Surface muons in IceTop

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Too many muons in air showers?

10000 PeV  **Auger Collab.**, Aab et al.  PRD 91, 032003 (2015)

Muon content above simulations (1.4 $\sigma_{\text{sys}}$ above EPOS-LHC)


Muon content above simulations (Compared to Sibyll-2.1, QGSJet01)
IceCube Neutrino Observatory

- CR energies 1 PeV to 1000 PeV
- DAQ since 2005, completed 2011

IceTop
- 1 km² ice-Cherenkov
- 125 m spacing
- Coverage $3 \times 10^{-4}$
- 2835 m a.s.l. 680 gcm$^{-2}$

Coverage = \frac{\text{instrumented area}}{\text{total area}}
IT Event reconstruction

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

- Cosmic ray direction
  - Timing resolution 3 ns
  - Angular resolution ~1°

- Cosmic ray energy
  - Energy proxy $S_{125}$ in VEM
  - Simulated-based energy calibration
    - Mixed-composition model H4a
  - Energy resolution <25 %
  - Systematic uncertainty ~10 %

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Peripheral muons in IceTop

**Peripheral muons** \( \sim 10 \text{ GeV} \)

Minimum-ionizing through-going particles

IceTop threshold \( \sim 0.2 \text{ VEM} \) (Auger: \( > 1 \text{ VEM} \))

**Charge histograms**

Binned in energy, zenith, lateral distance

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Statistically identify tanks with at least one muon through fits of charge histograms

\( \chi^2 / n_{\text{dof}} = 178.3 / 112 = 1.6 \)

\( \langle E_{CR} \rangle = 3 \text{ PeV} \)

\( \langle \theta \rangle = 13^\circ \)

\( \langle r \rangle = 646 \text{ m} \)

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Collect pulse charges in lateral bins

> 250 m from core over many events
Analysis outline (simplified)

- Peripheral muons
  - Low density at large lateral distances
  - Tanks usually get one or zero muons

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

But: \( N_{\text{tanks with trigger}} > N_{\text{tanks with muon}} \)

- Need to sort out triggered tanks without muon hits

- Muon signal \( \sim 1 \text{ VEM} / \cos \theta \)
  - VEM = Vertical Equivalent Muon

- EM signal contribution usually smaller, smooth distribution
Muon response model

Also see IceCube Collab., J.G. Gonzalez et al., arXiv:1501.03415 (2014)

Generated Cherenkov light proportional to track length: \( S \propto l \)

\[
f(S) = \int dl \, K(S; l) \, g(l)
\]

Signal distribution to one muon (\( k=1 \))

Detector response model: Exponentially-modified Gaussian

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

Track length length distribution for through-going particles (pure geometry)

Response to \( k \) muons is \( k \)-fold auto-convolution of \( k=1 \)

Generated Cherenkov light proportional to track length: \( S \propto l \)


Muon model reproduces simulations

Trigger suppression included in full model, but neglected here

Data points: Tank response simulated with Geant4
Muon model reproduces simulations

Trigger suppression included in full model, but neglected here

Data points: Tank response simulated with Geant4
Data set

- Data from 1 June 2010 to 31 May 2013
- Standard quality cuts
  - Zenith angle $\theta < 40^\circ$
  - Shower size $S_{125} > 1$ VEM ($\sim 1$ PeV)
- 47 M events

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IceCube Collab., M.G. Aartsen et al., PRD 88 (2013) 042004
Muon-LDF

One month of data (June 2011)

More checks needed for final publication – stay tuned
Final results will have larger energy range and several zenith angles (μ attenuation!)

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Summary

- **Analysis: Muon density from charge histograms**
  - High-resolution measurement of muon density from 250 m to 1000 m
  - No simulation input (except conversion S125 ↔ energy)
  - Systematic uncertainties expected to be small

- **Preliminary results**
  - Vertical showers from 1 PeV to 30 PeV from June 2011
  - $\rho_{\mu}(600m)$ bracketed by p/Fe showers simulated with CORSIKA / Sibyll-2.1 / Fluka

- **Road-map towards publication**
  - Analyse full data-set (statistic x 36) $E_{CR} \sim 1 – 100$ PeV, $\theta \sim 0 – 40^\circ$
  - Analyse muon attenuation with zenith angle and compare with simulations
    - Muon density + muon attenuation: Test of hadronic interaction model
  - Checks needed, against MC simulated events, time dependency, etc.
  - Systematic uncertainties need to be quantified