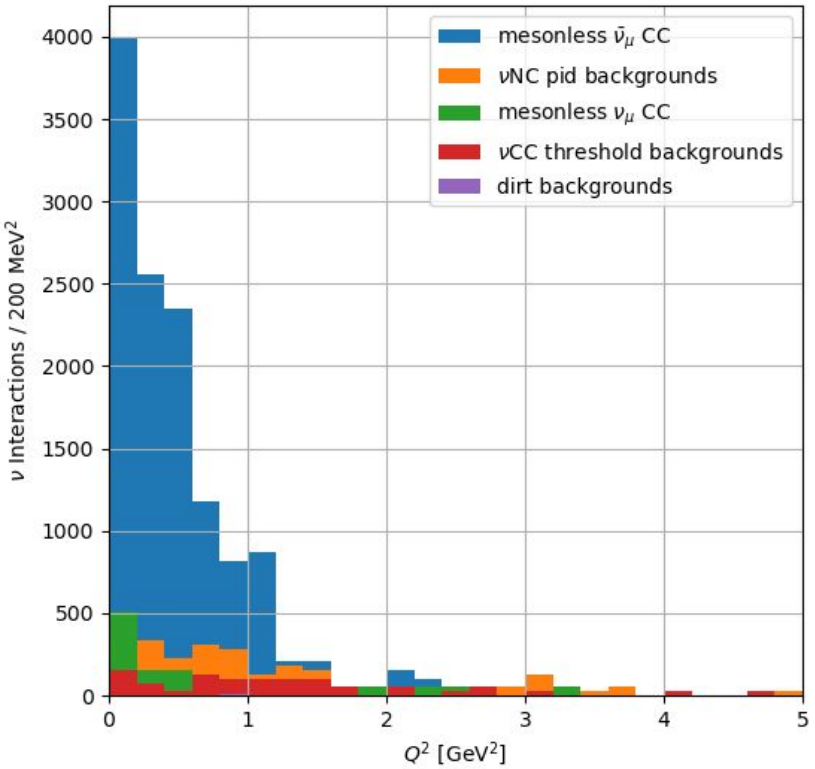
Primary Proton Multiplicity in Wrong Sign Background Events with Neutrons and Protons



Length of Longest Proton Track in Wrong Sign Background Events with Neutrons and Protons




mesonless $\bar{\nu}_\mu$ CC
νNC pid backgrounds
mesonless ν_μ CC
νCC threshold backgrounds
dirt backgrounds
ν Interactions / 500 MeV
ν Energy [GeV]


mesonless $\bar{\nu}_\mu$ CC
νNC pid backgrounds
mesonless ν_μ CC
νCC threshold backgrounds
dirt backgrounds
ν Interactions / 200 MeV^2
Q^2 [GeV^2]