Atmospheric Neutrino Oscillations and the Search for ν_τ Appearance at Super-Kamiokande

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(on behalf of the Super-Kamiokande Collaboration)

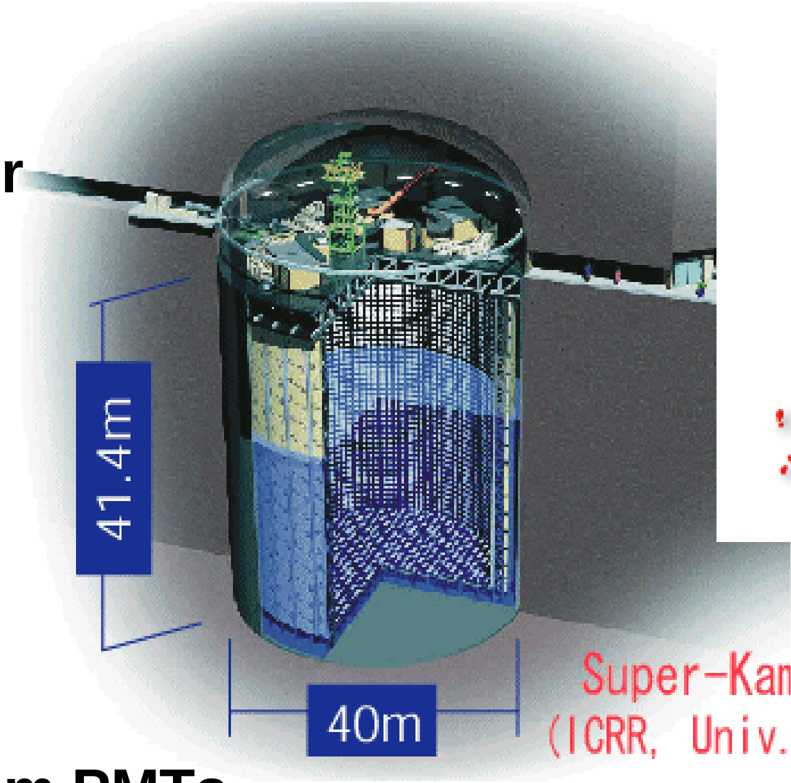
Outline : Two Main Parts

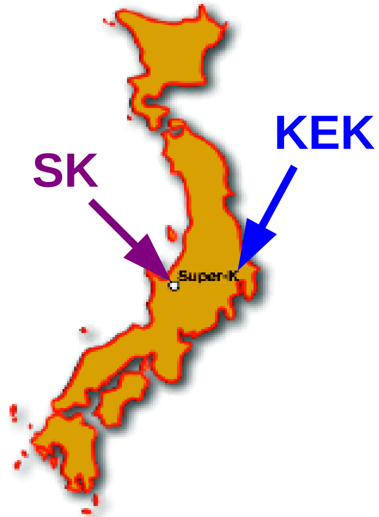
- Introduction to evidence for ν_μ to ν_τ oscillations
  - Updated analysis from 173 kton• yr exposure

- Search for ν_τ events at Super-Kamiokande
  - Results from previously published analysis from SK-I 91 kton• yr
  - Status of updated analysis for the 173 kton• yr exposure

Introduction to SK

50 kton water Cherenkov detector
22.5 kton fiducial volume





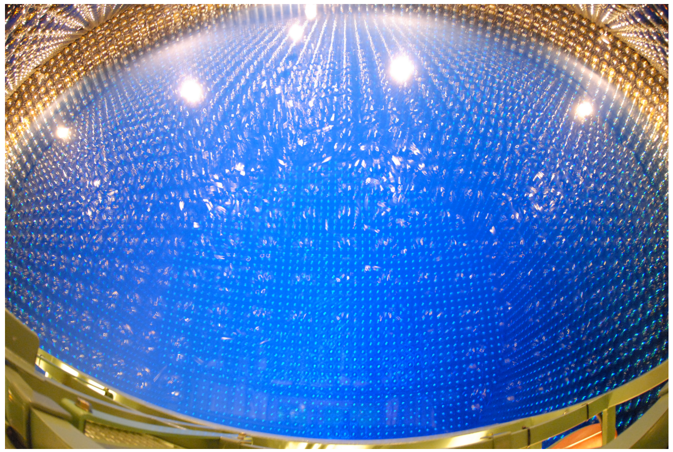
Depth of 2700 m.w.e

~130 Collaborators
~35 Institutions

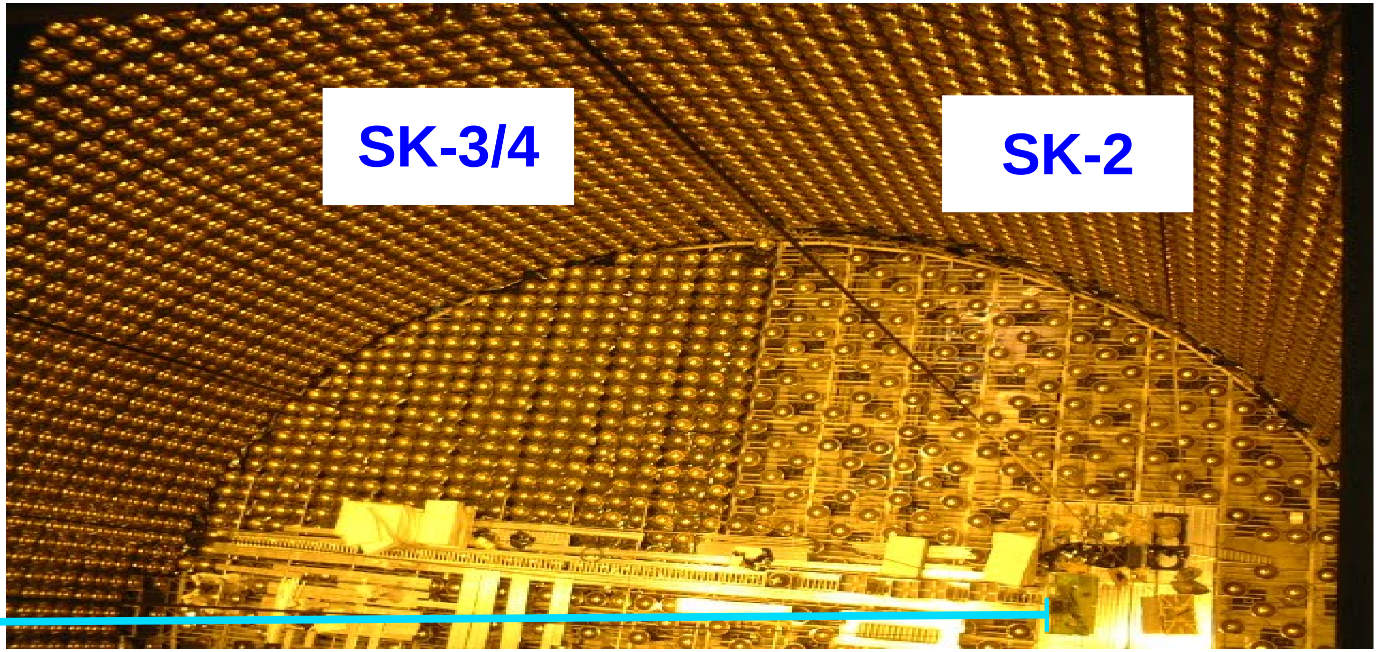
In operation since 1996

Inner detector (ID) ~11,146 50 cm PMTs
Outer detector (OD) 1,885 20 cm PMTs

Multi-purpose detector:
- Solar neutrinos
- Atmospheric neutrinos (this talk)
- Nucleon decay
- Supernova neutrinos (Relic SN's)
- Beam neutrinos (K2K, T2K...)
- Exotic particles



Super-K : Generations



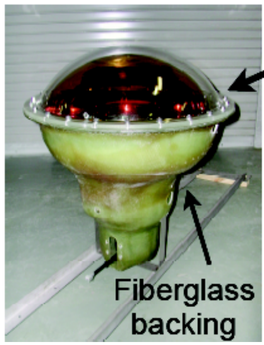
This Talk

1996 | 1997 | 1998 | 1999 | 2000 | 20 01 | 2002 | 2003 | 2004 | 2005 | 20 06 | 2007 | 2008 | 2009 | 2010 …

accident

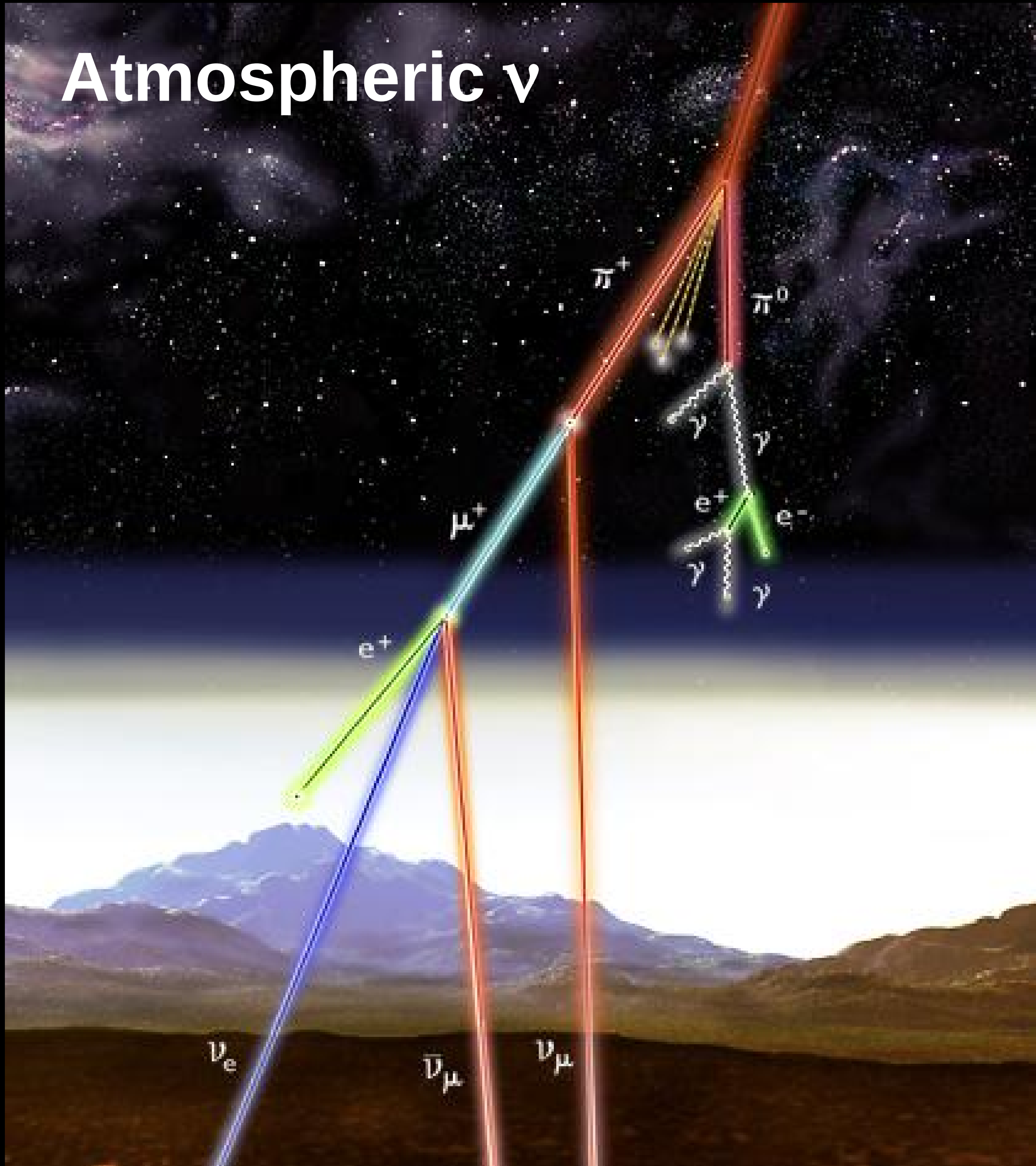
SK-I (1996-2001)
11,146 ID PMTs
(40% coverage)
1,885 OD PMTs

SK-II (2003-2005)
5182 ID PMTs
(19% coverage)
Acrylic shields added



SK-III (2006-2008)
11,129 ID PMTs (40% cov.)
OD segmentation
(top/barrel/bottom)

SK-IV (2008-...)
new front-end electronics
(ID and OD)
new DAQ
record-all-hit data-taking
+ software trigger

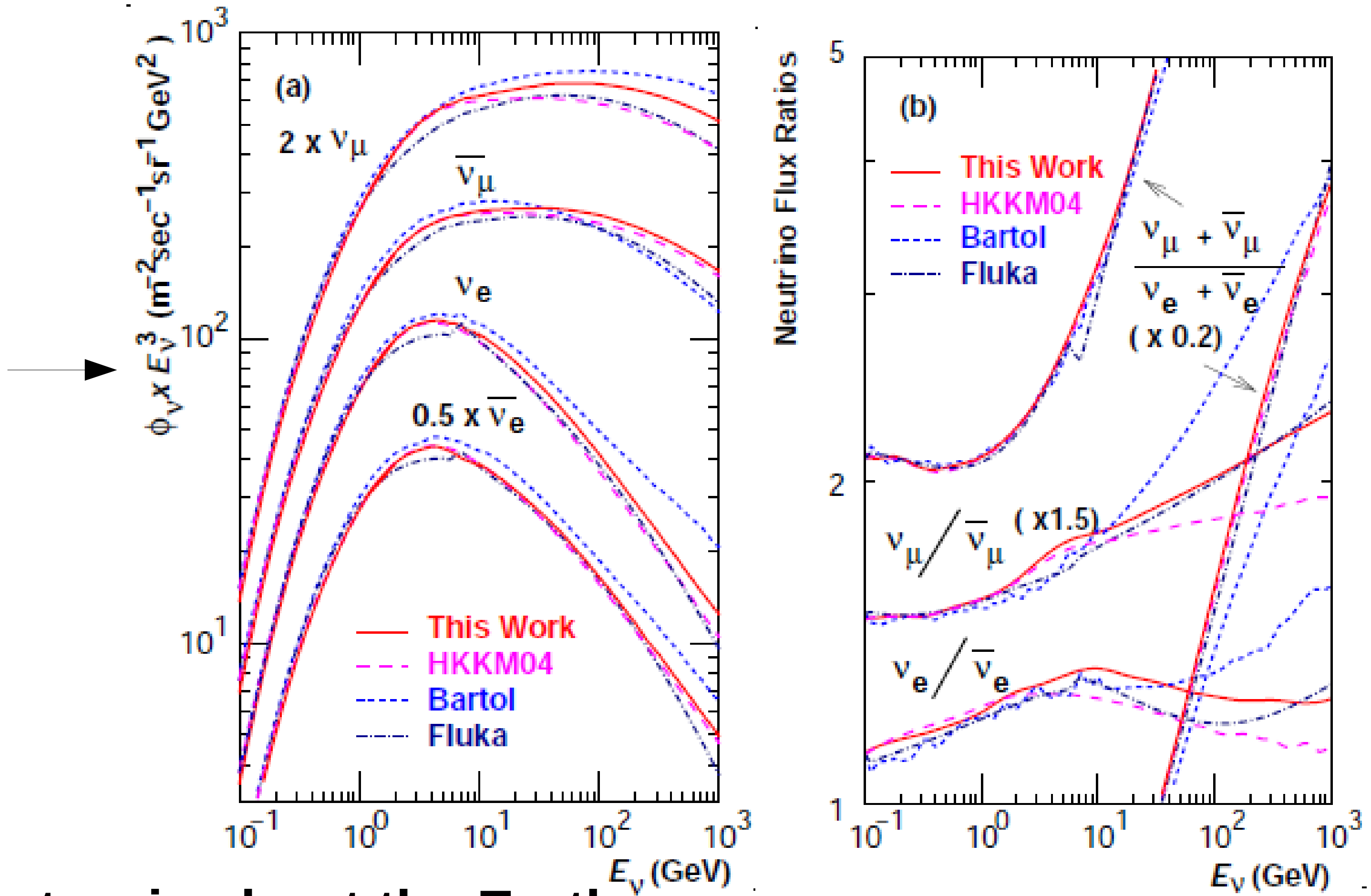


Roughly

$\nu_e : \nu_\mu \sim 1:2$

Atmospheric ν Fluxes

M. Honda, et. Al Phys.Rev.D75:043006,2007



Flux is isotropic about the Earth

- Large variation in ν pathlength ~ 10 - 10^4 km

Spanning several energy decades

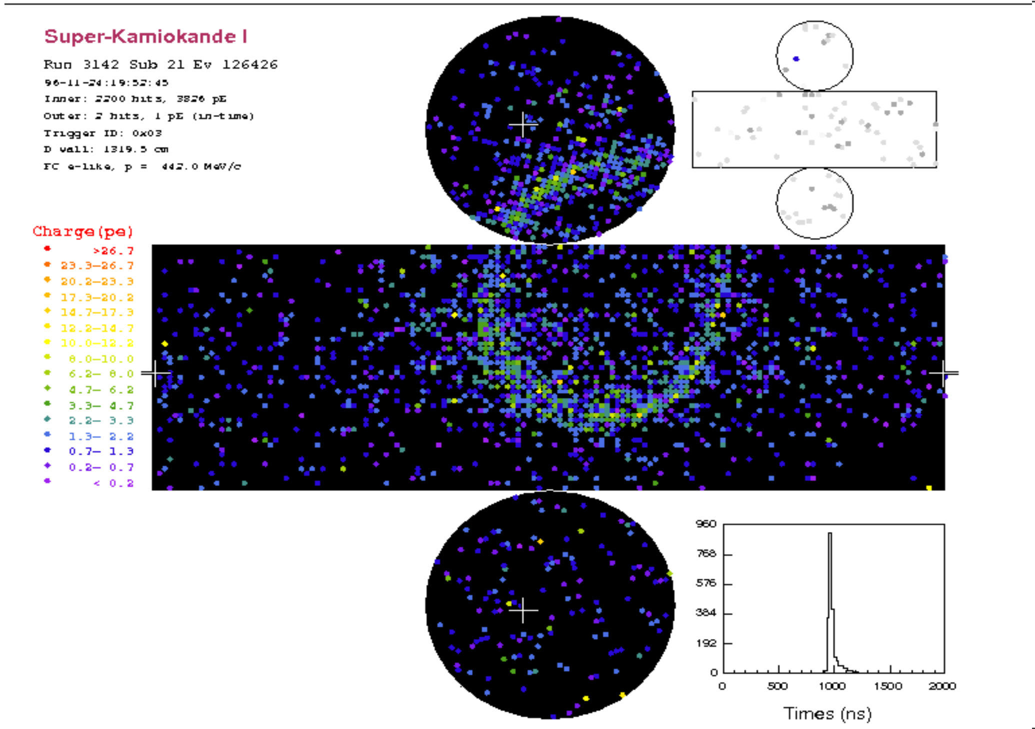
small primary ν_τ flux

though non-zero: hep-ph/9811268 , 1007.4989

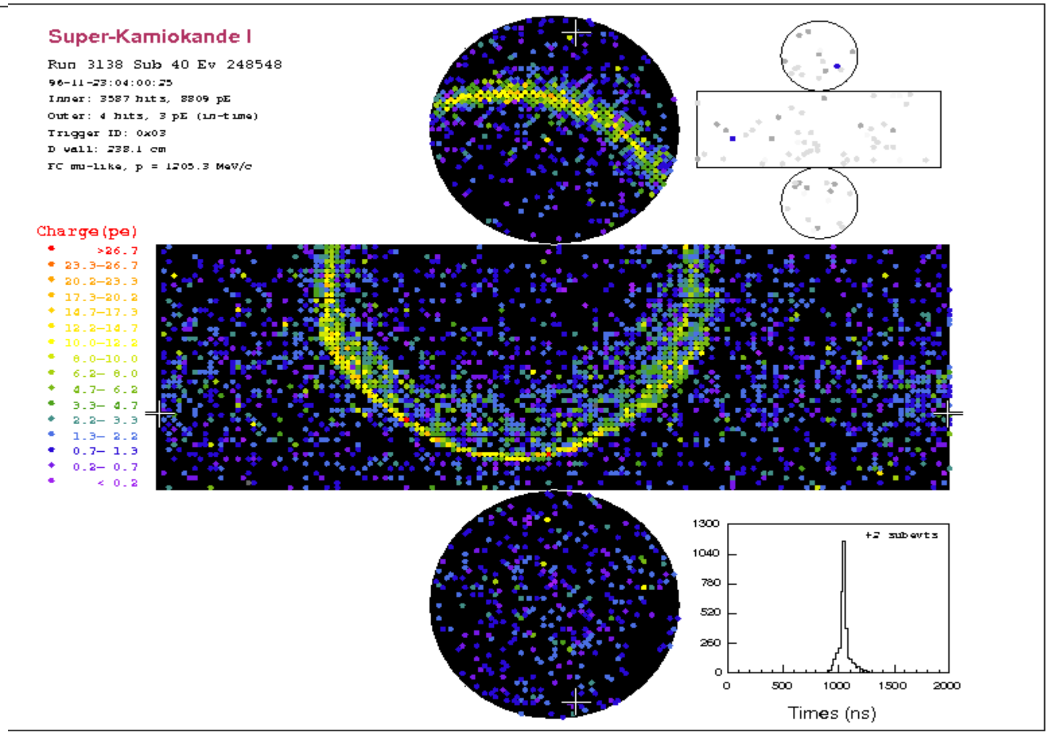
Large Variation in L/E
Good for osc. studies

SK-I Data

e-like / Showering



μ-like / non-showering

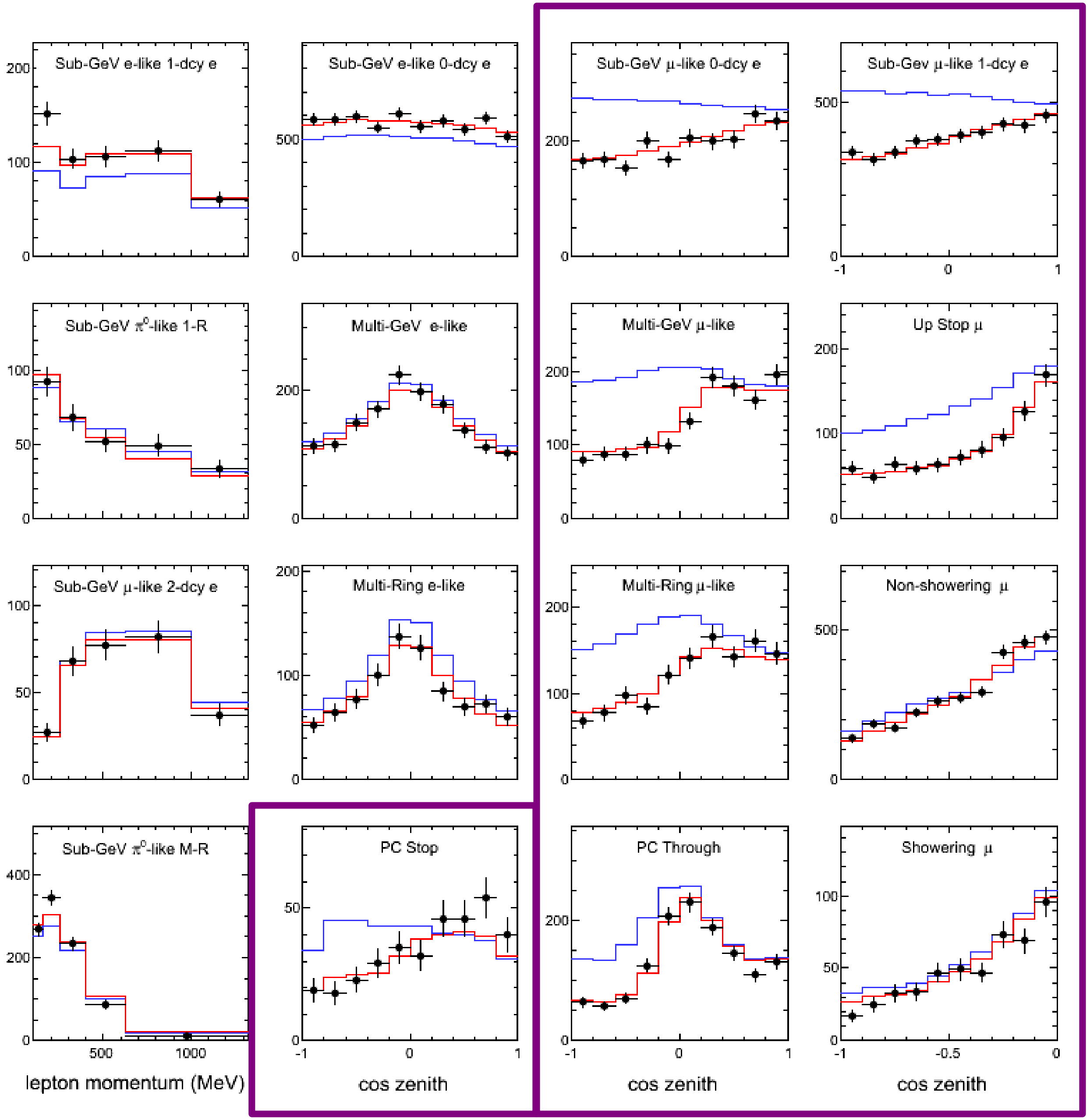


Events categorized by topology and energy:

- **Fully Contained, Partially Contained, upward-going μ**
- **Number of rings – Single / Multi- ,**
- **PID – e-like / μ-like**

} 16 samples total

Atmosheric ν data : SK-I + II + III , 2806 days



Unoscillated

Best Fit Osc.

● **Data**

- Unoscillated neutrino flux differs significantly from the observation in many sub-samples.
- Largest effect is in the upward-going high-energy μ-like samples

Primary out-going lepton is used for PID classification

- ~24,000 ν events

ν Oscillations In Two Domains: Atmospheric and Solar

$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$ ν mass eigenstates ≠ flavor eigenstates

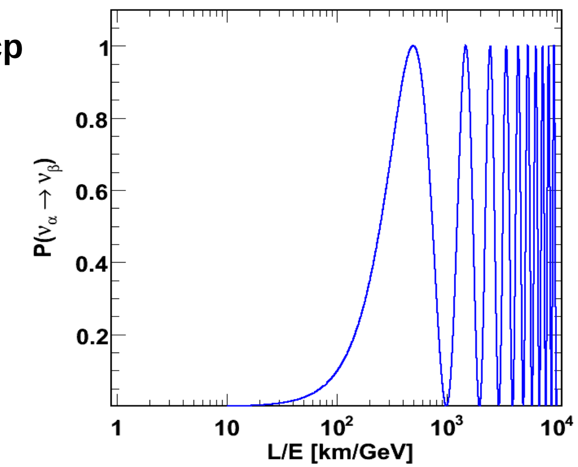
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric **Solar**

Additionally two mass splittings: Δm^2_{12} , Δm^2_{13} , δ_{cp}

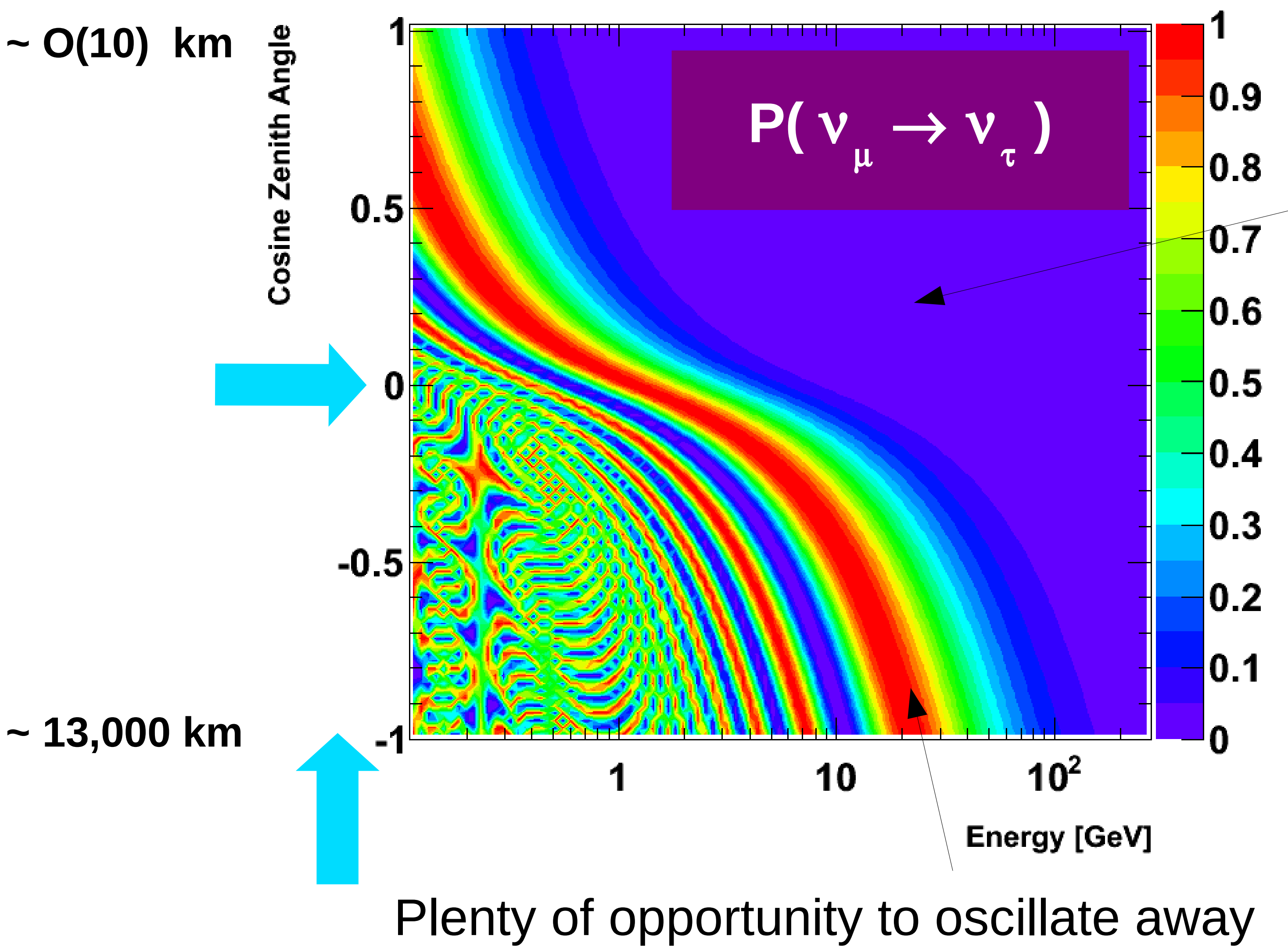
To good approximation, many experiments can be analyzed in the context of two active ν's:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right) \quad \left[\frac{eV^2\,km}{GeV}\right]$$



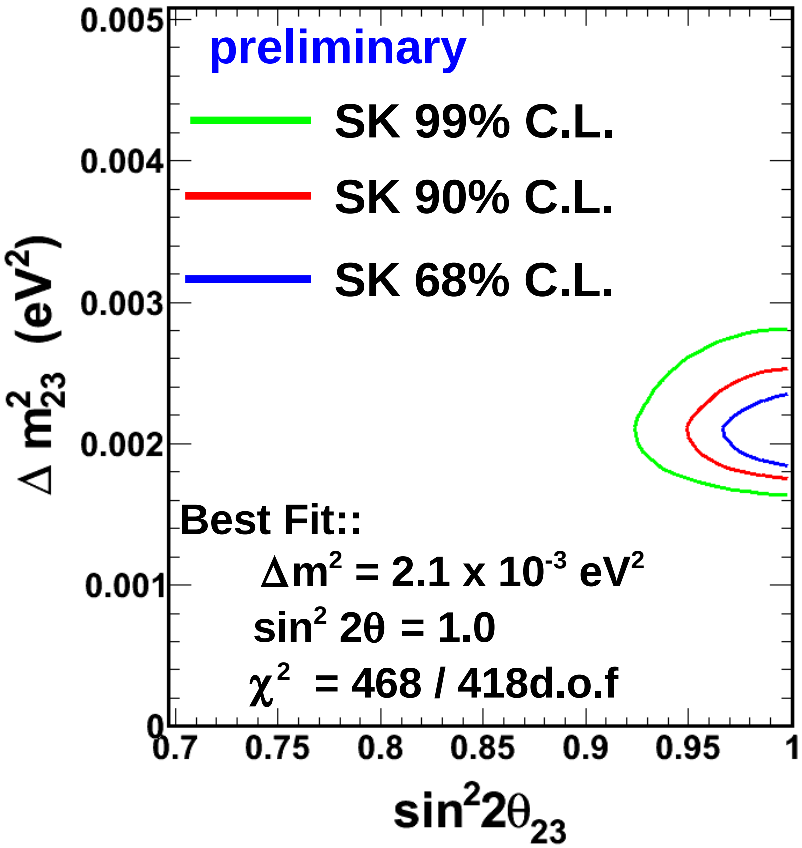
Oscillation interpretation

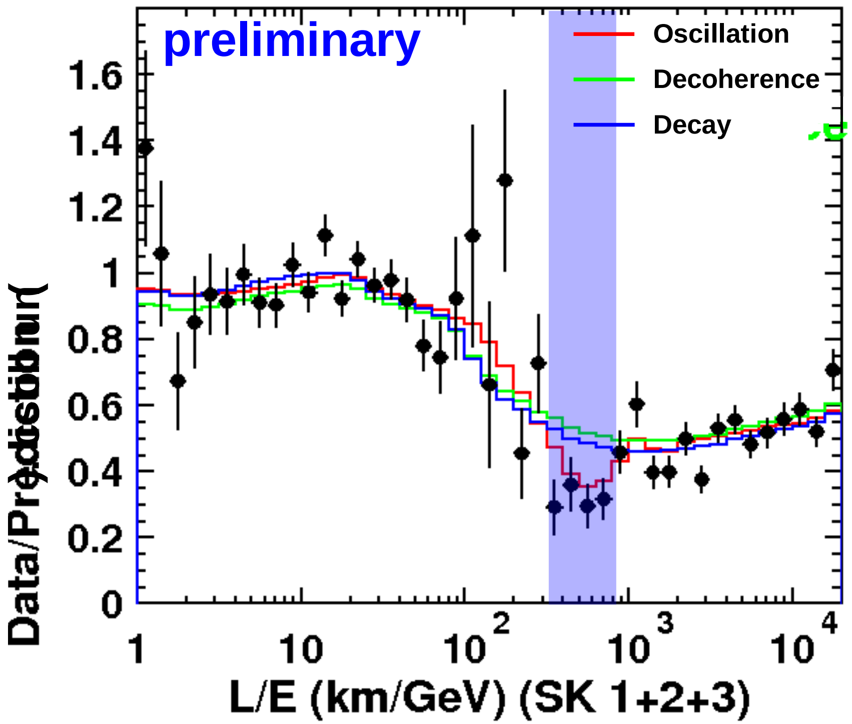
- SK data are well described by oscillations from ν_μ into ν_τ



We can further exploit this asymmetry in the search for tau events

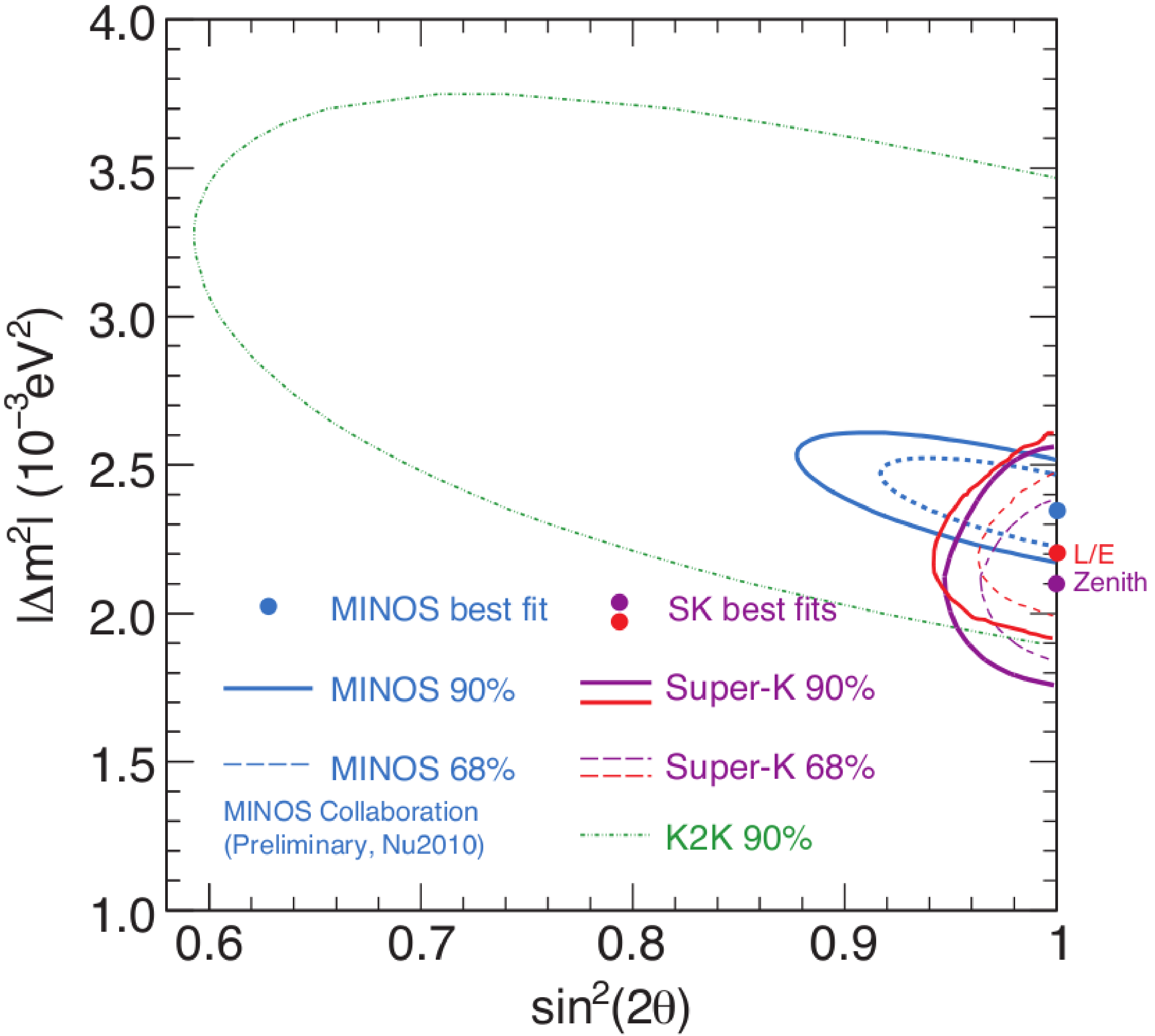
Super-Kamiokande SK-I+II+III: Atmospheric ν





- Uses 120 sources of uncertainty: x-scns, detector, Nuclear effects
- Other types of disappearance models are ruled out
  - Pure sterile disfavored at 7 σ, MaVaNs at 4^+ σ, ν decay 4-17 σ
- Super-K data strongly favor the standard oscillation hypothesis
  - We should look for tau appearance!

Global Picture of Oscillations Agrees



- Experiments are in good agreement about these oscillations

Search for ν_τ appearance events in SK-I

How many ν_τ are expected at Super-K ?

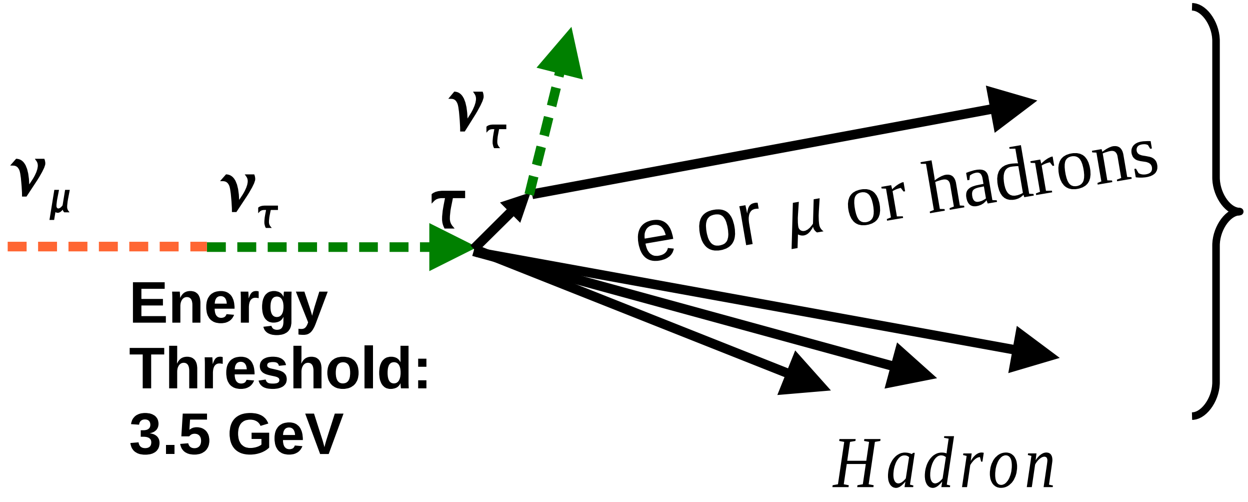
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric **Solar**

- If $\theta_{13} > 0$, Multi-GeV resonant enhancement of $\nu_\mu \leftrightarrow \nu_e$ is expected for upward-going neutrinos
  - Look like τ events, but SK data are consistent with $\theta_{13} = 0$ so this effect is considered as a systematic
- Solar oscillations exist ($\theta_{12} > 0$) so $\nu_e \leftrightarrow \nu_\tau$ is expected at low energies (< 500 MeV), well below τ production threshold

For 4.1 years / 22.5 kton
$\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.4\ 10^{-3}$ eV^2 , expect ~78 ν_τ

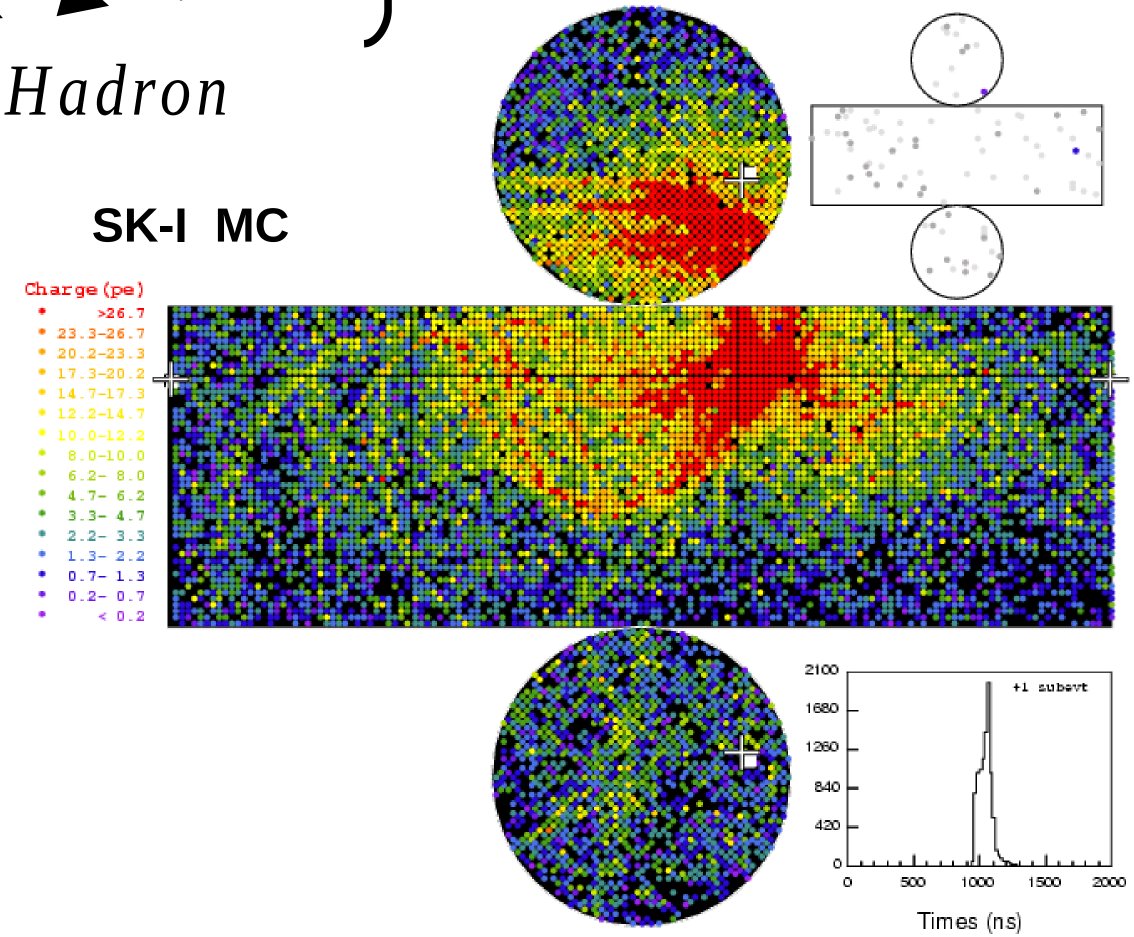
ν_τ events in Super-K : Focus on hadronic τ decays



Many light producing particles

Mostly Deep inelastic scattering events

- For energetic events of this type finding and identifying the leading lepton is complicated
  - Use a multivariate method



Analysis Details:
SK-I Data (1489 days)
200 years of Tau MC
200 years of Atm. ν BG MC
Tauola 2.6 used for tau decays
Decay polarization (Hagiwawa et al. 2003)
GRV 94 + Pythia/Jetset used for DIS.

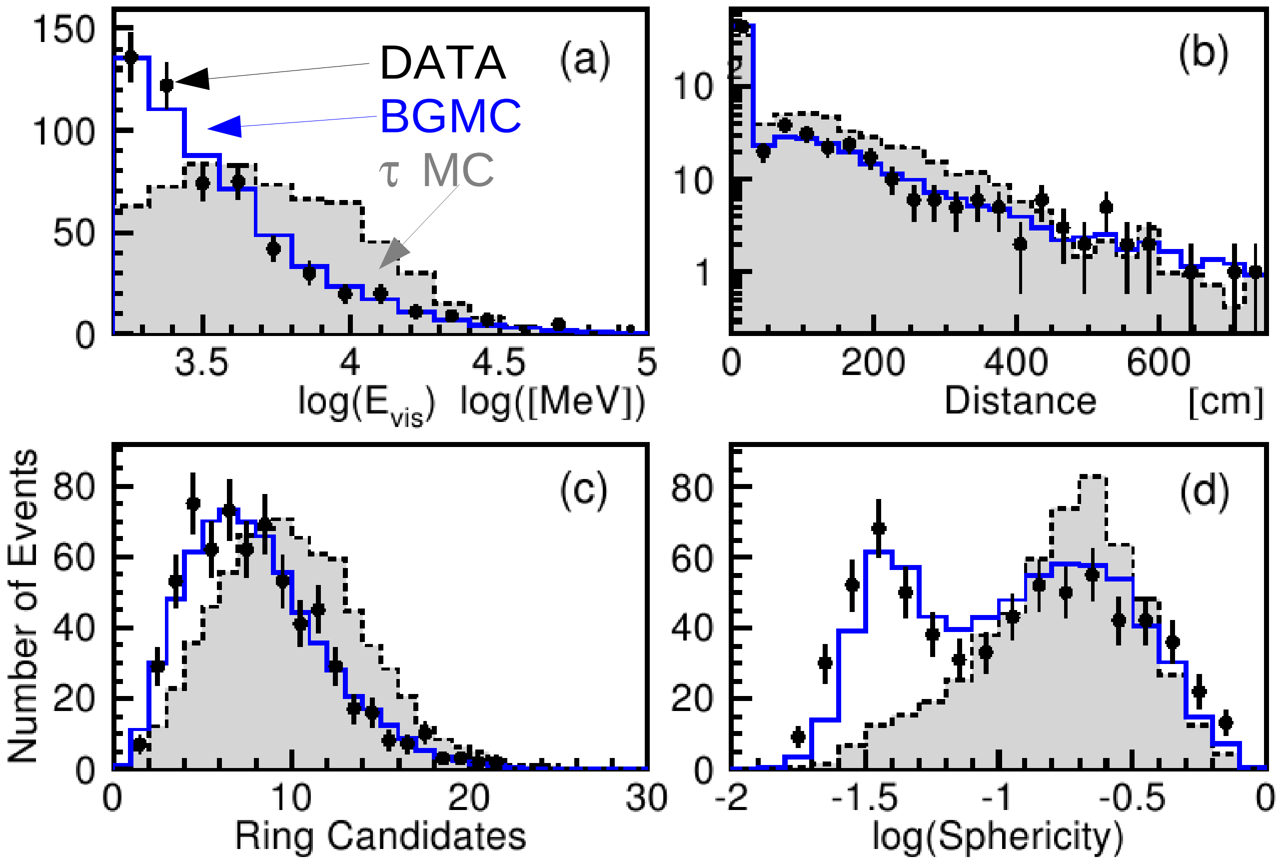
How to search for ν_τ events

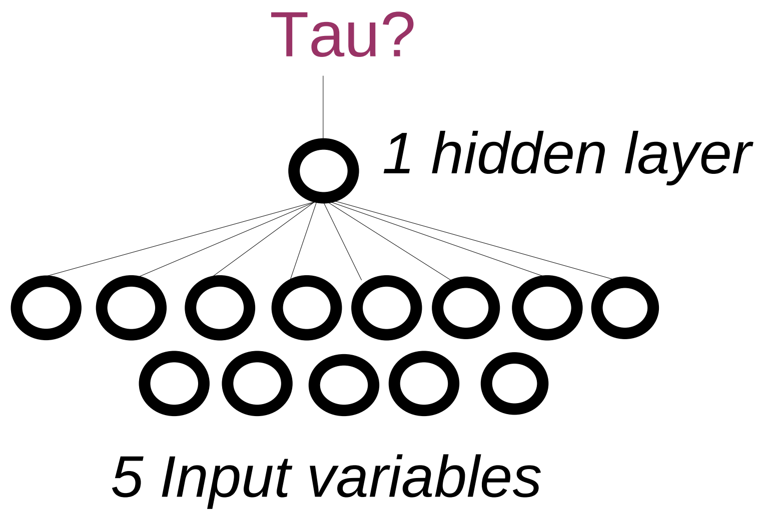
SK-I Data	$\nu_\mu + \nu_e$ BG MC	ν_τ Signal MC

Cut	Purpose
Generated > 200 cm from Wall	**Fiducial Volume Definition**
E_{vis} > 1.33 GeV ; N_{hit}^{OD} < 12	**High Energy, Fully Contained (decay is heavy)**
Most energetic ring is e-like	**τ should be showering**
Neural Network > 0.5	

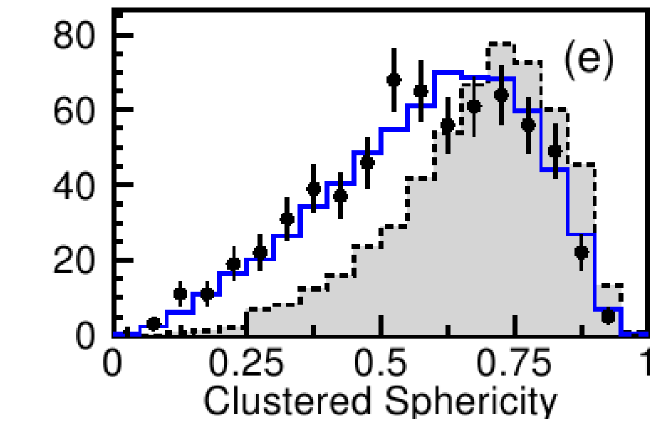
- All events passing the first three pre-cuts are passed to a neural net
  - Pre-cuts are expected to efficiently reduce BG since CC ν_τ production threshold is comparatively high
- Events that pass the neural net. selection are used to fit for the amount of tau appearance
  - Binned in Zenith Angle of out-going lepton

Neural Network Definition : Compare with down-going data





Data and BG MC agreement imply that the SK MC model these variables well

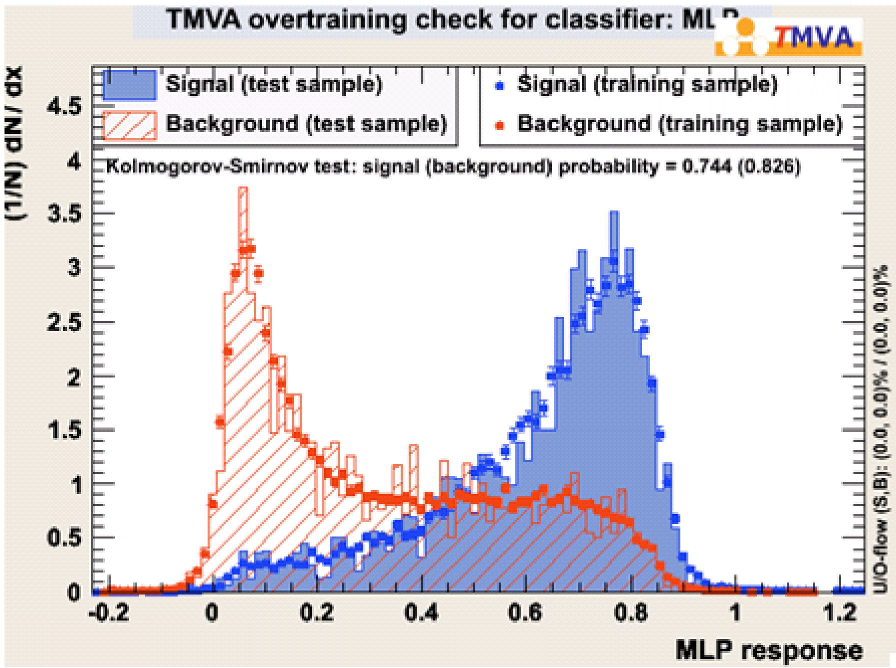


Variables used:

- Visible Energy
- Decay electron distance from vertex
- Number of ring fragment candidates
- Sphericity in lab frame
- Clustered sphericity in COM frame

How to search for ν_τ events

	SK-I Data	$\nu_\mu+\nu_e$ BG MC	ν_τ Signal MC
Generated > 200 cm from Wall		17135 (100%)	78.4 (100%)
E_{vis} > 1.33 GeV ; N_{hit}^{OD} < 12	2888	2943 (17.2%)	51.5 (65.7%)
Most energetic ring is e-like	1803	1765 (10.3%)	47.1 (60.1%)
Neural Network > 0.5	603	577 (3.4%)	30.6(39.0%)

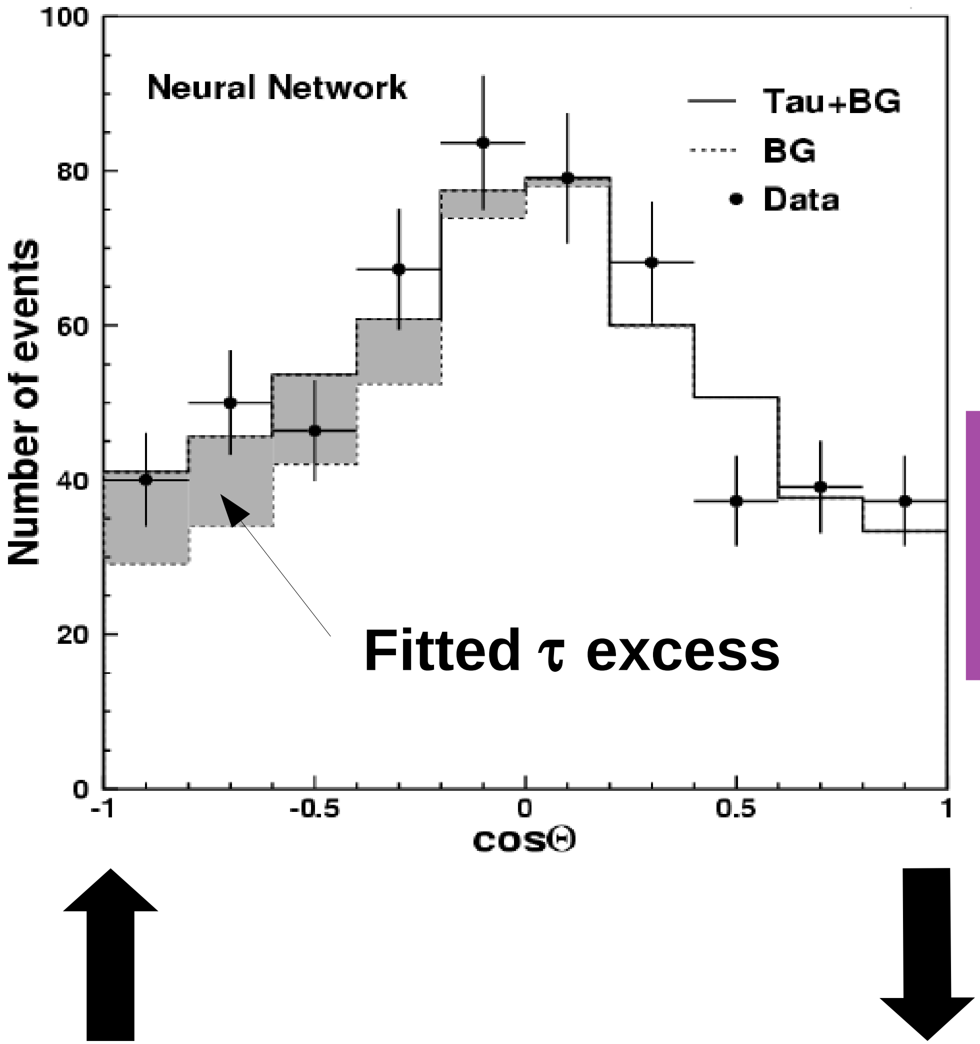


- Remaining backgrounds are mostly DIS events with multiple pions in the final state (CC DIS 61.4% and NC DIS 27.1%)

Good separation between signal and background in the NN variable

Zenith distribution of the τ-like events

Fit to Distribution: $f(\cos(\theta)) = \alpha \times (Tau) + \beta \times (No\ Tau)$



Tau Excess Background

- Fit is taken over the entire zenith angle distribution

No change to atm. MC normalization

$\alpha = 1.71,\ \beta = 0.99$

Fitted Excess: 52.3 ± 18.7

ε Corrected Excess: = 134 ± 48 (stat)

- Excess appears only in the upward-going data as expected

With τ : χ^2 / DOF = 9.8 / 8

Without χ^2 / DOF = 18.2 / 9

Systematic Errors

Systematic uncertainties for expected ν_τ	LH (%)	NN (%)
Super-K atmospheric ν oscillation analysis (23 error terms)	21.6	20.2
Tau related:		
→ Tau neutrino cross section	25.0	25.0
Tau lepton polarization	7.2	11.8
Tau neutrino selection efficiency	0.4	0.5
LH selection efficiency	4.8	–
NN selection efficiency	–	3.0
Total:	32.6	34.4

Systematic errors on the *expected* number of ν_τ

→ 78.4 ± 27 (syst.)

Systematic uncertainties for observed ν_τ	LH (%)	NN (%)
Super-K atmospheric ν oscillation analysis:		
Flux up/down ratio	6.5	5.7
Flux horizontal/vertical ratio	3.6	3.2
Flux K/π ratio	2.4	2.8
NC/CC ratio	4.3	3.8
Up/down asym. from energy calib.	1.4	< 0.1
Oscillation parameters:		
$0.0020 < \Delta m^2_{23} < 0.0027\,\mathrm{eV}^2$	$+5.8$ -2.6	$+8.8$ -3.3
$0.93 < \sin^2 2\theta_{23} < 1.00$	-3.3	-3.9
→ $0.0 < \sin^2 2\theta_{13} < 0.15$	-20.6	-17.9
Total:	$+10.7$ -22.9	$+12.0$ -20.3

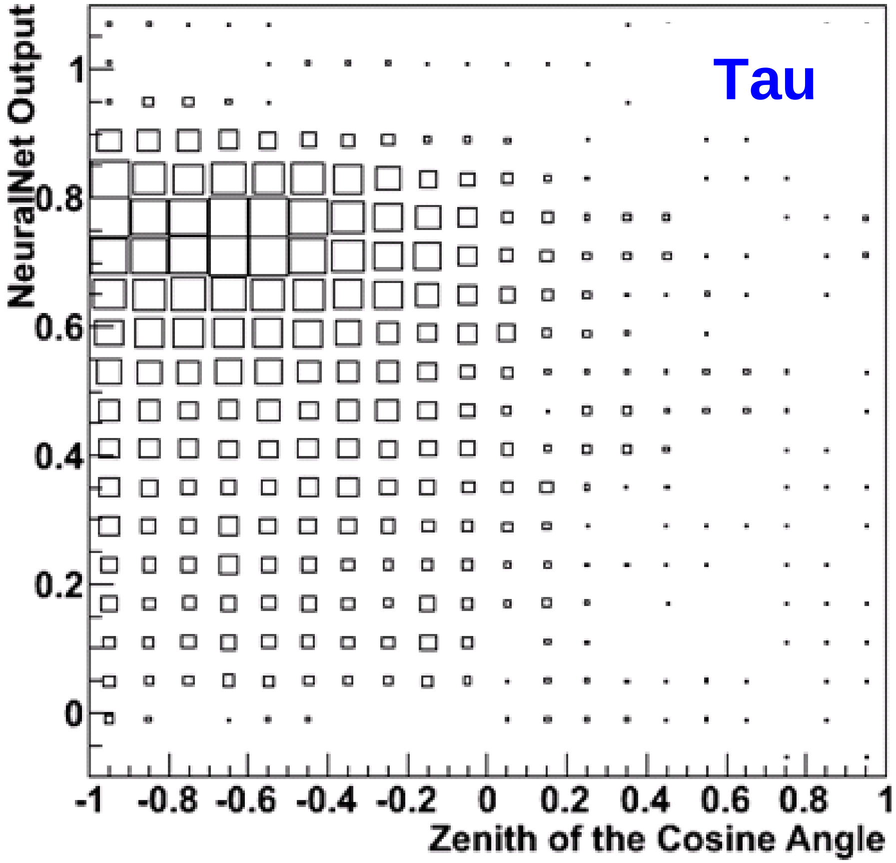
Systematic errors on the *observed* number of ν_τ

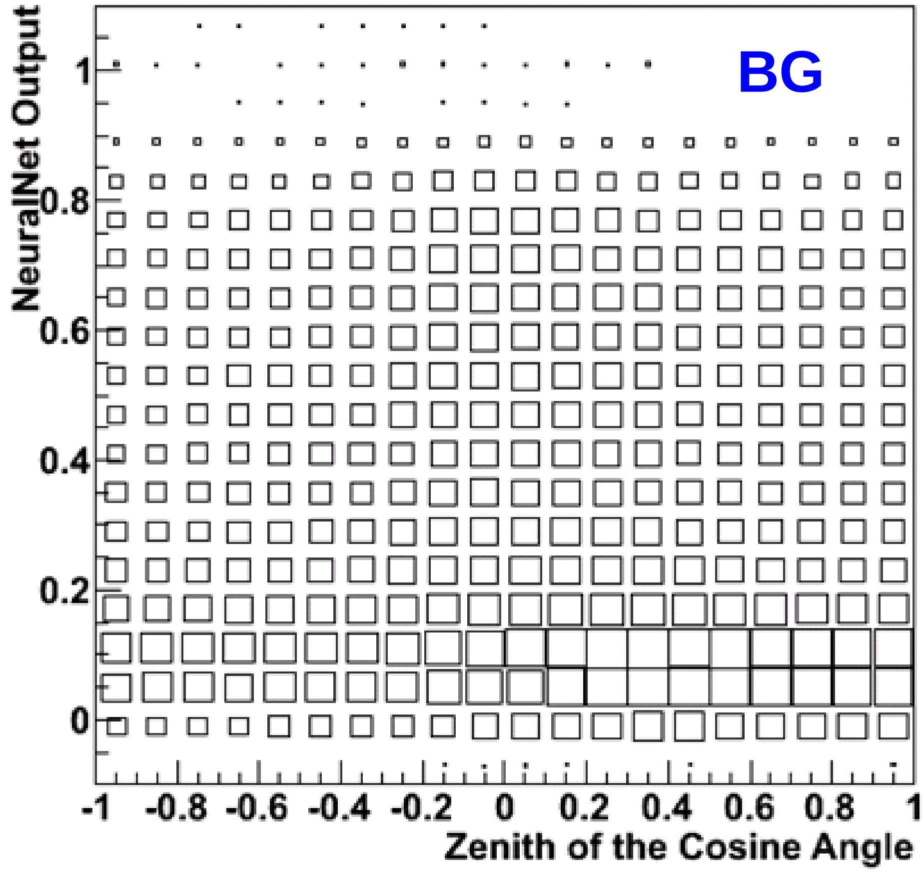
→ $134^{+16.0}_{-27.2}$ (syst.)

Improvements to ν_τ search for SK-I+II+III

An Updated Analysis for SK-I + II + III

- Add a variables to improve rejection of BG events (NC)
- Previous analysis only used events with NN > 0.5
- But the two-dimensional shapes are quite different





- Updated analysis uses uses an un-binned likelihood fit :
  Results Coming Soon

Summary and Conclusions

- Two-flavor oscillation analysis using the full SK-I+II+III data set has been performed

$\sin^2 2\theta = 1.0_{-0.05}$ $\Delta m^2 = 2.1^{+0.26}_{-0.29} \times 10^{-3}\ \mathrm{eV}^2$ (90% C.L.)

- In agreement with previous SK results and current world data
- Approximately 78 ± 27 Tau neutrino events are expected at these mixing parameters in the SK-I data set

- Super-Kamiokande observes $134 \pm 48\ (\mathrm{stat})\ ^{+16.0}_{-27.2}\ (\mathrm{sys.})$ τ-like events

This result is consistent with the expectation from the oscillation hypothesis and in disagreement with no observation at **2.4 σ**

- An improved analysis adding the SK-II and SK-III is underway

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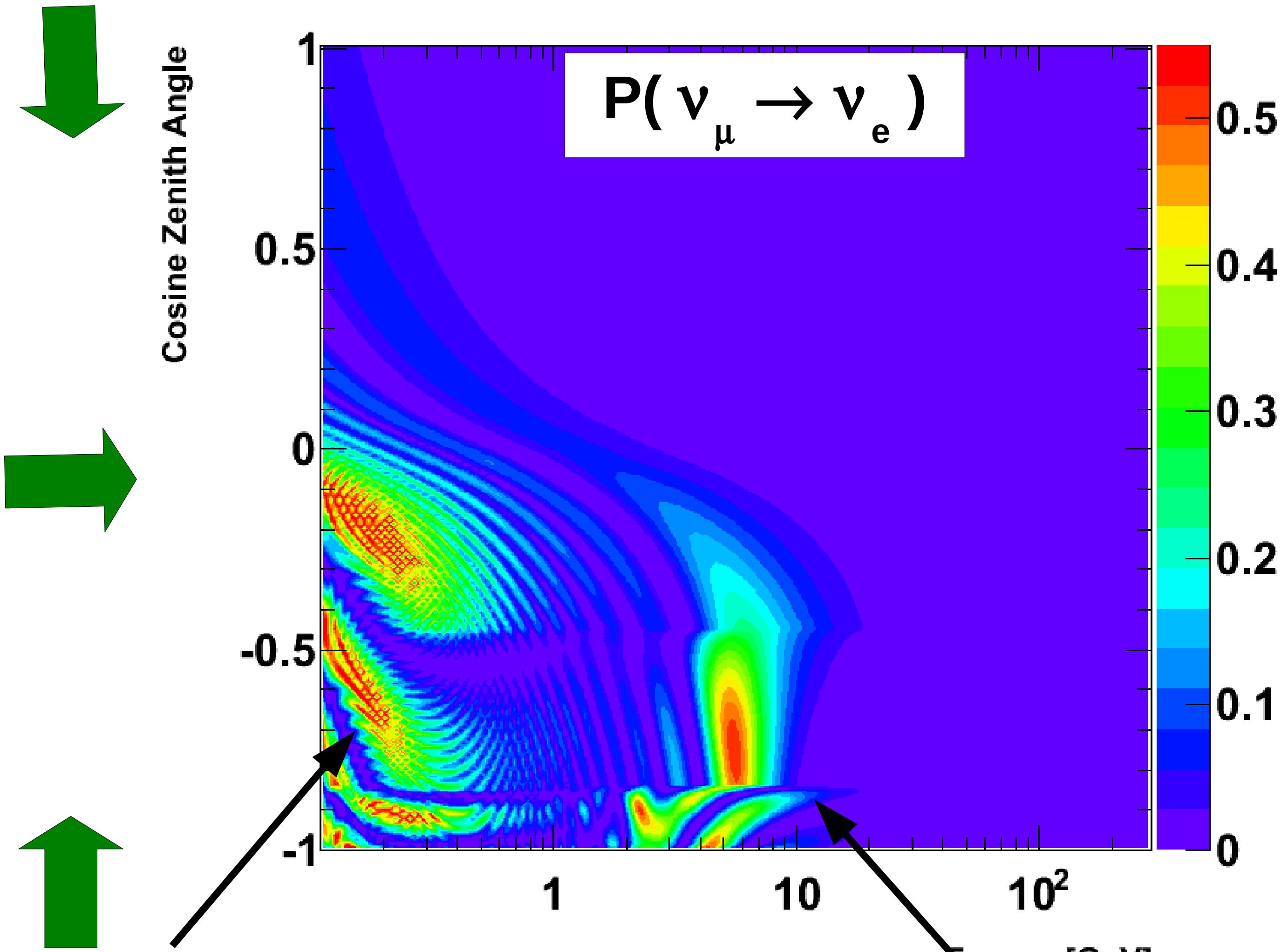
The Complete Story



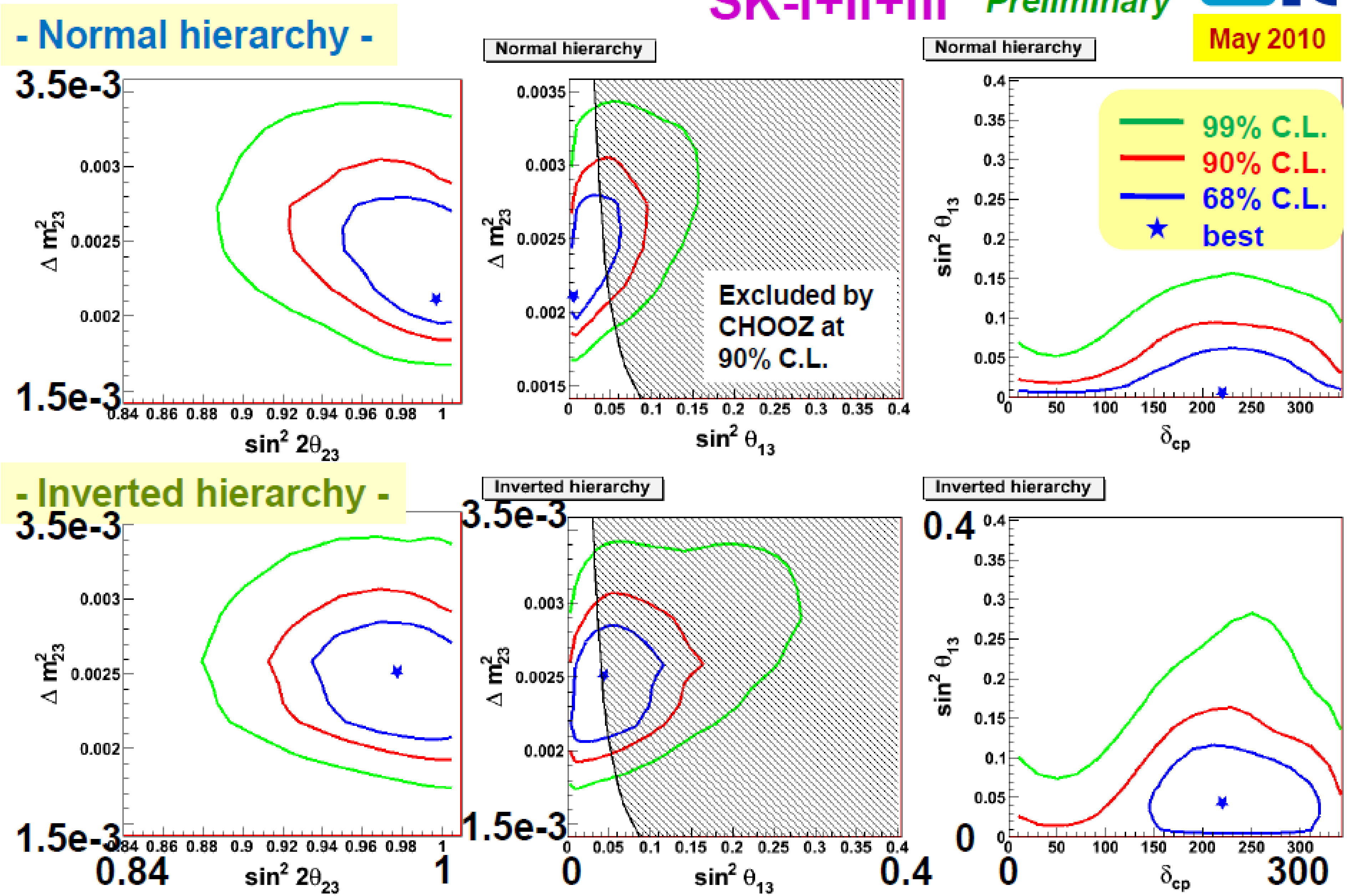
Induced by θ_{13} + solar terms

Induced by θ_{13} only

Full 3-flavor oscillation results

SK-I+II+III *Preliminary*

May 2010



Full 3-flavor oscillation results

SK-I+II+III *Preliminary*

May 2010

- Normal hierarchy -

χ^2_{min} = 469.94 /416dof

Parameter	Best point	90% C.L. allowed	68% C.L. allowed
Δm^2_{23} (x10^3)	2.11 eV^2	1.88 - 2.75 eV^2	1.99 - 2.54 eV^2
$\sin^2\theta_{23}$	0.525	0.406 - 0.629	0.441 - 0.597
$\sin^2\theta_{13}$	0.006	< 0.066	< 0.036
CP-δ	220°	-	140.8 - 297.3°

- Inverted hierarchy -

χ^2_{min} = 468.34 /416dof

Parameter	Best point	90% C.L. allowed	68% C.L. allowed
Δm^2_{23} (x10^3)	2.51 eV^2	1.98 - 2.81 eV^2	2.09 - 2.64 eV^2
$\sin^2\theta_{23}$	0.575	0.426 - 0.644	0.501 - 0.623
$\sin^2\theta_{13}$	0.044	< 0.122	0.0122 - 0.0850
CP-δ	220°	121.4 - 319.1°	165.6 - 280.4°

- No significant preference on hierarchy.
- No significant constraint on CP phase at 90% C.L.

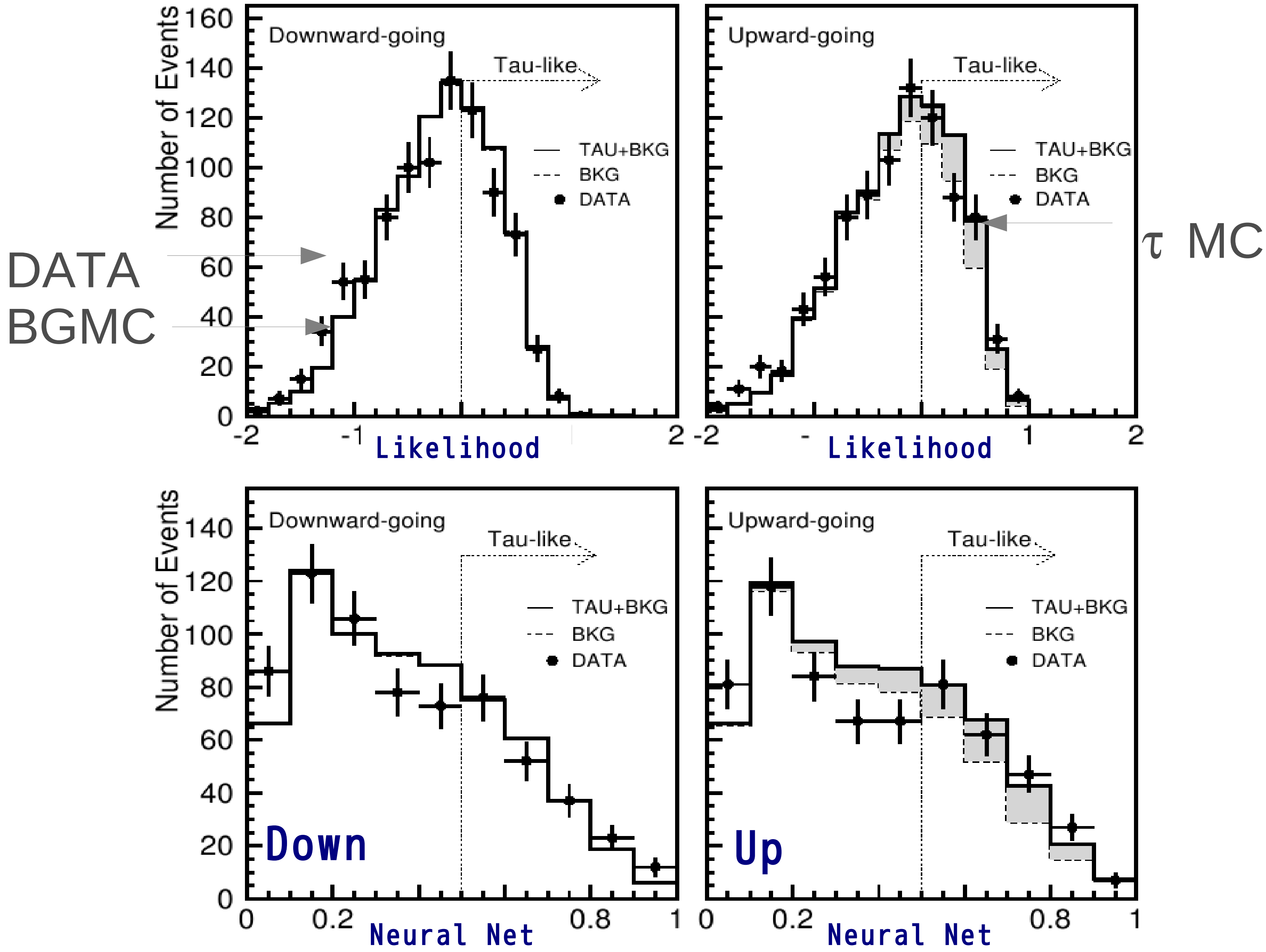
($\sin^2\theta_{12}$, Δm^2_{12}) are fixed at (0.304, 7.66x10^{-5} eV^2)

Where are the Super-K ν_μ going?

Model	Limit / Exclusion
$\nu_\mu \to \nu_s$	7.2 σ (SK-I + SK-II)
Sterile admixture (2+2)	23% allowed
Decay ($\sin^4\theta + \cos^4\theta\ e^{-\alpha L/E}$)	17 σ
Decay ($\sin^2\theta + \cos^2\theta\ e^{-\alpha L/E})^2$	3.9 σ
Decoherence	4.4 σ
LIV Limit	1.2×10^{-24}
CPTV Limit (GeV)	0.9×10^{-23}
MaVaNs	3.5 – 3.8 σ (SK-I)

- Other types of disappearance models are ruled out with high confidence

Output of Selection Functions with Rescaled MC



JAK	Decay Mode	BR/BR(1)
1	TAU- --> ELECTRON	1.0000
2	TAU- --> MUON	0.9696
3	TAU- --> PION	0.6058
4	TAU- --> RHO (->2PI)	1.3274
5	TAU- --> A1 (->3PI)	0.7194
6	TAU- --> KAON	0.0398
7	TAU- --> K*	0.0702
8	TAU- --> 2PI-, PI0, PI+	0.0840
9	TAU- --> 3PI0, PI-	0.0172
10	TAU- --> 2PI-, PI+, 2PI0	0.0634
11	TAU- --> 3PI-, 2PI+,	0.0289
12	TAU- --> 3PI-, 2PI+, PI0	0.0042
13	TAU- --> 2PI-, PI+, 3PI0	0.0042
14	TAU- --> K-, PI-, K+	0.0061
15	TAU- --> K0, PI-, K0B	0.0056
16	TAU- --> K-, K0, PI0	0.0005
17	TAU- --> PI0, PI0, K-	0.0061
18	TAU- --> K-, PI-, PI+	0.0315
19	TAU- --> PI-, K0B, PI0	0.0319
20	TAU- --> ETA, PI-, PI0	0.0109
21	TAU- --> PI-, PI0, GAM	0.0032
22	TAU- --> K-, K0	0.0181

CPT Violation Analysis : SK-I+II+III