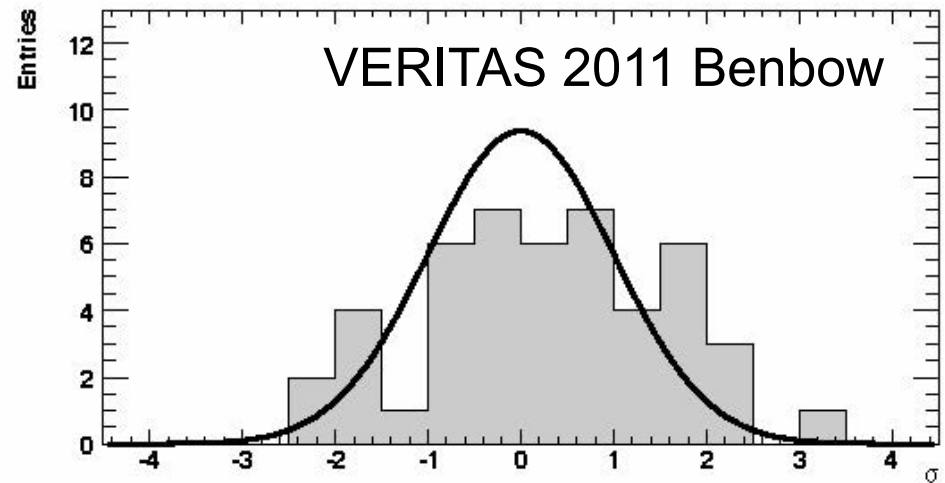
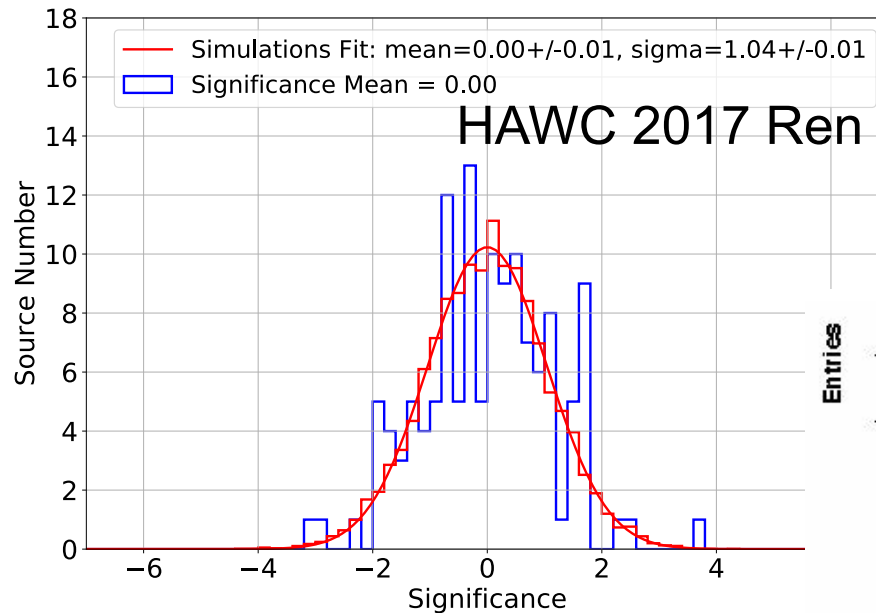


Lessons learned from <1 TeV Simulations

(Motivated by directed surveys of AGNs)



John Matthews (+ R. Lauer, Z. Ren), Physics and Astronomy, UNM
HAWC Collaboration meeting:
Cocoyoc, Mexico, Oct 29 ~ Nov 1, 2017

Overview ... IF we are allowed to dream!

HAWC works quite well for events > 1 TeV

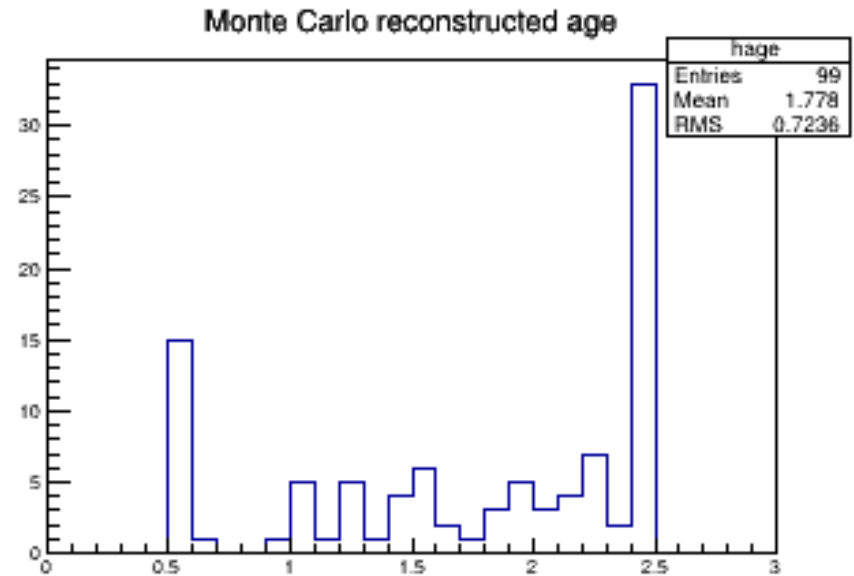
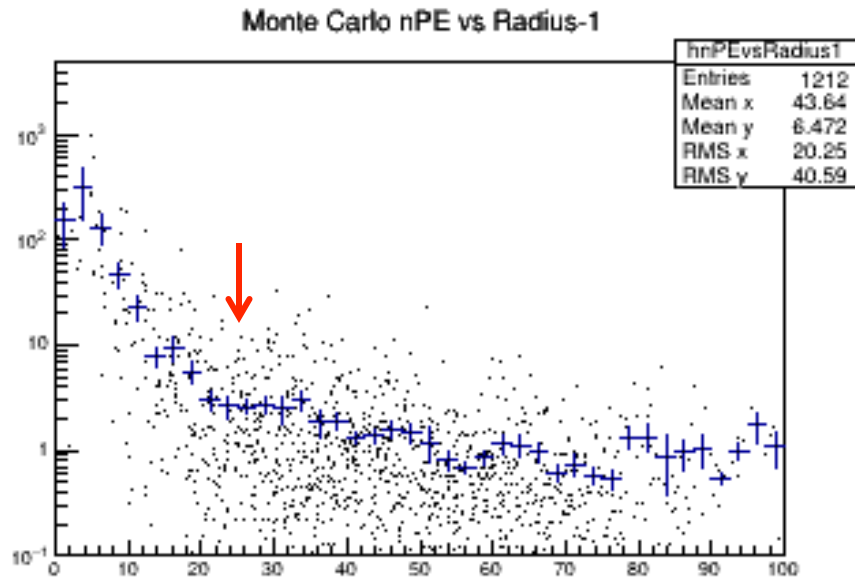
What might we do to improve HAWC performance for showers with energies < 1 TeV? (For example it would be nice to observe more than 2 AGNs ...)

Components considered:

- Increase area of *low-energy* array (to reduce edge effects)
- Increase elevation (to help *low-energy* shower particles reach the array)
- Increase tank sensitivity (so when there are tank *signals* we record them)

Increase area of *low-energy* array

Remember that HAWC tanks provide a calorimetric measurement of the shower. **For *low-energy* showers most of the signal is within ~25m of the core:**



Left: nPE versus distance (m) from core for gamma showers with $500 \text{ GeV} < E < 2000 \text{ GeV}$ and zenith $< 26^\circ$ and core in center of array and GamCore age = 0.5 (fit limit)

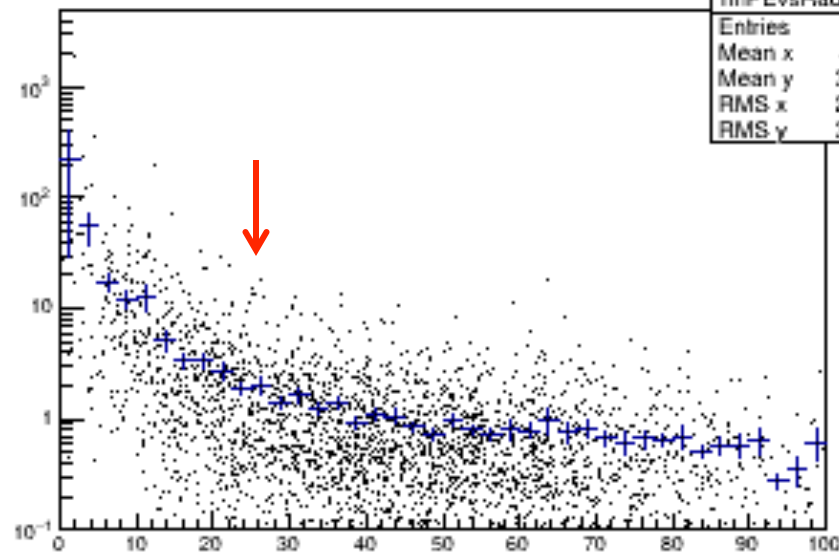
Right: GamCore reconstructed shower age distribution

Increase area of *low-energy* array

Remember that HAWC tanks provide a calorimetric measurement of the shower. For *low-energy* showers most of the signal is within $\sim 25\text{m}$ of the core (and about $1/3^{\text{rd}}$ of the showers have *no* core):

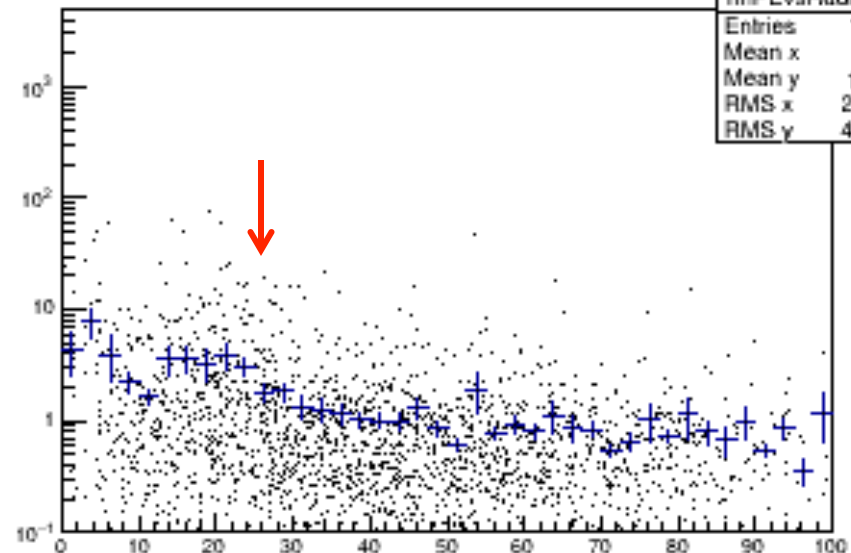
Monte Carlo nPE vs Radius-2

lnPEvsRadius2
Entries 2615
Mean x 42.81
Mean y 3.429
RMS x 21.48
RMS y 38.49



Monte Carlo nPE vs Radius-3

lnPEvsRadius3
Entries 1989
Mean x 41.7
Mean y 1.721
RMS x 22.49
RMS y 4.485



Left: nPE versus distance (m) from core for gamma showers with $500 \text{ GeV} < E < 2000 \text{ GeV}$ and zenith $< 26^\circ$ and core in center of array and GamCore age = 1 ~ 2

Right: nPE for showers with GamCore age = 2.5 (fit limit)

Increase area of *low-energy* array

Thus showers, and particularly *low-energy* showers, are negatively impacted when their core is within ~25m of the edge of the array. Cf John M. – Gamma Coreness **Data and Algorithms** talk, Sept 26, 2016 [see Backup figures in talk]

This negative impact decreases as the dimensions of the *low-energy* array are increased; for example:

- Effective area = $(150\text{m} - 2 \times 25\text{m})^2 = 0.44 \times (150\text{m})^2$ (I)
 - Effective area = $(300\text{m} - 2 \times 25\text{m})^2 = 0.69 \times (300\text{m})^2$ (II)
- ratio (II)/(I) = 6.25 VS 4.0

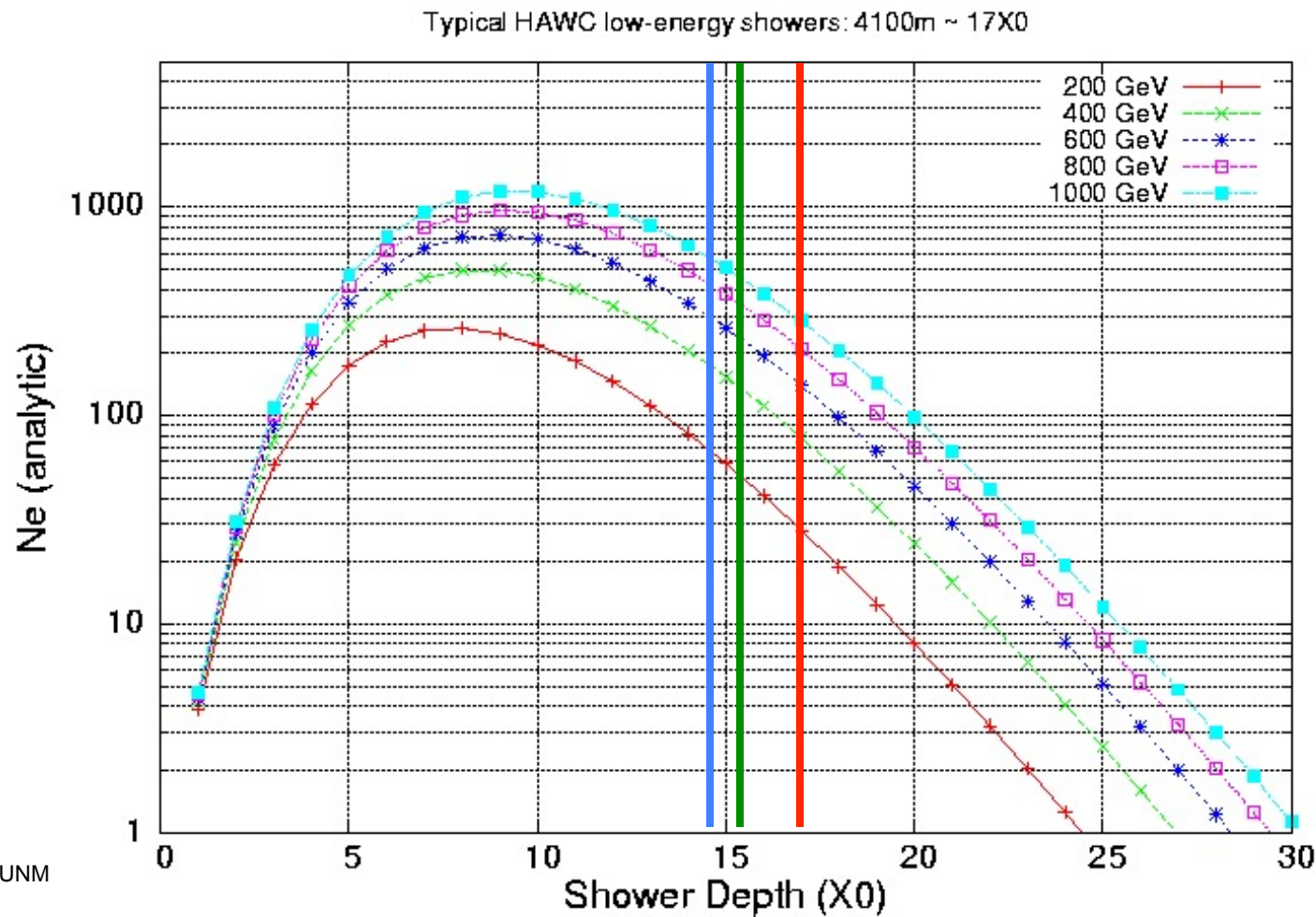
So bigger is (much) better!

Increase elevation

As HAWC is a ground array, low energy showers need to reach the array to be measured. So take the array to the showers ...

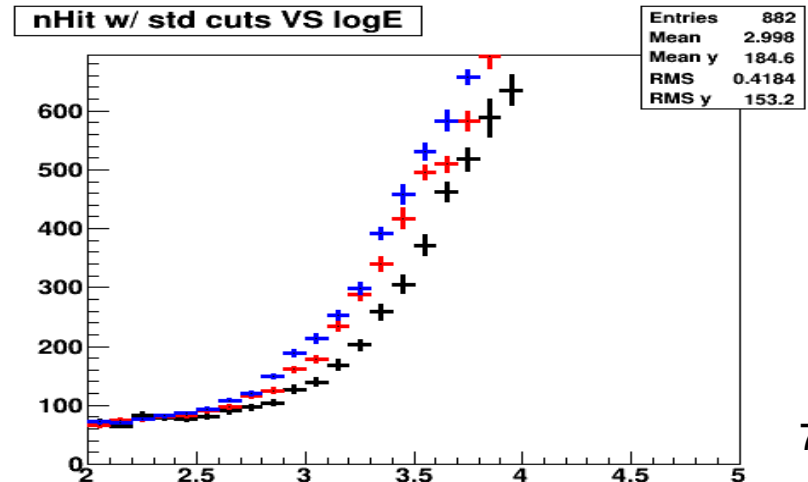
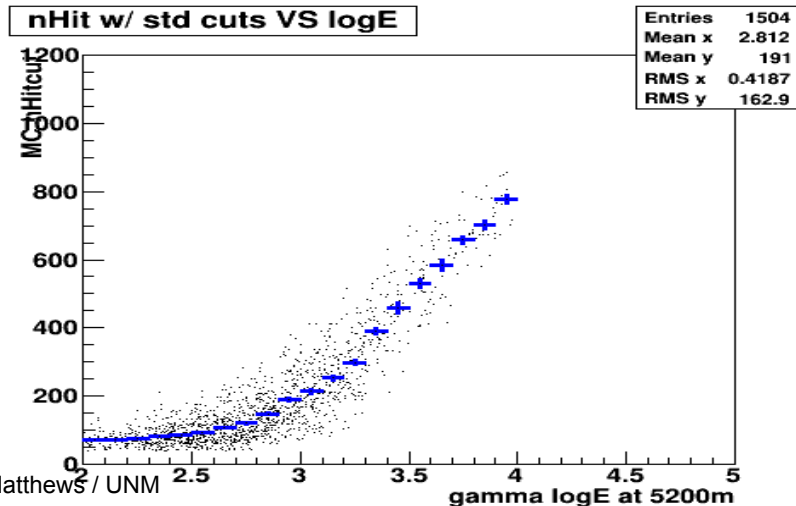
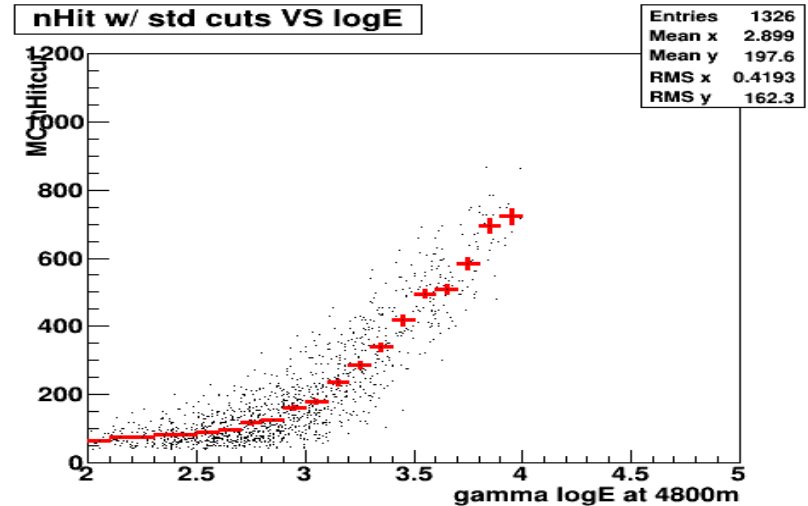
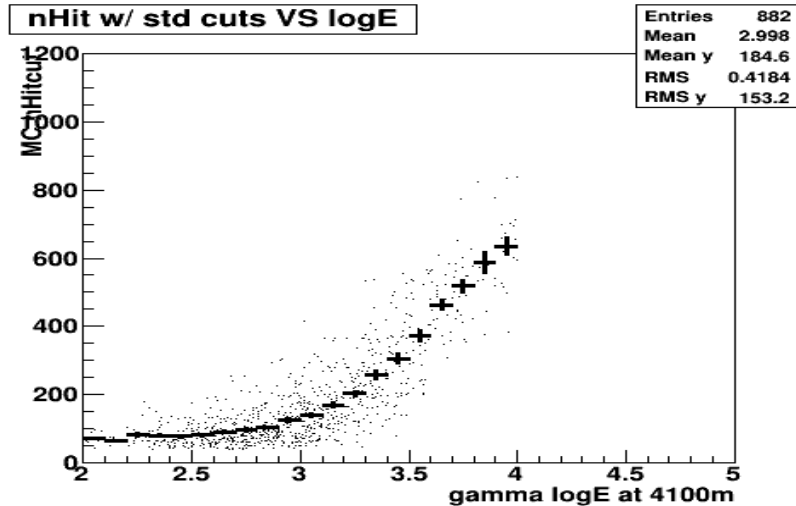
4100m $\sim 17.0 X_0$, 4800m $\sim 15.5 X_0$, and 5200m $\sim 14.7 X_0$

For the same N_e : 5200m should decrease HAWC *threshold* by $\sim 2x$



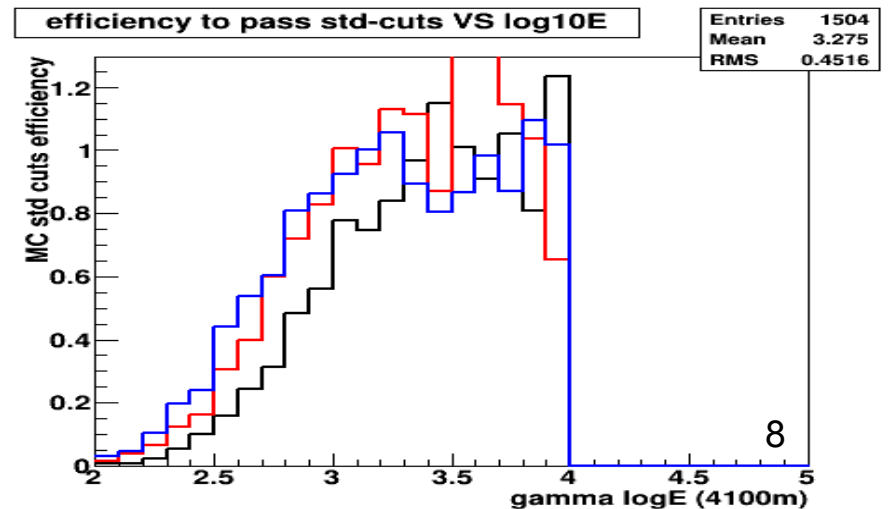
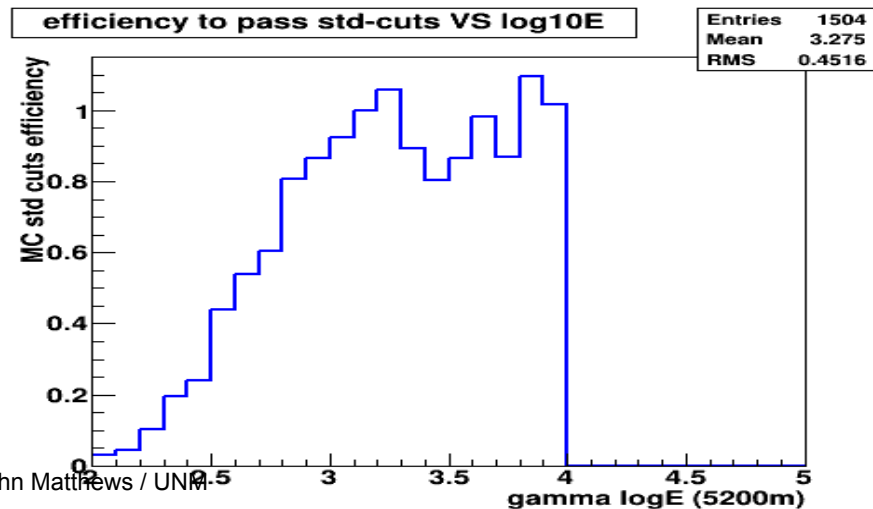
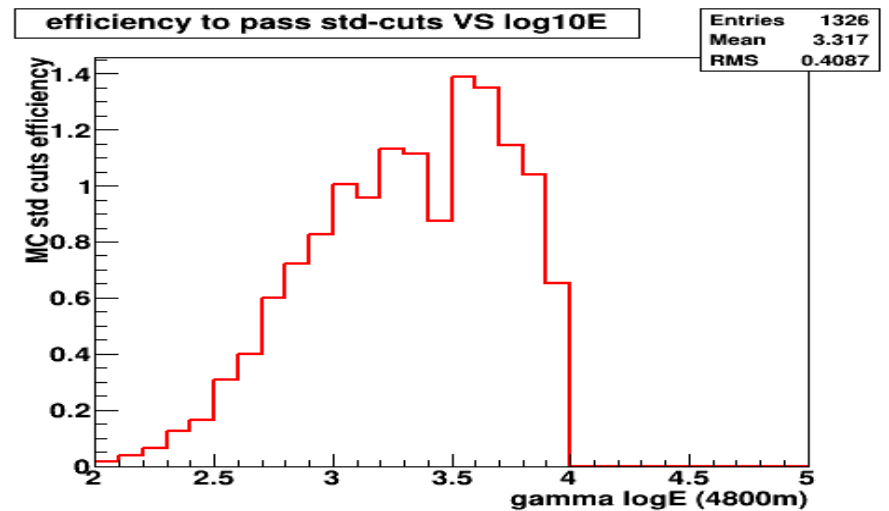
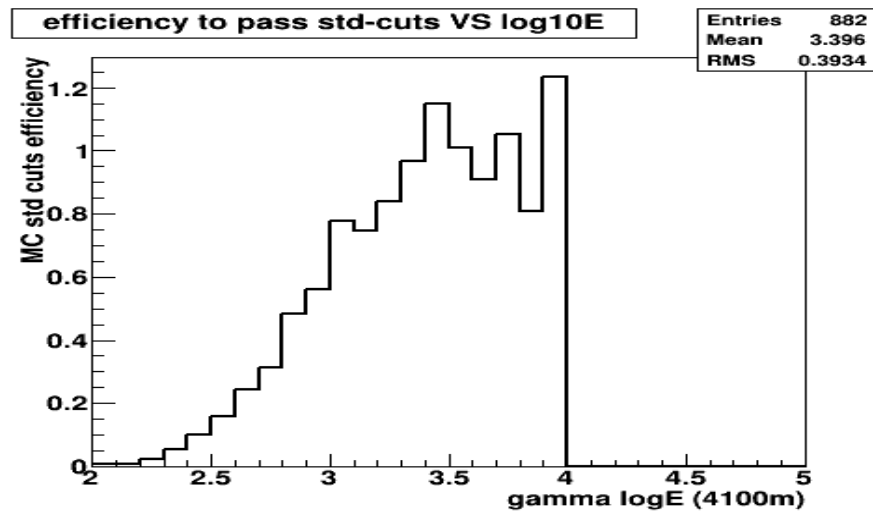
Increase elevation

Plot of **nHit** versus $\log_{10}E(\text{GeV})$ at 4100m, 4800m and 5200m for gamma showers with cores well within the (standard) HAWC array, zenith angle $< 26^\circ$, and w/ *standard* (but no G/H) cuts:



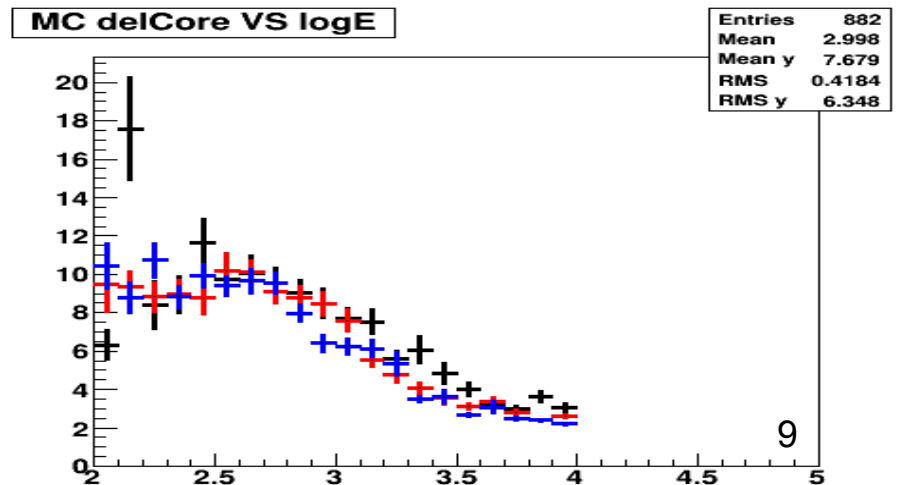
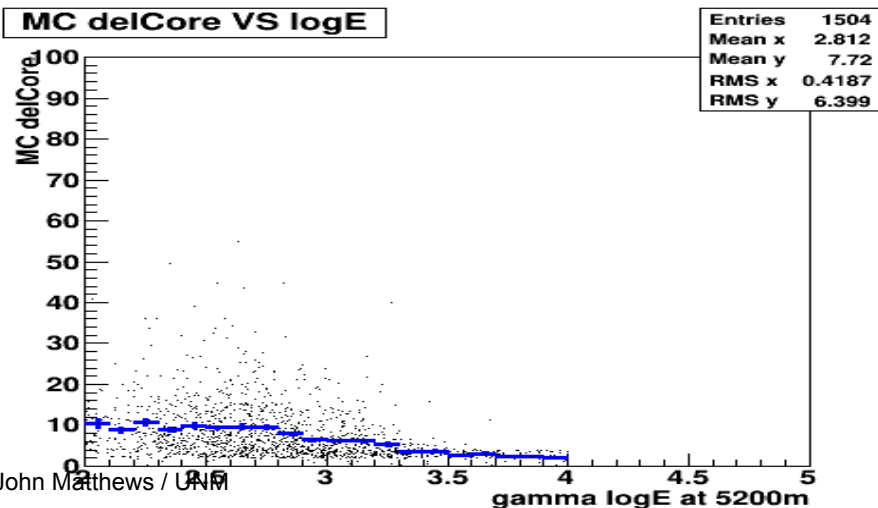
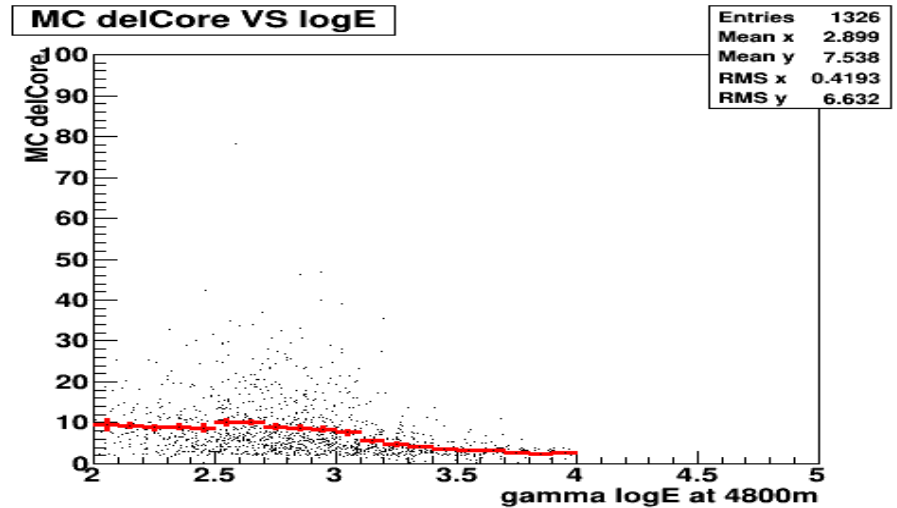
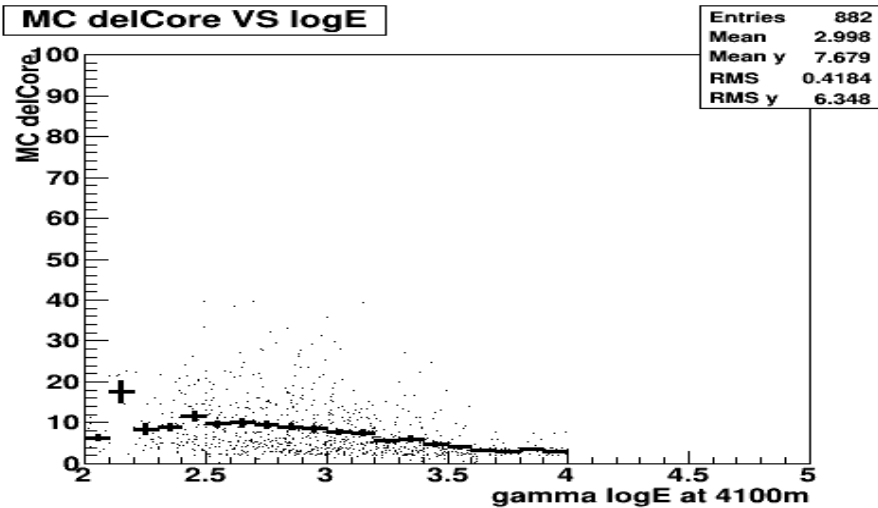
Increase elevation

Plot of HAWC **efficiency** (to pass *standard* (but no G/H) *cuts*) versus $\log_{10}E(\text{GeV})$ at 4100m, 4800m and 5200m. A decrease in HAWC's energy *threshold* by $\sim 2x$ would be a shift of -0.3 in $\log_{10}E$.



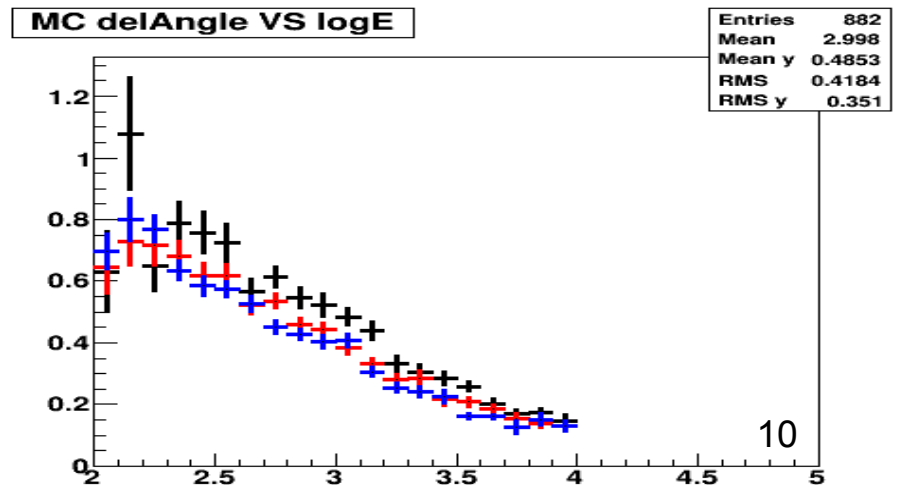
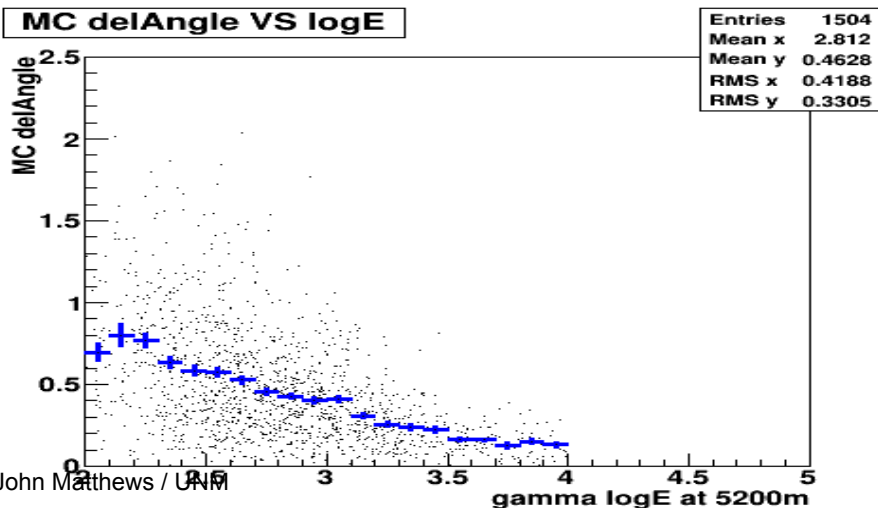
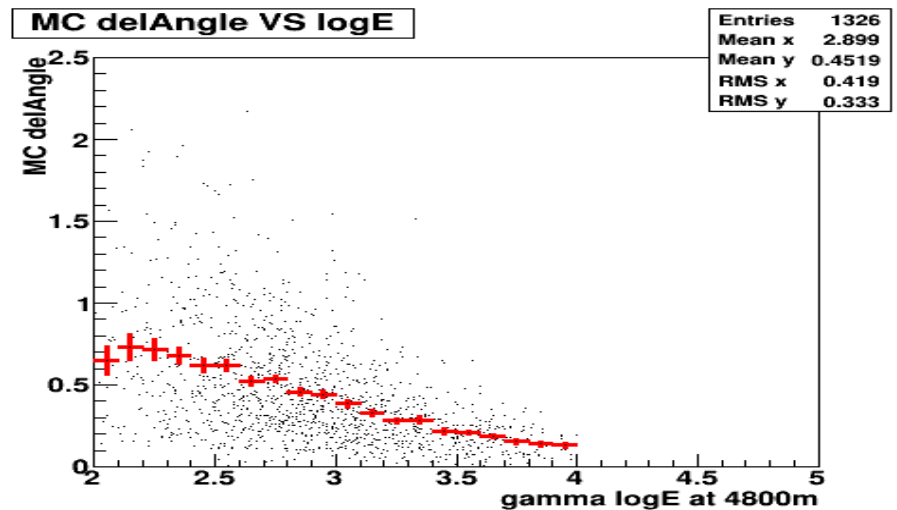
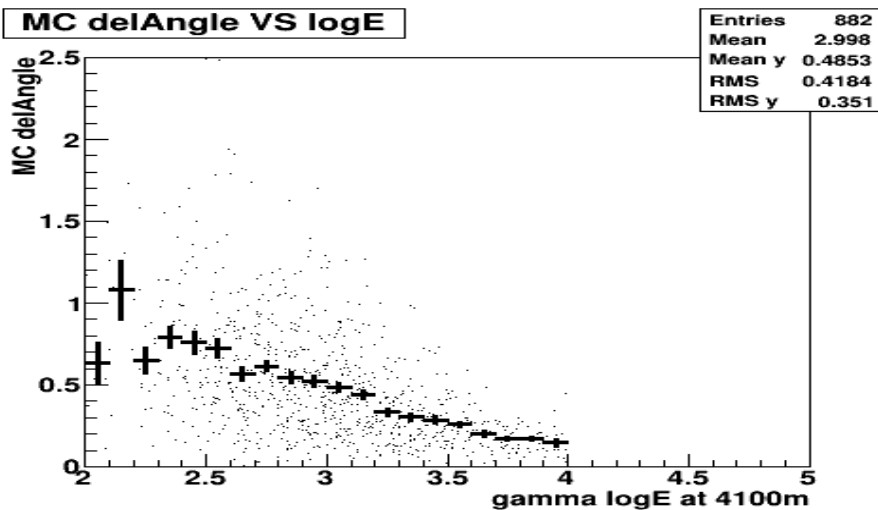
Increase elevation

Plot of **delCore(m)** versus $\log_{10}E(\text{GeV})$ at 4100m, 4800m and 5200m for gamma showers. The delCore distributions show only a small dependence on HAWC elevation.



Increase elevation

Plot of **delAngle**(°) versus $\log_{10}E(\text{GeV})$ at 4100m, 4800m and 5200m for gamma showers. Even with fixed nHit thresholds, the **delAngle** resolution decreases (improves) with increasing elevation



Increase tank sensitivity

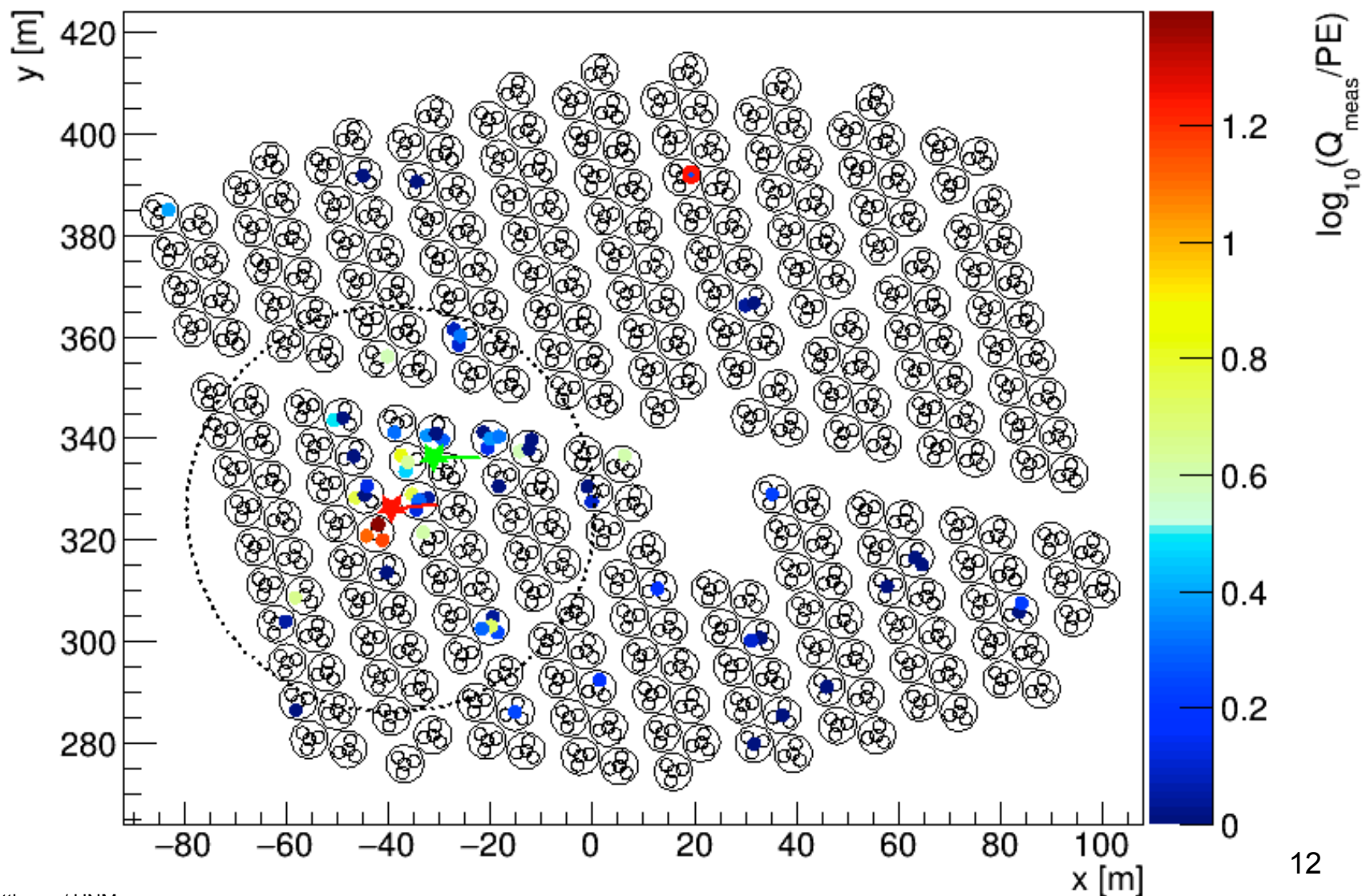
HAWC tanks have a bottom area of $\sim 41.85\text{m}^2$ instrumented by $\sim 0.148\text{m}^2$ of PMTs. So we have instrumented $\sim 0.35\%$ of the bottom tank surface.

What if we increased this from 0.35% to say 8.84% (a factor of 25x increase)? To do this we simply scaled the dimensions of the 8" and 10" PMTs in the HAWC GEANT4 simulation by **5x** and then ran the standard HAWC simulation and reconstruction programs:

- First look at a few gamma showers on the HAWC display (all events were run with `-splitter MultiPlaneFit` option enabled)
- Making only a change in the minimum nHit to accept showers, how do the distributions of e.g. **nHit** w/ cuts, **delCore** and **delAngle** versus $\log_{10}E$ compare to standard simulation results?

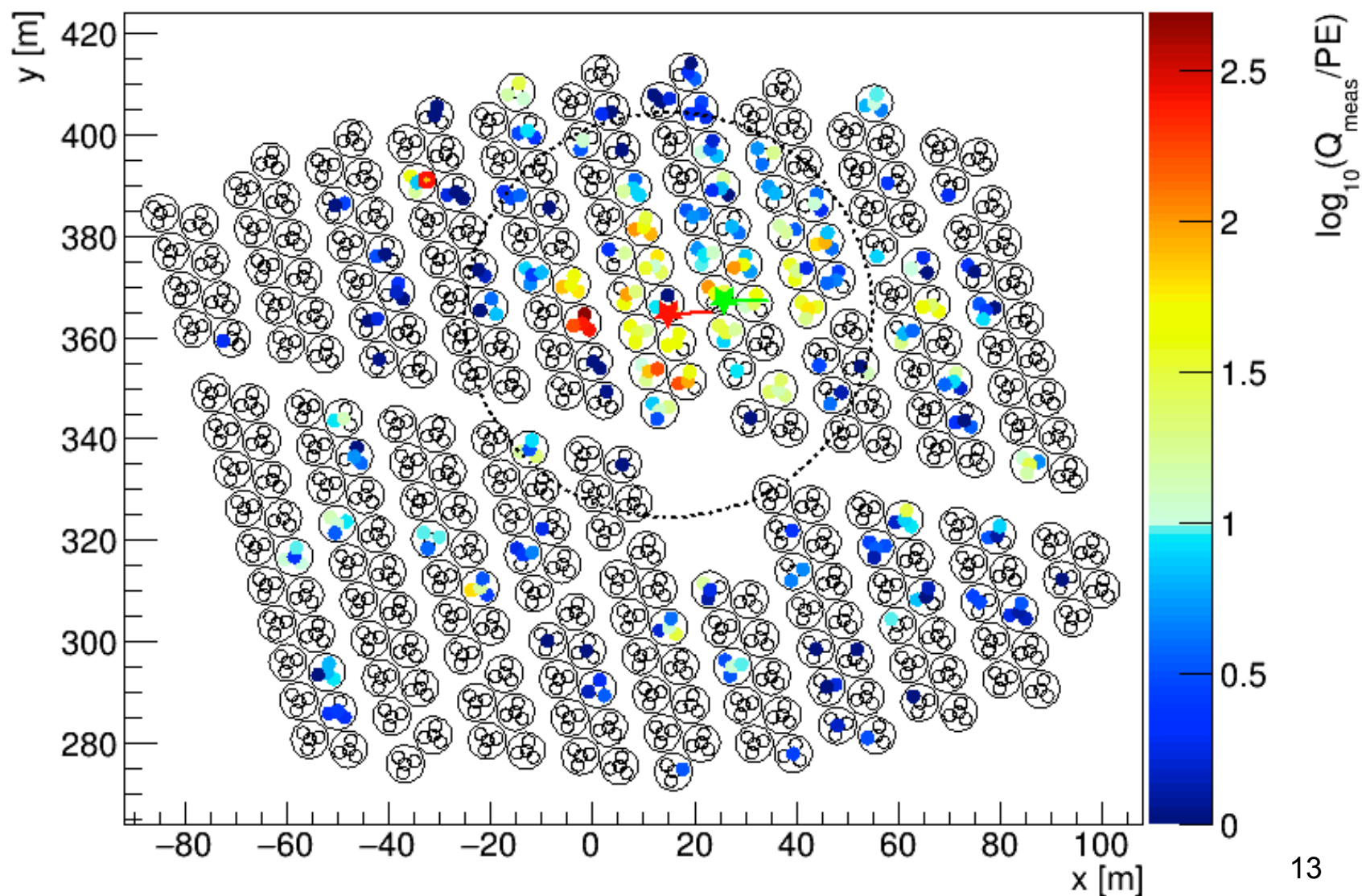
Std PMT event #5: 1.19 TeV

Run 304100, TS 0, Ev# 5, CXPE40= 1.81, RA= 21.5, Dec= 20.1



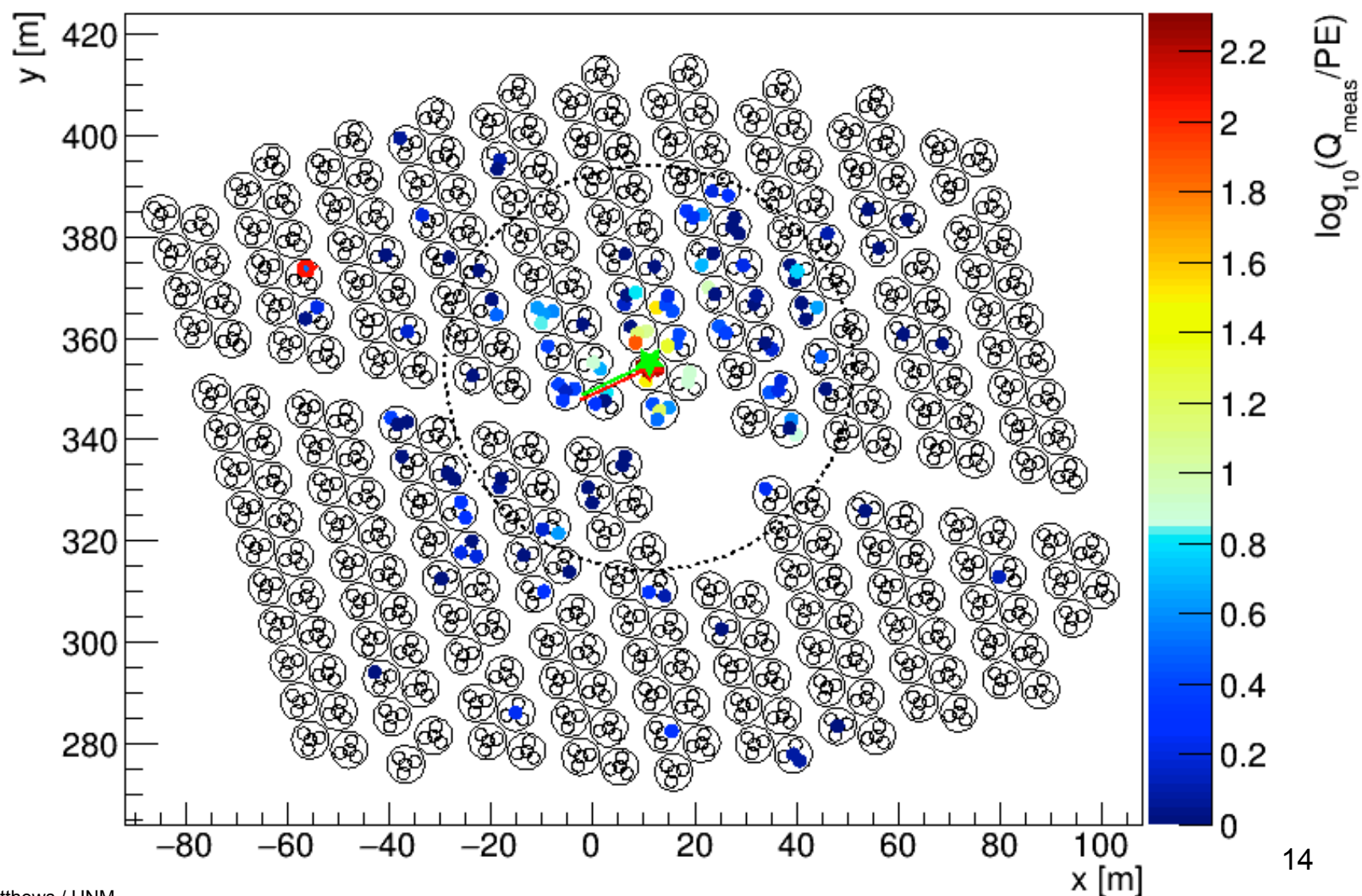
VeryLarge PMT event #5: 1.19 TeV _[new CoreX, CoreY]

Run 304100, TS 0, Ev# 5, CXPE40= 80.8, RA= 20.46, Dec= 19.5



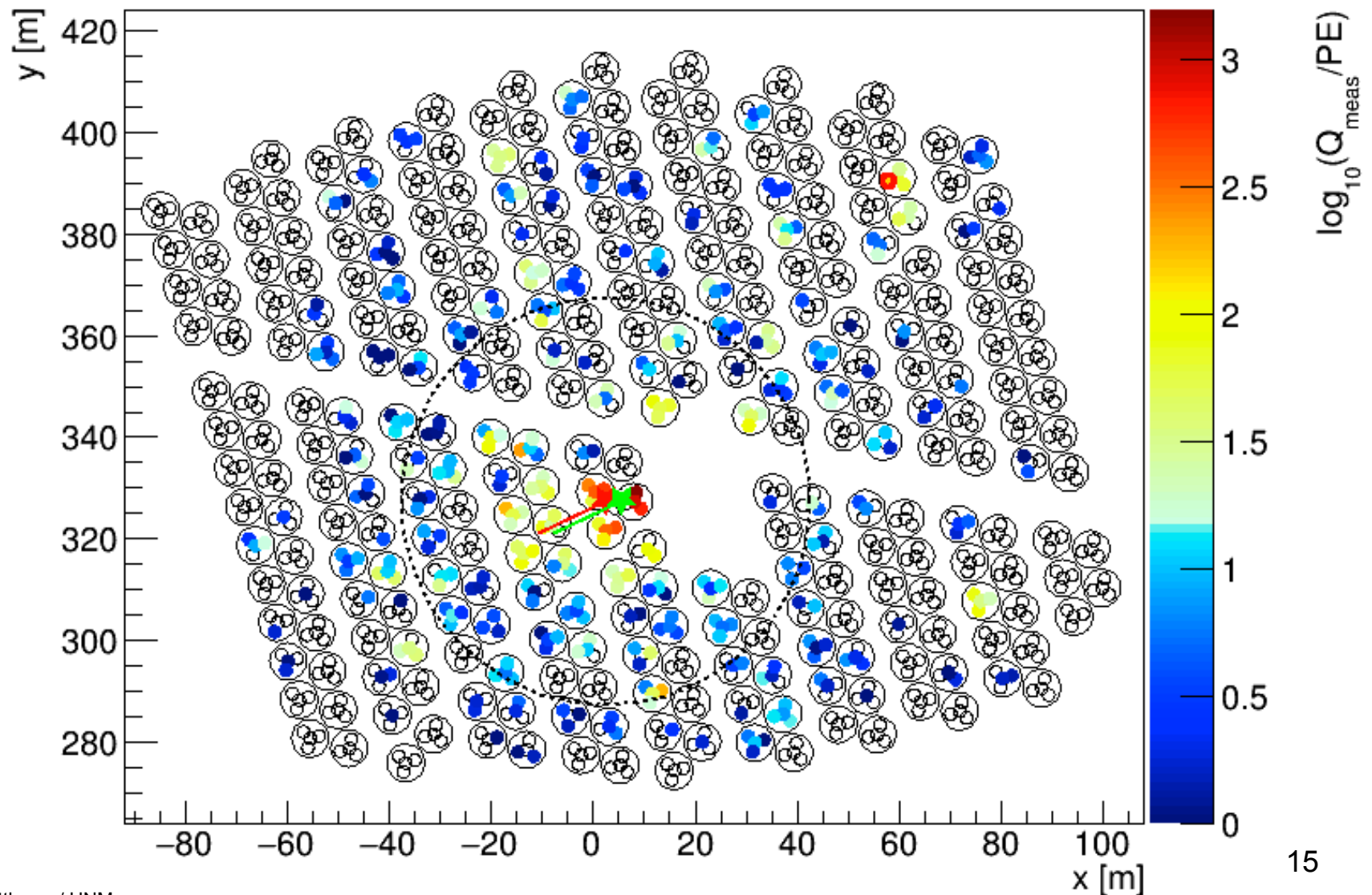
Std PMT event #42: 0.85 TeV

Run 304100, TS 0, Ev# 42, CXPE40= 3.51, RA= 347.7, Dec= 8.62



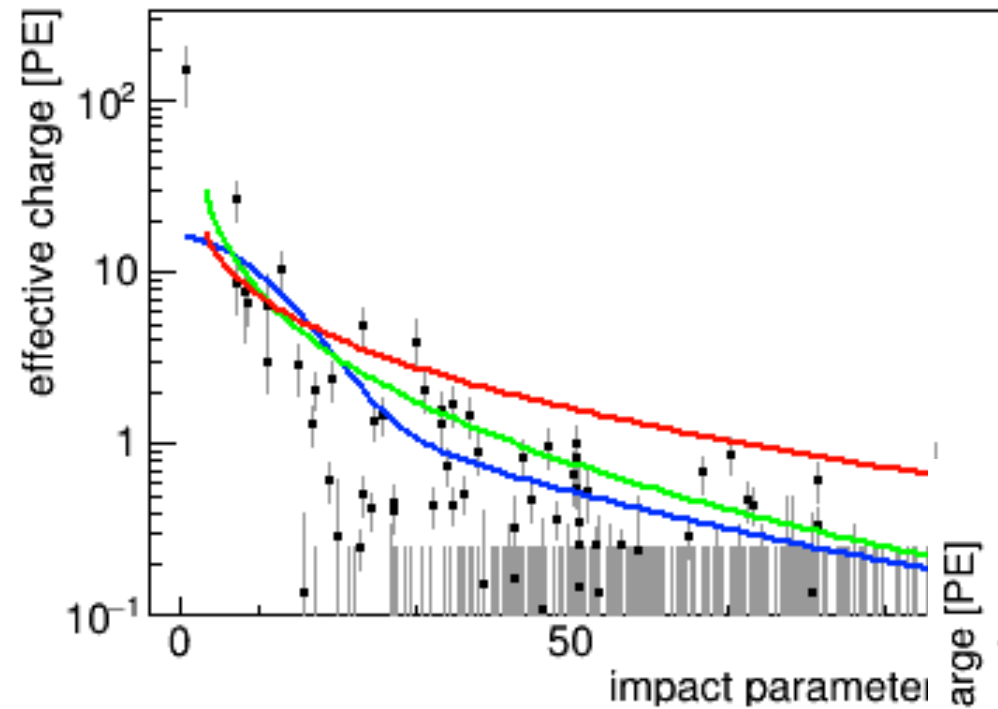
VeryLarge PMT event #42: 0.85 TeV [new CoreX, CoreY]

Run 304100, TS 0, Ev# 42, CXPE40= 168, RA= 348.1, Dec= 8.77

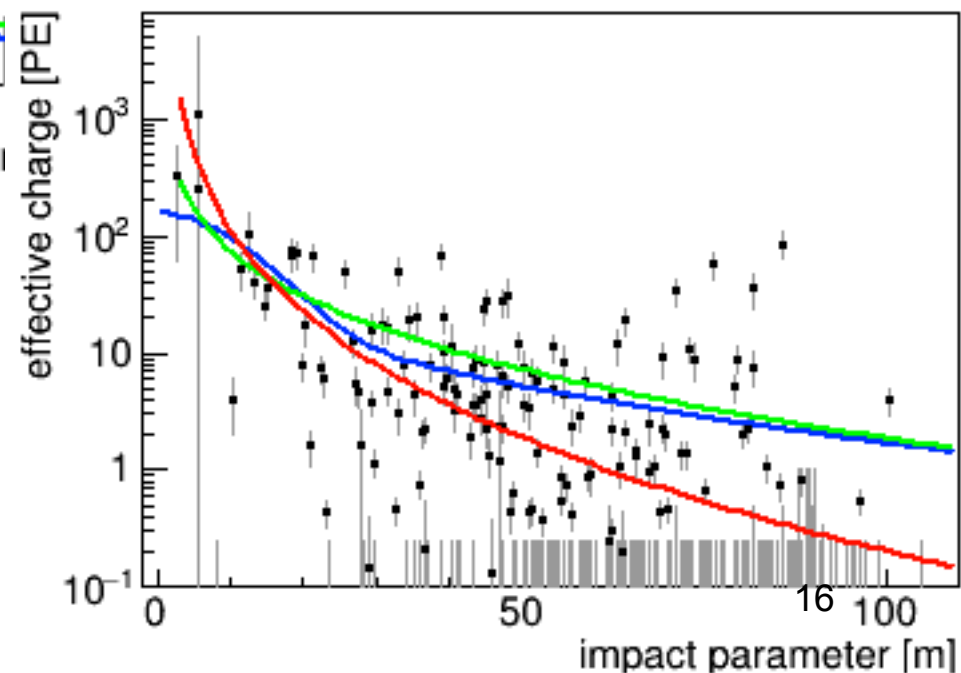


Std / VeryLarge PMT event #42: 0.85 TeV

Lateral distribution

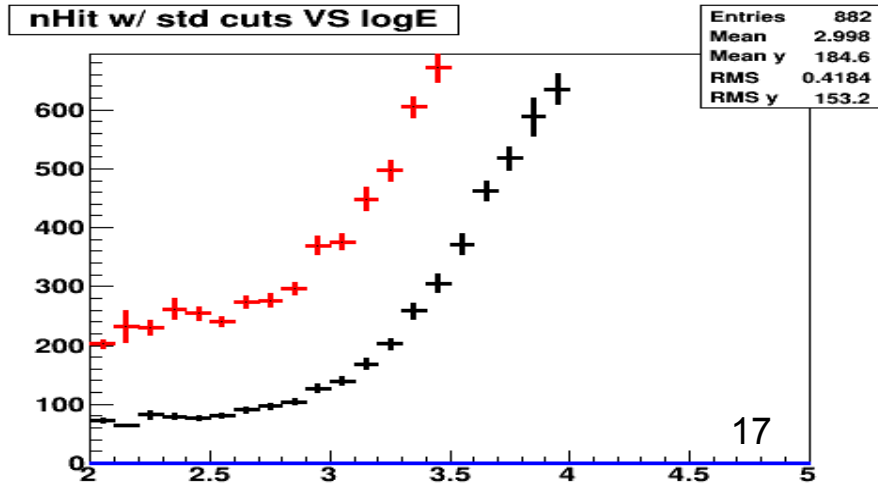
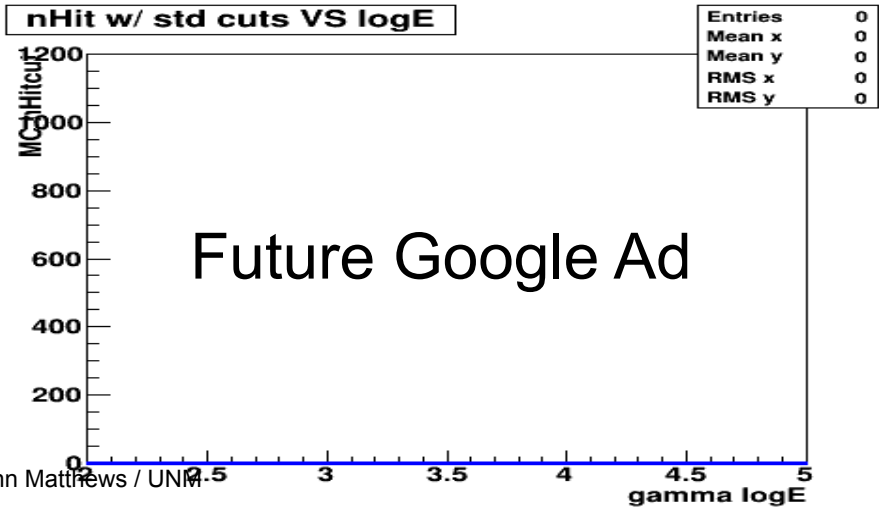
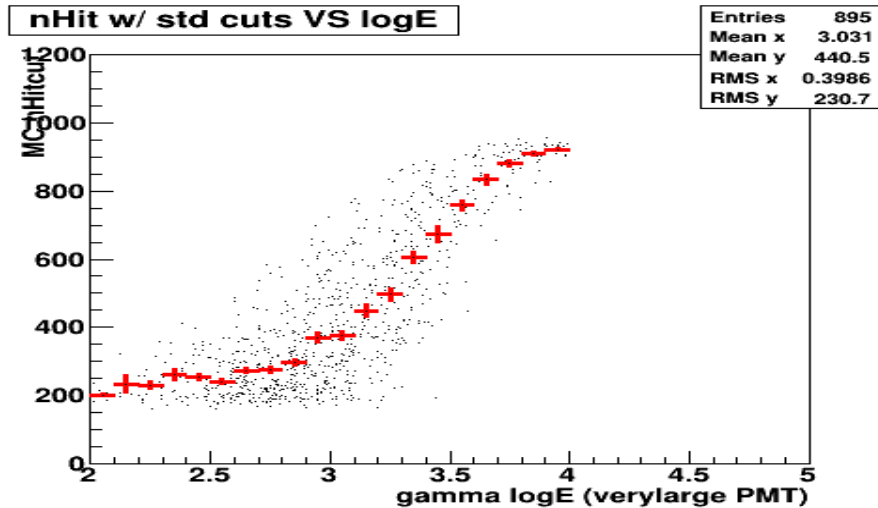
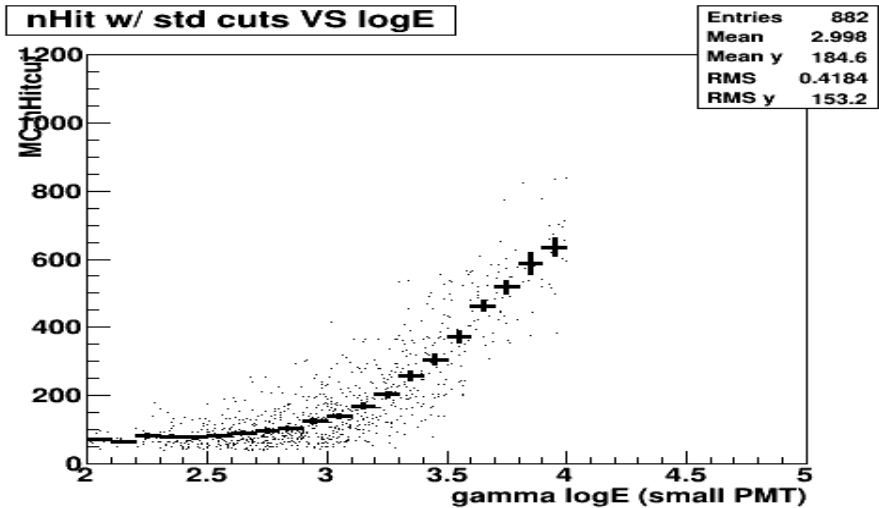


Lateral distribution



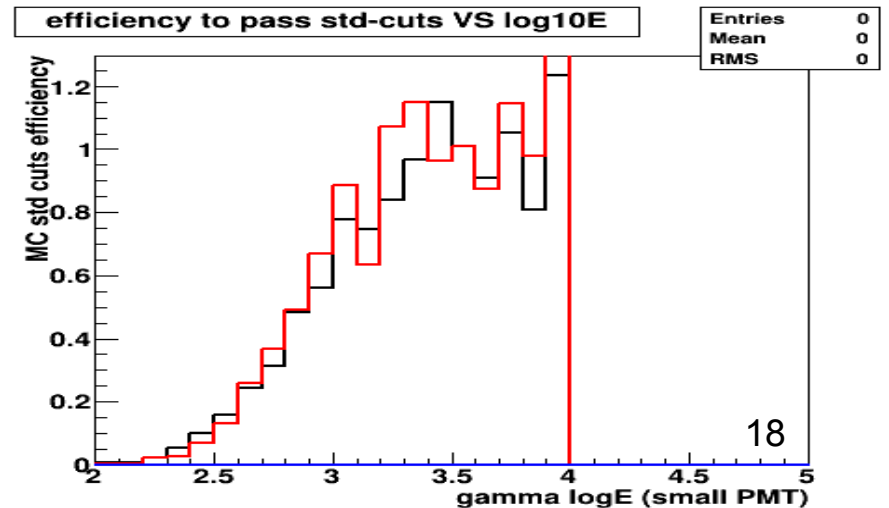
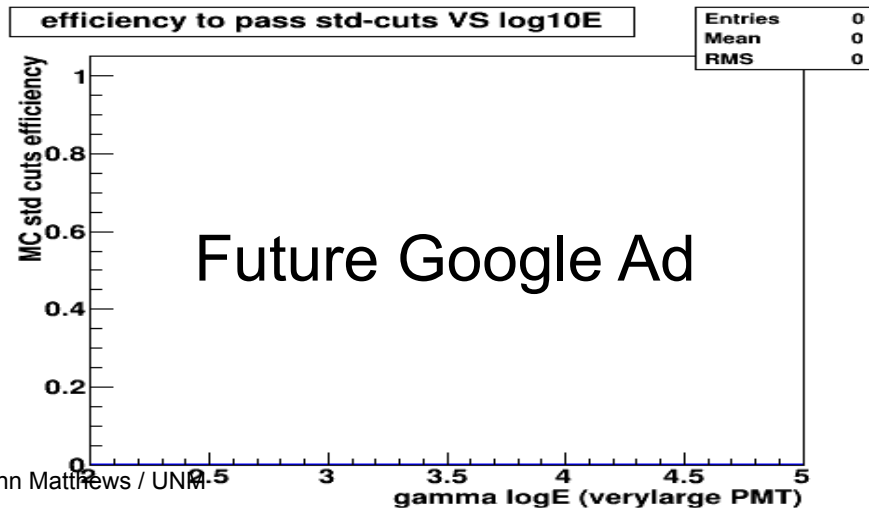
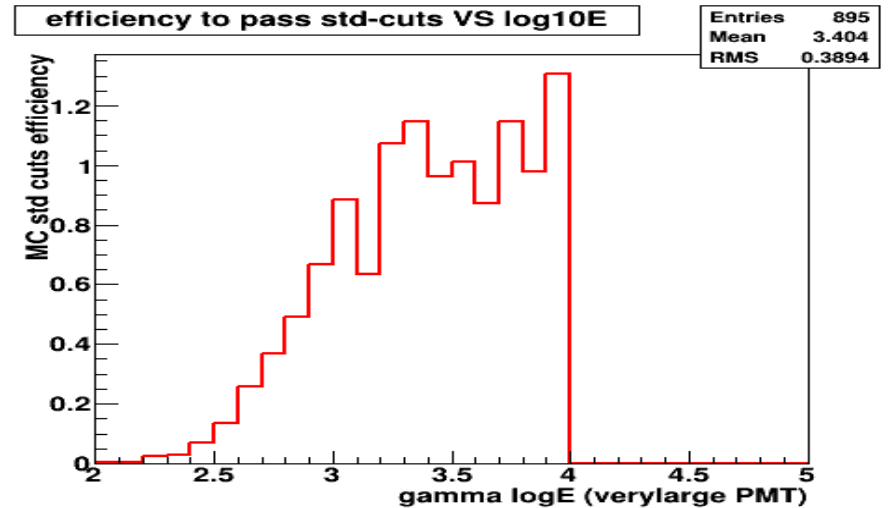
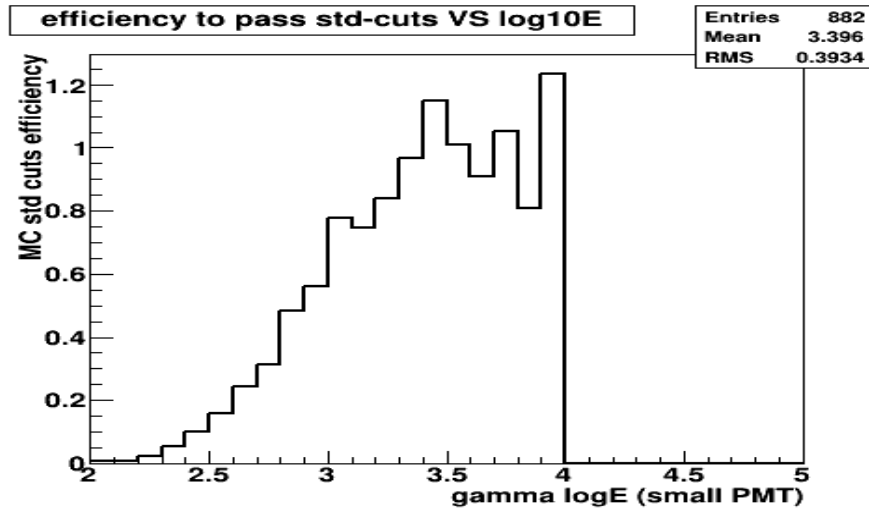
Increase tank sensitivity – (I)

Plot of **nHit** versus $\log_{10}E(\text{GeV})$ at 4100m for gamma showers with cores well within the (standard) HAWC array, zenith angle $< 26^\circ$, and w/ *standard* (but no G/H) cuts for **normal** (small) and **5x** (verylarge) PMTs. For plots (I), the nHit threshold with 5x PMTs is increased by 3.5x to match normal PMT rates.



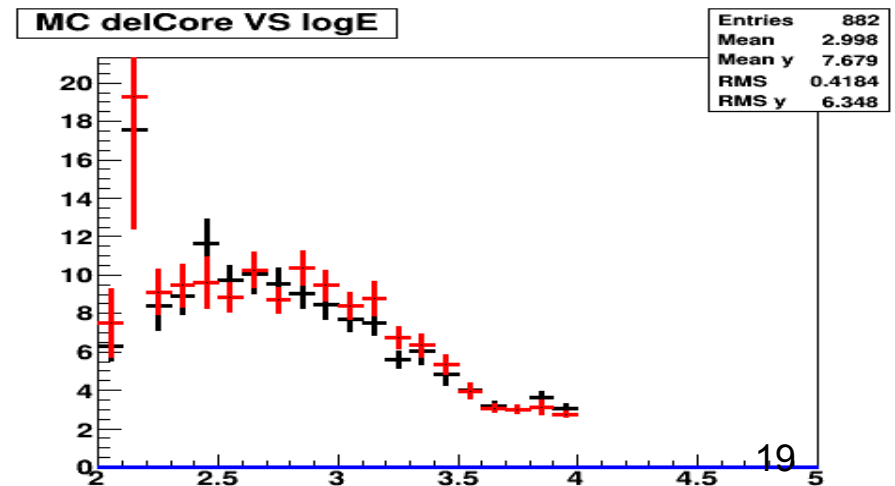
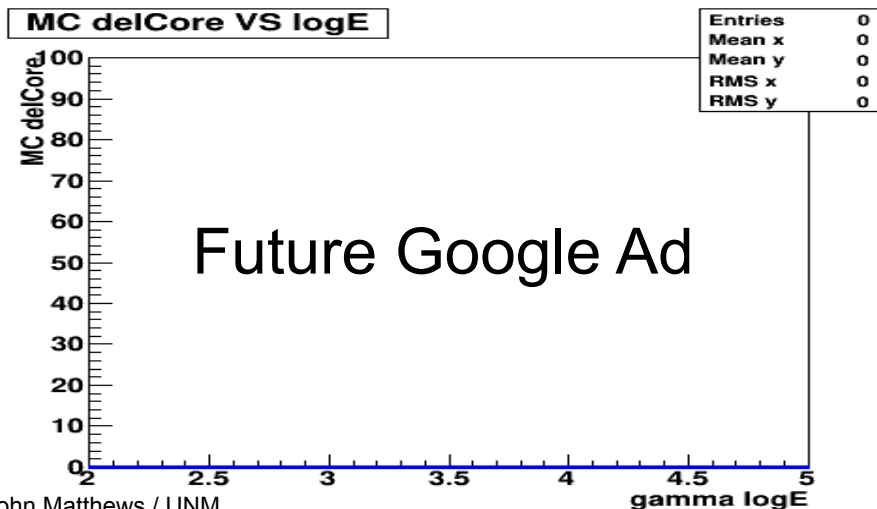
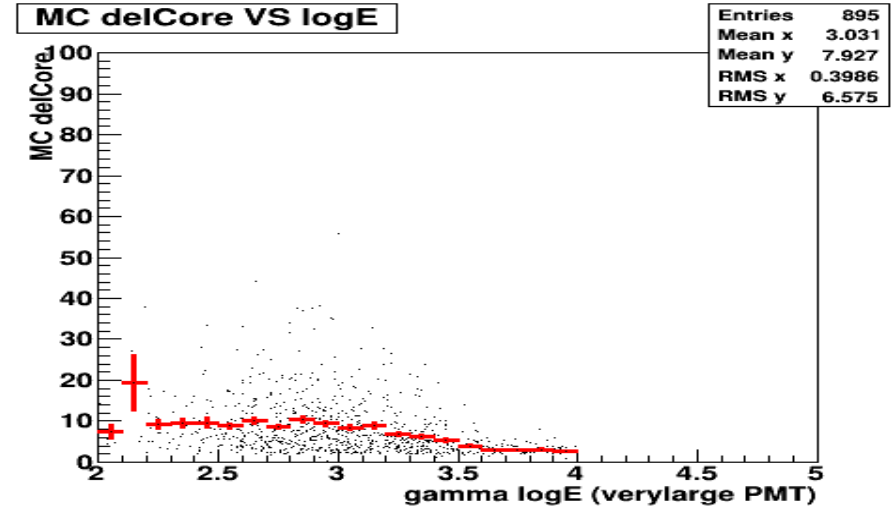
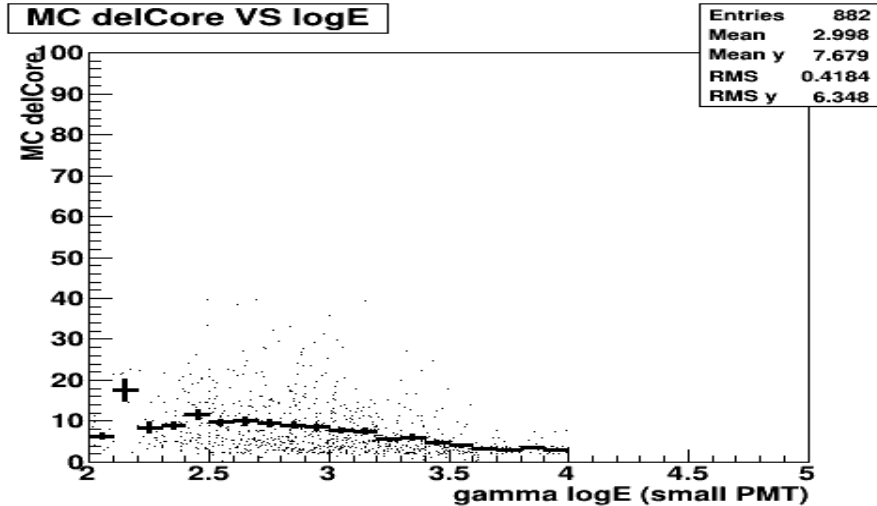
Increase tank sensitivity – (I)

Plot of HAWC **efficiency** (to pass *standard* (but no G/H) *cuts*) versus $\log_{10}E(\text{GeV})$ at 4100m for **normal** and **5x** PMTs. With this nHit threshold for **5x** PMTs, the energy threshold is unchanged.



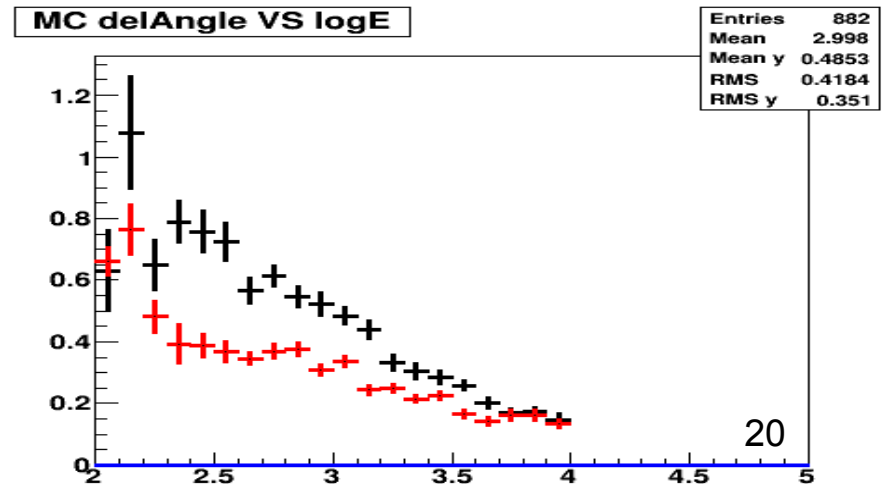
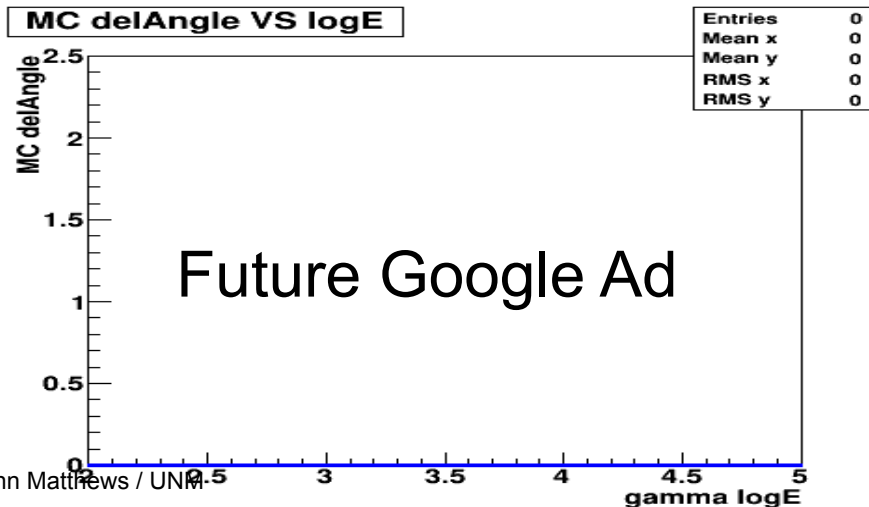
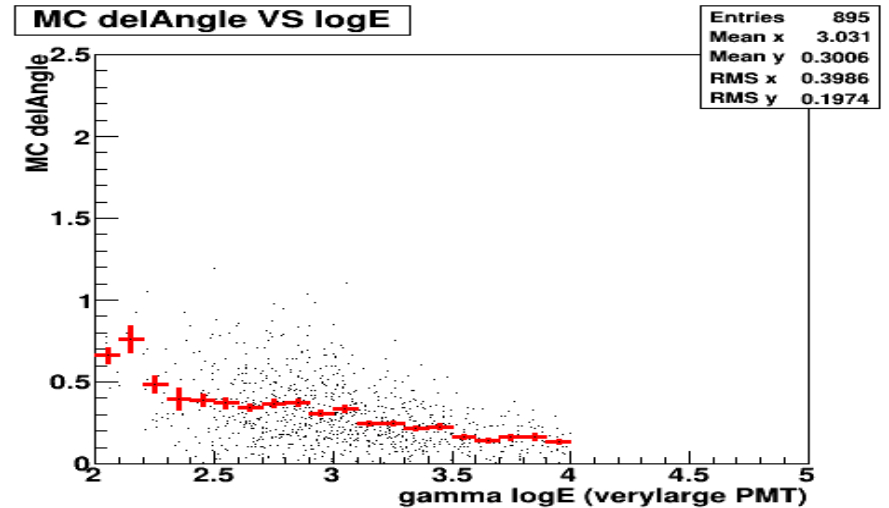
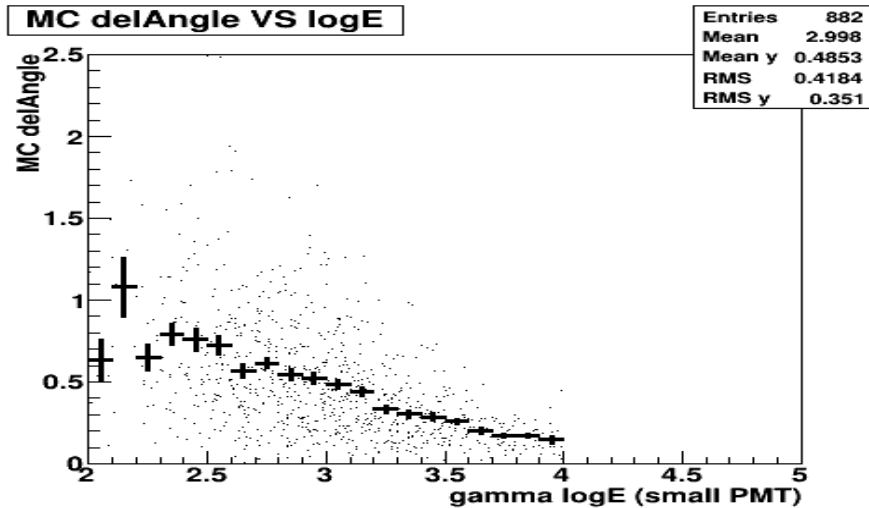
Increase tank sensitivity – (I)

Plot of **delCore(m)** versus $\log_{10}E(\text{GeV})$ at 4100m for **normal** and **5x** PMTs. The **delCore** distributions are curiously similar.



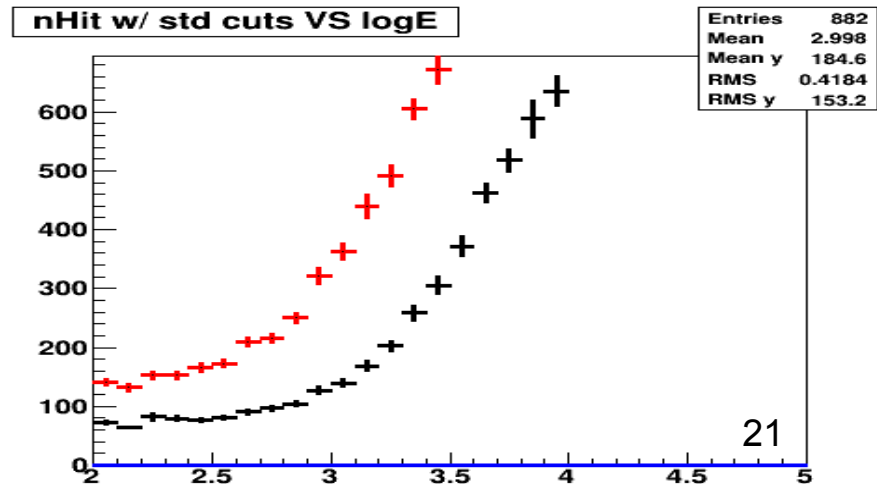
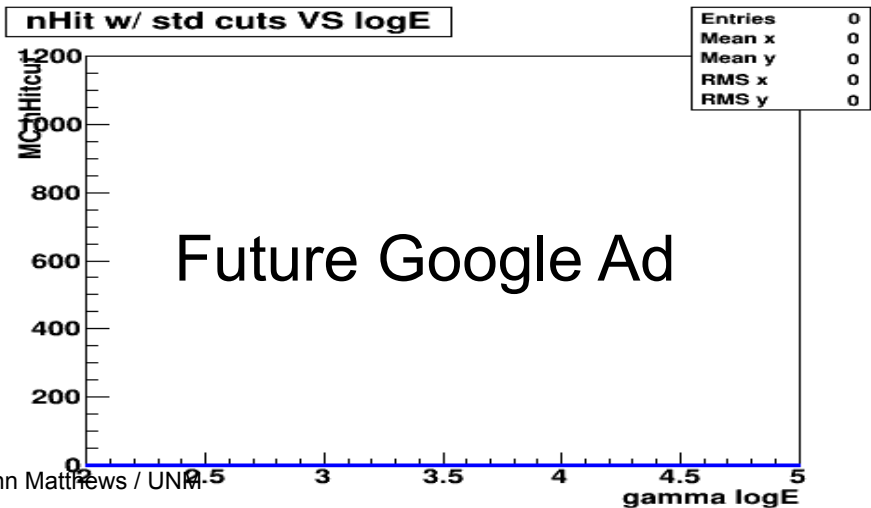
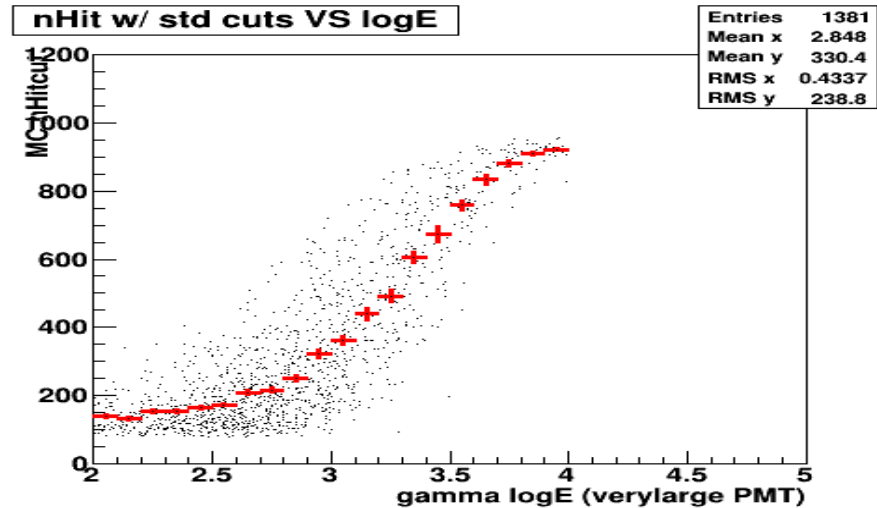
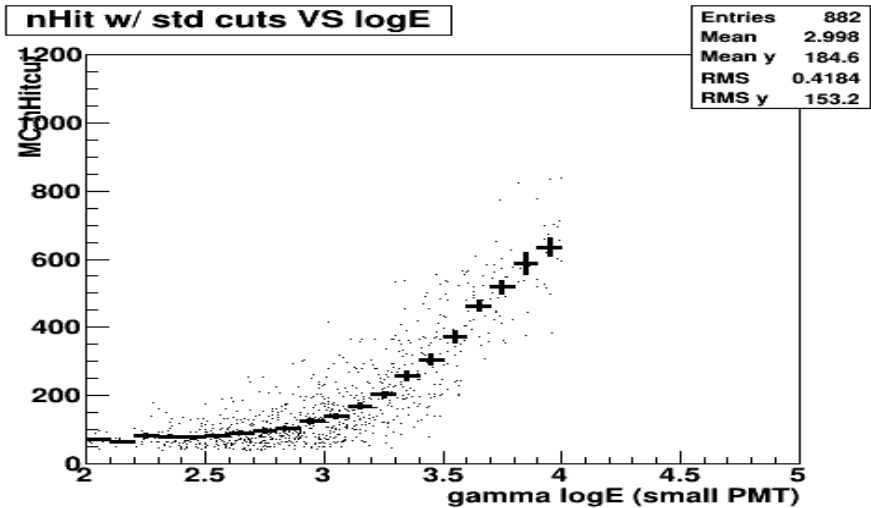
Increase tank sensitivity – (I)

Plot of **delAngle**(°) versus $\log_{10}E$ (GeV) at 4100m for **normal** and **5x** PMTs. At low energies the angular resolution with **5x** PMTs appears to be significantly (~50%) reduced!



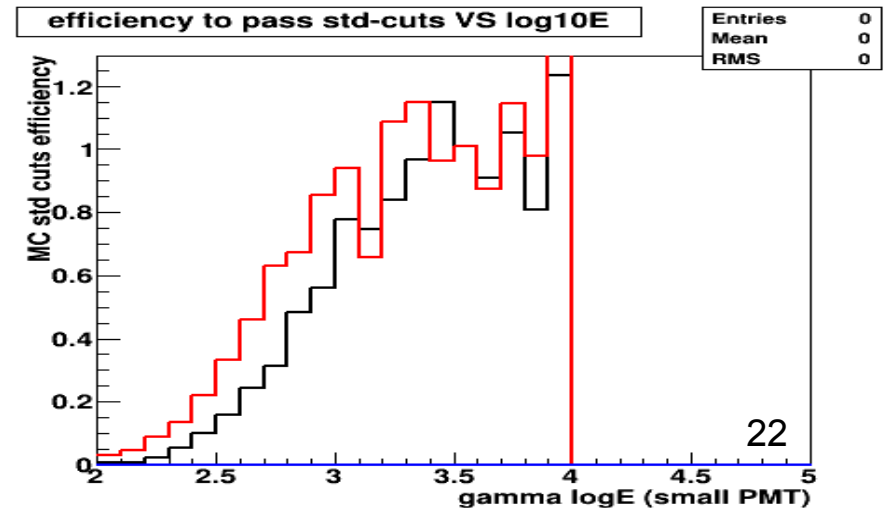
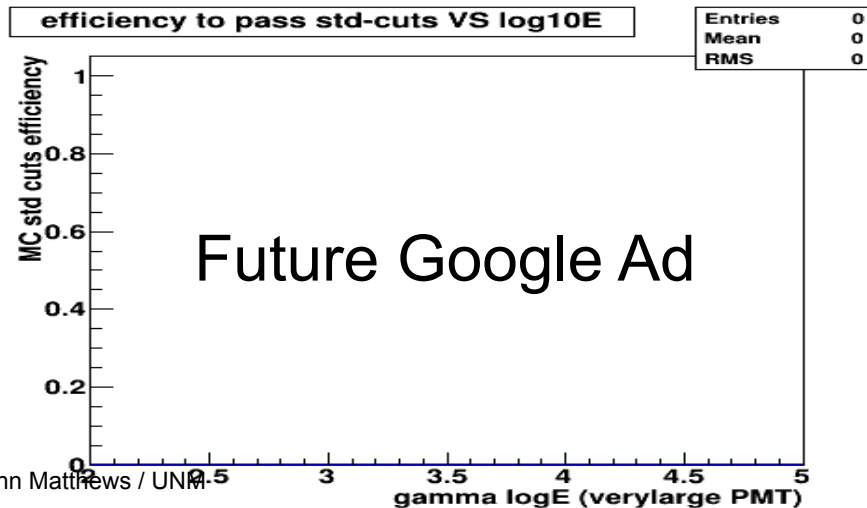
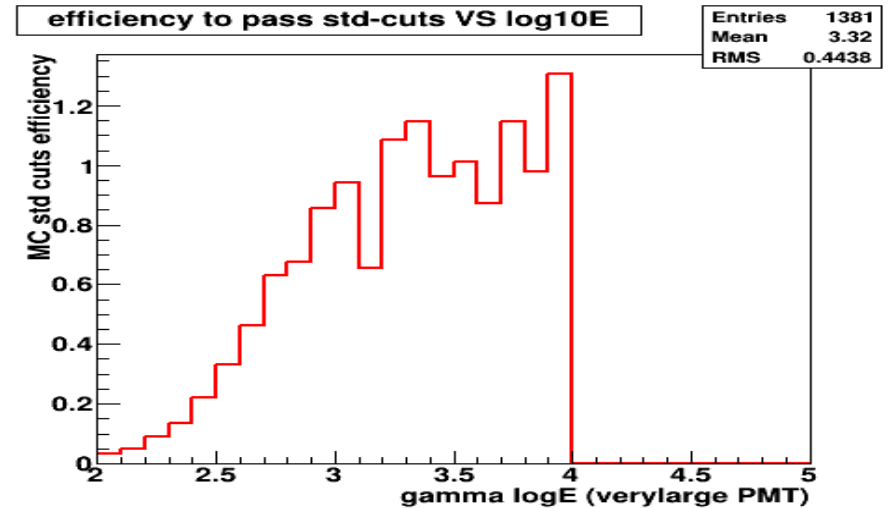
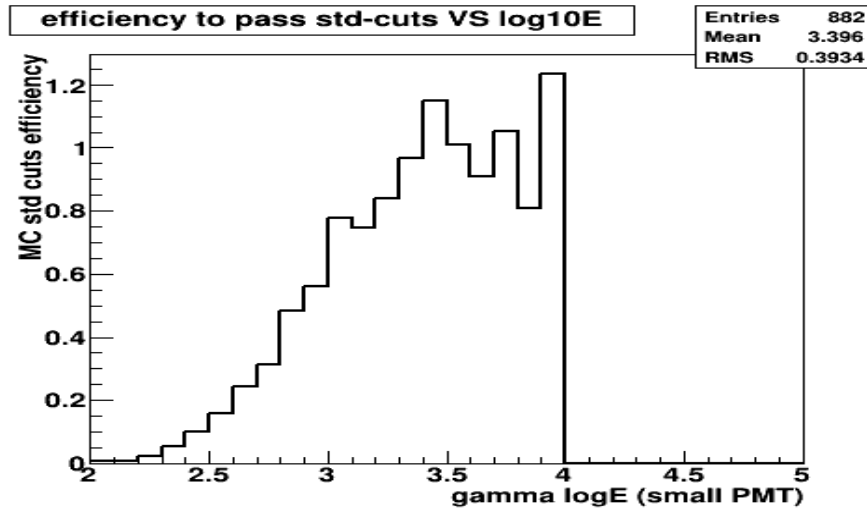
Increase tank sensitivity – (II)

Plot of **nHit** versus $\log_{10}E(\text{GeV})$ at 4100m for gamma showers with cores well within the (standard) HAWC array, zenith angle $< 26^\circ$, and w/ *standard* (but no G/H) cuts for **normal** (small) and **5x** (verylarge) PMTs. For plots (II), the nHit threshold with 5x PMTs is increased now by 1.75x.



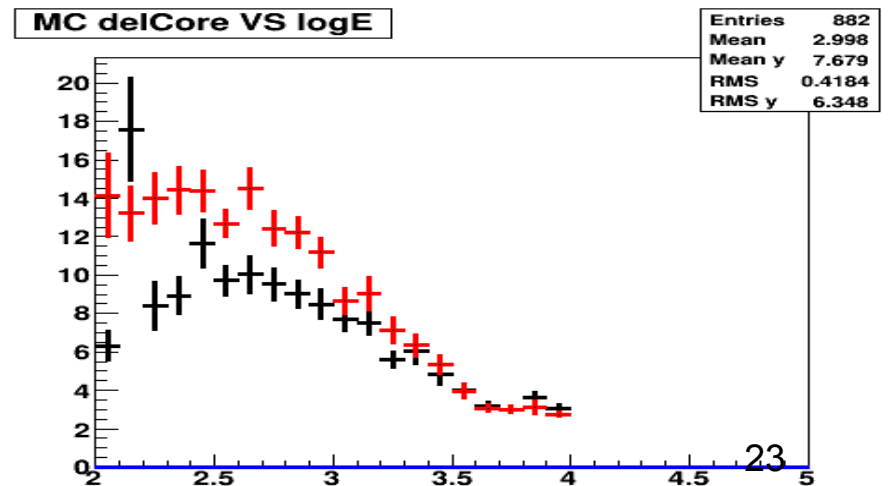
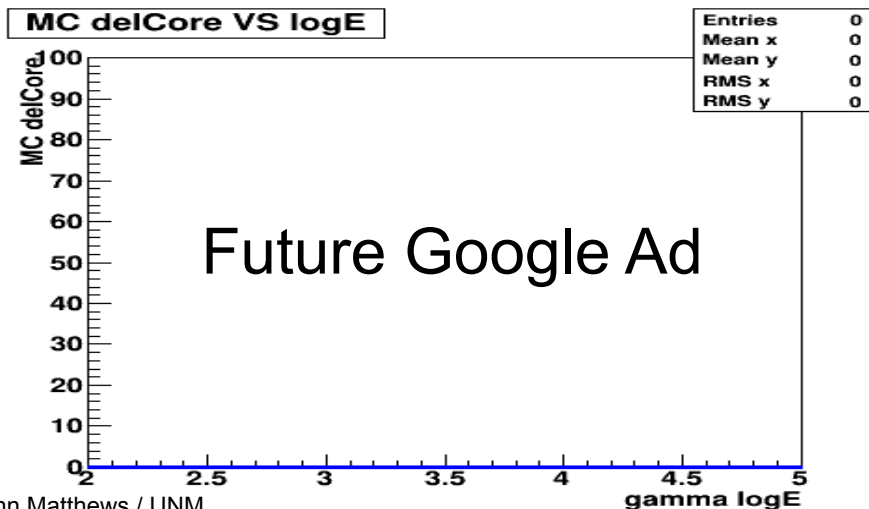
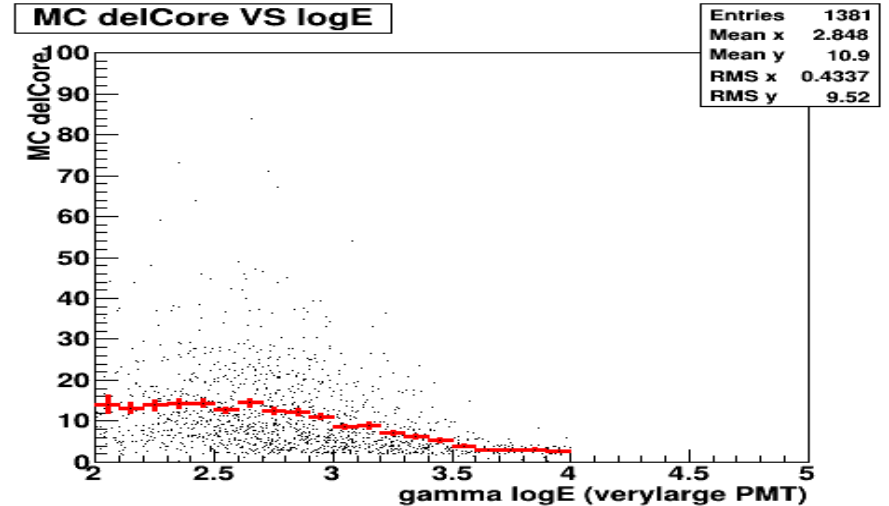
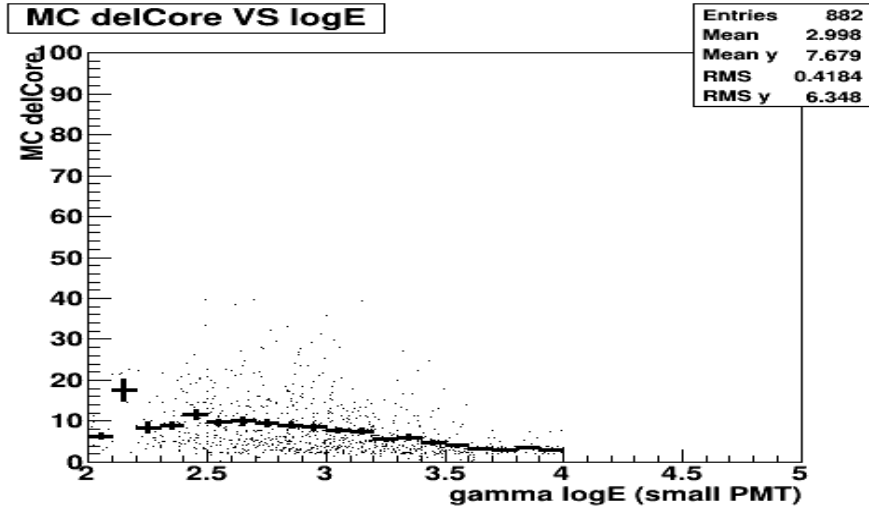
Increase tank sensitivity – (II)

Plot of HAWC **efficiency** (to pass *standard* (but no G/H) *cuts*) versus $\log_{10}E(\text{GeV})$ at 4100m for **normal** and **5x** PMTs. *With loosened (i.e. reduced nHit) threshold, the energy threshold with 5x PMTs decreases!*



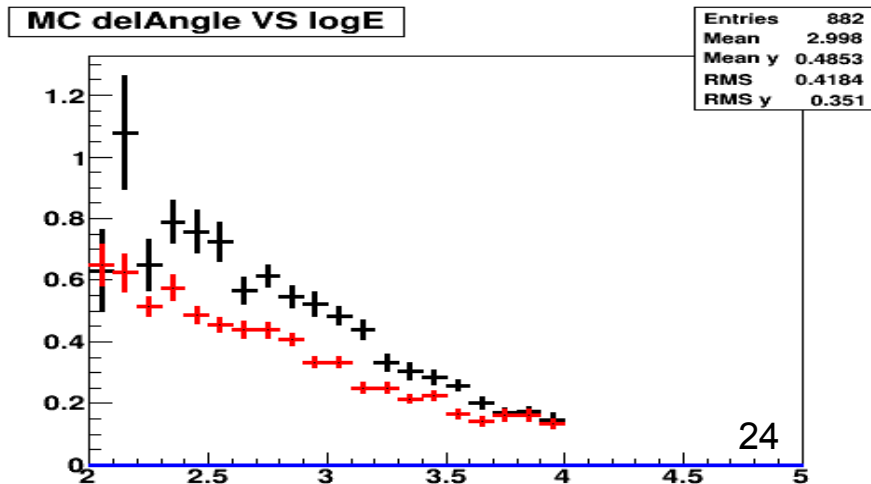
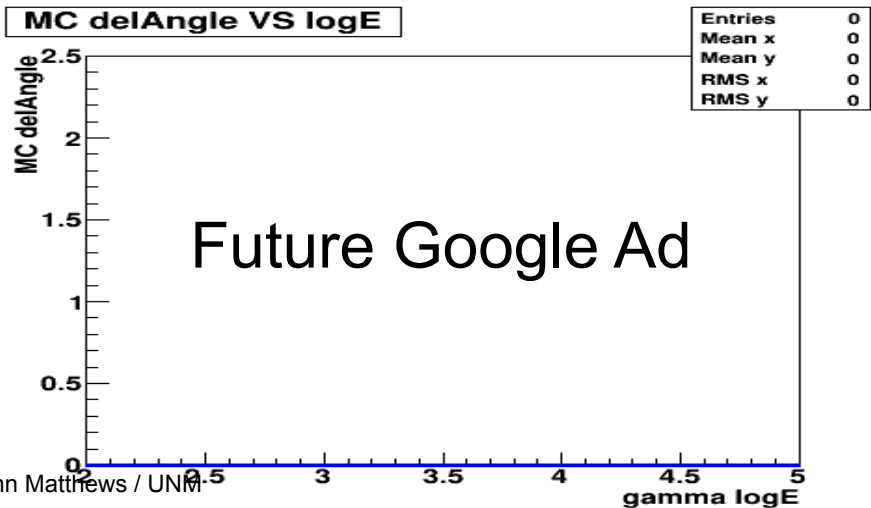
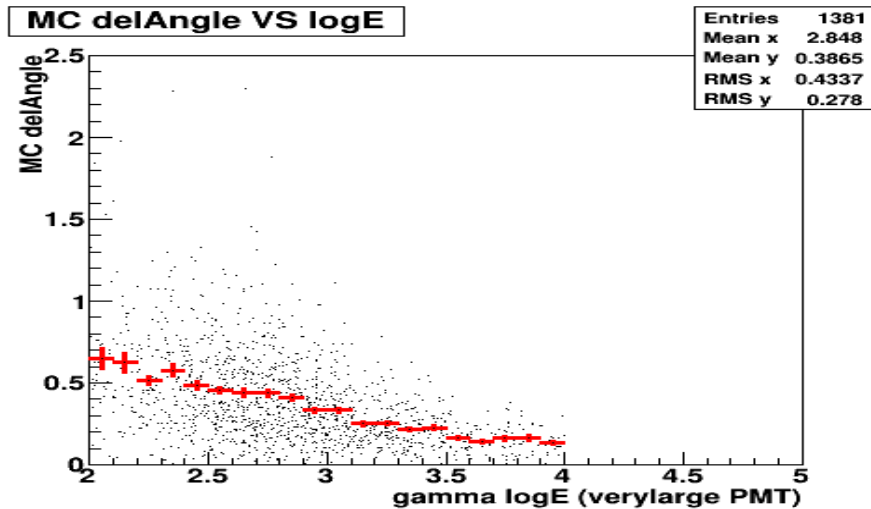
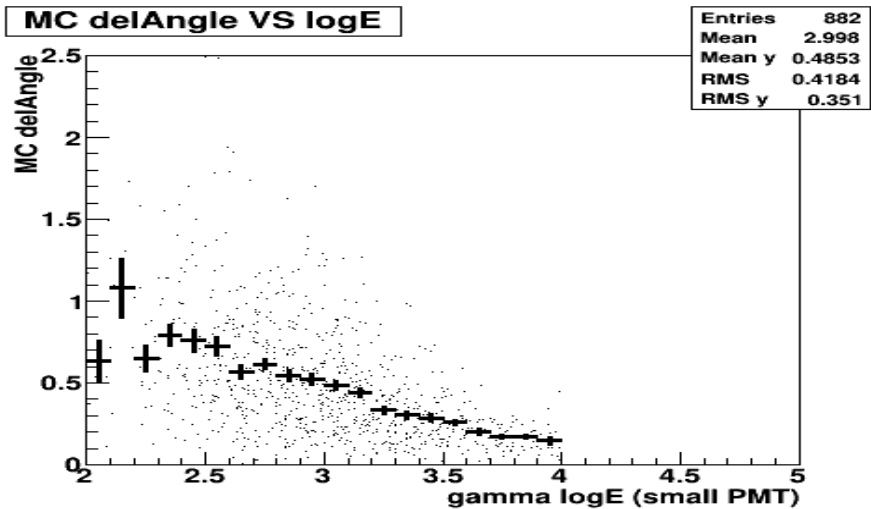
Increase tank sensitivity – (II)

Plot of **delCore(m)** versus $\log_{10}E(\text{GeV})$ at 4100m for **normal** and **5x** PMTs.
With loosened (*i.e.* reduced nHit) threshold, the **delCore** resolution with **5x** PMTs degrades.



Increase tank sensitivity – (II)

Plot of **delAngle**(°) versus $\log_{10}E$ (GeV) at 4100m for **normal** and **5x** PMTs. Interestingly the critical angular resolution with **5x** PMTs may still be better (*i.e.* reduced) versus **normal** PMTs.



Summary

To improve HAWC performance for showers with energies < 1 TeV we considered 3 possible modifications:

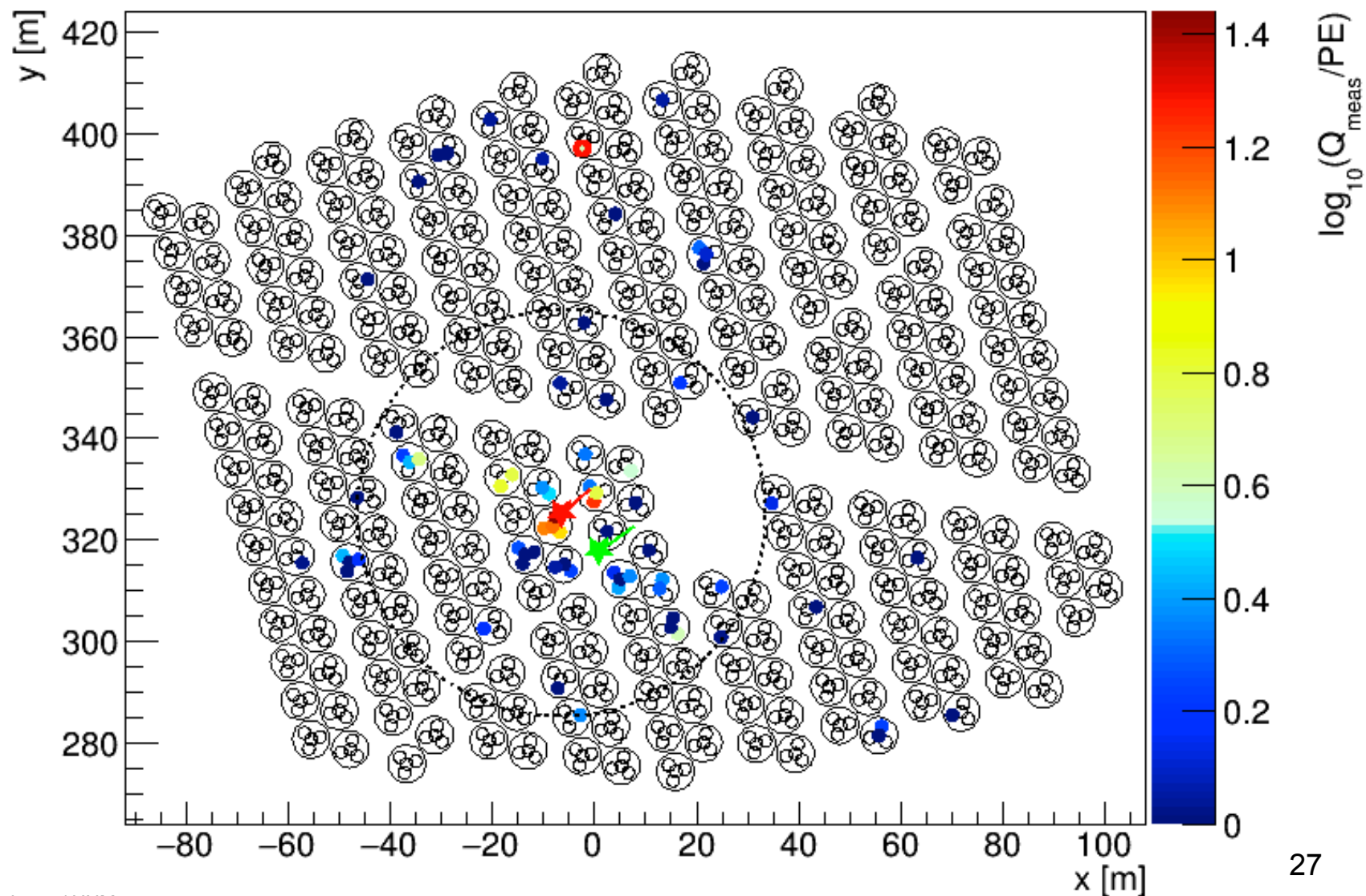
- Increase area of *low-energy* array (to reduce edge effects)
Toy simulation gain factor: $\sim \sqrt{6.25}$
- Increase elevation (to help *low-energy* shower particles reach the array). Toy simulation gain factor: $\sim 2^{(S.I.-1)} / \sqrt{\text{similar factor for bkg w/ } S.I.=2.5} \rightarrow \sim 2^{(S.I.-1.75)}$
- Increase tank sensitivity (so when there are tank *signals* we record them). Toy simulation gain factor: $\sim (1/0.5) = 2$
- Combining (optimistically) all 3 components, the toy simulation gain factor is ~ 10 (or more) ... which is good as most TeVCat AGNs have measured flux < 0.1 Crab.

All 3 possible modifications will/would improve the performance for *low energy* showers. For *soft-spectrum* sources, such as (most) AGNs with $S.I. > 3$, going **high** is very important.

Backup material

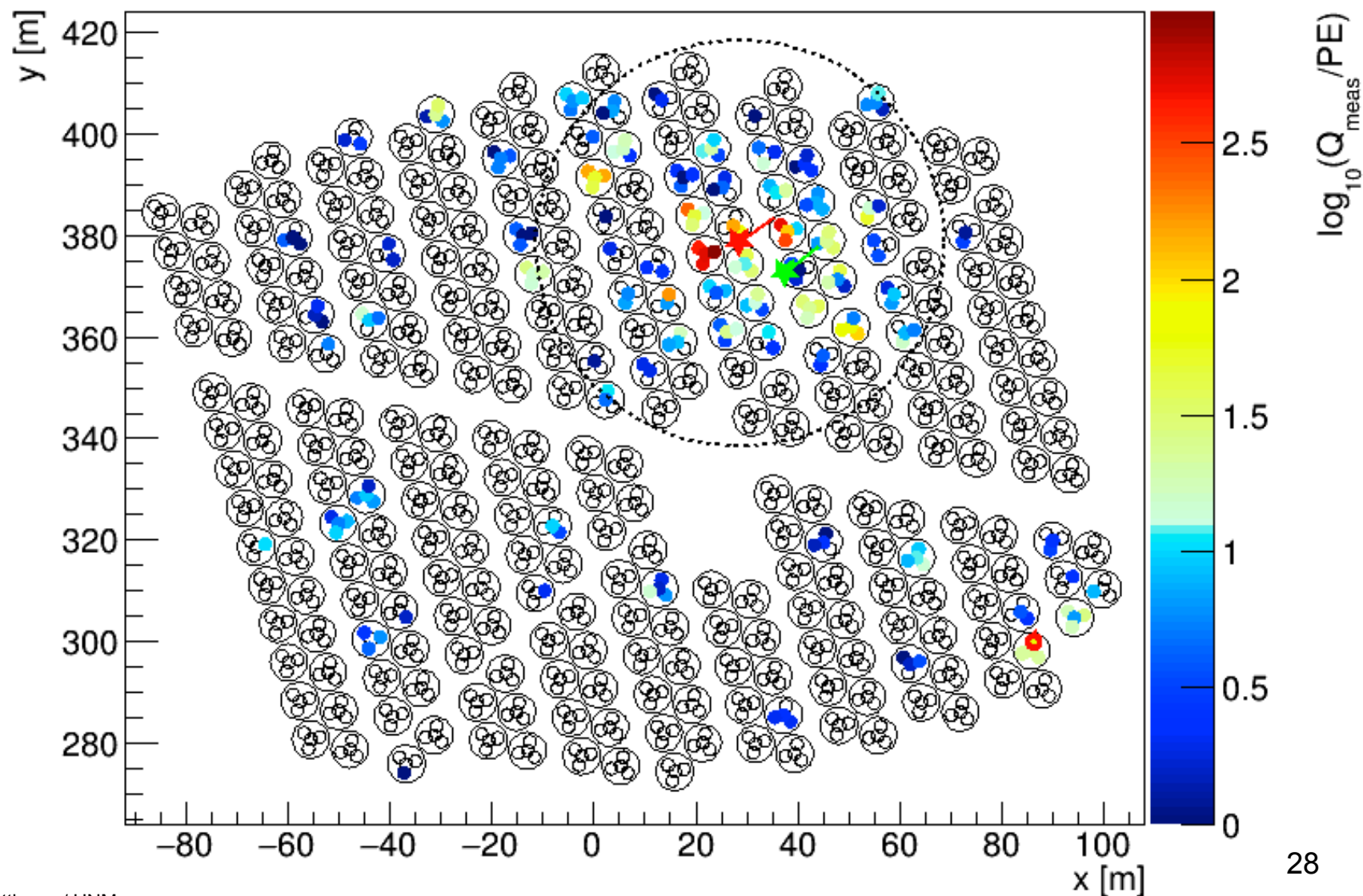
Std PMT event #8: 0.50 TeV

Run 304100, TS 0, Ev# 8, CXPE40= 3.89, RA= 16.67, Dec= 25.7



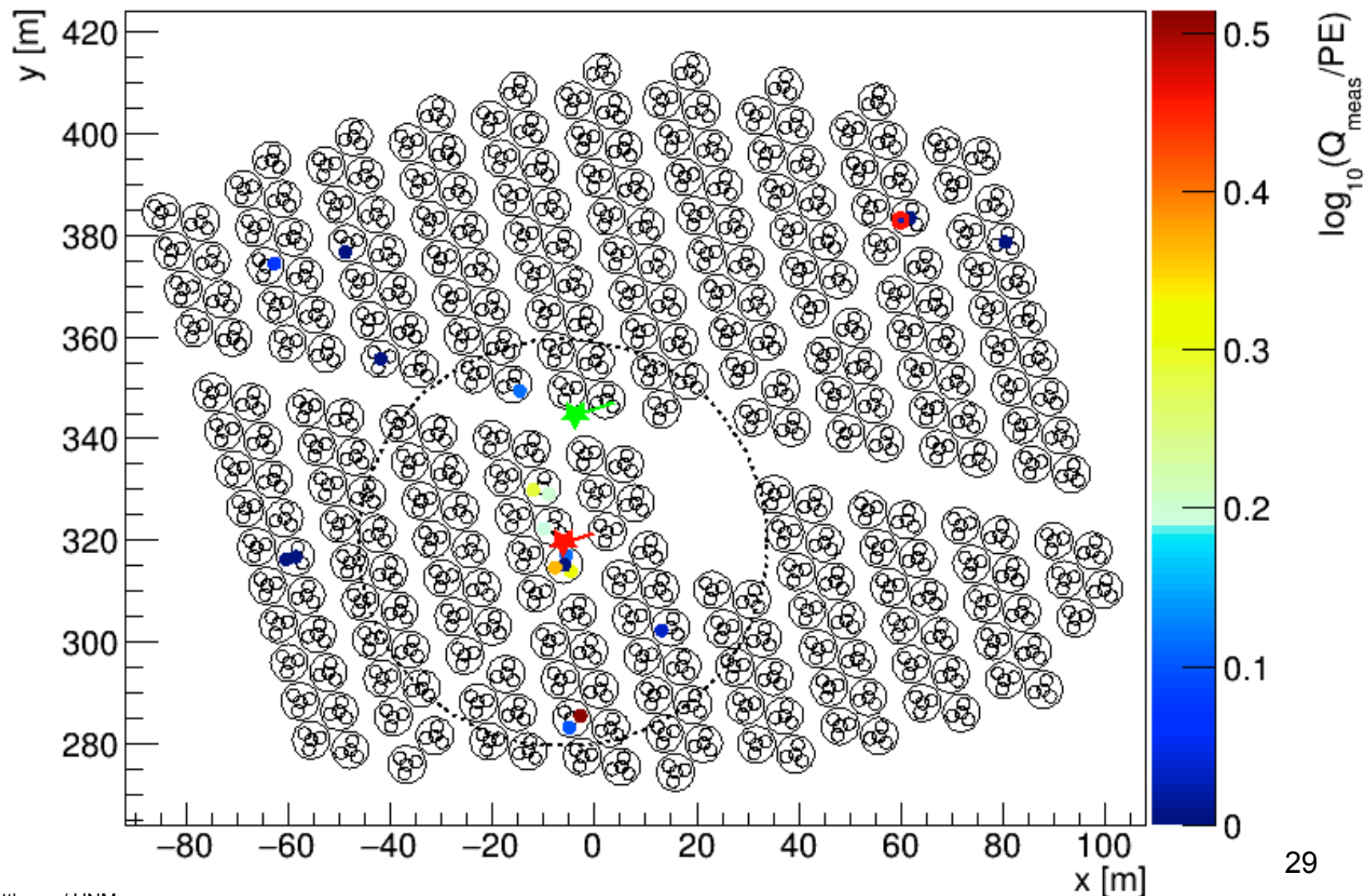
VeryLarge PMT event #8: 0.50 TeV [new CoreX, CoreY]

Run 304100, TS 0, Ev# 8, CXPE40= 61.8, RA= 18.3, Dec= 25.8



Std PMT event #13: 0.12 TeV

Run 304100, TS 0, Ev# 13, CXPE40= 1.06, RA= 16.74, Dec= 21.5



VeryLarge PMT event #13: 0.12 TeV [new CoreX, CoreY]

Run 304100, TS 0, Ev# 13, CXPE40= 9.3, RA= 20.02, Dec= 23.4

