Reconstruction of Nearly Horizontal Muons in the HAWC Observatory

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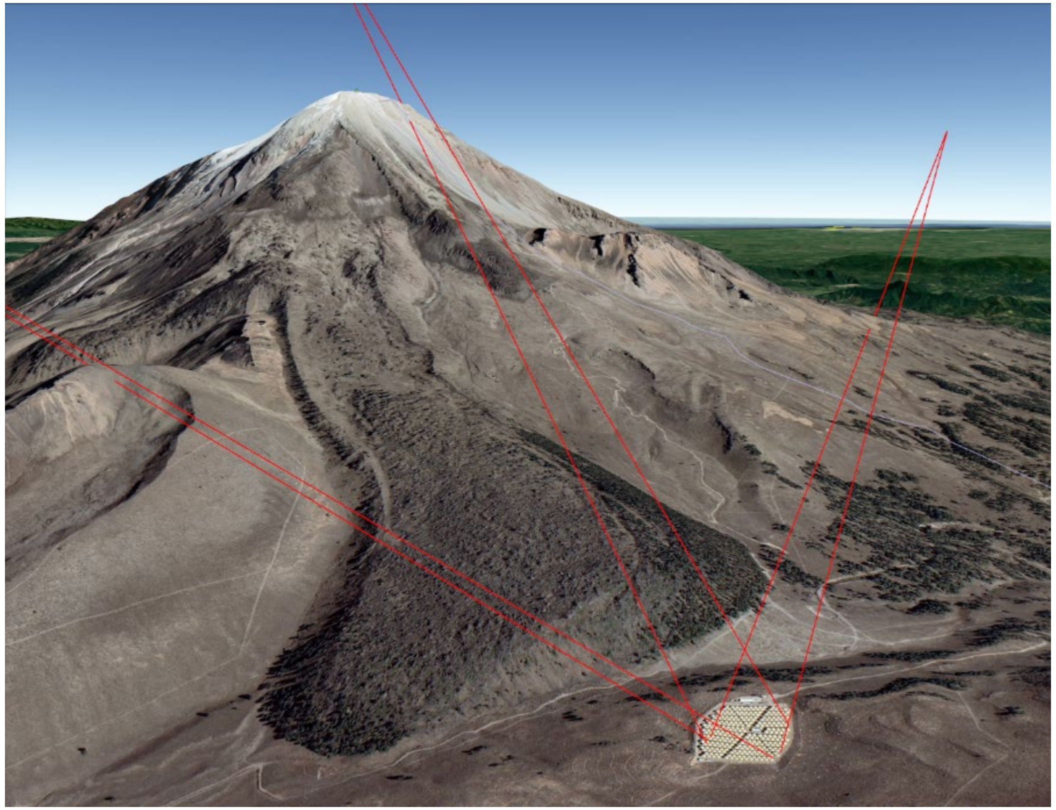
- Introduction
  - HAWC Observatory
  - Muon Intensity vs Depth
- Muon Identification & Trajectory Reconstruction
  - Hough 3D identification
  - Least Squares trajectory estimation
  - Semi-analytic simulation estimation
- Estimation of resolution and acceptance
- Exposure vs Depth Estimation
- Summary/Outlook



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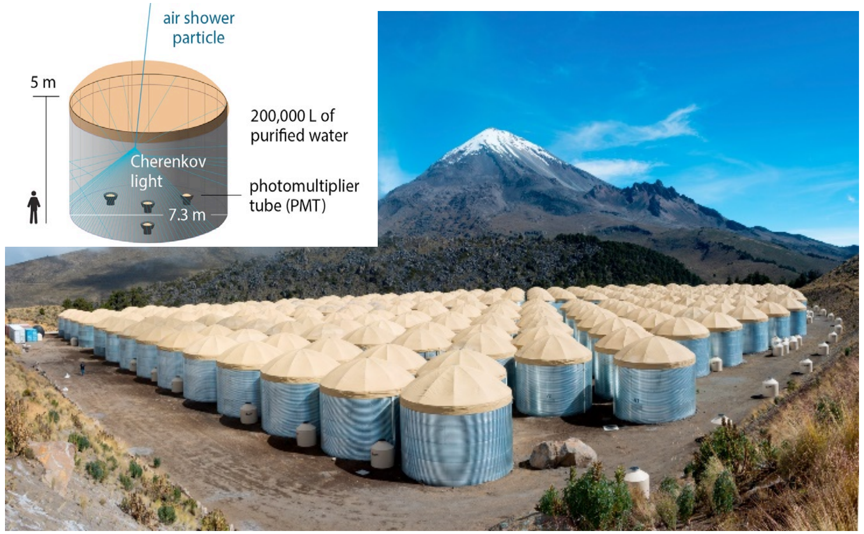
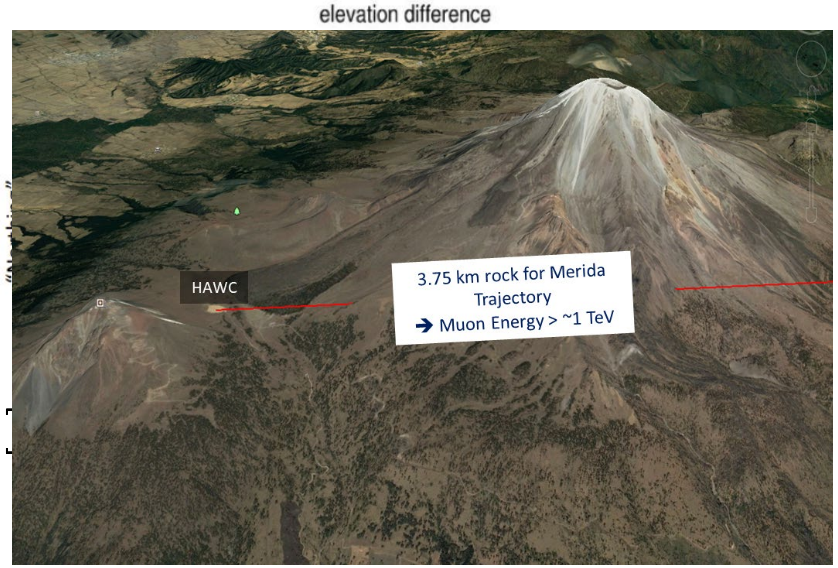
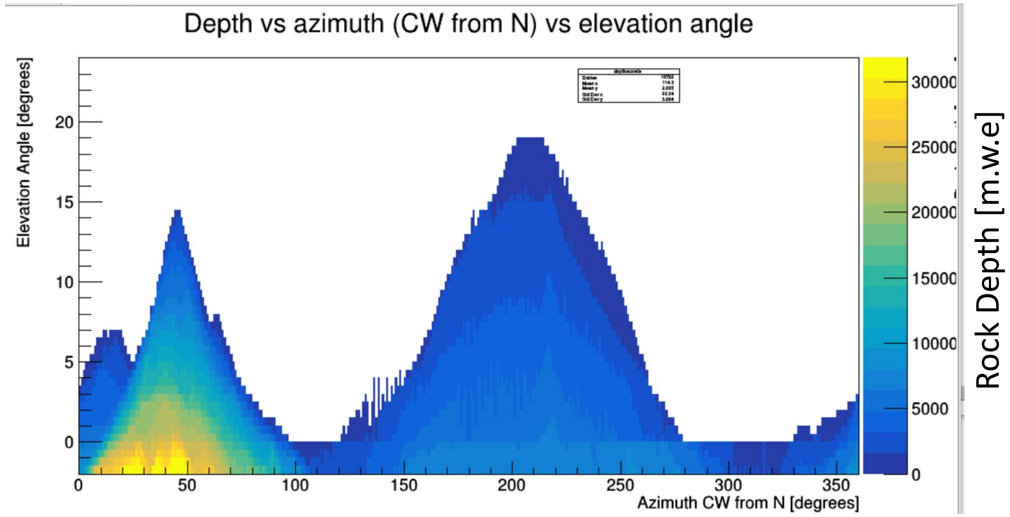
Online

HAWC Detector and Site



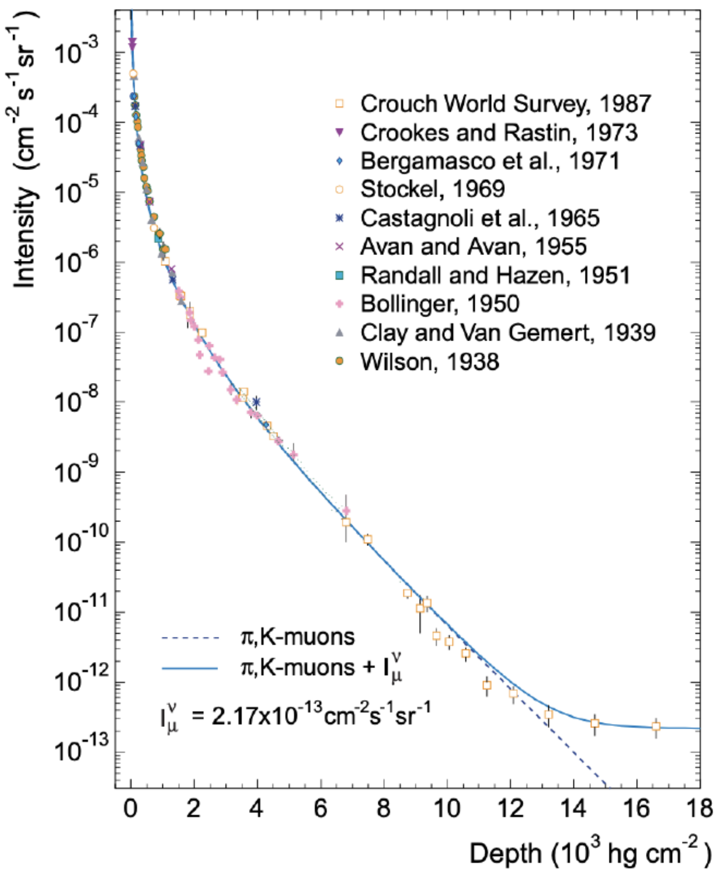




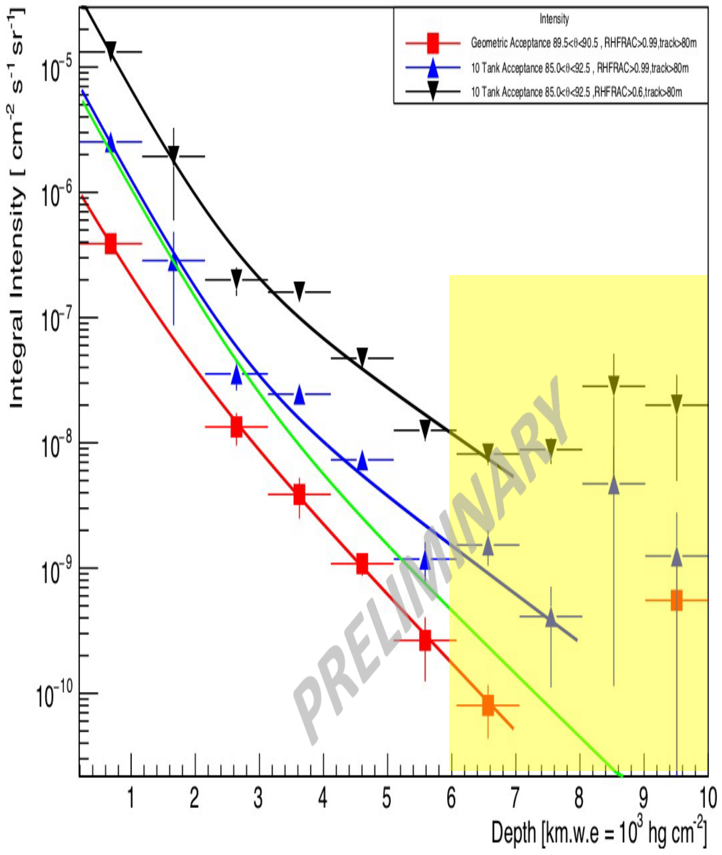
- **The HAWC detector**
  - 300 - 4.5 m high, 7.3 m diameter tanks covers a footprint of 22,000 m2.
  - Each tank contains 200,000 liters of purified water and is instrumented with 4 upward looking photomultiplier tubes (PMTs) .
- **The HAWC site**
  - Located at an altitude of 4100m a.s.l. adjacent 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.

Muon Integral Intensity vs Depth

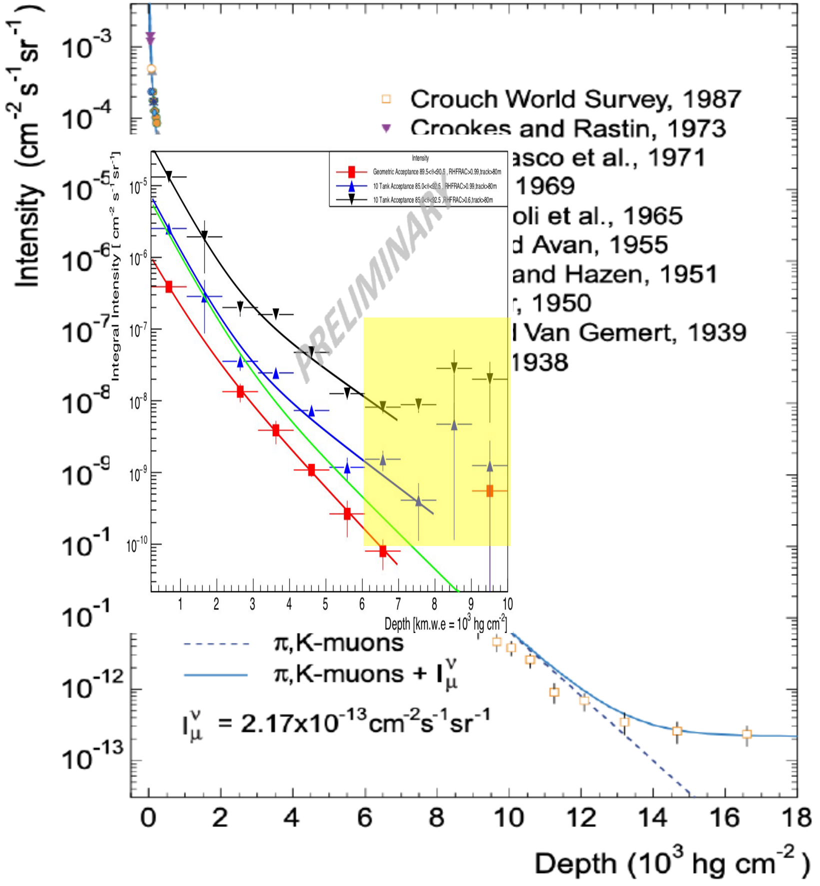
[7] E. V. Bugaev et al., Physical Review D **58** (1998).



Compilation of Deep-Underground Measurements



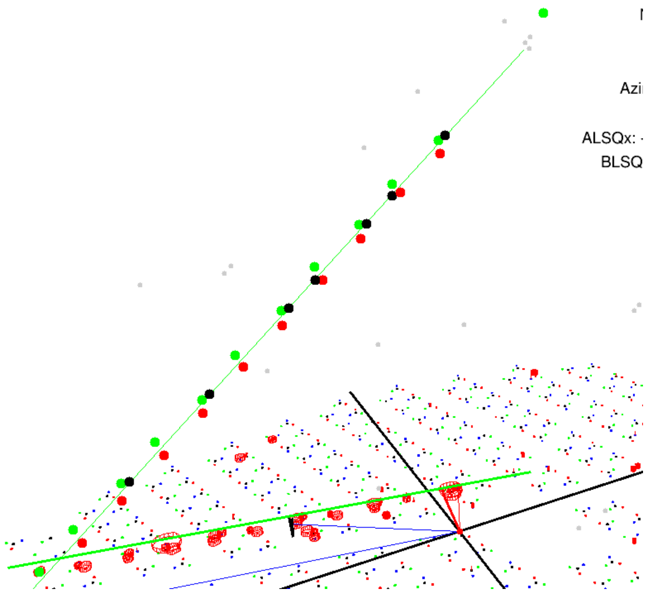
Preliminary HAWC Muon Intensity vs Depth



Overlay Showing need to reduce backgrounds to extend to higher depths

1 m^2 sr detector would take about 15 years to expect 1 neutrino-induced muon

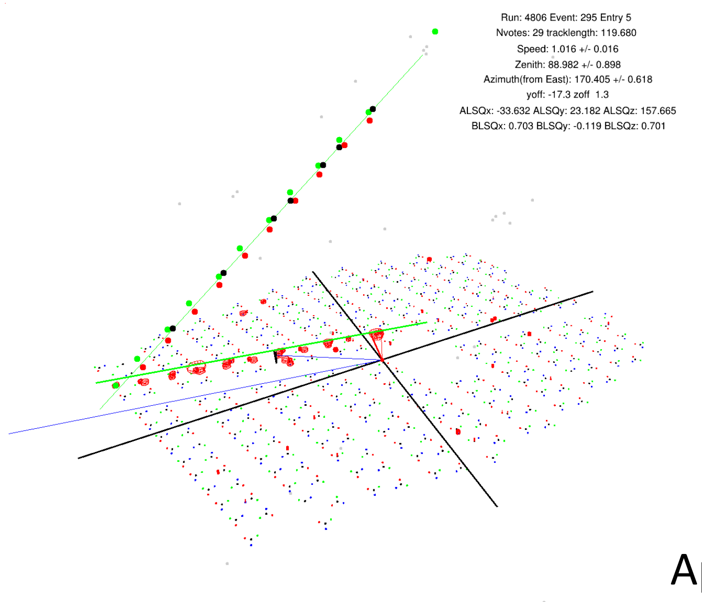
Muon Trajectory Reconstruction using linear least squares technique



The Hough code provides a parameter u that plays the role of independent variable x…It is actually all quite “elementary”!

- Hough Transform identifies PMT hits $x_i, y_i, z_i = ct_i$ that are consistent with a line in space-time consistent with a particle moving nearly horizontally at the speed of light.
- The code from Dalitz et al. provides direction and offset vectors. Any point along the “Hough line” may be expressed in terms of an independent parameter u.
- The PMT hits and the values of the parameter u determined from t are used in a linear least squares minimization procedure to obtain the arrival directions θ,ϕ as well as lateral and vertical offsets x_{off} and y_{off}

Muon Trajectory Reconstruction using linear least squares technique



Offset

$$A = \frac{\sum x_i^2 \sum y_i - \sum x_i \sum x_i y_i}{\Delta}$$

$$\sigma_A = \sigma_y \sqrt{\frac{\sum x_i^2}{\Delta}}$$

Slope

$$B = \frac{N \sum x_i y_i - \sum x_i \sum y_i}{\Delta}$$

$$\sigma_B = \sigma_y \sqrt{\frac{N}{\Delta}}$$

$$\Delta = N \sum x_i^2 - \left(\sum x_i\right)^2$$

$$\sigma_y = \sqrt{\frac{1}{N-2} \sum_{i=1}^{N} \left(y_i - A - Bx_i^2\right)}$$

Azimuth

$$\phi = \tan^{-1}\left(\frac{B_y}{B_x}\right) + \pi$$

Azimuth Uncertainty

$$\sigma_\phi^2 = \sigma_{B_y}^2 \left(\frac{\partial \phi}{\partial B_y}\right)^2 + \sigma_{B_x}^2 \left(\frac{\partial \phi}{\partial B_x}\right)^2 = \sigma_{B_y}^2 \left(\frac{1}{1+\left(\frac{B_y}{B_x}\right)^2} \frac{1}{B_x}\right)^2 + \sigma_{B_x}^2 \left(\frac{1}{1+\left(\frac{B_y}{B_x}\right)^2} \frac{B_y}{B_x^2}\right)^2$$

Apparent speed

$$v_{app} = \sqrt{\frac{B_x^2 + B_y^2}{B_z^2}}$$

Speed Uncertainty

$$\sigma_{v_{app}} = \sqrt{\left(\frac{1}{v_{app}} \frac{B_x}{B_z^2}\right)^2 \sigma_{B_x}^2 + \left(\frac{1}{v_{app}} \frac{B_y}{B_z^2}\right)^2 \sigma_{B_y}^2 + \left(\frac{1}{v_{app}} \frac{\left(B_x^2 + B_y^2\right)}{B_z^3}\right)^2 \sigma_{B_z}^2}$$

The Hough code provides a parameter u that plays the role of independent variable x…It is actually all quite “elementary”!

$$B_x = \frac{N \sum u_i x_i - \sum u_i \sum x_i}{\Delta} \qquad \Delta = N \sum u_i^2 - \left(\sum u_i\right)^2$$

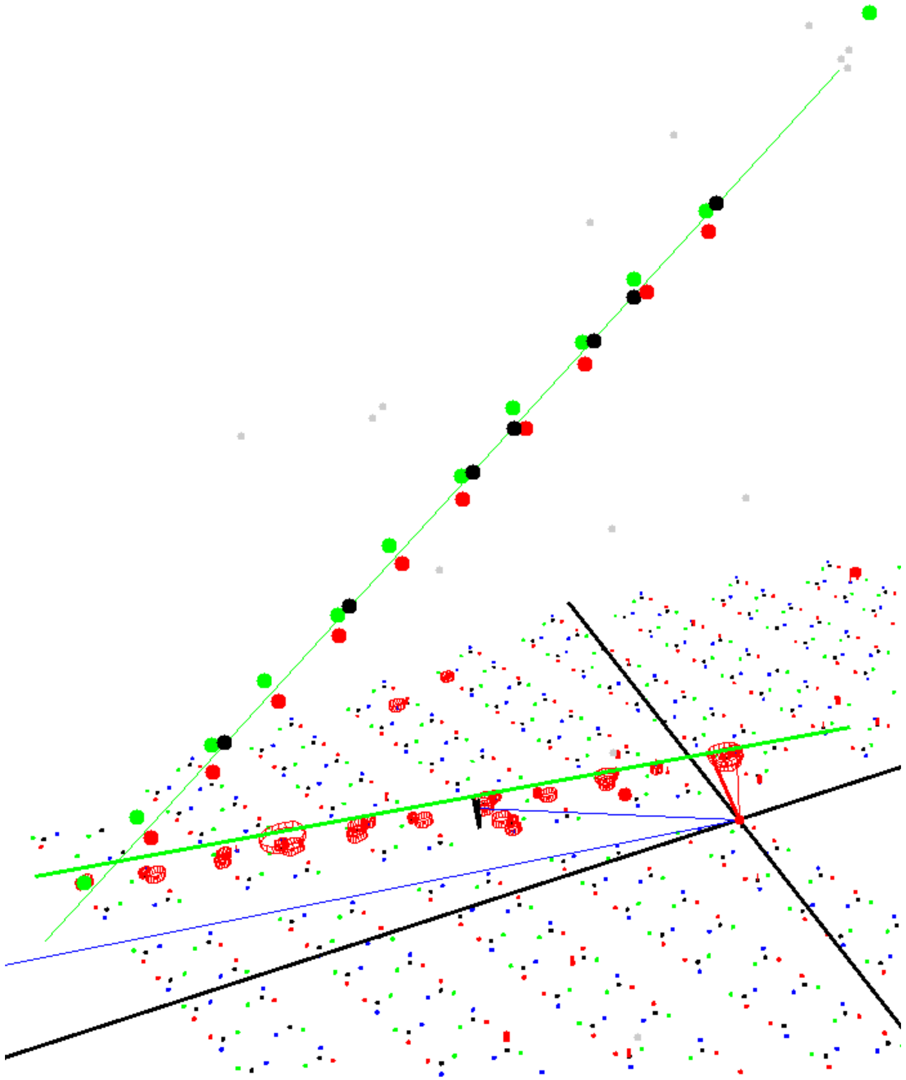
Zenith

$$\theta \approx \frac{\pi}{2} - \sin^{-1}(v_{app}/c - 1)$$

Zenith Uncertainty

$$\sigma_\theta \approx \left(\frac{1}{\sqrt{1 - \left(\frac{v_{app}}{c} - 1\right)^2}}\right) \sigma_{v_{app}}$$

Muon Trajectory Reconstruction using linear least squares technique



Run: 4806 Event: 295 Entry 5

Nvotes: 29 tracklength: 119.680

Speed: 1.016 +/- 0.016 ← $\sigma_{v_{app}}$

Zenith: 88.982 +/- 0.898 ← σ_{θ}

Azimuth(from East): 170.405 +/- 0.618 ← σ_{ϕ}

yoff: -17.3 zoff 1.3

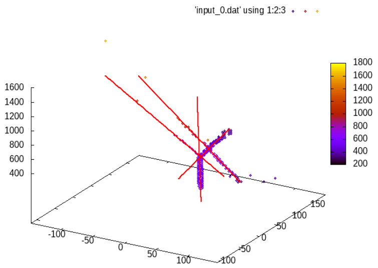
ALSQx: -33.632 ALSQy: 23.182 ALSQz: 157.665

BLSQx: 0.703 BLSQy: -0.119 BLSQz: 0.701

Uncertainties in zenith and azimuth calculate directly from data.

Muon Identification – Isolation to reduce EAS background

- **Isolation** - "hits" consistent with isolated straight track to suppress background from Extensive air showers



- **3D Hough Transforms** – Find muon track as isolated line. Look for a line of hits normal to muon track to identify EAS!

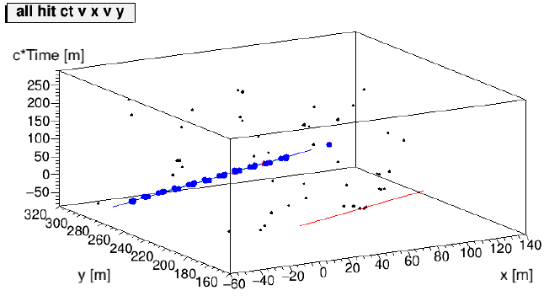


Figure 3.5: Event point cloud with a single muon (blue points)

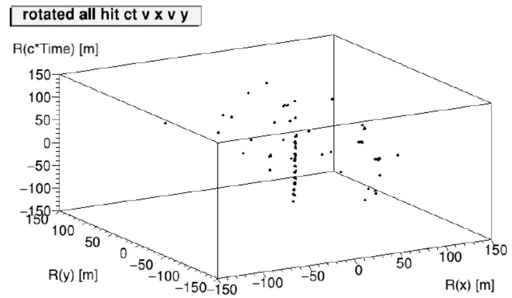


Figure 3.7: Single Muon in rotated coordinate point cloud, points associated with the muon are localized to the vertical line.

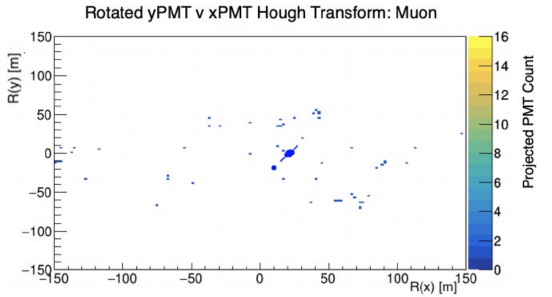


Figure 3.9: Projected 3D Hough Transform Muon confirms the highly localized line (figure 3.9 for the points associated with the muon.

RHFRAC =fraction of hits contained In muon cylinder

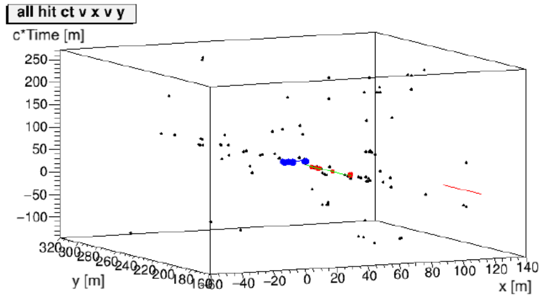


Figure 3.6: Event point cloud containing an EAS event plane.

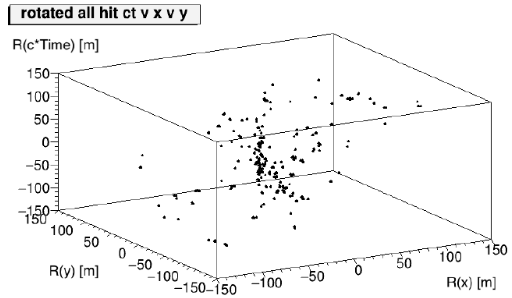


Figure 3.8: EAS in rotated Coordinate point cloud, the hough line found for the rotaiton illustrate no concise vertical.

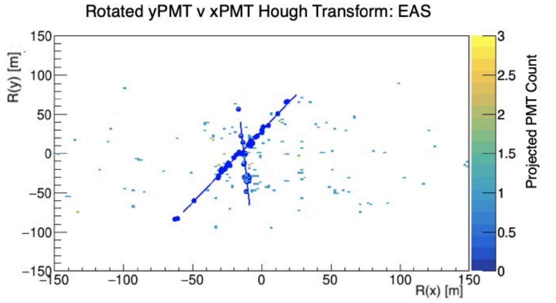
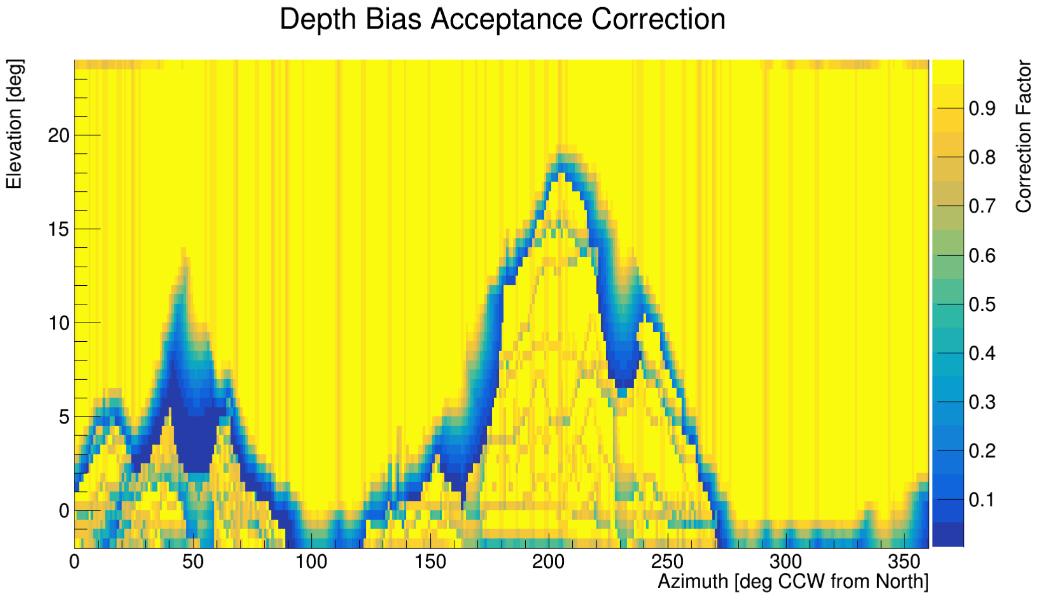


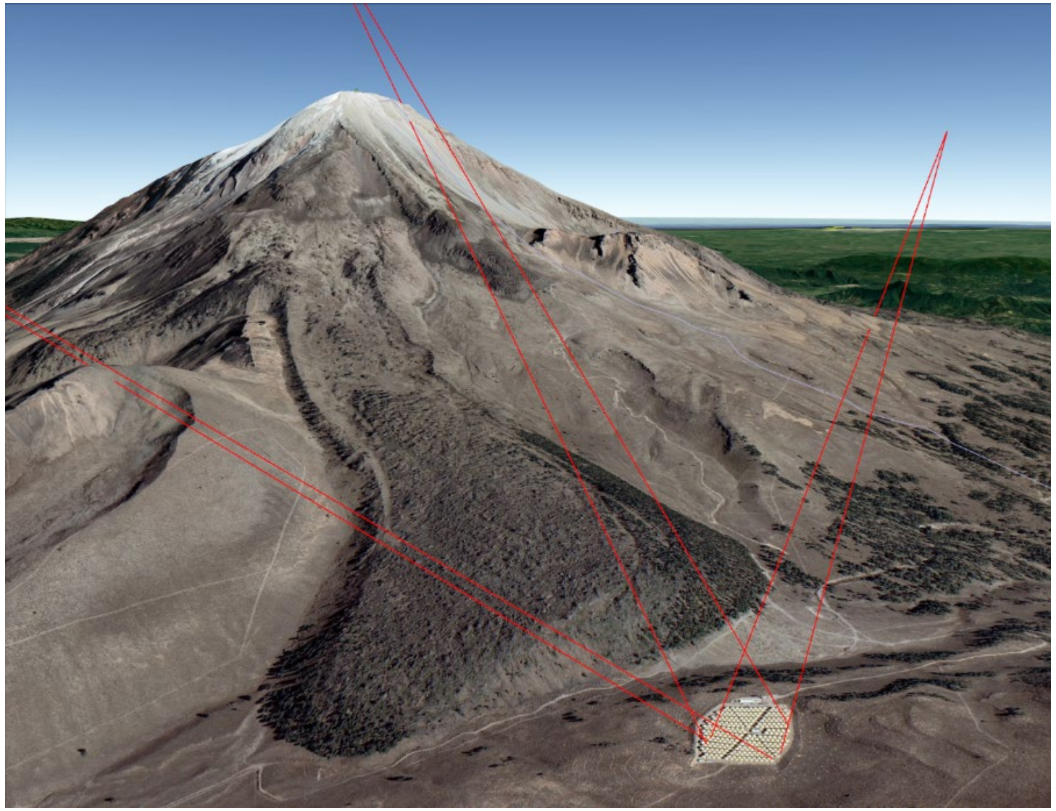
Figure 3.10: Projected 3D Hough Transform for EAS plane, an initial line is found in the plane and when rotated to it it then allows for the plane to be found in a second line.

Eliminate EAS

Muon Trajectory Reconstruction

- **Trajectory**
  - Arrival Direction – Azimuth, Zenith
  - Offset – Lateral, Vertical
- **Depth Correction**
  - Same arrival direction can intersect mountain when viewed from different offset position
  - Poor trajectory resolution ➔ wrong depth

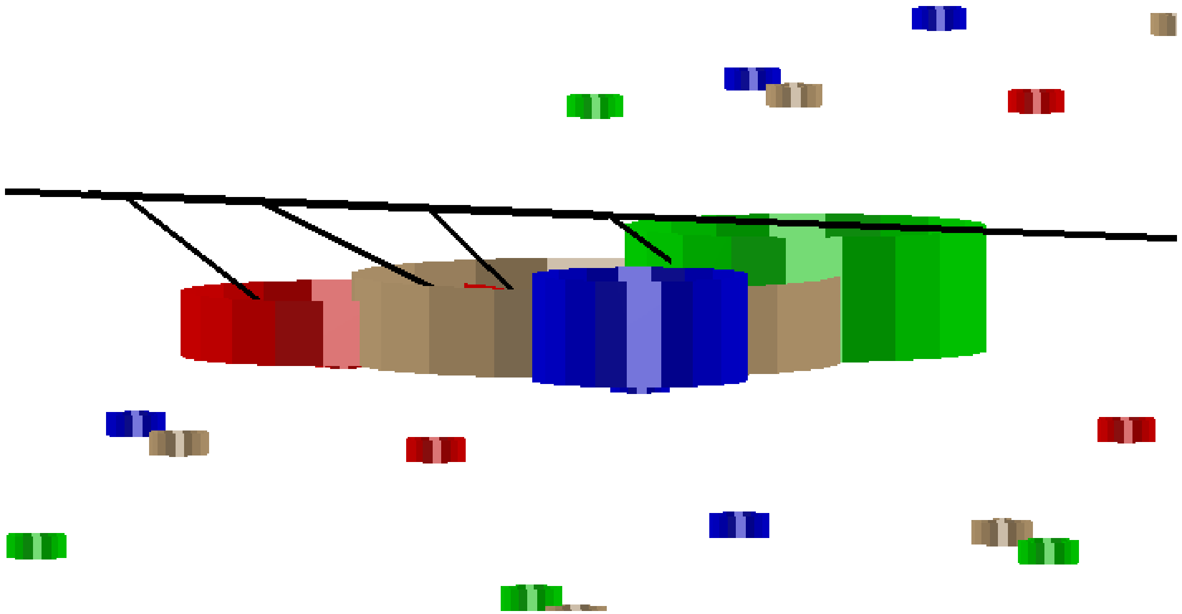




Muon trajectories with differing offsets for three arrival directions.

Analytic Simulation of Near-Horizontal Muon Response for reconstruction of trajectories.

- Find point on muon track where path to center of PMT is at the Cherenkov emission angle.
- Calculate time from point of muon entry in tank to Cherenkov photon arriving at center of each PMT that is directly illuminated (muon speed =c , light speed =2/3 c).
- Estimate charge by fraction of Cherenkov ring intercepted by PMT and attenuate photons with extinction length of 10.0m.
- Use inverse simulation to find muon trajectory that best matches PMT hit times and charges.



Chi-squared measure of "goodness" of trial trajectory timing

$$\chi^2_{\text{timing,trial}} = \sum_{i=1}^{N_{PMT}} \frac{\left(t_{i,\text{nominal}} - t_{i,trial}\right)^2}{\sigma^2_{i,\text{timing}}}$$

$t_{i,\text{nominal}}$: calculated time of i'th PMT hit for nominal trajectory az_nom, zen_nom, y_nom, z_nom

$\sigma^2_{i,\text{timing}}$: smearing of nominal time measurement (assumed 1ns PMT jitter for this talk)

$t_{i,\text{trial}}$: calculated time of i'th PMT hit for nominal trajectory az_nom+daz, zen_nom+dzen, y_nom+dy, z_nom+dz

trial trajectories span 4-dimensional grid centered on nominal trajectory

number of trials = n_az*n_zen*n_yoff*n_zoff=9*9*9*9 = 6561 trial points

az_range=-1^0,1^0

zen_range=-1^0,1^0

yoff_range=-1m,1m

zoff_range=-1m,1m

χ^2 mapped on this space to find where $\Delta\chi^2 = 1$ to determine resolution

$$\chi^2_{\text{charge,trial}} = \sum_{i=1}^{N_{PMT}} \frac{\left(npe_{i,\text{nominal}} - npe_{i,trial}\right)^2}{\sigma^2_{q,i,\text{nominal}}}$$

$t_{i,\text{nominal}}$: calculated time of i'th PMT hit for nominal trajectory az_nom, zen_nom, y_nom, z_nom

$\sigma^2_{q,i,\text{nominal}} = npe_{i,\text{nominal}}$

$t_{i,\text{trial}}$: calculated time of i'th PMT hit for nominal trajectory az_nom+daz, zen_nom+dzen, y_nom+dy, z_nom+dz

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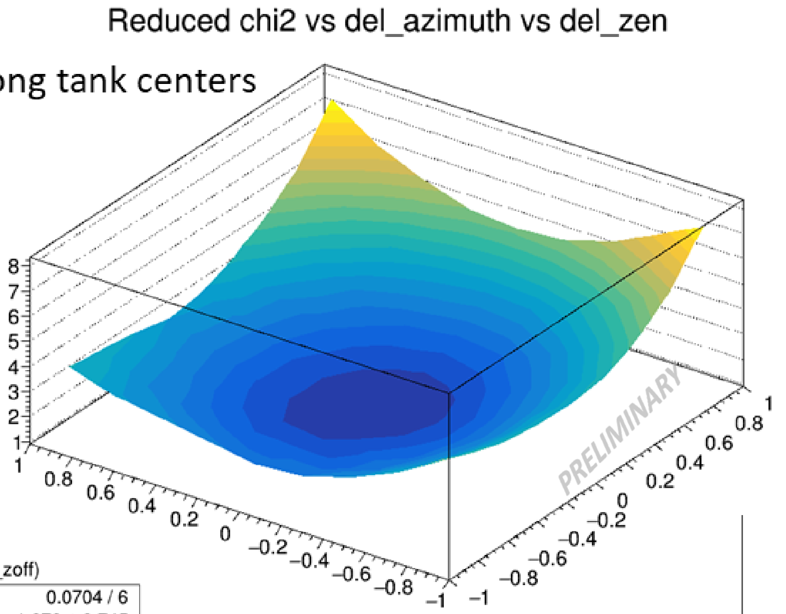
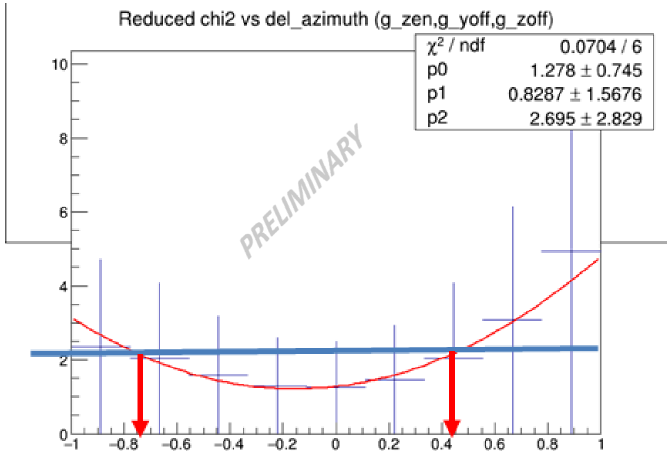
χ^2 mapped on this space to find where $\Delta\chi^2 = 1$ to determine resolution

Estimating Resolution of Trajectory Reconstruction from timing & charge

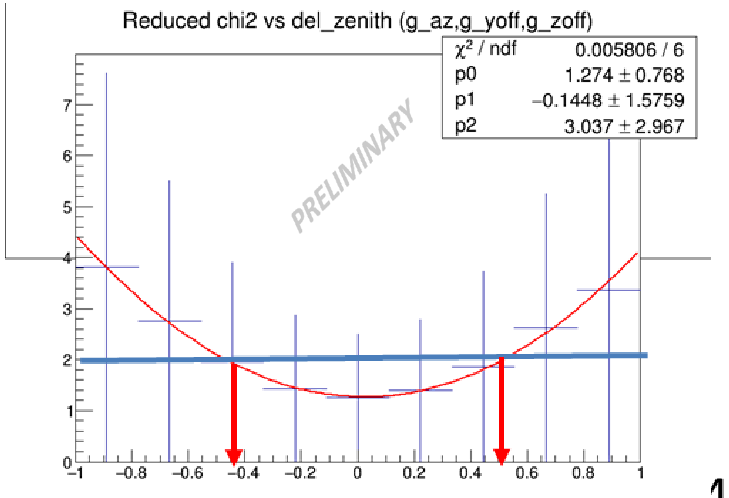
Nominal Trajectory nearly along tank centers



$\Delta\chi^2 = 1 \Rightarrow \sigma_\phi = (-0.7^0, 0.45^0)$



$\Delta\chi^2 = 1 \Rightarrow \sigma_\theta = (-0.45^0, 0.5^0)$



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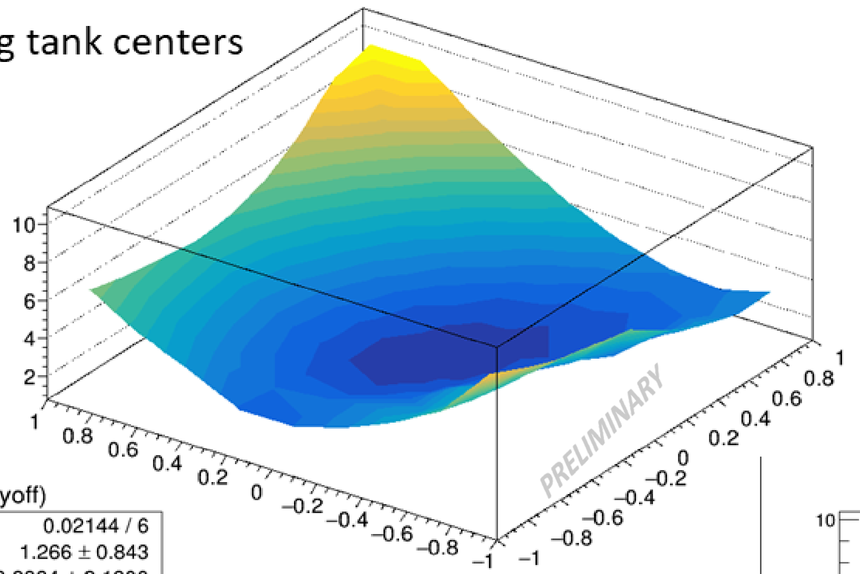
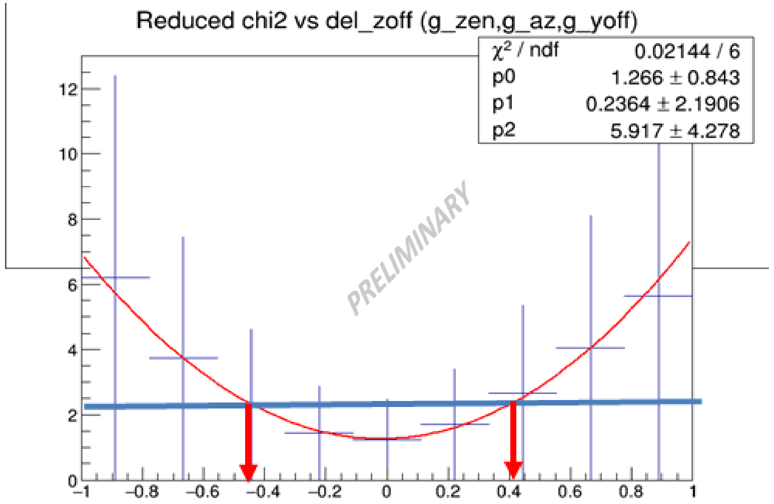
Estimating Resolution of Trajectory Reconstruction from timing

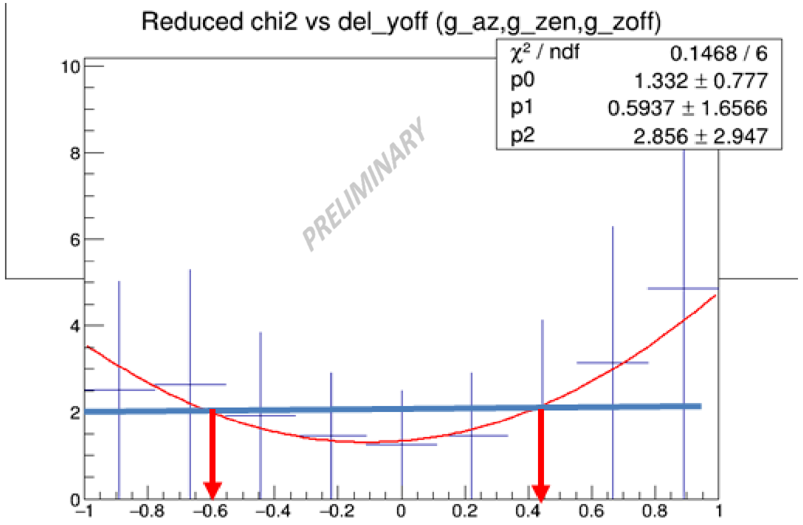
Nominal Trajectory nearly along tank centers



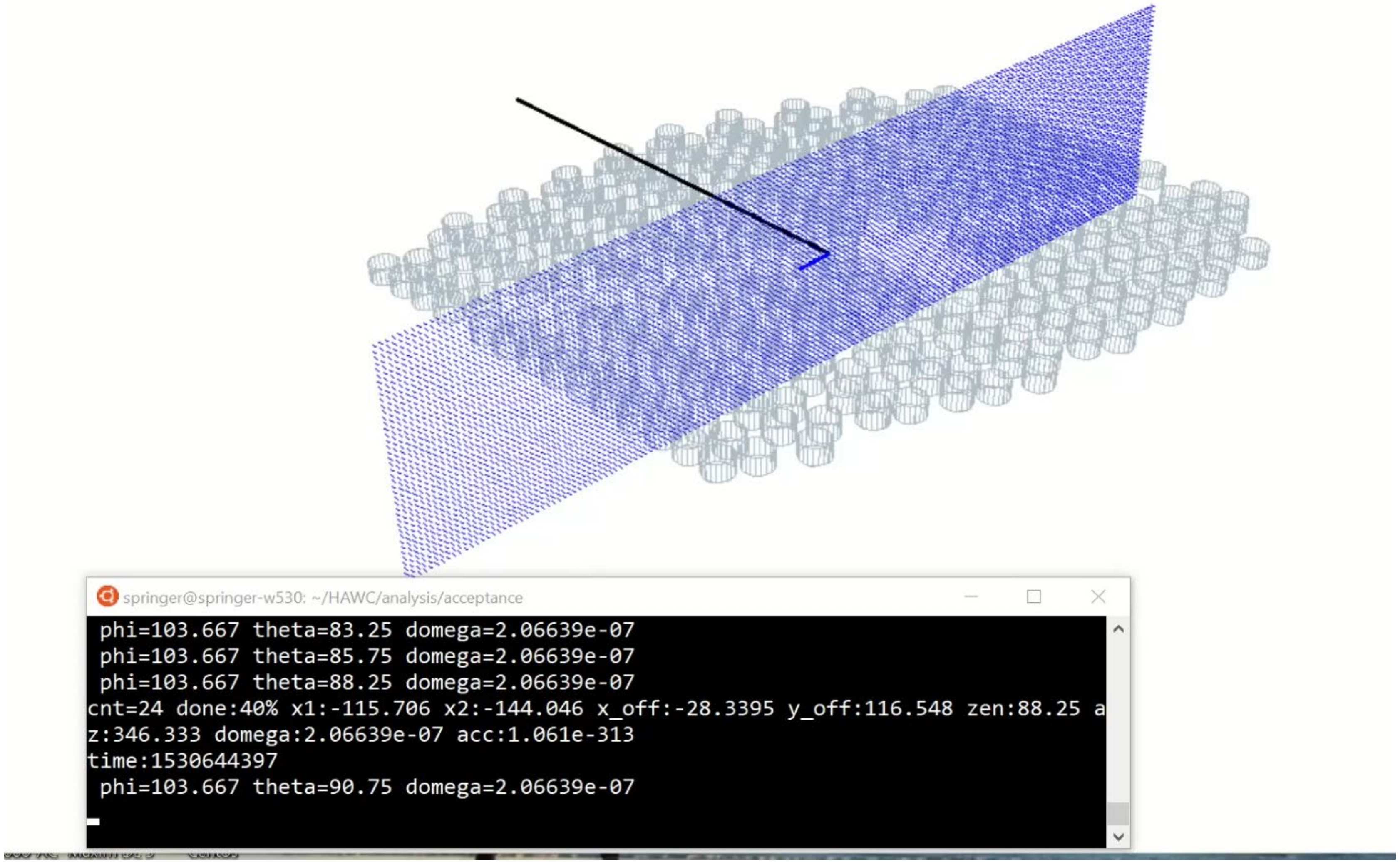
$\Delta\chi^2 = 1 \Rightarrow \sigma_z = (-0.45m, 0.4m)$



$\Delta\chi^2 = 1 \Rightarrow \sigma_y = (-0.6m, 0.45m)$



Effective Area for given trajectory tl6.5 ntank 10



Summary

- Techniques to identify, reconstruct and simulate muons with nearly horizontal trajectories in the HAWC observatory have been developed.
- Goal is to extend to greater depths the measurement of the muon integral intensity as a function of material depth using the volcanoes surrounding HAWC.
- Modified existing Hough transform software to calculate uncertainties on reconstruction parameters on an event-by-event basis directly from data, simulated or actual.
- Developed and started validating a semi-analytic simulation of the PMT response to nearly horizontal muons that will be used to calculate detector resolution and acceptance.
- The semi-analytic simulation has been incorporated in an inverse Monte Carlo method to perform trajectory reconstruction with improved resolution.
- After optimizing selection criteria, to suppress the considerable background, we will analyze the HAWC observatory data that provides several years of exposure potentially sensitive to intensities associated with neutrino-induced muons.

- Caveat – may encounter other backgrounds such as scattered muons