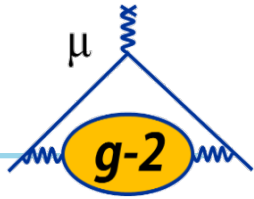
The Simulation Verification Package

Renee Fatemi

g-2 Computing Review

November 8, 2016

REQUIREMENTS

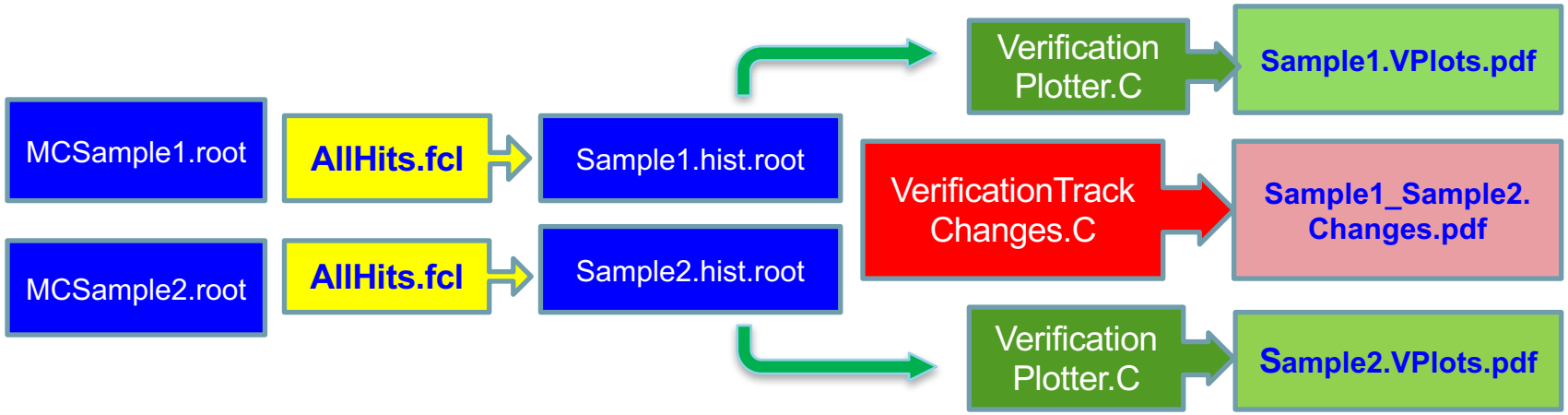


- Provide users with QUICK ACCESS to a suite of key distributions from the stored muon beam, calorimeter and tracker responses.
- Allow users to VISUALLY monitor the effect of changes to the simulation geometry on the detector response.
- QUANTITATIVELY compare distributions and determine if they are the same within the existing statistical precision.
- DOCUMENT the evolution of the simulation response.
- Could be an element in other packages, such as a NIGHTLY BUILD or in USER CODE REVIEW.

STATUS

The verification package consists of a set of art modules and analysis macros that can be run over a simulated sample of muons and/or muon decays.

- ***AllHits.fcl*** runs the art modules that populate a standardized set of histograms.
- The ***VerificationPlotter*** macro selects key histograms and stores them in a PDF for easy viewing and storage
- The ***VerificationTrackChanges*** macro provides the ability to compare two distributions and determine the probability they are from the same parent distribution. The output is also stored in a PDF.
- ***RunVerificationPackage.sh*** runs entire chain

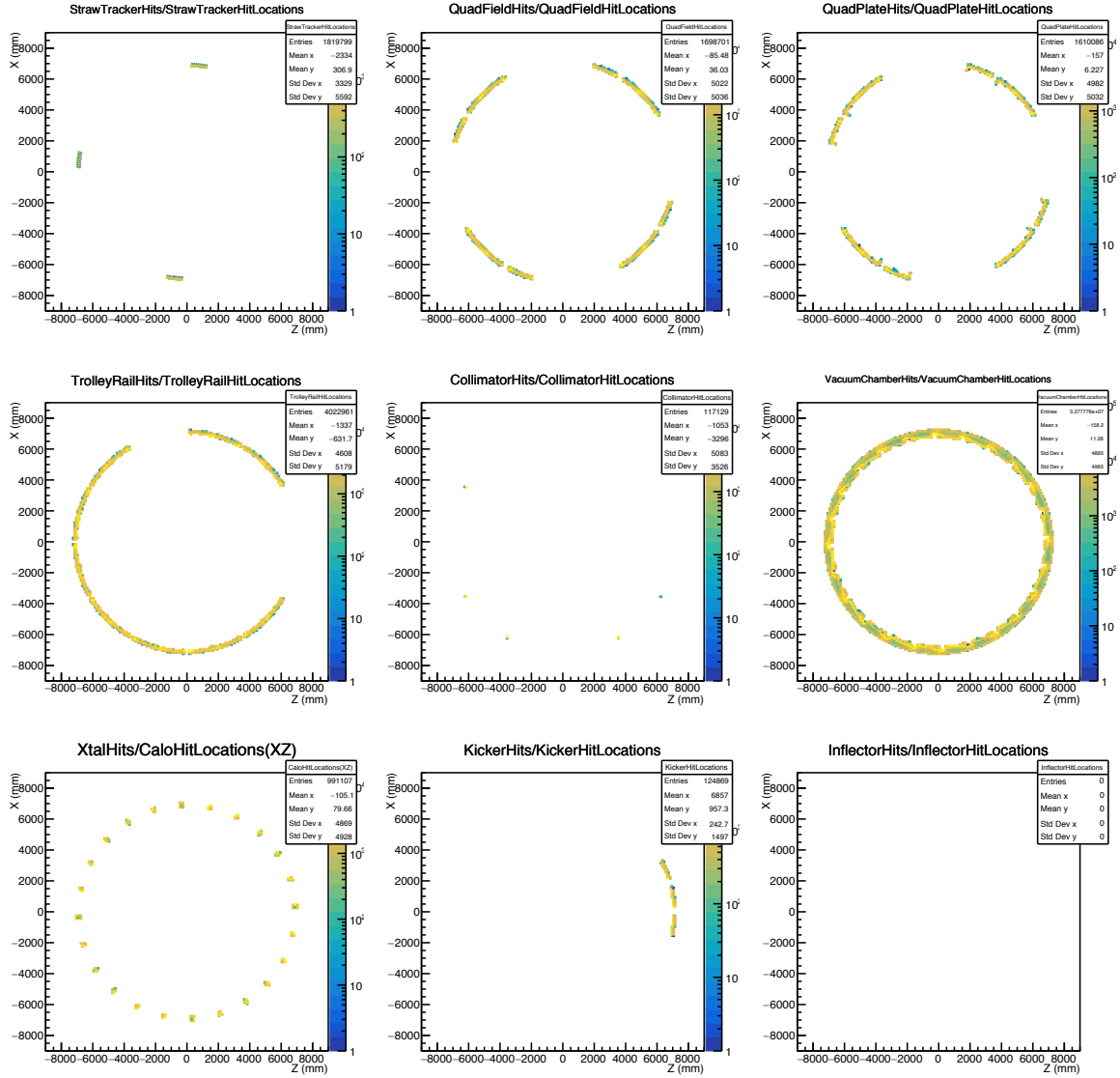


The ***VerificationPlotter*** macro selects key histograms and stores them in a PDF for easy viewing and storage.

Examples of Standardized Response Histograms

I. Detector Hits - Top down view of hits in the ring components. What is present? Where is it located?

Detector Hits

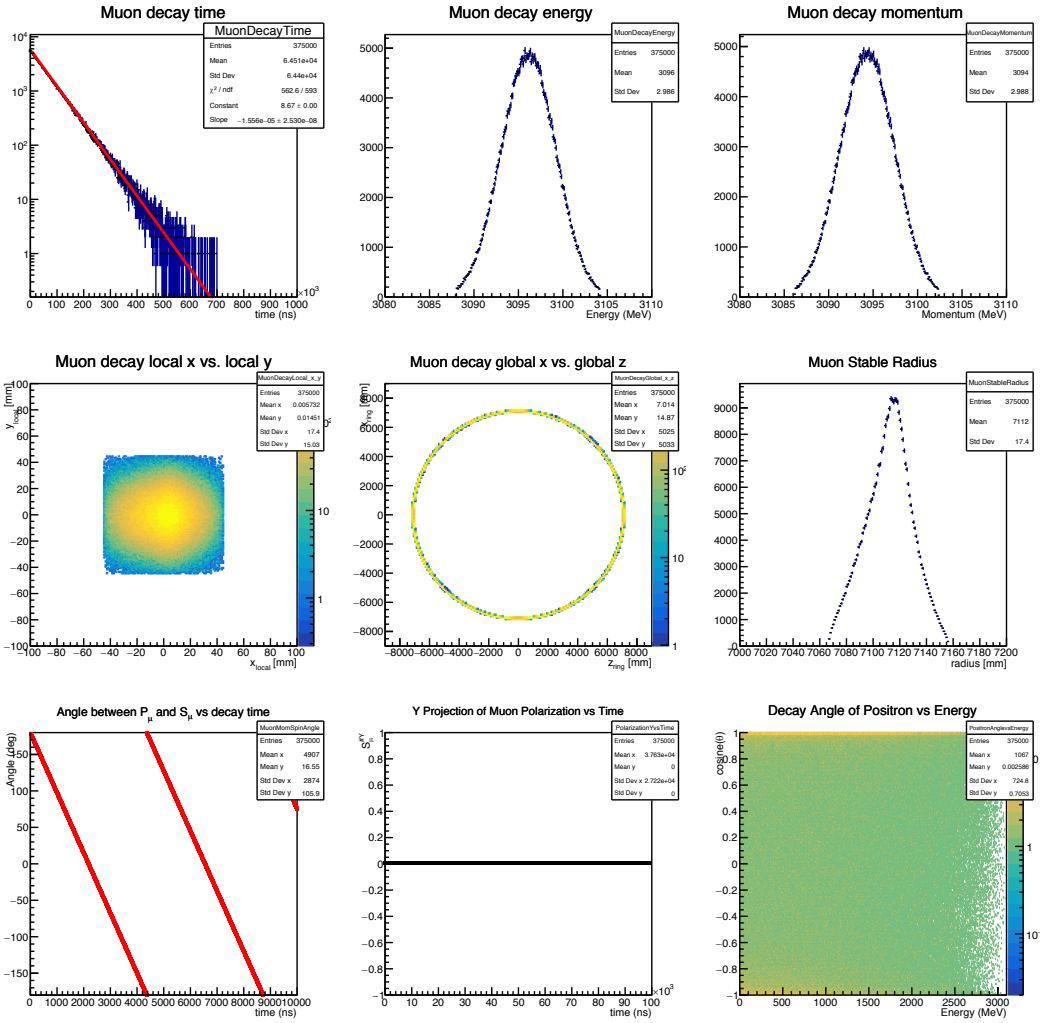


Standardized Response Histograms

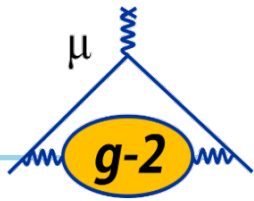
I. Detector Hits - Top down view of hits in the ring components. What is present? Where is it located?

II. Gas Gun - Check the beam parameters. Is the muon energy, lifetime correct? Is there an EDM component?

Gas Gun


Muon decay time
MuonDecayTime
Entries 375000
Mean 6.451e+04
Std Dev 6.44e+04
χ² / ndf 562.6 / 593
Constant 8.67 ± 0.00
Slope −1.556e−05 ± 2.530e−08
time (ns)
Muon decay energy
MuonDecayEnergy
Entries 375000
Mean 3096
Std Dev 2.986
Energy (MeV)
Muon decay momentum
MuonDecayMomentum
Entries 375000
Mean 3094
Std Dev 2.988
Momentum (MeV)
Muon decay local x vs. local y
MuonDecayLocal_x_y
Entries 375000
Mean x 0.005732
Mean y 0.01451
Std Dev x 17.4
Std Dev y 15.03
y_local [mm]
x_local [mm]
Muon decay global x vs. global z
MuonDecayGlobal_x_z
Entries 375000
Mean x 7.014
Mean y 14.87
Std Dev x 5025
Std Dev y 5033
x_ring [mm]
z_ring [mm]
Muon Stable Radius
MuonStableRadius
Entries 375000
Mean 7112
Std Dev 17.4
radius [mm]
Angle between P_μ and S_μ vs decay time
MuonMomSpinAngle
Entries 375000
Mean x 4907
Mean y 16.55
Std Dev x 2874
Std Dev y 105.9
Angle (deg)
time (ns)
Y Projection of Muon Polarization vs Time
PolarizationYvsTime
Entries 375000
Mean x 3.763e+04
Mean y 0
Std Dev x 2.722e+04
Std Dev y 0
S_y
time (ns)
Decay Angle of Positron vs Energy
PositronAnglevsEnergy
Entries 375000
Mean x 1067
Mean y 0.002586
Std Dev x 724.8
Std Dev y 0.7053
cosine(θ)
Energy (MeV)

Standardized Response Histograms

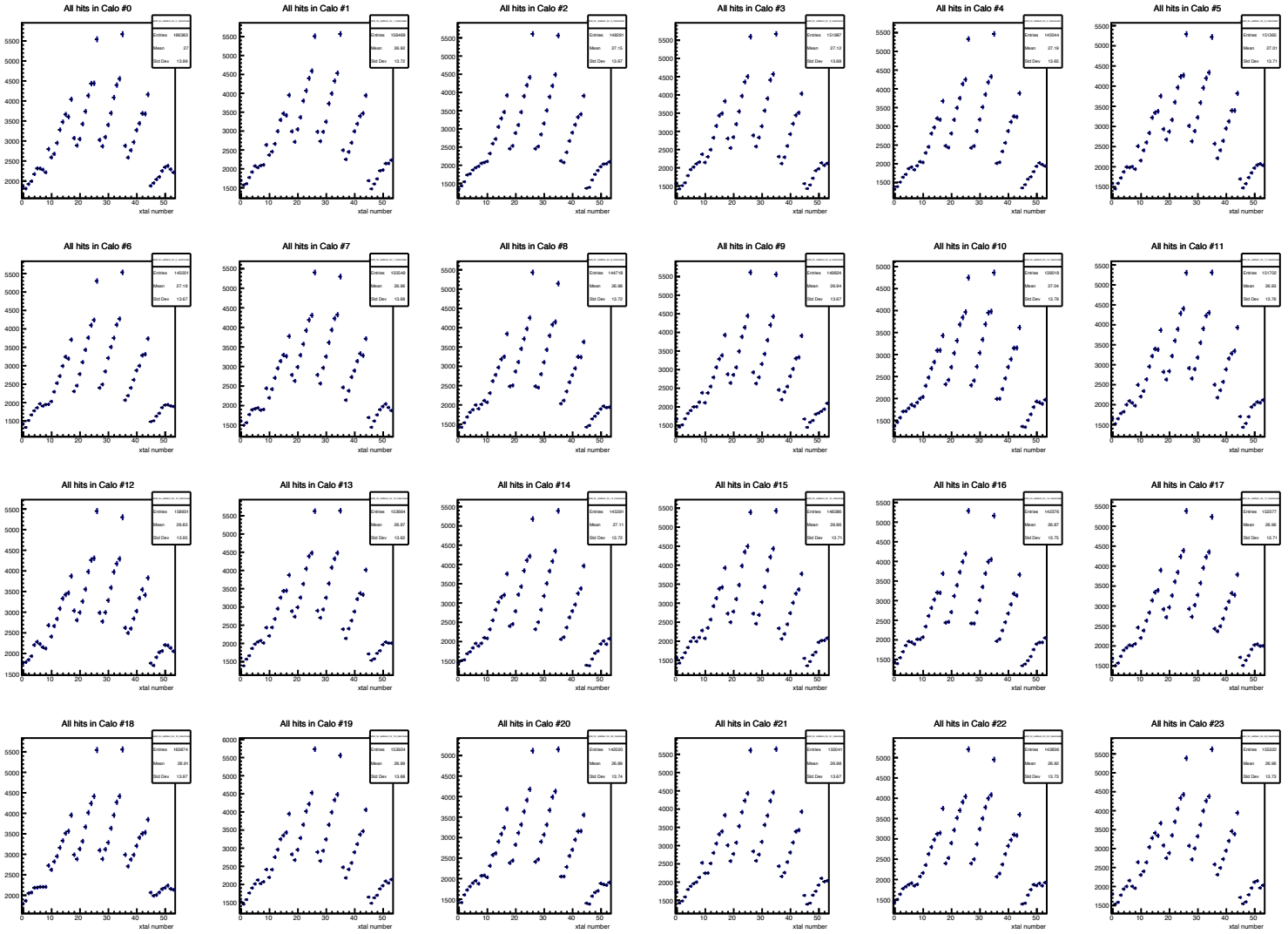


I. Detector Hits - Top down view of hits in the ring components. What is present? Where is it located?

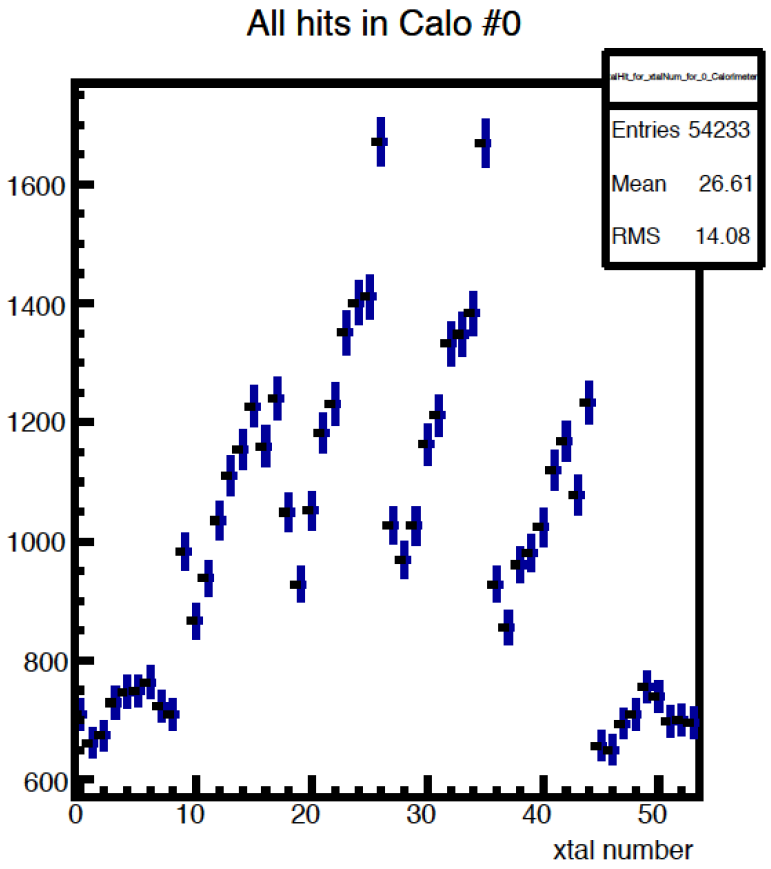
II. Gas Gun - Check the beam parameters. Is the muon energy, lifetime correct? Is there an EDM component?

III. Calorimeters - What is the spatial location of the hits in the calorimeter and in the crystals? How does this vary with particle type.

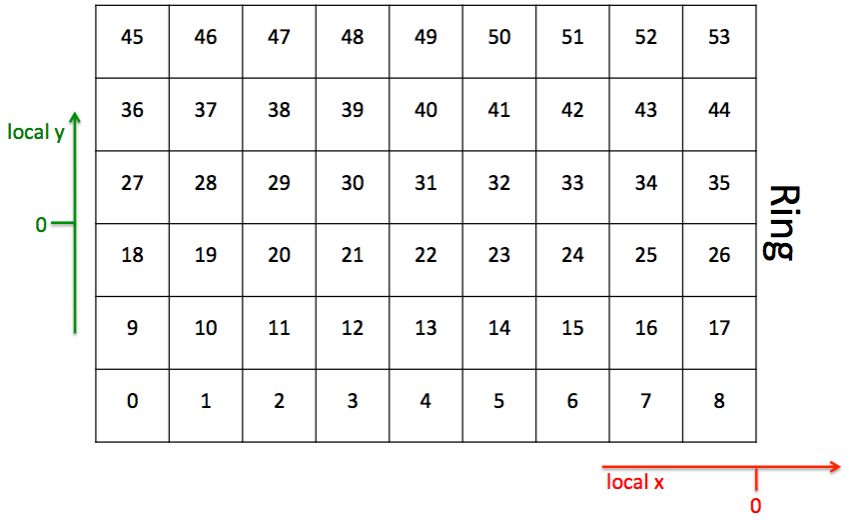
Calorimeter Crystal Hits



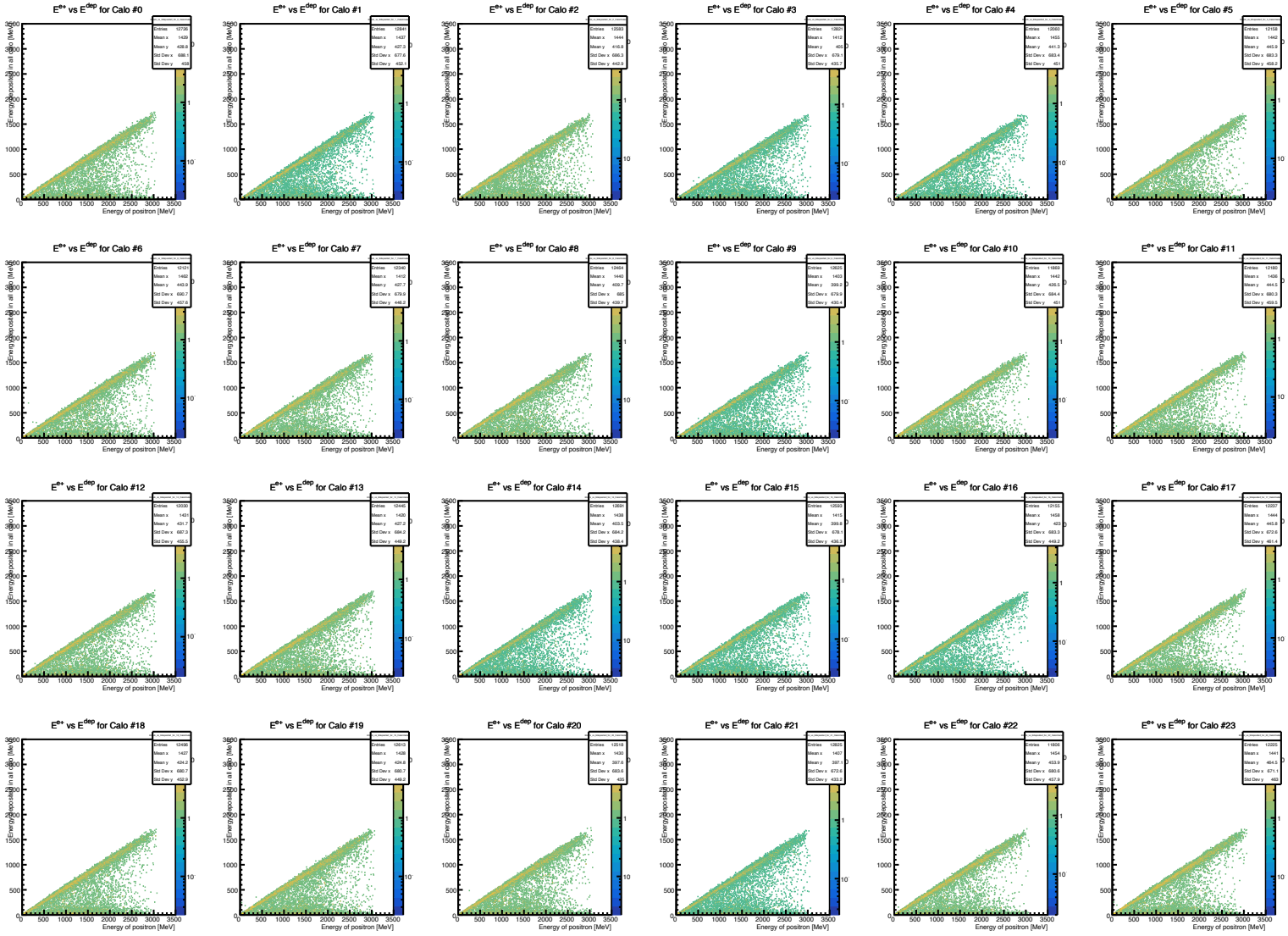
Calorimeter Crystal Hits



The crystals with the most hits are closest to the ring.



How much energy is deposited?



Standardized Response Histograms

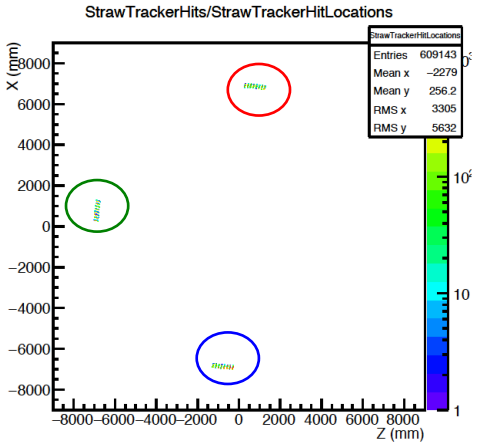
I. Detector Hits - Top down view of hits in the ring components. What is present? Where is it located?

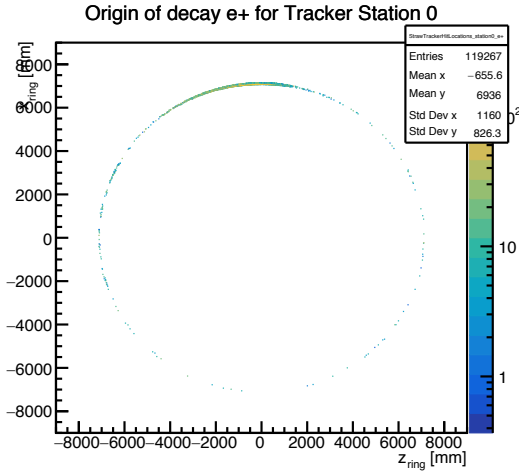
II. Gas Gun - Check the beam parameters. Is the muon energy, lifetime correct? Is there an EDM component?

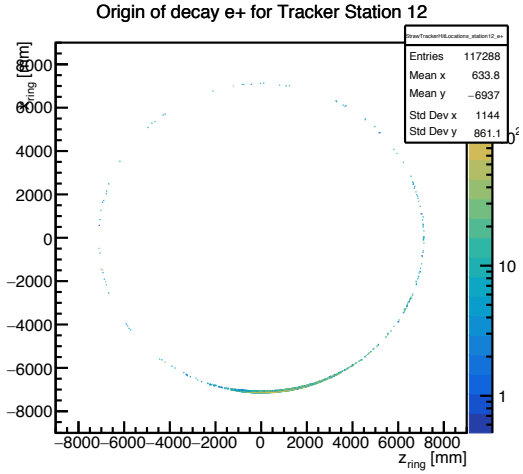
III. Calorimeters - What is the spatial location of the hits in the calorimeter and in the crystals? How does this vary with particle type.

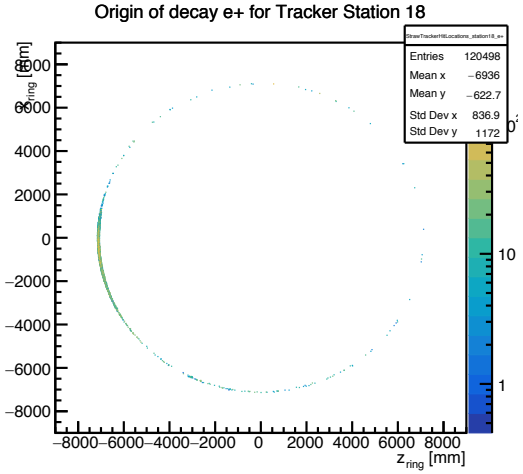
IV. Strawtrackers - Where do tracker hits originate? What do hit distributions in the straws look like for primary versus secondaries?

Where did the muons decay around the ring?









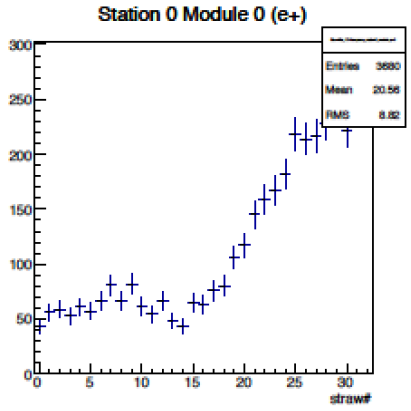
Tracker Station 0

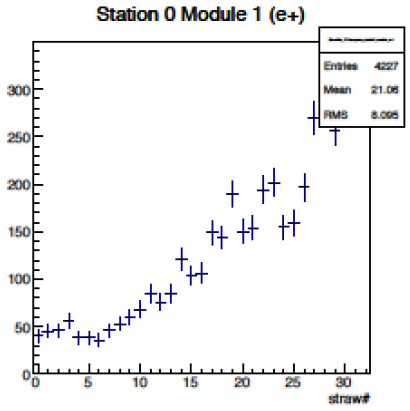
Tracker Station 12

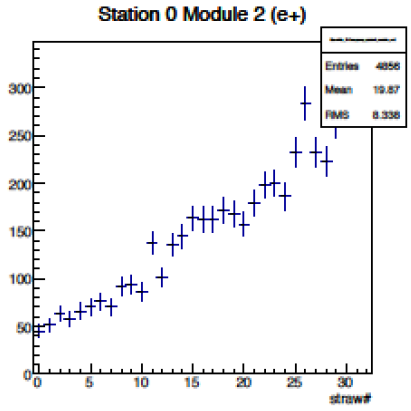
Tracker Station 18

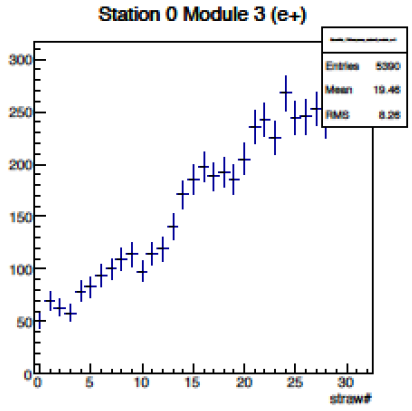
Fermilab

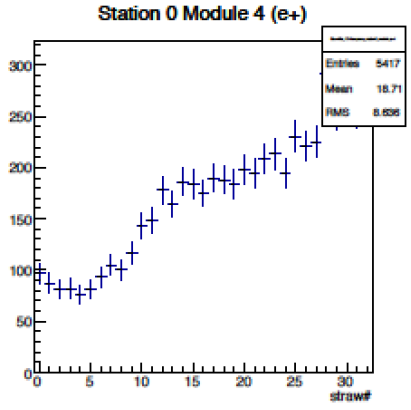
Where are the primary e+ hits?

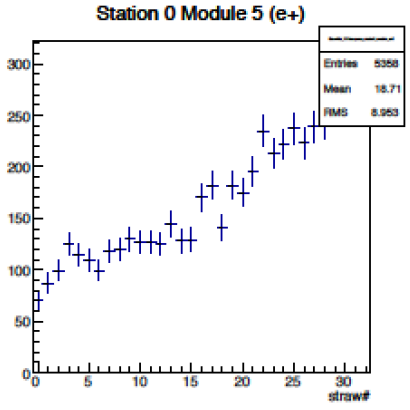


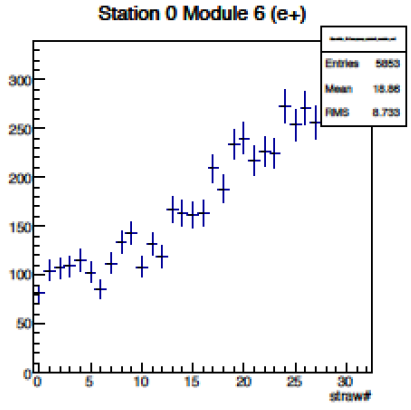


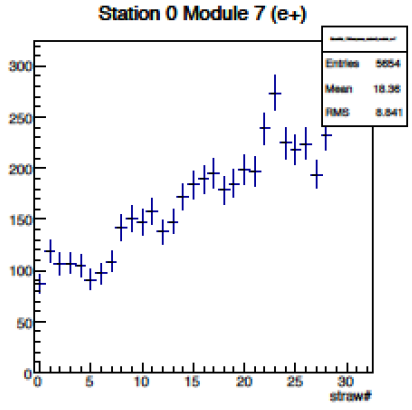




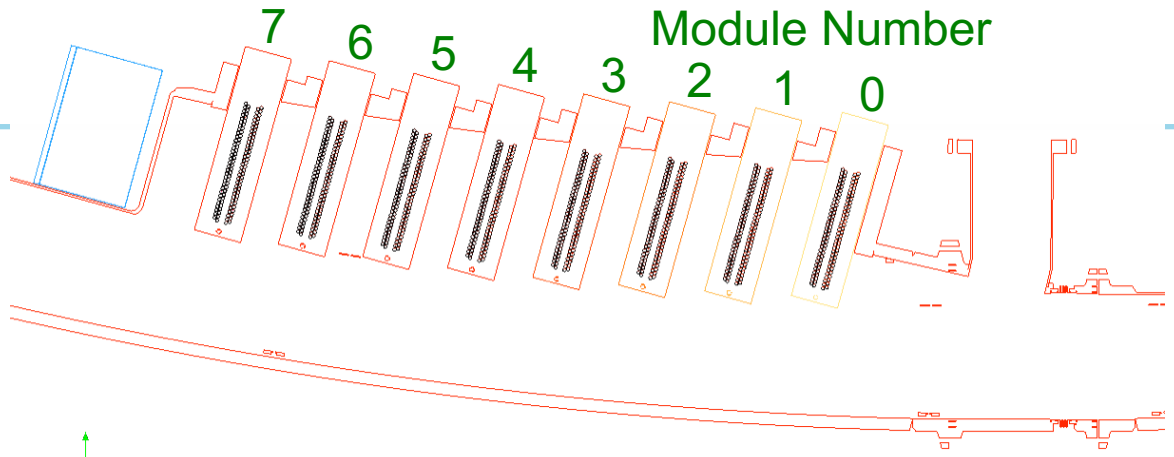


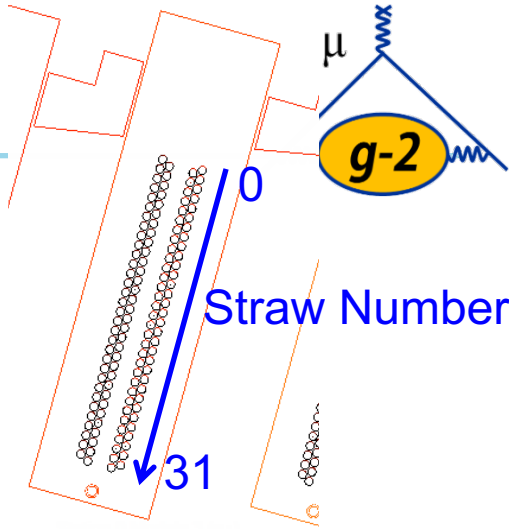


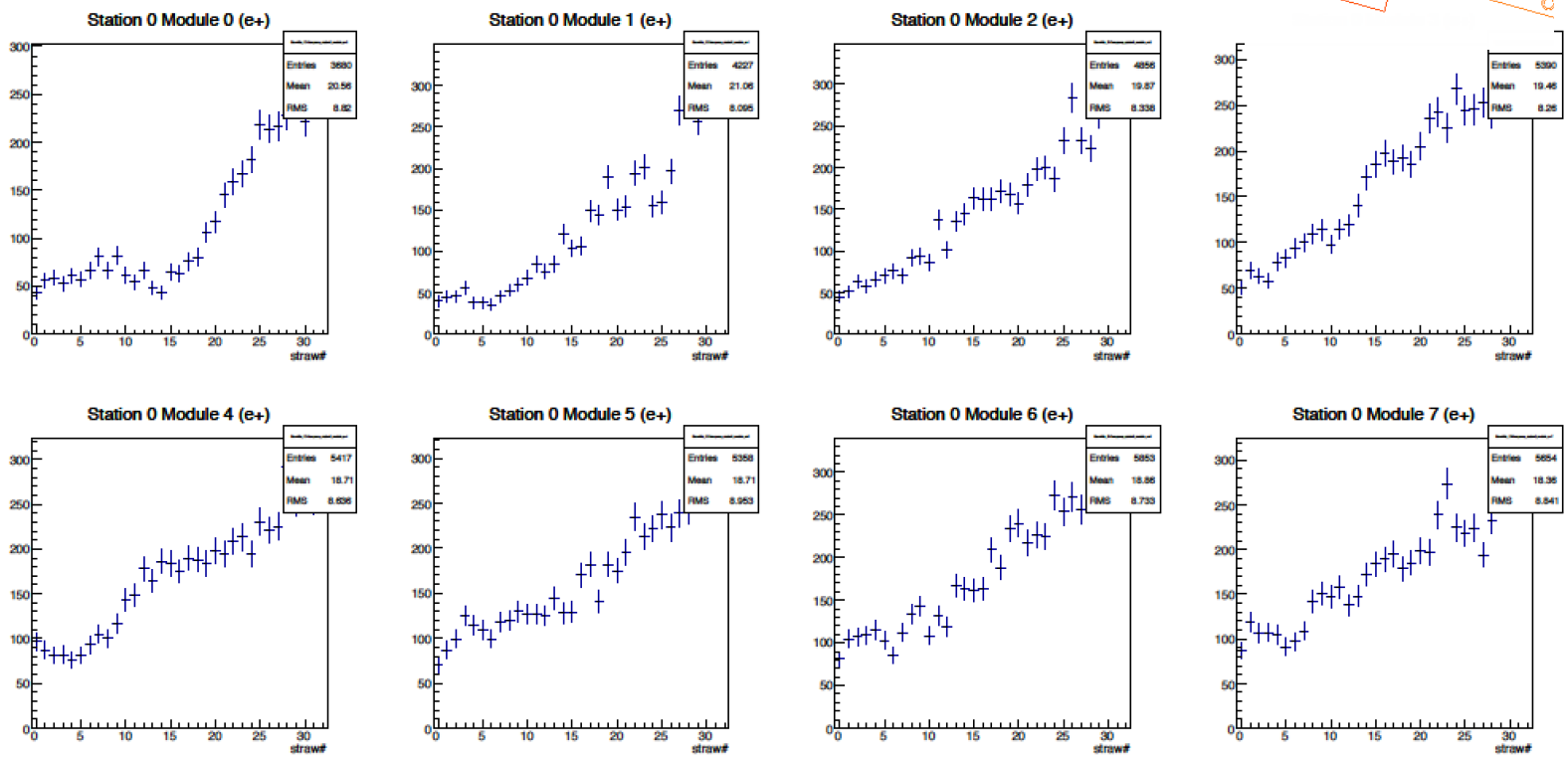




Fermilab

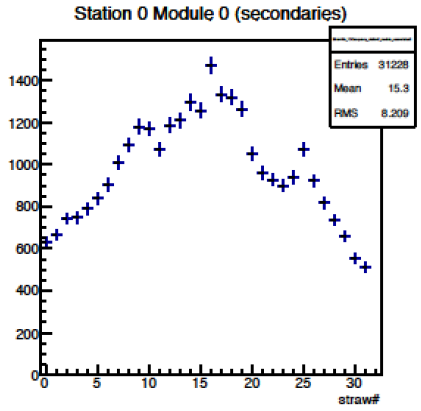

Module Number
7
6
5
4
3
2
1
0

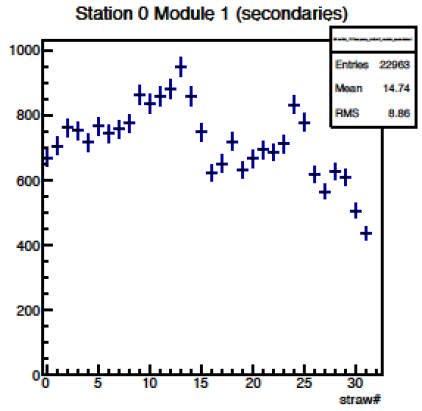

μ
g-2
0
Straw Number
31

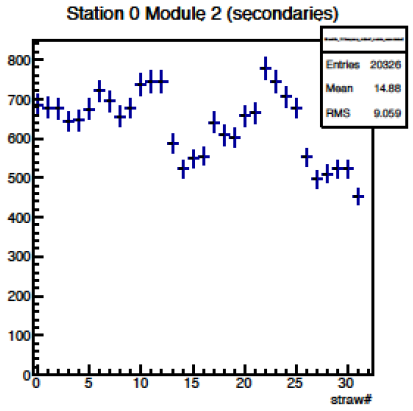

Station 0 Module 0 (e+)
Station 0 Module 1 (e+)
Station 0 Module 2 (e+)
Station 0 Module 4 (e+)
Station 0 Module 5 (e+)
Station 0 Module 6 (e+)
Station 0 Module 7 (e+)
straw#

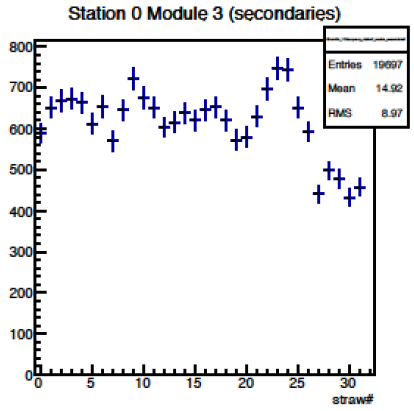
Fermilab

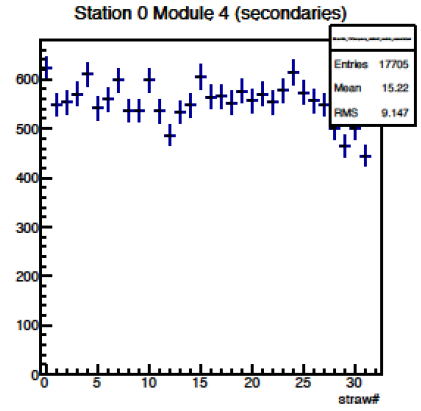
What about secondaries?

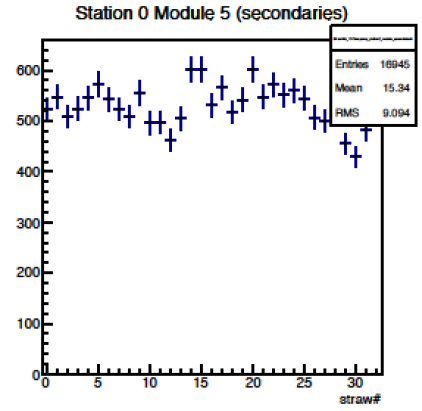


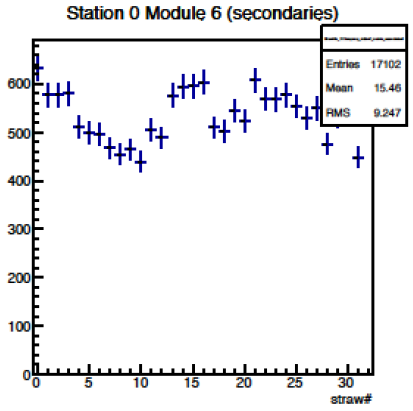


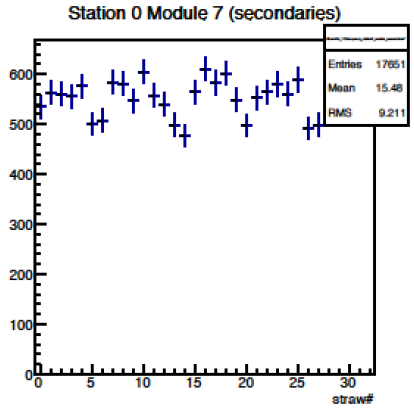






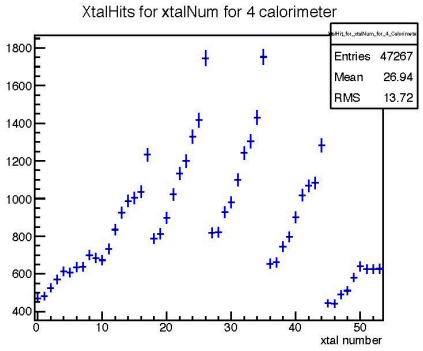


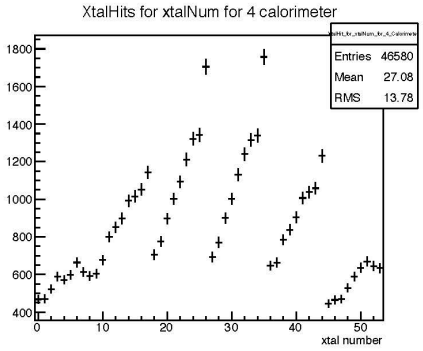


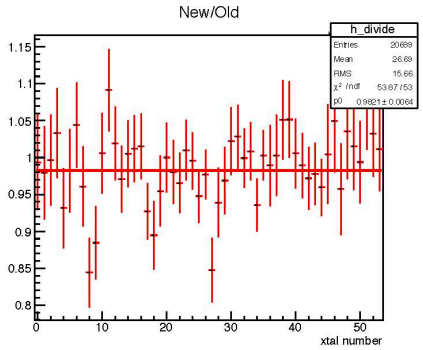


The ***VerificationTrackChanges*** macro provides the ability to compare two distributions and determine the probability they are from the same parent distribution. The output is also stored in a PDF.

How similar are two separate sets of histograms?



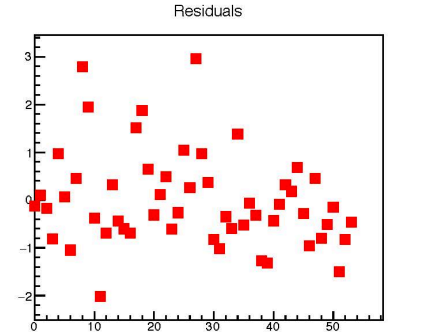


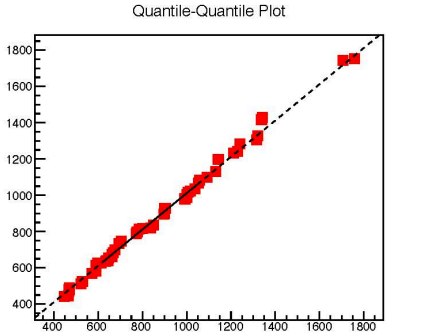


χ^2/NDF value = 0.96946

P- value = 0.53740

K-S test value = 0.163380





I. Visual Tests

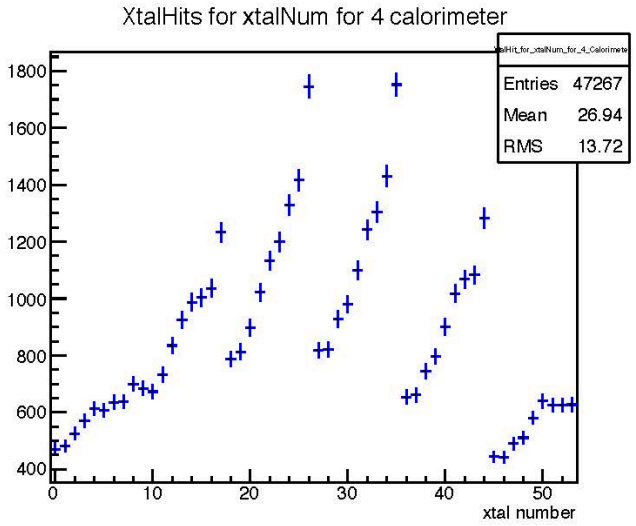
II. Pearson's χ^2 Test

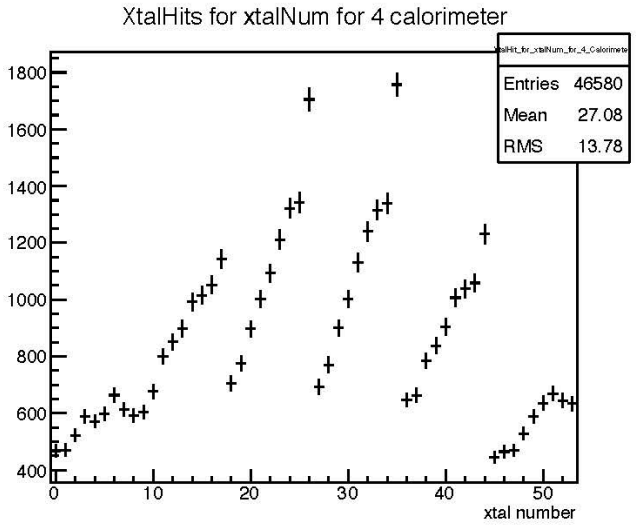
III. Kolmogorov-Smirnov (K-S) Test

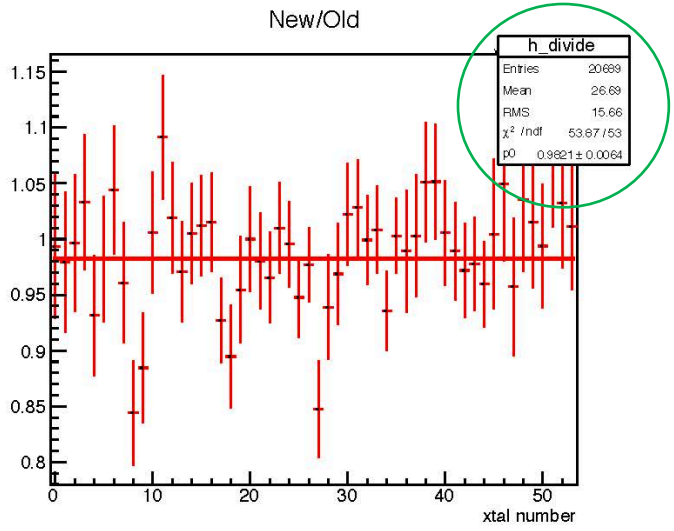
IV. Residuals Plots & Quantile-Quantile (Q-Q) Plots

Fermilab

Visual Test







h_divide	
Entries	20689
Mean	26.69
RMS	15.66
χ^2 / ndf	53.87 / 53
p0	0.9821 ± 0.0064

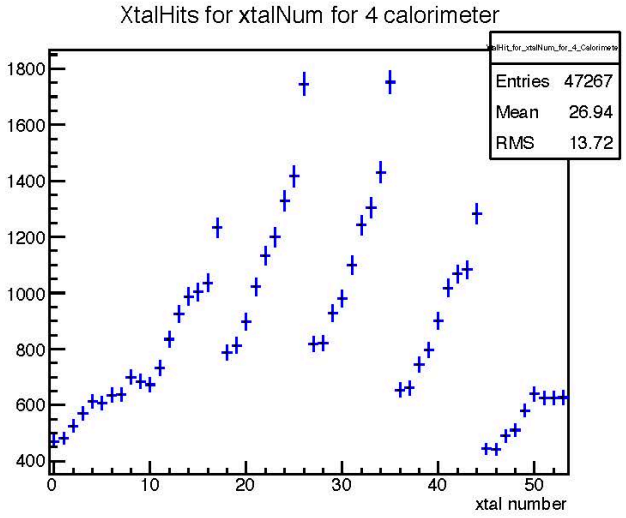
Plot both the old and the new histograms.

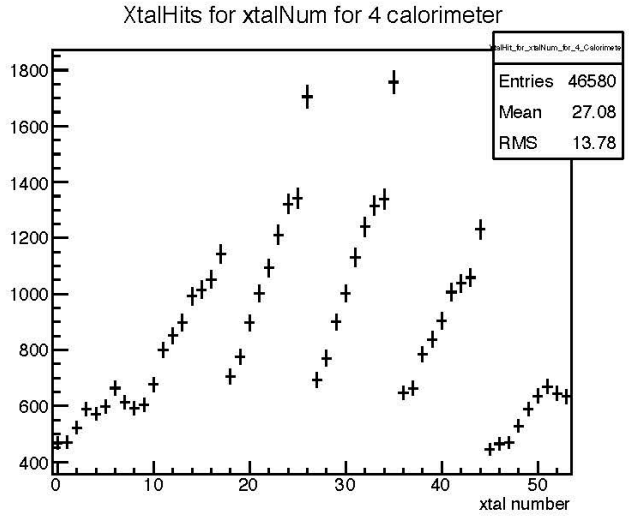
Plot the ratio of the two histograms and for 1D plots fit with a constant.

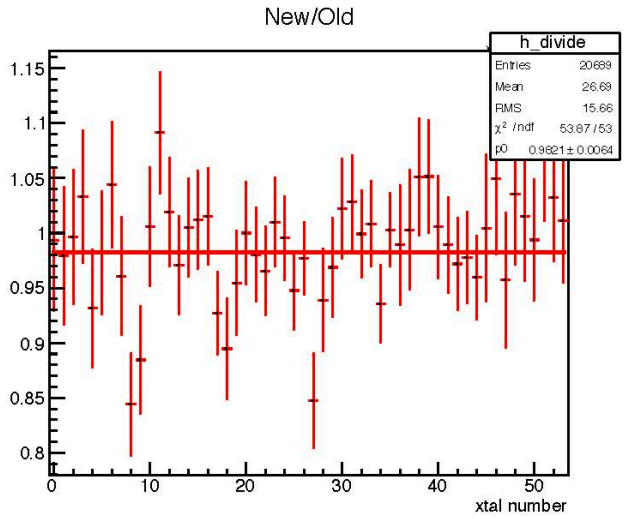
Check the value of the constant and the χ^2/ndf of the constant fit.

χ^2/ndf compares the ratio plot to a constant fit. A good fit should have χ^2/ndf ~ 1.

Pearson's χ^2 Test







χ^2/NDF value = 0.96946

P- value = 0.53740

K-S test value = 0.163380

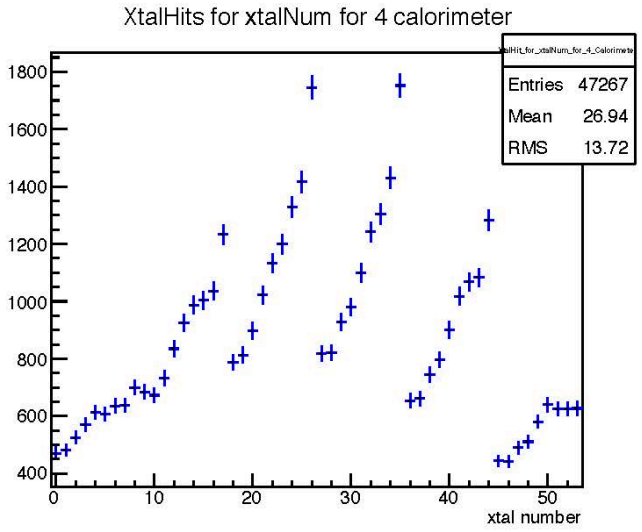
Pearson's χ^2 test compares two samples, giving the probability that they come from the same parent distribution.

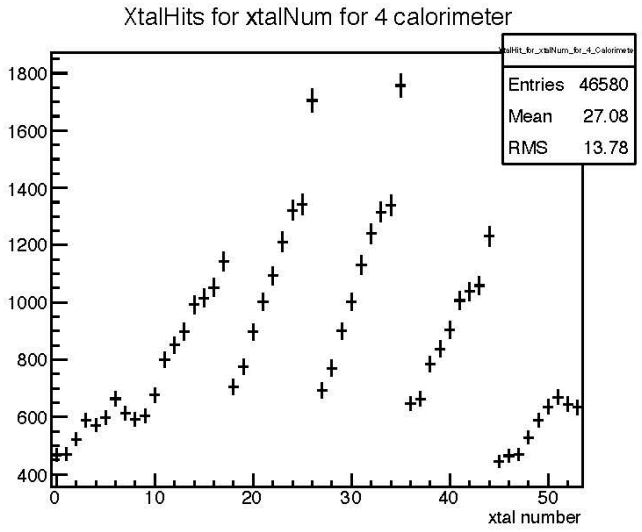
It returns the p-value and χ^2/ndf.

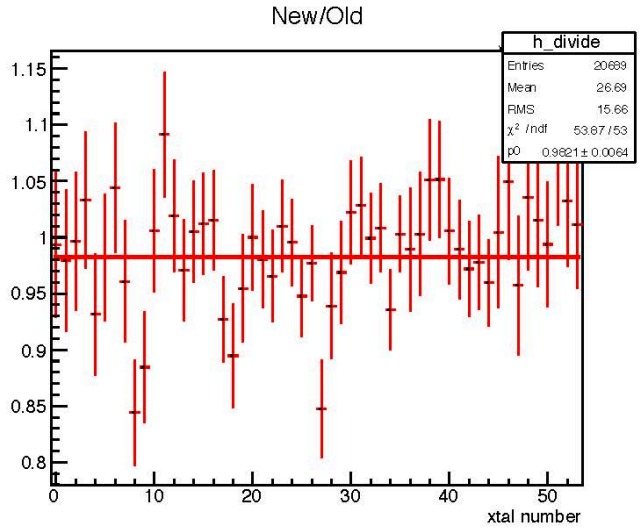
The p-value gives the probability that the differences arise from chance.

P-values below 0.01 indicate non-statistical differences and are highlighted in red.

Kolmogorov-Smirnov Test







χ^2/NDF value = 0.96946

P- value = 0.53740

K-S test value = 0.163380

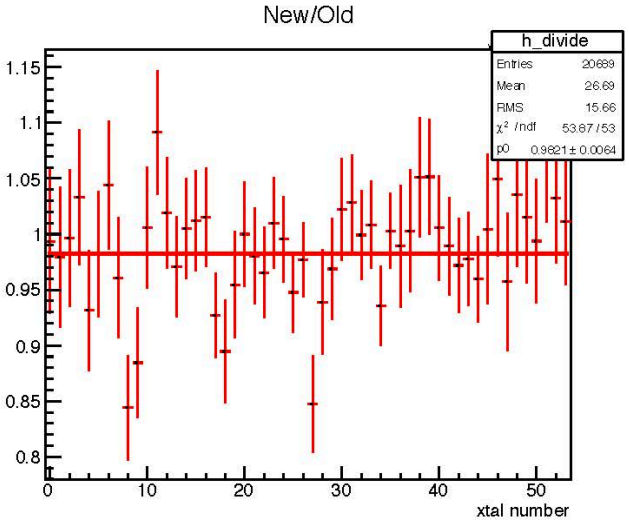
Like the p-value, the K-S test gives the probability that differences arise from chance.

The K-S test should, in theory, be used on unbinned data.

The K-S test is better for low statistics, which is where χ^2 breaks down.

Again, K-S values below 0.01 indicate non-statistical differences and are highlighted in red.

Residuals & Q-Q Plots



χ^2/NDF value = 0.96946

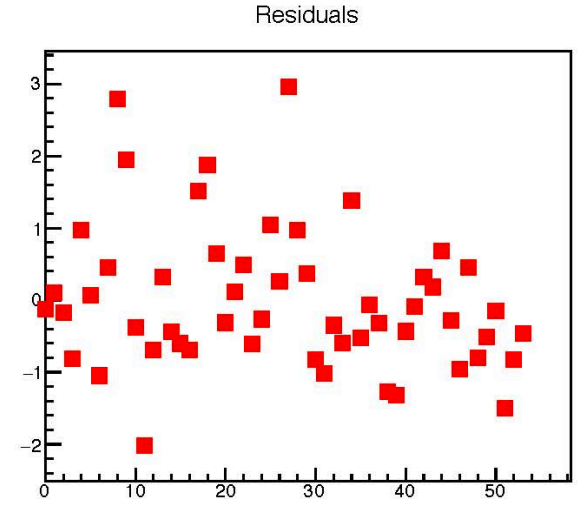
P- value = 0.53740

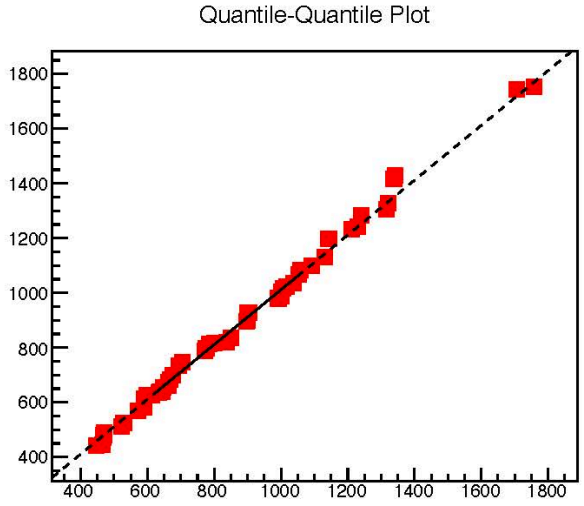
K-S test value = 0.163380

Residual Plot

Using residuals, we can find individual bins that contribute to large χ^2 values.

Residuals should be centered around zero and fall mostly between +/- 2.



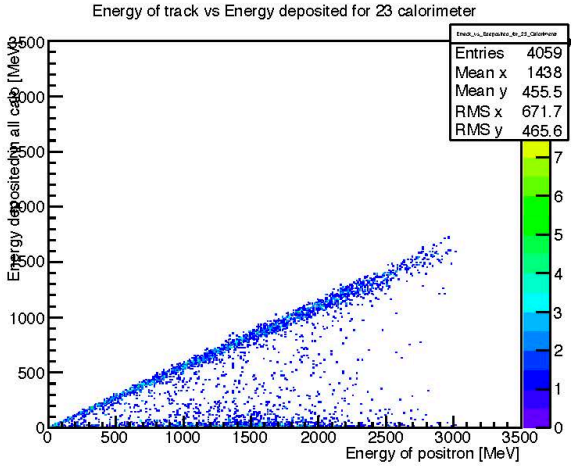


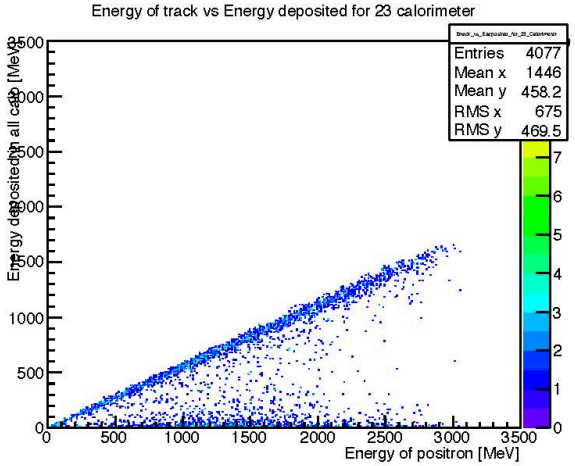
Quantile-Quantile Plot

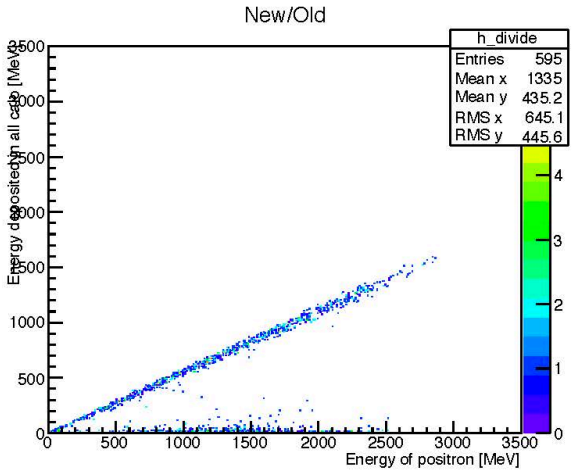
Samples from the same parent distribution will have points fall along a 45 degree line.

Good for identifying changes in symmetry and scale shifts between samples.

For 2D Plots







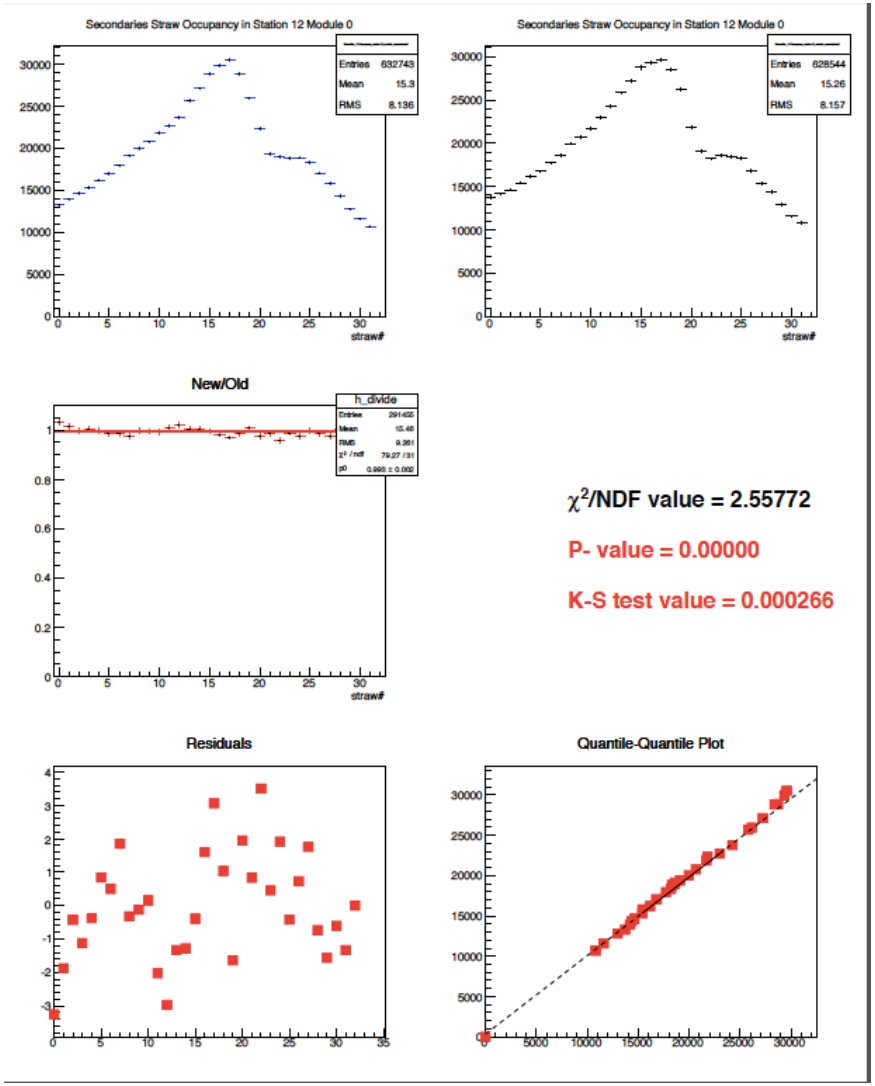
χ^2/NDF value = 0.99706

P- value = 0.55173

Currently, there is no K-S test for 2D plots. Therefore, we only do Pearson's χ^2 test.

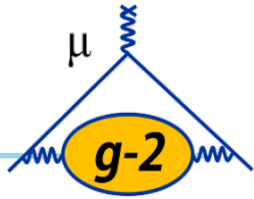
The reason the χ^2 value appears in red is because the test has found a bin with zero entries.

Error Calculations for Quantitative Comparisons



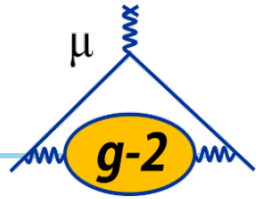
- Extensive tests on samples from the same geometry show a non-statistical distribution of p-values from both the χ^2 and K-S test, despite seemingly good visual comparisons.
- Samples originating from the same parent should have p-values that are uniformly generated between 0 and 1, resulting in 1% below our cutoff p-value of 0.01. Instead we find ~50% have p-value < 0.01
- Likely due to correlations between detector hits within a single event. Treating all counts as random results in understimation of errors.
- Histograms of stored beam characteristics, which by definition have one entry per event, show expected statistical distribution of p-values.

Conclusions and Future Plans & Schedule

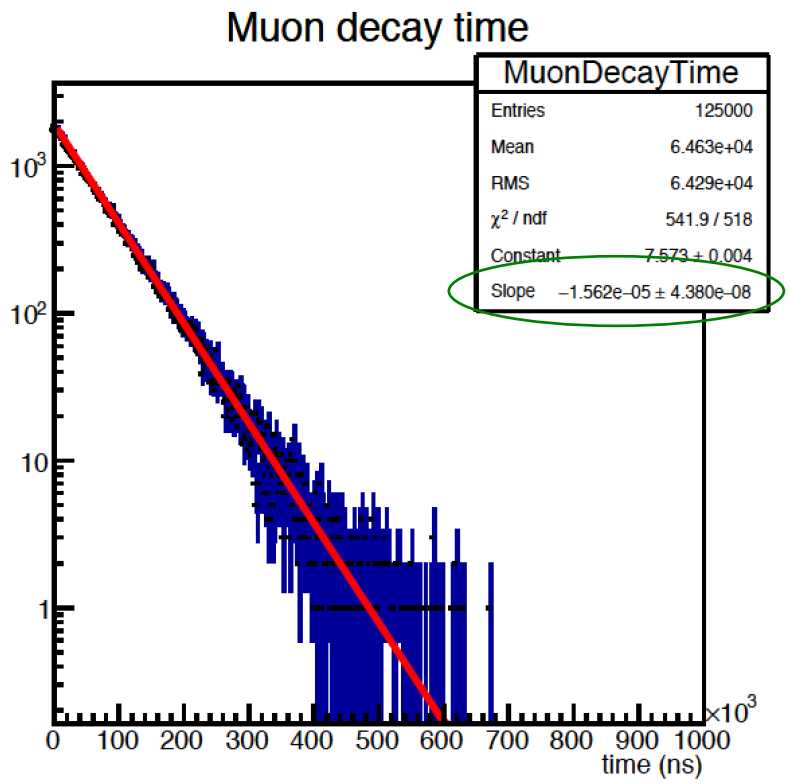


- The Verification Package has been used to understand our existing simulation and vet several code releases and package upgrades (for example Art and GEANT4).
- We will continue to add additional detector and gun plots as the simulation evolves.
- We will continue to investigate quantitative comparisons and work to make statistical analysis more robust.
- Identify storage site and develop searchable web interface for VP output files.
- Contributors to Verification Package include:
  - Renee Fatemi, Laura Kelton, Jesse Melhuish (Kentucky)
  - Bingzhi Li, Liang Li (Shanghi)
  - Cristina Schlesier (Illinois)

Backup



Is the lifetime of the muon correct?



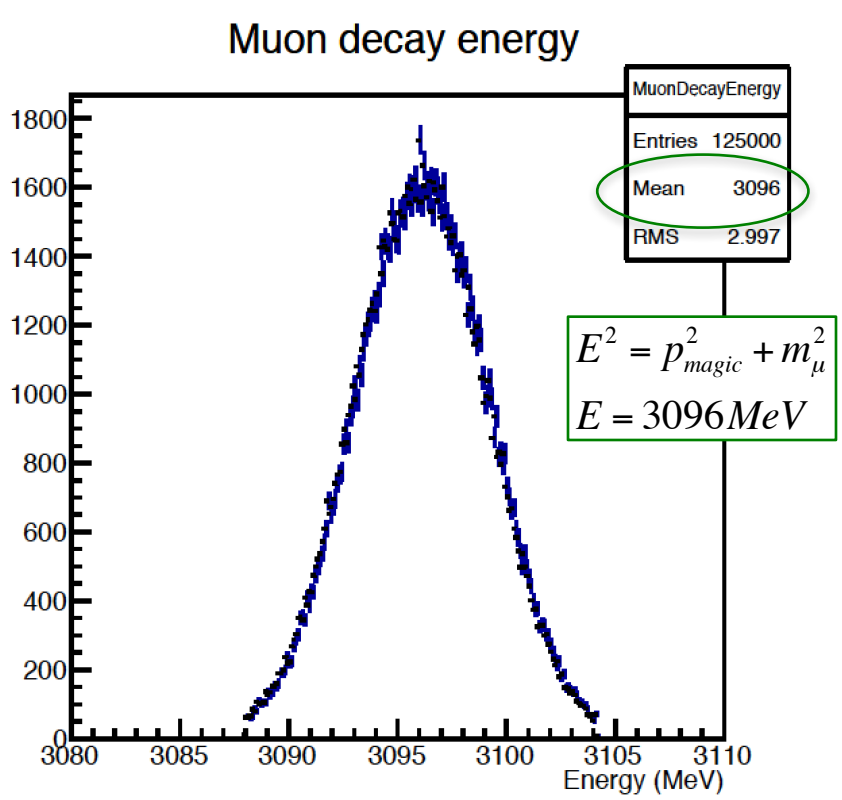
The muon distribution follows an exponential decay.

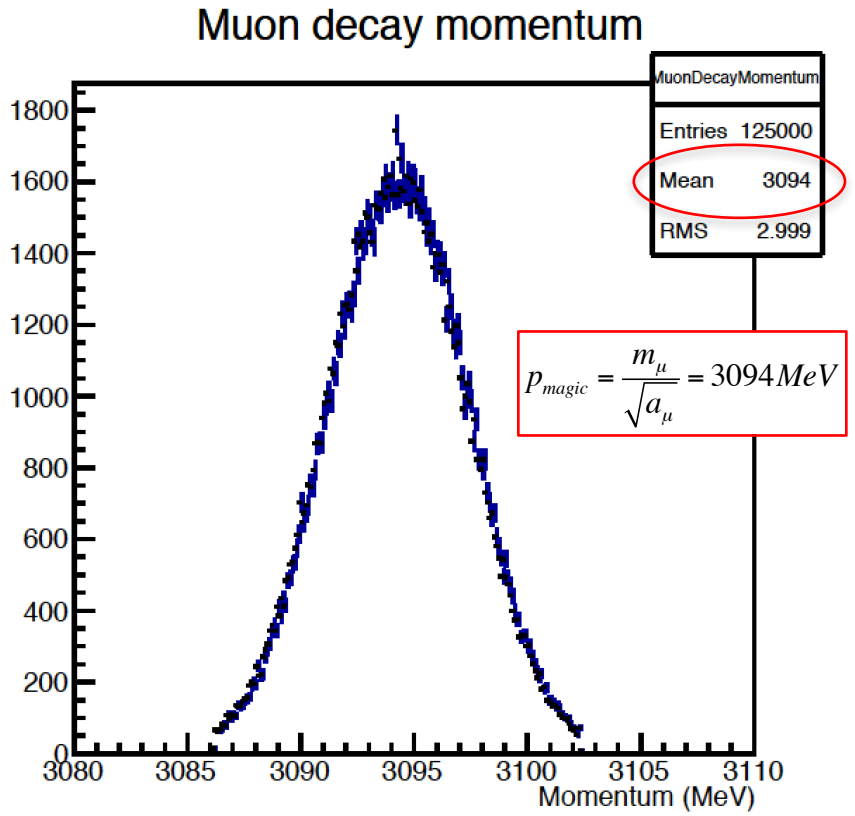
$$N \sim N_0 e^{-t/\gamma\tau}$$

Plotted on a logarithmic scale, we expect linear plot with a slope of

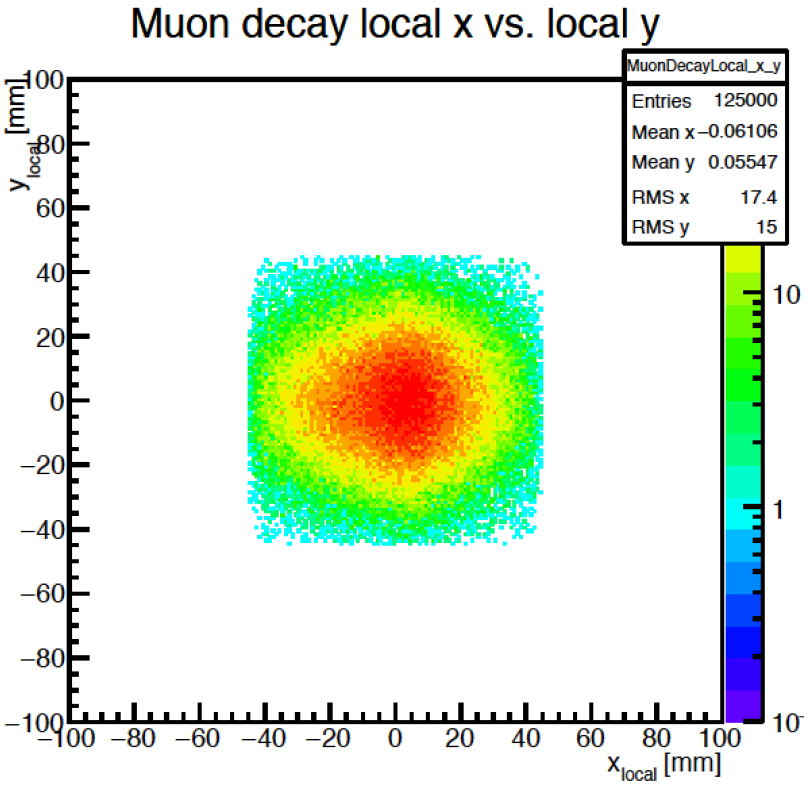
$$-1/\gamma\tau = -1.55 \times 10^{-5}\, ns^{-1}$$

How are the momentum and energy distributed?

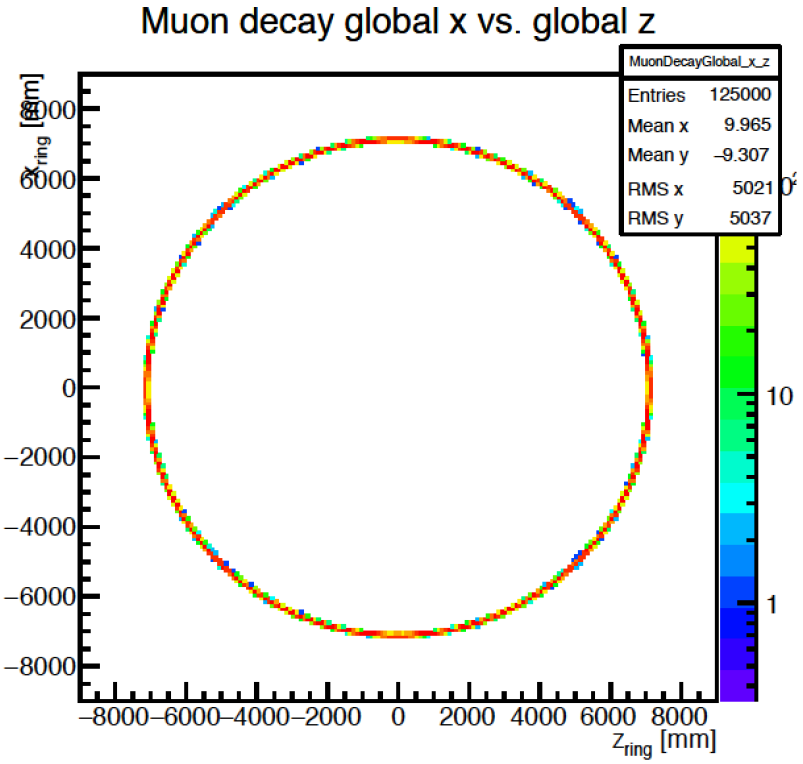




Where are the events happening?

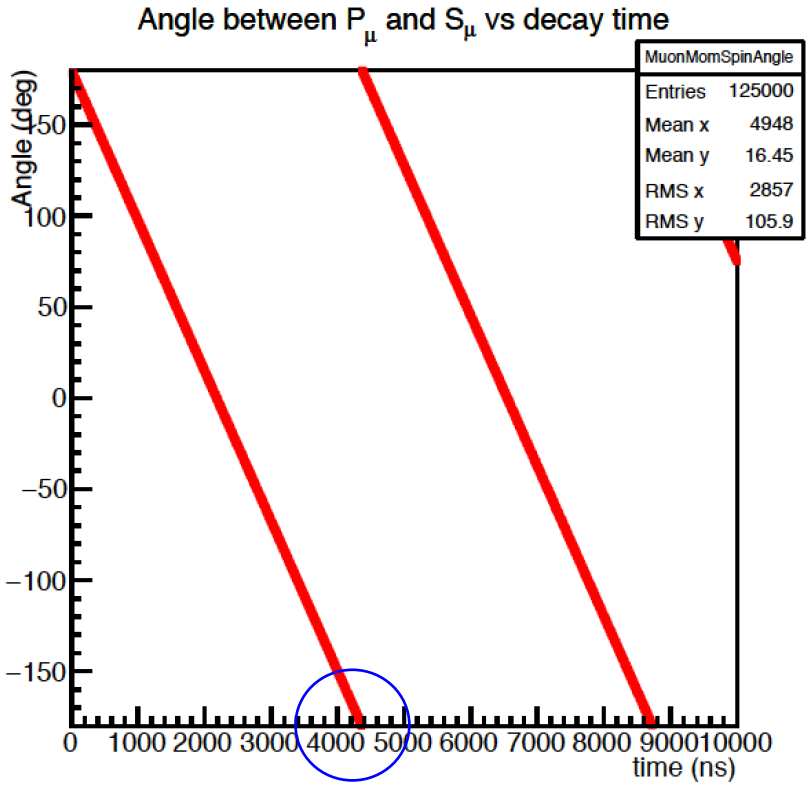


Beam cross section is Gaussian in x and y with CBO in x.



Events should be evenly distributed around the ring.

How does the spin precess with time?

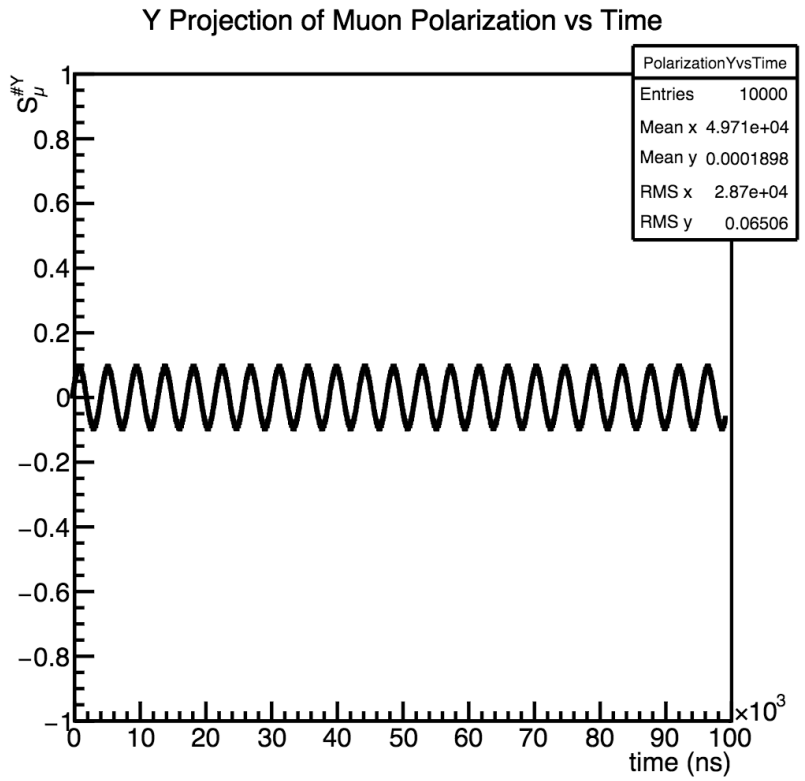


The spin angle is found by dividing the cross product by the dot product:

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

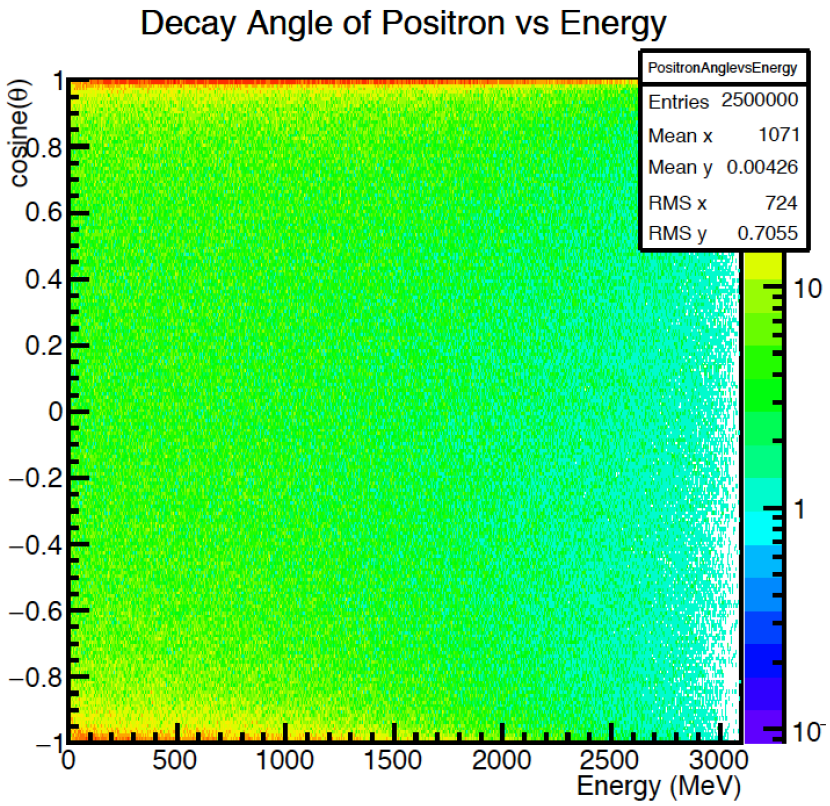
- The angle should be maximized at t=0.
- The period of precession is 4370 ns.

Is there EDM present?



When EDM is introduced, the y projection of the muon polarization oscillates with time.

How does the decay angle change with energy?



The decay angle was found by dividing the dot product by the magnitudes:

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

- At higher energy, the momentum of the decay positron preferentially aligns with the muon spin.

Fermilab

Quantile-Quantile Plot

- Quantiles of first data plot against quantiles of the second data.

  i. Sorts the data for each set in increasing order.

  ii. Plots corresponding values.