Measuring Low Energy Muons with IceTop

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for the IceCube Collaboration
Before We Begin...

- IceTop detects the low energy muons far away from the shower axis ($E > 200$ MeV, $r > 300$ m).

- It is expected that the number of muons correlates with primary mass.

- The muon number is expected to scale roughly as a power of the primary energy:

  $$N_\mu(r) \propto A \left( \frac{E}{A\epsilon_\pi} \right)^{p_\mu} \quad p_\mu \sim 0.78$$

  Mass number $A$, primary energy $E$, (0.83 in Akeno)

Discrepancy with simulations claimed by Pierre Auger coll. Aab et al. PRD 91, 032003 (2015)

We will look at the energy dependence of the muon density at a fixed reference radius for near-vertical events.
The IceCube Collaboration

Approximately 300 physicists from 45 institutions in 12 countries

Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
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The Swedish Research Council (VR)

University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
The IceCube Detector

Deployed in 6 seasons, completed configuration: 2011-12
IceTop event reconstruction

M.G. Aartsen et al., PRD 88 (2013) 042004

\[ S(r) = S_{125} e^{-\frac{d \sec \theta}{\lambda}} \left( \frac{r}{125 \, m} \right)^{-\beta - k \log\left( \frac{r}{125 \, m} \right)} \]

Attenuation due to snow

\[ t(x) = t_0 + \left( \frac{x_c - x}{c} \right) \cdot n + \Delta t(R) \]

\[ \Delta t(R) = aR^2 + b \left( \exp\left( -\frac{R^2}{2\sigma^2} \right) - 1 \right) \]
Example of a VEM calibration histogram for a particular tank, high-gain DOM in tank 61-A. IceCube Collaboration, ICRC 2011, Beijing
Charge-Distance to Axis Distribution

$28^\circ < \theta < 32^\circ$ \hspace{1cm} $10 \text{ PeV} < E < 12.6 \text{ PeV}$
Signal probability distribution:

\[ p(S|1, \theta) = \int g(l)K(S|l)dl \]

Track length distribution

Detector response

\[ K(S|\mu, \sigma, \lambda) = \frac{\lambda}{2} \exp\left(\frac{\lambda}{2}(2\mu + \lambda\sigma^2 - 2S)\right) \times \text{erfc}\left(\frac{\mu + \lambda\sigma^2 - S}{\sqrt{2}\sigma}\right) \]


1 VEM = 90 cm
Response to Multiple Muons

Single muons, various angles

Few muons, fixed angle (~10°)

Response to single muons obtained from Geant4 simulations of IceTop detectors

The response to n muons is the n-th order autoconvolution of the single-muon response

$$p(q|N_\mu, \theta) = \sum_n \frac{p^n e^{-\langle N_\mu \rangle}}{n!} p(q|n, \theta)$$

Expected number of muons

response to a number of muons

TAUP 2015, Torino
Comparison to Geant4

Data points: Tank response simulated with Geant4
Comparison to Geant4

Data points: Tank response simulated with Geant4

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\[ \rho_\mu \approx \frac{N_{\text{tanks with muons}}}{N_{\text{all tanks}}} \frac{1}{A_{\text{tank}}} \]

\[ p_{\mu \text{ hit}} = \frac{N_{\mu \geq 1}}{N_{\text{tanks}}} = 1 - e^{-\langle N_\mu \rangle} \]
Determination in Radial Bins

- Standard quality cuts
  (IceCube Collab., M.G. Aartsen et al., PRD 88 (2013) 042004)
- Zenith angle $\theta < 40^\circ$
- Shower size $S_{125} > 1$ VEM ($\sim 1$ PeV)
- One month of data (June 2011)
Muon Number Vs Energy

IceCube preliminary

\[ \rho_\mu(600 \text{ m}) / \text{m}^{-2} \]

\[ 10^0 \]
\[ 10^{-1} \]
\[ 10^{-2} \]
\[ 10^{-3} \]

\[ E / \text{PeV} \]

Fe

\( p \)

This work

IceCube 2014

HiRes-MIA 2000

IceCube collaboration, ISVHECRI 204, arxiv:1501.03415
Conclusion

• With IceTop we can measure the average number of muons at large distances from the shower axis. We used 600 m at this time.
  – High-resolution measurement of muon density from 250 m to 1000 m
  – No air shower simulation input (except conversion $S_{125} \leftrightarrow$ energy)

• We still draw no conclusion regarding primary composition.
  – $\rho_{\mu}(600\text{m})$ in vertical events bracketed by p/Fe showers simulated with CORSIKA / Sibyll-2.1 / Fluka

• Systematic uncertainties under study:
  – EM contribution. A change in parametrization can alter the result.
  – Snow can introduce small effects in threshold.
  – Checks with air shower simulations.