Semi-Analytic Simulation for a “HAWC-like” Detector

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What is the best way to spend Money

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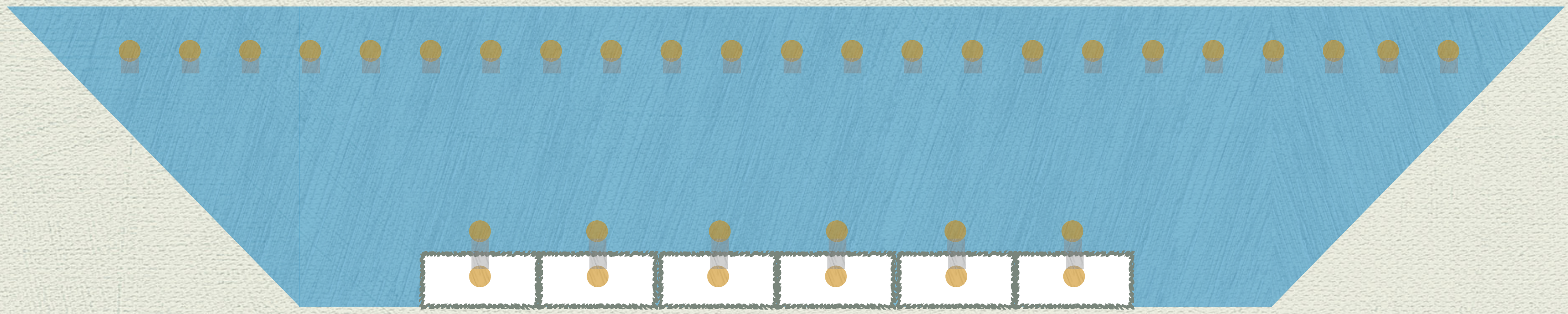
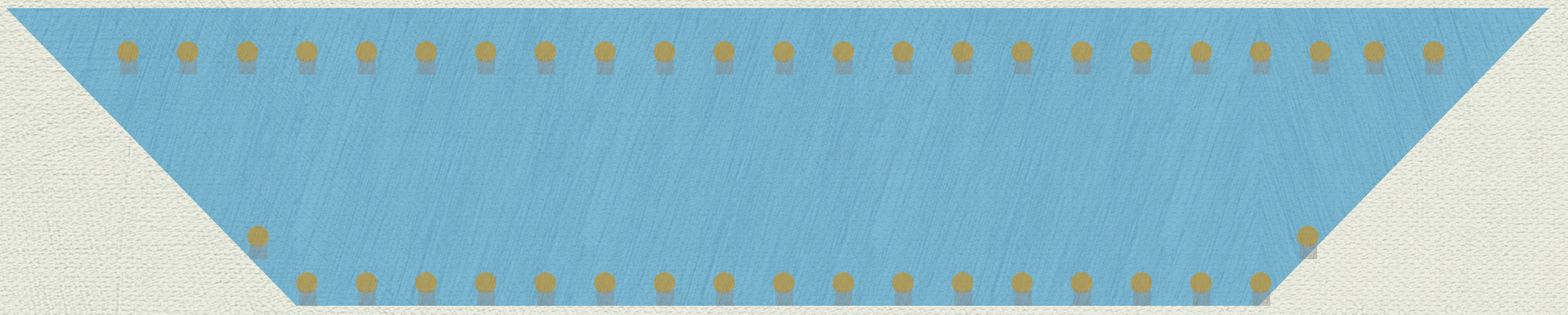
Milagro Original Design

3 layers, optically isolated muon detectors in the bottom of a 6m deep pond



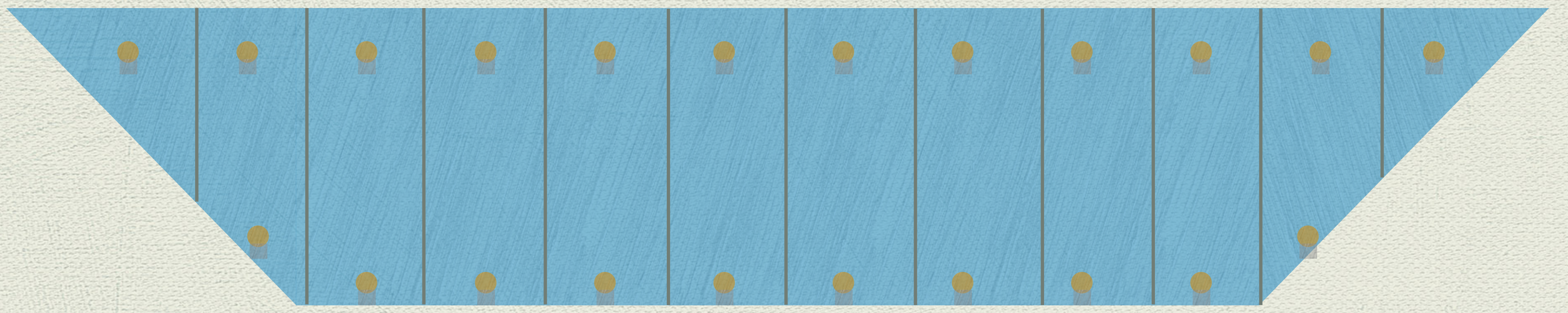
Milagro As Built

No Muon detectors, just upward looking deep PMTs
Identify muons as spikes in bottom layer



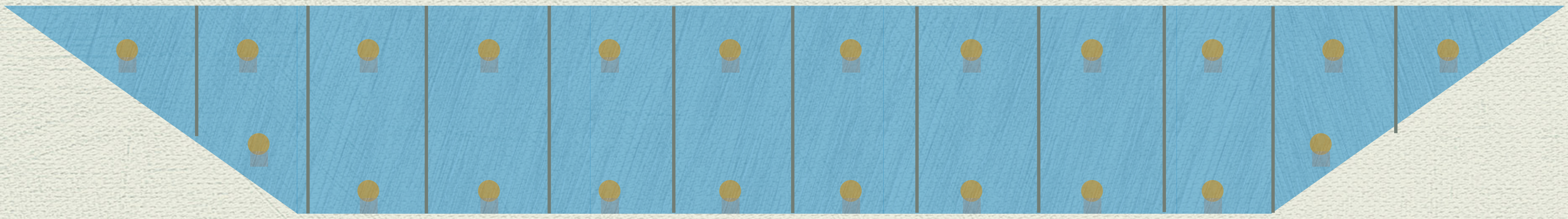
HAWC Early Design - “Super Milagro”

Milagro plus curtains for optical isolation
Lower PMT density: go from 2.7m to 4m spacing



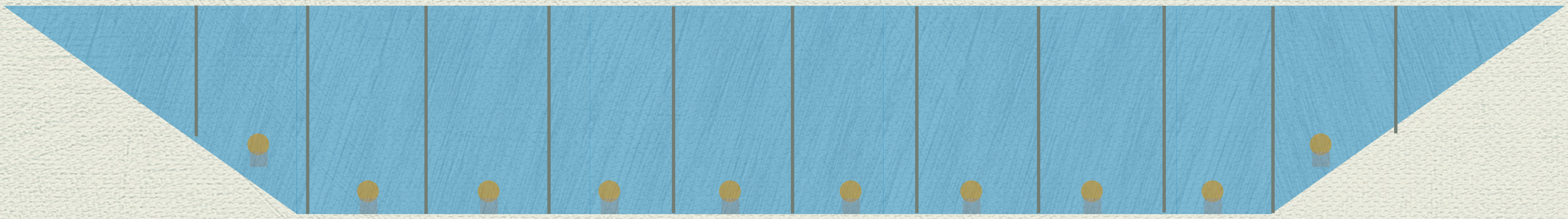
HAWC Early Design

Less depth is OK too.



HAWC Early Design

The bottom layer fits shower angles and cores just as well as the top

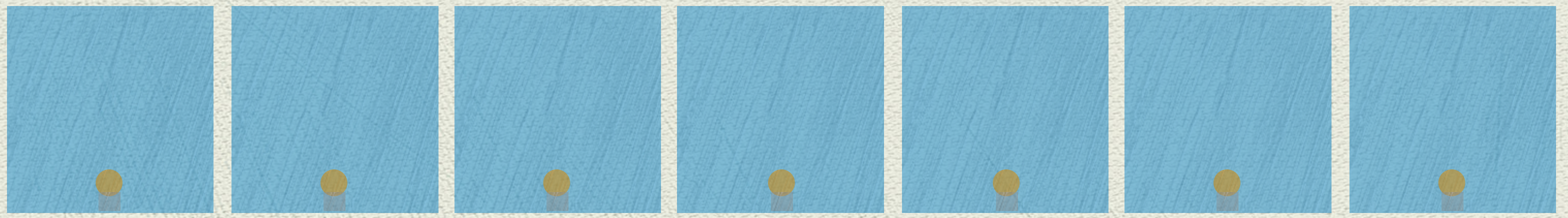


Tanks instead of Pond

4m diameter Plastic tanks

Simulated many tank depths and found:

1) Tanks need to be deep enough so that the EM particles range out above the PMT: no electrons near the PMT.
2) Tank diameter chosen so that width >~ depth

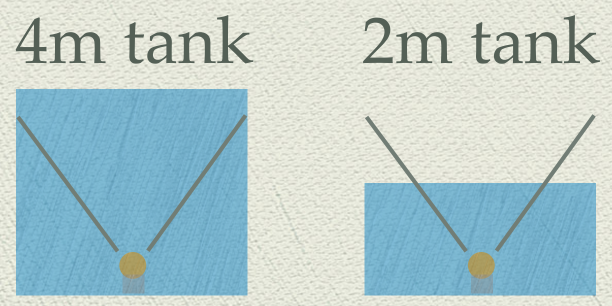


Metal tanks

7.3m steel tanks (3 PMTs each) are cheaper than 4m plastic tanks. 4th PMT added later.

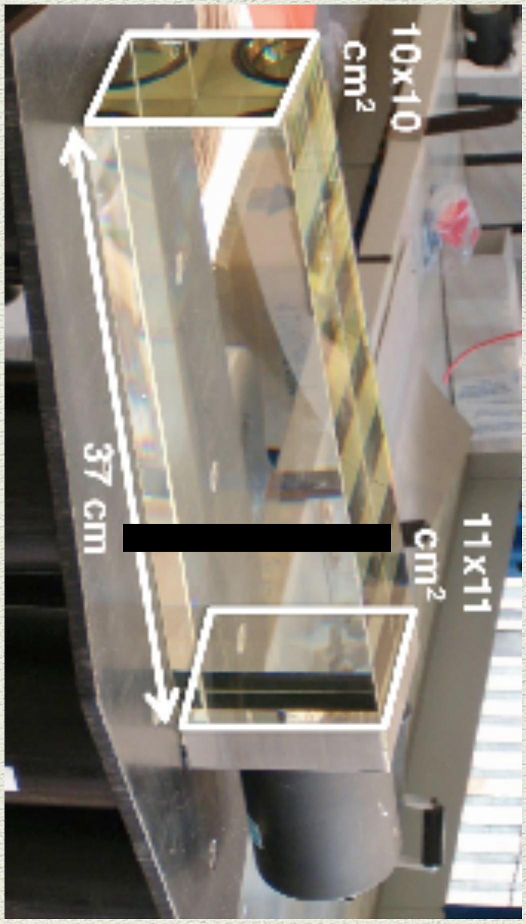
Why 4m depth

- For good gamma/hadron separation, electrons need to be stopped well away from the PMT. —> Depth of ~10 Xo.
- Shorter tanks would require smaller diameters —> more PMTs.



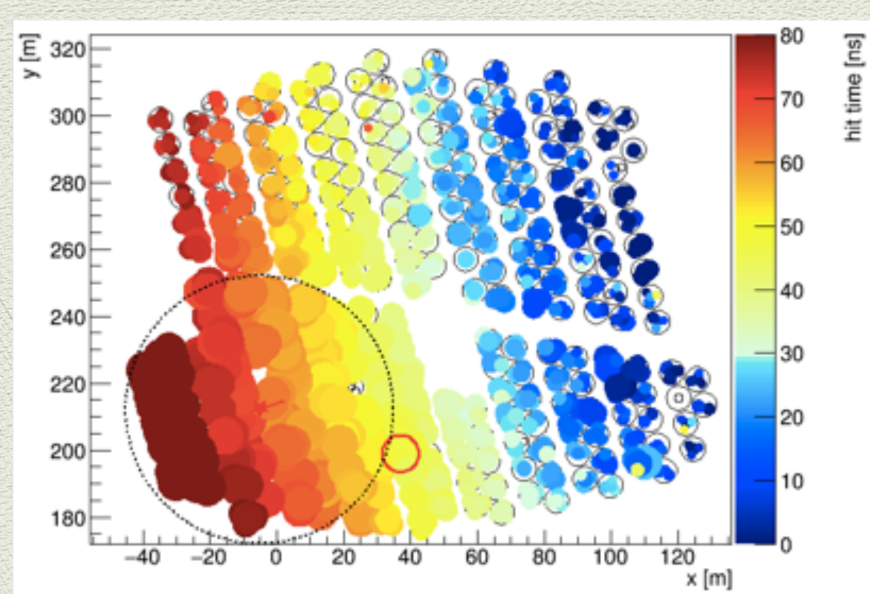
What does “HAWC-Like” mean?

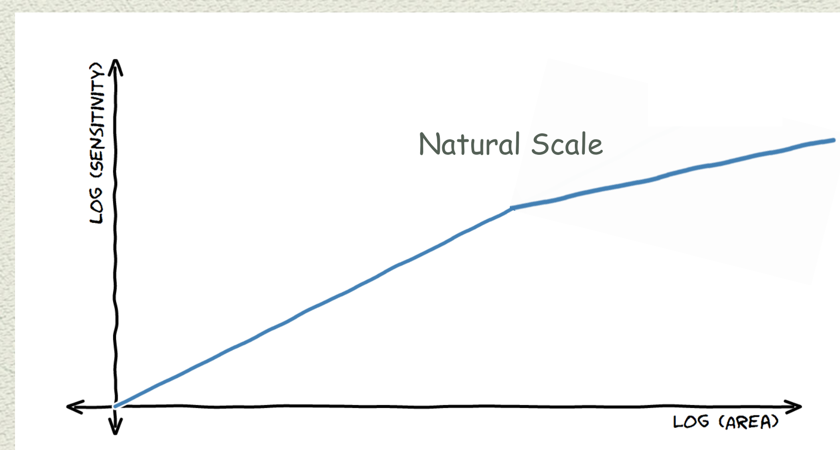
- IACT’s are calorimeters, which uses the atmosphere as a detection medium. The light in the detector ~ primary gamma-ray energy.
- Surface arrays are calorimeters, but the energy measured is not the total gamma-ray energy, it is the energy reaching the ground level.
- Attenuation length of blue light >> attenuation length of gamma rays.
- This work should be valid for any detector that counts particles or measures energy at the ground level. (ALTO, LATTES, etc.)



High Energy Sensitivity

- Physical Area vs Sensitivity at high energy (multi-TeV):
  - Aperture and background increase: ~Area, so Sensitivity increases by sqrt(Area)
  - But, angular resolution and background rejection also improve.
  - Finding from early HAWC simulations: Sensitivity ~ Area
  - “Natural Scale” is not well know. It is much larger than HAWC. Probably > 100,000m^2

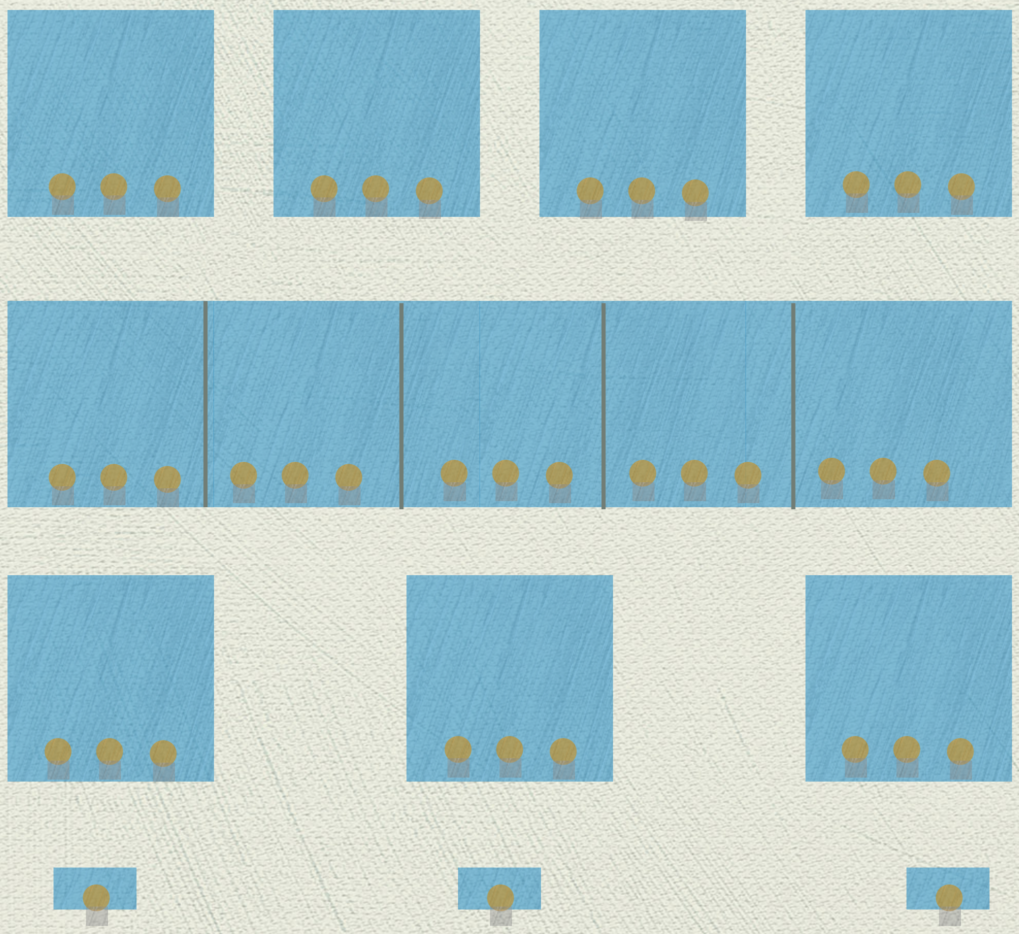




3 Questions:

- How does sensitivity at the lowest energies increase with elevation. (100 GeV)?
- How does the sensitivity at the lowest energies increase with physical area?
- How could gamma/hadron separation improve with increased area or muon detection capability below the EM calorimeter layer?

Detector Choices



HAWC-Like

High Hermeticity

Low Hermeticity

very low Hermeticity

Detector Choices (cont.)

HAWC-like Calorimeter layer

Optically Isolated Muon detector below

HAWC with muon detection in core region

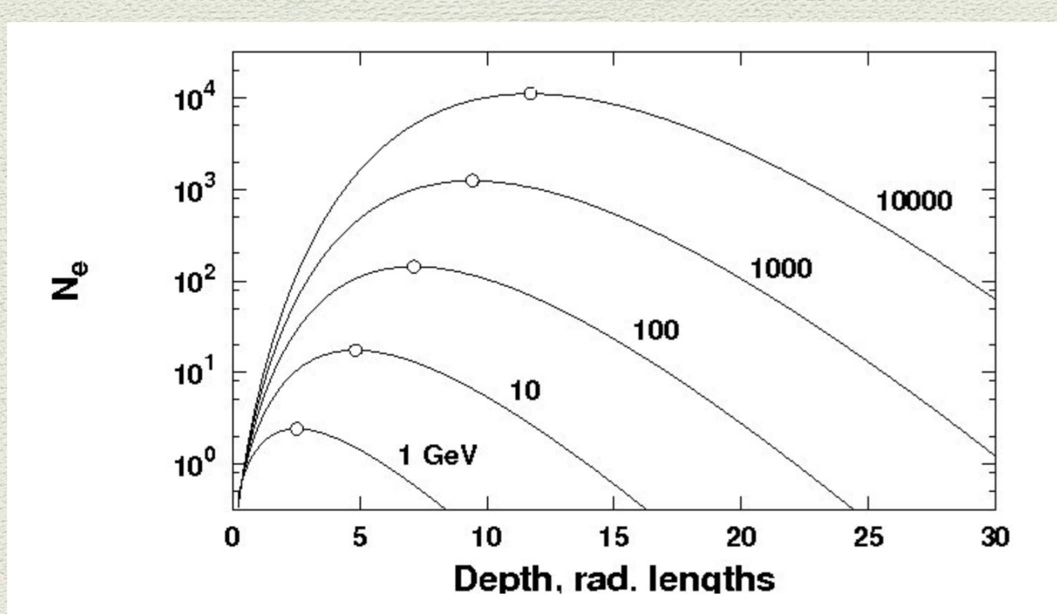
Compact
~5000–10,000 m^2
Milagro-Like

Medium
~25,000 m^2
(HAWC-like)

Big
~100,000 m^2
(LHAASO-Like)

Why Approx B, NKG and all that is not so useful?

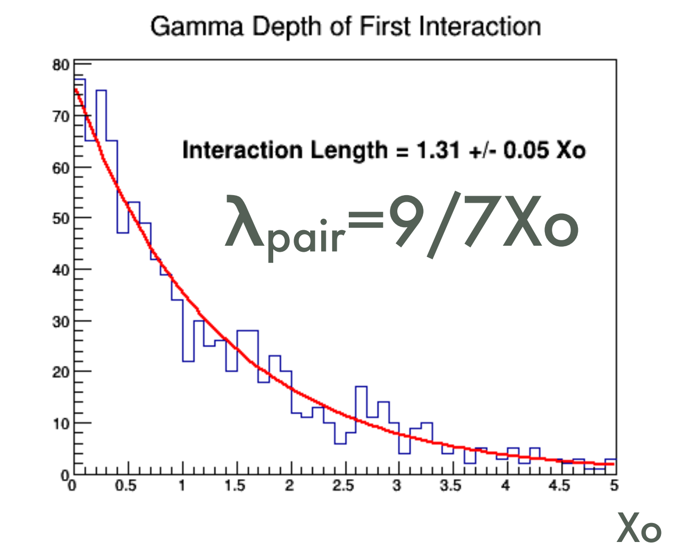
- We don't care about electrons (particle counts), we care about EM energy.
- No accounting for fluctuations, which are driven by fluctuations in shower max.

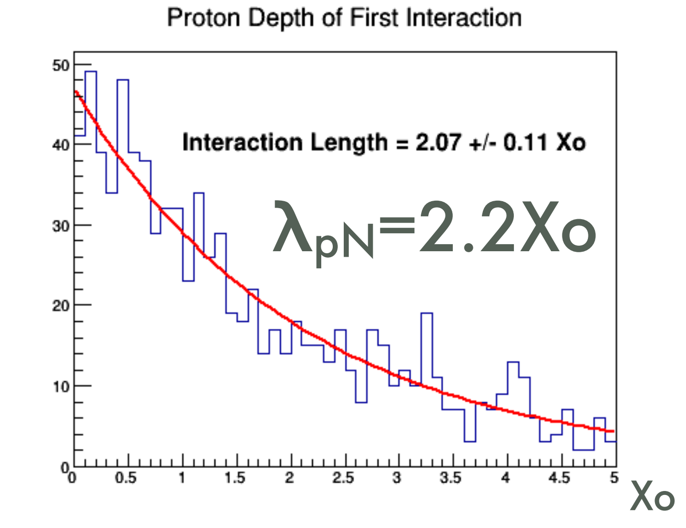


Greisen approx B.

$$\Pi\left(t\right) \approx \frac{0.31}{\sqrt{\beta_0}} e^{t\left(1-\frac{3}{2}\ln s\right)}$$

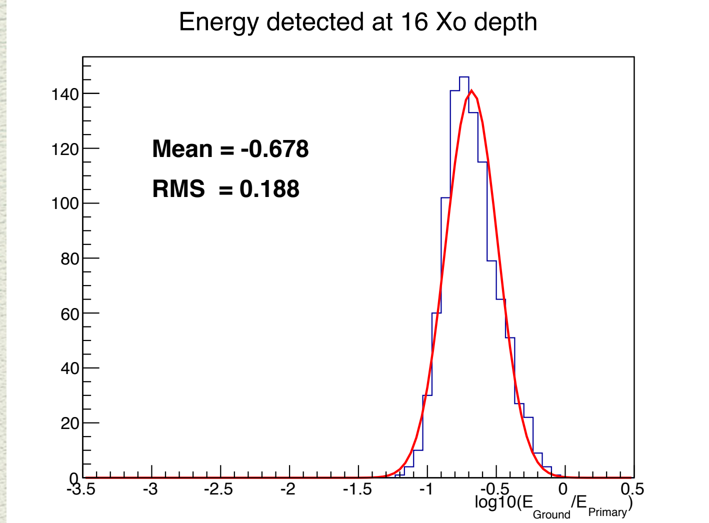
First Interaction Depth dominates Longitudinal Fluctuations

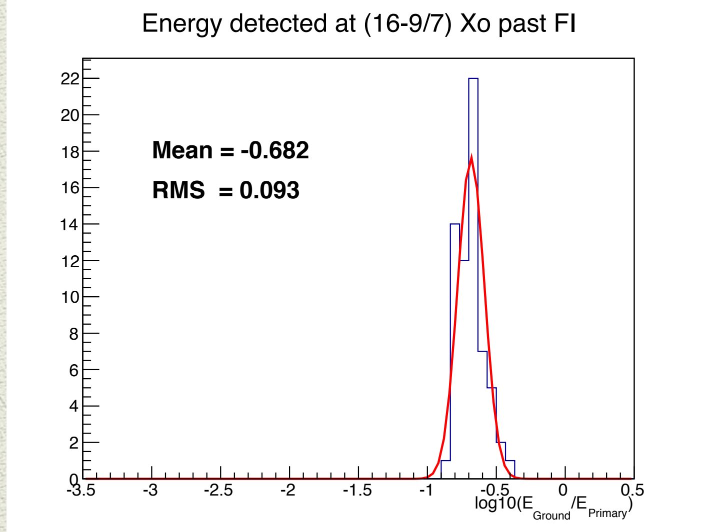




First Interaction depth distribution is easily predictable, depending only on λ_{pair} or hadronic interaction length

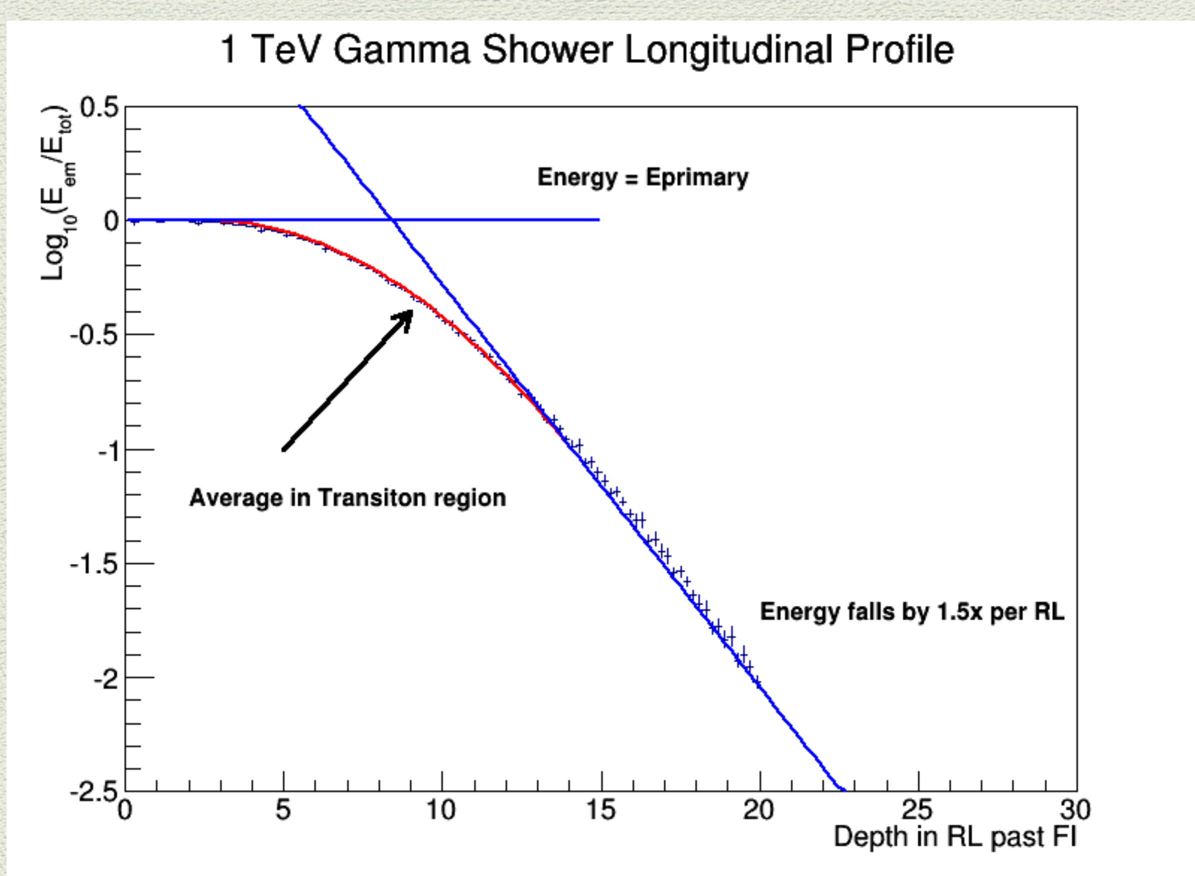
Fluctuations in energy at the ground is dominated by FI.





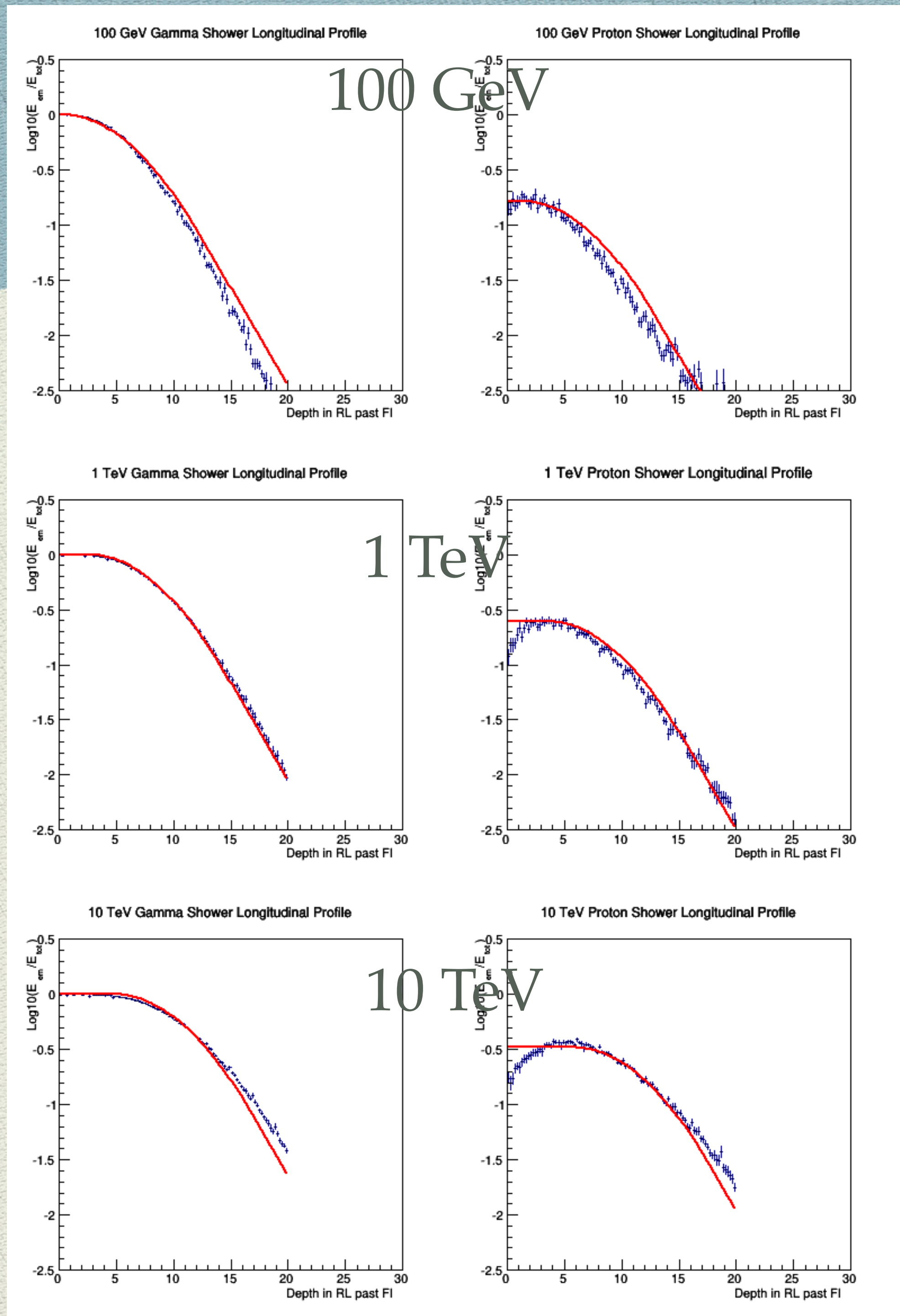
Simple model for energy vs level

- At low depths, energy “loss” dominated by brems. (e) and pair/Compton (gamma). No energy is lost from the shower.
- At high energies, gammas still lose energy through pair and Compton, but electrons lose most of their energy through ionization (1.5x loss per RL).
- Approximate the energy past the FI with 2 lines, where a smooth transition is achieved by averaging the curves. +/-3 RL.



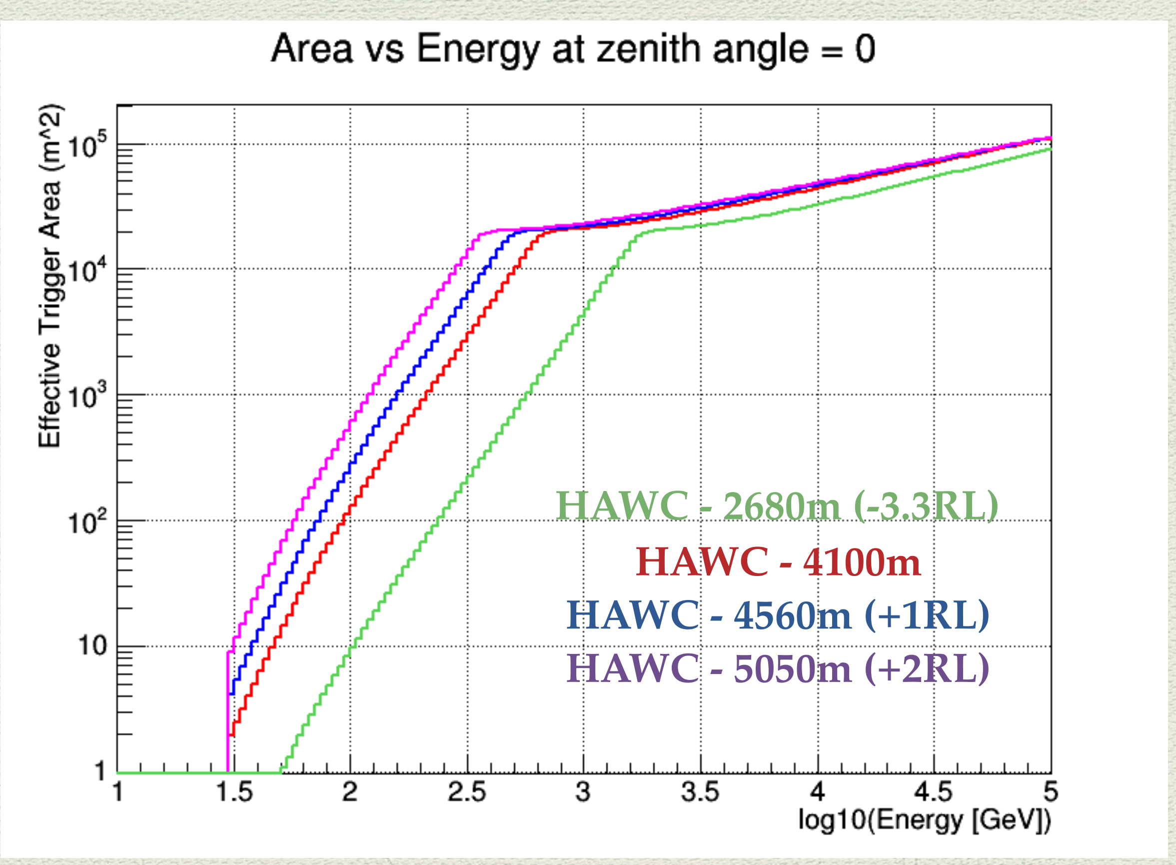
Depth of transition = log(E/Ec) + C

- Compare model to data. Works OK for gammas.
- Hadron:
    - p->X —> many Pions.
    - Some energy taken away by baryons.
    - Pions are equally produced in 3 types, +,-,0
    - $\pi 0$—> $\gamma\gamma$
    - π+/- —> $\mu\nu$ or re-interacts
- At low energy, charged pions decay: 1/3 of pion energy goes to EM particles.
- At high energy, charged pion re-interactions produces a larger EM component.
- EM component is energy dependent, approximate with:
    - fracE = 0.33*(log10(EPrimary)/4.);



Determining Sensitivity is an analytic process: Just do an integral.

- Integrate over: Core Radius, FI depth for a given primary Energy, Zenith Angle, Detector Parameters.
- Use NKG x (1/r) as profile for energy vs radius vs age.
- Detector is a round calorimeter with a radius and an energy threshold.
    - HAWC Thresh: 5-10 GeV
    - ~20PE/GeV, with ~4PE/hit at threshold
    - ~5 hits/GeV
- Configuration looks like:




```
double DetRadius = 80.;       // in meters
double DetElevation = 4100;   // in meters
double DetHermiticity = 0.60;   // hermeticity (fraction of area instrumented)
double DetThreshold = 10;     // detected energy needed to trigger in GeV
```

Low-Energy Sensitivity vs Elevation

- ~2.2 times area at low energy with each radiation length.
- Backgrounds increase by ~2.2x also
- Without γ/h separation: sqrt(2.2) = <u>1.5x</u> increase in low-energy sensitivity.
- However, γ/h separation gets worse, so expect less improvement than this.

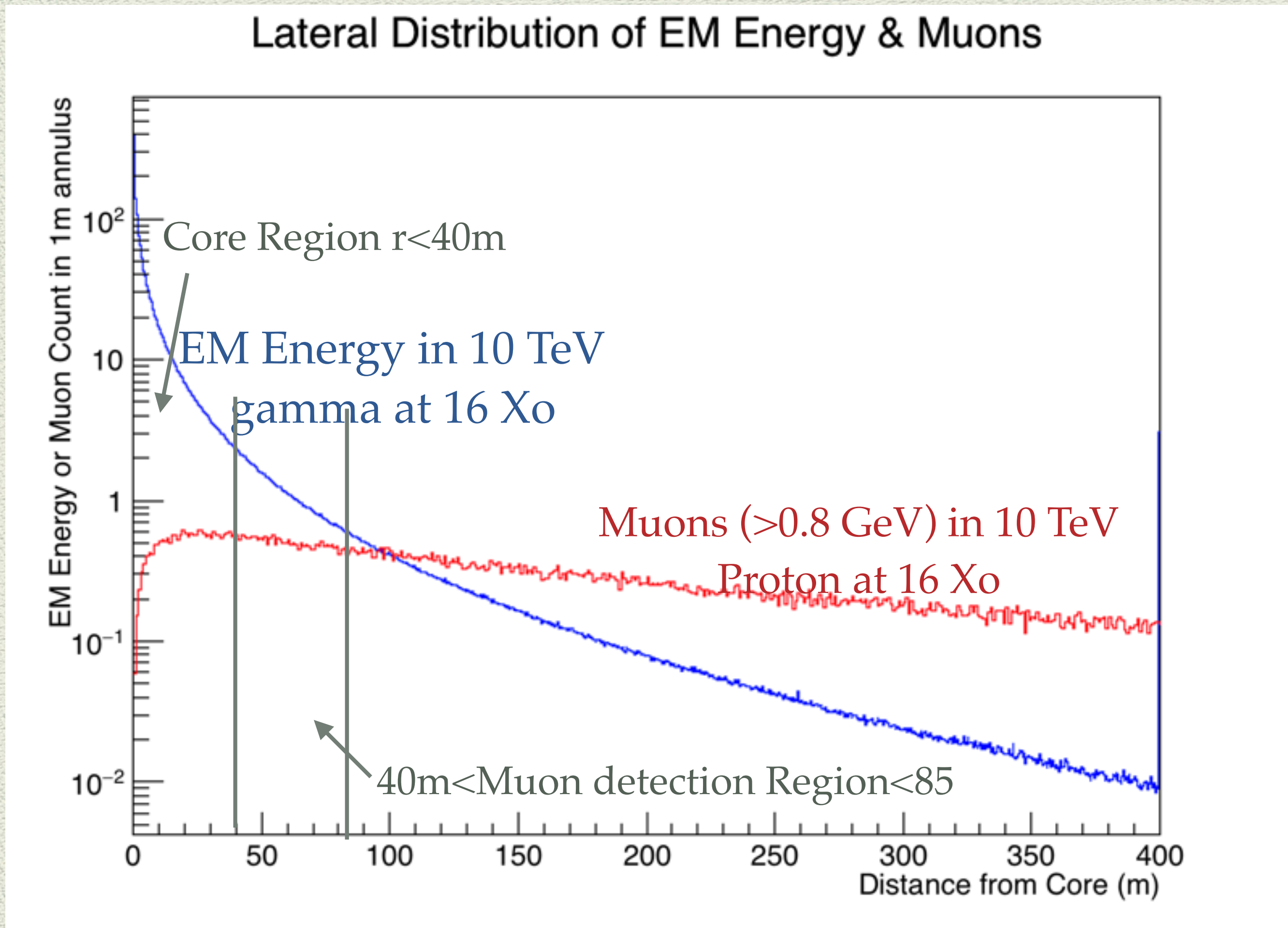
Low Energy: Improvement vs area

- 2x factor in detector size will increase the effective area by 2x. (HAWC —> 2x HAWC)
- Background also increase by 2x.
- Increase in sensitivity improves by sqrt(2) =<u>1.4x</u>
- γ/h separation improves due to improved muon collection, so improvement is better than 1.4.

Gamma/Hadron Separation: Lateral Distribution of EM energy and Muons

Muon lateral distribution is very broad

Imagine that γ/h separation is just muons



How many more muons might we get from a larger detector? Isolated muon layer?

Table shows number of muons in shower core region and surrounding regions

Bkg Passing ~ exp(-N_μ)

Imagine muon tagging off ~50%

HAWC: $N\mu = 1.4$, ε_{bkg}= **25%**
HAWC+ deep: $N\mu = 2.4$, ε_{bkg}= **9%**

Super HAWC: $N\mu = 3.8$, ε_{bkg}= **2.2%**
Super HAWC +deep: $N\mu = 4.8$, ε_{bkg}= **0.8%**

Large detector has Much better muon rejection

		Core Region	HAWC Muon Region	"Super HAWC" (100k m[2]) Muon Region
	All Muons	<40m	40m - 85m	85m - 180m
1 TeV	26.1	1.9	2.8	4.8
10 TeV	173	20.3	22.4	34.0

Number of Muons vs Core Distance

Conclusion: Sensitivity at lowest energies

- Ignoring γ/h separation:
  - Increasing elevation by 1 RL (~500m) is approximately equivalent to increasing the coverage by 2x.
- Including γ/h separation:
  - Maybe the case that a 2x larger detector is significantly more sensitive.

More Conclusions…

- Be careful about cold. (-6 deg C/1000m)
- There is a limit to how large a detector can be:
  - Random Muon rate ~200/m^2/s
  - ~1μ/50ns for a 100,000m^2 detector.
- Low energy gamma-ray showers are compact, so the trigger can be regional, so noise floor shouldn't be a limit.