PHYSICS AND ASTRONOMY WITH SHOWERING UPWARD MUONS IN SUPER-KAMIOKANDE

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Ph.D Final Oral Examination

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Outline of the Talk:

- Super-Kamiokande detector

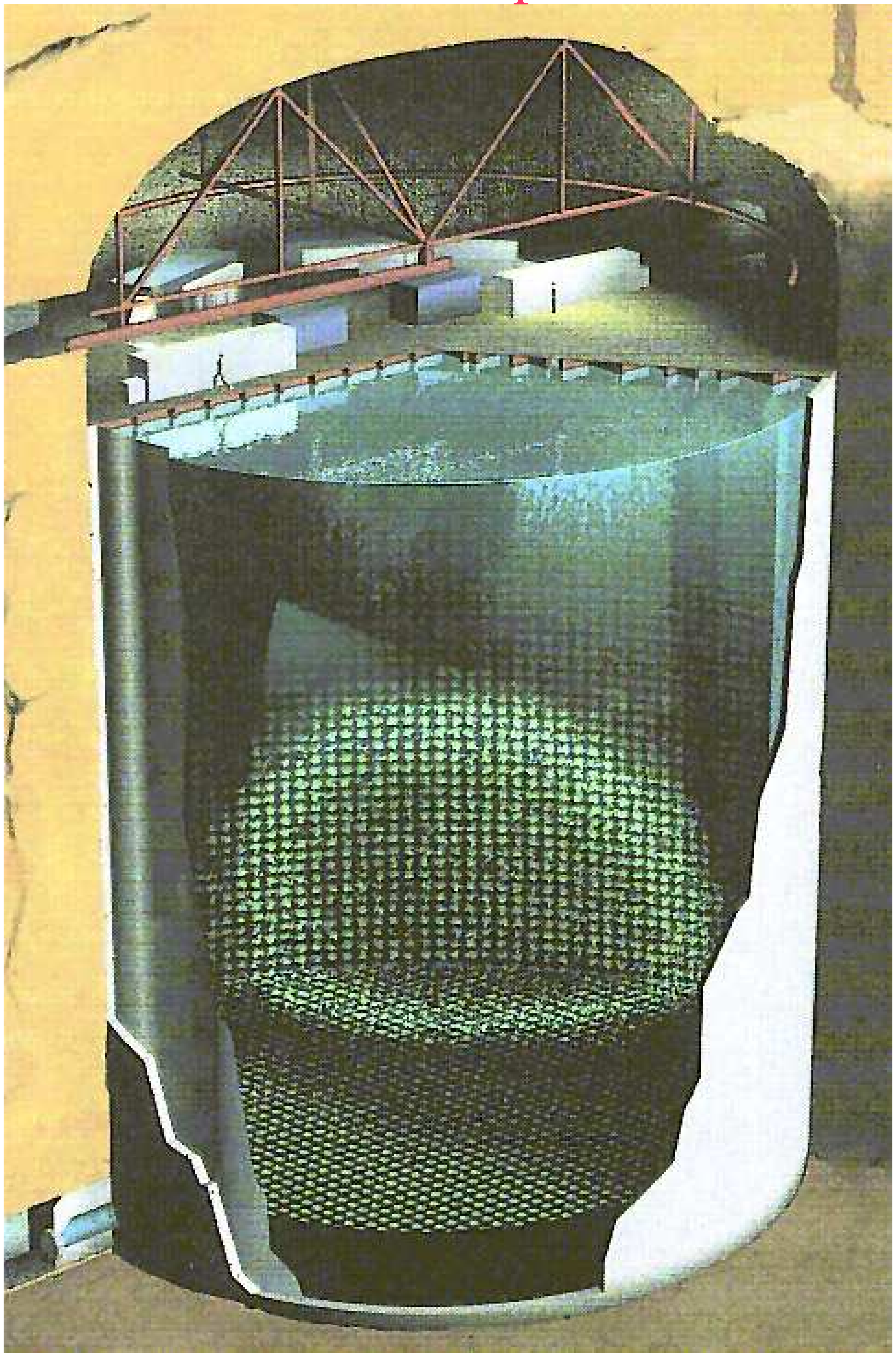
PHYSICS

- Dataset used and its classification (upward thru + stopping muons)
- Subdivision of upward thrugoing muons (showering + non-showering)
- Overview of algorithm used to identify upward showering muons
- Energy Spectrum of all 3 categories of events
- Oscillation Analayis using upward showering muons

ASTRONOMY

- Overview of astrophysical searches with upward muons
- Gamma-ray burst (GRB) and Soft-gamma-ray repeater (SGR) searches
- Diffuse flux searches
- WIMP searches

Super-Kamiokande Detector



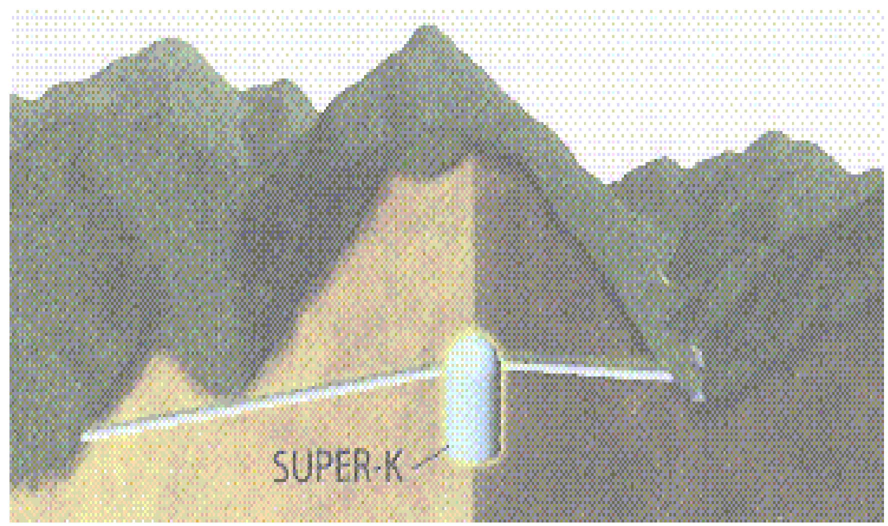
~ 40m X 40 m tank containing
50 kton of ultra pure water

Water Cherenkov detector

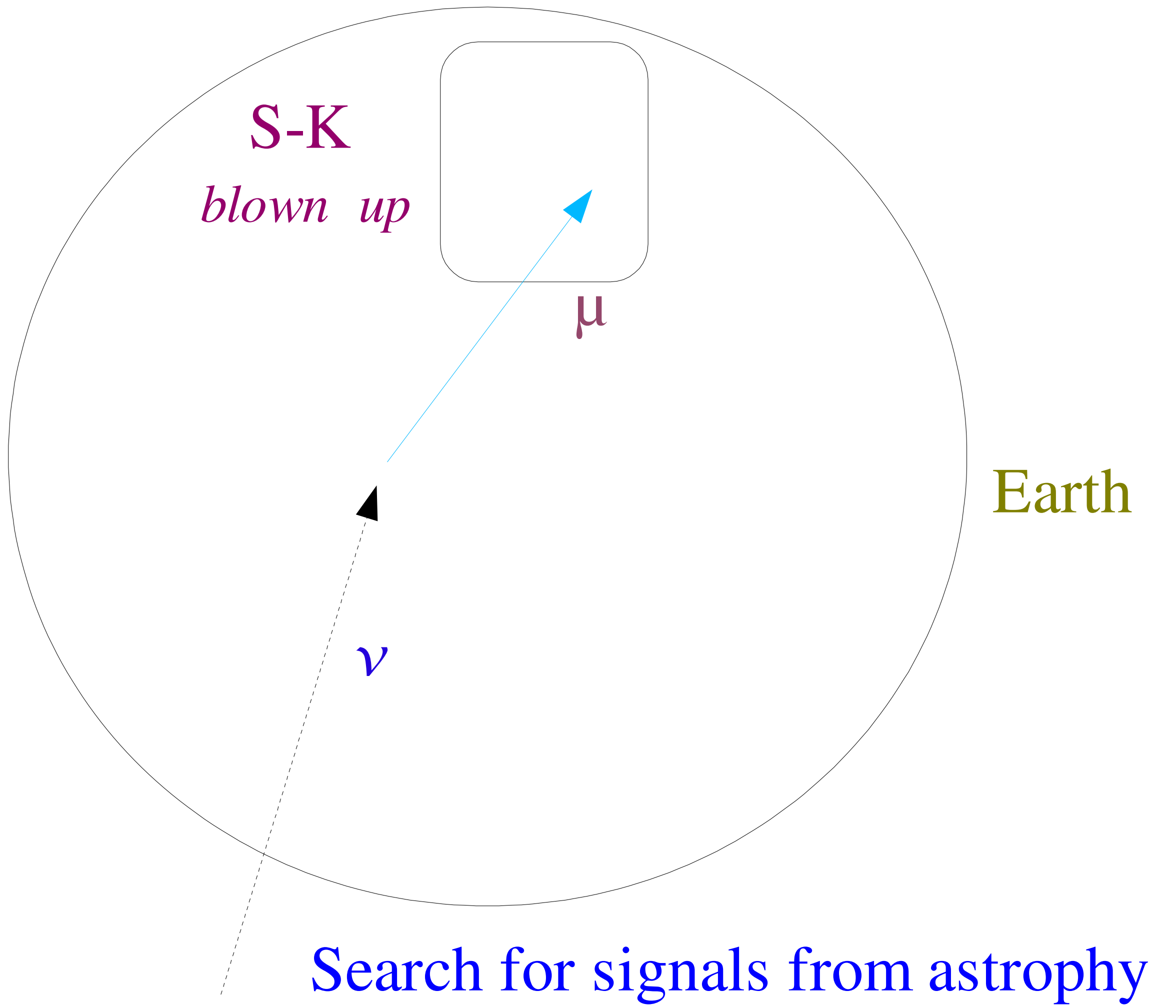
11146 20-inch PMTs in ID

1885 8-inch PMTs in OD

Located 1 km under mountain
in a Zn mine in Japan
Phase 1 : 1996 - 2001



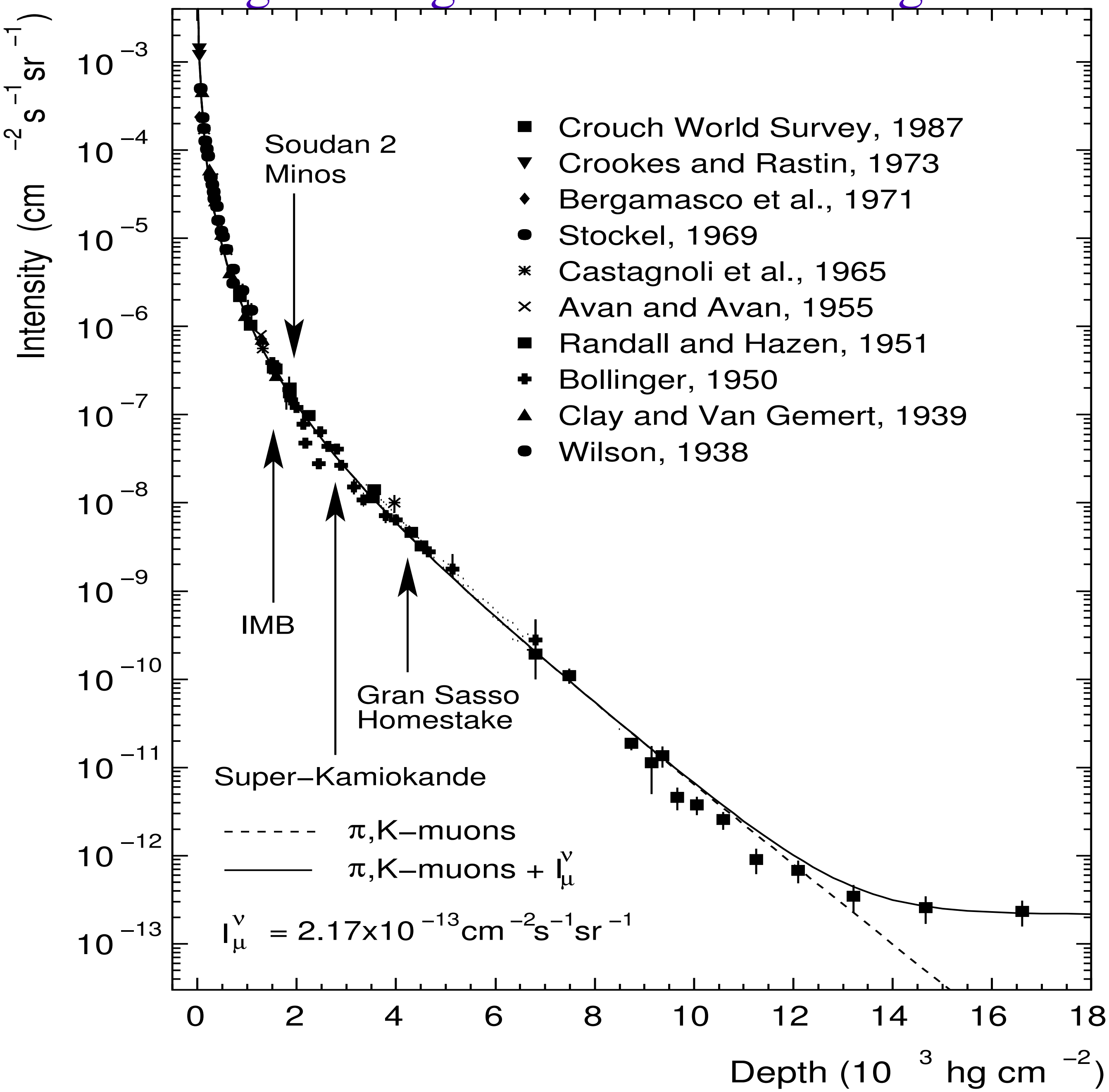
Subject of this Thesis = Upward Going Muon Events



Search for signals from astrophysical sources in upward going muons

Background from cosmic ray interactions in atmosphere on opposite hemisphere of earth

Need to go underground to reduce background from cosmic ray muons

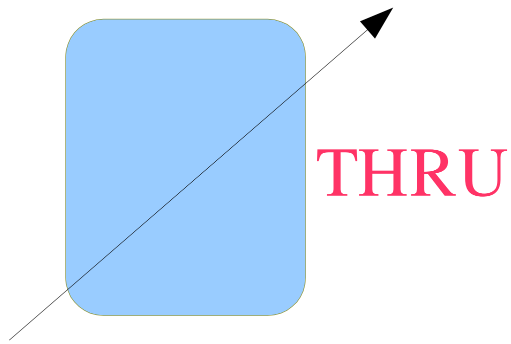


At Super-K depth

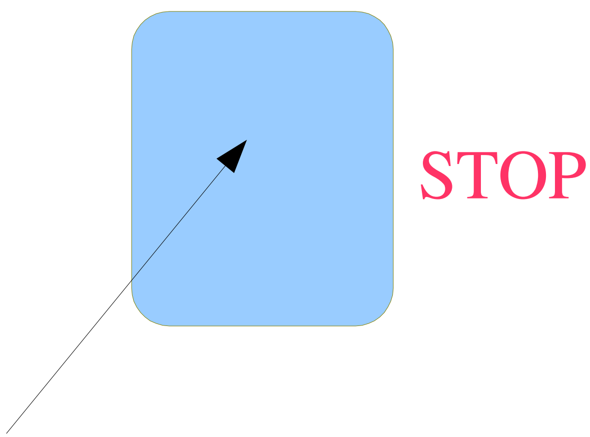
$$\frac{\mu\uparrow \text{ Flux}}{\mu\downarrow \text{ Flux}} \sim 10^{-5}$$

Bugaev et al 98

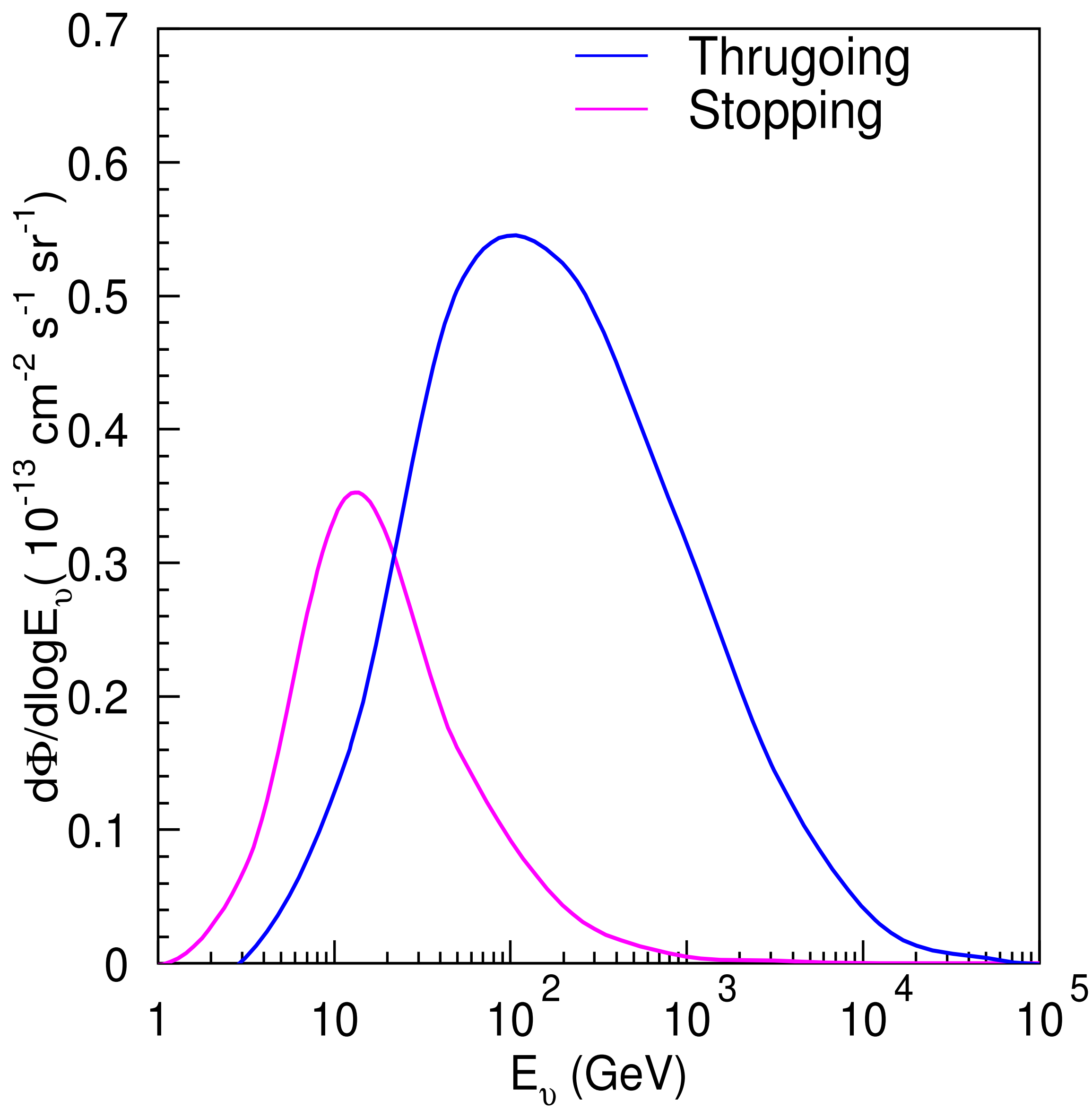
Upward Going Muons In Super-K



$$\langle E_\nu \rangle = 100\,GeV$$



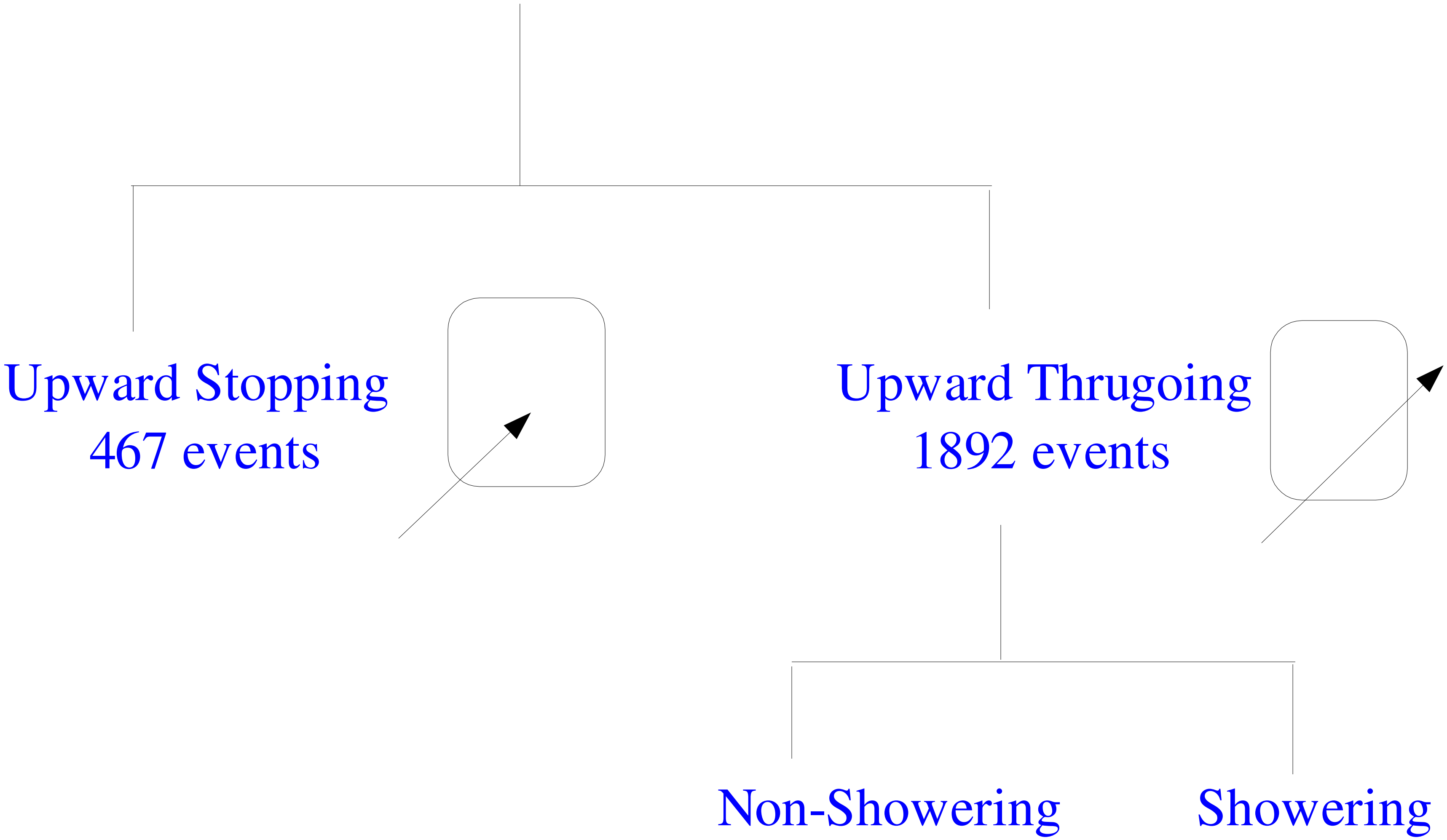
$$\langle E_\nu \rangle = 10\,GeV$$



Event display of an Upstop Muon

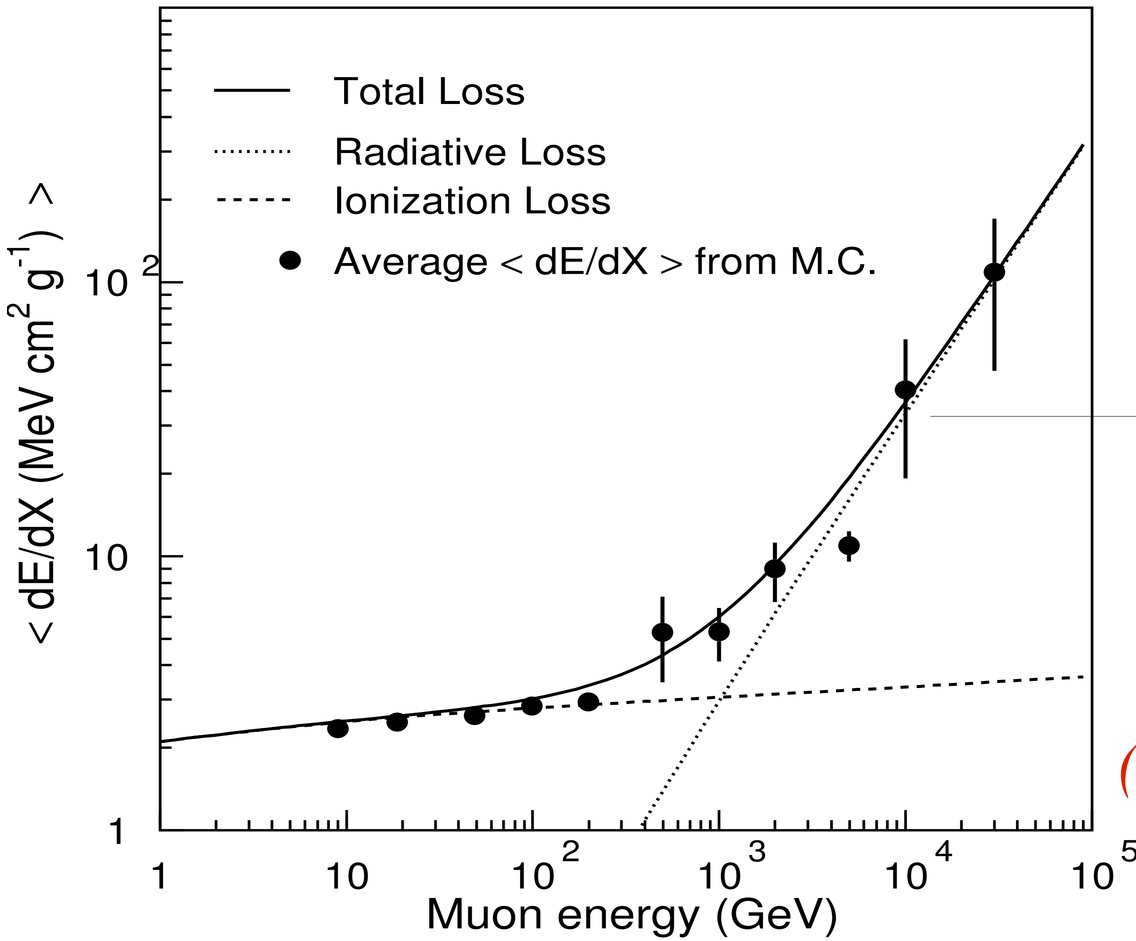
Event Display of Upthru Muon

Upward Muons originally divided into two categories



Non-Showering muons

Showering muons

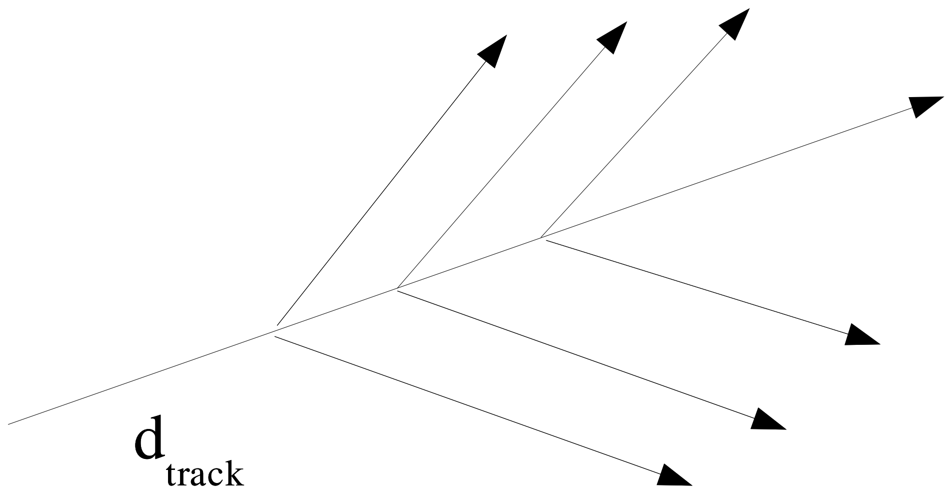


Muon energy loss in water

(Groom et al 02)

Muon critical energy in water ~ 1 TeV

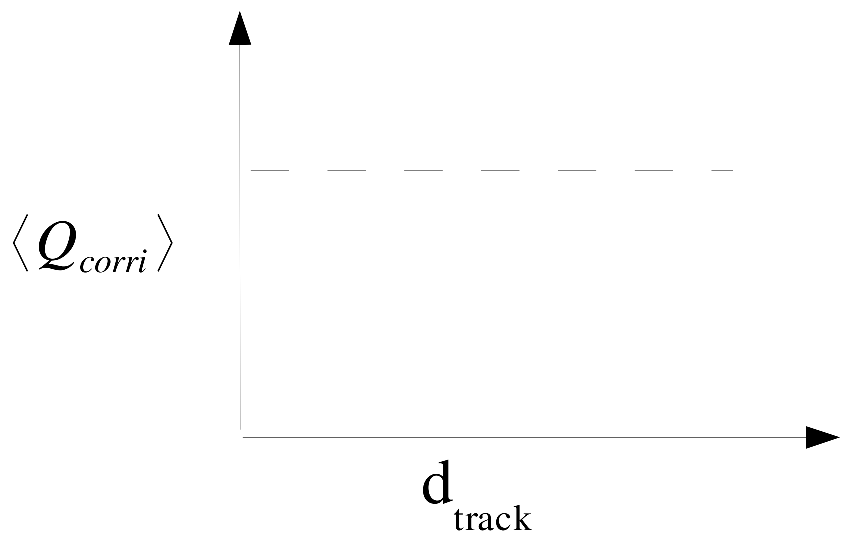
Monte-Carlo dE/dX agrees with theoretical curves



Muon track

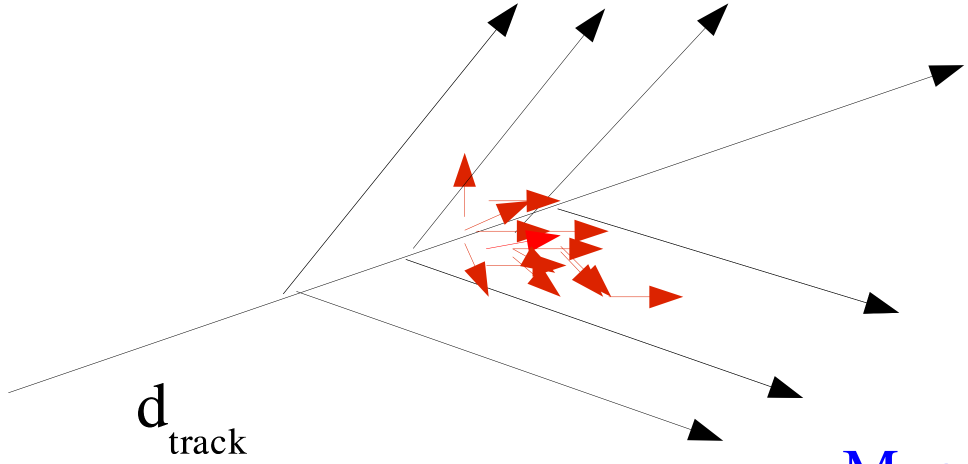
For each PMT in cone find point of projection along muon trajectory

Calculate avg corrected charge along each 0.5 m along muon track



For an ionizing muon

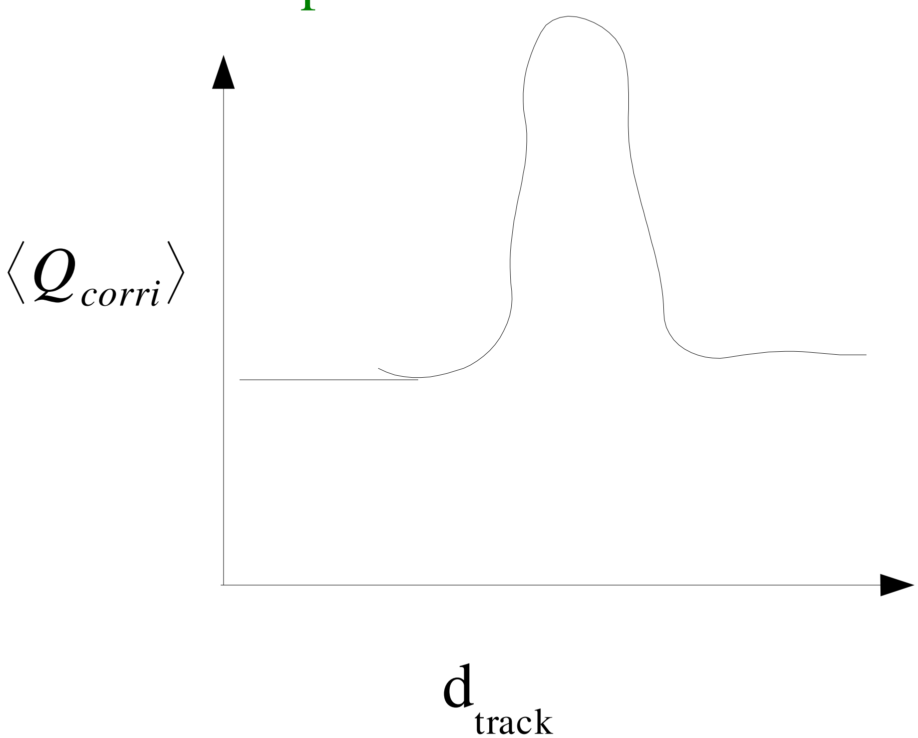
$<Q_{corri}>$ ~ constant along the muon track



Muon track

Extra Cerenkov light from $e^+ e^-$ pairs

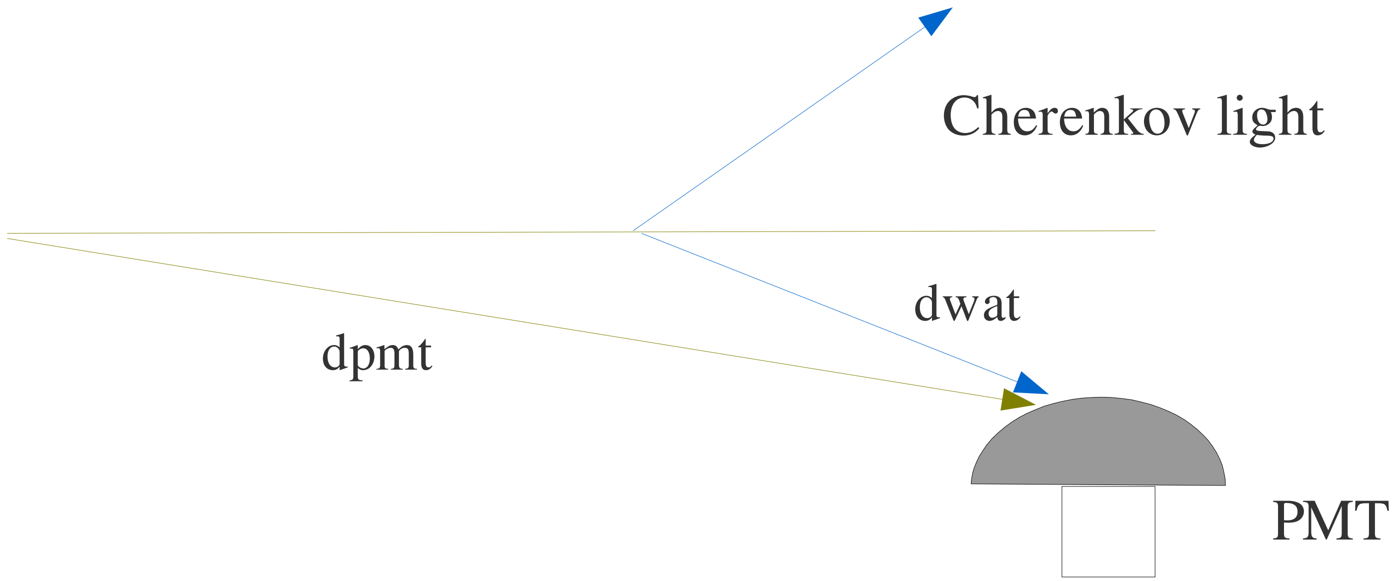
Muon which loses energy through radiative processes initiates an electromagnetic shower



A showering muon should show huge upward spikes along muon track

Strategy : Apply corrections to PMT charge to account for:

- PMT acceptance
- Light scattering
- Attenuation due to photon travel distance

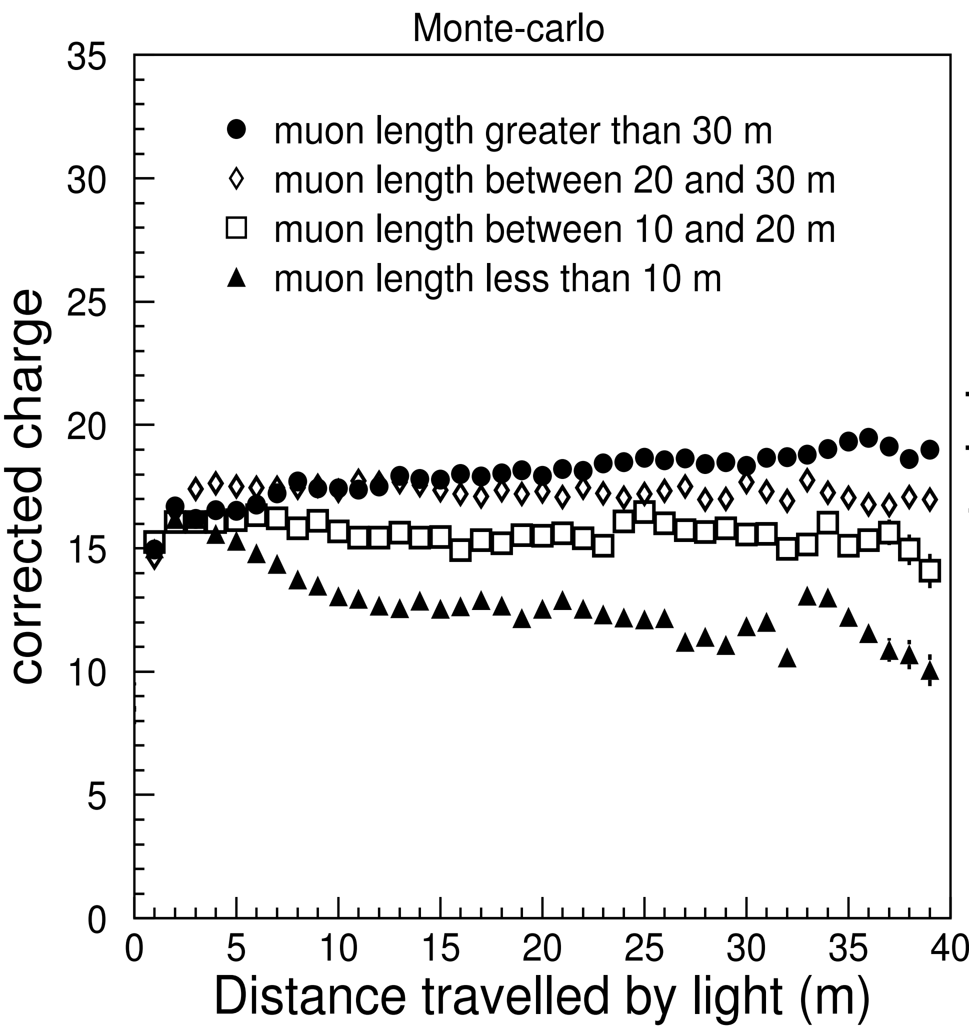


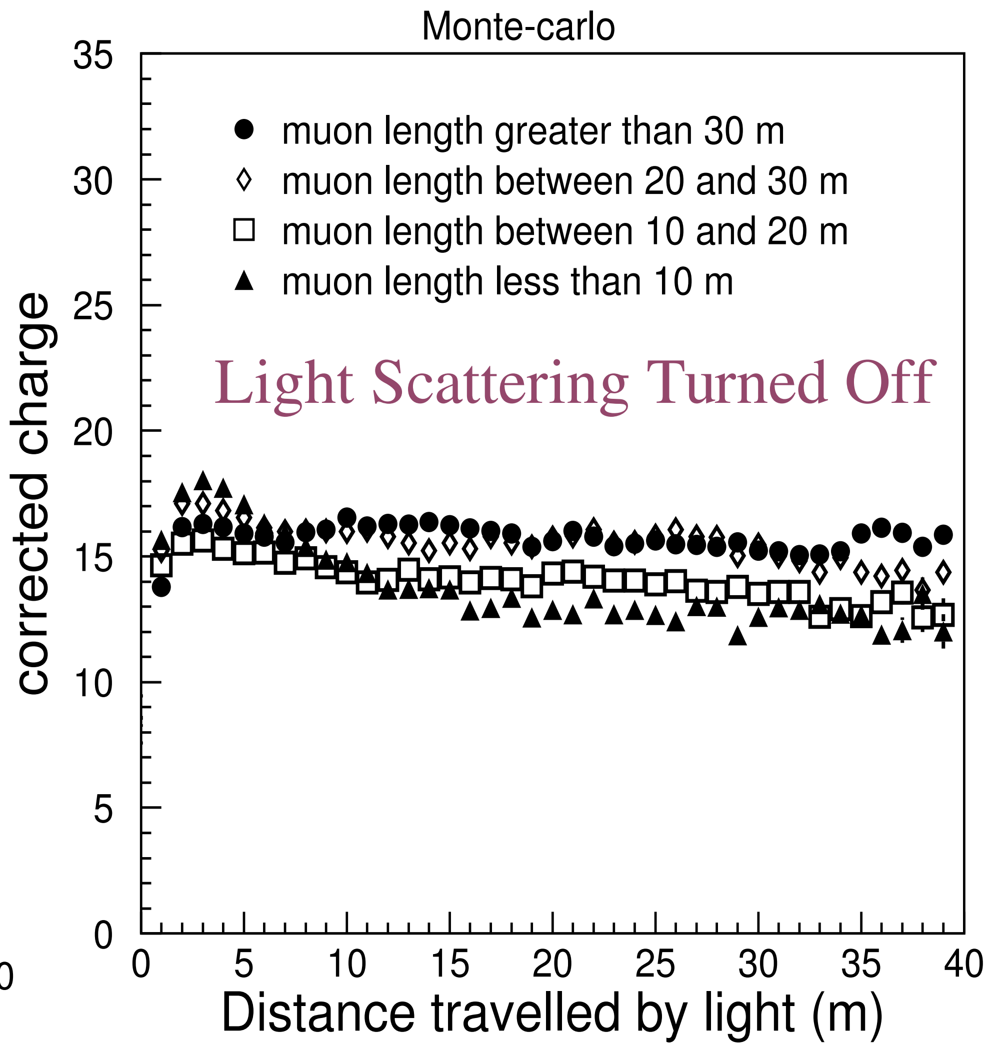
$$Q_{corr} = \frac{Q_{raw}\ d_{wat}\ \exp\left(d_{wat}/L_{atten}\right)}{F(\theta)}$$

L_{atten} = Light attenuation length

The above corrections not enough

Light scattering into the cone increases the effective charge as muon path length increases



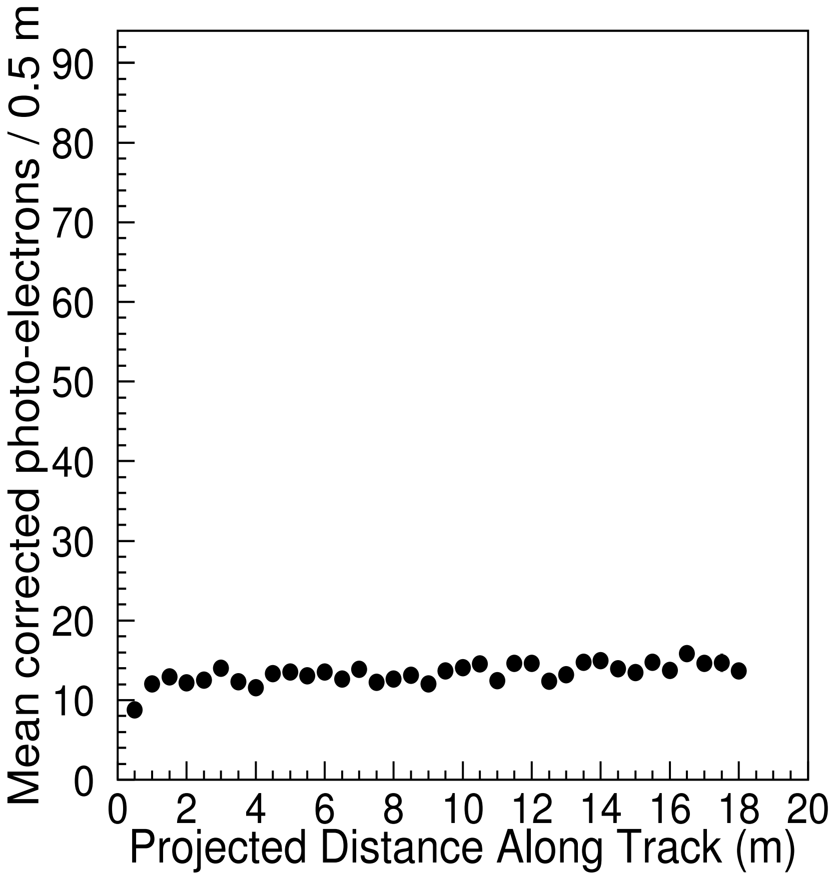


Fit the mean charge of an ionizing muon to 2nd order polynomial

Generated Monte-carlo samples with different
energies using track directions and entry points from downward muon data

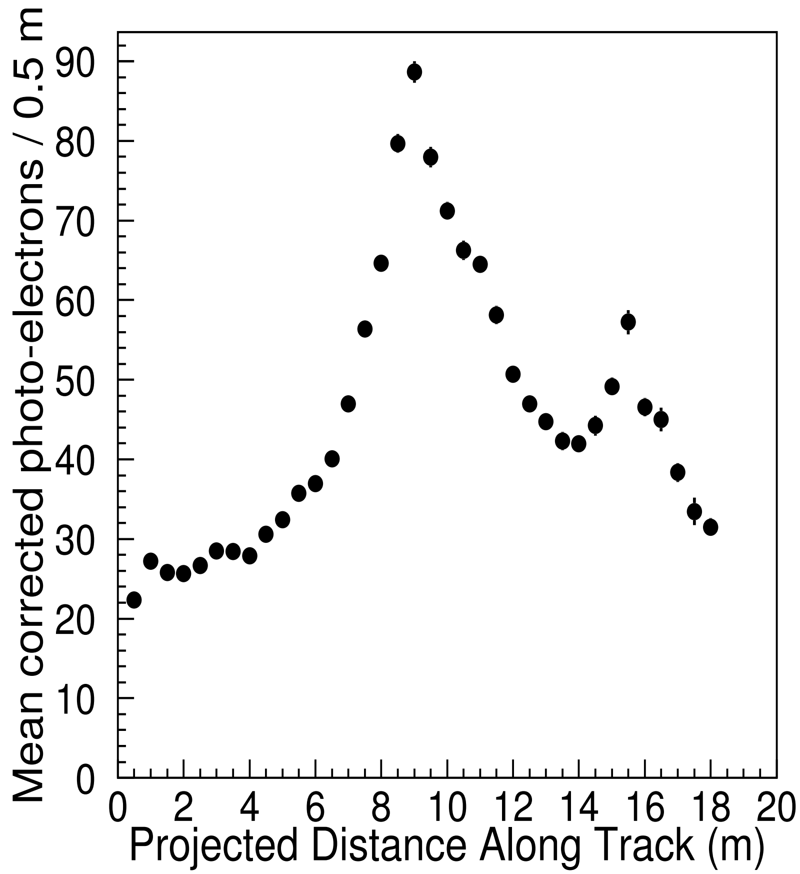
Both muons have same entry point and directions

Muon energy = 20 GeV



$$\langle dE/dX \rangle = 2.2\, MeV/cm$$

Muon energy = 10 TeV



$$\langle dE/dX \rangle = 8.5\, MeV/cm$$

Show Event Display of the 20 Gev muon event with and without corrections
and same for 10 TeV muon

For each upward muon event defined a : χ^2

$$\chi^2 = \sum_{i=3}^{n-2} \{[\langle Q_{corri} \rangle - \langle \bar{Q}_{corr} \rangle]^2 / \sigma^2_{Q_{corri}} + [\langle \bar{Q}_{corr} \rangle - q(l)]^2 / \sigma^2_{q(l)}\}$$

Shape Comparison Normalization Comparison

where

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

and

$q(l) = \langle \bar{Q}_{corr} \rangle$ for a ionizing muon as a function of path-length

Event considered showering iff :

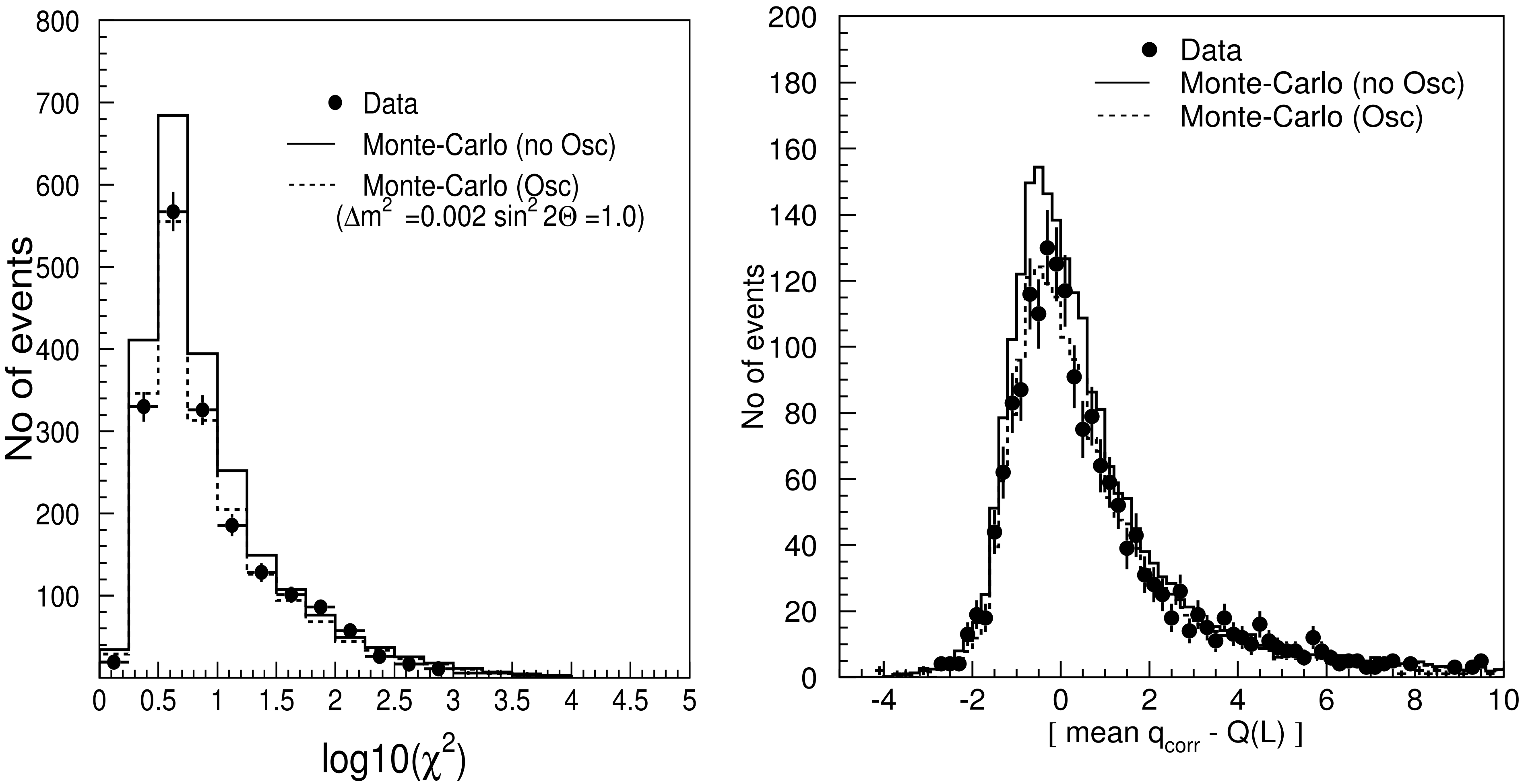
$\chi^2 / D.O.F. > 25$ and $[\langle \bar{Q}_{corr} \rangle - q(l)] > 2.0\ pe$

or

$[\langle \bar{Q}_{corr} \rangle - q(l)] > 4.0\ pe$

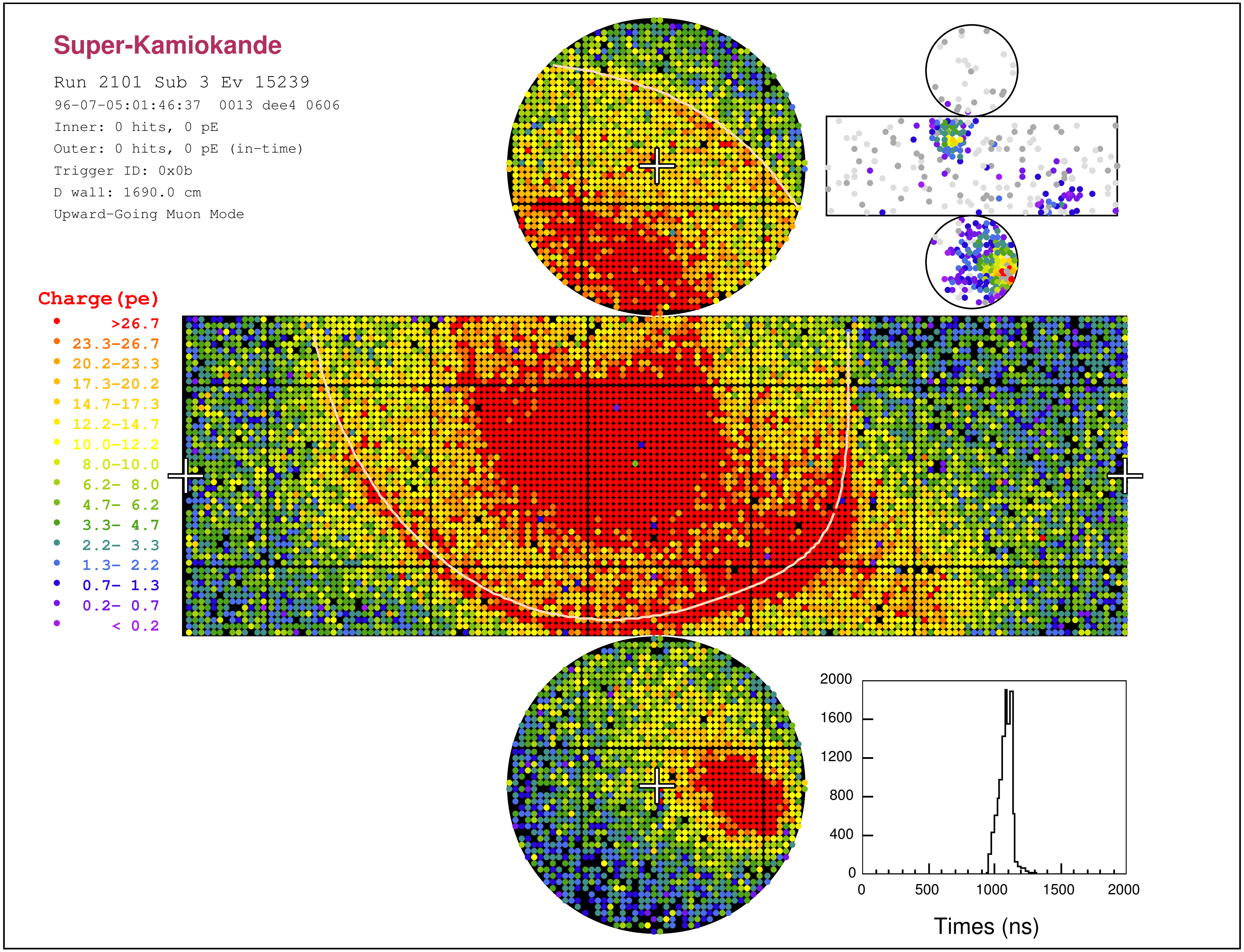
Consistency Check:

Does the distribution of showering variables agree for data and atmospheric neutrino monte-carlo?



Yes

EVENT DISPLAY OF AN UPWARD SHOWERING MUON

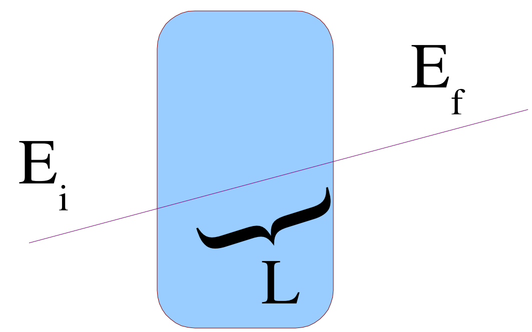


Showering Detection Efficiency

$$\text{Efficiency} = \frac{\text{\# of events identified by algorithm as showering}}{\text{\# of events with } \Delta E/\Delta X > 2.85 \text{ MeV/cm}}$$

where

$$\Delta E/\Delta X = (E_i - E_f)/L$$



where E_i , E_f
are true muon energies from monte-carlo

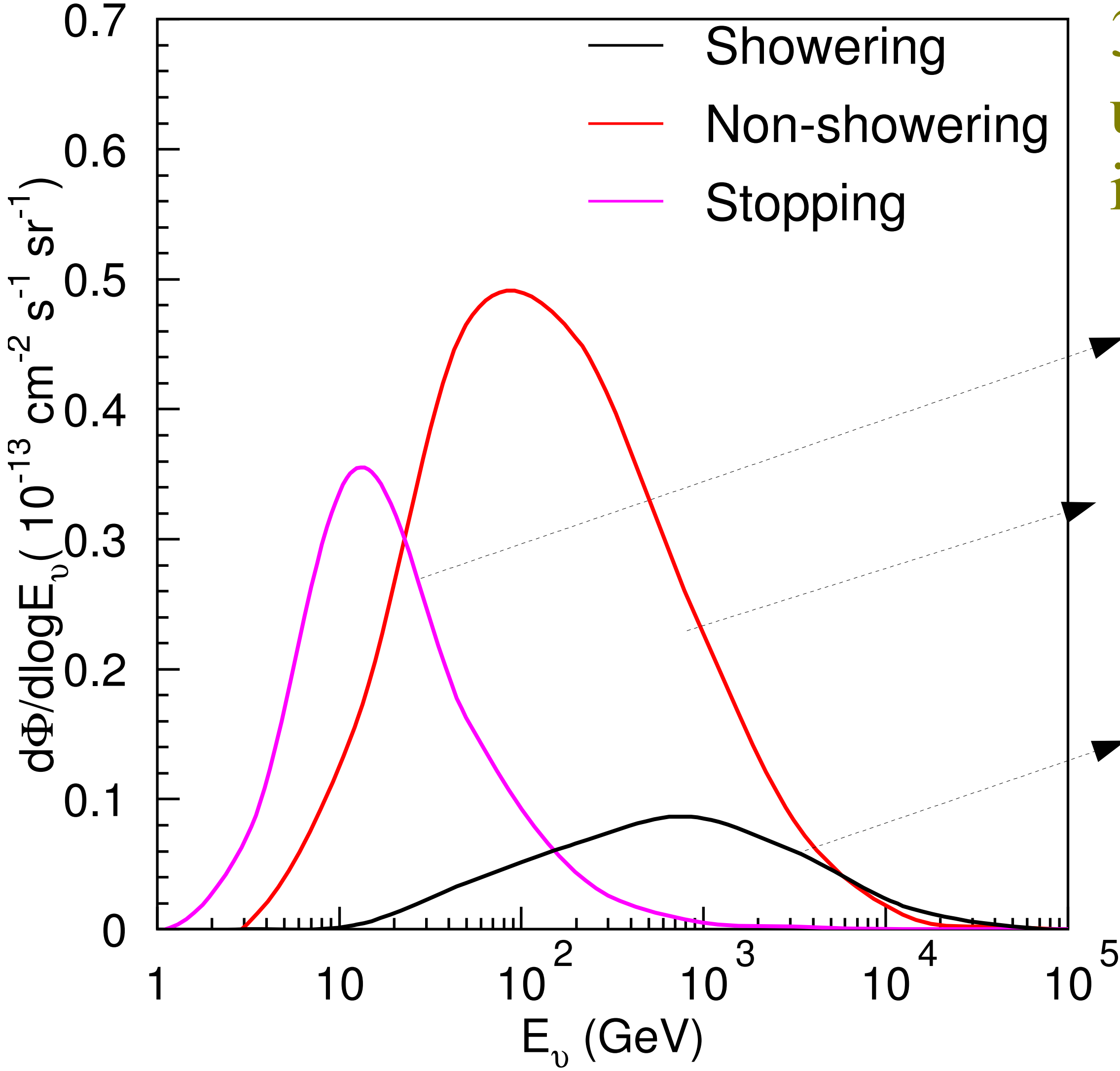
Efficiency ~ 75 %

Amount of background from non-showers ~ 5%

Total of 332 events in upthru dataset

Total of 3129 events in 40 year upthrumu monte-carlo

Applied Showering Algorithm to 40 yr. Monte-Carlo

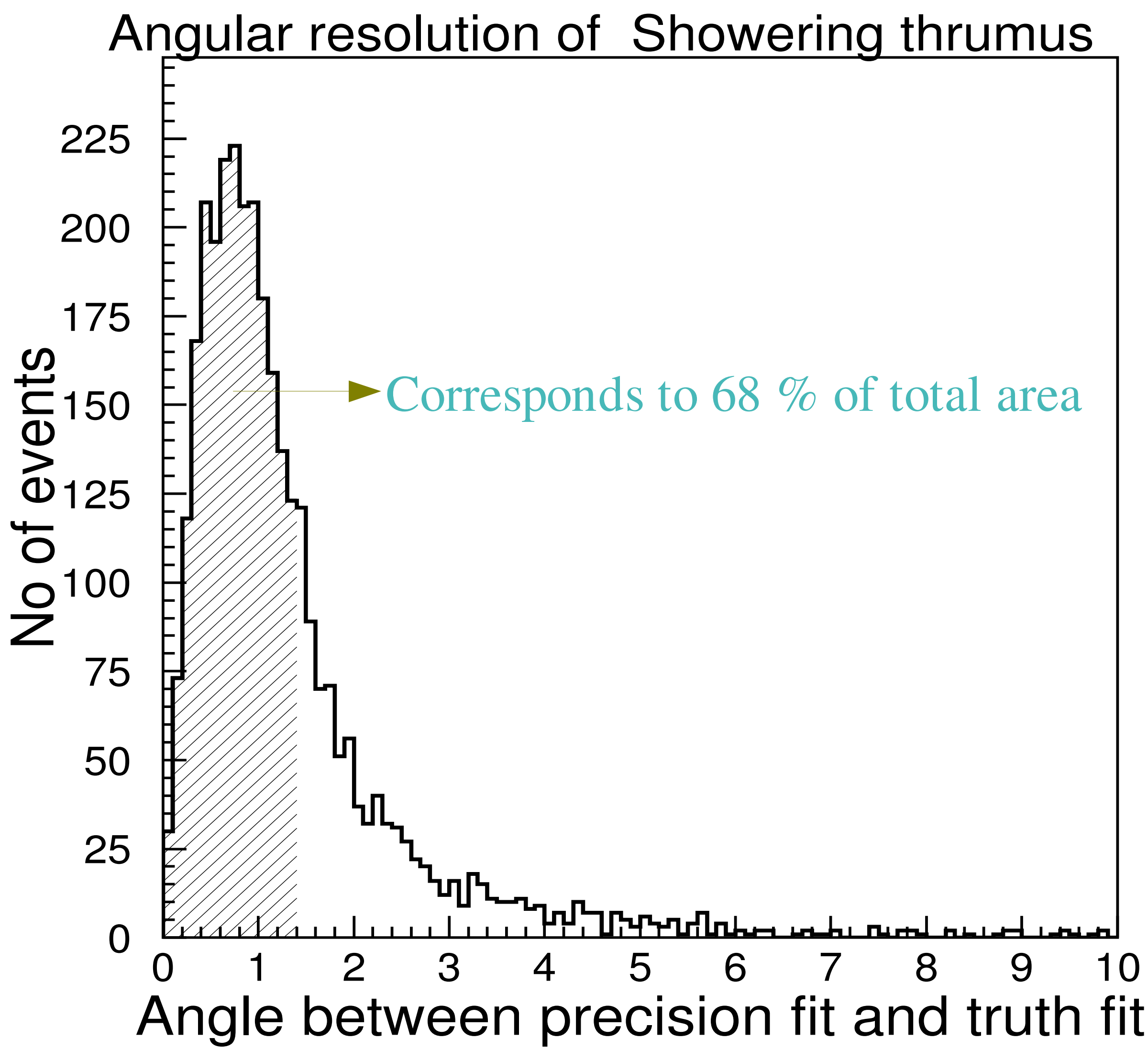


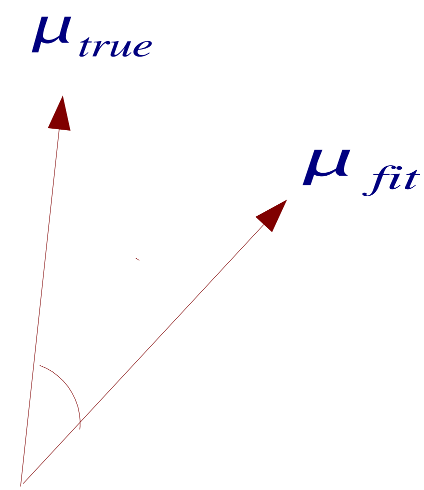
3 categories of upward muons seen in Super-K

$\langle E_\nu \rangle \sim 10\, GeV$

$\langle E_\nu \rangle \sim 100\, GeV$

$\langle E_\nu \rangle \sim 1\, TeV$

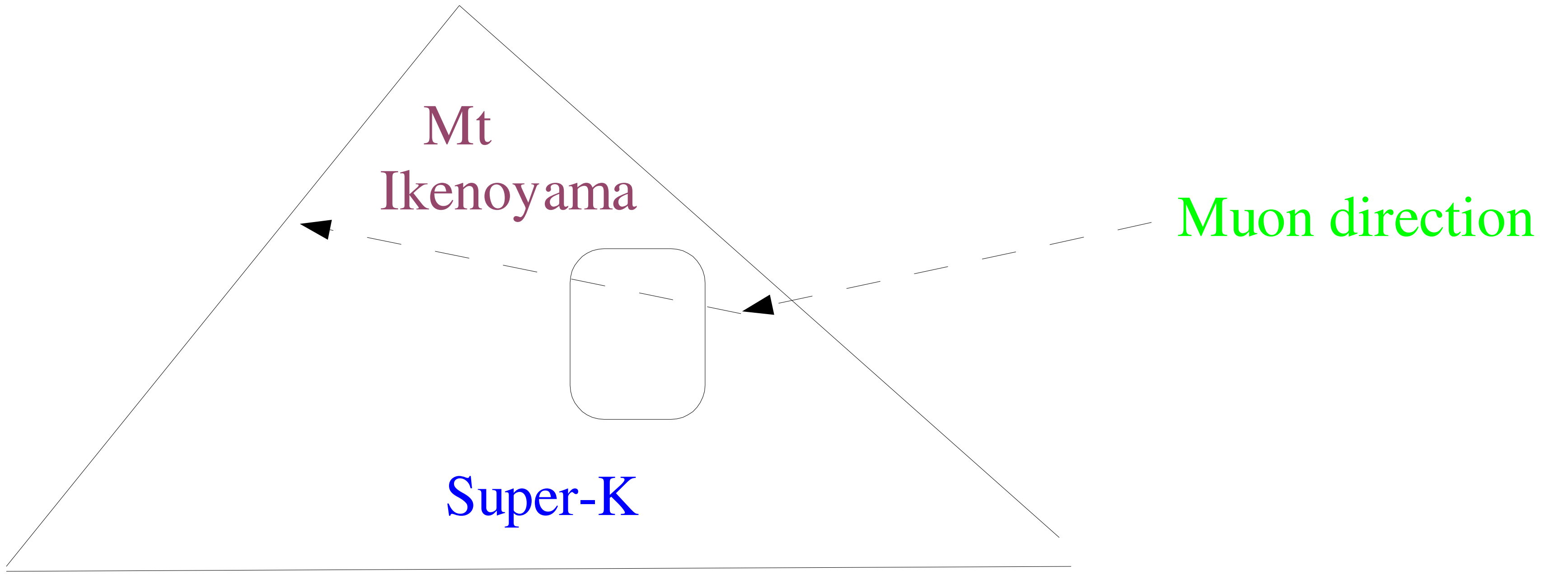




Angular resolution = 1.3 degrees

Stops : 1.5 degrees   Thrugoing: 1.0 degrees

Our sample not completely background free

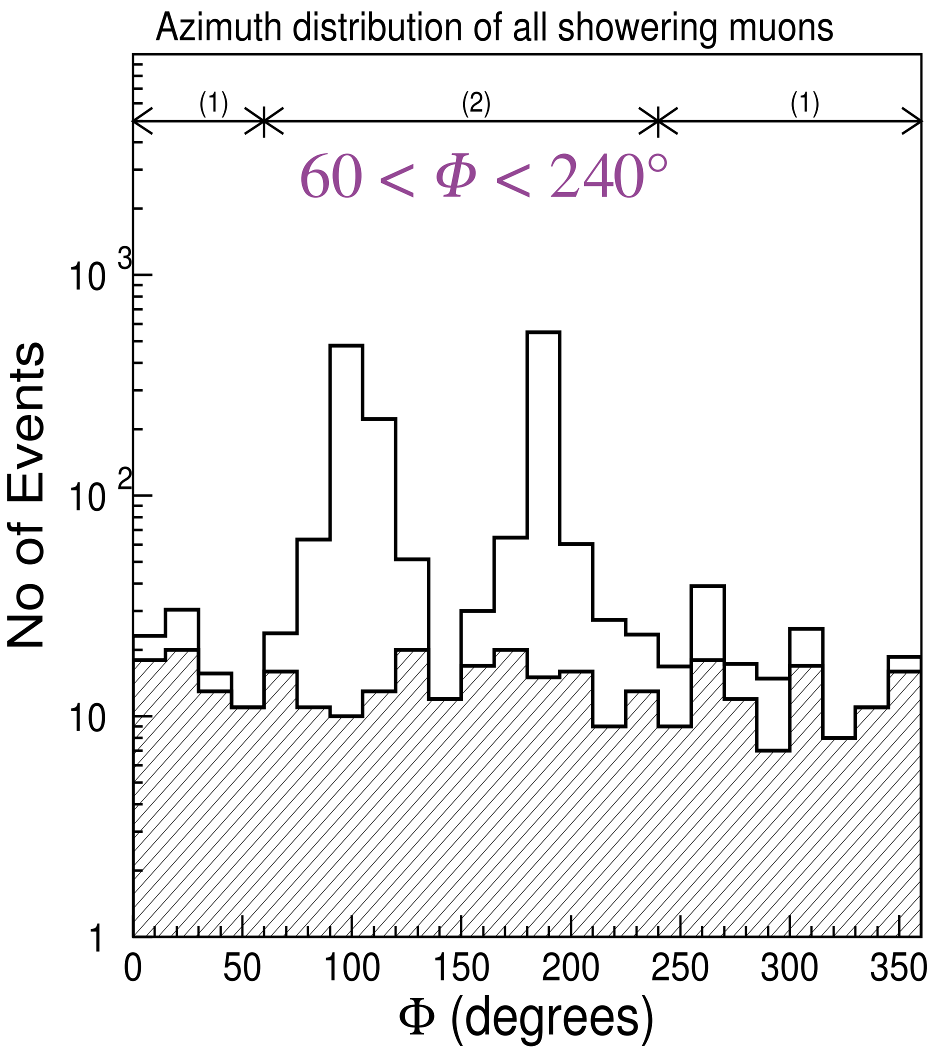


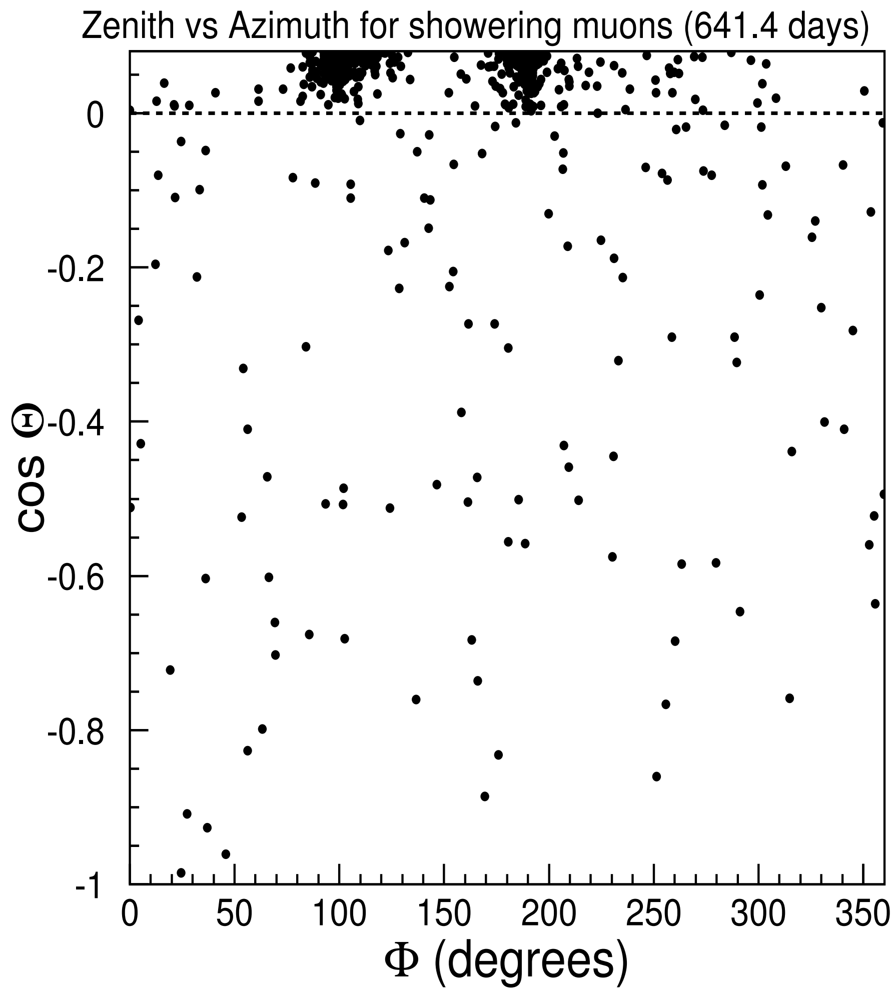
Downward μ near horizon could multiple-scatter and appear as upward μ

This background from horizontal muons needs to be subtracted from the upward showering muon dataset

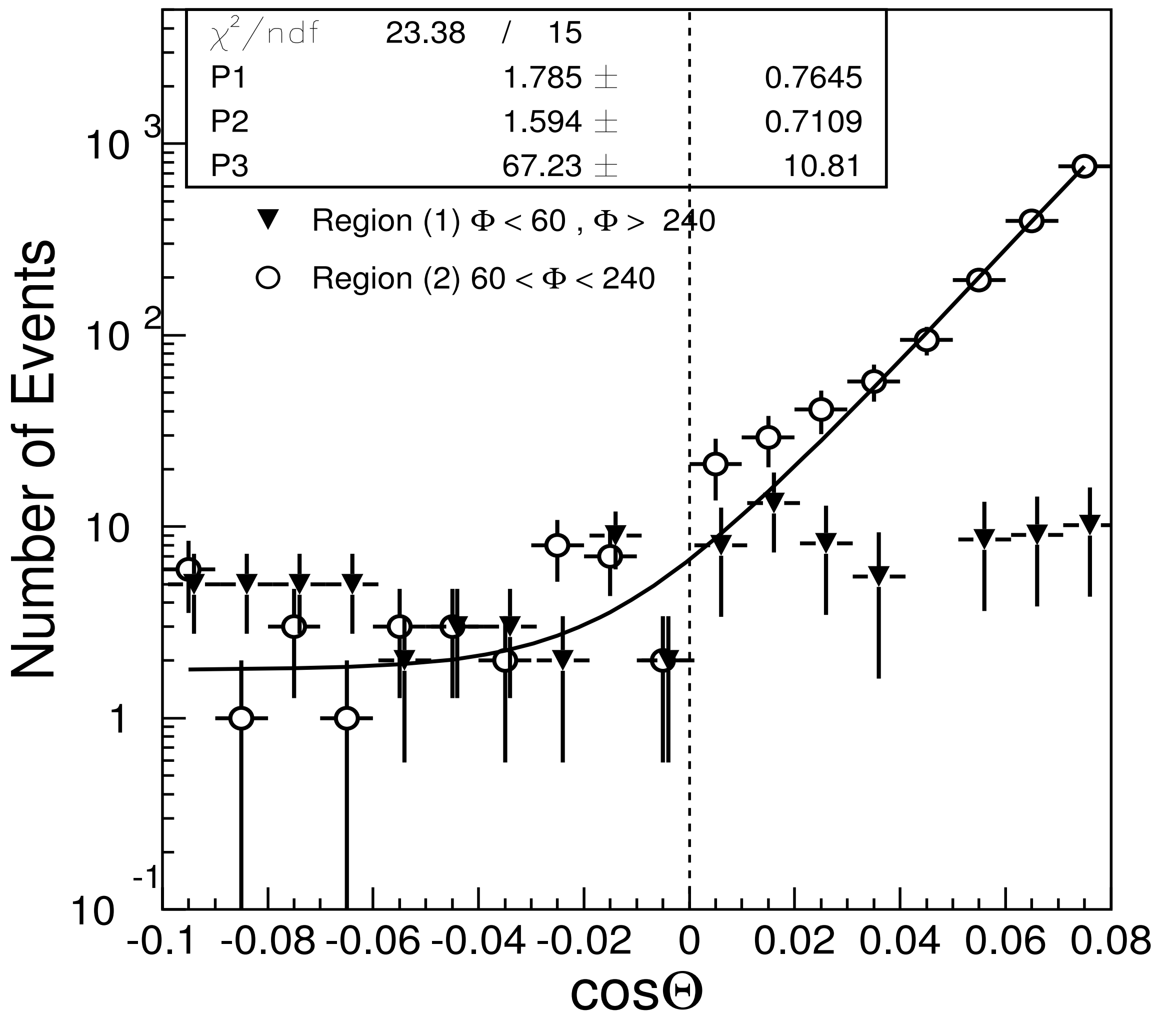
Mt. Ikenoyama not homogenous and isotropic
contamination from thin parts of mountain in dataset

Plotted the azimuthal distribution of upward + downward showering muons near horizon





Estimation of Background Subtraction



$N_{bkgd} = 8 \pm 7$ for $\cos\ \theta > -0.1$ out of 80 events

Oscillation Probability for a 2-neutrino beam

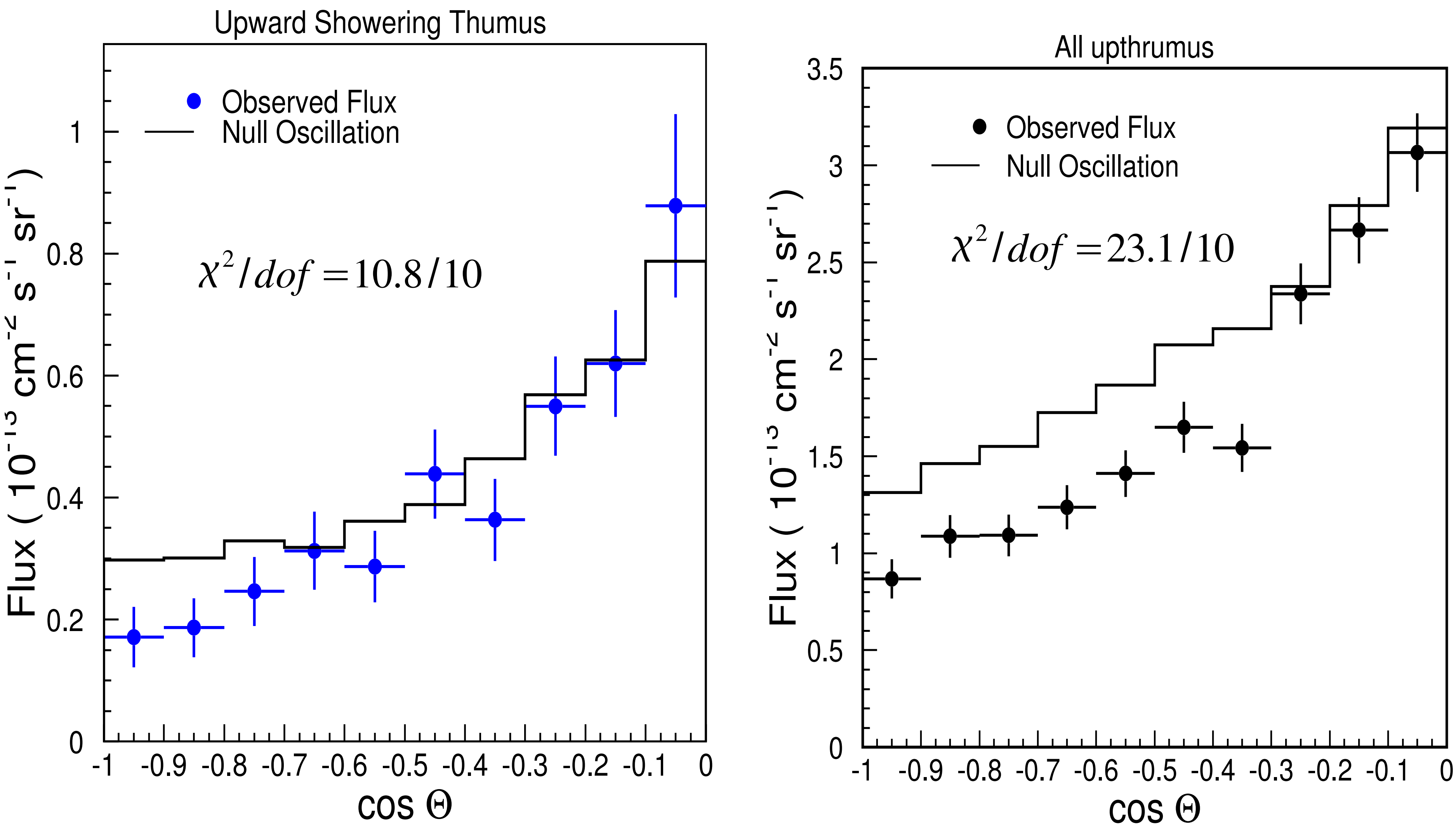
$$P(\nu_\mu \rightarrow \nu_\tau) \quad = \quad \sin^2(2\theta) \;\; \sin^2 [1.27\ \Delta m^2 (eV^2)\ L(km)/E\ (GeV)]$$

$$\Delta\ m^2 = m_1^{\ 2} - m_2^{\ 2}$$

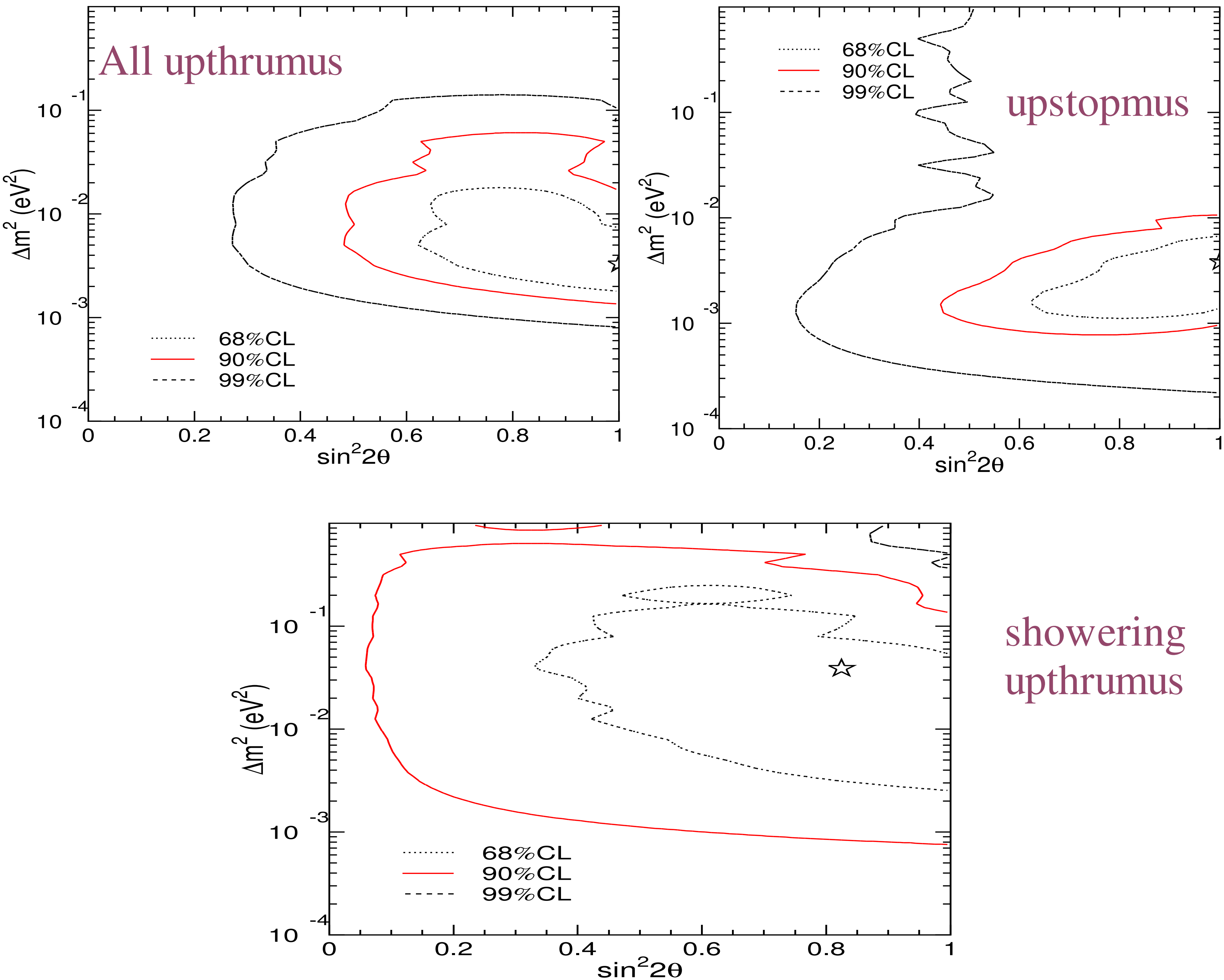
$\sin^2(2\theta)$ = Mixing angle

First smoking gun evidence for neutrino oscillation discovered in Super-K with $\Delta m^2 \sim 0.002 \;\; \sin^2(2\theta) \sim \; 1$ *(Messier 1999)*

Zenith Angle Distribution of Upward Showering Muons



$\Longrightarrow$ Zenith angle distribution of upward showering muons consistent with no oscillation as expected


All upthrumus
upstopmus
showering upthrumus
68%CL
90%CL
99%CL
Δm^2 (eV^2)
$\sin^2 2\theta$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1

Oscillation Analysis with all 3 Datasets

$$\chi^2 = \sum_{j=1}^{3} \sum_{i=1}^{10} \{(F_{data} - F_{MC})/\sigma\}^2$$

Weights applied to monte-carlo events :

Non -Showering Upthrumus : $(1+\alpha)\, F^{nonshower}$

Showering Upthrumus : $(1+\alpha)\,(1+\gamma)\, F^{shower}$

Stopping Upmus : $(1+\alpha)\,(1+\beta)\, F^{stop}$

α, β, γ kept as free parameters

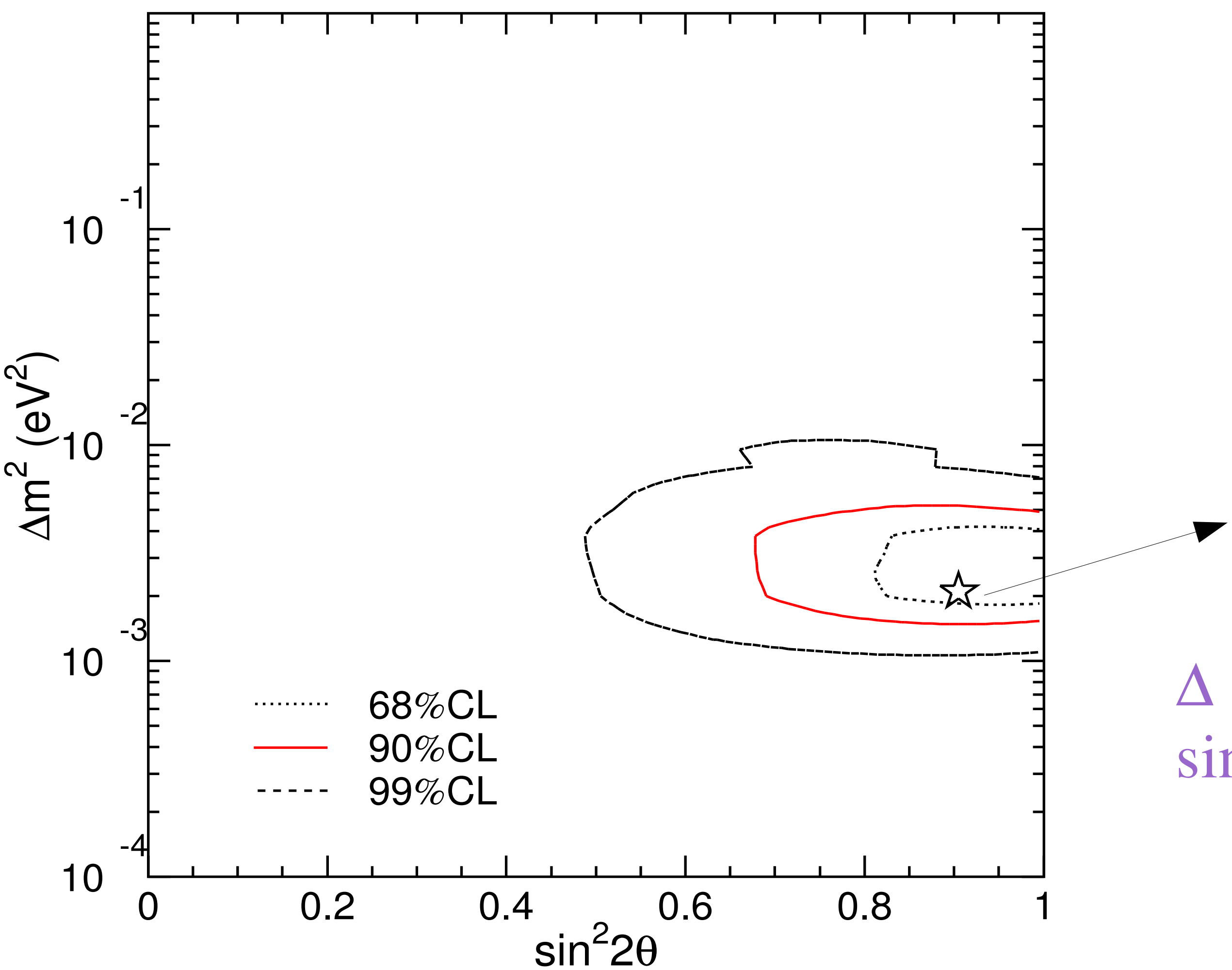
Following terms added to χ^2

$$(\alpha/\sigma_\alpha)^2 + (\beta/\sigma_\beta)^2 + (\gamma/\sigma_\gamma)^2$$

where $\sigma_\alpha = 0.22$ $\sigma_\beta = 0.14$ $\sigma_\gamma = 0.08$

Null Oscillation : $\chi^2 = 47.3$ for 30 dof

Best fit Oscillation : $\chi^2 = 22$ for 28 dof

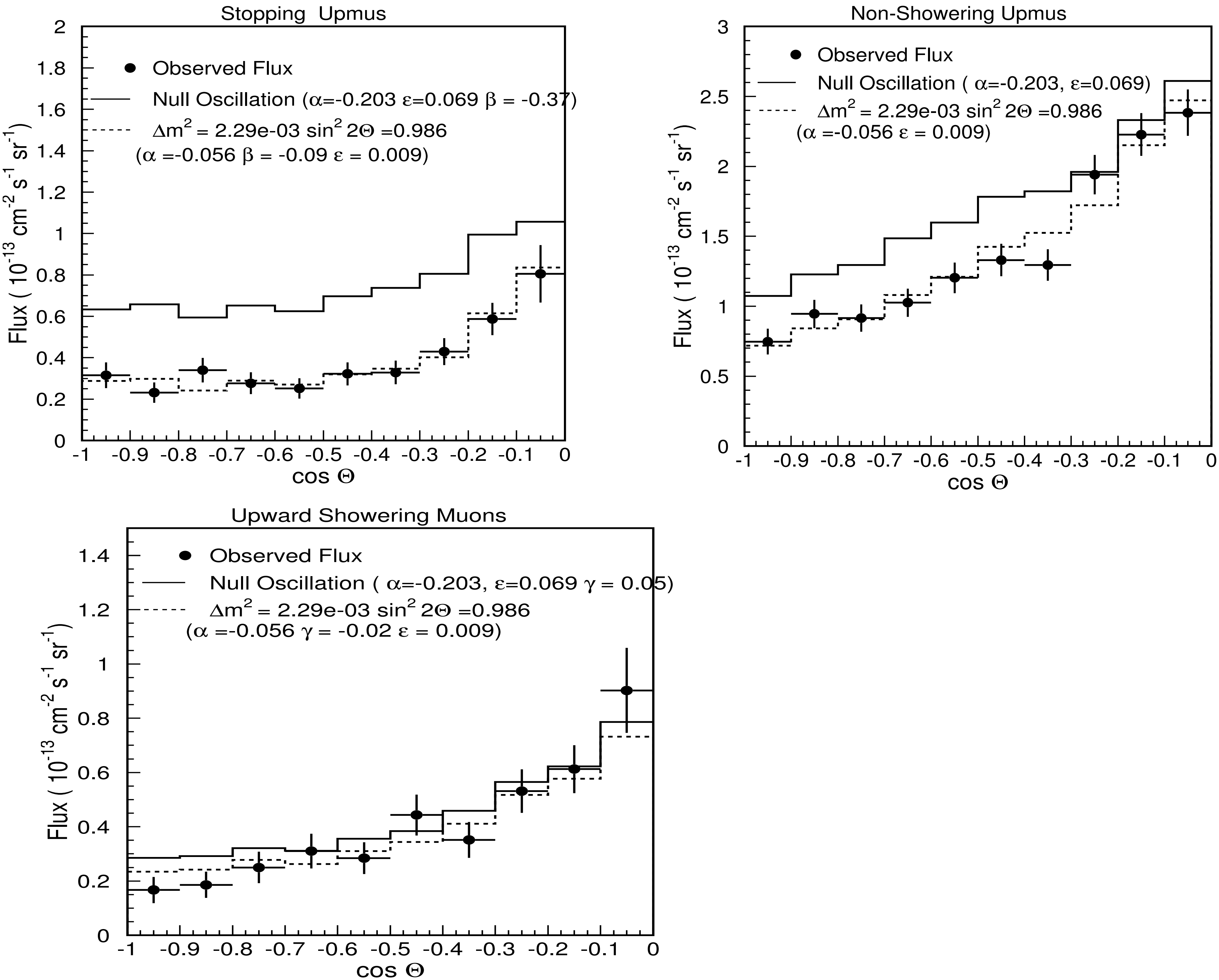


Best fit point

$\Delta m^2 = 0.0023$

$\sin^2 2\theta = 1$

Combined flux of all 3 samples consistent with oscillations


Stopping Upmus
Observed Flux
Null Oscillation (α=-0.203 ε=0.069 β = -0.37)
Δm² = 2.29e-03 sin² 2Θ =0.986
(α =-0.056 β = -0.09 ε = 0.009)
Flux (10⁻¹³ cm⁻² s⁻¹ sr⁻¹)
cos Θ
Non-Showering Upmus
Observed Flux
Null Oscillation (α=-0.203, ε=0.069)
Δm² = 2.29e-03 sin² 2Θ =0.986
(α =-0.056 ε = 0.009)
Flux (10⁻¹³ cm⁻² s⁻¹ sr⁻¹)
cos Θ
Upward Showering Muons
Observed Flux
Null Oscillation (α=-0.203, ε=0.069 γ = 0.05)
Δm² = 2.29e-03 sin² 2Θ =0.986
(α =-0.056 γ = -0.02 ε = 0.009)
Flux (10⁻¹³ cm⁻² s⁻¹ sr⁻¹)
cos Θ

Overview of Astrophysical Searches Done with Upward Muons

Point Sources Searches (both known and unknown) ✘

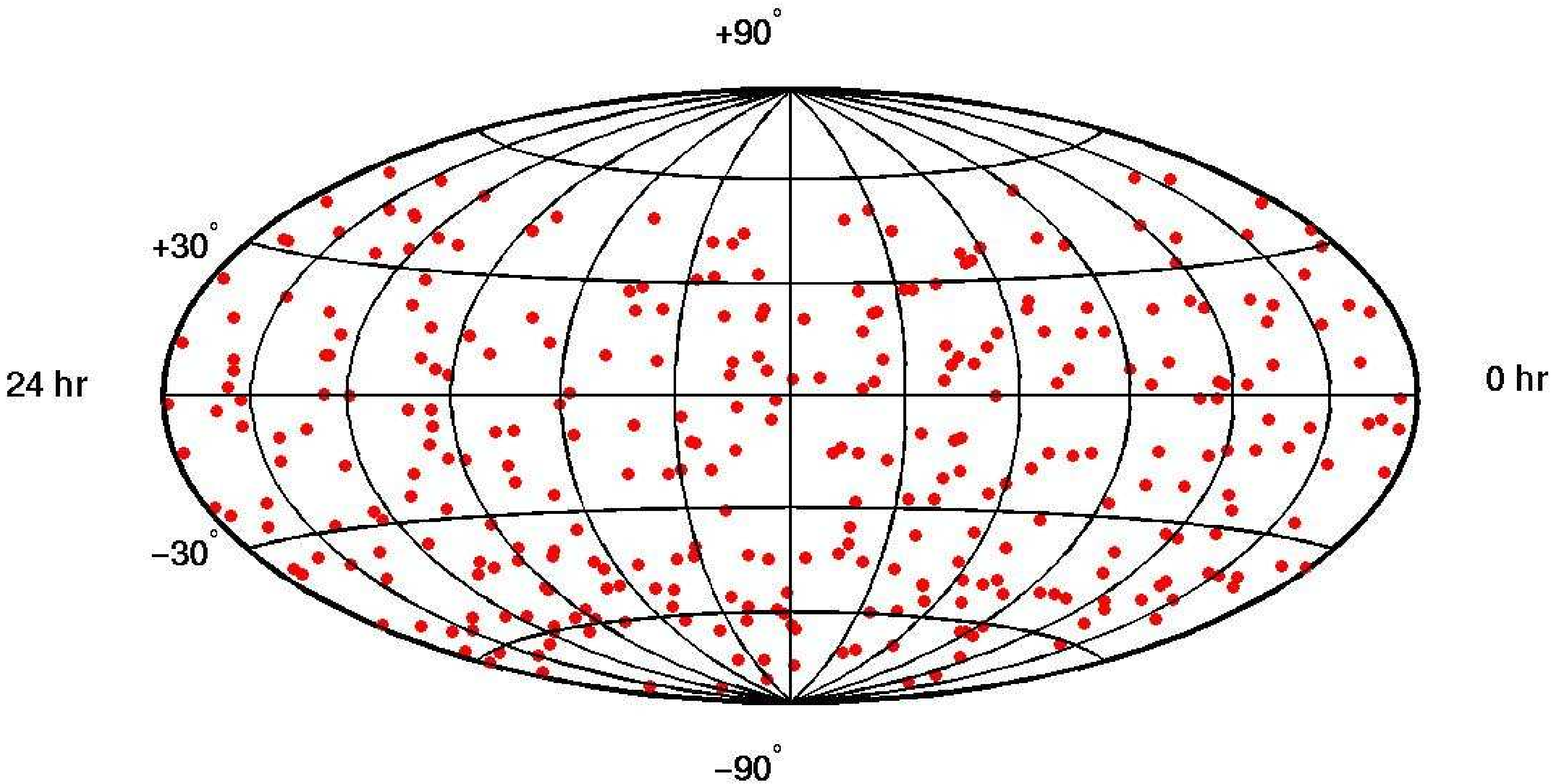
Space-time correlations with transient astrophysical sources such as GRBs and SGRs

Diffuse Flux from plane of Galaxy

WIMP searches from center of Earth, Sun , Galactic Center

Angular clustering and bootstrap techniques used to search for point sources in upward muon dataset *(Washburn, Clough)*

Upward showering muon sample suited for high energy astronomy because atmospheric neutrino background is reduced



Sky map distribution of upward showering muons

No evidence for point sources in showering upward muon dataset

Space-Time correlation studies with transient astrophysical sources like GRBs and SGRs

GRBs (~1600 bursts) : *astro-ph/0205304*

$\Delta t = \pm 1000$ sec $\Delta\theta = 5$ deg.

Result : 1 event found. Expected Background = 0.9

$\Delta t = \pm 1$ day $\Delta\theta = 5$ deg and look for more than 1 upward muon

No such events found

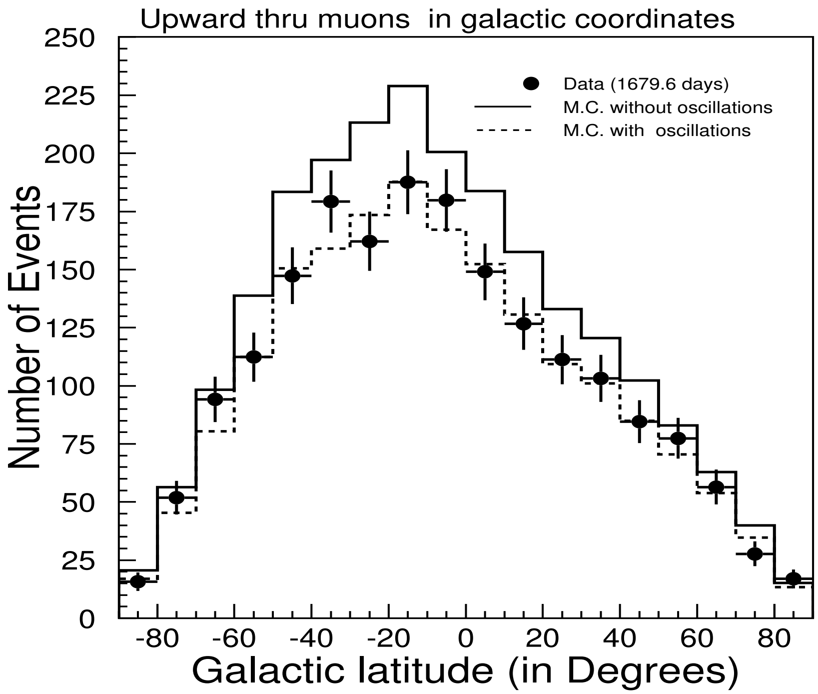
SGRs (~150 bursts):

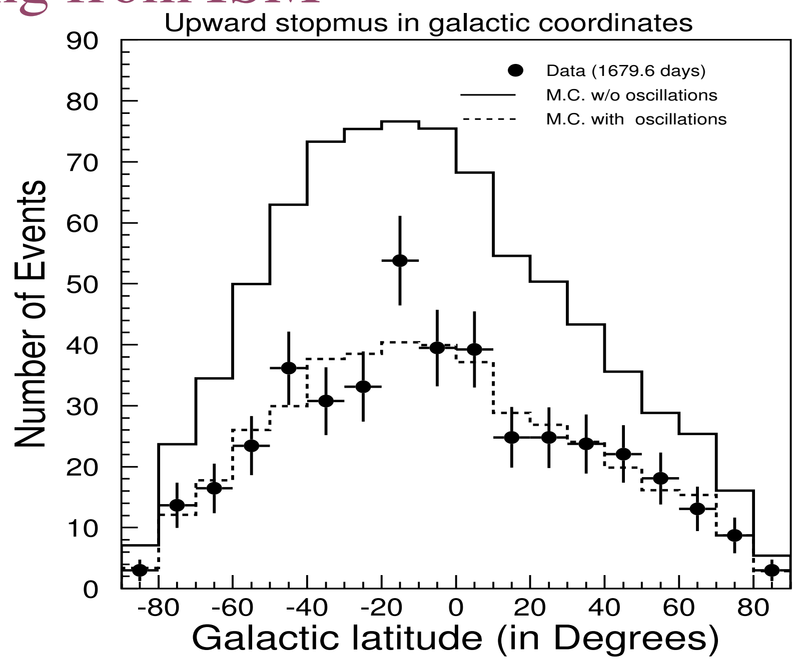
$\Delta t = \pm 1$ day $\Delta\theta = 5$ deg.

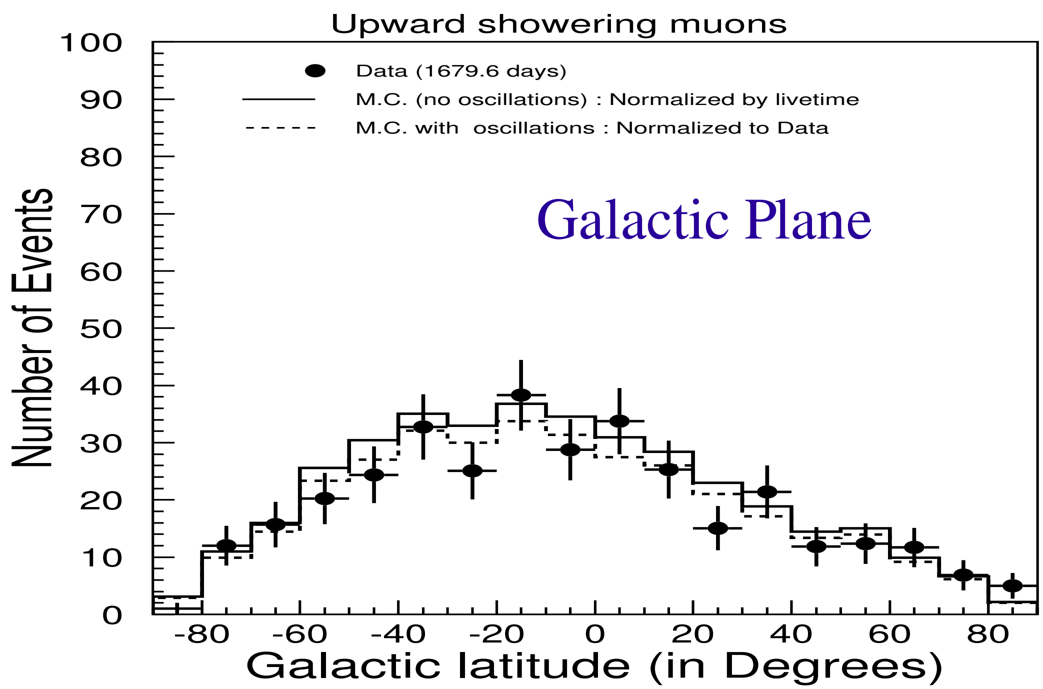
Result : 1 event found . Expected Background = 0.7

==> Expected coincidences with SGRs and GRBs consistent with background

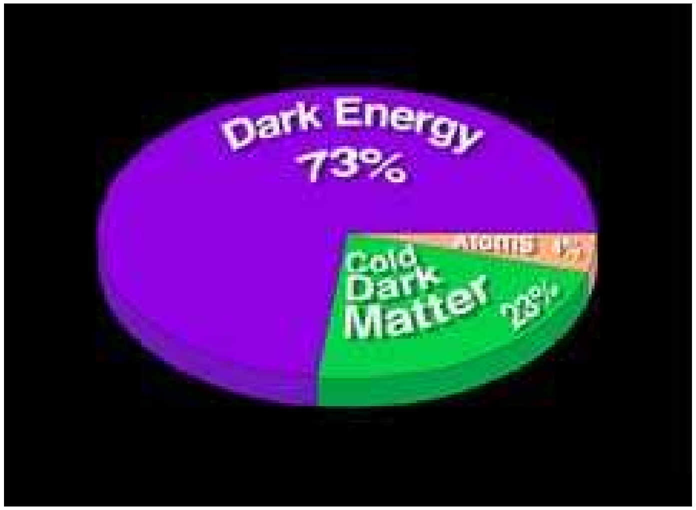
Look for ν from cosmic rays coming from ISM







Matter/ Energy Density Budget of the Universe

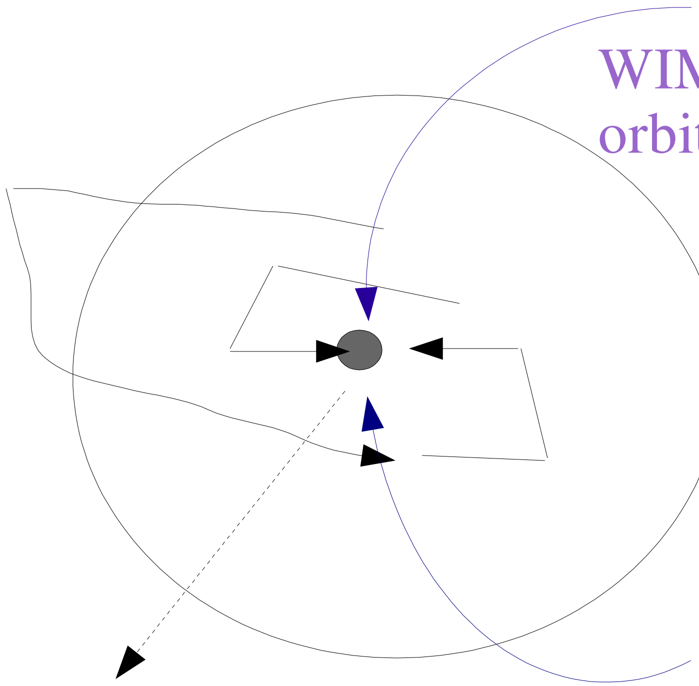


(WMAP Collaboration 2003)

One possibility for Cold Dark Matter are:
Weakly Interacting Massive Particles (WIMPs) *(Weinberg & Lee 77)*

- Masses in the GeV to TeV energy range
- Annihilation cross-sections ~ Electroweak scale
- Exist in Supersymmetric theories beyond Standard Model

INDIRECT WIMP SEARCHES



WIMP speed ~ 220 km/sec
WIMP Density ~ 0.3 GeV/cc

Potential Sources of WIMP annihilation

Earth : Only sensitive to WIMPs with scalar interactions

Sun : Mainly sensitive to WIMPs with spin interactions

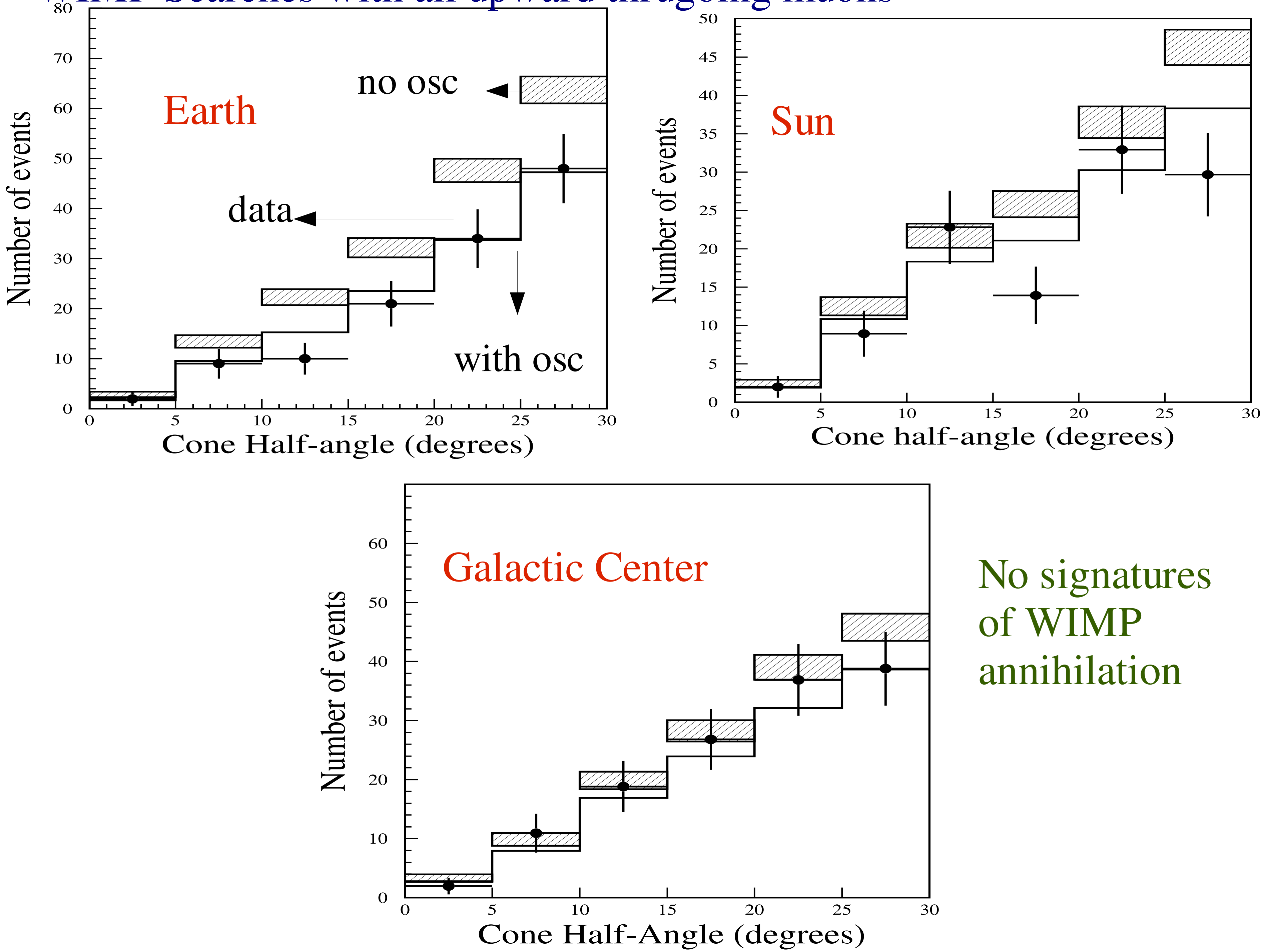
Galactic Center : WIMP annihilation due to spike in density distribution near central black hole *(Gondolo & Silk 99)*

$$\chi + \chi \rightarrow c\bar{c}\,,\ b\bar{b},\ H\bar{H},\ ZZ\,,\ t\bar{t}.\ \ W^+ W^-\,,\ \tau^+\tau^-$$

↓

Neutrinos

WIMP Searches with all upward thrugoing muons



No signatures of WIMP annihilation

WIMP Search with Upward Showering Muons

Upward Showering muons sensitive to high mass WIMPs

Looked for excess in direction of Earth , Sun and Galactic Center

Earth

Cone	Data	Atm ν Bkgd
3°	0	0.10
5°	0	0.30
10°	2	2.30

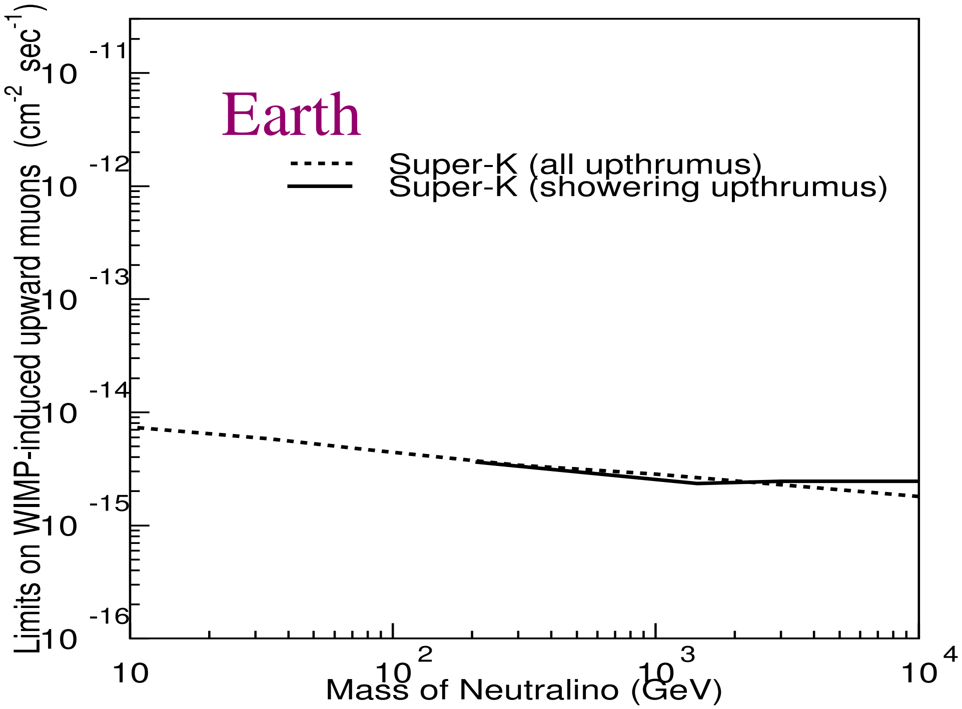
Sun

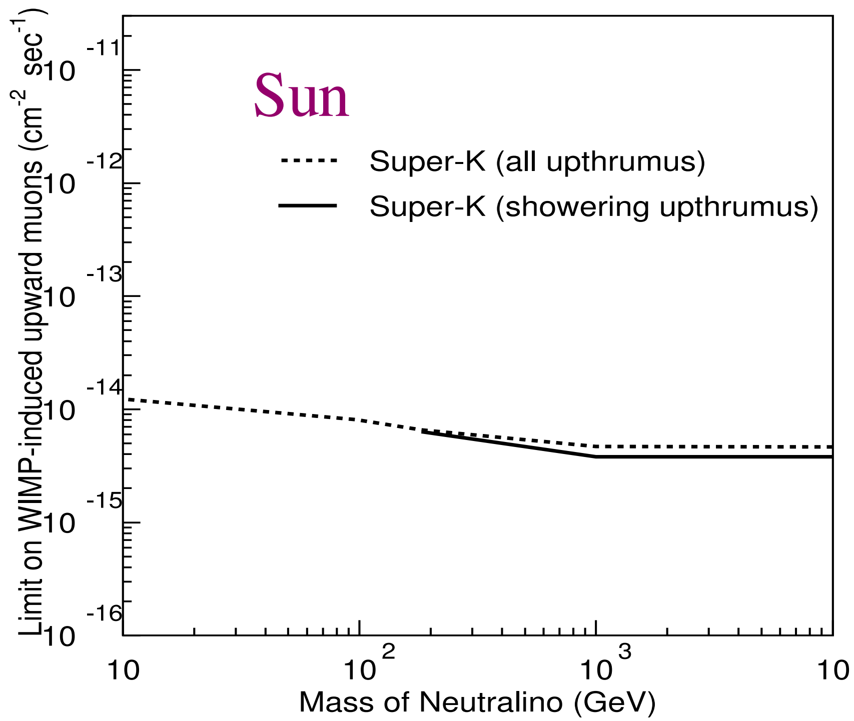
Cone	Data	Atm ν Bgd
3°	0	0.30
5°	0	0.40
10°	2	2.10

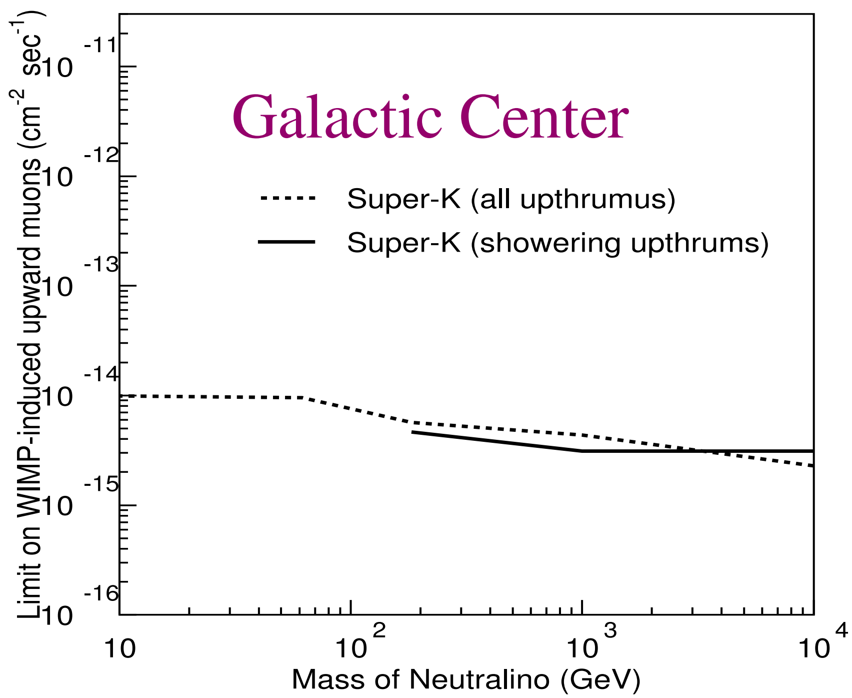
Galactic Center

Cone	Data	Atm ν Bgd
3°	0	0.50
5°	0	1.20
10°	2	3.30

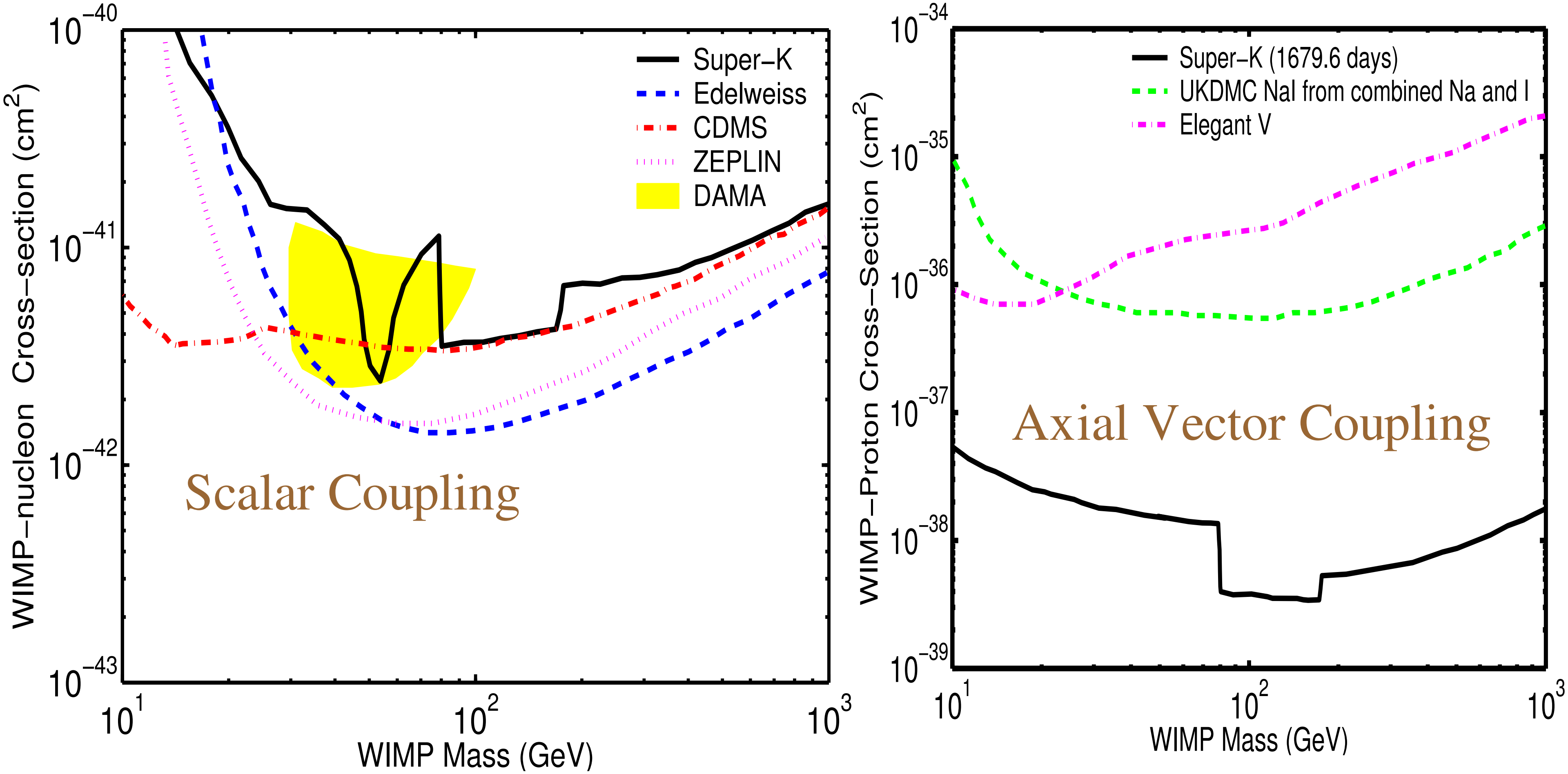
No possible signatures of WIMP-induced upward showering muons from Earth, Sun or Galactic Center


Earth
Super-K (all upthrumus)
Super-K (showering upthrumus)
Limits on WIMP-induced upward muons (cm^-2 sec^-1)
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10
10^2
10^3
10^4
Mass of Neutralino (GeV)


Sun
Super-K (all upthrumus)
Super-K (showering upthrumus)
Limit on WIMP-induced upward muons (cm^-2 sec^-1)
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10
10^2
10^3
10^4
Mass of Neutralino (GeV)


Galactic Center
Super-K (all upthrumus)
Super-K (showering upthrums)
Limit on WIMP-induced upward muons (cm^-2 sec^-1)
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10
10^2
10^3
10^4
Mass of Neutralino (GeV)

Using the flux limits from the Sun and Earth and results from from Kamionkowski et. al. (1994) allows to compare our results with direct detection WIMP searches using Si, Ge, NaI etc



We partially rule out the DAMA allowed region
Our limits on WIMP-proton spin cross-section ~ 100 times more sensitive than direct detection experiments

CONCLUSIONS

- A sample of upward through-going muons which lose energy through bremsstrahlung and other radiative processes has been isolated

- Mean energy of parent neutrinos of upward showering muons ~ 1 TeV

- Zenith angle distribution of only upward showering muons consistent with null oscillations. However combination of all 3 datasets consistent with oscillations

- Tried all possible tricks to search for signatures of high energy GeV neutrinos from astrophysical sources. Unfortunately no sources found