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

Andrew Cudd, Elise Hinkle, Saba Parsa, Brooke Russell, Tammy Walton

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University of Colorado Boulder
THE UNIVERSITY OF CHICAGO
LABORATORIUM FÜR HOCHENERGIEPHYSIK LHEP UNIVERSITÄT BERN
BERKELEY LAB
Fermilab

# Outline

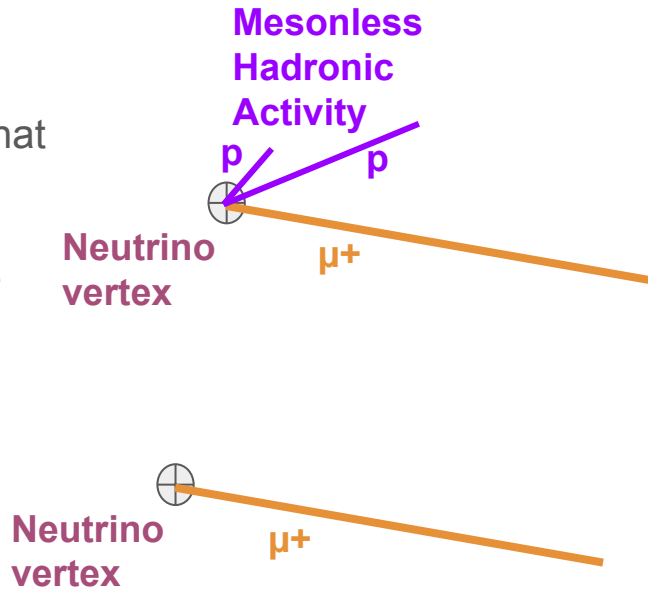
1. Review of Analysis Goals
2. Bern Single Module Data Reprocessing Activities
3. Preliminary Selection using ML Reco Information from CAFs

# Review of Analysis Goals

From: ND Prototypes Sept. 2023 Analysis Workshop CR Data/MC Study Slides

# **Mesonless $\overline{\nu}_\mu$CC Cross Section**: Signal Definition

- The goal of the group is to start with an exclusive channel having a **simple topology and realistic and practical measurements**
- The signal topology includes an interaction event in the 2x2 that has the following characteristics:
  - **Required:** a long track contained or exiting ProtoDUNE-ND which is identified as a muon candidate
  - **Not Required:** short track(s) contained in the 2x2 or MINERvA which are not identified as mesons
- The **proposed differential measurements** are:
  - **Proton** multiplicity in the vertex region
  - Leading **proton** momentum
  - Sub-leading **proton** momentum
  - Opening angle between the muon and leading **proton**
  - Opening angle between the leading and sub-leading **protons**

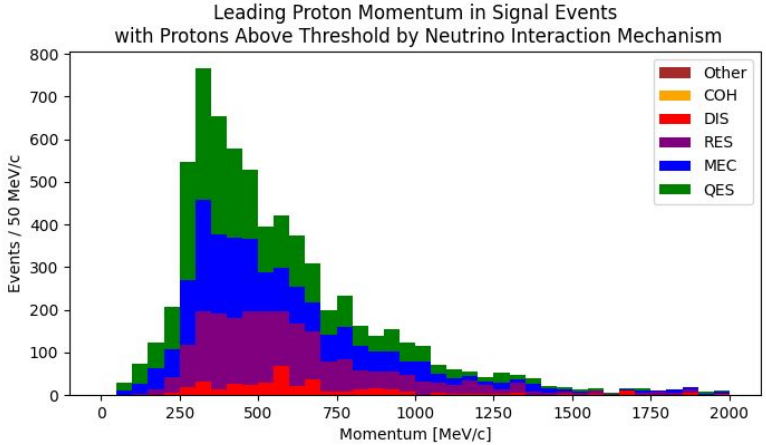


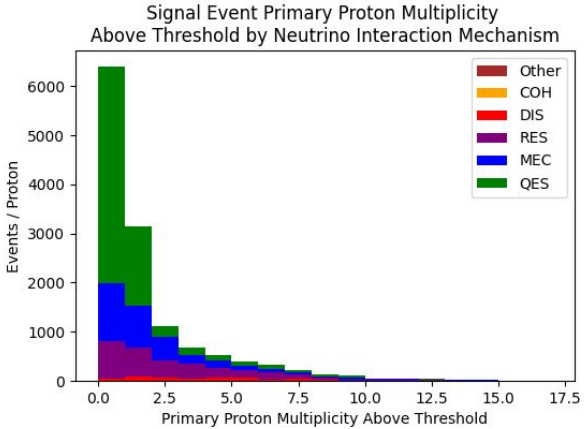
*From: [ND Prototypes Sept. 2023 Analysis Workshop Analysis Viability & Systematics Slides]*

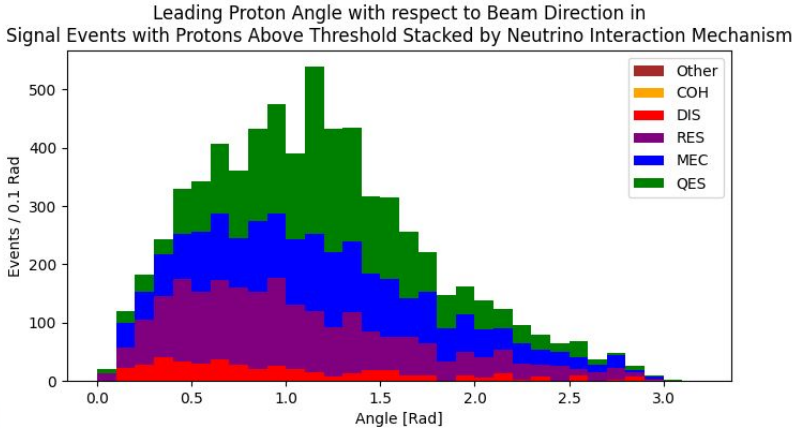
# Proton kinematics

Most likely report measurement in proton kinematics → momentum (or KE) and angle

Sharp edge on proton momentum due to threshold and nuclear effects

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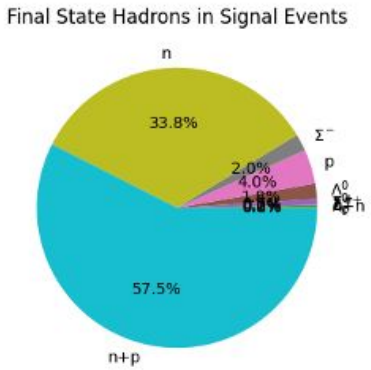
# Bern Single Module Data Reprocessing Activities

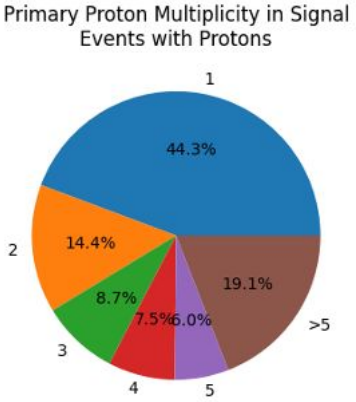
*Main contributor: Elise Hinkle*

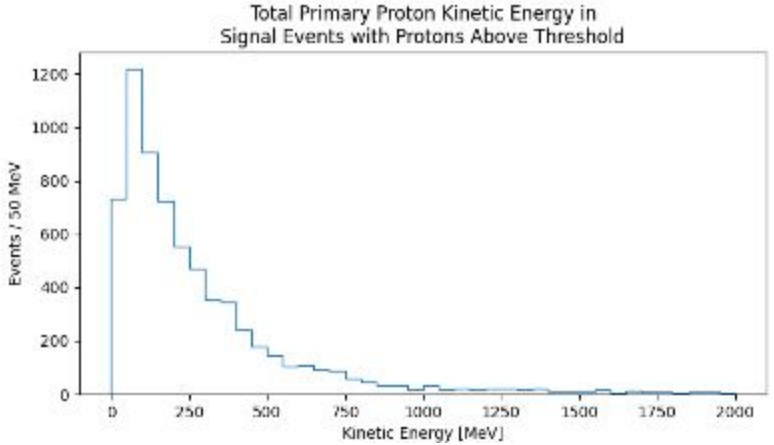
From: [ND Prototypes Sept. 2023 Analysis Workshop CR Data/MC Study Slides]

# **Mesonless $\overline{\nu}_\mu$CC Cross Section**: Events with Protons

- Based on truth studies, almost two-thirds of signal events are expected to include protons
- Of these events with protons, more than half are expected to include **more than one proton**
- **Note:** while we've performed some truth studies assuming a tracking threshold of 3 cm, the truth multiplicity studies below do not require any sort of tracking threshold
- **We also need to understand our tracking threshold better in order to define the "mesonless" aspect of our signal**



# Bern Module Data Usage Goals

- Implement selections on events with **high trigger density** (e.g. protons, neutrino-like vertices, etc.)
  - Started selection of **fully isolated proton tracks** with *module0_flow*-ed Bern single module data, but waiting for reprocessed data to continue
- Perform hit-, cluster-, and track-level comparisons of data/MC selections
- Identify and start to resolve challenges related to studying events with higher trigger density

***First step:*** *reprocessing Bern single module cosmics data*

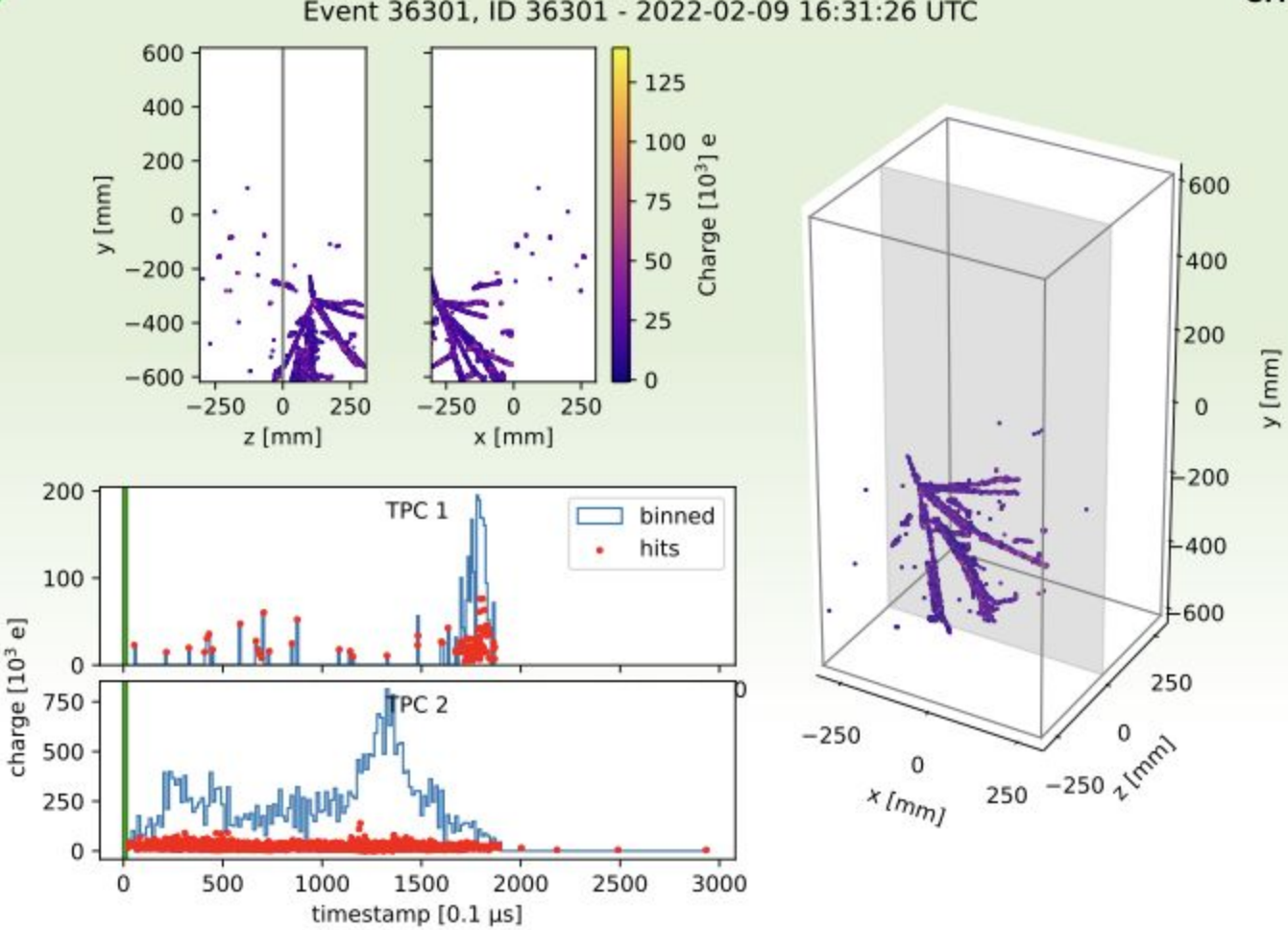
# Contribution #1: Flow Version Comparison

- **What did we do?**
  - Created snapshot of differences between tools available in *module0_flow* (old flow) and *proto_nd_flow* (new flow)
- **Potential use cases:**
  - Quickly identify tool inputs, dependencies, and outputs, check dataset references, and compare old and new flow structure without having to sift through code
  - Identify tools which still need to be implemented or updated for reflow of Bern Module Data with *proto_nd_flow*
- **Beyond the reflow, how does this help our analysis?**
  - Initially started to build proton selection around *module0_flow*, so understanding differences between flow versions is essential in successfully adapting selection to work with reflowed data

# Contribution #2: Validation Methods

- **What did we do?**
  - Adapted LArPix single module event display for reflowed single module data
  - Improved usability of event display by integrating into interactive Jupyter notebook
  - Event display now resides in relevant branch within *ndlar_flow* Git repository
- **Potential use cases:**
  - Visualize and evaluate charge-only reflowed single module data
  - Visually compare *charge/calib_prompt_hits*, *charge/calib_final_hits*, and *charge/raw_hits* datasets within *proto_nd_flow*-ed data and with *charge/hits* dataset from *module0_flow*-ed data
    - Examples in slides from Sept. 22 2x2 Simulation & Calibration Meeting
- **Beyond the reflow, how does this help our analysis?**
  - Enables visualization of reflowed Bern data events included in proton selection and future selections for charge data/MC studies

# charge/raw_hits

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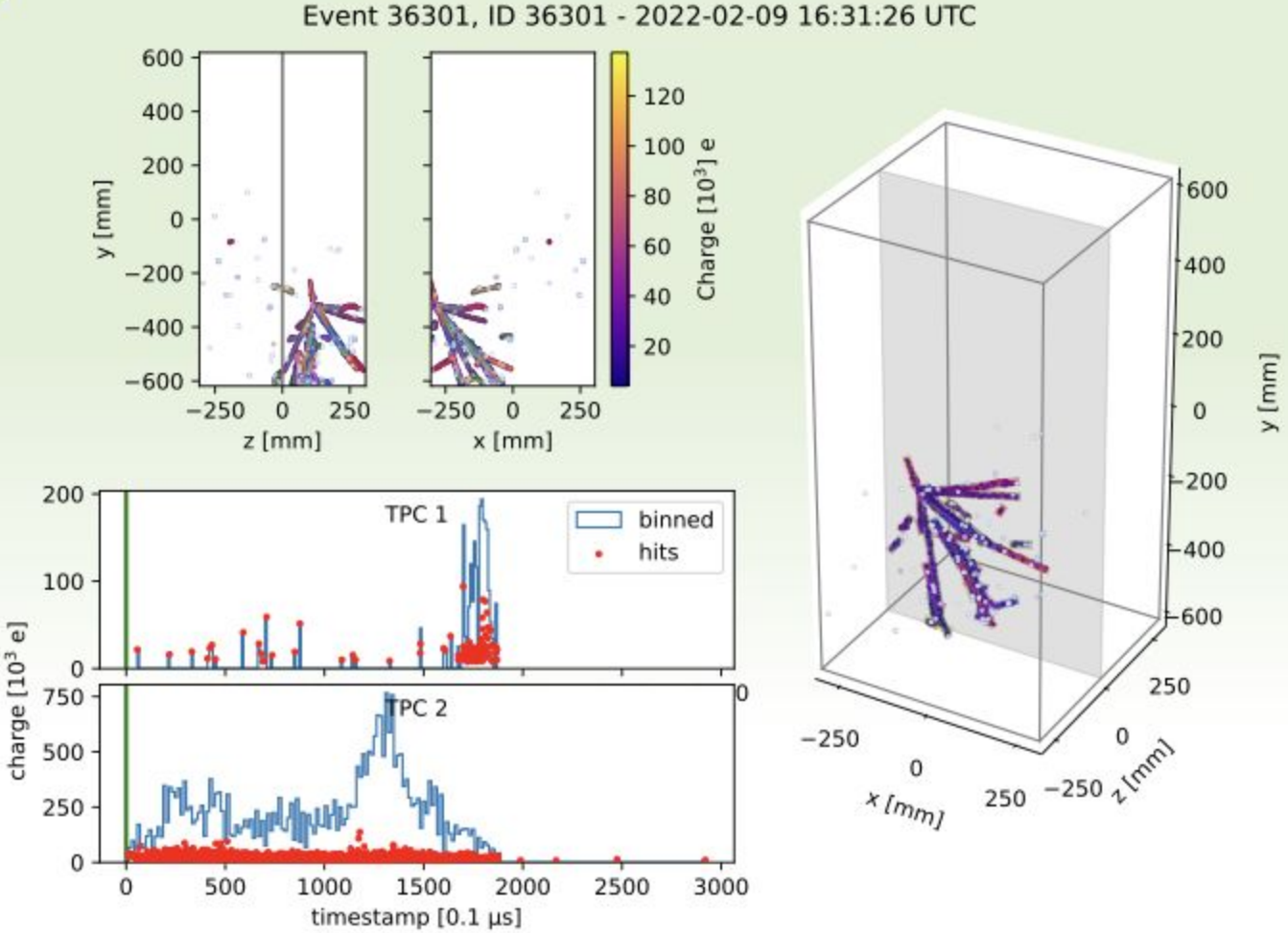
Event 36301, ID 36301 - 2022-02-09 16:31:26 UTC
y [mm]
z [mm]
x [mm]
Charge [10³] e
TPC 1
TPC 2
binned
hits
charge [10³ e]
timestamp [0.1 µs]
x [mm]
z [mm]
y [mm]

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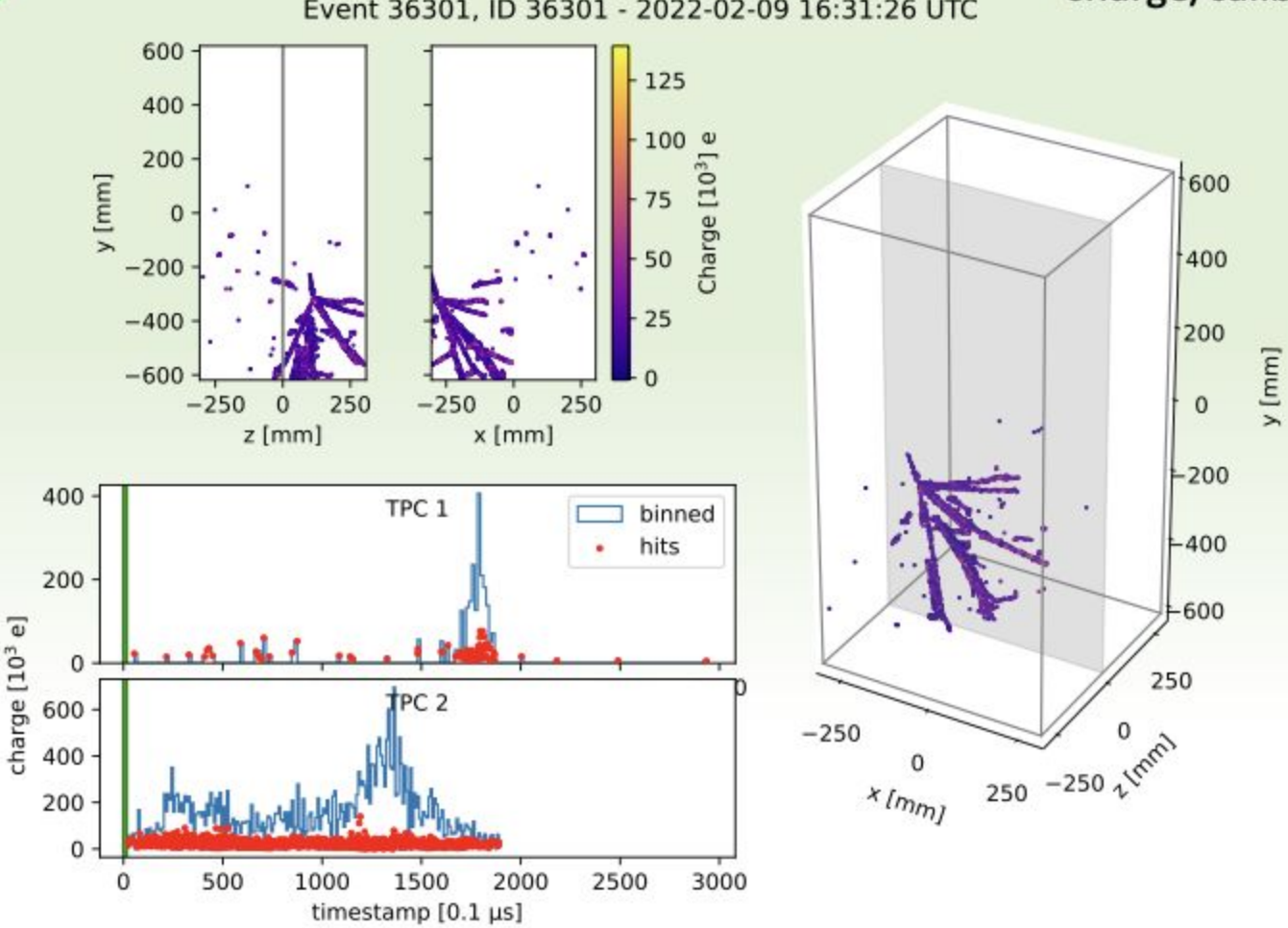
# charge/calib_prompt_hits

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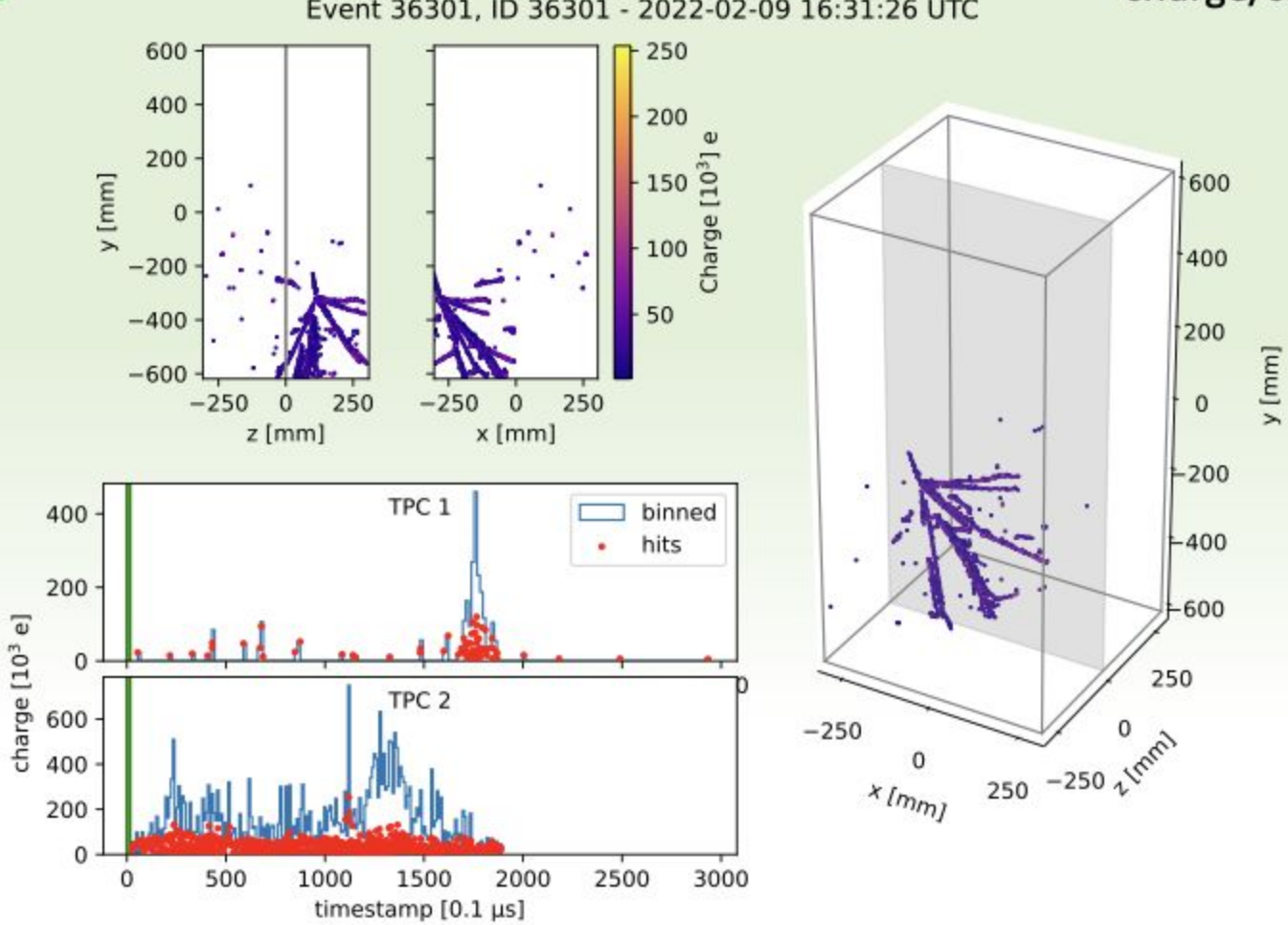
# charge/calib_final_hits

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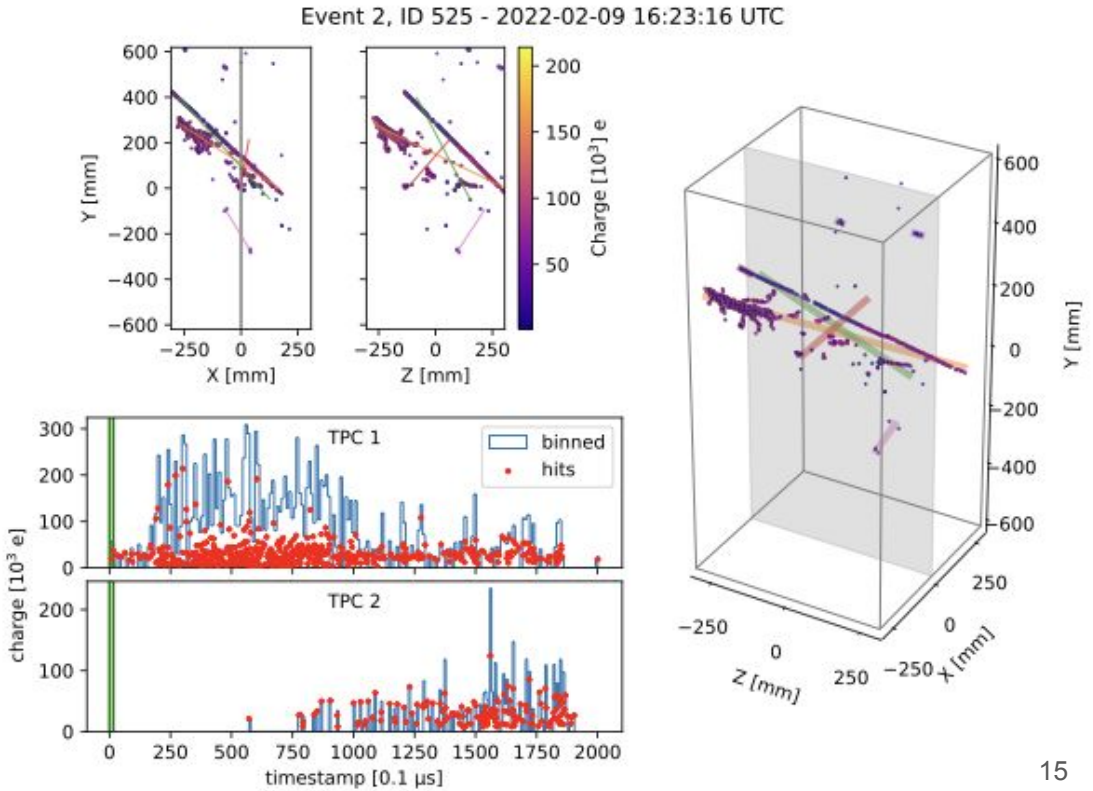
# Contribution #3: Low-Level “Reconstruction”

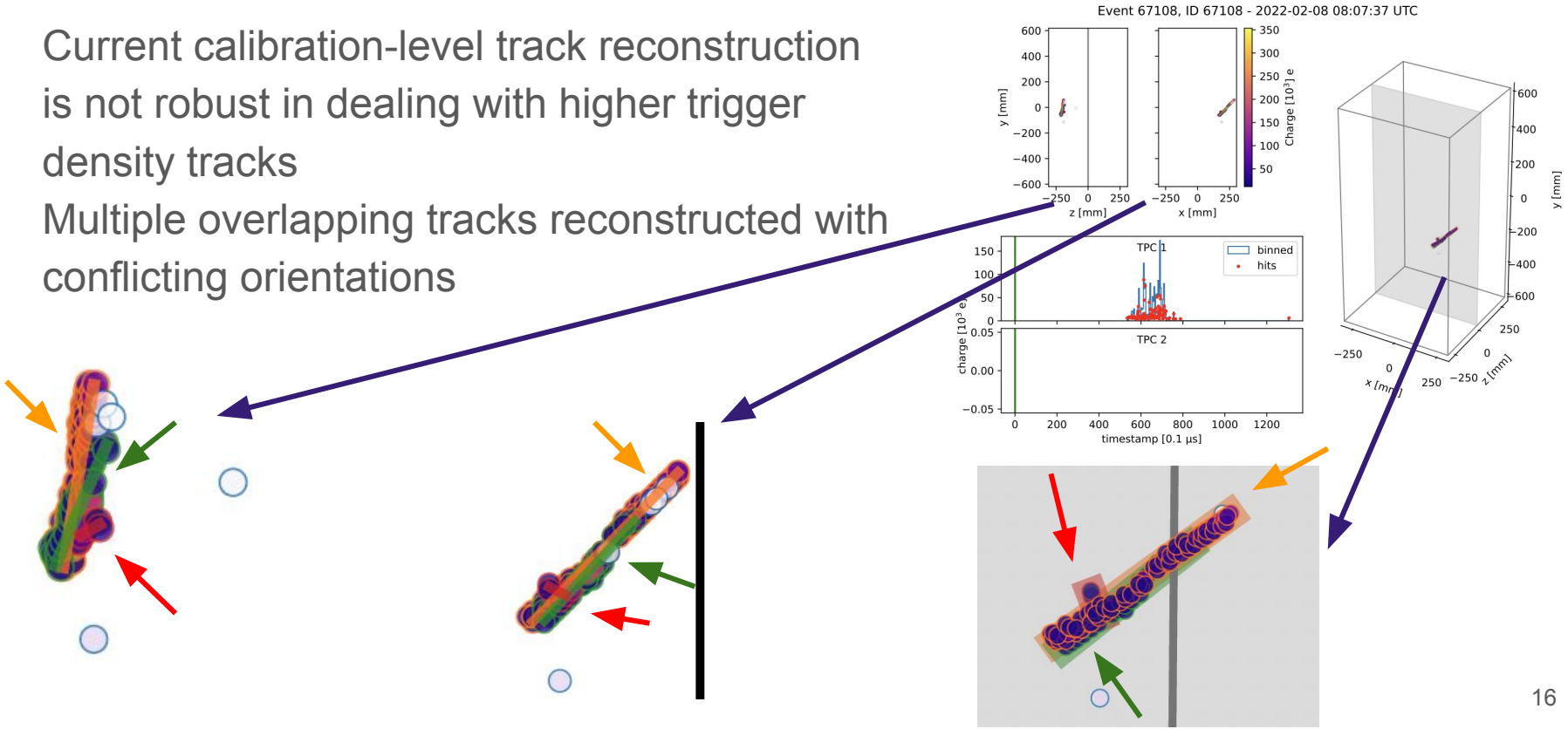
- **What did we do?**
  - Adapted tracklet reconstruction code from *module0_flow* to work with datasets in *proto_nd_flow*
  - Currently working to iterate on tracklet reconstruction to eliminate small, redundant tracklets



From: [ND Prototypes Sept. 2023 Analysis Workshop CR Data/MC Study Slides]

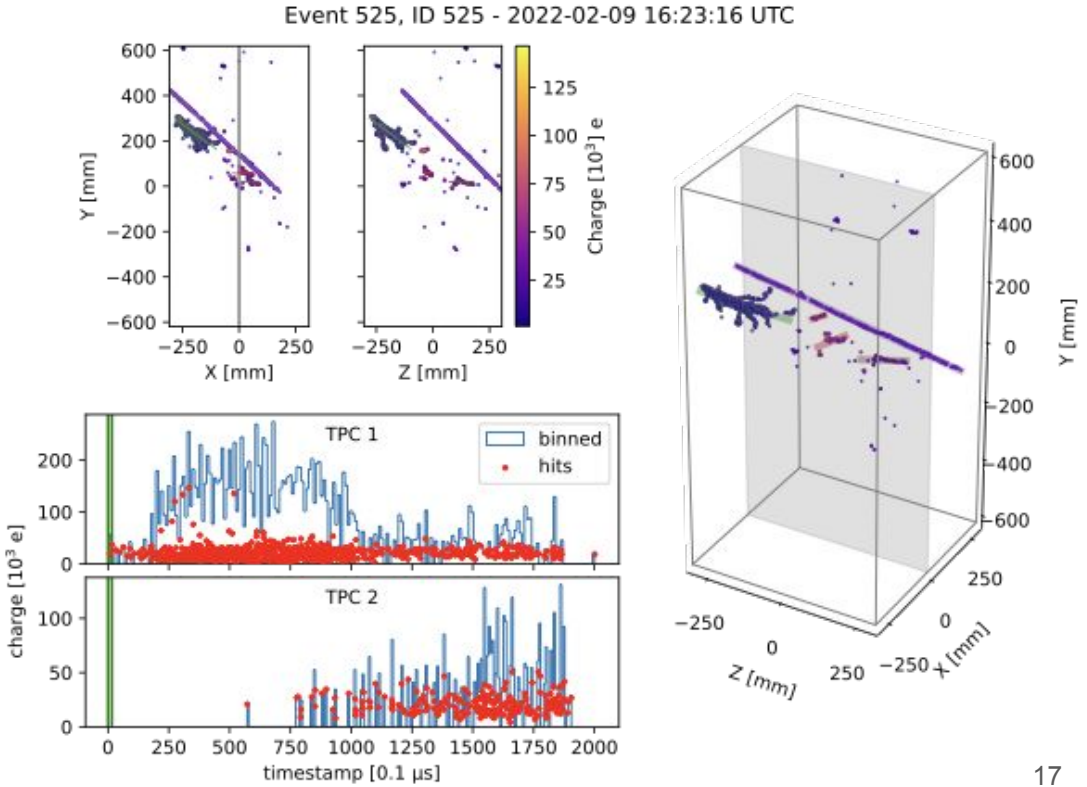
# Realities of Reprocessing Bern Module Data

- Current calibration-level track reconstruction is not robust in dealing with higher trigger density tracks
- Multiple overlapping tracks reconstructed with conflicting orientations



# Contribution #3: Low-Level “Reconstruction”

- **Potential use cases:**
  - Help in event selections for charge data/MC studies
  - Contribute to other calibration tasks using flow-level data and MC
- **Beyond the reflow, how does this help our analysis?**
  - Sorting hits into tracks is necessary for proton selection for data/MC studies
  - Improving on existing tracklet reconstruction code is necessary for use in proton selection (see [ND Prototypes Analysis Workshop Charge Data/MC Study slides])



# Next Steps

- Continue to **help with Bern module reflow** and low level reconstruction tasks in service of proton selection
- Adapt initial version of **fully isolated proton track selection** for reflowed files
- Make hit-, cluster-, track-level **data/MC diagnostic plots**
  - Reconcile any disagreements which arise
- Create **selections for more complex topologies** (e.g. neutrino-like vertices)

# Preliminary Selection using ML Reco Information from CAFs

*Main contributor: Andrew Cudd*

# Selection details

Attempted a rudimentary selection for mesonless (technically CC0pi) events using the CAFs (plots are from structured CAFs) – only reco information used

Selection steps – loop over each interaction in each spill:

- Require 1 muon (either +/-), 0 pions, and N protons as primary particles (no cuts on photons or electrons tagged as primaries)
- No requirement on the muon entering/exiting MINERvA
- No fiducial volume cuts
- No containment cuts

Basically selecting for particle content to obtain the most events

# Selection issues

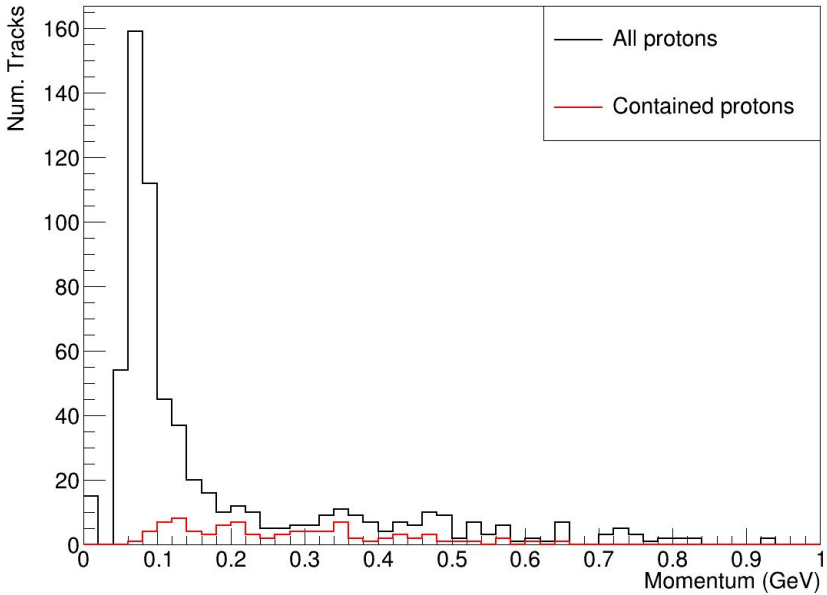
Main problem is the extremely low efficiency of selecting CC0pi events → out of 151353 spills we find **590 / 264139 ~ 0.2%** interactions that satisfy the particle selection criteria

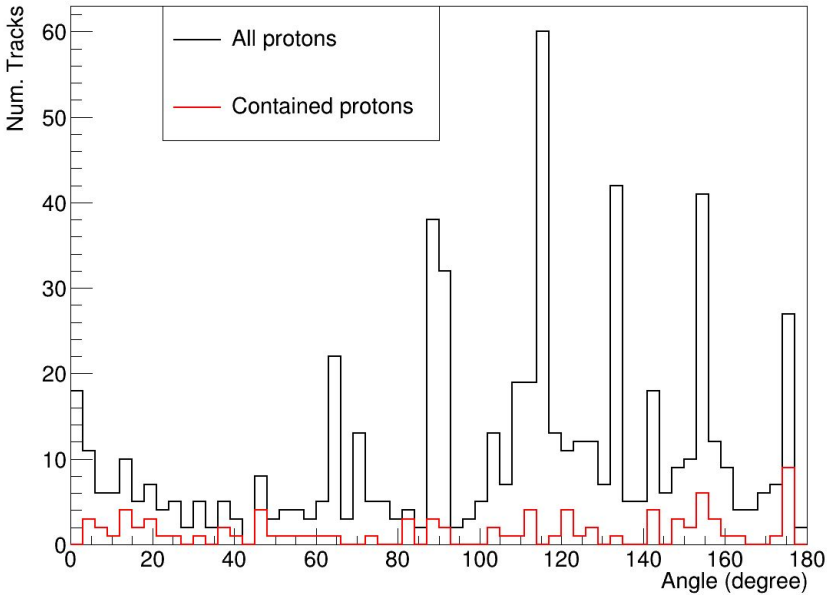
Related the primary particle multiplicity (muons/pions/protons) does not look as expected given the NuMI beam energy

For example, according to the CAFs, most interactions do not have a primary muon (i.e. more NC than CC events)

Kinematic distributions also may look somewhat strange, but these are either known effects or difficult to quantify without truth information

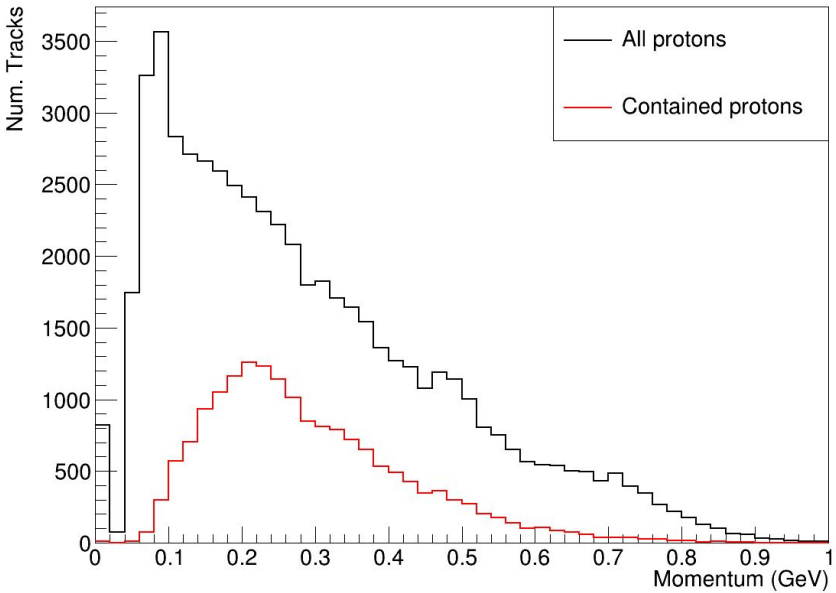
# Selected proton kinematic plots

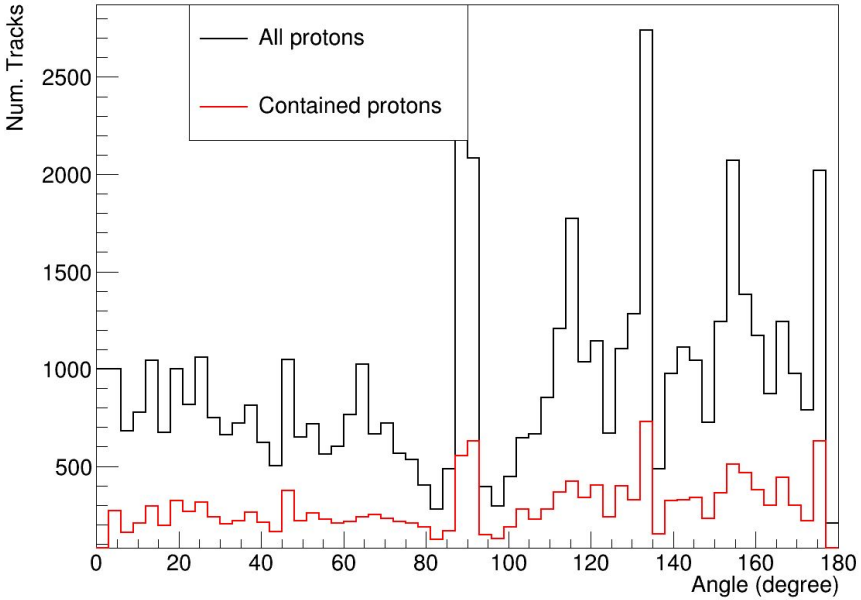



All = primary protons in selected interactions; and the contained protons sample also includes a length > 2 cm cut on track length

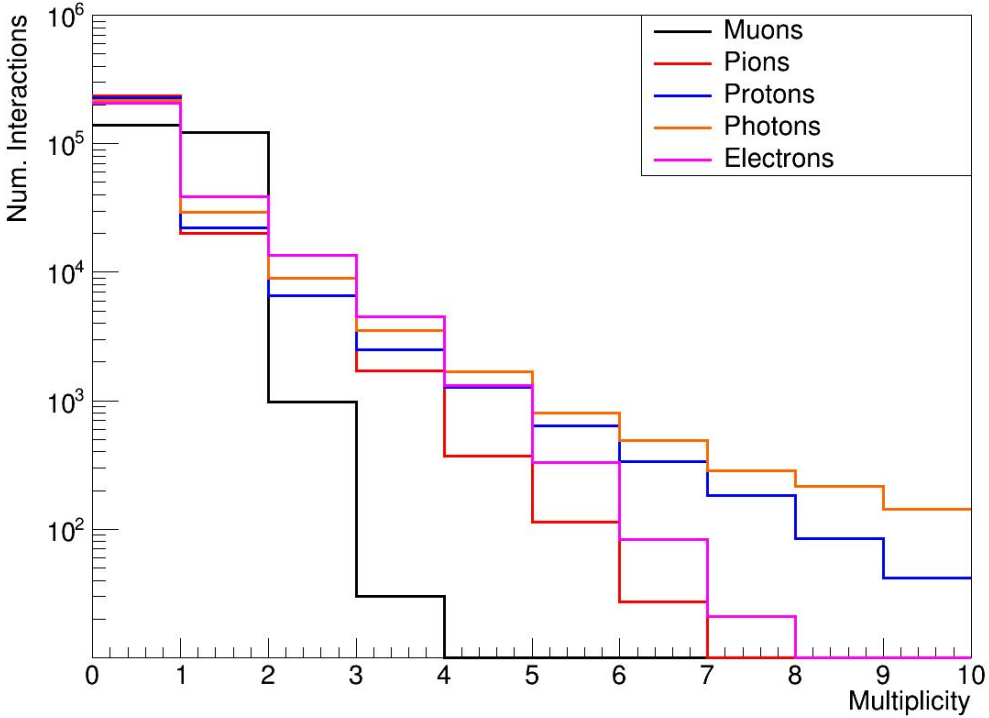
# All candidate proton kinematic plots




All = candidate primary protons from all interactions; and the contained protons sample also includes a length > 2 cm cut on track length

# Primary particle multiplicities




Counting number of particles of a given type tagged as primary

Particle type according to reconstructed PID

Most likely multiplicity for any particle type is zero

Average particle multiplicity is 1.4 total per interaction

# Summary

- Mesonless $\overline{\nu}_{\mu}$CC cross section measurements rely on (among other things):
  - Successful **proton reconstruction and identification**, which can be evaluated using reflowed Bern single module data
  - The ability to implement a **selection using CAF files**
- Our involvement in the Bern single module data reflow effort includes contributions to **documentation, visualization, and calibration-level reconstruction**
- Unexpected features found while implementing a selection using (ML Reco) CAF files, such as **more NC events than CC events** in all interactions, clear **substructure in proton kinematics** distributions, and a very **low selection efficiency** for our signal definition

# Backup Slides

From: ND Prototypes Sept. 2023 Analysis Workshop Analysis Viability & Systematics Slides

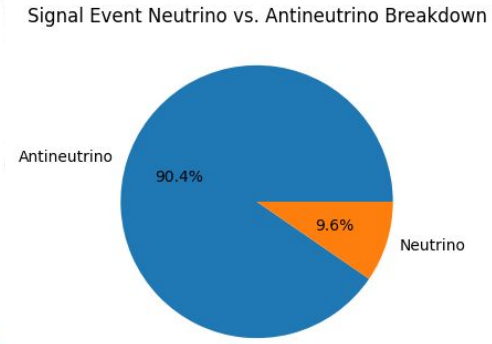
# Signal contribution

Signal events are roughly half quasi-elastic scatters, half meson-exchange and resonant pion production, and almost negligible deep inelastic contribution

All of this at least at the truth level, which may change once reconstruction is factored in

Primary signal/background migration will be mis-identifying pions (and kaons) as protons and vice versa

Additional contributions of particles near detection threshold and neutrino meson-less events as the signal signature is the same

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