Detection of Nearly-Horizontal Muons with the HAWC Observatory

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Detection of Nearly-Horizontal Muons with the HAWC Observatory

3.75 km rock for Merida Trajectory
→ Muon Energy > ~1 TeV
### 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 4100 m a.s.l. adjacent to two volcanoes, Pico de Orizaba (5636 m) and Sierra Negra (4580 m).
- Overburden depth varying from 0 to 32000 m.w.e → muon energy threshold varying from 0 to 520 TeV.
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 = cΔt.

**Hough Transform**

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

![Graph showing PMT hit Distance -cΔt and Angle [degree] with Hough Transform results](Image)

Detection of Nearly-Horizontal Muons with the HAWC Observatory
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 cΔt requirement.
- BNN (Biological Neural Network) can easily distinguish junk. Hough Transform works almost as well.

Detection of Nearly-Horizontal Muons with the HAWC Observatory
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
Observed Azimuthal Muon Rate

<table>
<thead>
<tr>
<th>Azimuth</th>
<th>Approximate direction</th>
<th>Rate</th>
<th>Rock depth at 90 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>Northeast to Southwest</td>
<td>0.21 mHz</td>
<td>7000 m</td>
</tr>
<tr>
<td>227</td>
<td>Southwest to Northeast</td>
<td>0.15 mHz</td>
<td>2500 m</td>
</tr>
<tr>
<td>165</td>
<td>South to North</td>
<td>2.7 mHz</td>
<td>1500 m</td>
</tr>
<tr>
<td>345</td>
<td>North to South</td>
<td>0.24 Hz</td>
<td>0 m</td>
</tr>
<tr>
<td>105</td>
<td>East to West</td>
<td>0.17 Hz</td>
<td>0 m</td>
</tr>
<tr>
<td>285</td>
<td>West to East</td>
<td>0.11 Hz</td>
<td>0 m</td>
</tr>
</tbody>
</table>

Detection of Nearly-Horizontal Muons with the HAWC Observatory
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.
Minimal Simulation of HAWC detector response to horizontal muons

- CORSIKA simulation of Perfect Cylindrically Symmetric Detector
  Effective Area vs Energy for cosmic ray primaries

- Detailed GEANT4-based simulation of Actual HAWC detector to muons
  Instrumental Response Efficiency vs Arrival Direction

- Attenuation calculation of muon momentum distribution vs depth
  Muon Flux reduction factor for each arrival direction

Effective Area (for CR primaries) vs Energy for each arrival direction
CORSIKA-based Perfect “Minimal Model” Detector Simulation

- CORSIKA showers are “thrown” 100 times at different radius $R_p$ and angle $\phi$ 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 > 40m.

Muon Momentum Spectrum for CORSIKA generated cosmic ray protons in the energy range 100 GeV to 10PeV with an energy spectral index=−2.7. Increasing muon multiplicity enhances acceptance for the primary particle detection at higher energies via nearly-horizontal muons.

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

Average Muon Opening Angle w.r.t shower-axis for the same sample of CORSIKA generated cosmic ray primaries. The opening angle constrains the value required for $R_{p,max}$ to be fully efficient for detector acceptance calculations.
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

Detection of Nearly-Horizontal Muons with the HAWC Observatory
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)
- See poster [CRI197] Simulation of Near Horizontal Muons and Muon Bundles for the HAWC Observatory with CORSIKA

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

[physics.ins-det]
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