Astrophysical Tau Neutrinos in the Pacific Ocean

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Physics of $\nu_\tau$
Astrophysical Neutrinos

- First detected in IceCube.
- Unobstructed view of Universe above tens of TeV.
- Energy 1000 times > highest neutrino produced in particle accelerators.
- Study the sources and production mechanisms. 3 flavours - electron, muon, tau.
- Each flavour has a characteristic signals.
Astrophysical Tau Neutrinos

- Double pulse signature.
- Important implications:
  - Reaffirm astrophysical origins of neutrinos
  - Oscillations on cosmological scales.
- 20-40% of astrophysical flux, but IceCube on verge of detection first $\nu_\tau$ only now. Why?
  - Scattering in ice
  - Low stats at higher energies

What if a neutrino telescope is deployed in water, where scattering is considerable less?
Pacific Ocean Neutrino Explorer
- Planned neutrino telescope in the Cascadia Basin near Vancouver Island.
- P-ONE + other neutrino telescopes = an increased sky coverage.
- P-ONE phase 1 - 1 segment, 10 strings and 200 DOMs,
- Long term goal - 7 segments, 70 strings, 1400 DOMs.

Can P-ONE phase 1 contribute in detecting astrophysical $\nu_e$?
Simulation
Simulation Chain

- **Neutrino Generator**: Inject Interactions at the vicinity of the detector

- **Particle Propagator**: Propagate resulting charged particles through the medium

- **Photon Generator**: Make Cherenkov photons and propagate them through the optical medium

- **PE Hit Generator**: Convert photons into photoelectrons by applying acceptance probabilities for an mDOM

- **Noise Generator**: Injecting Noise from STRings for Absorption Length in Water

- **RecoPulse Generator**: Simulating PMT Response
Simulation Parameters

- Absorption and scattering lengths of Cascadia Basin*.
- 24 3’’ PMTs and a flat angular acceptance of 0.811. The wavelength acceptance = IceCube DOM
- No granularity in hits.
- Hits within 3 ns are merged as on. 0 -1.5 ns smear is added to the timestamps
- 40,000 $\nu_\tau$ and $\nu_e$ events simulated in total between energies 100 TeV to 5PeV.

<table>
<thead>
<tr>
<th>Wavelength(nm)</th>
<th>Scattering Length(m)</th>
<th>Effective Scattering Length(m)</th>
<th>Absorption Length(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>365</td>
<td>32.30</td>
<td>163.16</td>
<td>9.21</td>
</tr>
<tr>
<td>405</td>
<td>56.78</td>
<td>286.81</td>
<td>17.56</td>
</tr>
<tr>
<td>465</td>
<td>66.87</td>
<td>337.78</td>
<td>31.87</td>
</tr>
</tbody>
</table>

* Taken from Andreas Gaertner's analysis
Interaction:
NuTau -> TauMinus + Hadrons
Primary
Type : NuTau
Energy: 2.46e+06GeV
Cascade
Type : Pi0
Energy: 8.46e+05GeV
Expected $\nu_\tau$ In A Year

- Desired $\nu_\tau$ events:
  - Charged Current interactions.
  - Interaction vertex should be within 100m around the detector volume in X and Y axis.

Expected CC $\nu_\tau$ events per year: 1.68
Goal of the Analysis

Develop an algorithm that identifies $\nu$ from the background

Background from atmospheric muons, CC $\nu_e$ and NC interactions from all flavoured neutrinos.
The Method

- The algorithm fits both a single exponential gaussian and double exponential gaussian to every DOM in the event.
- Single exponential gaussian (expGauss) - mean, width, amplitude and $k$ (defines how exponential the tail is).
- Double expGauss = expGauss$_1$ + exp Gauss$_2$

\[
f(x; \mu, \sigma, \lambda) = \frac{\lambda}{2} e^{\frac{\lambda}{2}(2\mu+\lambda \sigma^2 - 2x)} \text{erfc} \left( \frac{\mu + \lambda \sigma^2 - x}{\sqrt{2} \sigma} \right)
\]

The colours indicate the different $k$ values.
The Algorithm

Number of hits in DOMs > 200

Select hits within 200 nanoseconds

Histogram

Entries ratio = \( \frac{\text{entries in bins}}{\text{max bin entry}} \)

Entries Ratio > 0.2

Bins between first-2 and first+2 bins entries ratio

Number of bins >= 10
The Fit

- The minimizer minimizes the -log likelihood value. Takes bounds and initial values

\[ -\ln L = \sum_i \ln (n_i!) + \mu_i - n_i \ln \mu_i \]

- Multiple checks done to improve the algorithm.
- Sensitive to initial values - performing a grid search.
Parameters for Comparison

- **Time Difference** = $\text{position}_2 - \text{position}_1$
- **Width Difference** = $|\text{width}_2 - \text{width}_1|$
- **Amplitude Ratio** = $\text{amp}_1/\text{amp}_2$
- **k difference** = $|k_2 - k_1|$
- **LLH difference** = $2*(\text{LLH}_{\text{DeG}} - \text{LLH}_{\text{eG}})$
Separating $\nu_{\tau}$ from the background

- Some separation in log amplitude ratio.
- Most separation observed in log $2\Delta$LLH.
- Introducing cuts in the data using log $2\Delta$LLH(CUT VARIABLE) values will be most effective.
At cut variable 1.1 there is equal probability of the event being either a $\nu_\tau$ or background event.

Total $\nu_\tau$ events in a year is 0.39. Can this number be improved?
### Improving the Number of $\nu_\tau$ events/year

<table>
<thead>
<tr>
<th>Conditions Changed</th>
<th>Total Background Events</th>
<th>Total NuTau Events</th>
<th>Intersection Point</th>
<th>Tau Neutrino Events at Intersection Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of hits in DOMs &gt; 200</td>
<td>0.72</td>
<td>0.39</td>
<td>1.1</td>
<td>0.21</td>
</tr>
<tr>
<td>Number of hits in DOMs &gt; 100</td>
<td>1.11</td>
<td>0.59</td>
<td>1.3</td>
<td>0.22</td>
</tr>
<tr>
<td>Number of hits in DOMs &gt; 0</td>
<td>1.78</td>
<td>0.88</td>
<td>1.3</td>
<td>0.27</td>
</tr>
<tr>
<td>Number of bins &gt;= 9</td>
<td>1.87</td>
<td>0.9</td>
<td>1.3</td>
<td>0.27</td>
</tr>
<tr>
<td>Entries Ratio &gt; 0.1</td>
<td>2.1</td>
<td>0.97</td>
<td>1.5</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Energy Distributions

Energy distribution of signal and background at intersection point.

Cut Variable = 1.3

Signal

Background
Conclusions
• The algorithm is successful in separating $\nu_\tau$ from the background.

• LLH ratio between single/double ExpGauss fits is the most effective parameter that shows a clear separation between tau neutrino and background.

• $\sim 1$ $\nu_\tau$ events expected in a year if the algorithm is capable of identifying all $\nu_\tau$ from the background.

• $\sim 0.3$ tau neutrino events with cut variable $> 1.3$ are detected in a year in P-ONE phase 1.
THANK YOU!

Any Questions?

Credits: This presentation template was created by Slidesgo.
Back Up

Simulation Steps

More on Analysis
Step 1: Neutrino Generator (NuGen)

- Injected neutrinos are forced to interact within a given cylinder volume.
- Types of neutrino interactions:
  - CC - Charged Current - Makes charged leptons and hadronic or EM showers
  - NC - Neutral Charged Current - Makes a secondary neutrino and hadronic showers.
- Parameters given to NuGen:
  - Flavour: $\nu : \bar{\nu} : \nu : \bar{\nu} = 1:1:1:1$
  - Energy: 100 TeV to 5 PeV
  - Power law index: 2.19
  - Azimuth: 0 to 180 degrees
  - Zenith: 0 to 180 degrees
  - Height of cylinder: 1000m
  - Radius of cylinder: 500m
  - Events per file: 20
Neutrino Distributions

- Energy range given to the simulation is 100TeV - 5PeV
- Energy distribution looks as expected.
- Simulating events between Zenith(-45, 45) and Azimuth(0, 180), no bias observed.
Distributions of interactions of neutrinos to produce corresponding lepton

The dimensions of interaction cylinder given - Radius - 500m, height - 1000m, centered at (0, 0, 0)
Step2: PROPOSAL

- Propagates secondary charged particles in ice.
- Medium of propagation not changed to water since the difference is negligible.
- Verifying $\tau$ propagation:
  - Histogram of tau decay time fit to an exponential curve given by:
    \[ N = N_0 e^{\frac{-t}{T}} \]
    \[ T = \text{Life time of tau in rest frame} \]
  - The decay time given by:
    \[ N_0 = \text{Number of taus produced initially} \]

\[ E = \text{Energy of tau} \]
\[ m = \text{Mass of tau} \quad [1776.86 \text{ MeV}] \]
\[ \tau = \text{Lifetime of tau} \quad [2.9 \times 10^{-4} \text{ ns}] \]
Step 2: PROPOSAL

**Tau Energies - 100GeV to 200GeV**

\[ T \text{ from fit} = 0.025 \text{ ns +/- 5e-5} \]

\[ T \text{ calculated with average energy} = 0.025 \text{ ns +/- 0.005} \]

**Tau Energies - 500GeV to 550GeV**

\[ T \text{ from fit} = 0.086 \text{ ns +/- 2e-4} \]

\[ T \text{ calculated with average energy} = 0.086 \text{ ns +/- 0.002} \]

**Tau Energies - 997 GeV to 1000GeV**

\[ T \text{ from fit} = 0.160 \text{ ns +/- 0.002} \]

\[ T \text{ calculated with average energy} = 0.163 \text{ ns +/- 0.0001} \]
Step 3: CLSim - Changing the Medium

- Generate and propagate photons.
- To propagate photons in CLSim, medium should be changed to water.
- The optical properties in IceCube are defined by the following equations

\[
b_e = b_{e,400}(\frac{\lambda}{400})^{-\alpha}
\]

\[
a = a_{dust,400}(\frac{\lambda}{400})^{-\kappa} + Ae^{-B/\lambda(1 + 0.01\Delta T)}
\]

\[\text{Ignored, need more data}\]

- \(b_e\) - effective scattering coefficient at a given wavelength \(\lambda\)
- \(b_{e,400}\) - scattering coefficient at wavelength 400 nm
- \(a\) - absorption coefficient at a given wavelength \(\lambda\)
- \(a_{dust,400}\) - absorption coefficient at wavelength 400 nm

Exponential component of wavelength dependence is ignored.
Phase Function

- The phase function $P(\cos \theta)$ is chosen to be a combination of Henyey Greenstein (HG) and simplified Liu (SL).

$$P(\cos \theta) = f_{sl} \cdot \frac{SL(\cos \theta) \sin \theta}{\int_0^\pi SL(\cos \theta) \sin \theta d\theta} + (1 - f_{sl}) \cdot \frac{HG(\cos \theta) \sin \theta}{\int_0^\pi HG(\cos \theta) \sin \theta d\theta}$$

- $HG(\cos \theta) = \frac{1}{2} \frac{1 - g^2}{(1 + g^2 - 2g \cos \theta)^{\frac{3}{2}}}$

- $SL(\cos \theta) = \frac{1 + \zeta}{2} \left( \frac{1 + \cos \theta}{2} \right)^\zeta$, $\zeta = \frac{2g}{1 - g}$

- The phase function of water is closer to HG. Therefore, contribution by SL function is neglected by setting $f_{sl}$ (Fraction of Simplified Liu) to 0.

- $g$ - average scattering angle given by

$$\langle \cos \theta \rangle = \eta \cdot \langle \cos \theta \rangle_{\text{molecular}} + (1 - \eta) \cdot \langle \cos \theta \rangle_{\text{particulate}}$$
The simulation takes effective scattering length.

\[
\lambda_{\text{eff}} = \frac{\lambda_{\text{sct}}}{1 - \langle \cos \theta \rangle}
\]

\[
\langle \cos \theta \rangle = \eta \cdot \langle \cos \theta \rangle_{\text{molecular}} + (1 - \eta) \cdot \langle \cos \theta \rangle_{\text{particulate}}
\]

- \( \langle \cos \theta \rangle_{\text{molecular}} = 0 \)
- \( \langle \cos \theta \rangle_{\text{particulate}} = 0.924 \) (from Antares paper)
- \( \eta = 0.132 \) (Matthew Man’s Analysis)

Current STRAW analysis considers equal probability for forward and backward scattering.

For a more correct approach \( \eta \) (fraction of molecular scattering) is included.
Determining Parameters

- The simulation uses scattering coefficient \( b_{e,400} \), \( \alpha \), absorption coefficient \( a_{e,400} \) and \( \kappa \) obtained from the fit of the data points.

- Phase function in software defined by Simplified Liu(SL) and Henyey Greenstein(HG).
- Phase function of water closer to HG, thus SL ignored by setting \( f_{sl} = 0 \)
Verification: Simulating Multiple Flashers

- Simulating multiple flashers, spaced equally in cosine of zenith, for isotropic flashes.
- The pulse shape of multiple flashers is akin to pulse shape of a single flasher.
- DOM position is fixed and flasher position is changed accordingly.

![StartTime Distribution](image)

FWHM = 10ns
Flasher Isotropy

**Single flasher**

- PolarSigma = 180 Deg
- AzimuthSigma = 180 Deg

**Multiple flasher**

- PolarSigma = 0 Deg
- AzimuthSigma = 360 Deg
Number of flashers

- Number of flashers simulated should be large enough to avoid gaps in cosine zenith.
- Current analysis simulates 200,000 flashers
Great tool to test the inputs from STRAW analysis.
Step 4: PE Hit Generator - mDOM

- Once the photons reach a DOM, the probability of a photon generating a photo electron (PE) depends on:
  - Quantum efficiency of PMT
  - Wavelength Acceptance of DOMs (DOM efficiency)
  - Angular Acceptance of DOMs
  - Photon Weight

  \[
  \text{Probability of Hit} = \text{relative DOM eff} \times \text{DOM eff} \times \text{ang Acc} \times \text{photon weight}
  \]

- A simple custom code written to facilitate changes to properties of the DOM.
- Verified the accuracy compared against IceCube code
mDOM Properties

- The wavelength acceptance is set to be the same as IceCube's.
- Angular acceptance of mDOM = 0.811
Step 5: Noise Generator

- Time taken for the first and the last photon to hit a DOM in a tau neutrino event is about 1-3 microseconds.
- Considering an event window of about 7.2 microseconds.
- Since noise scales with area, 24 random chunks of 7.2 ms from STRAW data, overlaid on each other, to generate noise in mDOM.
For a single neutrino event the noise hits are chosen to be injected such that they are centered around the mean time of physics hits.
Weighting Events

\[ \text{weight}_{CC} = \frac{\phi_{astro} \times \text{OneWeight}}{N/4} \]

\[ \text{weight}_{NC,\nu_\mu} = \frac{(3\phi_{astro} + \phi_{atmo,\nu_\mu}) \times \text{OneWeight}}{N/2} \]

\[ \text{weight}_{NC,\bar{\nu}_\mu} = \frac{(3\phi_{astro} + \phi_{atmo,\bar{\nu}_\mu}) \times \text{OneWeight}}{N/2} \]

\( N \) = Number of files

\( \text{OneWeight} = \) Taken from I3MCWeight

\( \frac{d\Phi_{\nu+\bar{\nu}}}{dE} = (1.01^{+0.26}_{-0.23}) \left( \frac{E}{100\text{TeV}} \right)^{-2.19 \pm 0.10} \cdot 10^{-18} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \).
Bounds and Initial Values of the Fit

- Width needs to be negative, to change the direction of the exponential tail. However, the caveat here is that the minimizer outputs a NaN once it starts considering width values between (-0.999, 0.999)

<table>
<thead>
<tr>
<th>pos1</th>
<th>wid1</th>
<th>k1</th>
<th>amp1</th>
<th>pos2</th>
<th>wid2</th>
<th>k2</th>
<th>amp2</th>
<th>log likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>-14.4844</td>
<td>-0.0734752</td>
<td>0.134472</td>
<td>237.057</td>
<td>-5.96877</td>
<td>18.3955</td>
<td>6.09133</td>
<td>248.598</td>
<td>nan</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>pos1</th>
<th>wid1</th>
<th>k1</th>
<th>amp1</th>
<th>pos2</th>
<th>wid2</th>
<th>k2</th>
<th>amp2</th>
<th>log likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>-14.3644</td>
<td>-0.05513</td>
<td>0.427769</td>
<td>638.78</td>
<td>-5.99934</td>
<td>23.245</td>
<td>1.34232</td>
<td>74.7544</td>
<td>nan</td>
</tr>
</tbody>
</table>

- The same with k, values should be between (0, 0.99).
- Ideally large tau length would mean large cut variable value.
- What happens with DOMs with large tau length and small cut variable?
  - Vertices (Tau creation and tau decay) are outside the detector.
  - Tau decays into a muon
  - DOM is not at an ideal distance from the vertices.
Hist 2Ds for Exponential gaussian fits
Hist 2Ds for Exponential gaussian fits

- Log amplitude ratio vs. log time difference
- Log amplitude ratio vs. log time difference
Hist 2Ds for Exponential gaussian fits
Hist 2Ds for Exponential gaussian fits
Hist 2Ds for Exponential gaussian fits
Improving the Number of $\nu_e$ events/year

The intersection point moves to the right as the number of events included in the analysis increases.
The energy distribution shifts to the right as higher cut variable is imposed.

- Cut Variable = 0
- Cut Variable = 1.3
- Cut Variable = 3.0
Energy Distribution - NuE&NC events

- The energy distribution shifts to the right as higher cut variable is imposed.
Time Difference

- $t_1 =$ Time Taken for unscattered photons from first vertex to reach the DOM
- $t_2 =$ Time Taken for unscattered photons from second vertex to reach the DOM

Time Difference is mostly zero, implying that a lot of the DOMs will not have an ideal distance to the vertices

Time Difference between 2 Vertices

<table>
<thead>
<tr>
<th>Count</th>
<th>Time Difference(ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-1}$</td>
<td>-3000</td>
</tr>
<tr>
<td>$10^{0}$</td>
<td>-2000</td>
</tr>
<tr>
<td>$10^{1}$</td>
<td>-1000</td>
</tr>
<tr>
<td>$10^{2}$</td>
<td>0</td>
</tr>
<tr>
<td>$10^{3}$</td>
<td>1000</td>
</tr>
<tr>
<td>$10^{4}$</td>
<td>2000</td>
</tr>
<tr>
<td>$10^{5}$</td>
<td>3000</td>
</tr>
</tbody>
</table>