Study of isolating and identifying single Neutral Pion Production in MINERvA

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Outline of Talk

- Why Neutral Pion production ?
- Overview of MINERvA
- MINERvA Photomultipliers, Cross-talk studies
- Electromagnetic Shower Filter
- Electromagnetic reconstruction
  - Photon kinematics and energy
  - Pi0 invariant mass and energy

Why neutral pion production?

• One of the largest limitations of accelerator-based neutrino experiments comes from the incomplete experimental knowledge of neutrino cross sections in the GeV energy range.

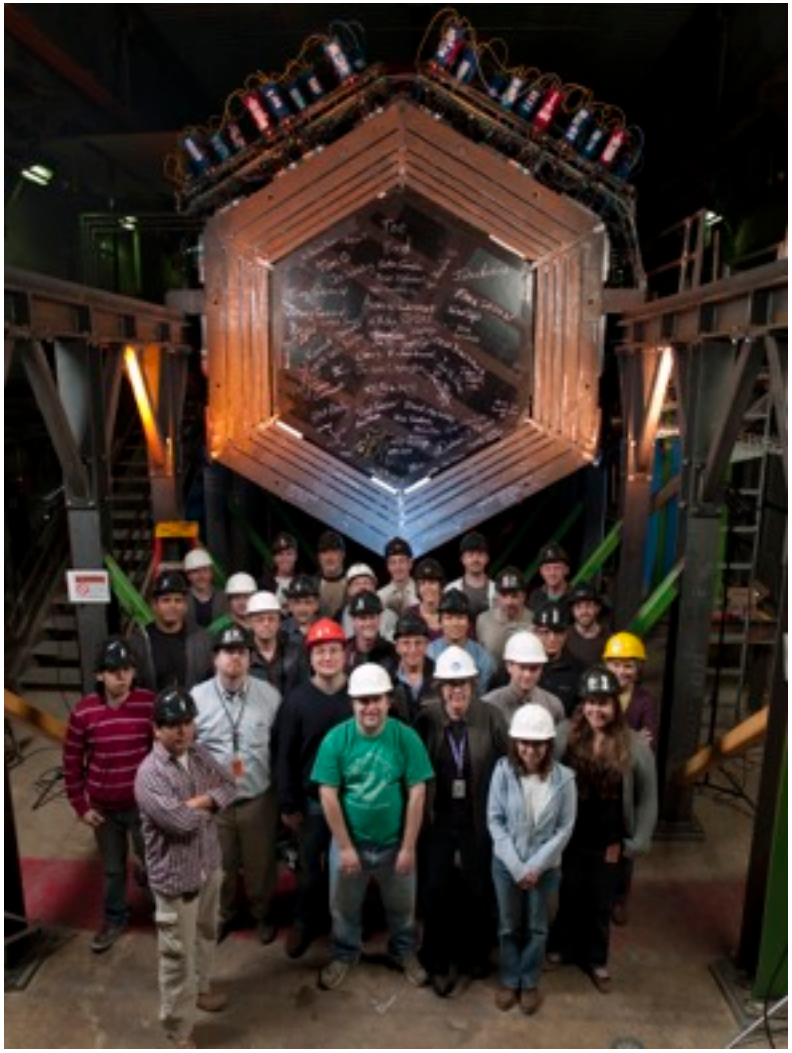
• Concerning about muon neutrinos oscillating into electron neutrinos, one of the main backgrounds to the electron neutrino signal(low probability) comes from neutral current interactions producing neutral pions.

• Experimental input on the rate of the related charged-current (CC) channel, and measurement of the neutral pion production momentum spectrum, allows better understanding of this background.

What is MINERvA?

Main INjector ExpeRiment v-A

- MINERvA is a high resolution neutrino cross section experiment in the Fermilab NuMI beamline upstream of the MINOS near detector.
- Goal is to measure exclusive and inclusive neutrino cross sections in the energy range of 1-20 GeV with greatly improved precision, and on several nuclei.
- Has a fully active core of scintillator used as both target and for tracking
- Targets of scintillator (C-H), He, C, water, Fe, and Pb



NuMI Beamline

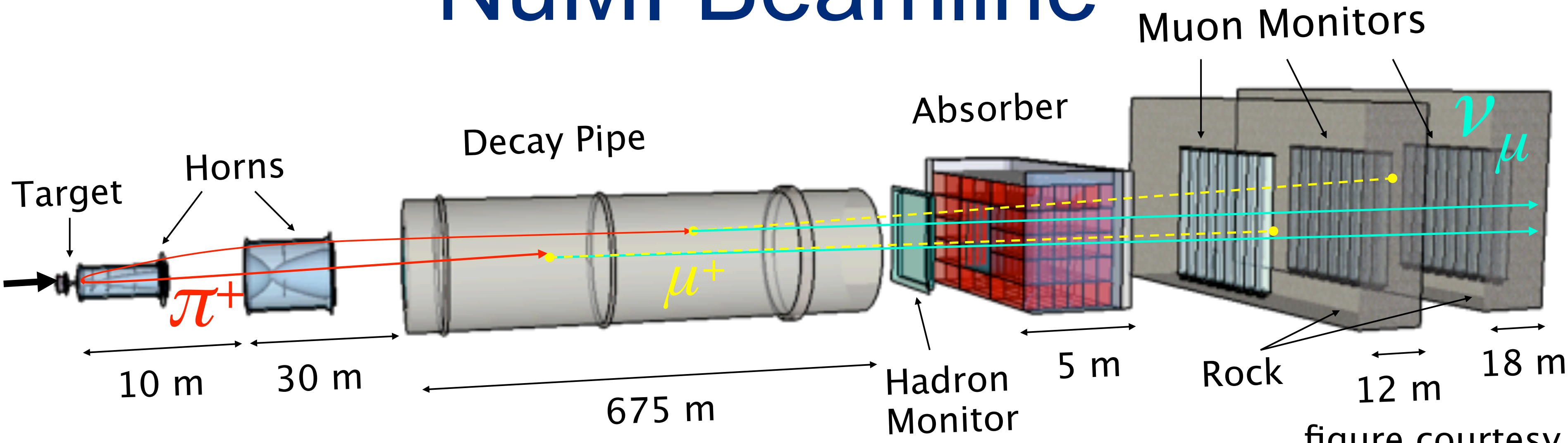
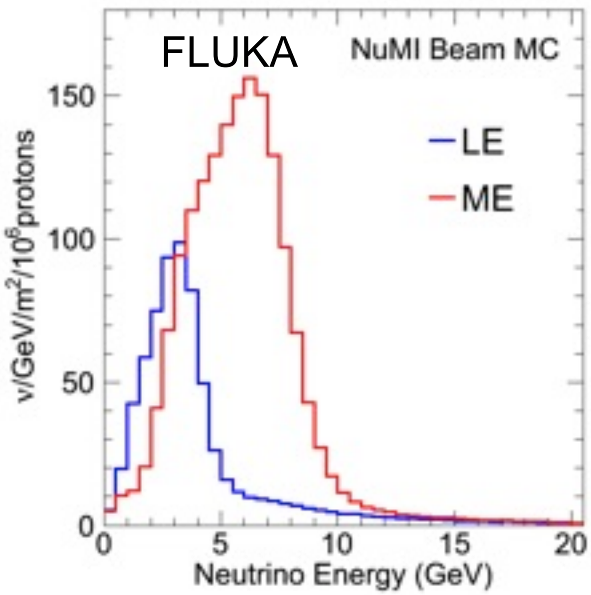
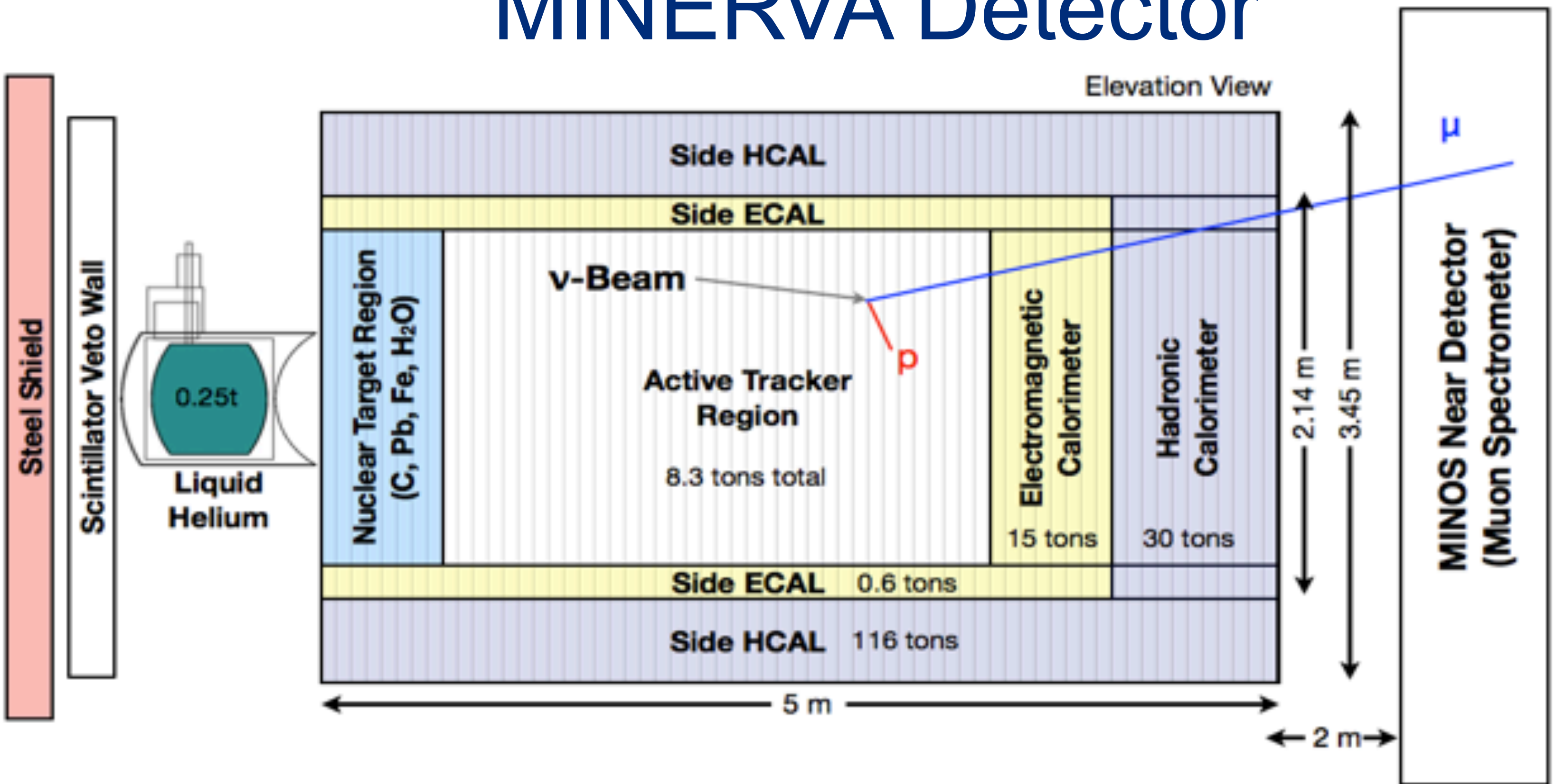


figure courtesy Ž. Pavlović

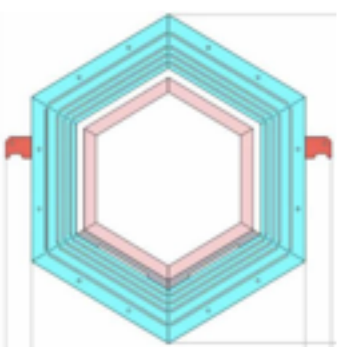


- 120 GeV P Beam → C target → $\pi^{+\,-}$ & $K^{+\,-}$
- Have roughly 35×10^{12} protons on target (POT) per spill at 120 GeV with a beam power of 300–350 kW at ~0.5 Hz
- 2 horns focus π^+ and K^+ only
- Mean E_ν increased by moving target and one horn
- π^+ and $K^+ \rightarrow \mu^+\nu_\mu$
- Absorber stops hadrons not μ
- μ absorbed by rock, $\nu \rightarrow$ detector
- Approved (for Physics) (4.9×10^{20} POT LE beam and run in ME beam along with Nova)

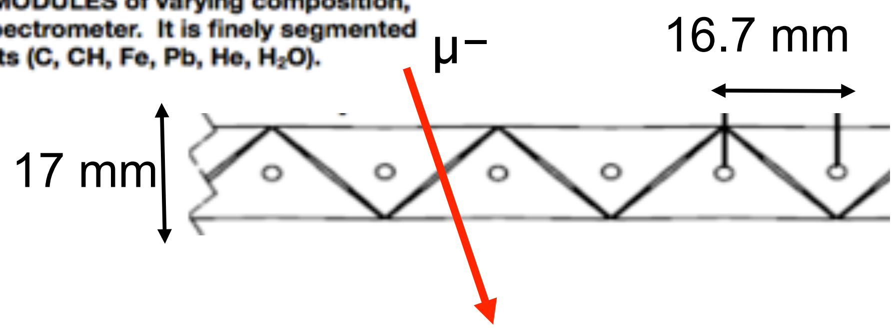
MINERvA Detector



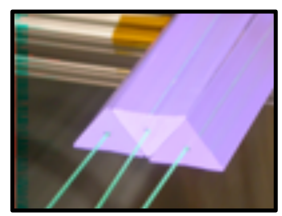
The MINERvA detector is comprised of a stack of MODULES of varying composition, with the MINOS Near Detector acting as a muon spectrometer. It is finely segmented (~32 k channels) with multiple nuclear targets (C, CH, Fe, Pb, He, H_2O).



127 scintillator strips per plane.



Tracker module = 2 planes
ECAL module = 2 planes + 2 (2 mm thick) sheet of lead
HCAL module = 1 plane + 1 (1 inch thick) sheet of steel



Triangular strip to allow charge sharing

The detector (nuclear targets)

- 5 nuclear targets + water target interspersed in target region with tracking modules between
- Helium target upstream of detector

Target	Fiducial Mass	ν_μ CC Events in 4e20 P.O.T.
Plastic	6.43 tons	1.36M
Helium	0.25 tons	56.0k
Carbon	0.17 tons	36.0k
Water	0.39 tons	81.3k
Iron	0.97 tons	215k
Lead	0.98 tons	228k

- NUGEN MC ν
- not acceptance corrected
- inside fiducial volume

He target

Water target

Iron/Lead

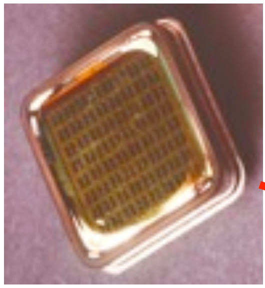
Lead

Lead/Iron/Graphite

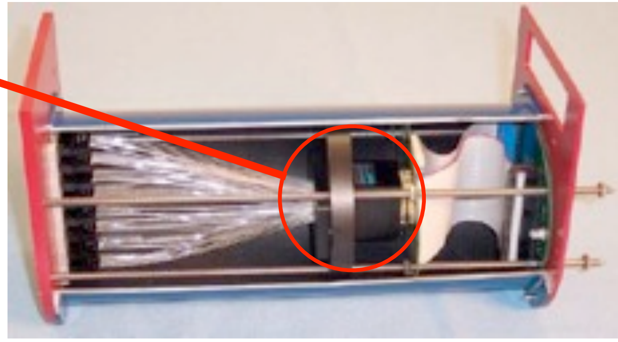
Lead/Iron

Iron/Lead

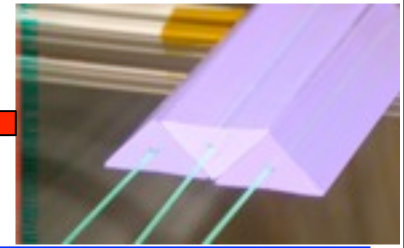
Optics and Electronics



Hamamtsu MA-64 PMTs

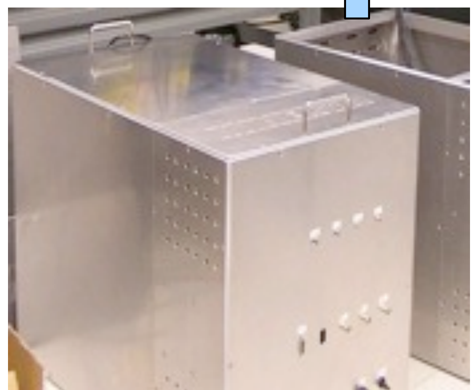


PMT Box (~ 500)



Extruded scintillator with
WLS fiber (30K channels)
2.5 mm pos. resol.

Front end board (FEB) with Trip-t
chips interface the PMTs(~500)



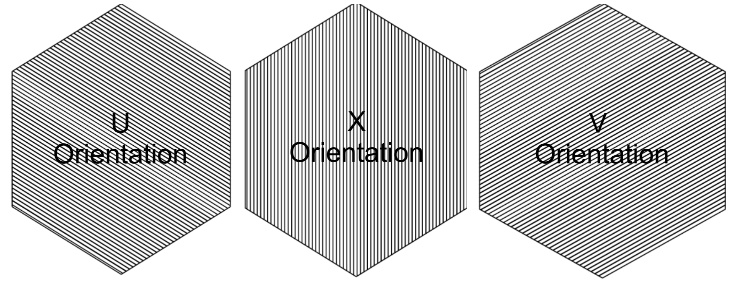
LI system
(dead channels, PMT
gain measurement)

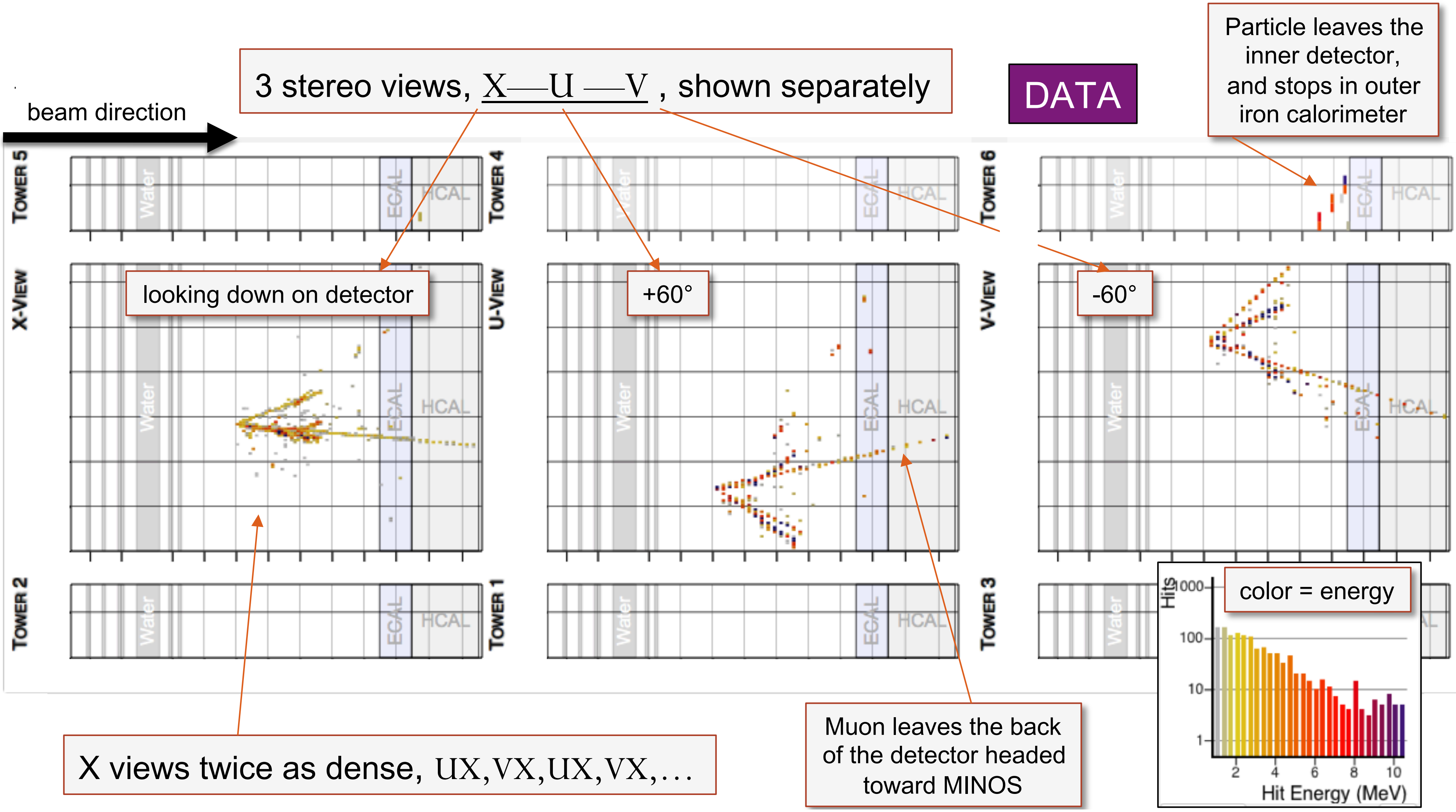
CROC/VME readout, Total of 12

DAQ Computer

Minerva Control Room

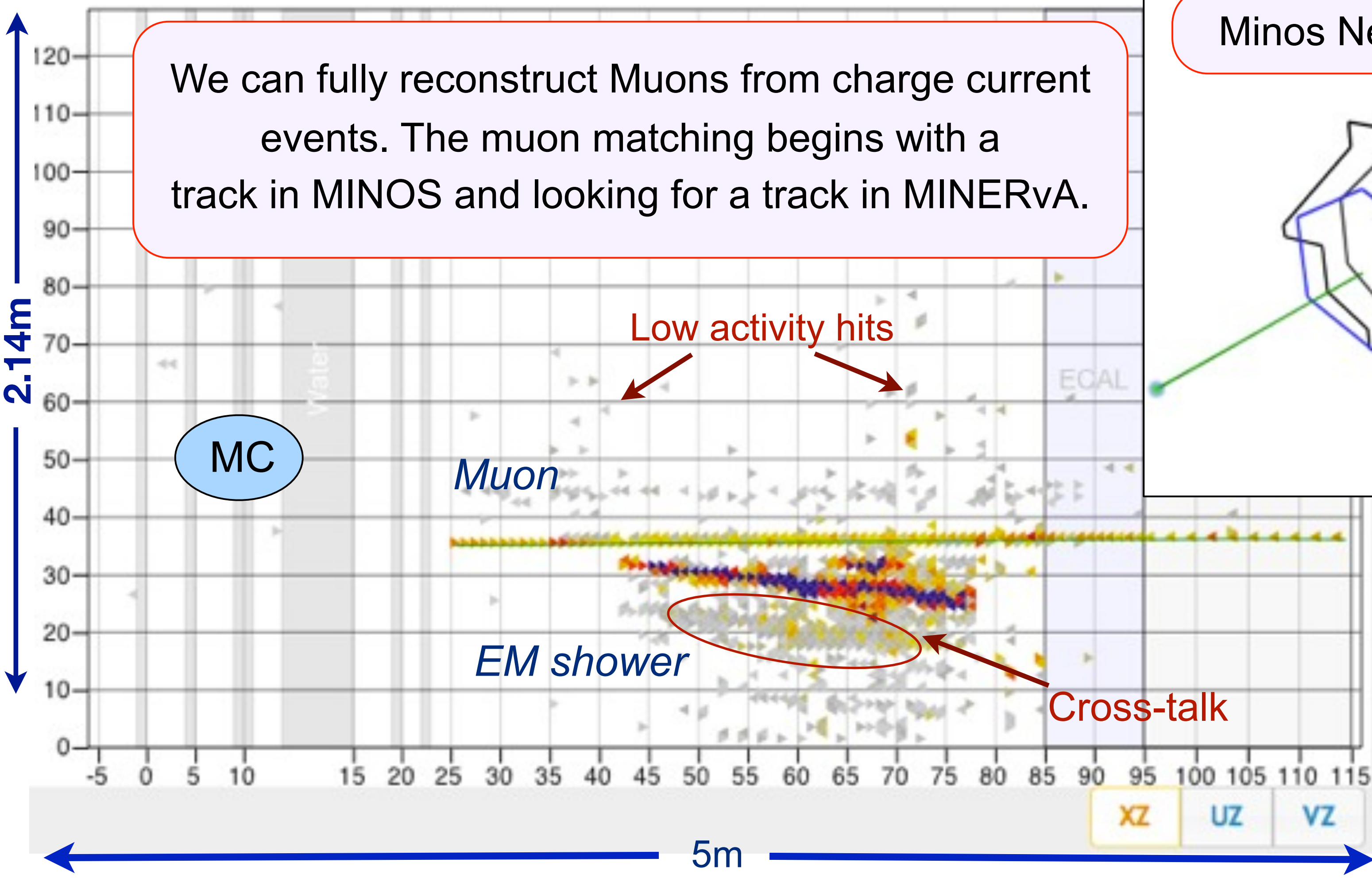
Events in MINERvA

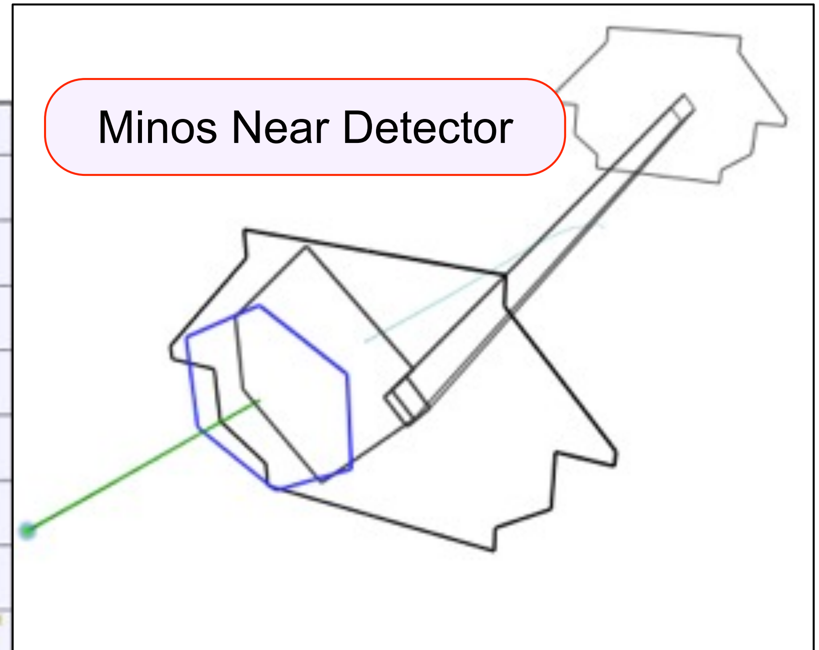




Events in MINERvA

We can fully reconstruct Muons from charge current events. The muon matching begins with a track in MINOS and looking for a track in MINERvA.





Muon going to Minos Near Detector

The cross-talk was a problem to reconstruct events in MINERvA, let me show you how I studied it.

Photomultiplier studies

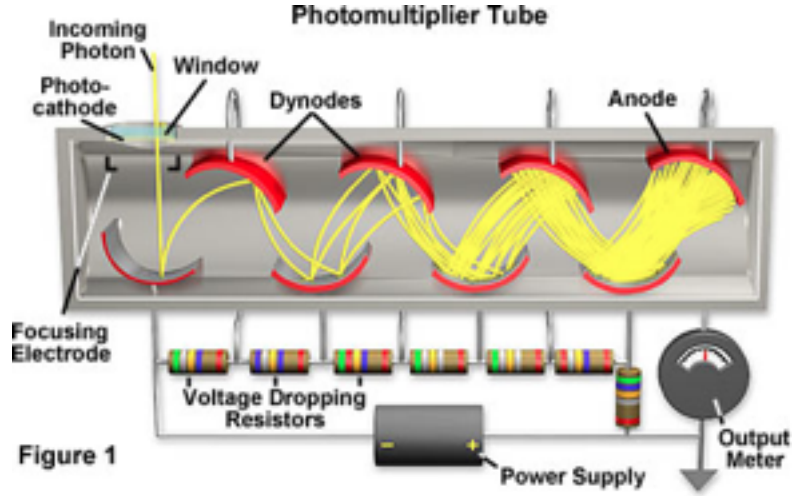


Figure 1

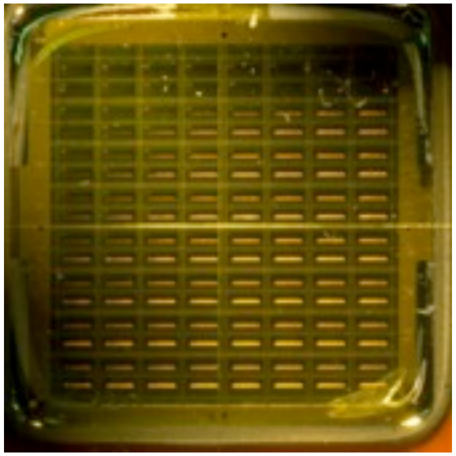
MINERvA Photomultipliers

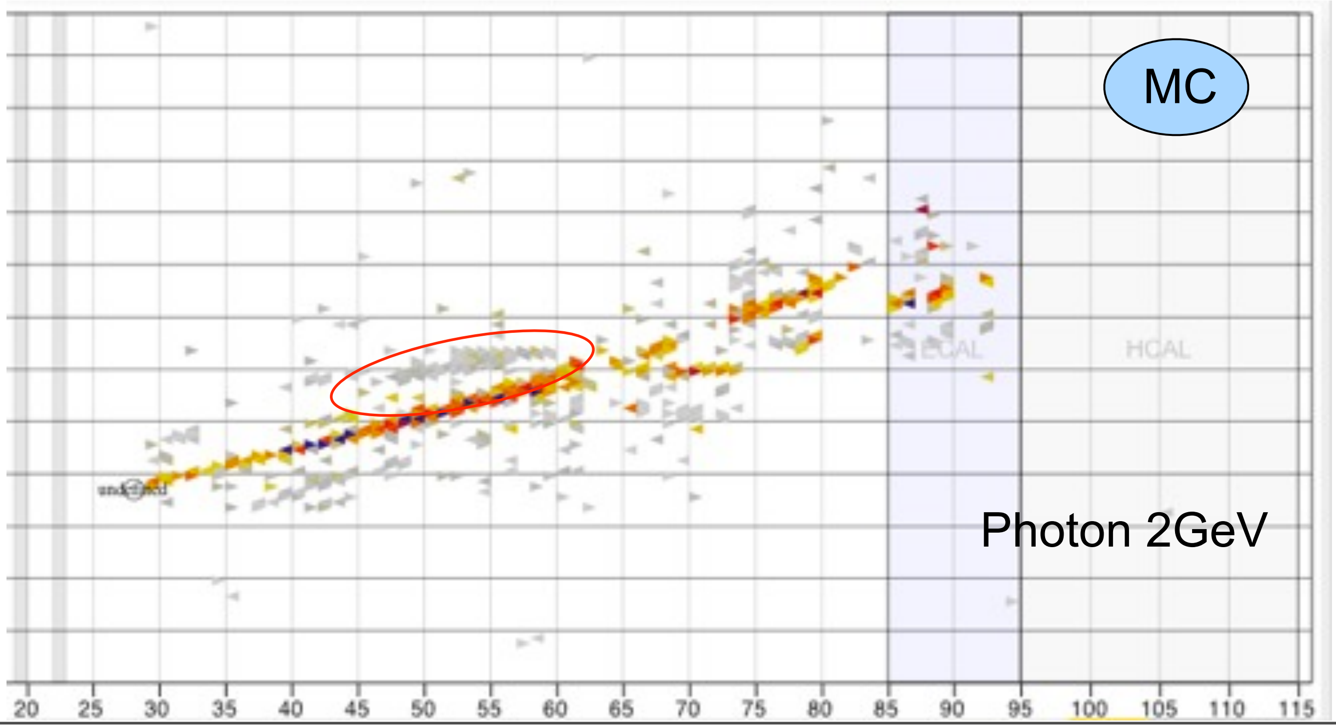
The detector contains ~30K channels and in order to build a not complicated detector, photomultipliers should be small with many pixels(64 anodes). Small region means interference between anodes(Cross-talk).

Cross-talk: Ratio of signals on the sum of neighboring pixels to flashed pixel signal, when a single pixel is flashed with light.

Cross-Talk can be a problem, when we need to reconstruct the events.

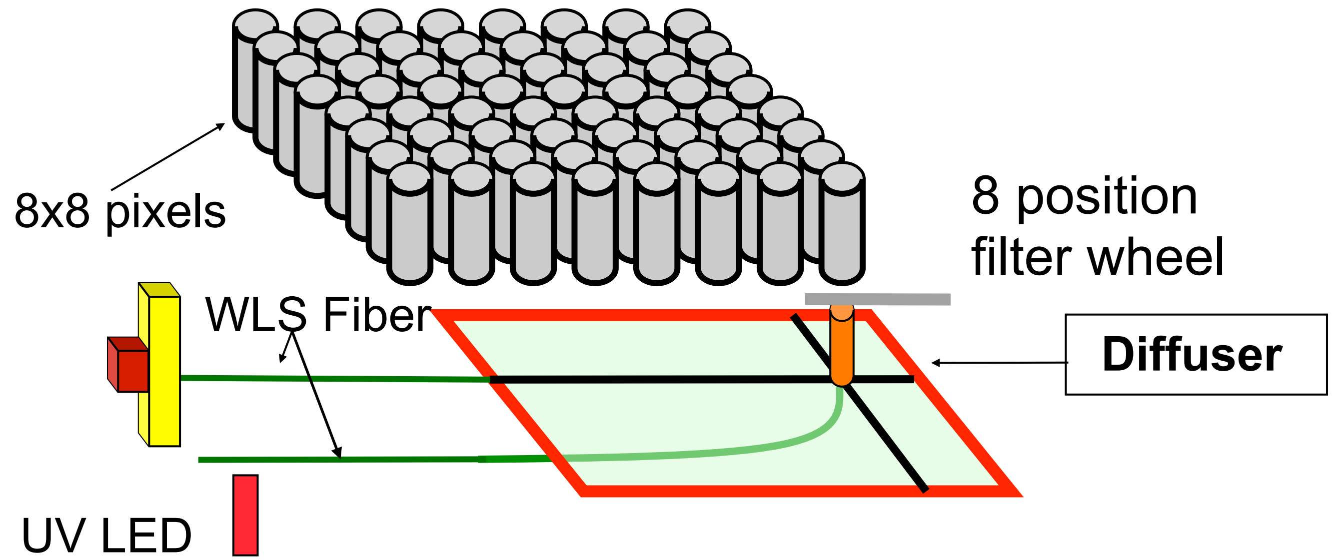
Photomultiplier Face





PMT Cross Talk Calculations

Rutgers Test Stand:
6 PMTs illuminated at once. One "witness" PMT



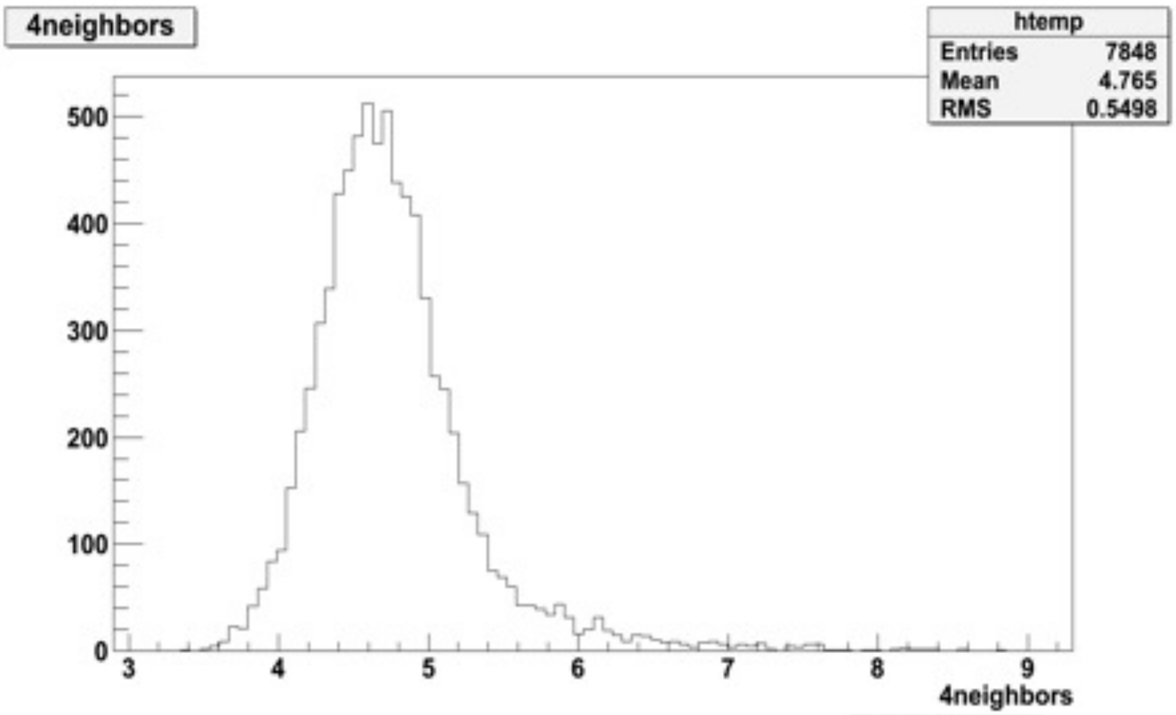
We calculated the PMT cross talk values using two different Test Stands at Rutgers and Fermilab in order to check the values after and before the PMT Box assembly. The following results come from the Rutgers Test Stand.

To perform these studies we need to use the charge distributions. We followed these expressions to convert from ADC distributions to charge distributions using Front End Board calibrations.

- Histo_qdark(entry) = *F*(qhi.ADC(entry) – qhi.PedestalMean).
- Histo_qflash(entry)=*F*(qlo.ADC(entry) – qlo.PedestalMean).
- XT(flash->dark)=100*q(dark)/q(flashed)
- *F* is the FEB calibration to convert ADC to charge.

PMT Cross Talk

Before



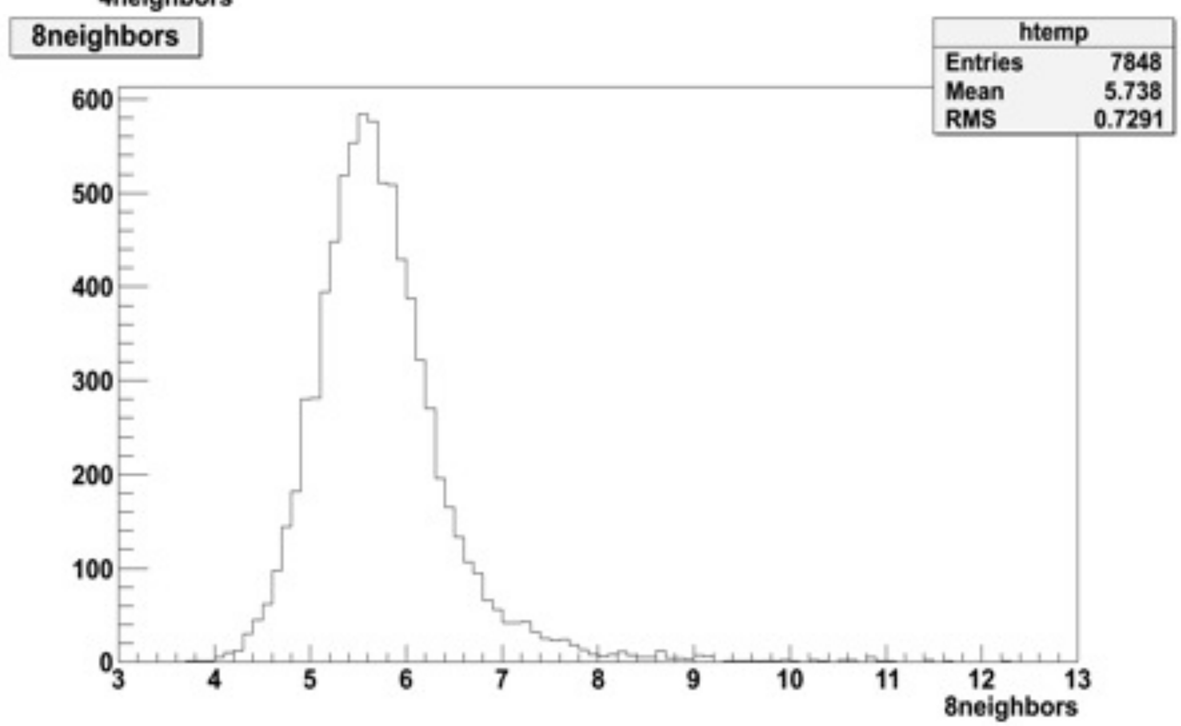
MINERνA XT 4 neigh. 4.8%
MINERνA XT 8 neigh. 5.7%

MINOS XT 4 neigh. 3.8%
MINOS XT 8 neigh. 4.7%

Front End Board contribution to the cross talk is about 1%

Every entry is the XT calculated per pixel flashed, we are only showing results from 36 pixels per PMT.

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56
57	58	59	60	61	62	63	64

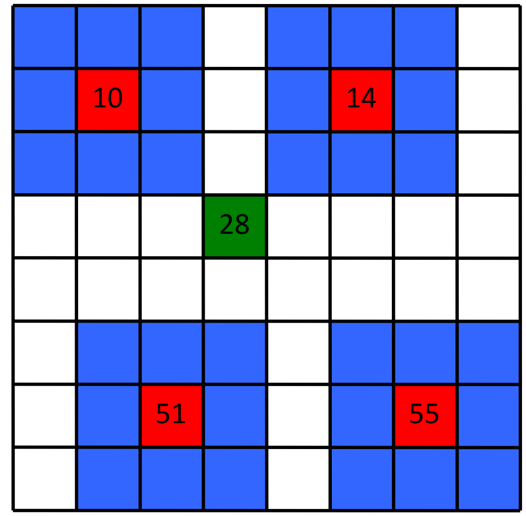


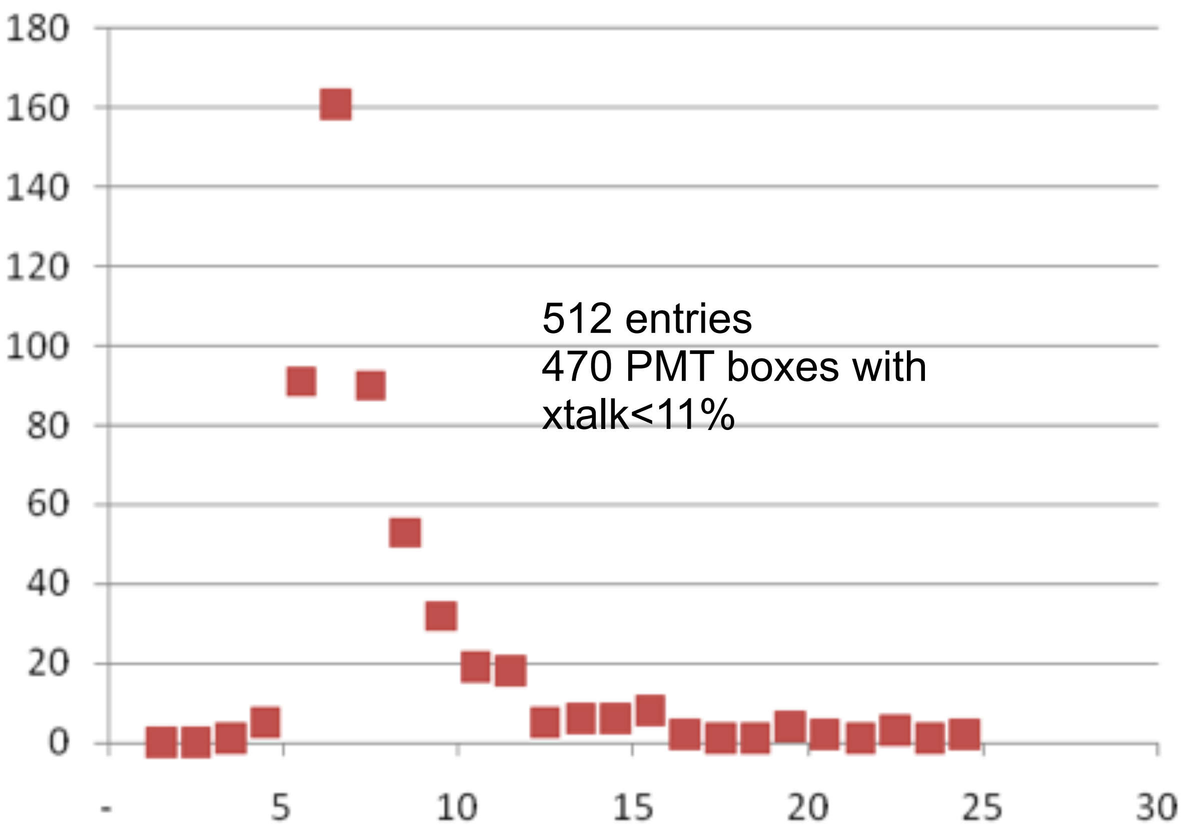
64 pixels xt calculation has been done.

PMT Cross Talk

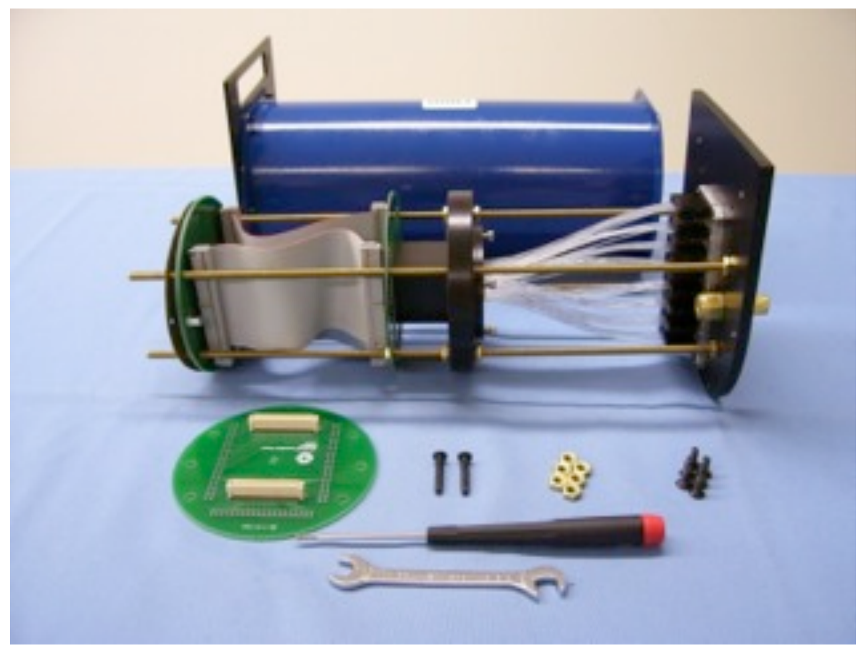
After

With the Fermilab Test Stand, we illuminate 4 pixels in this study, and we require less than 11% cross talk on boxes to be installed.

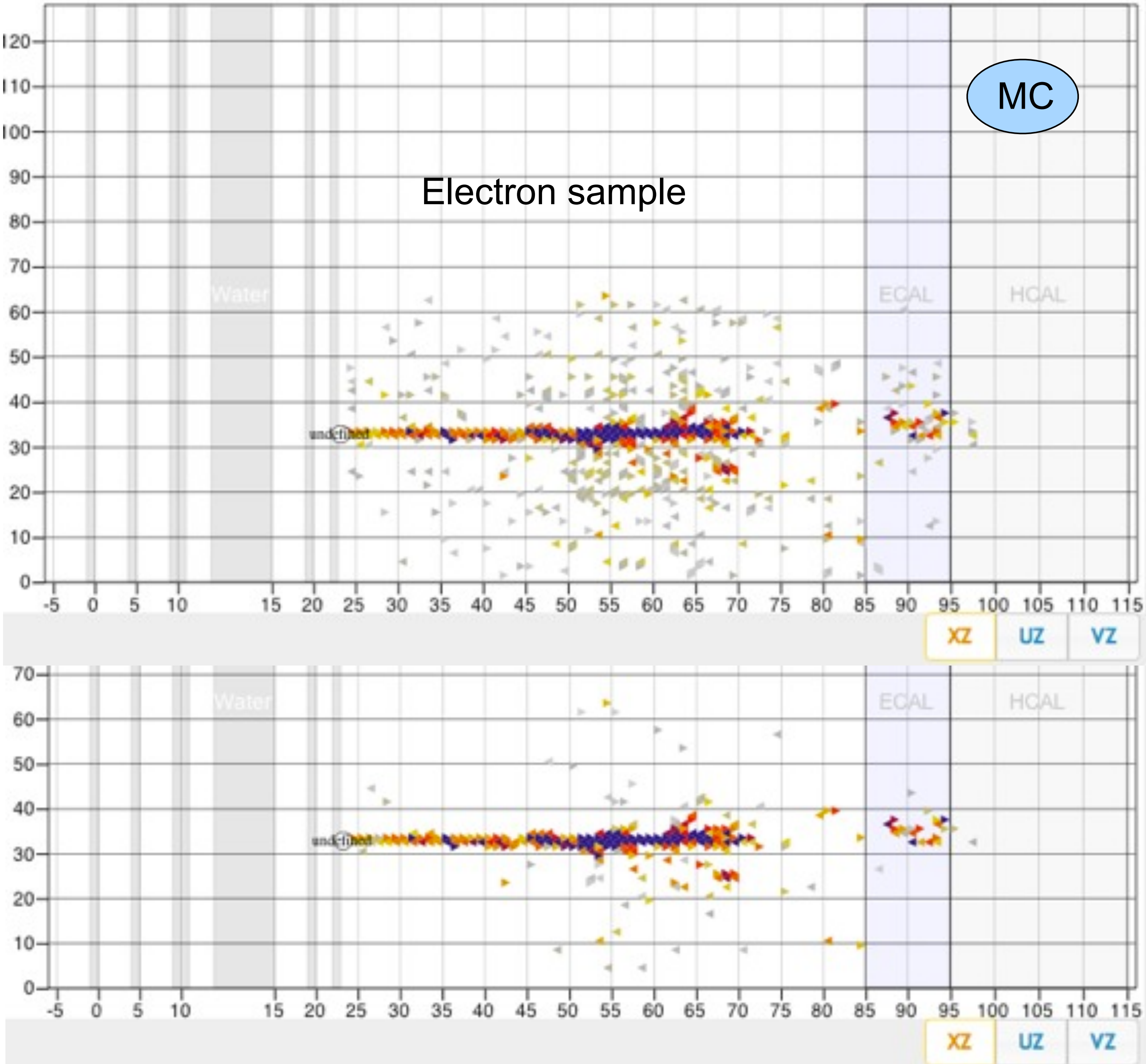




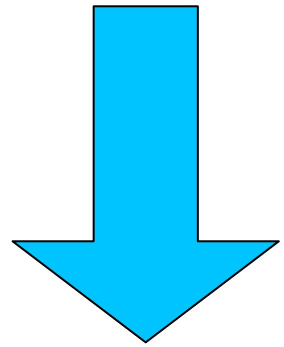
xtalk distribution



PMT Cross Talk

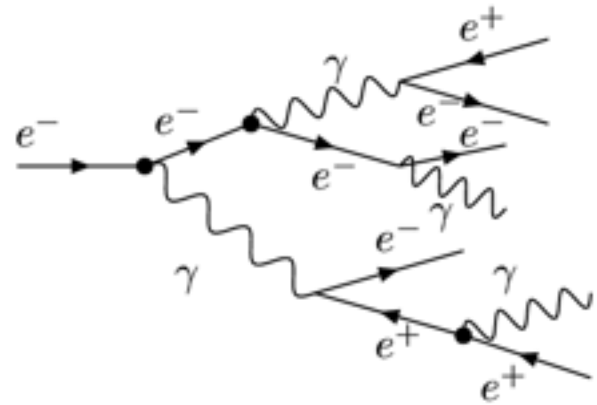


Remove cross-talk



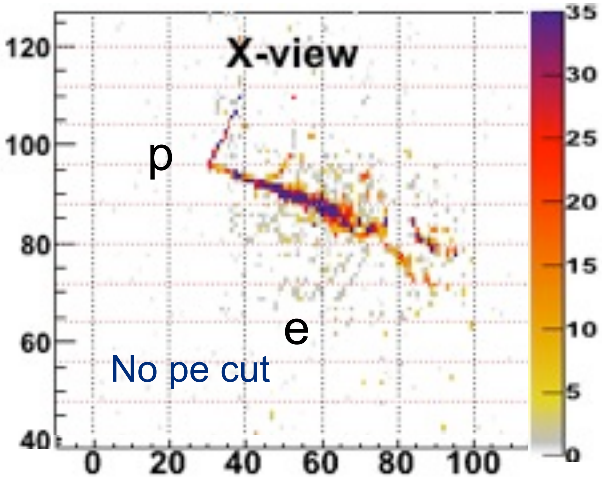
Sample will be clean to reconstruction. Let's find showers

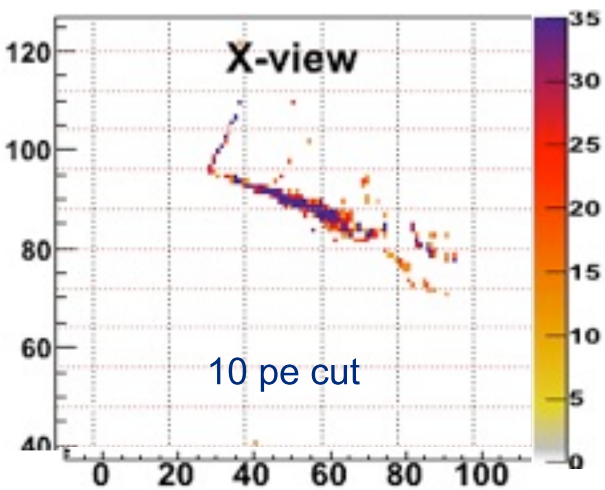
Electromagnetic Shower - Filter



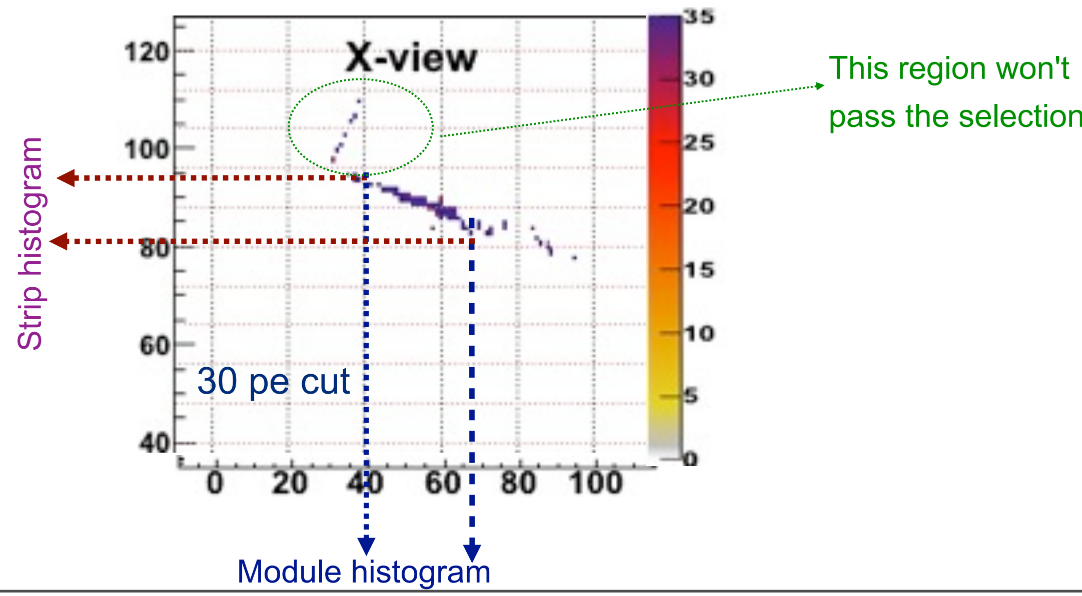
Electromagnetic Shower Filter

v QE candidate

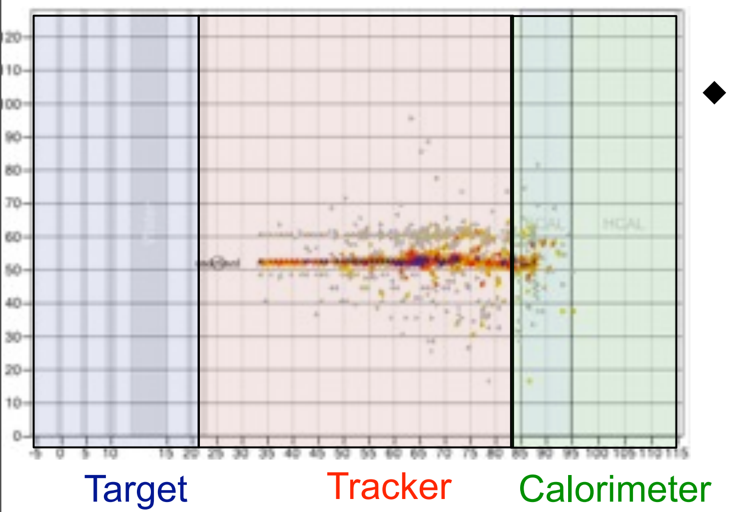




- I started using an event sample with obvious shower topologies (no tracks) selected by “hand scan”. Then I applied an appropriate energy cut to isolate the main core of the shower.
- The shower core was projected into Module and Strip histograms, the distributions in these histograms had to pass RMS threshold and minimum number of entries requirements.



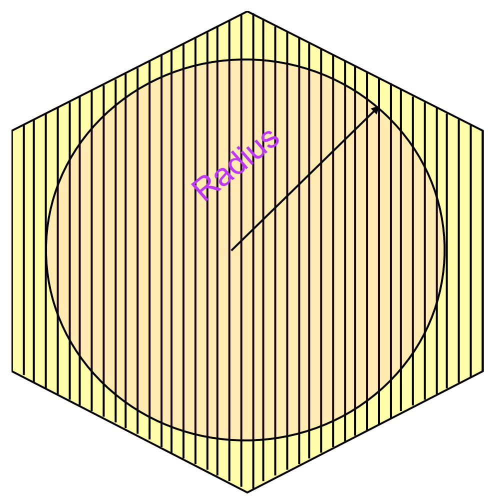
Shower Filter



- I took a sample for efficiency studies:
  - MC Low Energy mode (ν_u and ν_e) ~ 100K events.
- Additional cuts:
  - Incoming neutrino energy 1 – 20GeV.
  - Vertex Z position inside the Tracker Region.
  - Transversal vertex position has to be inside circular region (Radius = 800mm).

Potential Candidates (e^-'s,γ's, π^0's).

Main Candidates (e^-'s > 1 GeV, γ's > 1GeV and π^0's > 1.5GeV).



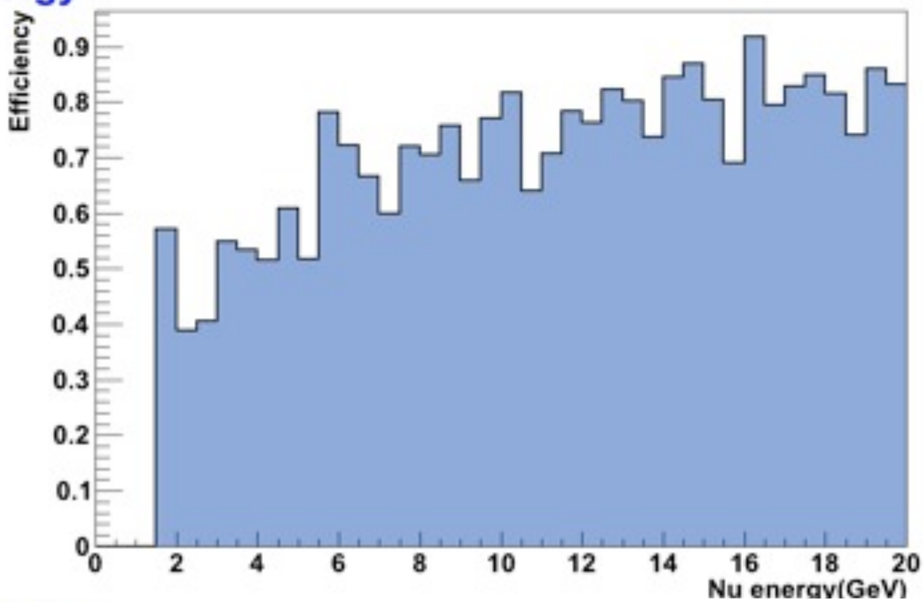
$$\text{Efficiency} = \frac{\text{\#Main Candidates (pass filter)}}{\text{\#Main Candidates}}$$

$$\text{Purity} = \frac{\textit{\#Potential Candidates(pass filter)}}{\textit{\#Events(pass filter)}}$$

Shower Filter - Efficiency

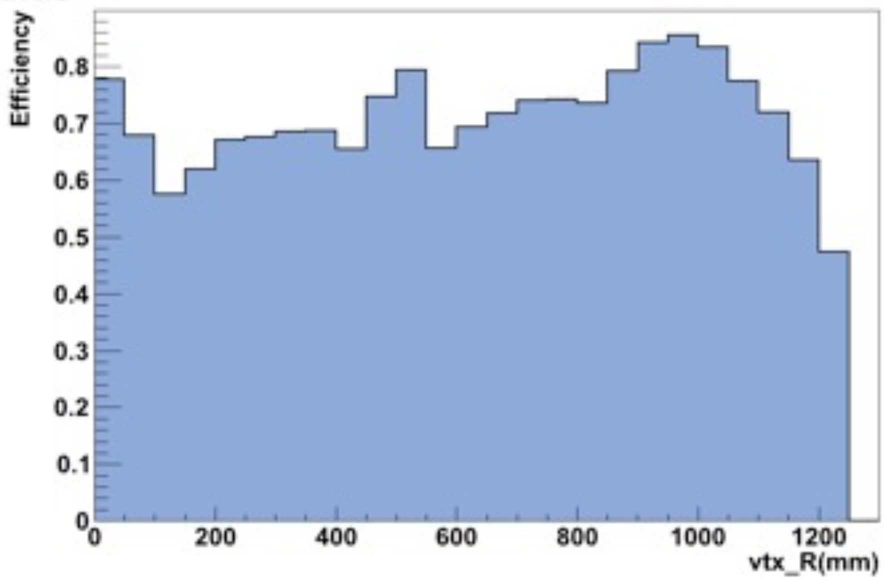
MC

Energy

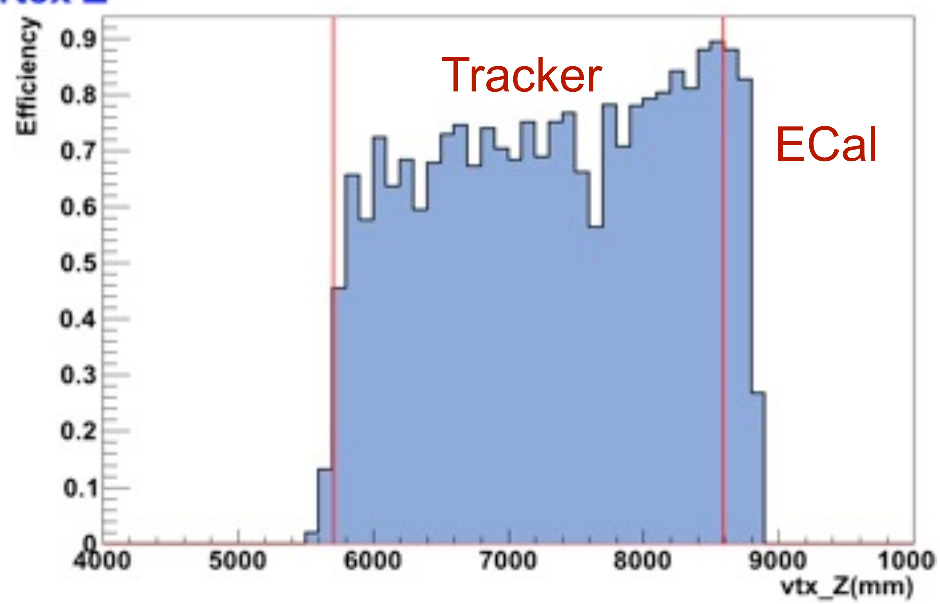


Purity is ~88%, most of the remaining 12% are coming from DIS channel.

Radius



Vertex Z

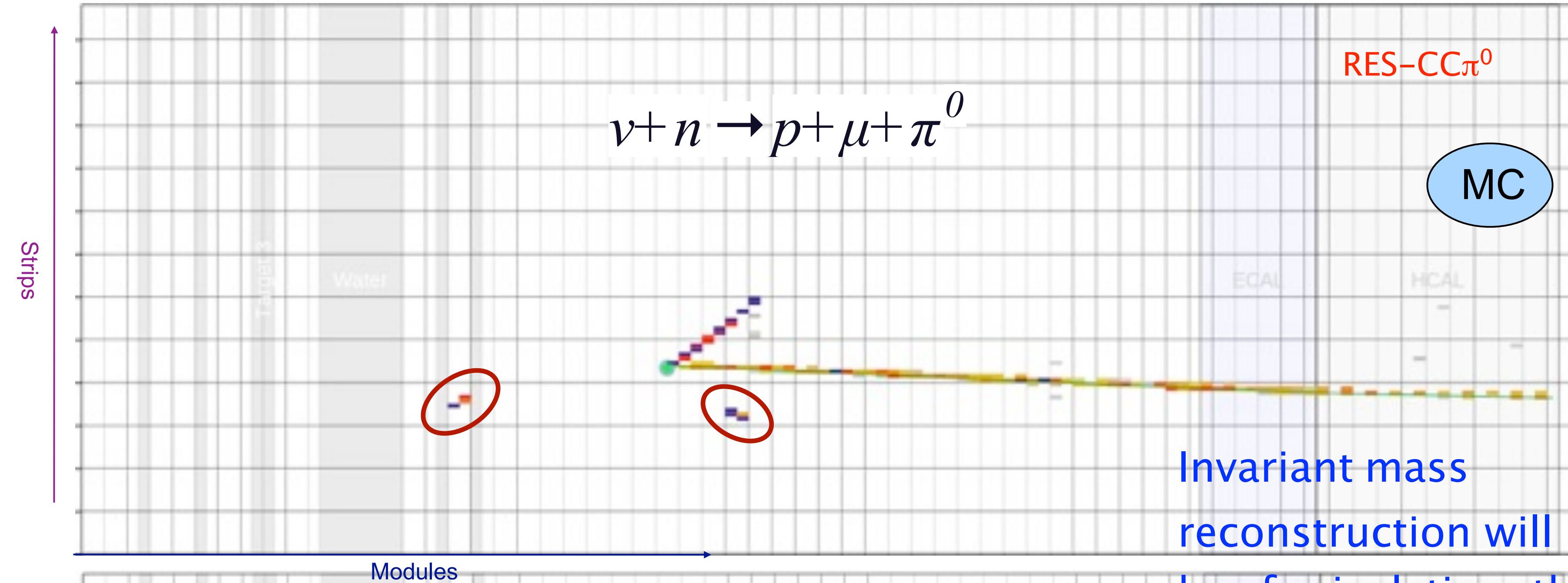


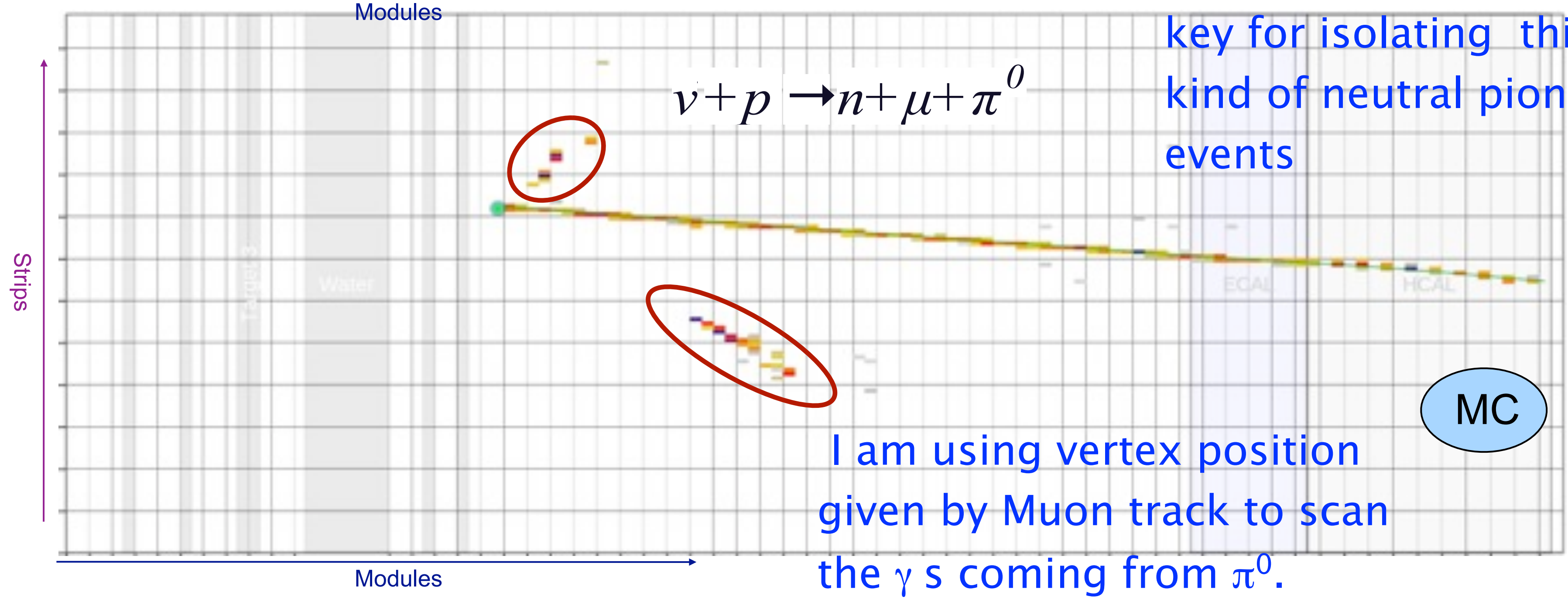
We can find electromagnetic showers, but we still need to isolate and reconstruct them

**Blob: spatially continuous regions of hits*

Blob reconstruction

Motivation

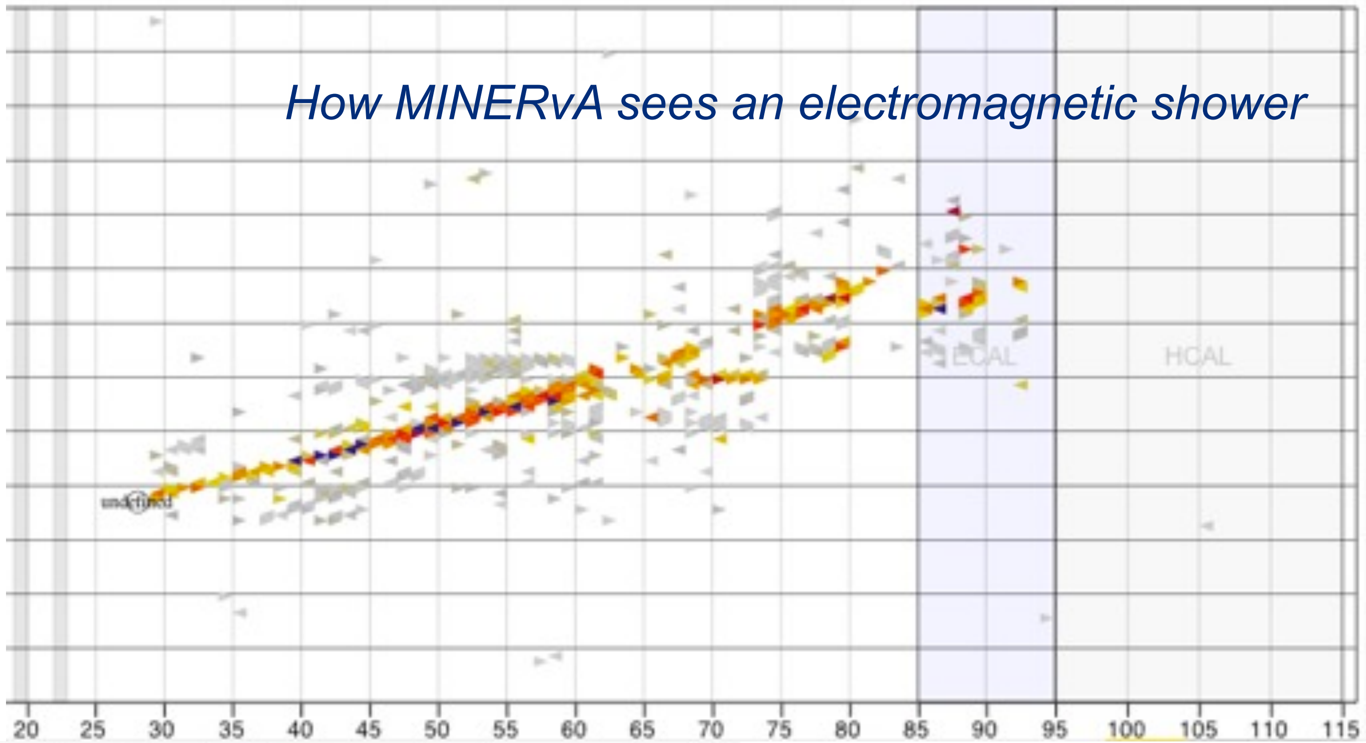


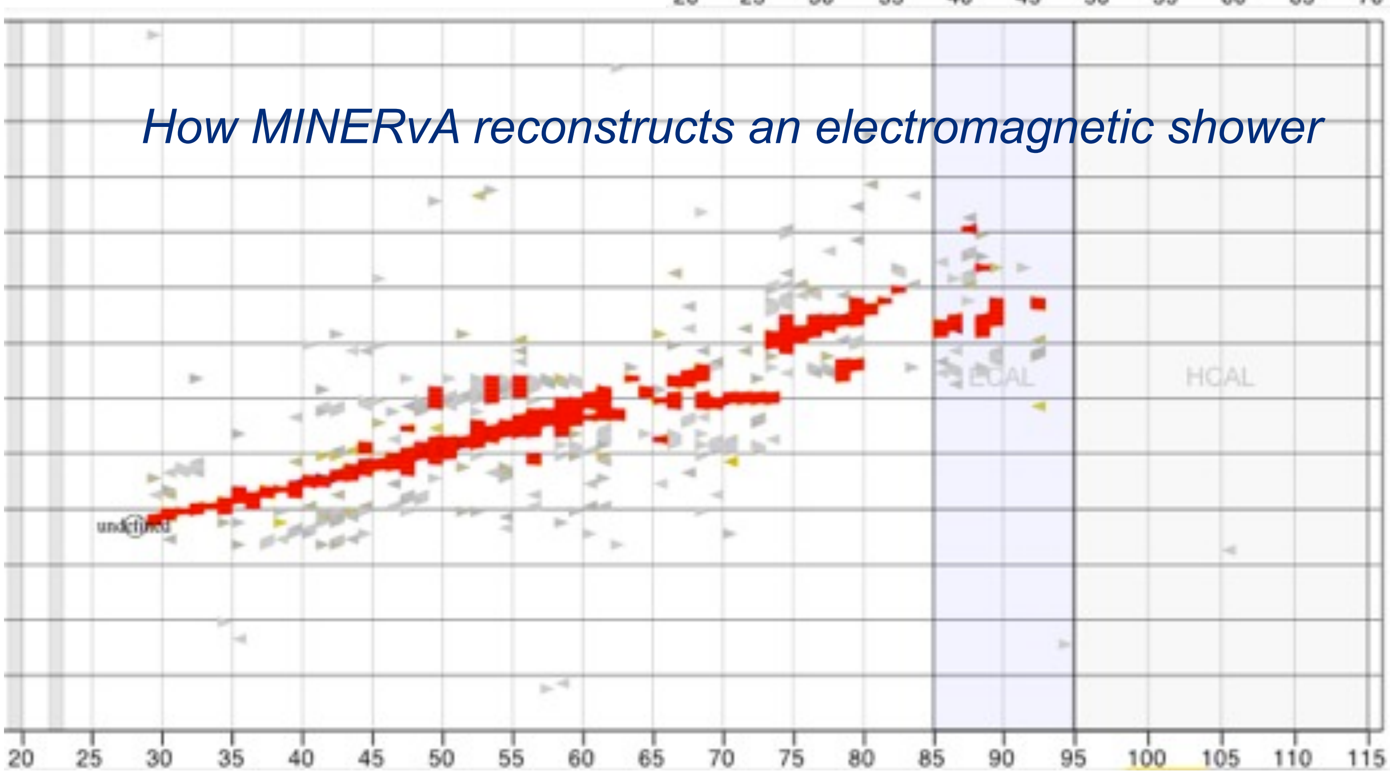


Invariant mass reconstruction will be key for isolating this kind of neutral pion events

I am using vertex position given by Muon track to scan the γ s coming from π^0.

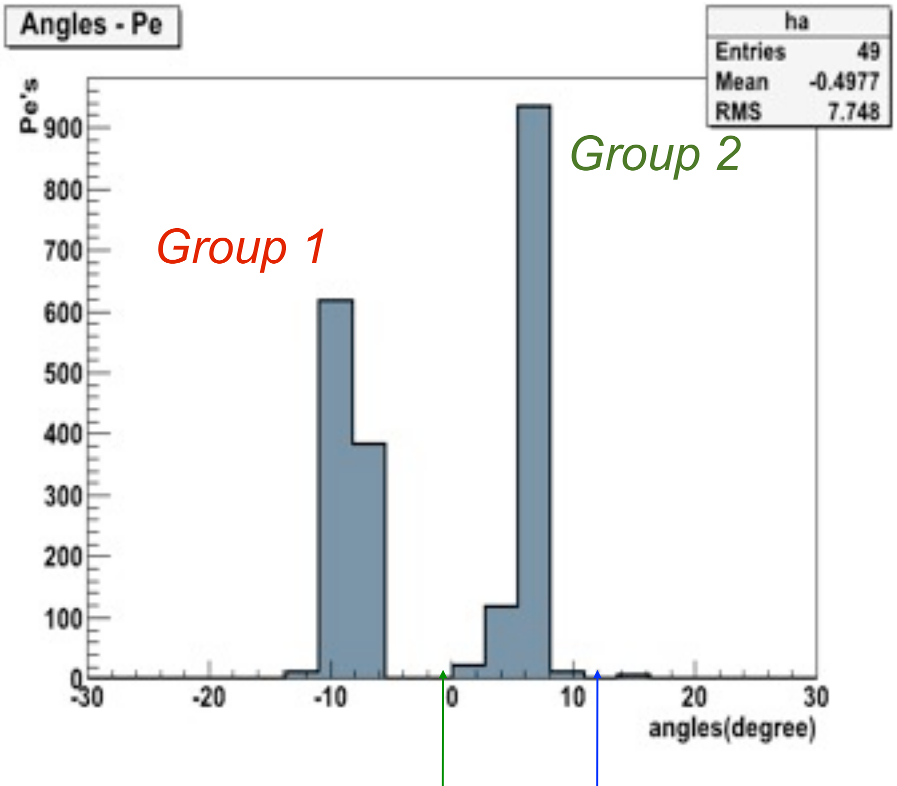
Showers in Minerva

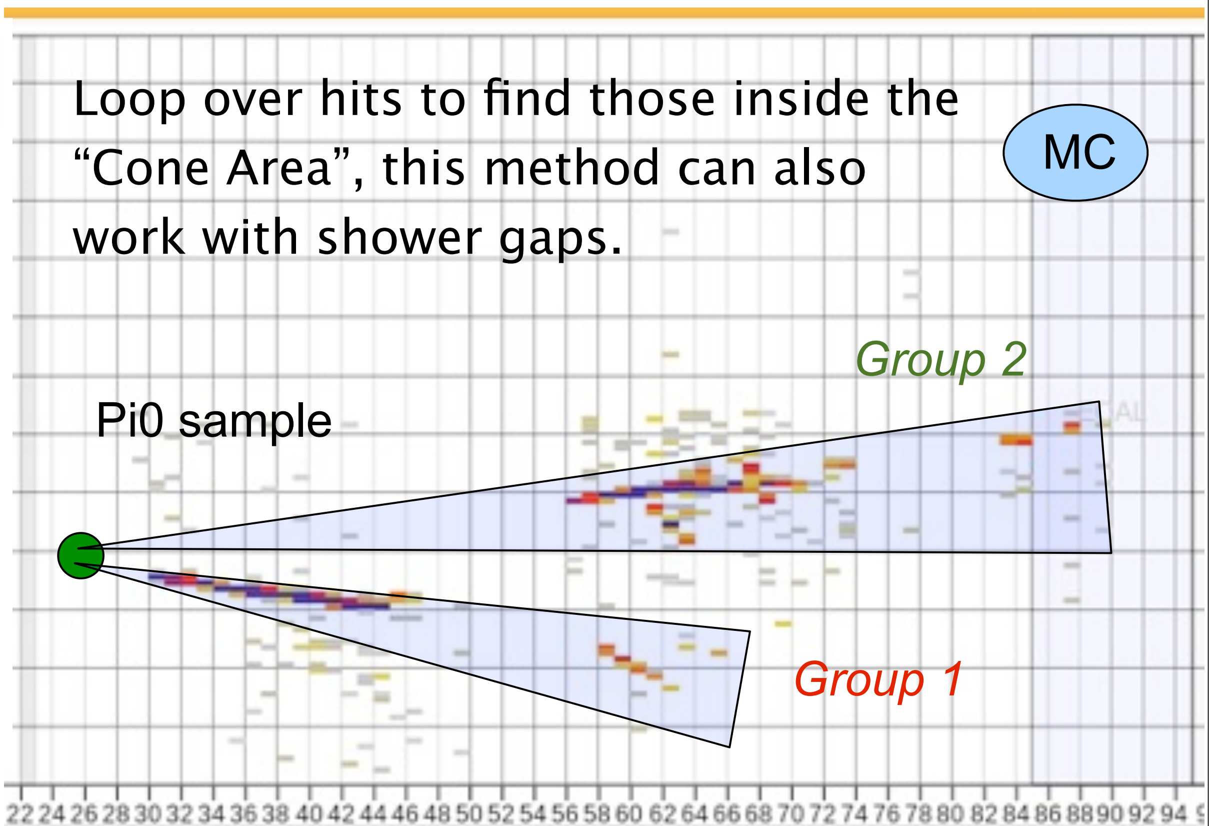




Not every hit is included in the reconstructed object. Cross-talk and low activity hits are being excluded.

Blob to contain Photons

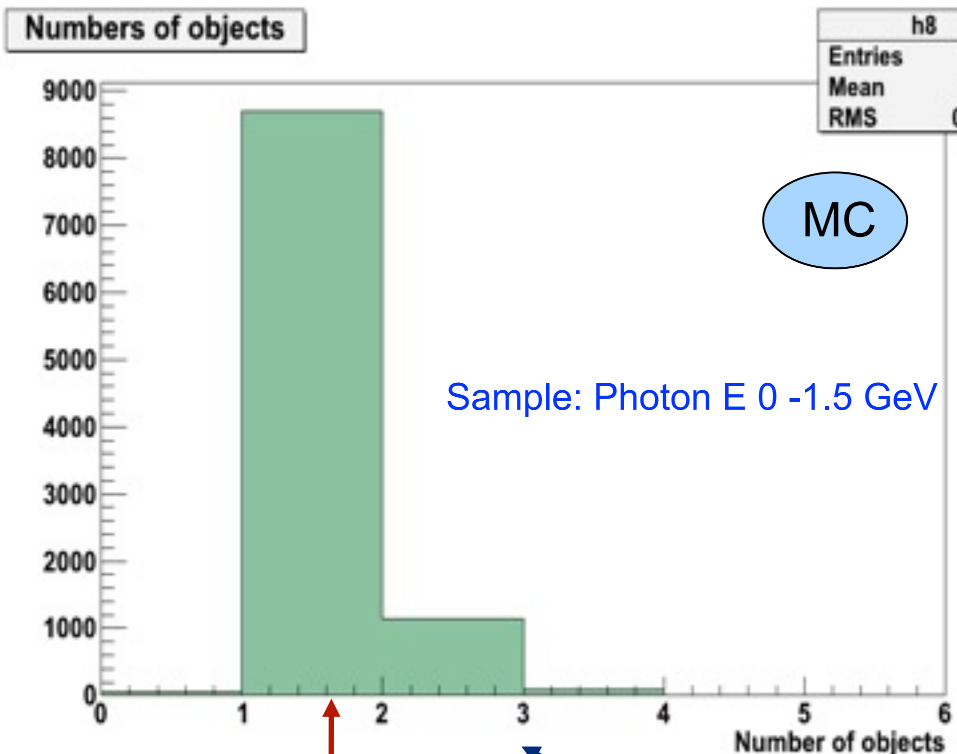




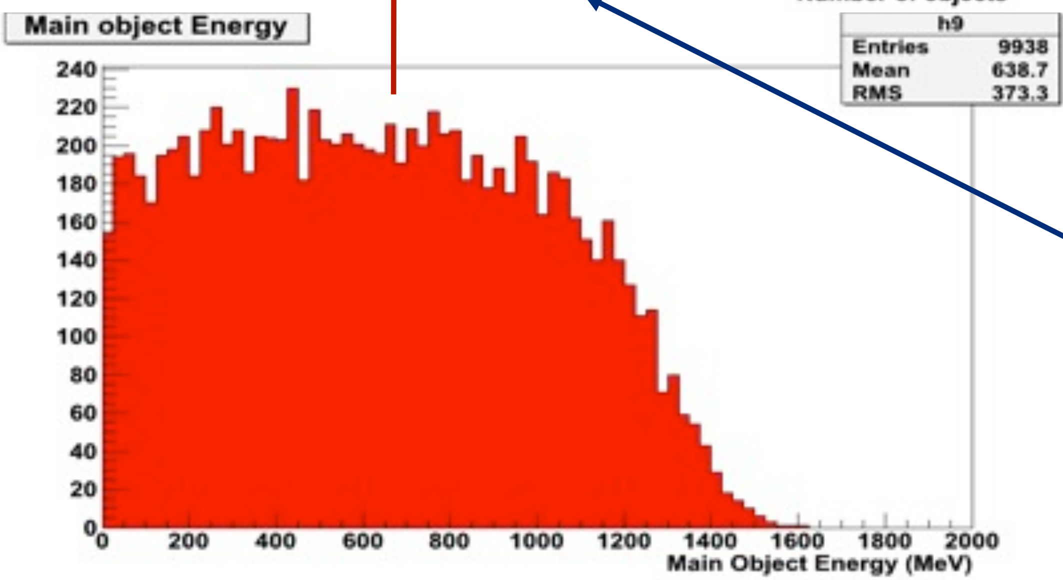
Every group (particle) inside the histogram will have a minimum angle and maximum angle

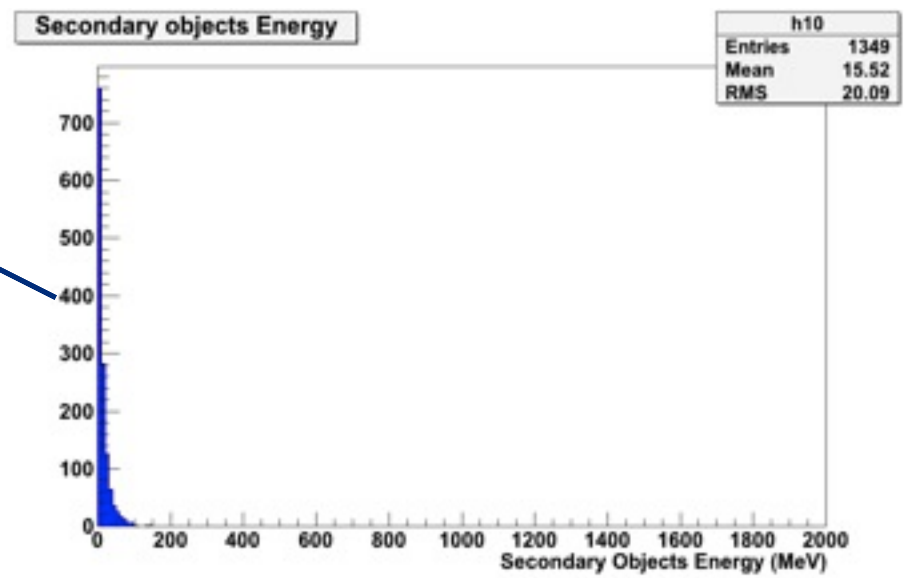
Using vertex like reference point, I fill out a 1D histogram, where every entry is the angle between every hit and the vertex, weighted by its charge. Similar to Hough Transformation with r = 0.

Number of blobs - Photon sample



The number of blobs for this sample should have an average equal 1. In some events this number is greater than 1 because not every secondary particle follows shower direction. But this contribution is not significant like the main object.





Steps to Reconstruct Pi0

Work with events containing 1 muon and 2 photons in the final state:

1) Muon Reconstruction(Minos match).

2) Photon full kinematic and energy reconstruction(EM showers).

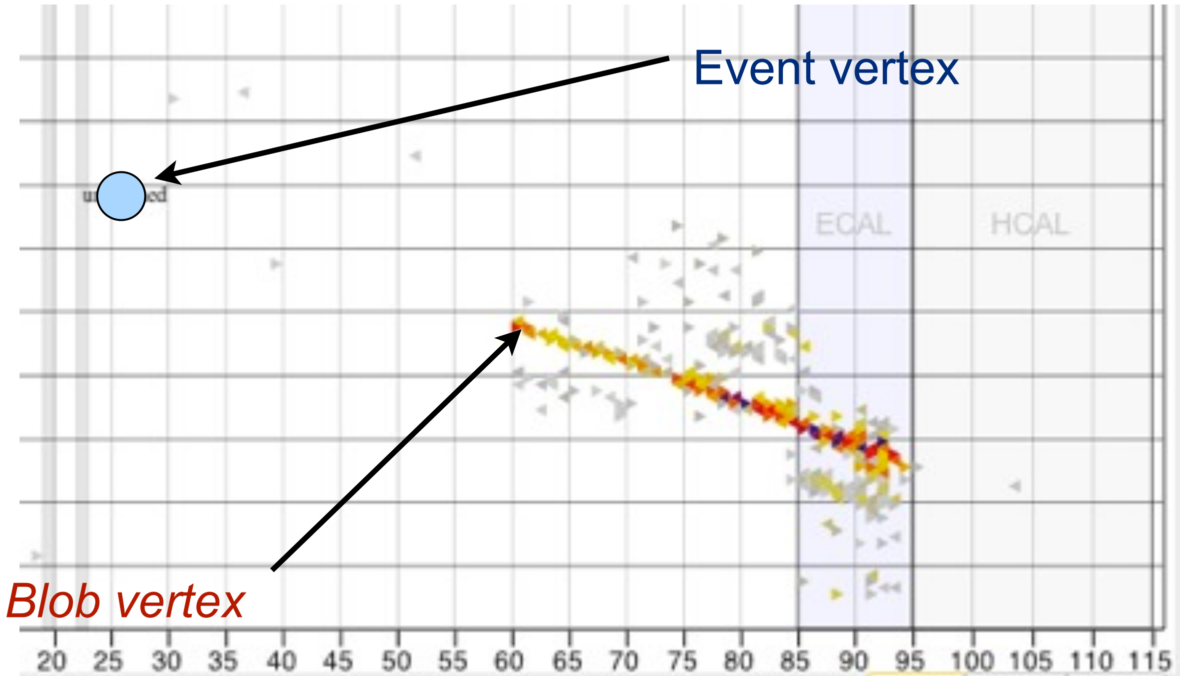
3) Find Pi0 in events(Invariant mass trigger) using photon reconstruction.

4) Pi0 Energy reconstruction, important for Neutrino events analysis.

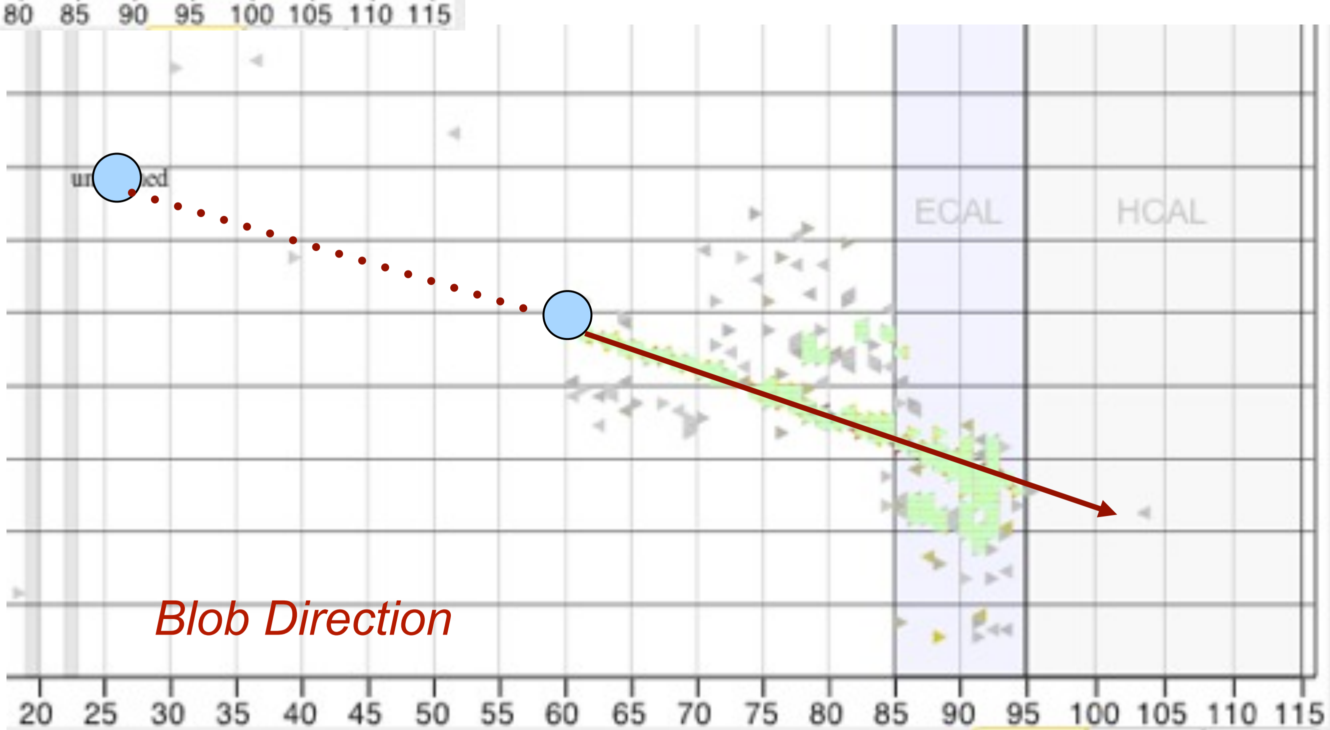
Done

Currently I am working

Blob Kinematics Reconstruction



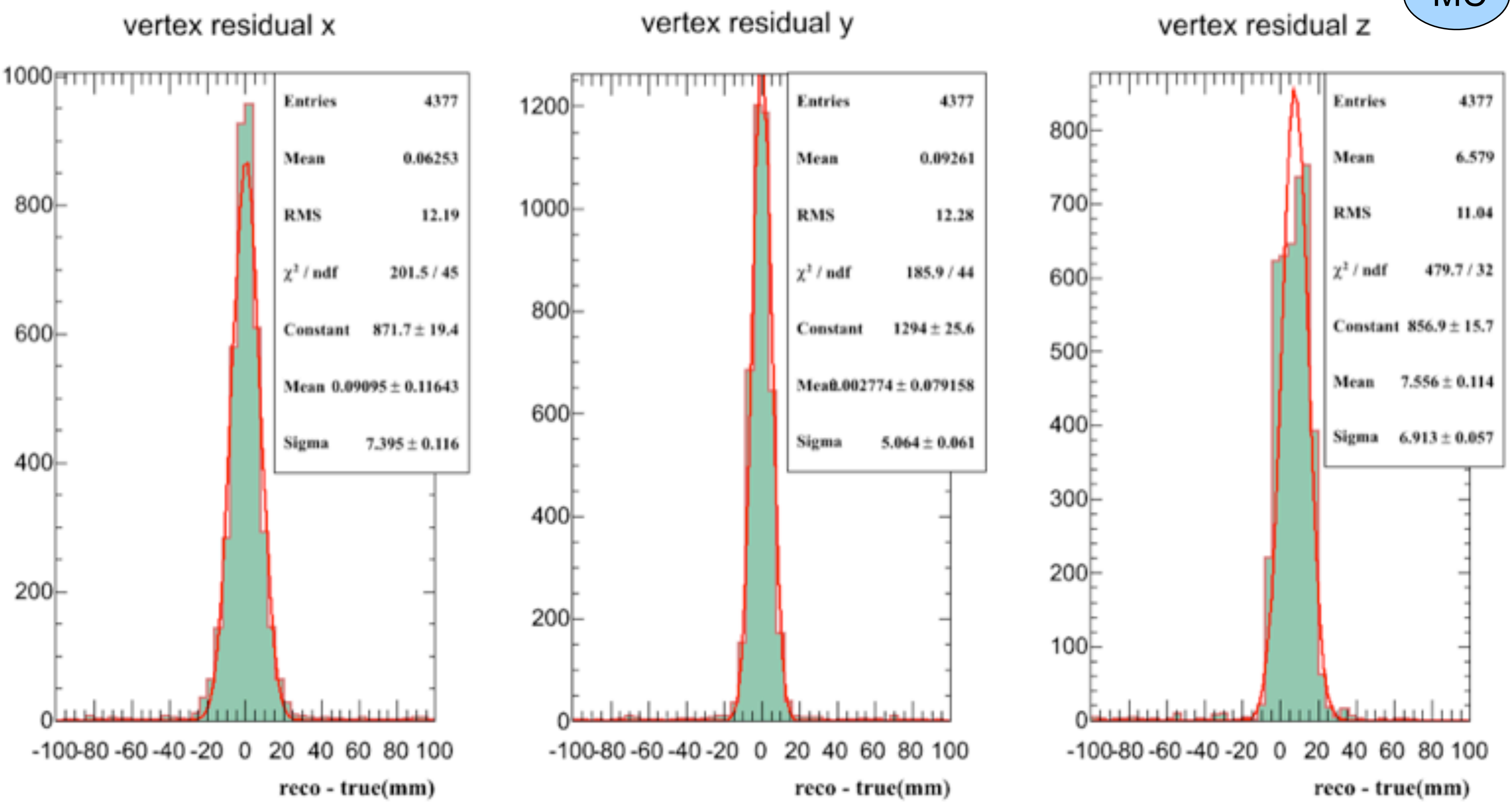
Blob Vertex:
closest hit position to the event vertex given by the muon vertex



Blob Direction:
Slope between event vertex and blob vertex

Blob Vertex Residual

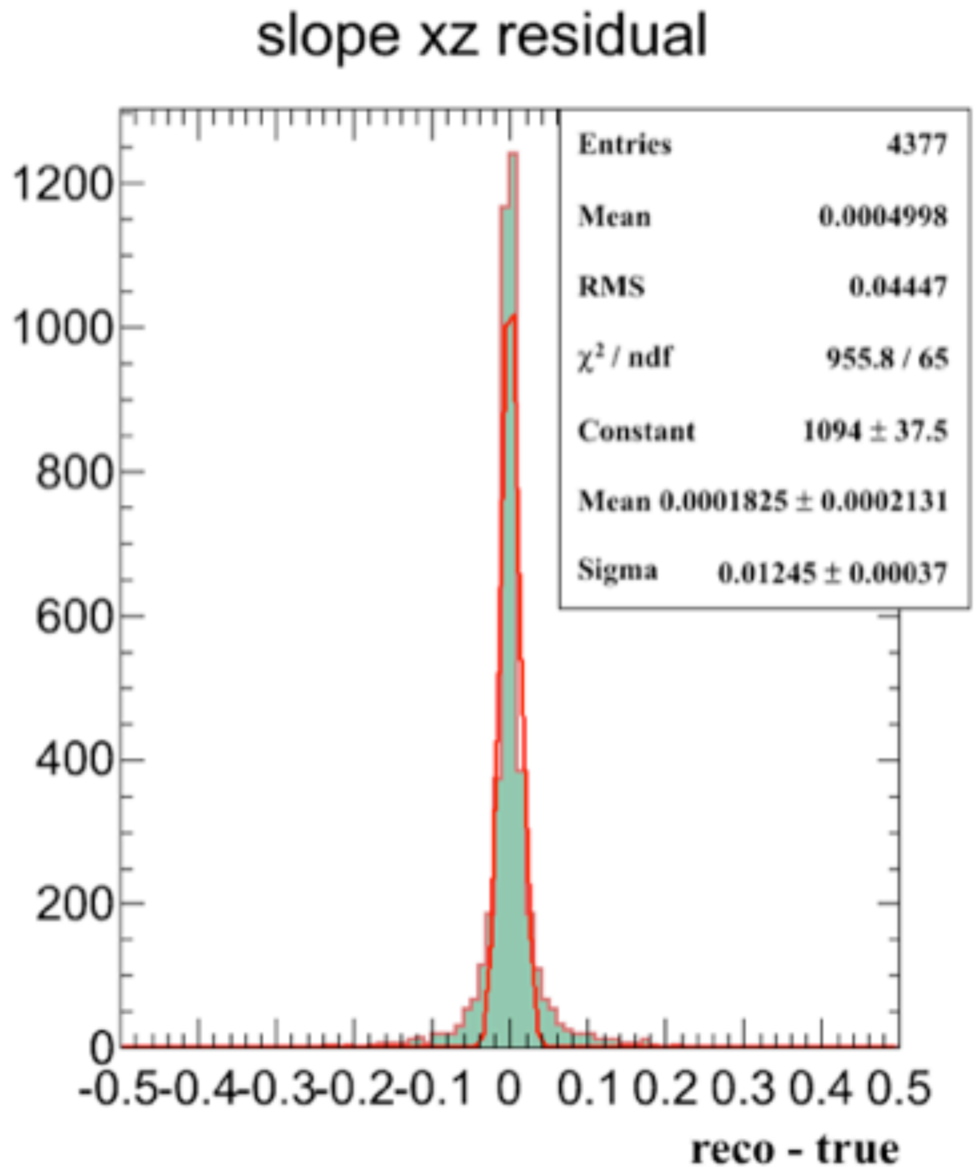
MC

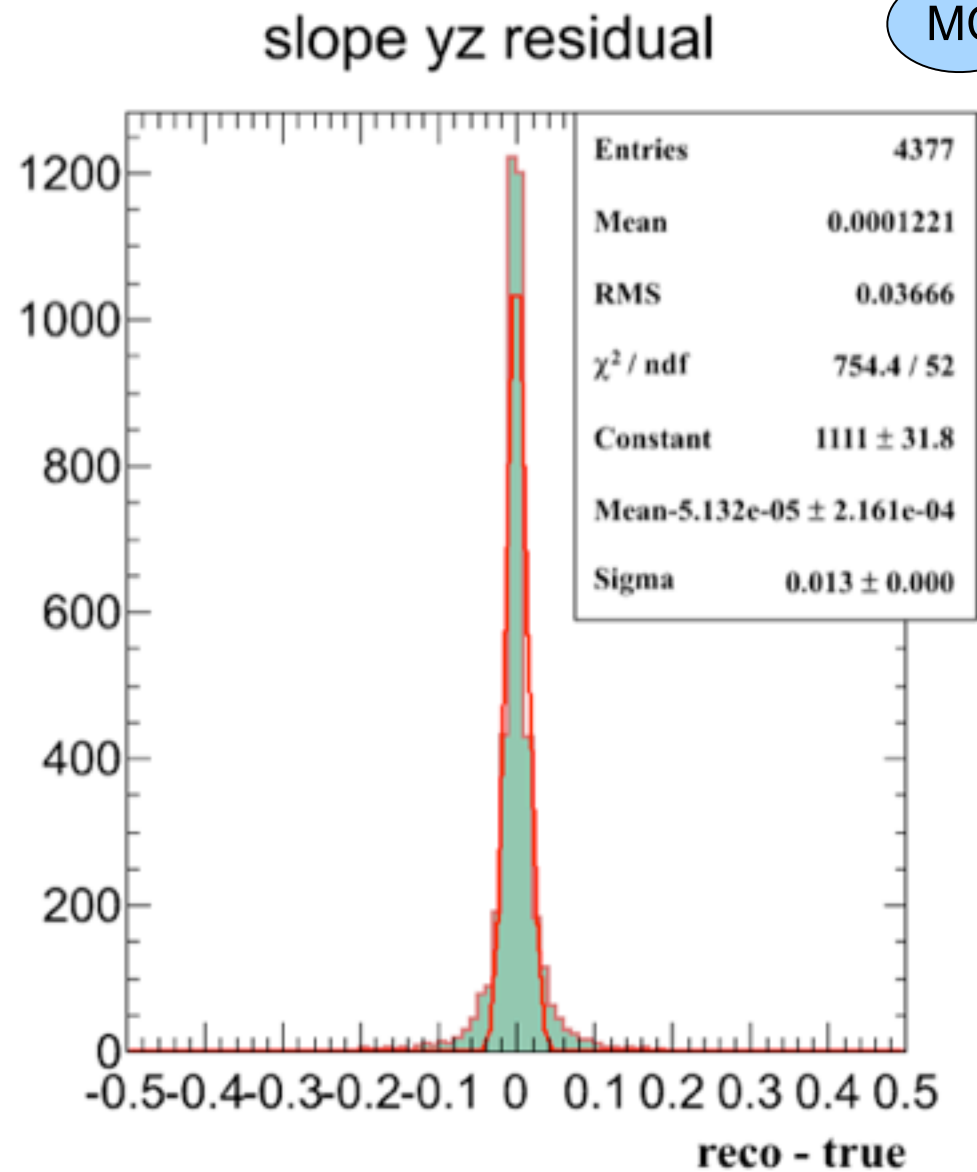


Events with 1 blob, ID contained and should have hits in each view

Photon Slope residual

MC

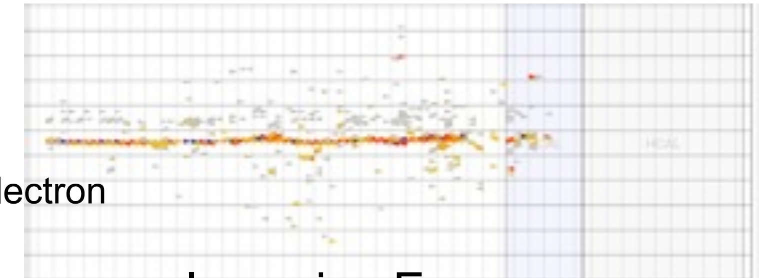




Energy reconstruction

All hits are included to calculate calorimetric constants

electron



$$k = \frac{\text{Incoming Energy}}{\text{Visual Energy}}$$

$$E_{True} = \alpha\,(E_{tracker} + k_E\,E_{ECal} + k_H\,E_{HCal})$$

Sub-Detector	Constants
α	1.213
K_E	2.274
K_H	10.55

There are minimum requirements for events when are reconstructed

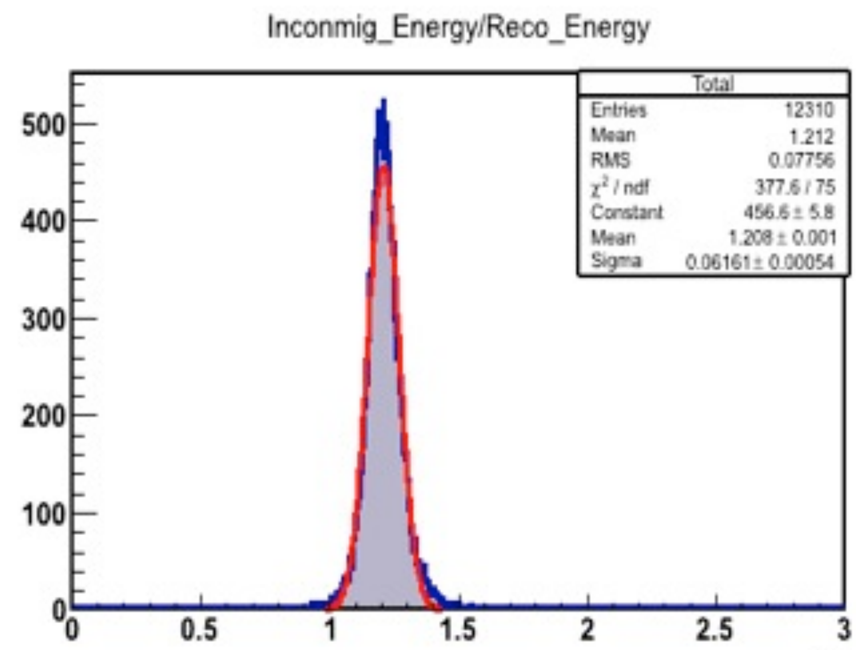
Calorimeter	# of hits
Electromagnetic	20
Hadronic	25

Number of hits in Calorimeter is Required

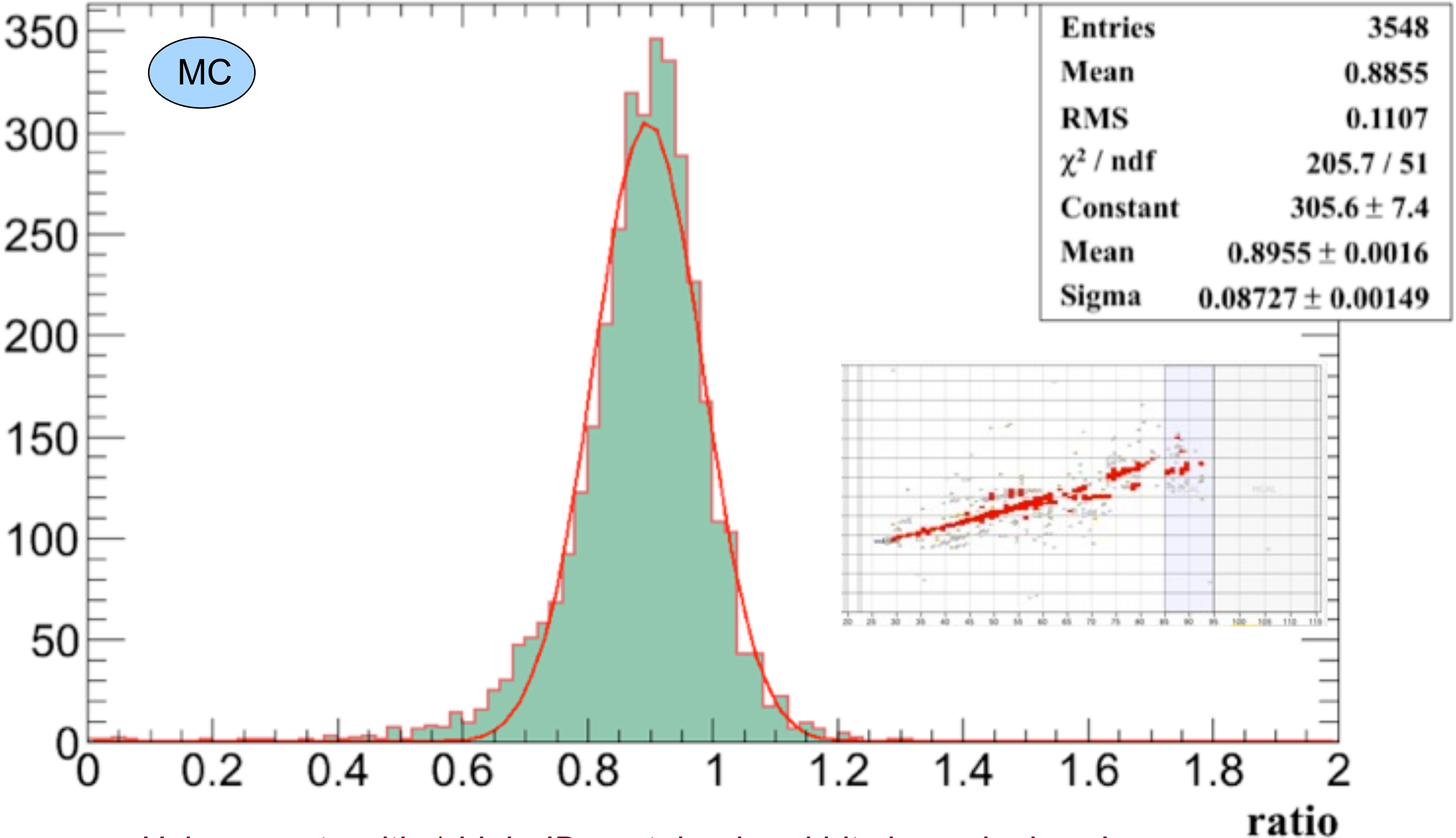
SubDetector	Reconstructed Energy(MeV)
Tracker	41.36
ECal	36.26
HCal	15.63

No well defined for low energy

Constant for Tracker



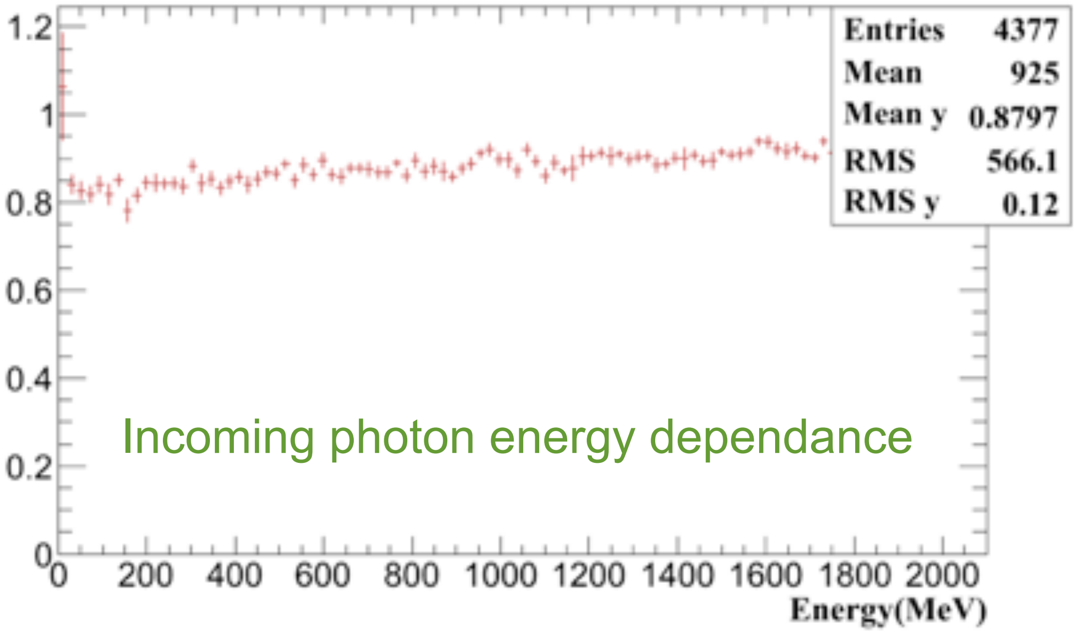
Reconstructed Energy/True Energy



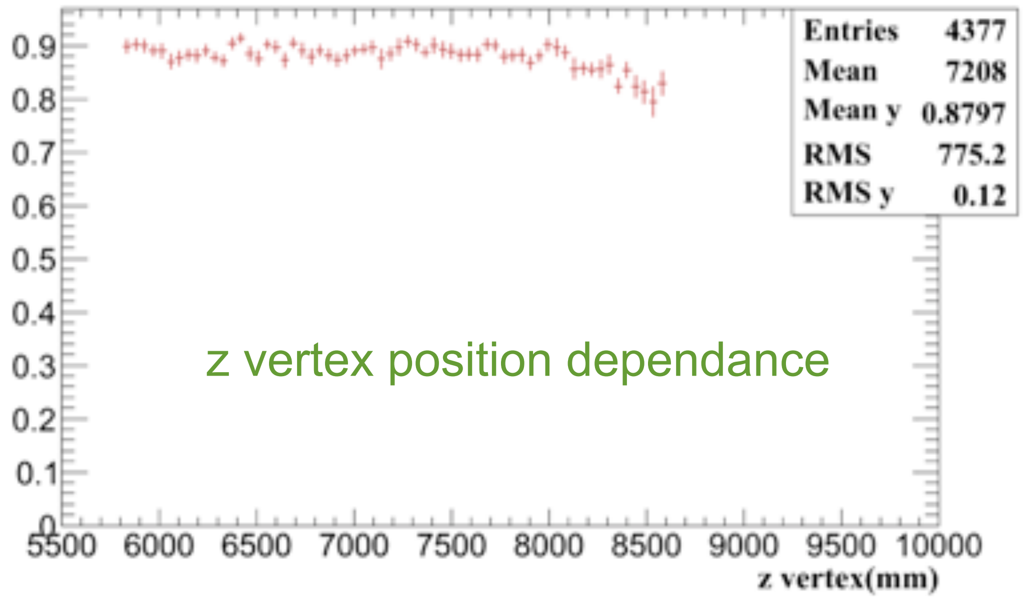
Using events with 1 blob, ID contained and hits in each view, I am using the Mean value to rescale the energy.

MC

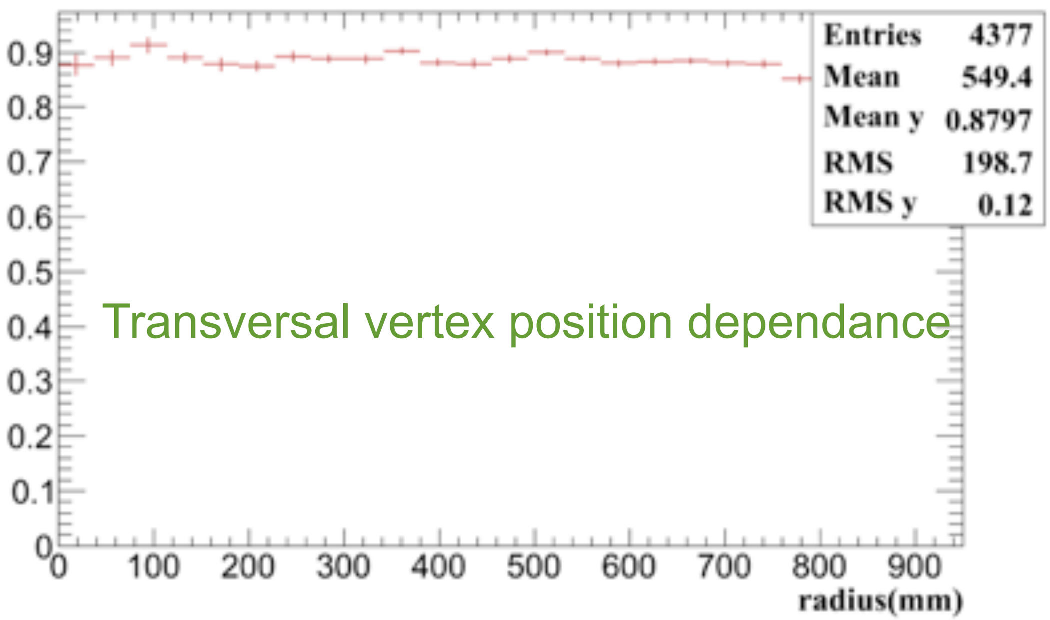
Ratio vs Energy

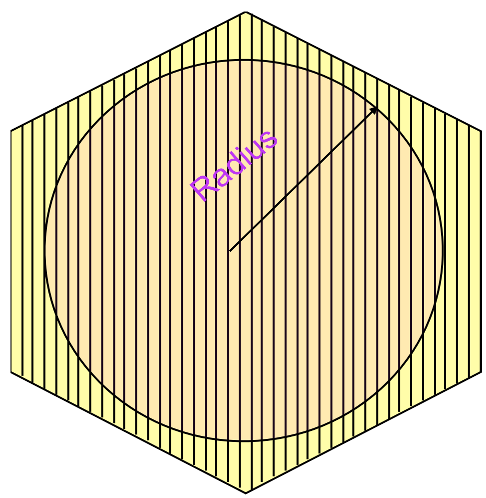


Ratio vs Z position



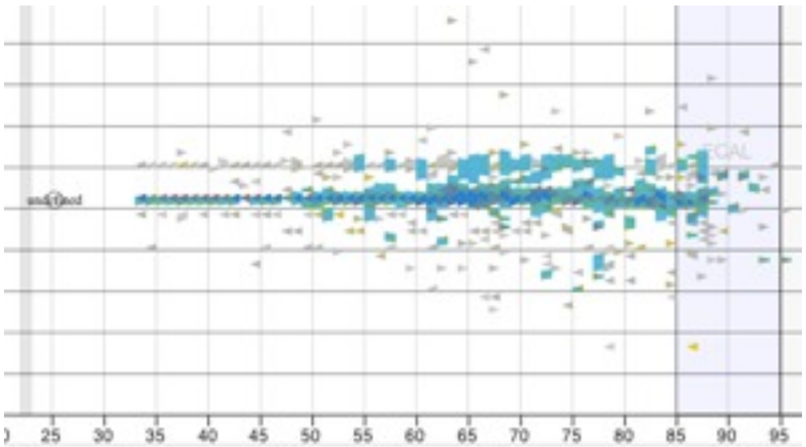
Ratio vs Radius



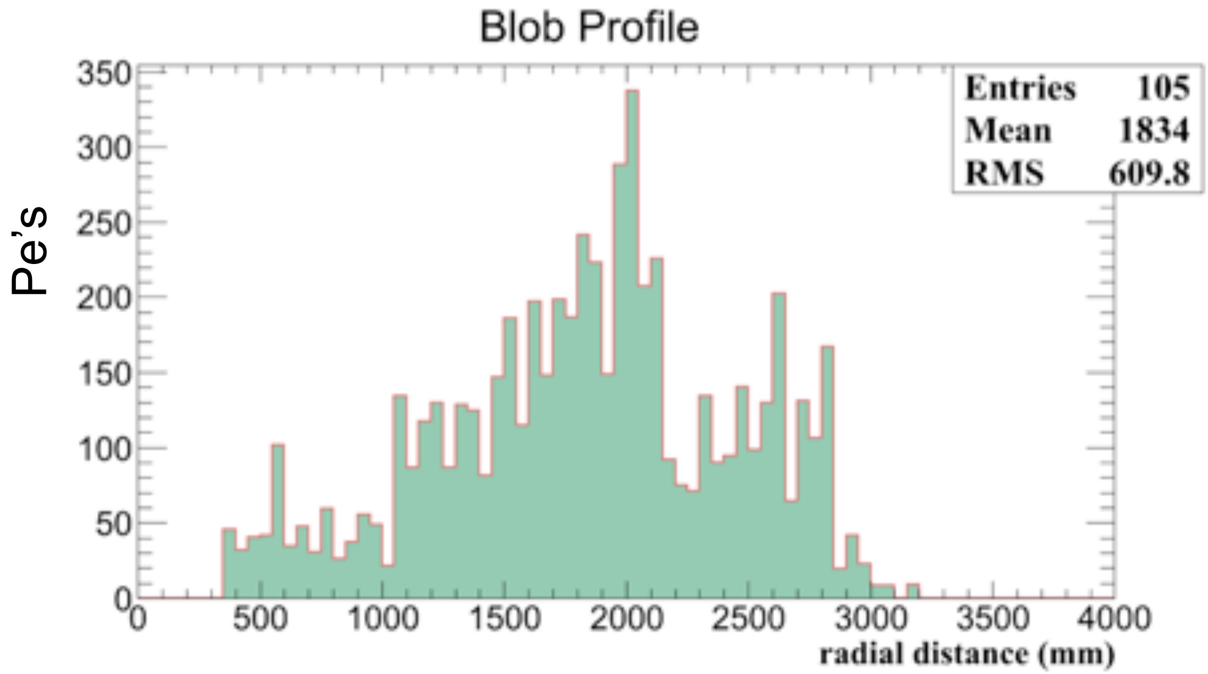


Photon identification

I want to loop just over photon blobs, when an event has more than 2 blobs.



Blob profile histogram using radial distance and PE weight

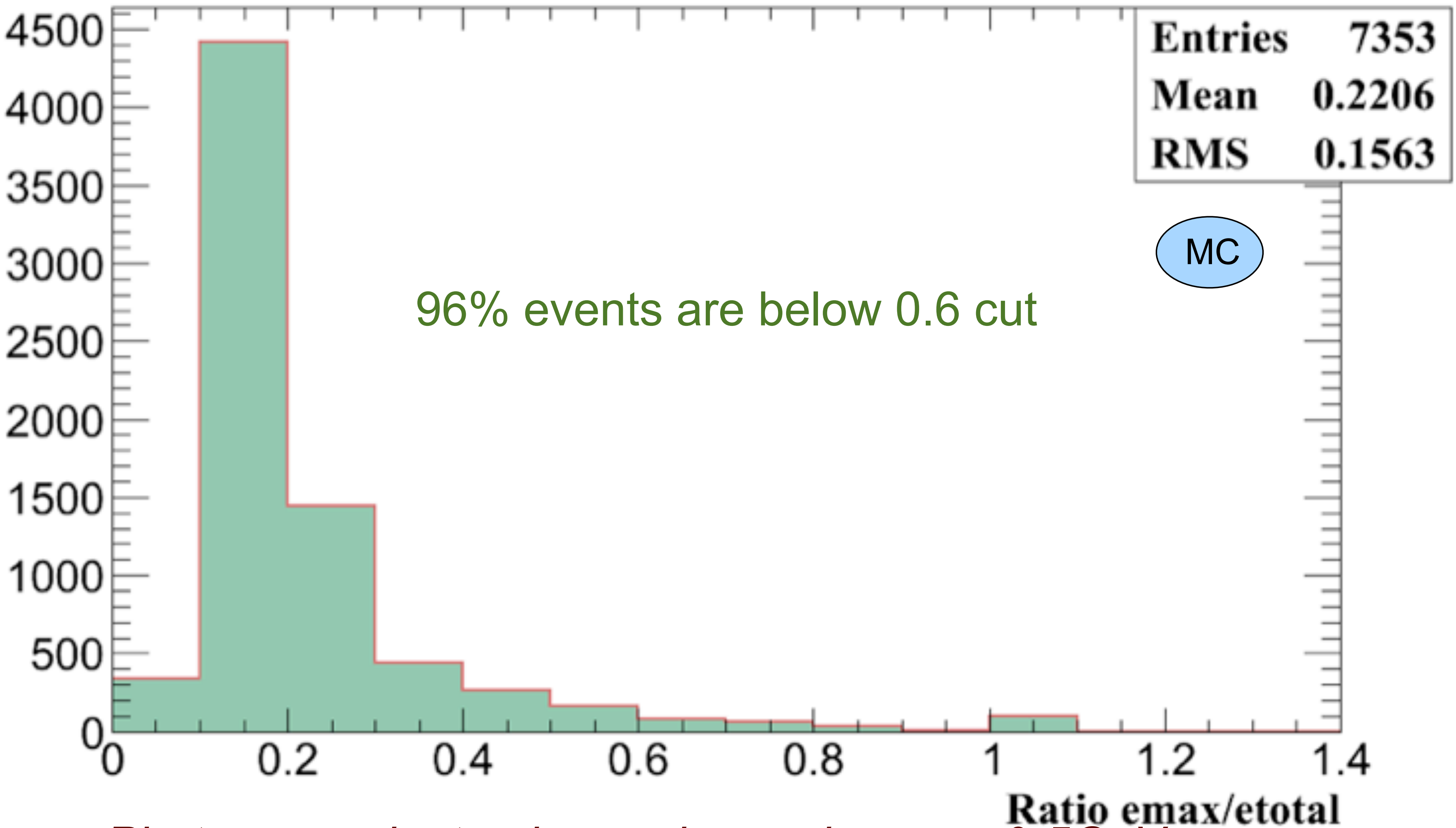


Radial distance = distance between vertex and cluster position.

Blob profile Energy ratio = Energy Peak/Total Energy Integral.

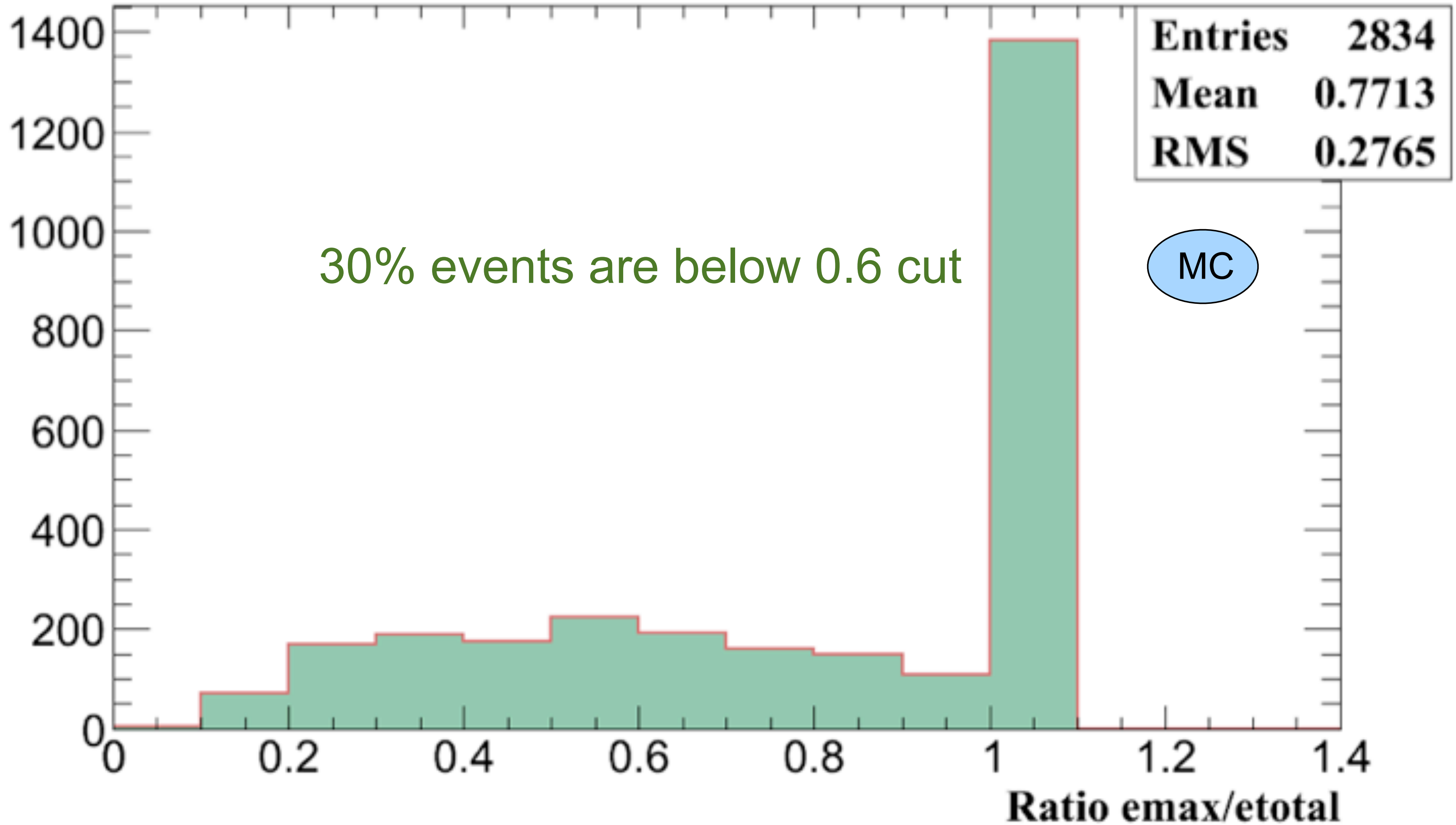
*Photons Blobs coming from Pi0 should have blob vertex not close to event vertex.

Blob profile energy ratio to Photons



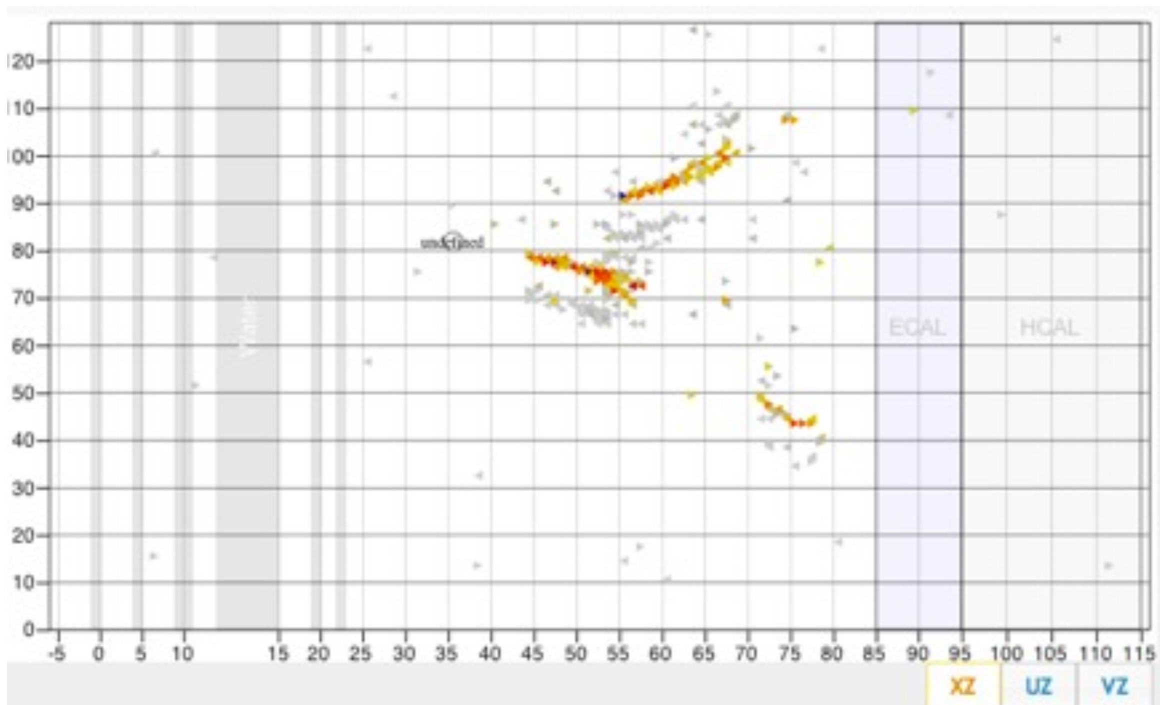
Photon sample, tracker region and energy 0-5GeV

Blob profile energy ratio to Neutrons



Neutron sample, tracker region and energy 0-5GeV

Pi0 reconstruction - Pi0 sample



Important formulas for Pi0 reconstruction

Reconstructed Energy for electromagnetic showers:

$$E_{reco} = \alpha(E_{tracker} + k_{ECal}E_{Ecal} + k_{HCal}E_{HCal})$$

Opening angle: $$p_{\gamma_1}.p_{\gamma_2} = |p_{\gamma_1}||p_{\gamma_2}|cos\theta_{\gamma\gamma}$$

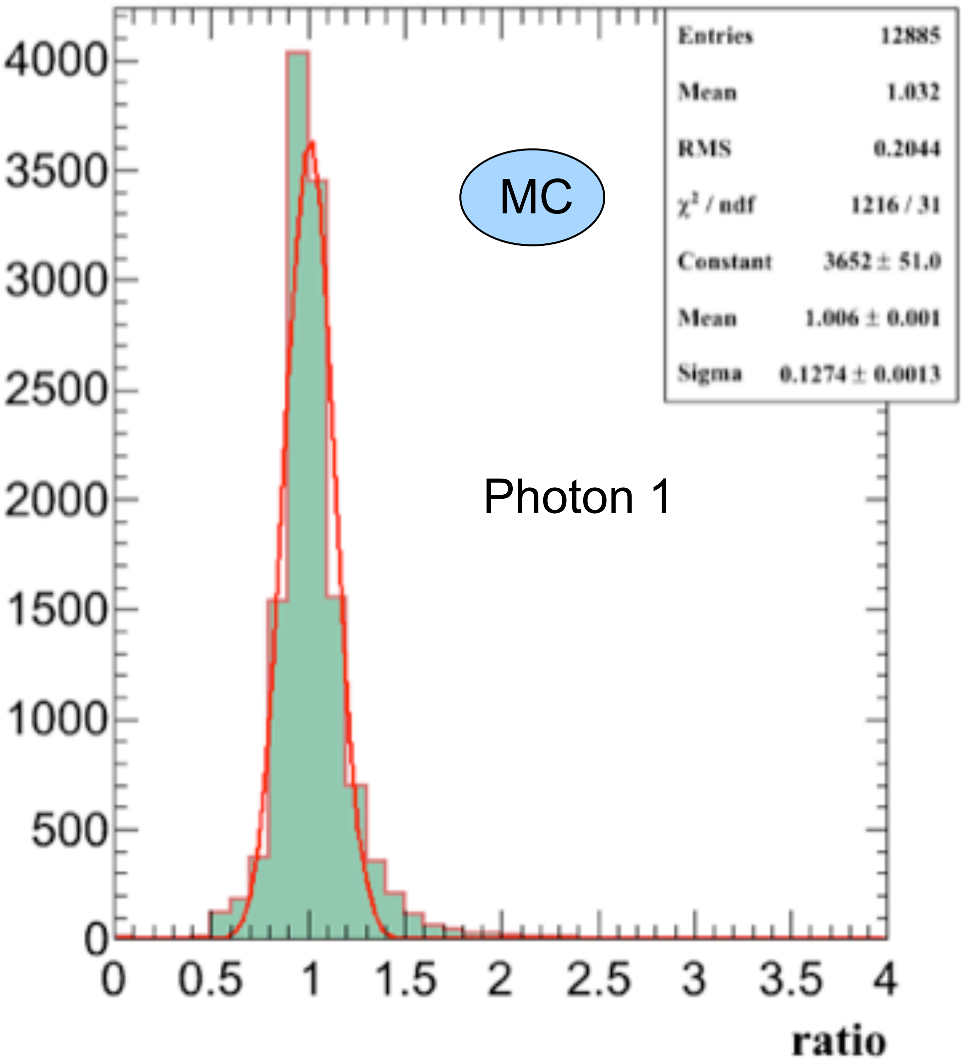
Invariant mass: $$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{\gamma\gamma})}.$$

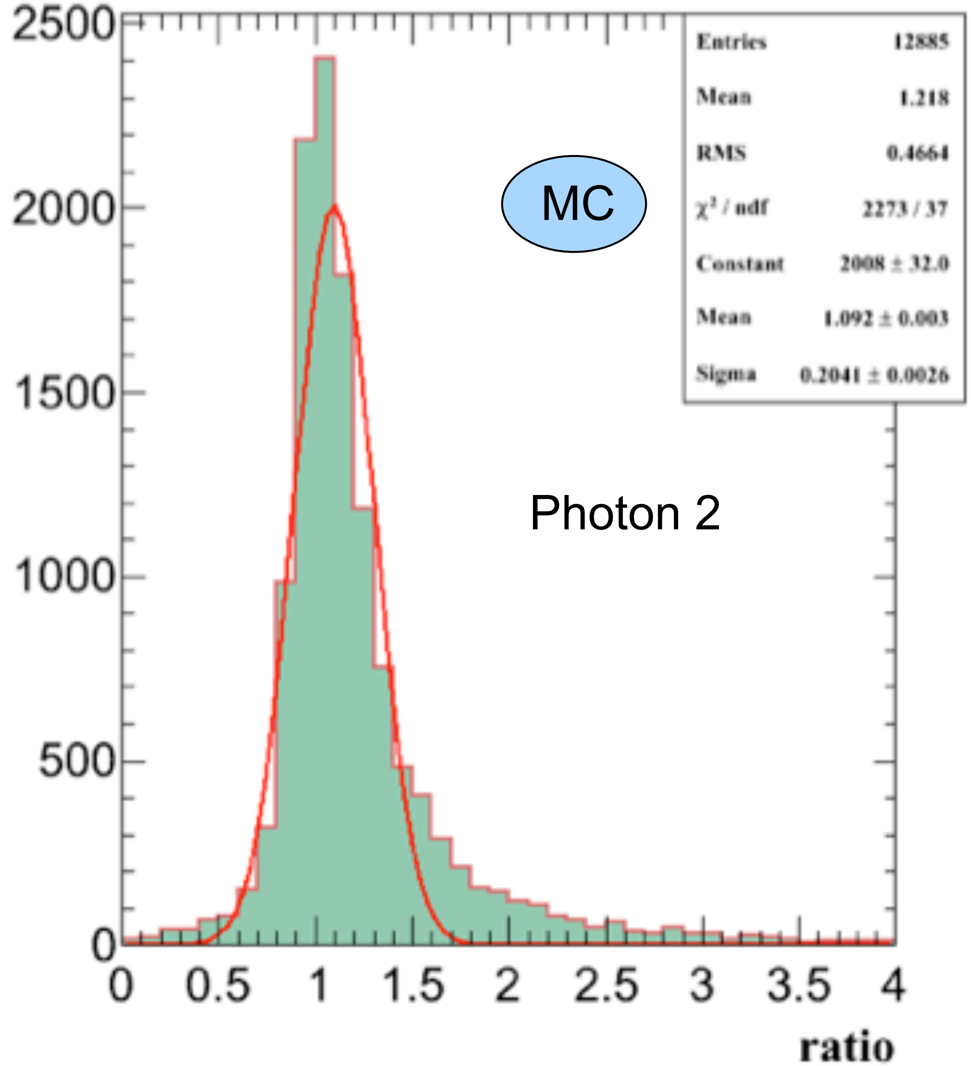
Pi0 energy: $$E_{\pi} = E_{\gamma 1} + E_{\gamma 2}$$

Pi0 momentum: $$\boldsymbol{p}_{\pi} = \boldsymbol{p}_{\gamma_1}^{\text{REC}} + \boldsymbol{p}_{\gamma_2}^{\text{REC}}$$

Energy Reconstructed/Energy True

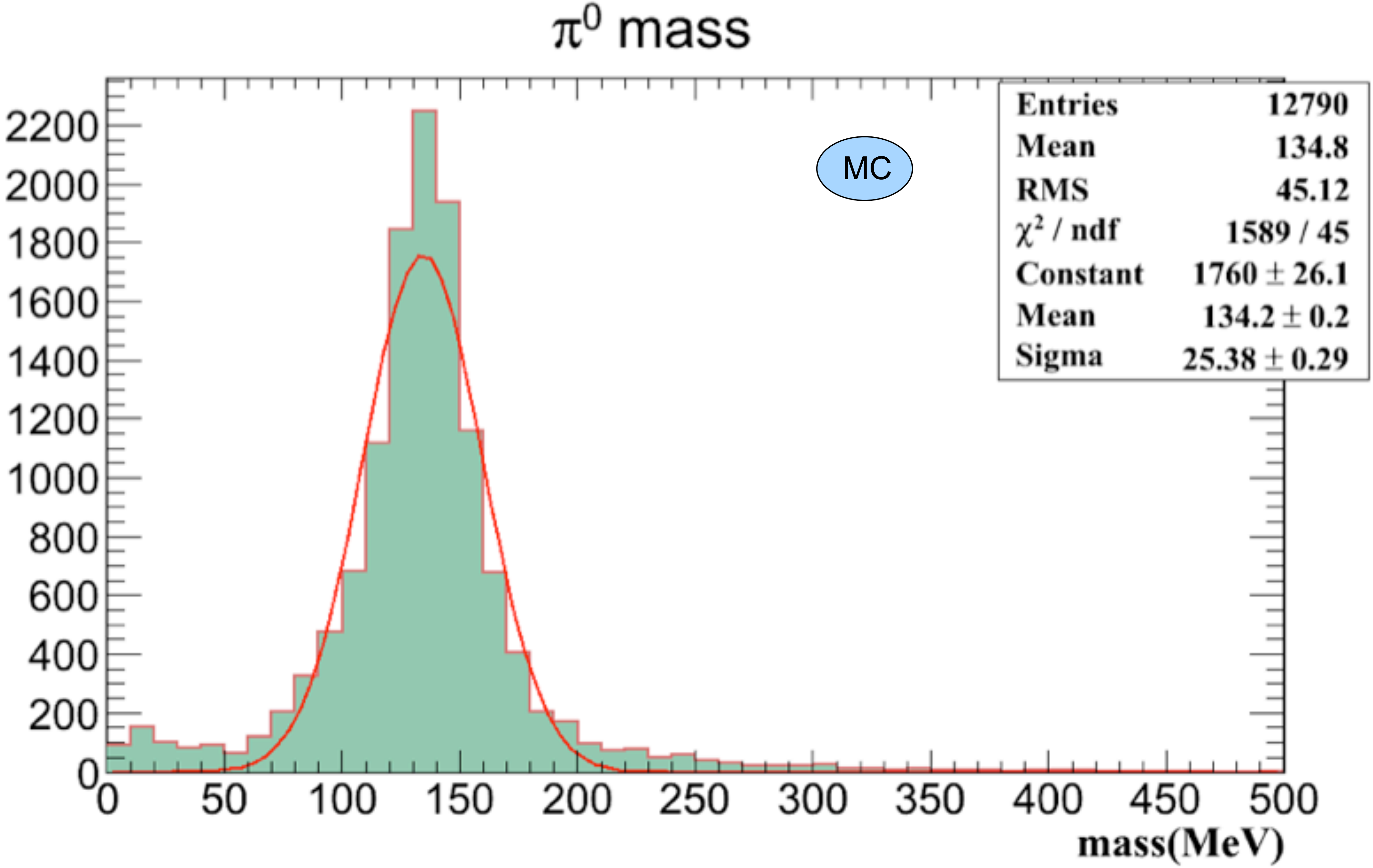
Neutral Pion



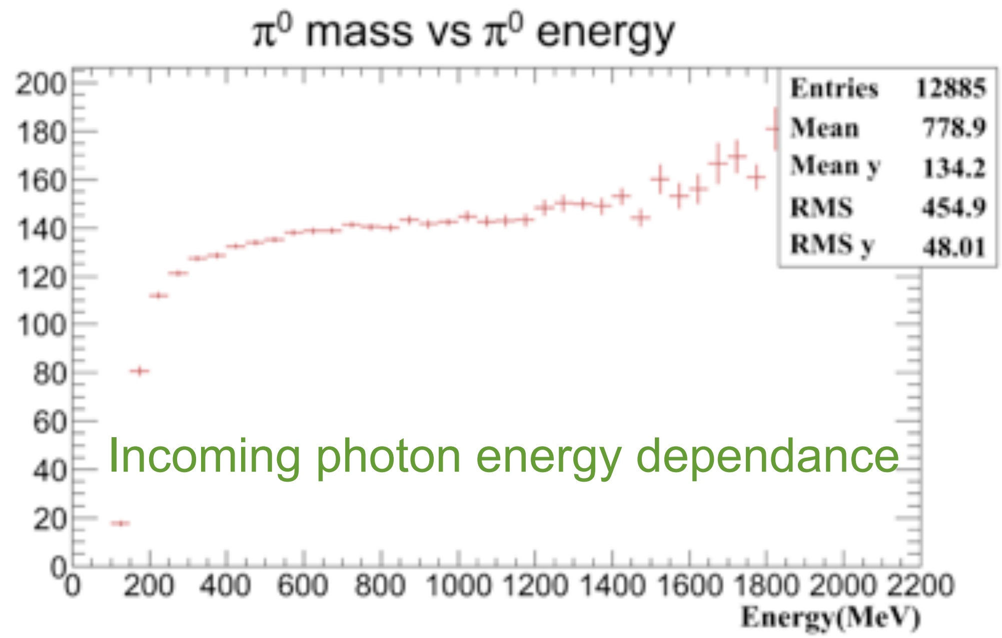


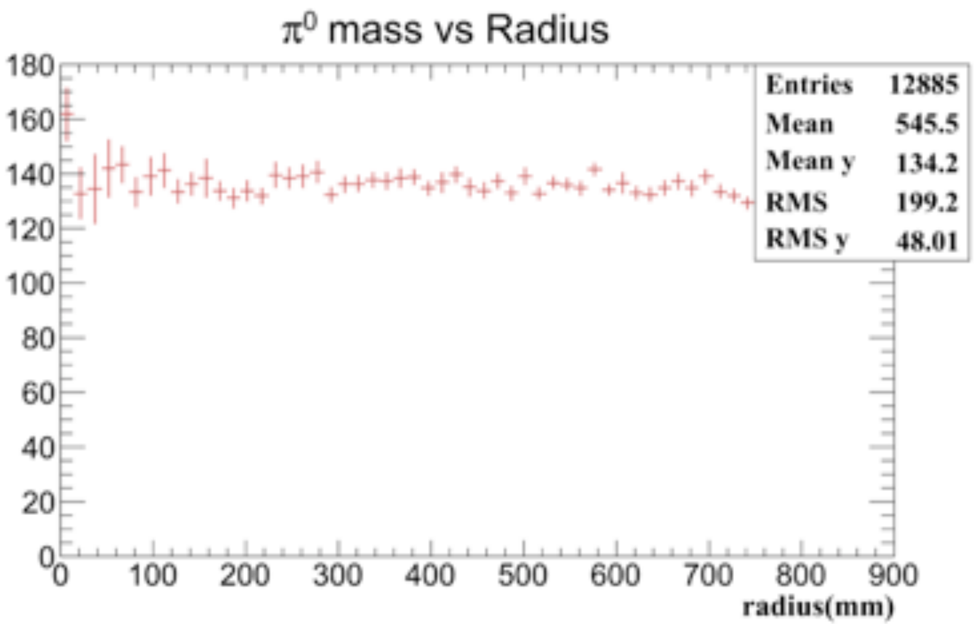
Energy of Photon 1 > Energy of Photon 2

Pi0 mass calculation on Pi0 sample

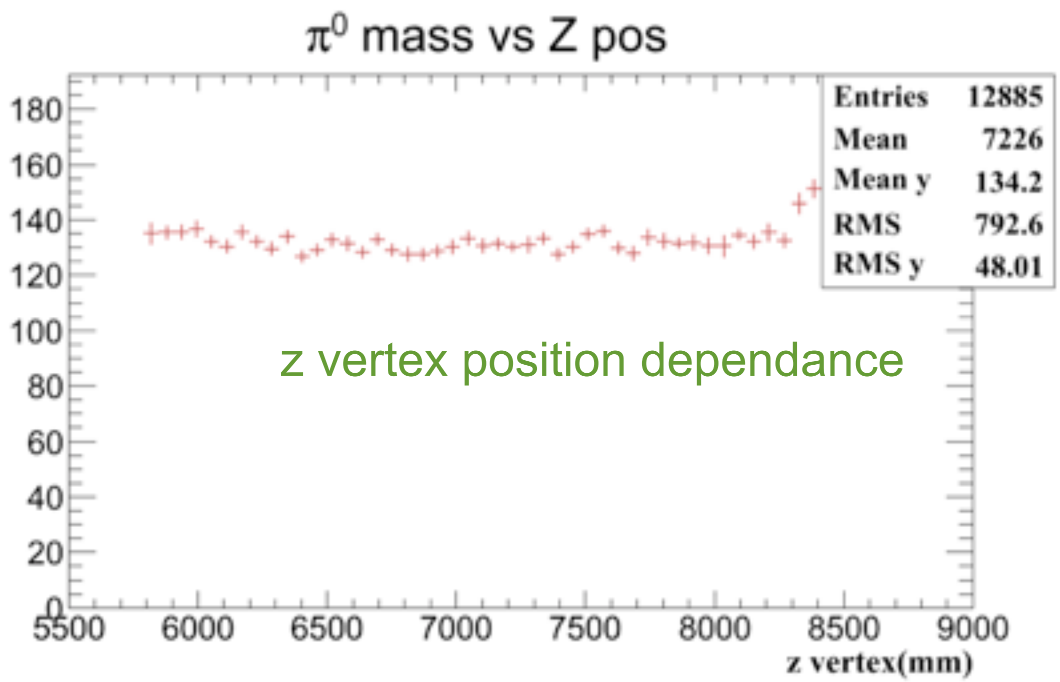


Pi0 mass dependance

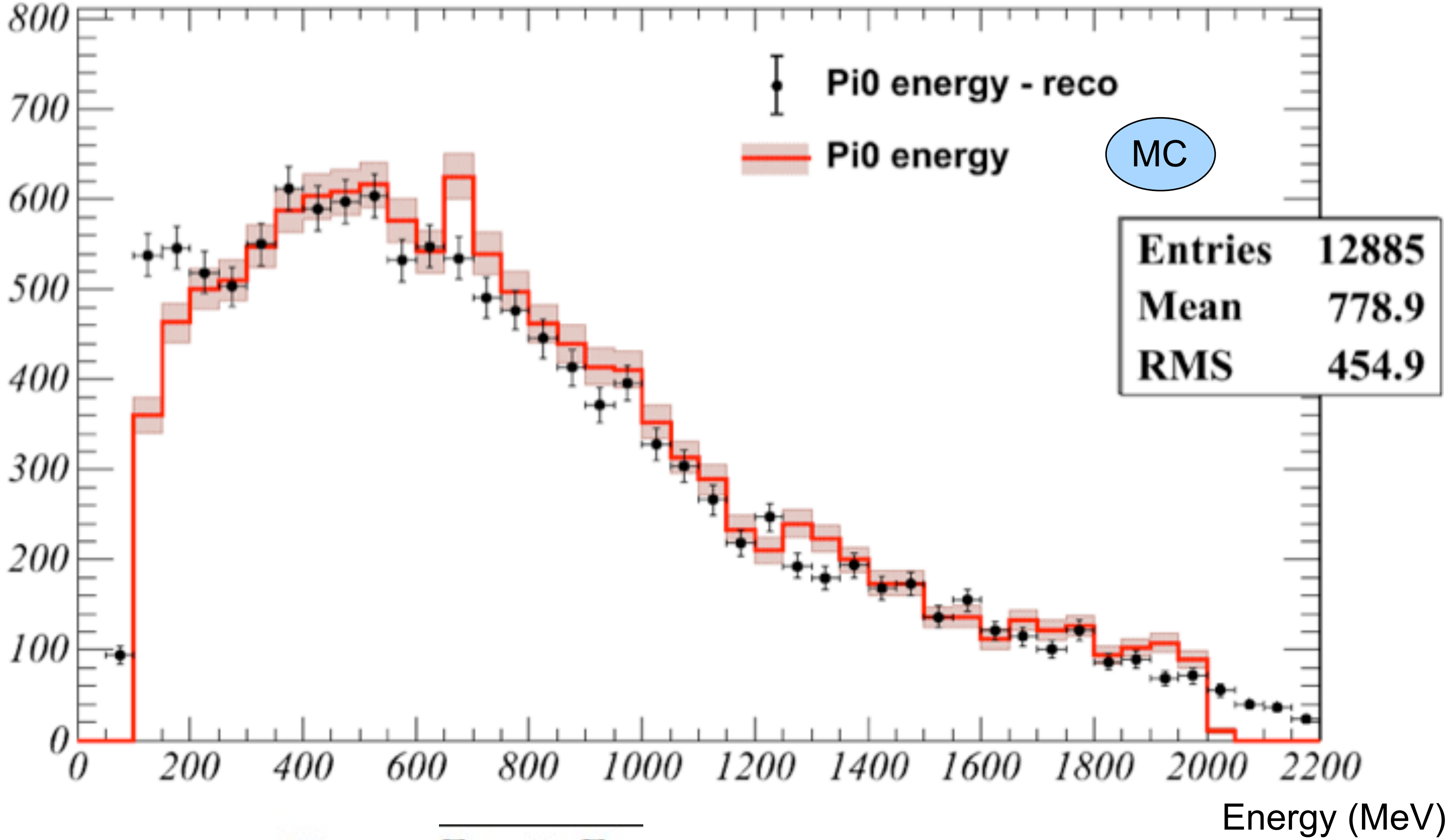




Transversal vertex position dependance

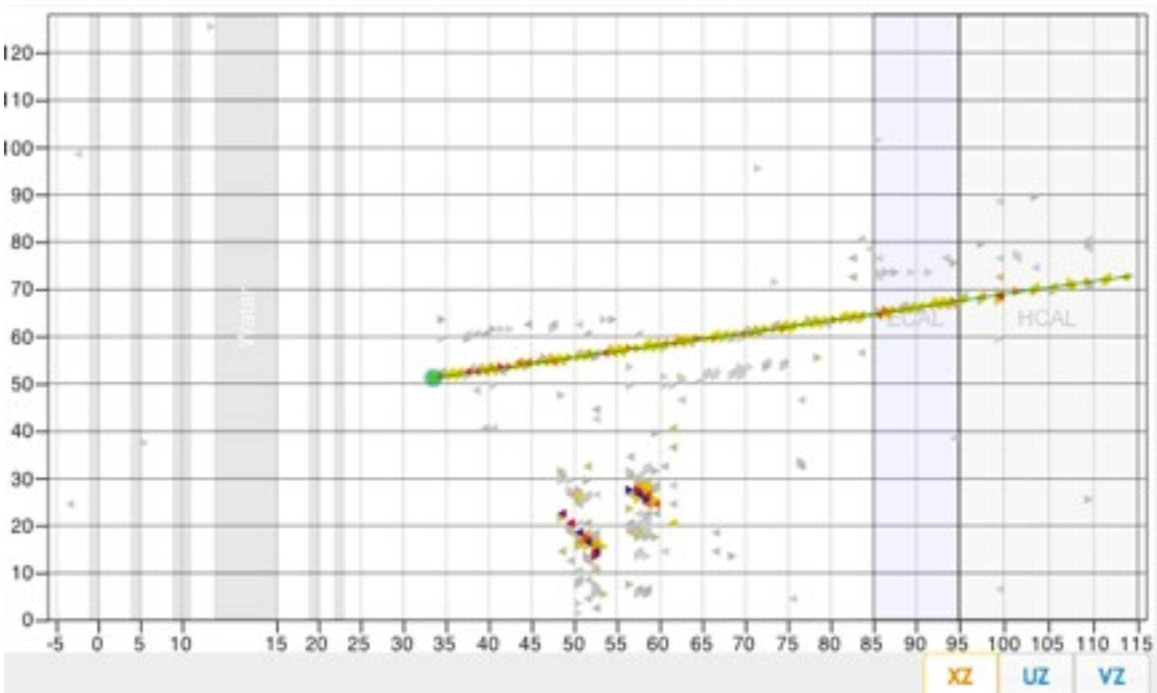


Pi0 Energy reconstruction



$$E_\pi = \overline{E_{\gamma 1} + E_{\gamma 2}}$$

Pi0 reconstruction - Neutrino sample



Event selection from Neutrino sample

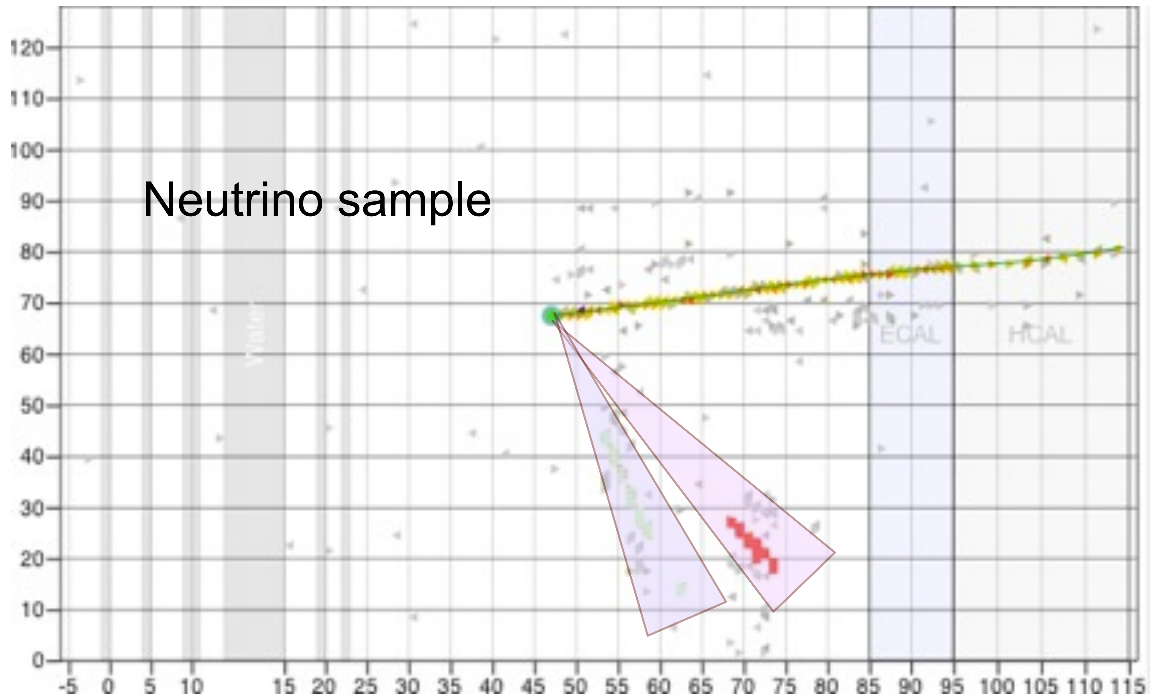
Pi0 events are being selected from exclusive events.

Pi0, neutron and anti-muon must be selected from the final state particles.

First attempt is to select 2 blobs + 1 anti-muon.

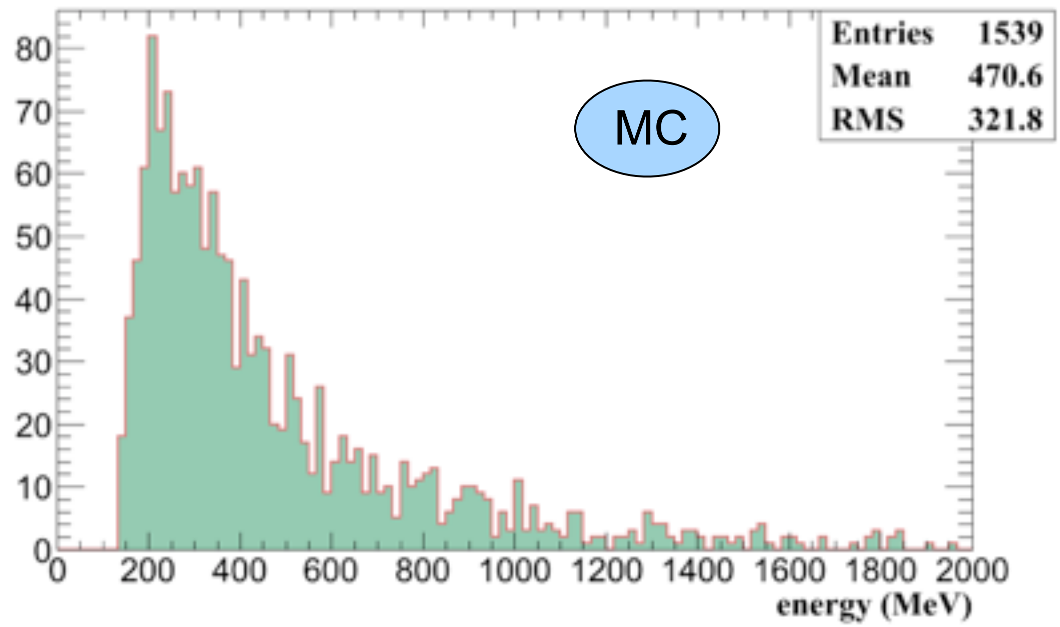
Reconstructed Muon vertex (event vertex) should be inside the tracker region.

Neutrino Energy



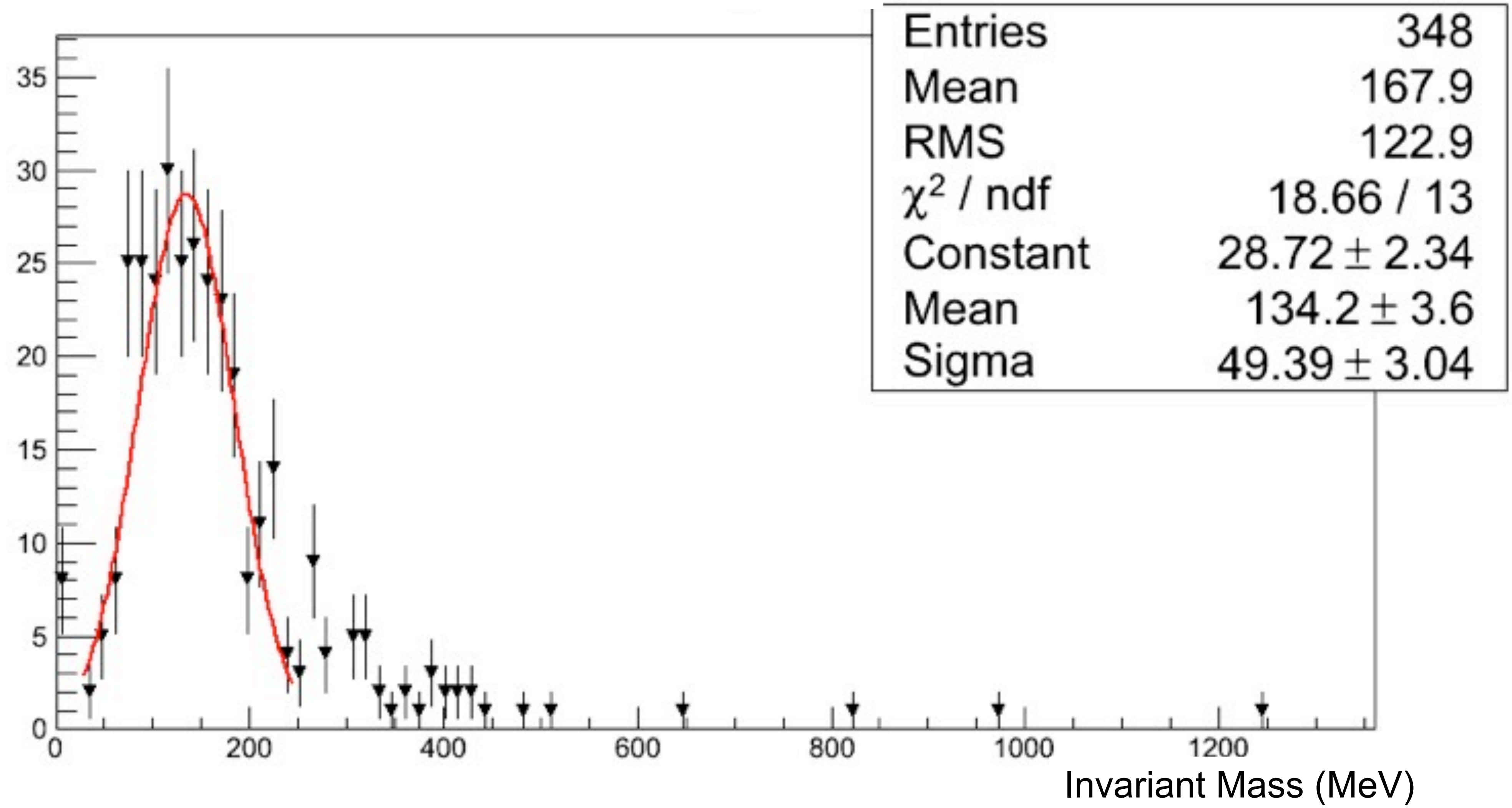
~50% of events contain exactly 2 blobs. However to reconstruct Pi0 mass, extra requirements has to be applied. About ~23% of events reconstructed after cuts.

Pi0 energy from total exclusive events



Pi0 energy distribution. Mean value 470MeV. It means electromagnetic showers with “low energy”

Pi0 mass - first attempt



Summary

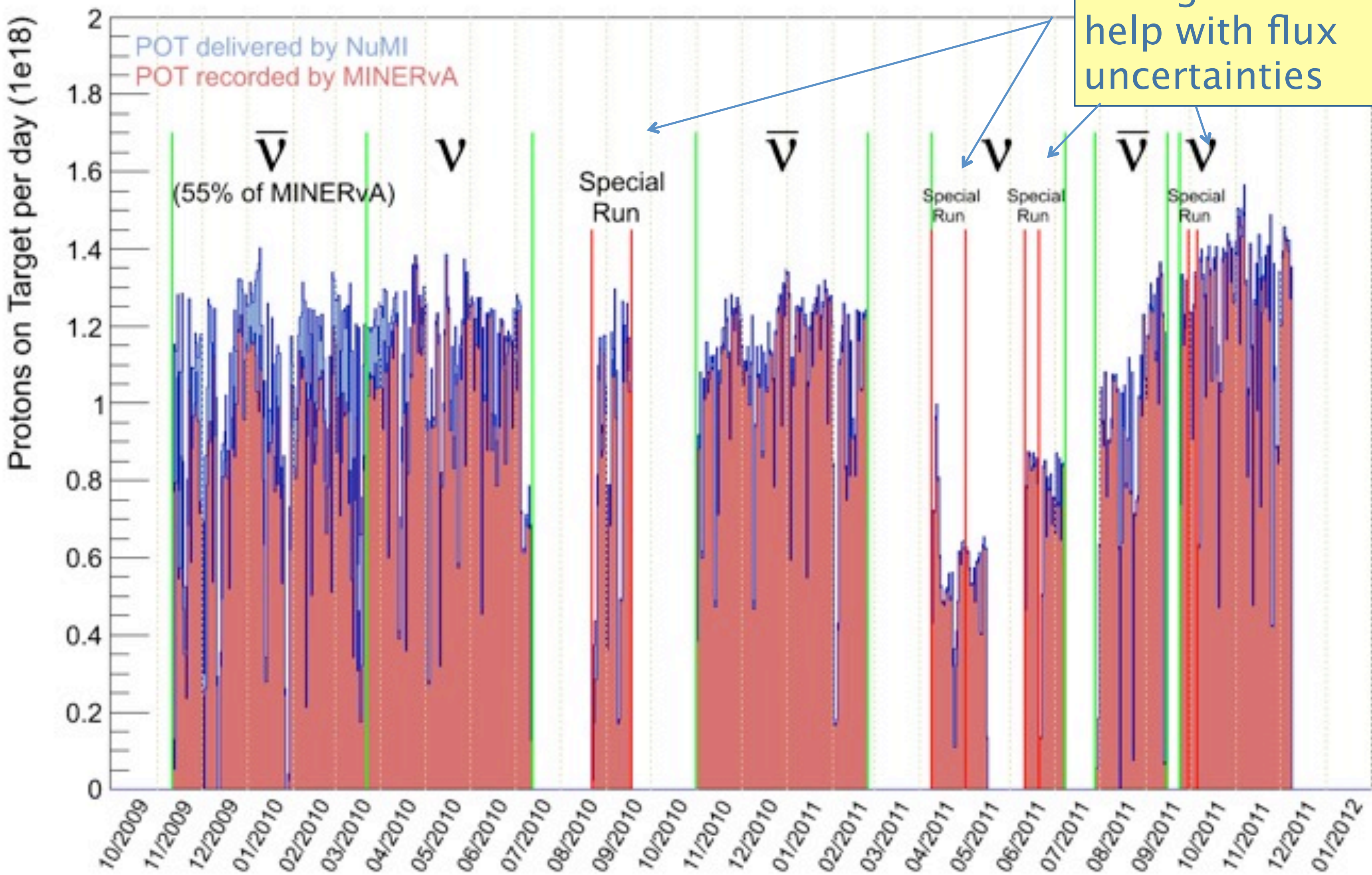
- MINERvA has the capability to study neutral pion production in various nuclei for both neutrino and anti-neutrino beam is important to be able to measure CP-violations and neutrino oscillation backgrounds.
- Cross-talk studies in photomultipliers are very important for accurate event reconstruction. My studies are now used by the MINERvA experiment to address this.
- Shower filter has a high efficiency for neutrino events(1-20 GeV region).
- The algorithm to isolate, reconstruct and identify electromagnetic showers is working good enough for neutral pion identification.
- The reconstruction of Neutral pions is acceptable to estimate their invariant mass, direction and energy, I have made considerable progress for MINERvA in this direction.

Backup Slides

MINERvA Data Collection

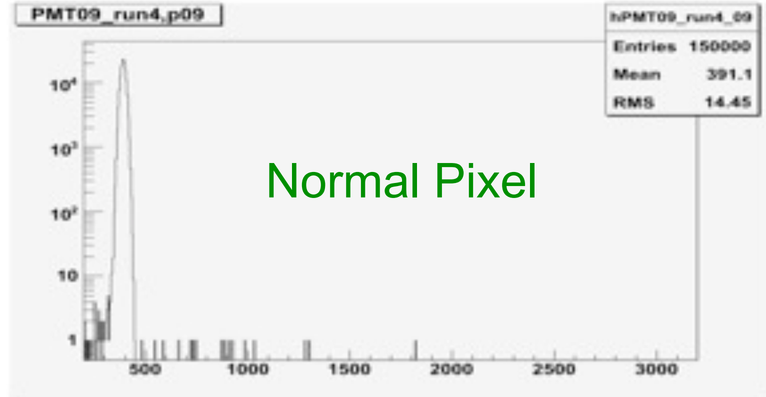
- MINERνA has been running with high efficiency and collected data in both the neutrino and antineutrino (LE) mode
- Less than 100 dead channels out of 32k channels

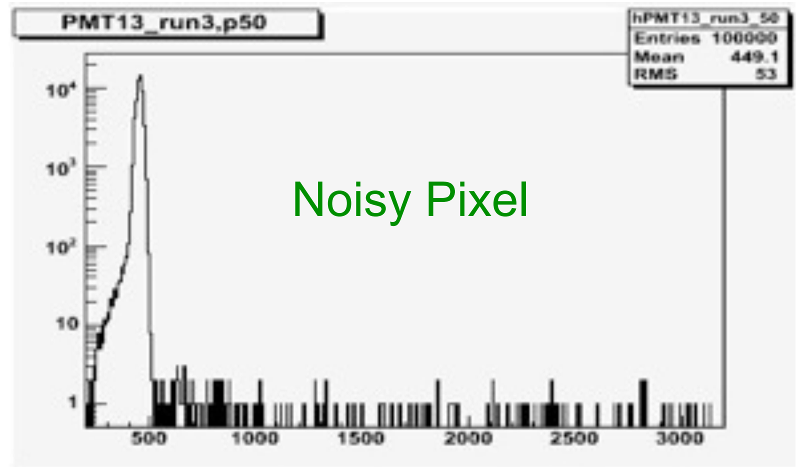
"special runs" in differing beam configurations to help with flux uncertainties

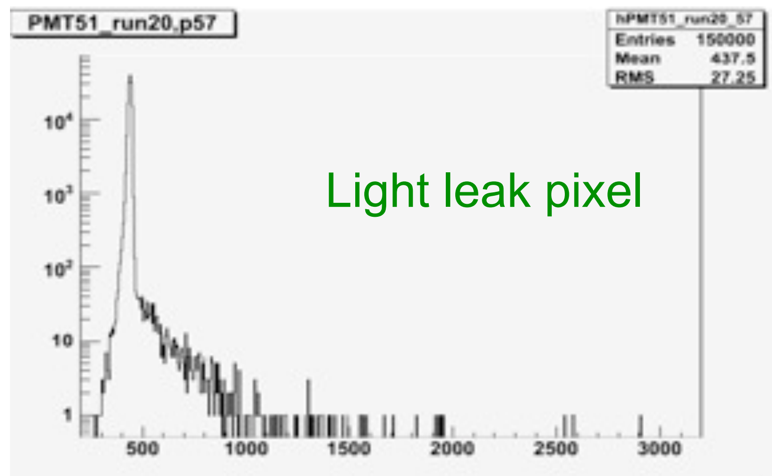


PMT Dark Noise Avg = 41.52 Hz

Methodology (abbreviated)
•Fit pedestal peak with Gaussian
•Measure rate of counts above pedestal +3.75 σ, for every pixel
•If rate is > 42Hz at 950V: need double check.







In this PMT:

the noise rate Avg = 76 Hz

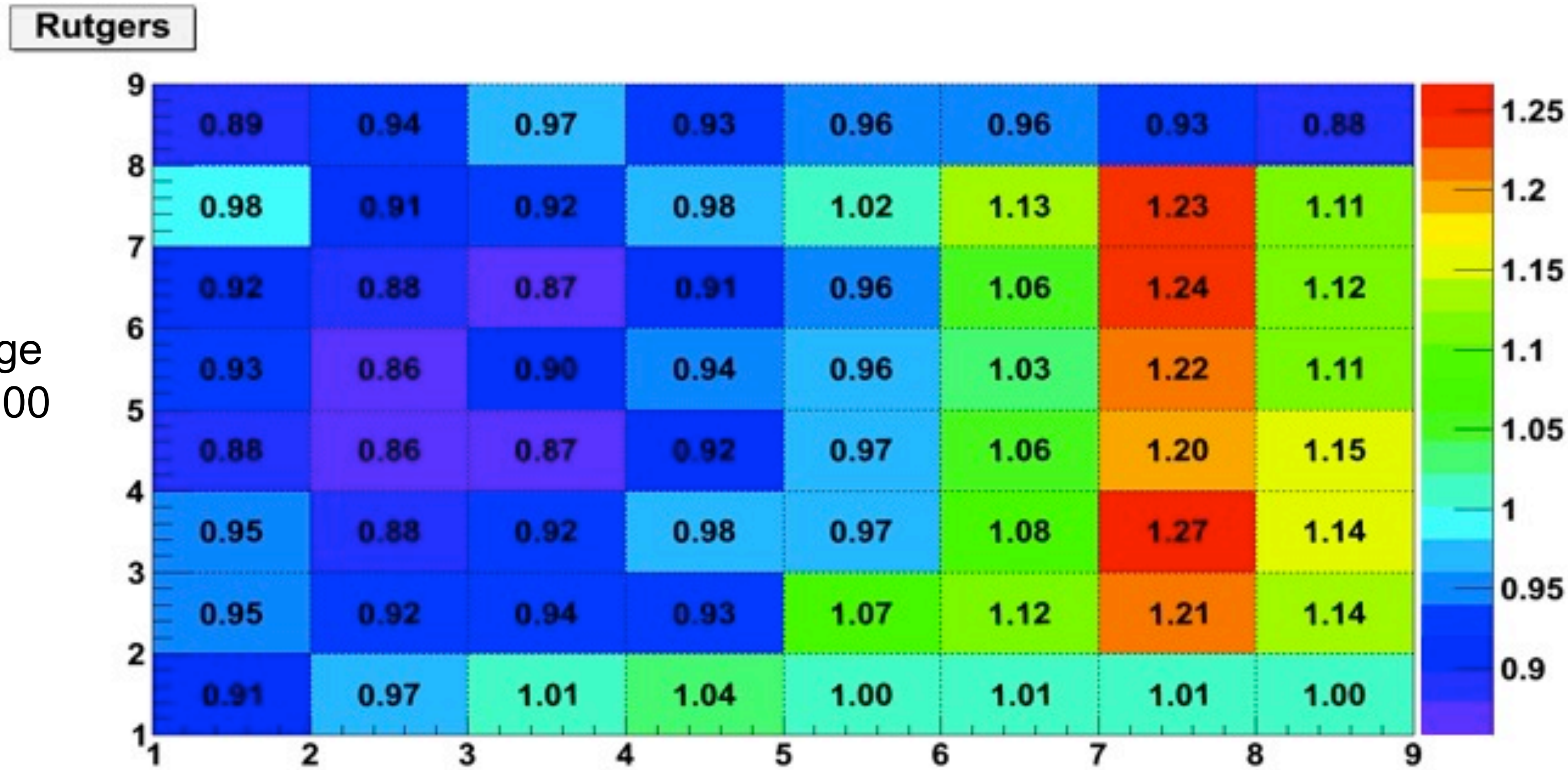
Covering the border this problem goes away

PMT

91	65	65	35	41	59	181	464
61	47	53	65	77	91	152	306
53	46	32	33	54	56	96	176
52	38	60	45	73	77	63	116
93	77	39	37	31	36	45	106
53	48	42	45	63	35	80	117
72	55	35	38	62	40	76	67
96	73	46	47	72	41	62	99

The red Pixels have more than 100Hz noise rate

PMT Relative Gains



Average over 200 PMTs

$$\text{Npe} = \frac{\text{Charge (mean)}^2}{\text{Charge(RMS)}^2 - \text{Pedestal(RMS)}^2}$$

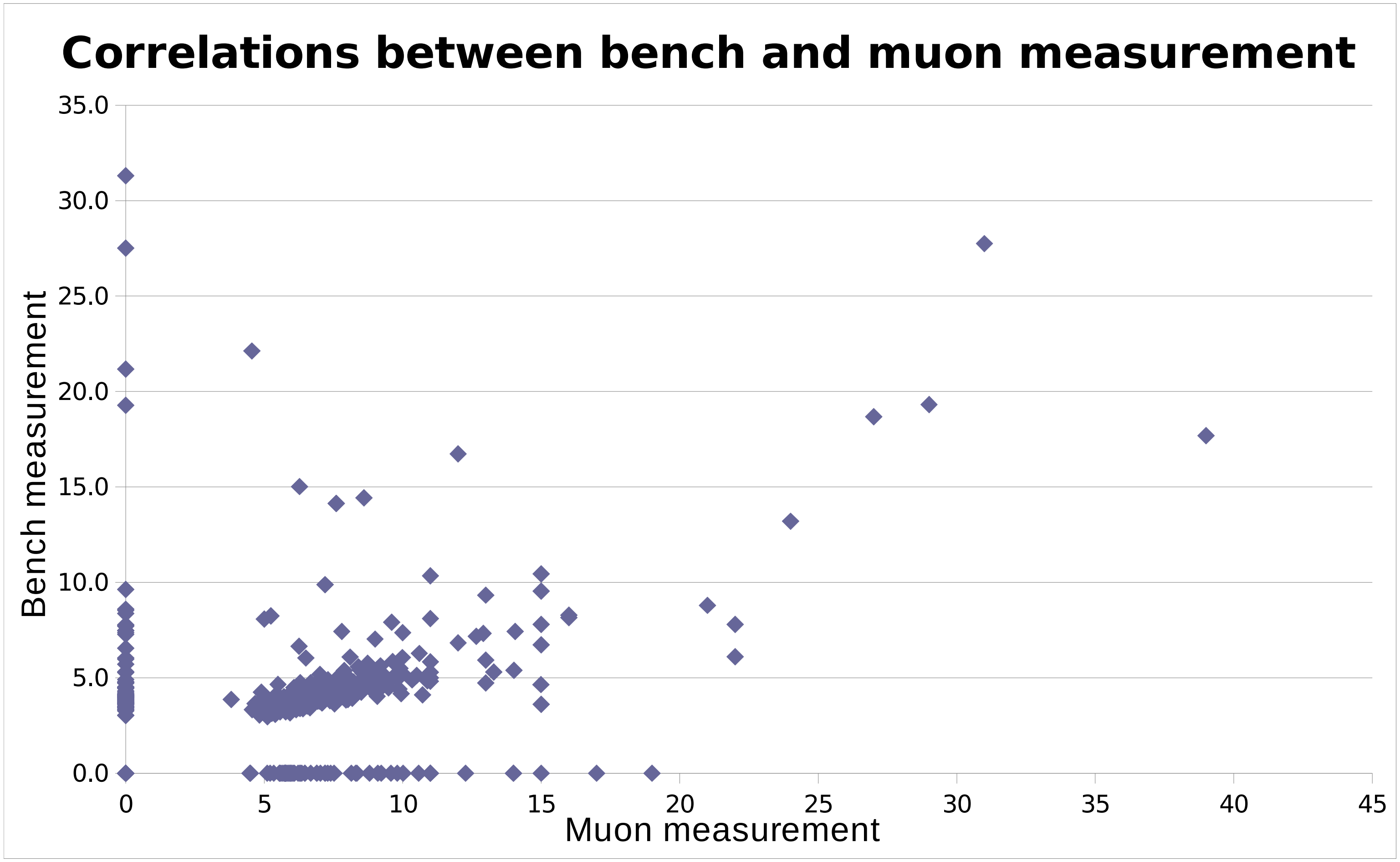
$\text{Ne} = \text{Charge(mean)} \times 1.6 \times 10^{-7}$

Gain= Ne/Npe

Gain Relative = Gain/ Average Gain

- Gain measured by,high PE Poisson statistics.
- Left area and upper edge have low gains.
- Very similar with the Hamamatsu Relative Gains.

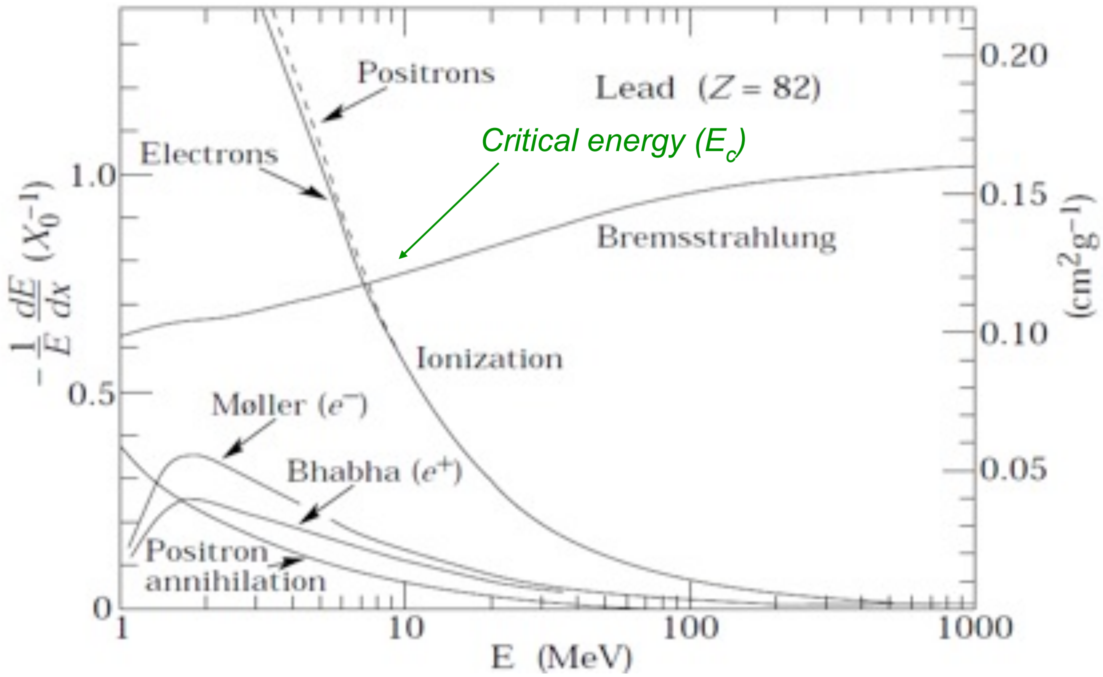
Cross-talk: measurement

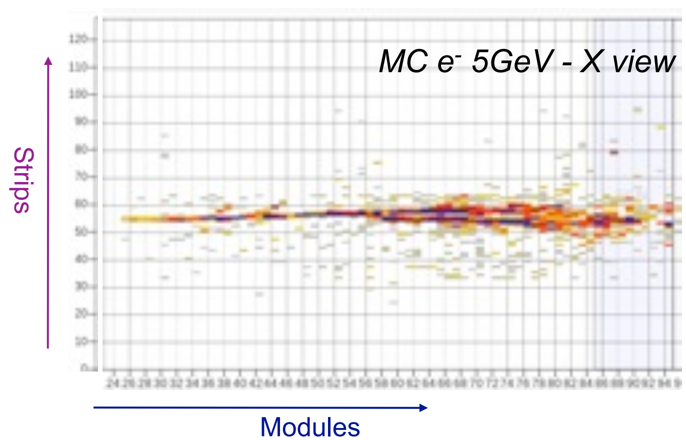


Correlation between muon and bench measurements of total cross-talk fraction.

EM showers

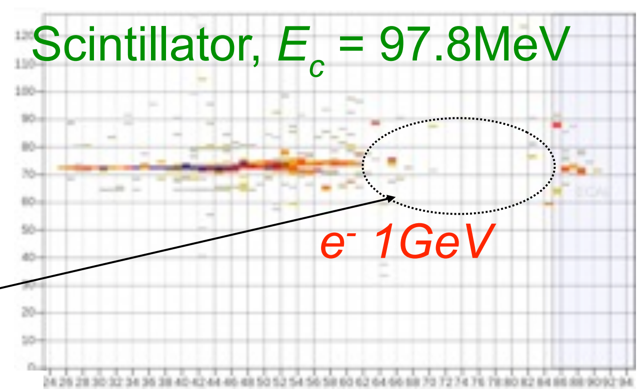
- Particle multiplication driven by bremsstrahlung(e^- and e^+) and pair production(γ).
- Ionization process is the most basic mechanism to deposit energy.

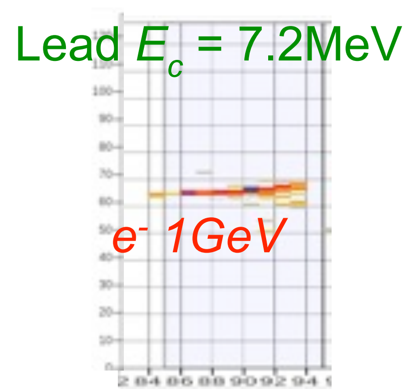




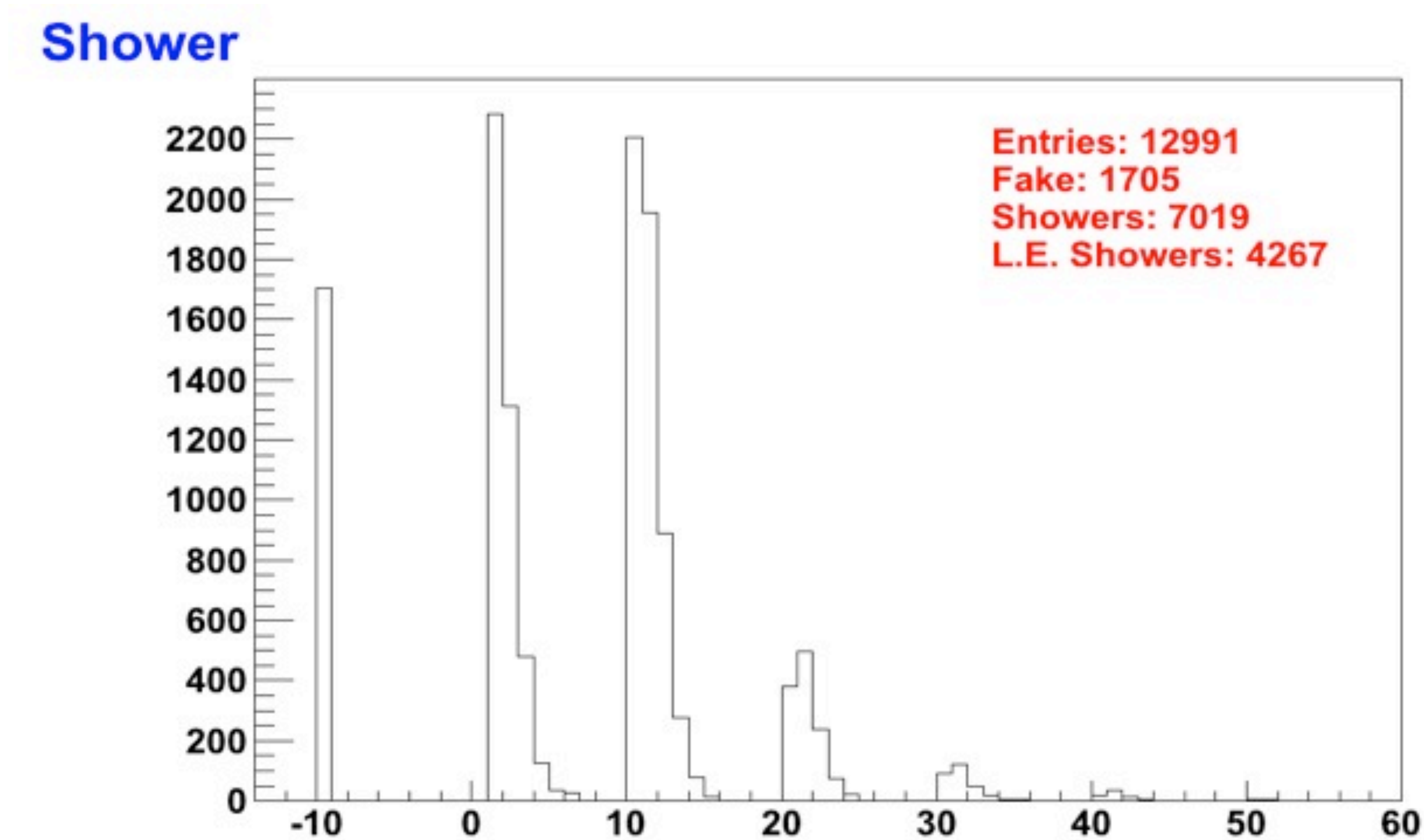
$$E_c = \frac{610\ \text{MeV}}{Z + 1.24}$$

- Particle multiplication is dominant when E_c(Z high) is lower than shower energy.
- There can be gaps when there are non energetic showers and high E_c.

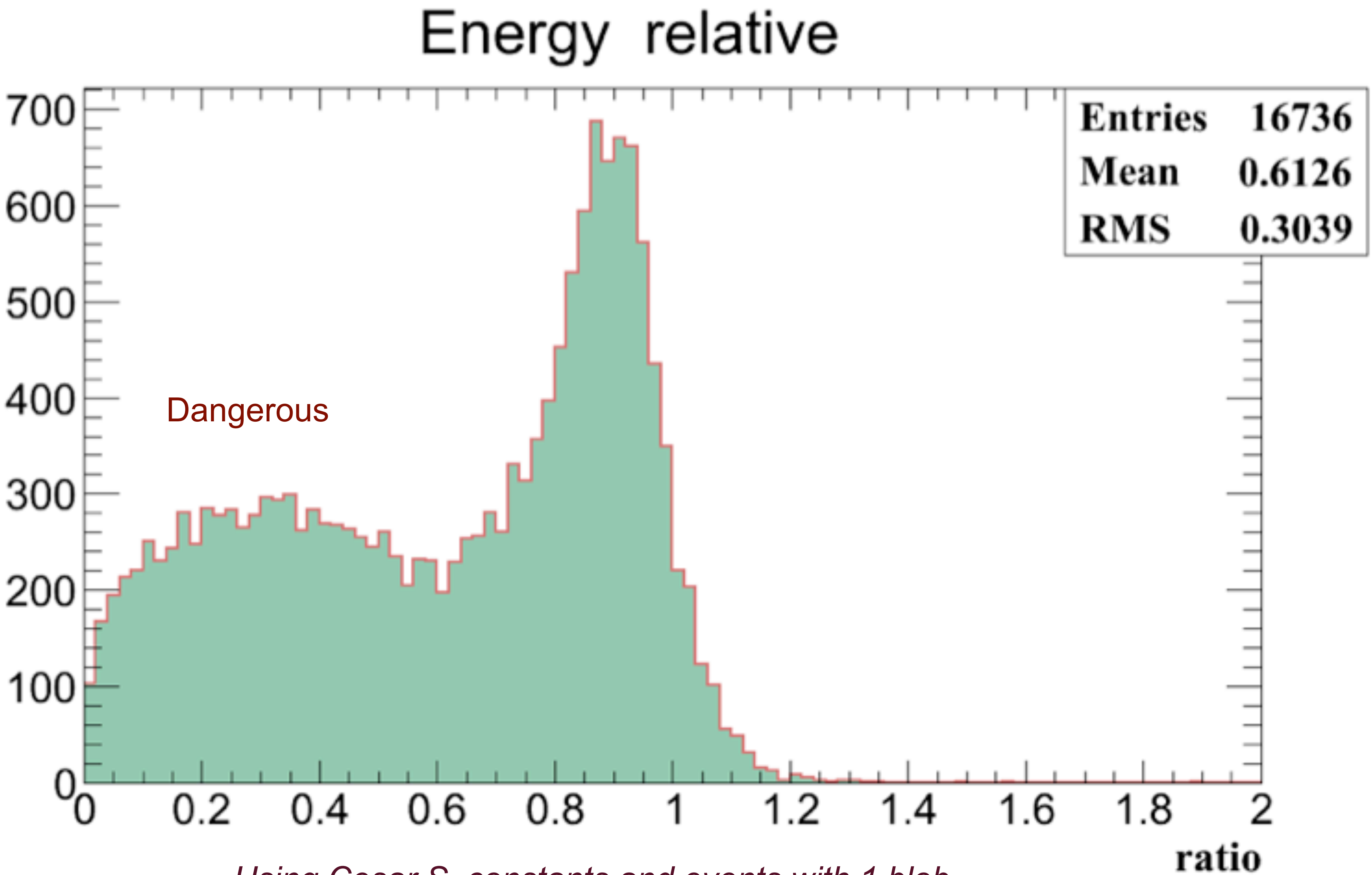




Shower Purity

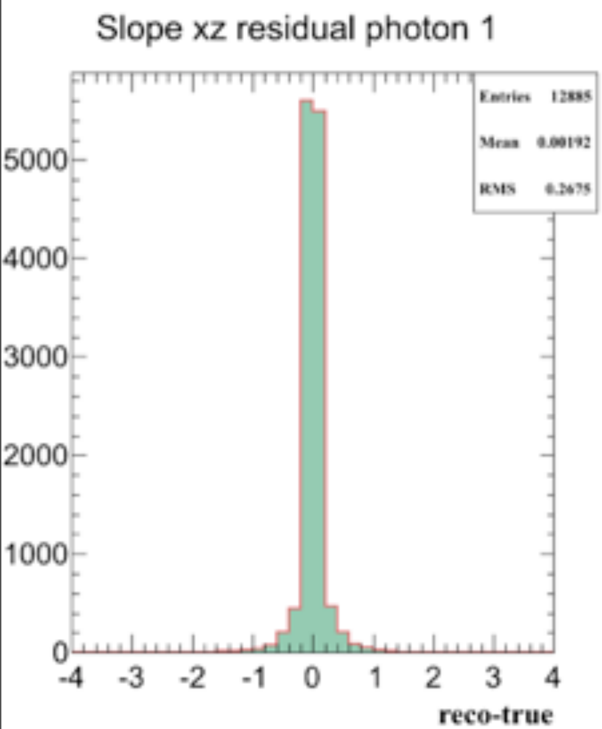


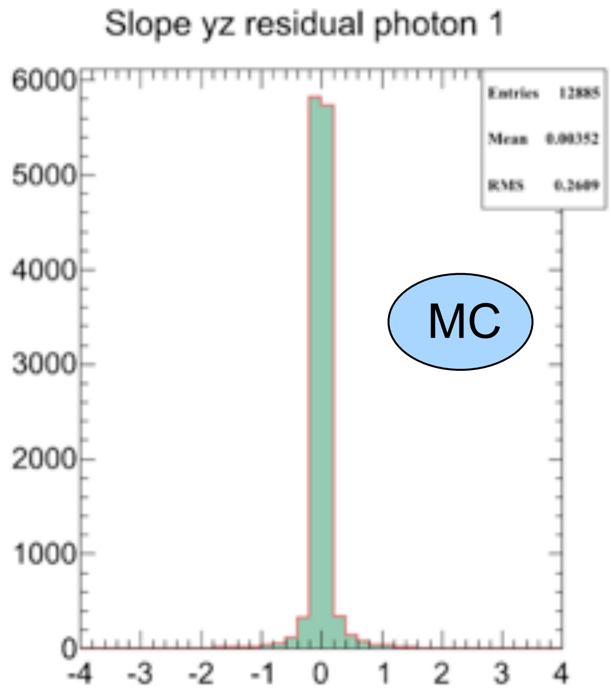
Reco Energy/True Energy



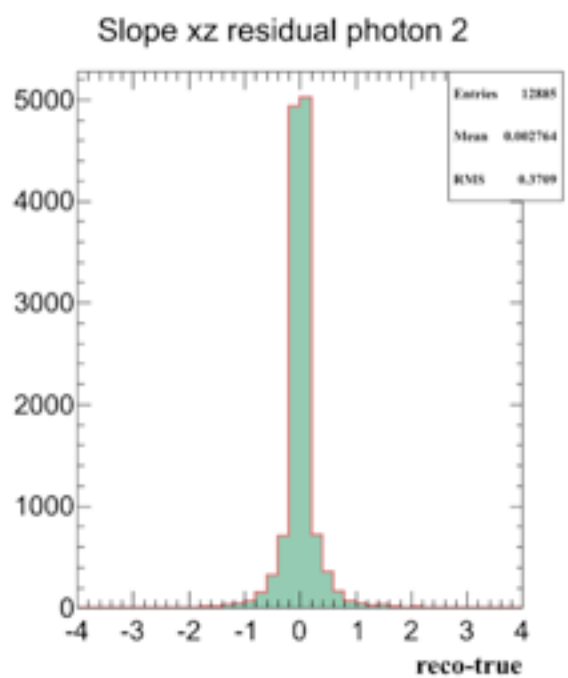
Using Cesar S. constants and events with 1 blob

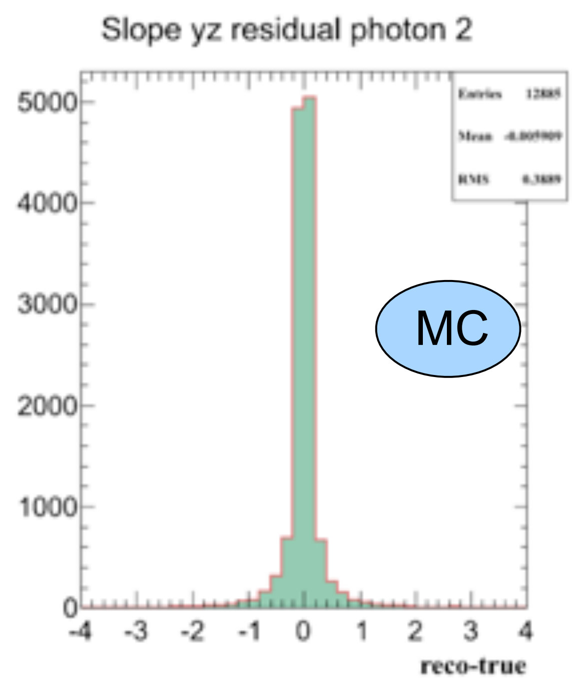
Slope residual - Photons(Pi0)

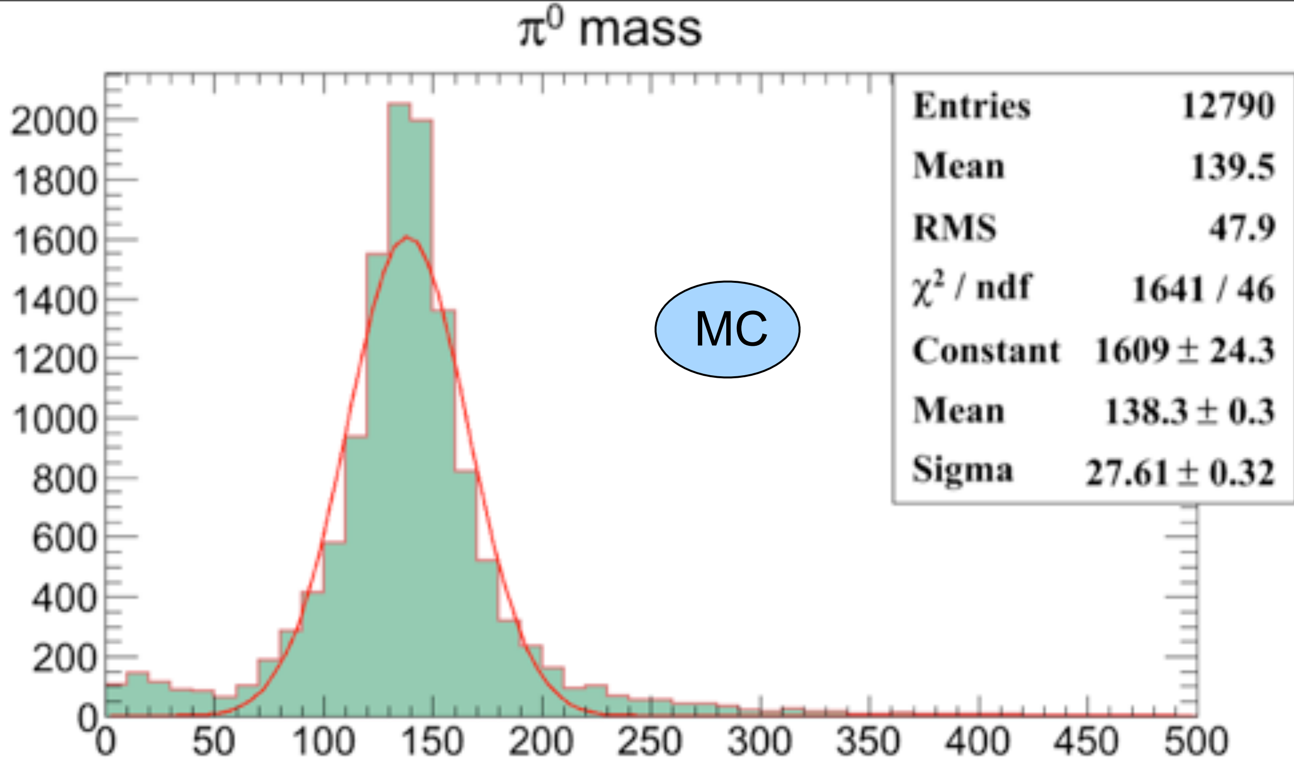




Slope is calculate using event vertex and blob(photon) vertex

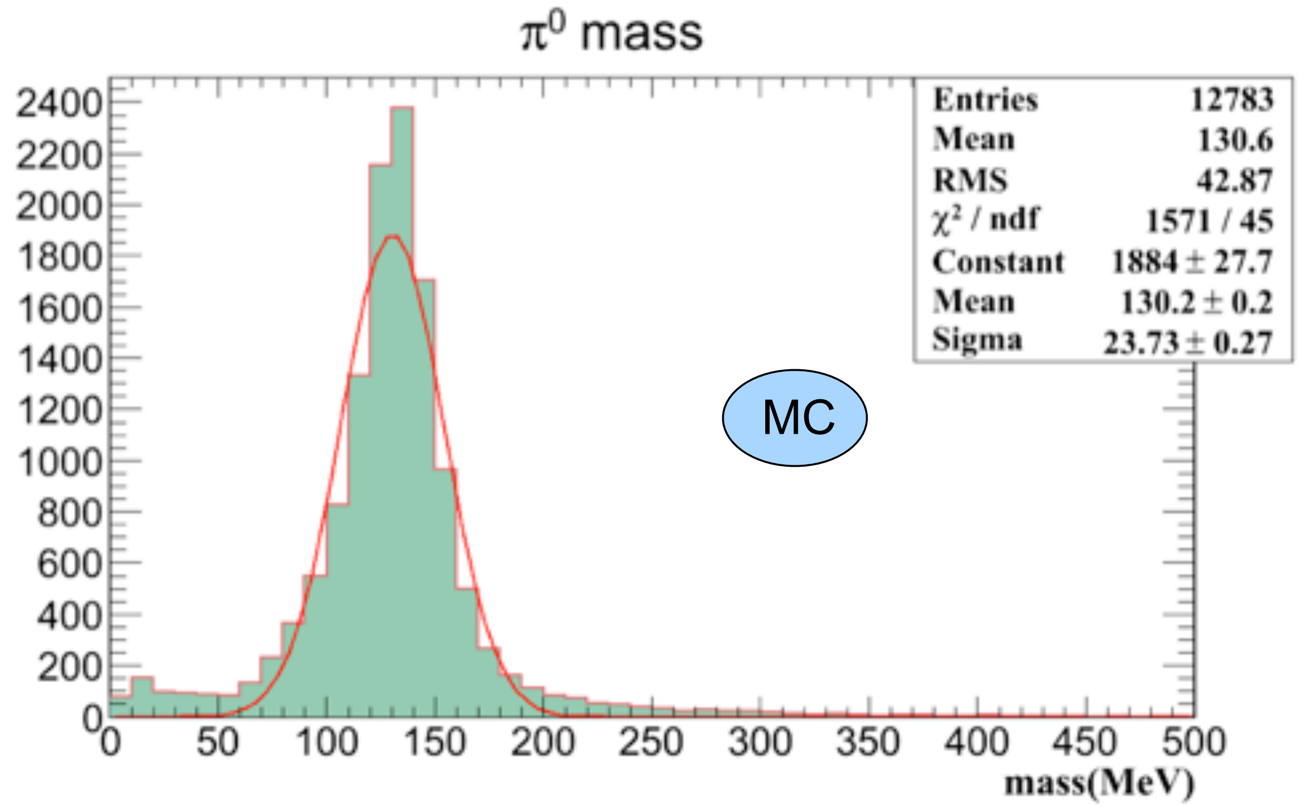


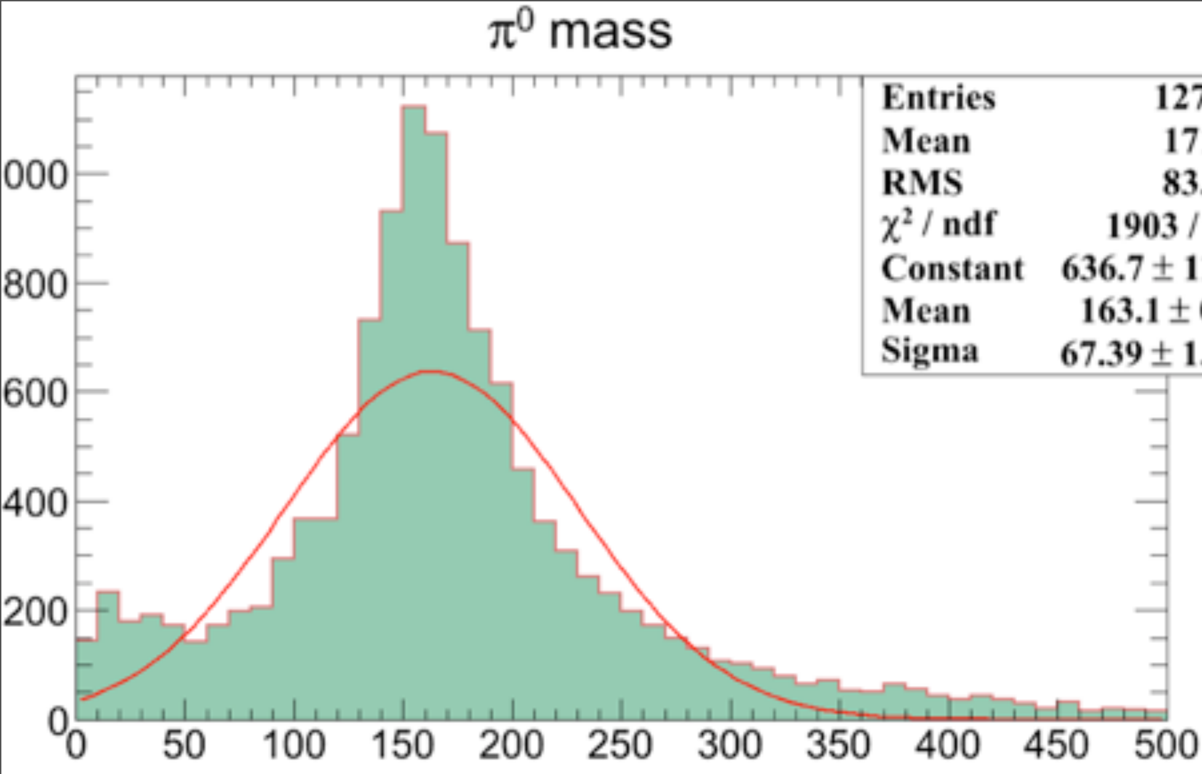




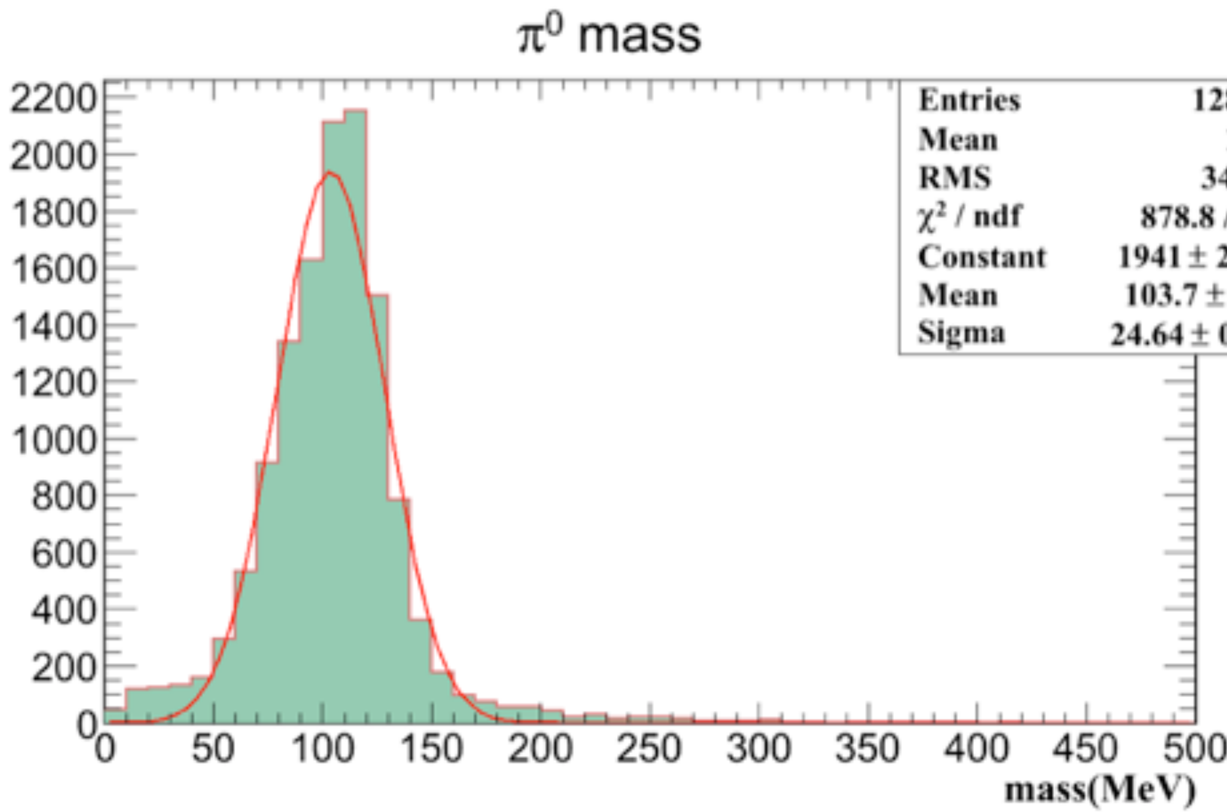
vtx_z + 10mm

vtx_z - 10mm



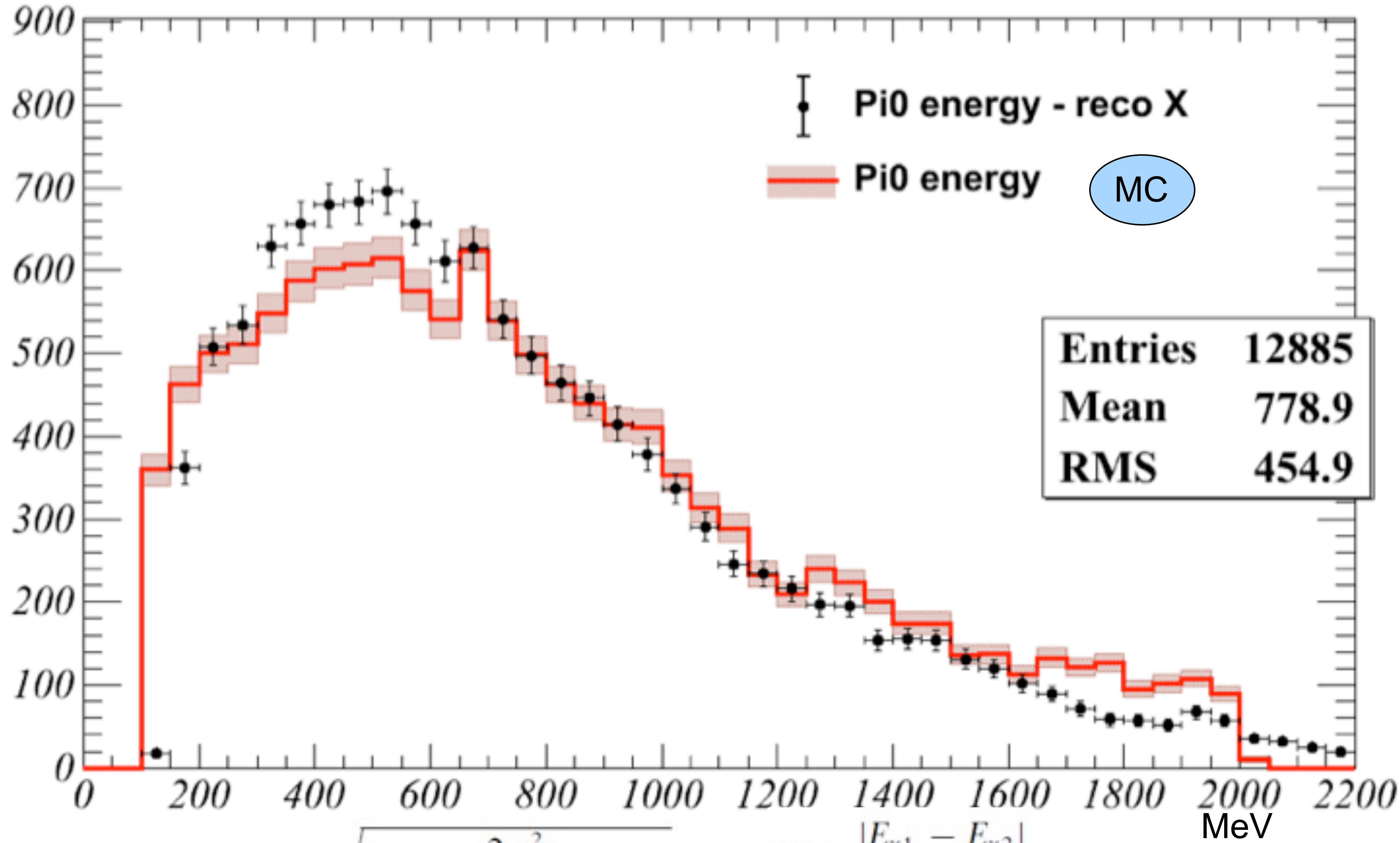


vtx_z + 100mm



vtx_z - 100mm

Pi0 Energy reconstruction



$$E_\pi = \sqrt{\frac{2m_\pi^2}{(1-X^2)(1-\cos\theta_{\gamma\gamma})}} \qquad X = \frac{|E_{\gamma 1} - E_{\gamma 2}|}{E_{\gamma 1} + E_{\gamma 2}}$$