Simulation Studies and Information
Pertaining to STAR EndCap Strip SMD
Primarily for Cosmic Ray Response

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INTRODUCTION

There are a number of issues in the use of the Argonne cosmic ray test stand to do quality control and calibration of the STAR EndCap Shower Max Detectors. The shower max. detector is made up of 12 sectors of 30 degrees. Each sector has two planes of triangular scintillator strips. The strips in a plane are assembled with alternating direction of the triangles in order to use energy sharing for position measurement. The strips are 1 cm wide, 7 mm high, and range in length from a few cm to over a meter.

There was a previous MC study of the physics of the SMD done at IUCF, which indicated a minimum requirement of 2 photoelectrons per mip at the vertex of the triangular scintillator strips. We needed to know if this is a measurable quantity, how to measure it on 288 narrow strips each week, how well we could measure it with the trigger setup available, and what the results meant.

There are currently two analyses being done on the cosmic ray data, one using the average pulse height from all tracks, and one using the method of adjacent vetos to localize the cosmics.

This study is also relevant to physics analysis utilizing energy sharing between triangular strips, although no EM shower simulations were done here.

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Some specific issues were:

1) Momentum spectrum and dedx spectrum for cosmics with our lead brick spectrum hardener.

2) Effects due to angles of the cosmics going through the SMD strips.

3) Many aspects of using adjacent inverted triangular scintillator strips in veto:
   a) How well could the cosmics be localized by this method, given the low photostatistics and low efficiency of vetoing, which was a function of position in the triangular strips.
   b) What relationship would the measured quantity have to the desired characterization of the scintillator strip, i.e., number of pe at the apex?
   c) What was the effect of the angular distribution of cosmics on this method compared to other methods?
   d) How uniform would the response be across our fiducial area, which has a different angular distribution in different places?

4) Aspects of a simpler scheme of simply averaging all the cosmic responses of a strip. This method would avoid the possible effect of a weak veto strip making the strip under study appear weak by allowing tracks far from the apex of the triangle.
   a) What is the relationship of the overall observable average to the desired characterization of number of pe at the apex?
   b) What are the effects of the various angular acceptances for cosmics in different parts of the trigger fiducial area?

5) What was meant by the original requirement of 2 pe at the apex? Was this poisson mean or observable average? The MC analysis used gaussian smearing of each pe.

   In addition, we were led during this study to a number of other questions:

1) What is the relationship of a poisson mean to an observed mean, when the zeros of the poisson cannot be observed?

2) What is the relationship of observed signals, particularly the means, to some idea of the poisson mean for a collection of tracks which give low photostatistics (many are not observable) and which also have different means at different positions in the triangular strip?

3) What is the signal response of a triangular scintillator when the pulse height cannot go to zero where the thickness of the triangle goes to zero, because the minimum observable is 1 pe? How will this affect the eventual analysis of physics events with low pulse heights?

4) What is the relationship of what we can see to what we want to measure in the region between 1 pe where the response is entirely due to PMT gain, and 3 pe where the
response is primarily the product of the pmt gain and the quantum efficiency? How does this relationship vary when there is a variation (unmeasured) in the quantum efficiency?

5) How does a pulse height cut on a realistic spectrum out of a phototube affect the observed mean of the spectrum?

Note that in all the simulations of the response of a triangular scintillator producing a pmt spectrum, there is a sum of poisson's of different means, and most of the summations did not utilize the statistical smearing of npe peaks in the pmt because it was found to have a very small effect even with the ADC cut.

**SUMMARY**

To begin, we have done a heuristic simulation of smearing within a pmt for various $\langle n_{pe}\rangle$. This was done in order to study the effects of the ADC cuts which are done on real data to eliminate the pedestal. This assumed sigma/mean for 1 pe was 0.4, and that sigma/mean for each n pe grew as square root of n. This is shown in Figure 1.

For the Cosmic ray response, there are 3 simulations:

a) One done with a rather simple program for light output with vertical cosmics, (summing over a poisson dist (with or without zeros) for each track) This includes efficiency calculations and using adjacent veto efficiency calculated from number of pe. The results are described in detail below, and shown in figures 2 and 3 a-d.

b) Path length of cosmics in the scintillator for the range of angles in the ANL cosmic test stand. Comparing ranges between +-3 deg, +-8 deg, +- 13 deg, +- 18 deg, +- 23 deg. The main difference from the above light simulation is that at large angles a small percentage of cosmics can miss the fiber hole and have paths greater than 6 mm. For the case of looking at the average with no adjacent vetos, the variation in path due to angular acceptance is only 3 %. For the case of perfect, 100% efficient, adjacent vetos, some strips see averages up to 16% more cosmic path length than others. (In reality, the light does not vary this much due to actual veto inefficiencies) These results are shown in Figure 4.

c) A more complete simulation with cosmics over angular ranges, and with poission distribution for each cosmic path, and with veto efficiency.

Note that in all these simulations, we have assumed that the poisson mean is proportional to the path length of the track in the scintillator. The maps we did of strip response using a radioactive source with a small spot and subsequent attempts at unfolding this are consistent with this assumption.

Also there were simulations in addition to the cosmic ray response:
Numerical Simulation was done for comparison of observed mean and poisson mean for a case of many PMT seeing an average of 2 pe, but with a spread of +- 30% in gain and +- 30% in quantum efficiency. The ratio of observed mean to poisson mean has a large spread (from 1.63 to 1.046) because at 1 pe we see only the gain and by 3 pe we see mainly the product of gain and QE. One could conclude that that $\langle \text{npe}\rangle = 2$ is a bad place to operate.

Also:

A study of the cosmic ray muon spectrum at the earth's surface [2] was used along with dEdx vs momentum information [3] and the calculated momentum cutoff from our lead brick hardener in a numerical integral to find average energy deposit in scintillator compared to minimum ionizing. The spectrum decreases below 300 Mev, and there is a factor of 10 uncertainty due to building materials below 100 Mev. Our cutoff is about 250 MeV where the dE/dx is almost min ionizing. The variation in dEdx is almost entirely from the relativistic rise of a factor of 1.5 at 10 GeV, (but the flux is down a factor of 10 at 10 GeV)

RESULTS OF SCINTILLATOR + PHOTOTUBE SIMULATION

The ADC spectrum from cosmics perpendicular to the SMD plane was simulated. A sigma / mean of 0.4 for the 1 pe peak approximately matches our actual data from cosmics with a Hamamatsu multi-anode PMT. The smearing of the spectrum occurs because of the statistics inside the phototube, while the smearing of the pedestal is due to the electronic noise outside the PMT.

The zeros of a poisson show up in the pedestal. In the actual cosmic ray test, there is a factor of 50 or more excess counts in the pedestal because the area of the trigger counters is larger than the area of a scintillator strip.

A typical spectrum is shown in Figure 1 for the case of $\langle \text{npe}\rangle = 4$ at the apex (with a fiber hole). The spectrum from the triangular scintillator has much more at 1 pe than a poisson distribution would.
RESULTS of SIMPLE SIM. with VERTICAL COSMICS

In principle this calculation can be used to relate strip measurements using adjacent veto to measurements without any veto. Also, it can in principle relate both kinds of measurements to a hypothetical triangular strip with \(<npe>\) at the peak.

This study was done by looking at various kinds of means of the pulse height spectra. Smearing by the pmt was not included in most of the study because it was observed that the means did not change much as the ADC cut was moved from 0.1 to 0.25 of the 1 pe peak position.

I have made a numerical calculation which is equivalent to the following:

A) vertical cosmic rays or tracks perpendicular to the SMD plane.
B) efficiency of detection of tracks, requiring at least one pe.
C) efficiency of veto of adjacent strips, requiring at least one pe.
D) loss of light due to missing material in the fiber hole.
E) calculated for cases of 2,3,4,5 \(<npe>\) at the apex of a triangle with a fiber hole.

There are two quantities which go into the results, the efficiency and the pulse height.

I calculated 5 kinds of averages over the equivalent to using a large number of particles, but only numbers 3 and 5 are really relevant to analysis.

1) an idealized case, assuming we could reconstruct the poisson zeros working back from fits to the observed signals, and normalize to all the tracks hitting a strip, including those which leave no observable signal. (the distribution over a triangle is a sum of poissons which is not at all poisson, so the reconstruction is probably not possible in this case, nor is the normalization using unobservable events.)

2) The signals including reconstructed zeros, but normalized to observable events. (those having a least one pe)

3) means of the observable parts of the signals, normalized to observable tracks.

4) using adjacent strip vetos, the signals using reconstructed zeros, normalized to tracks which make at least one pe in the strip being studied, and do not make at least one pe in the adjacent strips.
5) using adjacent strip vetos, the averages of the observed signals, normalized to tracks which make at least one pe in the strip being studied, and do not make at least one pe in the adjacent strips.

The results:
The poisson $u$ and the observable means in the following table are shown as Figure 2. The table corresponds to the integrals over Figures 3 a through d for $<N_{pe}>$ at apex, (fiber hole losses are included) of 2,3,4,5 pe. (averaged of the strip width)
(all values in $<n_{pe}>$ units) 
( the / indicates normalization)

<table>
<thead>
<tr>
<th>N apex</th>
<th>$u_{po}$</th>
<th>$u_{obs}$</th>
<th>$u_{obs}$</th>
<th>$u_{obs-nv}$</th>
<th>$u_{obs-nv}$</th>
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<td>obs</td>
<td>obs</td>
<td>obs-nv</td>
<td>obs-nv</td>
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<td>0.853</td>
<td>1.396</td>
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For the veto style analysis the graph of the mean surviving the veto can be used as a crude look-up to see what measurements of 2.9 to 3.5 pe mean in terms of a perfect triangle with a perfect measurement at the peak. For the analysis using an average over all of each strip in real data we see a pulse height about 3 times the 1 pe pulse height, and we could interpret this using the graph of the mean.

There are calibration questions from this (what is meant by the requirement of 2 pe?)

And physics questions of adding strip pulse heights for either single muons or showers And interpreting non linear response across the strip in reconstructing showers and pairs of showers, both pulse height and position.
RESULTS of SIMULATION INCLUDING ANGLE OF COSMICS

This looks remarkably like the results of the simulation for vertical cosmics. There is about a 5 % spread in the light output for the various angular bins.

In the cosmic ray test stand, there are planes of scintillators roughly 1.5 meter above 1.2 meter below the SMD being studied. The planes are segmented along the SMD strip direction, but not perpendicular to a strip. The angular range of accepted cosmics ranges from 0 near the edge of the fiducial area, to +- 23.5 degrees near the center of the area. This is the range of the angle around the axis of a strip. With the so-called tight trigger the angular range is extremely limited in the other direction, along the strip.

The results are summarized in figure 5, for comparison with figure 2.

RESULTS of Range and DeDx studies

We have 10 cm of Pb in the hardener. This is 135 grams/cm^2. In the range table this gives a cutoff of about 250 MeV for muons. Fig [6]

Muons are basically minimum ionizing at this energy. There is a relativistic rise in dedx of a factor of 1.5 by 10 GeV, but the spectrum is down a factor of 5 at 5.5 GeV and a factor of 10 at 10 GeV. Fig[7]

A numerical integration to find the average dedx:

<table>
<thead>
<tr>
<th>Range of integral</th>
<th>ratio avg to mip</th>
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<tr>
<td>0.075 to 14 GeV</td>
<td>1.25 mip</td>
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<tr>
<td>0.25 to 14 GeV</td>
<td>1.25 mip</td>
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<tr>
<td>0.25 to 7.4 GeV</td>
<td>1.19 mip</td>
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RESULTS OF <NPE>=2 PMT SIMULATION

In thinking about doing anything at 2 pe, I was worried that since the 1 pe adc count is sensitive only to PMT gain, not to quantum efficiency, and 3 pe is really the product of gain and quantum efficiency, that 2 pe might be in a difficult crossover region.

I wrote a simple program that assumes we put in light which would be 2 pe for the average of a number of phototubes. However, I then vary the gain by +- 30%, and the Quantum efficiency by +- 30 %. I generate pe distribution for each case using a poisson analytic formula, not MC.

I then try to reconstruct the original signal size (the real signal size for each tube, not the average of 2 pe for many tubes). This is just finding the mean of each distribution without the zeros.
What I find is that the ratio of the reconstructed signal to the real signal varies from 1.049 to 1.629. (the reconstructed is always larger because we can't see zeros)

Of course this has to do with the real number of pe in the signal varying, but what is shows is that the variation of the observed mean to the real main is extremely sensitive to variations away from exactly 2 pe, and of course we don't know what the size of the signal is a-priori.

I conclude that 2 pe is a really difficult region, whether for LED or cosmics or physics data.

<table>
<thead>
<tr>
<th>actual u avg PMT</th>
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References


Figure 1. Simulated ADC spectrum from cosmics perpendicular to the SMD plane. The spectrum from the triangular scintillator with $<n_{pe}> = 4$ at the apex (with a fiber hole) has much more at both 0 pe and 1 pe than a poisson distribution would. The smearing of the spectrum occurs because of the statistics inside the phototube, while the smearing of the pedestal is due to the electronic noise outside the PMT. A sigma / mean of 0.4 for the 1 pe peak approximately matches our actual data from cosmics with a Hamamatsu multi-anode PMT.
Figure 2. Results of simple simulation with vertical cosmics in horizontal triangular SMD strips and poisson photoelectron distributions for each path in the scintillator. The lines are either poisson means or observed averages in units of pe, vs the input normalized to pe in 6.03 mm of scintillator.

Top, dashed, curve (brown) using adjacent veto, observed mean normalized to observed tracks

Next (right side) (blue) using adjacent veto, poisson u for observed tracks

Next (green) observed mean for all observed tracks

Second from bottom (red) Poisson u normalized to observable tracks

Bottom (black) Poisson u normalized to all tracks generated for a strip

The most relevant results, green line for average over strip with no veto, and brown dashed line for average over strips with adjacent strips in veto, are quite similar to the results from a different simulation with full angular range of cosmics. An observed mean of 3.5 with veto corresponds to about 4 pe in 6 mm, and an observed mean of 3 without veto corresponds to about 4.4 pe in 6 mm.
Figure 3a  Calculated quantities across a strip profile, assuming vertical cosmics.  i) The second curve down from the top (black) is the amount of scintillator normalized to a poisson mean of 2 pe in the center, and it dips in the middle because of the fiber hole.  ii) The top (red) curve is the mean observed pulse height vs position of the cosmic, using a poisson but not observing the zeros. Note that the observed mean is higher than the poisson mean, about 2.3 at the peak where the poisson is 2.0 pe generated, and 1 pe at the edge where the poison mean goes to zero.  ii) The concave downward curve (green) is the efficiency, and the concave upward (blue) the inefficiency.  v) The brown dashed curve is the product of efficiency in the scintillator under study times the inefficiency of the adjacent veto. This tells us how well the adjacent vetoing localizes the measurement.

mean, eff, pe for 2 pe in 6 mm of scint
Figure 3b Calculated quantities across a strip profile, assuming vertical cosmics. 

i) The second curve down from the top (black) is the amount of scintillator normalized to a poisson mean of 3 pe in the center, and it dips in the middle because of the fiber hole.  

ii) The top (red) curve is the mean observed pulse height vs position of the cosmic, using a poisson but not observing the zeros. Note that the observed mean is higher than the poisson mean, about 3.2 at the peak where the poisson is 3.0 pe generated, and 1 pe at the edge where the poison mean goes to zero. 

iii) The concave downward curve (green) is the efficiency, and the concave upward (blue) the inefficiency. 

v) The brown dashed curve is the product of efficiency in the scintillator under study times the inefficiency of the adjacent veto. This tells us how well the adjacent vetoing localizes the measurement.

ave pe, effic., with and without adj. veto for 3 pe in 6 mm of scint.
Figure 3c Calculated quantities across a strip profile, assuming vertical cosmics. 

i) The second curve down from the top (black) is the amount of scintillator normalized to a poisson mean of 4 pe in the center, and it dips in the middle because of the fiber hole. 

ii) The top (red) curve is the mean observed pulse height vs position of the cosmic, using a poisson but not observing the zeros. Note that the observed mean is higher than the poisson mean, about 4.1 at the peak where the poisson is 4.0 pe generated, and 1 pe at the edge where the poisson mean goes to zero. 

iii) The concave downward curve (green) is the efficiency, and the concave upward (blue) the inefficiency. 

iv) The brown dashed curve is the product of efficiency in the scintillator under study times the inefficiency of the adjacent veto. This tells us how well the adjacent vetoing localizes the measurement.
Figure 3d  Calculated quantities across a strip profile, assuming vertical cosmics.  i) The second curve down from the top (black) is the amount of scintillator normalized to a poisson mean of 5 pe in the center, and it dips in the middle because of the fiber hole.  ii) The top (red) curve is the mean observed pulse height vs position of the cosmic, using a poisson but not observing the zeros. Note that the observed mean is similar to the poisson mean at the peak where the poisson is 5.0 pe generated, but 1 pe at the edge where the poison mean goes to zero. ii) The concave downward curve (green) is the efficiency, and the concave upward (blue) the inefficiency. v) The brown dashed curve is the product of efficiency in the scintillator under study times the inefficiency of the adjacent veto. This tells us how well the adjacent vetoing localizes the measurement.
Figure 4. Path length of cosmics in the triangular scintillator strips for various ranges of the angular distribution. Basically, at large angles, a few cosmics can miss the fiber hole and see 7 to 7.5 mm of scintillator instead of the 6.03 maximum for vertical cosmics. The top curve is an average assuming perfect, 100% vetoing by adjacent strips, with a 1 mm opening at the apex. The bottom curve is an average over a strip with no vetoing.
Figure 5. Simulation using the angular distributions of cosmics around the fiber axis for various parts of the acceptance within our fiducial area. Bins are the ranges within +-3.5 degrees, within +-8.5 deg, within+- 13.5 deg, within +- 18.5 deg, and within +- 23.5 deg.

Top band of curves (green, blue) using adjacent veto, observed means for observed tracks (highest curve for +- 23.5 deg. Range)

Middle (orange, green) observed means for observed tracks

Bottom (blue, violet) Poisson u normalized to all tracks generated.

While the spread in average path length over our acceptance assuming perfect veto power is about 16%, the top curves show that the variation in mean light is only about 5%, because the vetoing is not perfect. The band of curves has less spread at low pe, where one would expect it to have more spread because of imperfect veto, presumably because the range of possible signal pulse heights is restricted to be above 1 pe at the lower end.
Figure 6. Range for muons in Pb, and de/dx for muons in carbon, etc. From Particle Data Group, 1988. We can see that with our range cutoff of 250 MeV, the variation in de/dx is almost entirely from the relativistic rise of a factor of 1.5 at 10 GeV, (but the flux is down a factor of 10 at 10 GeV)
Figure 8

Theoretical sea-level cosmic rays. Theoretical calculation of the flux of cosmic ray particles at New York City. The most abundant particles are muons, which physically act like heavy electrons except that they are unstable and have a lifetime of less than 2 $\mu$s. The next most abundant particles are neutrons, which are very penetrating because they are neutral and do not lose energy to the electron sea of the atmosphere. There are as many protons as neutrons produced in the upper atmosphere cosmic ray showers, but the protons are charged and hence constantly lose energy to the atmospheric electrons and disappear faster than the neutrons at lower altitudes. The pions, like the muons, are unstable, and there are 100 pions for every pion at sea level, but pions are far more effective in causing soft fails in electronic circuits [28]. All flux curves below 0.1 GeV have limited accuracy because local building materials can vary the absorption and production of the particles by more than 100% [26].

Figure 7. Calculated spectrum of cosmosics at ground level. From

Reading from the graph, the flux is down a factor of 4.95 at 5.54 GeV, and down more than a factor of 10 at 10 GeV