Muon Reconstruction in IceCube

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Introduction
IceCube is....

- A cubic-kilometer neutrino telescope
- Detects Cherenkov right
  - Leptons (CC)
  - Hadron cascades (CC,NC)
- Under construction at the South Pole (2008: half size of final design)
Messengers from Universe

Gamma Ray Burst

Active Galactic Nuclei

Other physics:
Exotic particles (Monopole, SUSY, etc...) 
Dark Matter (WIMP), etc...

Super Nova

Deflection Angle < 1 deg

$\nu_e$
Atmospheric Neutrino as a probe of the Earth core

- The Earth core absorbs part of upgoing atms. neutrino
- See zenith dependence of event number
- Statistics of Atms. neutrino is increasing everyday

Practically...

We need to reject downgoing muons first!
Muon Tomography with IceCube

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Radiography of Earth's Core and Mantle with Atmospheric Neutrinos


- Use upgoing atmospheric muon-neutrino events as a probe of Earth’s core
- Requires good zenith angle resolution (~ a few degree)
- Requires good energy resolution for ~10 TeV muons ($\log_{10} E(\text{TeV}) \sim 0.1$)

Ratio of expected events vs zenith angle for the Preliminary Reference Earth Model (PREM) over an homogeneous Earth matter model.
IceCube detector and track reconstruction
IceCube

- InIce detector
- 80 strings
- 60 optical sensor (DOM) per string
- IceTop detector
- 4 DOMs per string
Optical Sensors (DOM)

From DOM waveform we get arrival time of PEs and total number of PEs.
Geometry Reconstruction

- time residual depends on propagation distance
- Dusty ice causes larger time residual

Build likelihood using knowledge of glacier ice and obtained time-residual

\[ L_{\text{time}} = \prod P_{1}(t_{\text{res},i} | a = d_{1i}, \eta_{1i}, ..., d_{1i}, \eta_{1i}, ...) \]

then minimize \( \log L_{\text{time}} \) (LogLikelihood reconstruction, LLH)
Energy Reconstruction

- Count number of hit DOMs per event
- Total charge of all hit DOMs per event
- Accumulated charge per unit track path
- Waveform LLH (geometry LLH with charge weighted hits)
Event display

Type: NuMuBar
$E(\text{GeV})$: 2.47e+08
Zen: 134.58 deg
Azi: 299.94 deg

Upgoing NuMuBar
Event display (cont’d)

downgoing mu
reconstructed upword
Event selection

Type: NuMuBar
E(GeV): 3.57e+06
Zen: 103.28 deg
Azi: 82.57 deg

Reco track

MC Truth
downgoing event rejection

- Pole filter
  - Processed at the South Pole (to reduce data size)
  - rejects downgoing muons with simple fast reconstruction
  - Contains huge number of downgoing muons misreconstructed as upgoing
    (upmu : downmu ≈ 1:10$^6$)

- LogLikelihood reconstruction
  - apply cut at zenith > 80deg
  - upmu : downmu ≈ 1:1000
Quality cuts

- Direct hits (hits made by non-scattered photons) indicates “quality of the reconstruction”
- Log Likelihood quality
  - Value of log likelihood?
  - How narrow the log likelihood minimum is?

Usually poor quality events have less number of hit DOMs
Another background source: Coincidence event

- Two muons coincidently path through detector
- Reconstructed as an upgoing single muon
- May survive high-quality cuts because of high-multiplicity of hit DOMs
Case of IC22 (zenith resolution)

- Black: LLH zenith > 80 deg
- Red: after quality cuts

Muon Energy (MCTruth) > 10 TeV

IC22 180days

| reco zenith - MC zenith | [deg] |
Possible systematics at detector site and Calibration
Possible systematics (for reconstruction)

- Ice Property
- DOM sensitivity: ~10% (Lab measurement)
- DOM depth
Ice calibration

Flasher LEDs on DOM
6 horizontal
6 tilted

Dust Logger

Power
RS-485(digital)
PMT current(analog)
Source intensity

Light source

Brushes

Backscatter PMT

Transmission PMT

Standard Candle
What we are doing now...

- Ice layer calibration
- dust logger
- Monte-Carlo calibration with downgoing muons
- Energy calibration
  - Standard Candle (337 nm, N2 Laser) equips internal PMT for absolute energy calibration
  - LED flasher (405 nm LEDs)
    Max intensity $\sim 9 \times 10^9$ photons with 12 LEDs
    Energy resolution $\sim 30$
- DOM position (depth) calibration
  - measure LED right from neighboring strings
Summary

- Muon tomography for investigation of Earth’s core is now in preparation in the IceCube collaboration.
- We have enough experience to reconstruct track geometry of probe muons (atmospheric neutrino origin).
- Needs additional studies to improve track reconstruction, especially for energy reconstruction.
- Calibration is quite important to achieve required resolution. We are working hard for several calibration studies.