Upward Showering Muons in Super-Kamiokande

Shantanu Desai / Alec Habig
For
Super-Kamiokande Collaboration

ICRC 2005 Pune
Upward Going Muons in Super-K

\[
d\phi/d\log E_u = 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}
\]

Graph showing the distribution of upward-going muons with energy, comparing throughgoing and stopping events.
Muon Energy loss as a function of Energy

Non-Showering muon  Showering Muon

Reasonably good agreement of Monte-Carlo with PDG

Aim of this analysis is only to separate a given muon into showering/non-showering

\[ \frac{dE}{dX} = \frac{(E_i - E_f)}{L} \]

Distribution asymmetric for each muon energies

(Groom et al 03)
Corrections to raw PMT charge

Muon track

Apply following correction for every PMT in Cherenkov Cone

\[ q_{corr} = q_{raw} \frac{d_{wat}}{\exp(d_{wat}/L_{atten})} \]

where \( L_{atten} \) = Water attenuation length,
\( d_{wat} \) = Distance from PMT to point of projection to \( \mu \) track
\( F(\theta) \) = PMT acceptance + shadowing

Divide the muon track into 50 cm bins. For each bin, calculate average corrected charge and its statistical error as follows:

\[ Q_{corr}^i = \sum_{1}^{N_{pmt}} \frac{q_{corr}}{N_{pmt}} \]

where \( N_{pmt} \) = No of pmts within the given projected distance corresponding to each bin

\[ \sigma_{Q_{corr}^i}^2 = \frac{1}{N_{pmt}^2} \sum_{1}^{N_{pmt}} \frac{q_{corr}^2}{q_{raw}} \]
Corrected Charge Distribution Comparison of ionizing vs showering muon

Muon Energy = 20 GeV

\[ \frac{dE}{dX} = 2.16 \text{ MeV/cm} \]

Muon Energy = 10 TeV

\[ \frac{dE}{dX} = 8.5 \text{ MeV/cm} \]

Both simulated muons have same entry point and direction
Variables used for showering/non-showering separation

\[ \chi^2 = \sum_{i=3}^{n-2} \left\{ \left[ Q_{corr}^{i} - \langle Q_{corr} \rangle \right]^2 / \sigma_{Q_{corr}}^2 \right\} \]

**Shape Comparison**

\[ \langle Q_{corr} \rangle = \frac{\sum_{i=4}^{n-3} Q_{corr}^{i} / \sigma_{Q_{corr}}^2}{\sum_{i=4}^{n-3} 1 / \sigma_{Q_{corr}}^2} \]

(Average corrected charge averaged over entire muon length)

and

\[ q(l) = \langle Q_{corr} \rangle \]

for a ionizing muon as a function of path-length

\[ \Delta = [\langle Q_{corr} \rangle - q(l)] \]

Difference in average corrected charge of given muon – same for ionizing muon

**Absolute Corrected Charge Comparison**
Variables when applied to 100yr upmu NEUT Monte-Carlo

$\chi^2$ comparison for data and monte-carlo

$\Delta$ comparison for data and monte-carlo
**SHOWERING CUT USED**

\[ \chi^2 / \text{DOF} > 40 \text{ and } \Delta > 1.0 \quad \text{OR} \quad \chi^2 / \text{DOF} > 30 \text{ and } \Delta > 2.0 \]

\[ \text{OR} \quad \chi^2 / \text{DOF} > 20 \text{ and } \Delta > 2.5 \quad \text{OR} \quad \chi^2 / \text{DOF} > 50 \text{ and } \Delta > 0.5 \]

\[ \text{OR} \quad \Delta > 4.5 \]

Total no of showering events = 5575 (out of 37301) in 100 year upmu NEUT Monte-carlo

Efficiency = 71% where,

Efficiency = \frac{\text{No of events Identified by algorithm}}{\text{No of events with } \Delta \text{E} / \Delta \text{X} > 2.85 \text{ MeV/cm}}

\[ \Delta \text{E} = \text{Energy deposited by muon in inner detector} \]

\[ \Delta \text{X} = \text{Length of muon in inner detector} \]
NEUTRINO ENERGY SPECTRA

$E_u (\text{GeV})$

$\frac{d\Phi}{d\log E_u} \left( 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \right)$

- Showering
- Non-showering
- Stopping

$<E_u> \sim 10 \text{ GeV}$

$<E_u> \sim 100 \text{ GeV}$

$<E_u> \sim 1 \text{ TeV}$
Event Display of upward showering muon
Angular Resolution of showering muons

Shaded region contains 68% of total area

Angular resolution = 1.25°

Thrugoing muons: Angular resolution ~ 1°

Stopping muons: Angular resolution ~ 1°
Zenith-angle distribution of showering muons

Showering muons relatively insensitive to oscillation

\[ \Delta m^2 = 0.0025 \sin^2 2\theta = 1.00 \]

For this dataset chi-square for null-oscillation should be very good fit
Background Subtraction

Applied the showering algorithm to horizontal thrugoing muon with $0 < \cos(\theta) < 0.08$

Fit to thin rock zenith angle distribution: $f[\cos(\theta)] = p1 + \exp[p2+p3 \cos(\theta)]$

$N_{\text{bkgd}} = 8.63^{+12}_{-5}$ for $\cos(\theta) > -0.1$ (Asymmetric distribution because of bump near horizon)
Showering Muon Oscillation Results

Best-fit (physical region) :
\[ \chi^2 = 4.68 / 7 \text{ dof for } (\Delta m^2, \sin^2 2\theta) = (0.0104 \text{ eV}^2, 0.9) \]

Best-fit (null oscillation) :
\[ \chi^2 = 6.51/9 \text{ dof} \]

![Graph showing null oscillation normalized by livetime at best fit point.](image)
Null oscillation allowed even at 68% confidence level as expected for this high energy $\nu_\mu$ with mean energy of ~1 TeV.
Comparison with all upward throughgoing muons

Best-fit: $\chi^2 = 7.64 / 7$ dof for $(\Delta m^2, \sin^22\theta) = (0.0024 \text{ eV}^2, 0.96)$

Best-fit at null oscillation: $\chi^2 = 19.6/9$ dof

Upward throughgoing muons sensitive to neutrino oscillation
CONCLUSIONS

- A sample of upward thrugoing muons which lose energy through radiative processes have been identified.

- Mean energy of parent neutrinos of upward showering muons $\sim 1$ TeV.

- 5575 showering muons in 100yr neut Monte-carlo and 309 events in 1679.6 days data

- Zenith angle distribution of upward showering muons consistent with null oscillations

- This dataset will now be used for oscillation analysis with all datasets by providing an extra energy bin at highest energies.

- A variety of astrophysical searches with upward showering muons done. Nothing found. *(S. Desai thesis 2003. Also A. Habig poster)*