Astrophysical $\nu_\tau$ search in IceCube.

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Astronomical messengers

- photons: absorbed above 10 TeV.
- protons: deflected below 10 EeV and attenuated above 50 EeV.
- neutrinos: cover all energy range.
- neutrinos are hard to detect -> very large detector is needed (~1km$^3$) IceCube detector.
Astrophysical neutrino

Possible astrophysical neutrino sources are:
➢ active galactic nuclei
➢ gamma ray bursts
➢ supernova remnants
➢ ...

Production mechanism:
\[ p+p(\text{or } \gamma) \rightarrow \pi^0 \rightarrow \gamma \]
\[ \rightarrow \pi^\pm \rightarrow \mu^\pm + \nu_\mu \]
\[ \rightarrow e^\pm + \nu_\mu + \nu_e \]

\(\nu\)'s initial flavor ratio is (1:2:0) \(\rightarrow\) (1:1:1) ratio due to oscillation. There is a prediction of (1:1.8:1.8) flavor ratio at high energies.

\[ \frac{dN}{dE} \sim E^{-2} \] - astrophysical neutrino spectrum.
Why $\nu_\tau$?

Atmospheric $\nu$'s are background for astrophysical $\nu$'s.

Production mechanism:

conventional:

$$p+p(\text{or } \gamma) \rightarrow \pi^0 \rightarrow \gamma$$
$$\rightarrow \pi^\pm \rightarrow \mu^\pm + \nu_\mu$$
$$\rightarrow e^\pm + \nu_\mu + \nu_e$$

(1:2:0) flavor ratio.

prompt decay:

$$c \rightarrow s + l + \nu_l$$

Atmospheric $\nu_\tau$ background is almost negligible.
Digital Optical Module (DOM)

- detect cherenkov light
- convert and amplify light signal with PMT
- digitize the voltage signal and makes a waveform
- each waveform bin correspond to 3 ns
- contain flasher board with 12 LED's
Flasher board

- contain 12 405 nm LED's
- 6 horizontal and 6 tilted at ~40 degrees upward
- LED's can be flashed separately with different brightness
- each LED produces a pulse from 5-65 ns
- 16+1 boards have LED's with different wavelength (cDOMs), all horizontal
ν signals in IceCube

cascade and track (CC interaction)

e or h's

e-m cascade (CC interaction) or hadron cascade (NC interaction)

2 cascades and track (CC interaction)
Possible types of $\nu_\tau$ signals in IceCube

- Double bang
- Lollipop
- Double pulse
- Both cascades are indistinguishable
- $\nu_\mu$ like event
Double bang analysis (intro)

Double bang analysis (Seon-Hee Seo)

➢ it was done for IC22 detector configuration
➢ targeted energy range is $E_\nu > 1$ PeV
➢ the analysis is based on the event topology:
  ➢ Signal: $\nu_\tau$ event contains one or two cascades and a track
  ➢ BG: $\mu$ event contains only a track
  ➢ BG: NC or $\nu_e$ event contains just a cascade
Double bang analysis (1)

- **to remove track-like events**
- **Sliding time window**
- **Inverted-lollipop**
- **Cascade** (CC $\nu_\tau$ interaction)
- **Tau track**

\[ \Delta T_{on} = \text{sliding time window} \]
\[ \Delta T_{off} = T_{tot} - \Delta T_{on} \]
\[ \Delta Q_{on} = Q_{inside} \Delta T_{on} \]
\[ \Delta Q_{off} = Q_{tot} - \Delta Q_{on} \]

**Current ratio**

\[
\left| \frac{\text{Current}_{on} \ (= \Delta Q_{on}/\Delta T_{on})}{\text{Current}_{off} \ (= \Delta Q_{off}/\Delta T_{off})} \right|_{\max} > 1 \quad \text{(for $\nu_{\tau}$)}
\]
\[ \approx 1 \quad \text{(for $\mu_1$)} \]

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Double bang analysis (2)

- To remove certain bremsstrahlung $\mu$

- Local charge densities in two regions $(Q/T)_1$, $(Q/T)_3$

- Choose maximum between 1st and 3rd

$(Q/T)_1^{\text{signal}} > (Q/T)_1^{\text{BG}}$

To be selected by this cut.

Not to be selected.
Double bang analysis (3)

Signal (all flavor): 3.18 events in 200 live days (WB)
BG (atm. $\mu$, atm. $\nu$): 0.76 events in 200 live days

<table>
<thead>
<tr>
<th>Event type</th>
<th>E spectrum</th>
<th>Flux model</th>
<th>Live time</th>
<th>#. Events at final cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>NuTau</td>
<td>E-2</td>
<td>WB</td>
<td>200 d</td>
<td>0.97</td>
</tr>
<tr>
<td>NuMu</td>
<td>E-2</td>
<td>WB</td>
<td>200 d</td>
<td>0.64</td>
</tr>
<tr>
<td>NuE</td>
<td>E-2</td>
<td>WB</td>
<td>200 d</td>
<td>1.57</td>
</tr>
<tr>
<td>All Nu</td>
<td>prompt</td>
<td></td>
<td>200 d</td>
<td>0.25</td>
</tr>
<tr>
<td>NuMu + NuE</td>
<td></td>
<td>Bartol</td>
<td>200 d</td>
<td>0.05</td>
</tr>
<tr>
<td>Atm. muons</td>
<td></td>
<td></td>
<td>200 d</td>
<td>0.46</td>
</tr>
<tr>
<td>S.Pole (30%)</td>
<td>---</td>
<td>---</td>
<td>82.4 d</td>
<td>0</td>
</tr>
</tbody>
</table>

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Double bang analysis (4)

$E^2 \Phi_\nu < 6.54 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ st$^{-1}$ (all flavor, preliminary)

$5.53 < \text{Log10}(E/\text{GeV})_{90\%} < 8.30$
Double pulse analysis

- energy range $10 \text{ PeV} > E > 0.1 \text{ PeV}$.
- assuming $E^{-2}$ spectrum, double pulse must have more events than double bang.
- based on analyzing single waveform shape
- or based on analyzing shower shape using likelihood method (Patrick Toale)
- double pulse waveform finding algorithm was tested using flasher and toy simulation data.
An example of two flasher double pulse waveforms registered at DOM 39-12 and generated by DOMs 39-11 and 39-14. Each light pulse contained \( \sim 8 \times 10^8 \) photons (\( \sim 8 \) TeV cascade).

There is a plan to have a large flasher run in January 2011.
Toy double pulse generator

**Toy double pulse generator:**
- two hadronic cascades (one mimics $\nu_\tau$ interaction, the other mimics $\tau$ decay); this event is called double pulse event later
- event can be anywhere with any direction
- each cascade gets 50% energy
- “track length” can be set
- no $\tau$ track simulation
- if only one cascade produced with all energy, the event is called single pulse event (used for bg estimate)

**Event sample:**
- contain 1000 double and single pulse events
- each event has energy within 0.1-10 PeV
- $\nu_\tau$ interaction point is close to DOM 63-51 ($\pm100$ m in x and y, $\pm17$ m in z)
- angular distribution is uniform in $\phi$ from 0 to 360 and in $\theta$ from 0 to 90
Double pulse waveforms

Energy, track length and possible delay time between first and second pulses

<table>
<thead>
<tr>
<th>E, PeV</th>
<th>0.2</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_{track}, m</td>
<td>10</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
<td>150</td>
<td>200</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>dt, ns</td>
<td>13-200</td>
<td>33-400</td>
<td>66-600</td>
<td>99-800</td>
<td>131-1200</td>
<td>197-1600</td>
<td>262-2000</td>
<td>328-394-2400</td>
<td></td>
</tr>
</tbody>
</table>
Change point algorithm

- based on cumulative sum $S(i) = S(i-1) + x_i + <x>$, where $S(0) = 0$, $x_i$ is a current value of the waveform, $<x>$ is waveform average.
- iterative algorithm
- provides set of points and tell if waveform is rising or falling at this point.
Peak quality

\[ R_{\text{max}} = (x_{\text{max}} - p_{\text{max}})/p_{\text{max}} \]

Cut selected:
\[ R_{\text{max}} < 0.2 \]
Waveform parameters

Type 1, $\frac{p_{\text{max1}}}{p_{\text{max2}}} > 0.7$:
- cut value: slr1 > 2
- Signal eff. - 0.685
- BG eff. - 0.132

Type 2, $\frac{p_{\text{max1}}}{p_{\text{max2}}} < 0.7$:
- cut value: slr2 > 2
- Signal eff. - 0.258
- BG eff. - 0.058

Combined:
- Signal eff. - 0.943
- BG eff. - 0.190
Waveform parameters

**Type 1:**
cut value: $pwidth_2 > 25$

- Signal eff. - 0.663
- BG eff. - 0.068

Combined:
- Signal eff. - 0.914
- BG eff. - 0.077

**Type 2:**
cut value: $pch_2 > 0.5$

- signal eff. - 0.251
- BG eff. - 0.009
Double pulse waveform selection

**Selection strategy:**

- **Charge cut**
  - *relatively high energy events*
  - *dp waveform is wider (two peaks)*
- **Pulse selection**
  - *change point algorithm*
  - *peak quality check*
- **Waveform selection**
  - *individual waveform properties cuts (slope ratio, peak width, peak charge,...)*
- **Event selection**
  - *number of double pulse waveforms in event*
  - ???
Summary

- Astrophysical $\nu_\tau$ search in IceCube is pursued in both ultra high (double-bangs) and low energies (double pulses).
- Double-bang search with IC22 resulted in good upper limit on all flavors compared to AMANDA, ANTARES.
- Triggering online double-pulse $\nu_\tau$ events in IceCube is intended as multi-wavelength analysis with other exp.
- Real double pulse waveforms (from flashers) can be registered in IceCube.
- Toy MC gives a promising result for finding double pulse waveforms.
- Further MC studies are need, especially for backgrounds.