Super-Kamiokande Atmospheric Neutrinos Results

The Super-Kamiokande Experiment

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March 6, 2000

Sub-GeV event Summary

Evis < 1.33GeV
P_e > 100MeV/c
P_μ > 200MeV/c

	DATA	MC(Honda)	MC(Bartol)
1R	5652	6740.4	6577.4
e-like	2864	2667.6	2625.3
μ-like	2788	4072.8	3952.2
2R	1492	1737.2	1710.3
≥3R	667	847.9	846.1
TOTAL	7811	9325.5	9133.8

$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.638 \pm {}^{0.017}_{0.017}\,(\text{stat.}) \pm 0.050\,(\text{sys.}) \text{ (Honda)}$$

$$= 0.647 \pm {}^{0.017}_{0.017}\,(\text{stat.}) \pm 0.051\,(\text{sys.}) \text{ (Bartol)}$$

Multi-GeV event Summary

(1) FC (Evis > 1.33GeV)

	DATA	MC(Honda)	MC(Bartol)
1R	1184	1451.1	1473.6
e-like	626	612.8	635.7
μ-like	558	838.3	838.0
2R	495	634.1	649.5
≥3R	823	1014.0	1058.2
TOTAL	2502	3099.1	3181.4

(2) PC

	DATA	MC(Honda)	MC(Bartol)
TOTAL	754	1065.0	1123.4

*All events are assumed to be μ-like.
*Fraction of CC ν_μ, $\bar{\nu}_\mu$ events in the PC sample is estimated to be (97-98)%.

$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}}$

FC + PC

$$= 0.675 \pm {}^{0.034}_{0.032}\,(\text{stat.}) \pm 0.080\,(\text{sys.}) \text{ (Honda)}$$

$$= 0.679 \pm {}^{0.034}_{0.032}\,(\text{stat.}) \pm 0.080\,(\text{sys.}) \text{ (Bartol)}$$

FC only

$$= 0.652 \pm {}^{0.039}_{0.037}\,(\text{stat.}) \pm 0.095\,(\text{sys.}) \text{ (Honda)}$$

$$= 0.676 \pm {}^{0.041}_{0.038}\,(\text{stat.}) \pm 0.099\,(\text{sys.}) \text{ (Bartol)}$$

Summary of Upward Through-going μ's in Super-K

Selection Criteria

- Zenith angle $-1 \leq \cos\Theta \leq 0$
- Total $Q > 12000$p.e. and track length $\geq$ 7m
- Veto counter signal at entrance and exit points

Data

- 1268 live-days (04/96)$\rightarrow$ (04/00)
- 1416 Events (minus BG in last $\cos\Theta$ bin 10.2 ± 0.9)
- Observed flux:
  $\Phi_t = 1.70 \pm 0.05(\text{stat.}) \pm 0.02(\text{syst.}) \times 10^{-13}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$
- Expected flux:
  $\Phi_{theo} = 1.97 \pm 0.44(\text{theo.}) \times 10^{-13}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ (Bartol)
  $\Phi_{theo} = 1.84 \pm 0.41(\text{theo.}) \times 10^{-13}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ (Honda)

Systematic Error

Track Length	$\pm0.5\%$	Livetime	$\pm1.0\%$
Effective Area	$\pm0.3\%$		
Efficiency	$\pm1.2\%$	(bin-by-bin)	
$\Delta\Theta_{fit}$	$\pm1.0\%$	(only for horizontal bin)	

Summary of Upward Stopping μ's in Super-K

Selection Criteria

- Zenith angle $-1 \leq \cos\Theta \leq 0$
- Total $Q > 12000$p.e. and track length $\geq$ 7m
- Veto counter signal only at entrance

Data

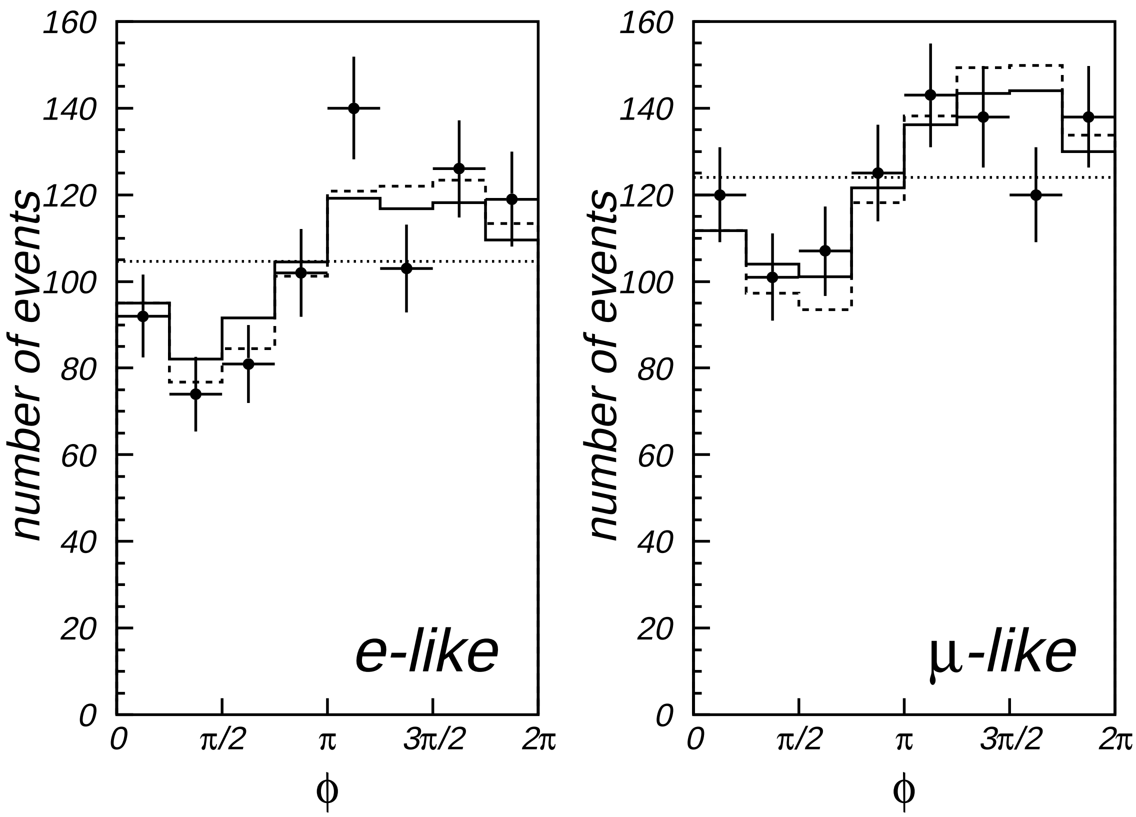
- 1247 live-days(04/96)$\rightarrow$ (04/00)
- 345 Events (minus BG in last $\cos\Theta$ bin 23.1 ± 9.2)
- Observed flux:
  $\Phi_s = 0.41 \pm 0.02(\text{stat.}) \pm 0.02(\text{syst.}) \times 10^{-13}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$
- Expected flux:
  $\Phi_{theo} = 0.73 \pm 0.16(\text{theo.}) \times 10^{-13}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ (Bartol)
  $\Phi_{theo} = 0.68 \pm 0.15(\text{theo.}) \times 10^{-13}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ (Honda)
- Observed $\mathcal{R} = \Phi_s/\Phi_t$:
  $0.242 \pm 0.017(\text{stat.})^{+0.013}_{-0.011}(\text{syst.})$
- Expected $\mathcal{R} = \Phi_s/\Phi_t$:
  $0.372^{+0.049}_{-0.045}(\text{theo.})$ (Bartol) $0.368^{+0.049}_{-0.044}(\text{theo.})$ (Honda)
- Double Ratio $\frac{(\Phi_s/\Phi_t)_{data}}{(\Phi_s/\Phi_t)_{theo}}$:
  $0.649 \pm 0.043(\text{stat.}) \pm 0.092(\text{syst.}) = 0.649 \pm 0.102(\text{all error})$ (Bartol)

Systematic Error

Track Length	$^{+4.9}_{-4.1}\%$
Livetime	$\pm1.0\%$
Efficiency	$\pm1.0\%$

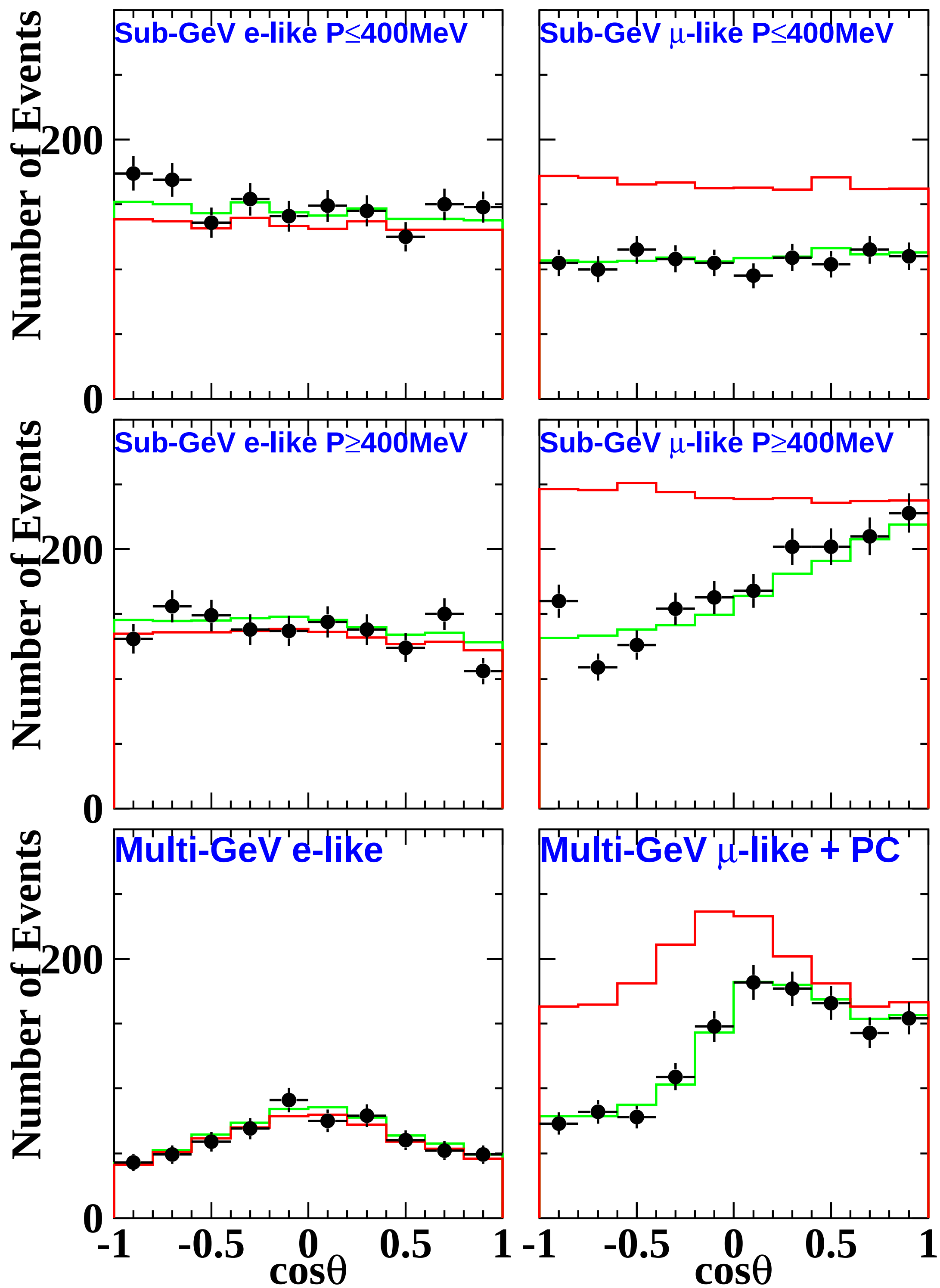
East/West Asymmetry of the ν Flux

- Events with momentum between 300–3000 MeV/c
- Events are horizontal, $|\cos\theta_z| < 0.5$

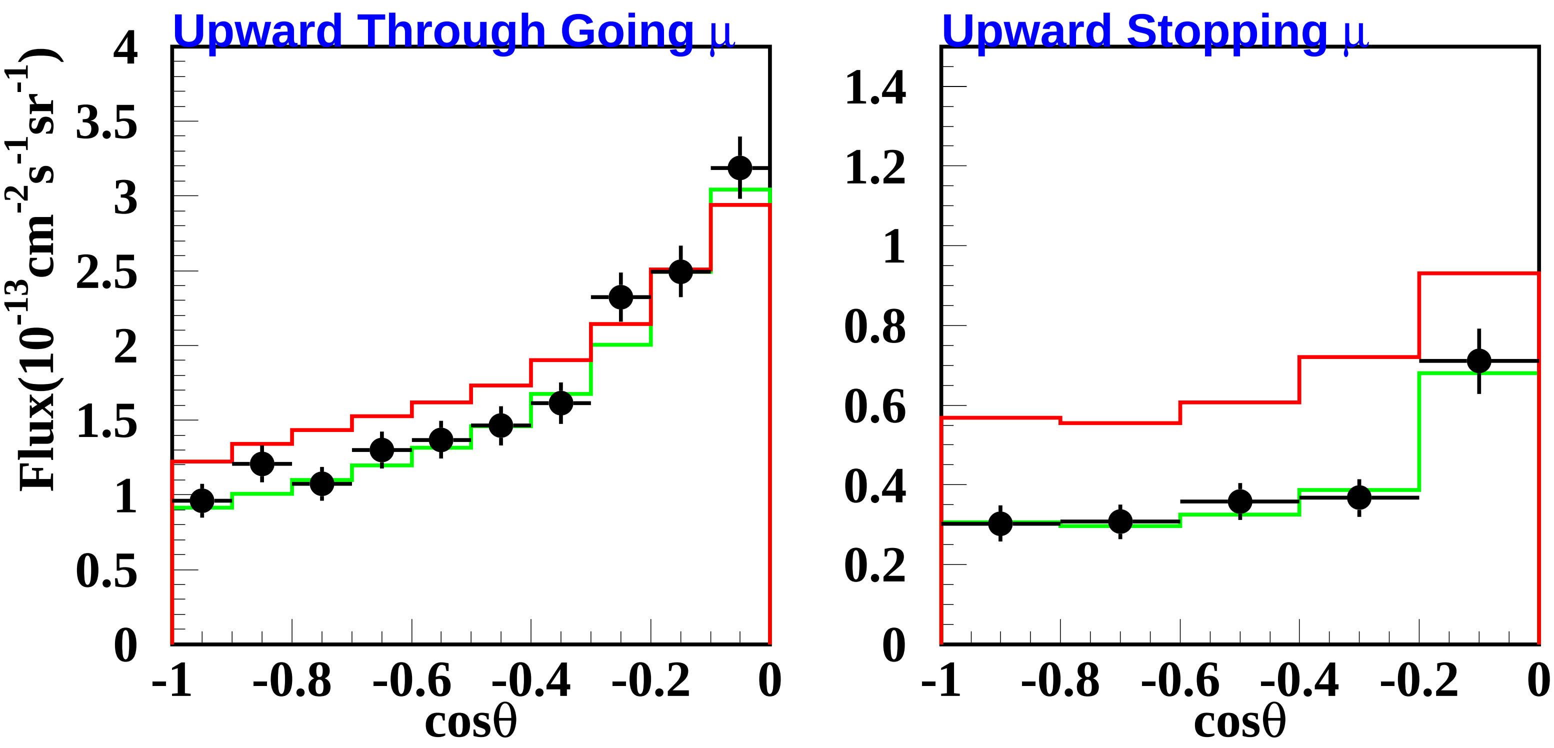


1144 days

Contained Vertex Data

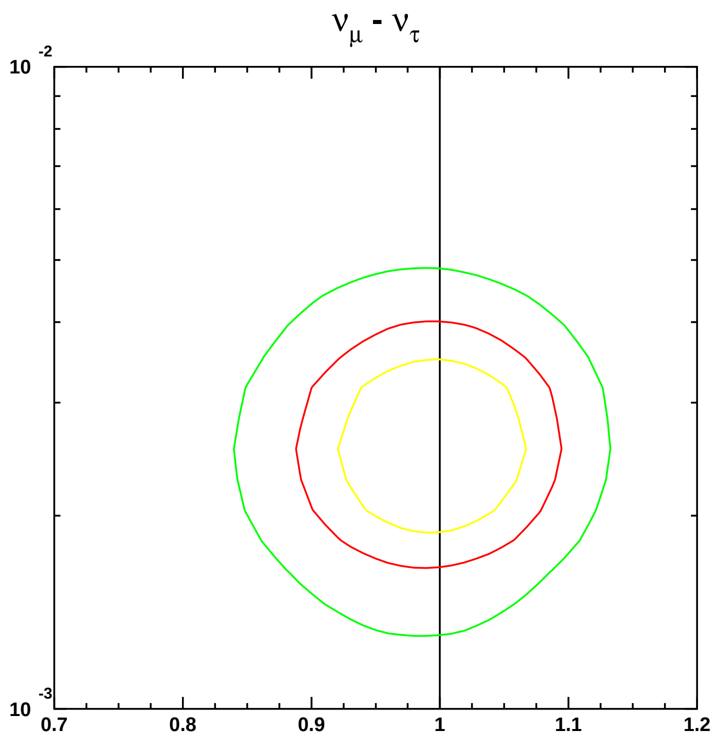


Up-Going Muon Events



Super-Kamiokande Combined Fit

$\nu_\mu \leftrightarrow \nu_\tau$



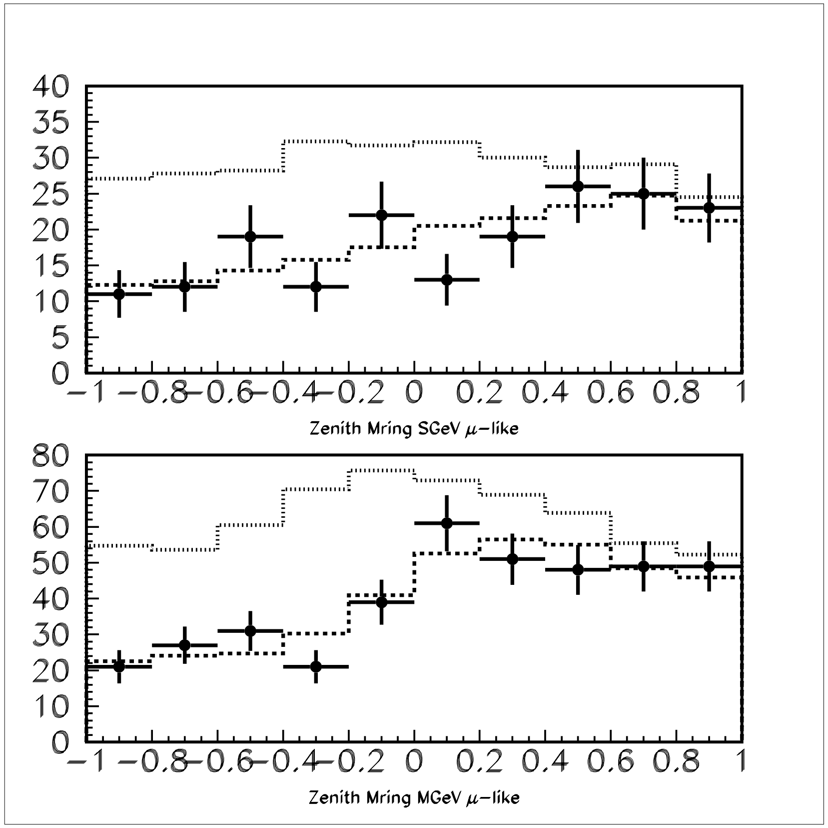
- Fully Contained
- Partial Contained
- Upward Going μ

$$\chi^2_{min} = 142.1/152\text{d.o.f.}$$

$$\sin^2 2\theta = 1.0$$

$$\Delta m^2 = 2.5 \times 10^{-3}\ \text{eV}^2$$

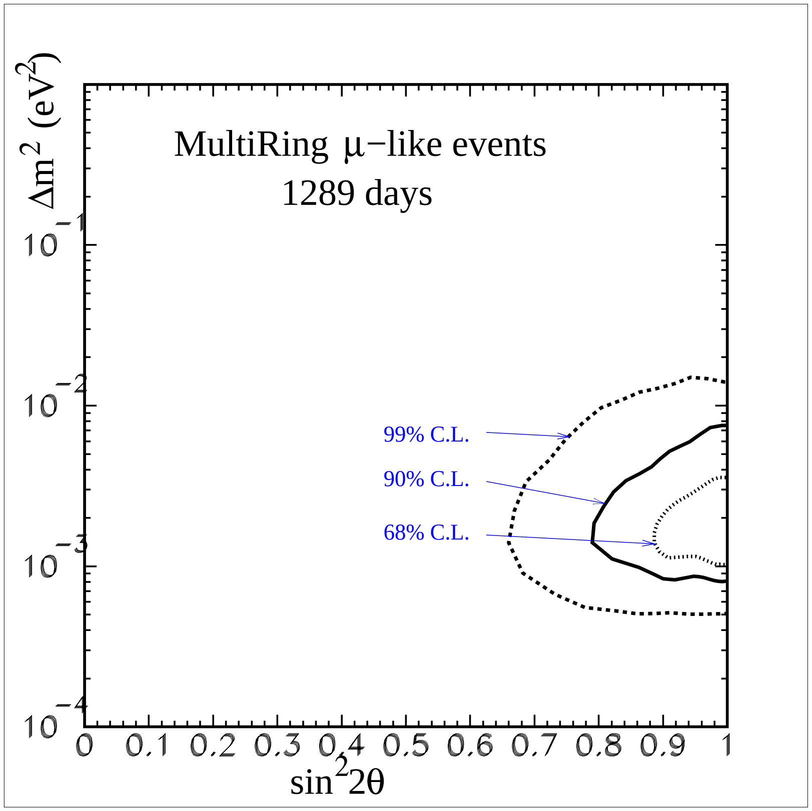
Multi-Ring μ-like Events



Same as Fully Contained, except:

- More than 1 ring
- Primary Ring μ-like
- Sub-GeV: $P_\mu > 600$ GeV

$\nu_\mu \leftrightarrow \nu_\tau$ Allowed Region from Multi-Ring Events



- Best fit:

$$\sin^2 2\theta = 1.06$$

$$\Delta m^2 = 1.90 \times 10^{-3}\ \mathrm{eV}^2$$

$$\chi^2_{min} = 14.64/16 \text{ d.o.f.}$$

- Best fit in physical region:

$$\sin^2 2\theta = 1.0$$

$$\Delta m^2 = 1.98 \times 10^{-3}\ \mathrm{eV}^2$$

$$\chi^2_{phys} = 14.95/16 \text{ d.o.f.}$$

Distinguishing $\nu_\mu \leftrightarrow \nu_\tau$ from $\nu_\mu \leftrightarrow \nu_s$

ν_μ and ν_s have different interactions with matter

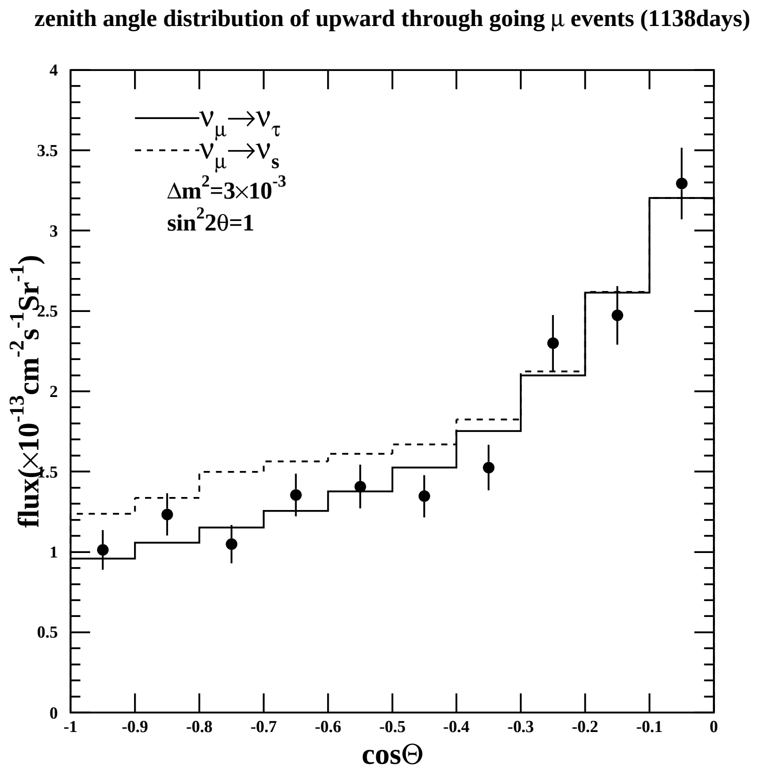
- Induces an MSW like matter effect.
- Changes the expected zenith angle distribution.

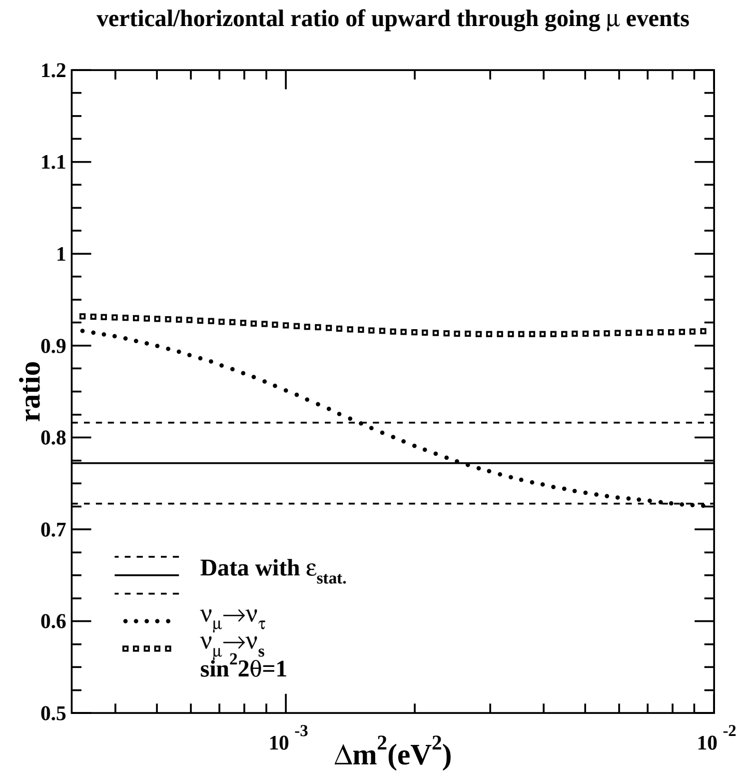
$\nu_\mu \leftrightarrow \nu_s$ can be tested with:

- Up-going through muon data
- Partially contained data
- Fully contained NC enriched data

Use up/down ratios to gain statistical weight.

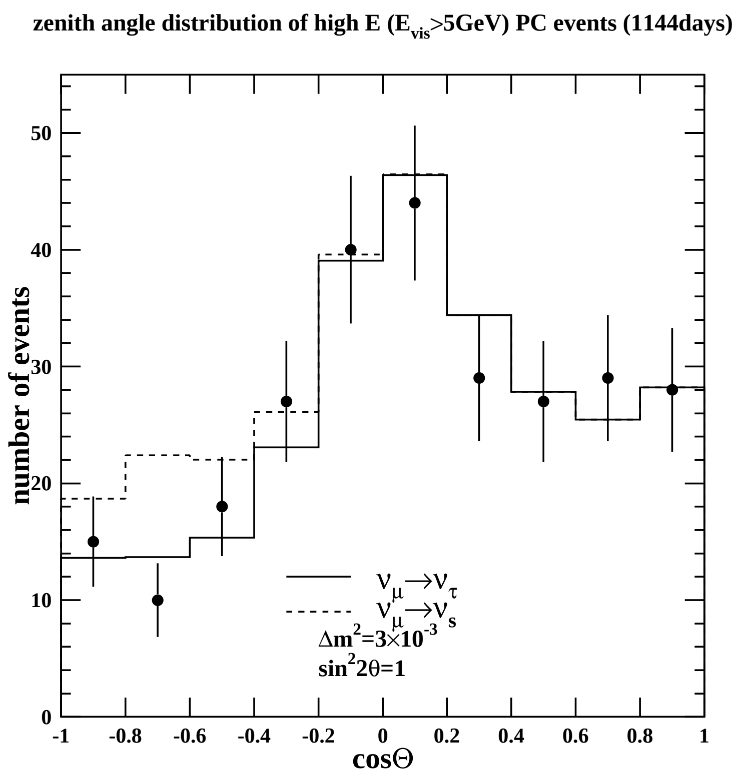
Up-Going Through Muon Events

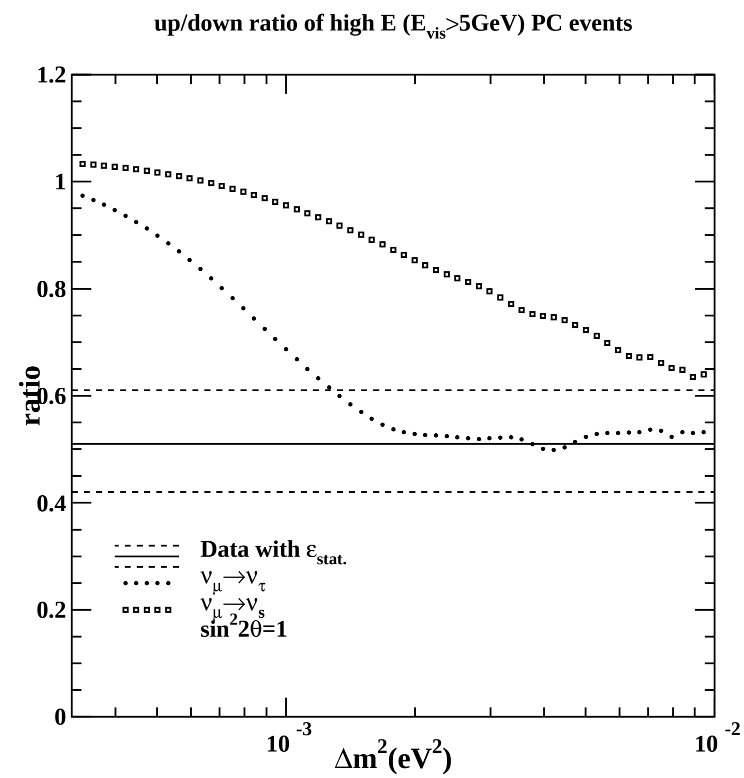




1144 days

Partially-Contained Events

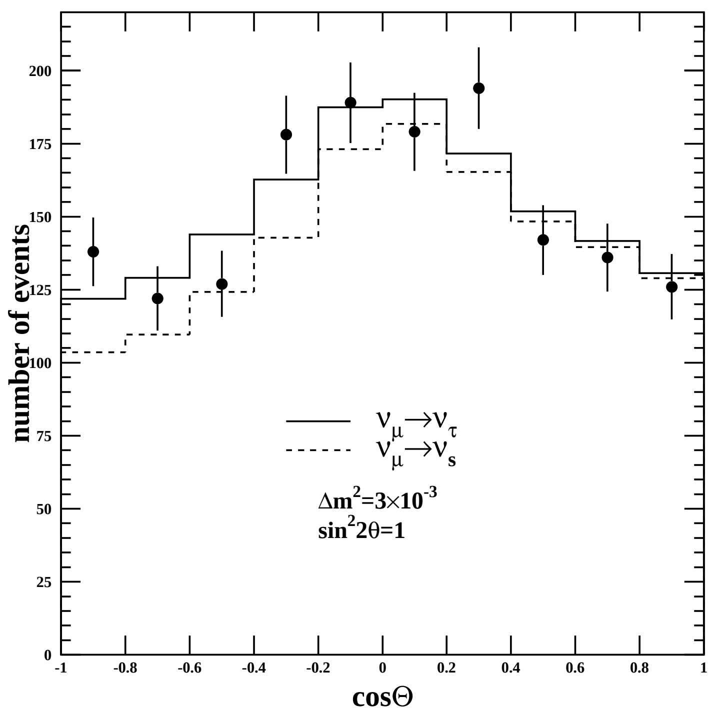




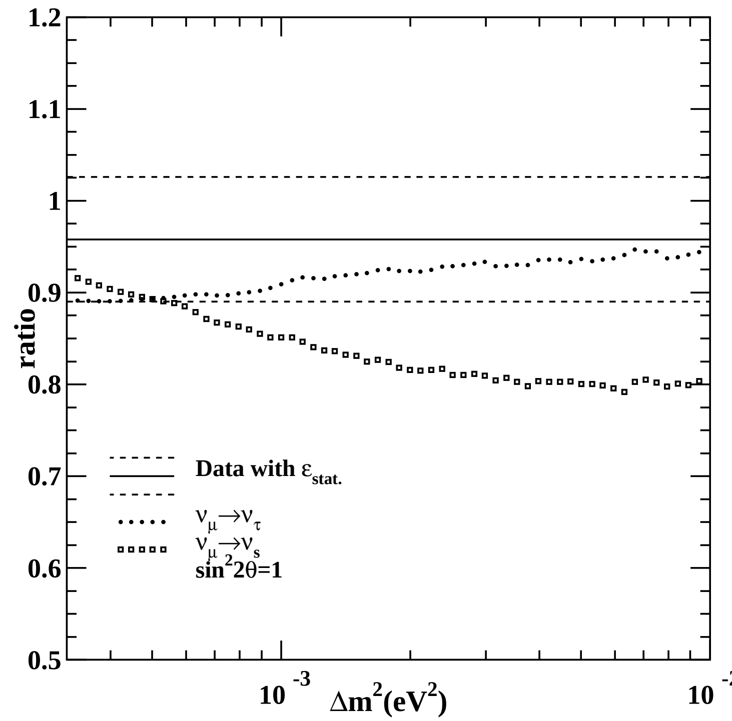
1144 days

Multi-Ring Events

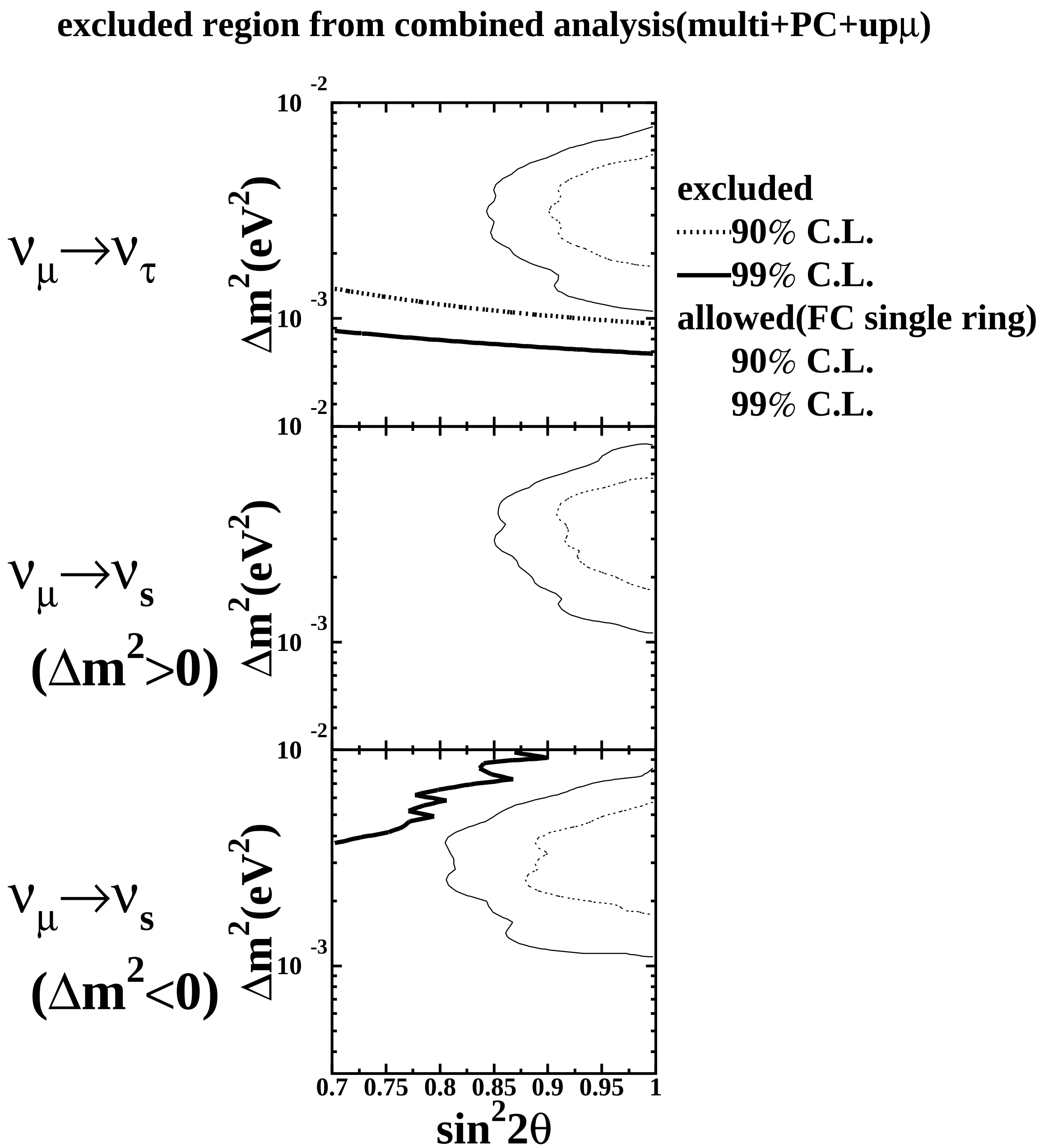
zenith angle distribution of N.C. enriched multi-ring events (1144days)



up/down ratio of N.C. enriched multi-ring events



1144 days



Two component $\nu_\mu \leftrightarrow \nu_s$ excluded at 99%

The FC+PC+up-μ analysis limits the admixture of ν_τ+ν_s to

$\nu_s < 32\%$ @ 90% confidence

τ Appearance in Super-Kamiokande

Observation $\nu_\mu \leftrightarrow \nu_\tau$ is favored.

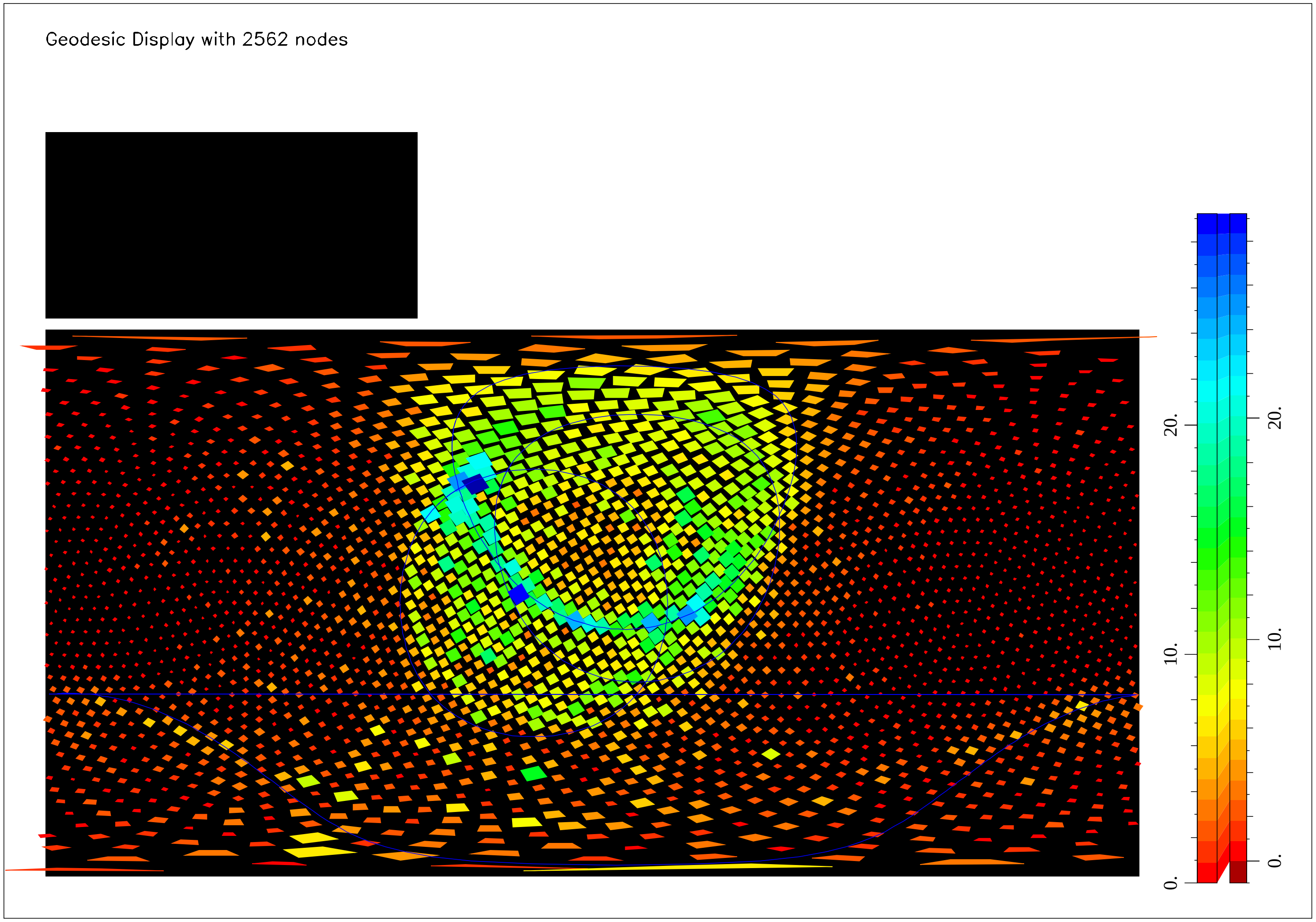
Assume $\nu_\mu \leftrightarrow \nu_\tau$ is established as the dominant oscillation.

- For Δm^2=3$\times 10^{-3}$ eV^2, 74 ν_τ CC events expected
  - Signal to Noise of 0.7%
- Three different analyses done (not statistically independent)
  - **Likelihood** Analysis using “standard” SK variables.
  - **Neural Net** Analysis using “standard” SK variables.
  - **Energy Flow** Analysis using event shape variables.

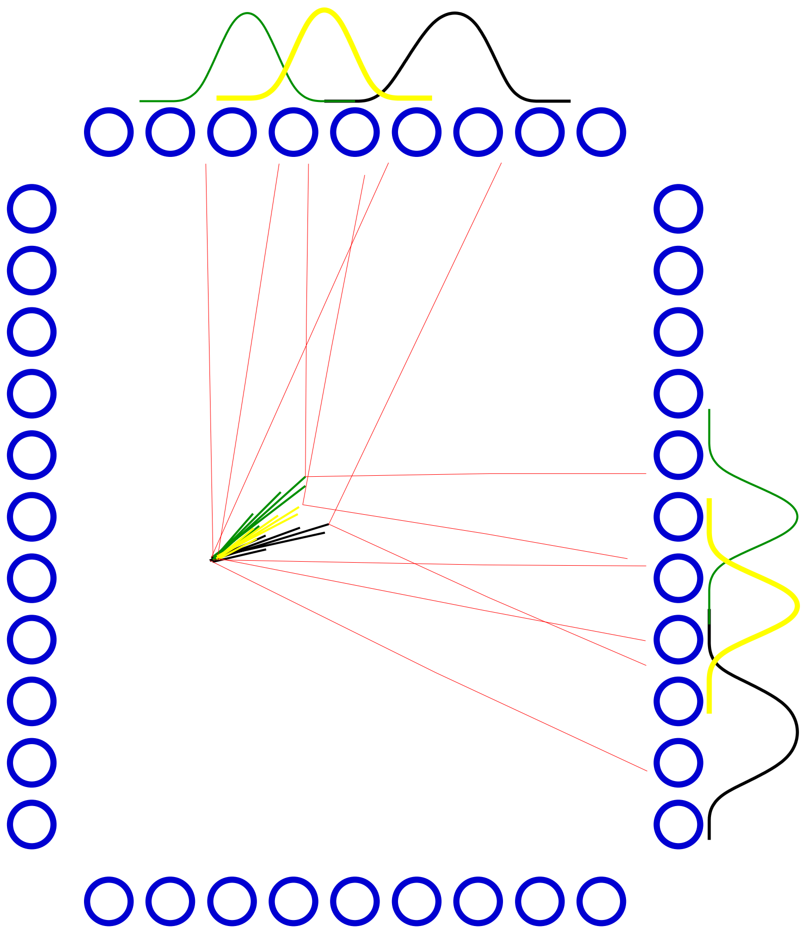
What should CC ν_τ events look like?

- 82% are “showering” (no muon).
  - A combination of electron and hadron showers.
- 96% have > 0 pions.
  - mean: 6.1 pions per event.
- 80% of leptonic decays have > 0 associated π.
  - mean: 3.3 pions per event.

Visible Energy: 3.5GeV



Cherenkov Energy Flow



- Using known Cherenkov patterns Energy Flow can be reconstructed.
- Energy flow in each direction is assigned to a “pseudo-particle” and jets are reconstructed.

The Math

Solve:

$$\chi^2 = \sum_i (\mathcal{Q}_i - \sum_j R_{ij}\mathcal{P}_j)^2 / \sigma^2_{\mathcal{Q}_i}$$

Caveat: Not meaningful if elements of $\vec{\mathcal{P}}$ are negative!

Solution:

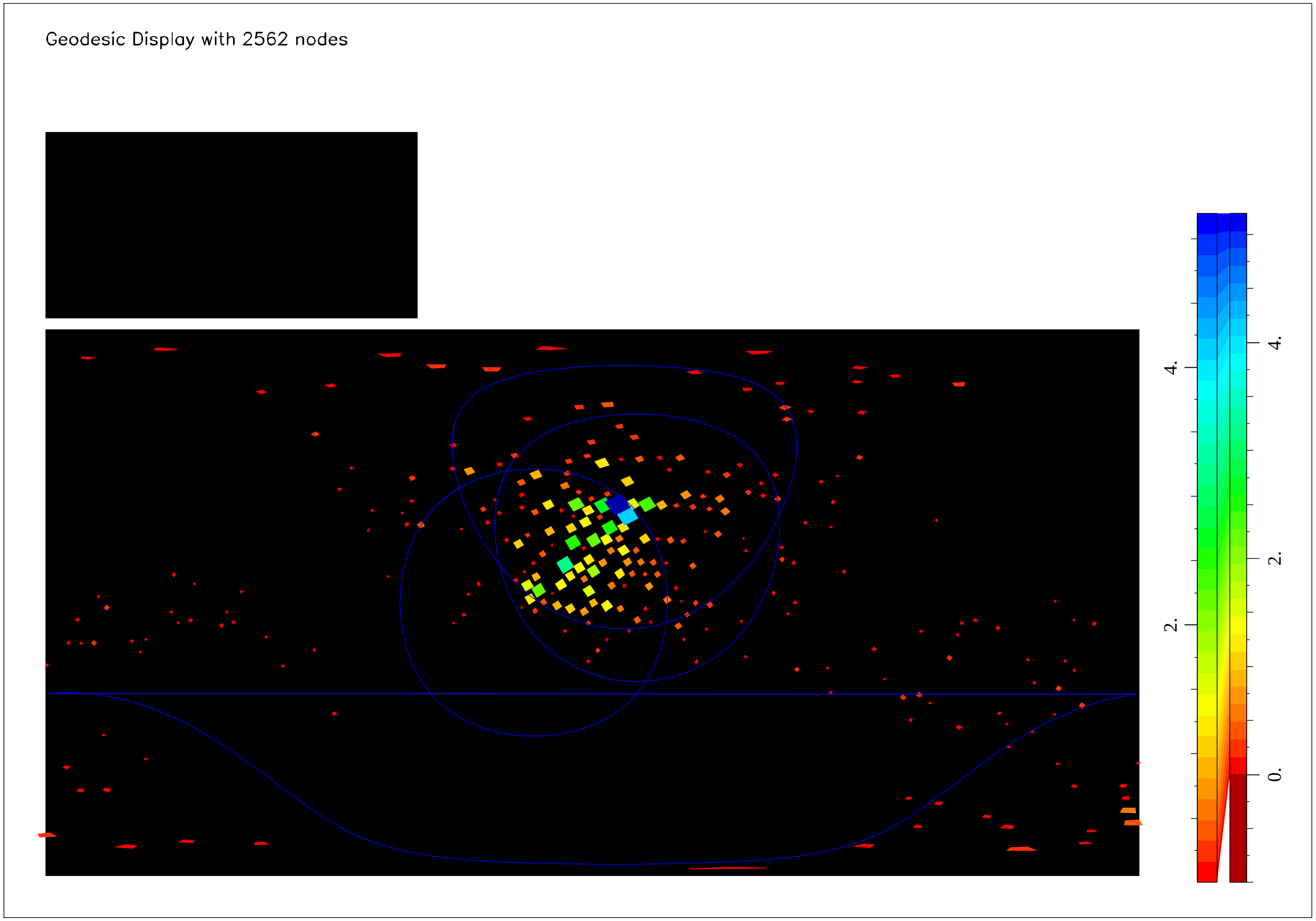
1. Solve equation.
2. Set negative $\mathcal{P}_i$ to zero.
3. Resolve equation.
4. Repeat until remaining $\mathcal{P}_i$ are positive.

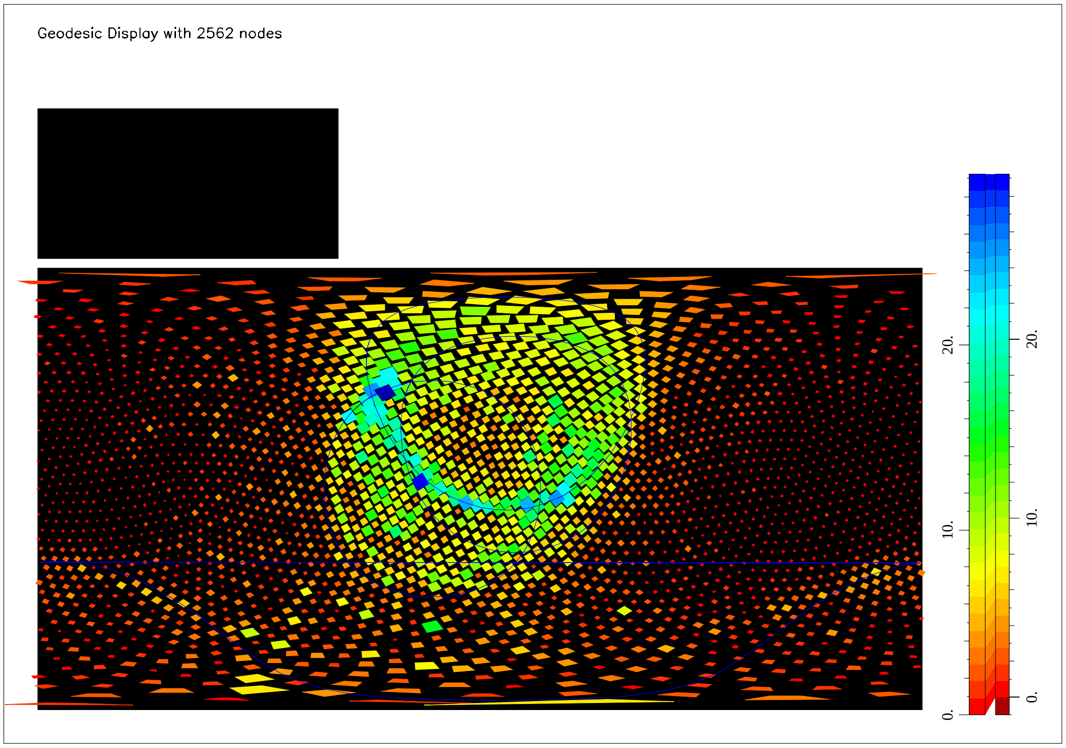
There is a unique solution to this equation.

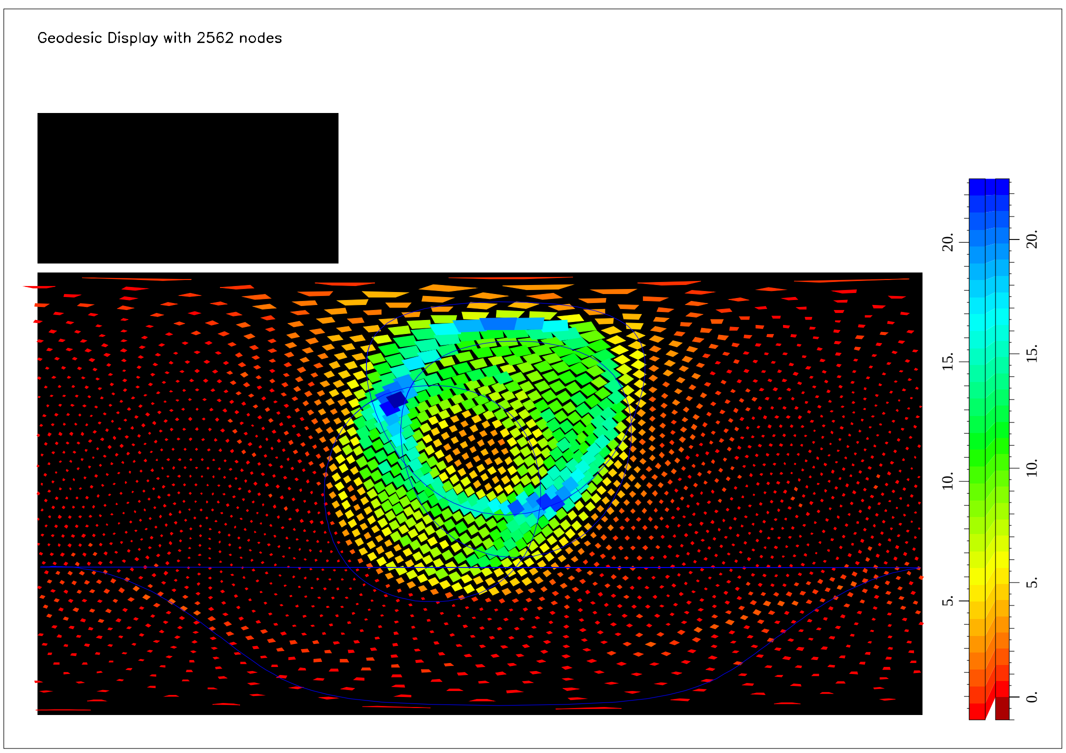
$\mathcal{P}_i$ represent the "momenta" of massless pseudo-particles.

Which are used to construct jet variables (like sphericity).

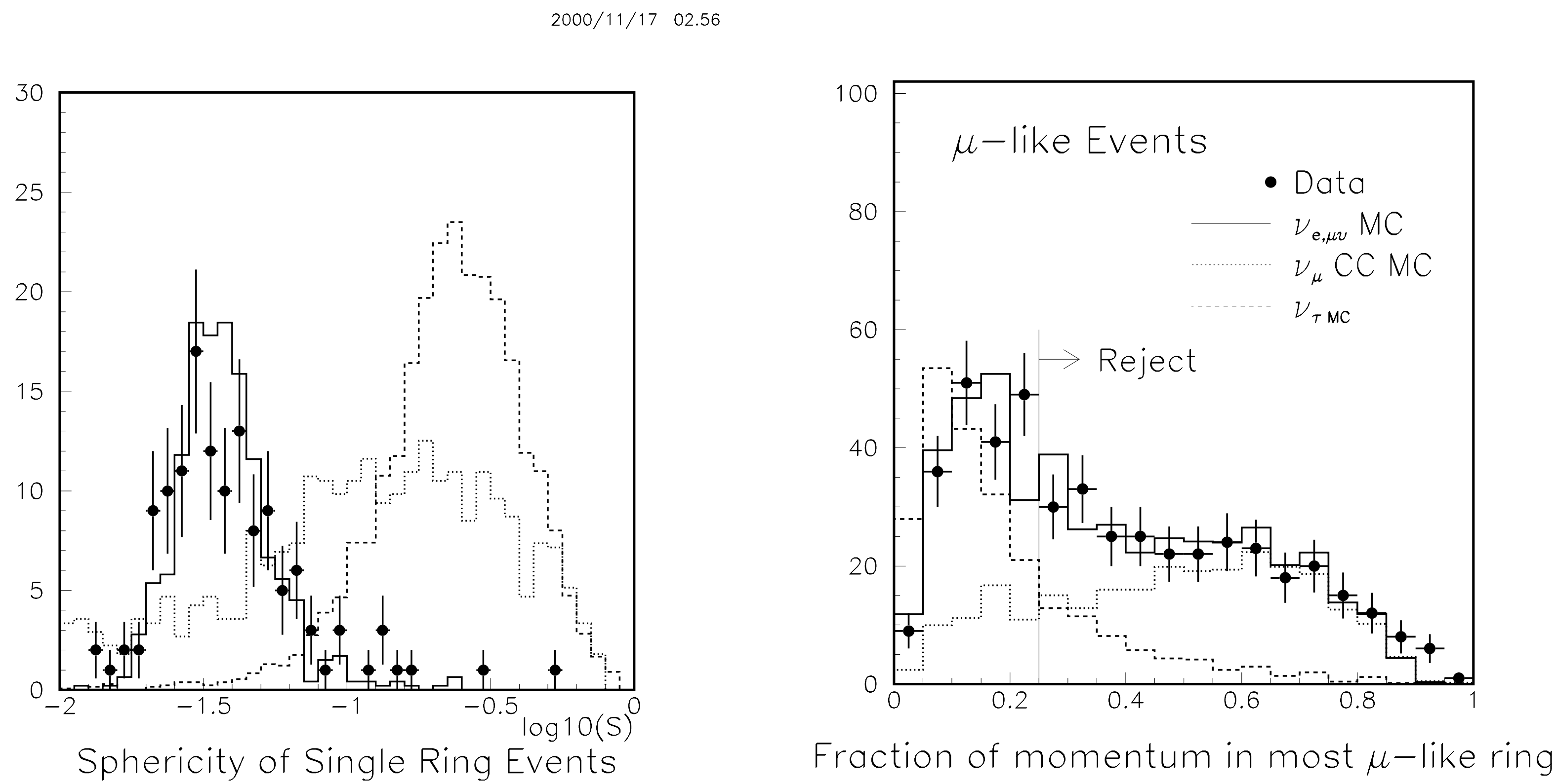
Fit Result



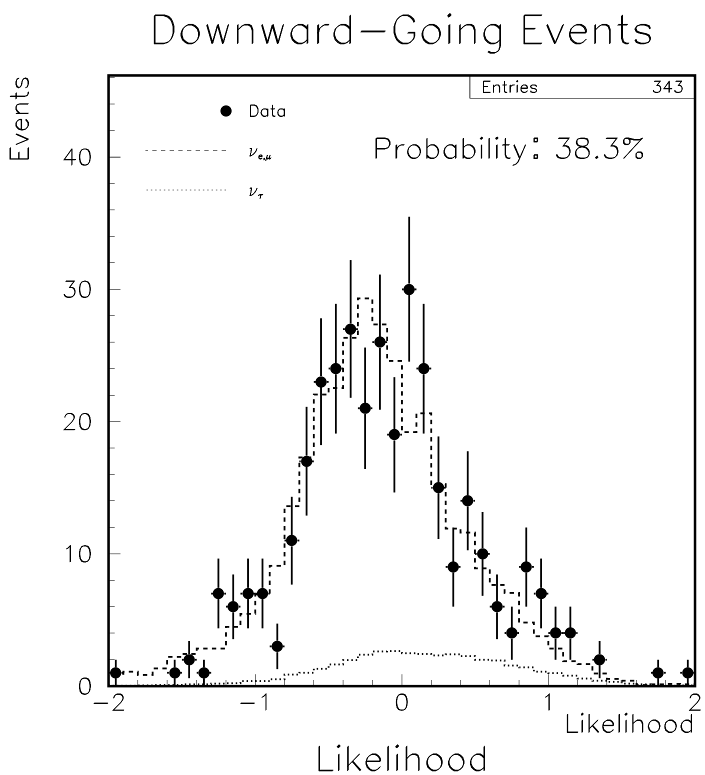

Geodesic Display with 2562 nodes
0.
10.
20.
0.
10.
20.


Geodesic Display with 2562 nodes
5.
10.
15.
20.
0.
5.
10.
15.
20.

Cuts


2000/11/17 02.56
log10(S)
Sphericity of Single Ring Events
μ−like Events
Data
$\nu_{e,\mu\upsilon}$ MC
ν_μ CC MC
ν_τ MC
Reject
Fraction of momentum in most μ−like ring

The Likelihood



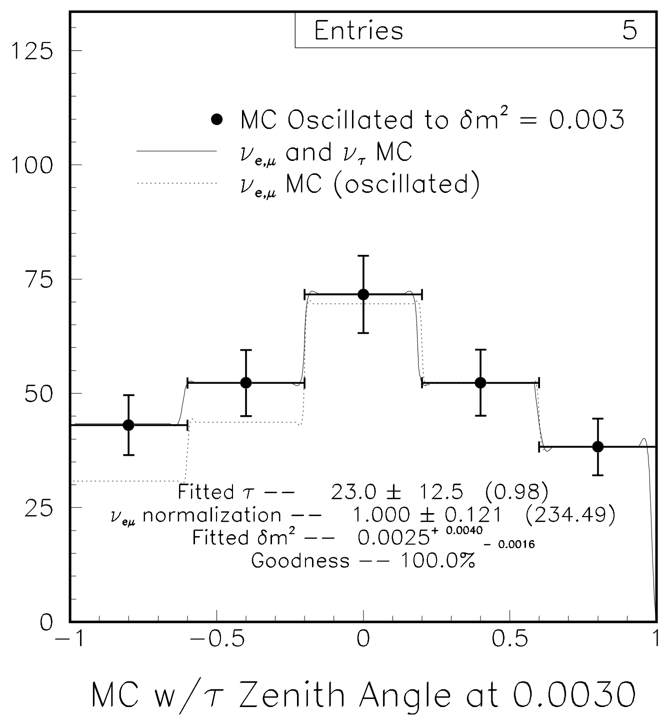
Likelihood $>$ 0 is τ-like

- Visible energy: E_{vis}
- Number of μ decay signals
- Sphericity of first 10 jet clusters
- Sphericity in "rest" frame.
- Sphericity after clustering to $M_{max} > 150$ MeV
- Ratio of energy in largest cluster (10 deg cone)
- Boost Factor, γ, for "Center of Mass"

Cuts and Efficiency

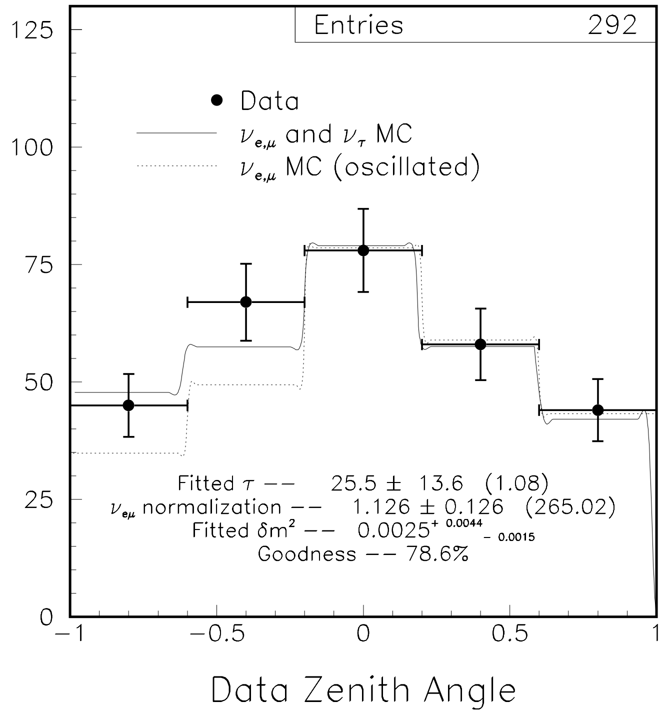
Cut	τ	$\nu_{e,\mu}$	Data
Initial	4069	65786	10594
$E_{vis} > 1330$ MeV	3411 (84%)	15657 (24%)	2525 (24%)
NHITAC $\leq$ 10	3377 (99%)	15500 (99%)	2502 (99%)
$\geq$ 1 showering track	3073 (91%)	8627 (56%)	1476 (58%)
Cluster	2642 (86%)	5521 (64%)	989 (67%)
μ-like	2503 (95%)	4091 (74%)	731 (74%)
Likelihood $>$ 0.0	1251 (50%)	1391 (34%)	292 (40%)
Total	1251 (31%)	1391 (2.1%)	292 (2.7%)

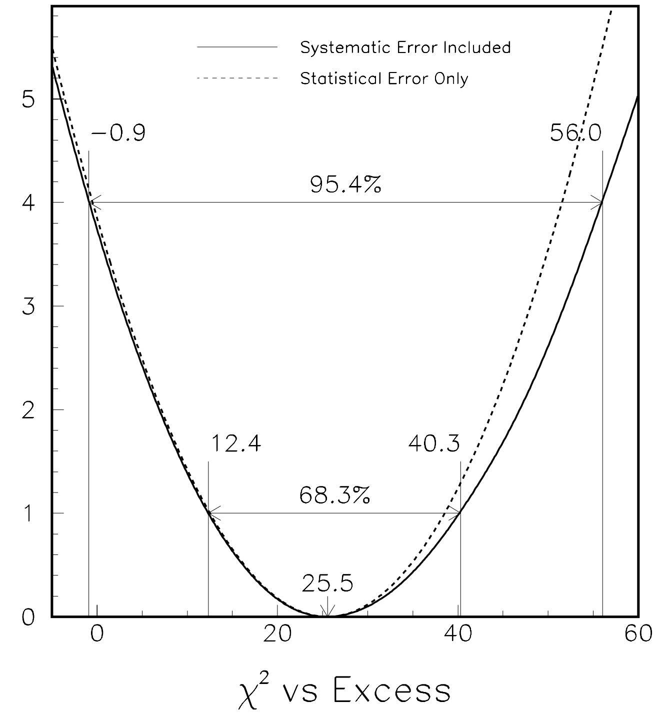
Fit Zenith Angle



- Expect a 1.85σ excess.
  - Should exclude zero by $> 90\%$
- Flavor content:
  - ν_{nc}: 28%, ν_e: 39%, ν_μ: 33%
- Systematics:

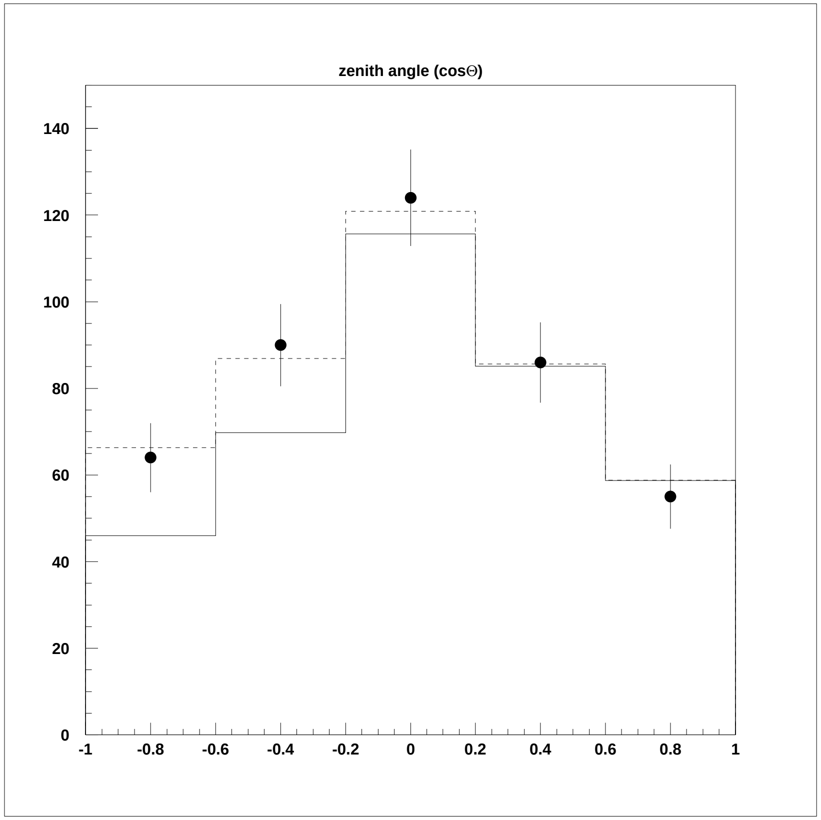
NC/e ratio	30%
μ/e ratio	12%
Δm^2	$(1.6 - 4) \times 10^{-3}\ \mathrm{eV}^2$

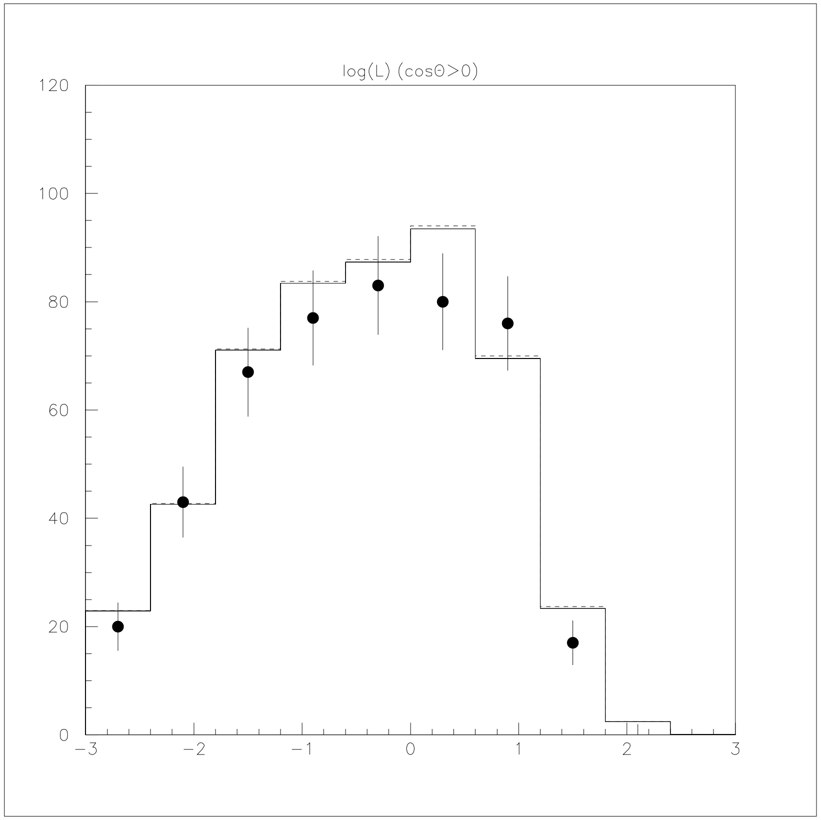




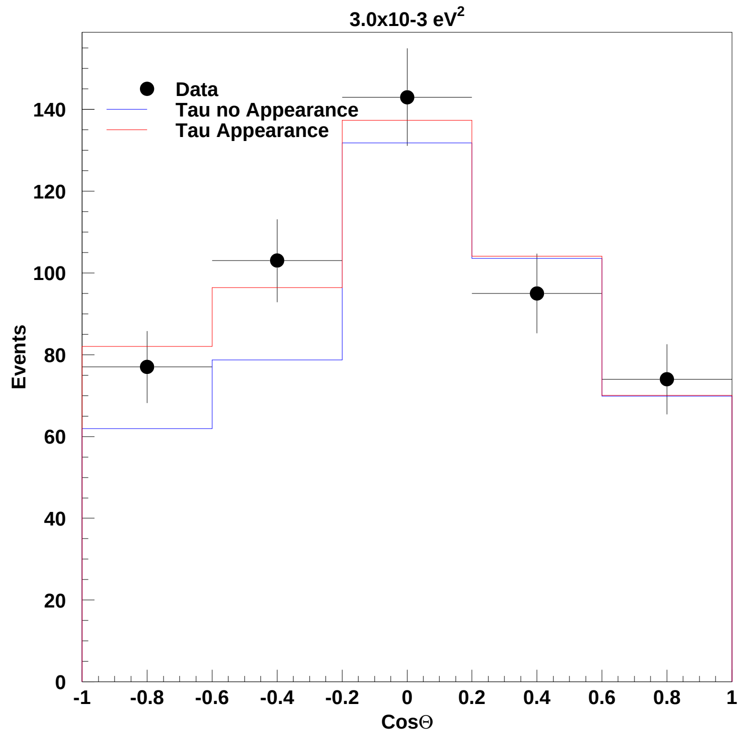
$$\chi^2 = \sum_i \frac{(N_i - \alpha N_i^\tau - \beta N_i^{bg})^2}{\sigma_i^2} + \sum_j \frac{\epsilon_j^2}{\sigma_j^2}$$

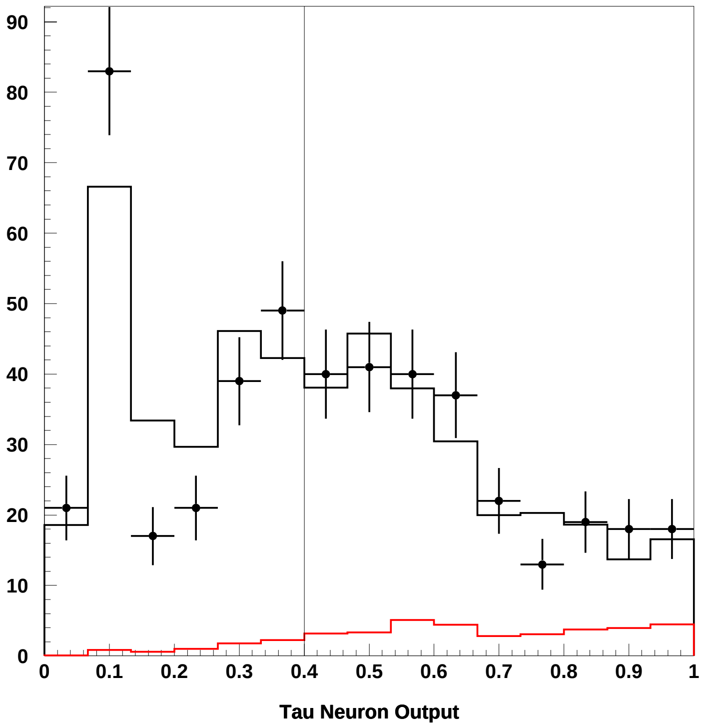
Likelihood Analysis





Neural Network Analysis





Comparison of Results

	Likelihood	NN	Event Shape
Expected Significance			
	1.6σ $(1.8\sigma$stat$)$	1.5σ $(1.7\sigma$stat$)$	1.9σ (stat + sys)
Fitted Excess			
	43 ± 17 (stat.)$^{+8}_{-11}$ (sys.)	44 ± 20 (stat.)$^{+8}_{-12}$ (sys.)	25.5^{+14}_{-13}(stat + sys)
Efficiency			
	41%	45%	32%
Fitted Excess (Efficiency Corrected)			
	103 ± 41 (stat.)$^{+18}_{-26}$ (sys.)	98 ± 44 (stat.)$^{+18}_{-27}$ (sys.)	79^{+44}_{-40}(stat + sys)

3-flavor mixing increases uncertainty by $\sim$ $^{+0}_{-18}$ events.

These results are highly correlated

Summary

- All of the data is consistent $\nu_\mu \leftrightarrow \nu_\tau$ oscillations
  - $\sin^2 2\theta > 0.88$
  - $1.6 \times 10^{-3}\,\mathrm{eV}^2 < \Delta m^2 < 4 \times 10^{-3}\,\mathrm{eV}^2$
- Multi-ring data is being studied in detail for use in oscillation fits.
- Two component $\nu_\mu \leftrightarrow \nu_s$ is excluded with 99% confidence
- Multi-GeV data is consistent with ν_τ appearance.