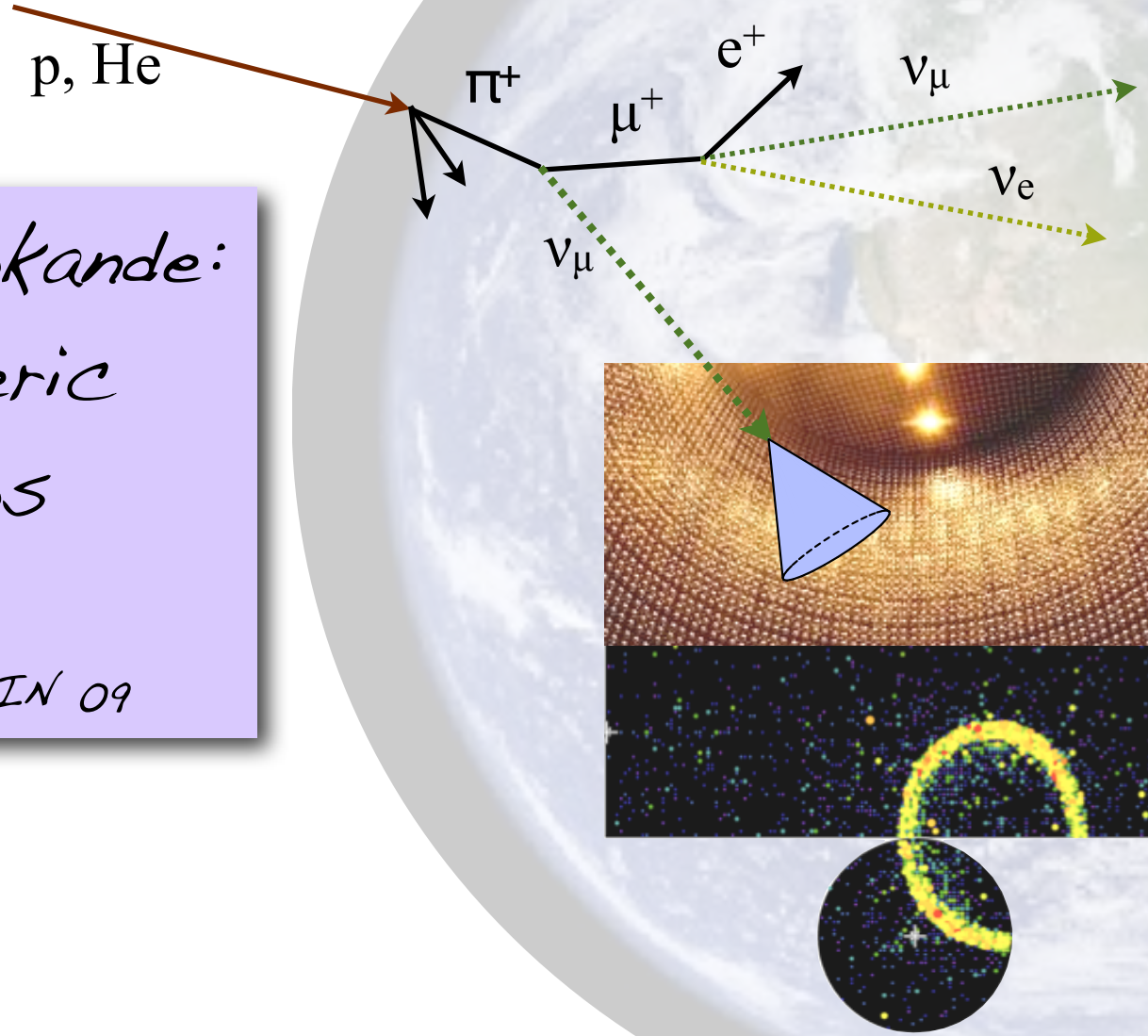
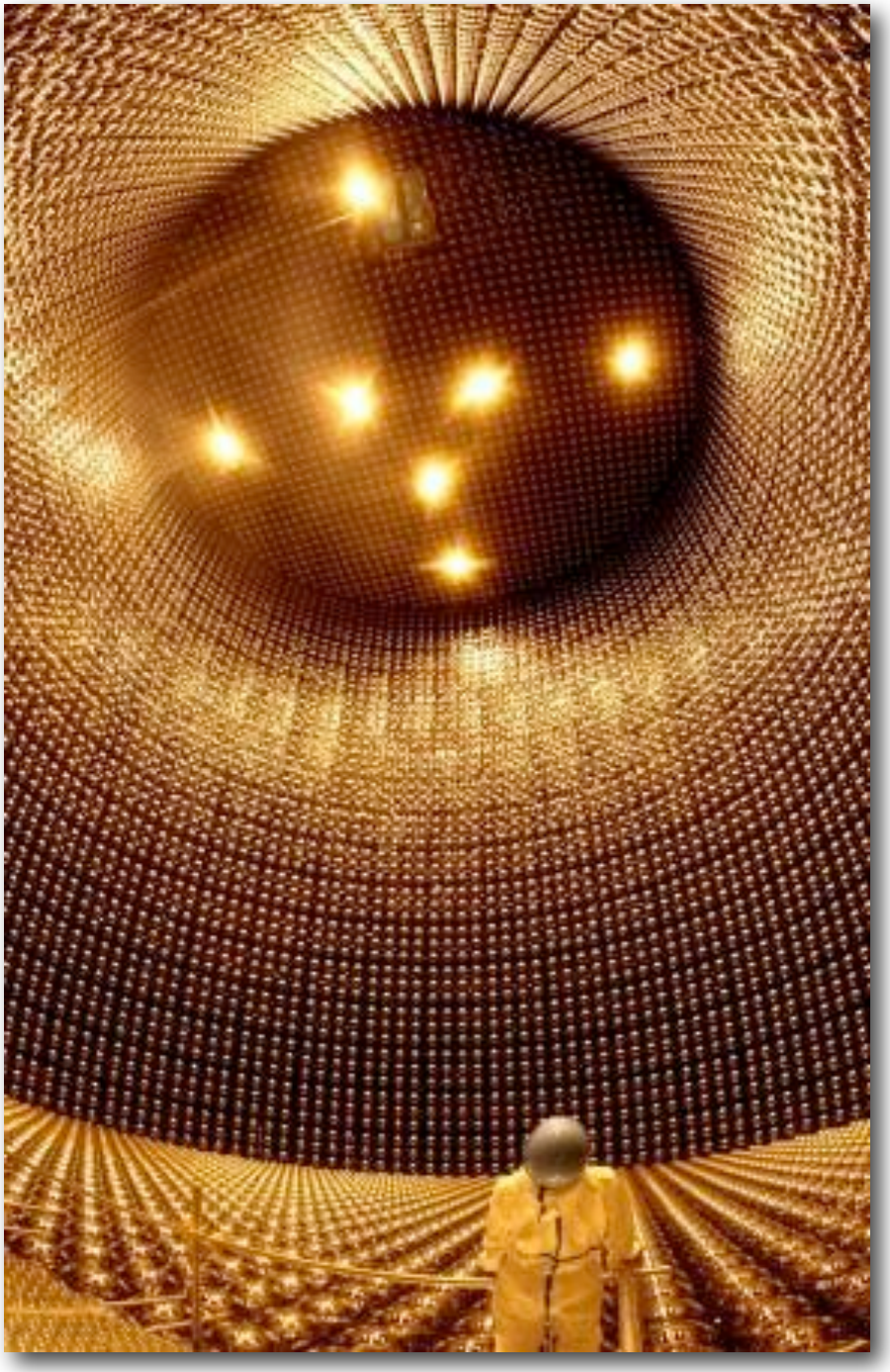
Super-Kamiokande: Atmospheric neutrinos

Fanny Dufour WIN 09



Outline

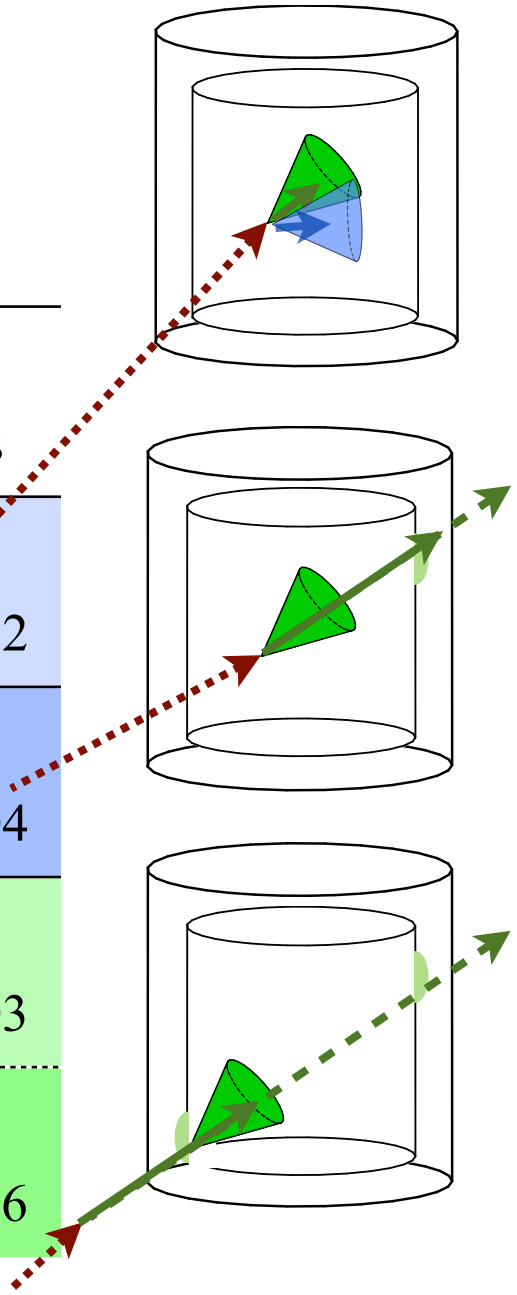
- Events summary
- Standard 2 flavor analysis:
  - Zenith angle analysis
  - L/E analysis
- New 2 flavor analysis:
  - Solar term analysis
- Three flavor analysis



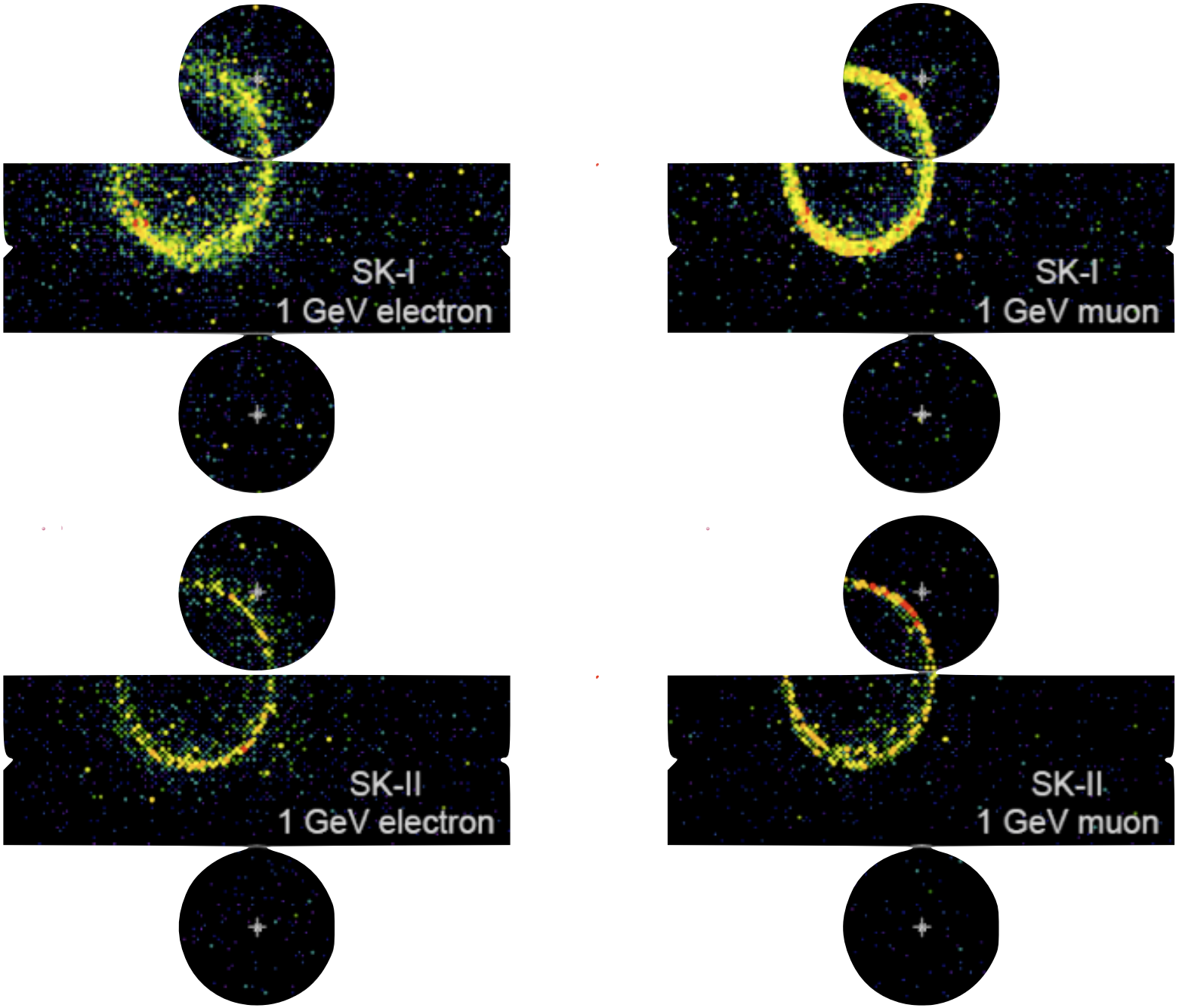
Event summary

More than 28‘000 events recorded!

Events type	Event rates per day		
	SK-I	SK-II	SK-III
Livetime	1489 days	798 days	518 days
Fully-contained			
0.1-10 GeV	8.18 ± 0.07	8.22 ± 0.10	8.31 ± 0.22
Partially contained			
1-100 GeV	0.61 ± 0.02	0.54 ± 0.03	0.66 ± 0.04
Up-mu stopping			
3-100 GeV	0.25 ± 0.01	0.28 ± 0.02	0.24 ± 0.03
Up-mu through-going			
5 GeV-1 TeV	1.12 ± 0.03	1.07 ± 0.04	1.11 ± 0.06



1 GeV events example in SK1 and SK2



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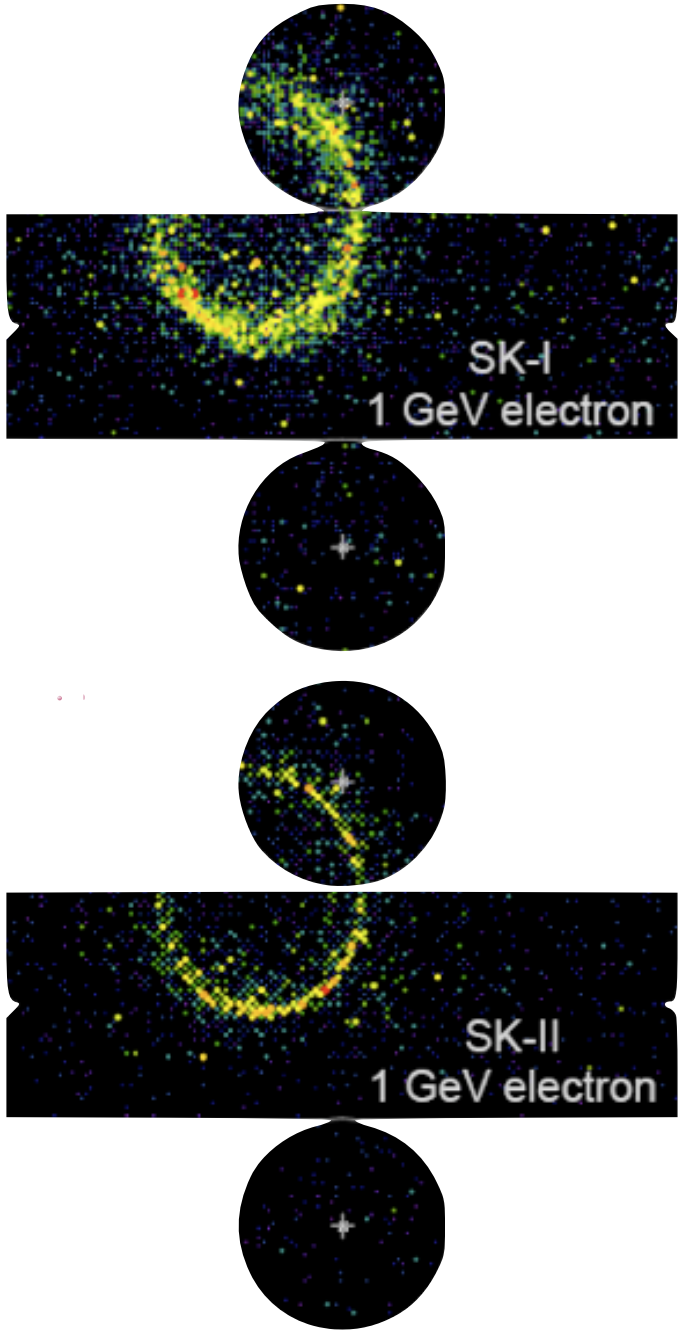

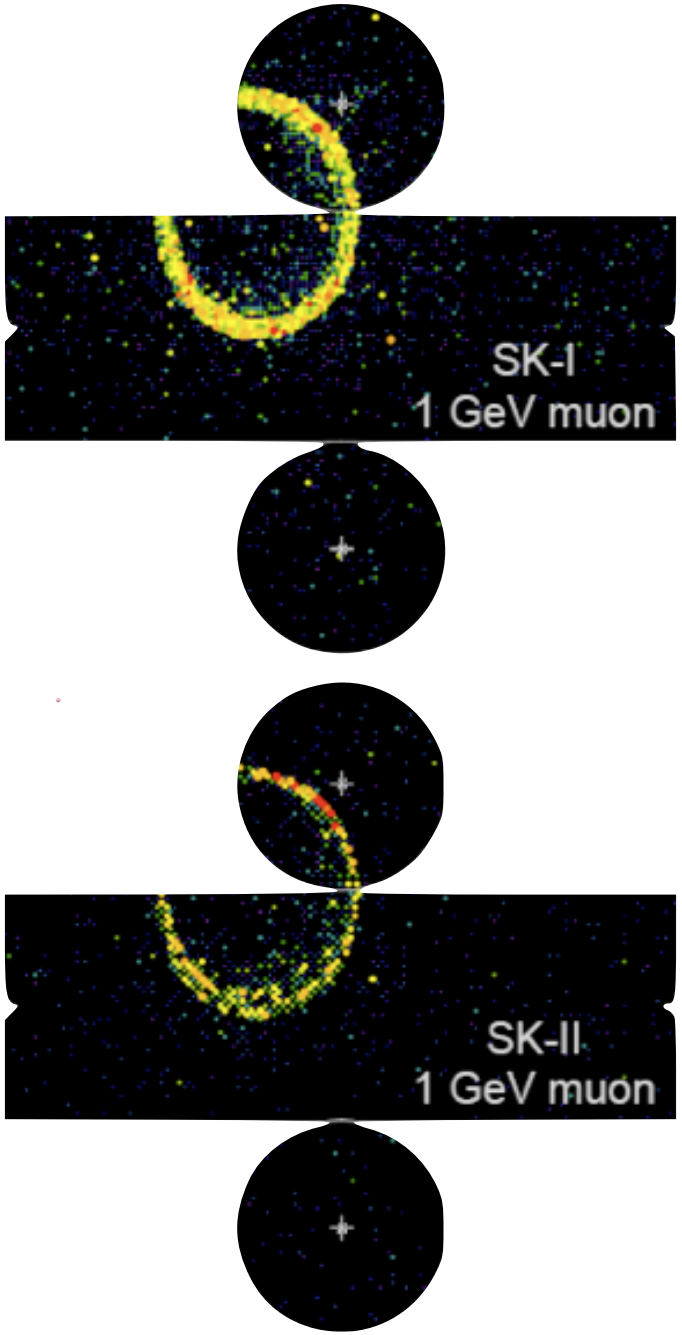

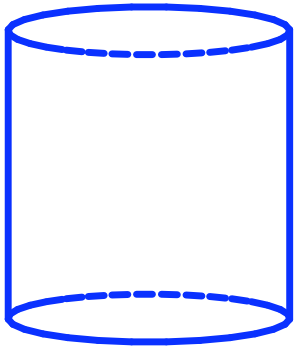

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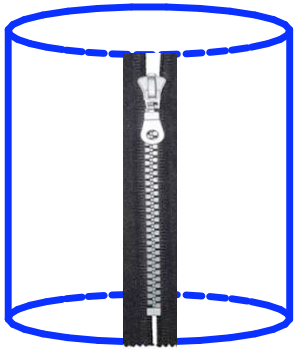
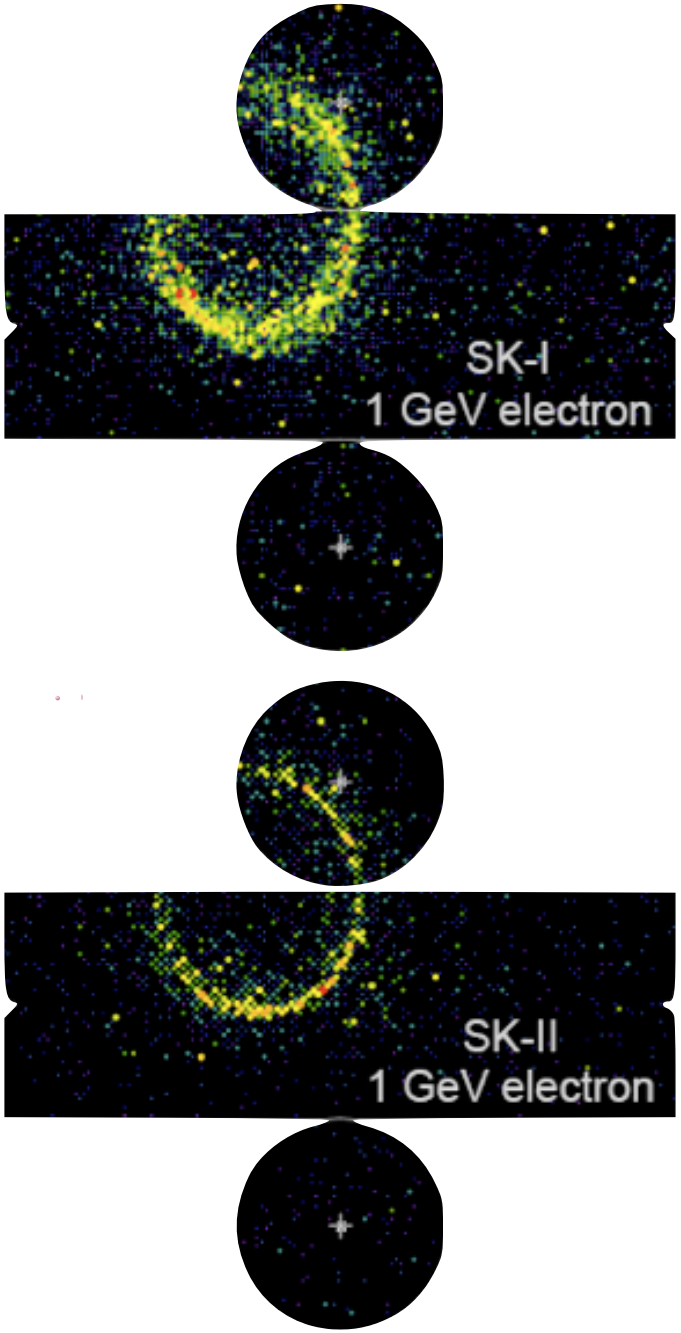
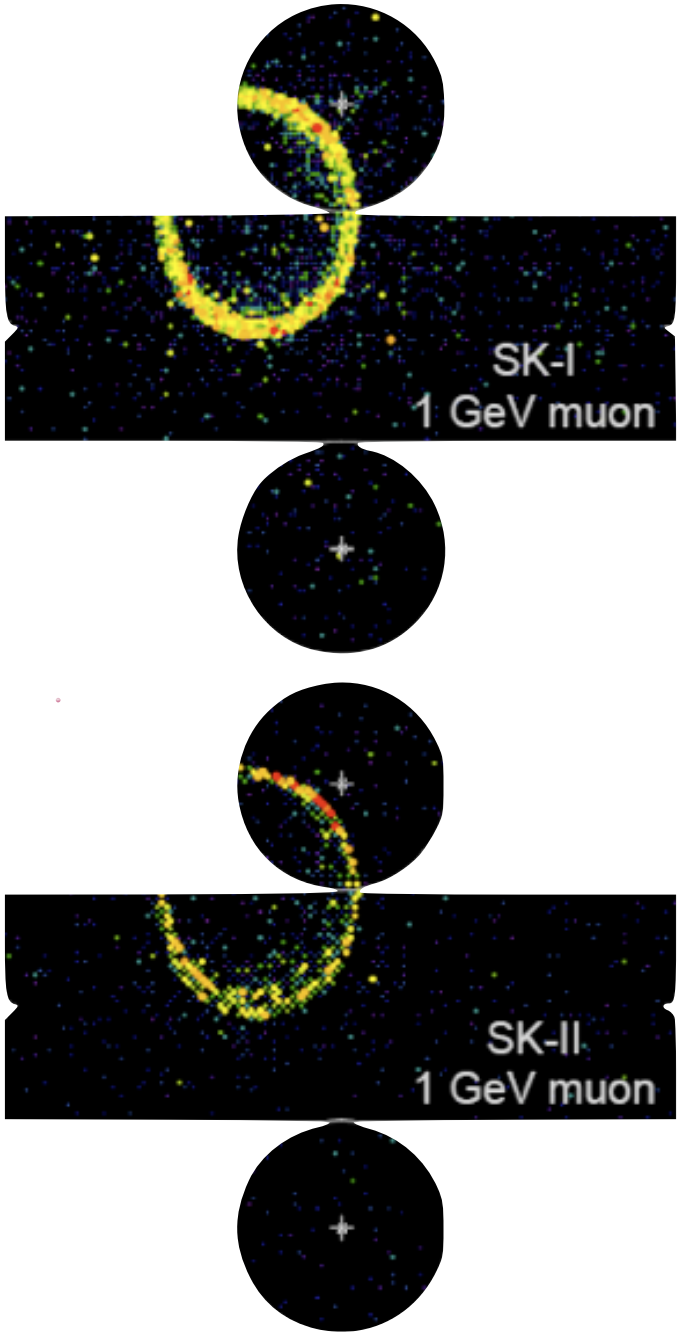
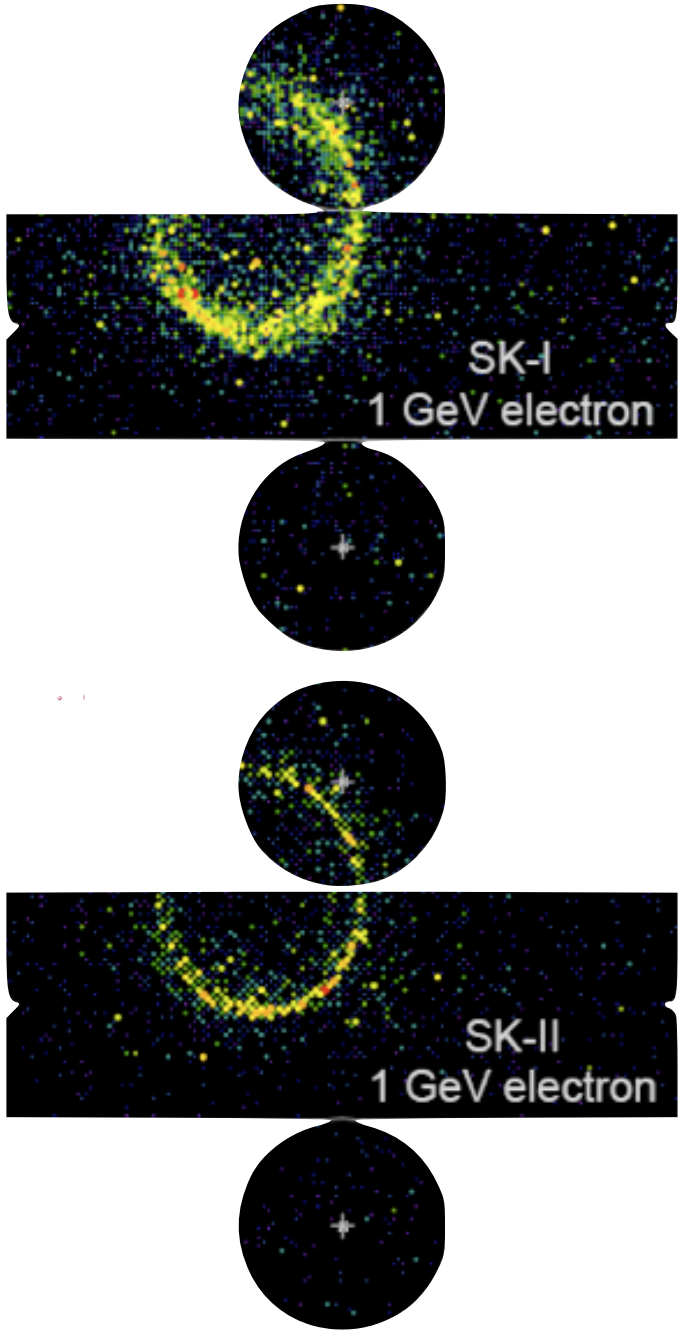
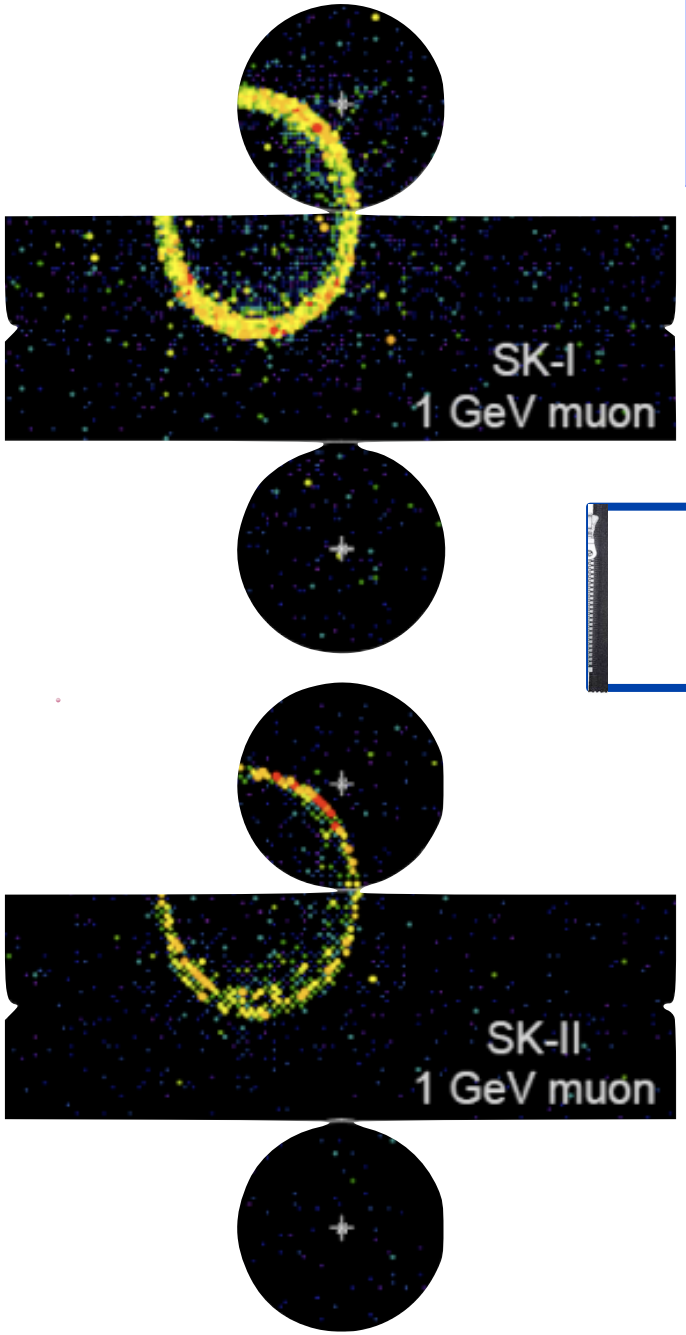


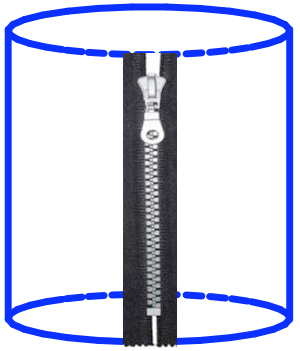


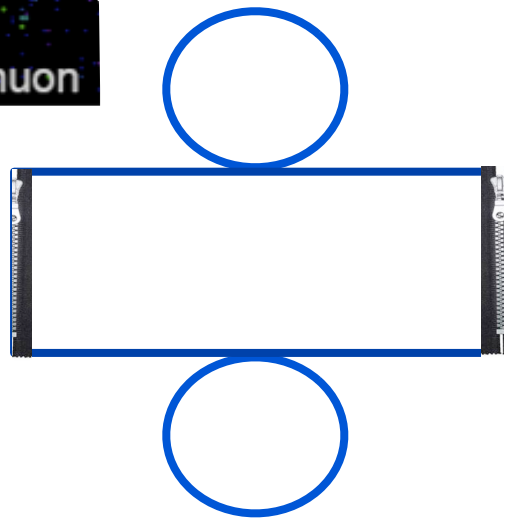


1 GeV events example in SK1 and SK2









How to use atmospheric neutrinos?

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{-i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"2-3 sector" — Atmospheric

"1-3 sector" — Accelerator / reactor

"1-2 sector" — Solar

$C_{ij}=\cos\theta_{ij}$
$S_{ij}=\sin\theta_{ij}$

Atmospheric mixing parameters:

- Zenith angle analysis → mainly $\sin^2(2\theta_{23})$
- L/E analysis → mainly Δm^2
- Solar term analysis → octant degeneracy

θ_{13} and mass hierarchy:

- 3 flavors zenith angle analysis

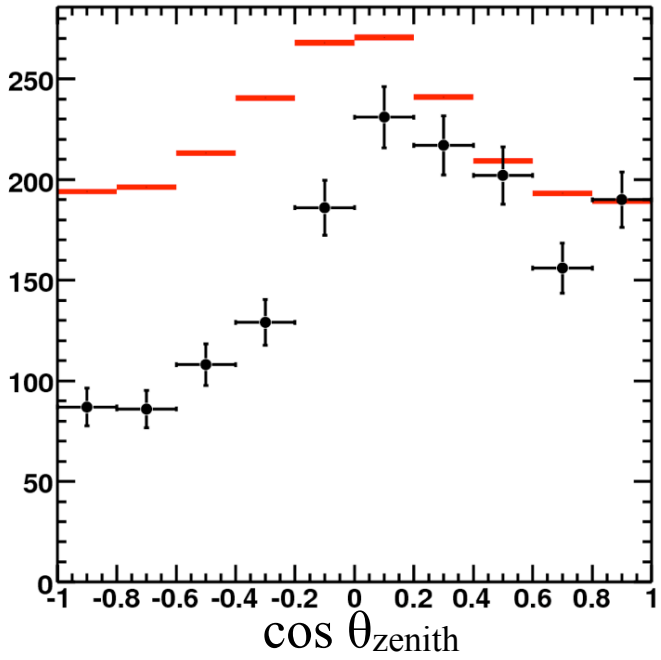
Non-standard interactions are not covered in this talk

Two standard analysis: Zenith & L/E analysis

Zenith angle analysis

Goal is to observe a **deficit** of upward going muon neutrinos.

Uses all the events described before.

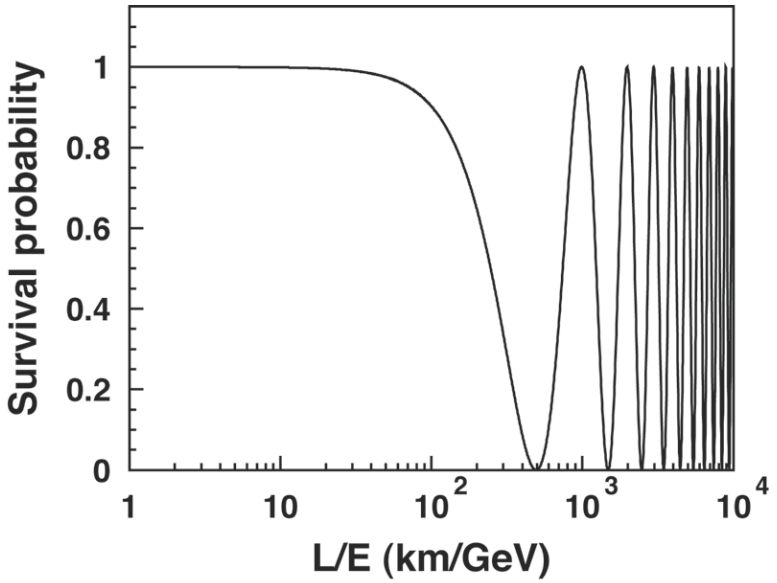


L/E analysis

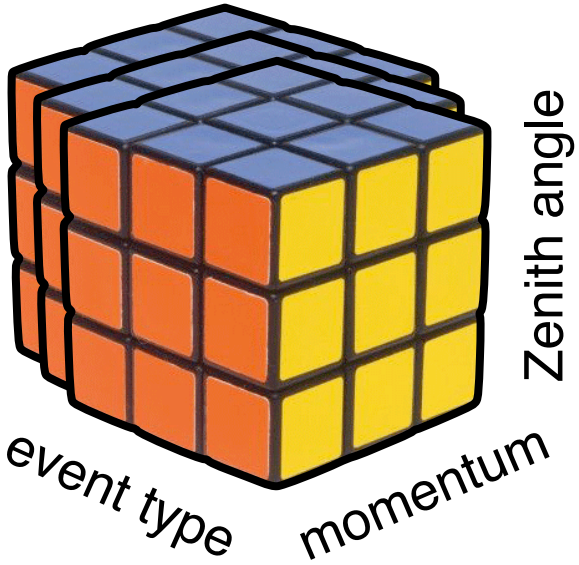
Goal is to actually see the first **oscillation** dip.

Need events with good path-length (L) and energy (E) resolution.

Uses a subsample of events with good resolution.



Zenith angle analysis



} 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

Bin the data

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

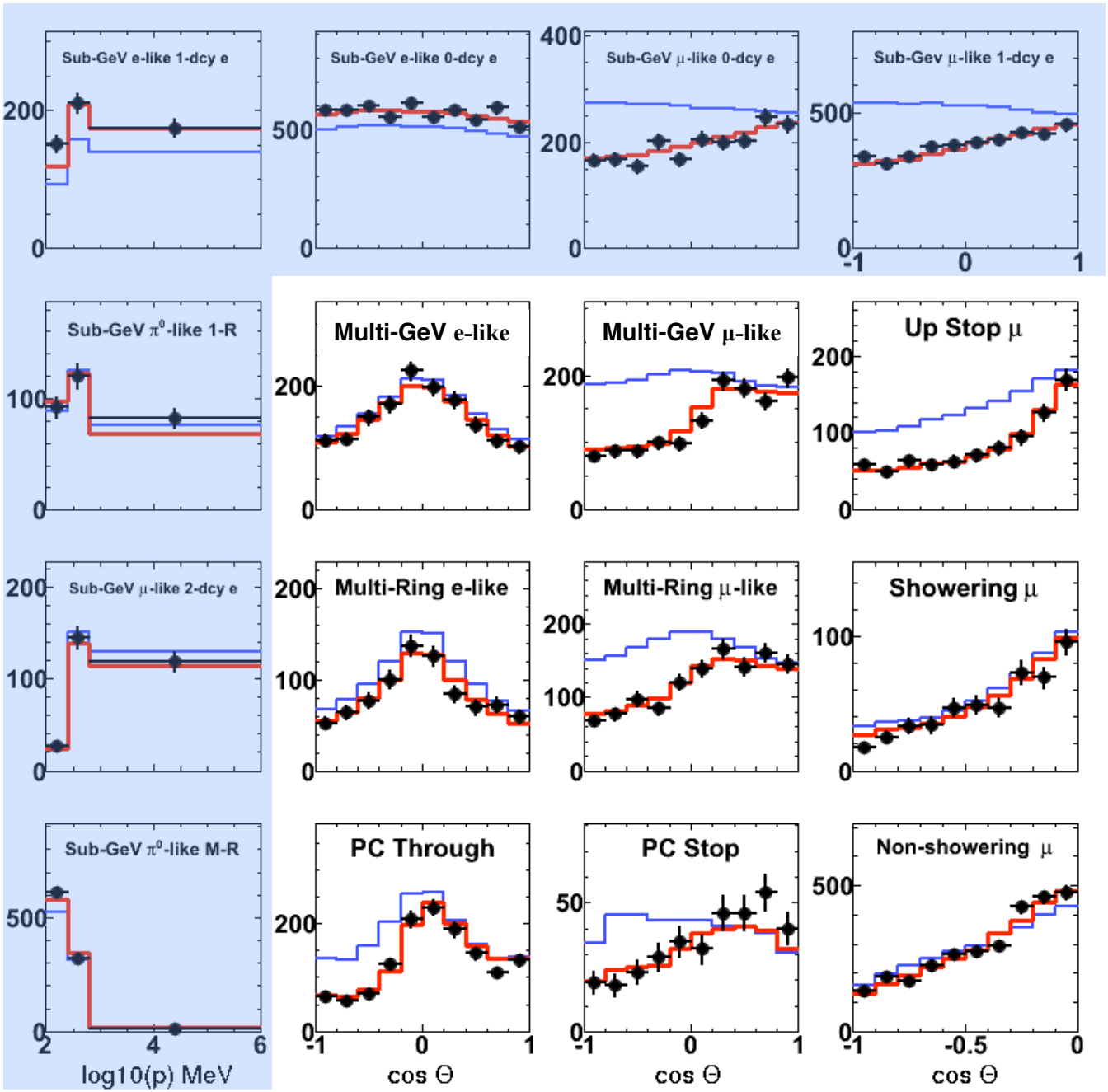
Make a χ^2 fit

122 systematic error terms to account for uncertainties in:

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

Account for systematics

Zenith analysis results

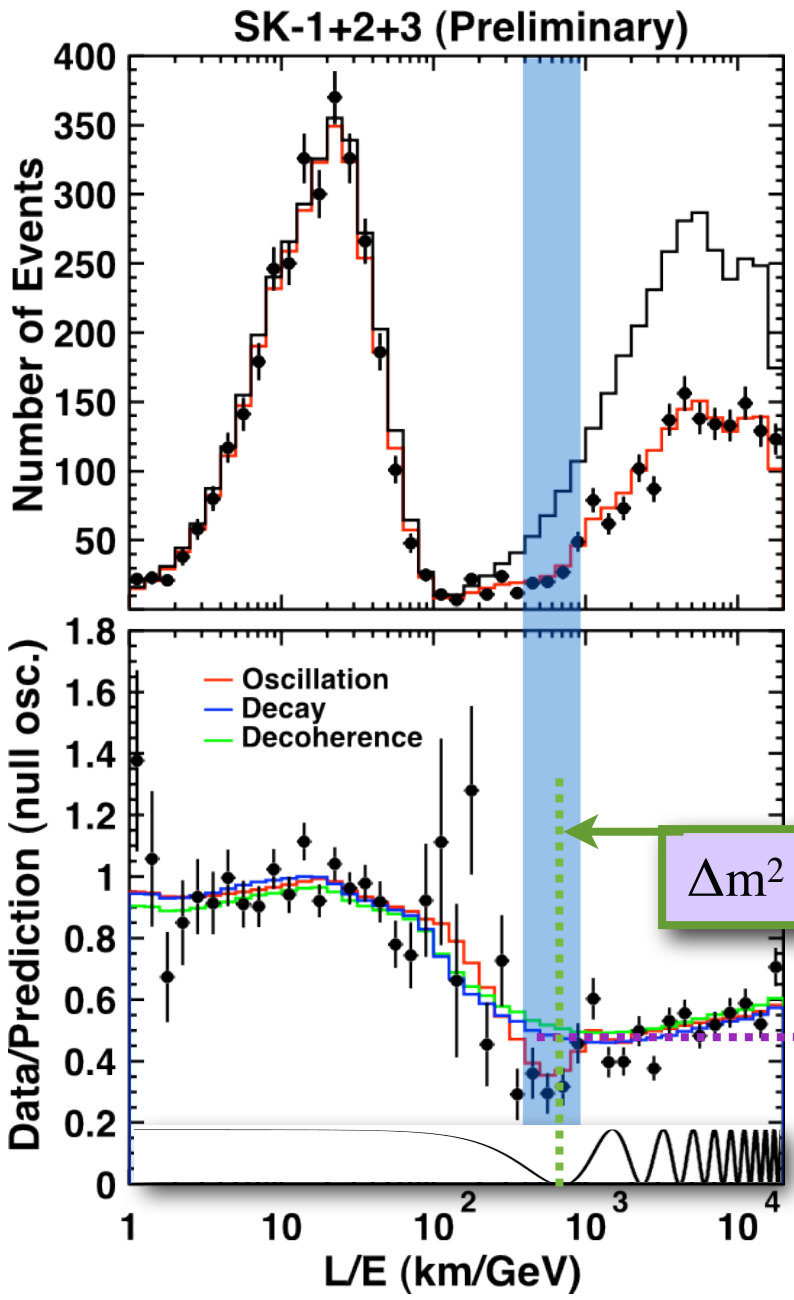


- Data
- MC (no oscillations)
- MC (best fit oscillations)

16 sub-samples are used for the oscillation analysis

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

L/E analysis results



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

We do see **oscillation** and not just disappearance and we compare against:

Neutrino decay (disfavored @ 4.4σ)

Neutrino decoherence (5.4σ)

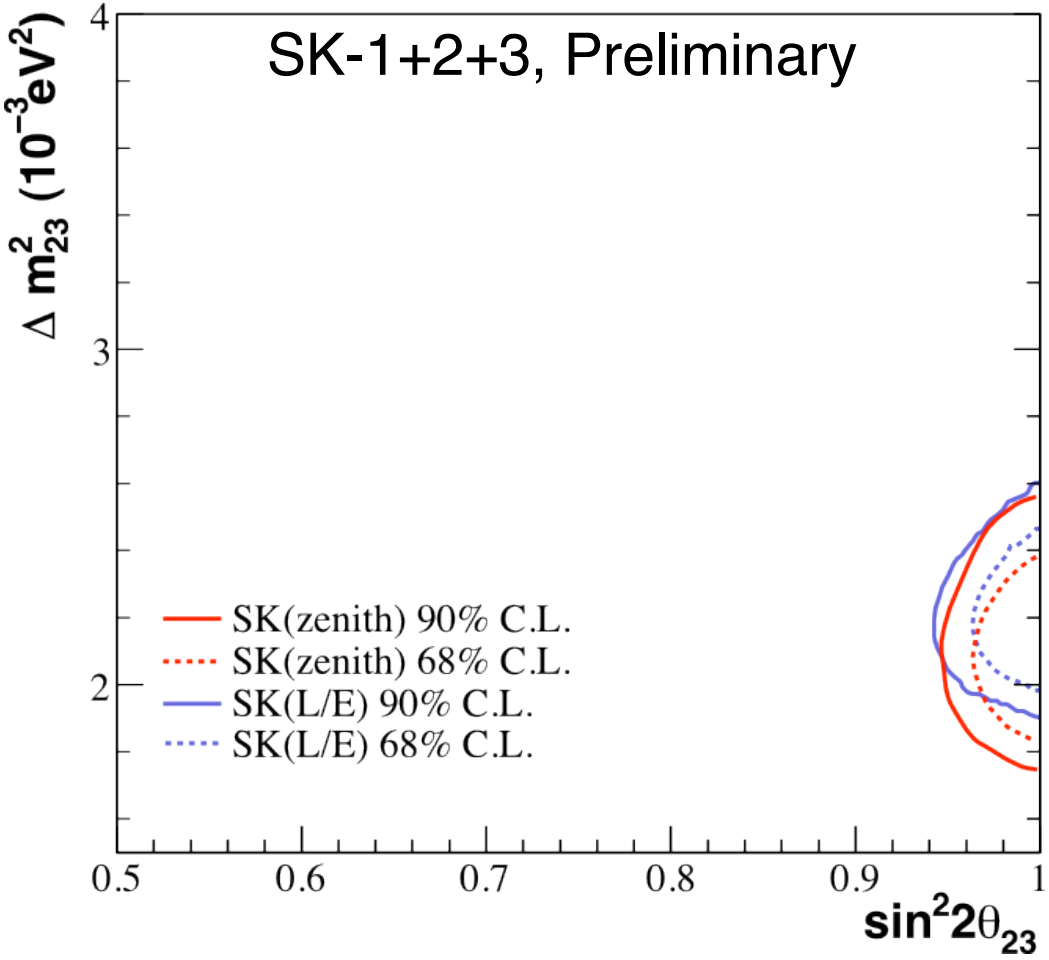
Grossman and Worah: hep-ph/9807511
Lisi *et al.*: PRL85 (2000) 1166
Barger *et al.*: PRD54 (1996) 1, PLB462 (1999) 462

$\Delta m^2 = 2.2 * 10^{-3}\ eV^2$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23} L_\nu}{4 E_\nu}\right)$$

$\sin^2(2\theta_{23})=1.0$

Results of 2 flavors analyses for SK 1+2+3



Zenith angle analysis best fit

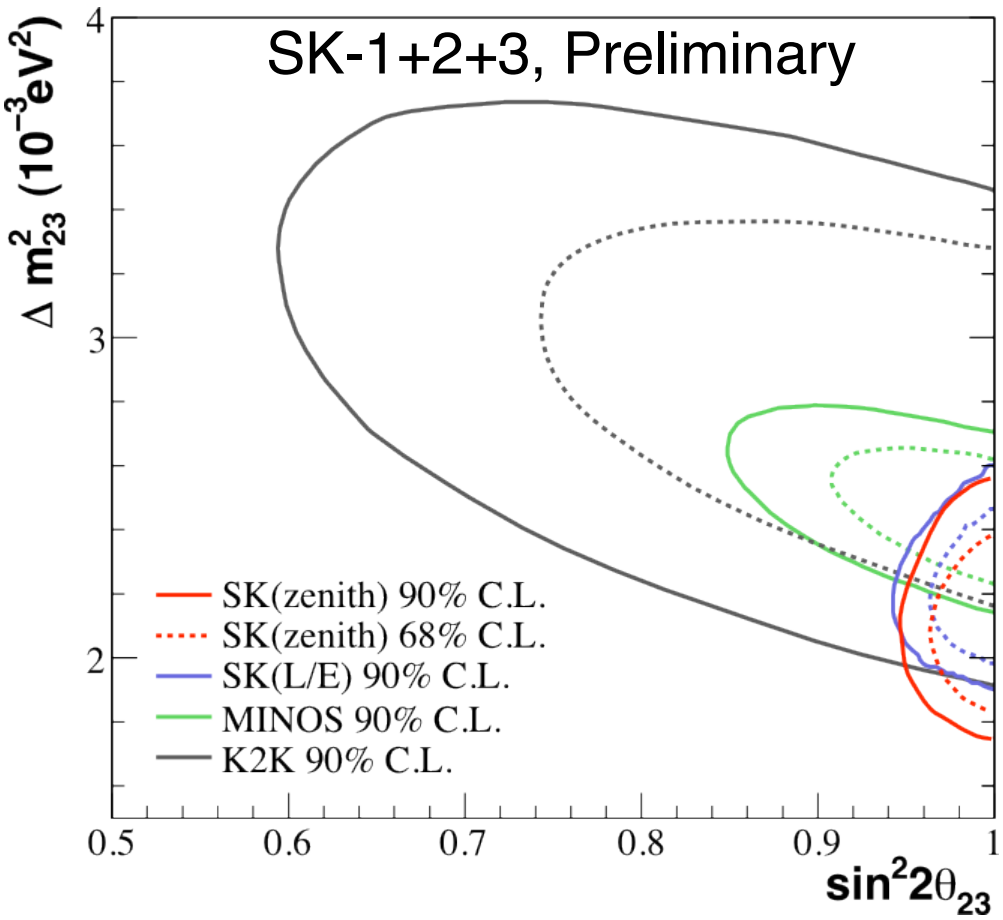
$$\sin^2 2\theta_{23} = 1.0$$
$$\Delta m^2_{23} = 2.1 \times 10^{-3} eV^2$$
$$\chi^2/d.o.f. = 468/420$$

L/E analysis best fit

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

These two analyses are complementary:
L/E has stronger Δm^2 constraint
Equally strong $\sin^2 2\theta_{23}$ constraint

Comparing with MINOS and K2K



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L/E analysis best fit

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

The results agree well with other experiments

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

Comparing Δm^2_{23} with MINOS (1-D fit, 68% C.L $\Delta\chi^2$=1.0)

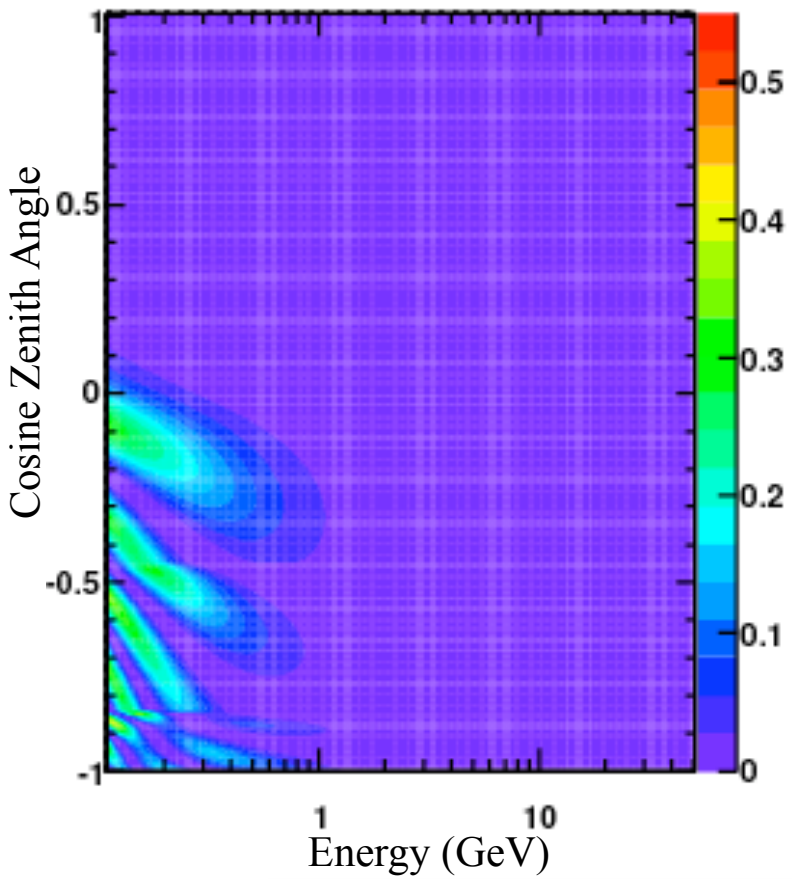
Zenith: $2.11^{+0.11}_{-0.19} \times 10^{-3} eV^2$

L/E: $2.19^{+0.14}_{-0.13} \times 10^{-3} eV^2$

MINOS: $2.43^{+0.13}_{-0.13} \times 10^{-3} eV^2$

Solar terms analysis - Octant degeneracy

Look for changes in low energy ν_e flux induced by solar (12)-sector oscillations, assuming $\theta_{13} = 0$.



Driven by Δm^2_{12} and θ_{12}.

In constant density matter:

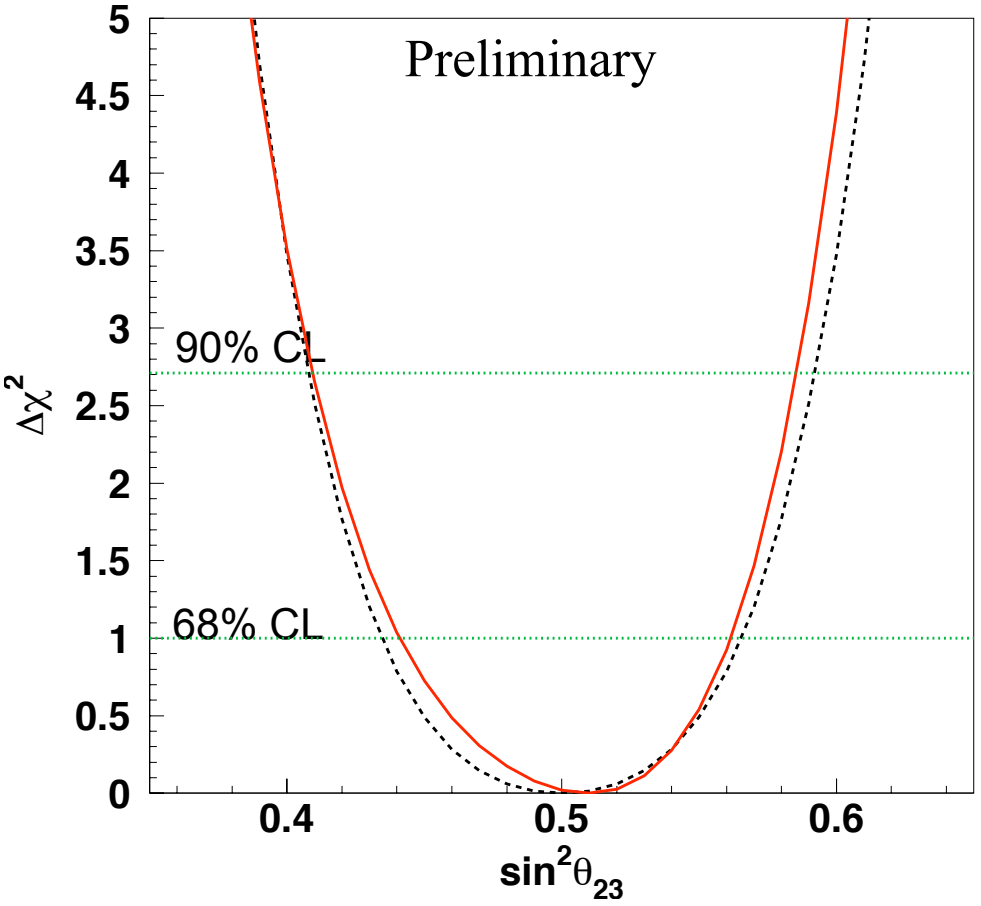
$$P(\nu_e \leftrightarrow \nu_\mu) = \cos^2\theta_{23}\, P(\nu_e \rightarrow \nu_x)$$

$\cos^2\theta_{23} < 0.5$	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 term analysis - Results

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



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

Solar terms off (best fit)

$$\Delta m^2_{12} = 0$$
$$\Delta m^2_{23} = 2.1 \times 10^{-3}\text{eV}^2$$
$$\sin^2\theta_{12} = 0$$
$$\sin^2\theta_{23} = 0.50$$
$$\chi^2/dof = 470.2/418$$

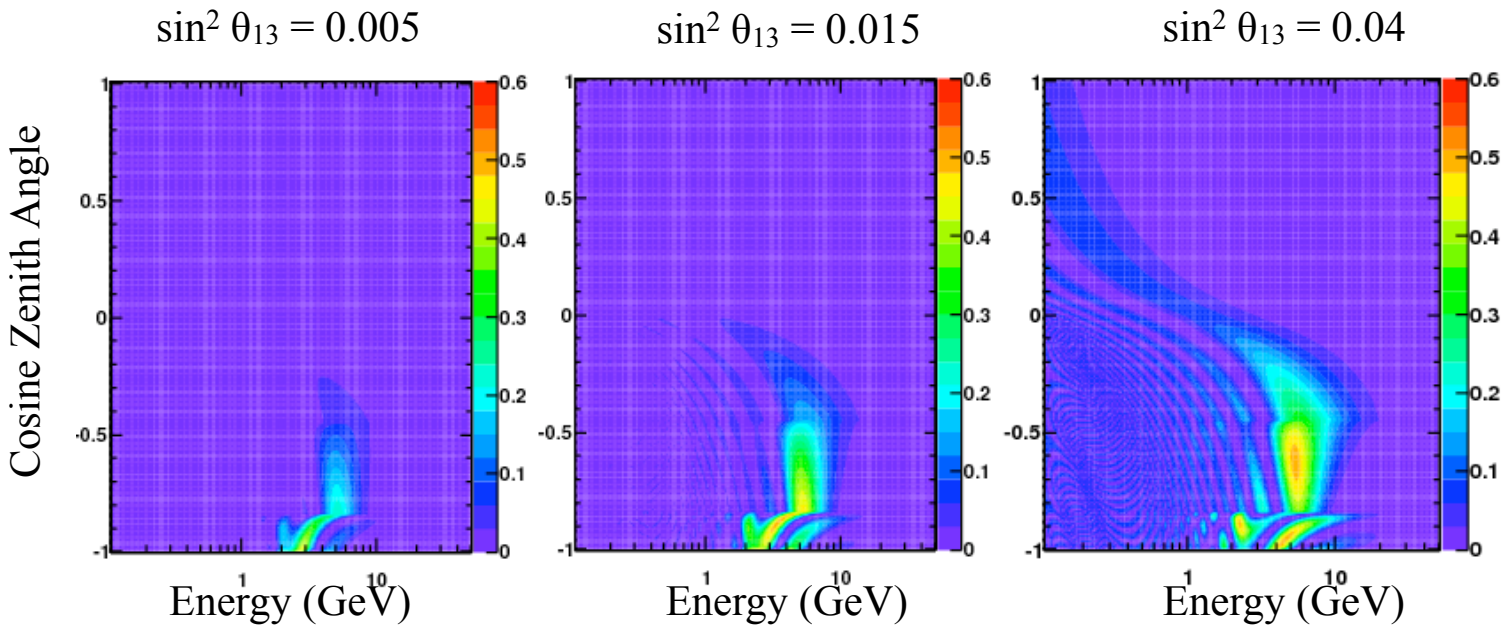
Solar terms on (best fit) *

$$\Delta m^2_{12} = 7.59 \times 10^{-5}\text{eV}^2$$
$$\Delta m^2_{23} = 2.1 \times 10^{-3}\text{eV}^2$$
$$\sin^2\theta_{12} = 0.30$$
$$\sin^2\theta_{23} = 0.51$$
$$\chi^2/dof = 471.2/416$$

* 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)

θ_{13} with atmospheric neutrinos



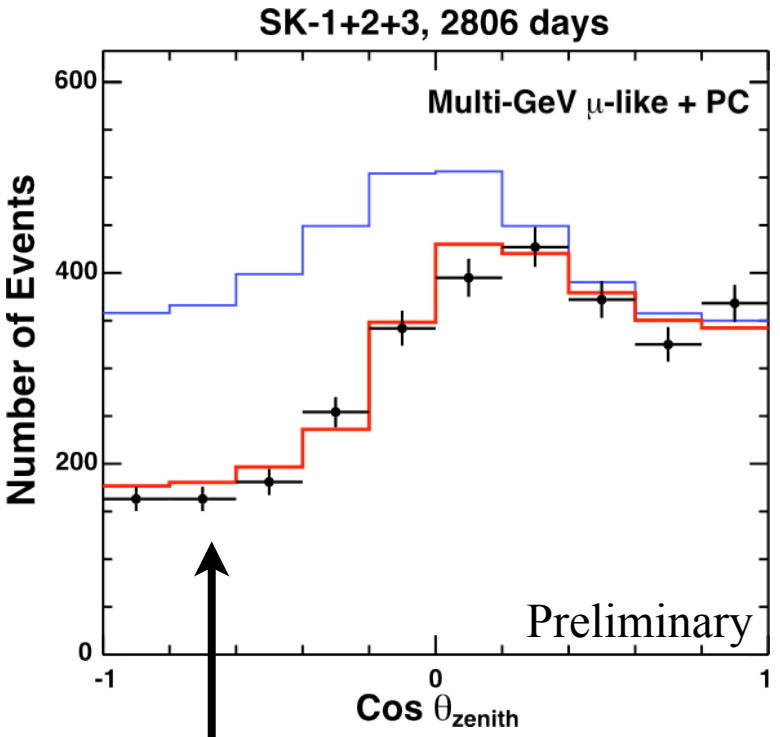
$P(\nu_\mu \rightarrow \nu_e)$

MSW effect gives rise to additional scattering amplitudes in matter (for ν_e only). The clearest indication of non-zero θ_{13} at Super-K is a resonance @ ~2-10 GeV for up-going e-like events

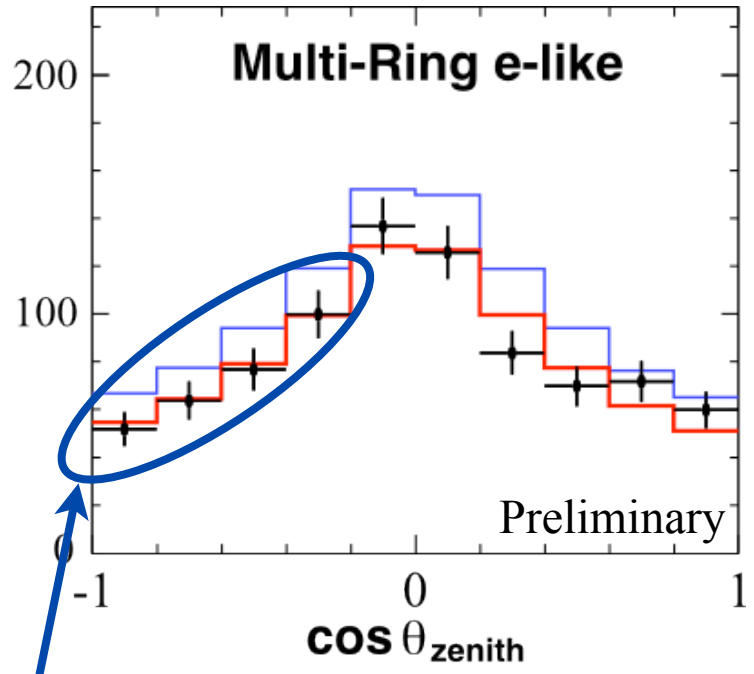
Normal hierarchy $\Rightarrow$ neutrino enhancement
Inverted hierarchy $\Rightarrow$ anti-neutrino enhancement

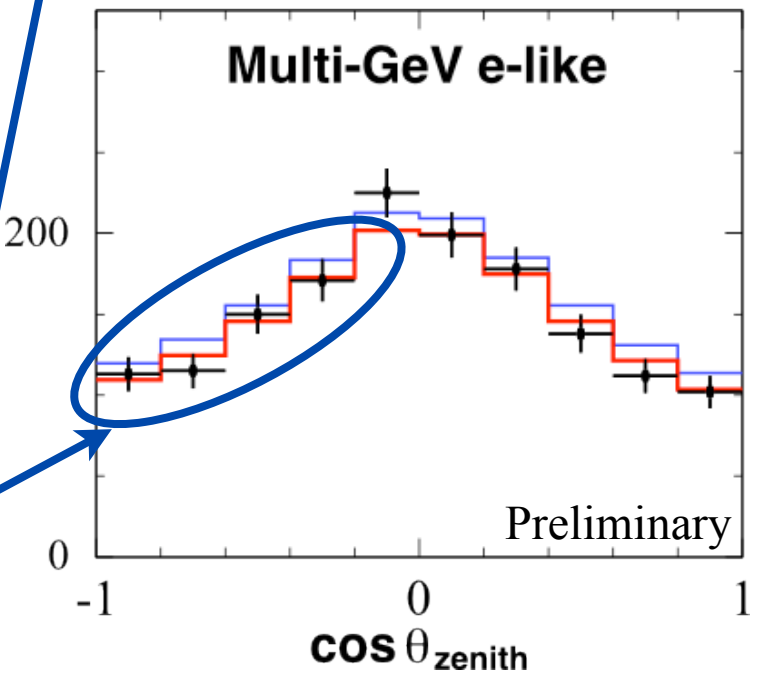
Analysis uses 3 parameters ($\sin^2\theta_{13}$, $\sin^2\theta_{23}$, Δm^2_{23})
assuming a single "dominant mass scale" ($\Delta m^2_{23} \gg \Delta m^2_{12}$).

Three flavors zenith angle



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

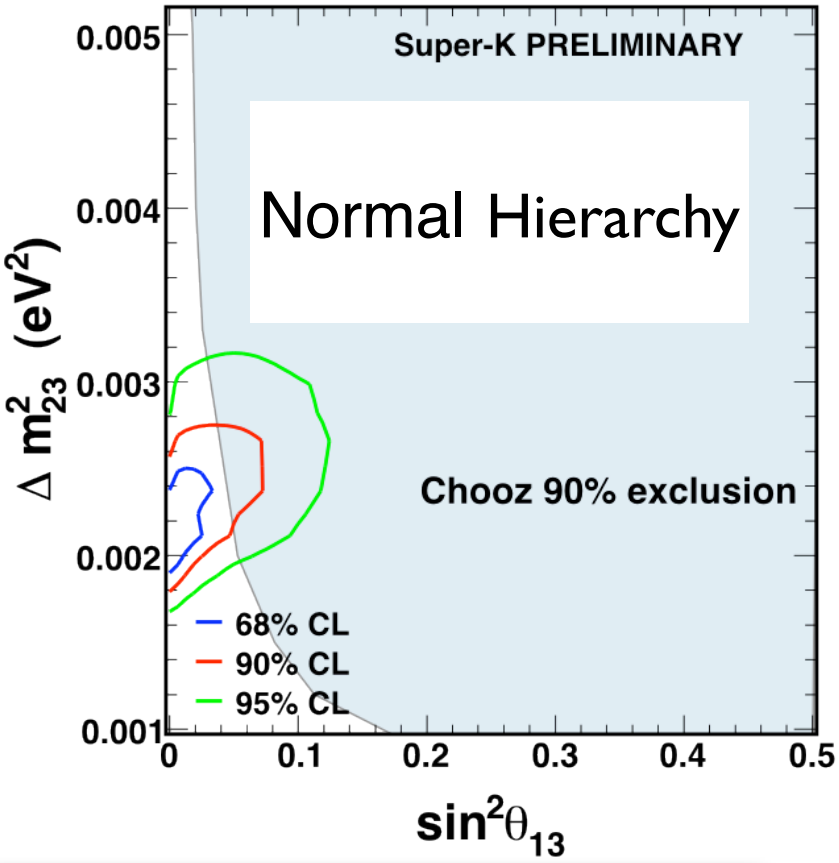


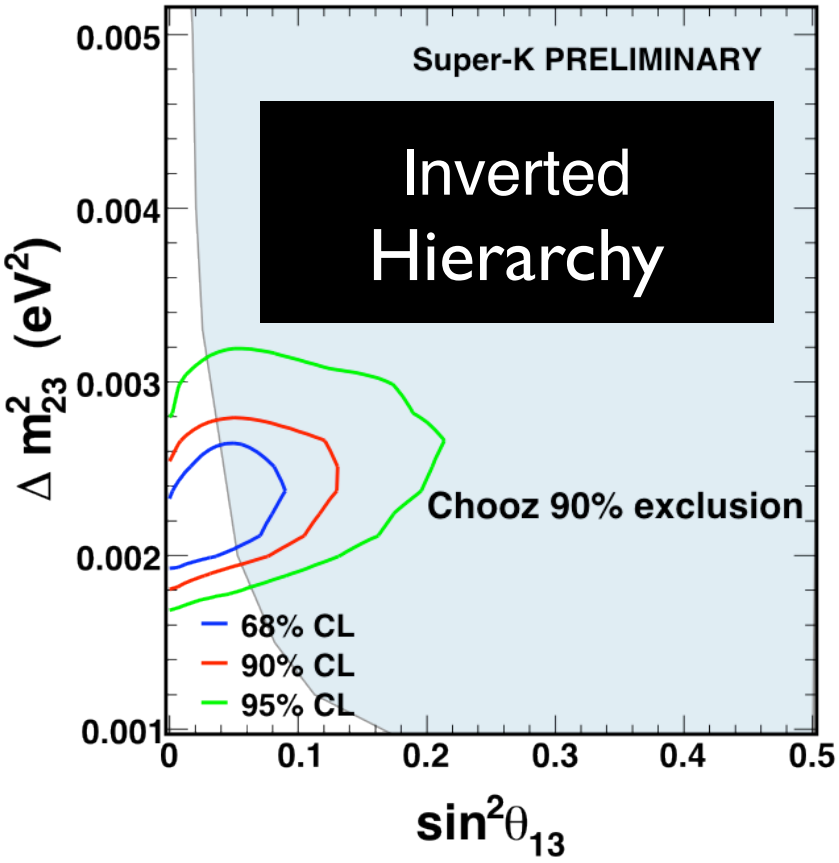


Clear distortion of muon-like zenith distribution, well-described by 2-flavor $\nu_\mu \rightarrow \nu_\tau$ disappearance...

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

Three flavors results

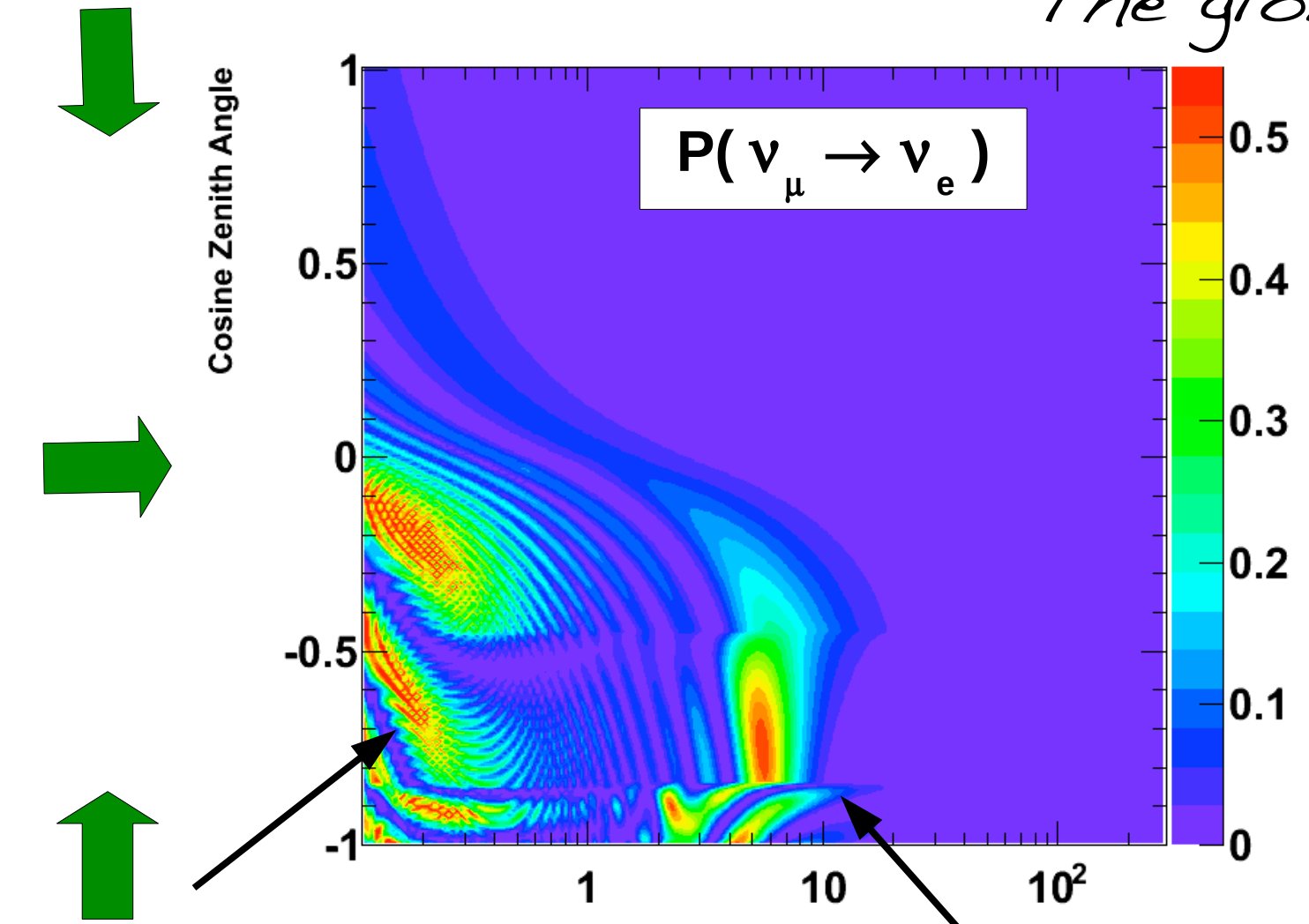




Data consistent with both hierarchies; no electron-like excess observed.
Analysis assumes $\Delta m^2_{12} = 0$, next update will include solar terms.

Best fit	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

The global picture



By combining the solar term analysis and the three flavor analysis we can get the global pictures: Analysis underway, no results yet.

Conclusions

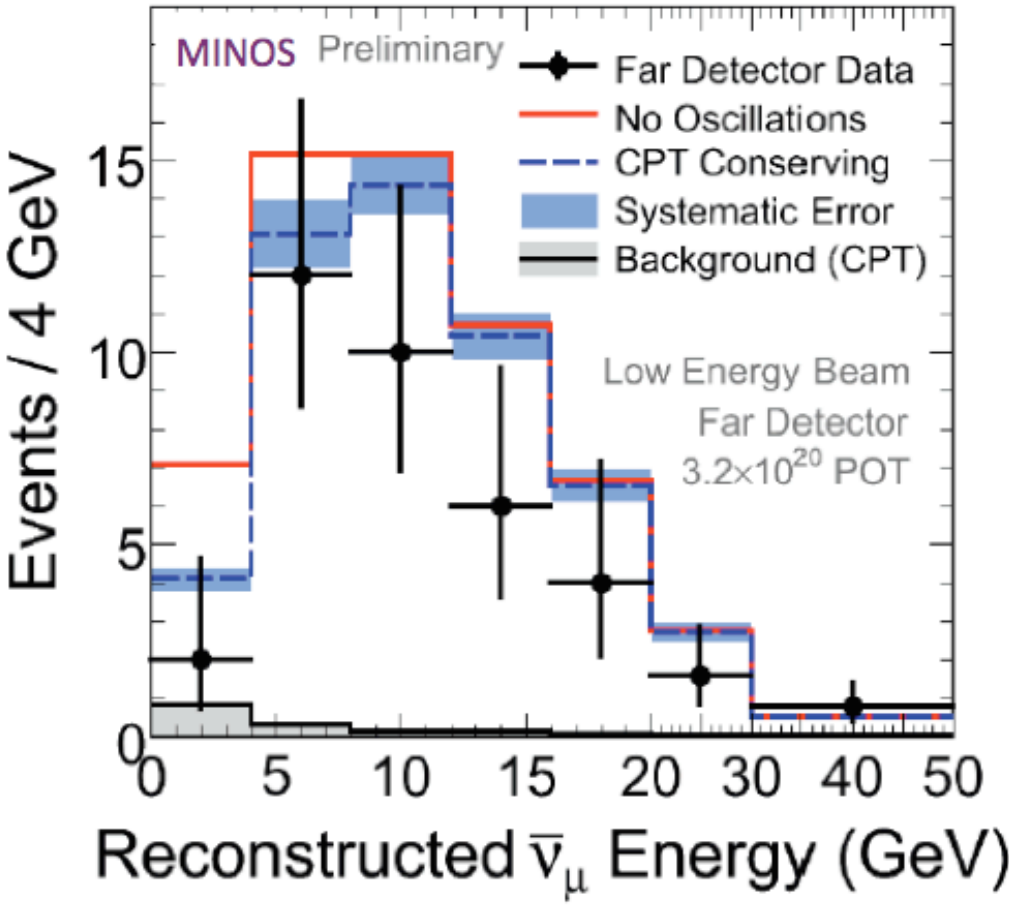
- The Super-Kamiokande atmospheric dataset now has more than 28‘000 events.
- The standard two-flavor analyses, zenith angle and L/E, are very efficient to measure the atmospheric oscillation parameters.
- The solar term analysis is a way to measure the octant degeneracy, but no deviations from $\pi/4$ has been found so far.
- The three flavor analysis try to measure θ_{13} but the results are still consistent with zero and larger than the CHOOZ limit.

Thank you!

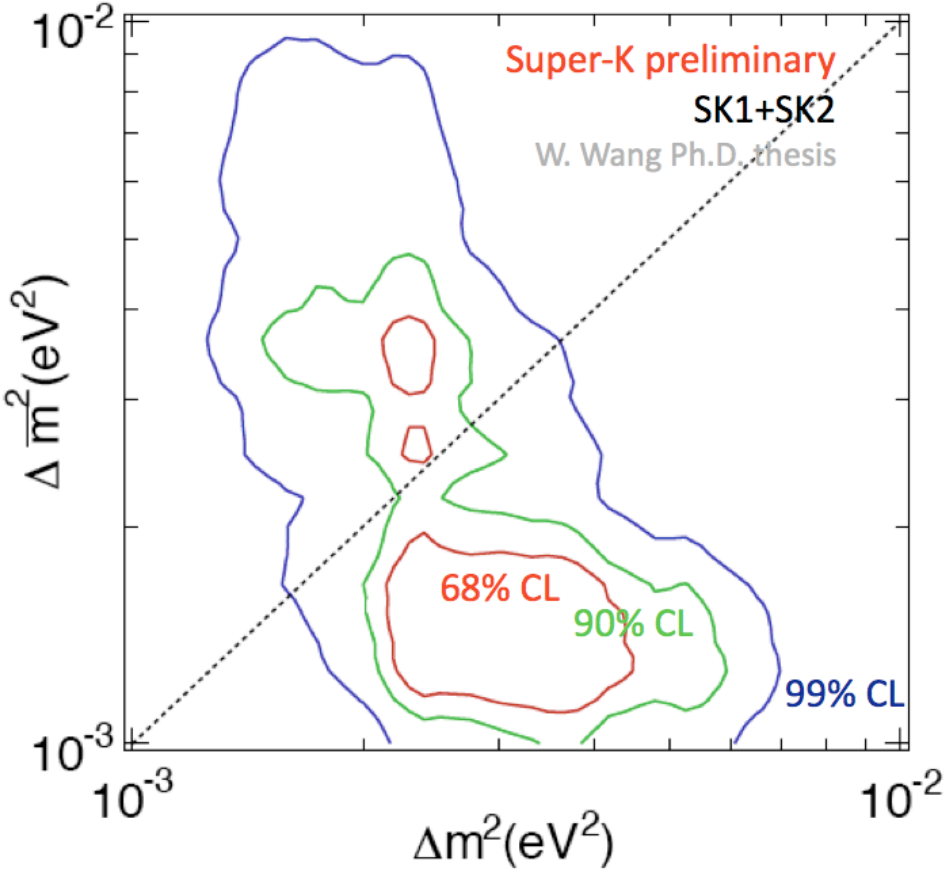
Backups

Neutrinos vs. anti-neutrinos

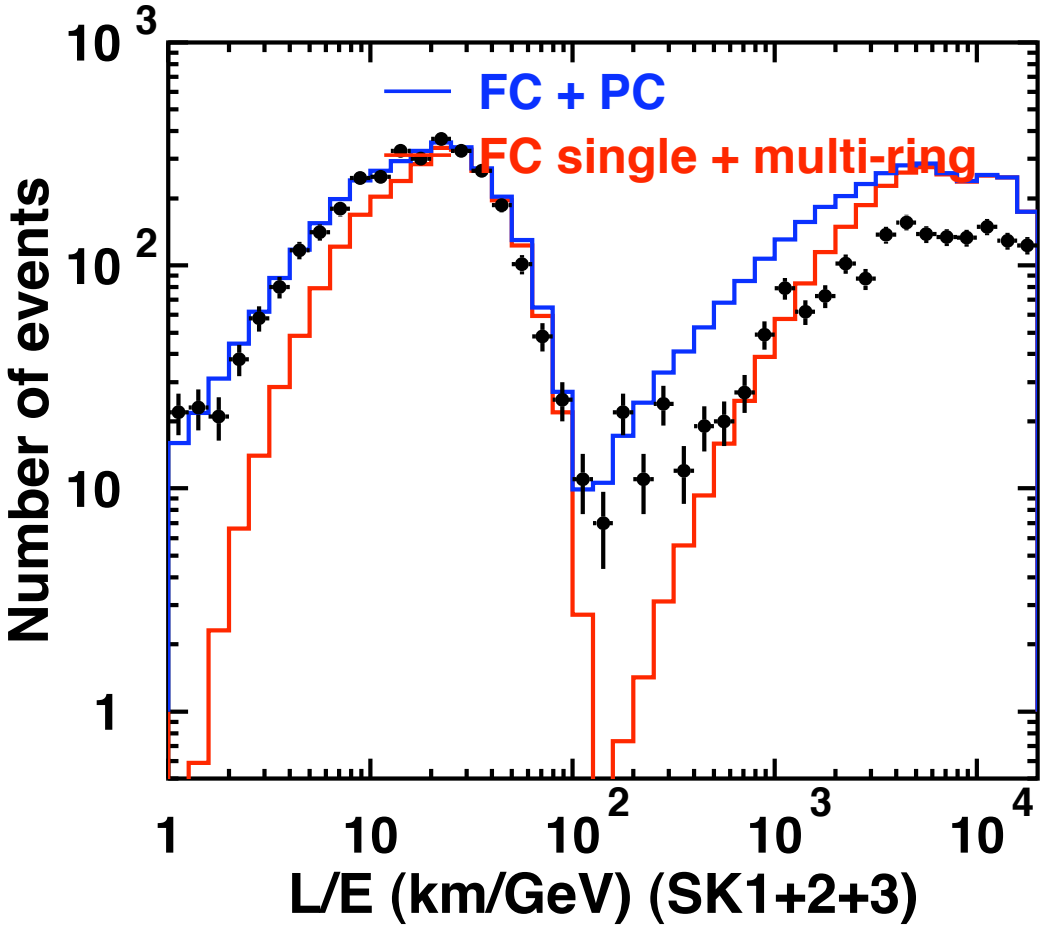
MINOS can distinguish neutrinos from anti-neutrinos on an event-by-event basis by +/-charged particle discrimination.



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?

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

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

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

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-1 + 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

Lepton non-universality

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

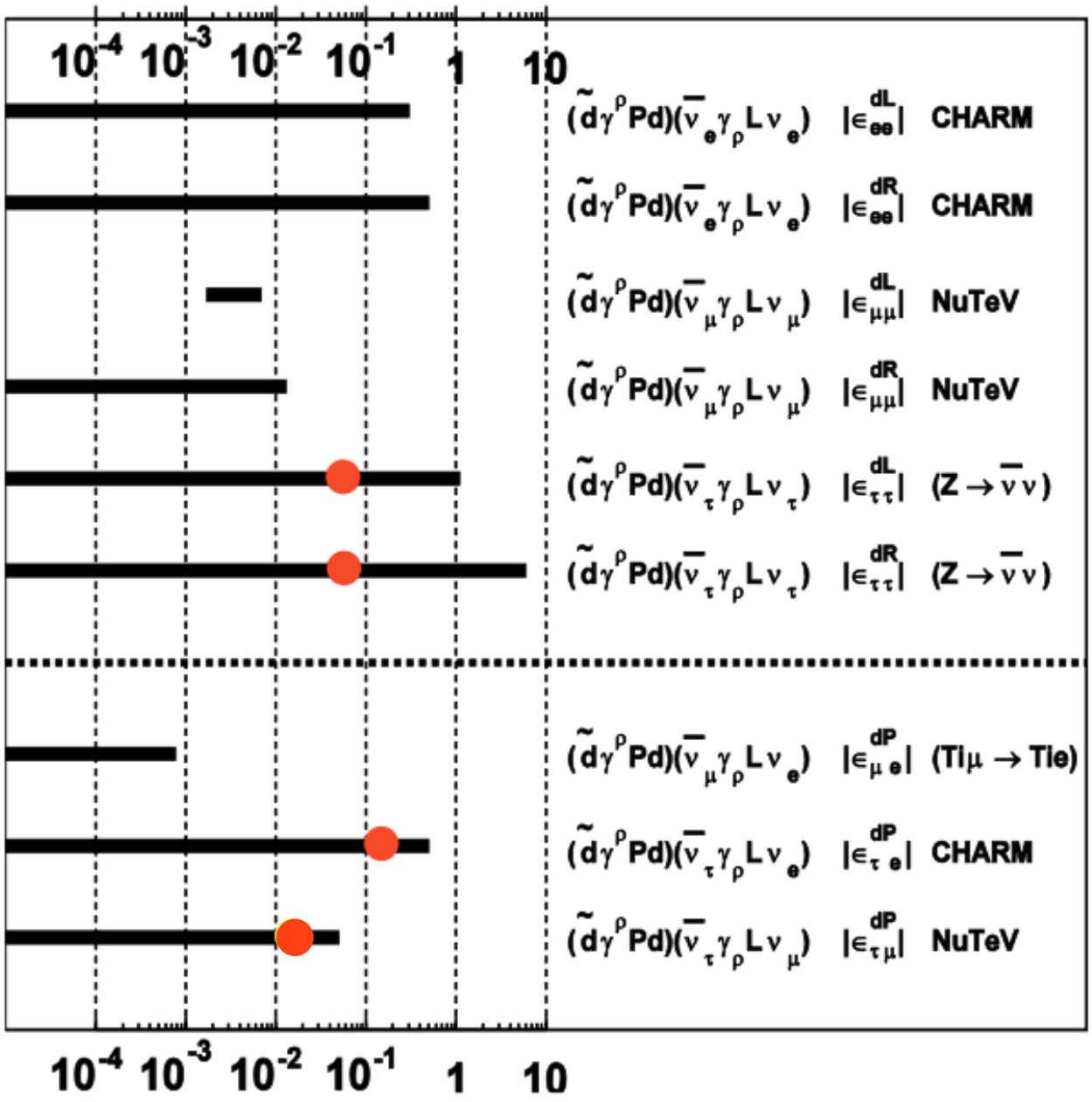
Determine best fit parameters for NSI under an oscillation + NSI hypothesis

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

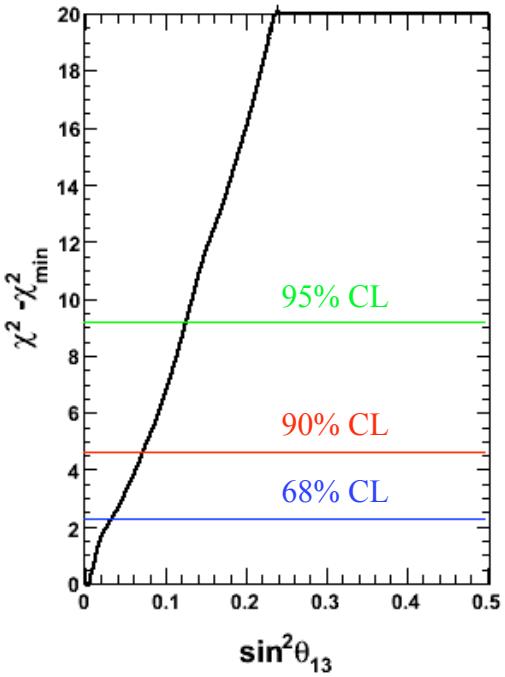


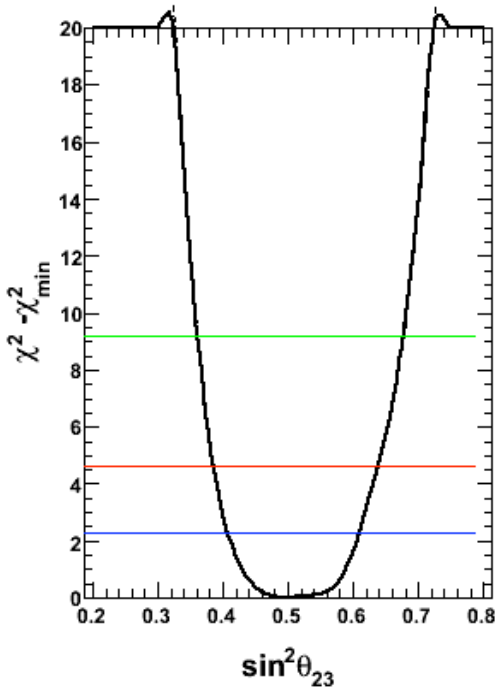
SK-1+2 limit (90% CL)

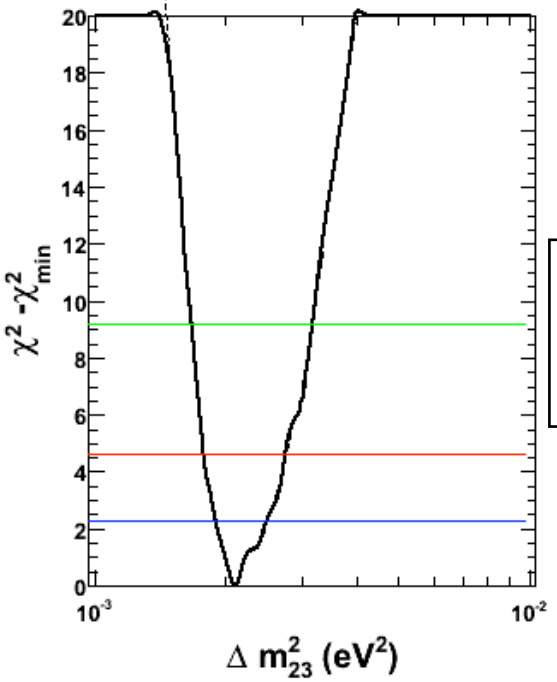
Lepton Non-Universality

Flavor Changing
Neutral Currents

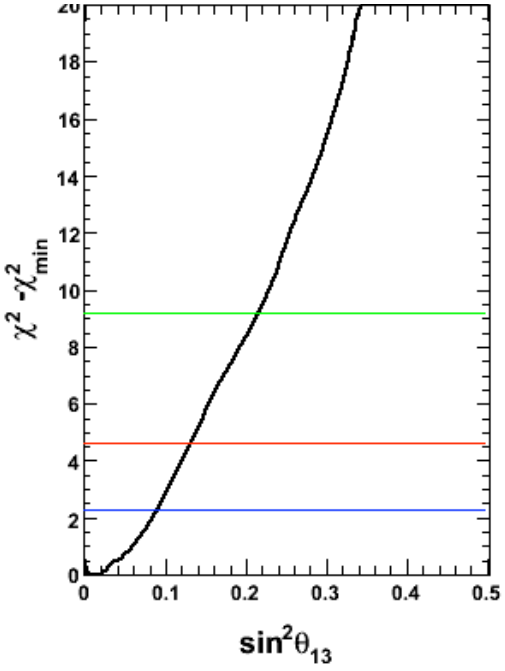
Three-flavor results

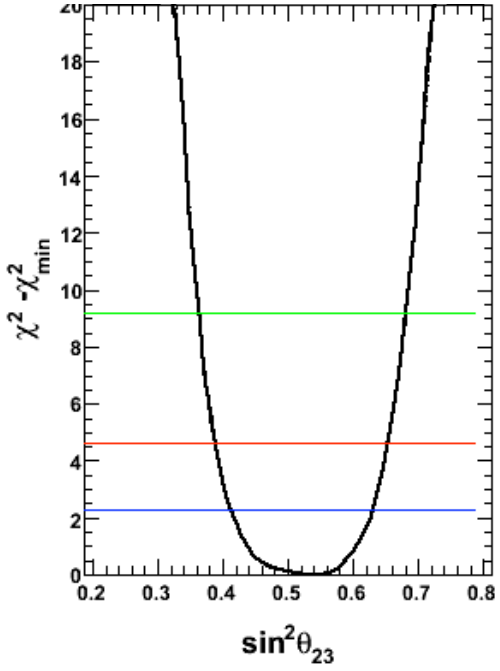


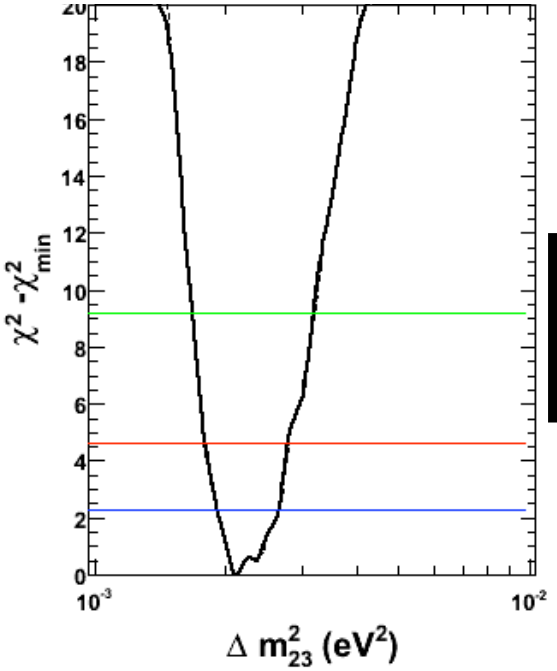




Normal Hierarchy







Inverted Hierarchy

CHAVROB