Verification Package

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1 How to Run the Verification Package

The following are the detailed steps on how to run the verification package. These steps are encapsulated in the RunVerificationPackage.sh script.

1. Create a list file that contains the `paths/filenames` of the simulation files you want to use as input. For these instructions I will refer to two lists named sample1.list and sample2.list.

2. Pull and compile the `gm2analyses/` package. The code that fills the histograms in the verification package are located in the Verification directory and the macros that analyze the histograms are in the macros directory. The RunVerificationPackage.sh script is in the the macros directory as well.

3. Run AllHits.fcl over the list file and produce a hist.root file with the same naming convention as the list file.

   > gm2 -c AllHits.fcl -S sample1.list -T sample1.hist.root

4. Run the VerificationPlotter.C macro over sample1.hist.root file and produce a sample1.list.VPlots.pdf file. Note the backslash syntax required in front of the open (close) quotes and parentheses when running from the command line. The default setting produces plots for all detector and beam packages. If you would like to select a specific detector package change the first option from "0" to the desired number (see code).

   > root.exe -b -q VerificationPlotter.C\(0,\"sample1.hist.root\",
   \"sample1.VPlots.pdf\"\)

5. The VerificationTrackChanges.C macro requires two input histogram files, so repeat steps 1 and 3 and produce sample2.list and sample2.hist.root. Then run VerificationTrackChanges.C over the sample1.hist.root and sample2.hist.root and produce a sample1_sample2.Changes.pdf file with the same naming convention that reflects the naming convention of the two hist.root input files.

   > root.exe -b -q VerificationTrackChanges.C\(\"sample1.hist.root\",
   \"sample2.hist.root\",

`\"sample1_sample2.Changes.pdf\",0\)`

6. Load the output files from steps 3-5 into samweb. Move hist.root and pdf files to /pnfs/GM2/scratch/users/ and setup the environment. Note it is assumed that sample1.hist.root was previously loaded.

   > cd `/pnfs/GM2/scratch/users/Verification`

   > setup `fife_utils v2_8`

   > kinit

   > kx509

   > export `SAM_EXPERIMENT = gm2`

   > `sam_add_dataset -d pnfs/GM2/scratch/users/Verification -n sample2.hist.root`

   > `sam_add_dataset -d pnfs/GM2/scratch/users/Verification -n sample2.VPlots.pdf`

   > `sam_add_dataset -d pnfs/GM2/scratch/users/Verification -n sample1_sample2.Changes.pdf`

   > update metadata for each set if necessary

7. Steps 3 and 4 can be run by executing the RunVerificationPackage.sh script with one input list file

   > ./RunVerificationPackage.sh sample1.list

8. Steps 3, 4 and 5 can be run by executing the RunVerificationPackage.sh script with two input list files

   > ./RunVerificationPackage.sh sample1.list sample2.list

9. Steps 3, 4, 5 and 6 can be executed by setting the samweb flag (to be implemented)

   > ./RunVerificationPackage.sh sample1.list sample2.list -sam

2 Description of plots produced by Verification-Plotter.C

2.1 Detector Hits in Ring Coordinates

Figure 1 shows the location and orientation of the major ring and detector components.

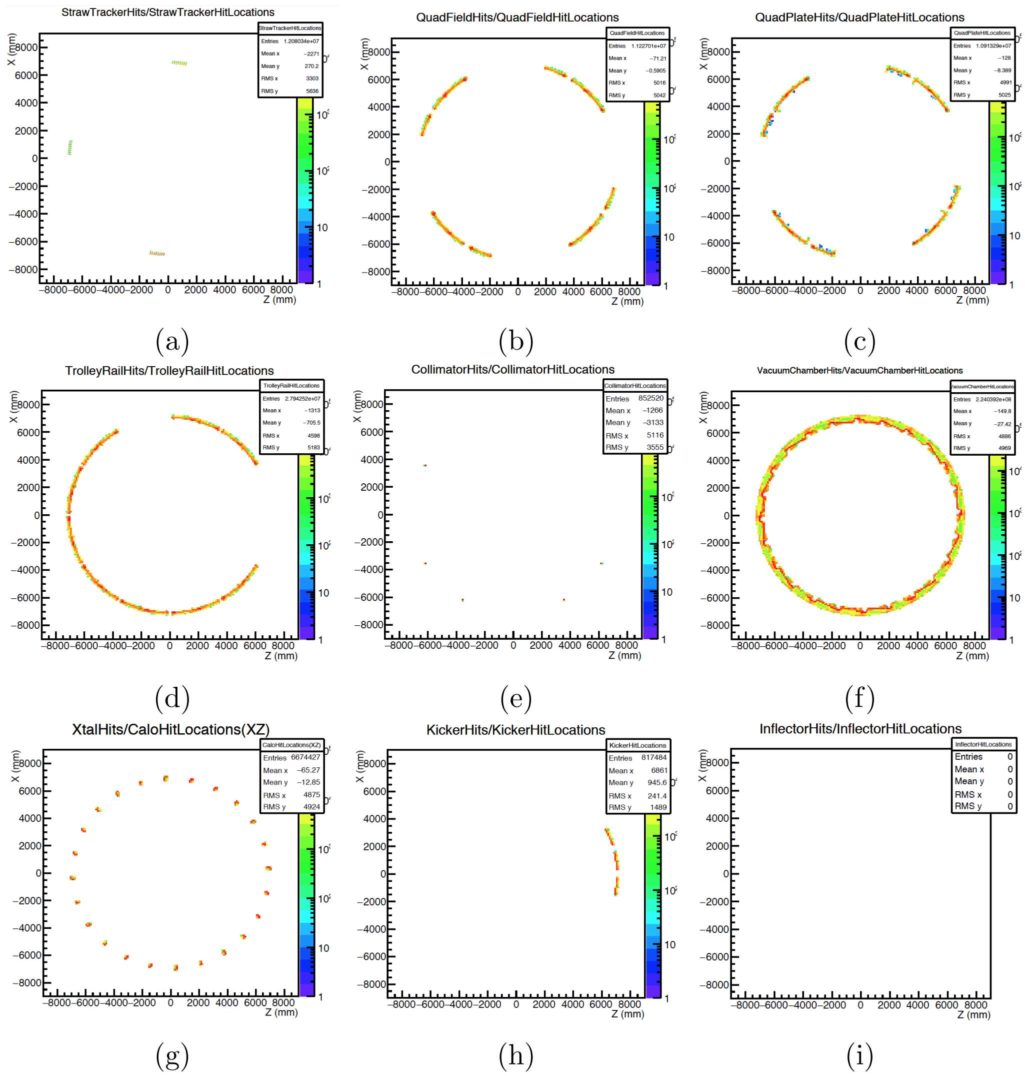


Figure 1: Detector Hit Location Plots (Page 1 of *list_name*.VPlots.pdf)

a. Straw Tracker Hit Locations
There are 3 straw trackers located in stations 0,12,18 around the ring. Station 0 is located at the top of the ring and the station numbers count up clockwise around the ring.

b. Quad Field Hit Locations
The field region is defined as the space bounded by the inside of the vacuum chamber wall and the outside of the trolley rails and quad plates. There should be four quad field regions since they span the same angular region as the quad plates.

c. Quad Plate Hit Locations
There are four quad plate regions, labeled 0 - 4 starting from the upper right and going clockwise. Each region consists of a short and long quad plate. The short (long) pairs of plates are located in vacuum chambers 0,3,6,9 (1,4,7,10).

d. Trolley Rail Hit Locations
In reality trolley rails span the entire ring. Currently, the inflector and kicker portions are still being designed and thus are not included in the simulation. This is the reason for the two gaps in hits found in Figure 1d. Those will be added when they are finalized.

e. Collimator Hit Locations
There are 5 full collimators located in vacuum chambers 4,5,7,8,10.

f. Vacuum Chamber Hit Locations
We expect the vacuum chamber hits to be distributed around the entire ring. Following the trajectory of the decay positrons, the hits increase towards the center of the ring.

g. Calorimeter Hit Locations (XZ)
There are 24 calorimeters evenly distributed around the ring, one in each station.

h. Kicker Hit Locations
There are three kickers located on the right side of the ring used to kick the muons into the correct orbit.

i. Inflector Hit Locations
Currently, the inflector hits are not included in the simulation since we are using a gas gun to place hits in the ring.

2.2 Gas Gun

The 9 charts in Figure 2 are designed to check different aspects of the muon gas gun used to fill the ring and produce hits.

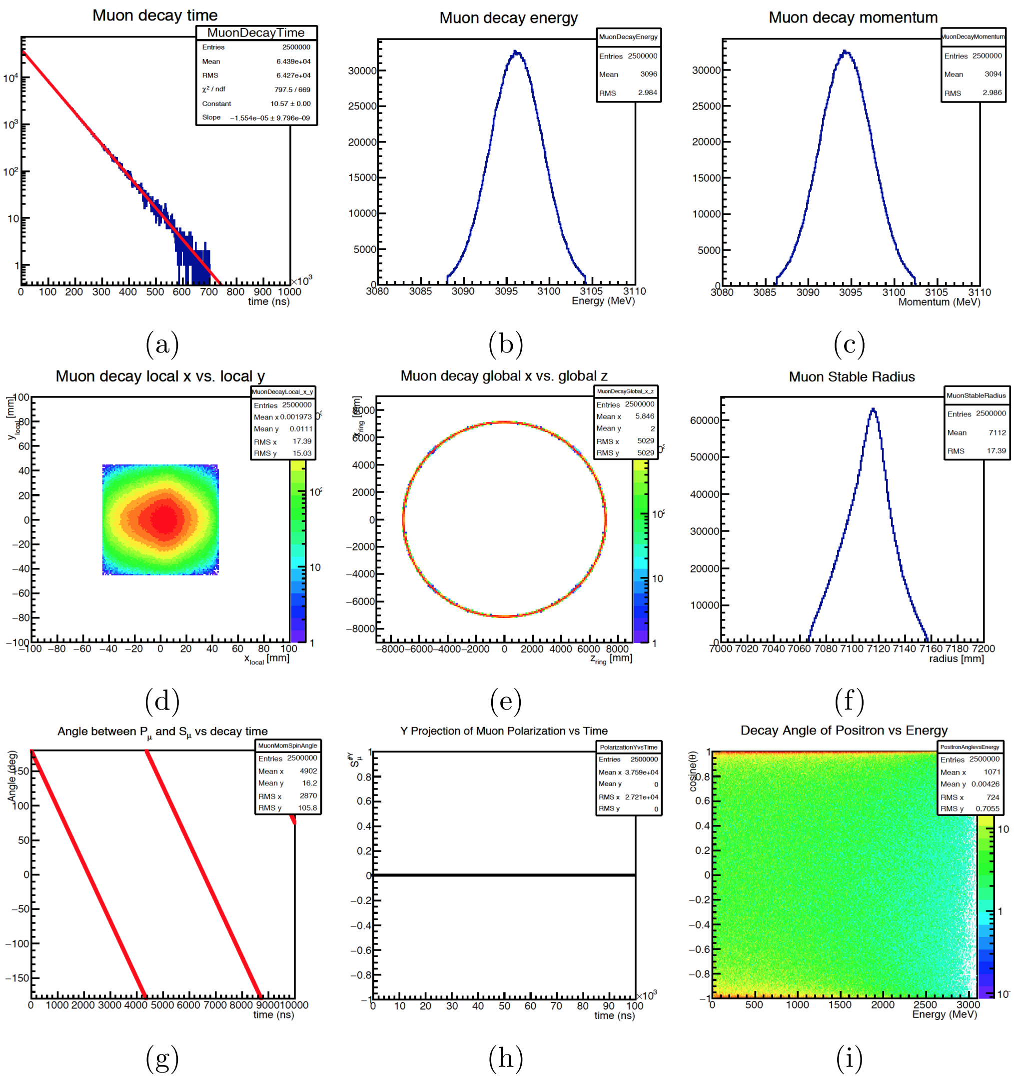


Figure 2: Gas Gun Plots (Page 2 of *list_name*.VPlots.pdf)

a. Muon Decay Time

The muon distribution is expected to follow an exponential decay of the form

$$N \sim N_0 e^{-t/\gamma\tau} \tag{1}$$

where τ is the lifetime of the muon in the muon rest frame. By plotting time on a logarithmic scale, we expect to get a linear plot with a slope of $-1/\gamma\tau = -1.55 \times 10^{-5} ns^{-1}$.

b. Muon Decay Energy

The energy distribution is expected to be Gaussian and centered around the energy, E, corresponding to the magic momentum, p_{magic}, and mass of the muon, m_μ,

$$E^2 = p_{magic}^2 + m_\mu^2 \tag{2}$$

$$E = 3096\, MeV$$

The width is expected to be about 1% of the mean.

c. Muon Decay Momentum

The momentum is expected to be a Gaussian distribution, centered around the magic momentum which is

$$p_{magic} = \frac{m_\mu}{\sqrt{a_\mu}} = 3094\, MeV \tag{3}$$

The width is expected to be about 1% of the mean.

d. Muon Decay (local x vs. local y)

This plot provides a cross-sectional view of the muon decay locations in the ring. We expect the decays to be centered at $localx = localy = 0$ and to follow a gaussian distribution with a width of 15 mm each.

e. Muon Decay (global x vs. global z)

This figure is a global view of the muon decays around the ring.

f. Muon Stable Radius

The radius of orbit should peak at the magic radius of 7112 mm.

g. Angle Between P_μ and S_μ vs Decay Time

The angle between P_μ and S_μ was found by taking the arctangent(atan2) of the cross product over the dot product:

$$\frac{P_\mu \times S_\mu}{P_\mu \cdot S_\mu} = \frac{|P_\mu||S_\mu|sin\theta}{|P_\mu||P_\mu|cos\theta} = tan\theta \tag{4}$$

The angle should be maximized at time zero and decrease for a period. This period should match the period of the precession with respect to momentum, 4370 ns.

h. Y Projection of Muon Polarization vs Time
When a nonzero EDM is present, this will oscillate, otherwise it should be a flat line at y = 0.

i. Decay Angle of Positron vs Energy
The cosine of the angle between P_{e^+} and S_μ was found by dividing the dot product by the magnitudes:

$$\frac{P_{e^+} \cdot S_\mu}{|P_{e^+}||S_\mu|} = \frac{|P_{e^+}||S_\mu|cos\theta}{|P_{e^+}||S_\mu|} = cos\theta \tag{5}$$

As expected, the momenta of higher energy decay positrons preferentially align with the muon spin.

2.3 Calorimeter

2.3.1 All Calorimeters

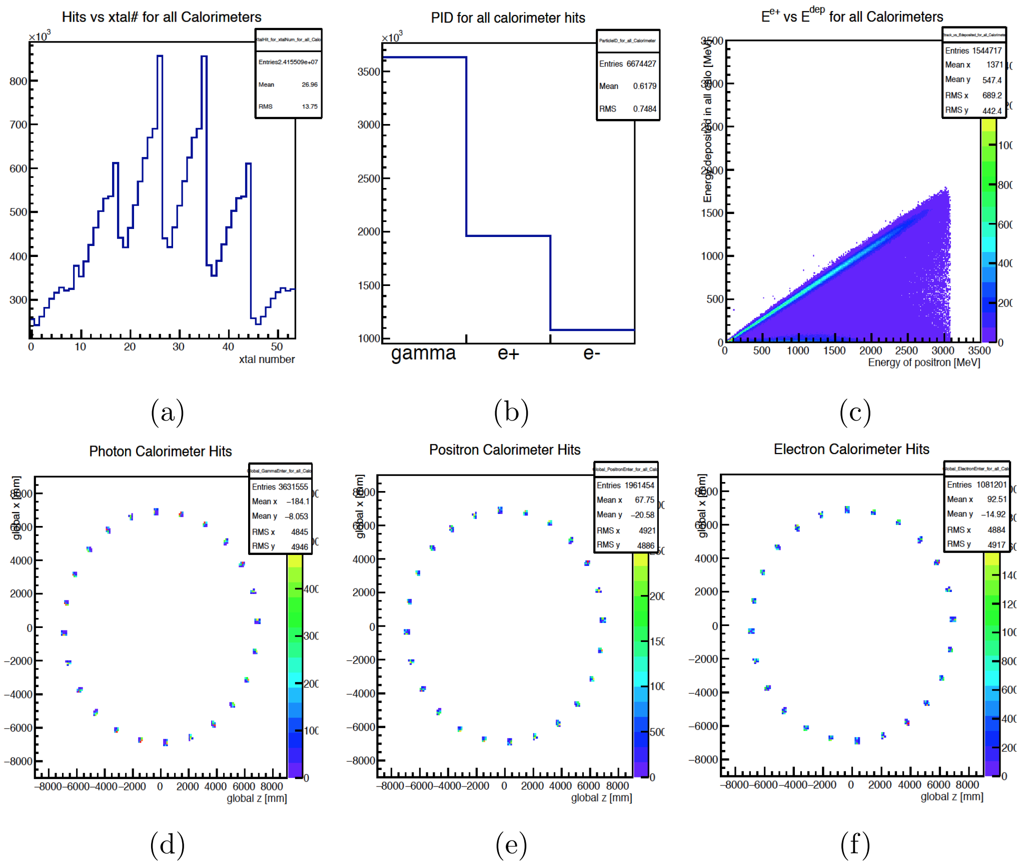


Figure 3: All Calorimeter Hits (Page 3 of *list_name*.VPlots.pdf)

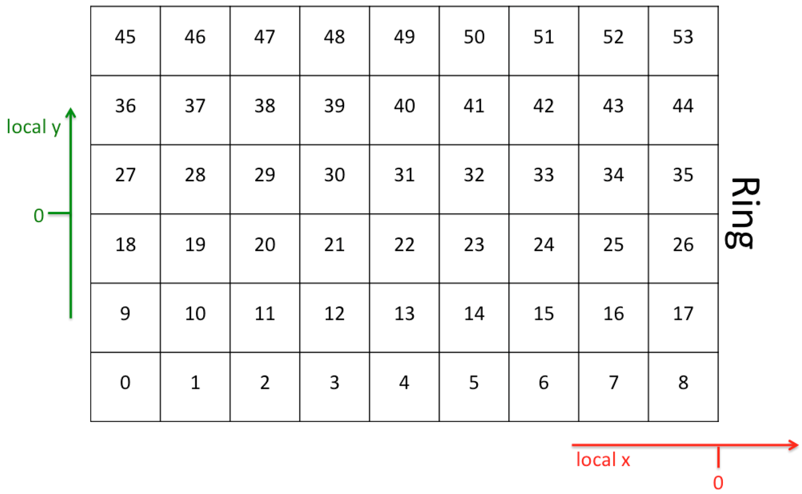


Figure 4: Crystal Configuration in Calorimeters

a. **Hits vs Xtal for All Calorimeters**
In each calorimeter, there are 54 crystals. Figure 4 shows the numbering scheme of the crystals. The crystals with the most hits are those closest to the ring.

b. **PID for All Calorimeter Hits**
This plot gives the number of photon, positron, and electron hits in the calorimeters. As expected, there should be more positron hits than electron hits.

c. **E_{e^+} vs E_{dep} for All Calorimeters**
This plot compares the energy of the decay positron with the energy that it deposits in the crystals of all the calorimeters.

d. **Photon Calorimeter Hits**
A global view of photon hits in the calorimeters.

e. **Positron Calorimeter Hits**
A global view of positron hits in the calorimeters.

f. **Electron Calorimeter Hits**
A global view of electron hits in the calorimeters.

2.3.2 For Each Calorimeter

The crystals in the calorimeters are arranged as seen in Figure 4.

a. Hits vs Xtal for Each Calorimeter
In Figure 5, there are 24 plots, one for each calorimeter. Each plot displays the distribution of hits in the corresponding calorimeter by crystal number.

b. PID for All Hits for Each Calorimeter
In Figure 6, there are 24 plots, one for each calorimeter. Each plots gives the number of photon, positron, and electron hits in the calorimeter.

c. Hit Locations (local x vs local y) for Each Calorimeter
Figure 7 is a two dimensional view of the hits in each calorimeter. Notice that there are more hits located on the right side of the calorimeters. The thin vertical streaks located more near the center and not on the edges are often due to single positrons that are trapped in the face of the calorimeter. This is reflected in PID plots as well. Pages 8-10 show the same plots for photons, positrons, and electrons. Notice in the photon plots the outline of the manifold structure can be seen in Calorimeters 0,12,18.

d. E_{e^+} vs E_{dep}
Figure 8 shows the decay positron energy vs the energy deposited in the calorimeter for each of the twenty four calorimeters.

Hits by Type for Each Calorimeter
The hits in each calorimeter have been further divided into the three different types of particles (photons, positrons, electrons).

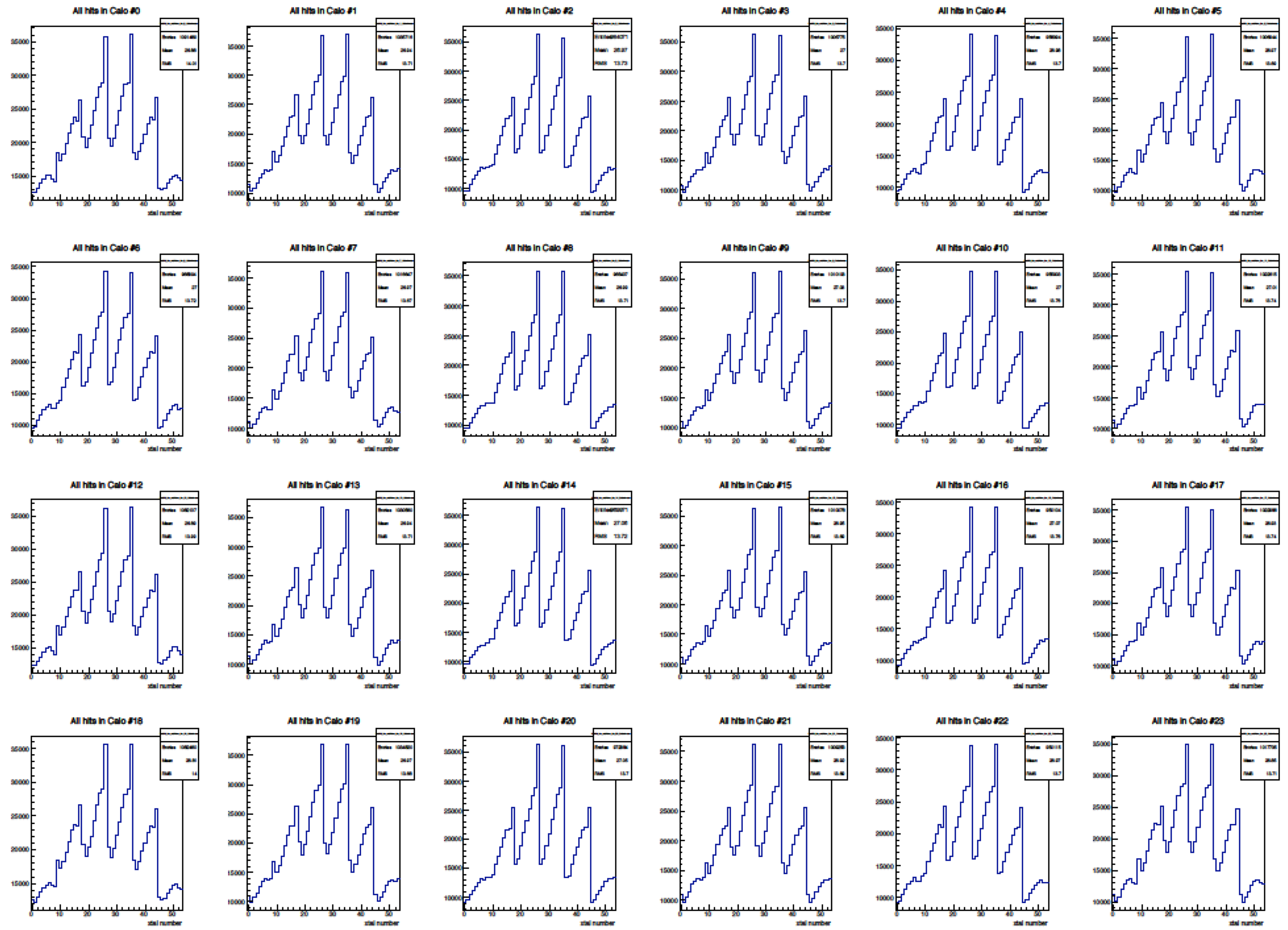


Figure 5: Hits vs Xtal for Each Calorimeter (Page 4 of *list_name*.VPlots.pdf)

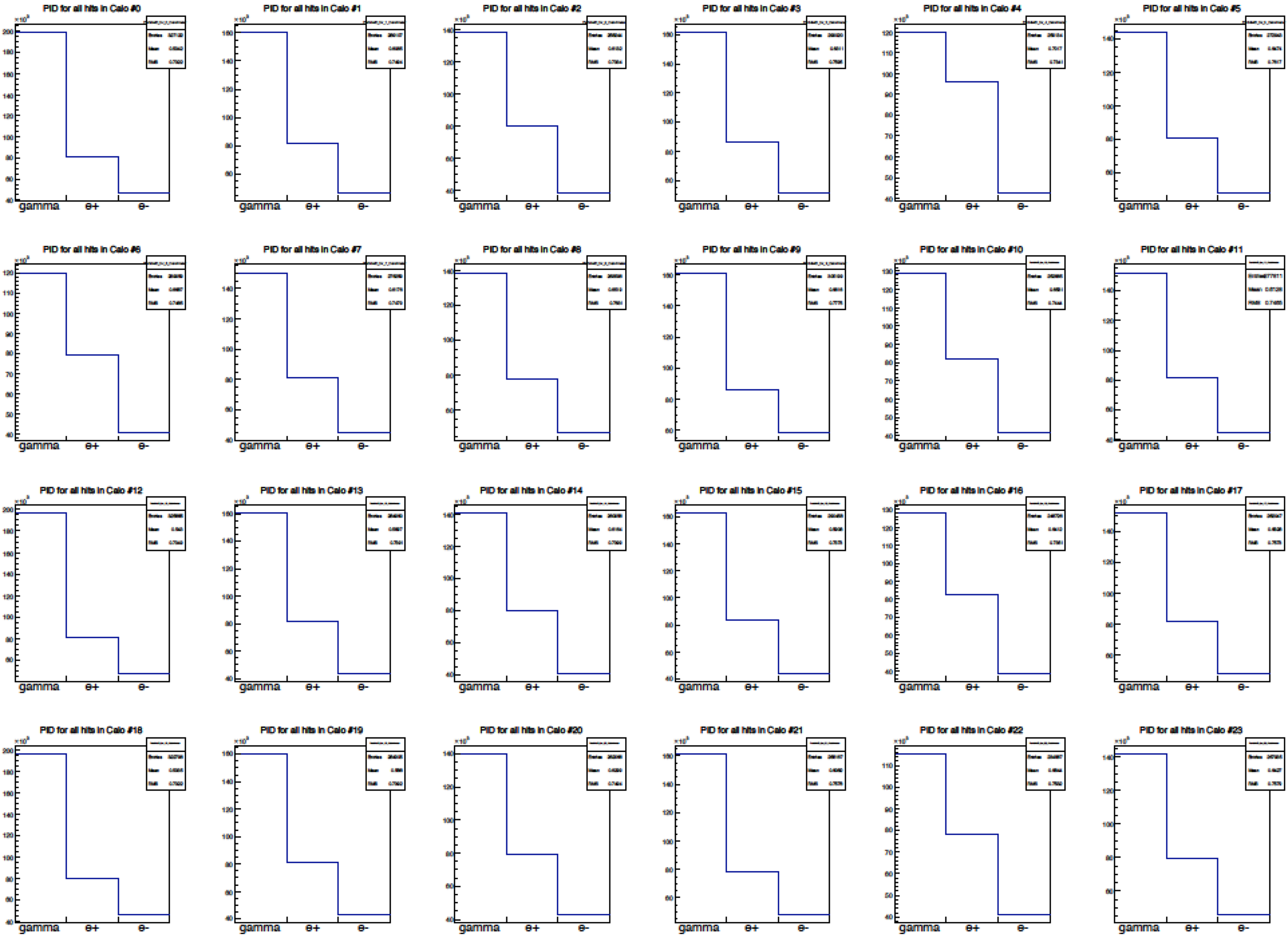


Figure 6: PID for Each Calorimeter (Page 5 of *list_name*.VPlots.pdf)

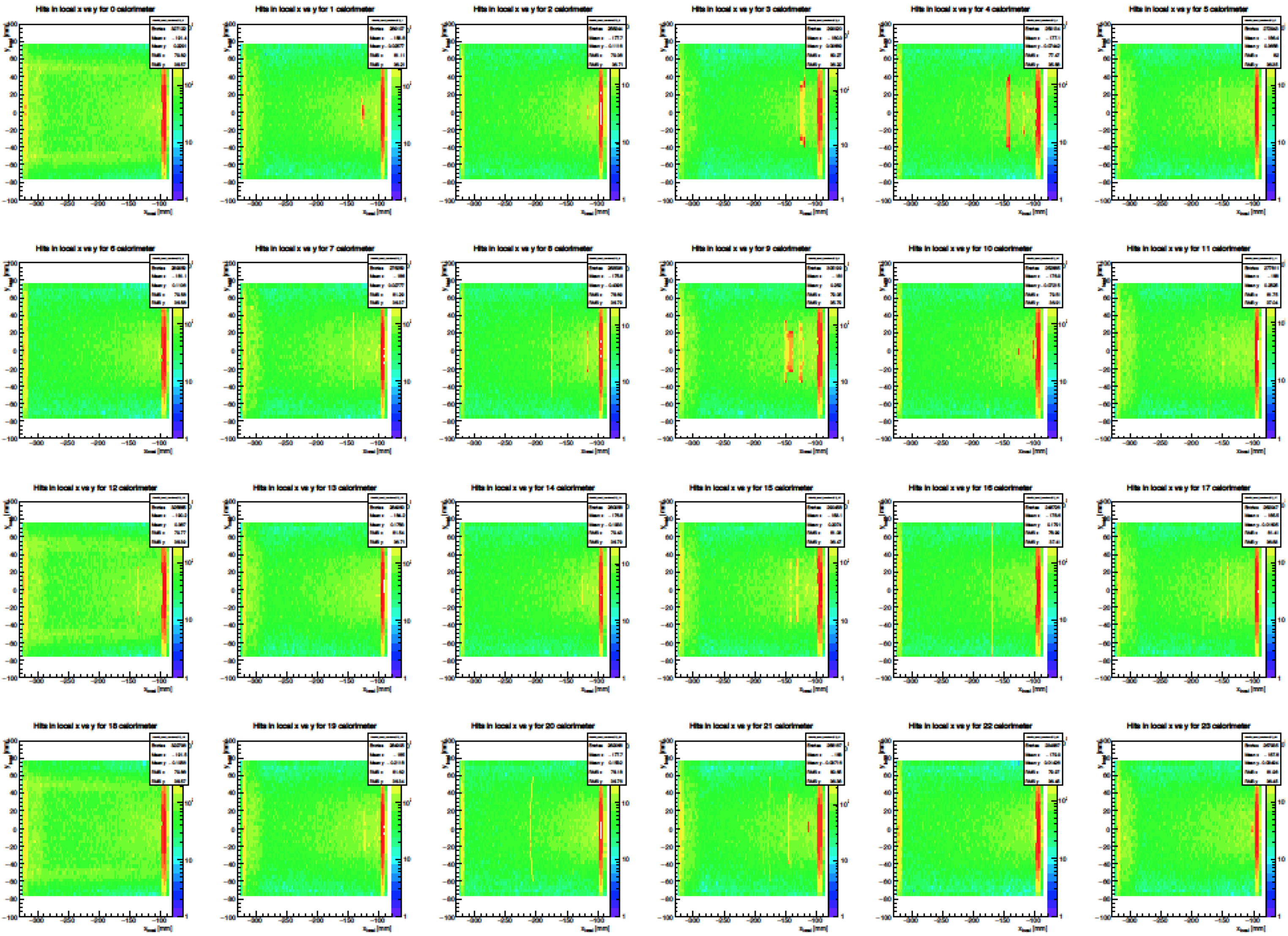


Figure 7: Hit Locations for Each Calorimeter (Page 6 of *list_name*.VPlots.pdf)

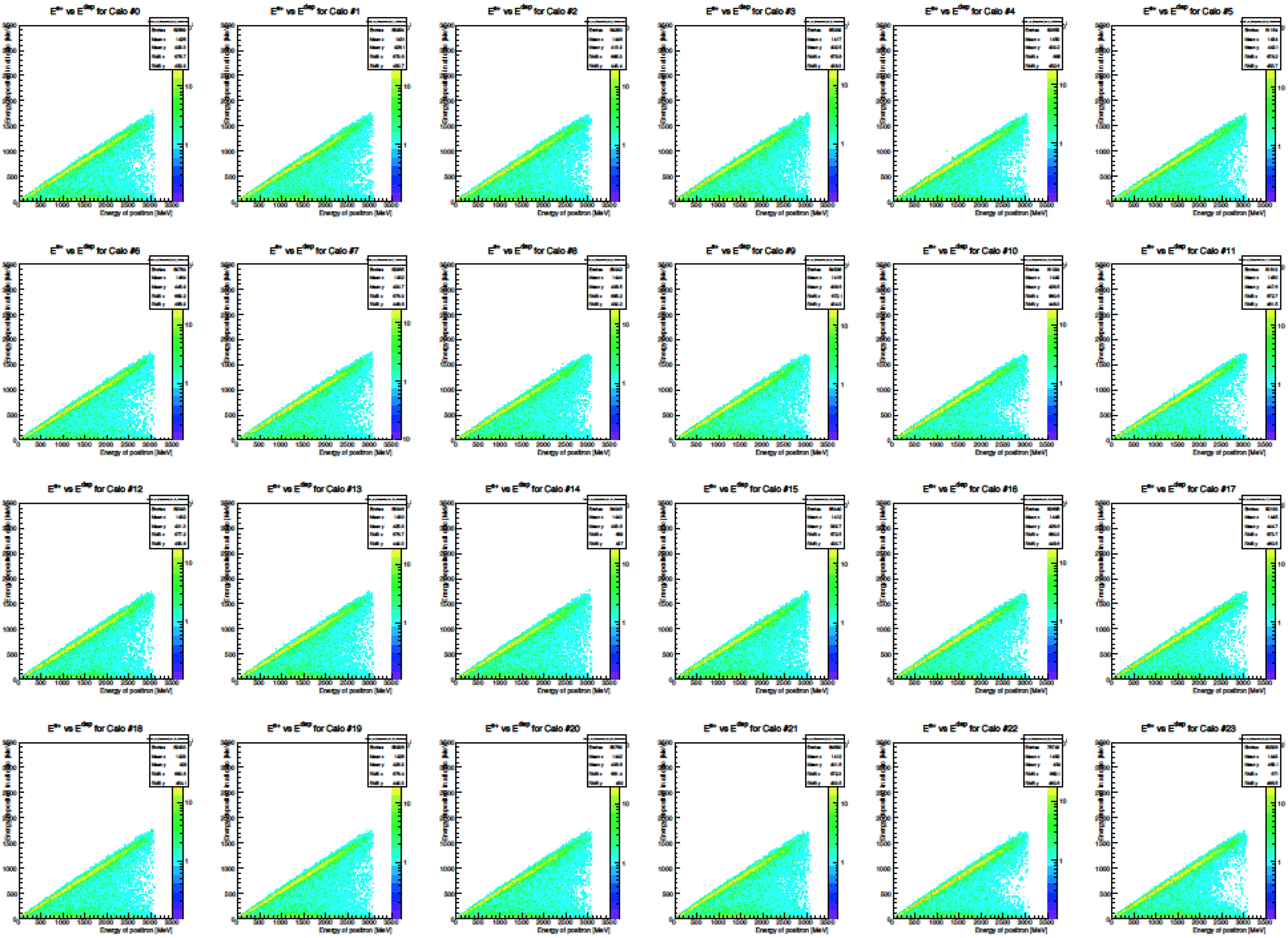
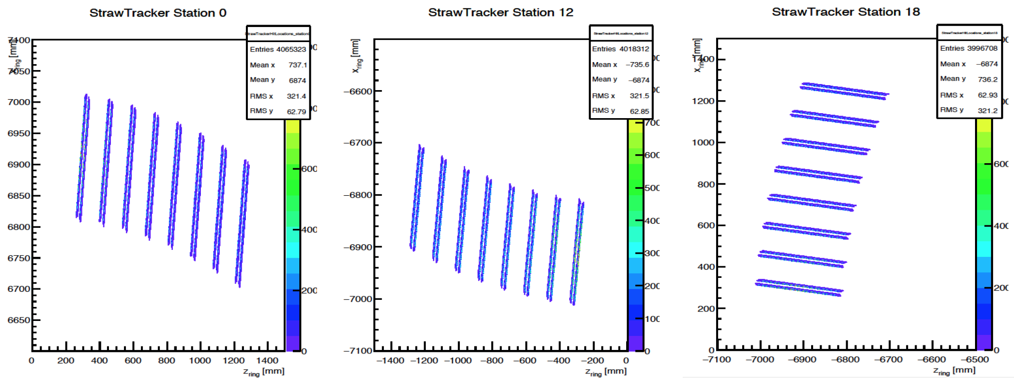


Figure 8: E_{e^+} vs E_{dep} for Each Calorimeter (Page 7 of *list_name*.VPlots.pdf)

2.4 Straw Trackers

2.4.1 Straw Tracker Hit Locations

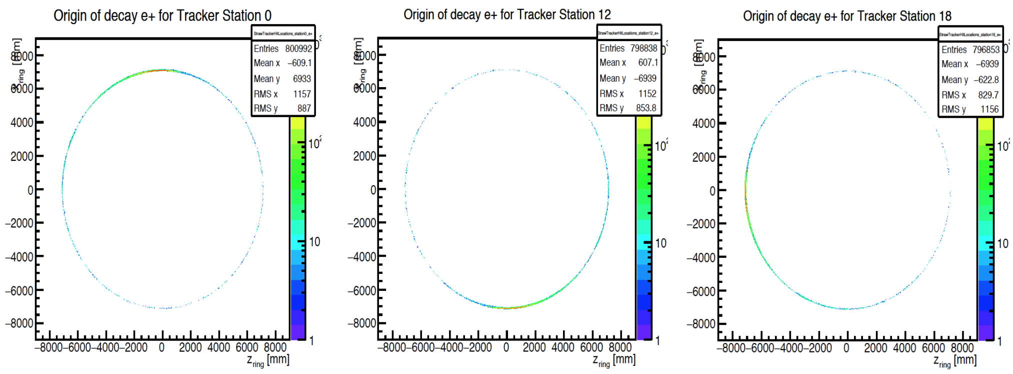


(a) (b) (c)

Figure 9: Straw Tracker Hits (Page 11 of *list_name*.VPlots.pdf)

There is a plot for each of the 3 straw tracker stations. Since the hits are plotted in global coordinates, the orientation of the straw trackers changes depending on the station's location on the ring.

2.4.2 Origin of Decay Positron



(a) (b) (c)

Figure 10: Origin of Straw Tracker Hits (Page 12 of *list_name*.VPlots.pdf)

These plots show the birth location of the decay positron that hit the straw trackers.

2.4.3 Straw Tracker Hits by Module

Each straw tracker has 8 modules and each module has 4 layers. The top two rows of Figure 11 shows the distribution of decay positron, e^+, hits in the four different layers of each module in the Station 0 Straw Tracker. The bottom two rows show the distribution of hits by straw number integrated over all layers. The subsequent pages (14-15) in *list_name*.VPlots.pdf show similar plots for the decay e^+ hits in modules 12 and 18. Pages 16-18 show similar plots for hits from secondary particles (electrions, photons, postitrons) in each of the modules.

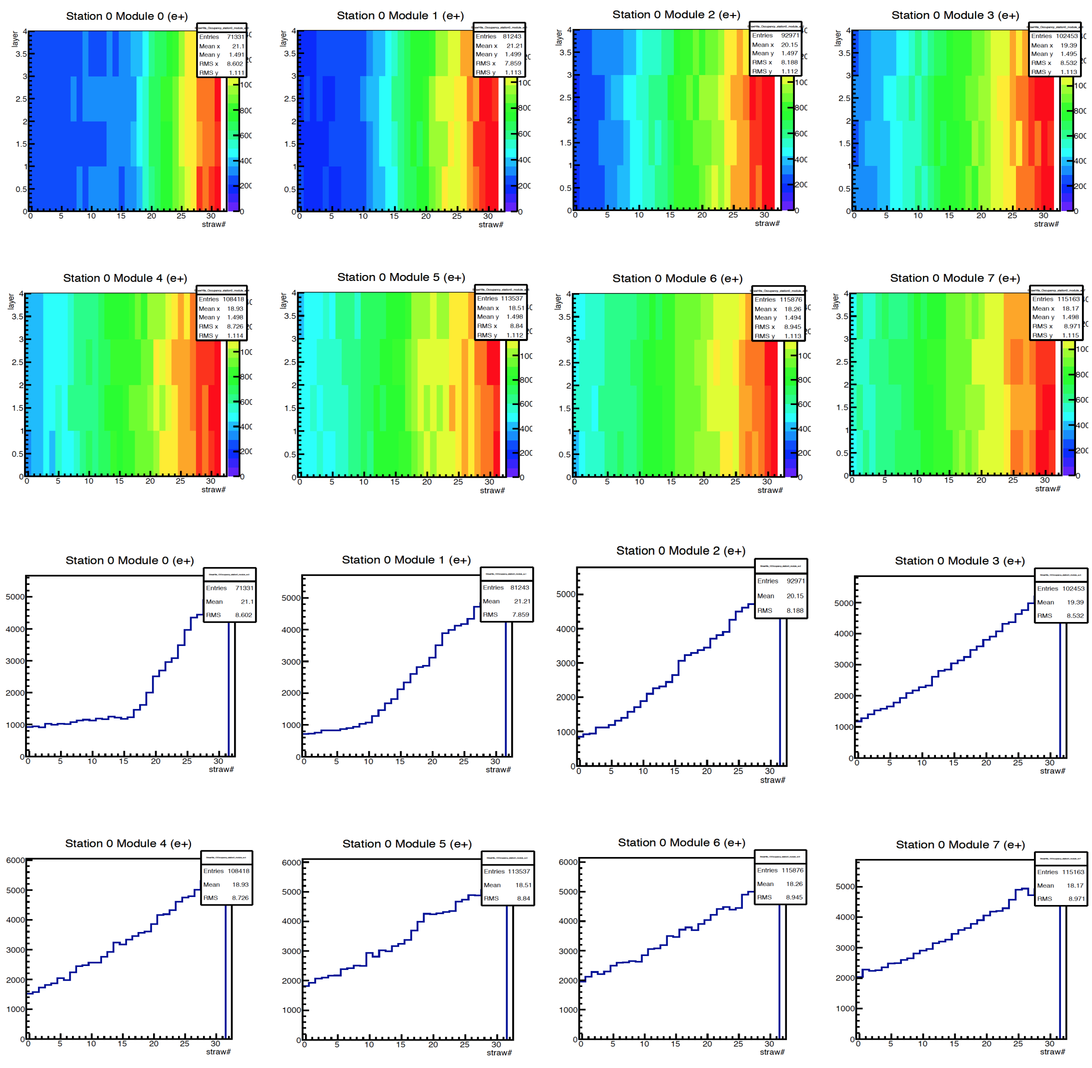


Figure 11: Straw Tracker Hits by Layer (Pages 13-18 of *list_name*.VPlots.pdf)

3 Description of plots produced by VerificationTrackChanges.C

The VerificationTrackChanges.C allows the user to compare the same verification plots displayed in VerificationPlotter.C from two different samples. The macro loops over all the histograms in the first sample, finds the same histogram in the second sample, plots both distributions and their ratio. If the histograms are 1D then the ratio plot is fit with a zeroth order polynomial and the constant and χ^2/ndf are displayed in the stat box. If the distributions are same within statistics we would expect the χ^2/ndf to be $\sim$1 and the constant equal to the ratio of the total number of events in the two histograms being compared.

In addition to this visual comparison this macro reports the χ^2/ndf and p-value from the Pearson's χ^2 test of homogeneity (for references please see the description of the Chi2Test() function in the description of the TH1 class at root.cern.ch). The p-value denotes the probability that the differences observed between the two samples is arises solely due to chance. Traditionally p-values less than 0.1, 0.05 and 0.01 have been used to signal non-statistical differences. Note that the p-value distribution from two samples that are derived from the the same parent distribution is flat, so it is always possible, though unlikely, that two samples with a small p-value are consistent. On these plots the p-value is highlighted in red if it is < 0.01. The χ^2/ndf is highlighted in red if the test finds any bins in either histogram with zero entries, as this will skew the χ^2 results high.

The χ^2 test may be performed on 1,2 or 3D histograms. In the case of 1D histograms a residual is included to help identify the bins that lead to an increase in the χ^2. Ideally the residual points will be scattered randomly around zero with most the points lying within +/-2. A Q-Q plot, which shows the quantiles of the first sample versus quantiles of the second sample, is also included for 1D histograms. A quantile is the percentage of points below a given value. If the two samples come from the same parent distribution then the points on the Q-Q plot should fall approximately along the 45 degree reference line. Q-Q plots are useful for isolating changes in symmetry or shifts in scale between the two samples.

The Kolmogorov-Smirnov (K-S) Test is also calculated for 1D histogram. As with the χ^2 test the output gives the probability that the differences between the two samples arises solely from chance. In theory the K-S Test should only be used on continuous or unbinned data. The effect of using binned data is to bias the returned probability high. The size of this effect depends on the size of the bins relative to detector resolutions etc. The motivation for including this test is because it is expected to be more robust in the case of low statistics, the case where the above χ^2 test starts to break down. The Anderson-Darling test is a variant of the K-S test and may be more robust against binning effects. We are currently investing including this test in the Verification package. For additional details on: K-S test see http://www.itl.nist.gov/div898/handbook/eda/section3/eda35g.htm. A-D test see http://www.itl.nist.gov/div898/handbook/eda/section3/eda35e.htm.

Please note that some of the comparisons will be made on empty histograms. While it is trivial to exclude these comparisons we decided to keep them in order to track detectors that are absent from he simulation package.