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Estimation of Signal Efficiency and Background Rejection for a Liquid Argon Detector in the NuMI Off-Axis Beam

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Abstract

In this note we describe a small study carried out at Tufts University to evaluate the signal efficiency and background rejection capabilities of liquid argon detectors for sub-dominant $\nu_\mu \to \nu_e$ searches in the NuMI beam. The analysis is based on a blind scan of 450 events.

1 Introduction

The Tufts University High Energy Physics group has extensive experience with high-resolution neutrino detectors, from the Argonne 12' bubble chamber through more recent experiments such as Soudan 2 and DONUT. The opportunities provided by new high-resolution devices for oscillation physics have interested our group for some time, and in Dec. 2004 were approached by Adam Para to discuss some of the pattern recognition challenges for liquid argon detectors. As a consequence of these discussions the Tufts group agreed to conduct a scan analysis to quantify the signal efficiency and NC background rejection capabilities of liquid argon.

2 Method

The Liquid Argon Interactive Reconstruction (LAIR) program by Adam Para and Robert Hatcher was used for the scanning. Event samples were prepared by Adam Para and involved a full GEANT 3 simulation of the events. neugen3 was used as the event generator to produce the initial neutrino interactions. The fluxes were those at an XX mrad off-axis location and oscillated samples events were generated with $\Delta m^2 = XeV^2$. An energy preselection was applied, all events had a visible energy between 1.5 and 4.5 GeV. (check numbers with Adam). An energy cut of this type would certainly be applied to any real analysis as it focuses on the expected signal region, reducing the background from beam ν_e by a large factor and reducing the NC event rate by a factor of six [**?**].

2.1 Scanner Training

Four undergraduate students from J. Schneps undergraduate E&M class volunteered to participate in the project. Over the 2005 spring semester they worked 5-10 hours per week scanning and reconstructing events. These students, two sophomores and two juniors, had no previous exposure to particle physics. In preparation for the blind scan the students underwent a training program consisting of the following:

1. General introduction to particle detectors, neutrinos, and characteristic topologies produced in LAr by various particles.

2. Introduction to LAr detectors, stereo geometry and software. Students scanned single particle events with single electrons, muons, and photons of known energy and angle in the detector. This process helped motivate the difference between e and γ-induced showers, the single muon files were invaluable in understanding the geometry of the stereo views.

3. Scanned samples of around 50 events from each of ν_e and ν_μ CC and NC samples

4. Scanned samples of around 50 ν_e events, both NC and CC, checking results against truth. Repeat a few times with varying amounts of input from "experts".

5. Scan several dozen events from specially selected "hard" samples: $y > 0.8$ ν_e CC events, NC events with 3 or more π^os.

2.2 Blind Scan

Once the training process was completed, students scanned a sample of 450 events. Each event was scanned independently by 2 students and was assigned a score from 1 (sure background) to 5 (sure signal). The students then compared their results, and scanned as a group any events where their individual scores differed by more than one unit, or other events flagged as meriting further scrutiny. Events receiving a score of 3 or higher by at least one student were considered to pass the student scan and were then scanned by the experts for final classification. The expert scan was carried out by at least two of Gallagher, Mann, Schneps, and assigned a binary signal/background decision to each event.

2.3 Reconstruction

In addition to event classification, the students performed an interactive reconstruction of each event using the LAIR program. First they located the position of the event vertex in 2 of the 3 detector views. The program would then place a symbol at this 3d-location in each of the 3 views; that the vertex assignment in the 3rd view corresponded to their prediction provided a strong constraint in interpreting the overall event structure. Similarly the scanners would identify a point in 2 views for every vertex track and isolated shower in the event. Each was classified as one of "non-showering", "electron candidate", "gamma conversion", or "neutron star". With a knowledge of the detector geometry this gives the (x,y,z) location of the event vertex and a point along each track/shower in the event. These can subsequently

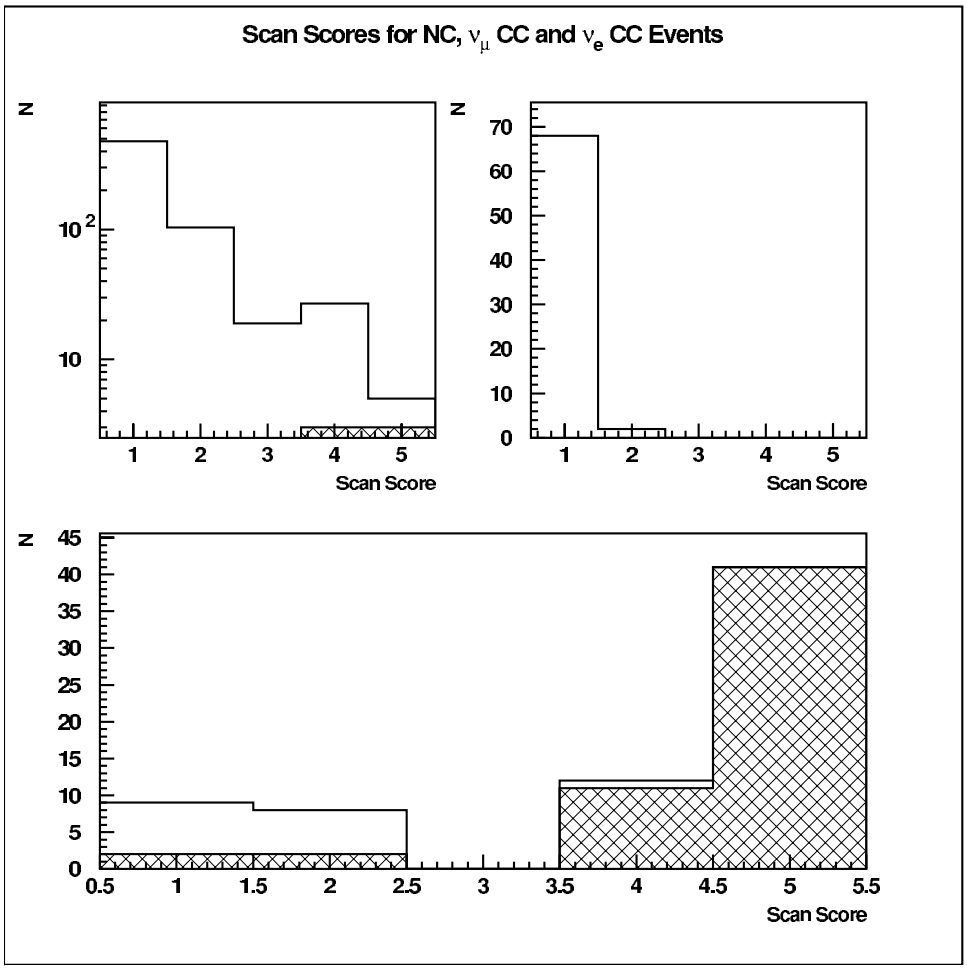

Figure 1: Student scan scores for events in the NC (top left), ν_μ CC (top right), and ν_e CC samples. Dashed histogram indicates the events flagged as "signal" in the expert scan. Since each event is scanned independently by two students, each event contributes two entries to each histogram. Note the log scale on the NC distribution.

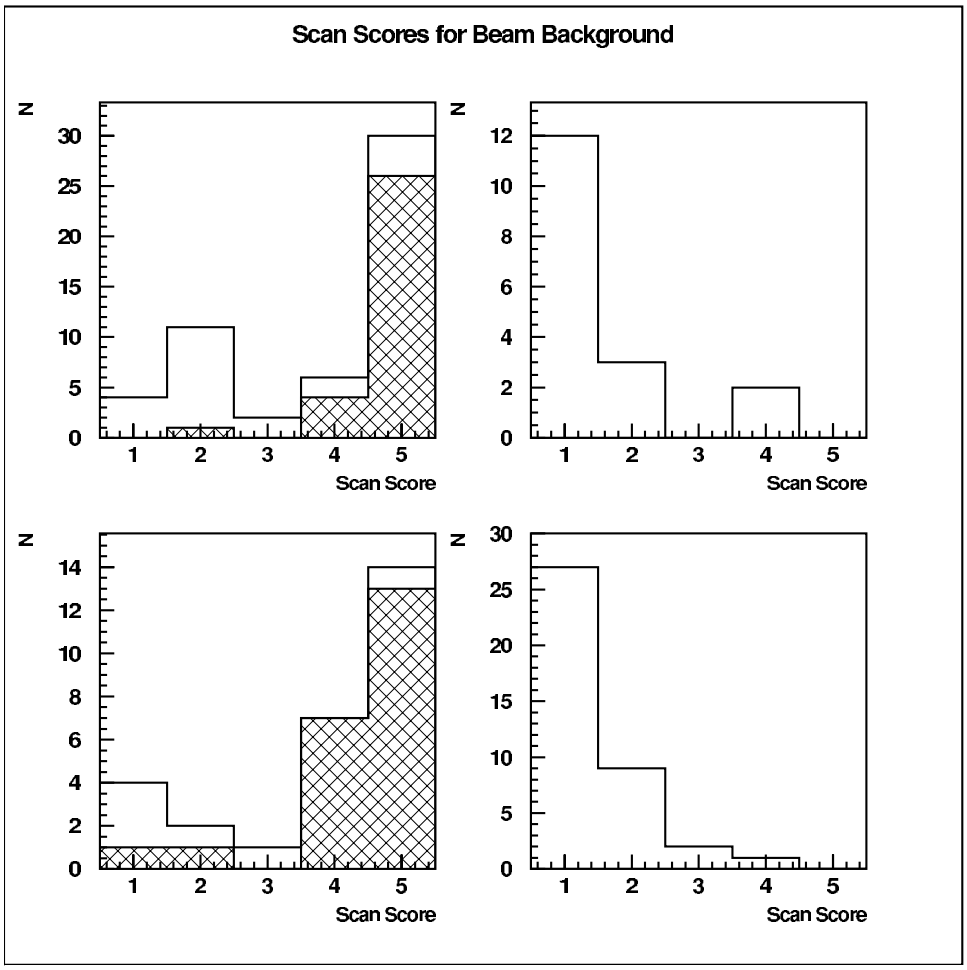

Figure 2: Student scan scores for events from the beam background ν_e sample (CC = top left, NC = top right) and $\overline{\nu}_e$ samples (CC = bottom left, NC = bottom right). . Dashed histogram indicates the events flagged as "signal" in the expert scan. Since each event is scanned independently by two students, each event contributes two entries to each histogram.

	1	**2**	**3**	**4**	**5**
1	202	24	0	1	0
2	24	15	3	1	1
3	2	2	1	3	0
4	1	1	2	4	0
5	0	0	0	2	1

Table 1: Correlation matrix between individual scanner decisions for NC events. Columns are scanner 1 scores, rows are scanner 2 scores.

	1	**2**	**3**	**4**	**5**
1	2	0	0	0	0
2	1	2	0	1	1
3	1	0	0	0	0
4	1	1	0	5	0
5	0	0	0	3	14

Table 2: Correlation matrix between individual scanner decisions for ν_e CC events.

be used as seeds for track finding/fitting software and to further characterize events identified as signal and background, though they were not used further for the analysis described in this note.

3 Results

Tables 1 and 2 show the correlation between the scores assigned to each event by the two scanners. A high degree of correlation is clearly evident. 282 of 290 NC events and 27 of the 32 CC events had scan scores differing by no more than one unit. This suggests that the scanners were applying the same set of criteria in making their event classifications and agreeing on the topological features that served as the basis for their event classification decisions. The latter bodes well for the prospects of converting the decision making procedures employed by the students to software algorithms.

Table 3 shows the numbers of events from each sample to be classified as signal through the two scans. 26/32 signal events and 4/290 NC events passed the scan analysis for a signal efficiency of 81±7% and a background rejection factor of 73±31. Combined with the factor of 6 rejection on NC background coming from the energy pre-selection gives a total NC rejection of 435. Figures 3 4 and 5 show the event characteristics for the CC ν_e signal, CC ν_e beam background, and CC $\overline{\nu}_e$ CC background. In each plot the top histogram is the full sample and the dashed histogram are events that pass the scan. The signal efficiency as a function of y can be roughly characterized as 100% below y of 0.5, and still nearly 50% for $y > 0.8$. The fact that high-y showers tend to be at large angles, and therefore

		N	pass	ϵ	η
NC		290	4	-	73±31
signal ν_e	CC	32	26	0.81±0.07	-
Beam ν_e	CC	24	14	0.58±0.10	-
	NC	8	0	-	/
Beam $\overline{\nu}_e$	CC	13	10	0.77 ± 0.09	-
	NC	19	0	-	/
ν_μ	CC	32	0	-	/
$\overline{\nu}_\mu$	CC	32	1	-	/

Table 3: Scan results for various event categories. ϵ is signal efficiency and η is the background rejection. "/" indicate samples where the event size is too small to draw meaningful conclusions.

spatially separated from other activity in the event, provide a compensating advantage for these events.

A noticeable difference is seen in the signal efficiencies between the signal ν_e CC events and those from the ν_e beam background, 81±7% vs. 58±10%. An examination of the energy distributions in Figures 3 and 4 may provide a partial explanation. The background distribution shows (with low statistics) a possible energy dependence to the signal efficiency, as 0/4 events with energy greater than 3.5 GeV made it through the scan. This energy dependence may be partly the result of bias in the training based on the samples used.

4 Conclusion

From a blind scan of 450 events the signal efficiency and background rejection for NuMi off-axis events in a liquid argon detector with a pre-selection on visible energy are found to be 81%±7% and a background rejection of 73±31. These results were obtained in a blind scan carried out in two stages, the first by a group of undergraduates and a second by physicists who reviewed all events passed in the first stage. The accepted events therefore comprise the *AND* of the two scans.

Figures 6 and 7 show event displays of two high-y events that were passed as signal in the analysis. Both received a "4" score from both scanners. Though the showers are relatively low energy, the fact that they are spatially separated from the rest of the event makes positive identification possible.

Figures **??** show three signal events which did not pass the scan. In the latter two events the electrons shower early, and coupled with the fact that the shower is either small or at a large angles led to low scores in the first pass scan. The third event passed the first scan but was rejected by the experts. The other 3 rejected signal events did not pass through the first scan, for reasons that are not clear.

Figures **??** show the four background events which were called signal in the scan. The second has a track overlapping the shower in several views, which complicate the tracking

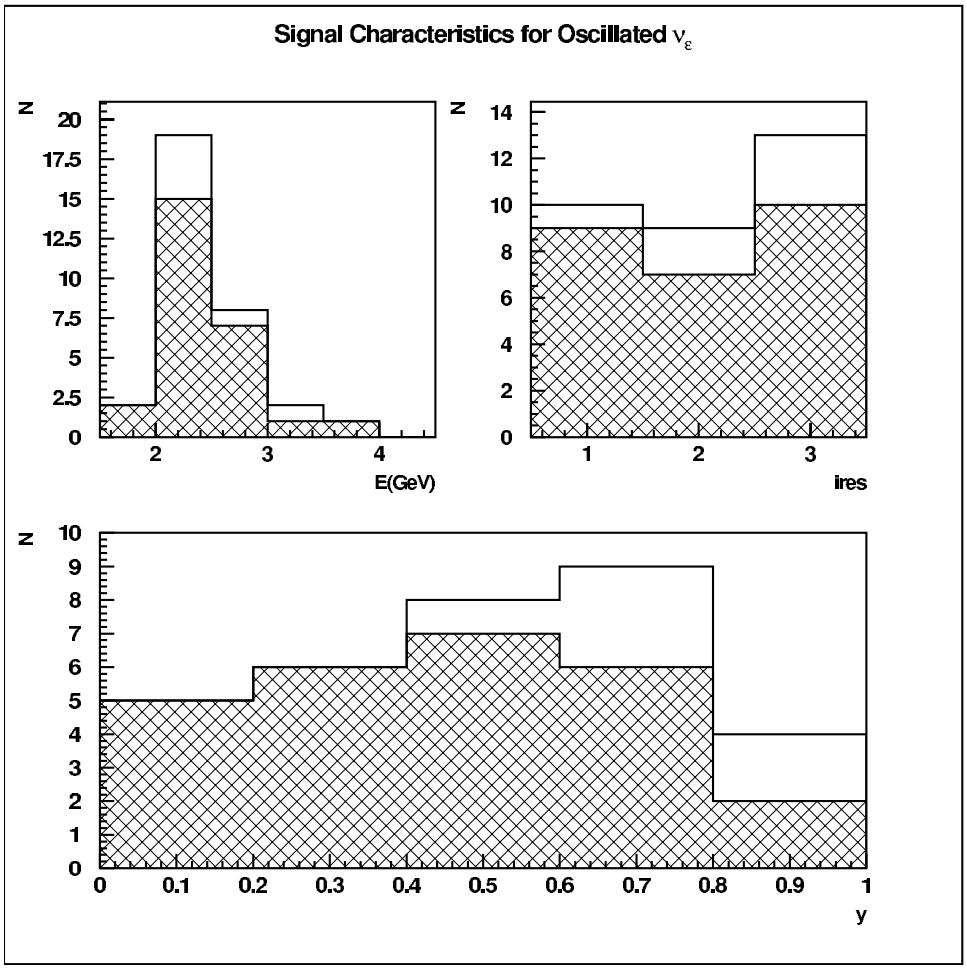

Figure 3: Event characteristics for ν_e CC events selected from the oscillated parent distribution. Solid histograms are all events, dashed are those which were passed as signal through the 2 scans. **Top Left: Neutrino Energy. Top Right: Interaction type (quasi-elastic, resonance production, DIS). Bottom: y.**

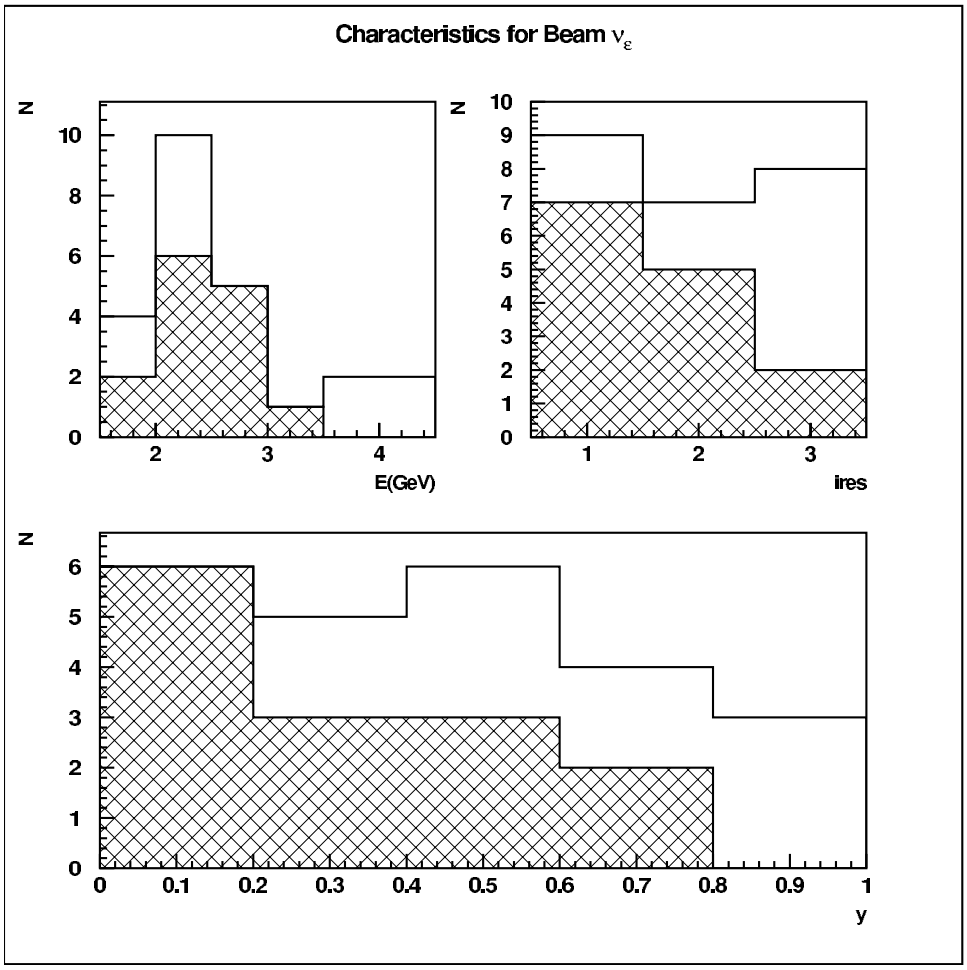

Figure 4: Event characteristics for ν_e CC events selected from the ν_e beam background distribution. Solid histograms are all events, dashed are those which were passed as signal through the 2 scans. **Top Left: Neutrino Energy. Top Right: Interaction type (quasi-elastic, resonance production, DIS). Bottom: y.**

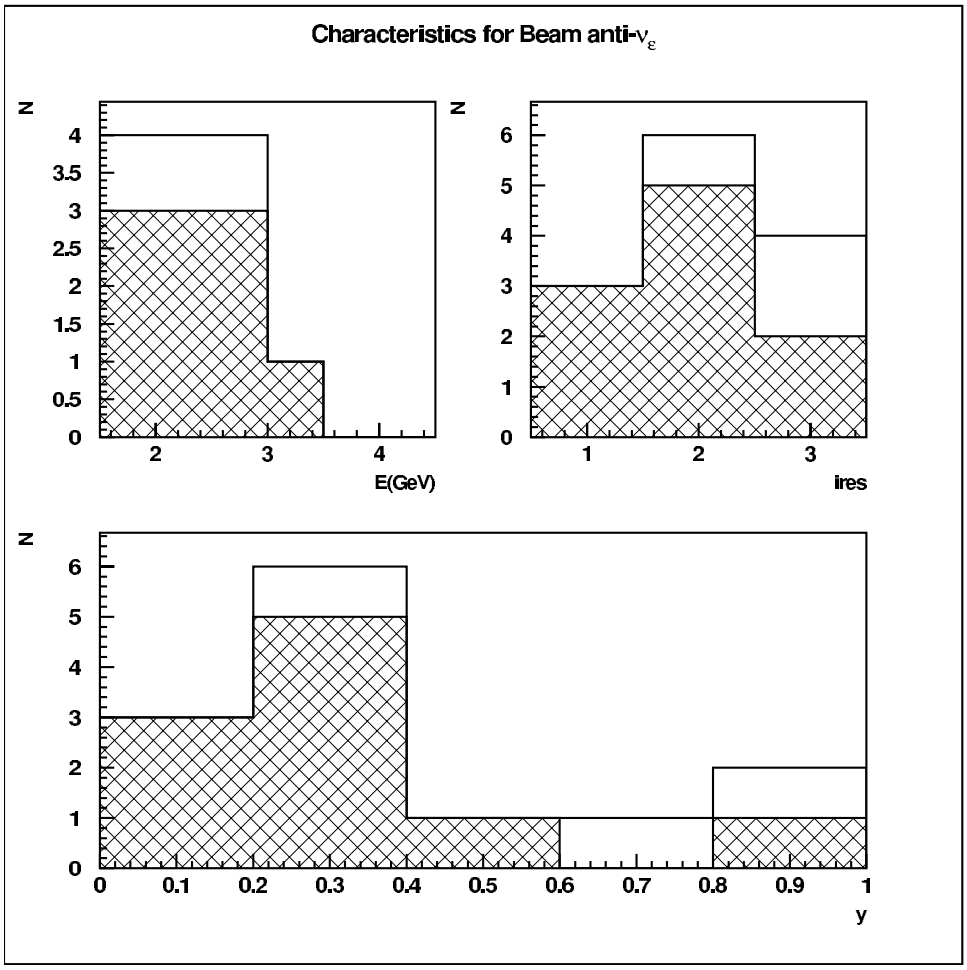

Figure 5: Event characteristics for $\overline{\nu}_e$ CC events selected from the beam background parent distribution. Solid histograms are all events, dashed are those which were passed as signal through the 2 scans. **Top Left: Neutrino Energy. Top Right: Interaction type (quasi-elastic, resonance production, DIS). Bottom: y.**

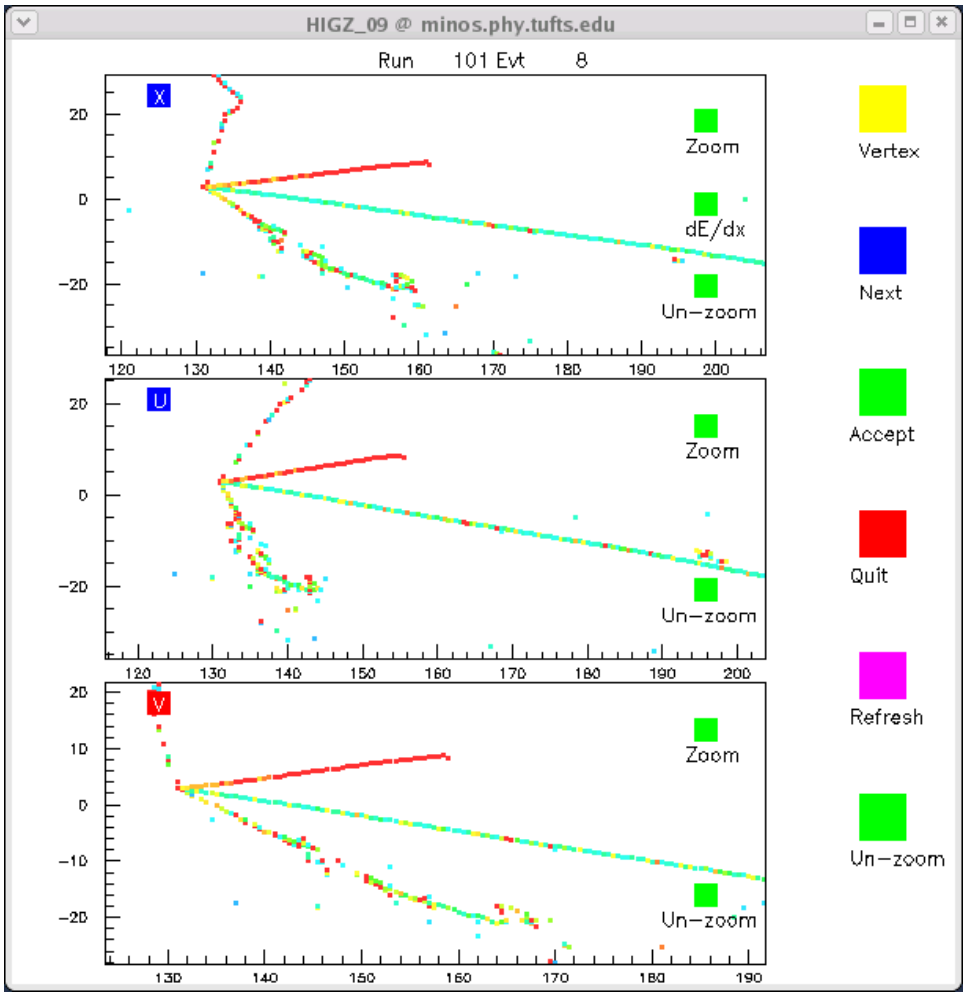

Figure 6: Signal event selected, 2.2 GeV DIS ν_e CC with y=0.89. The electron shower is clearly visible.

to the vertex. In other events a photon from a π^o decay showers close to the vertex, and the ionization information is not sufficient to identify it as double-minimum ionizing.

References

[1] Robert Hatcher and Adam Para, http://www-off-axis.fnal.gov/flare/index.html.

[2] Adam Para, presentation to the 2nd FNAL Review on LAr detectors. April 2005.

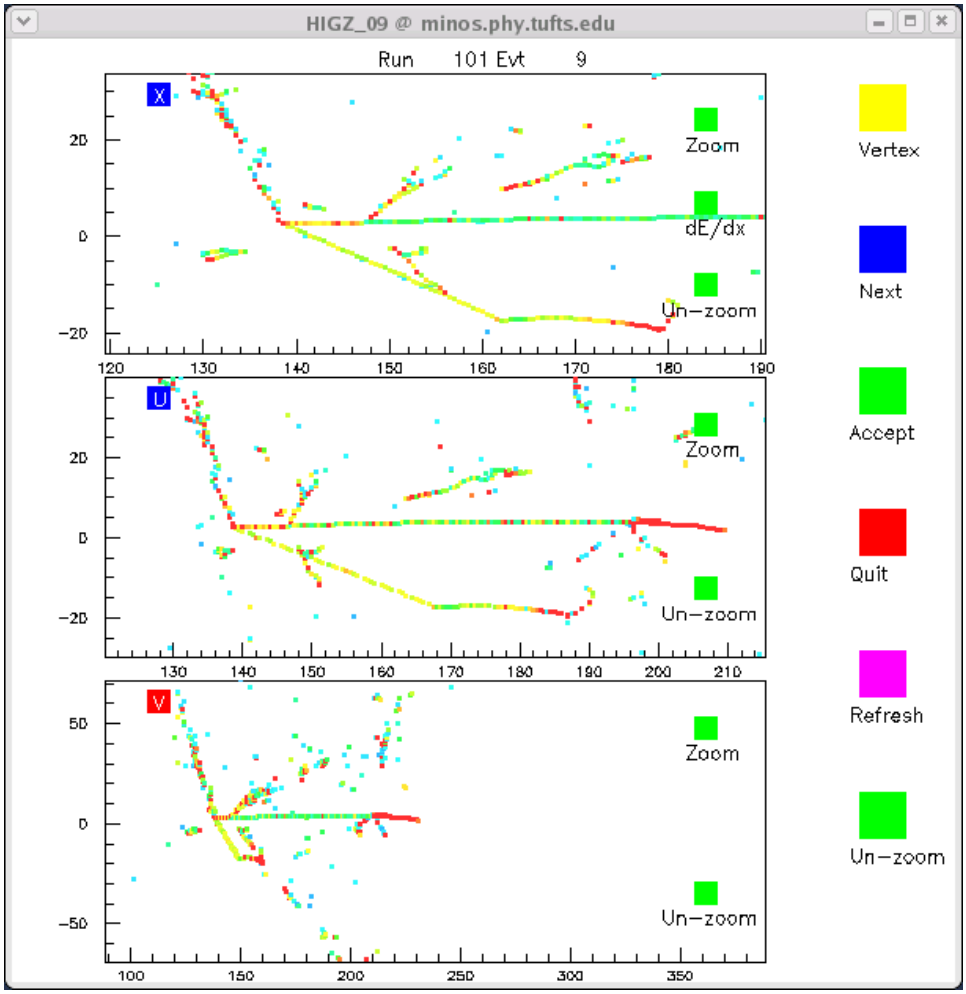

Figure 7: Signal event selected, 2.4 GeV DIS ν_e CC with y=0.87. The electron shower is clearly visible.

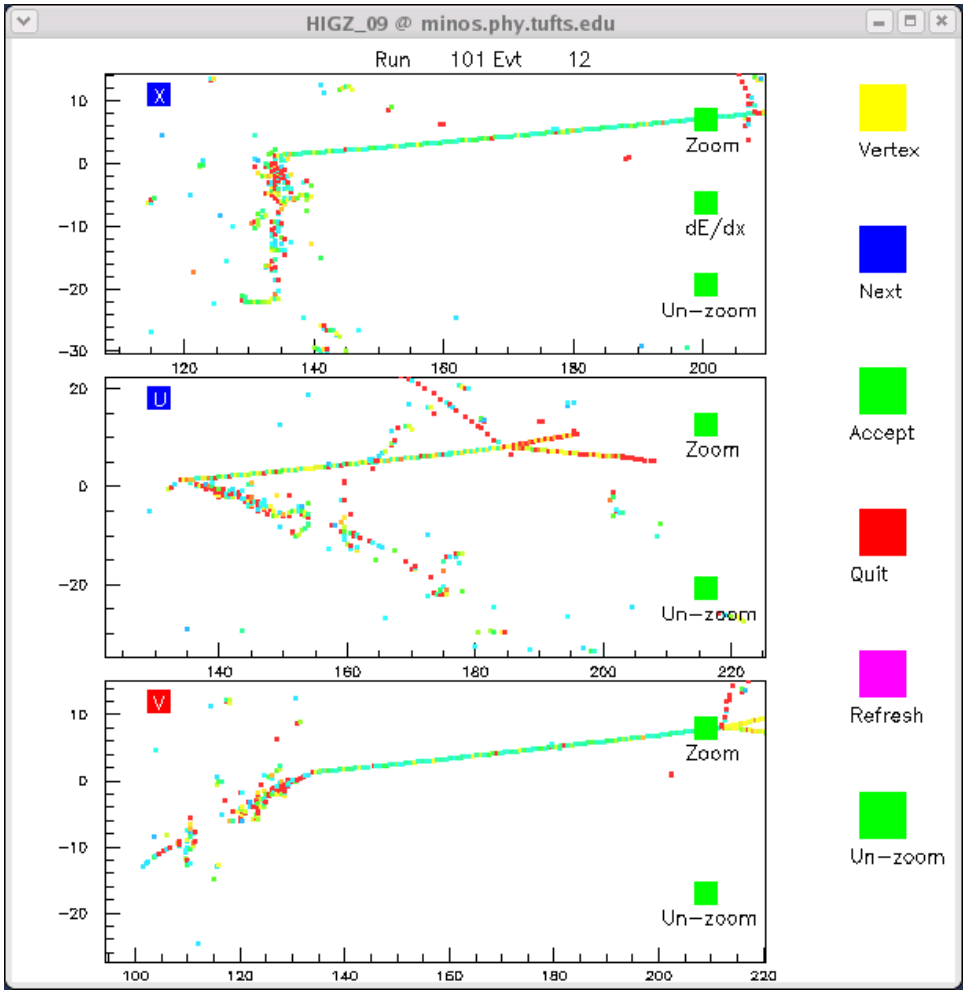

Figure 8: Signal event failing the scan, scored as a "2" by both scanners. The event is a 2.4 GeV QEL event with y = 0.68. The electron shower is seen at large angle, and showers early.

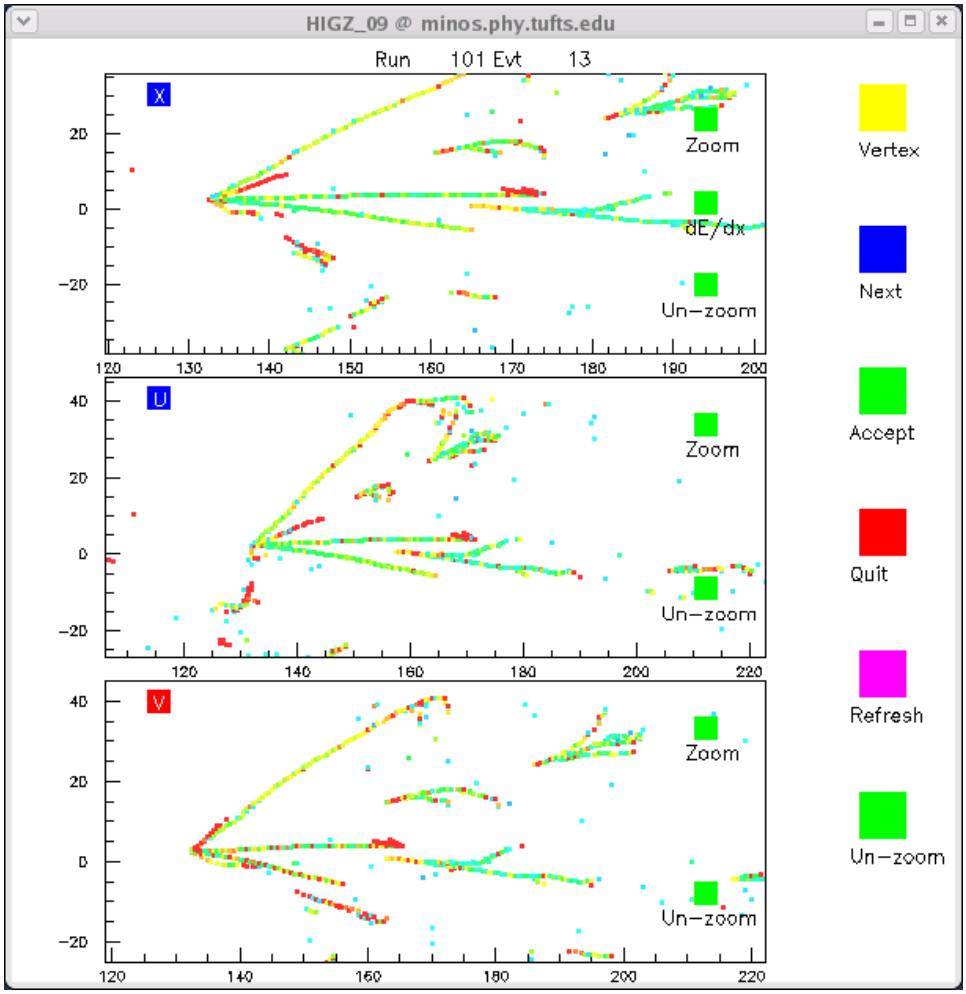

Figure 9: Signal event failing the scan, scored as a “2” and a “1” by the scanners. The event is a 2.3 GeV DIS event with y = 0.88. The electron showers early.

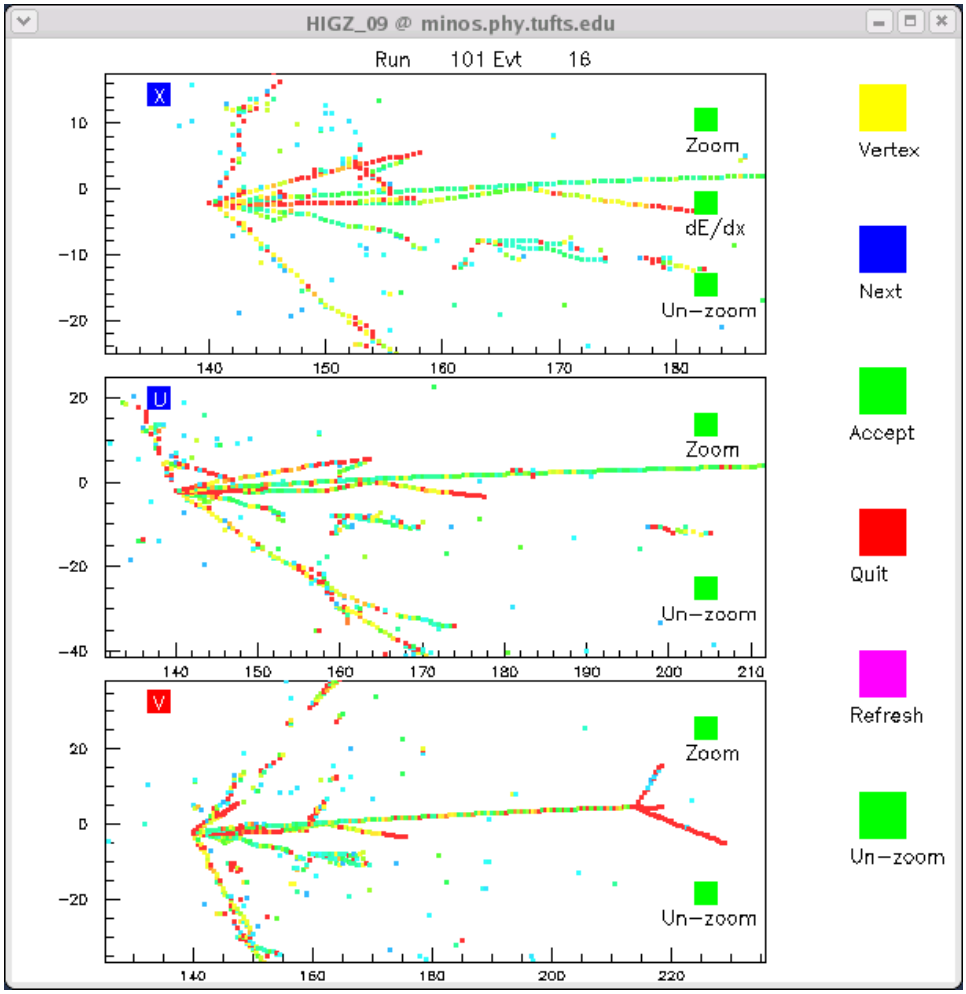

Figure 10: Signal event failing the scan, scored as a "4" and a "2" by the scanners but rejected by the "experts". The event is a 2.3 GeV DIS event with y = 0.87.

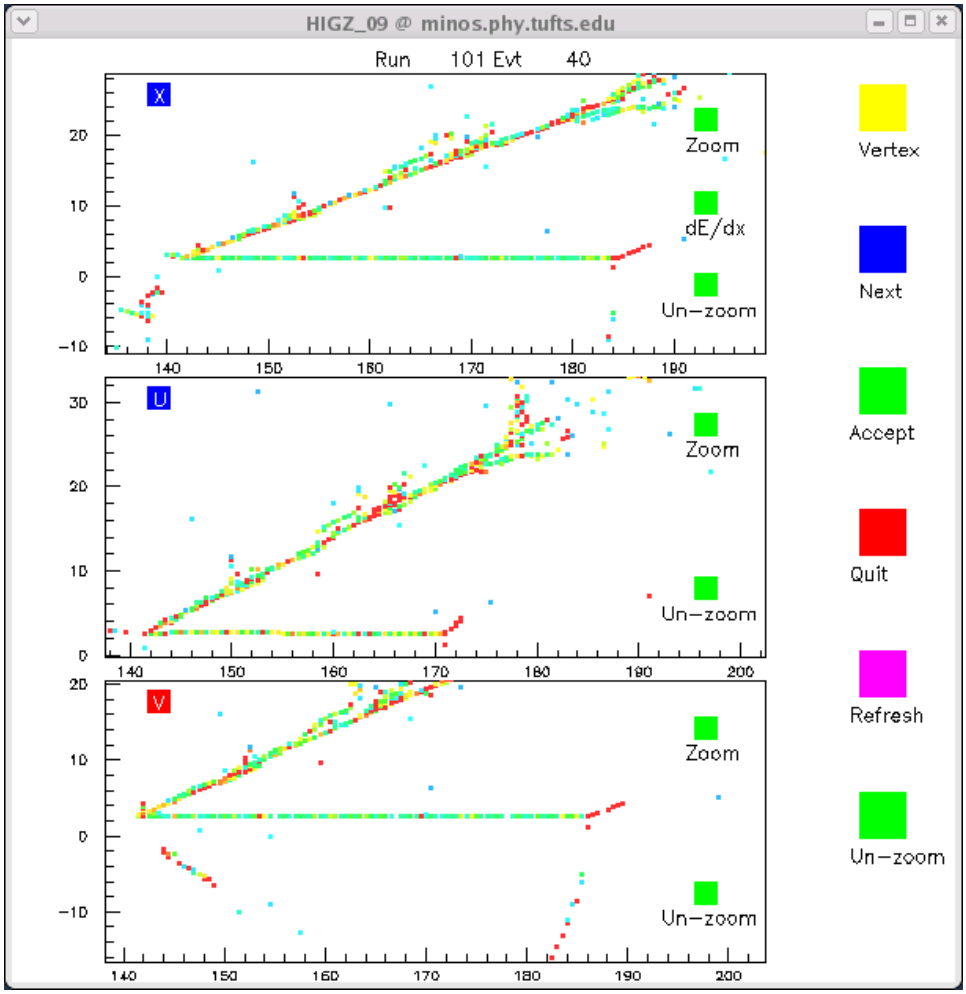

Figure 11: NC event called signal in the scan.

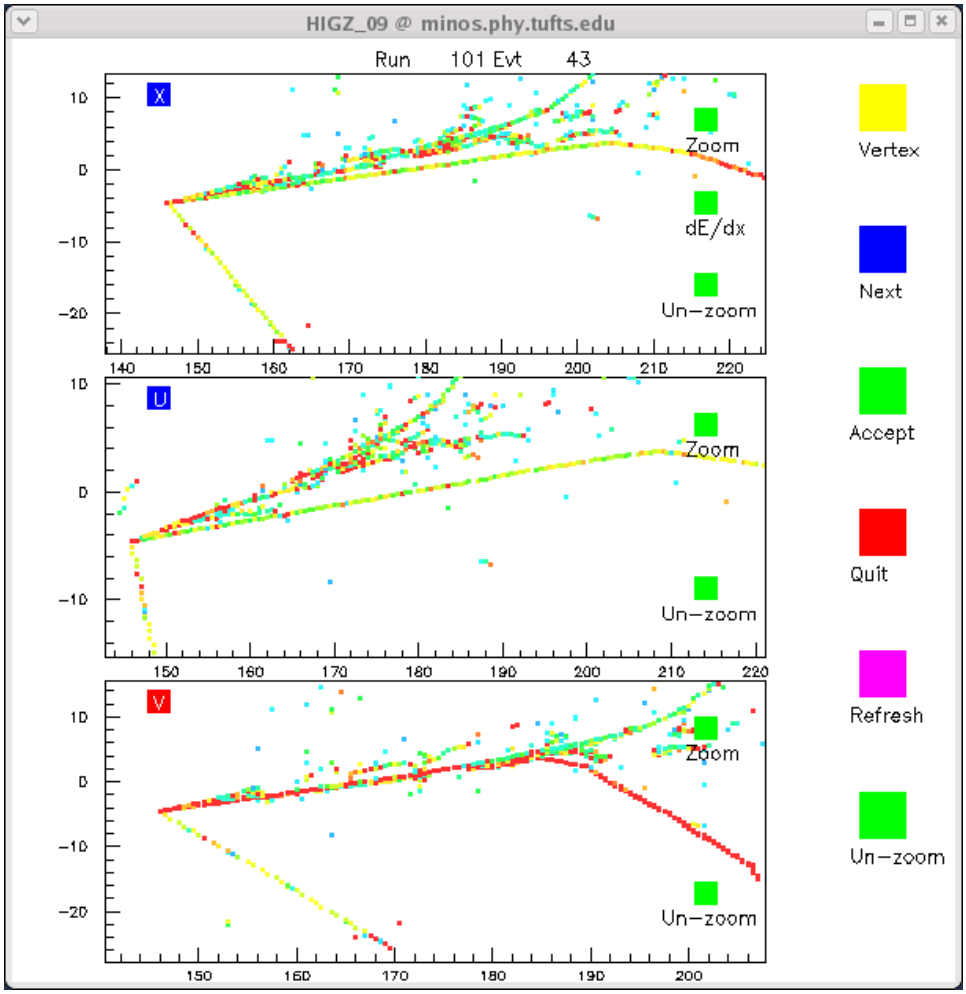

Figure 12: NC event called signal in the scan. Overlapping track and shower are evident

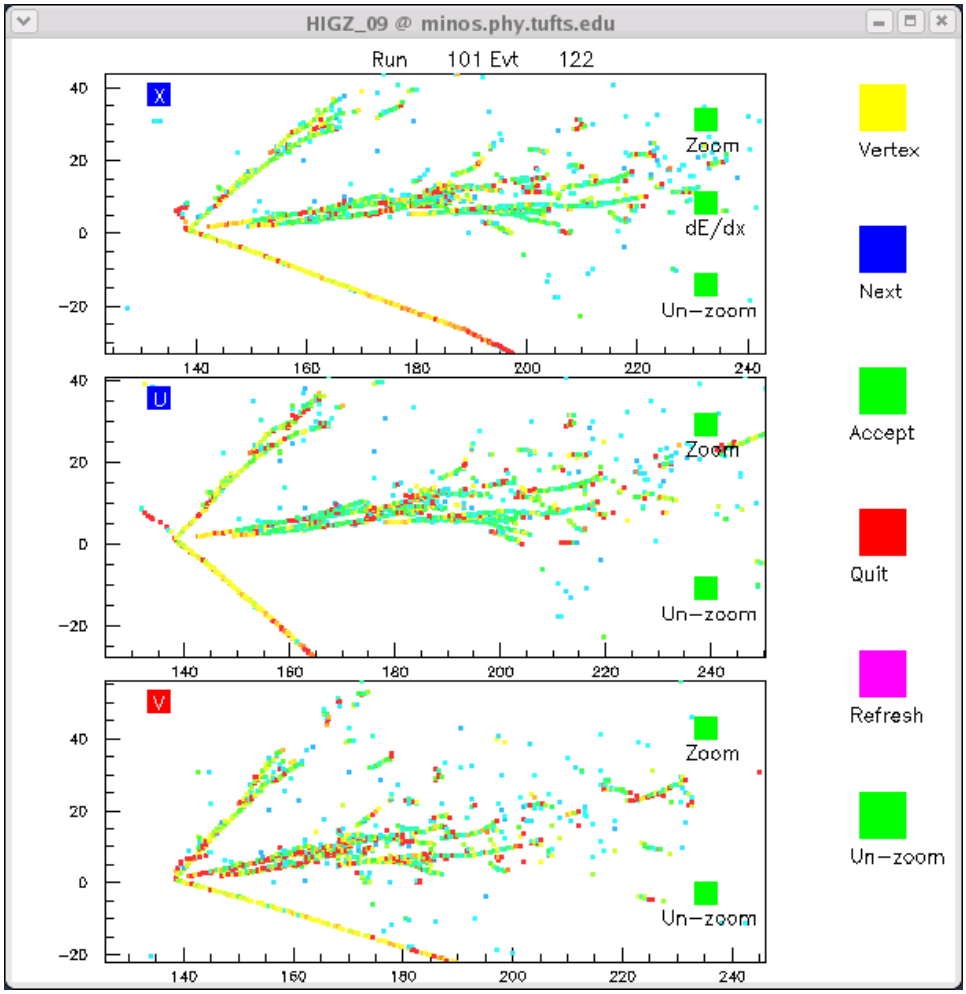

Figure 13: NC event called signal in the scan.

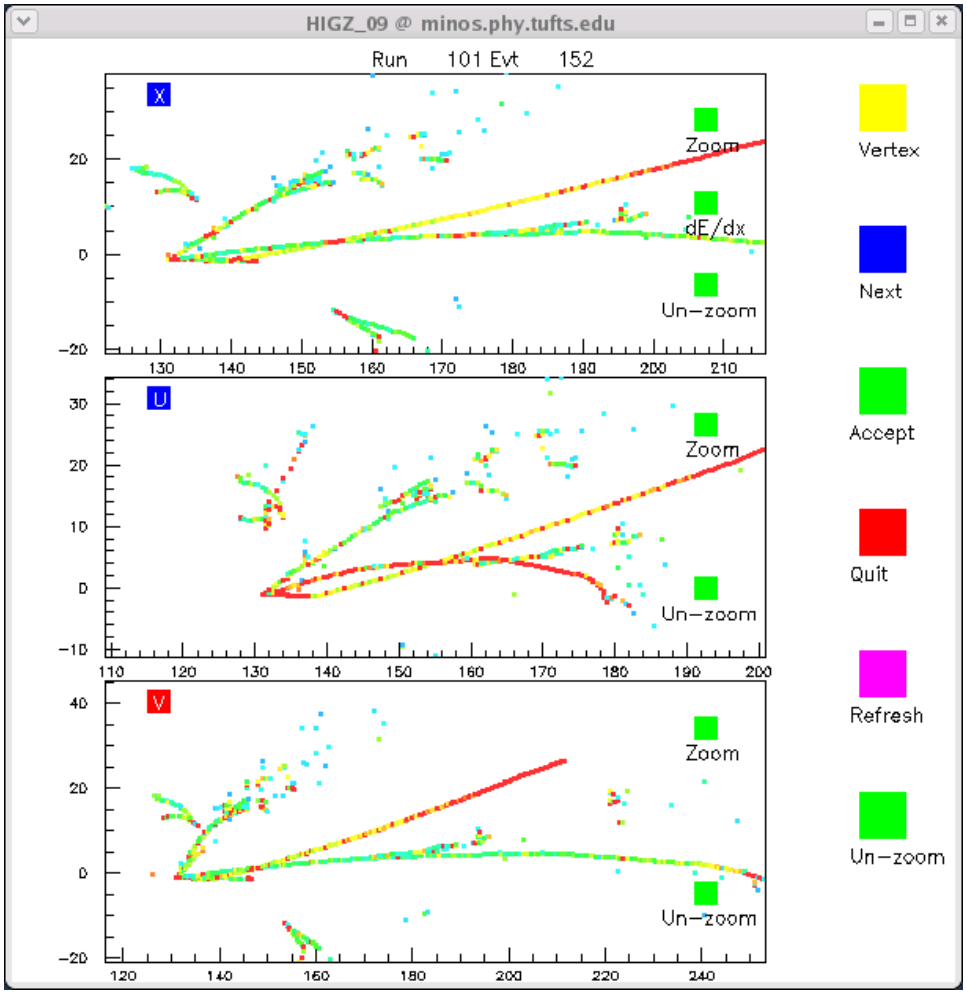

Figure 14: NC event called signal in the scan.