Off-axis Simulations

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- What has been simulated?
- Will the experiment work?
- Can we choose a technology based on simulations?
- Still very much work to be done, it is only early days yet.

What has been simulated?

- A somewhat idealized RPC detector
- A more realistic scintillator detector
  - Liquid
  - Solid
- Three analyses have been written up and are available as off-axis notes
  - Fermilab (RPCs)
  - SLAC (RPCs)
  - Minnesota (Scintillator)
- I am most familiar with the scintillator analysis and I will describe this in more detail. The RPC analyses are similar in principle and obtain broadly similar results.

Liquid Scintillator Detector Simulation

- Used the MINOS simulation framework.
- Used NEUGEN3 for the event generation.
- Simulated a detector ~ 30m x 15m x190m, absorber density = 0.7 g/cc, readout planes separated by 0.33 of a radiation length, 50ktons total weight.
- Liquid scintillator strips were 4cm wide x 2.9cm thick x 15m long, read out by a looped fiber to an APD pixel.
- Light collection and attenuation simulated according to measurements of prototype 15m fibers and the experience of MINOS.
- Light level set to average 35 photo-electrons read out from a normal minimum ionizing particle at the far end of a strip.
- APD readout, including noise, simulated according to the experience of CMS.

Event Samples

- A detector at the proposed site, 820km from Fermilab and 12km off-axis was simulated
- Neutrino events were generated with a flat event distribution from 100 MeV to 20 GeV and uniformly throughout the detector. Equal numbers of events were generated between 100 MeV and 3 Gev and 3 GeV and 20 GeV.
- Charged current ν_μ, charged current ν_e and neutral current events were generated separately
- Beam spectra for the site were imposed by weighting the events
- A 50kton detector, run for 5 years with 4🔔10^{20} pot/year
- Oscillations with Δm^2=0.0025, $\sin^2 2\eta_{23}$=1 and $\sin^2 2\eta_{13}$=0.1 were assumed.
- Samples of ~0.5M events in each category were used to define the analysis procedure and cuts and a similar, separate, sample to calculate the event selection efficiencies.

Event Reconstruction

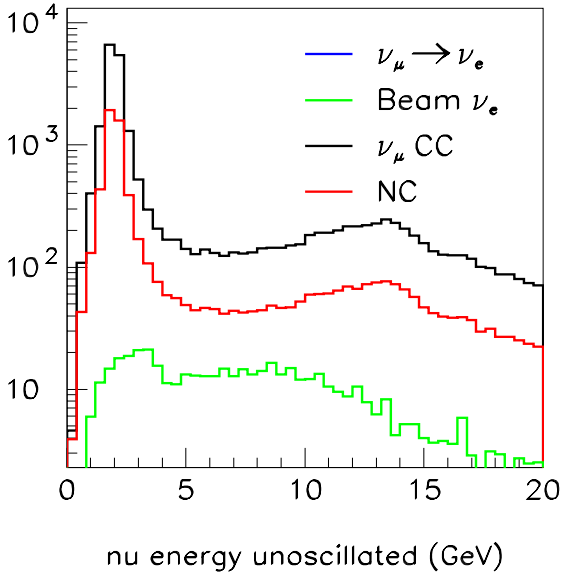
- Firstly a clustering algorithm was applied which collected all hits which were within 2m of their nearest neighbour.
  - Three hits were required to establish a cluster.
  - The clusters in the two views were matched and the largest matched clusters in the two views taken as the event. Usually there was only one cluster in each view.
  - Using the reconstructed position of the event in space the hit pulse heights were corrected for attenuation
  - A straight line was fitted to the event hits in the two views and the residuals, unweighted and weighted by the pulse height were calculated
- Secondly the dominant track in the event was found using a Hough Transform method.
  - A straight line was then fitted to the hits assigned to this track and the pulse height weighted and unweighted residuals calculated

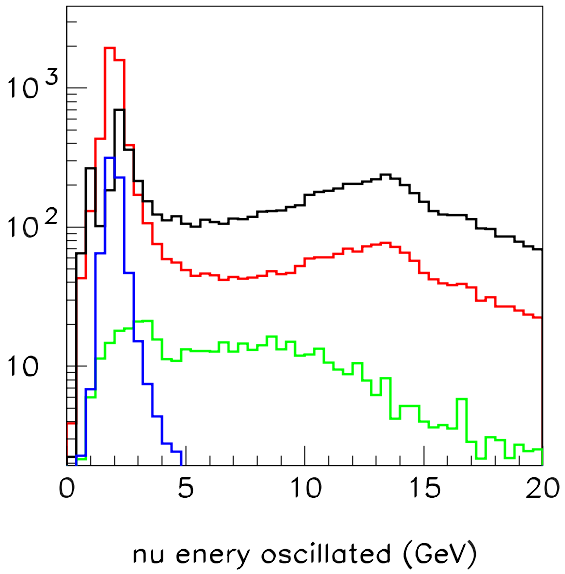
Event selection

1. A series of cuts were made on distributions where the background events can be separated reasonably cleanly from the electron events.
2. Pdfs for the different event classes were calculated from distributions where the events had substantial overlaps.
3. A likelihood ratio was calculated for the oscillated electron events versus the muon CC, neutral current and electron beam events.
4. Cuts were applied to these distributions to produce an electron CC event sample and the amount of background from the other categories calculated.
5. The scintillator and RPC analyses are similar in principle but different cut and pdf variables were used.

Events

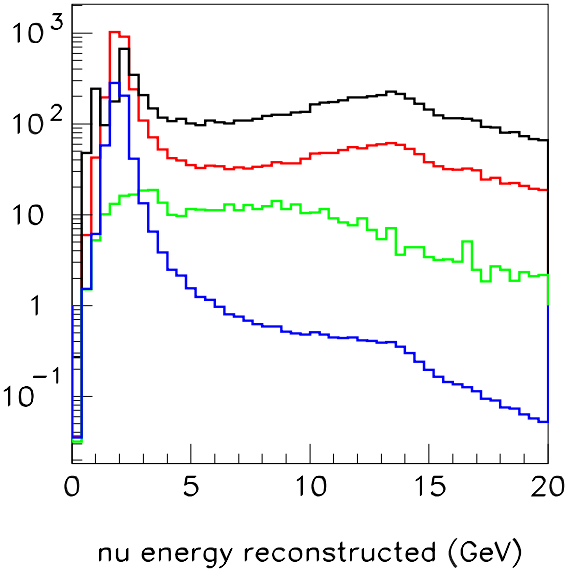
Unoscillated beam events as a function of truth neutrino energy

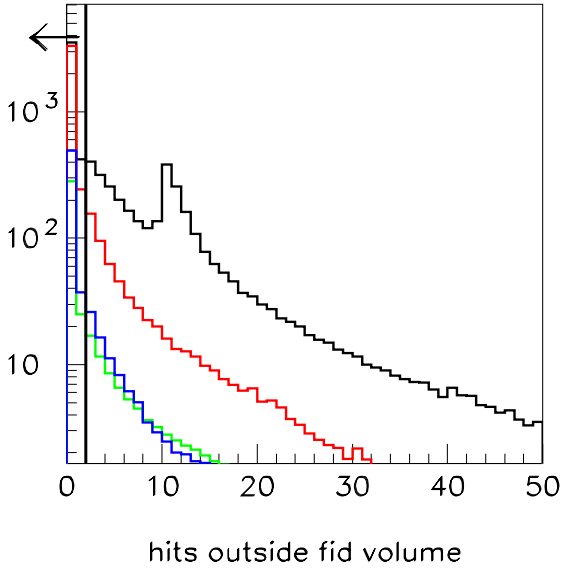




Truth neutrino energy after oscillations

Truth neutrino energy distribution after reconstruction



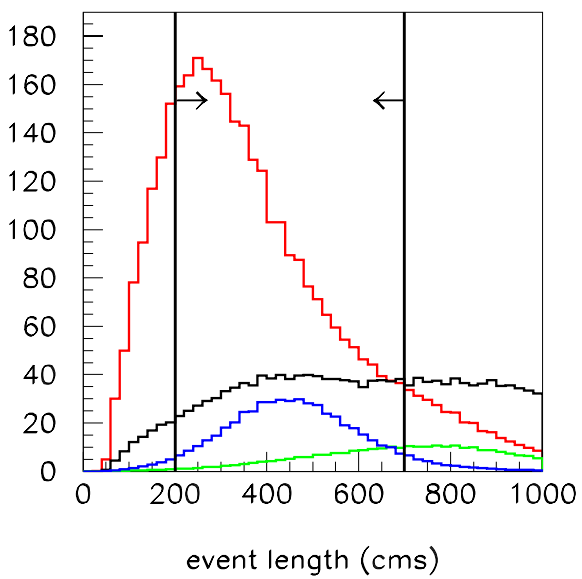


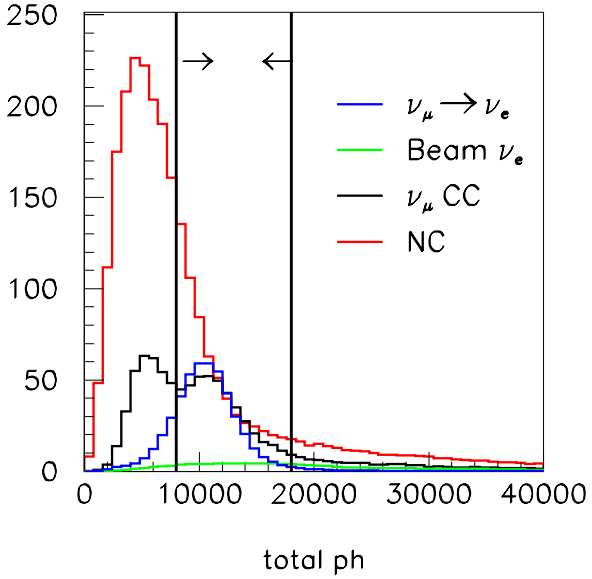
Number of hits outside fiducial volume (50cm lateral, 200cm longitudinal). Events with more than 2 hits outside are rejected. 84% efficiency

Cuts

Event length

Rejects ν_μ CC events



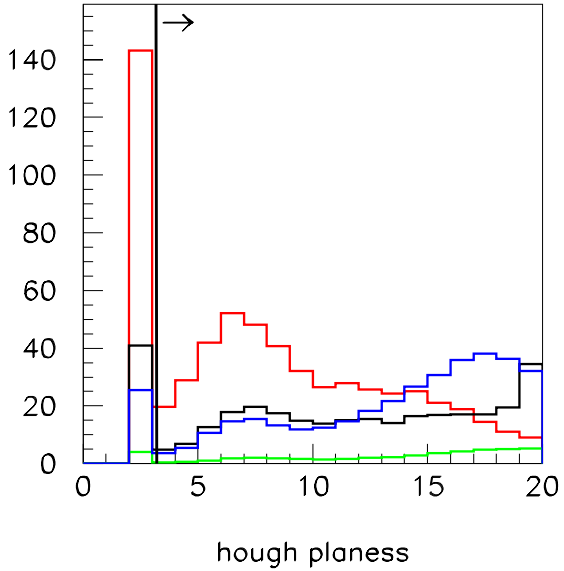


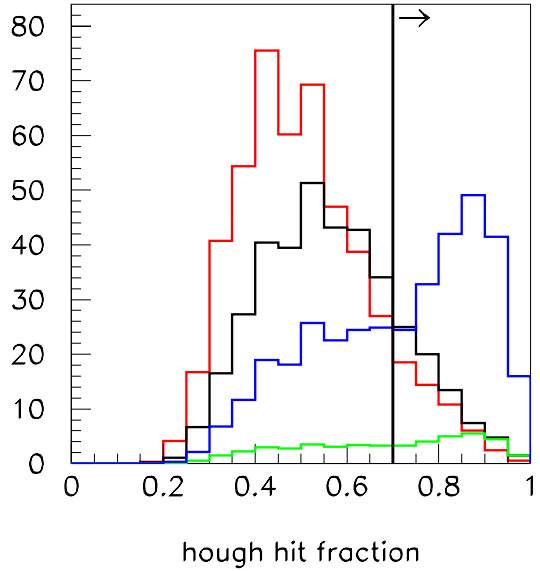
Total pulse height

Rejects high energy ν_e CC events and low visible energy events

Number of planes in the Hough track.

Requires a good track

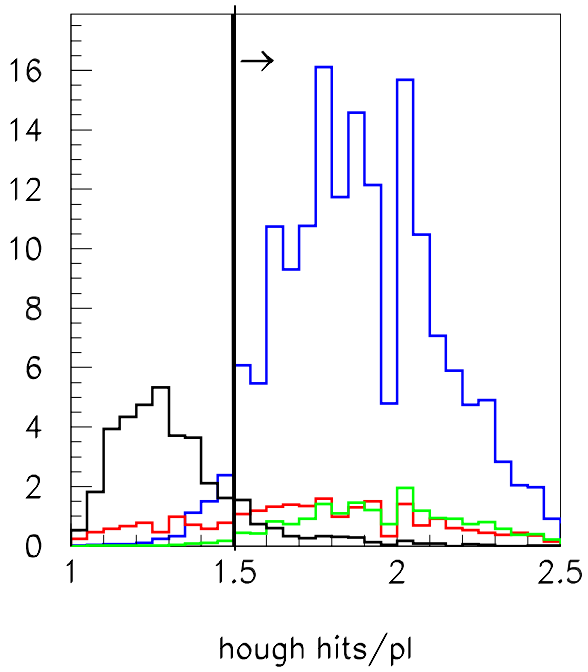


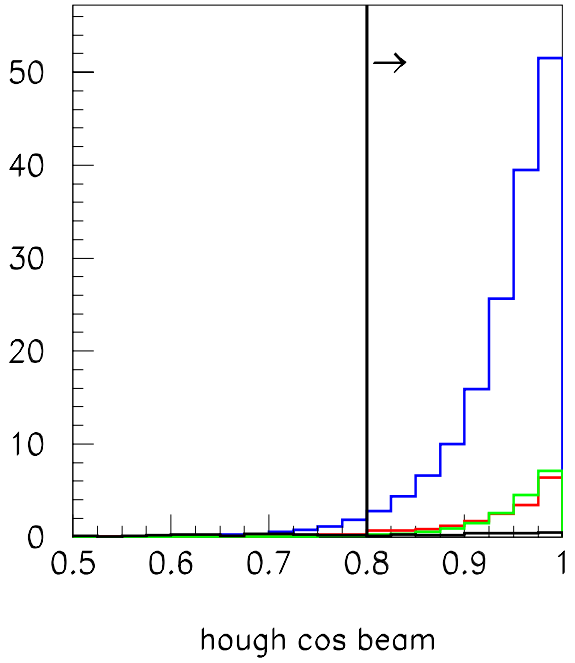


Fraction of hits in the Hough track

Selects low-y or quasi-elastic events

Cuts

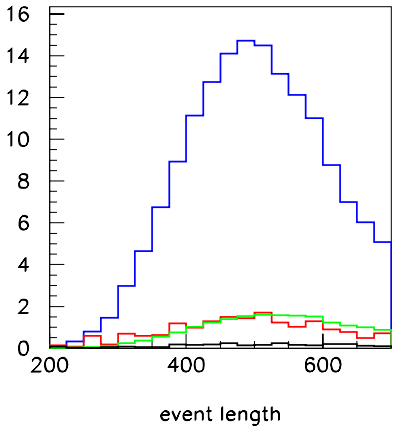


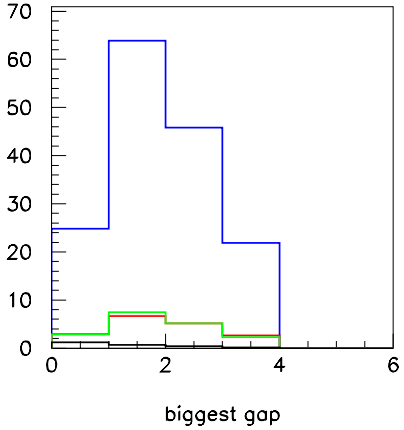


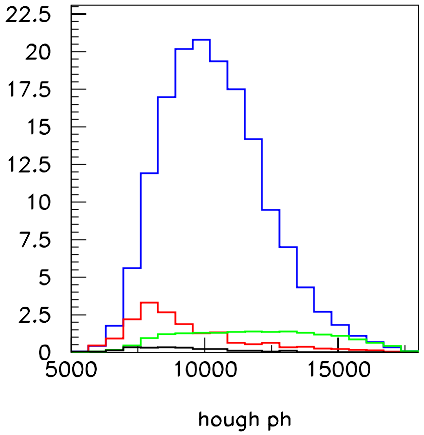
Hits/plane on the Hough track
Selects “fuzzy” electron tracks

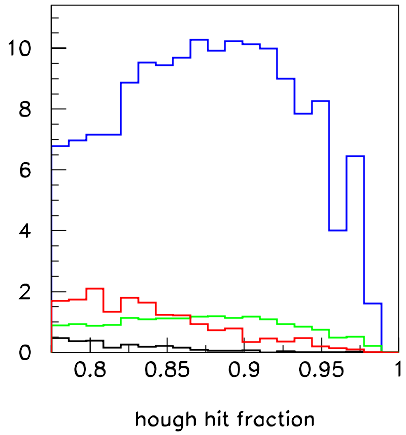
Angle of Hough track to beam
Rejects a few mis-reconstructed events

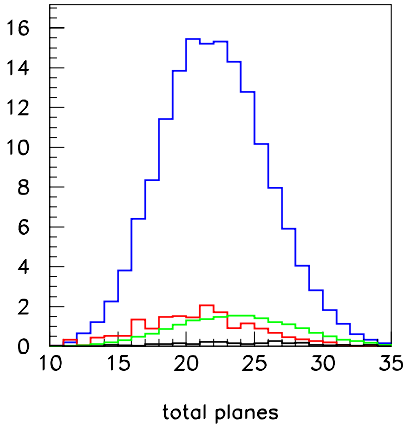
Likelihood PDFs (sample)

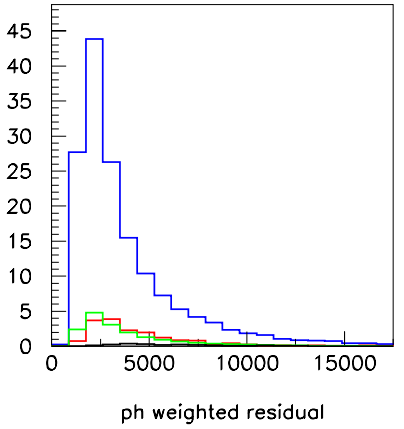


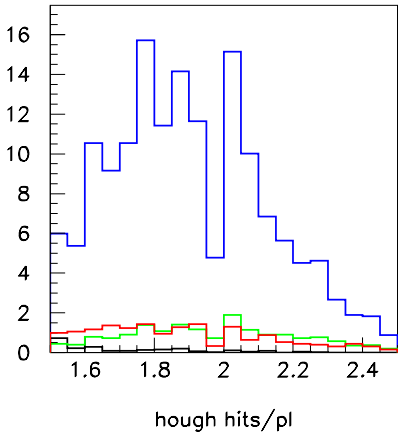


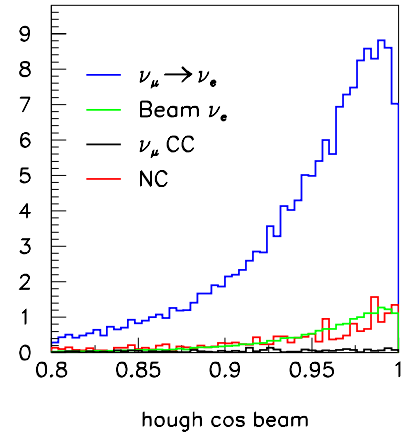




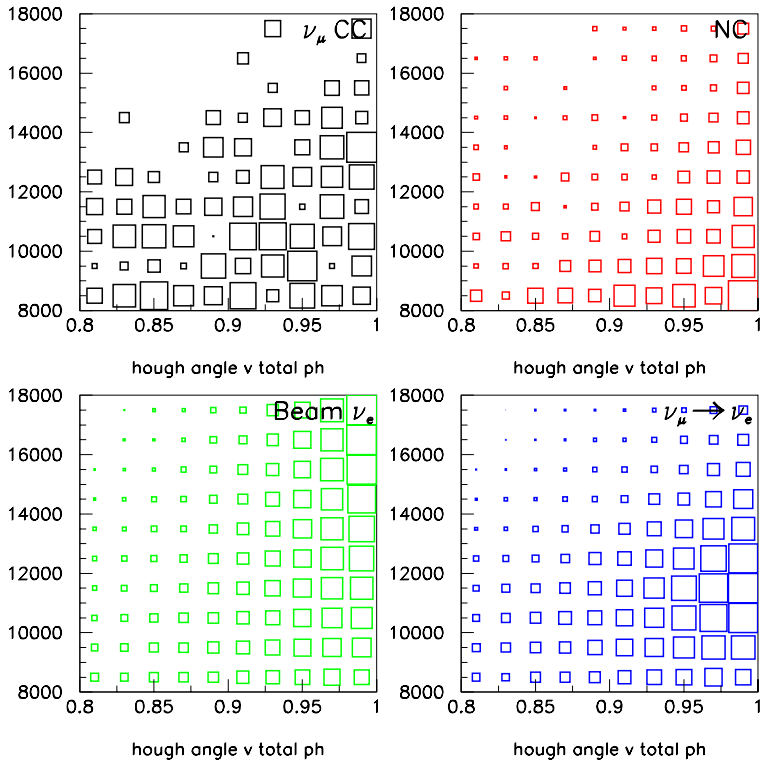




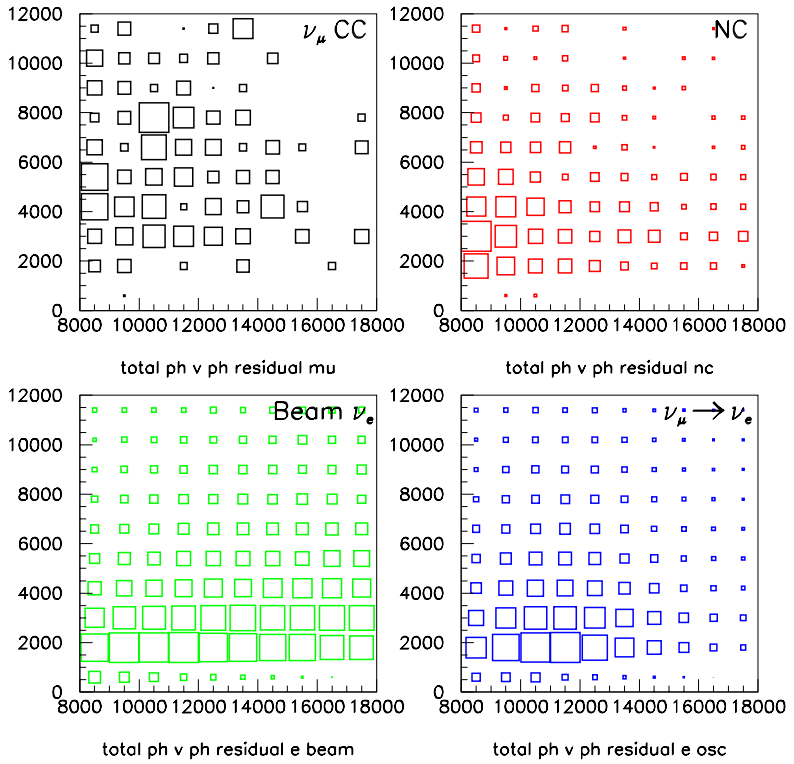




Likelihood pdfs (sample)



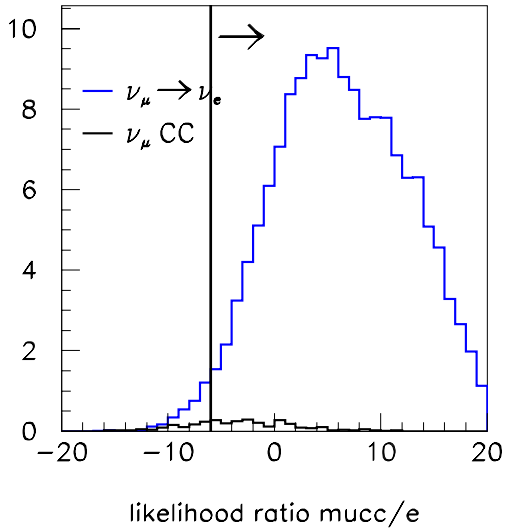
Angle of Hough track to beam versus total pulse height

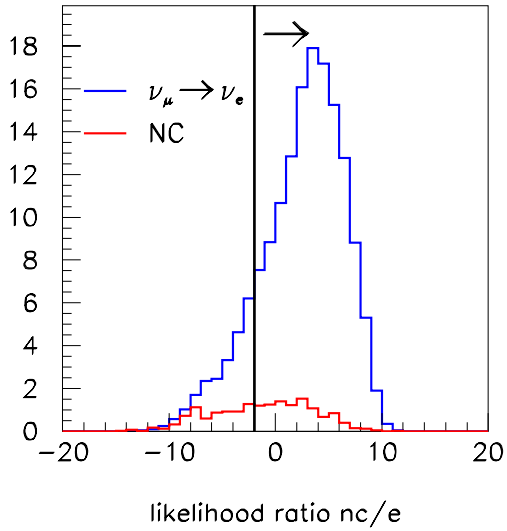


Total pulse height v pulse height weighted residual to fitted line

Likelihood Ratios

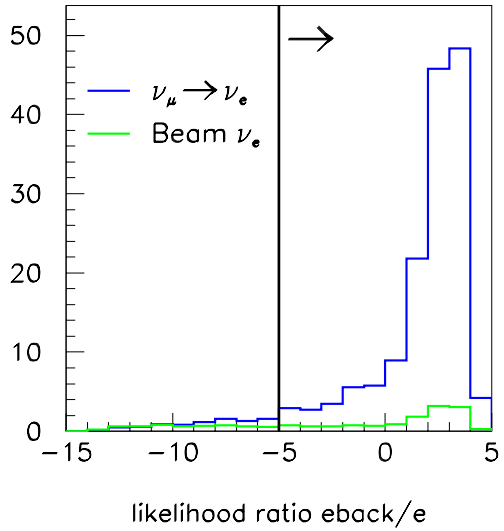
ν_e oscillated versus ν_μ CC





ν_e oscillated versus NC

ν_e oscillated versus ν_e beam



Select as ν_e events those to the right of the cut line in all three plots

Numbers

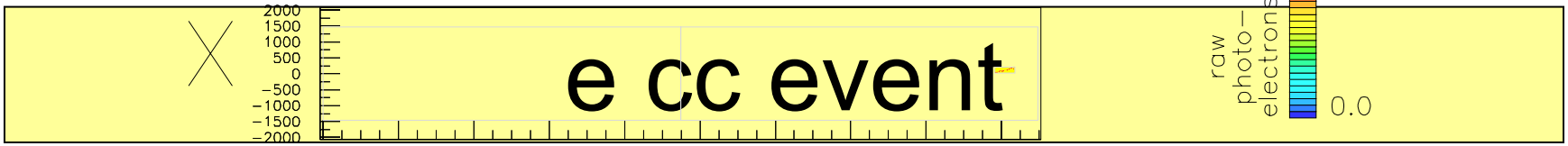
Cut	ν_μ CC	NC	beam ν_e	$\nu_\mu \rightarrow \nu_e$ signal
generated events	474517	461891	488439	
beam weighted	18606	5692	394	
beam weighted +osc	6434	5692	394	603
events with good clusters	6105	3530	344	538
fiducial volume	3937	3216	288	486
event length	776	2155	121	417
total ph	364	549	46.0	334
planes in Hough track	330	425	42.2	312
Hough fraction	31.6	20.0	16.0	141
Hough hits/plane	5.2	15.6	15.6	136
Beam angle	2.6	14.2	15.2	132

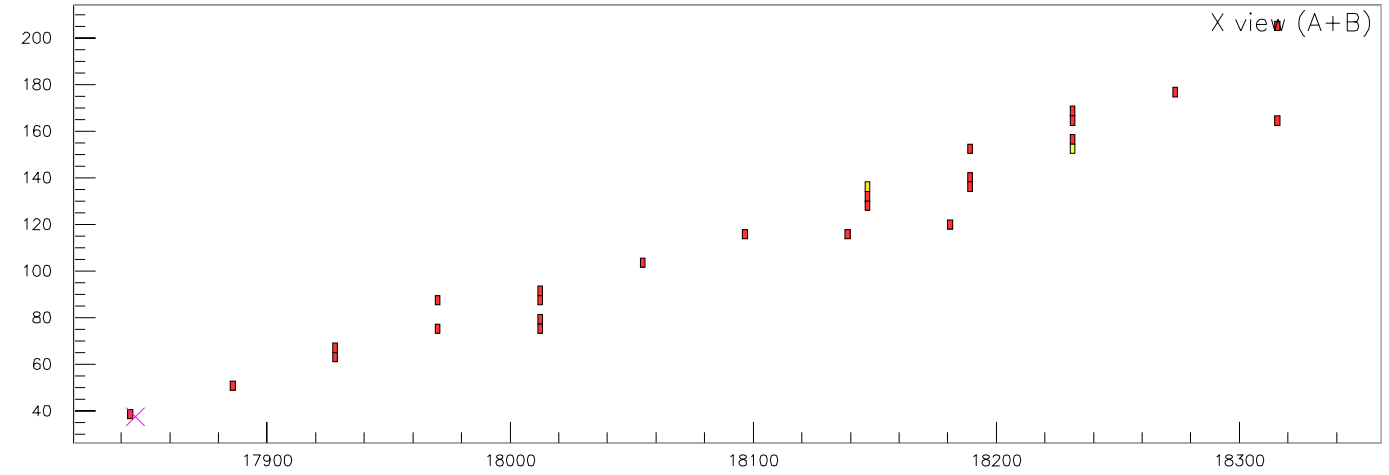
Final likelihood cut	1.1	7.5	9.1	106
Efficiency/rejection	5.9×10^{-5}	1.3×10^{-3}	2.3×10^{-2}	0.18

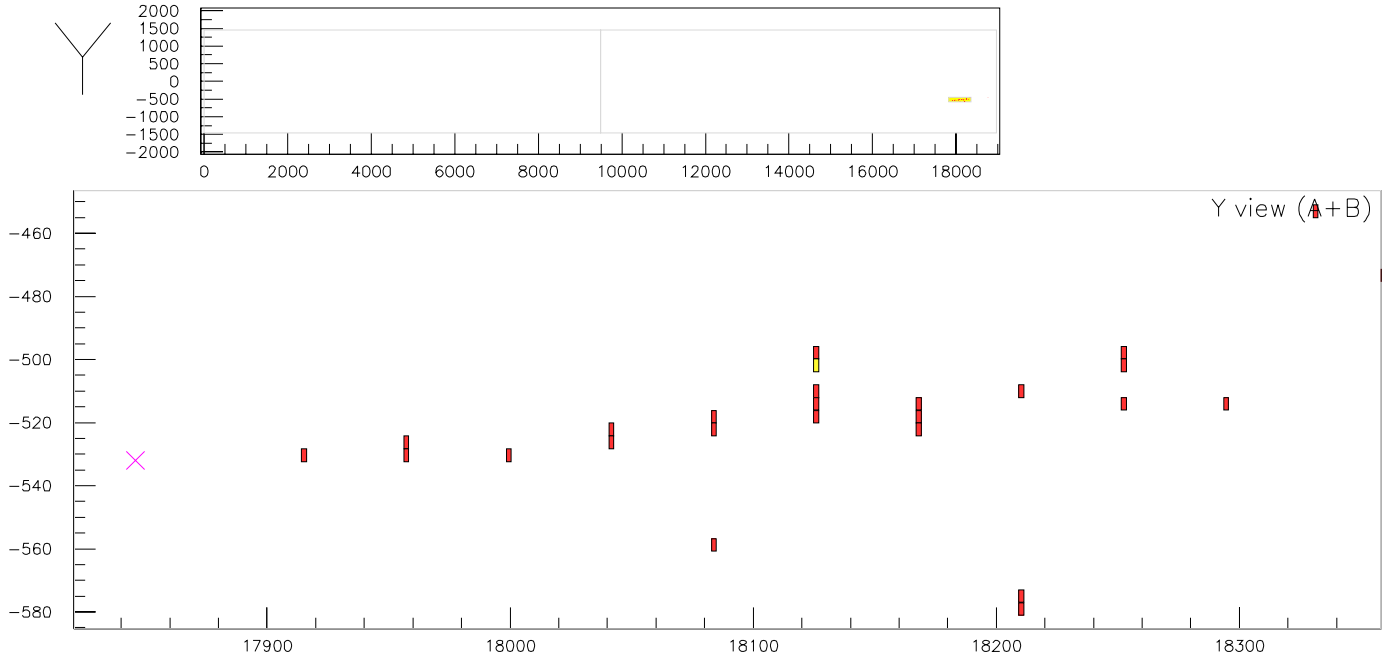
Figure of Merit = Signal/Background = 25.3 0.4

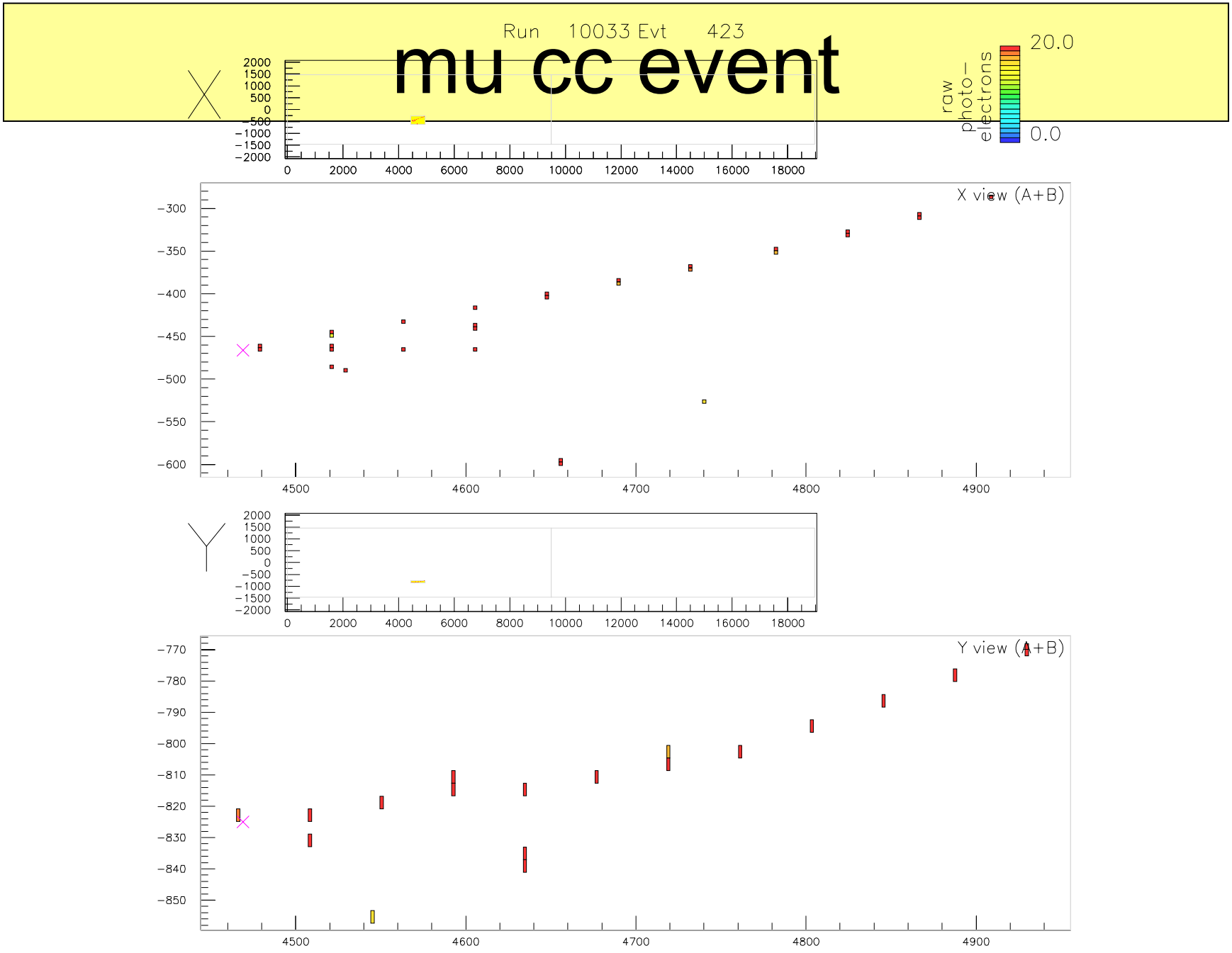
Run 20025 Evt 85

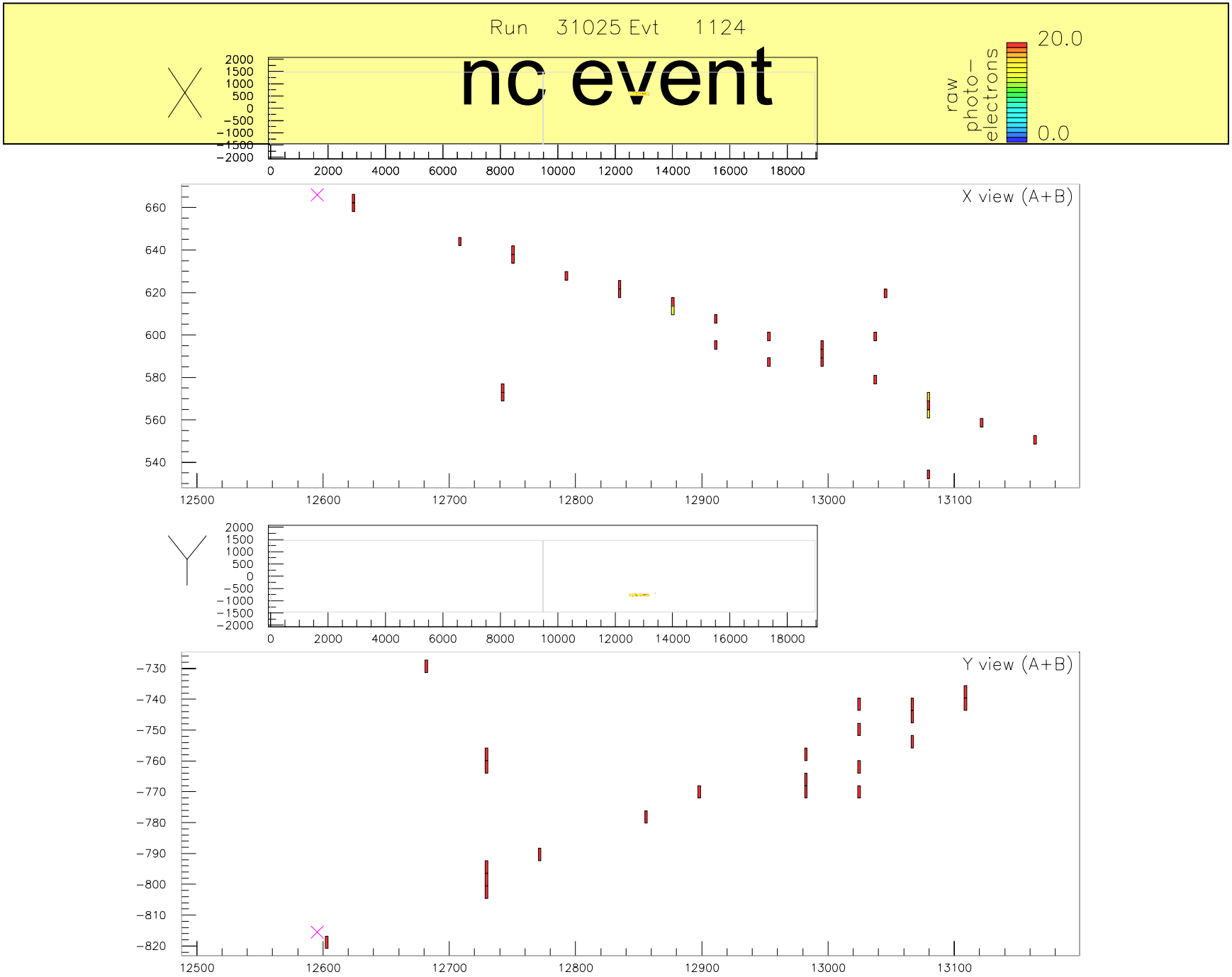
e cc event



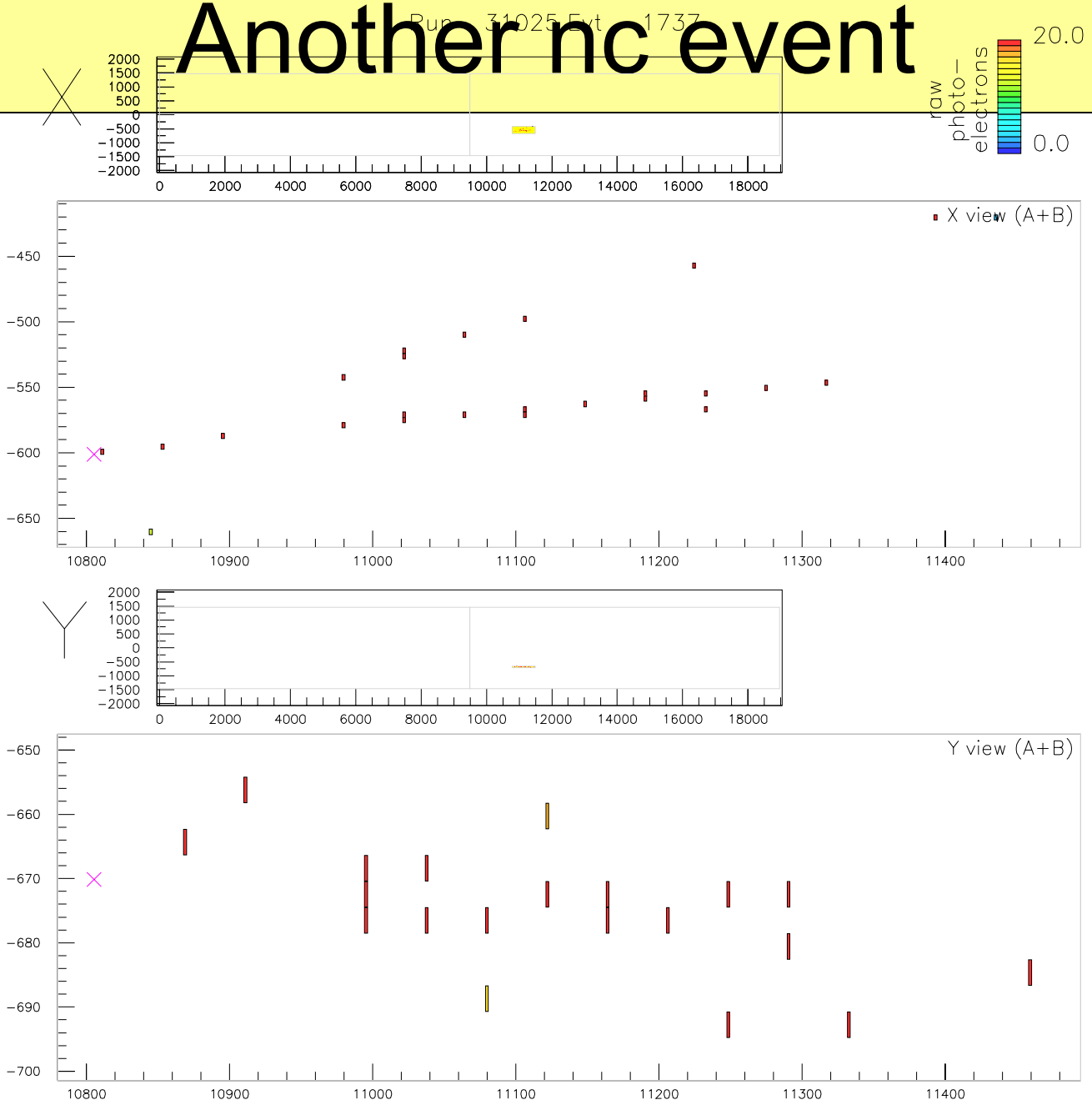





Run 10033 Evt 423
mu cc event
raw photo-electrons
20.0
0.0
X view (A+B)
Y view (A+B)


Run 31025 Evt 1124
nc event
raw photo-electrons
20.0
0.0
X view (A+B)
Y view (A+B)

Another nc event



RPC or Scintillator?

- Simulations in principle can help in the choice of technology
- BUT the simulations need to be comparable in everything but the technology choice.
  - ➔ Not the case at present, the RPC simulation is less complete than the scintillator, we are working towards a true comparison for the proposal.
- An RPC with one dimensional readout is in principle very similar to a scintillator strip with no pulse height measurement, the differences are in the details of the readout.
- RPCs can have two dimensional readout of a single active plane which can help in the pattern recognition and particle counting
- Scintillator strips can measure pulse height which counts minimum ionizing particle equivalents
- Which gives most gain is a detailed problem to which we do not yet have an answer.

Conclusions

- Simulations show that 50kton detector constructed either with RPC or scintillator at this site and with this beam flux will give a very strong signal for $\sin^2 2\eta_{13}=0.1$ and $\Delta m^2=0.0025$ eV^2.
- The current simulations would give a 90% confidence limit just based on statistics of ~1/10th of this value with this detector and beam flux.
- The simulations are far from final, better algorithms may be developed.
- Currently the simulations cannot differentiate between the technologies, more complete and comparable simulations are needed which are being worked on.