MicroBooNE–Note–1012–PUB

Demonstration of 3D Shower Reconstruction on MicroBooNE Data

The MicroBooNE Collaboration

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Utilizing a sample of ν_μ inclusive charged current events we select four events which visually contain π^0 decays associated with a neutrino interaction vertex. This sample of charged current induced π^0s provides us with data-driven photon showers to vet our reconstruction. The π^0 provides us with a standard candle to study how our shower reconstruction performs. The vertex of the interaction is determined by the start point of the long muon track in the event and the π^0 production point. We utilize two different methods to cluster the charge coming from these showers and reconstruct the 3D properties of the showers.

I. SHOWER RECONSTRUCTION IN LIQUID ARGON TPCS

Two attractive properties of liquid argon TPCs (LArTPC) are the millimeter scale spacial resolution coupled with totally active calorimetry. Together these can be leveraged to suppress photon induced backgrounds misidentified as an electron shower in the search for ν_e charged current interactions. MicroBooNE is part of a group of LArTPC collaborations leading the way in the development of efficient 3D reconstruction of these showers. This note contains a demonstration of two methods for reconstructing showers in MicroBooNE data.

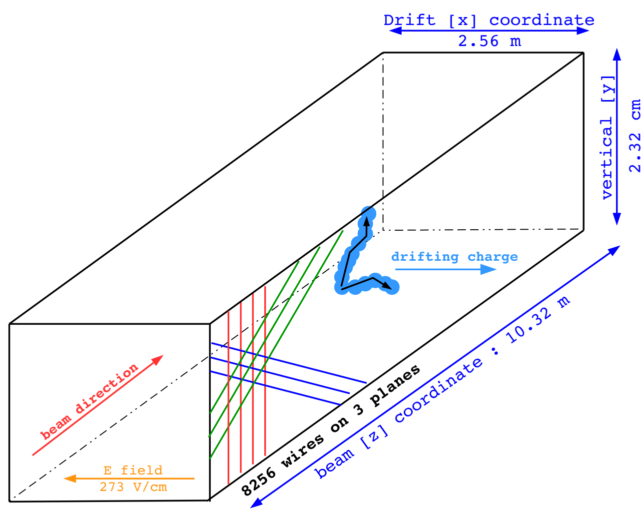


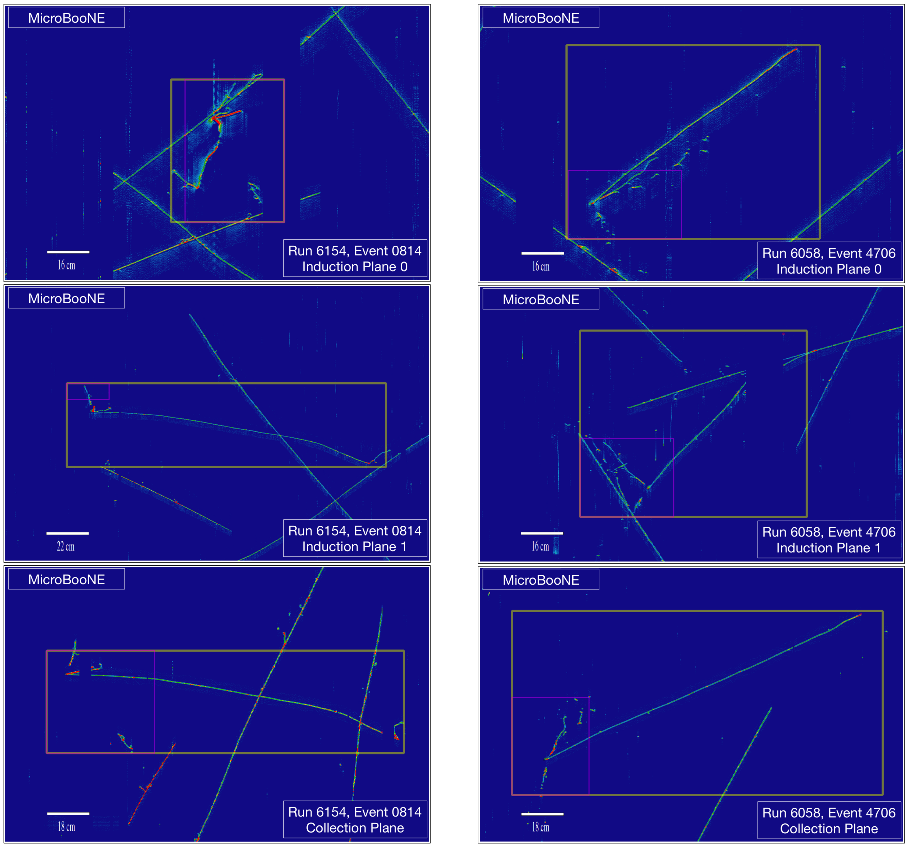
FIG. 1: *A schematic of the MicroBooNE detector showing the coordinate system and wire planes.*

The MicroBooNE LArTPC includes three readout wire planes, two induction and one collection (shown in Fig. 1), which provide three distinct 2D readouts of any event. Using correlations between charges seen on these three 2D planes coupled with PMT activity we can reconstruct 3D objects in the detector. Our 3D coordinate system has the x along the drift direction, y along the vertical, and z along the direction of the beam, as shown in Fig. 1.

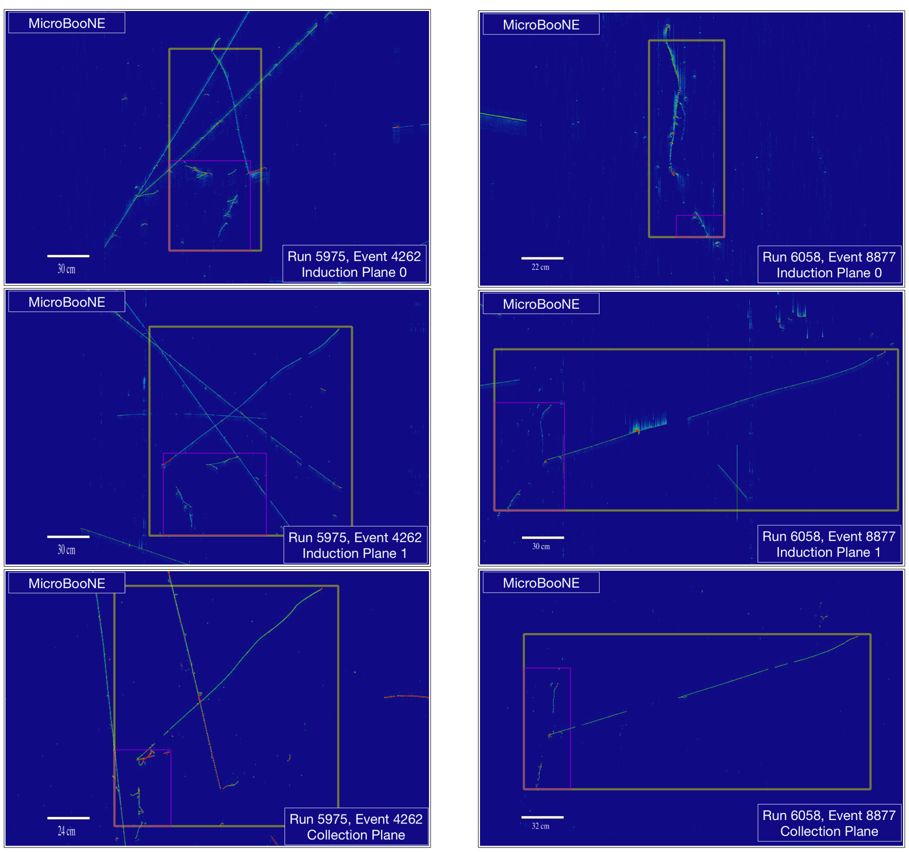
An open question within the LArTPC community is where in the reconstruction chain to begin 3D reconstruction. One can take two approaches: (1) promote the 2D charge depositions into 3D points to compute 3D variables, or (2) cluster the charge in the 2D planes and then compute 3D information from these clusters. Both types of shower reconstruction paths are described in this note. Once the 3D information of the showers is computed we rely on a unified calorimetry method to compute the energy of the shower. To demonstrate this capability in data we have selected four events extracted from a sample of ν_μ charged current events [1] which each contain two correlated showers pointing back to the event vertex.

II. CHARGED CURRENT π^0 EVENTS IN DATA

By utilizing a selection described in Ref. [1] we can build a sizable sample of ν_μ charged current inclusive events. We can sort through these events and search for two correlated detached showers that point back to the beginning of the muon track. We can enclose this region with a bounding box, assigning a region of interest (ROI). These ROI are intended to encompass the ionization charge associated with the event in all three views. To search for this ROI we rely on the output of the Pandora pattern recognition chain [2,3] and surround the 2D shower-like objects and the overall event separately. Although Pandora currently does not calculate 3D topological properties of these 2D shower-like objects, they aid in the localization of events and provide a seed for the downstream shower reconstruction. We select four events returned by this stage, shown in Fig. 2.



(a) (Run 6145, Subrun 16, Event 814) **(b)** (Run 6058, Subrun 94, Event 4706)



(c) (Run 5975, Subrun 85, Event 4262) **(d)** (Run 6058, Subrun 177, Event 8877)

FIG. 2: *Four MicroBooNE events selected from data to test our shower reconstruction. These events are intended to contain a neutrino induced muon and two photon showers originating from the neutrino interaction vertex. The yellow box is the interaction-wide ROI while the red box is the shower-wide ROI, which attempts to encompass all the charge associated with the two shower-like objects.*

III. 3D-BASED SHOWER RECONSTRUCTION PATH

Our first method for reconstructing 3D showers attempts to create 3D objects as early as possible. It does this by relying on an initial stage of reconstruction to create 'space-points'. Space-points are 3D representations of the location of 2D charge depositions as seen on the wire-planes. The Pandora package produces such space-points. We rely on Pandora to sort 2D clusters into shower-like or track-like objects and then study the space-points associated with the shower-like clusters.

Now that we have a sample of 3D space points associated to the shower-like objects we can reconstruct the 3D start point and direction of this shower. The 3D start point of the shower is designated as the 3D vertex associated to the shower-like particle determined by Pandora. The 3D direction of this shower is assigned by using the full set of 3D space points associated to that shower object. We perform a 3D principal components analysis (PCA) and select the eignvector that corresponds to the largest eigenvalue. This is taken as the 3D direction of the shower.

We can then take these showers and project them back down onto the 2D view from which they were derived. When plotting the reconstructed shower we want to characterize more properties of the shower including the length and opening angle. Since the eigenvalues derived from PCA represent the variance of a distribution in the semi-axis, the square root of the largest eigenvalue corresponds to one standard deviation in the semi-axis of the largest spread of the distribution of the space points. The shower length in this approach is defined as three standard deviations of the distribution of the space points in the most-spread axis, and is thereby determined by twice (from the semi-axis to the full axis) the square root of the largest eigenvalue from PCA multiplied by three (three standard deviations). Finally, we also define the shower opening angle as twice the arctangent of the square root of the ratio of the 2^{nd} largest to the largest eigenvalue. In Figs. 3–6 we can see the projection of the showers overlaid by the hits that were used to determine the space-points. We can see in all the events the showers are accurately pointing back towards the vertex where the muon emanates.

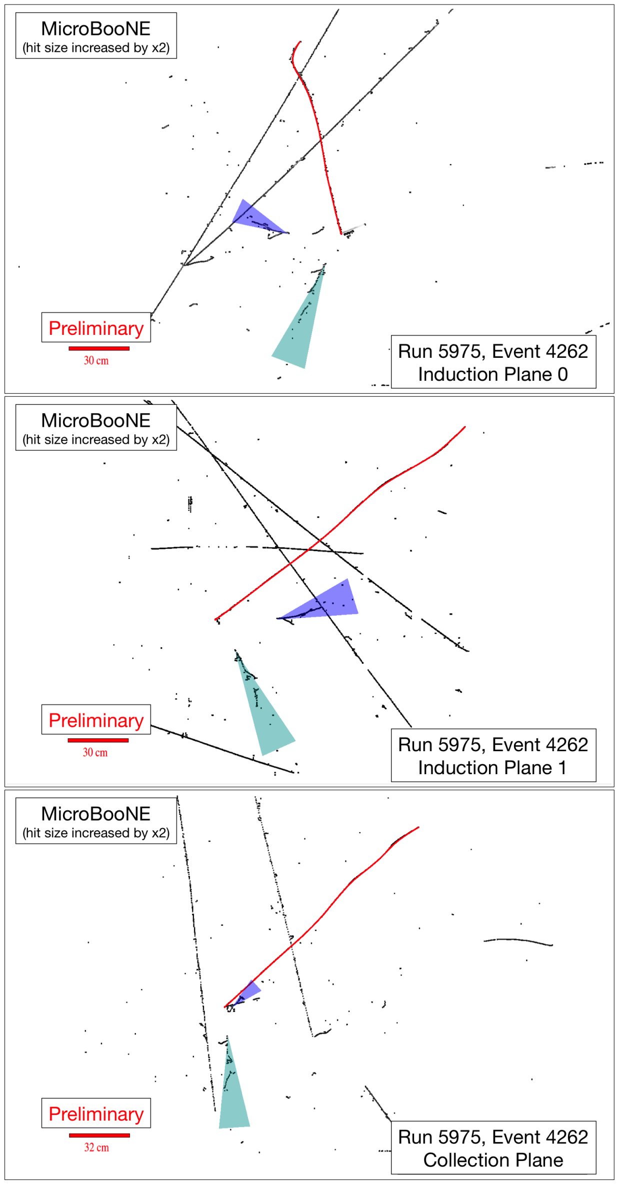


FIG. 3: *Run 5975, Subrun 85, Event 4262, The green and blue triangles show the reconstructed showers associated with the π^0 decays. Both appear to have been well reconstructed. The red track corresponds to the muon selected by the ν_μ filter, and the blue tracks are other tracks associated to the neutrino interaction. We note that in the Induction 2 view the blue triangle misses a few of the hits, but that the overlap in the other two planes looks good.*

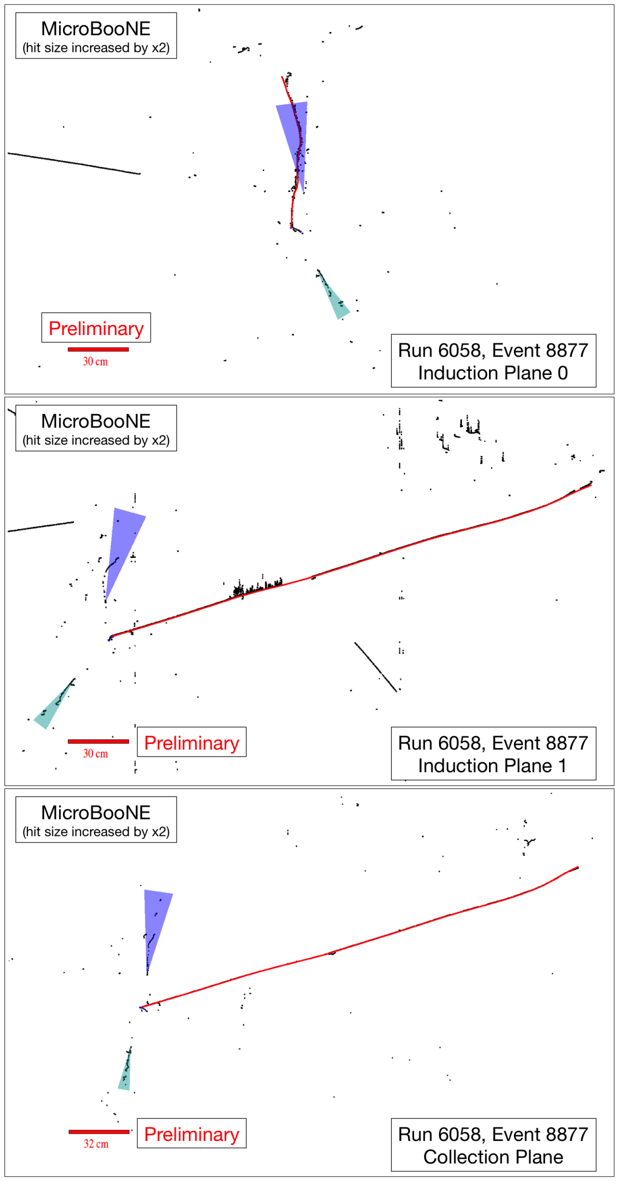


FIG. 4: *Run 6058, Subrun 177, Event 8877, The green and blue triangles show the reconstructed showers associated with the π^0 decays. Both appear to have been well reconstructed. The red track corresponds to the muon selected by the ν_μ filter.*

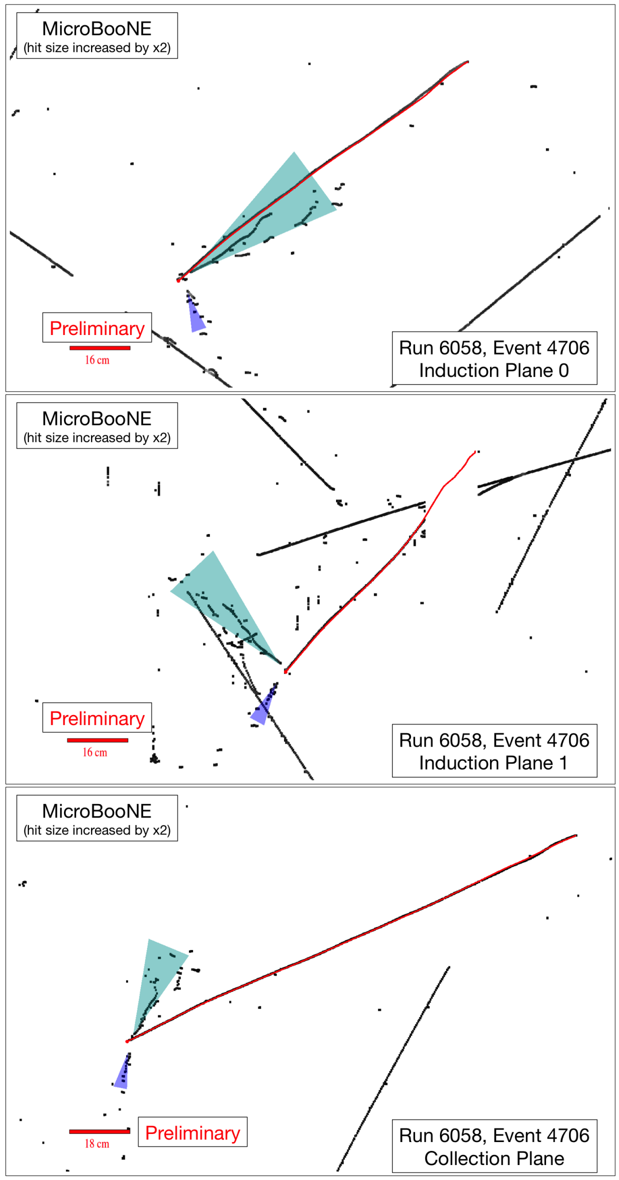


FIG. 5: *Run 6058, Subrun 94, Event 4706, The green and blue triangles show the reconstructed showers associated with the* π^0 *decays. Both appear to have been well reconstructed. The red track corresponds to the muon selected by the* ν_μ *filter.*

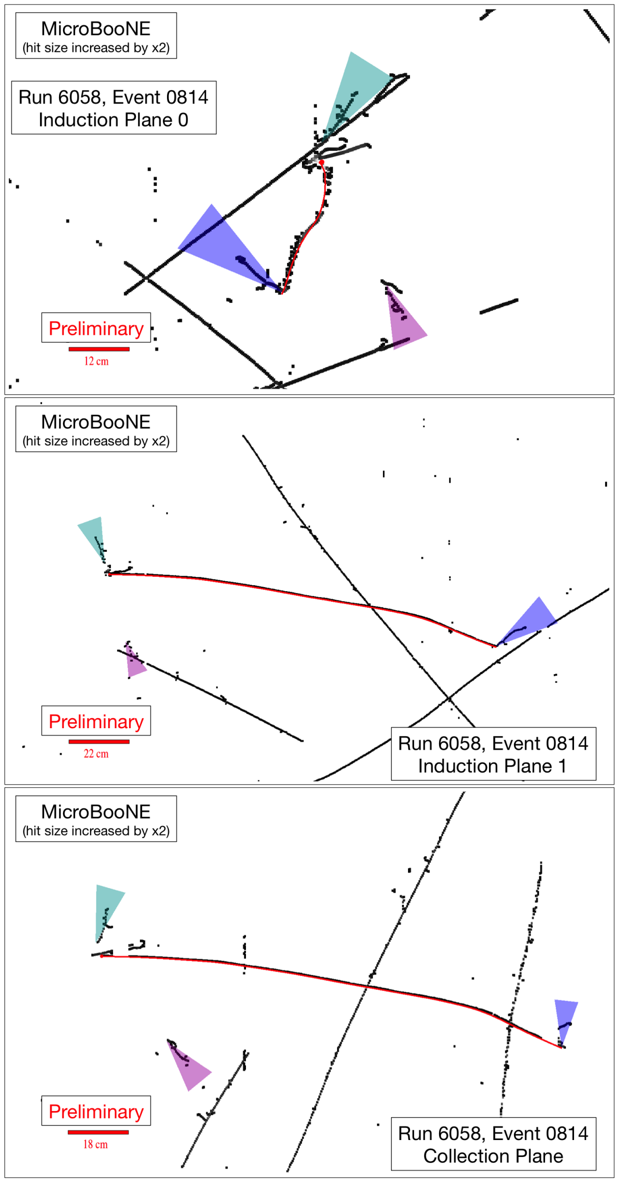


FIG. 6: *Run 6145, Subrun 16, Event 814, The green and pink triangles show the reconstructed showers associated with the π^0 decays. Both appear to have been well reconstructed. The red track corresponds to the muon selected by the ν_μ filter, and the blue tracks are other tracks associated to the neutrino interaction. The blue shower reconstructed at the end of the muon track is a candidate Michel electron.*

IV. 2D-BASED SHOWER RECONSTRUCTION PATH

In the previous section we relied on 3D space-points from Pandora to reconstruct our 3D shower properties. In this section we pursue a different method. We use the reconstructed clusters to seed a topology-based clustering procedure intended to gather more of the charge associated with the shower-like object into the initial clusters. One major challenge of shower reconstruction in LArTPCs is the grouping of causally correlated hits together into groups that are associated with single particles. The approach pursued here performs a second clustering pass based on the OpenCV framework [4] which uses open source computer visualization tools to cluster charges which are localized.

To do this we start with the ROIs selected above and remove any hits which are associated to tracks. We then take each of the views and attempt to re-cluster the hits in 2D within the ROI. This is done by reading in the 2D hits not associated to a track in each plane that fall within the ROI. First, we convert charge readout from each plane into single channel gray scale images. Per plane we then dilate pixels to begin connecting neighboring hits, use a Gaussian filter to smooth edges, and apply a threshold to convert our gray-scale image into a binary one. The final image, as shown in Fig. 7, can then be used to cluster by searching for closed contours.

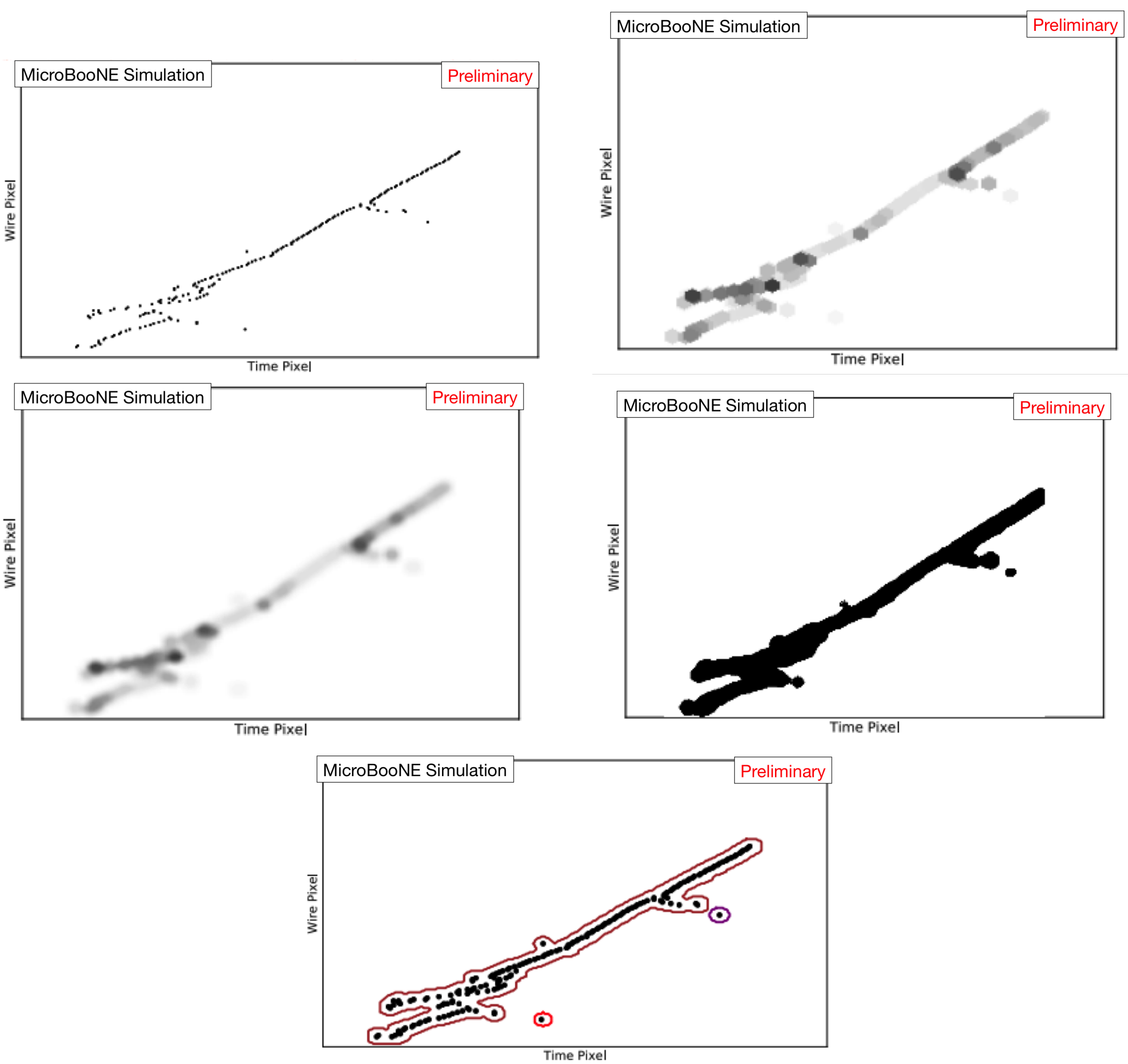


FIG. 7: *From* **top left** *to* **right** *Original hits that make up a single cluster; Dilate pixels to "connect" nearby hits; Blur image to smooth edges and smear charge. From* **bottom left** *to* **right**. *Threshold converts grayscale image to binary; OpenCV contour finding on threshold image produces a polygon which now encloses the original hits.*

We rely on the interaction vertex, marked as the start point of the muon track, to help inform the next steps. The start point of the clusters is chosen based on which end of the cluster is closer to the interaction vertex. Using a 2D PCA we can also derive a 2D direction that is used in a cluster merging step. Using this direction we can merge in small clusters that are collinear with this cluster. Finally, before these 2D clusters can be used to create a 3D shower we need to be able to match a cluster from one plane to at least one other plane. To do this we compute a match score based on the overlap in time between the clusters in various views. The matches with the highest score are selected.

From these matched 2D clusters we can then compute 3D properties of the showers we want to reconstruct. The (y,z) coordinate of the 3D start point is computed by selecting the location where the wires defining the 2D cluster start points intersect. The x-coordinate is determined by averaging the time between the two 2D start points. To reconstruct a 3D direction we start by assessing a more accurate 2D cluster direction. This is done by taking the charge-weighted vector sum of all 2D vectors pointing from the interaction vertex to each hit in the cluster. These 2D directions, computed on multiple planes, are then used to calculate a 3D direction of the shower.

With this 3D start point and direction we can then project these 3D showers back down into 2D and show them overlaying the hits that created them, in Figs. 8–11. We see in Fig. 8 that one of the main showers is broken into two showers, and the second shower was not reconstructed. Such pathologies can be addressed by more aggressive merging procedures and refinements to the cross plane matching. The remaining events appear to be well reconstructed.

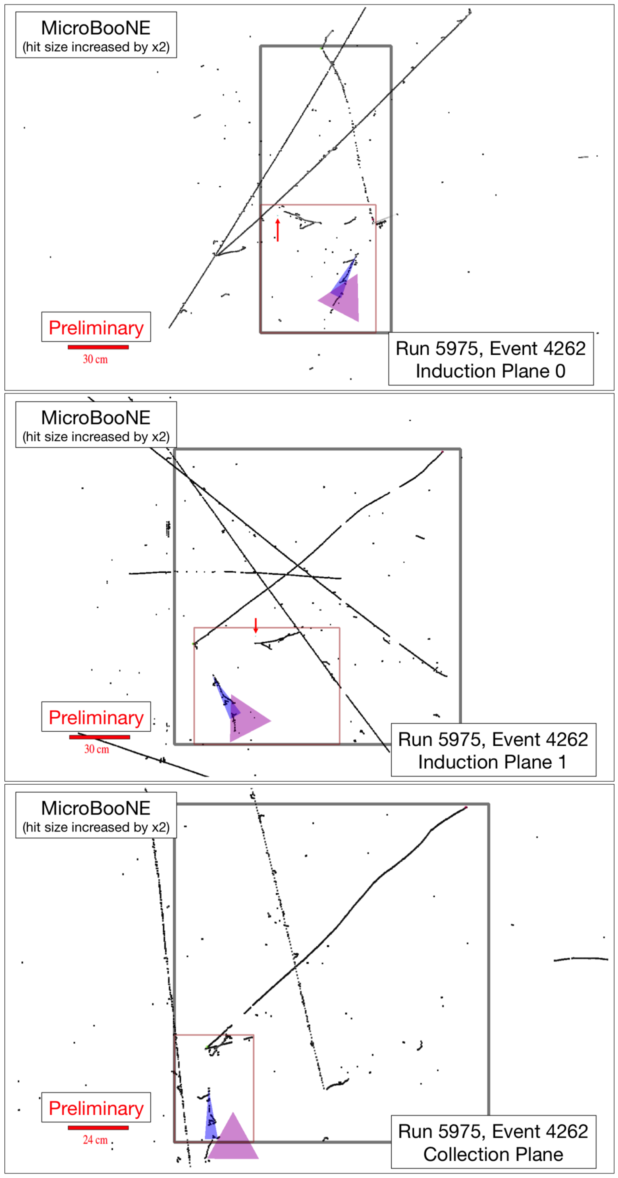


FIG. 8: *Run 5975, Subrun 85, Event 4262, Three showers are reconstructed in this event: a blue and red one, associated with the same EM shower, which was broken up in the reconstruction. A third, very small green shower associated with the green cluster (highlighted by the red arrow) can be found. The red box overlaid is the ROI which helps to guide the shower reclustering.*

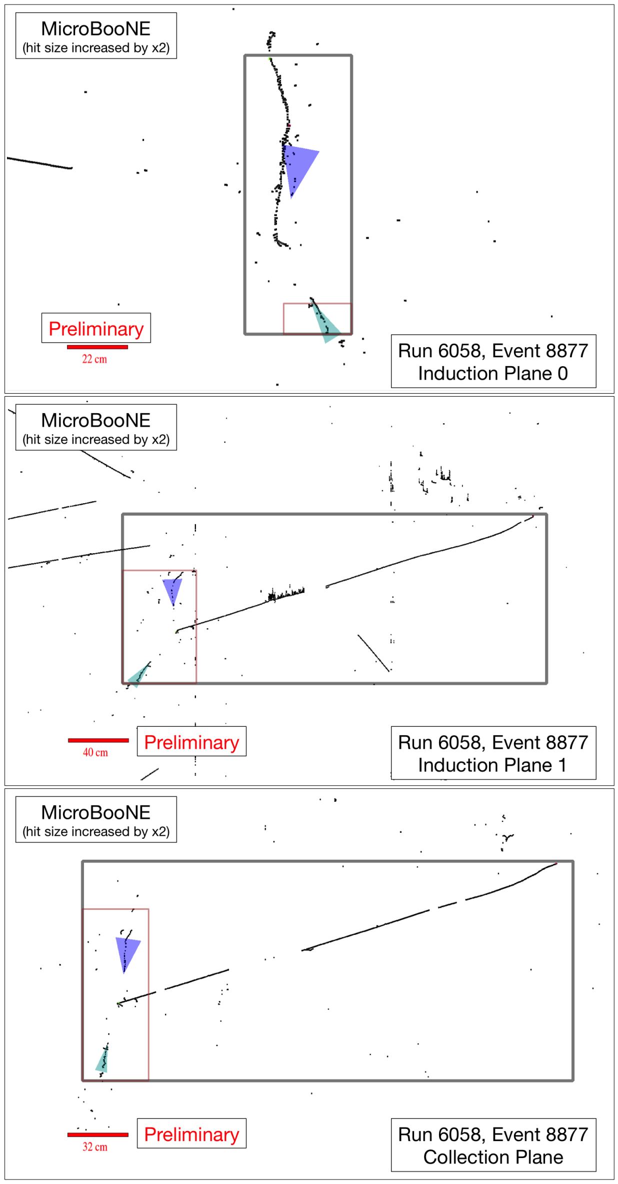


FIG. 9: *Run 6058, Subrun 177, Event 8877, The green and blue triangles show the reconstructed showers associated with the* π^0 *decays. Both appear to have been well reconstructed. The red box overlaid is the ROI which helps to guide the shower reclustering.*

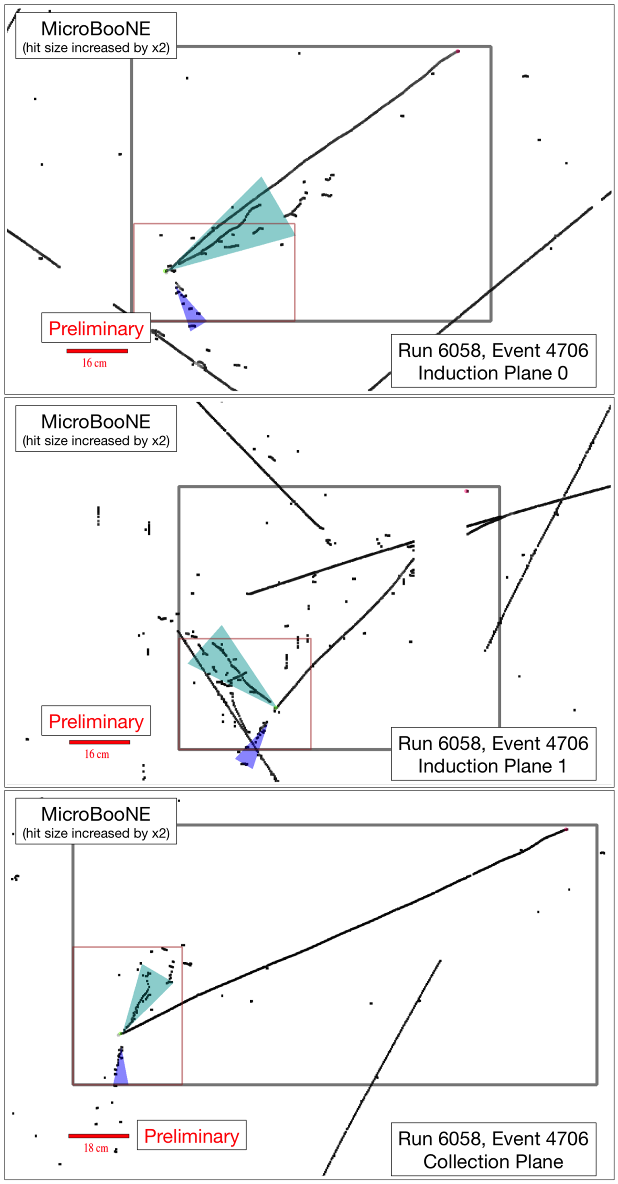


FIG. 10: *Run 6058, Subrun 94, Event 4706, The green and blue triangles show the reconstructed showers associated with the π^0 decays. Both appear to have been well reconstructed. The red box overlaid is the ROI which helps to guide the shower reclustering.*

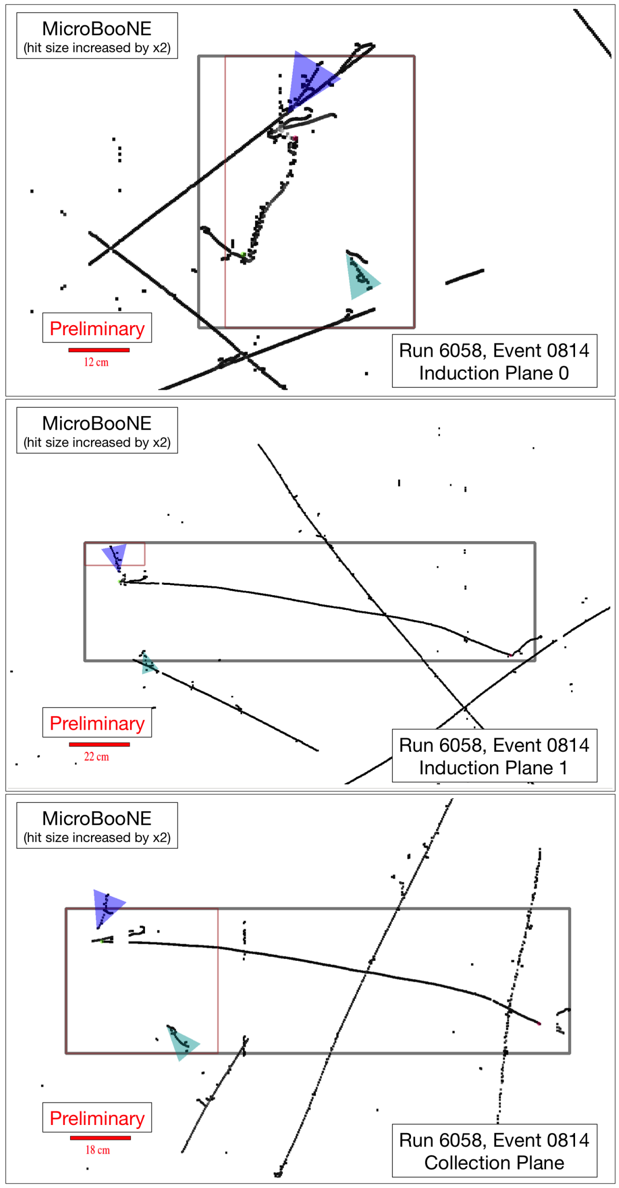


FIG. 11: *Run 6145, Subrun 16, Event 814, The green and blue triangles show the reconstructed showers associated with the π^0 decays. Both appear to have been well reconstructed. The red box overlaid is the ROI which helps to guide the shower reclustering.*

TABLE I: *Event-per-event reconstructed shower properties for our two reconstruction passes. These include the collected energy, E^{Coll}, the angle between the two showers, $\theta_{\gamma\gamma}$, and the reconstructed diphoton masses. These values also contain uncertainties discussed in the text.*

(Run, Subrun, Event)	Shower Reconstruction	$E_1^{\mathrm{Coll}} \pm \sigma_{E_1}$ [MeV*]	$E_2^{\mathrm{Coll}} \pm \sigma_{E_2}$ [MeV*]	$\theta_{\gamma\gamma} \pm \sigma_{\theta_{\gamma\gamma}}$ [°]	$m_{\gamma\gamma} \pm \sigma_{m_{\gamma\gamma}}$ [MeV*]
(6145, 16, 814)	3D-Based	62 ± 22	59 ± 21	120 ± 14	105 ± 28
	2D-Based	58 ± 20	61 ± 21	112 ± 5	99 ± 25
(6058, 94, 4706)	3D-Based	95 ± 34	41 ± 15	103 ± 14	97 ± 27
	2D-Based	94 ± 33	41 ± 14	87 ± 5	85 ± 22
(6058, 177, 8877)	3D-Based	64 ± 23	55 ± 20	156 ± 14	116 ± 30
	2D-Based	63 ± 22	54 ± 19	134 ± 5	107 ± 27
(5975, 85, 4262)	3D-Based	117 ± 42	96 ± 35	81 ± 14	138 ± 40
	2D-Based	-	-	-	-

V. SHOWER ENERGY

For both reconstruction chains described above we need to return to 2D to calculate the energy deposited by the showers. To do this we study the 2D hits associated with the shower on the collection plane. Each 2D hit carries information about the amount of charge collected by a wire in a specific time-interval. For the first two planes the charge is induced on the wire as the charge drifts past the wire, while on the final plane the charge is collected. Owing to the uni-polar pulse on the collection plane extracting calorimetric information is easiest from this plane. For this reason in this note we only use the collection plane for estimating the calorimetry associated to the hits.

The charge of the hits in each cluster is summed and is initially measured in ADC counts. To convert this to an energy scale we apply a preliminary calibration that is computed by using a sample of through-going muons. Since this scale is preliminary and does not represent the final energy scale calibration of MicroBooNE we use this to compute the shower energy in terms of pseudo-MeV (MeV*). We then apply two corrections to this collected energy: one for the signal attenuation from electro-negative impurities in the argon and one to account for the ion-recombination. Each of these contains an inherent uncertainty. At this stage, we estimate an energy scale uncertainty of 35% (future analyses will directly study our energy scale and the uncertainty on it). Further spreads and biases are introduced when charge is radiated outside of the detector volume and when our clustering algorithms fail to collect all the relevant charge. We elect to not correct for these biases and instead report our shower energies in terms of "collected energy", E^{Coll}. The reconstructed energy of the showers can be found in Table I, we see that the two shower reconstruction methods provide consistent shower energies even with different clustering inputs.

VI. $m_{\gamma\gamma}$ RECONSTRUCTION

Finally, to verify that our reconstruction is performing well we attempt to reconstruct the π^0 mass from the two decay photons. We expect our reconstructed masses to be below the expected value due to the fact that we are not correcting for the biases pointed out in Sec. V. Furthermore, using a higher statistics sample of reconstructed π^0 masses we can verify our energy scale calibration. For this note we utilize the four events that we have reconstructed and calculate the mass by combining the angle, $\theta_{\gamma\gamma}$, between the two reconstructed showers and their energies, E_1 and E_2, via:

$$m_{\gamma\gamma} = \sqrt{2E_1E_2\left(1 - \cos\theta_{\gamma\gamma}\right)}. \tag{1}$$

The reconstructed masses, listed in Table I, are compatible with expected value of the π^0 mass.

When assessing the uncertainties on the reconstructed masses we have to take into account both the uncertainty on the shower energy and reconstructed angle between the showers. We estimate the latter by studying the angular resolution from a single particle Monte Carlo sample. We find that both types of reconstruction have slightly different resolutions but that these are small compared to the uncertainties on the shower energy scale. We see that, within our presently large uncertainties, all measured masses are compatible with the expected π^0 mass, and in the three events for which both methods yield masses, these are consistent with each other.

VII. CONCLUSIONS

This note demonstrates the application of two different shower reconstruction paths on MicroBooNE data. Both of these show promise and consistently reconstruct the kinematic properties of ν_μ charged current π^0candidate events. The uncorrected diphoton mass is compatible with an expected π^0 mass. Future iterations of this analysis will be focused on the automatic selection of π^0 decays and a high statistics π^0 sample. The latter will be used to obtain our measure of the π^0 mass and hence establish our energy scale and resolution.

[1] MicroBooNE Collaboration, MicroBooNE–1010–PUB.
[2] J. S. Marshall and M. A. Thomson, Eur. Phys. J. C **75**, 439 (2015).
[3] MicroBooNE Collaboration, MicroBooNE–1015–PUB.
[4] G. Bradski, Dr. Dobb's Journal of Software Tools, 2236121 (2000).