Atmospheric Neutrinos at Super-Kamiokande

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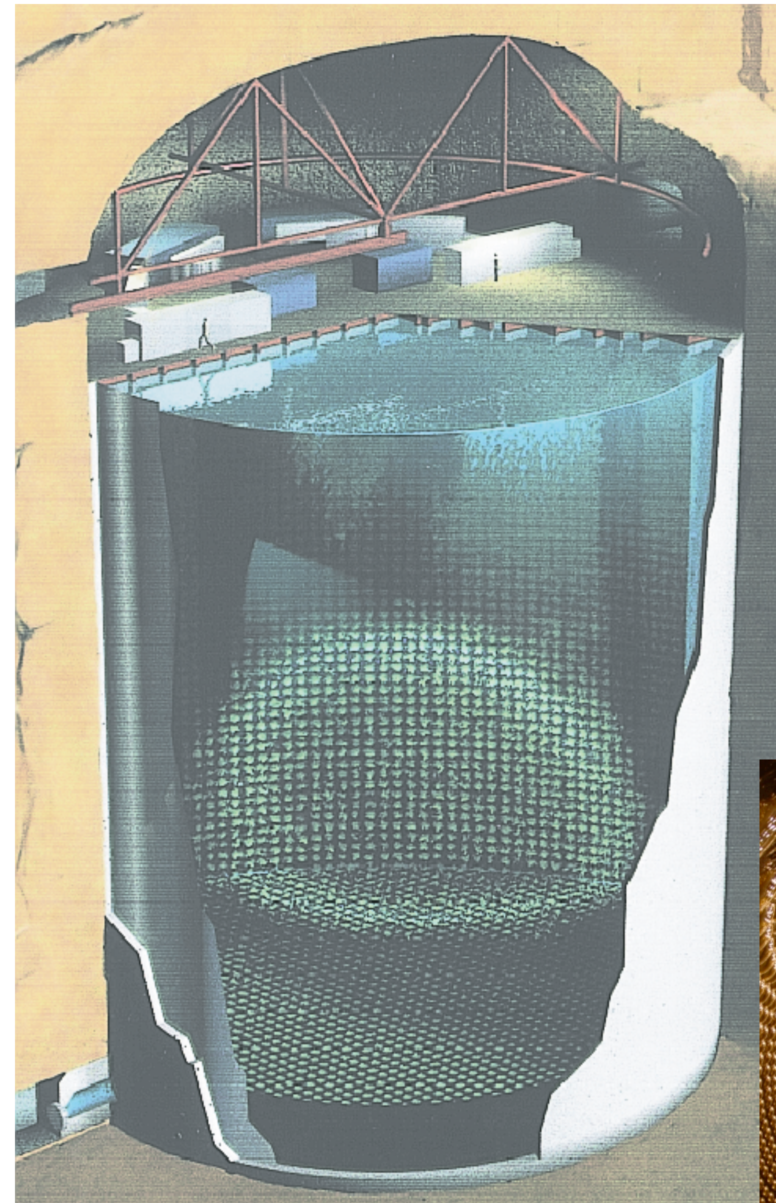
APS/DPF Meeting
Wayne State University
July 27, 2009

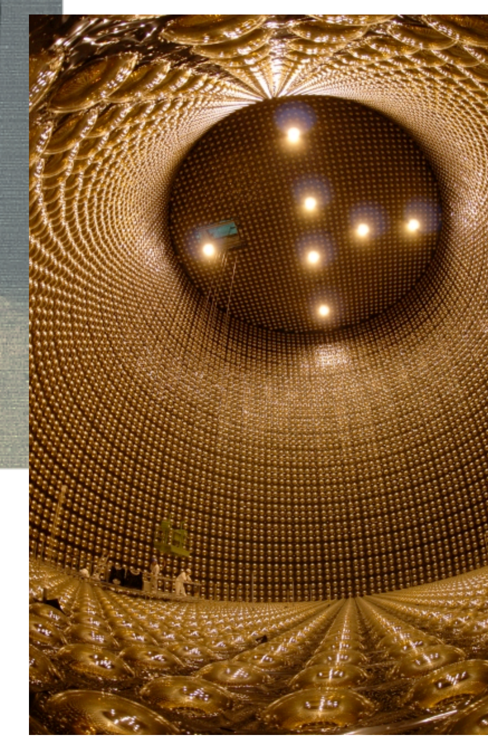
Super-Kamiokande



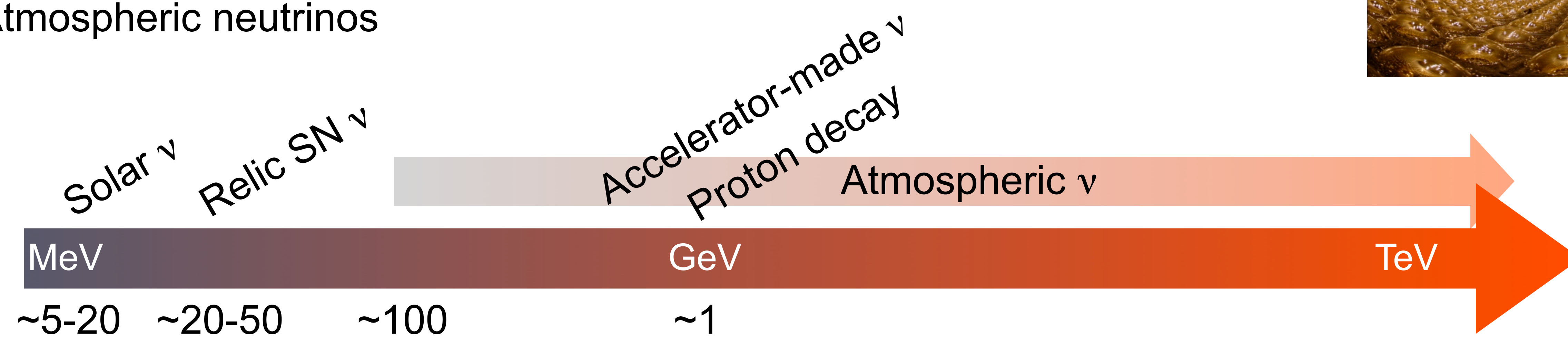
Kamioka-Mozumi zinc mine
1 km (2700 meters-water-equiv.) rock overburden

Water Čerenkov detector
  50 ktons (22.5 ktons fiducial)

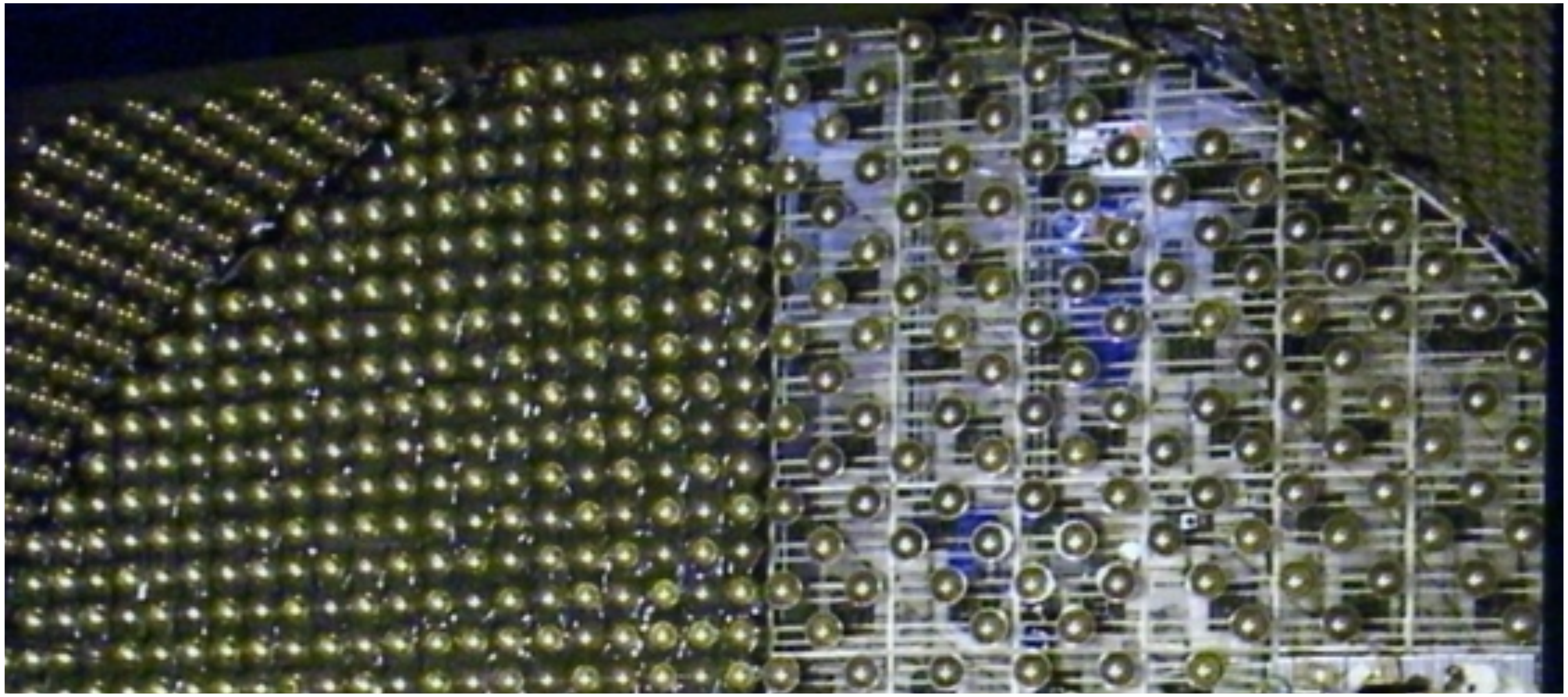
Instrumented with
  50-cm PMTs in Inner Detector (ID)
  20-cm PMTs in Outer Detector (OD)



Goals of Super-K
  Solar neutrinos
  Supernova neutrinos (+ relic SN)
  Accelerator-made neutrinos (T2K)
  Proton decay
  Atmospheric neutrinos



Timeline



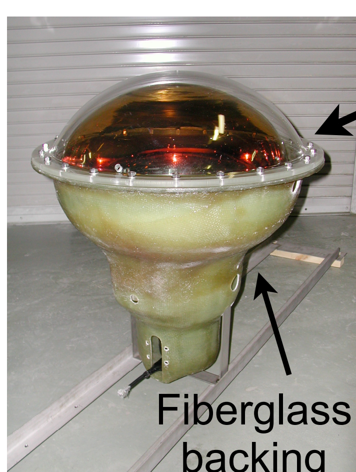
During SK-III construction

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

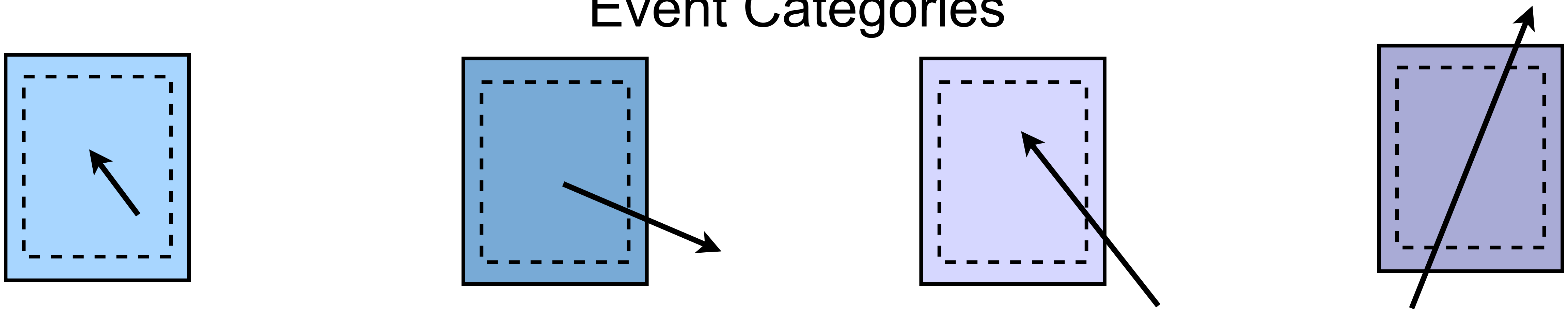


SK-III (2006-2008)
11,129 ID PMTs (40% cov.)
OD segmentation
(top/barrel/bottom)

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

Atmospheric ν's

Event Categories

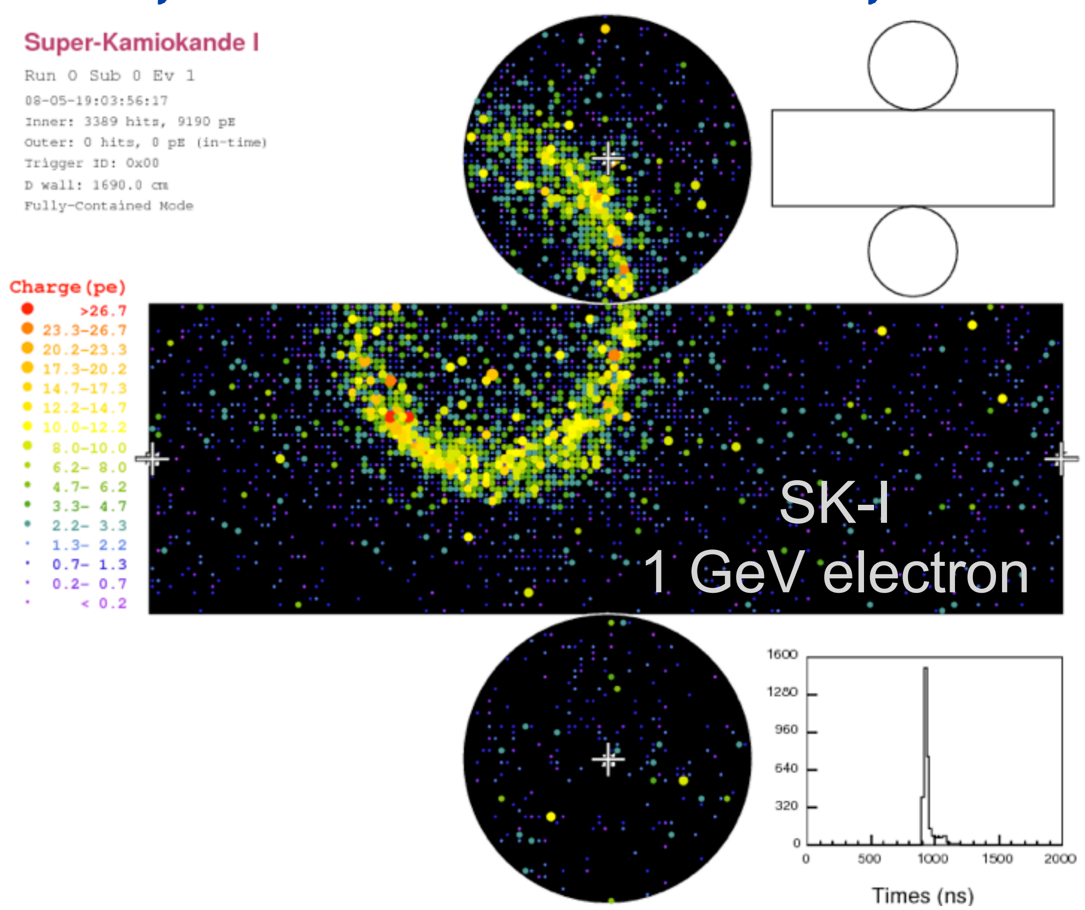


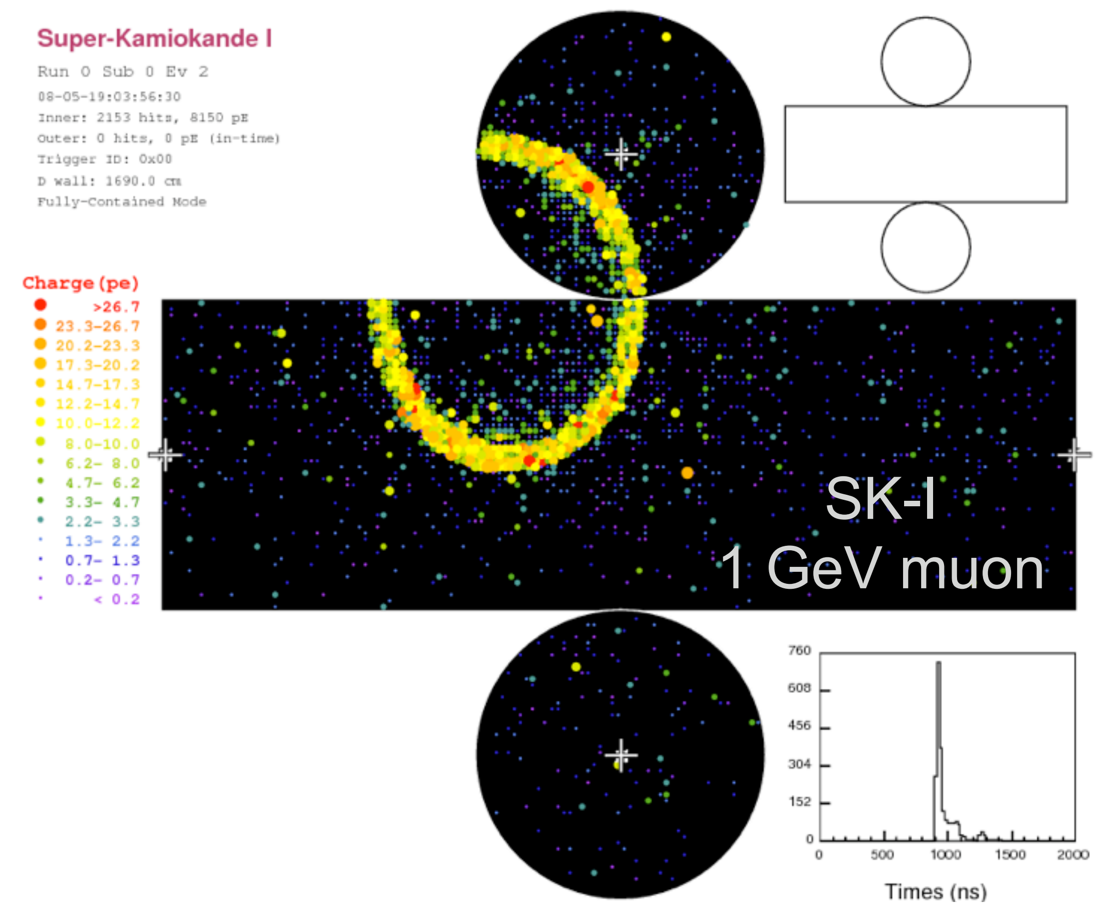
Fully-Contained | Partially-Contained | Upward Stopping Muon | Upward Through-going Muon

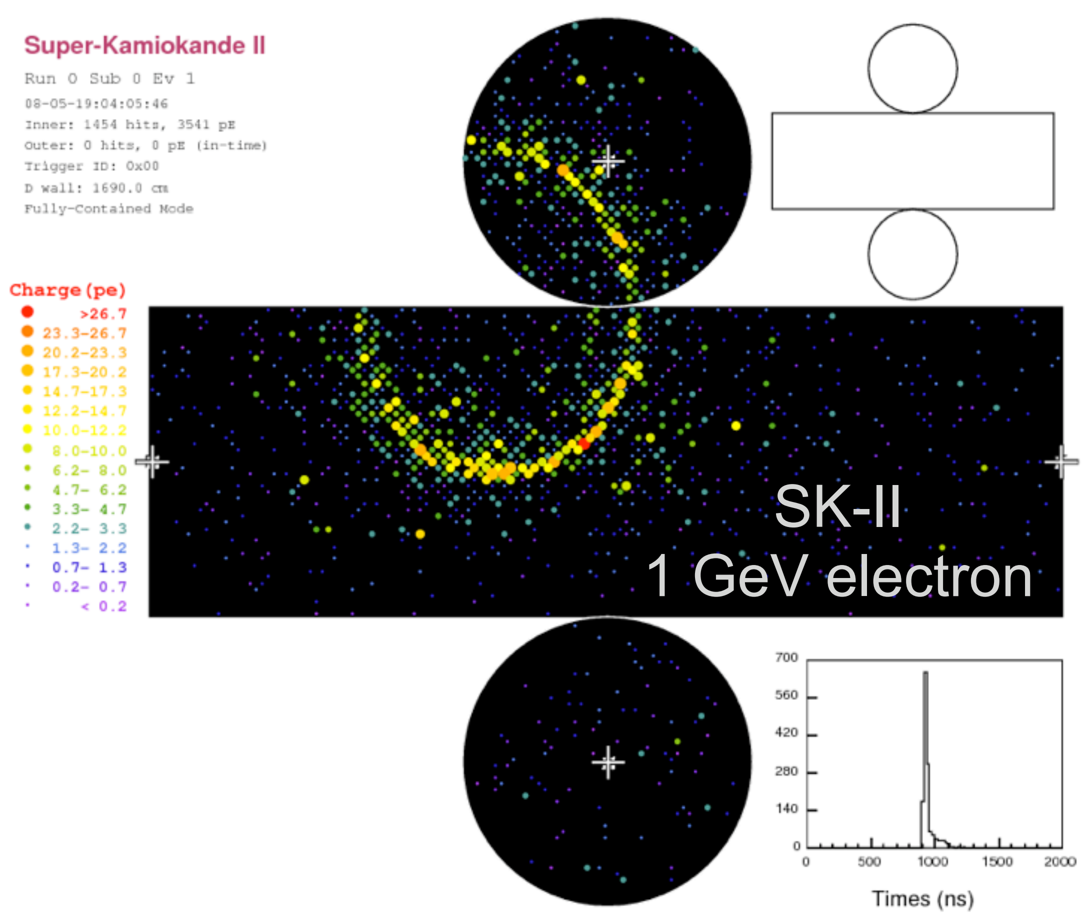
Event Category	Event Rate (events/day)		
	SK-I (1489 days)	SK-II (798 days)	SK-III (518 days)
Fully Contained (FC)	8.18 ± 0.07	8.22 ± 0.10	8.31 ± 0.22
Partially Contained (PC)	0.61 ± 0.02	0.54 ± 0.03	0.66 ± 0.04
Upward-stopping μ (Upstop)	0.25 ± 0.01	0.28 ± 0.02	0.24 ± 0.03
Upward-thrugoing μ (Upthru)	1.12 ± 0.03	1.07 ± 0.04	1.11 ± 0.06

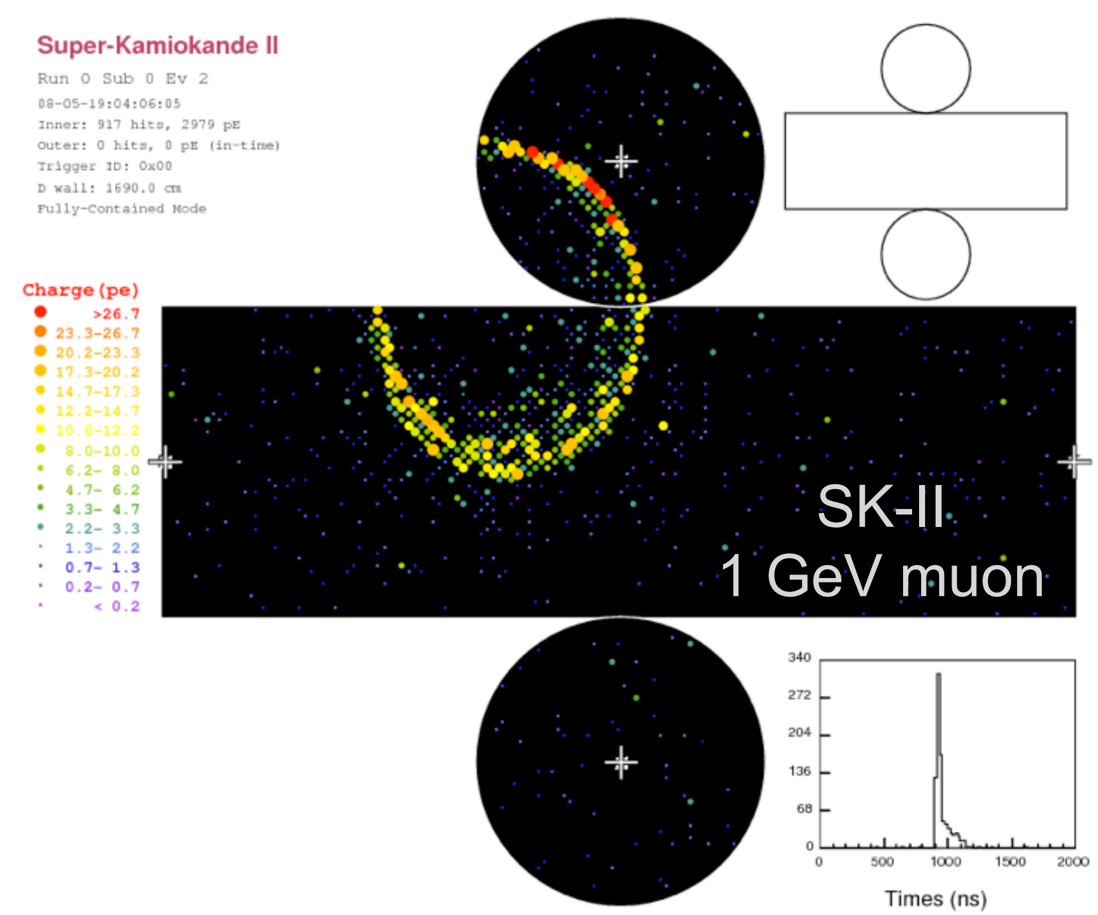
Event rates consistent across all phases of SK

Atmospheric ν's at Super-K (simulated events)









What can we learn from atmospheric neutrinos?

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$s_{ij} \equiv \sin\theta_{ij}$
$c_{ij} \equiv \cos\theta_{ij}$

Atmospheric Mixing Parameters

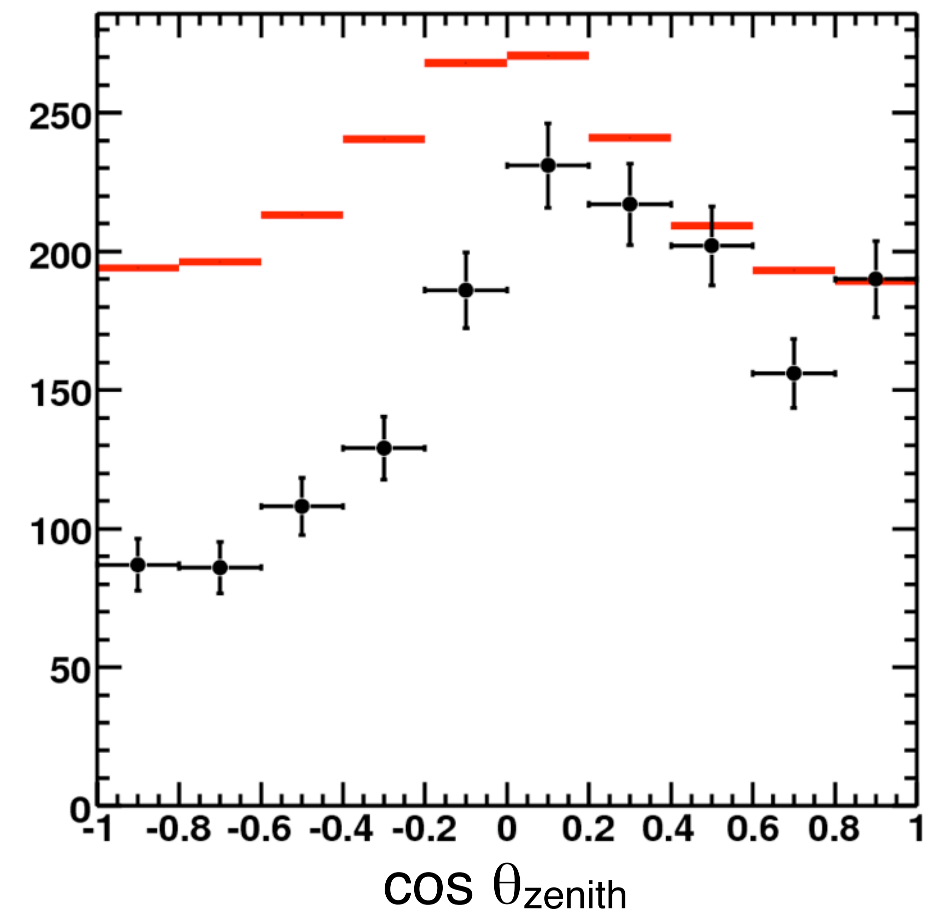
- Two-flavor zenith angle analysis
- L/E analysis
- Solar terms analysis

Mass Hierarchy and Value of θ_{13}

- Three-flavor zenith angle analysis

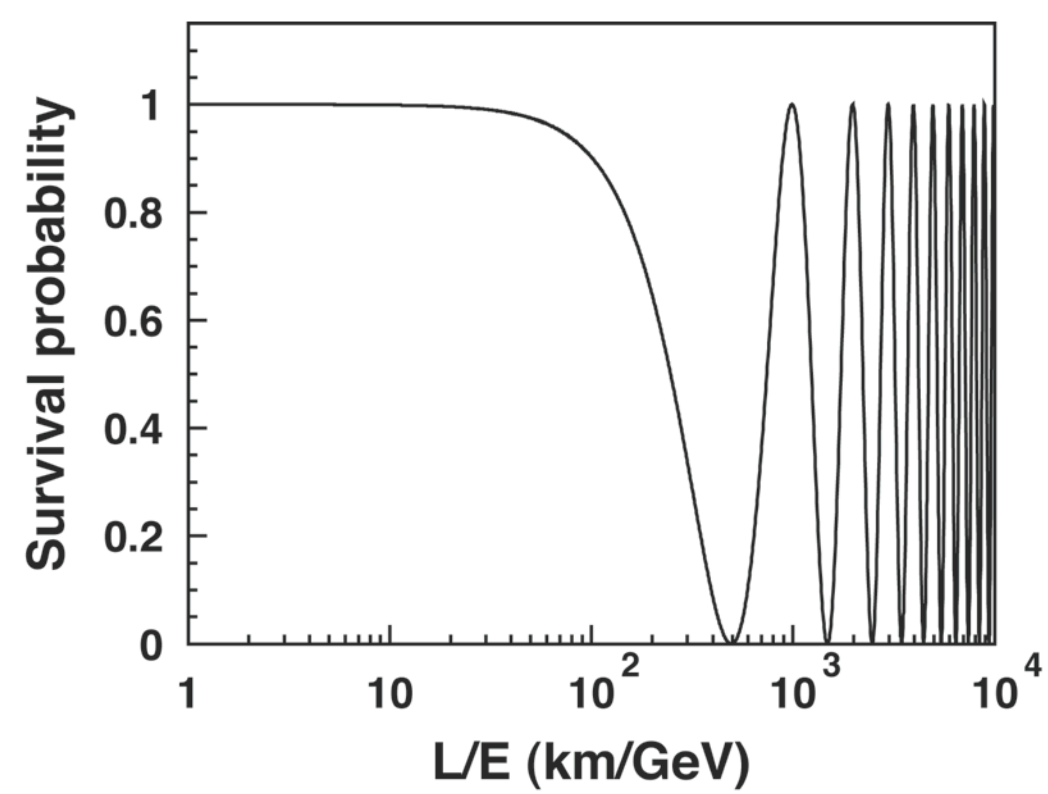
Several methods for probing different neutrino sectors using Super-K data.

Oscillation Analyses



Zenith angle analysis (fine-binned)

Use many subsamples of data
Look for zenith angle distortion



L/E analysis

Use much more selective subsample of data
Require good L/E resolution
Look for first oscillation dip

Zenith Angle Analyses

Data binned according to:

event type
+
momentum
+
zenith angle

} 420 bins for SK-I
420 bins for SK-II
420 bins for SK-III

Datasets	
SK-I FC/PC:	1489 days
SK-I Upmu:	1646 days
SK-II FC/PC:	798 days
SK-II Upmu:	828 days
SK-III FC/PC:	518 days
SK-III Upmu:	635 days

χ^2 fit in bins of zenith angle with systematic error pull terms:

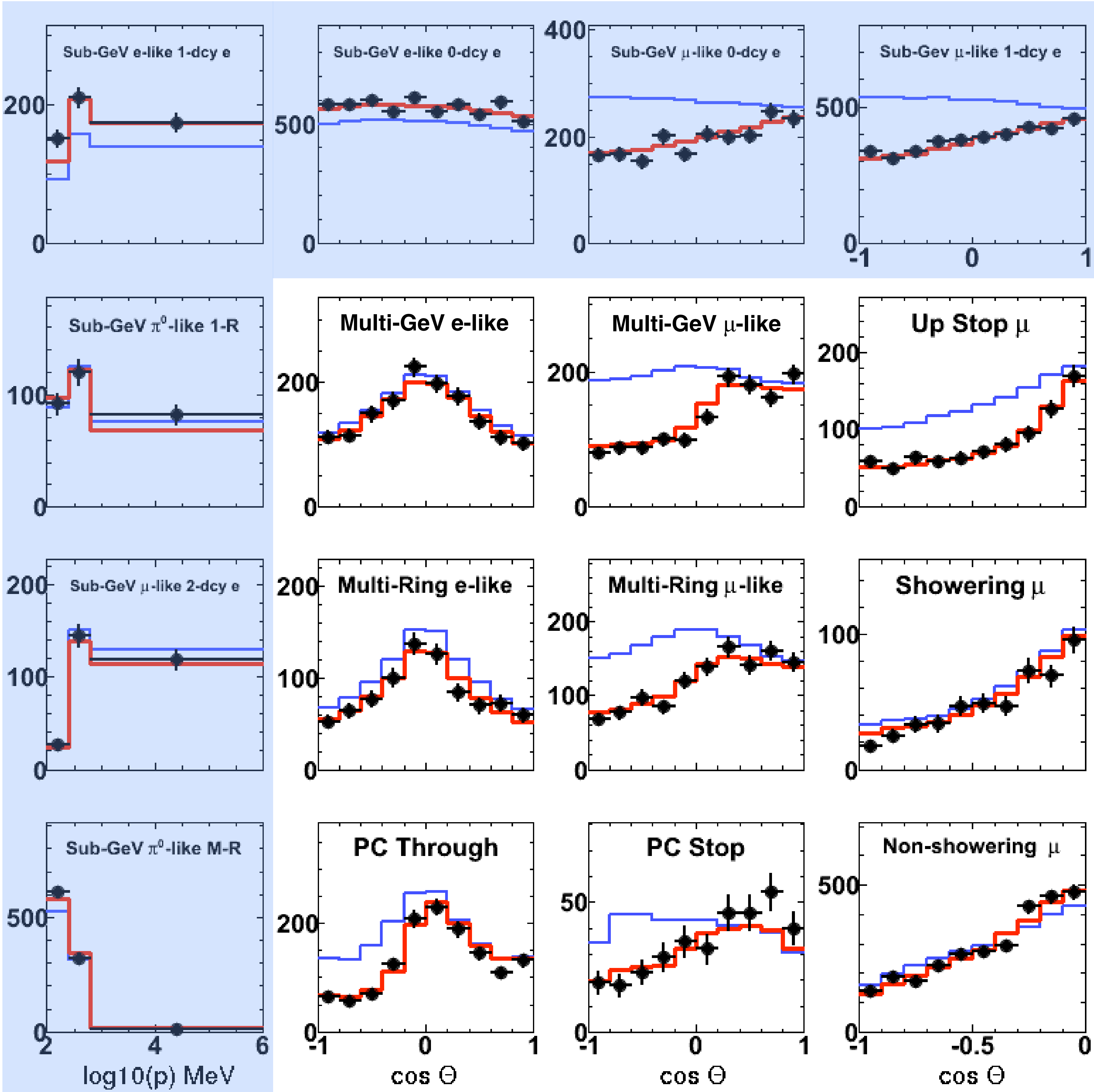
$$\chi^2 = \sum_{i=1}^{N_{bins}} 2\left(N_i^{exp} - N_i^{obs} + N_i^{obs} \ln \frac{N_i^{obs}}{N_i^{exp}}\right) + \sum_{j=1}^{N_{sys}} \left(\frac{\varepsilon_j}{\sigma_j^{sys}}\right)^2$$

where $N_i^{exp} = N_i^0 \cdot P\left(\nu_\alpha \rightarrow \nu_\beta\right)\left(1 + \sum_{j=1}^{N_{sys}} f_j^i \varepsilon_j\right)$

122 systematic error terms to account for uncertainties in:

- Neutrino flux
- Cross sections
- Event reconstruction
- Data reduction

SK-1+2+3 Data (Preliminary)



Sub-GeV samples subdivided to improve sensitivity to low energy oscillation effects

- ● Data
- MC (no oscillations)
- MC (best fit oscillations)

L/E Analysis: SK-1+2+3

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

Datasets	
SK-I FC/PC μ-like:	1489 days
SK-II FC/PC μ-like:	798 days
SK-III FC/PC μ-like:	518 days

Use only event categories with good L/E resolution:

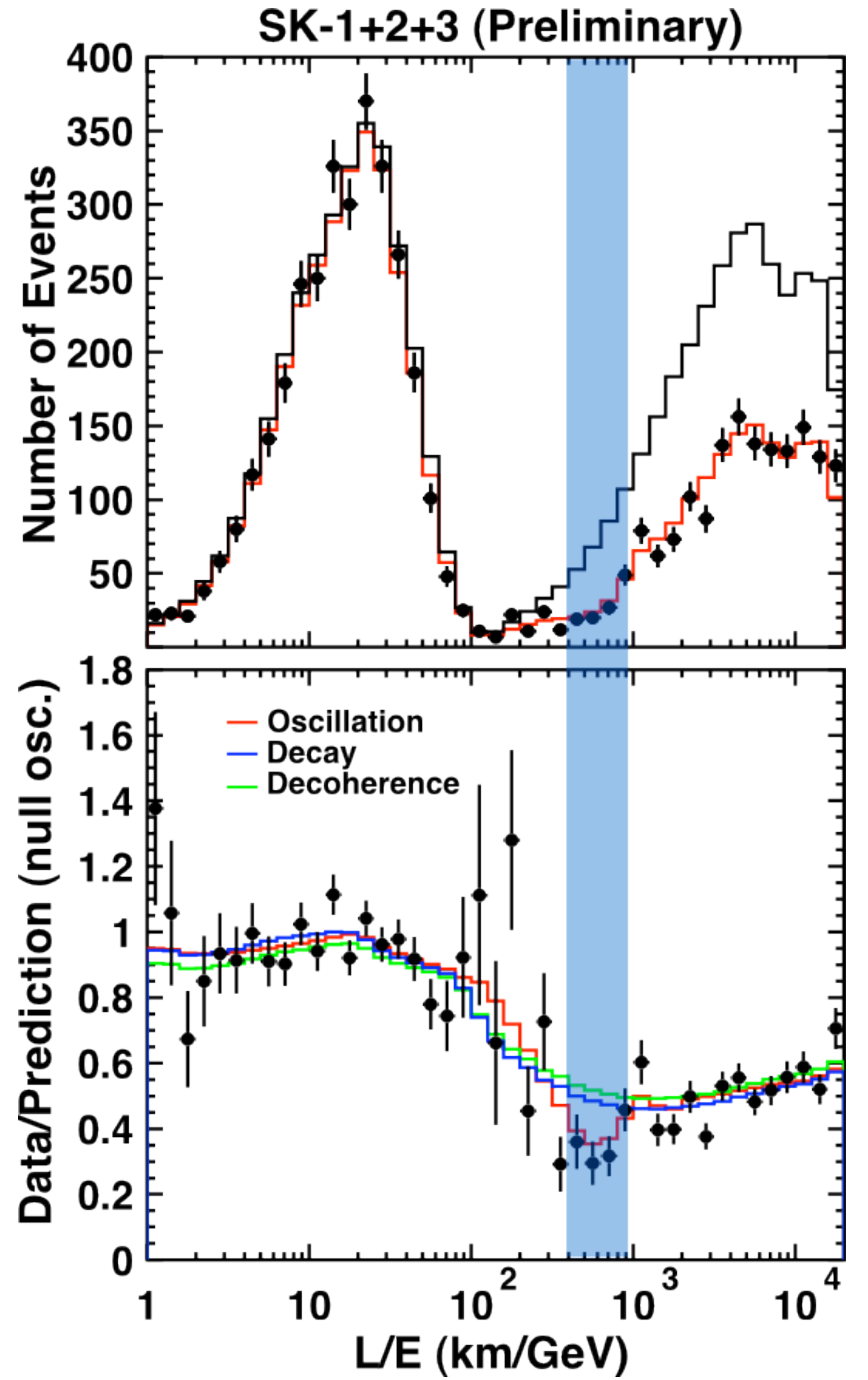
- Partially-contained muons
- Fully-contained muons

χ^2 fit to 43 bins of $\log_{10}$(L/E) with 29 systematic error terms

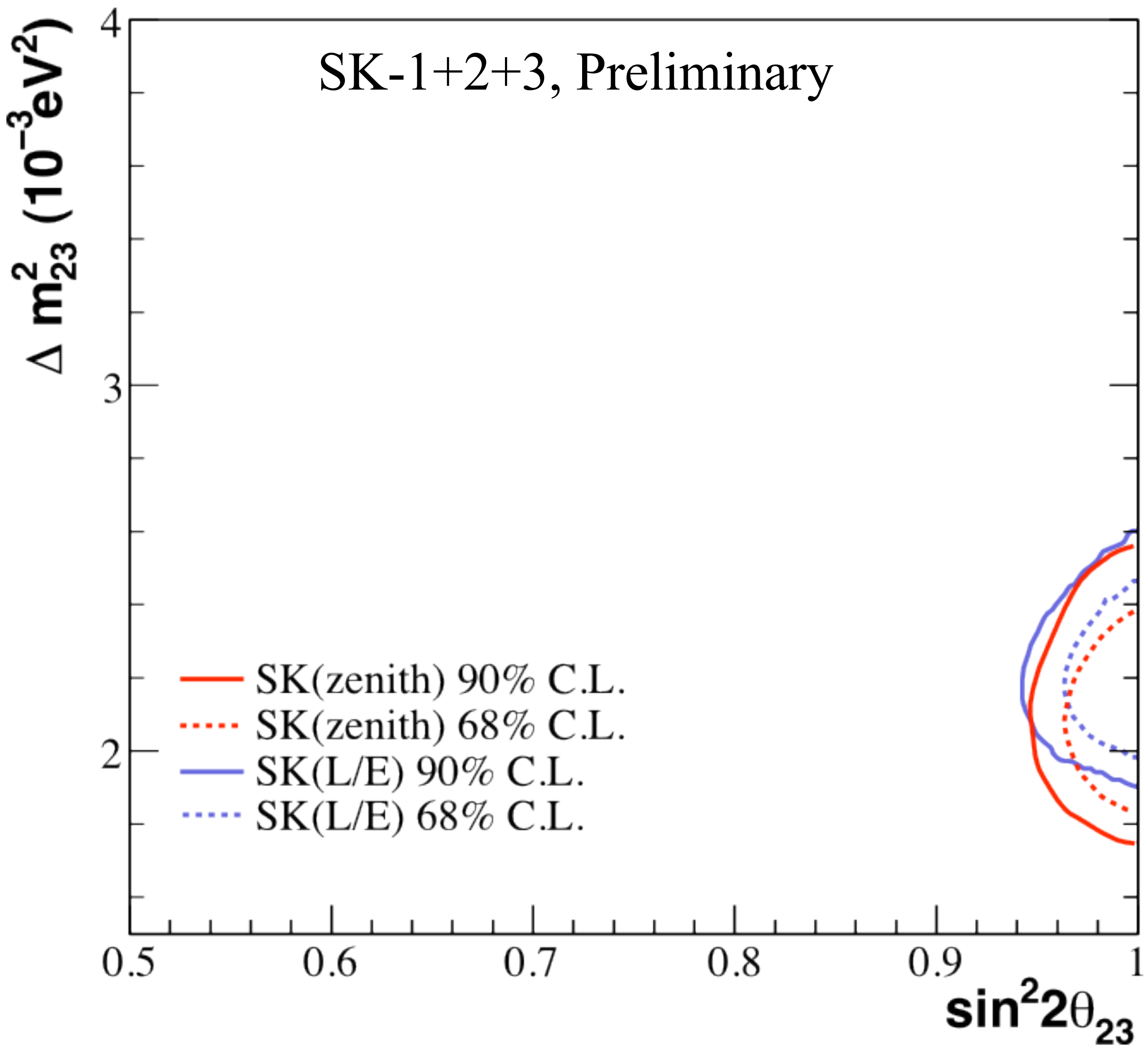
Compare against:

- Neutrino decay (disfavored @ 4.4σ)
- Neutrino decoherence (5.4σ)

Grossman and Worah: hep-ph/9807511
Lisi *et al*.: PRL85 (2000) 1166
Barger *et al*.: PRD54 (1996) 1, PLB462 (1999) 462



Results of two-flavor oscillation analyses



Zenith angle analysis best fit

$$\sin^2 2\theta_{23} = 1.0$$
$$\Delta m^2_{23} = 2.1 \times 10^{-3} eV^2$$
$$\chi^2/d.o.f. = 468/420$$

L/E analysis best fit

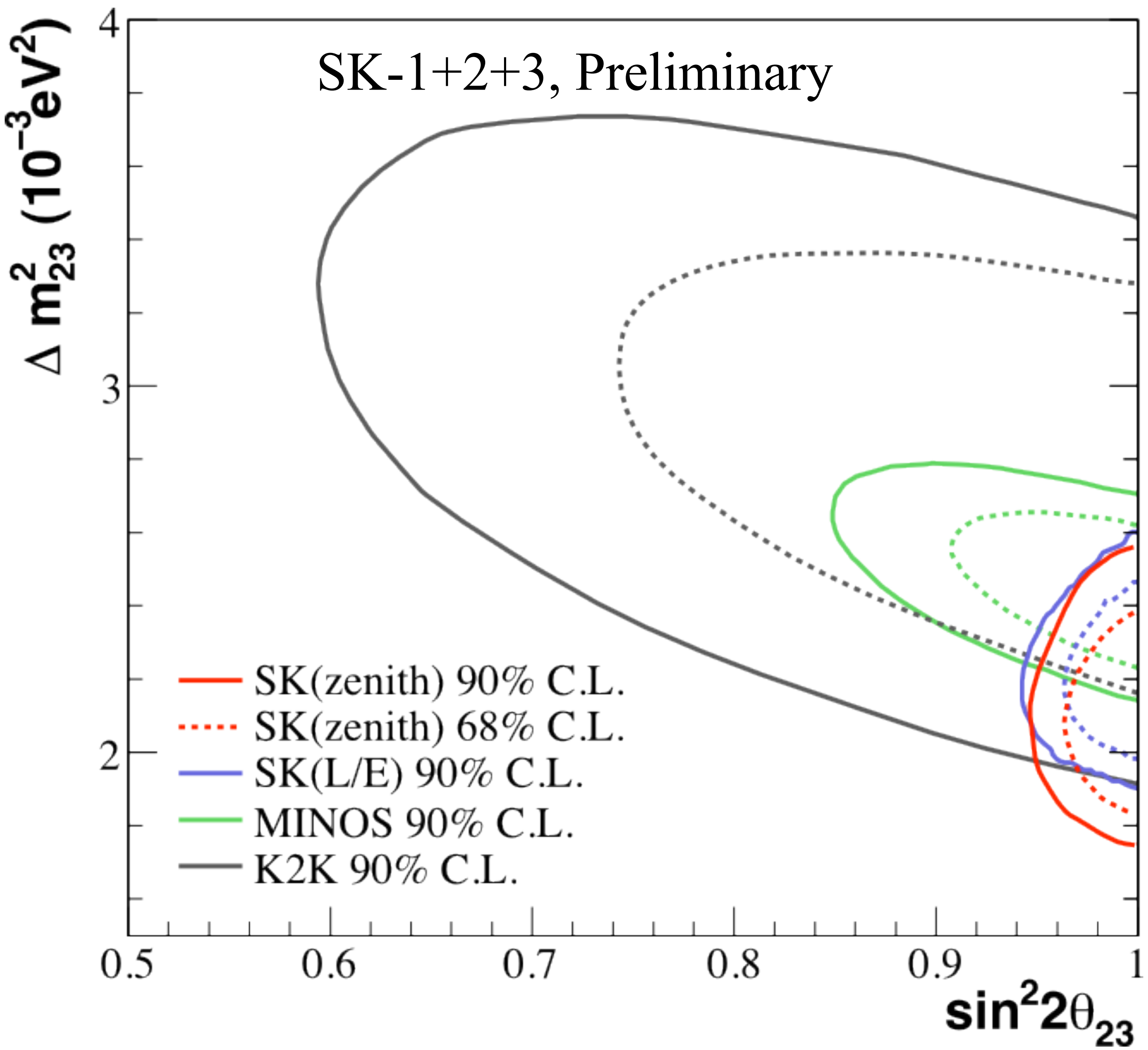
$$\sin^2 2\theta_{23} = 1.0$$
$$\Delta m^2_{23} = 2.2 \times 10^{-3} eV^2$$
$$\chi^2/d.o.f. = 119/126$$

Complementary analyses:

L/E has stronger Δm^2 constraint

Equally strong $\sin^2 2\theta_{23}$ constraint

Results of two-flavor oscillation analyses



Zenith angle analysis best fit

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L/E analysis best fit

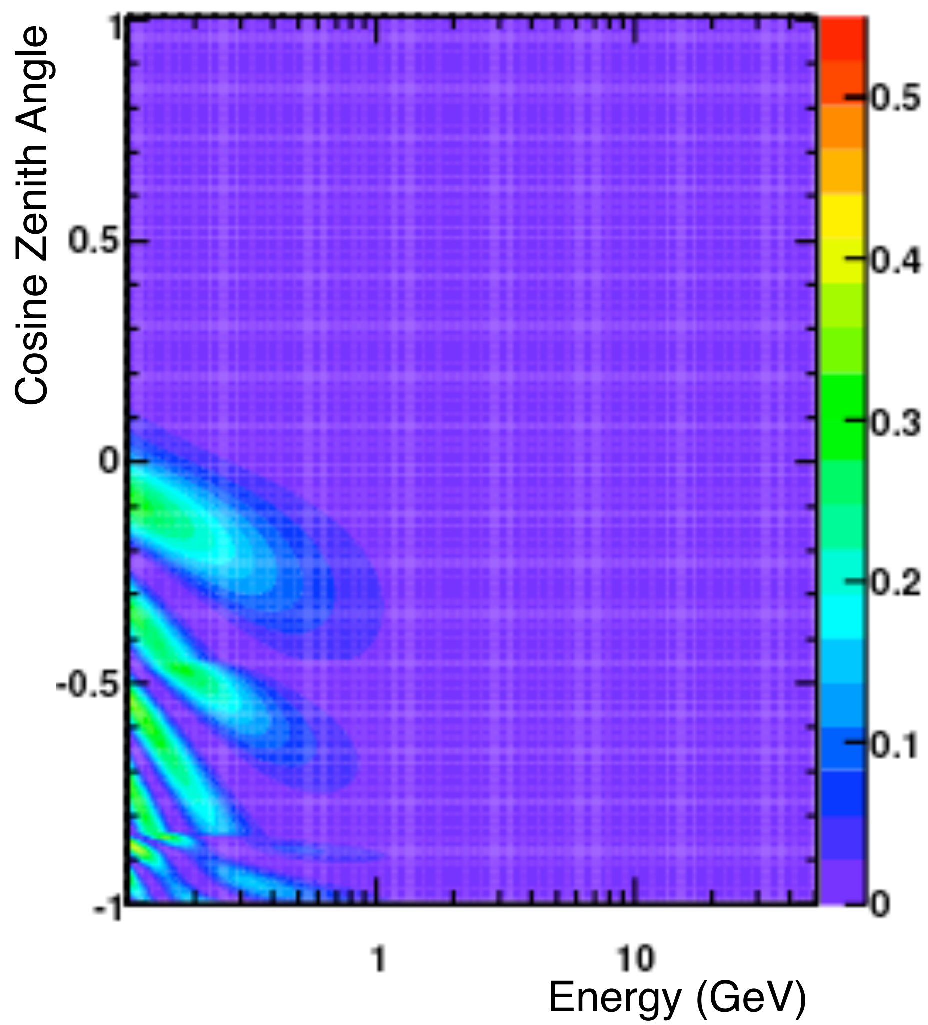
$$\sin^2 2\theta_{23} = 1.0$$
$$\Delta m^2_{23} = 2.2 \times 10^{-3} eV^2$$
$$\chi^2/d.o.f. = 119/126$$

Results agree well with other experiments

- LBL better constrains Δm^2
- Atmospheric still has stronger $\sin^2 2\theta$ constraint

Solar Terms Analysis

Look for changes in low energy ν_e flux induced by solar-sector oscillations, assuming $\theta_{13} = 0$.



Driven by Δm^2_{12} and θ_{12}.

In constant density matter:

$$P(\nu_e \leftrightarrow \nu_\mu) = \cos^2\theta_{23}\, P(\nu_e \rightarrow \nu_x)$$

$\cos^2\theta_{23} < 0.5$ ν_e flux reduction

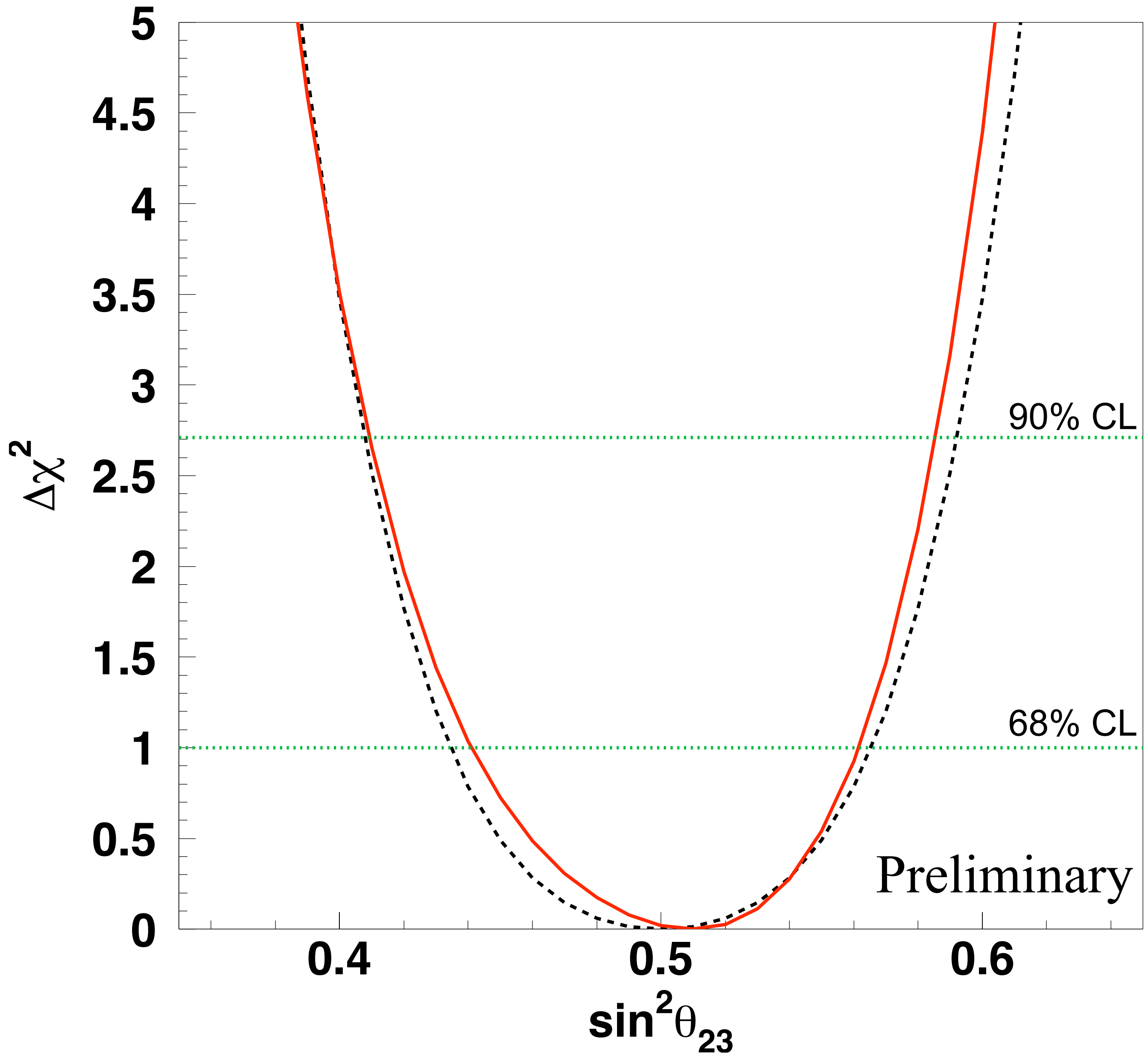
$\cos^2\theta_{23} = 0.5$

$\cos^2\theta_{23} > 0.5$ ν_e flux enhancement

May be possible to determine octant of θ_{23} by observing changes in the flux of low-energy e-like samples.

Solar Terms Analysis

Fit using 3-flavor oscillation probabilities with and without solar terms, assume θ_{13} = 0.



Solar terms off (best fit)

$\Delta m^2_{12} = 0$ (fixed)
$\Delta m^2_{23} = 2.1 \times 10^{-3} \mathrm{eV}^2$
$\sin^2\theta_{12} = 0$ (fixed)
$\sin^2\theta_{23} = 0.50$

$\chi^2/dof = 470.2/418$

Solar terms on (best fit)*

$\Delta m^2_{12} = 7.59 \times 10^{-5} \mathrm{eV}^2$
$\Delta m^2_{23} = 2.1 \times 10^{-3} \mathrm{eV}^2$
$\sin^2\theta_{12} = 0.30$
$\sin^2\theta_{23} = 0.51$

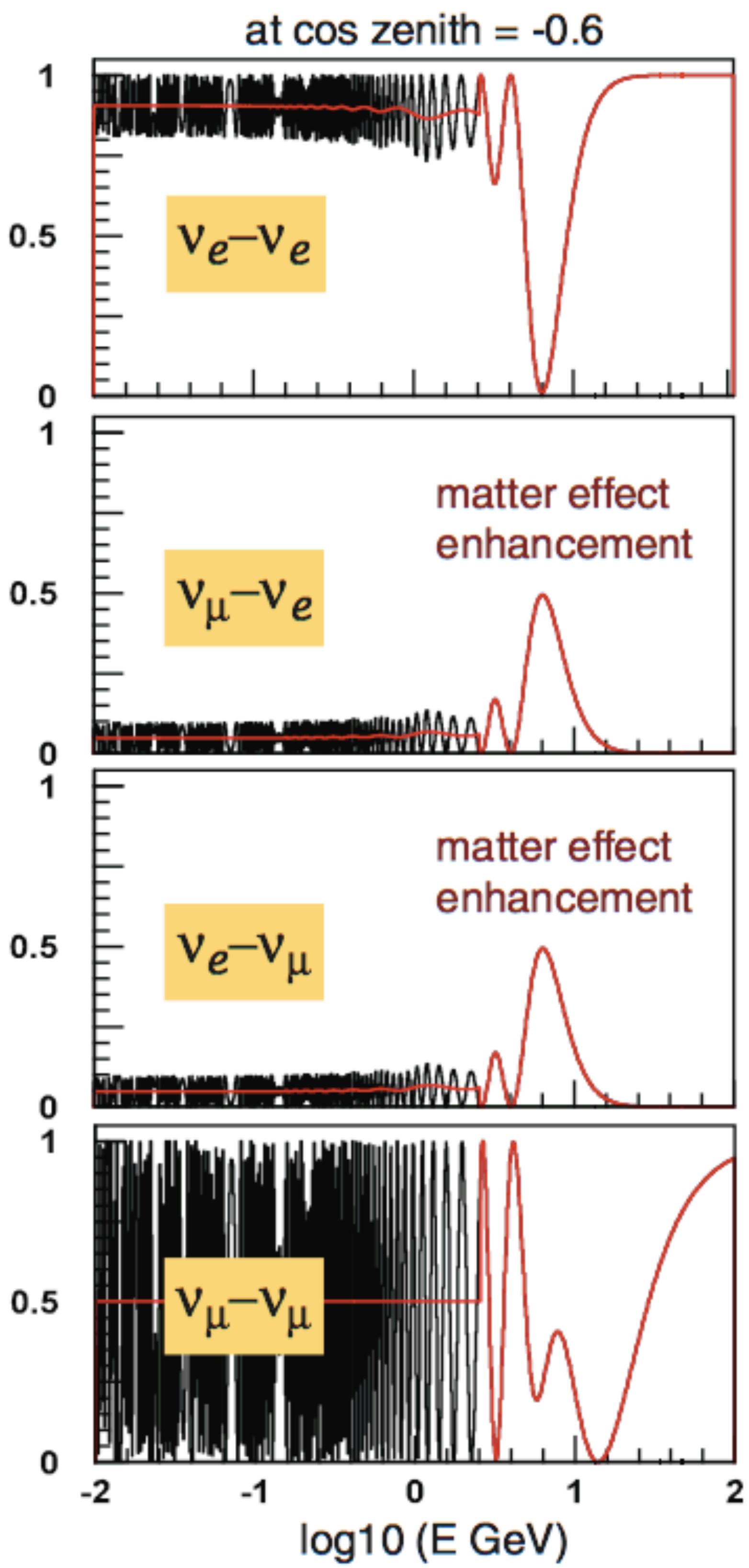
$\chi^2/dof = 471.2/416$

*Solar parameters are constrained with $\Delta\chi^2$ map information from combined fit to solar neutrino experiment data + KamLAND data.

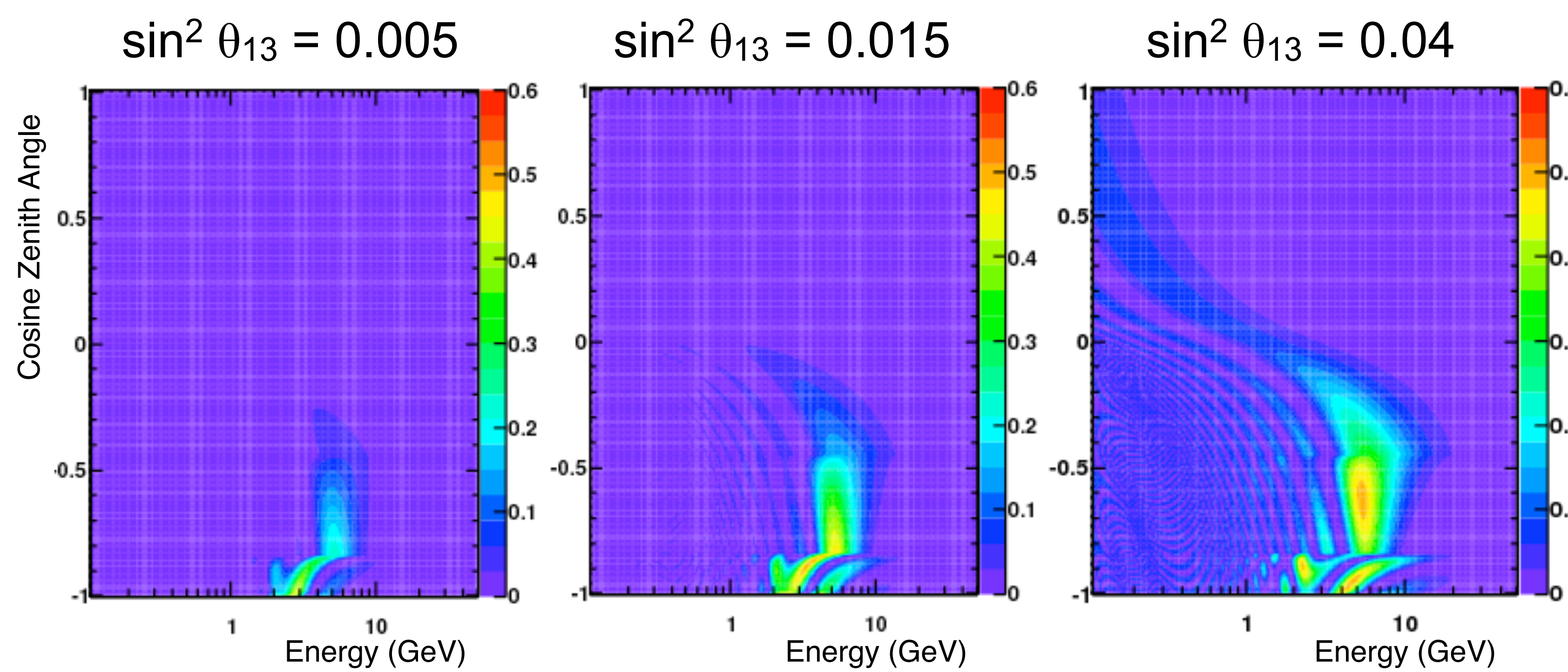
Fogli *et al.* (hep-ph/0808.2016)

Addition of solar terms shows no significant deviation of θ_{23} from $\pi/4$.

Addressing non-zero θ_{13} at Super-K



$P(\nu_\mu \rightarrow \nu_e)$



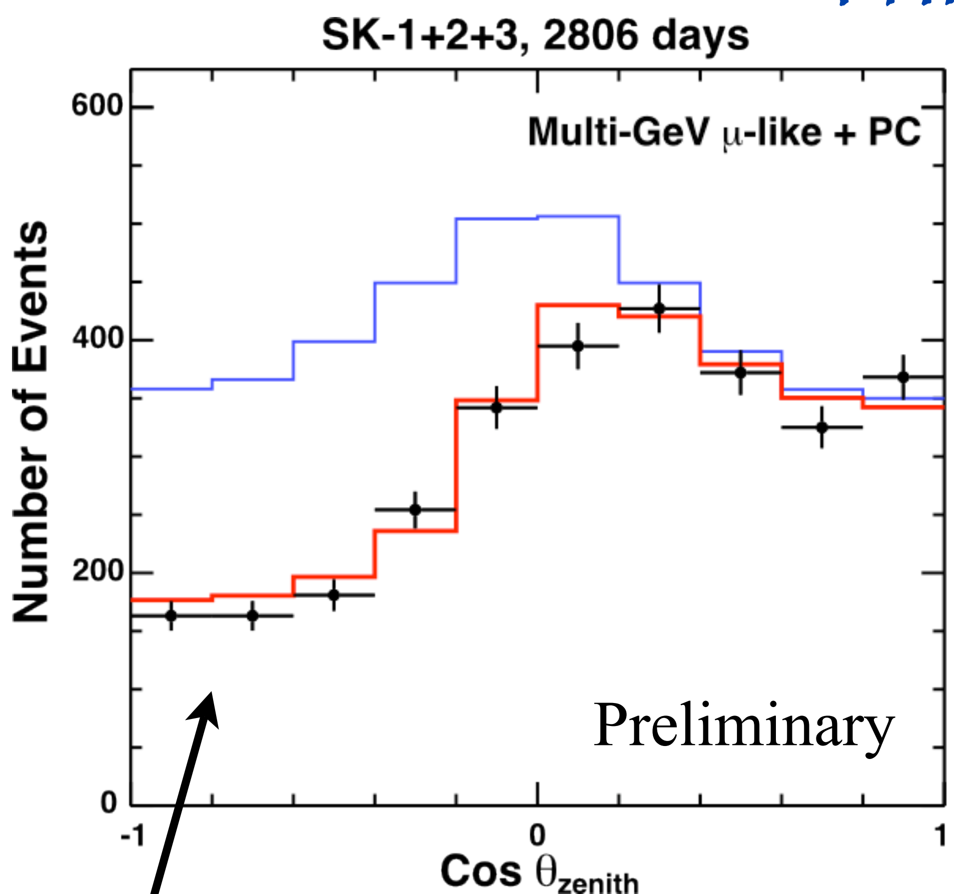
MSW effect gives rise to additional scattering amplitudes in matter (for ν_e only).

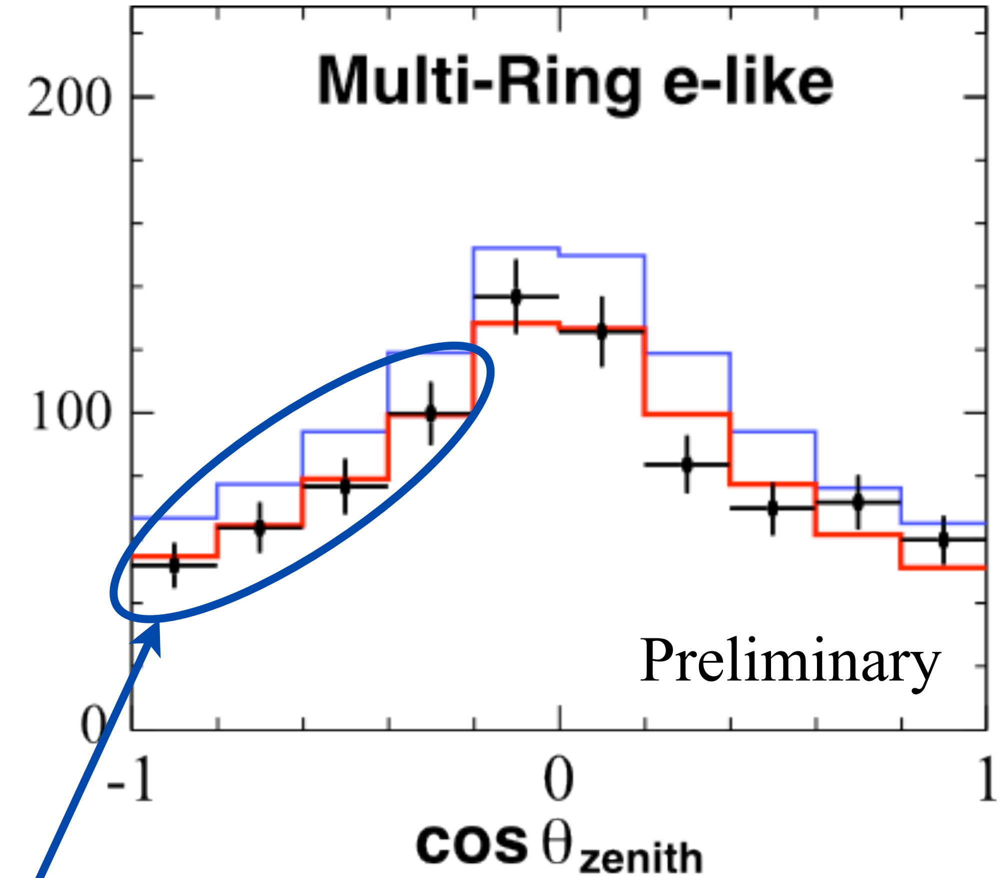
Clearest indication of non-zero θ_{13} at Super-K:
resonance @ ~2-10 GeV for up-going e-like events

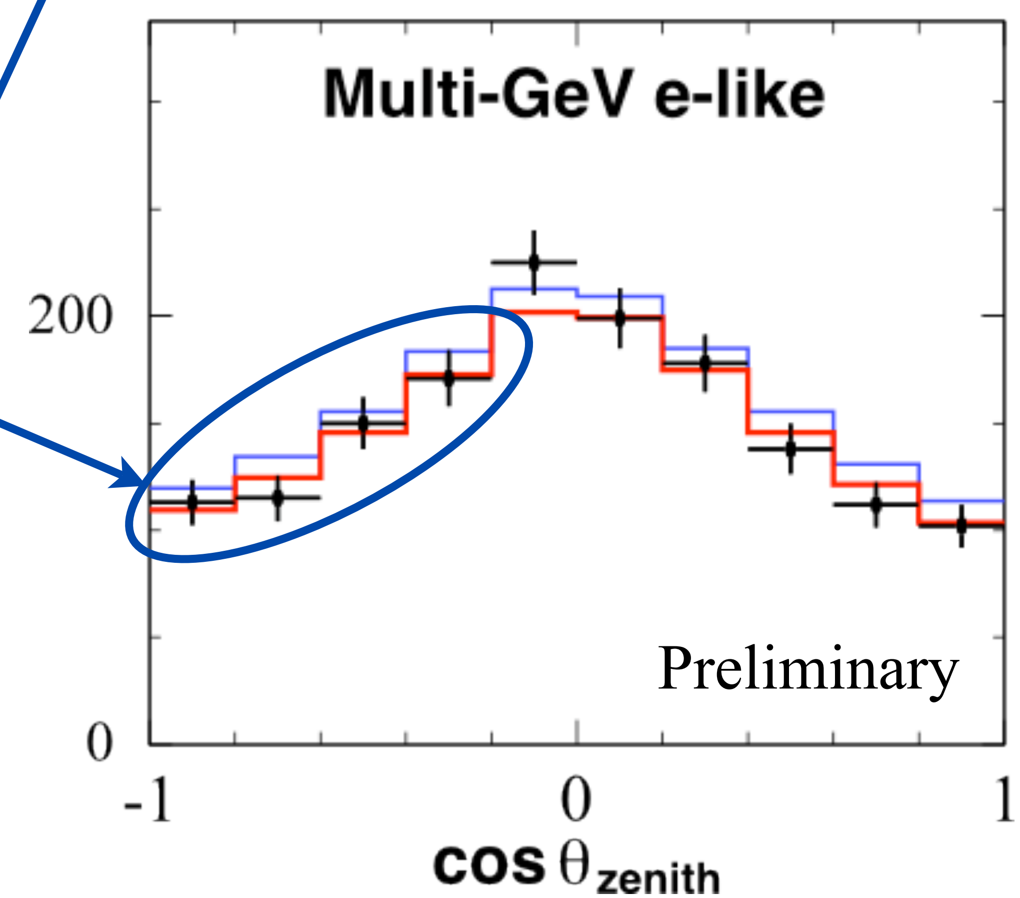
Normal hierarchy ⇒ neutrino enhancement
Inverted hierarchy ⇒ anti-neutrino enhancement

Analysis uses 3 parameters ($\sin^2\theta_{13}$, $\sin^2\theta_{23}$, Δm^2_{23}) assuming a single "dominant mass scale" ($\Delta m^2_{23} \gg \Delta m^2_{12}$).

Three-flavor zenith angle analysis





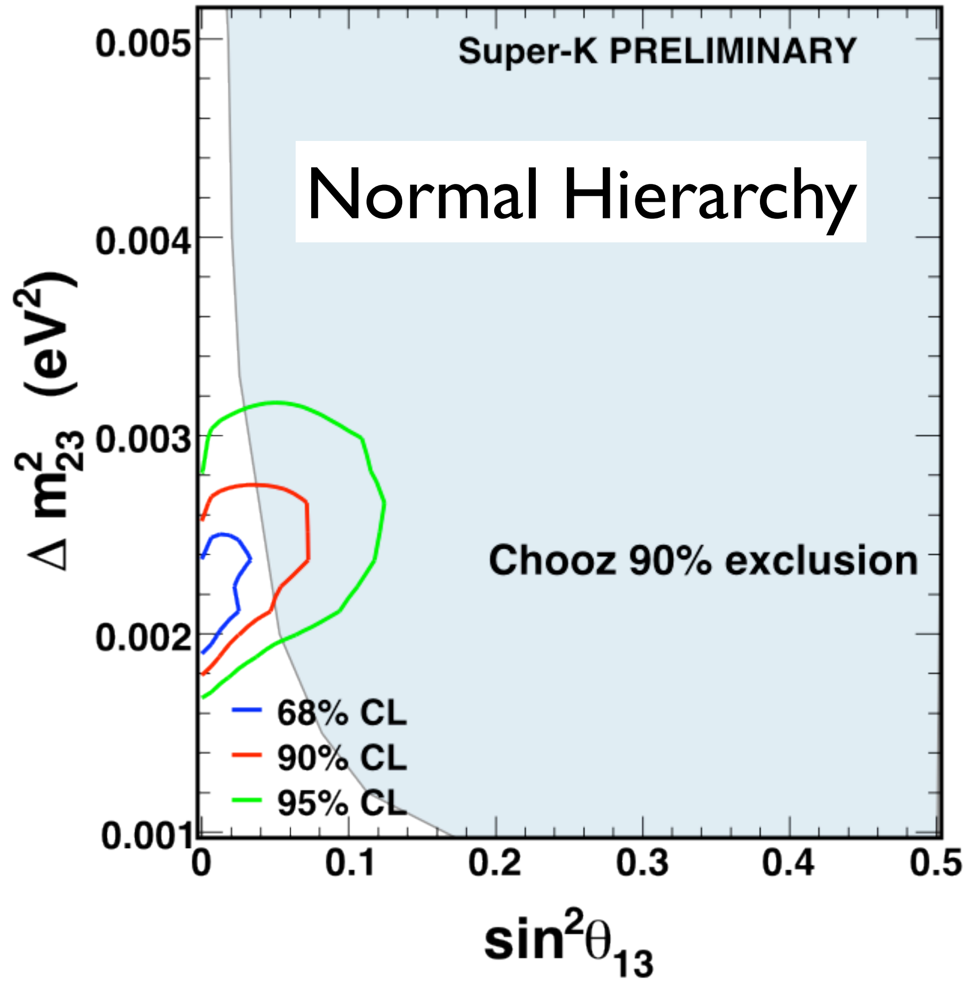


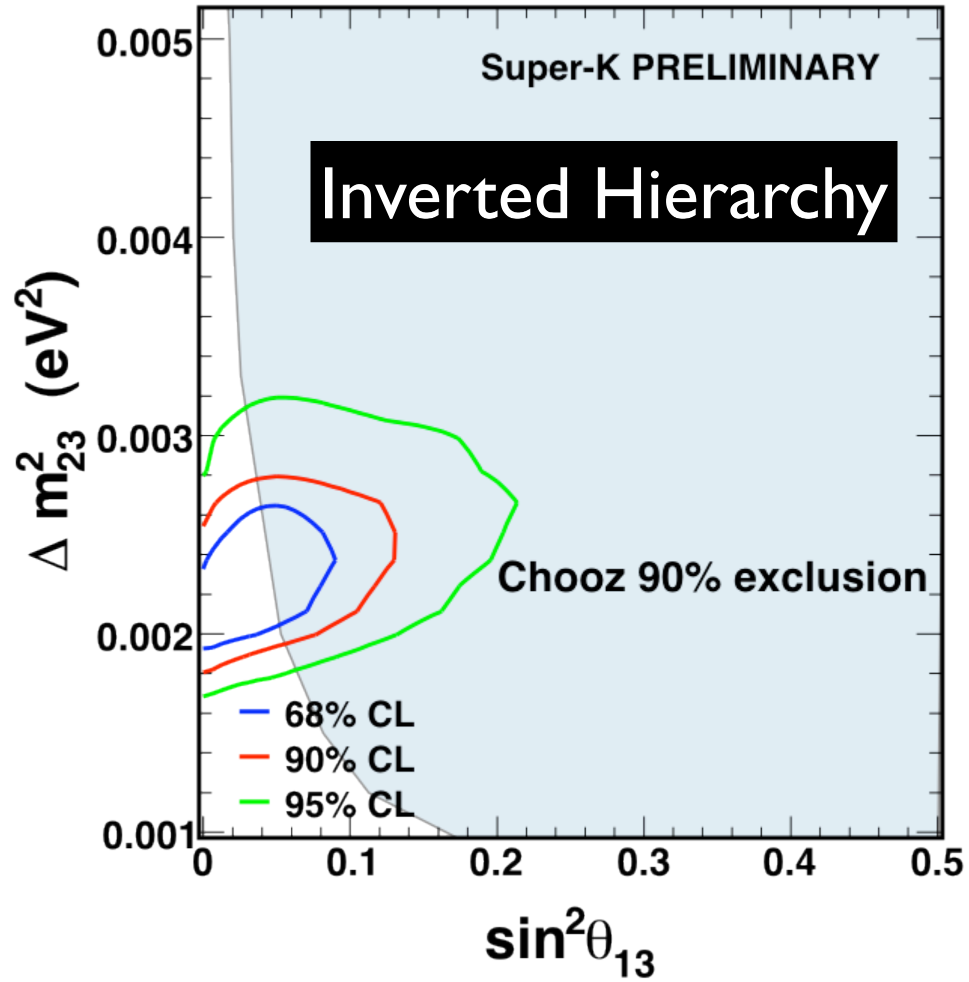
Clear distortion of muon-like zenith distribution, well-described by 2-flavor $\nu_\mu \rightarrow \nu_\tau$ disappearance...

Allow also $\nu_\mu \rightarrow \nu_e$ appearance in 3-flavor analysis, look for enhancement of high-energy upward-going e-like events.

No distortion in electron-like samples...
no evidence for matter-enhanced ν_e appearance.

Three-flavor results





	χ^2/dof	Δm^2_{23}	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$
Normal	469/417	2.1×10^{-3}	0.50	0
Inverted	468/417	2.1×10^{-3}	0.55	0.01

Data consistent with both hierarchies; no electron-like excess observed.

Analysis assumes $\Delta m^2_{12} = 0$, next update will include solar terms.

Conclusions

Super-K's atmospheric neutrino dataset is useful in studying oscillations and other phenomena

Updated physics results using >28,000 events from 3 phases of the experiment

- Probe atmospheric mixing (2-3 sector) and sub-dominant effects
  - Two-flavor oscillation (zenith angle and L/E analyses)

    $\Delta m^2_{23} = 2.1\text{x}10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$
  - Two-flavor oscillation with solar terms

    Observe no significant deviation from $\sin^2 \theta_{23} = 0.5$

    Best fit with solar terms on: $\Delta m^2_{12} = 7.59\text{x}10^{-5}$ eV^2, $\sin^2 \theta_{12} = 0.30$

- Search for non-zero θ_{13}
  - Three-flavor oscillation

    θ_{13} consistent with 0

    No preference for mass hierarchy

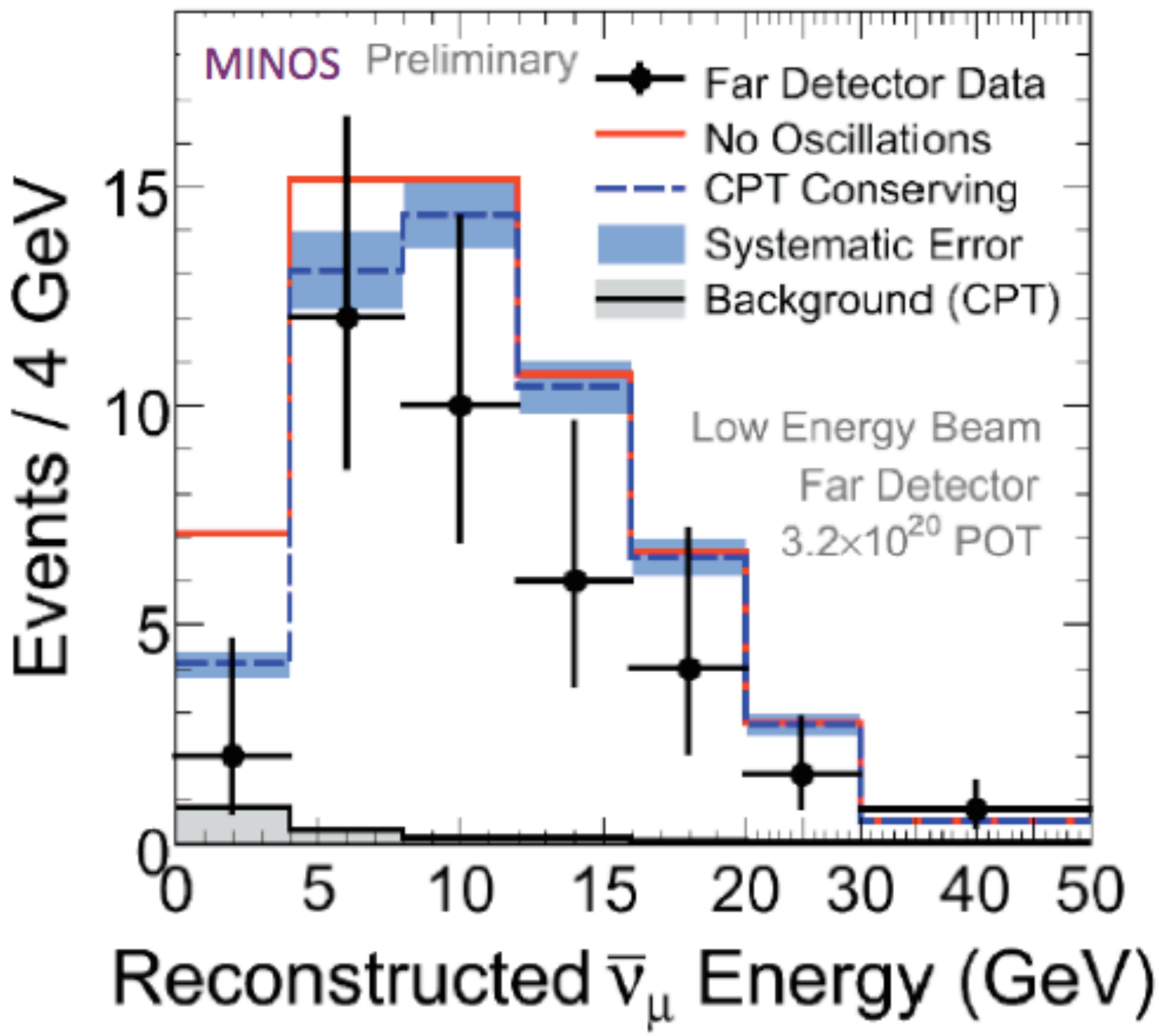
Full three-flavor analysis including solar terms is currently underway...

Thank you!

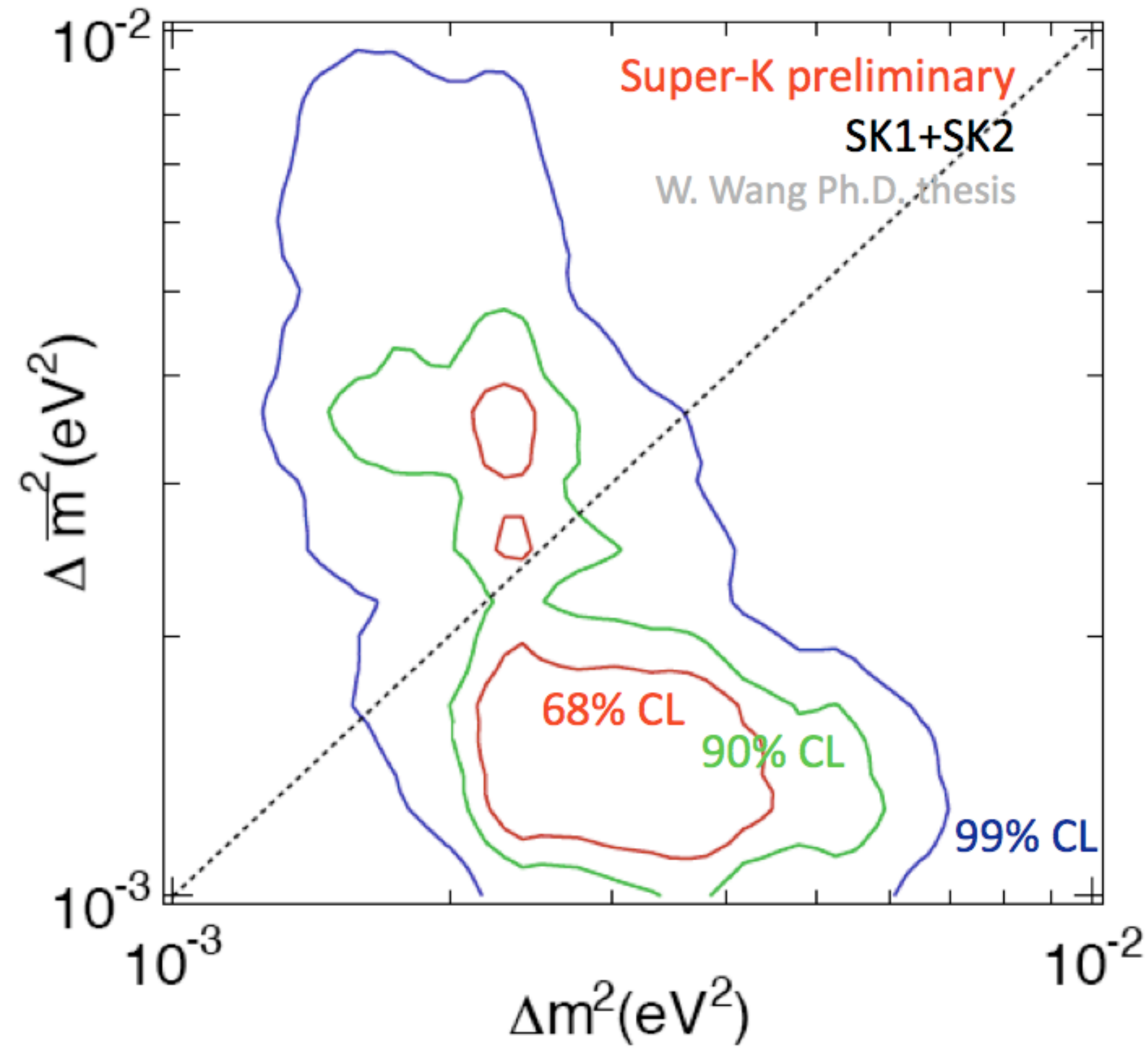
Extras

Neutrinos vs. anti-neutrinos

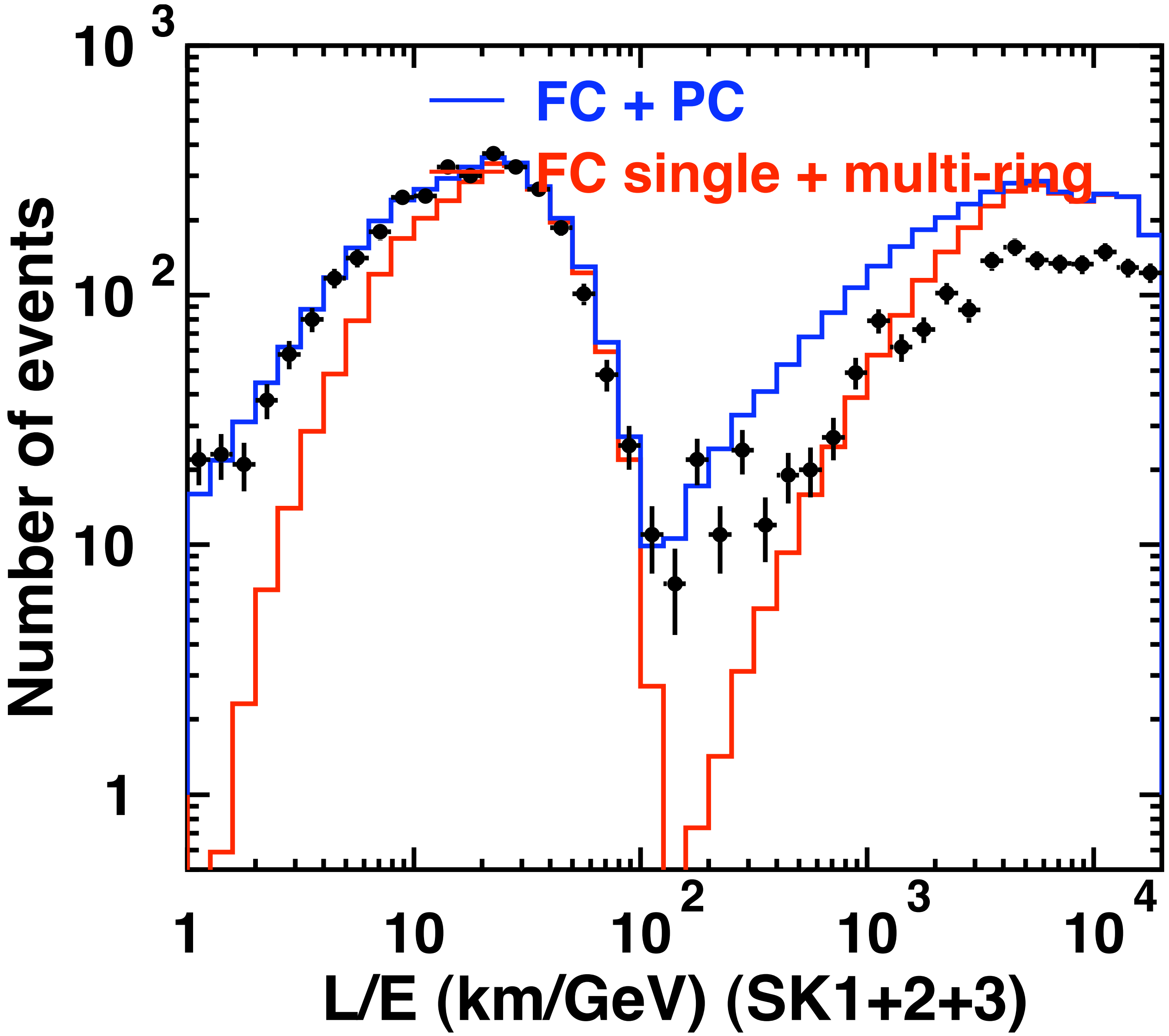
MINOS can distinguish neutrinos from anti-neutrinos on an event-by-event basis by +/-charged particle discrimination.



Super-K must rely on statistical sensitivity from different fluxes, cross sections, etc.



L/E event distribution



Events in “dip” region mostly PC through-going
- good L/E resolution

High purity sample: >93% CC ν_μ interactions

What can we learn from atmospheric neutrinos?

$$\partial_x \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[U M U^\dagger + A \right] \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$s_{ij} \equiv \sin\theta_{ij}$
$c_{ij} \equiv \cos\theta_{ij}$

Atmospheric Mixing Parameters

- Two-flavor zenith angle analysis
- L/E analysis
- Solar terms analysis

Mass Hierarchy and Value of θ_{13}

- Three-flavor zenith angle analysis

Value of Potential A

- Non-standard interactions analysis

Not covered in this talk

Non-Standard ν Interactions (NSI): SK-I + SK-II

Non-standard interactions (beyond Standard Model) may coexist with ν oscillations, but would be subdominant:

- matter-dependent
- could enhance or suppress oscillations (variety of signatures)

$$A_{NSI} = \sqrt{2} G_f N_f \begin{pmatrix} \varepsilon_{ee} & 0 & \varepsilon_{e\tau} \\ 0 & 0 & 0 \\ \varepsilon^*_{e\tau} & 0 & \varepsilon_{\tau\tau} \end{pmatrix}$$

Flavor-changing neutral currents ($\varepsilon_{e\tau}$)

Lepton non-universality ($\varepsilon_{\tau\tau}$)

Assume 2-flavor oscillation parameters ($\nu_\mu \rightarrow \nu_\tau$): $(\sin^2\theta, \Delta m^2) = (0.5, 2.1 \times 10^{-3})$

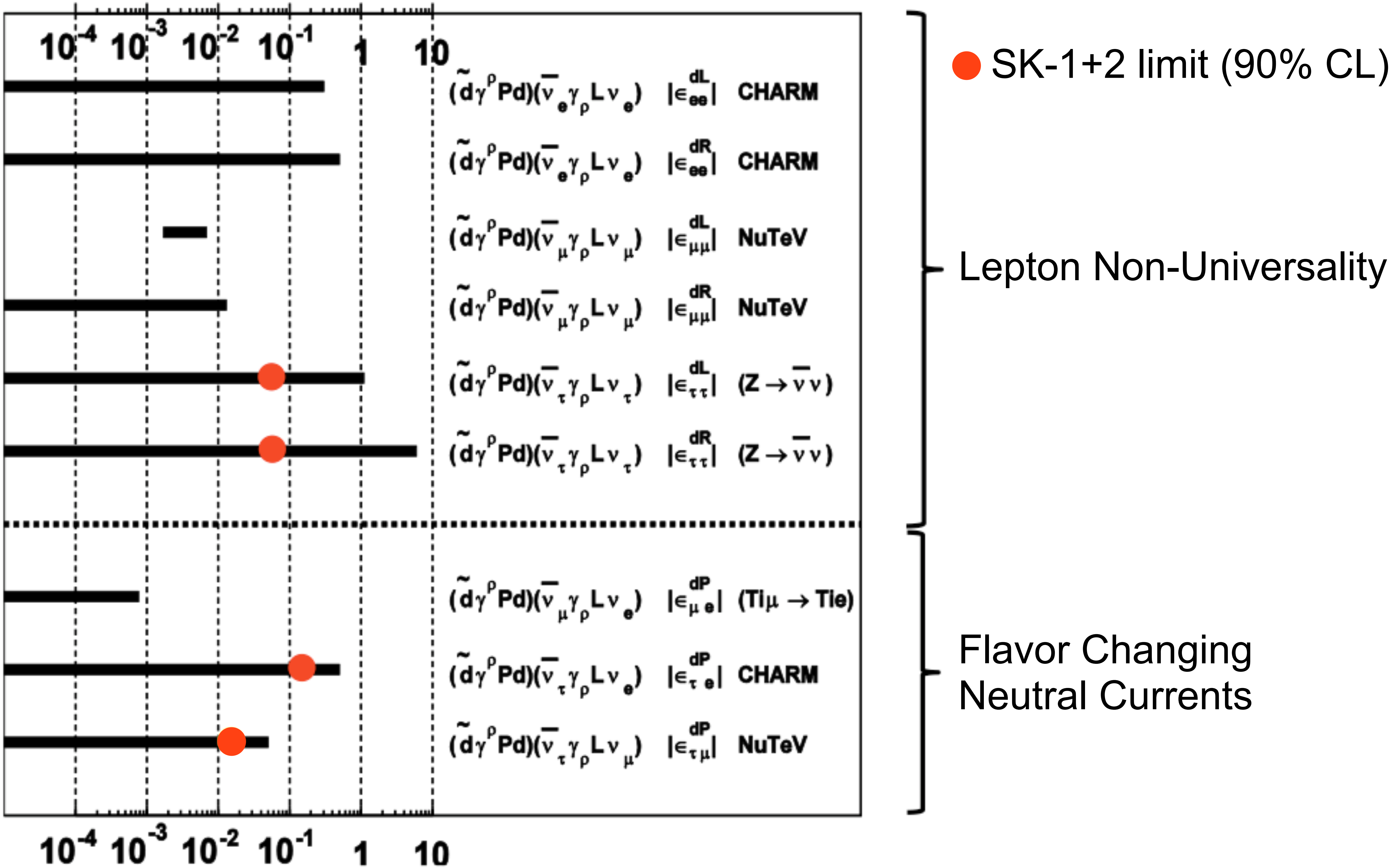
Determine best fit parameters for NSI under an oscillation + NSI hypothesis

Best fit NSI parameters:

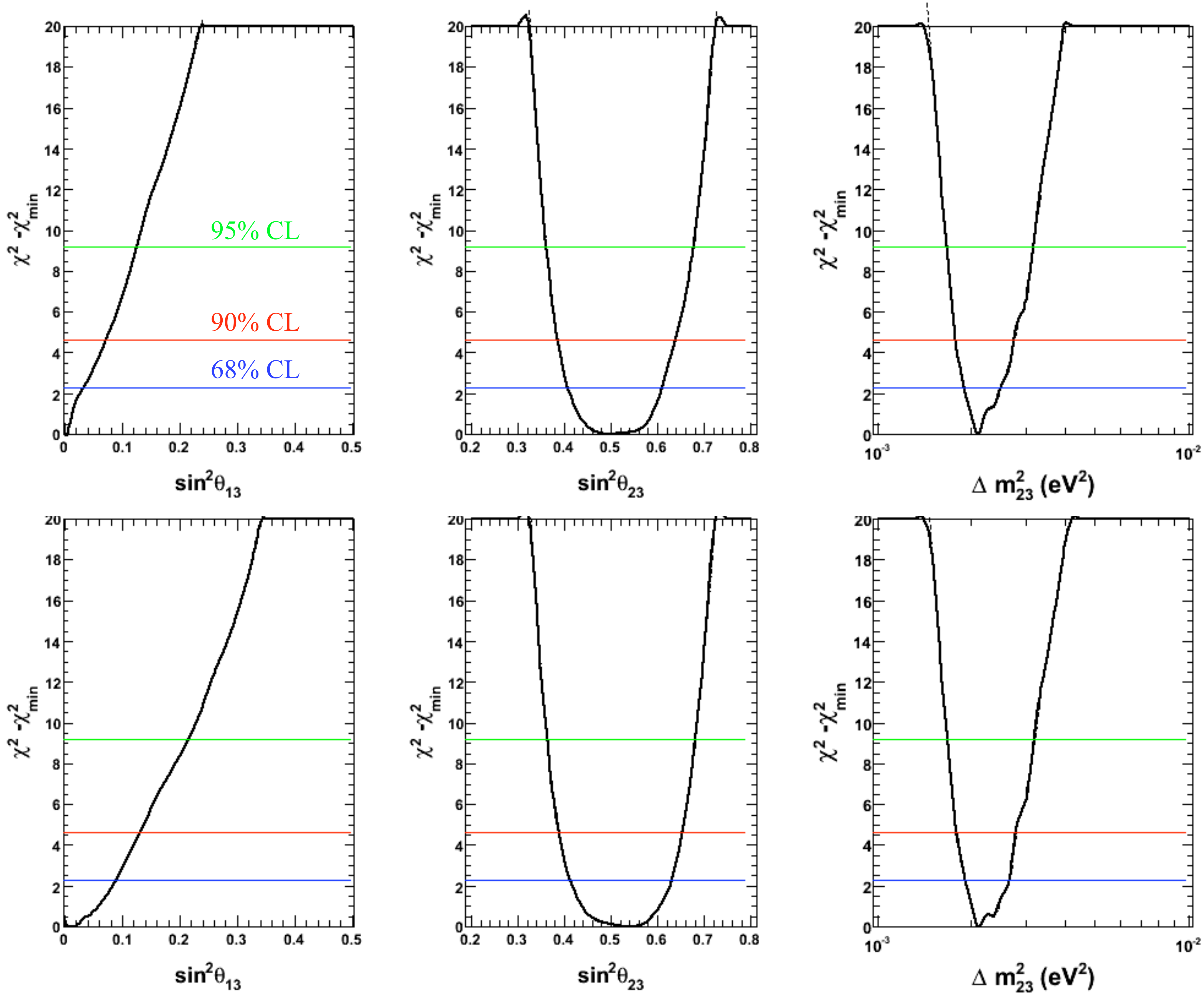
$$(\varepsilon_{ee}, \varepsilon_{e\tau}, \varepsilon_{\tau\tau}) = (-0.250, 0.016, 0.024)$$

$$\chi^2_{min}/d.o.f = 830/747$$

Limits on Non-Standard Interactions



Three-flavor results



Normal Hierarchy

Inverted Hierarchy