On 2x2 Charged Track Multiplicity

(Update: May 31, 2024)

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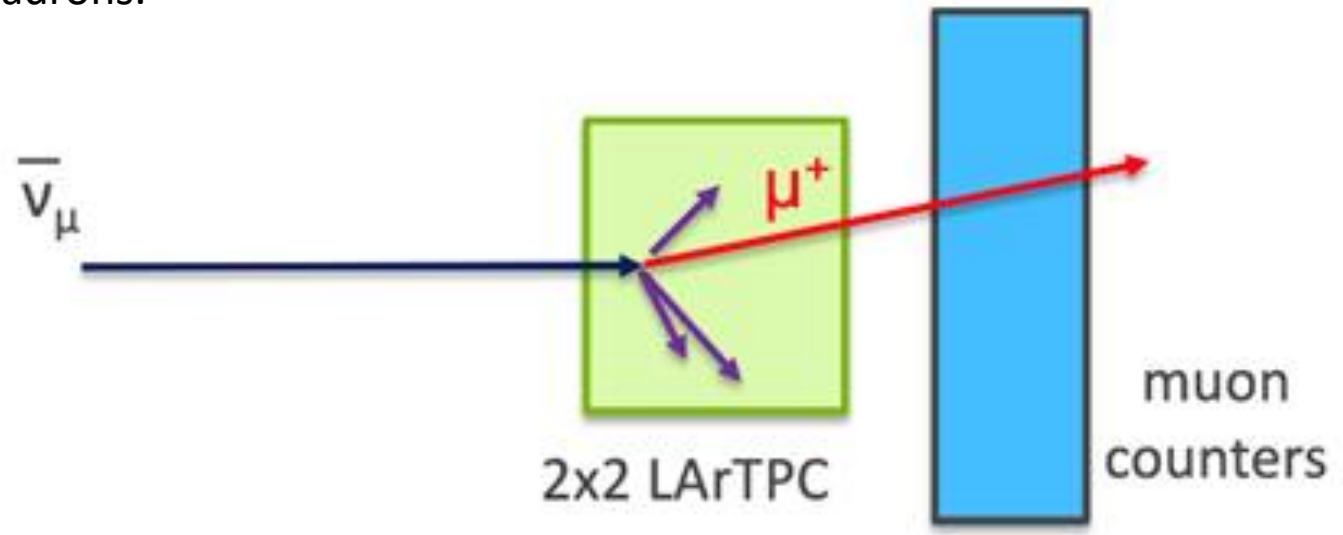
Motivation for Multiplicity Studies with ND Prototype (2×2)

- Perform a first measurement of multiplicity of the charged-particle tracks generated by ν (or $\bar{\nu}$) interactions
- **Definition:** Number of final state charged hadrons in selected neutrino (or antineutrino) interactions with single muon and associated charged hadrons.



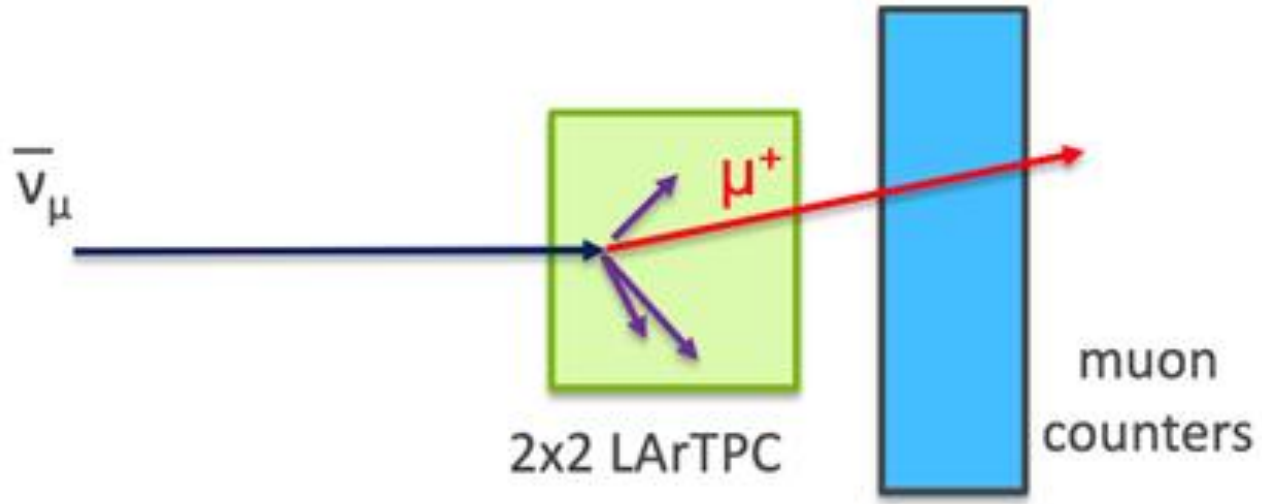
What are the goals and what have we achieved so far?

- We developed a *selection criteria* and used this to analyze the produced simulated data
- Prepare this analysis to be run on the measured data when available (later this year)
- The goal is now to perform measurement on data from 2×2 and compare to predictions based on simulation
- More details on the recent work can be found at Link1, Link2, Link3 and Link4.

Signal Selection

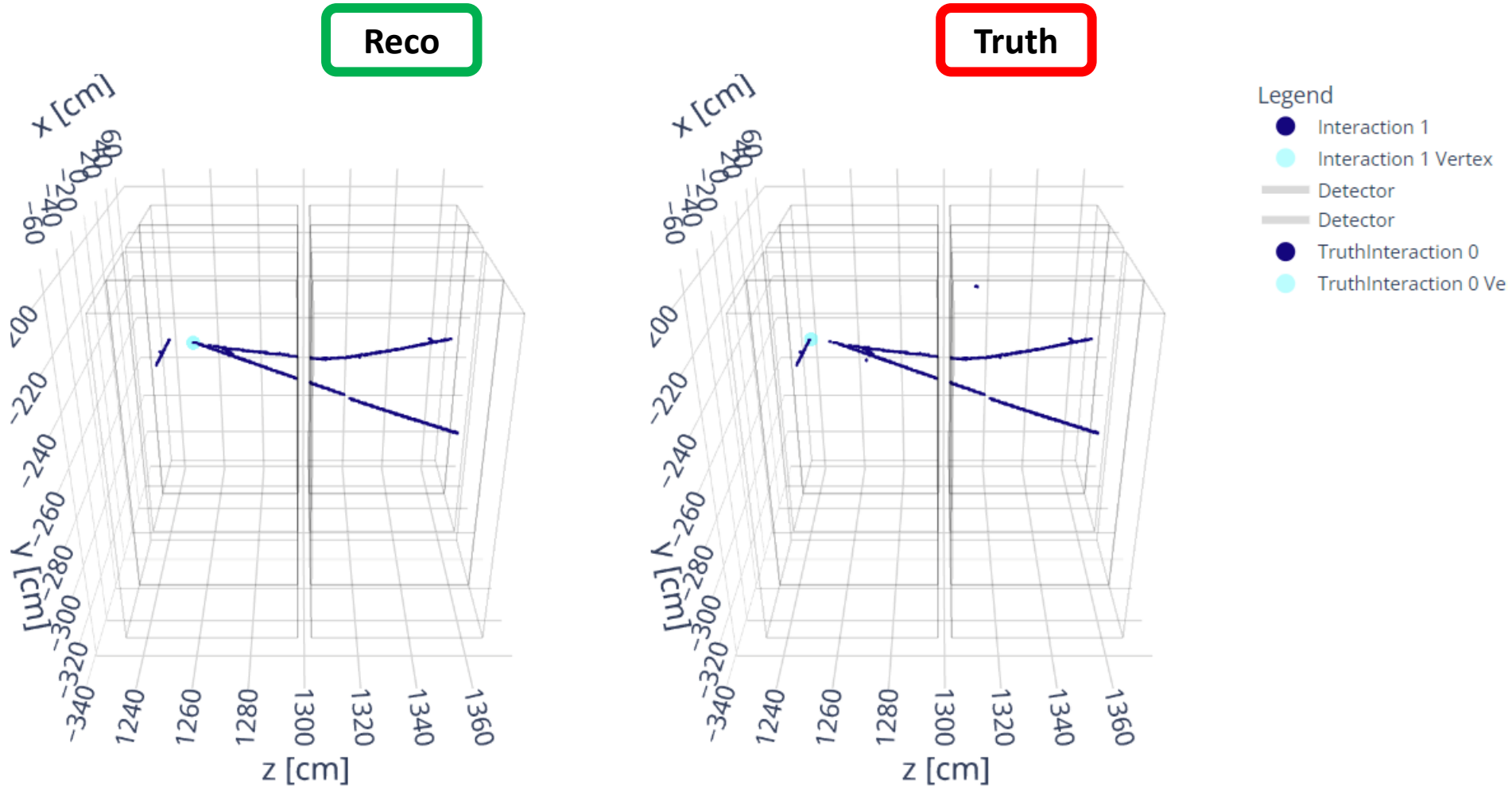
- We are using the latest production sample**:** MiniRun5 Beta1 CAFs
  - 1E19 POT; data of 3.5 days
  - This data is written in high-level analysis files - Common Analysis Format (CAFs) in Root framework.
  - In CAFs, we have MC simulated neutrino interactions, and reconstructed events based on ML.
- Before selection, there are approximately $422\mathrm{k}$ neutrino interactions.

- **Signal Definition:** A neutrino CC interaction within Liquid Argon Fiducial Volume (LArFV)



How does an interaction look like?

- Event reconstruction is performed using AI/ML techniques (GitHub Repo)
- Generated using ML-Reco event display
  - A typical event - MiniRun4.5: output_27024464_1-larcv_mlreco_ana.h5 (Event 16)



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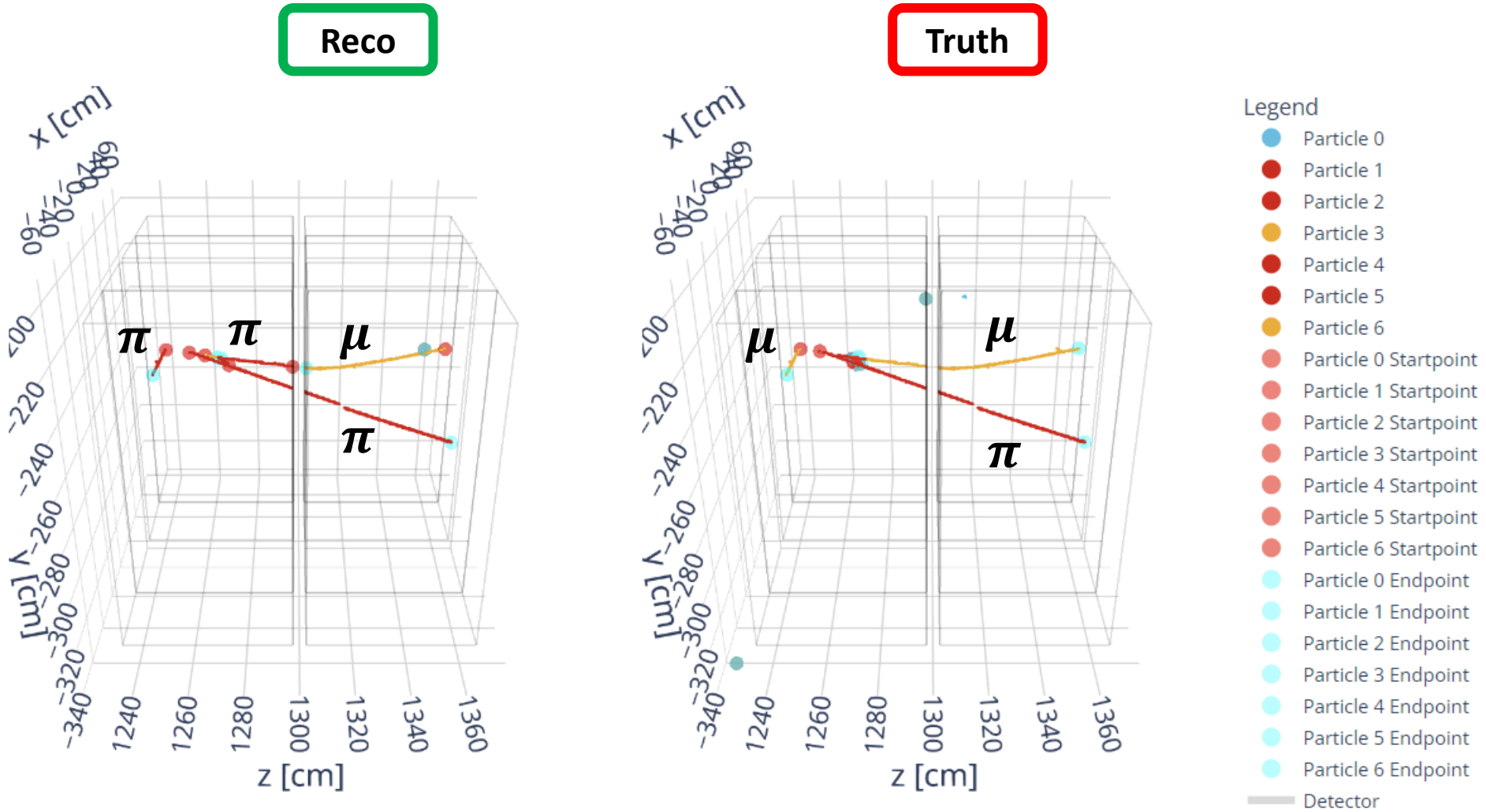
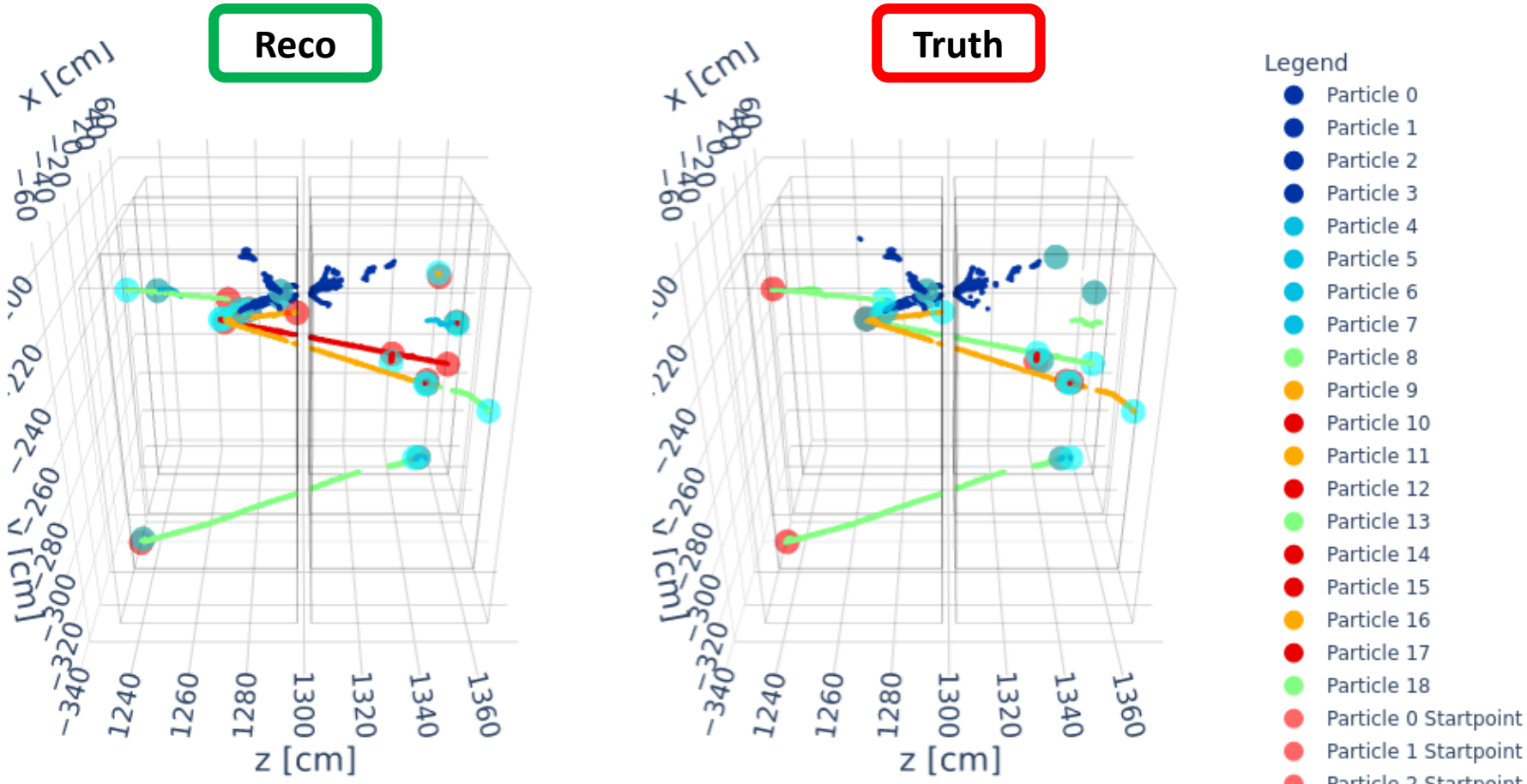


How does an event look like? (Another Example)

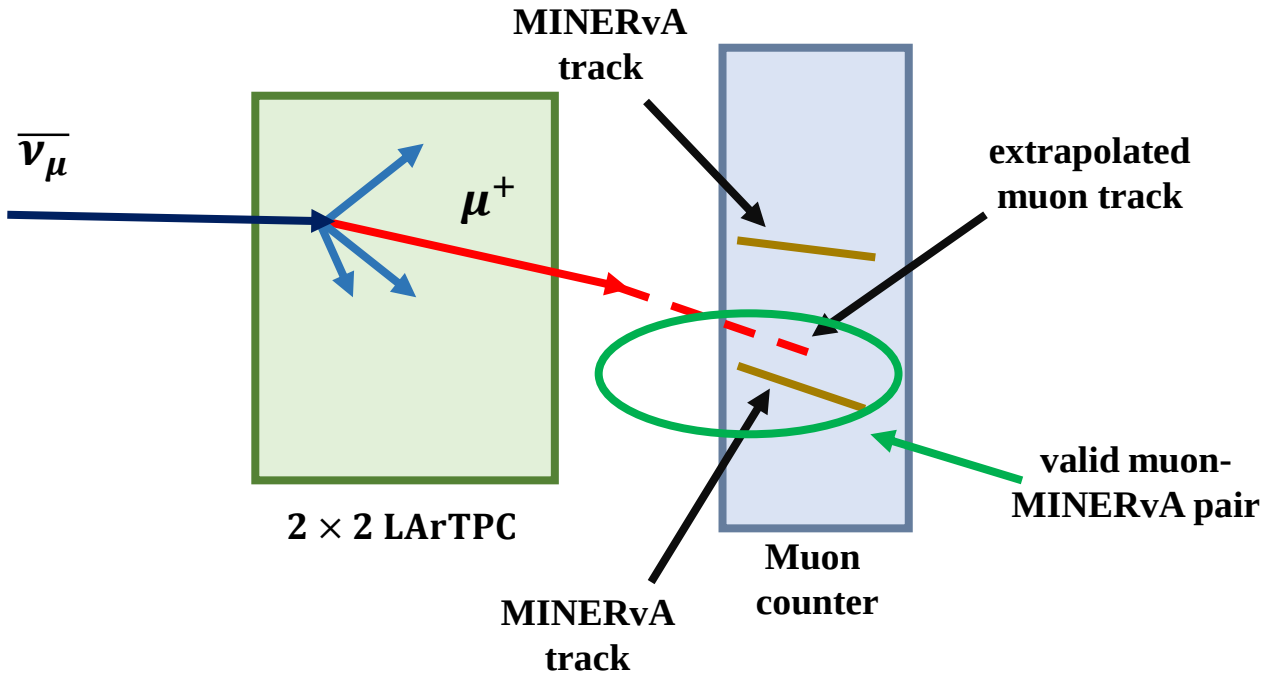
- Event reconstruction is performed using AI/ML techniques (GitHub Repo)
- Generated using ML-Reco event display
  - A typical more complicated event - MiniRun4.5: output_27023276_64-larcv_mlreco_ana.h5 (Event 30)

	Reco	Truth
γ	4	4
e	4	1
μ	3	3
$\pi^{\pm}$	3	3
p	5	6



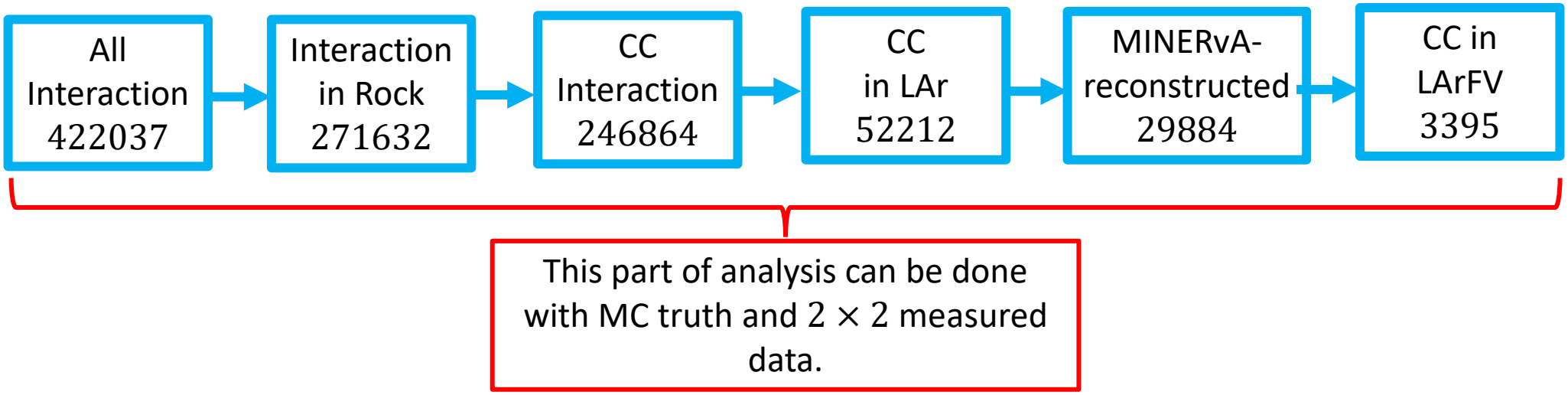
Signal Selection

- A neutrino CC interaction within Liquid Argon Fiducial Volume (LArFV)
- We require a muon starting point to be 5 cm away from detector boundaries including walls between modules
- Count charged hadrons around this interaction vertex (this number is our definition of charged hadron multiplicity)
- In the current selection presented here, we require minimum track length of 5 cm and vertex should be within LArFV and 5 cm away from inner and outer boundaries of LAr TPC modules
- Muons have longer track and will not be contained in 2×2 but detected in the muon counter, so the event selection is developed with and without pairing the muon track component in LAr with those in MINERvA
- All codes used in this analysis can be found in this GitHub repository.



Event Selection for Neutrino Interactions

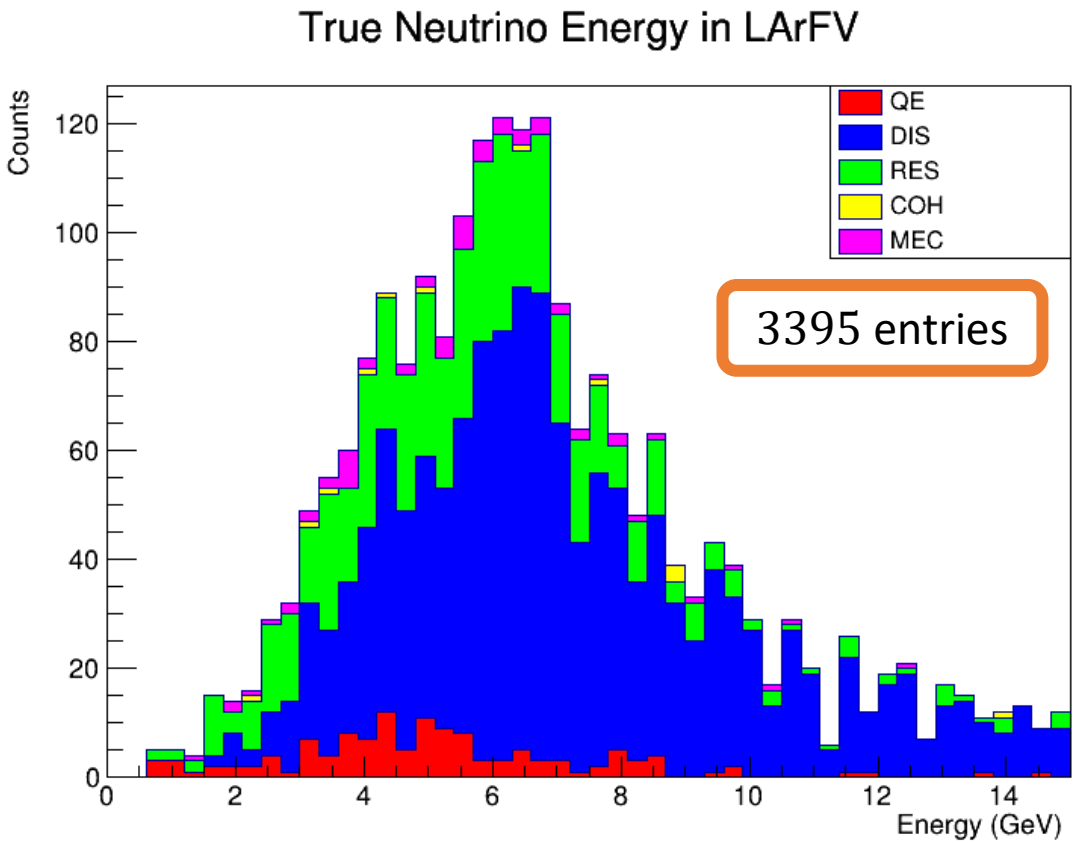
- Selection steps (for reconstructed interactions) are as follows



- Must have one out-going muon (CC interaction) in liquid argon
- Muon candidate has liquid argon component of the track which is paired with the MINERvA track component
- Interaction vertex must be within liquid argon fiducial volume (LArFV) and at least $5\ \mathrm{cm}$ away from any walls
  - Following fiducial volume bounds are used in this study:
    - x: $(-63.931, +63.931)$; y: $(-62.076, +62.076)$; z: $(-64.538, +64.538)$
- And now we count the number of charged hadronic tracks (this is the measured multiplicity)

True Neutrino Energy

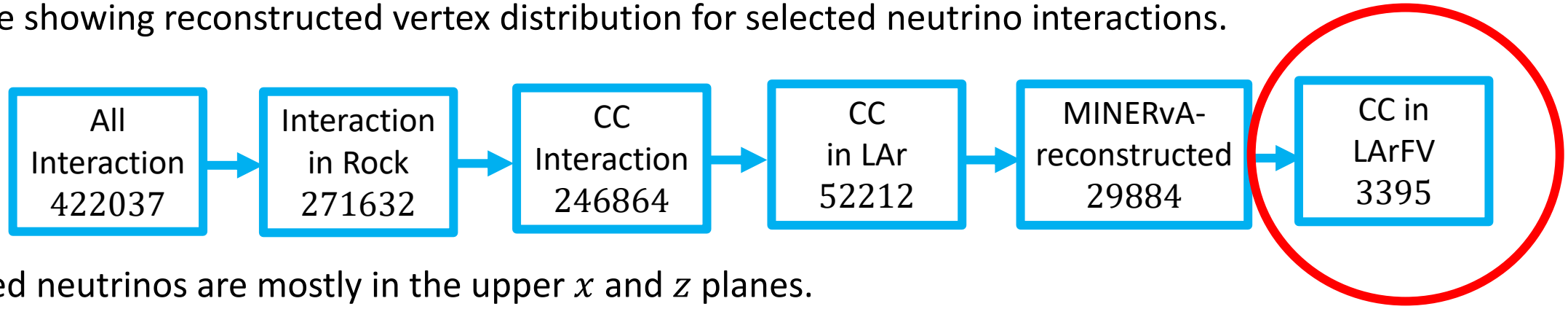
- For selected interactions, true neutrino energy is shown.



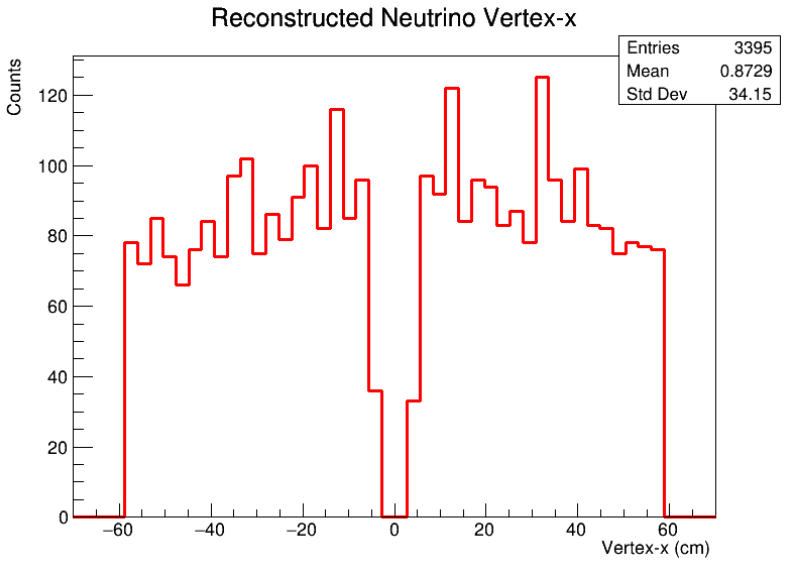
- It peaks around $6\ \mathrm{GeV}$ which is also the DUNE's NuMI on-axis $\bar{\nu}$ beam range.
- This signal topology encompasses a broad range of physics processes including QE, MEC, RES etc.

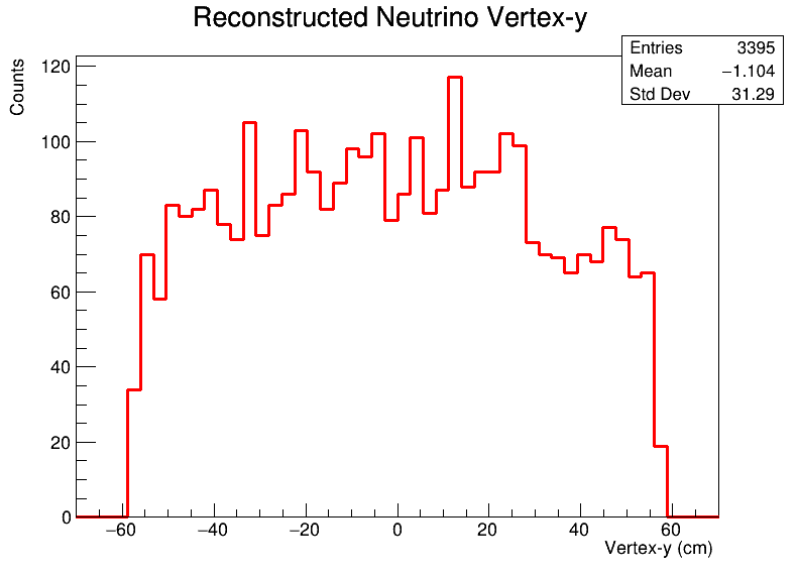
Reconstructed CC Neutrino Vertices

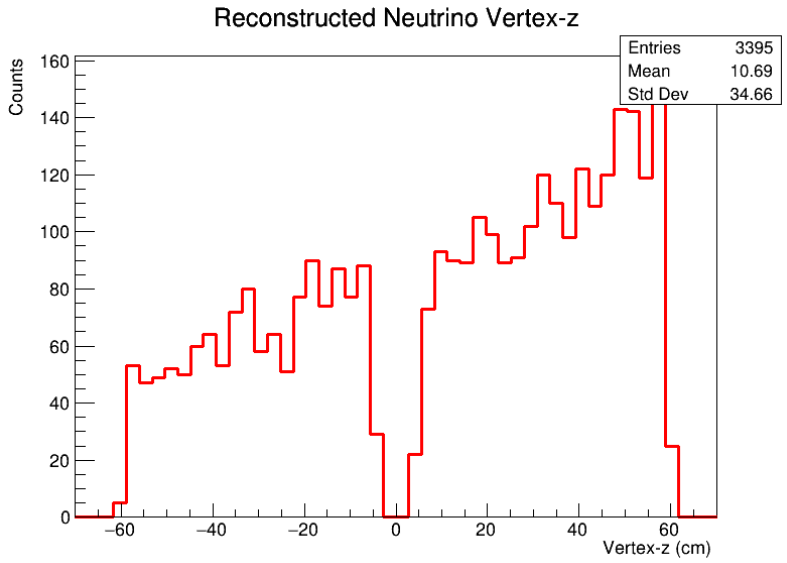
- We are showing reconstructed vertex distribution for selected neutrino interactions.



- Selected neutrinos are mostly in the upper x and z planes.
- A peak around cathode ($x = +35$ cm) can also be observed.



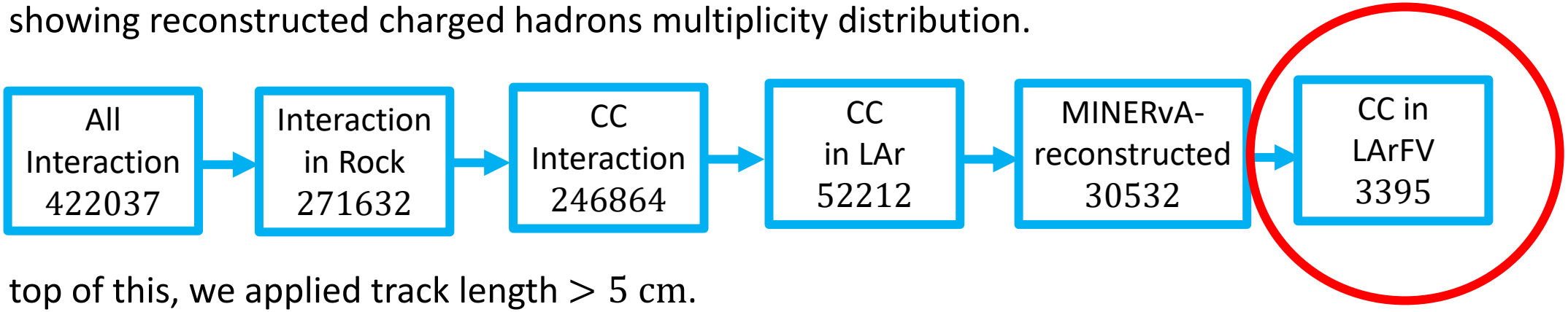




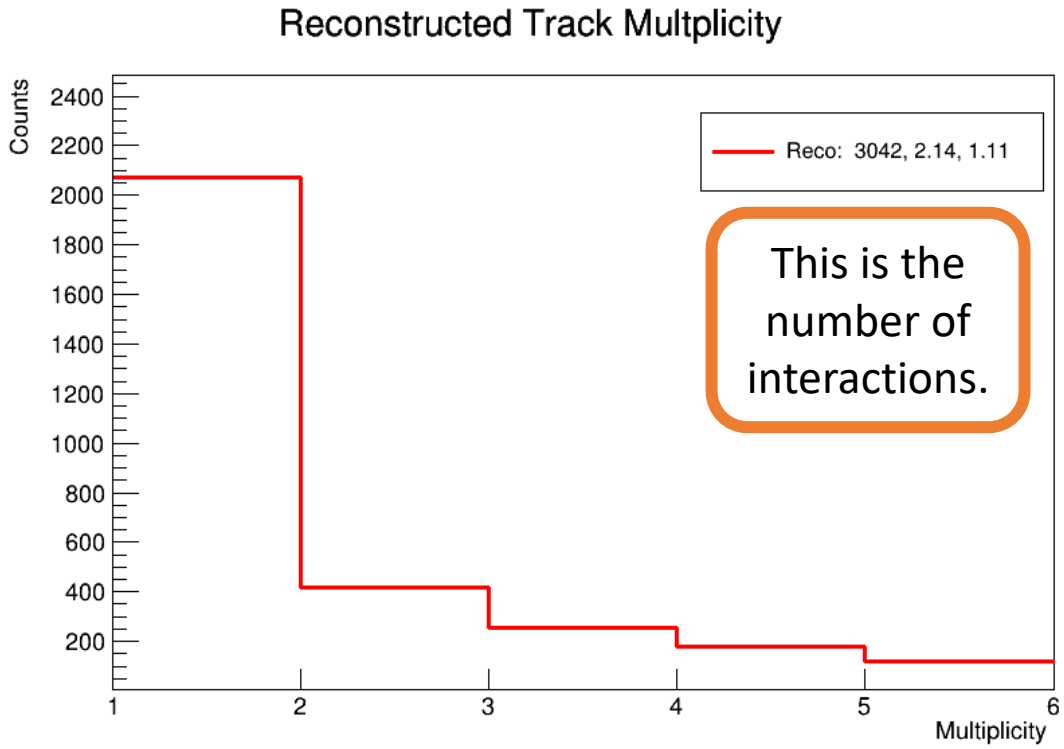
- The shape of these distributions may significantly change when we vary the MINERvA cut.

Hadronic Multiplicity Distributions within LArFV

- We are showing reconstructed charged hadrons multiplicity distribution.

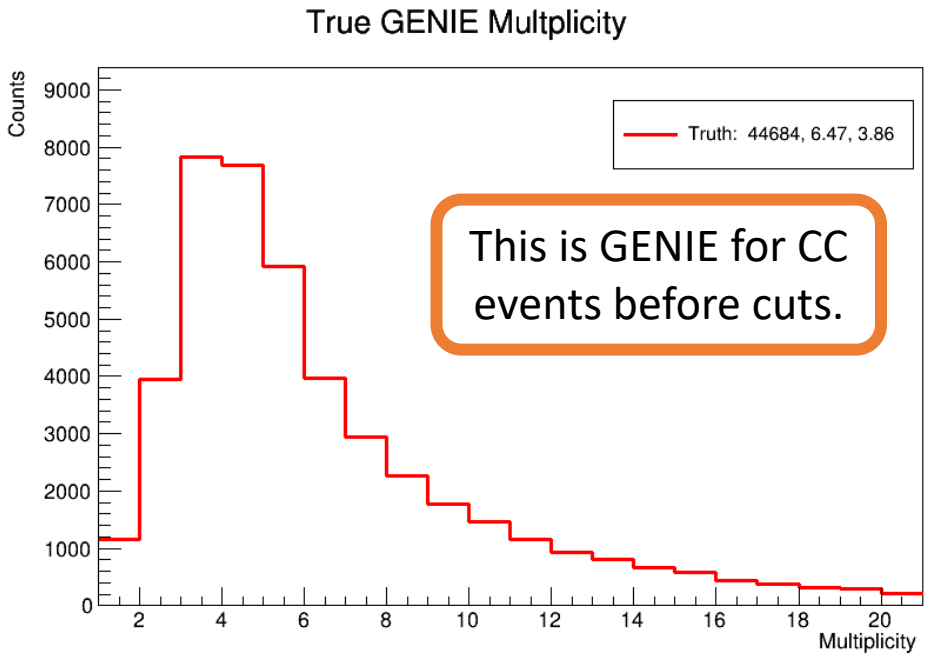


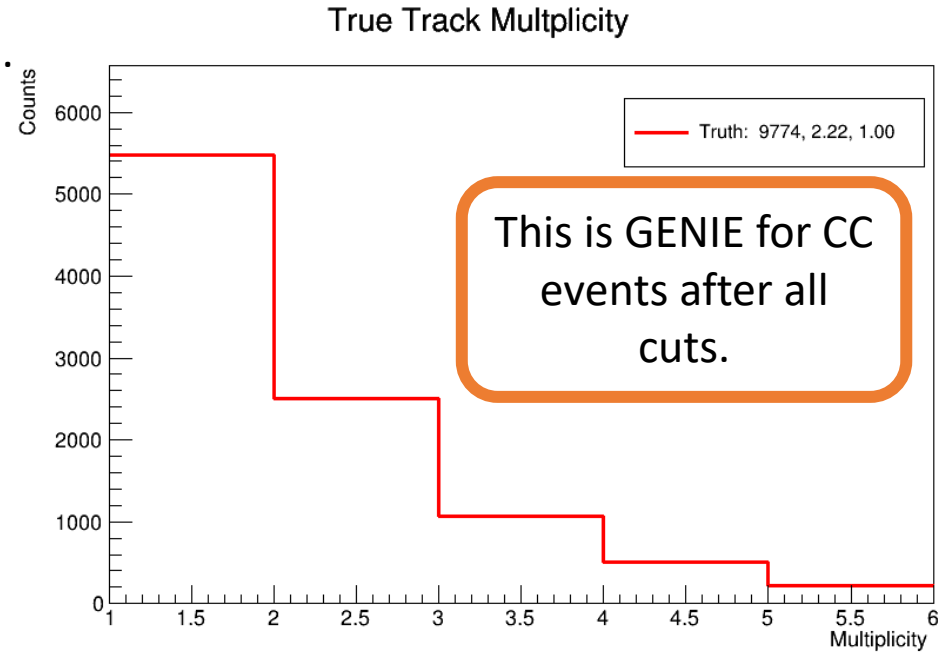
- On the top of this, we applied track length > 5 cm.



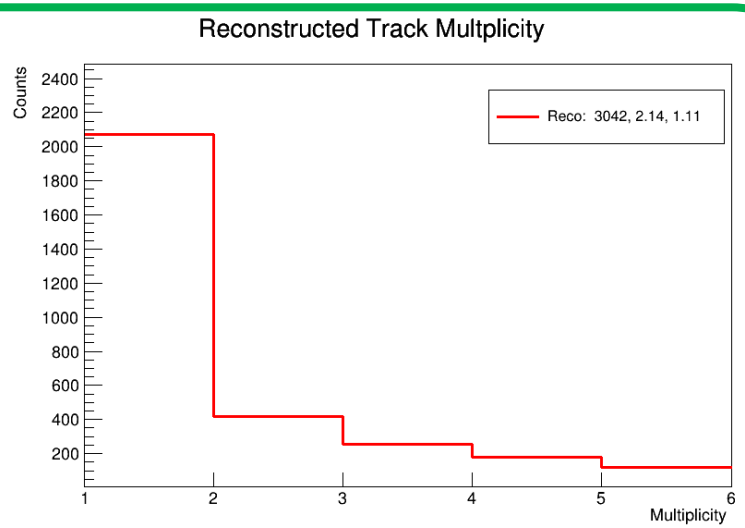
True Charged Hadronic Multiplicity

- We want to compare reconstructed multiplicity to GENIE predicted multiplicity.
- Following cuts are applied to true tracks (within LArFV, track length > 5 cm).



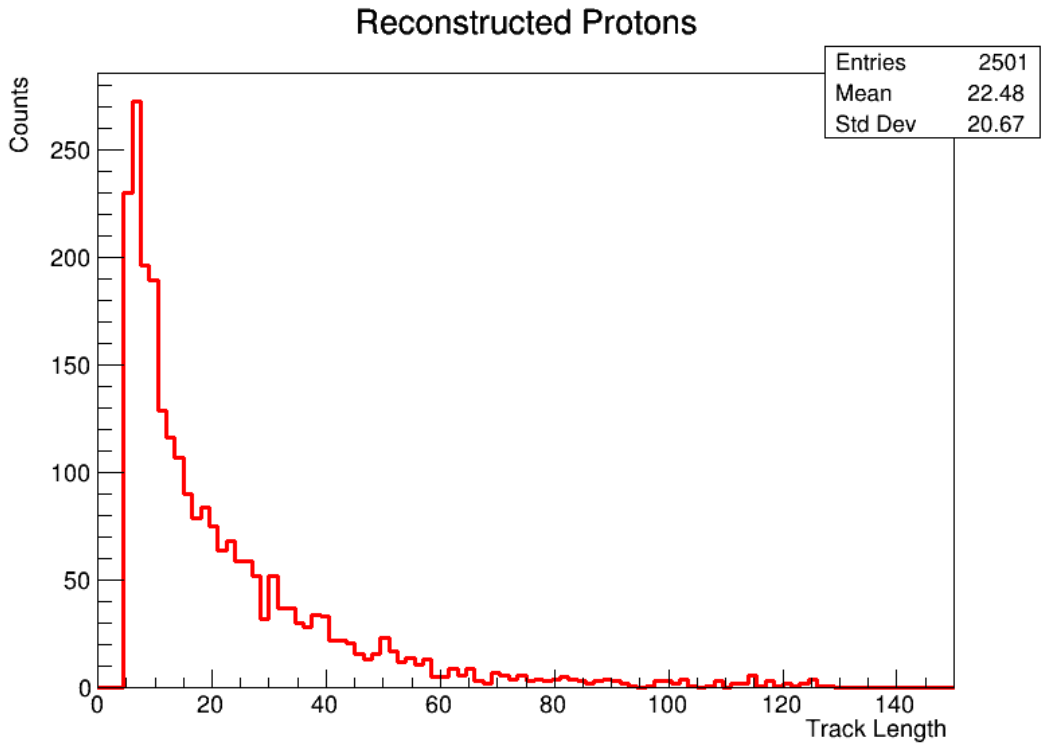


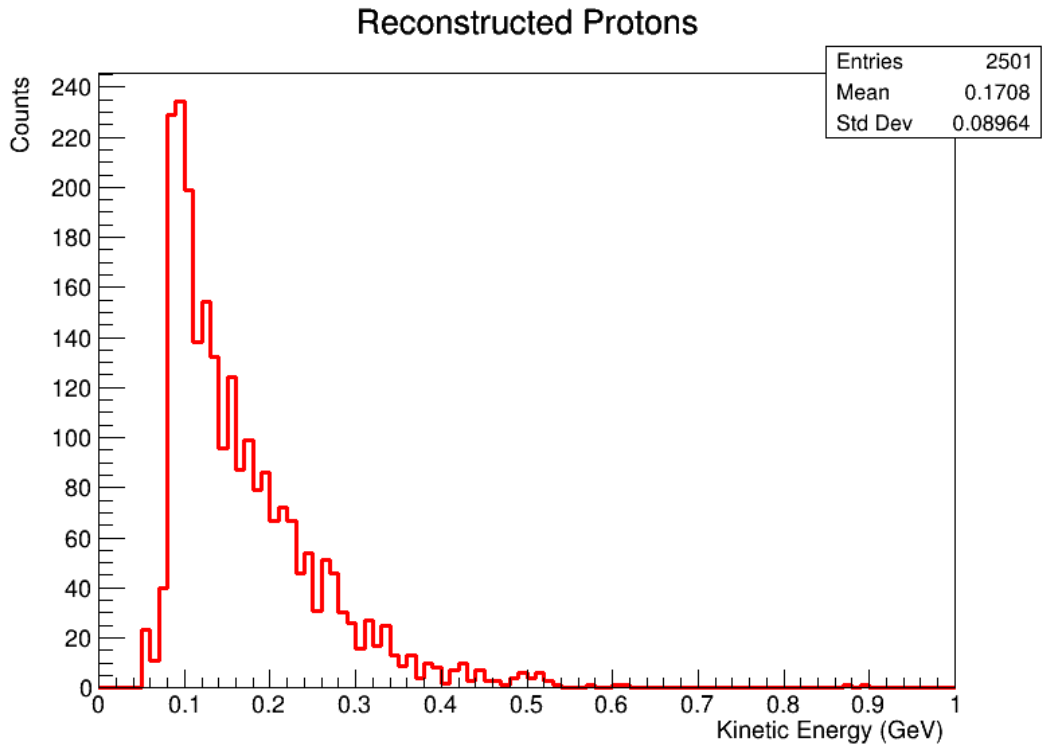
- This is the reco multiplicity distribution from previous slide (for comparison).
- There are many truth tracks which are not being reconstructed.



Distributions of Reconstructed Protons

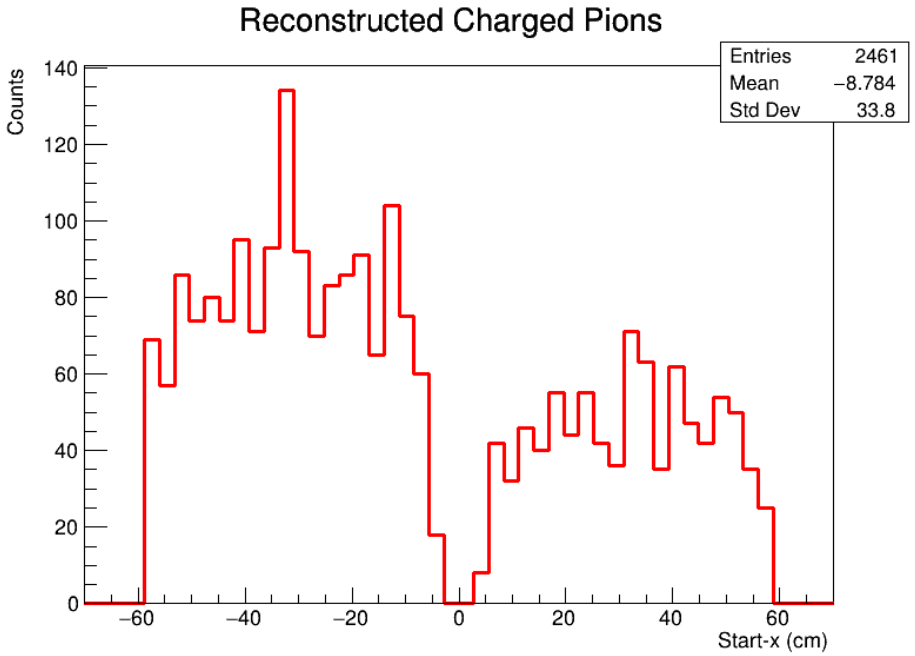
- We present different features of the reconstructed protons because these are important.
- Tracks are within LArFV and > 5 cm.
- The track length (in cm) and kinetic energy distributions of reconstructed protons are shown here.
- Kinetic energy is peaked at smaller values indicating proton traverse short distances in the the detector.

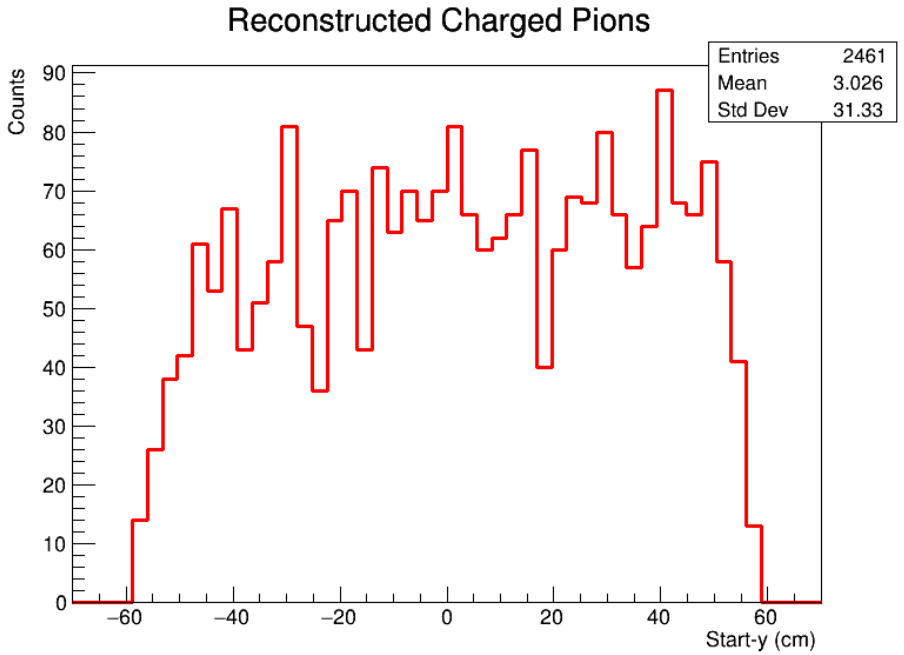


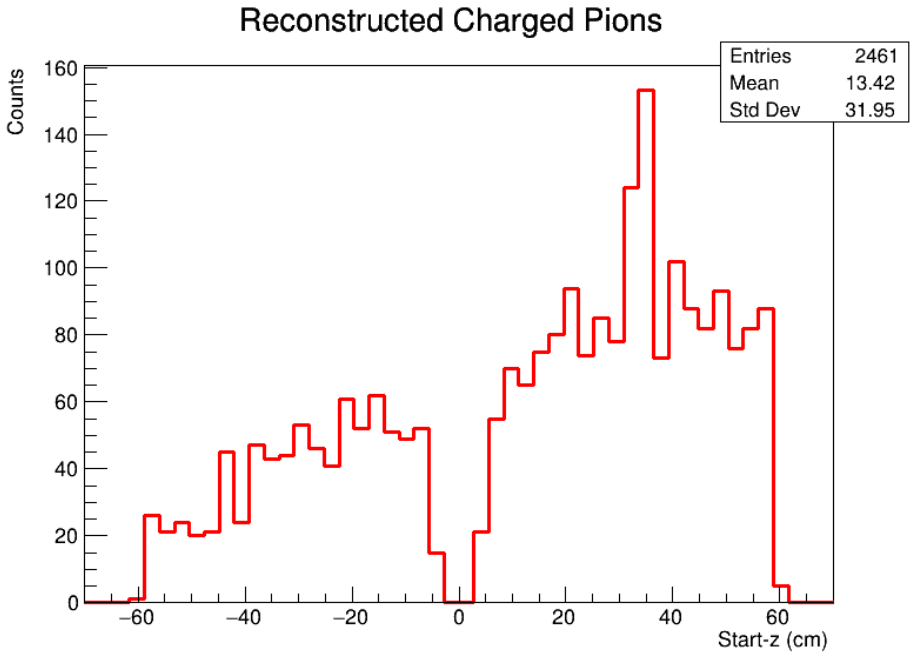


Start Positions of Reconstructed Charged Pions

- We present different features of the reconstructed charged pions showing how they distribute within the FV.
- These pions have track length > 5 cm.
- Peaks around $x = \pm 35$ cm (cathodes) can be observed.
- A good accumulation of reconstructed charged pions can be seen in the positive z −half of the module.

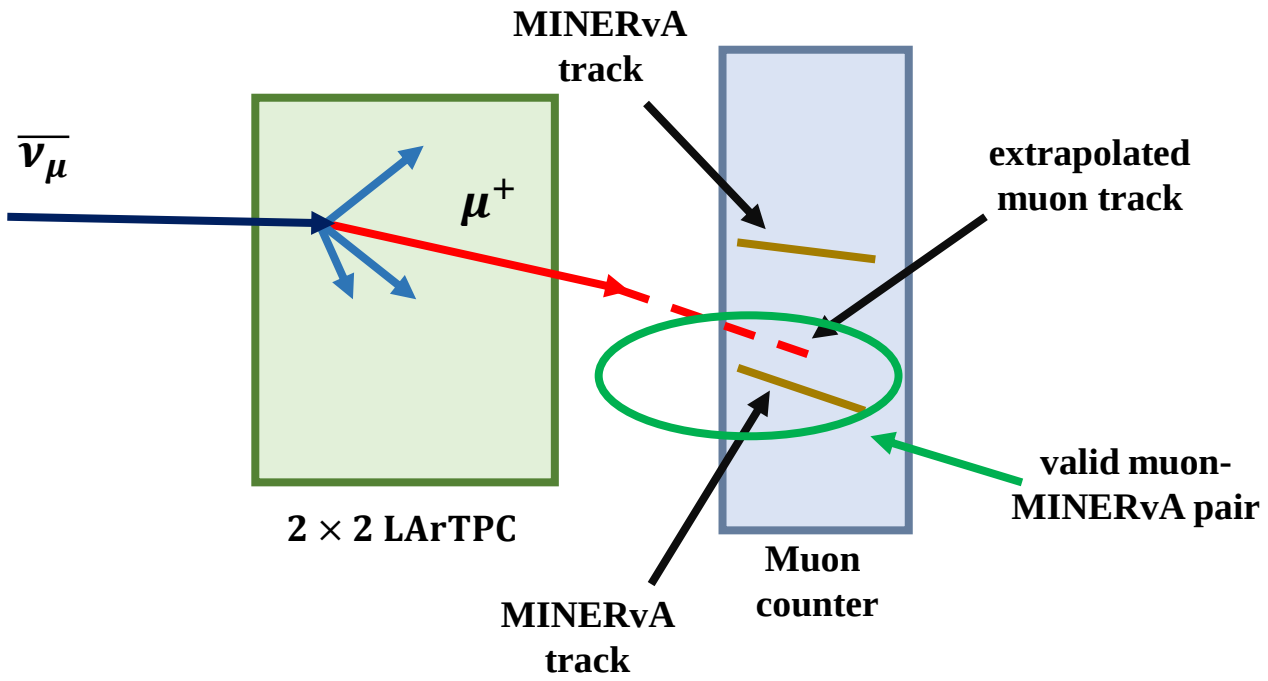






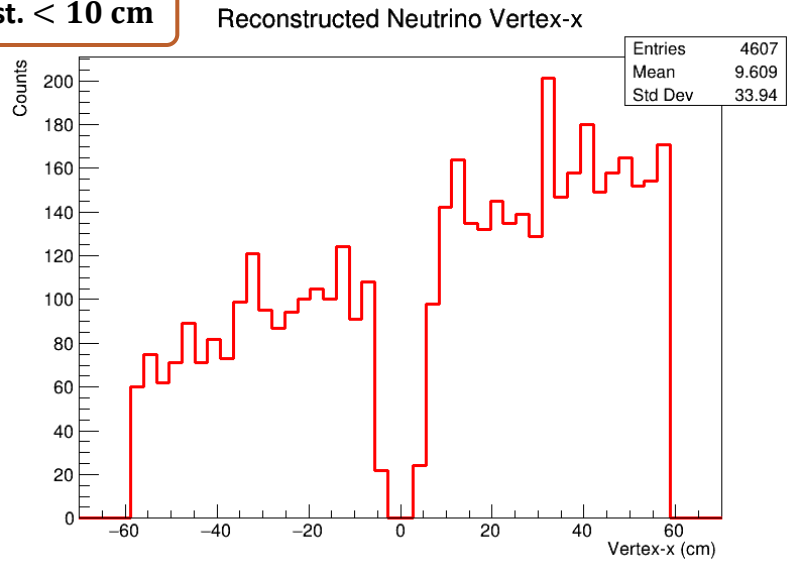
A Step towards Optimization of Event Selection

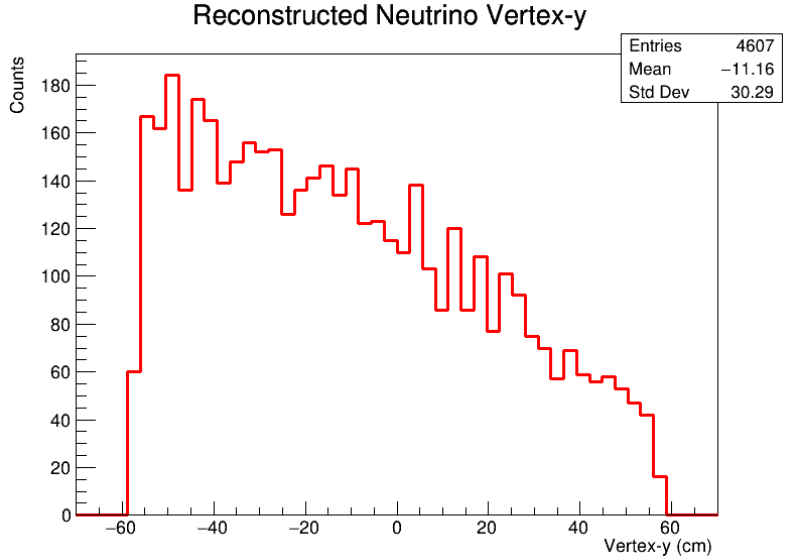
- We also studied reconstructed neutrino vertex distribution under two different MINERvA-pairing criteria.
- One simple selection criteria is that a match is identified if
  - the distance between MINERvA and reconstructed track is less than 10 cm.
- In second selection, a match is identified if
  - the distance between MINERvA and reconstructed track is less than 10 cm;
  - and dot product between MINERvA and reconstructed track exceeds 0.9975.
- We found out neutrino vertex distribution is sensitive to MINERvA-pairing (see next slide).

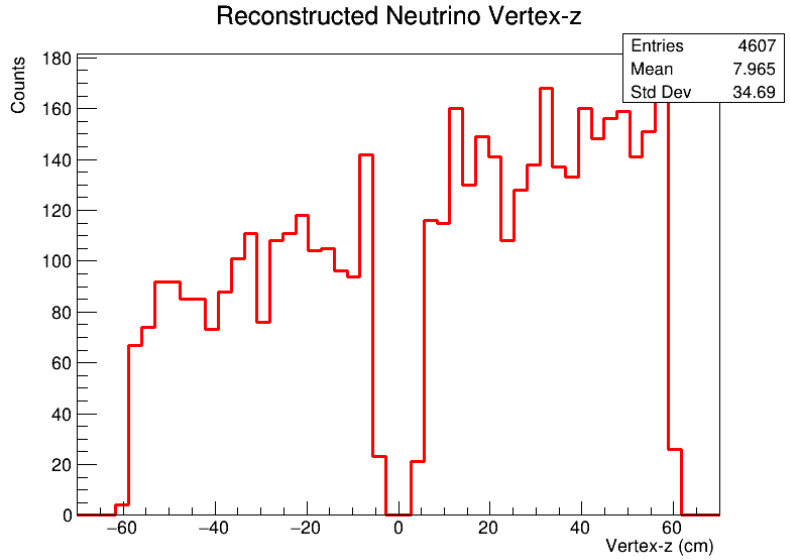


MINERvA-Pairing and Neutrino Vertex Distribution within LArFV

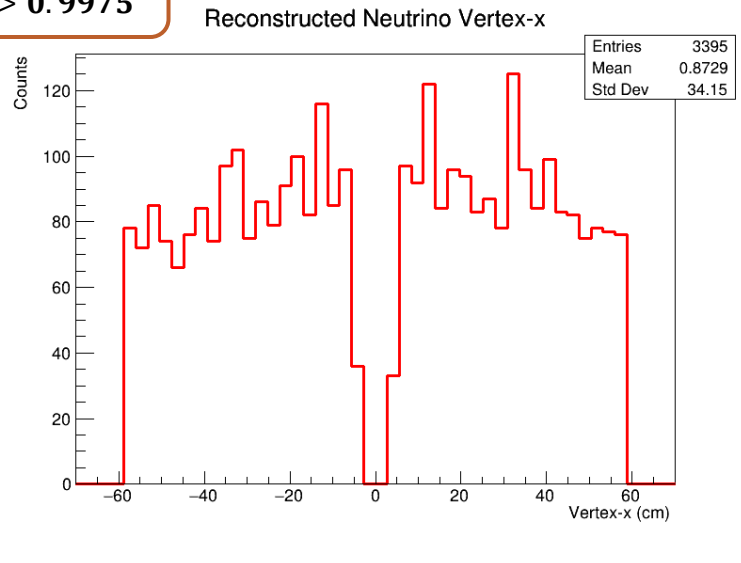
dist. < 10 cm

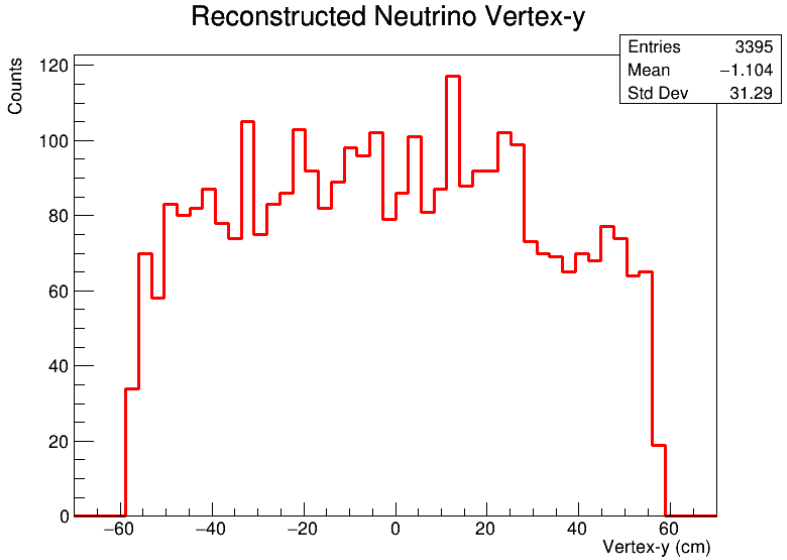


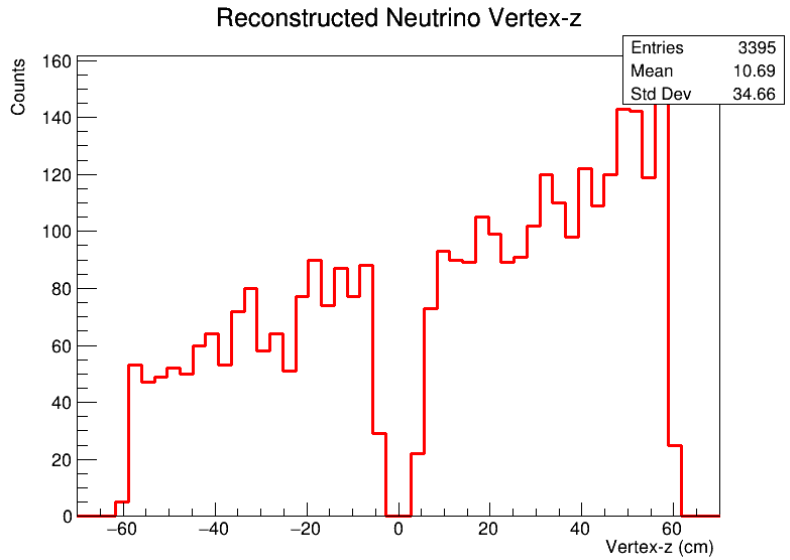




dist. < 10 cm
Dot > 0.9975



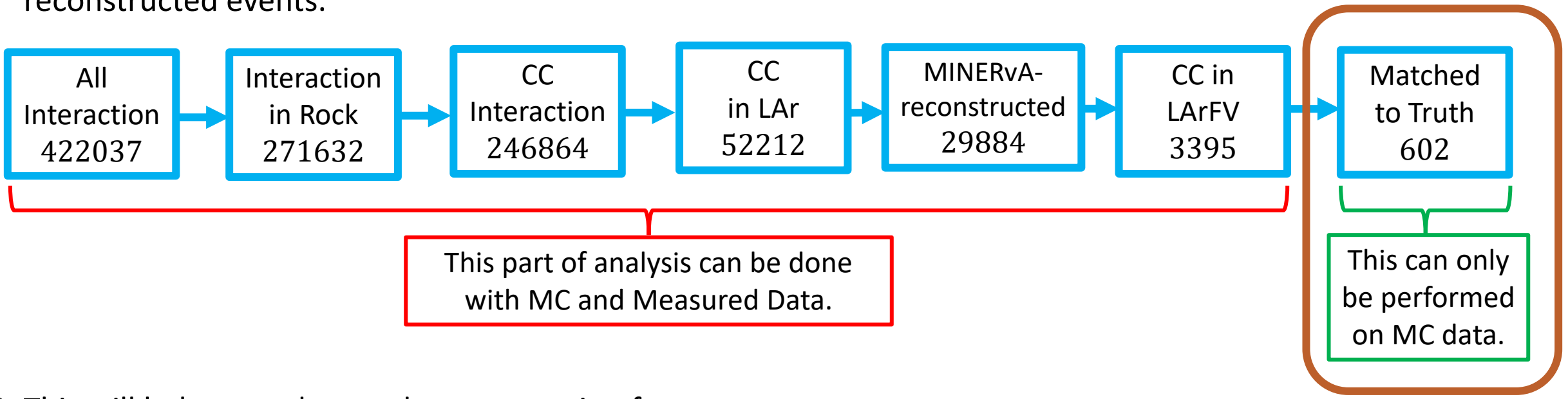




Additional Studies to Characterize Reconstruction: Matching Mechanism for Reco-to-Truth Interactions and Tracks

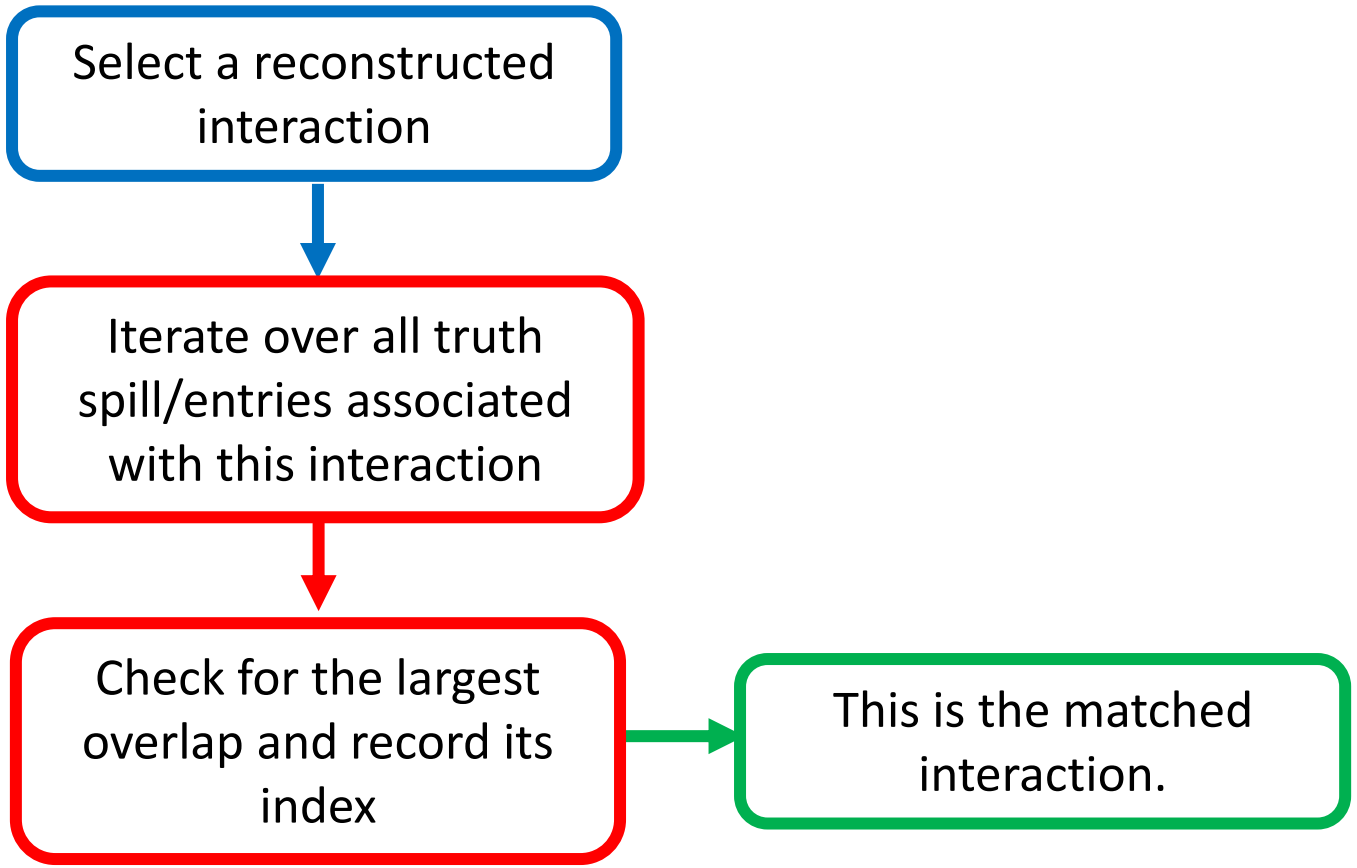
Additional Studies (Reco-to-Truth Matching)

- ML-Reco will ultimately be used to look at the real 2×2 measured data.
- Additional studies are done to test and understand agreement between MC truth events and corresponding reconstructed events.



- This will help us understand reconstruction features.
- To achieve this, we are matching:
  - Reco interactions with truth (MC) interactions
  - Reco tracks with truth (MC) tracks
- In next few slides, we will show some interesting features of reco interactions matched to the truth (MC) interactions.

How this interaction matching is being implemented?

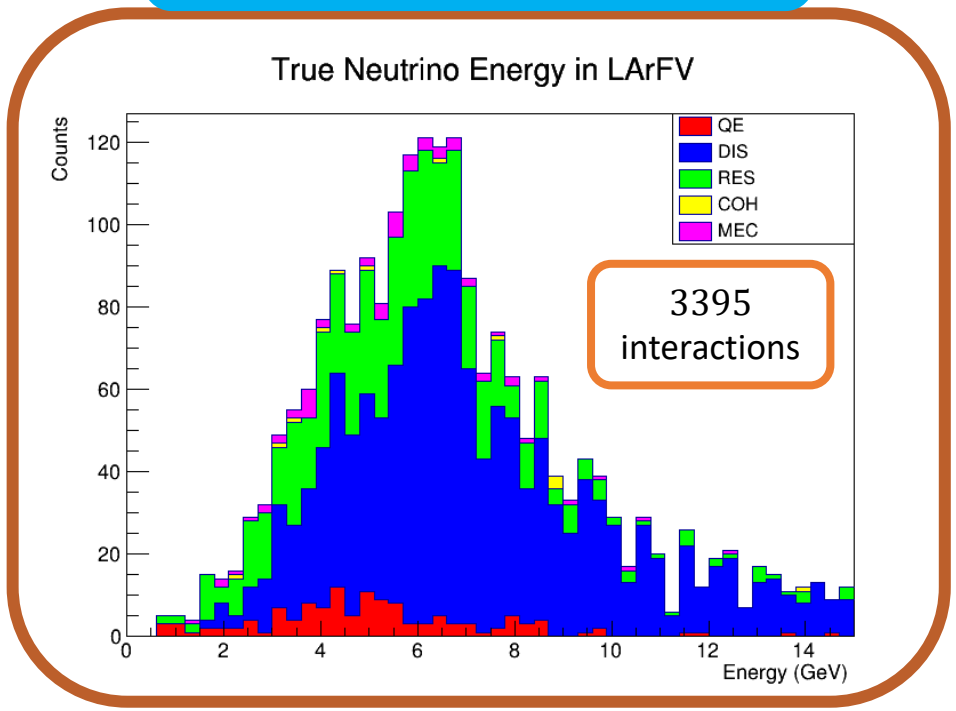


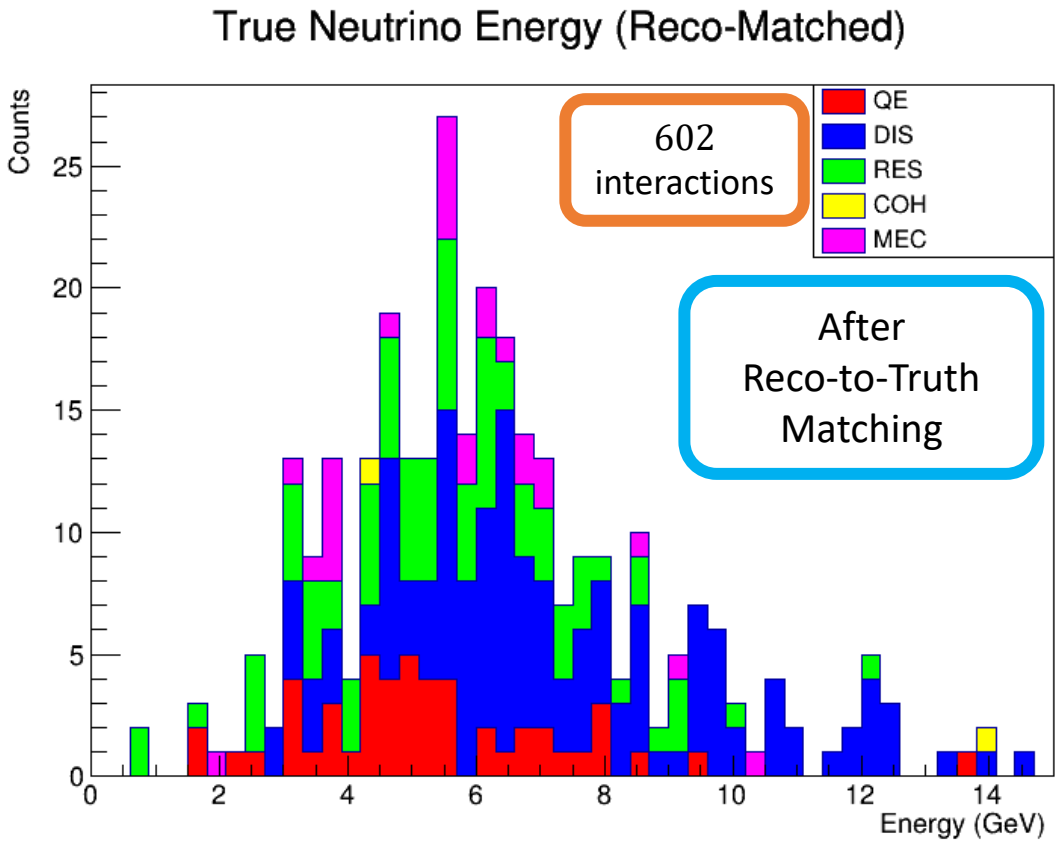
➢ With these steps, we are able to match reconstructed interaction to the most probable truth interaction.

True Neutrino Energy within LArFV

- We are matching reconstructed interactions to truth interaction and showing true neutrino energy.
- Only CC interactions within LArFV are matched.

All CC Reconstructed interactions within LArFV (before matching)

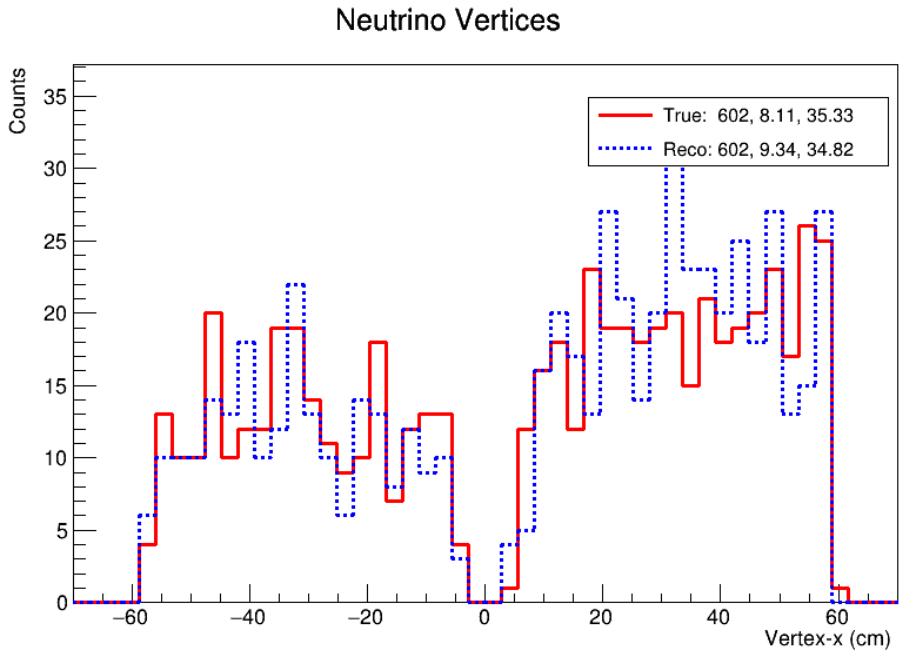




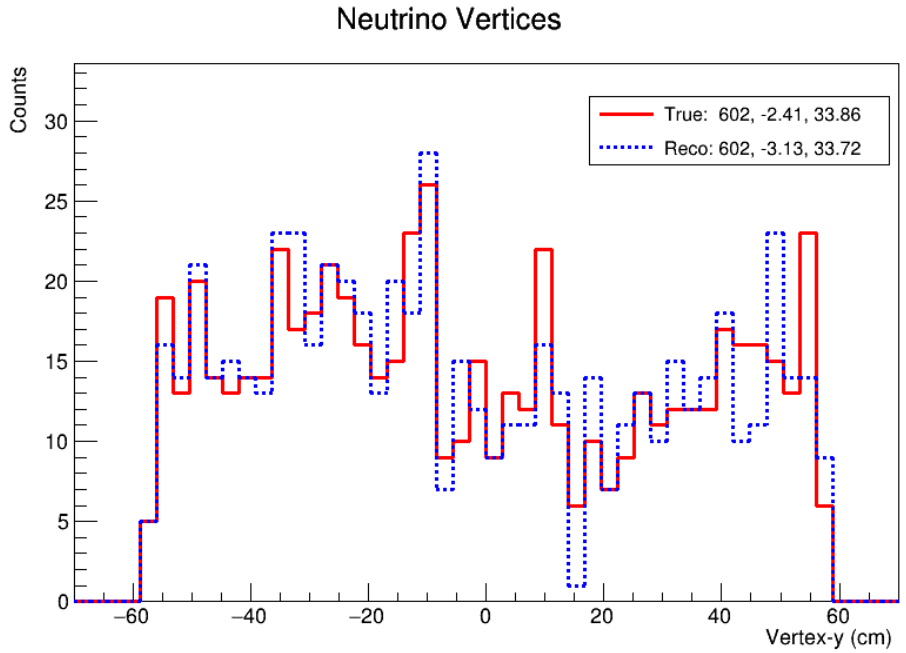
- Only $\sim 17\%$ interactions are matched $(602$ out of $3395)$.

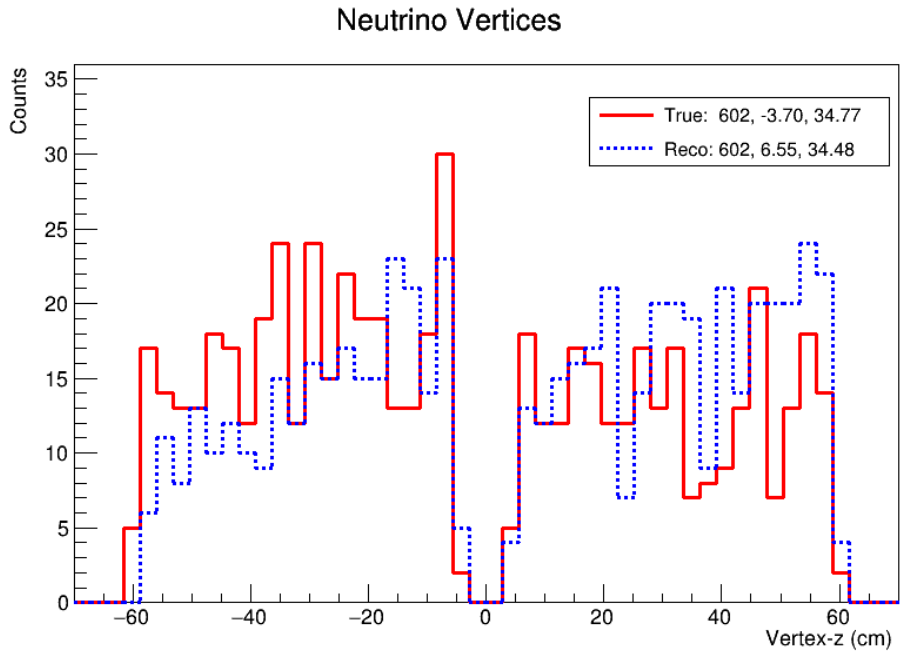
Selected Neutrino Vertices within LArFV

- Selected neutrino vertices are uniformly distributed through the liquid argon fiducial volume.
- There are slightly more reconstructed vertices in the upper x and z regions and more truth in the lower z region of modules but on average we see a uniform distribution.



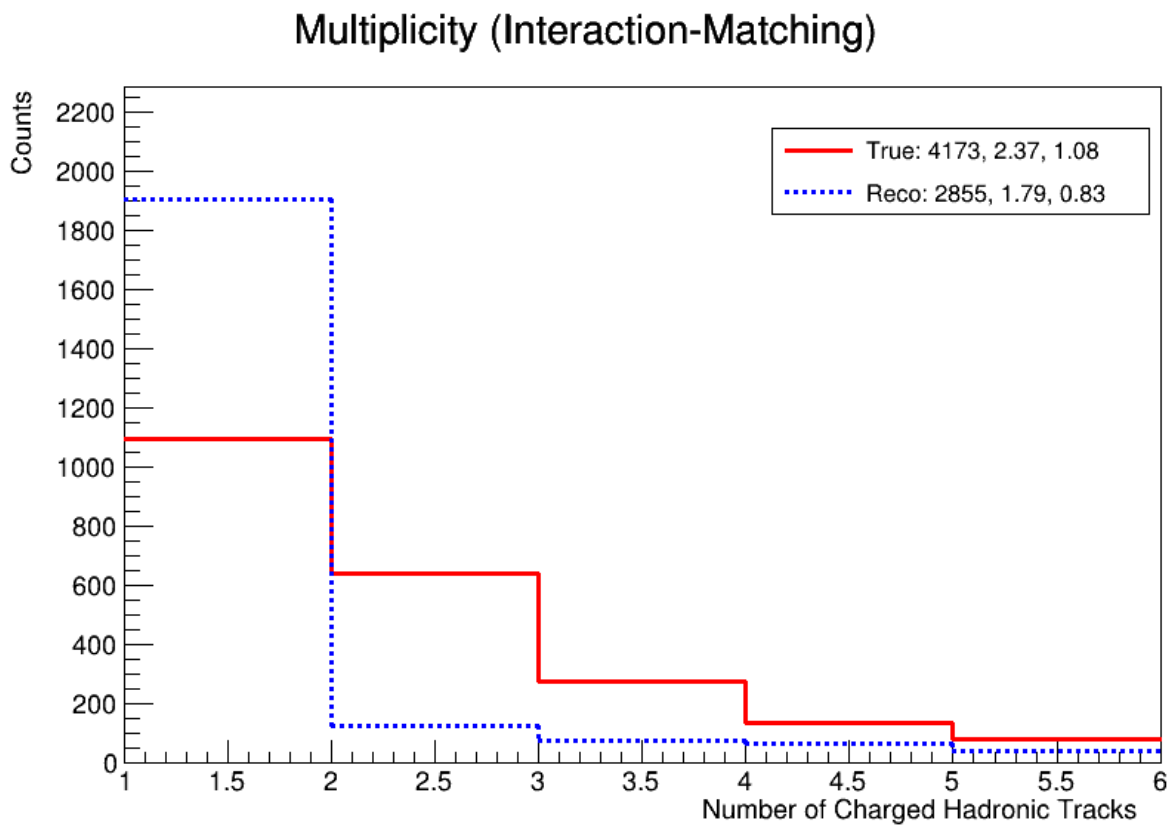
- The shape of these distributions may significantly change when we vary the MINERvA cut.





Charged Hadronic Multiplicity

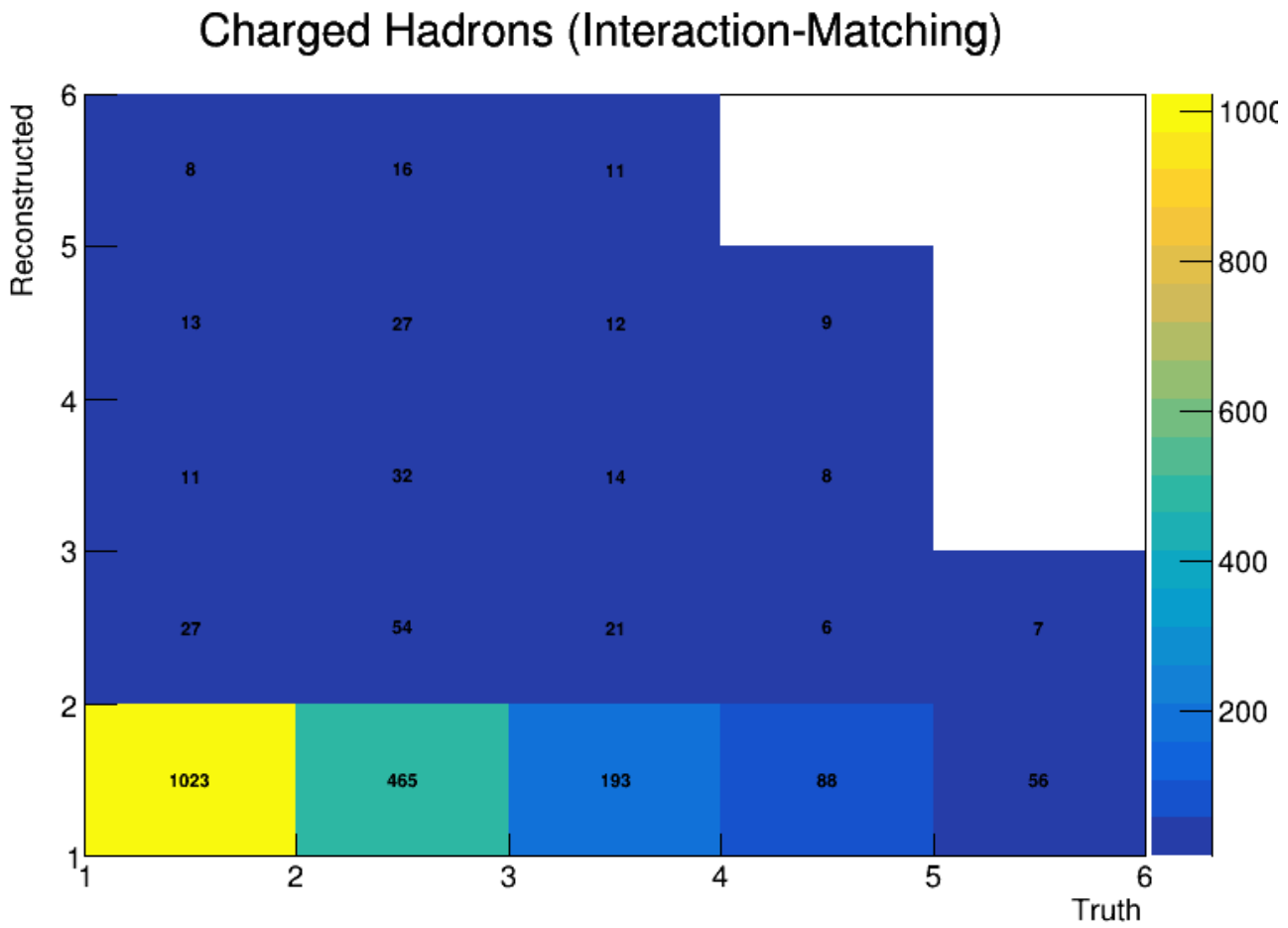
- Multiplicity of charged hadronic tracks is plotted under following conditions:
  - Reco Interactions (CC within LArFV) are matched to truth interactions.
  - All hadrons should have track length > 5 cm.
- Truth tracks are greater than reco tracks indicating there are many truth tracks which are not reconstructed.



This is charged hadrons multiplicity.

Multiplicity Distribution Confusion Matrix (after interaction matching)

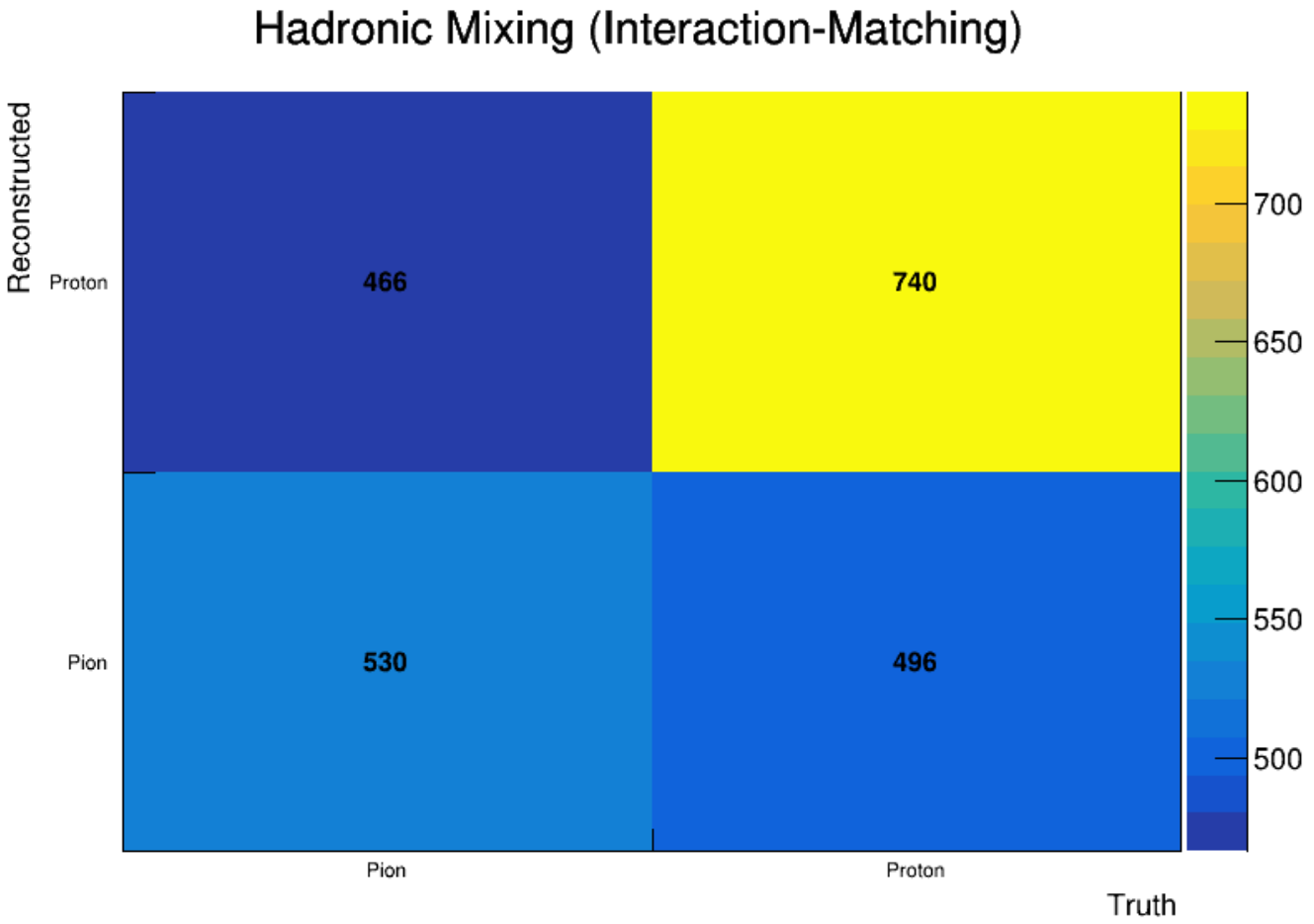
- Bin-to-Bin comparison of reco-to-truth hadronic multiplicity is shown.
- A good portion of single tracks is being reconstructed as double tracks.
- The fraction of diagonal entries decrease with higher multiplicities.



No Normalization on this matrix

Hadronic Mixing Matrix

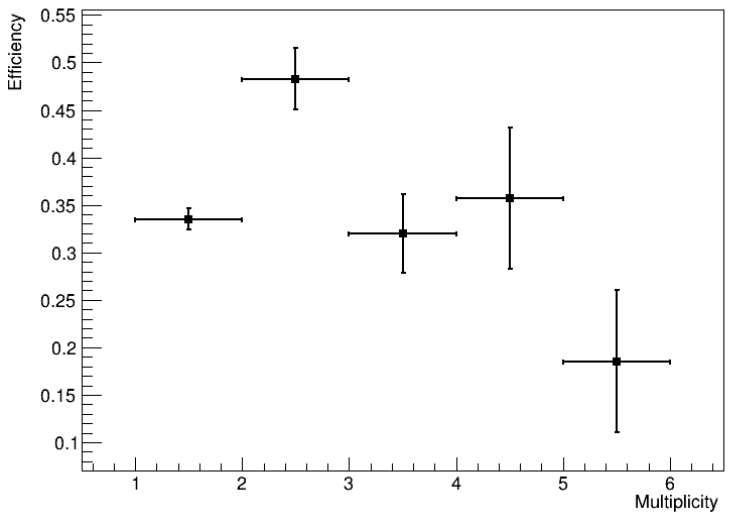
- Now I separate final state hadrons into charged pions and protons.
- The **mixing matrix** indicates the number of correctly matched charged hadrons.
- Protons show a better correctness than charged pions.

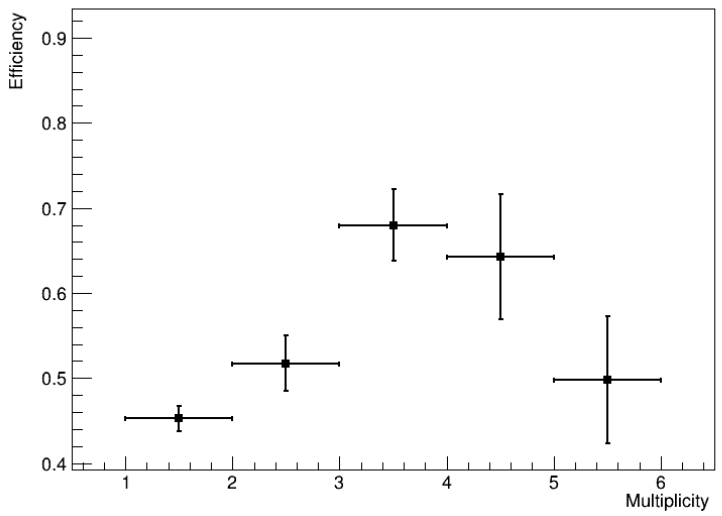


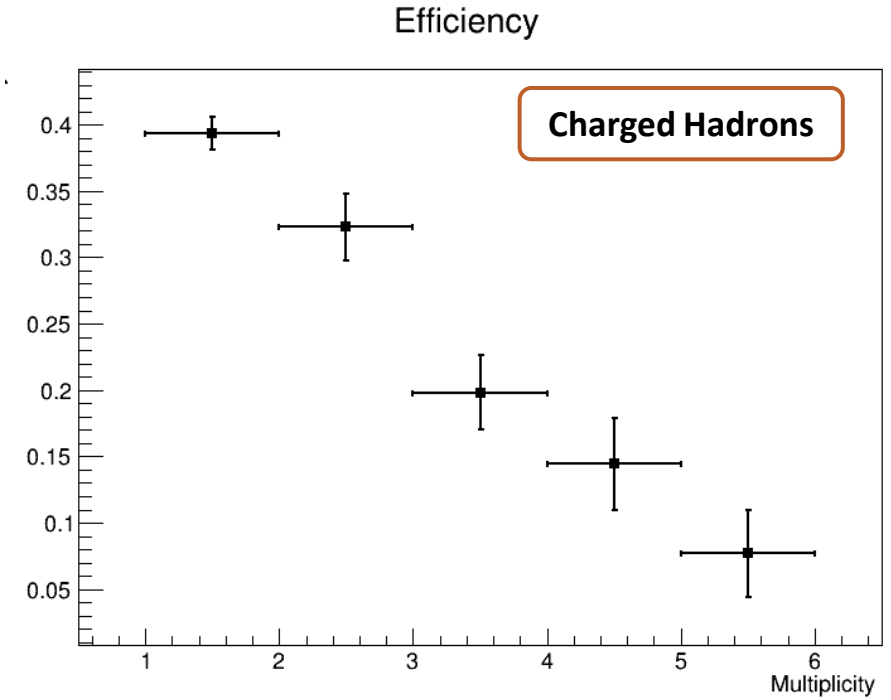
No Normalization on this matrix

Efficiency of Charged Hadrons as a Function of Multiplicity

- Efficiency, for charged pions and protons, (track length > 5 cm) as a function of multiplicity is shown.
- It is the measure of the fraction of true events that are correctly reconstructed by the ML-Reco.
- Efficiency decreases as multiplicity increases.

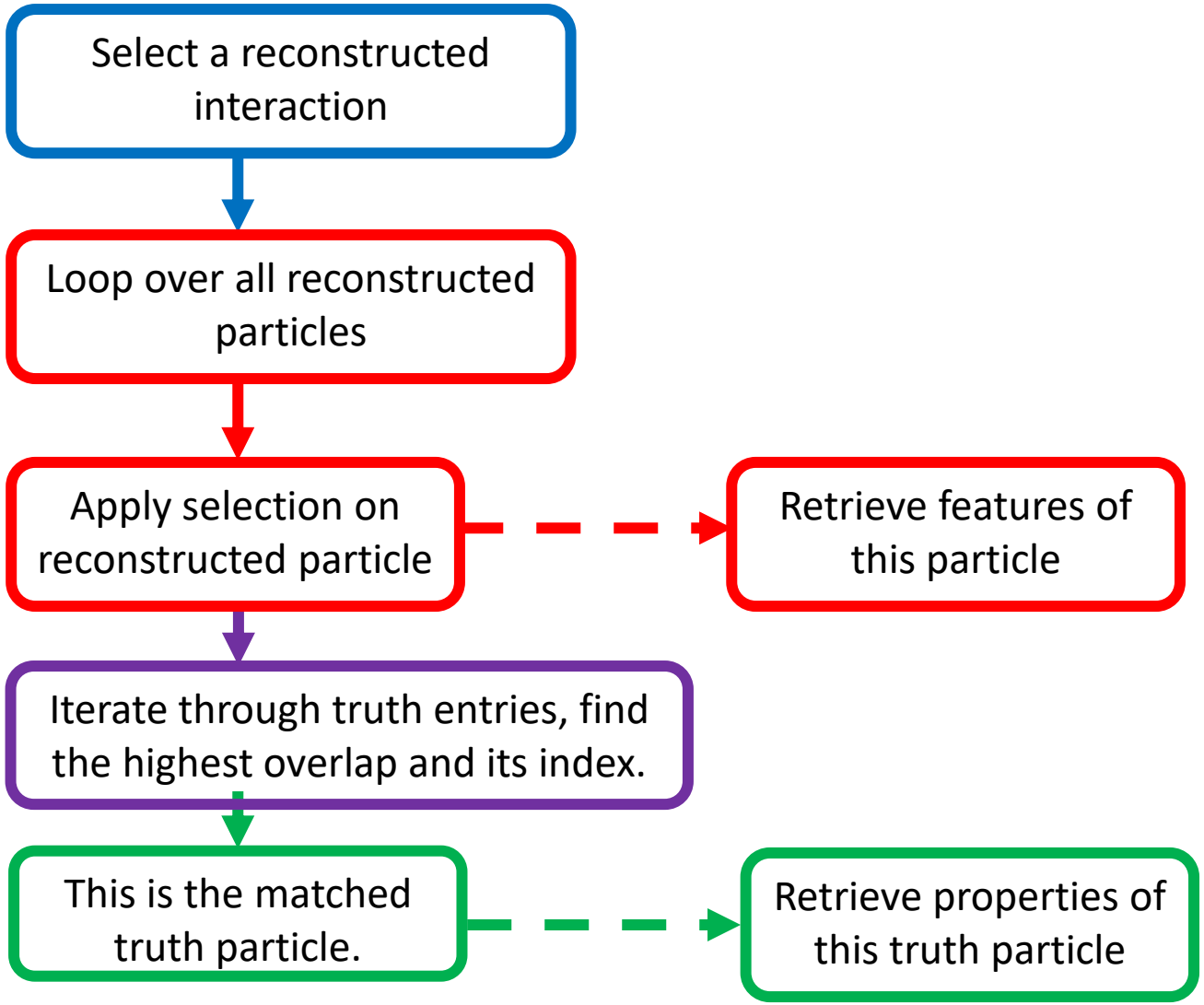






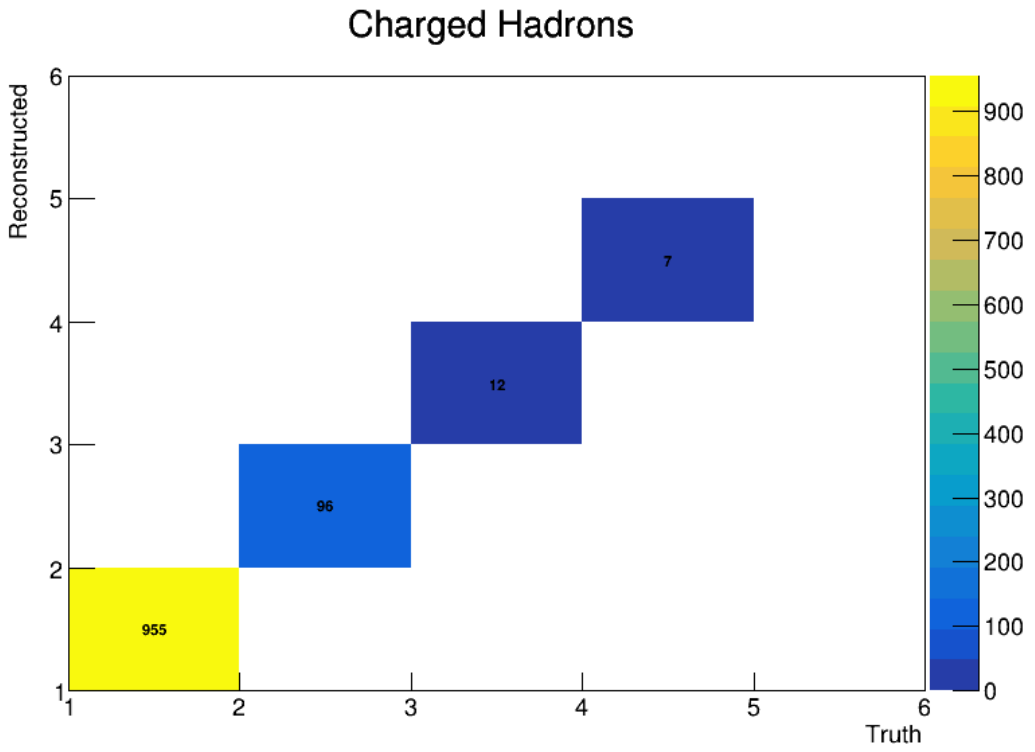
Additional Studies (Reco-to-Truth Track Matching)

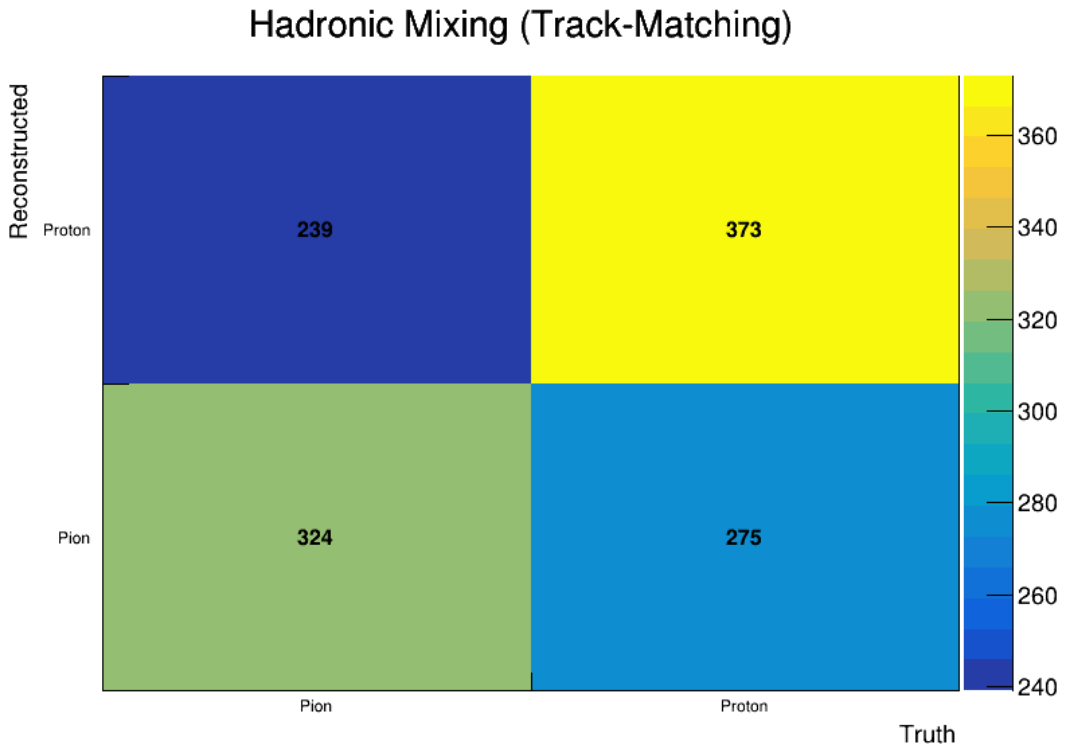
- In the previous slides, we showed some interesting features for the matched interactions.
- Then, we further enhanced this study by matching tracks (track length > 5 cm) for the matched interactions.
- With these steps, we are able to match reconstructed track to the most probable truth tracks to characterize reconstructed tracks.



Additional Studies (Reco-to-Truth Track Matching)

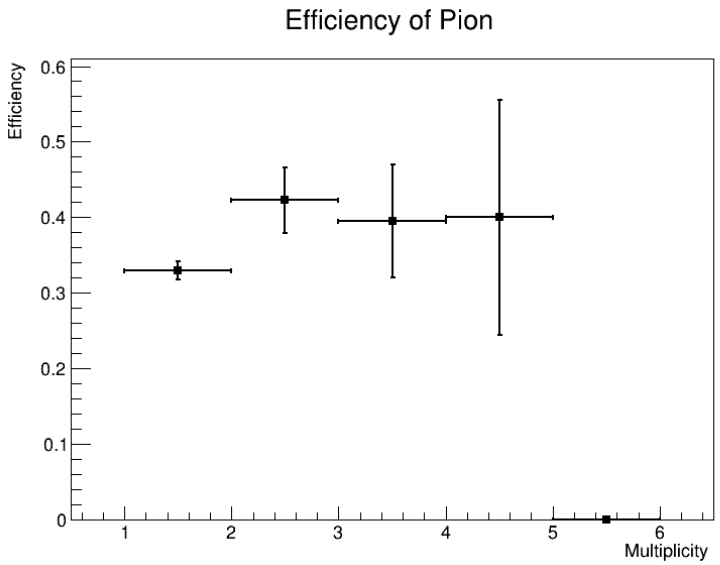
- For matched tracks, we will have the same multiplicity in both reco and truth (left plot) but to understand the correctness of matched tracks, a confusion matrix (right plot) is presented.
- Reco-truth one-to-one matching effectiveness and correctness increases in track-matching.
- Track-matching essentially improves correctness which is even better for charged pions while for protons it is roughly the same.
- No normalization is applied on these matrices.

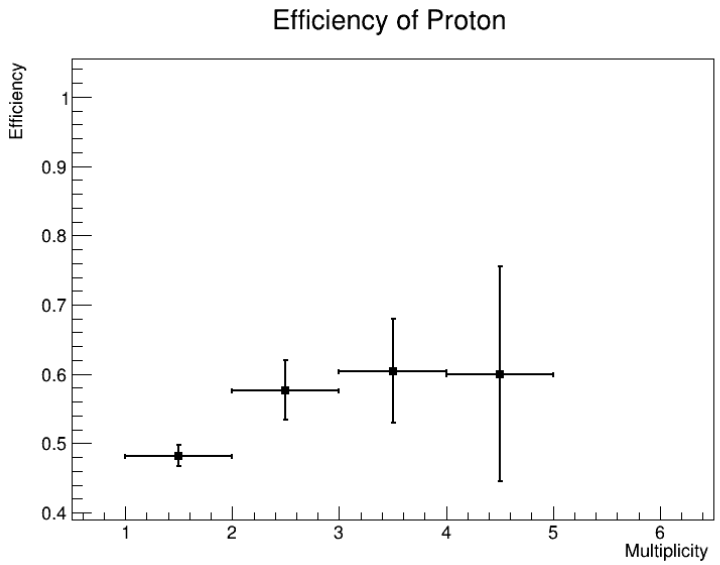


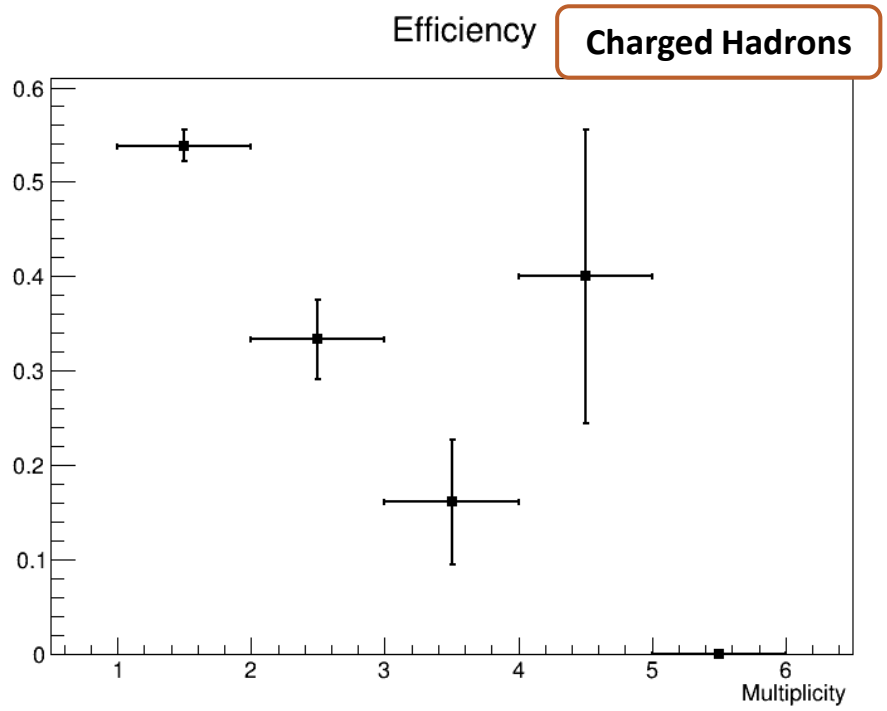


Efficiency of Charged Hadrons as a Function of Multiplicity

- Efficiency, for charged pions and protons, as a function of multiplicity is shown.
- Efficiency is defined as the truth hadrons over reconstructed hadrons and error bar is the statistics.
- Track-matching impacts efficiency positively.

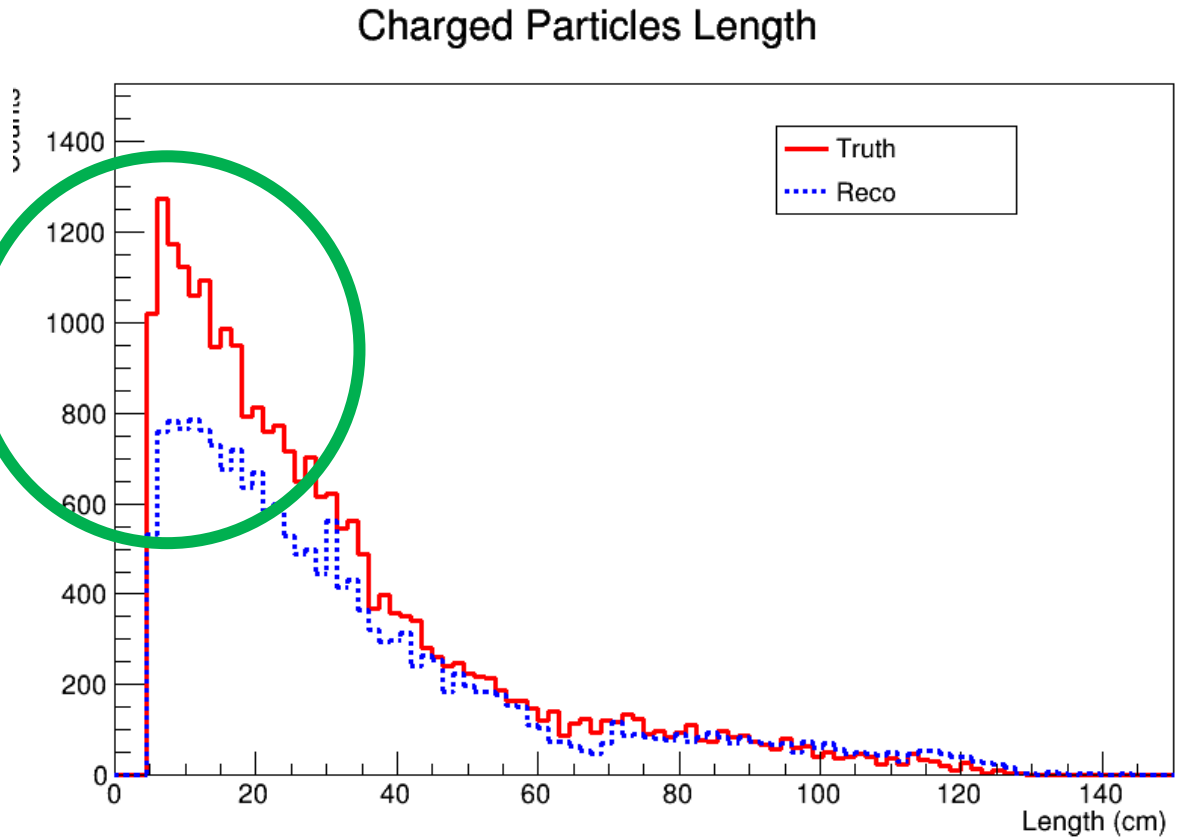


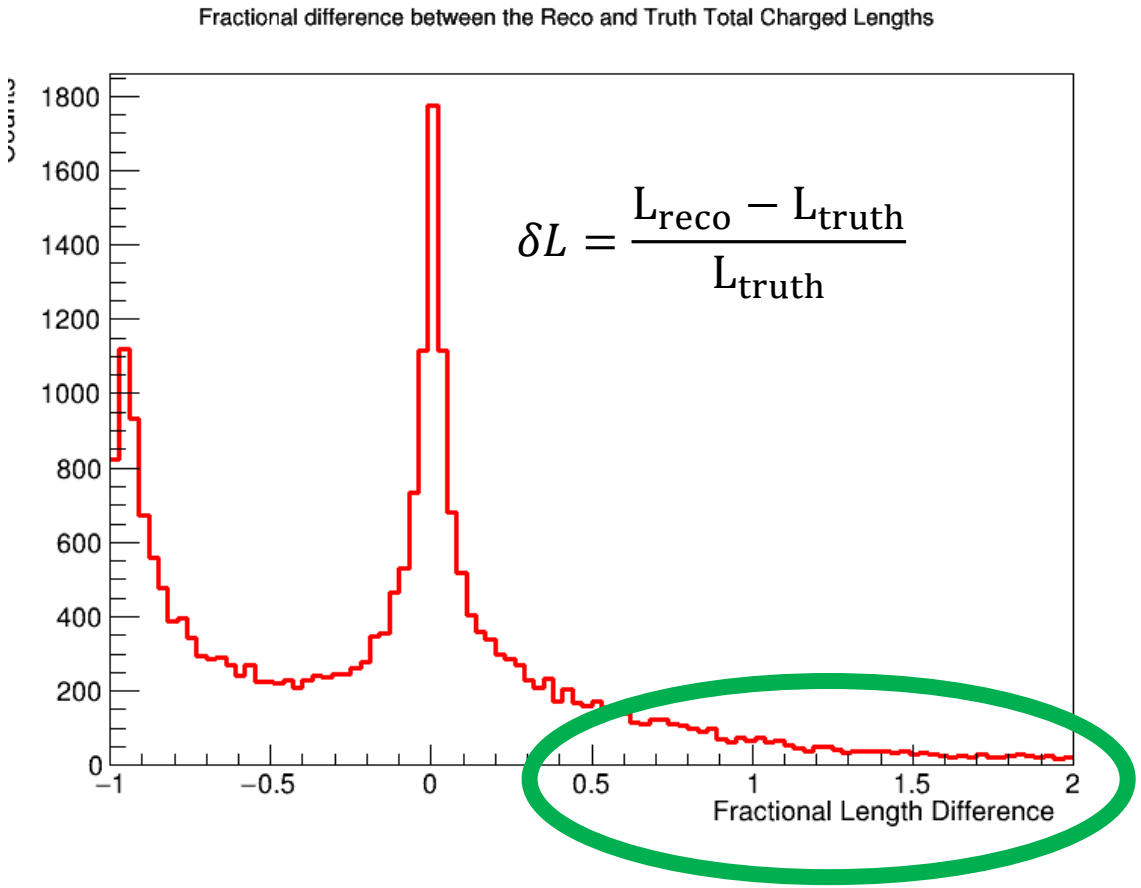




Track Length Distribution of Charged Hadrons

- Here we are showing some of the reconstructed features for the track lengths.
- Comparison of reco and truth charged hadronic track lengths, for matched tracks, is shown.
- Track length > 5 cm is applied on both truth and reco tracks separately.
- There are more short truth tracks from 5 to ~ 40 cm.





Pre-Preliminary Look at Systematics

Pre-Preliminary Studies with Systematically Varied Samples *(Ongoing)*

- We have official simulated production files MiniRun5 Beta1 Flow files with an average energy to create an ion-pair $W_{\text{ion}} = 23.6\ \text{eV}$ (central value) and $1\text{E}19\ \text{POT}$.

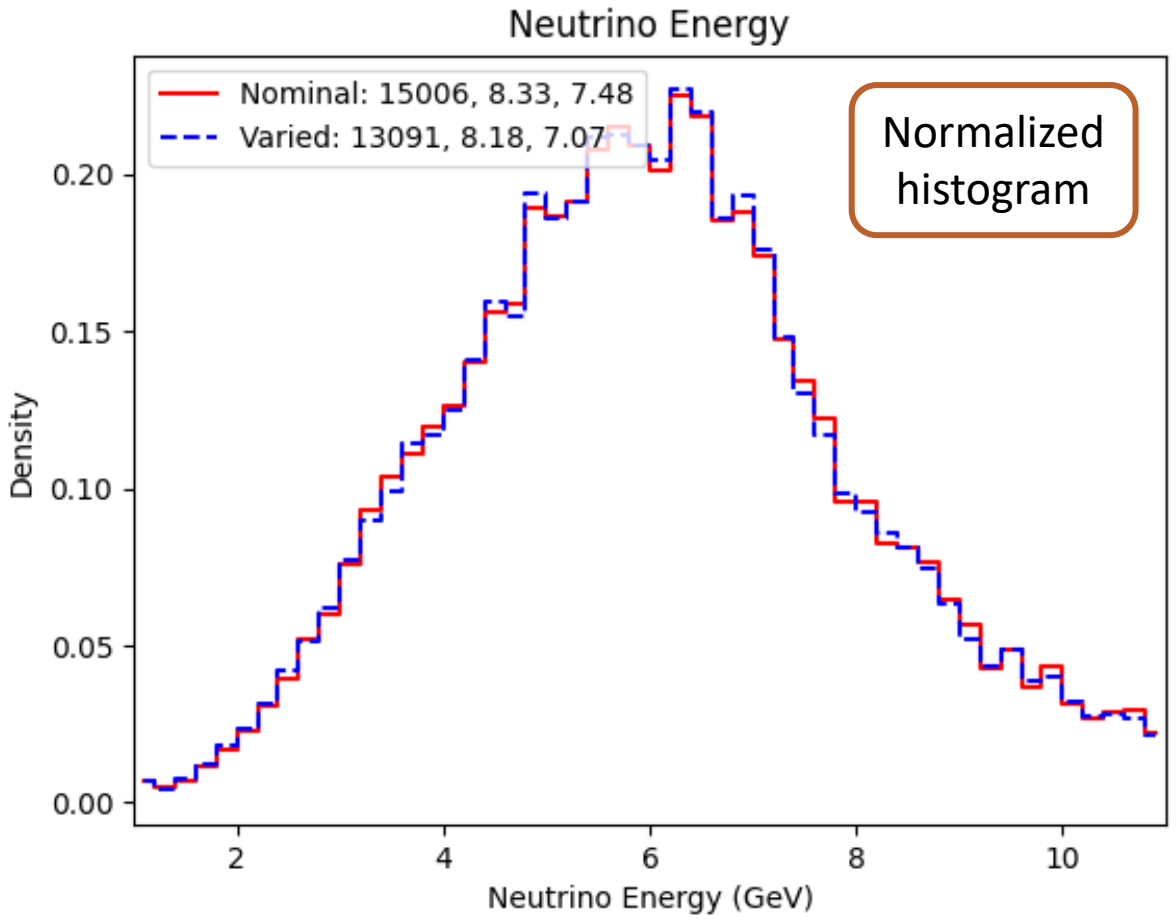
- We started production of systematically varied samples.
  - Aleena and Fathima produced a sample at ANL with varied value $W_{\text{ion}} = 22.7\ \text{eV}$ and $1\text{E}17\ \text{POT}$.
  - This change is introduced in the `larnd-sim` stage (see more).
  - **Directory:** `/pnfs/dune/persistent/users/fmaha/productions/MiniRun5_Systematics_W_ION_22.7/MiniRun5_Systematics_W_ION_22.7.flow`

What Next?

- Run current analyses and quantify the differences in results
- Use these samples to facilitate further development of systematic tools

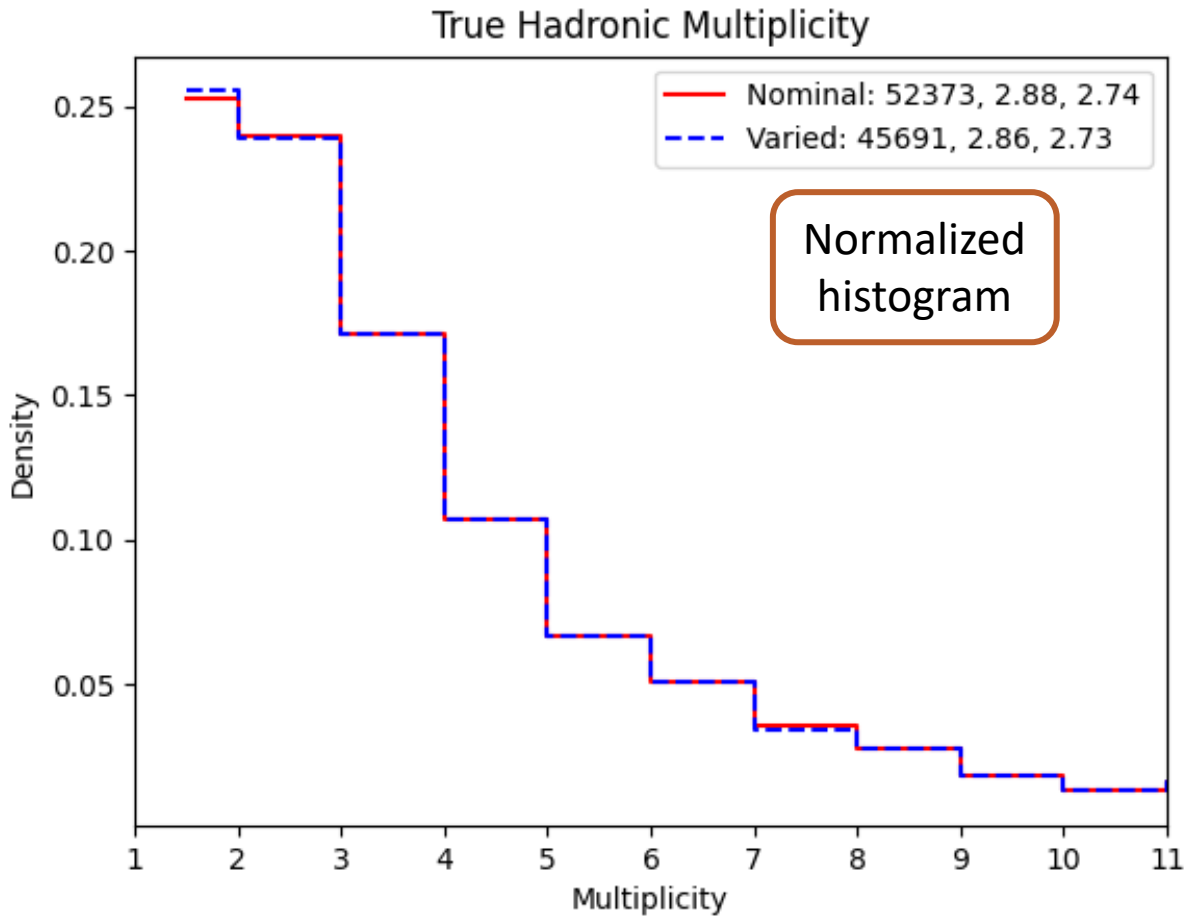
True Neutrino Energy *(Ongoing)*

- Neutrino energy is shown for both samples (with central value $W_{\mathrm{ion}} = 23.6\ \mathrm{eV\ (Nominal)}$ and with a varied sample $W_{\mathrm{ion}} = 22.7\ \mathrm{eV\ (Varied)}$).
- All interactions must be CC and within LArFV.



True Hadronic Multiplicity *(Ongoing Next Steps)*

- Hadronic multiplicity (for CC interactions within LArFV) is shown for both samples (with central value $W_{\text{ion}} = 23.6$ eV (Nominal) and with a varied sample $W_{\text{ion}} = 22.7$ eV (Varied)).
- All tracks have length > 5 cm.



Summary and Conclusion

- Studied the 2×2 multiplicity selection with the latest production files.
- We developed and implemented the muon-MINERvA reconstructed track pairing.
- Good agreement between Genie truth and ML-reco truth is demonstrated.
- Presented reconstructed distributions provide a guidance on what to expect from experimental 2×2 data.
- Some features of the simulated data set still need be studied.
- Additional studies based on interaction- and track-matching are also presented.
- Efficiency decreases with higher multiplicities but shows improvement with additional constraints.
- ML-Reconstruction can be compared to the 2×2 measured data. However, for one-to-one track-matching between reco and truth, MC simulated truth data would be needed.
- We also presented some results from the ongoing studies with the systematically varied samples produced at ANL and compared it with the official production.

Next Steps

- Exciting time is ahead since we are about to collect first real data from 2×2.
- We will need to understand data in comparison to MC and will continue tuning the.
- This is right time to incorporate the systematic uncertainties in the charged track multiplicity analysis.

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