Sensitivity of a surface array as a function of various parameters.

Andrew Smith
University of Maryland

What is the point of this talk?

- Detector design is always a tradeoff.
- To maximize the sensitivity to the highest energy showers (>10 TeV), it is clear that very large detectors (>>20,000 m^2) are optimal.
- At low energies (<500 GeV) the optimal tradeoffs are less clear.
  - Obvious answer seems to be elevation is everything (higher = lower threshold, right?)
  - Be careful, because larger detectors have an improved sensitivity at lower energies too, through improved collection area and improved gamma/hadron separation.

Questions for Detector Designers:

- How does the sensitivity change with increasing detector elevation?
- How does the sensitivity change with increasing Area?
- What role do angular resolution, background rates and gamma/hadron separation play?

My Principle Concern

Assume:

1) There exists some very high elevation site with limited area.

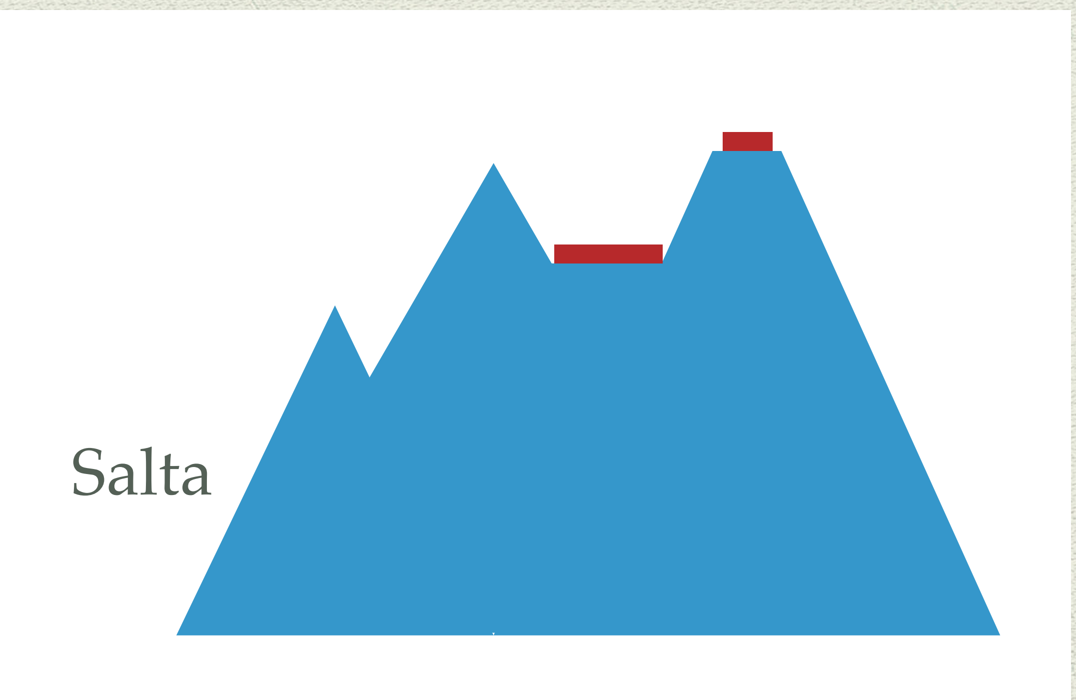
2) There exists a somewhat lower elevation site that can accommodate a larger detector.

Concern:

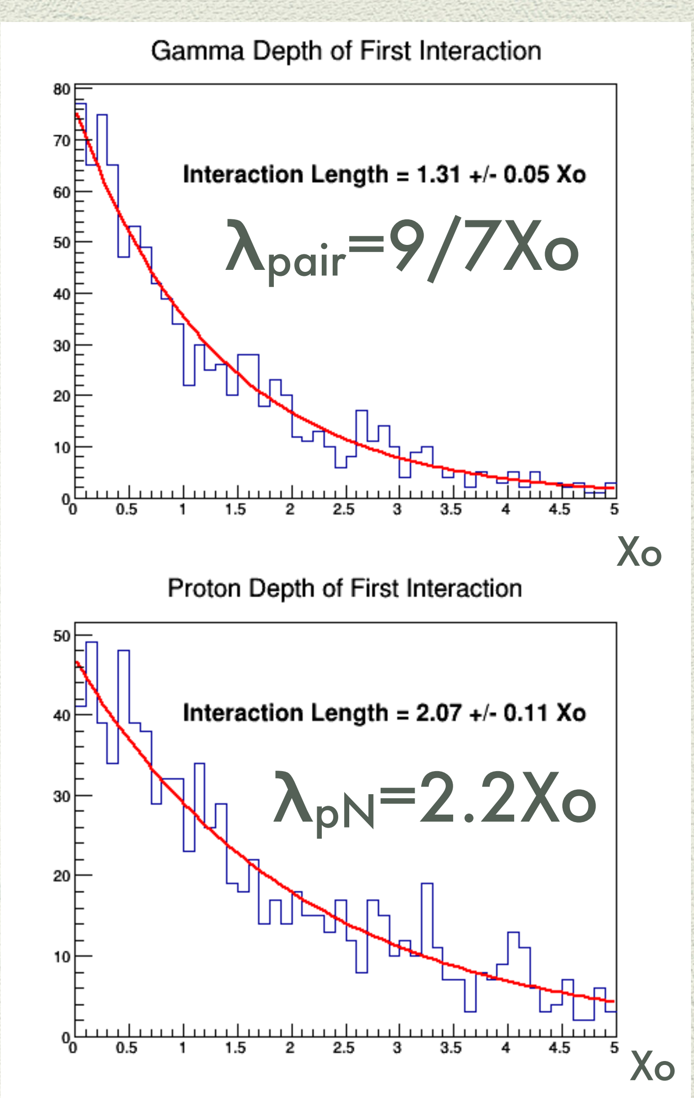
People argue about tradeoffs between high energy (lower, bigger) and low energy sensitivity

Hope:

A larger lower detector can be better for both low and high energies.

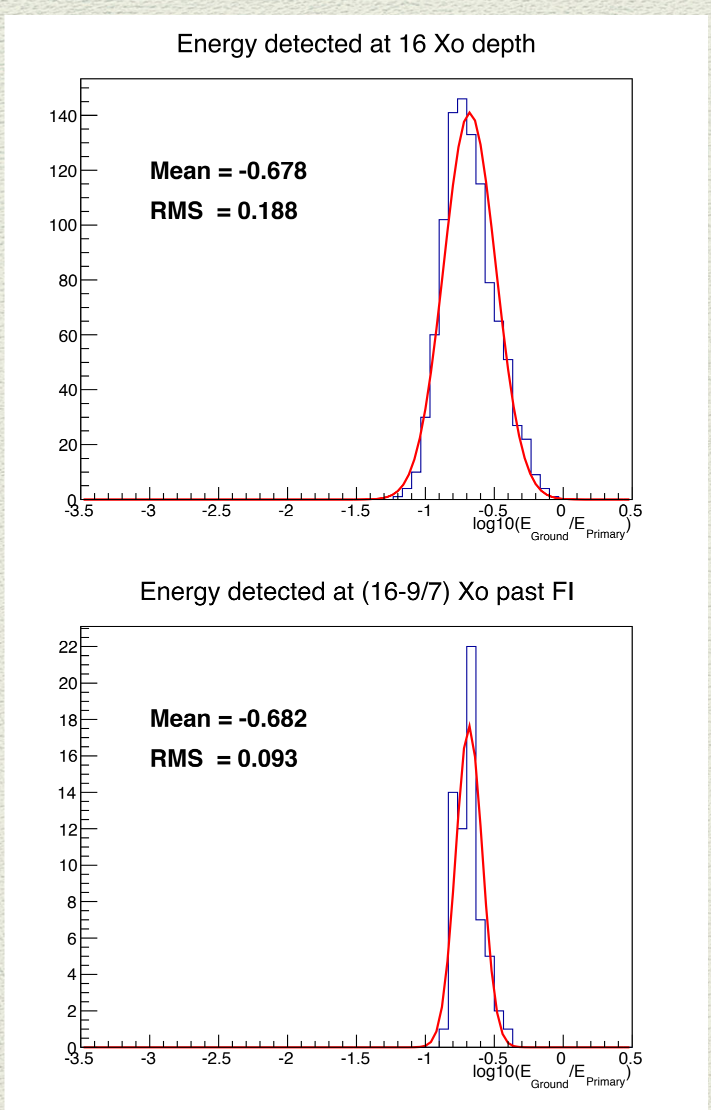


First Interaction Depth dominates Longitudinal Fluctuations



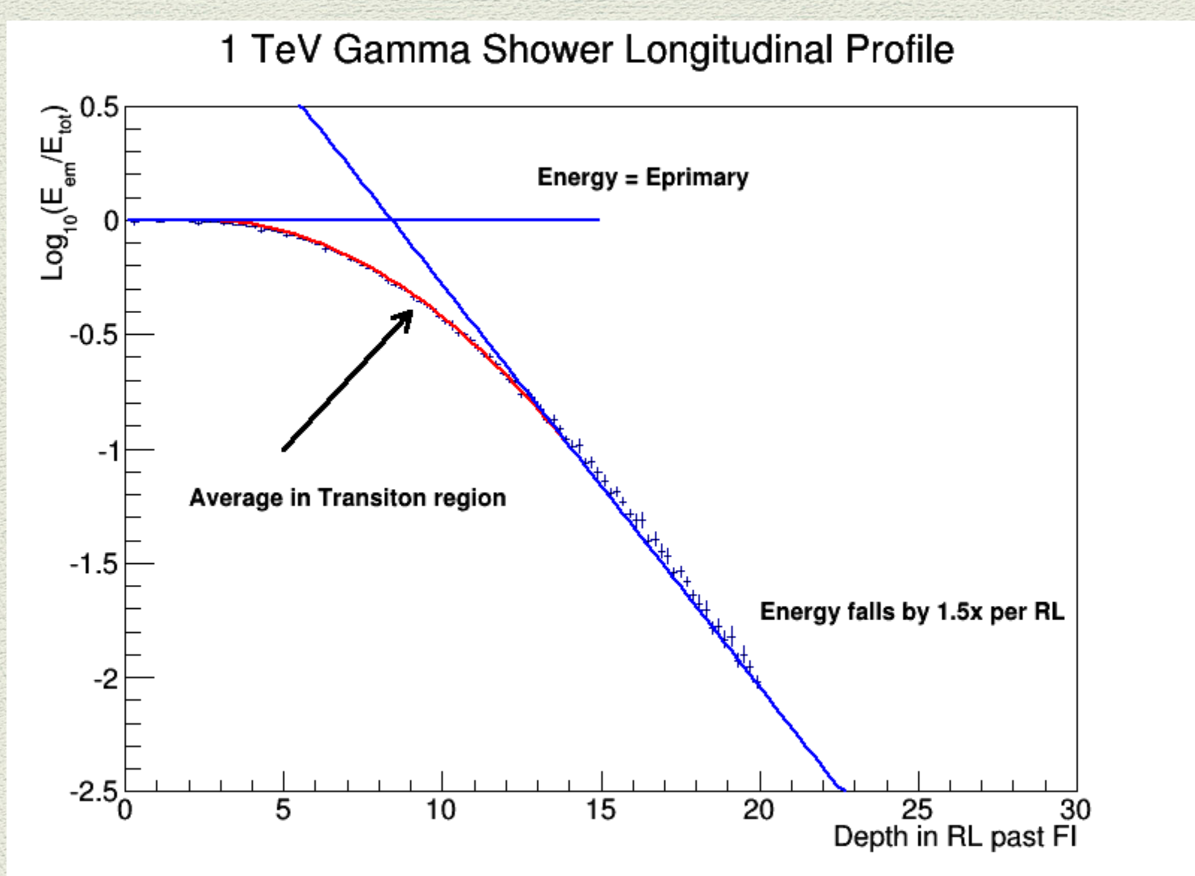
First Interaction depth distribution is easily predictable, depending only on λ_{pair} or hadronic interaction length

Fluctuations in energy at the ground is dominated by FI.



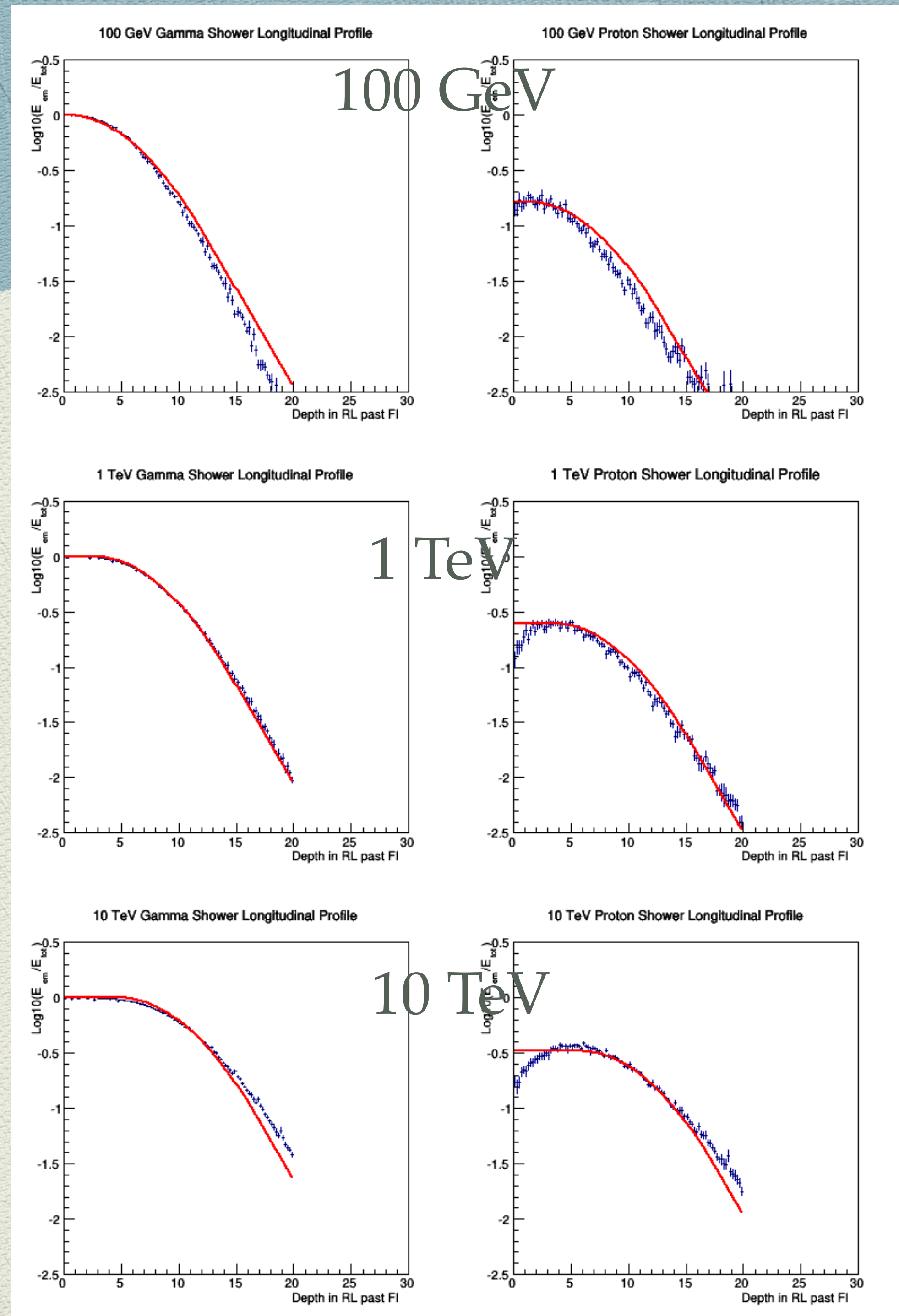
Simple model for energy vs level

- 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.



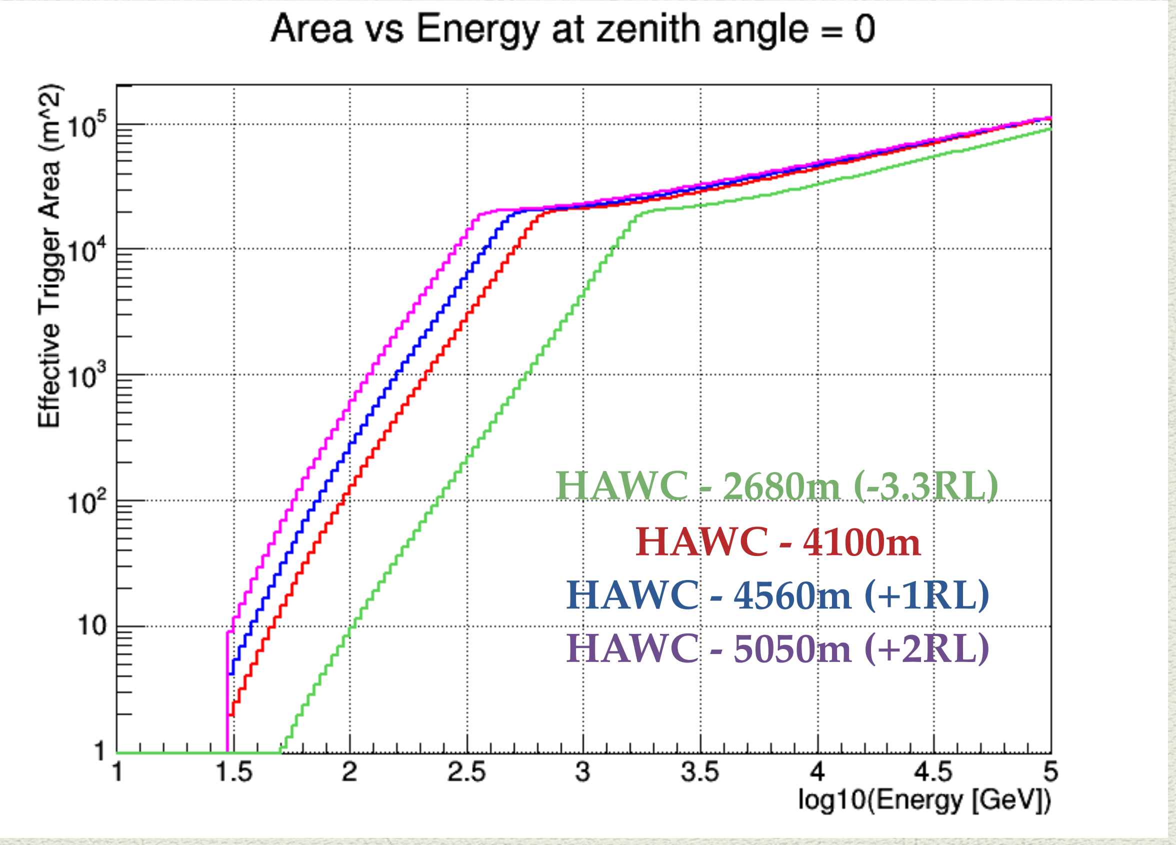
Depth of transition = log(E/Ec) + C

- 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
```

Effect of increasing elevation:

- Increase by 1 RL and sensitivity to ~100-500 GeV showers:
  - gamma rate increases by $e^{7/9} = 2.2$
  - hadron rate increases by $e^{37/82} = 1.6$
    (not sure about this since hadron energy is not the same as gamma energy)
  - $Q_{Elevation} = 2.2/\mathrm{sqrt}(1.6)$ per RL = **1.7**
- 1RL ~= 500m, so **1.11x increase per 100m**

Effect of Increasing Area:

- Detector needs to be large enough to contain showers.
- Moliere radius is ~20m. Assume 10m edge is not usable, so effective area for a circular detector is something like:

$$A_{Eff} = \pi(\mathrm{sqrt}(A/\pi)\text{-}10m)^2$$

- Background and Signal proportional to A_{Eff}:
- Effect of doubling detector size:
  - $5000m^2$ —-> $10,000m^2$: A_{Eff} —> 2.41x
  - $10,000m^2$ —> $20,000m^2$: A_{Eff} —-> 2.26x
  - $20,000m^2$ —> $40,000m^2$: A_{Eff} —-> 2.17x

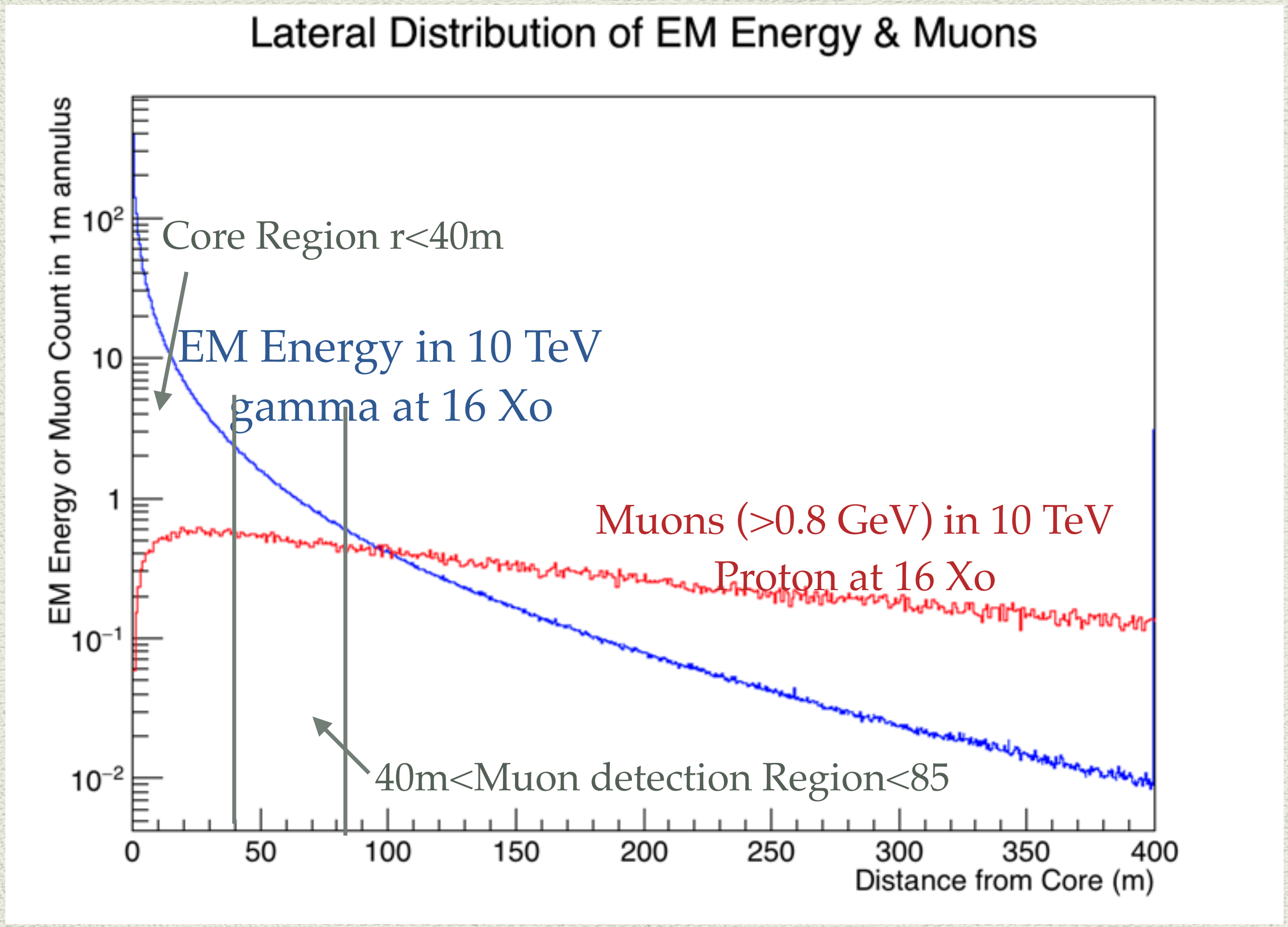
$Q_{\text{Double Area}}$ ~=1.5

Gamma-Hadron Separation

- Note, muons generally penetrate deeply and are not attenuated by the atmosphere.
- What's missing from the previous calculation is that the gamma/hadron separation efficacy depends on area and elevation also:
  - Large Area = more collection area for muons
  - High Elevation = Backgrounds from lower energy hadrons, which have fewer muons.

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

Muon lateral distribution is very broad!



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

Increasing area by a factor of 4x increases number of muons by a factor of ~2x

Doubling area gives ~1.4x increase in muons detected.

Muon count roughly proportional to energy.

Bkg Passing ~ $\exp(-N_\mu)$

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

	All Muons	<40m	40m - 85m	85m - 180m
1 TeV	26.1	1.9	2.8	4.8
Area (m^2)		5000	22000	100000
Muon Increase			x2.5	x2.0
Area Increase			x4.5	x4.5

Number of Muons vs Core Distance

Larger Detector

- At one detector size, we expect N muons.
- Double the area and get 1.4xN muons

$Q = \exp(-N)/\exp(-1.4N)$

- Background for low-energy events is typically from 200-500 GeV hadrons.
- Likely Q is 1.5 or larger.
- Combined Q-factor for γ/h and increasing collection area:

$Q = 1.5 \times 1.5 = 2.3$

N	0.5	1	2
1.4xN	0.7	1.4	2.8
Q	1.2	1.5	2.2

Pulling it all Together:

- Increasing elevation by 100m (Q=1.11) has same improvement as increasing the area of the detector by about 9%.
- A detector at 5000m a.s.l. (1.8 RL above HAWC) would have $1.7^{1.8}$ = **2.6x** better sensitivity than HAWC to the lowest energy showers.
- A HAWC-like detector that is only 10,000m^2 (45% of the area of HAWC, or -1.15 doublings) would have a sensitivity $2.3^{1.15}$ = **2.6x** worse than HAWC's

A note on angular resolution

- Angular Resolution Depends only on ground energy.

Ang Difference between ground particle momentum and primary