Super Kamiokande atmospheric & solar neutrinos

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ICRR

for Super-Kamiokande collaboration

Contents

Recent results of neutrino oscillation analysis

- Atmospheric Neutrinos

  $\nu_\mu \leftrightarrow \nu_\tau$ 2 flavor oscillations from

  I. Zenith angle analysis

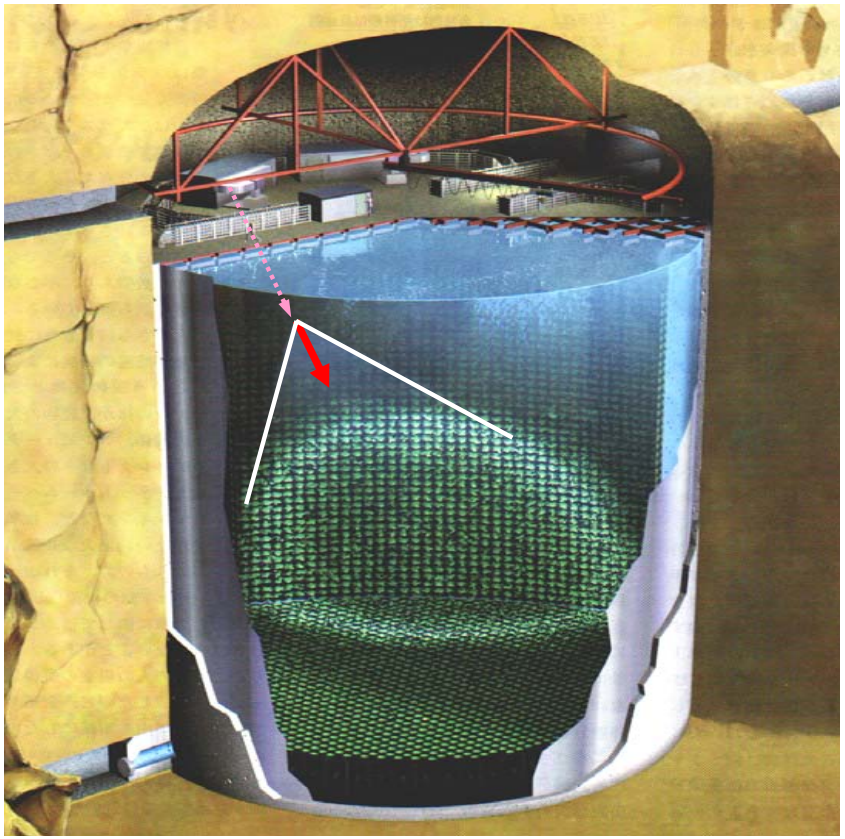
  II. L/E analysis

- Solar Neutrinos

  Results from SK un-binned maximum likelihood method

  Combined result with all solar + KamLAND experiments

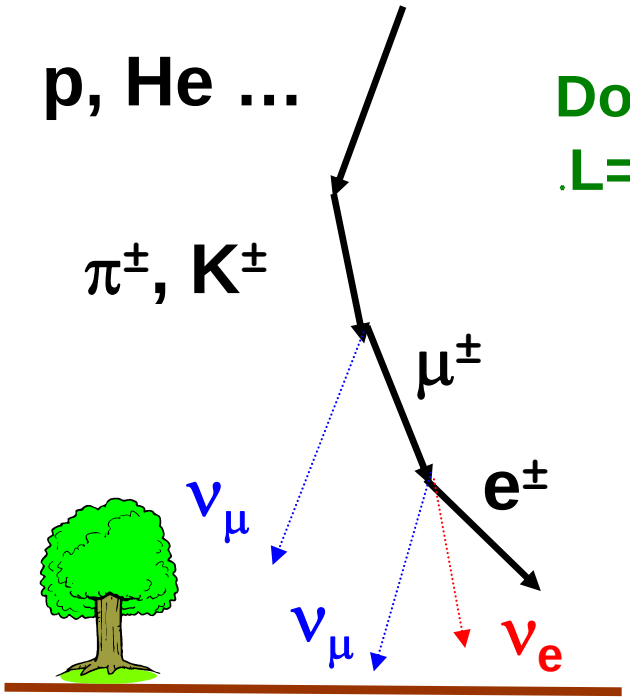
Super-Kamiokande-I detector



Water Cherenkov detector

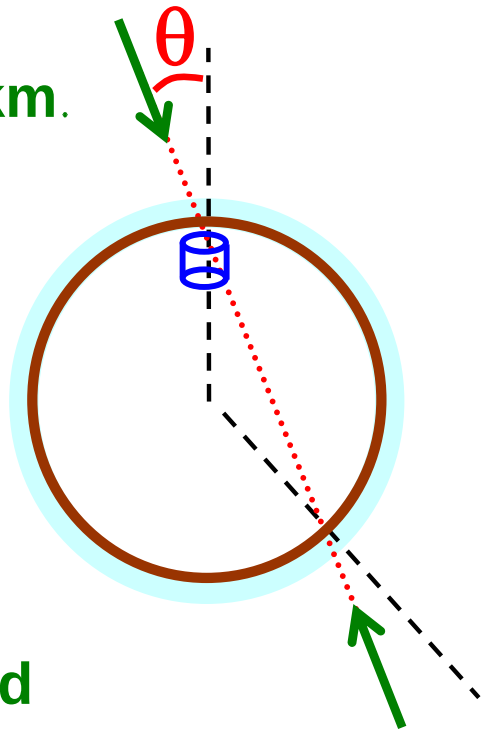
- 1000 m underground
  (2700 m of water equivalent)
- 50,000 ton of pure water
- 2 concentric cylindrical region
- 11,146 20 inch PMTs
  (40% photocathode coverage)
- 1,885 anti-counter PMTs

Atmospheric neutrinos



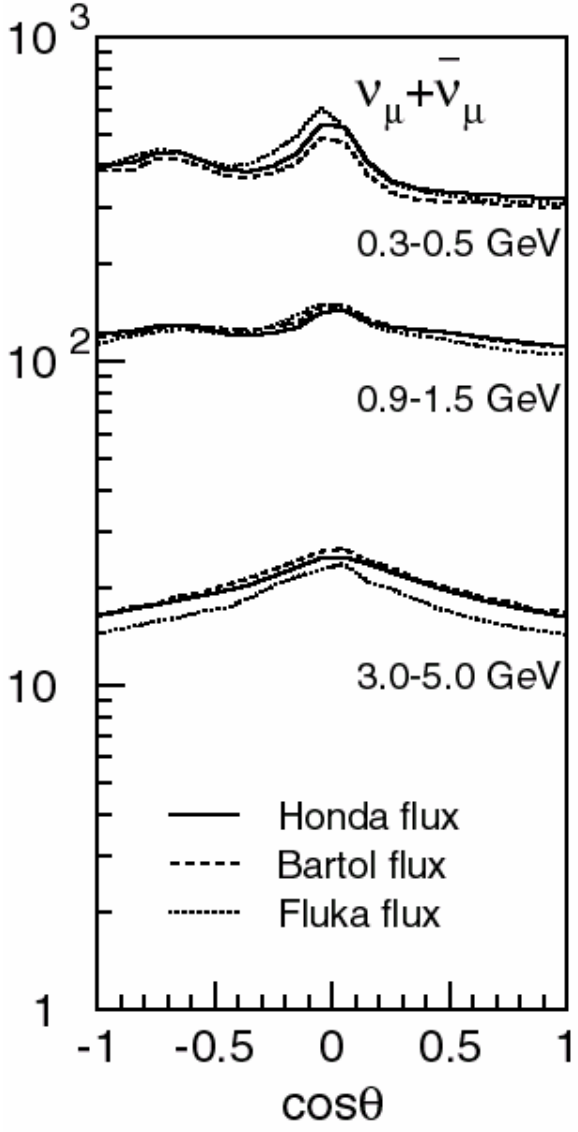
Zenith angle

Downward
.L=10~100 km.



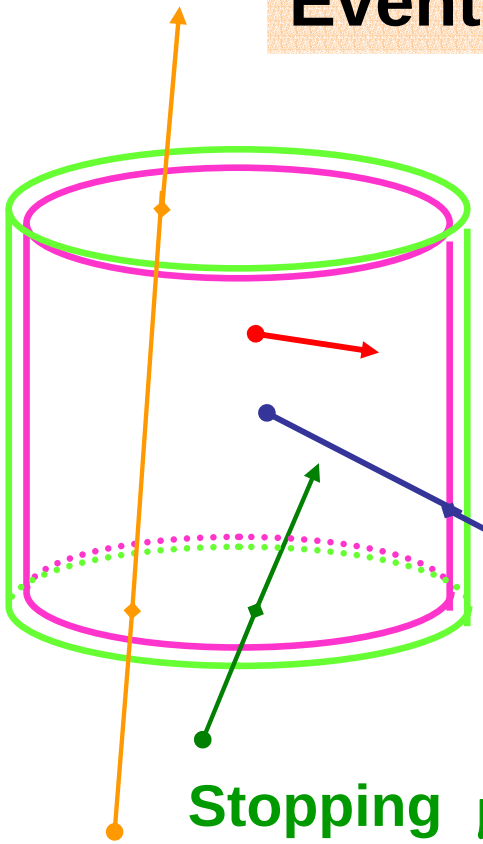
Upward
.L=up to 13000 km.

Up/Down Symmetry



Atmospheric neutrinos in SK

Event classification

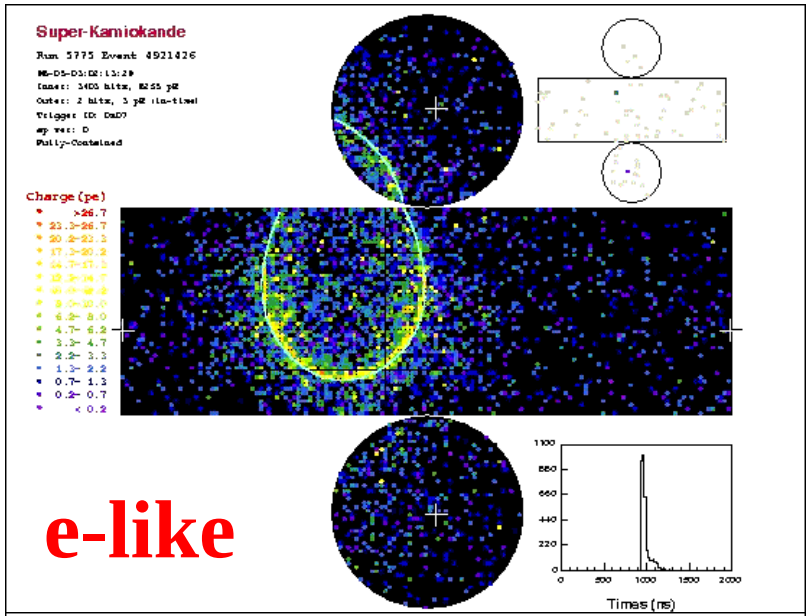


Fully Contained
(E_ν ~1GeV)

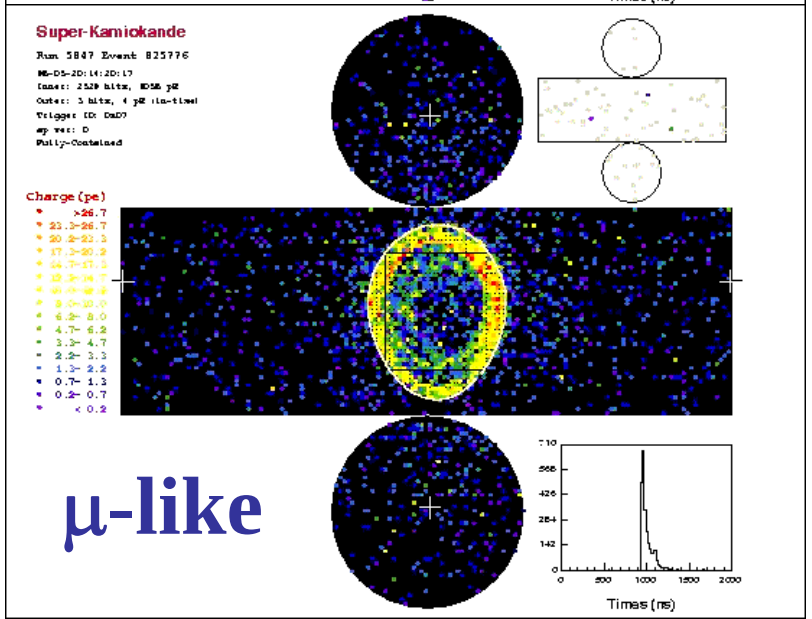
Partially Contained
(E_ν ~10GeV)

Stopping μ (E_ν ~10GeV)

Through-going μ (E_ν ~100GeV)



e-like



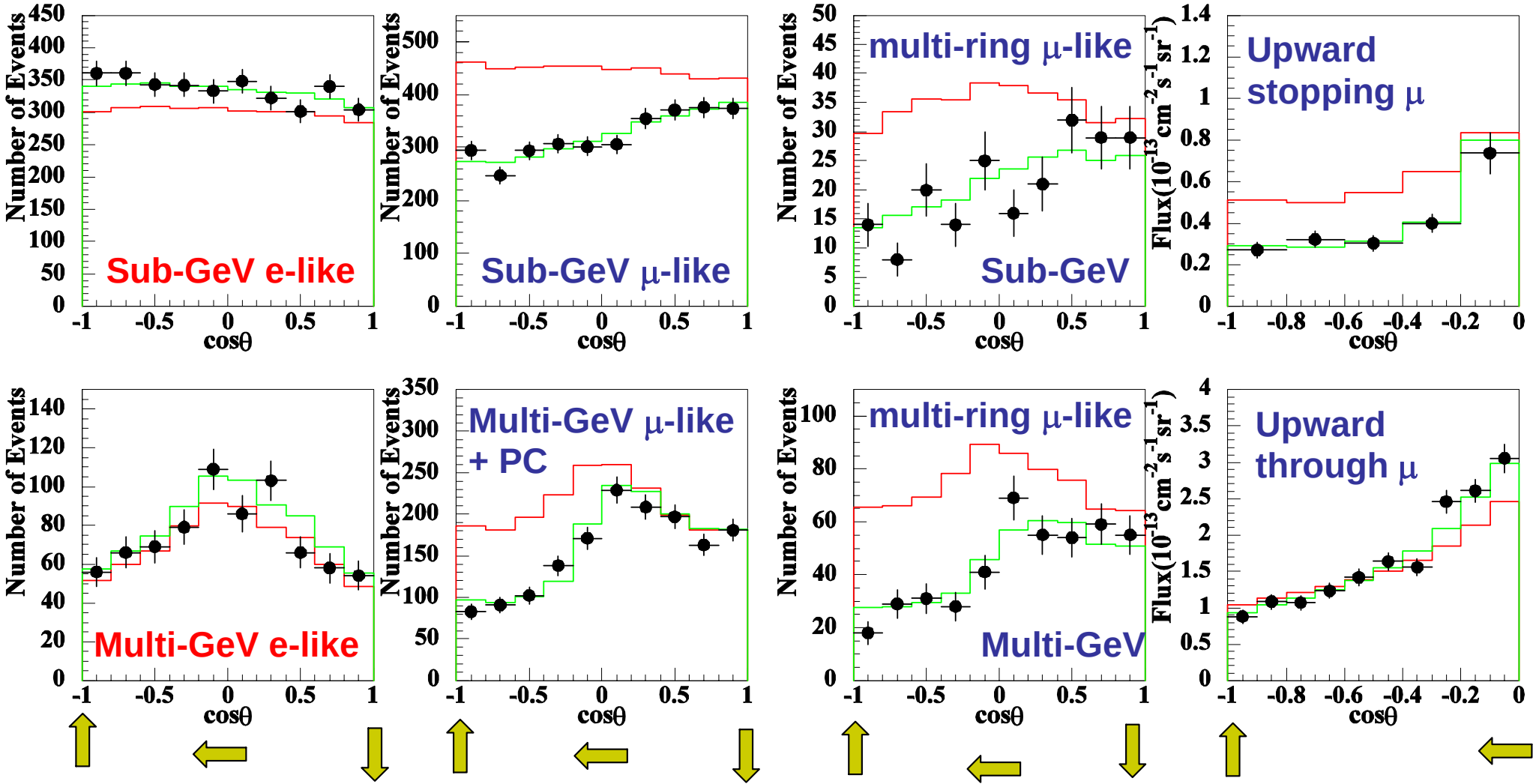
μ-like

Zenith angle distributions

$\nu_\mu \leftrightarrow \nu_\tau$
2-flavor oscillations

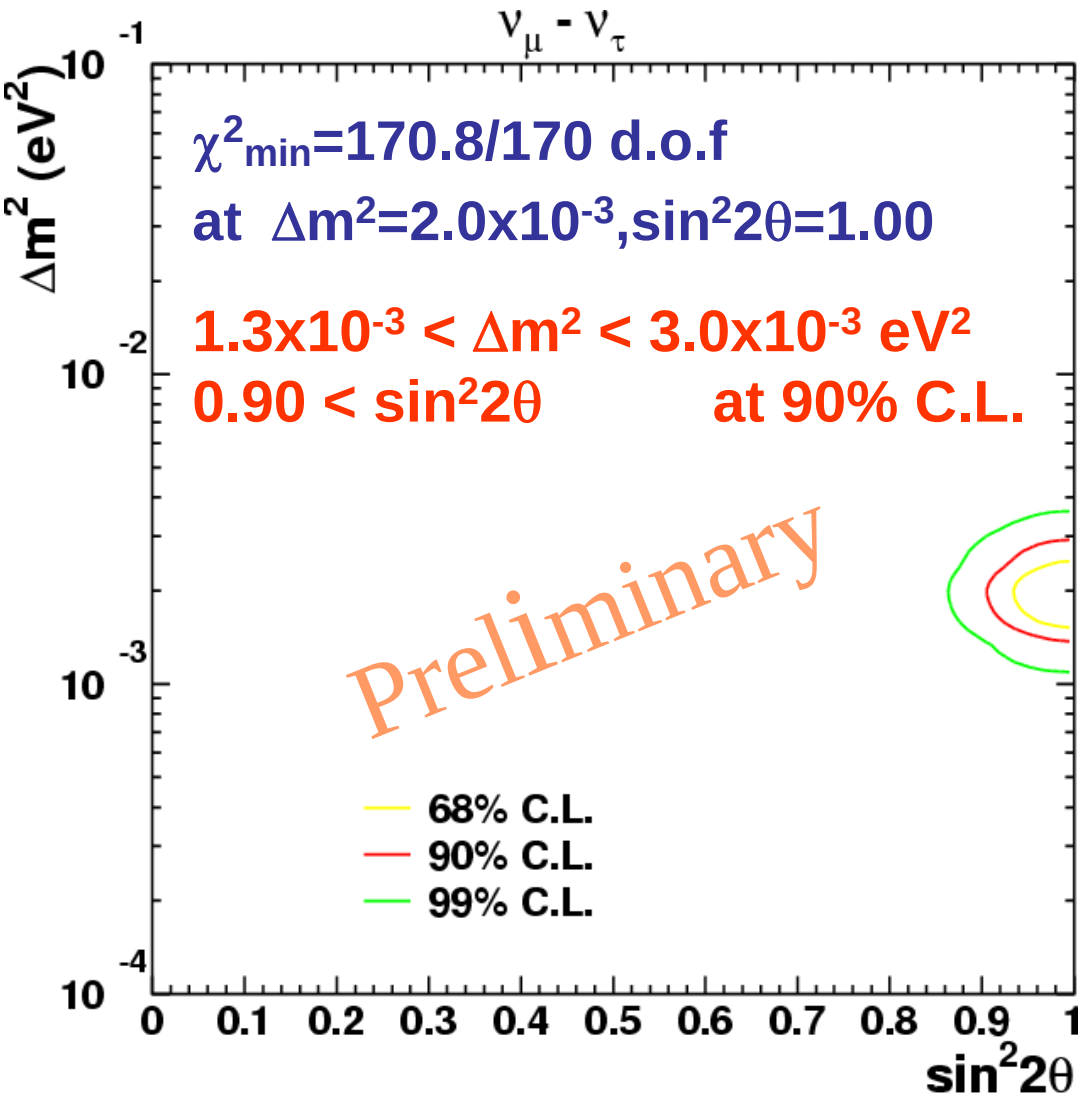
Null oscillation

Best fit: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.0 \times 10^{-3}$ eV^2



Allowed oscillation parameters region

FC+PC+up-μ zenith angle analysis



Fof SK-I final result …

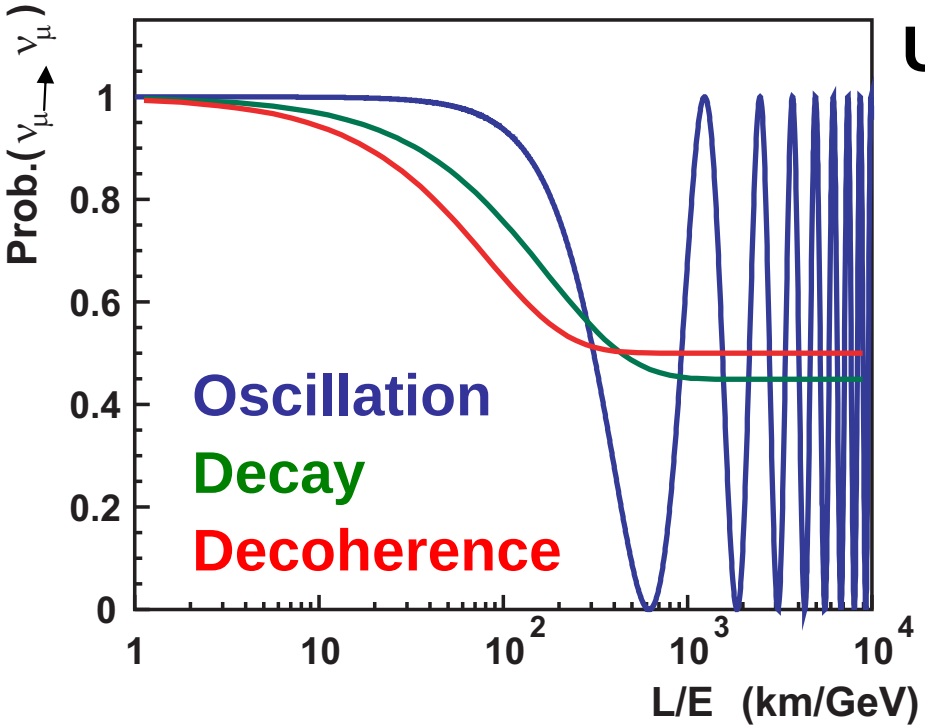
Improvements of systematic errors

L/E analysis

Neutrino oscillation : $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$

Neutrino decay : $P_{\mu\mu} = \left(\cos^2\theta + \sin^2\theta \times \exp\left(-\frac{m}{2\tau}\frac{L}{E}\right)\right)^2$

Neutrino decoherence : $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times \left(1 - \exp\left(-\gamma_0 \frac{L}{E}\right)\right)$



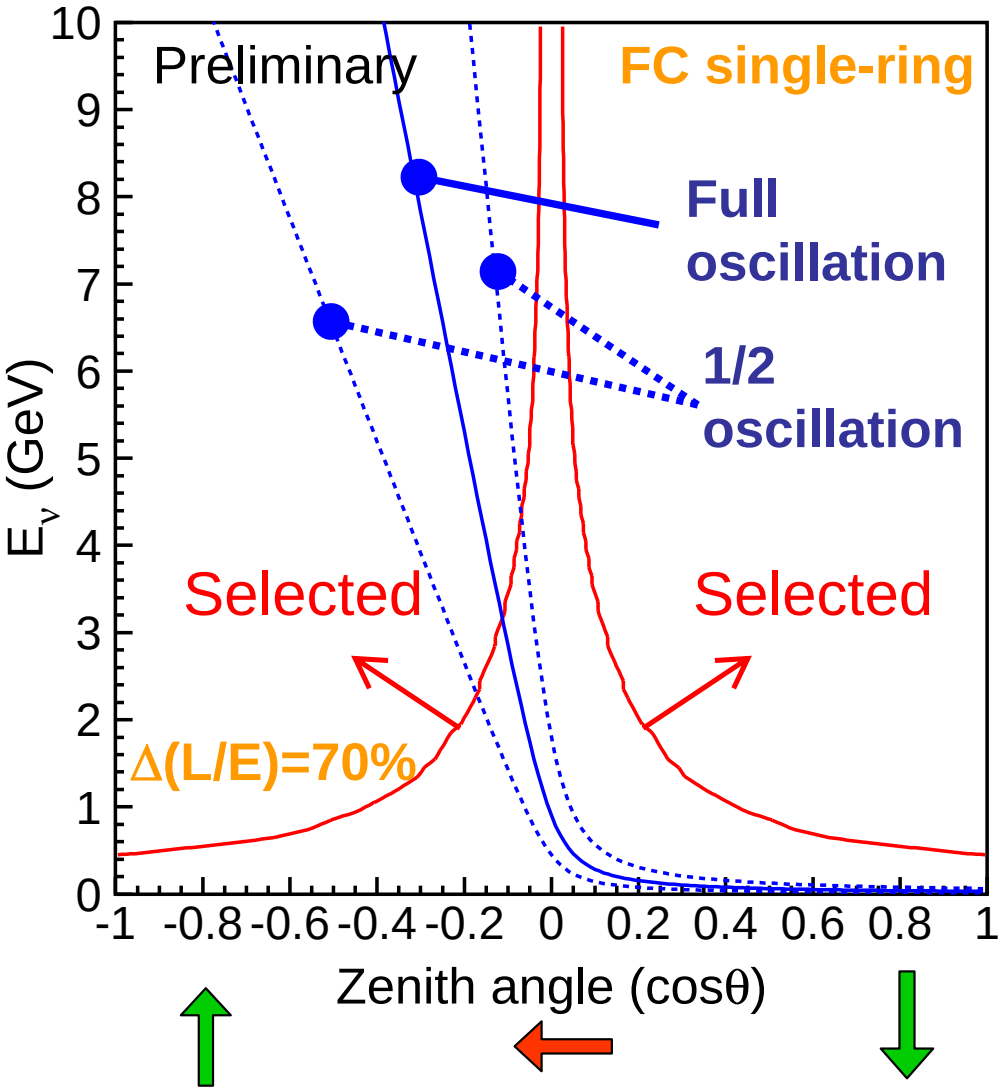
Use events with high resolution in L/E

→ **The first dip can be observed**

→ Direct evidence for oscillations

→ Strong constraint to oscillation parameters, especially Δm^2 value

L/E resolution cut



Select events with high resolution in L/E

Bad L/E resolution for

horizontally going events
→ due to large dL/dcosθ

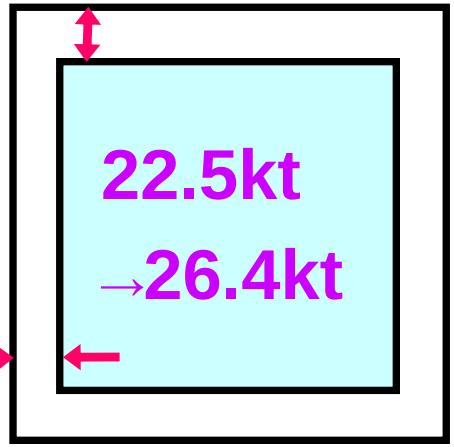
low energy events
→ due to large scattering angle

Event samples in L/E analysis

FC single-ring, multi-ring μ-like

1.5m from top & bottom

1m from barrel



Expand fiducial volume

→ More statistics for high energy muons

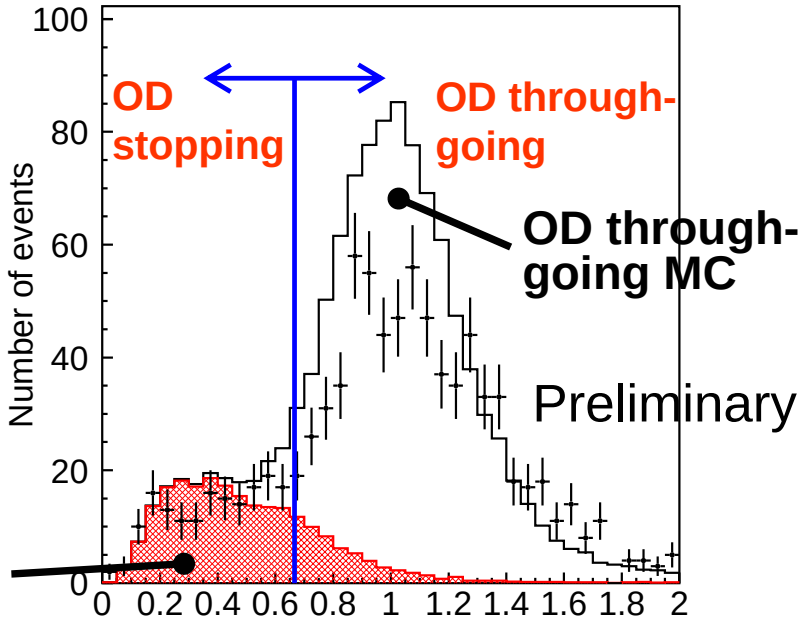
PC

Classify PC events using OD charge

I. **OD stopping**
II. **OD through going**

→ Different L/E resolution

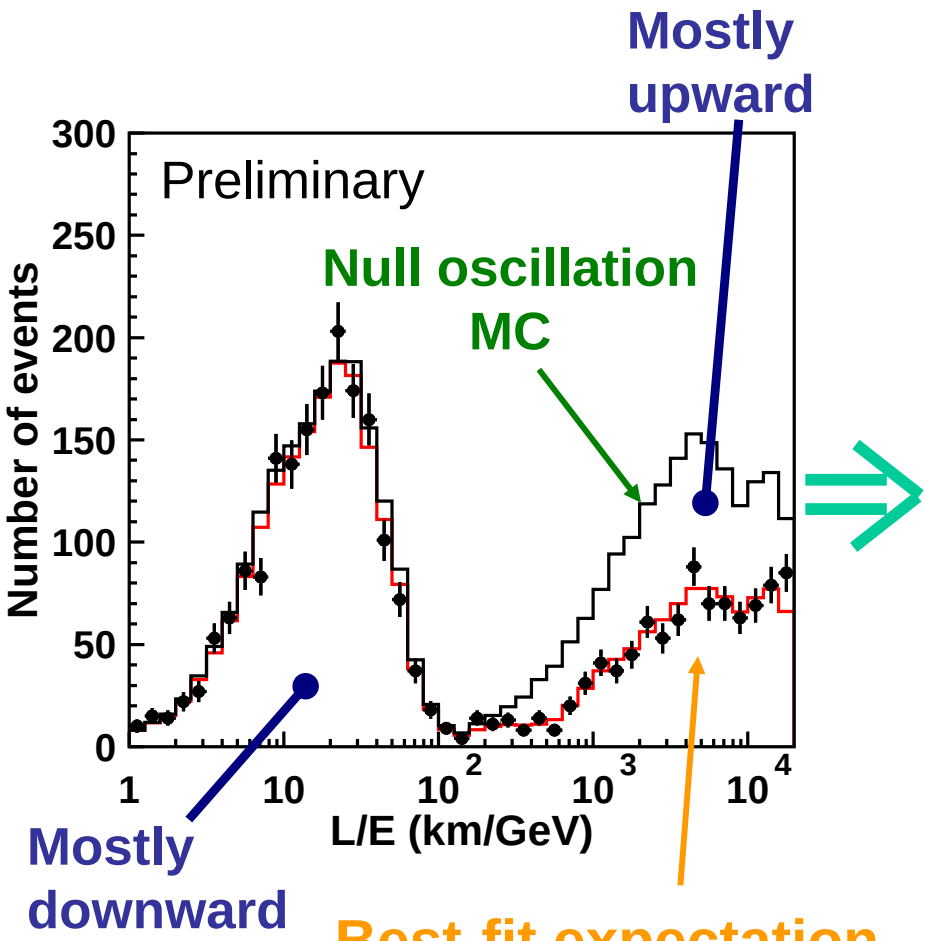
observed charge / expectation from through-going



Event summary of L/E analysis

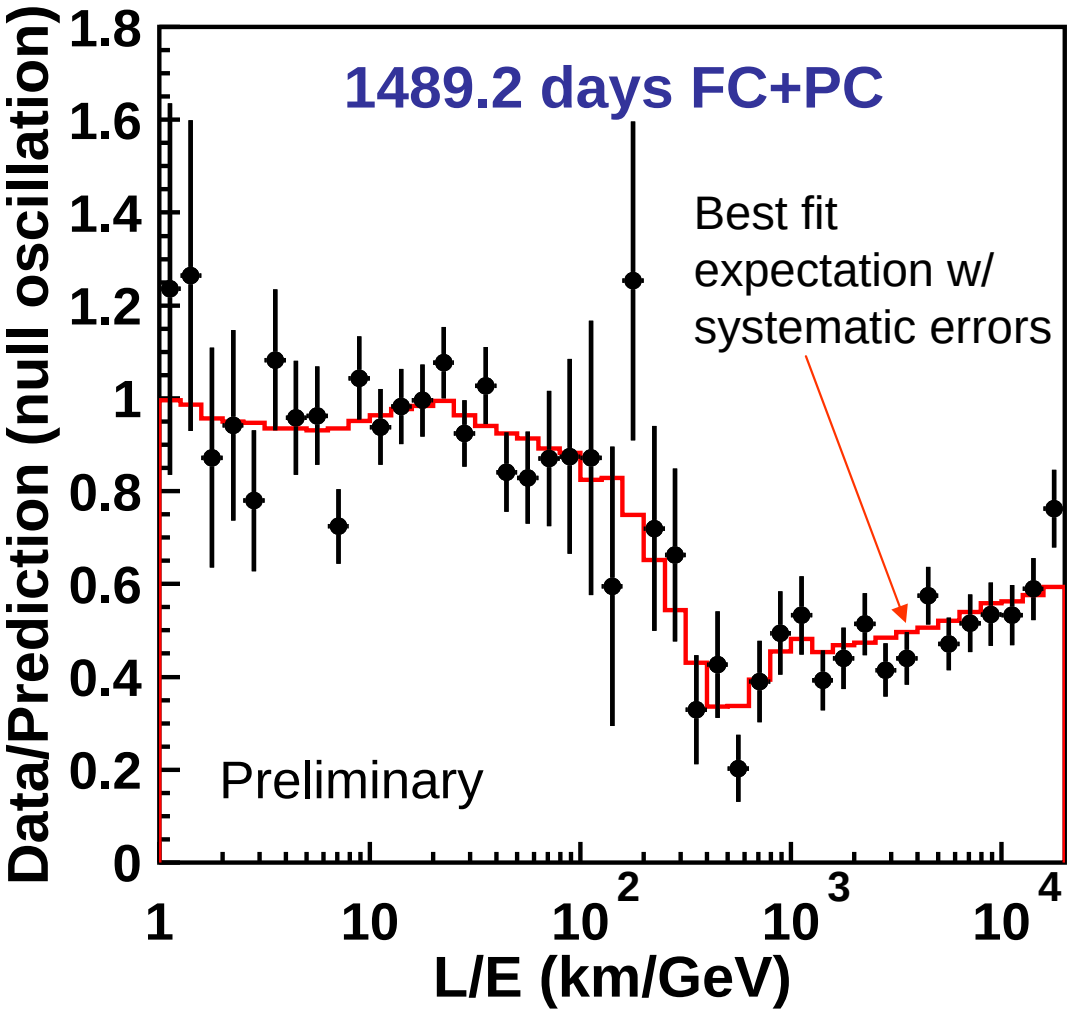
FC	Data	MC	CC ν_μ
single-ring μ-like	1619	2105.6	(98.3%)
multi-ring μ-like	502	813.0	(94.2%)
PC			
stopping	114	137.0	(95.4%)
through-going	491	670.1	(99.2%)
Total	2726	3725.7	

L/E in atmospheric neutrino data



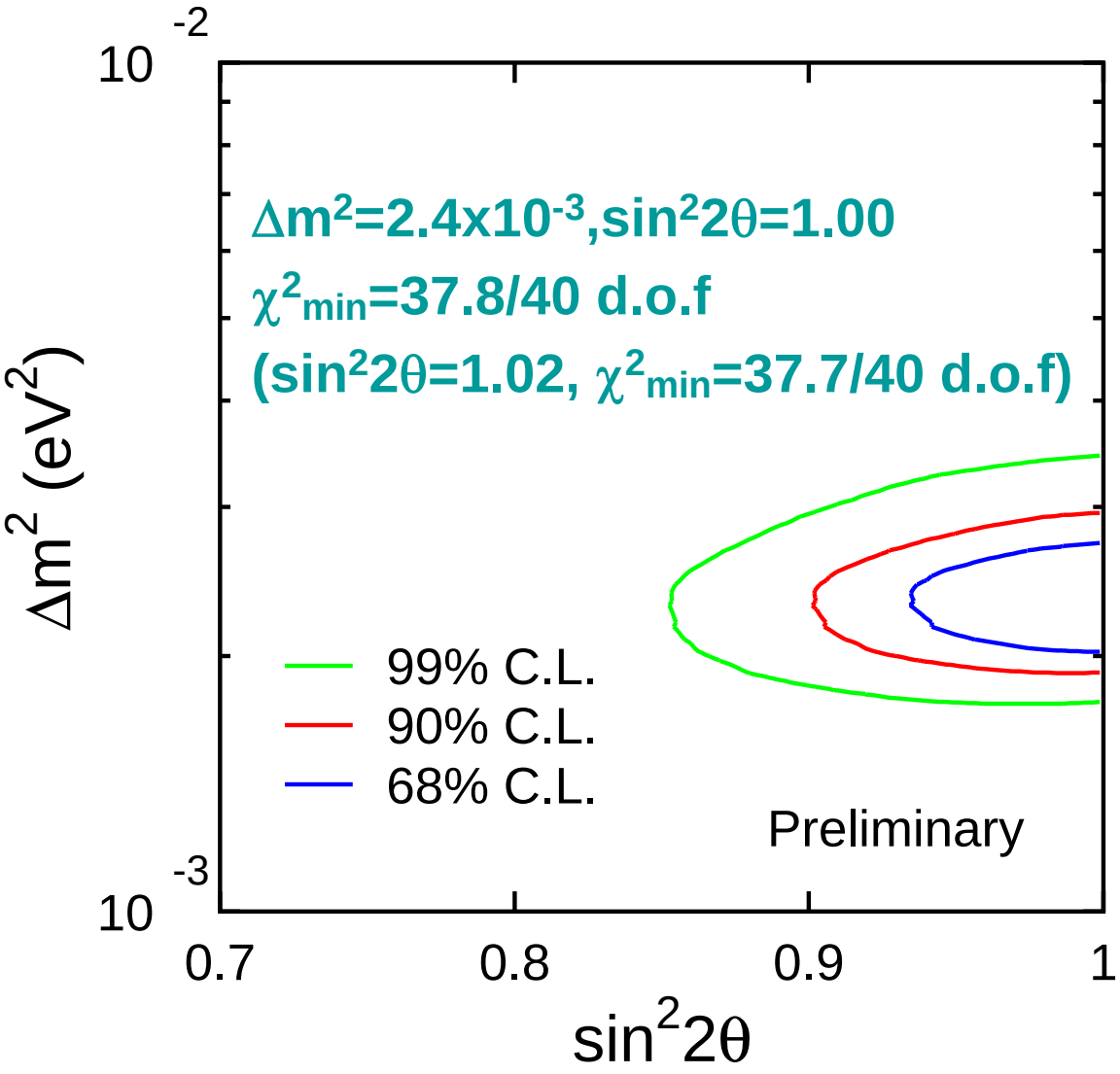
$\Delta m^2=2.4\times10^{-3}, \sin^2 2\theta=1.00$

$\chi^2_{min}=37.8/40$ d.o.f



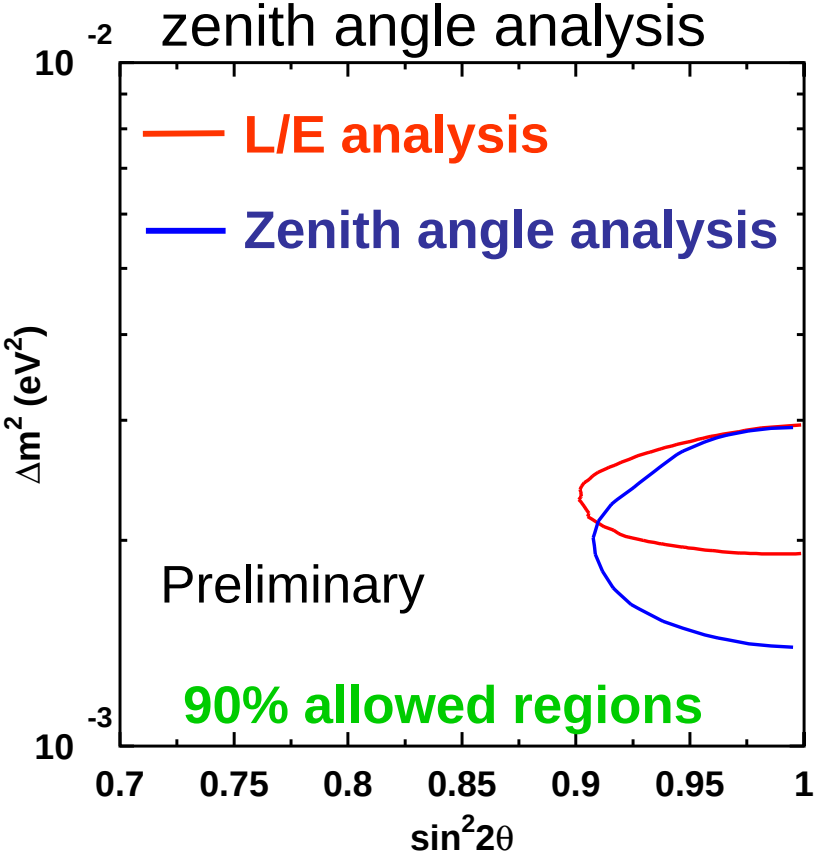
First dip is observed as expected from neutrino oscillation

Constraint to neutrino oscillation parameters

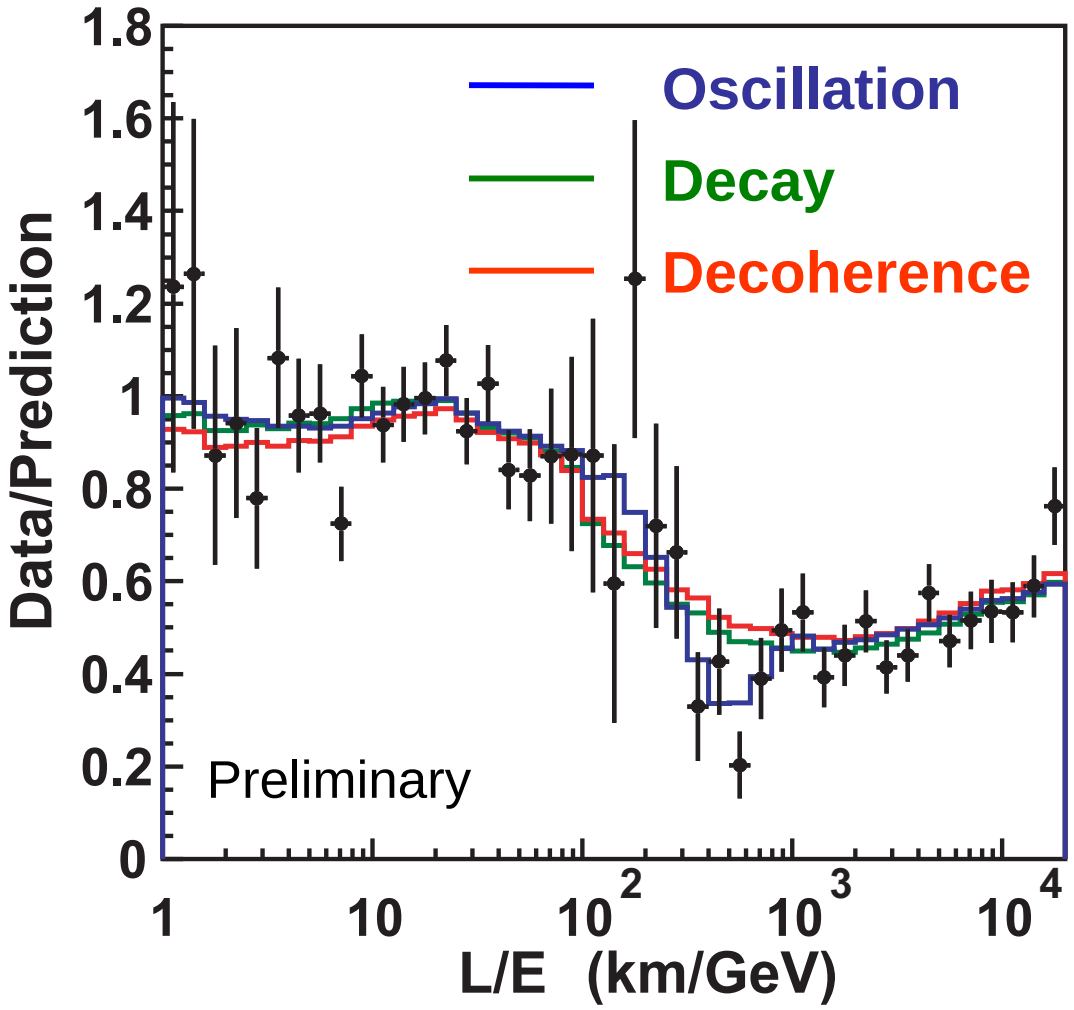


$1.9\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}$ eV^2
$0.90 < \sin^2 2\theta$ at 90% C.L.

Consistent with standard zenith angle analysis



Tests for neutrino decay & decoherence



χ^2_{min}=37.8/40 d.o.f

χ^2_{min}=49.2/40 d.o.f → $\Delta\chi^2$ =11.4

χ^2_{min}=52.4/40 d.o.f → $\Delta\chi^2$ =14.6

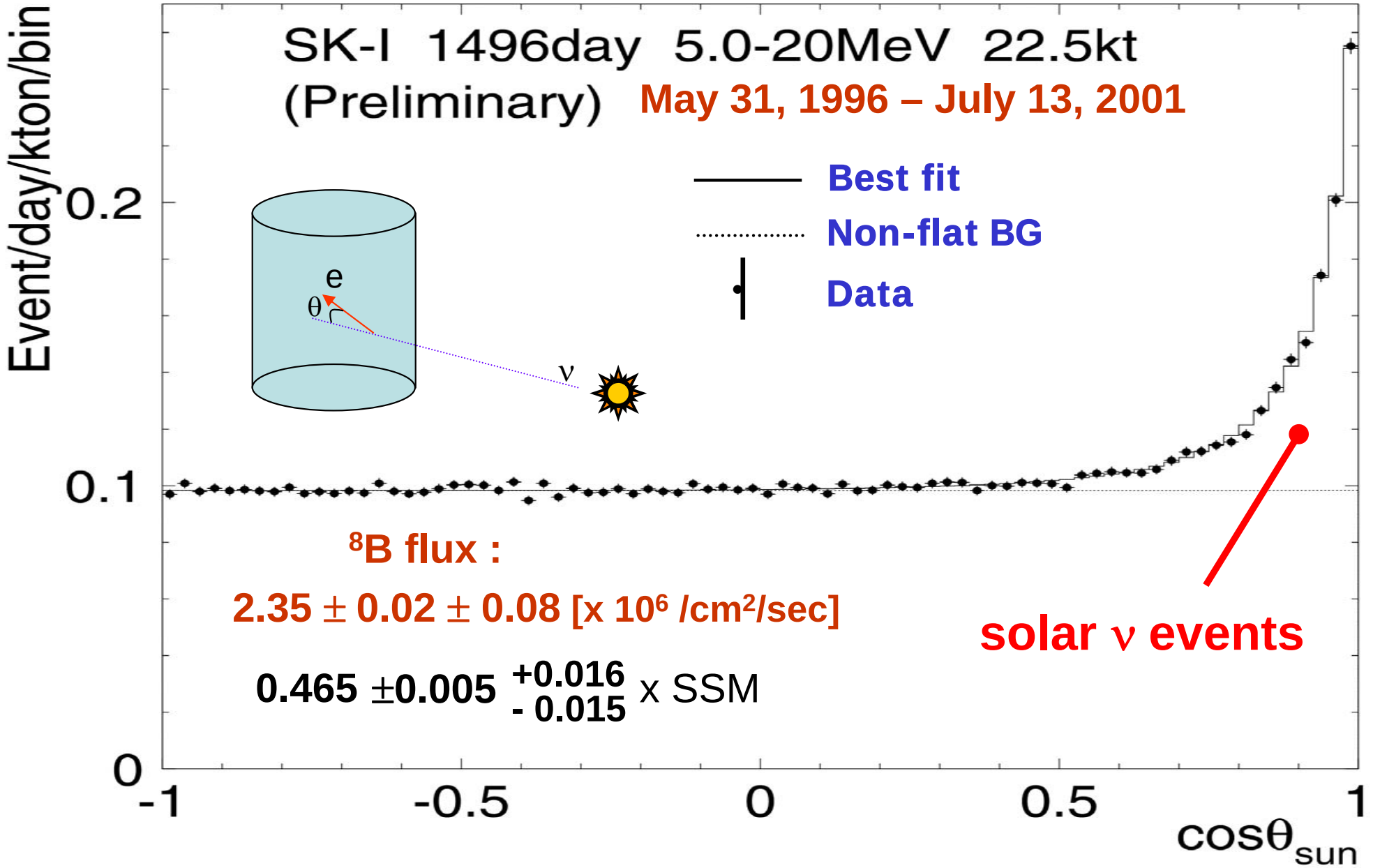
3.4 σ to ν decay

3.8 σ to ν decoherence

First dip observed in data cannot be explained by alternative hypotheses

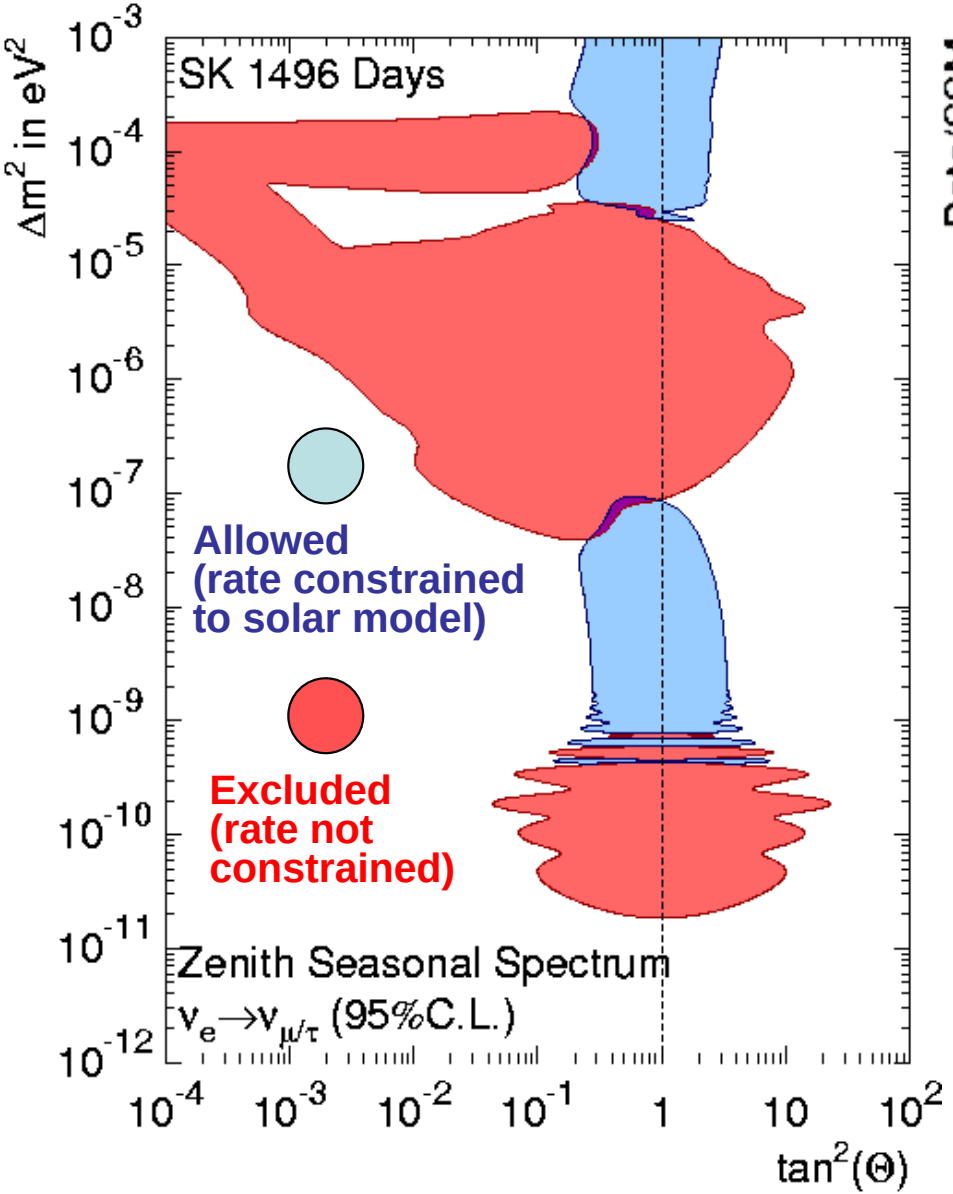
First evidence that neutrino transition probability obeys sinusoidal function as predicted in neutrino oscillation

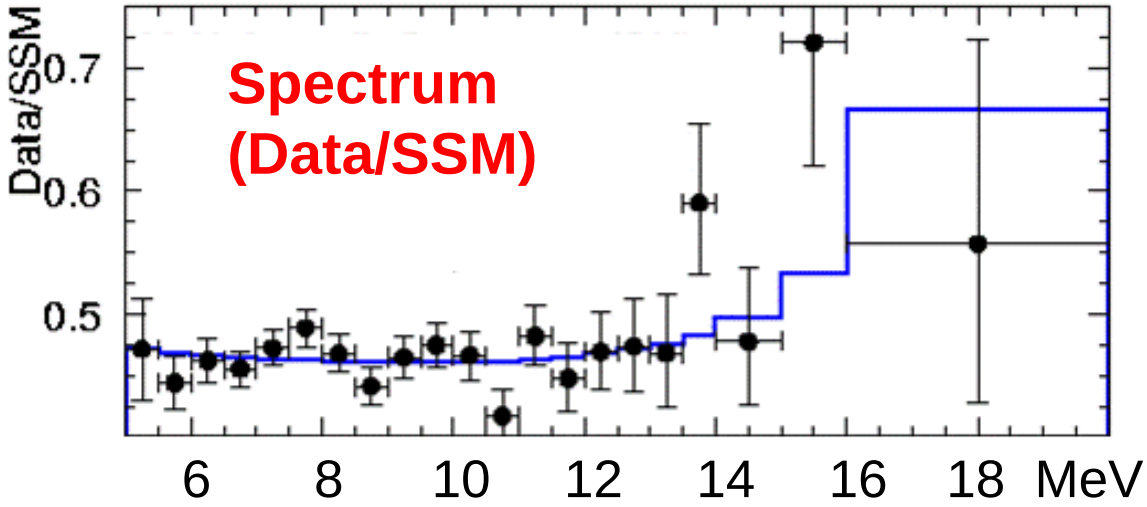
Solar neutrinos in SK

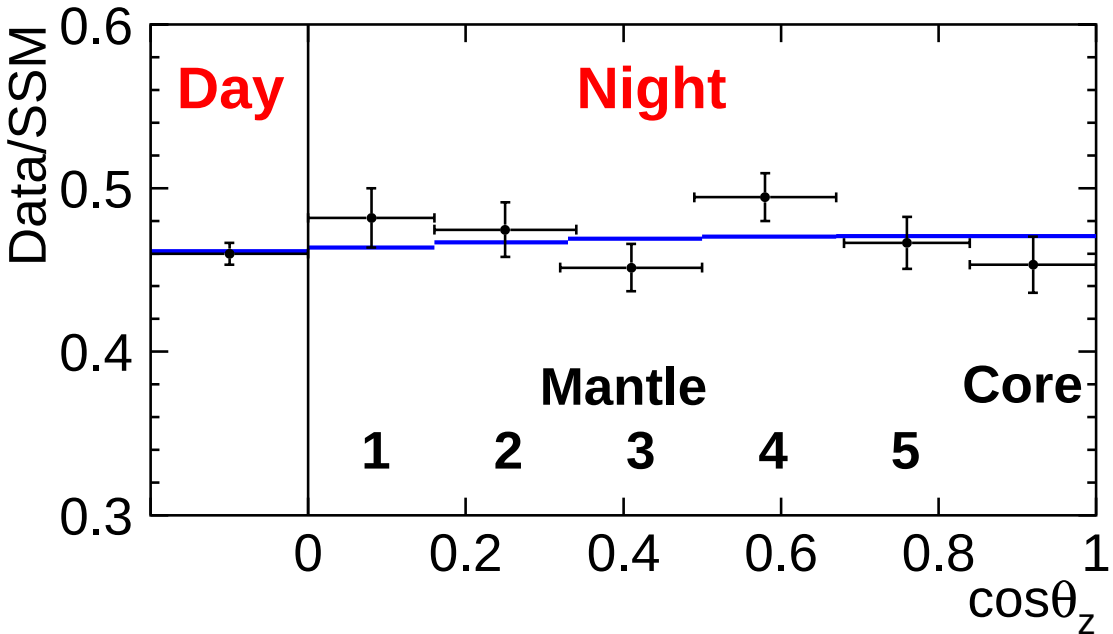


Constraints from SK solar ν

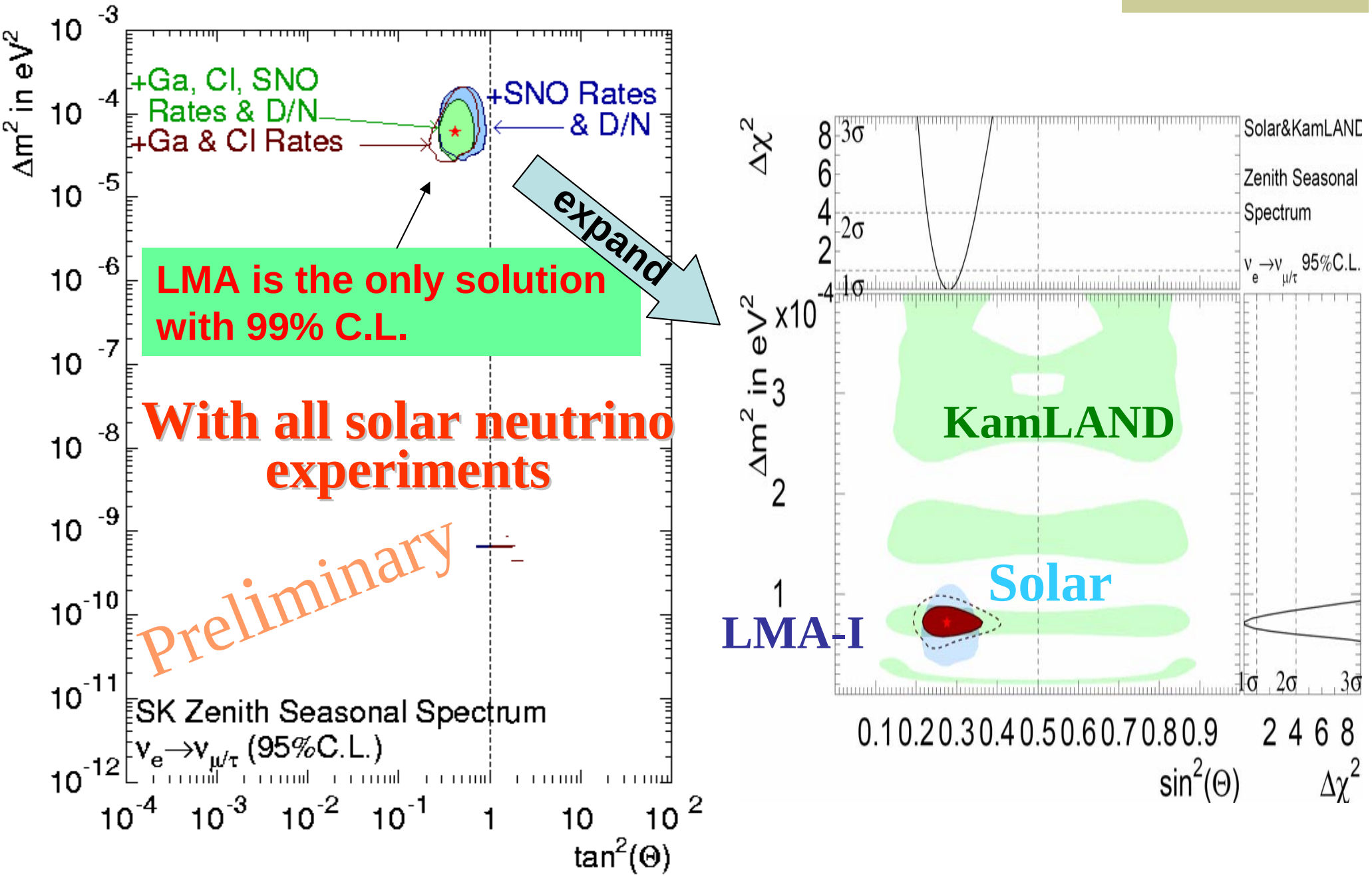
Un-binned maximum likelihood method (with time variation)







Combined oscillation fits with other experiments



Conclusions (1)

- Atmospheric neutrino oscillation studies :

  Zenith angle analysis

  – $1.3\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}$ eV^2, $0.90 < \sin^2 2\theta$ at 90% C.L.

  – SK-I final result will be published with improved systematic errors

  L/E analysis

  – First dip was observed as expected from neutrino oscillation

  → cannot be explained by alternative hypotheses
  (3.4 σ to ν decay, 3.8 σ to ν decoherence)

  – $1.9\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}$ eV^2, $0.90 < \sin^2 2\theta$ at 90% C.L.

  → consistent with zenith angle analysis

  First evidence that neutrino transition probability obeys sinusoidal function as predicted in neutrino oscillation

Conclusions (2)

- Solar neutrino oscillation studies :
  - – New analysis method (un-binned maximum likelihood method) has been installed.
  - – No day/night asymmetry nor spectrum distortion is observed in SK
  - – Only LMA-I solutions remain at 99%C.L. combined with all the solar neutrino data.