Upward Showering Muons in Super-Kamiokande

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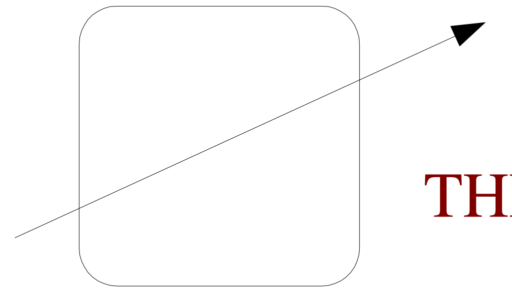
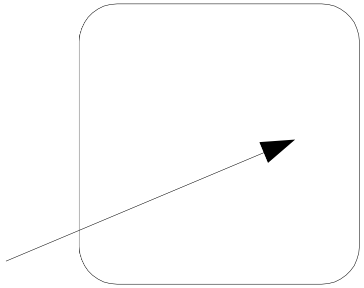
For
Super-Kamiokande Collaboration

ICRC 2005 Pune

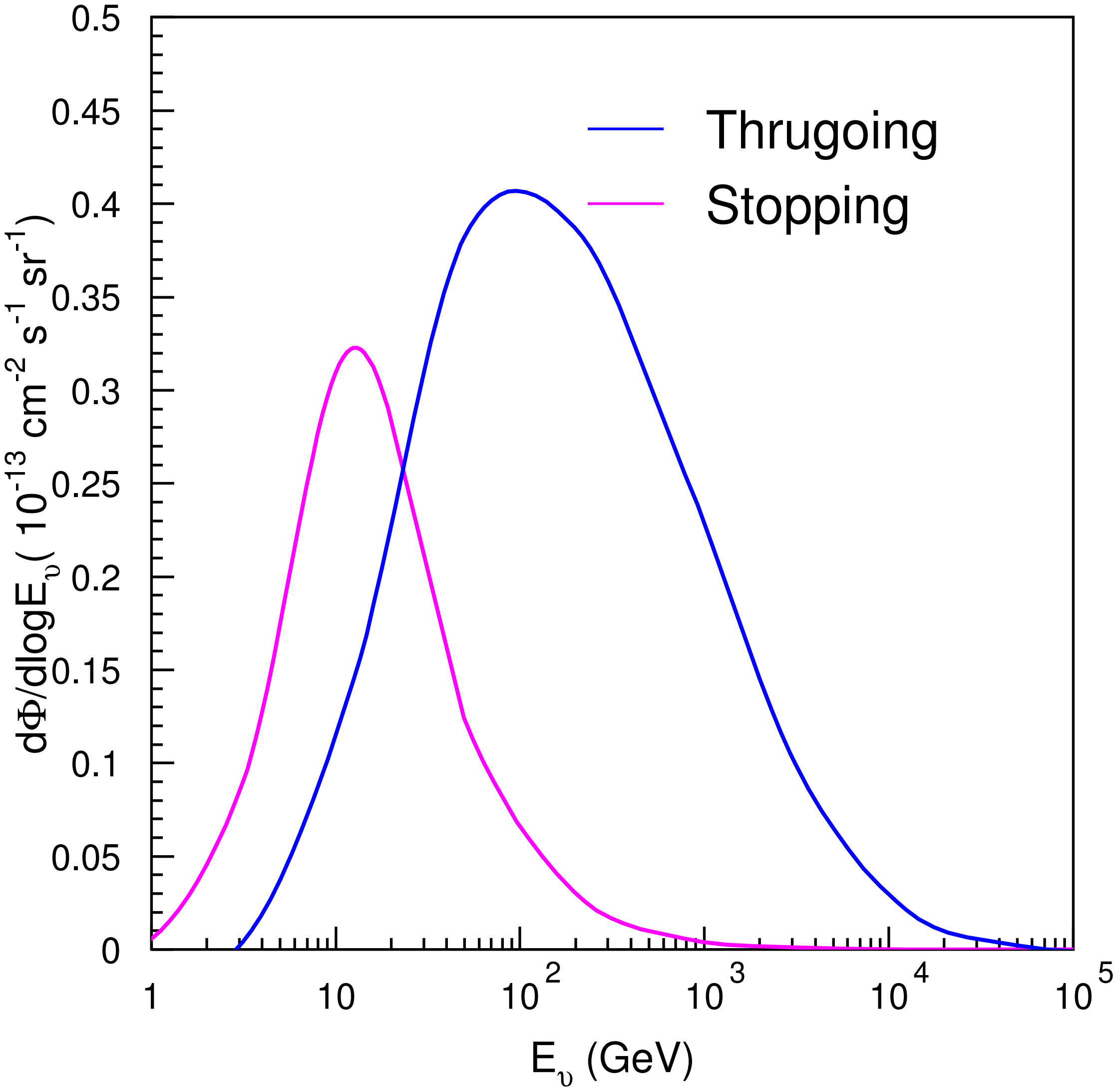
Upward Going Muons in Super-K



THRU

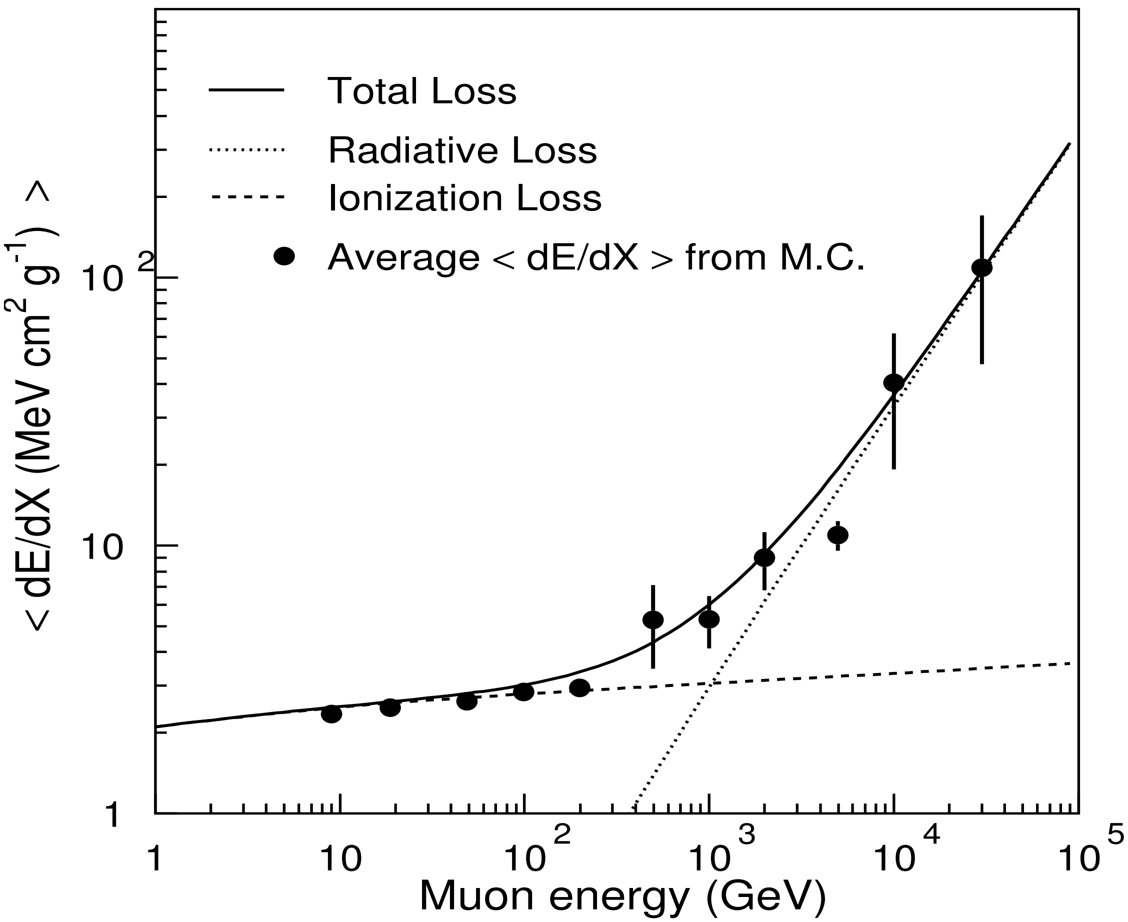


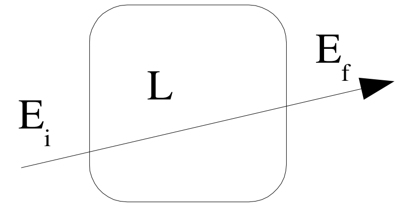
STOP



Muon Energy loss as a function of Energy

Non-Showering muon ⟵ ⟶ Showering Muon





$dE/dX = (E_i - E_f)/L$

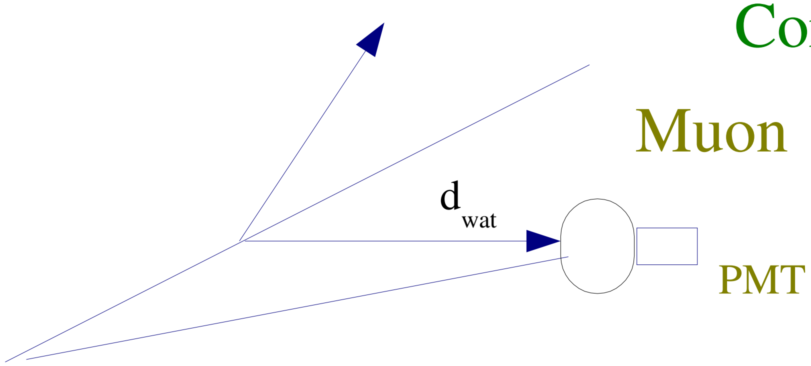
Distribution asymmetric for each muon energies

(Groom et al 03)

Reasonably good agreement of Monte-Carlo with PDG

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

Corrections to raw PMT charge



Apply following correction for every PMT in Cherenkov Cone

$$q_{corr} = \frac{q_{raw}\, d_{wat}\, \exp(d_{wat}/L_{atten})}{F(\theta)}$$

where L_{atten} = Water attenuation length,
d_{wat} = Distance from PMT to point of projection to μ 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:

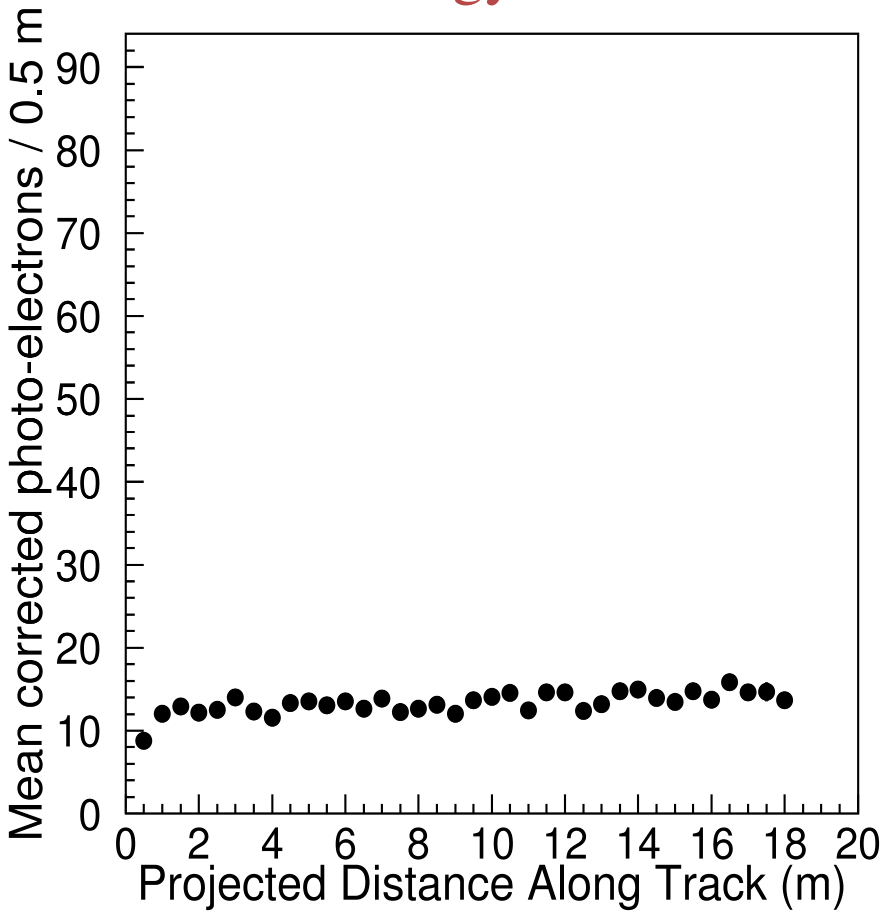
$$Q^i_{corr} = \sum_1^{N_{pmt}} \frac{q_{corr}}{N_{pmt}}$$

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

$$\sigma^2_{Q^i_{corr}} = \frac{1}{N^2_{pmt}} \sum_1^{N_{pmt}} \frac{q^2_{corr}}{q_{raw}}$$

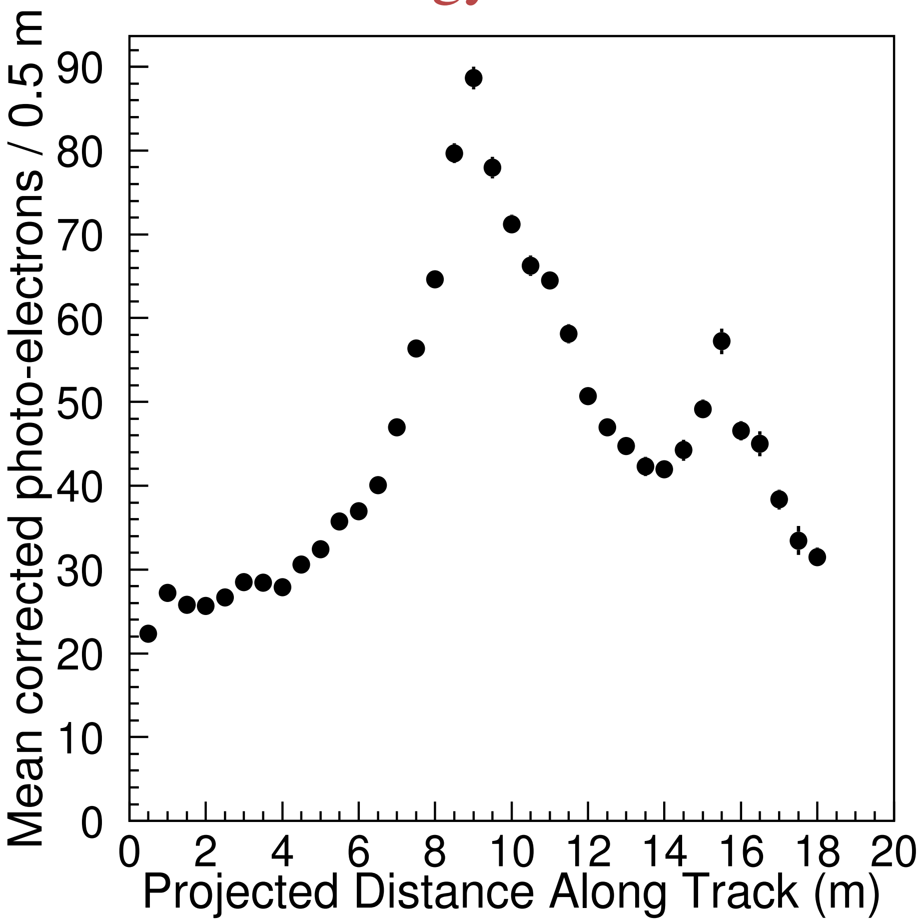
Corrected Charge Distribution Comparison of ionizing vs showering muon

Muon Energy = 20 GeV



dE/dX = 2.16 MeV/cm

Muon Energy = 10 TeV



dE/dX = 8.5 MeV/cm

Both simulated muons have same entry point and direction

Variables used for showering/non-showering separation

$$\underbrace{\chi^2 = \sum_{i=3}^{n-2} \{ [Q^i_{corr} - \langle Q_{corr} \rangle]^2 / \sigma^2_{Q^i_{corr}} \}}_{\text{Shape Comparison}}$$

where

$$\langle Q_{corr} \rangle = \frac{\sum_4^{n-3} Q^i_{corr} / \sigma^2_{Q^i_{corr}}}{\sum_4^{n-3} 1/\sigma^2_{Q^i_{corr}}}$$

(Average corrected charge averaged over entire muon length)

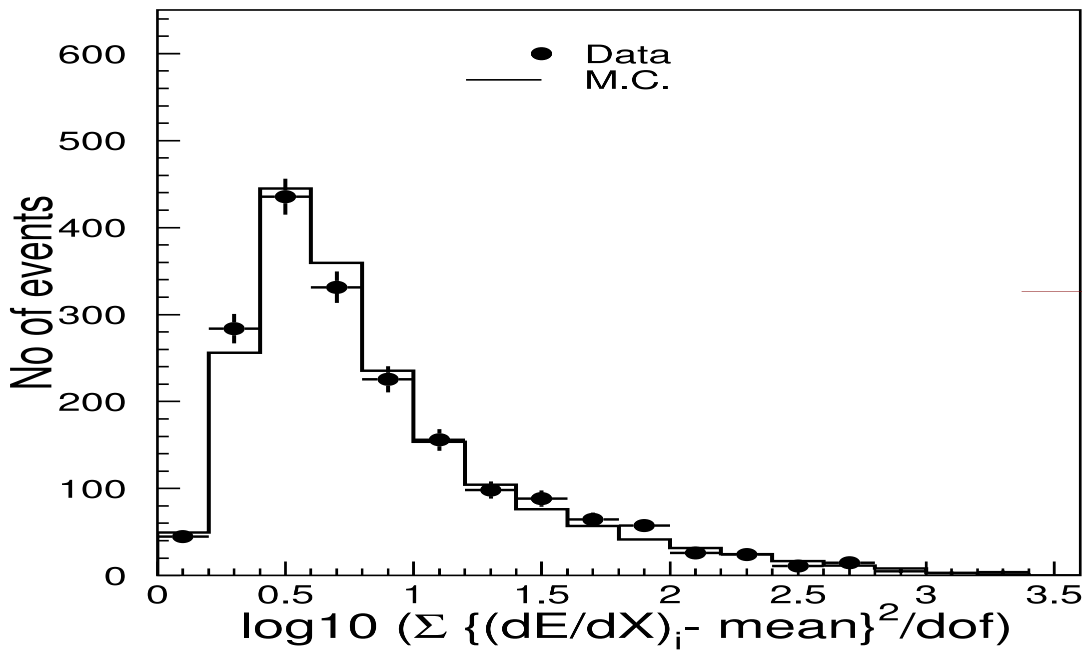
and

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

for a ionizing muon as a function of path-length

$$\underbrace{\Delta = [\langle Q_{corr} \rangle - q(l)]}_{\text{Absolute Corrected Charge Comparison}} \longrightarrow$$

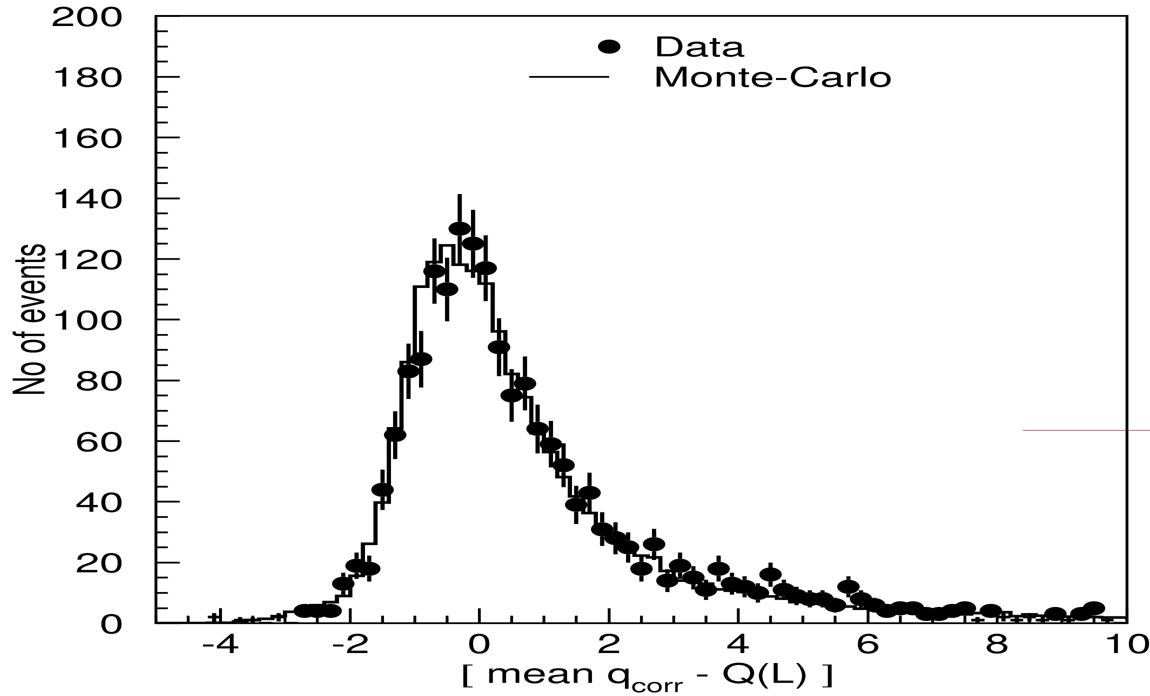
Difference in average corrected charge of given muon – same for ionzing muon



Variables when applied to 100yr upmu NEUT Monte-Carlo

χ^2 comparison

for data and monte-carlo



Δ comparison

for data and monte-carlo

SHOWERING CUT USED

$\chi^2/DOF > 40$ and $\Delta > 1.0$ OR $\chi^2/DOF > 30$ and $\Delta > 2.0$

OR $\chi^2/DOF > 20$ and $\Delta > 2.5$ OR $\chi^2/DOF > 50$ and $\Delta > 0.5$

OR $\Delta > 4.5$

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

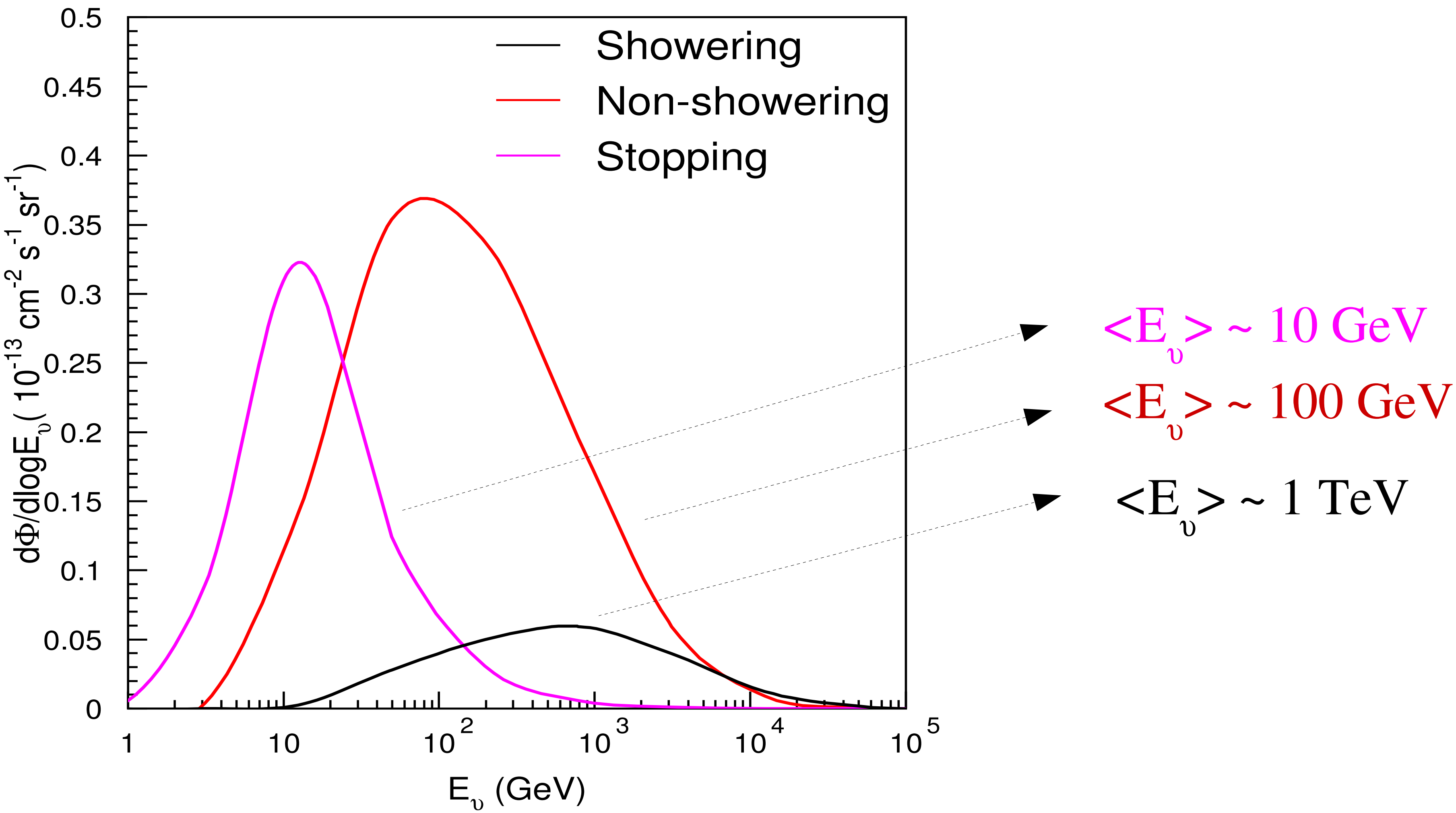
Efficiency = 71 % where,

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

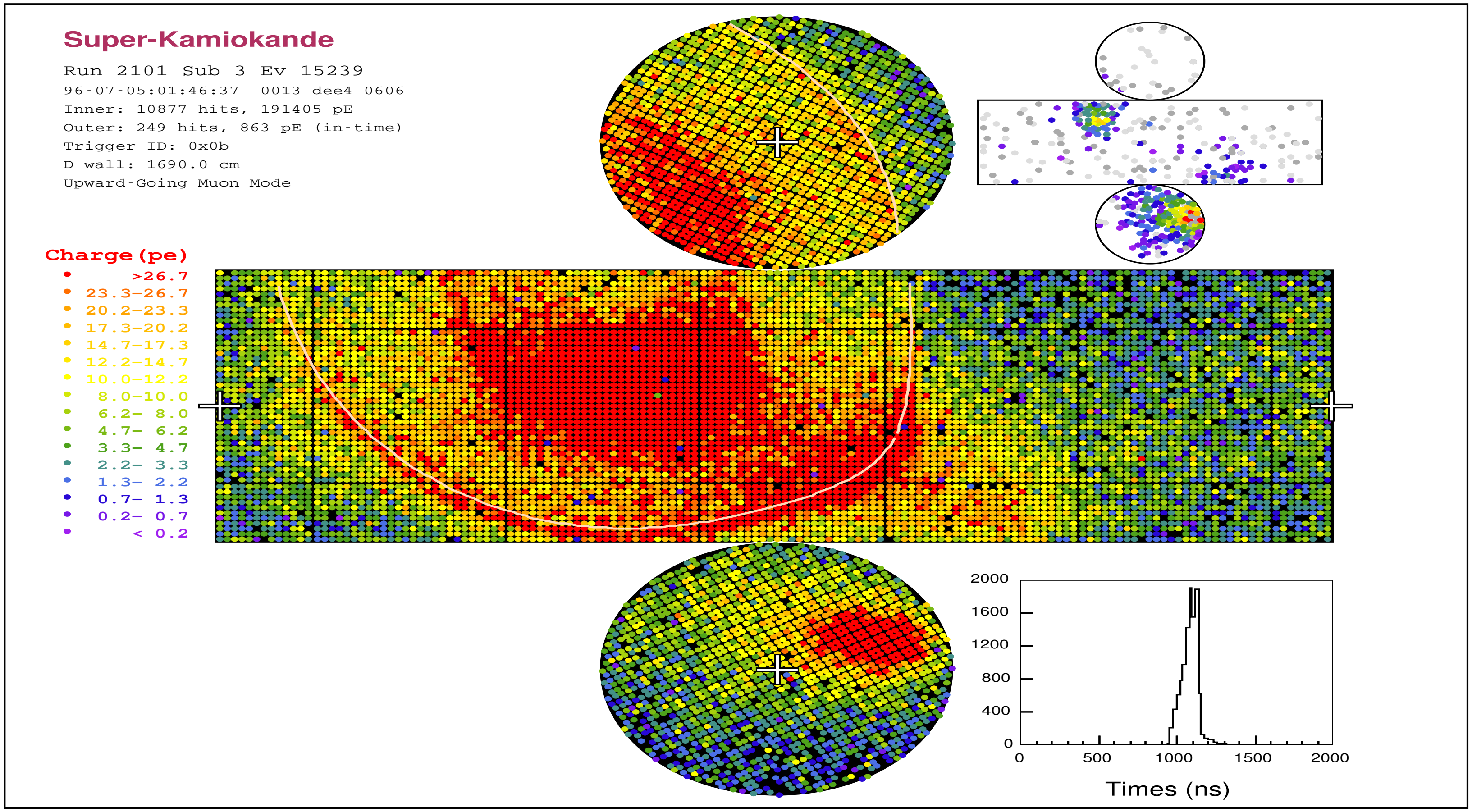
ΔE = Energy deposited by muon in inner detector

ΔX = Length of muon in inner detector

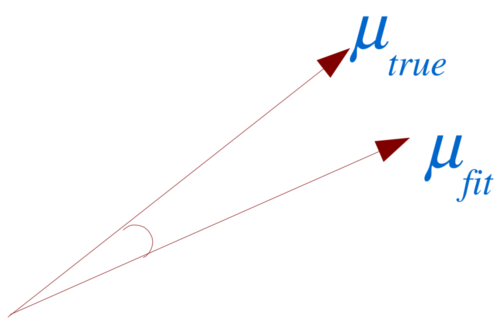
NEUTRINO ENERGY SPECTRA

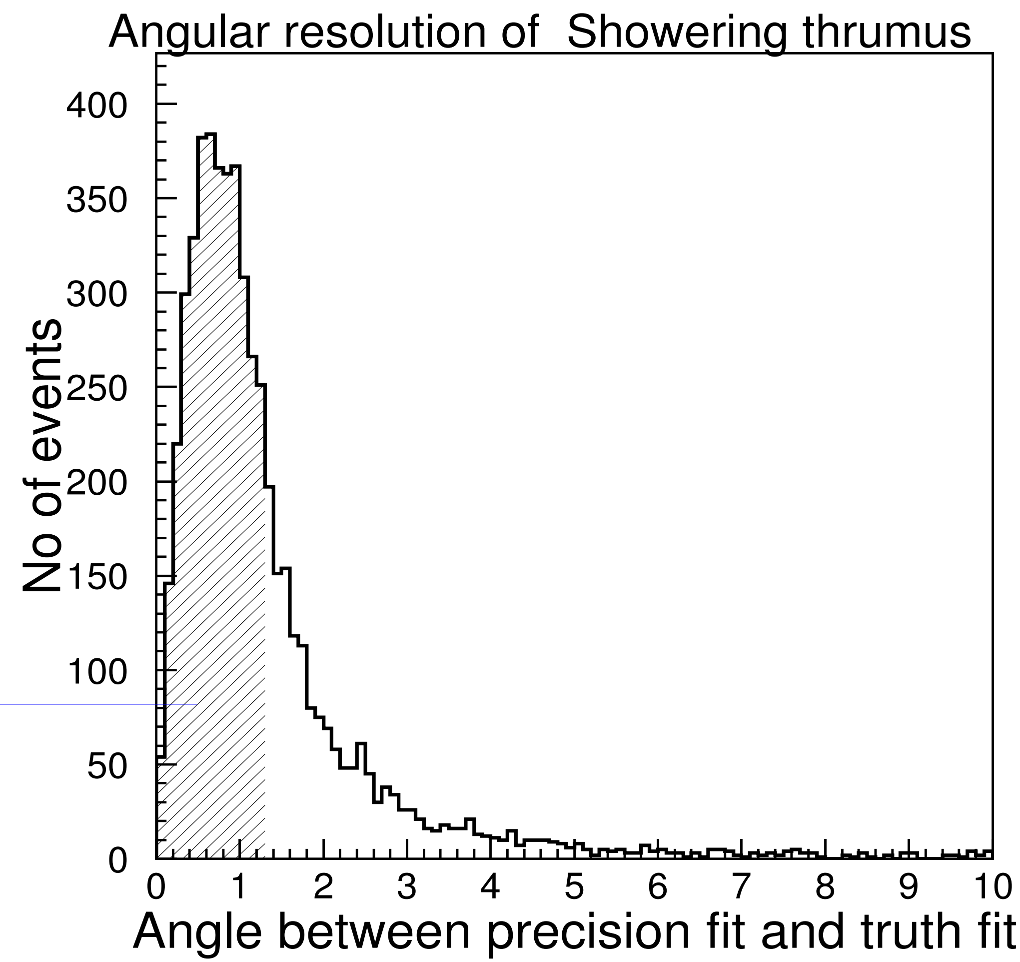


Event Display of upward showering muon



Angular Resolution of showering muons





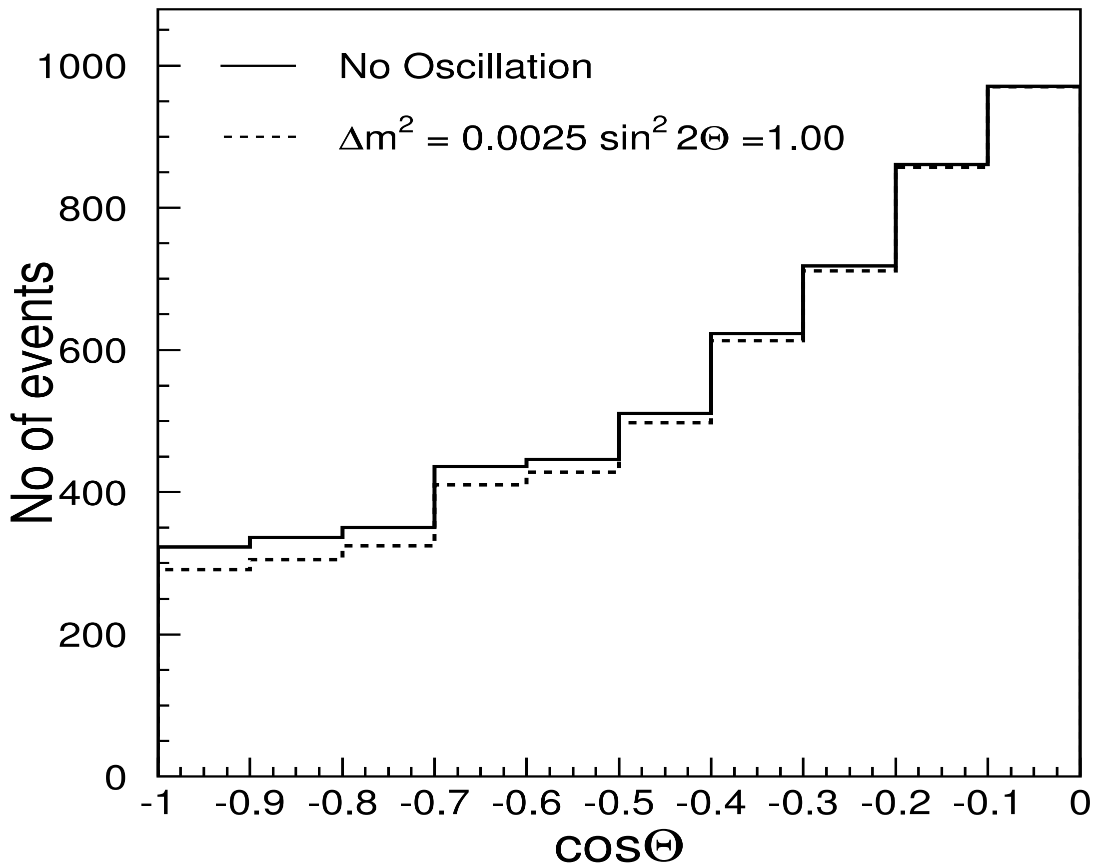
Shaded region contains 68 % of total area

Angular resolution = 1.25°

Thrugoing muons : Angular resolution ~ 1°

Stopping muons : Angular resolution ~ 1°

Zenith-angle distribution of showering muons

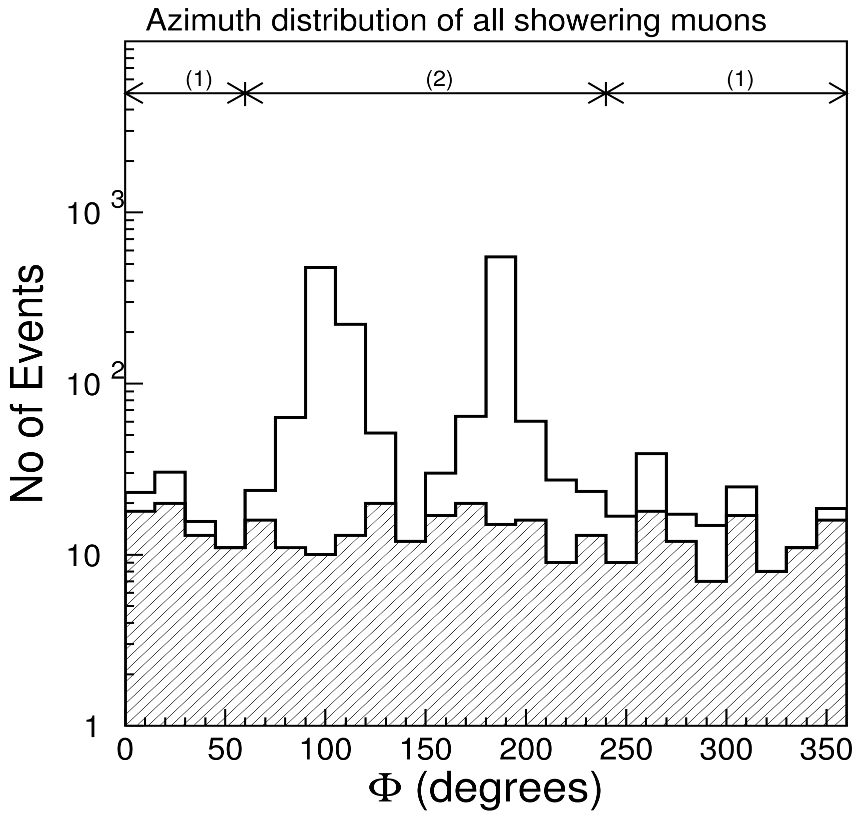


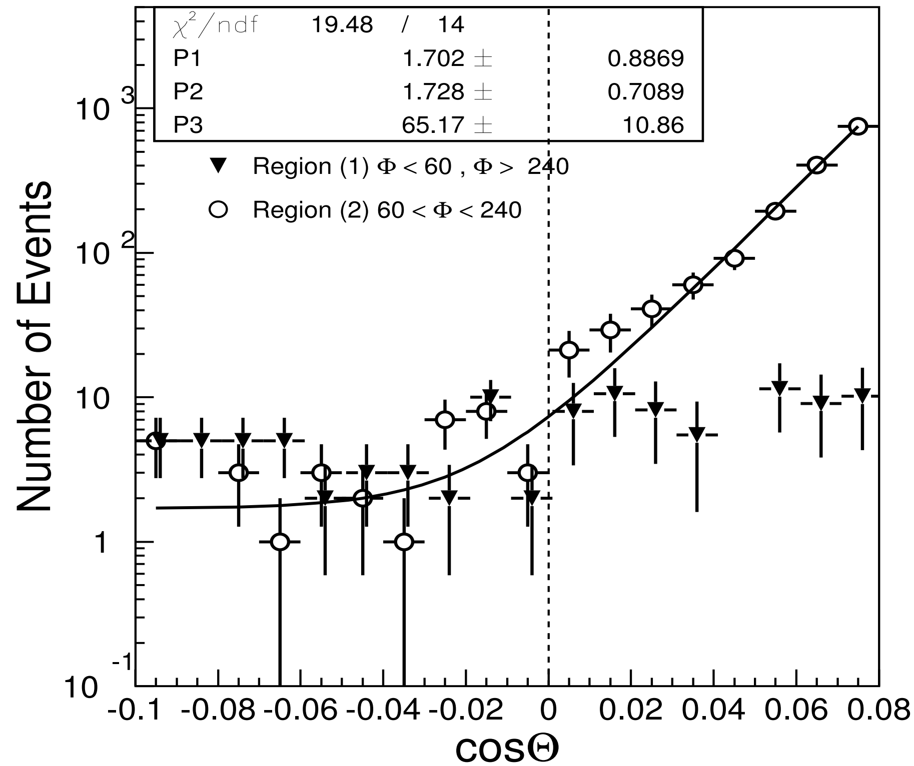
Showering muons relatively insenstive to oscillation

==> 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: $f[\cos(\theta)] = p1 + \exp[p2 + p3\cos(\theta)]$

$N_{bkgd} = 8.63^{+12}_{-5}$ for $\cos(\theta) > -0.1$

(Asymmetric distribution because of bump near horizon)

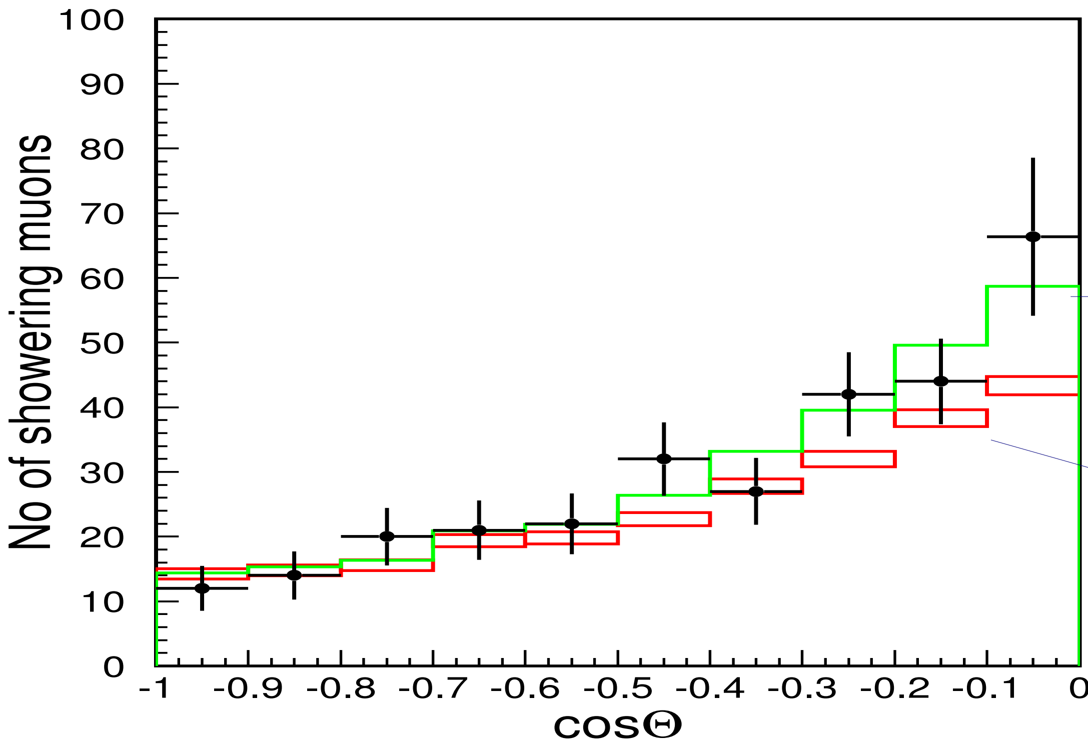
Showering Muon Oscillation Results

Best-fit (physical region) :

$\chi^2 = 4.68 / 7$ dof for $(\Delta m^2, \sin^2 2\theta) = (0.0104\ \mathrm{eV}^2, 0.9)$

Best-fit (null oscillation) :

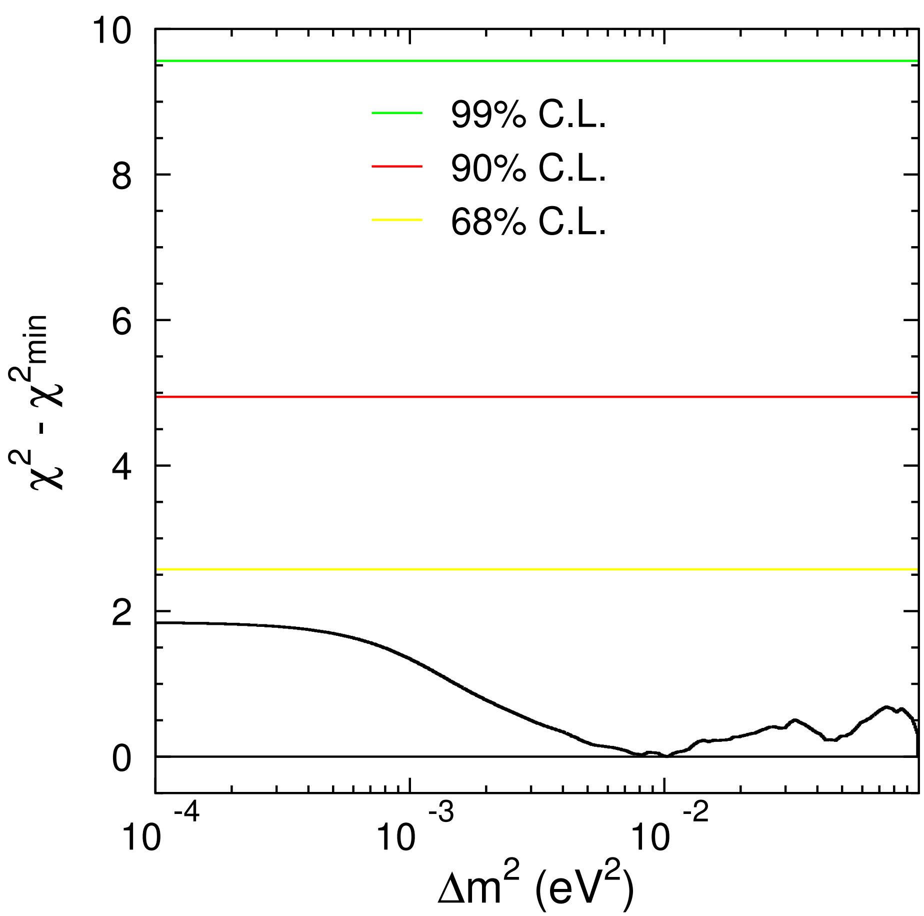
$\chi^2 = 6.51/9$ dof

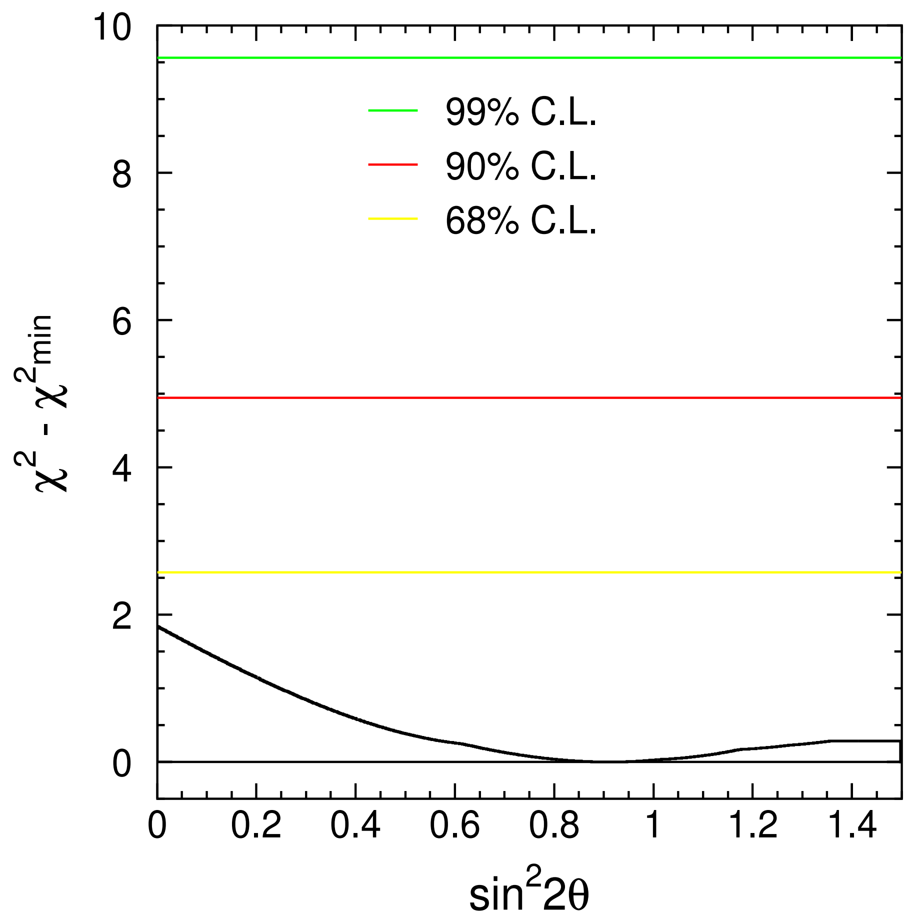


Zenith angle comparison at best fit point

Null oscillation normalized by livetime

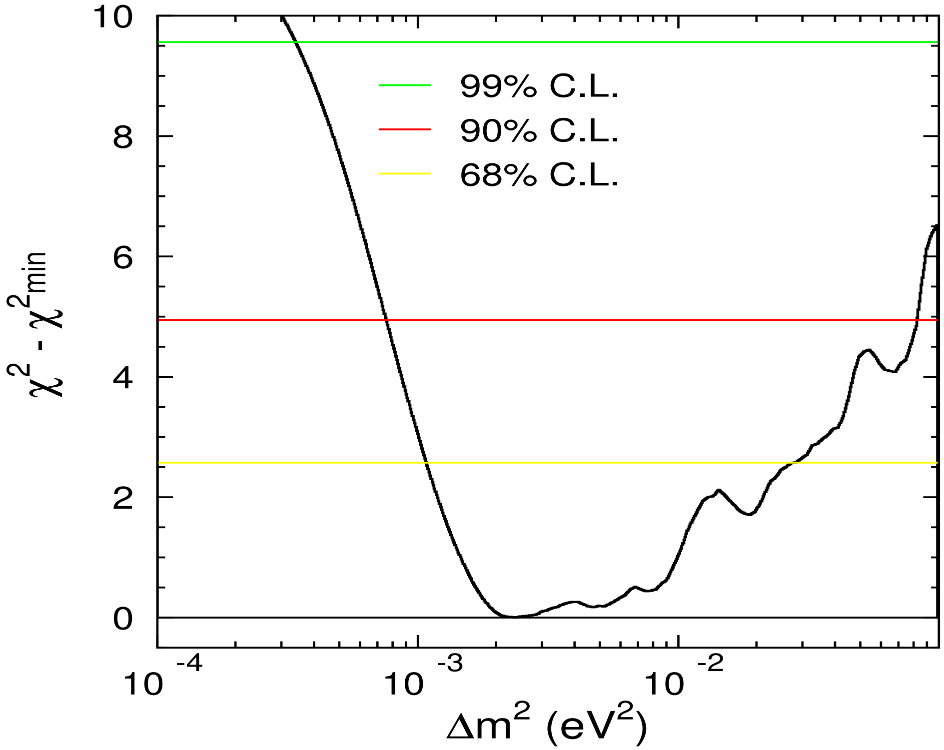
Projections of chi-square distributions for showering muons

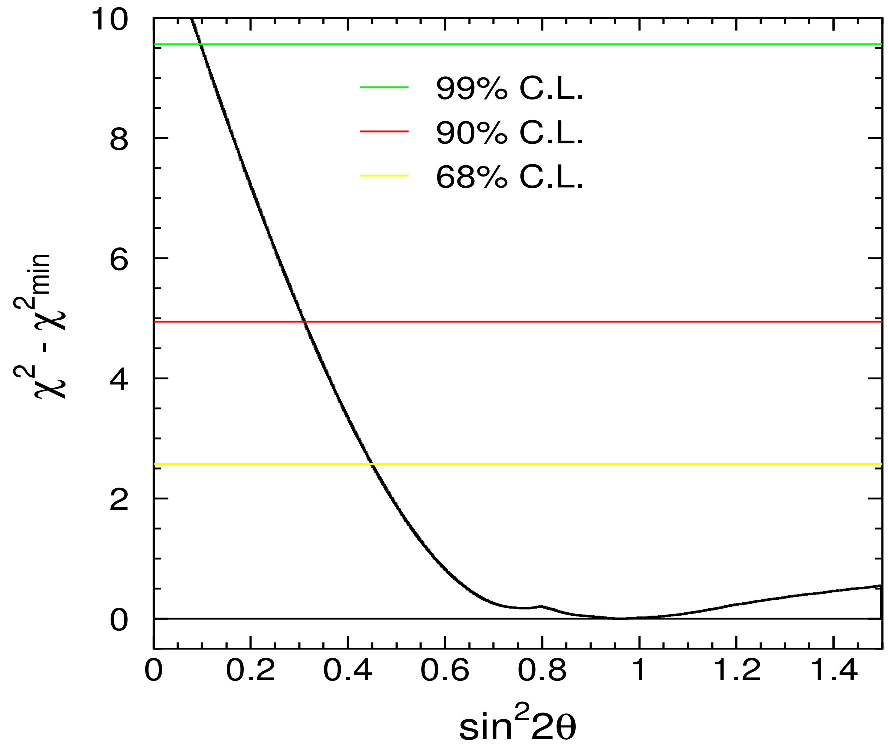




Null oscillation allowed even at 68 % confidence level as expected for this high energy ν_μ with mean energy of ~ 1 TeV

Comparison with all upward thrugoing muons





Best-fit : χ^2 = 7.64 / 7 dof for (Δm^2, $\sin^2 2\theta$) = (0.0024 eV^2, 0.96)

Best-fit at null oscillation : χ^2 = 19.6/9 dof

→ Upward thrugoing 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 ~ 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)*