

Detection of Nearly-Horizontal Muons with the HAWC Observatory

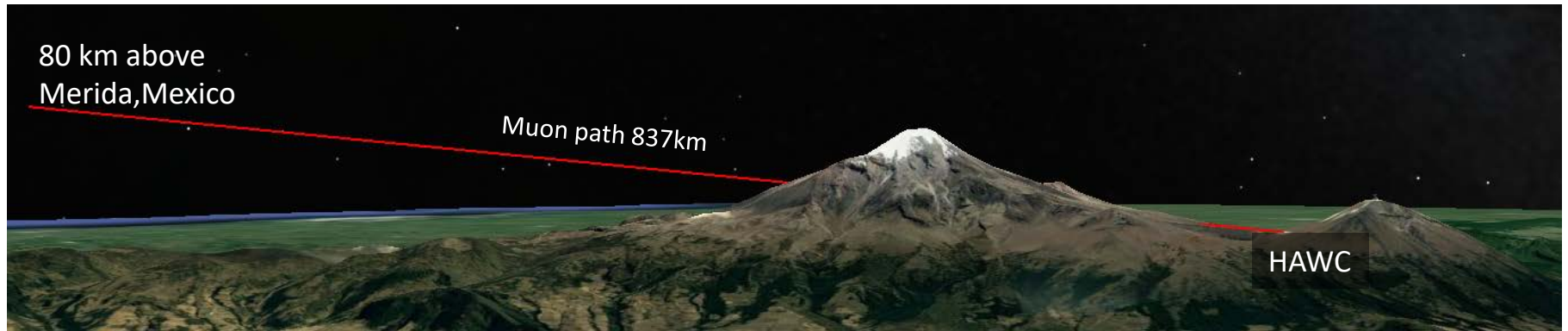
Ahron S. Barber^a , David B. Kieda^a and R. Wayne Springer^{a*} for the HAWC Collaboration^b

^aDepartment of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA

^bFor a complete author list, see

www.hawc-observatory.org/collaboration/icrc2017.php.

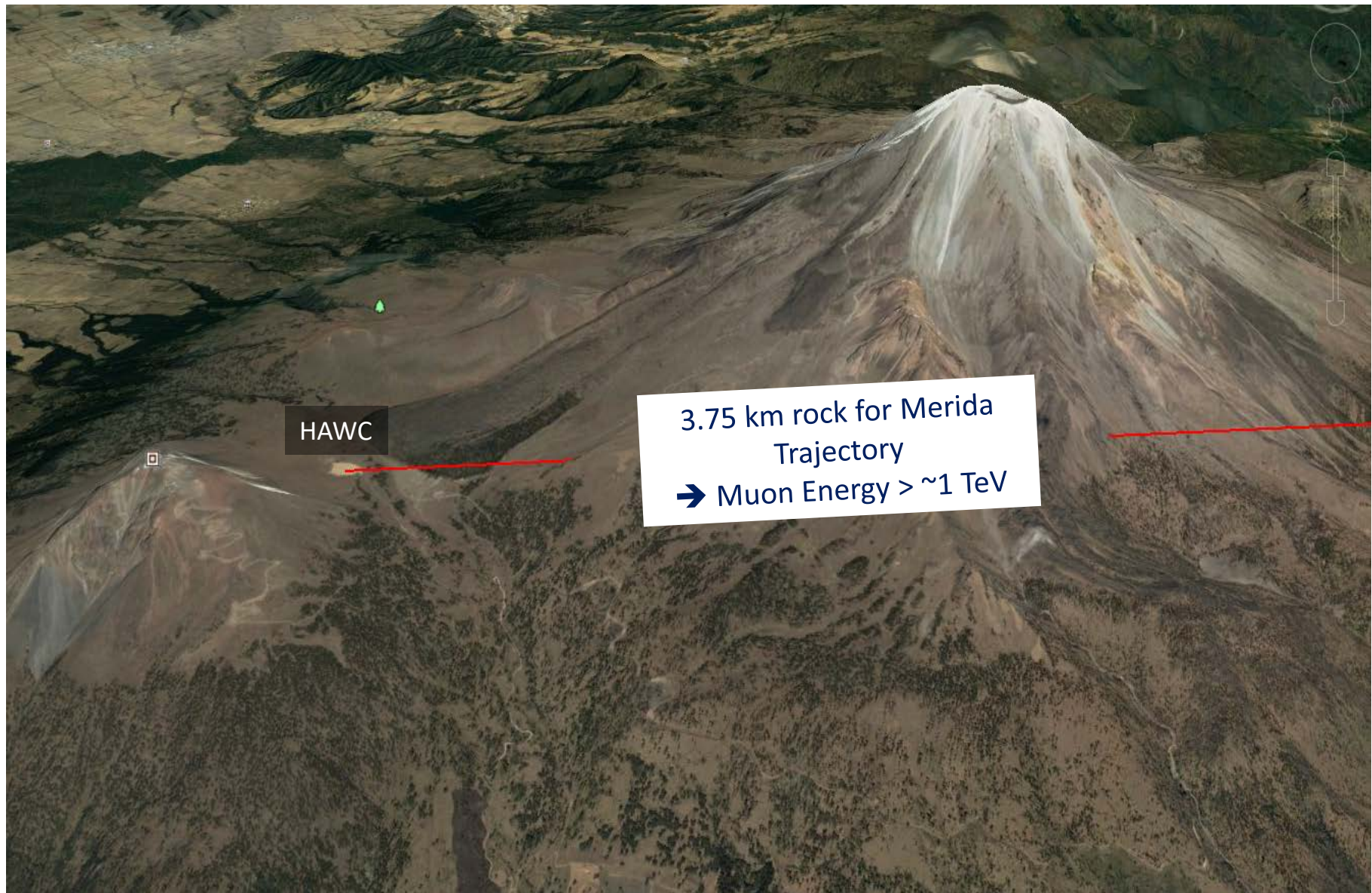
Email: ahron.barber@utah.edu, dave.kieda@utah.edu, wayne.springer@utah.edu



August 17, 2017

KIAA- WAP II

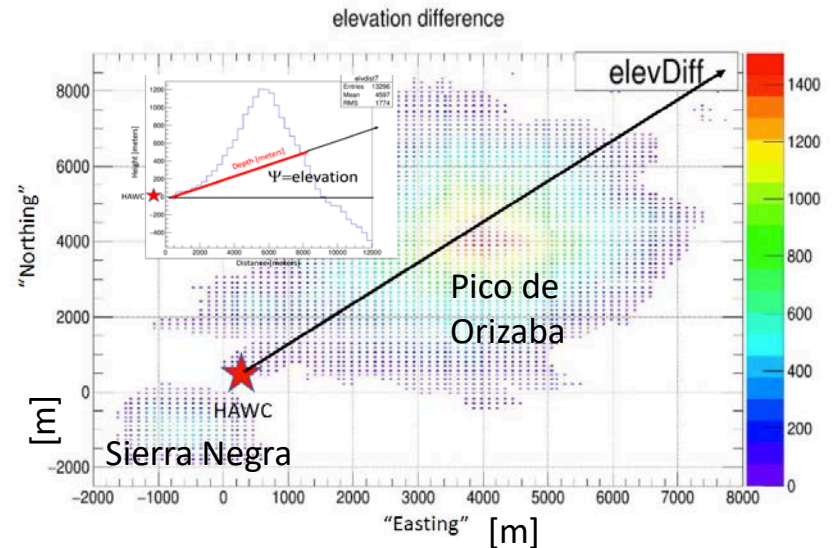
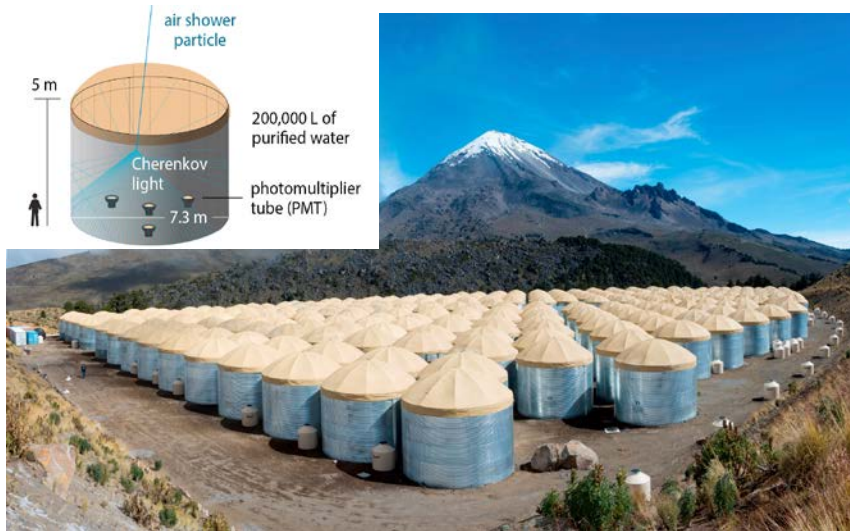
Peking University, Beijing, China



HAWC

3.75 km rock for Merida
Trajectory
→ Muon Energy > ~1 TeV

HAWC Detector and Site



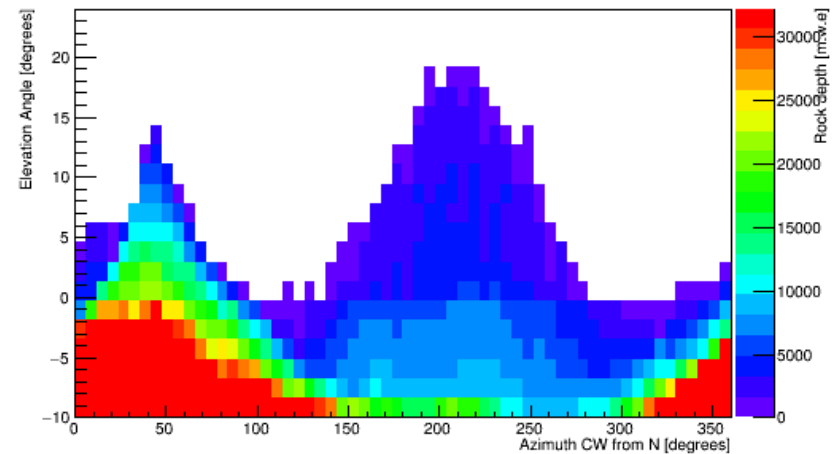
■ The HAWC detector

- 300 - 4.5 m high, 7.3 m diameter tanks covers a footprint of 22,000 m².
- Each tank contains 200,000 liters of purified water and is instrumented with 4 upward looking photomultiplier tubes (PMTs) .

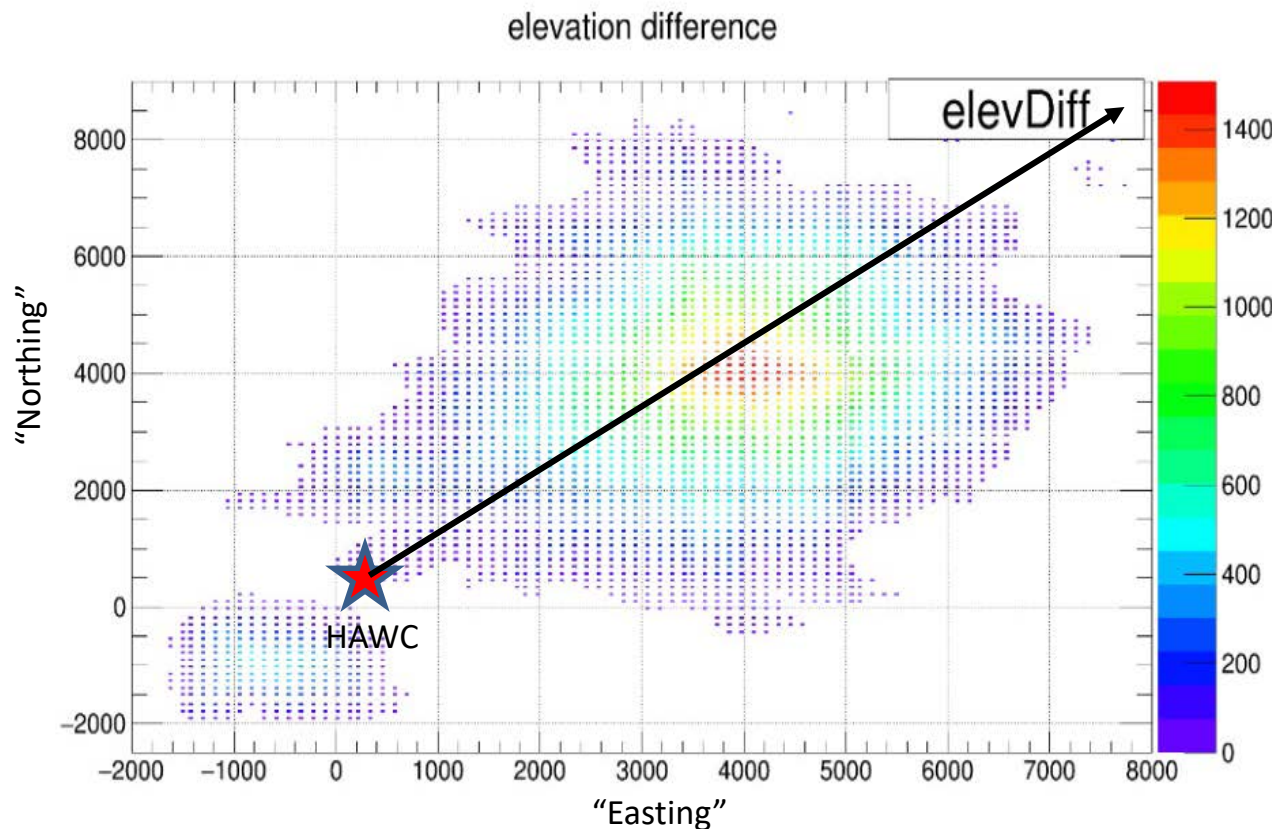
■ The HAWC site

- Located at an altitude of 4100m a.s.l. adjacent to two volcanoes, Pico de Orizaba (5636m) and Sierra Negra (4580m).
- Overburden depth varying from 0 to 32000 m.w.e
→ muon energy threshold varying from 0 to 520 TeV.

Depth vs azimuth (CW from N) vs elevation angle



Elevation profile

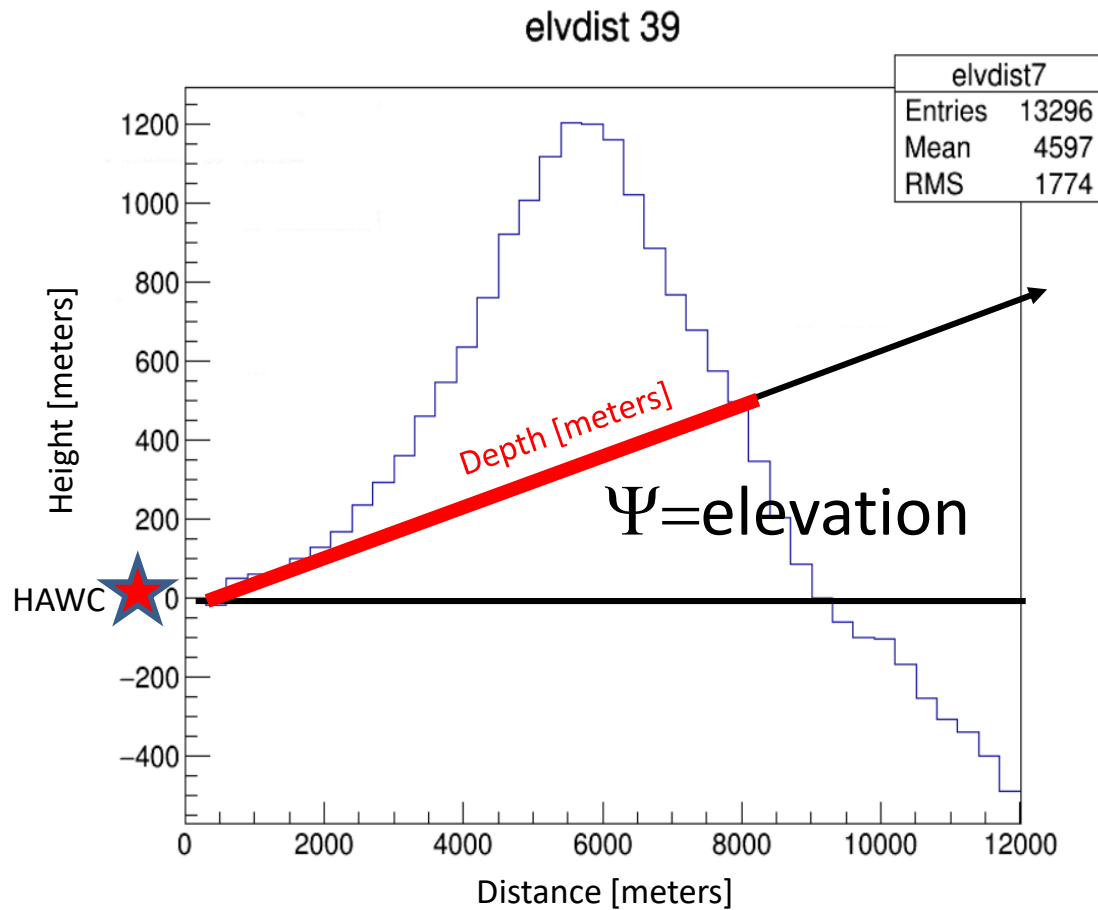


Sample elevation above HAWC as a function of distance along azimuth rays.

Thanks....
Hermes Leon Vargas

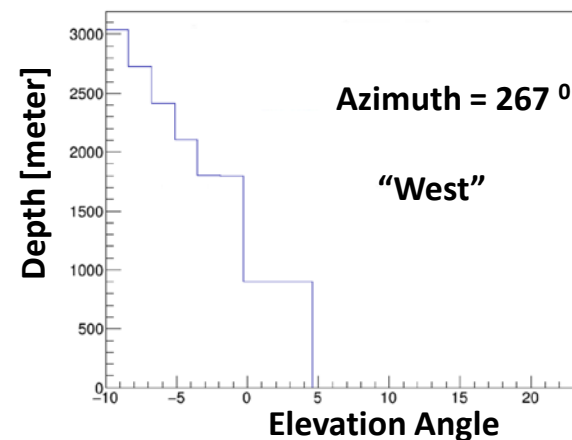
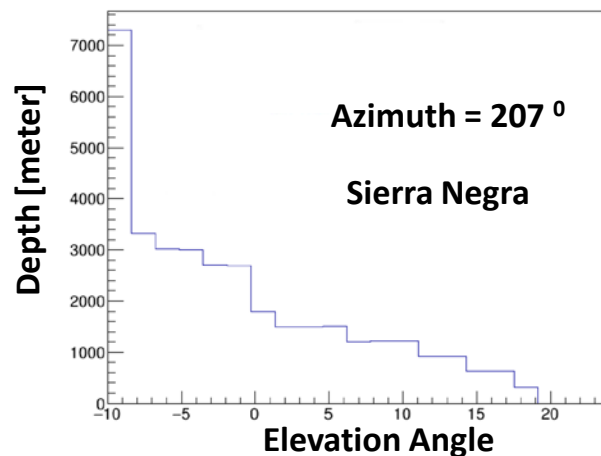
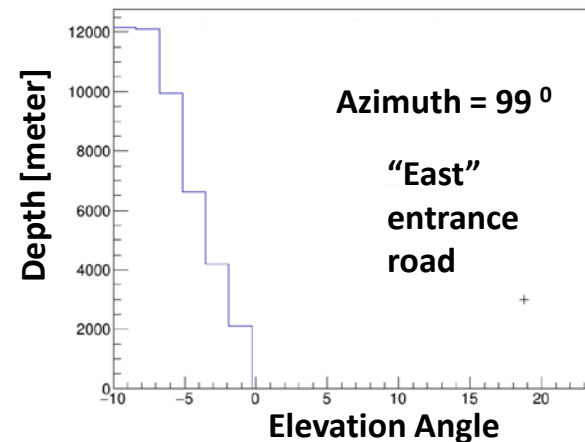
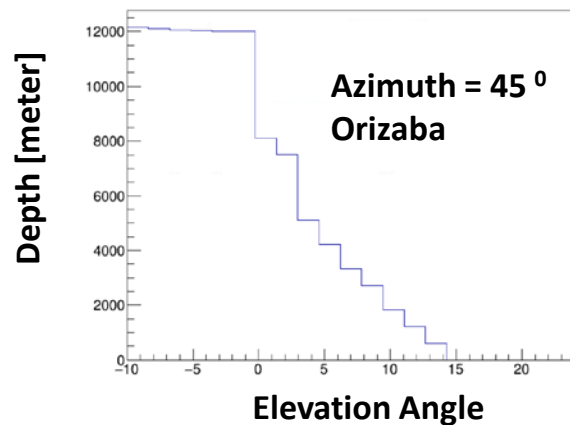
INEGI. Continuo de elevaciones mexicano 3.0 (cem 3.0), 2012. URL <http://www.inegi.org.mx/geo/contenidos/datosrelieve/continental/continuoelevaciones.aspx>. Cited 25 Dec 1999.

Mountain Depth vs Arrival Direction

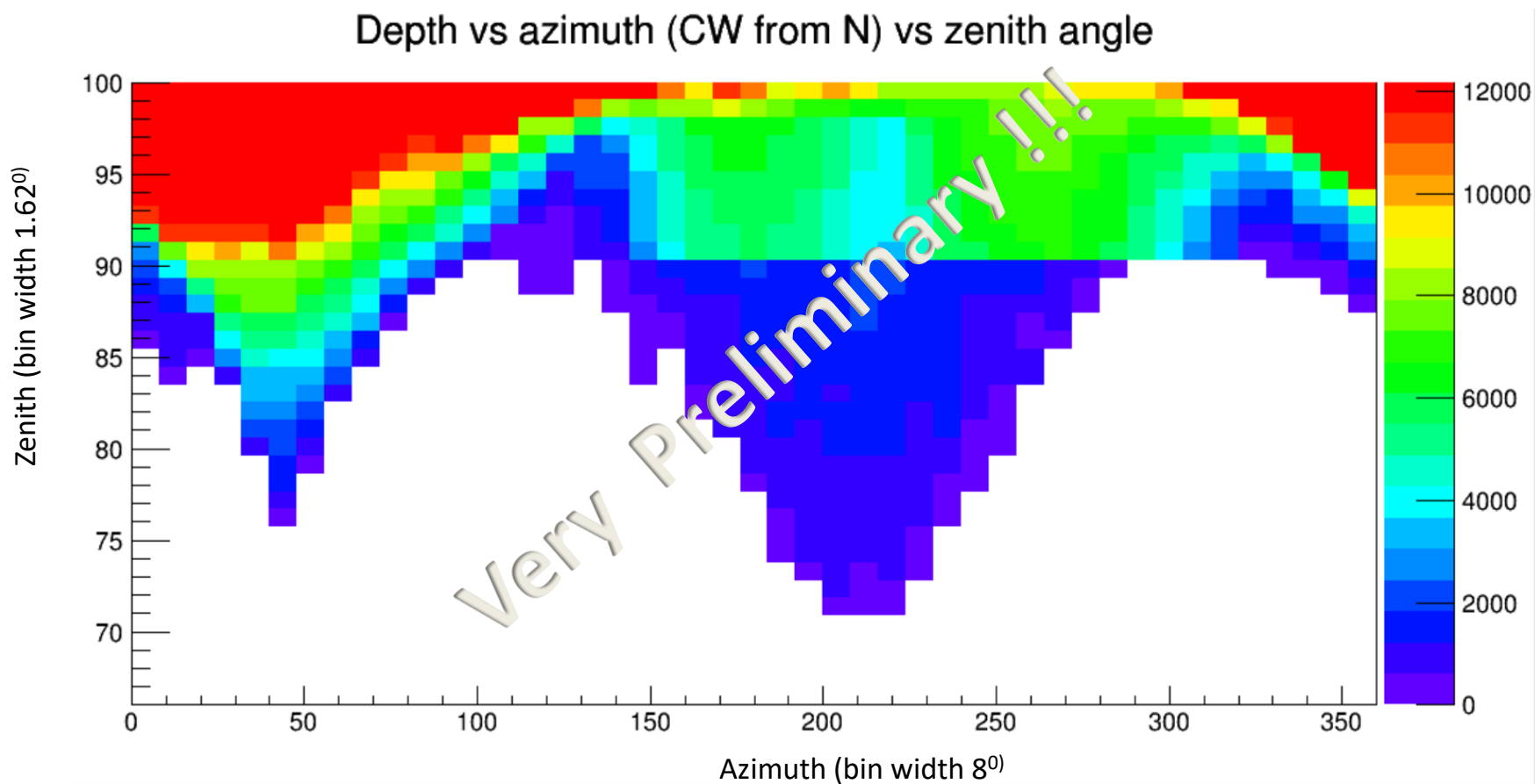


Along elevation
rays add length
while mountain
profile above
ray

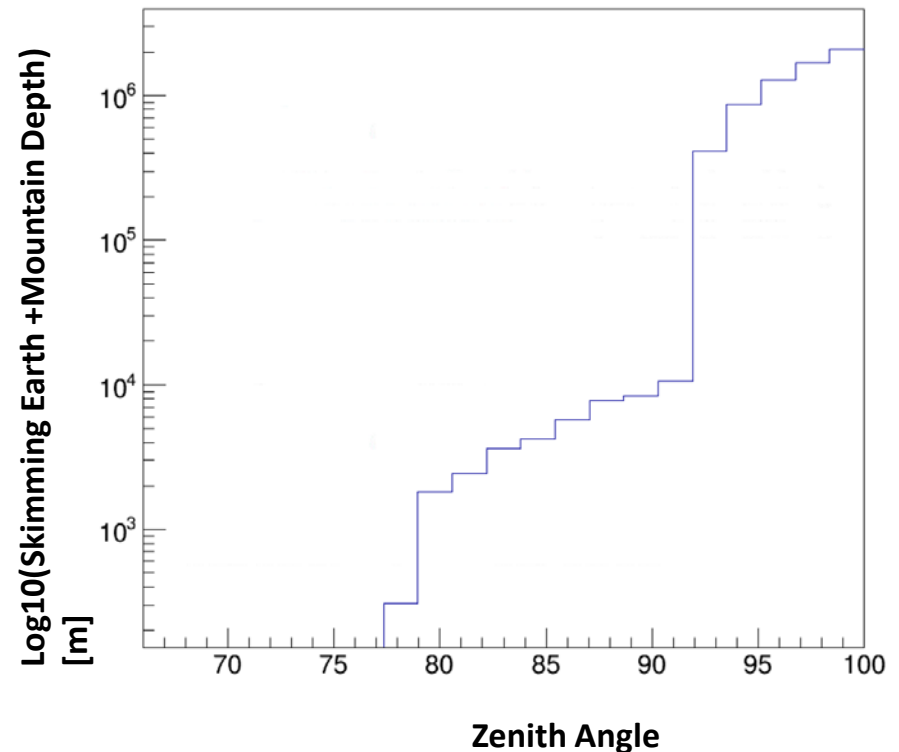
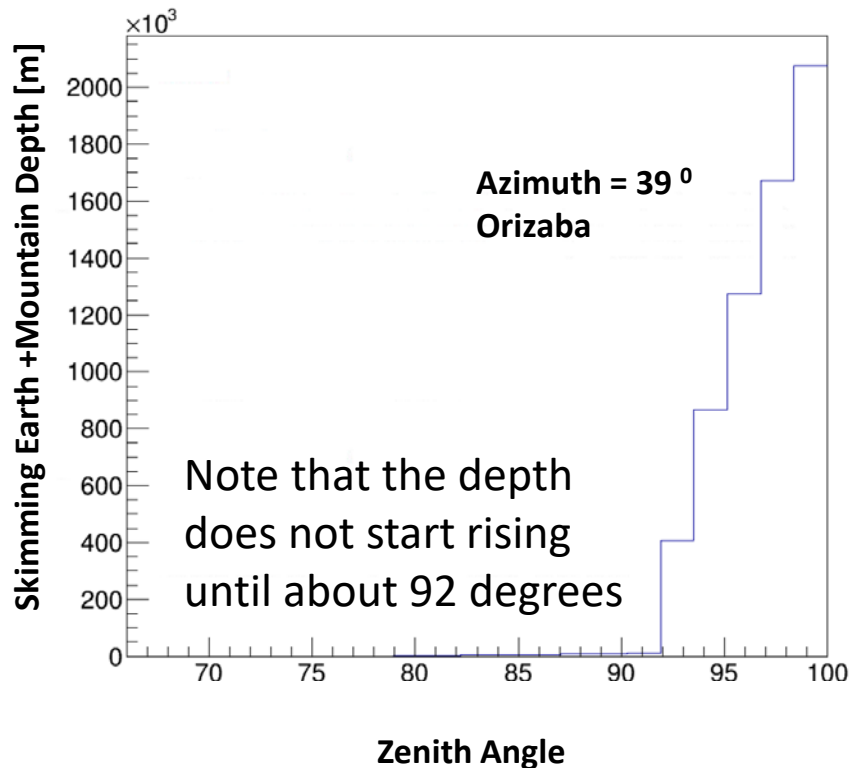
Depth vs Elevation Angle at Az CW from N



Depth vs Azimuth vs Zenith

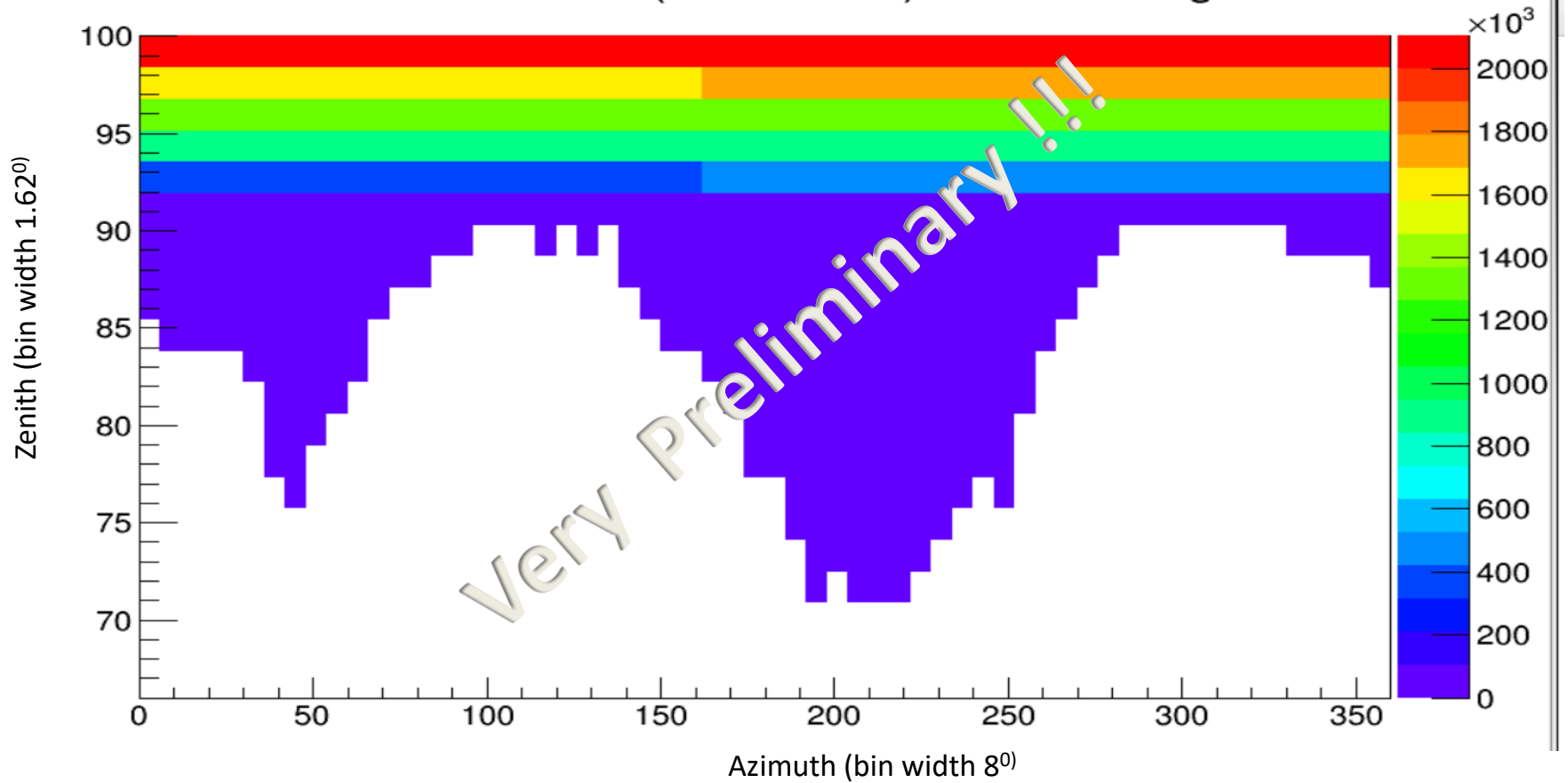


Don't forget about earth's surface and curvature



Earth vs Azimuth vs Zenith

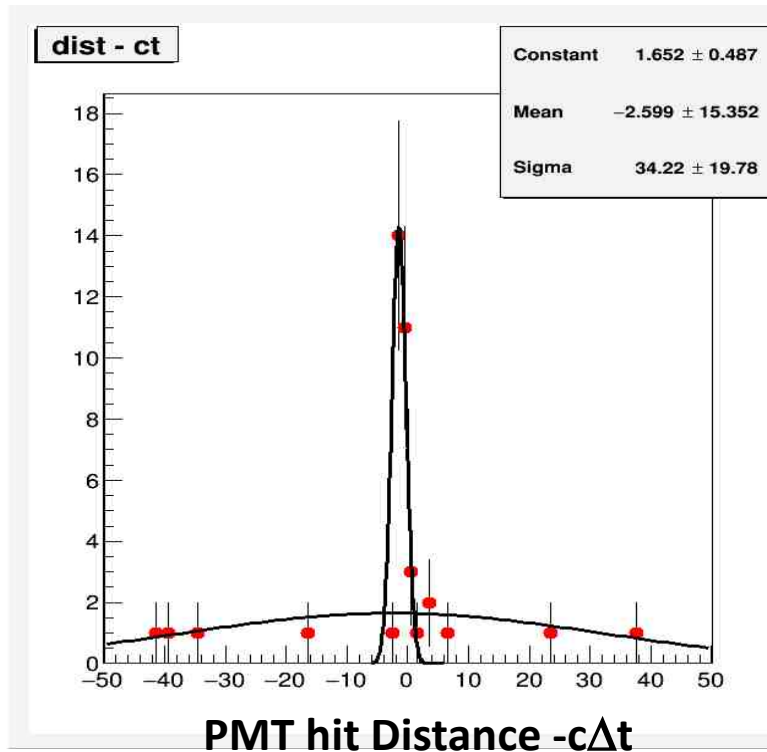
Earth vs azimuth (CW from N) vs zenith angle



Nearly-Horizontal Muon Identification

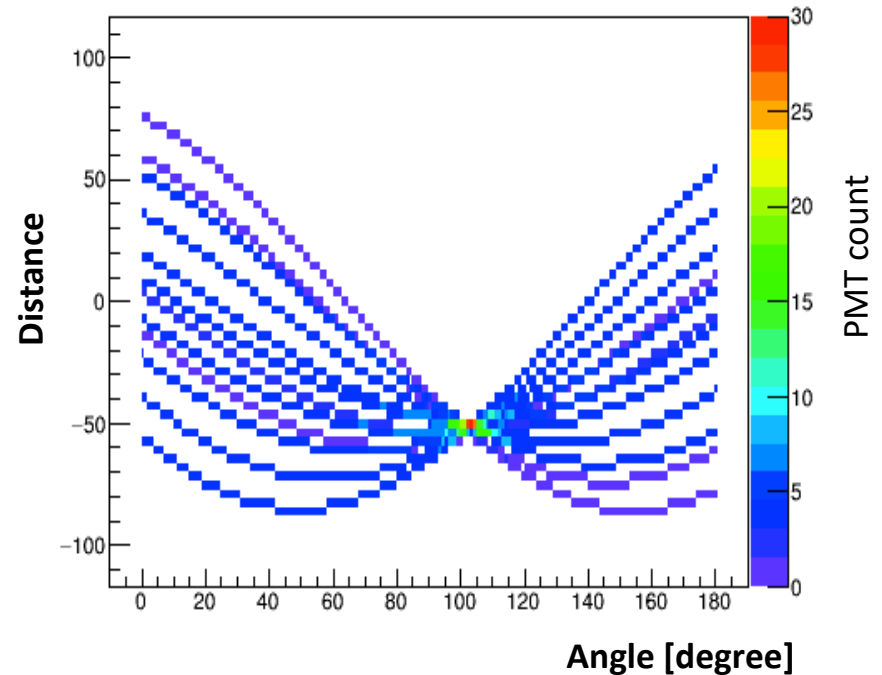
Speed of light propagation

Identify patterns of PMT hits in time and space that are consistent with a particle moving nearly horizontally at the speed of light. Their locations and hit times satisfy the relation distance = $c\Delta t$.



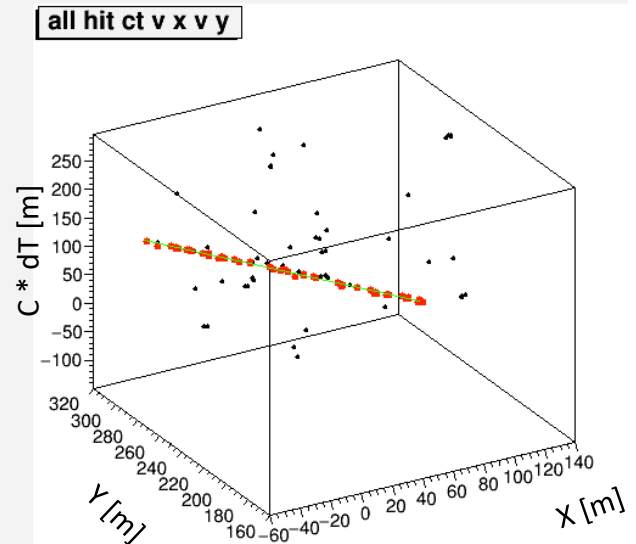
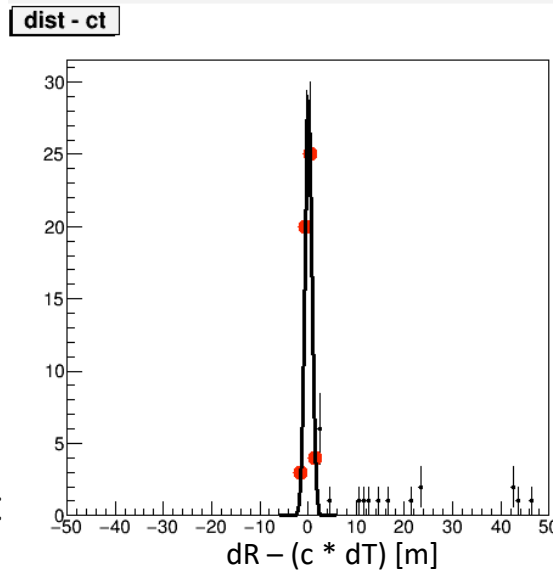
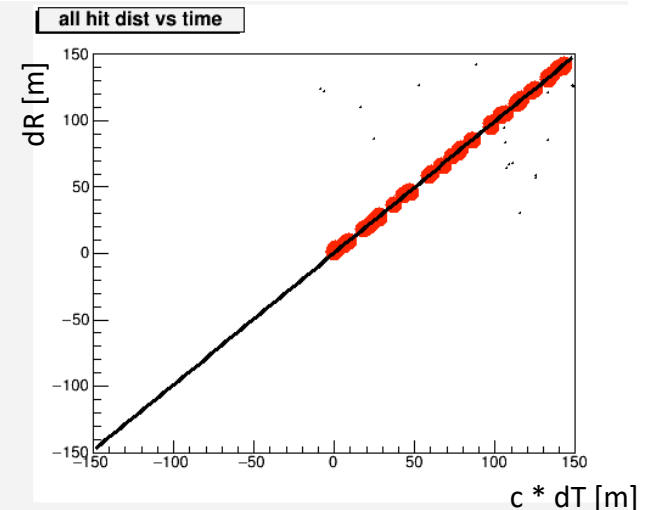
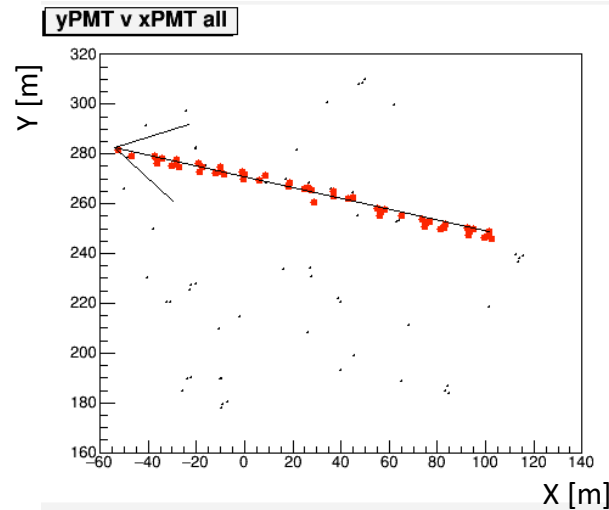
Hough Transform

Apply Hough transformation algorithm to further require isolated lines reduces the background from air shower events.



A “typical” Nearly-Horizontal Muon Event in HAWC data

- ☐ Precise & accurate timing
- ☐ Very clear signature
 - ☐ high zenith
 - ☐ Alignment in azimuth
- ☐ EAS with noise can occasionally satisfy distance vs $c\Delta t$ requirement.
- ☐ BNN (Biological Neural Network) can easily distinguish junk. Hough Transform works almost as well.



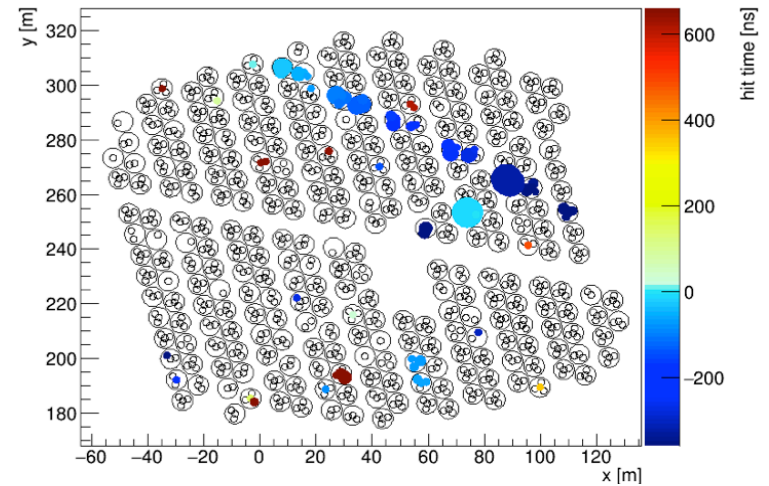
Nearly-Horizontal Muon Event Data Sample

- ❑ 20 days worth of data from January 2016 analyzed so far (still tuning algorithms)
- ❑ Triggered archive data.
 - ❑ Optimized for EAS Cosmic and Gamma rays
 - ❑ 25 kHz of triggered Events.
- ❑ Muon Rate in 10 min segments:
 - ❑ 1.24 Hz with 0.09 standard deviation

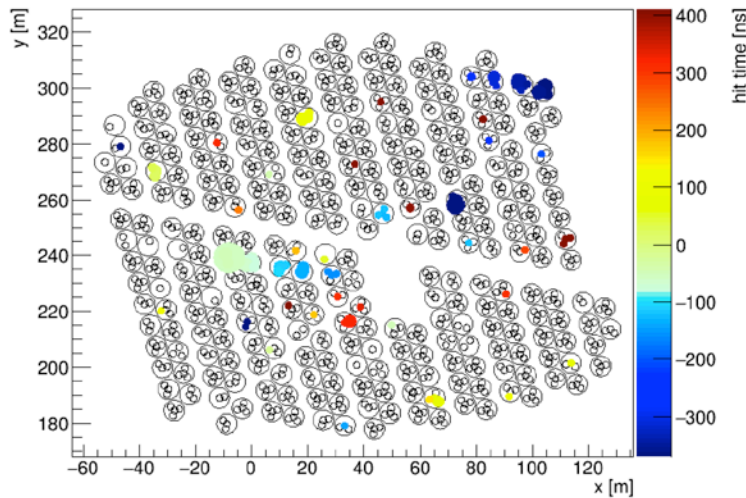
Some Observed Nearly-Horizontal Muon Events

- ❑ Events from HAWC “EAS-triggered” data
- ❑ Single muon rate of ~ 1.25 Hz for (track-length > 50 m)
- ❑ Multiple Muons (muon bundles) are observed

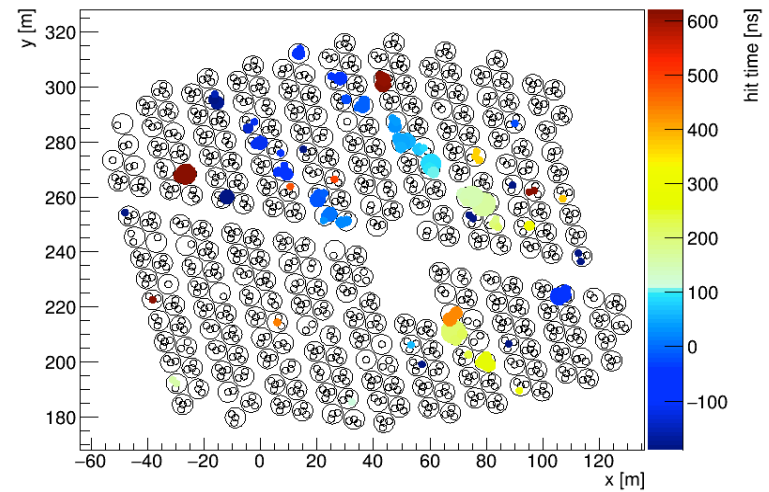
Run 4500, TS 495441, Ev# 83



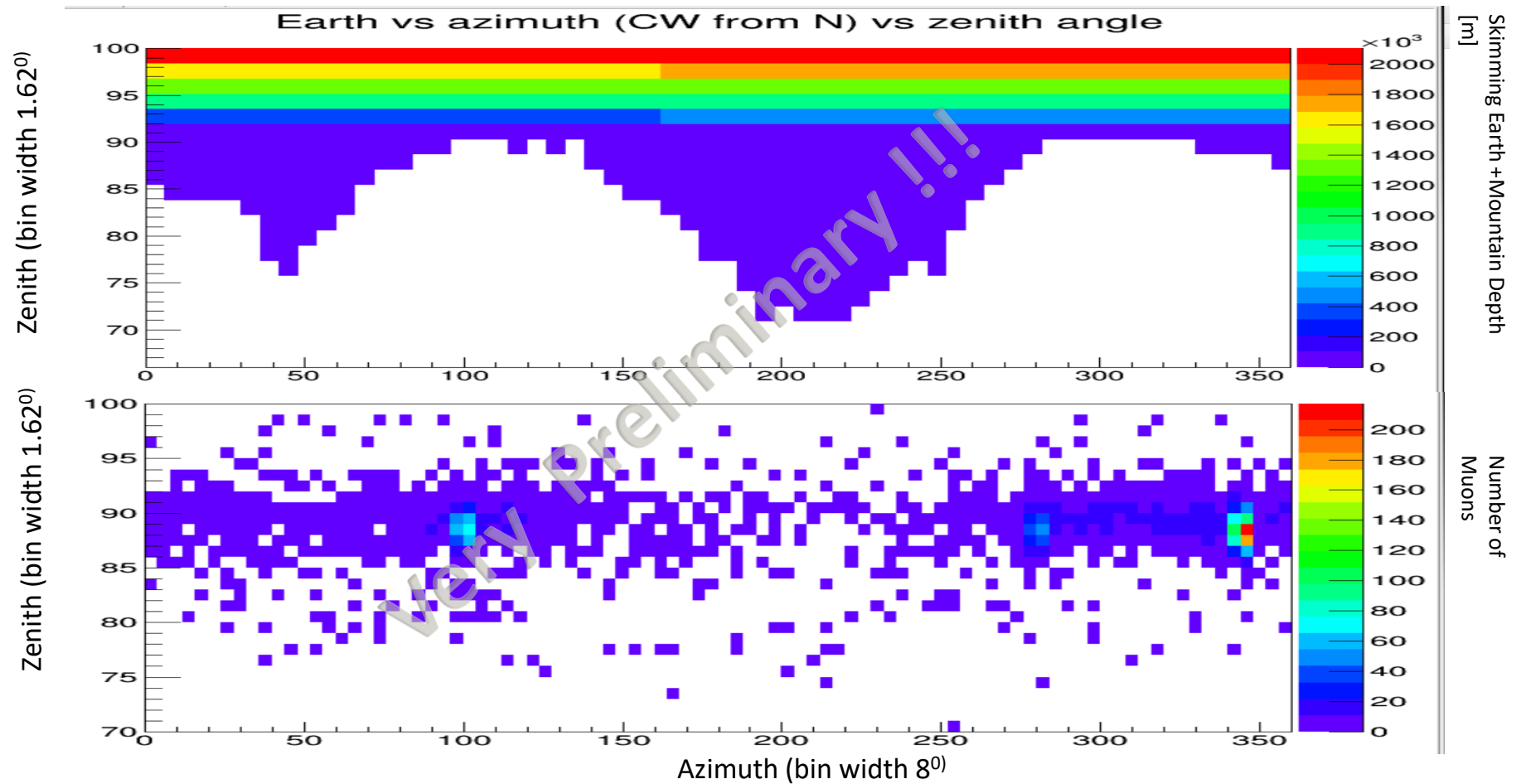
Run 4500, TS 4, Ev# 598



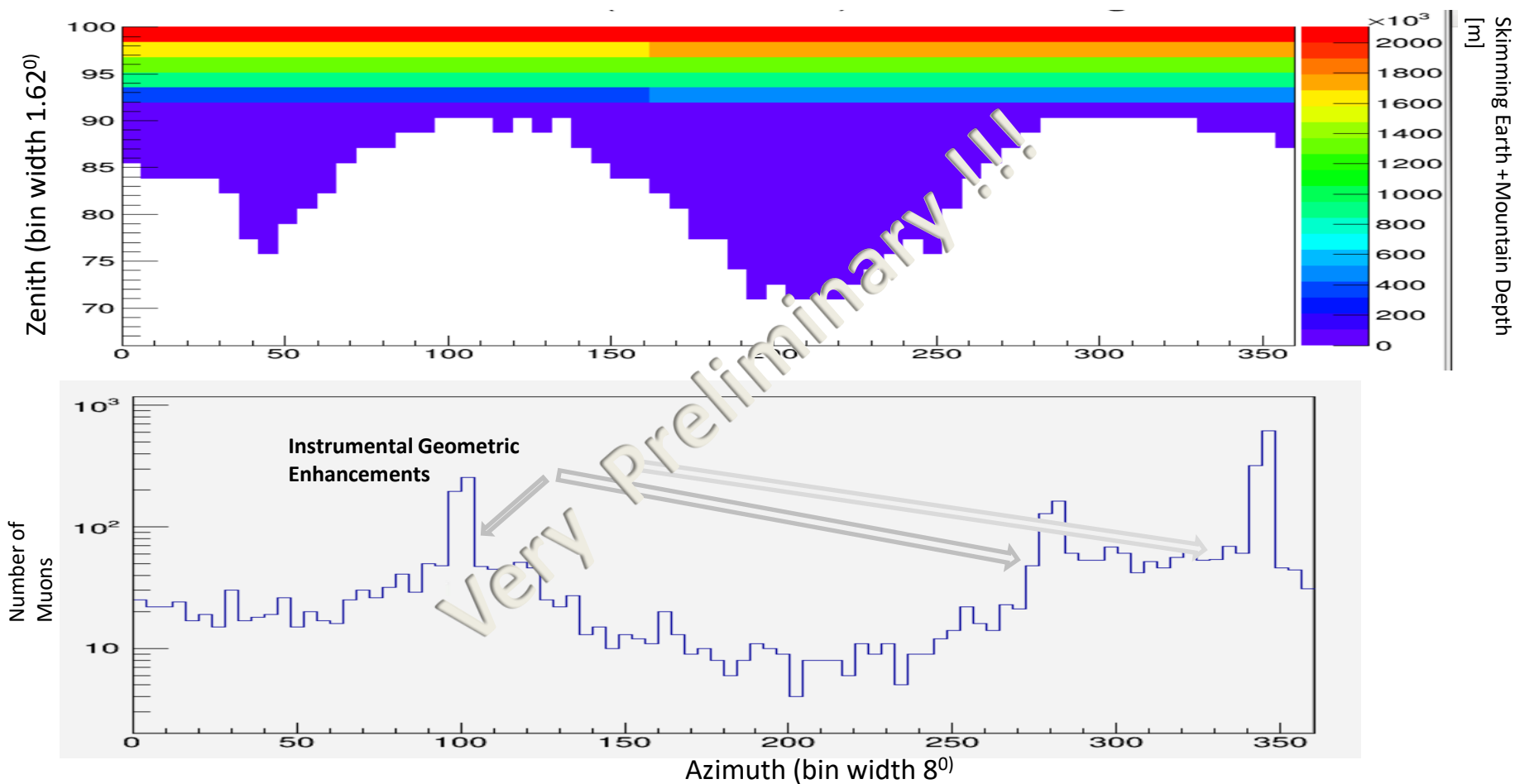
Run 4806, TS 1811, Ev# 348



Earth & Nmuon vz Azimuth vs Zenith Run 4513

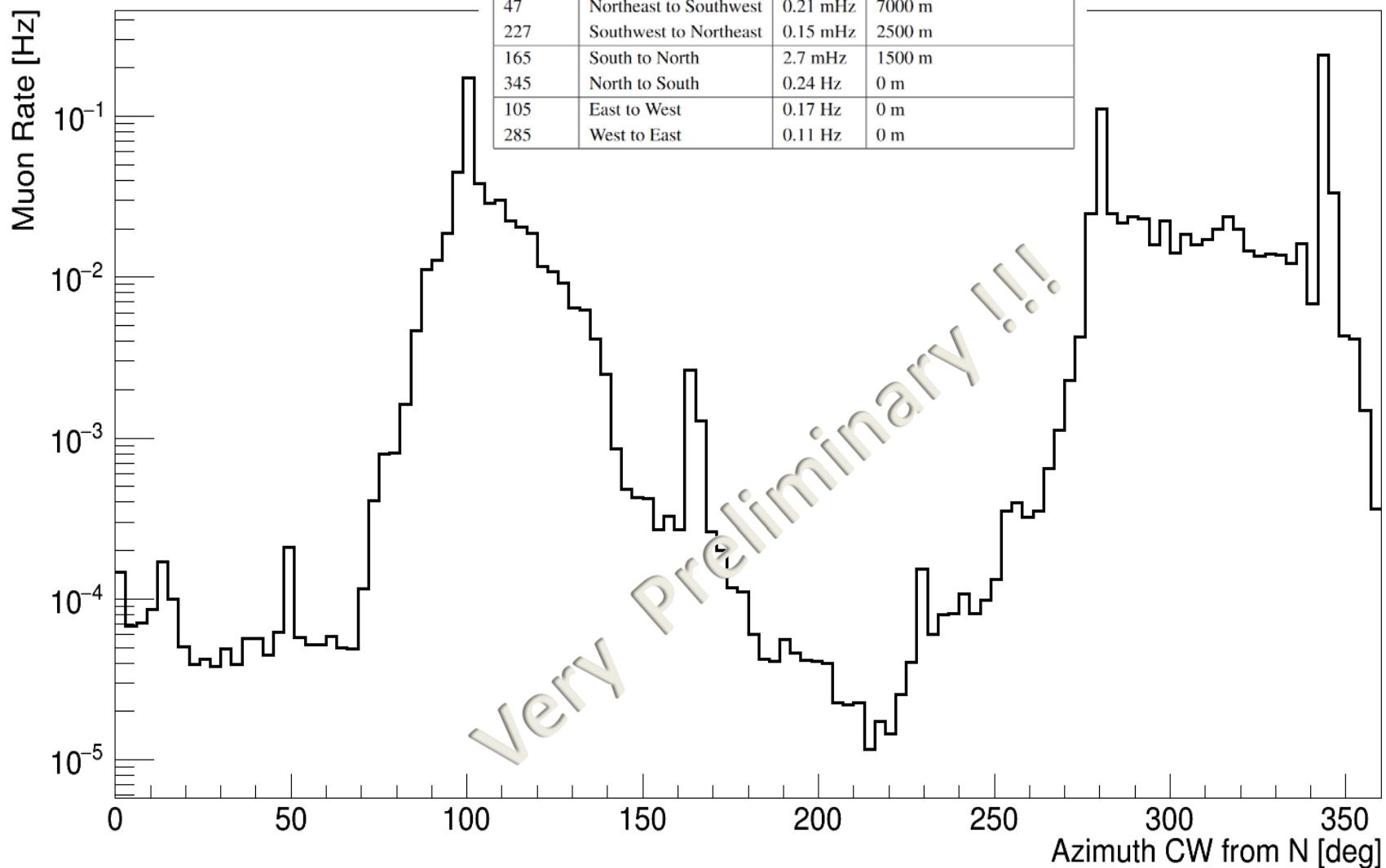


Earth vz Azimuth vs Zenith – Nmuon v azimuth (1 day exposure)



Observed Azimuthal Muon Rate

Azimuth	Approximate direction	Rate	Rock depth at 90 degrees
47	Northeast to Southwest	0.21 mHz	7000 m
227	Southwest to Northeast	0.15 mHz	2500 m
165	South to North	2.7 mHz	1500 m
345	North to South	0.24 Hz	0 m
105	East to West	0.17 Hz	0 m
285	West to East	0.11 Hz	0 m



Science Goals using Nearly Horizontal Muons

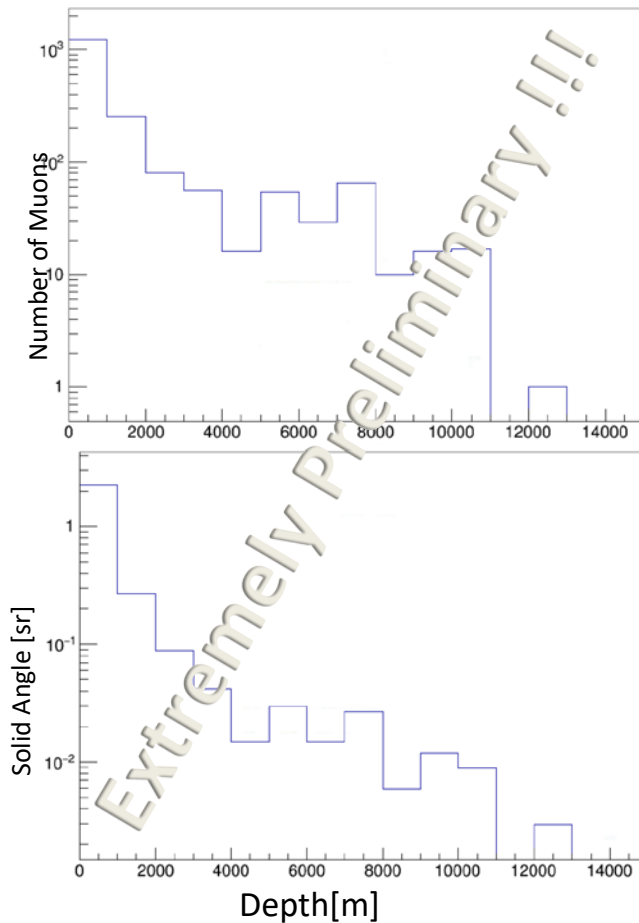
- ☐ Cosmic Ray Composition & Integral Energy Spectrum.
 - ☐ Requires extensive simulation work that has begun.

- ☐ Muon Tomography of the Volcanoes.
 - ☐ Pico de Orizaba is dormant....

- ☐ Neutrino conversion in Mountains
 - ☐ Near Horizontal Muons are the background.

“Muon” Flux vs depth

Nmuon vs depth & Solid Angle vs Depth



$$flux_{CosmicRay}(depth) \approx \frac{N_{muon}(depth)}{A_{eff}(depth)\Omega(depth)\Delta t}$$

- ❑ $N_{muon}(depth)$: assign depth penetrated by muon by the arrival direction. Count muons in each depth bin.
- ❑ $\Omega(depth)$: calculate total solid angle of the az-zen bins associated with each depth bin
- ❑ Assume the flux v zenith over this range varies little compared to effect of depth attenuation
- ❑ Most of the shown muon candidates at high depths are probably junk at this point

But what is

$flux_{CosmicRay}(depth)$?

Flux, Aperture and Sensitivity

$$J(E) = \frac{dN / dE}{A\Omega(E)\Delta t}$$

$$J(E) = \frac{\Delta N(E_i) / \Delta E_i}{\langle A\Omega(E_i) \rangle \Delta t}$$

$$R(E) \equiv \frac{dN}{dt} = \int_S \vec{\mathcal{J}}(E) \cdot d\vec{S}$$

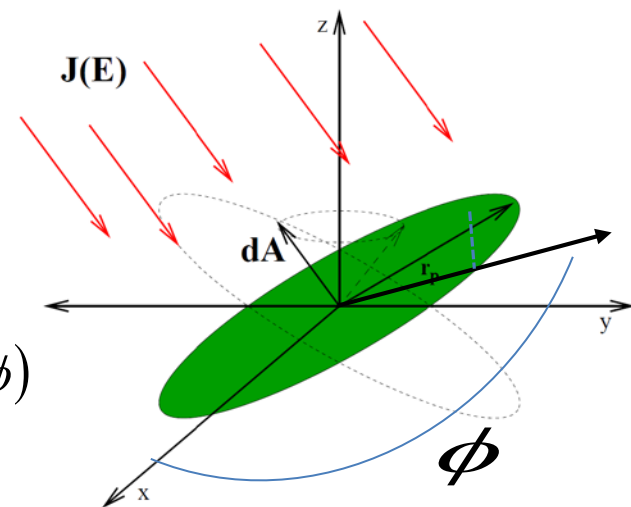
$$\mathcal{J}(E) = J(E)dE$$

$$R(E) = \mathcal{J}(E) \int dA d\Omega \eta(E, r, \theta, \phi)$$

$$R(E) = \mathcal{J}(E) \int_0^{2\pi} d\phi \int_0^{R_{P,\max}(E_i)} r dr \int_0^{2\pi} d\phi \int_0^{\pi/2} \sin \theta d\theta \eta(E, r, \theta, \phi)$$

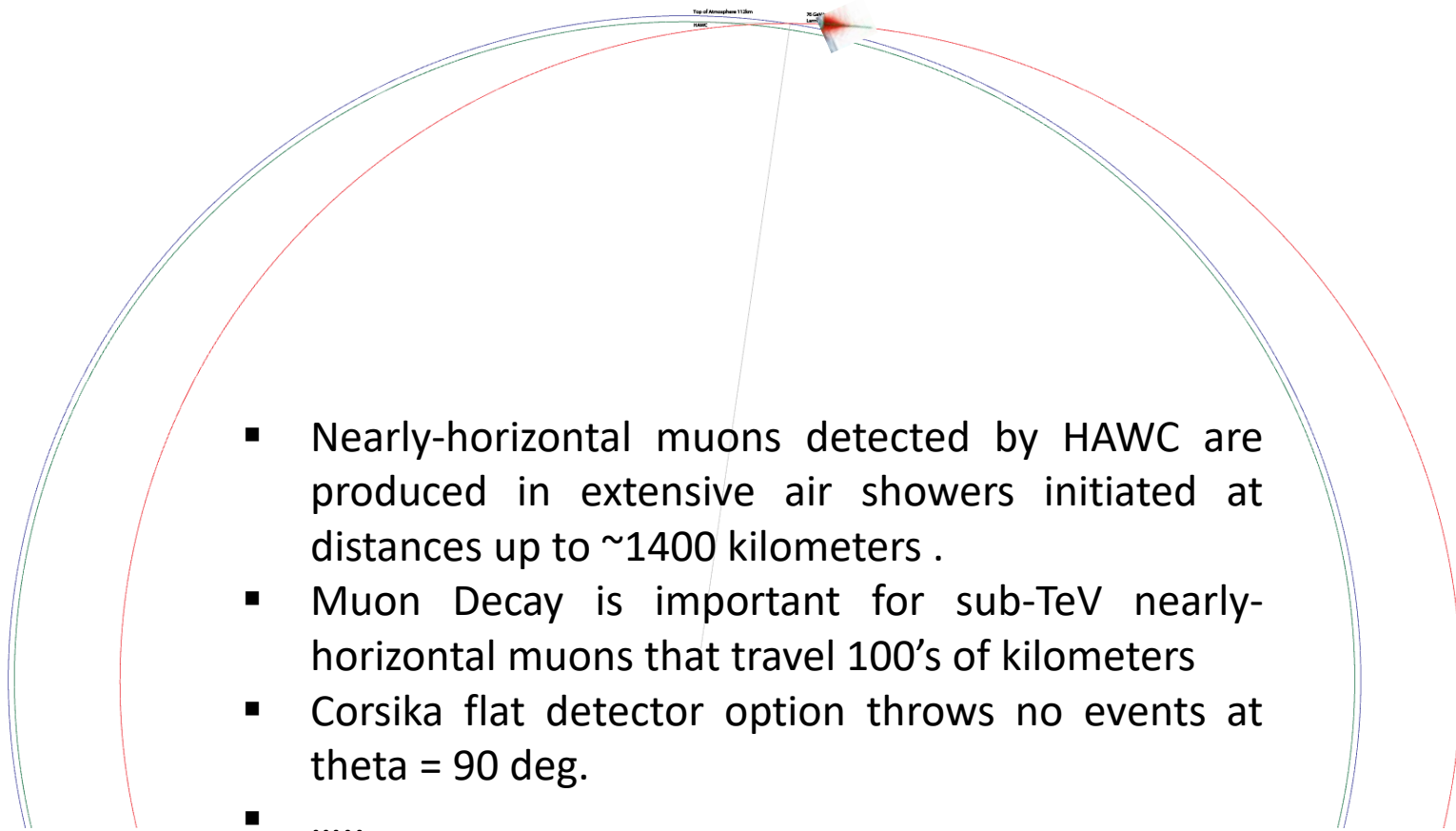
$$\eta(E, r, \theta, \phi) \equiv \frac{n_{\text{triggered}}(E, \theta, \phi)}{n_{\text{thrown}}(E, \theta, \phi)}$$

$$dA = \pi r_{\text{max}}^2$$



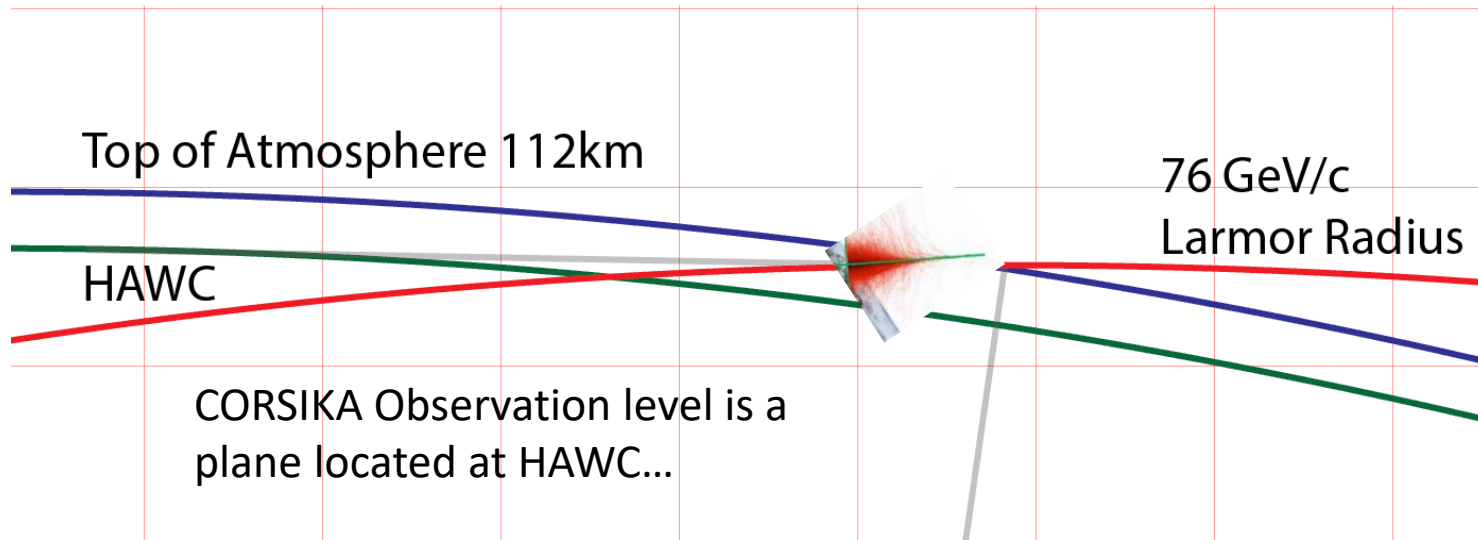
Acceptance calculation on a Spherical Earth with a thin atmosphere and B -field

Need to calculate acceptance of HAWC for detecting **cosmic ray primaries** using muons



- Nearly-horizontal muons detected by HAWC are produced in extensive air showers initiated at distances up to ~1400 kilometers .
- Muon Decay is important for sub-TeV nearly-horizontal muons that travel 100's of kilometers
- Corsika flat detector option throws no events at $\theta = 90^\circ$.
-

Magnetic Deflection – Deflected bullets..



Magnetic Field at HAWC (remember CORSIKA coordinate system aligns to B field)

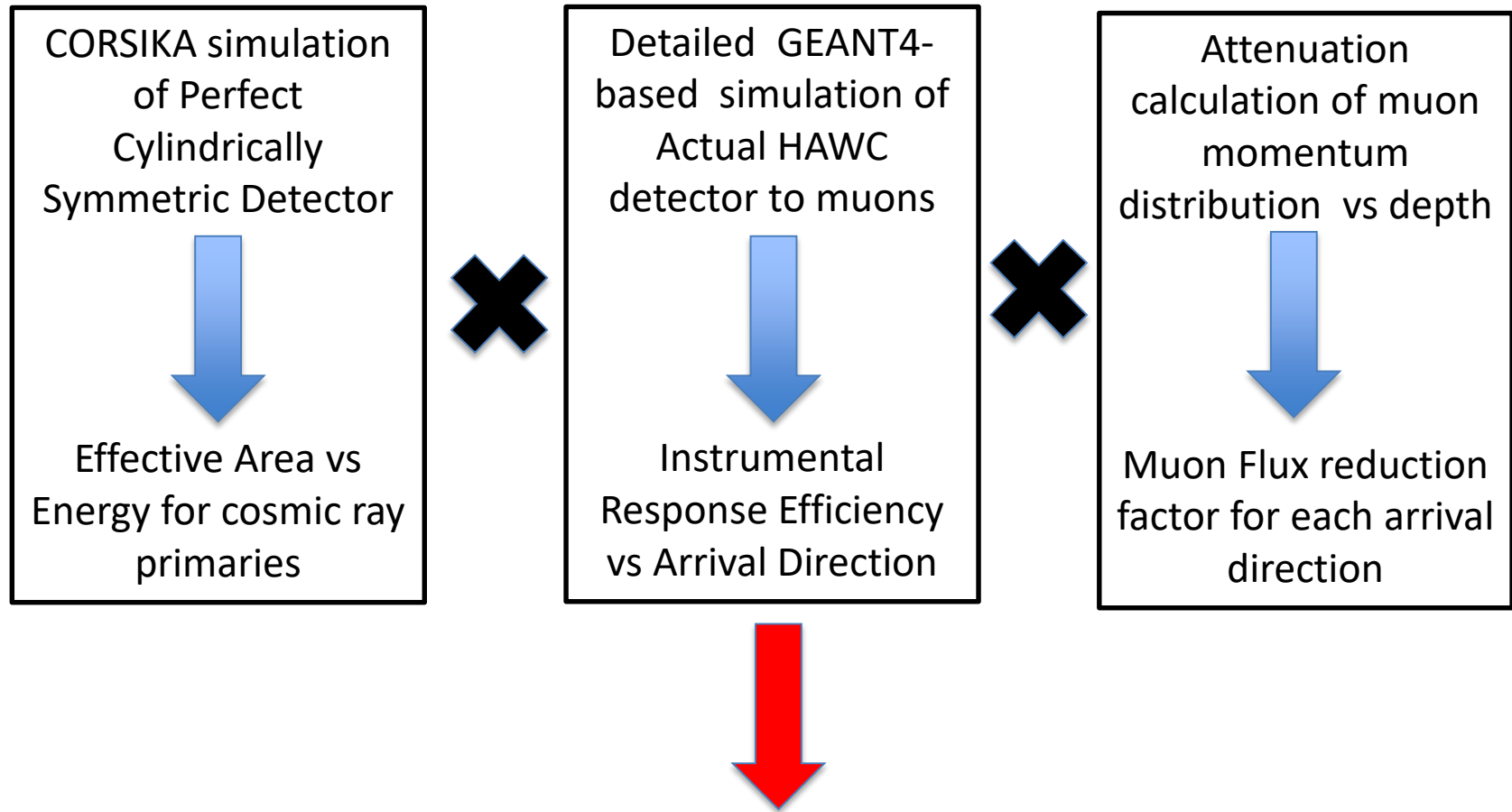
$$\vec{B}_{mag} = (27.17, 0, 29.907)$$

$$\vec{B}_{rot} = (27.17 \cdot \cos \varphi_{dec}, 27.17 \cdot \sin \varphi_{dec}, 29.907)$$

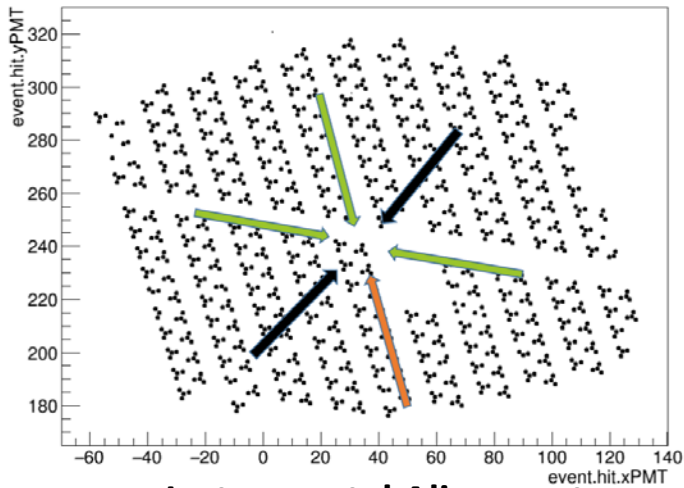
$$\varphi_{dec} = 4.08 \text{ deg}$$

$$\vec{B}_{rot} = (27.10, 1.933, 29.907)$$

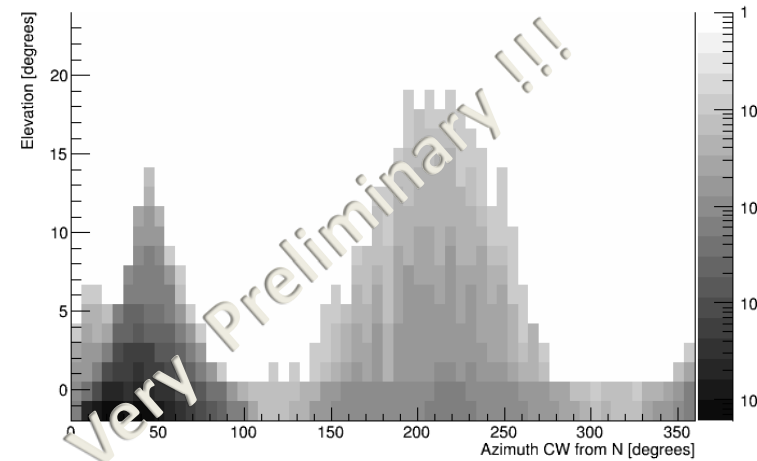
Minimal Simulation of HAWC detector response to horizontal muons



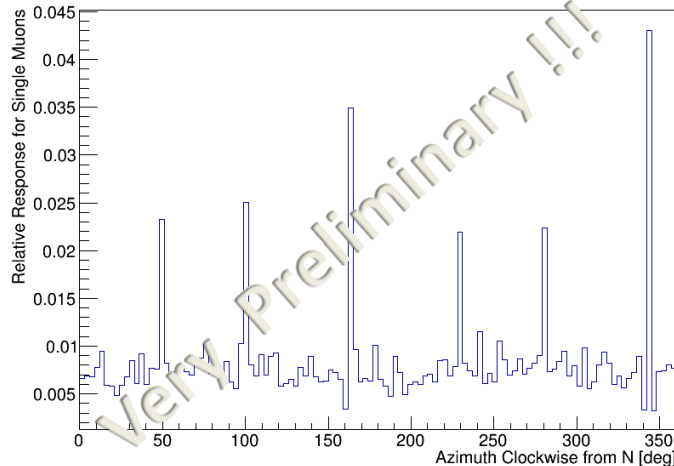
Preferred Directions due to tank alignment & overburden



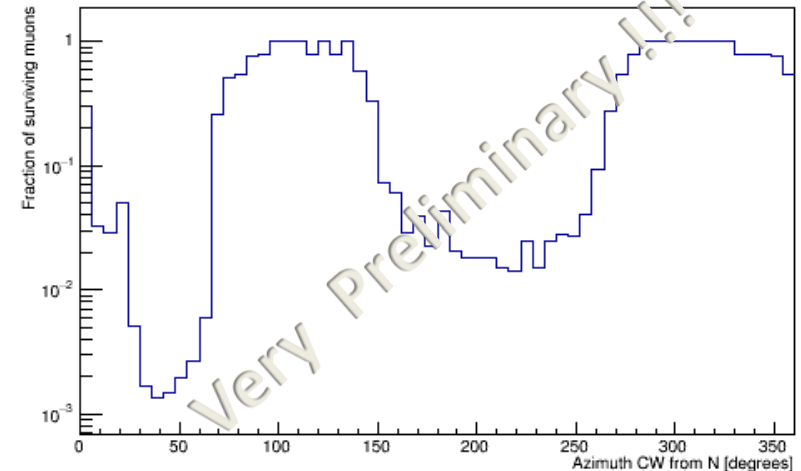
Instrumental Alignment



Overburden Flux Reduction vs arrival direction



HAWCSIM Simulated Response vs Azimuth



Calculated Flux Reduction vs Azimuth

Corsika Version & Settings

- CORSIKA simulation software package [6] generates extensive air showers (EAS) in the atmosphere.
 - CORSIKA “tree-level” observable distributions in conjunction with geometrical considerations guides detailed simulation studies.
 - CORSIKA Data files containing trajectories and momenta of shower particles further processed by either a perfect cylindrical “toy model” or detailed GEANT4-based [7] detector model simulation.
 - The “toy model” performs faster simulations to develop an understanding of the general behavior and response of a perfect detector.
 - Detailed detector simulation using injected single muons determines basic instrumental response.
- ☐ Corsika version 7.5
 - ☐ 64 bit
 - ☐ QGS JET II
 - ☐ Gheisha (not fluka)
 - ☐ Non-Flat Volume detector Geometry
 - ➔ thrown as $I = A \cdot \sin\theta$ not $I = A \sin\theta \cos\theta$
 - ☐ Curved, Upward
 - ☐ Primary particle energy range from 100 GeV to several PeV.

Extensive Air Shower (EAS) simulation with CORSIKA

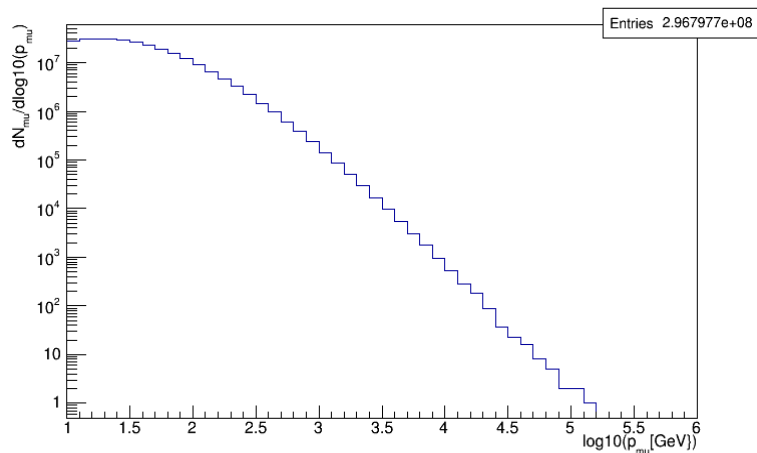


Figure 4: Muon Momentum Spectrum for a sample of 1 billion CORSIKA generated cosmic ray primaries generated in the energy range 100 GeV to 10PeV with a energy spectral index=-2.7. muons.

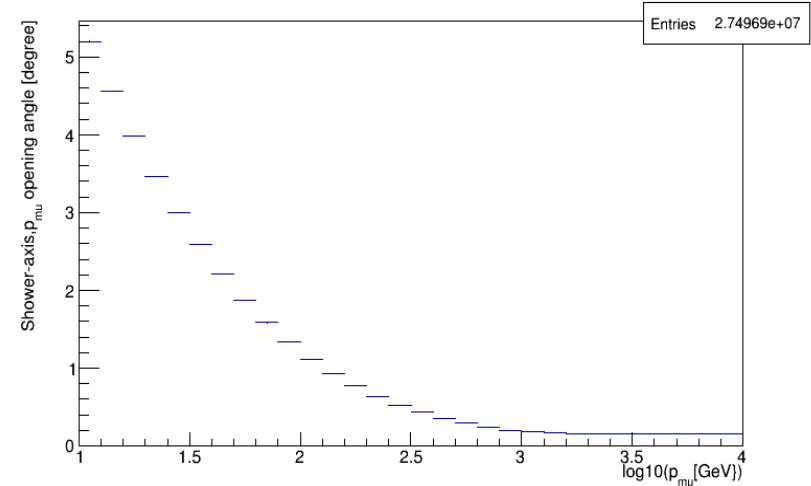
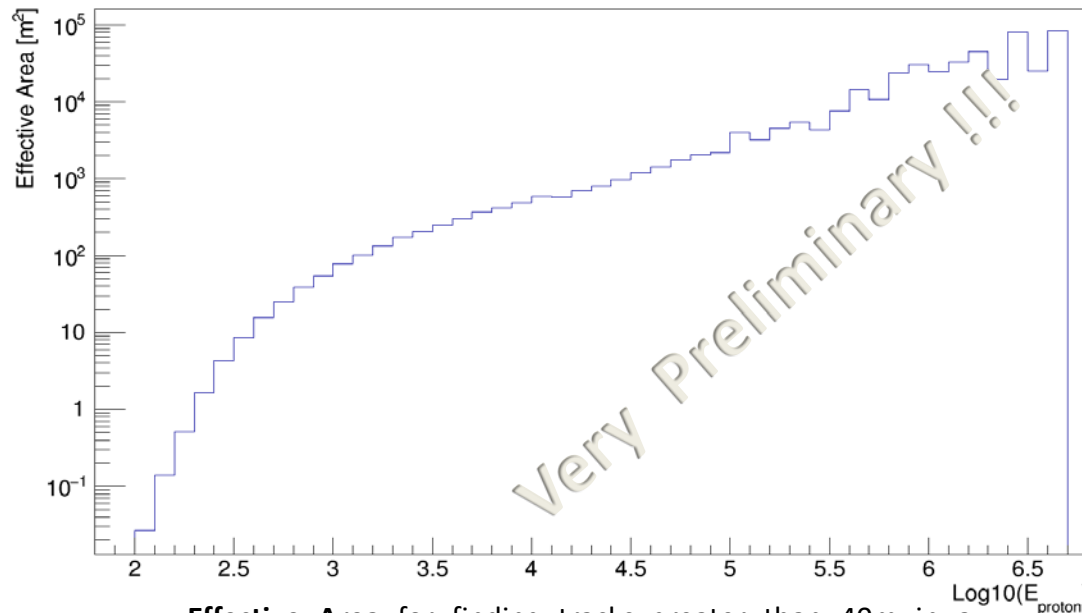


Figure 5: Average Muon Opening Angle w.r.t shower-axis for the same sample of CORSIKA generated cosmic ray primaries.

- Muon multiplicity increases with primary particle energy. Muon energy spectrum is harder than primary.
- Muon opening angle w.r.t shower direction decreases with energy. Constrains required $R_{p,max}$.

CORSIKA-based Perfect “Minimal Model” Detector Simulation

- ❑ CORSIKA showers are “thrown” 100 times at different radius R_p and angle ϕ on circle perpendicular to shower axis.
- ❑ Cylindrical detector has surface area and height of HAWC.
- ❑ Muon identification performed by requiring length of trajectory intersecting the cylinder be $> 40\text{m}$.



Effective Area for finding tracks greater than 40m in a perfect cylindrically symmetric detector as a function of cosmic ray primary proton energy for $R_{p,\text{max}}=2\text{km}$.

Summary/Outlook

- ❑ Calculate effective area as a function of arrival direction for the detection of cosmic ray primaries that produce nearly horizontal muons.
 - ❖ Working on full simulation of instrumental response and volcano overburden (GEANT4)
 - ❖ Extending calculation beyond zenith=90

- ❑ Measure the energy spectrum of cosmic rays using observed muon rates as a function of arrival direction by exploiting the direction dependent energy threshold.
 - ❖ Possibly sensitive to muon production mechanisms

- ❑ Improve identification and reconstruction of muon bundles.
 - ❖ Measure the cosmic ray primary composition as well as energy spectrum.

- ❑ Develop an online Nearly-Horizontal Muon Trigger
 - ❖ independent of the EAS trigger.
 - ❖ Shorter Tracks
 - ❖ Better Near Horizontal Muon detection Efficiency
 - ❖ Multiple Muon Identification algorithm

References

- [1] O. Kambeitz for the Pierre Auger Coll., EPJ Web of Conf. submitted, arXiv:1609.05456 (2016).
- [2] “Measurement of Muon Spectrum by Mutron”, Kitamura, T., et. al., 08/1975, 1975ICRC....6.2031K
- [3] M. Sioli, arXiv:hep-ex/0002051v1
- [4] “NEVOD-DECOR experiment: results and future”, O. Saavedra, et. al., 2013 J. Phys.: Conf. Ser. 409 012009
- [5] “Muon tomography applied to active volcanoes”, Jacques Marteau, et. al. 2015, arXiv:1510.05292v1
[physics.ins-det]
- [6] “Neutrino Telescope Array (NTA) - Towards Survey of Astronomical ?? Sources”, George W. S. Hou, arXiv:1409.0477v1 [astro-ph.IM]
- [7] “Capability of the HAWC gamma-ray observatory for the indirect detection of ultra-high energy neutrinos”, H. Vargas, et. al., arXiv:1610.04820v2 [astro-ph.IM]
- [8] “Simulation of Near Horizontal Muons and Muon Bundles for the HAWC Observatory with CORSIKA”, R. Wayne Springer, et. al., ICRC2017
- [9] Instituto Nacional de Estadística y Geografía (INEGI) Continuo de elevaciones mexicano 3.0 (cem 3.0), 2012. URL <http://www.inegi.org.mx/geo/contenidos/datosrelieve/continental/continuoelevaciones.aspx>.
- [10] Shape Detection in Computer Vision Using the Hough Transform, V.F. Leavers, 1992, DOI 10.1007/978-1-4471-1940-17