Super-Kamiokande Atmospheric Neutrino Oscillation Results

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for the Super-Kamiokande collaboration

Contents

- This talk is based on two papers
  - PRD97, 072001 (2018):

    Atmospheric neutrino oscillation analysis with external constraints in Super-Kamiokande I-IV

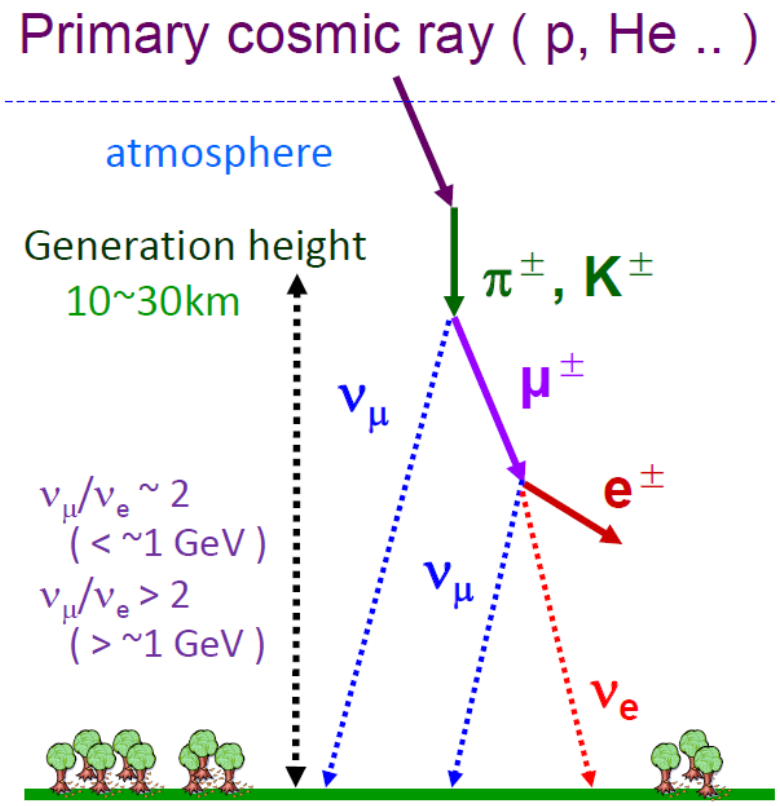
  - PRD98, 052006 (2018):

    Measurement of the tau neutrino cross section in atmospheric neutrino oscillations with Super-Kamiokand

    .. already shown on Wednesday by first author Li Zepeng

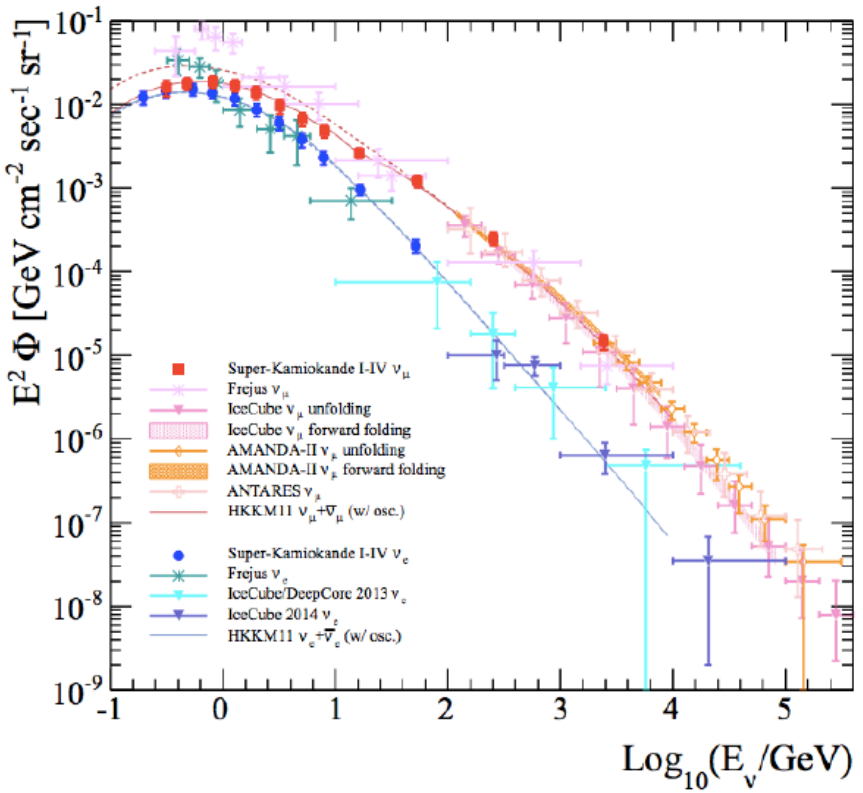
- Statistics is almost all SK 5326 days, 328 kt·yr (out of 6042 days taken so far, ~88%)

Atmospheric Neutrino



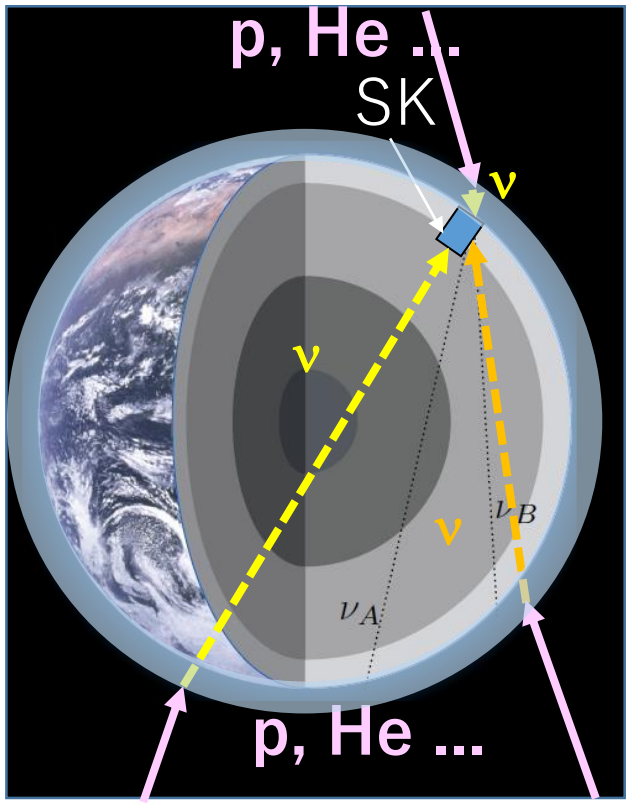
- generated in decay chain from primary
- ν_μ/ν_e ~2 in low energy, increase in high

Energy spectrum measured



- E peaked at several hundreds of MeV, extended to TeV
- good flux model is available (HKKM)

Atm. Neutrino Oscillation



- travel distance (L) expand from 10km (thickness of air) to 13,000km (diameter of earch)
- L is correlated with zenith angle observed in SK

→ possible to probe oscillation parameters in wide range of L/E

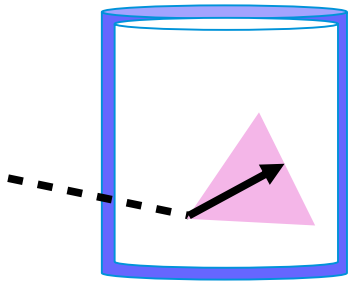
$$P(\nu_\mu \to \nu_\mu) \cong 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}(1 - \cos^2\theta_{13}\sin^2\theta_{23}) \times \sin^2\left(\frac{1.27\Delta m^2_{31}L}{E}\right) \qquad \Delta m^2_{31} \approx \Delta m^2_{32}$$

- ν_μ disappearance dominate
- due to matter effect, ν_e appearance play a role
- large statistics of SK enables us to probe ν_e appearance, and also ν_τ appearance

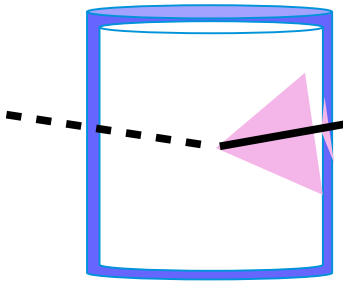
→ atmospheric neutrino sensitive to most of osc. parameters

Event Topology in SK

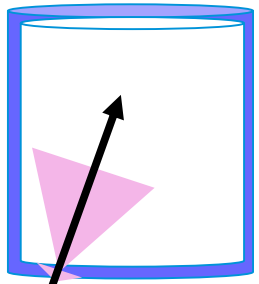
Fully Contained (FC)



Partially Contained (PC)

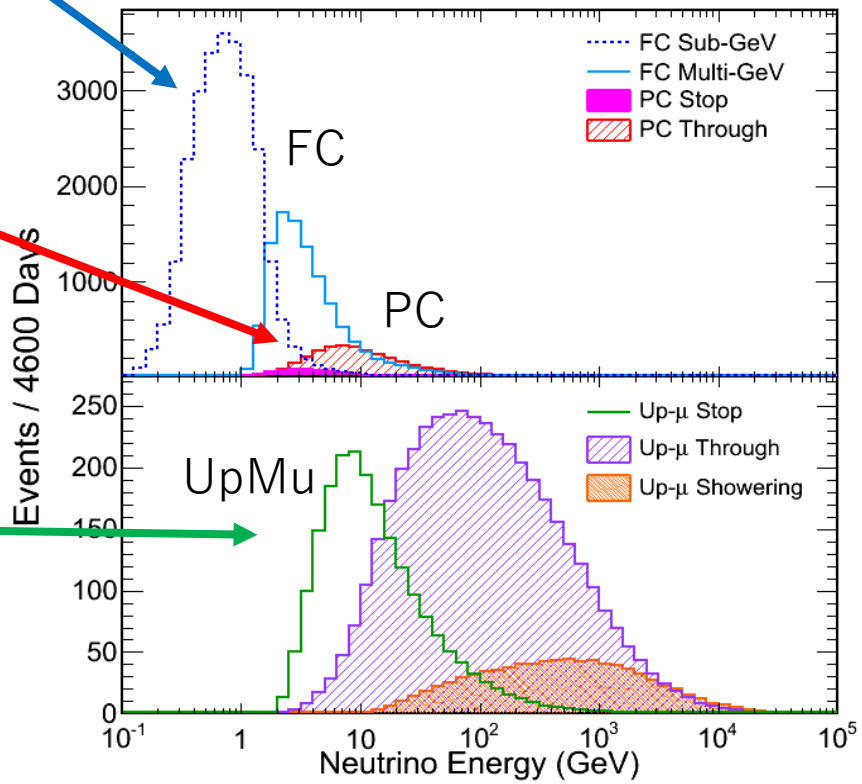


Upward-going Muons (Up-μ)



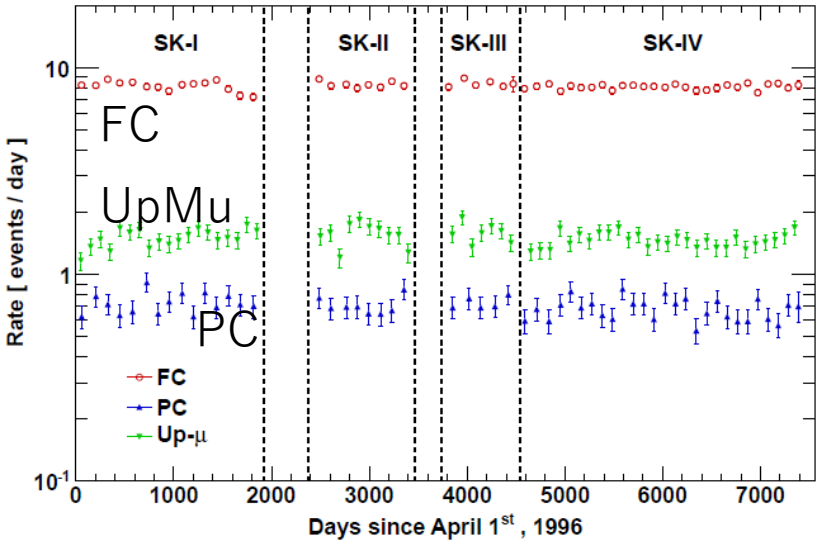
Average energies

- FC: ~ 1 GeV
- PC: ~ 10 GeV
- UpMu: ~ 100 GeV

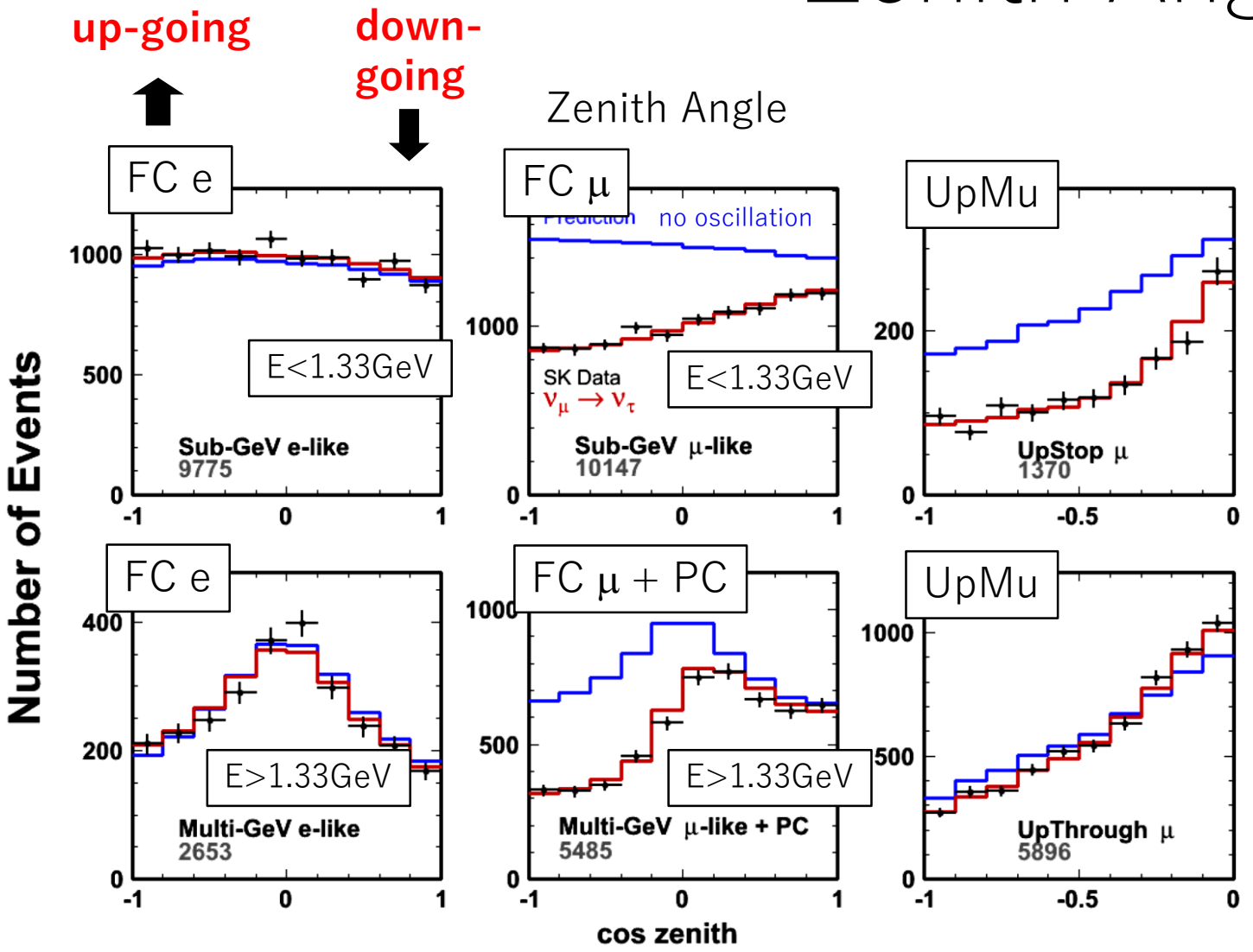


Average rates (/day)

- FC: ~ 8.3 events
- PC: ~ 0.73 events
- UpMu: ~ 1.49 events



Zenith Angle



*data is not latest in this plot

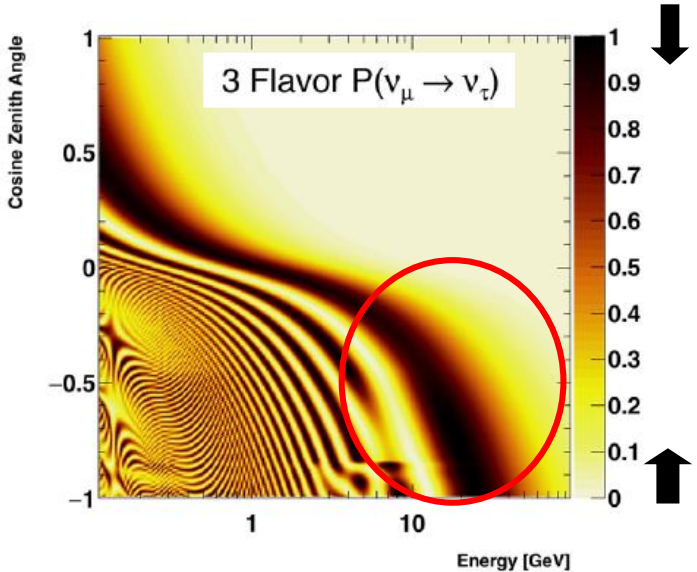
- Analysis based on zenith angle
- divided into samples
  - topology (FC, PC, UPMU)
  - energy (sub-GeV, multi-GeV)
  - flavor (e-like, mu-like)
- measurement of oscillation parameters performed by fitting these plots in bins
- dominated by ν_μ disappearance
- large statistics revealing subdominant effect (ν_e , ν_τ)

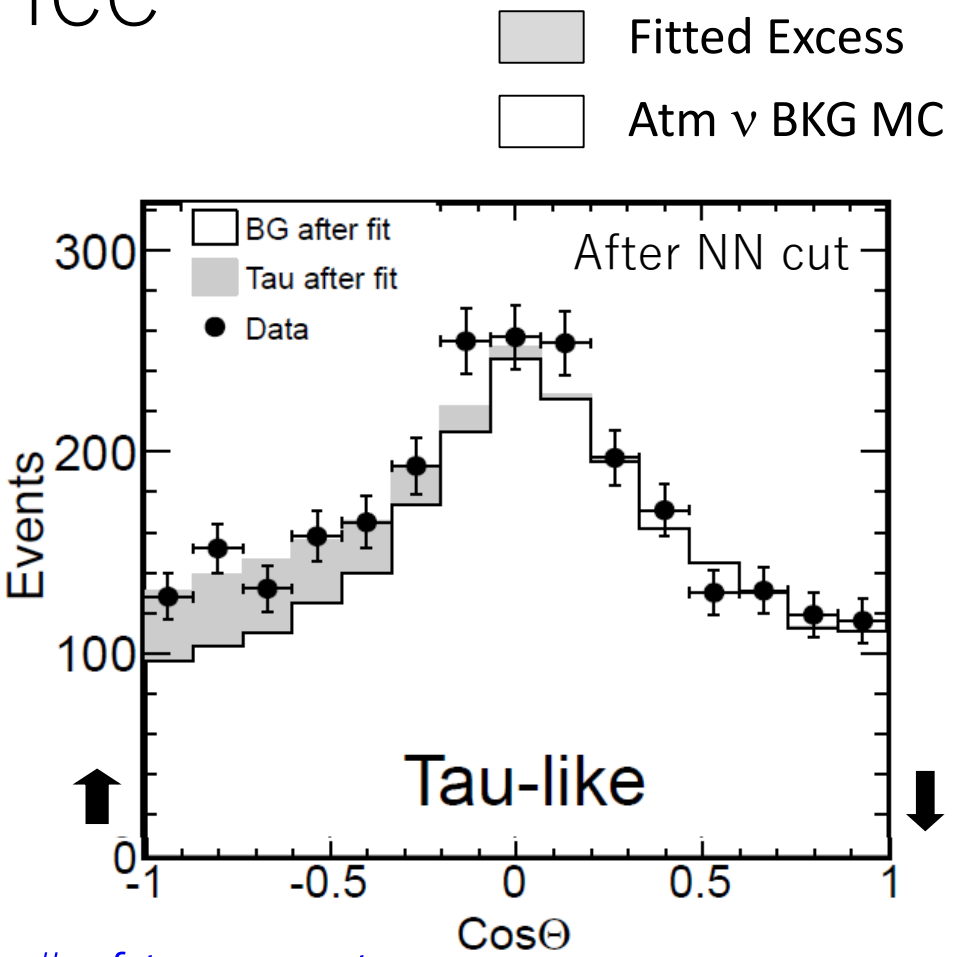
ν_τ appearance

- Where is missing ν_μ?
- It's not so easy to see because
  - ✓ interaction is rare due to threshold 3.5GeV
  - ✓ topology is similar to DIS events

→ NN to suppress BG, and statistically search

ν_τ must be oscillation induced
expected to be observed only in upward-going





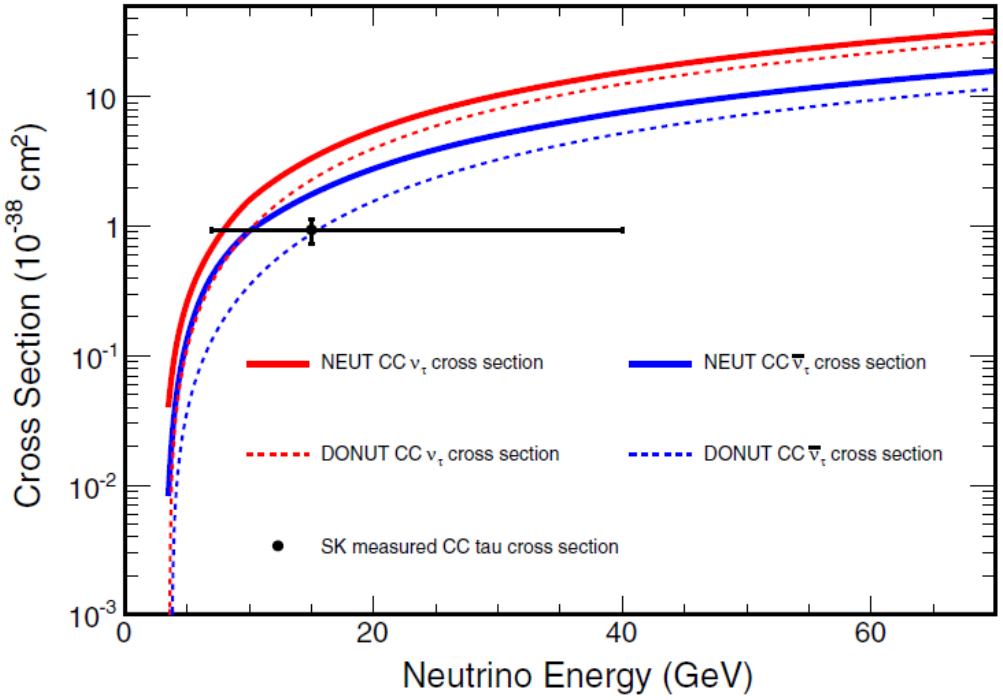
# of tau events

338.1 ± 72.7 (stat.+ sys.)

reject no-tau-appearance @ 4.6σ.

ν_τ cross section measurement

extracted CC ν_τ cross-section



Horizontal line : 90% of energy range

Average cross-section
between 3.5 and 70 GeV

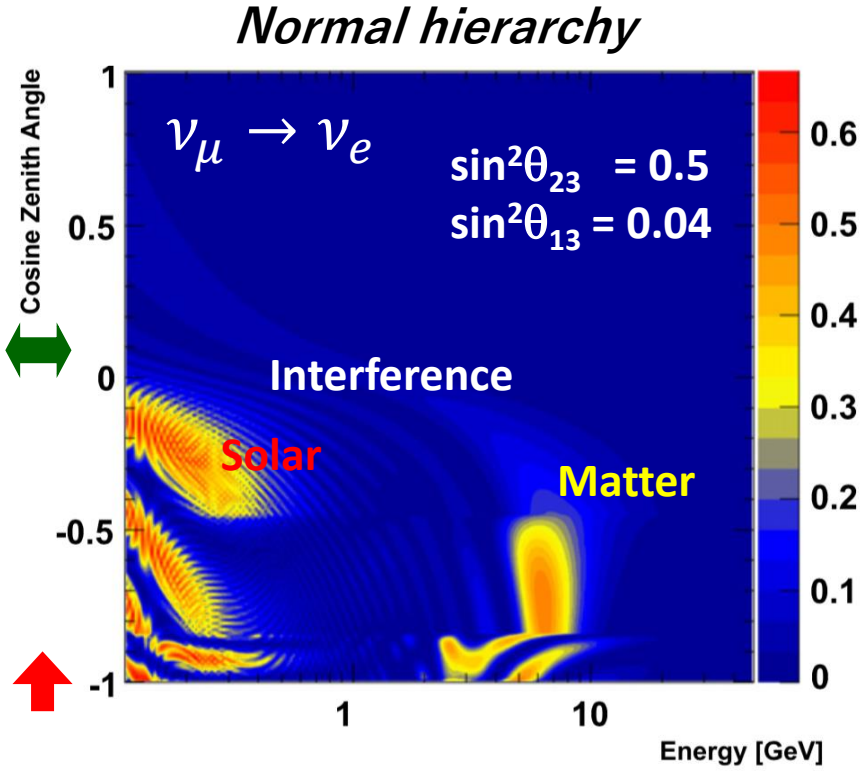
$$(0.94 \pm 0.20) \times 10^{-38}\mathrm{cm}^2$$

Flux averaged theoretical cross-section

$$(0.64) \times 10^{-38}\mathrm{cm}^2$$

consistent in 1.5 σ
also consistent with DONUT result

ν_e appearance



- ν_e appearance brings information of parameters (θ_{13}, δ cp)

Difference in # of electron events:

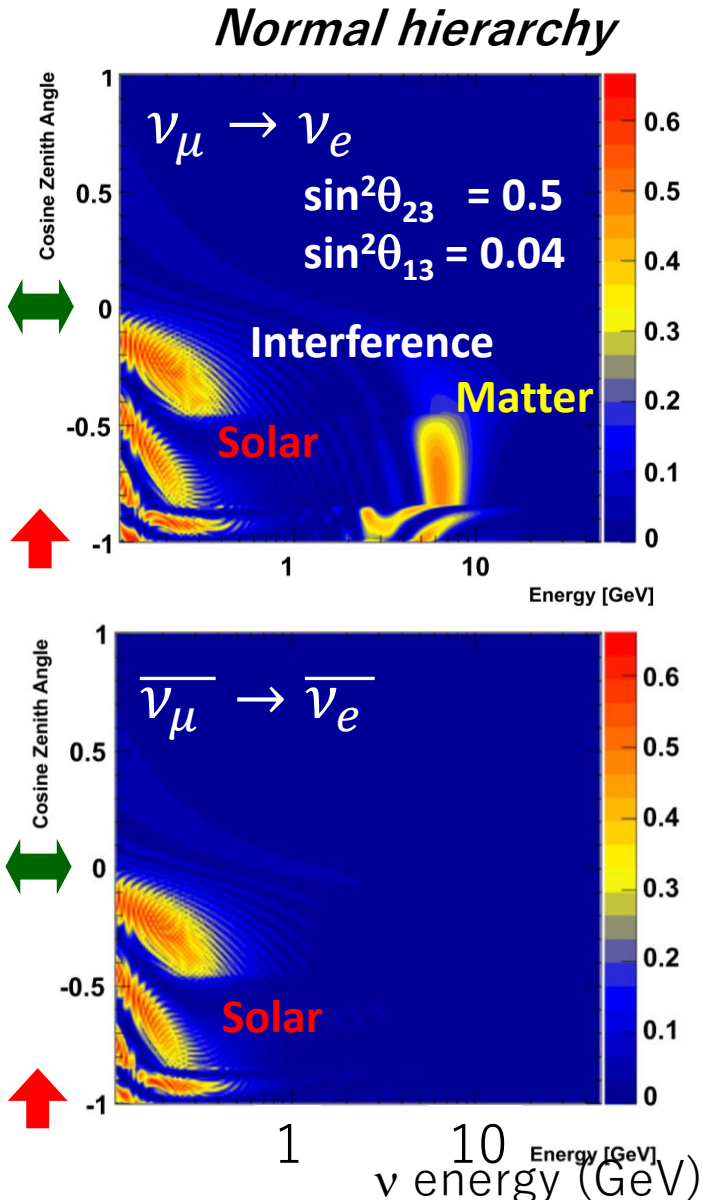
$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) + \Delta_2(\Delta m^2_{12}) + \Delta_3(\theta_{13}, \Delta m^2_{12}, \delta)$$

← Matter effect
← Solar term
← Interference

- ➢ matter effect .. maximize effective missing, enhance ν_e sensitive to mass hierarchy
- ➢ solar term .. sensitive to θ_{23} octant degeneracy
- ➢ interference .. sensitive to CP phase

→ high statistics of SK data enable us to probe it

Matter Effect for ν_e, $\overline{\nu_e}$



- sensitive to mass hierarchy
  in case normal hierarchy → neutrino enhanced
  in case inverted hierarchy → antineutrino enhanced

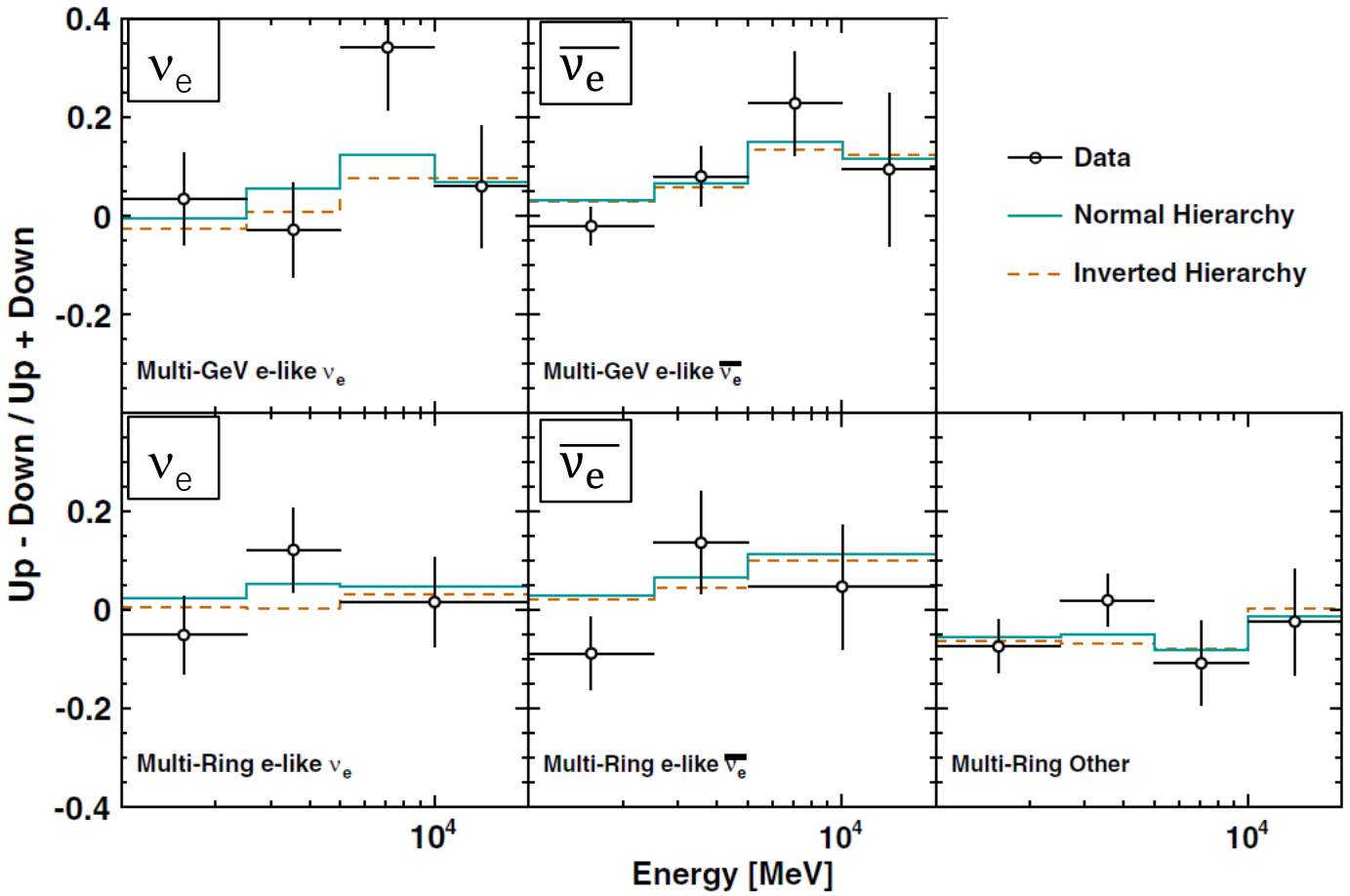
- separation of neutrino/antineutrino in up-going e-like events (2~10GeV) has information of mass hierarchy

- It's not so easy, but differential cross-sections are different, biased samples (ν_e-like, $\overline{\nu_e}$-like) could be defined

Observables	ν_e *CC*	$\overline{\nu_e}$ *CC*
Number of rings	More	Fewer
Transverse momentum	Larger	Smaller
# of decay electrons	More	Fewer
Signal efficiency	52.9%	71%
Purity	58.4%	27.5%

Mass Hierarchy

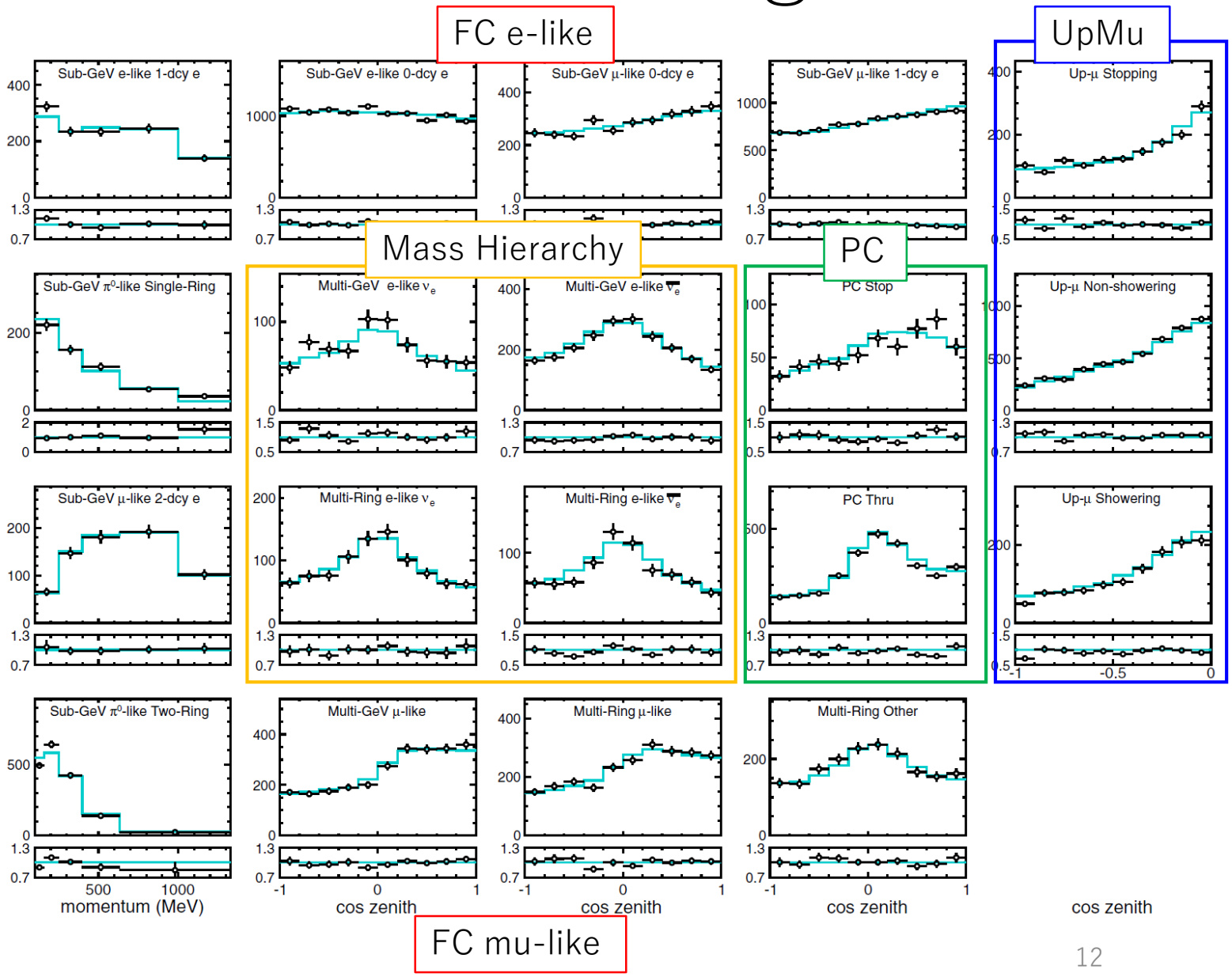
up-down asymmetry



- although low statistics and purity, data looks favoring normal hierarchy
- fitting result shown later

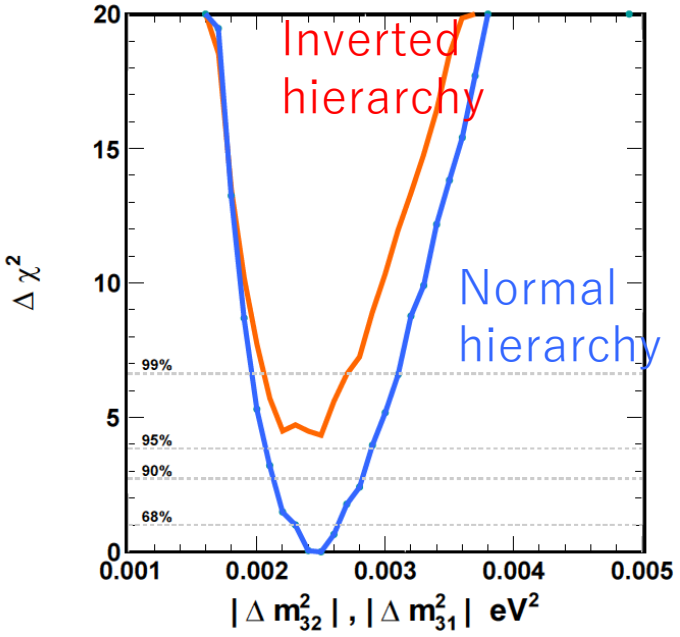
Oscillation Parameter Fitting

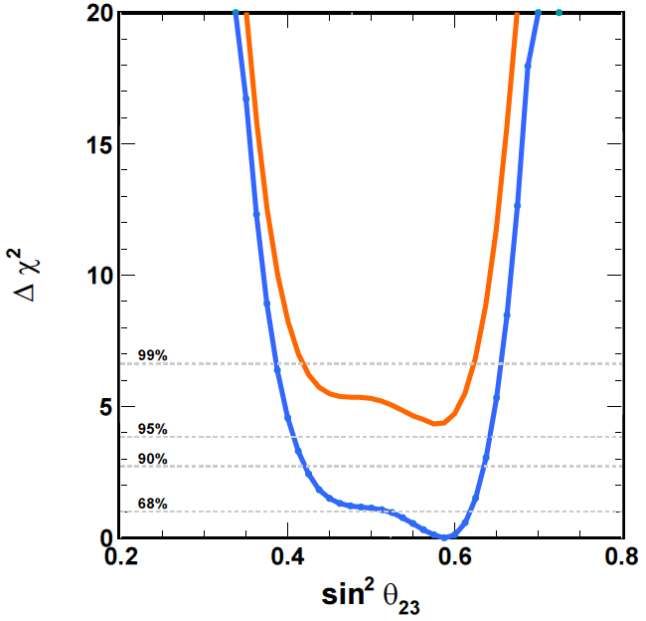
- 19 histograms based on topology, energy, flavor
- minimum χ^2 fitting on bins of zenith angle, energy
- with three types of constraints
  - ➢ constraint on θ_{13} from reactor
  - ➢ no constraint on θ_{13}
  - ➢ constraints from T2K public result



Fitting Results with θ_{13} Constraint

SK-I to SK-IV, 5326 days (2519 days from SK-IV), 328 kt·yr





$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\mathrm{ev}^2$,
$\sin^2\theta_{12} = 0.304 \pm 0.014$,
$\boxed{\sin^2\theta_{13} = 0.0219 \pm 0.012}$
from reactor

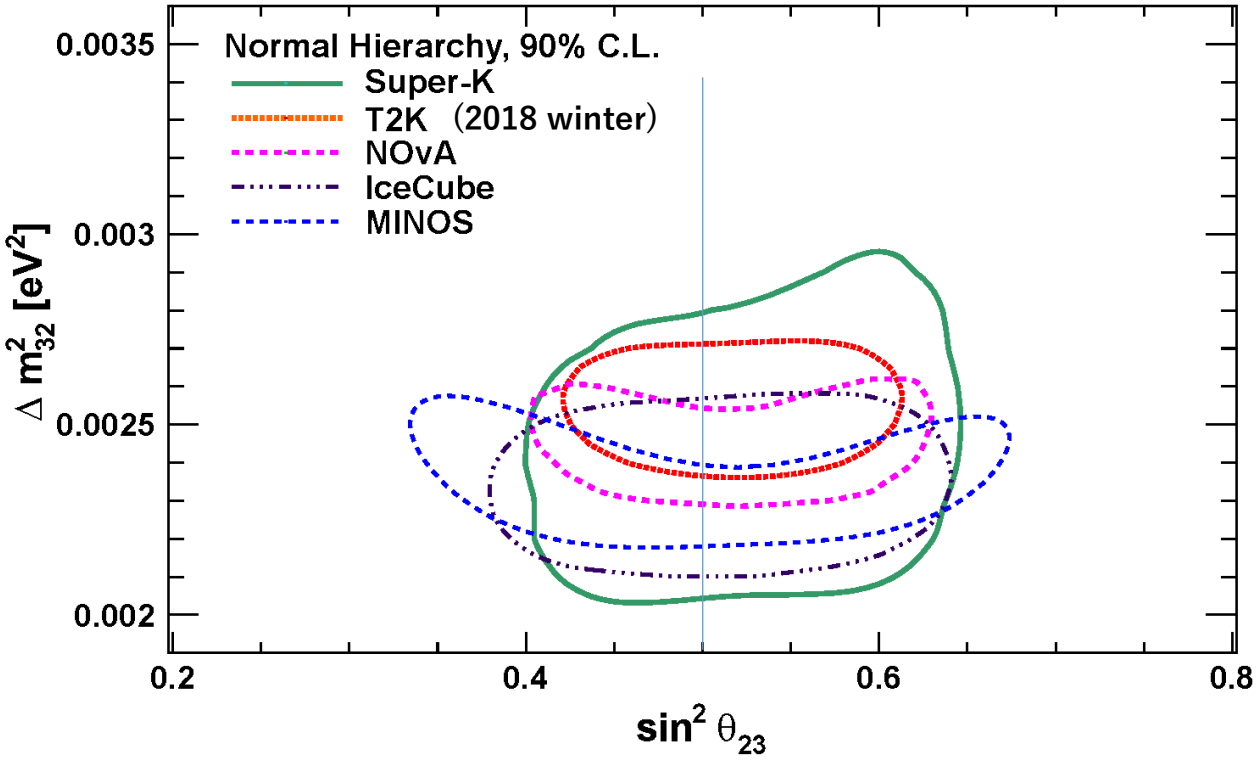
- slightly favor second octant
- e-like sample favor NH

$|\Delta m^2_{32}| = 2.50^{+0.13}_{-0.20} \times 10^{-3}\mathrm{eV}^2$

$\sin^2\theta_{23} = 0.588 \pm^{0.031}_{0.064}$

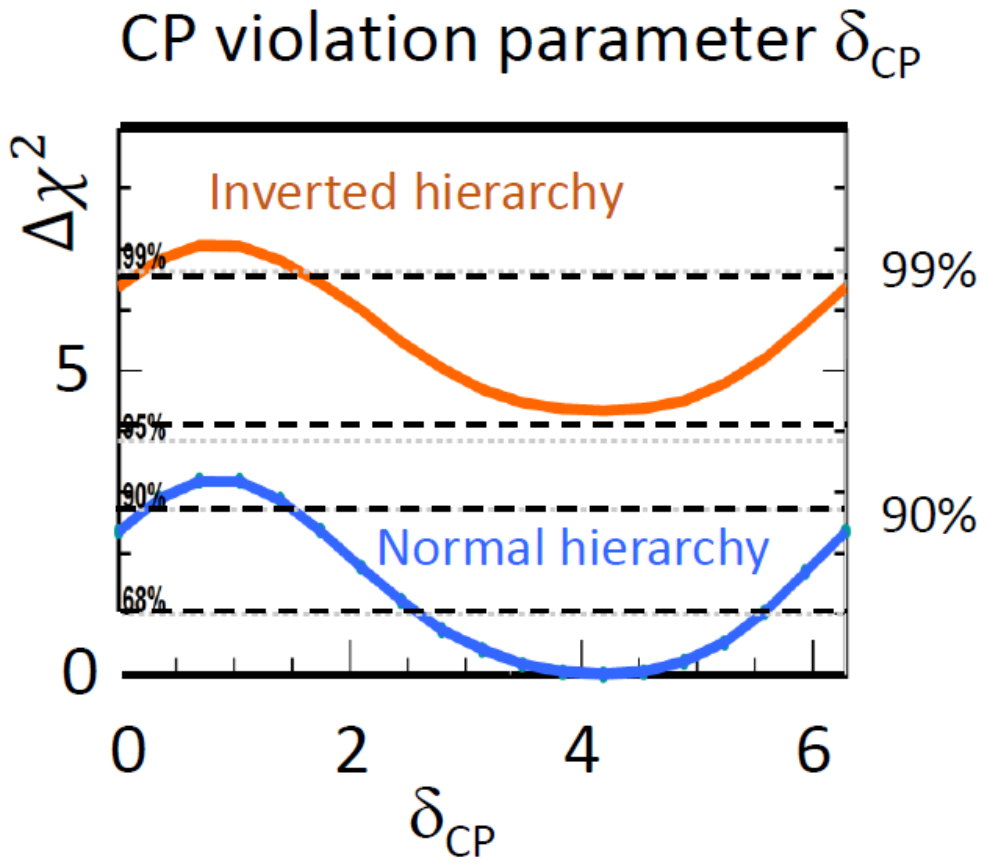
$(\chi^2_{NH,min} - \chi^2_{IH,min} = -4.34)$

Comparison to Experiments



- consistent with experiments
- CL region mostly overlapped

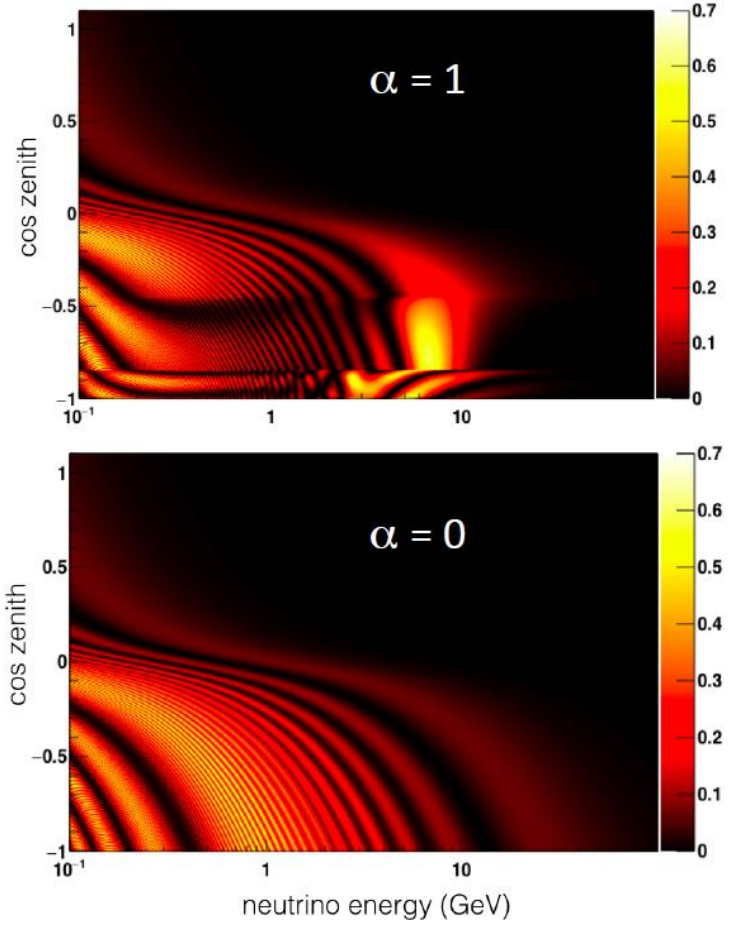
CP Violation Phase (δ_{CP})

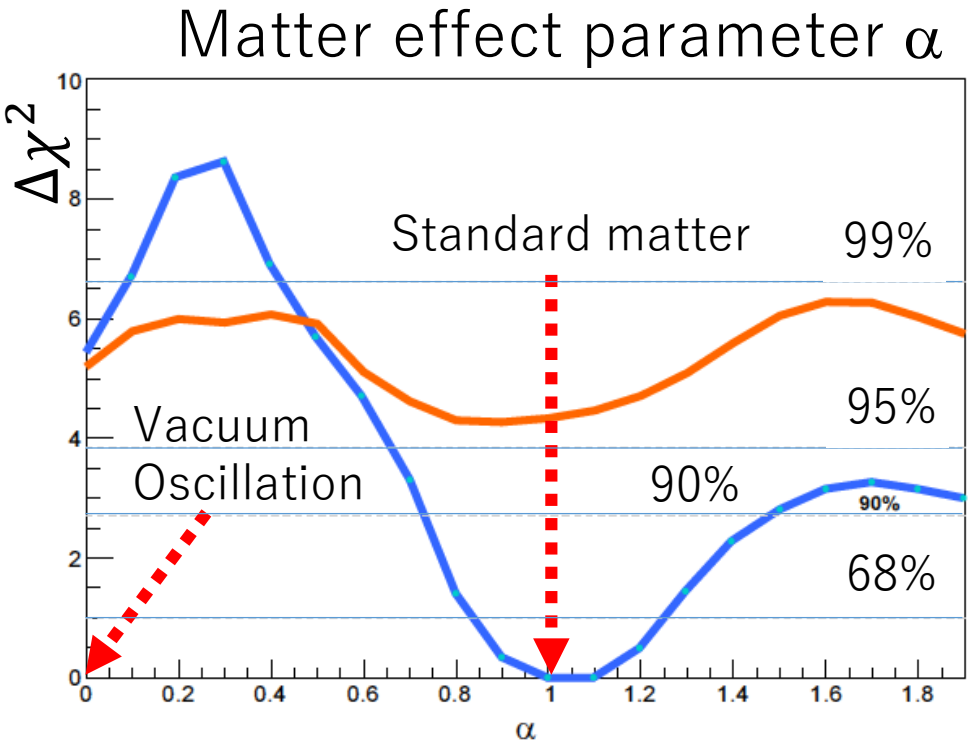


$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\text{ev}^2,$$
$$\sin^2\theta_{12} = 0.304 \pm 0.014,$$
$$\sin^2\theta_{13} = 0.0219 \pm 0.012$$

- best fit 4.18 (3.84)
- slightly suggest nonzero δ cp

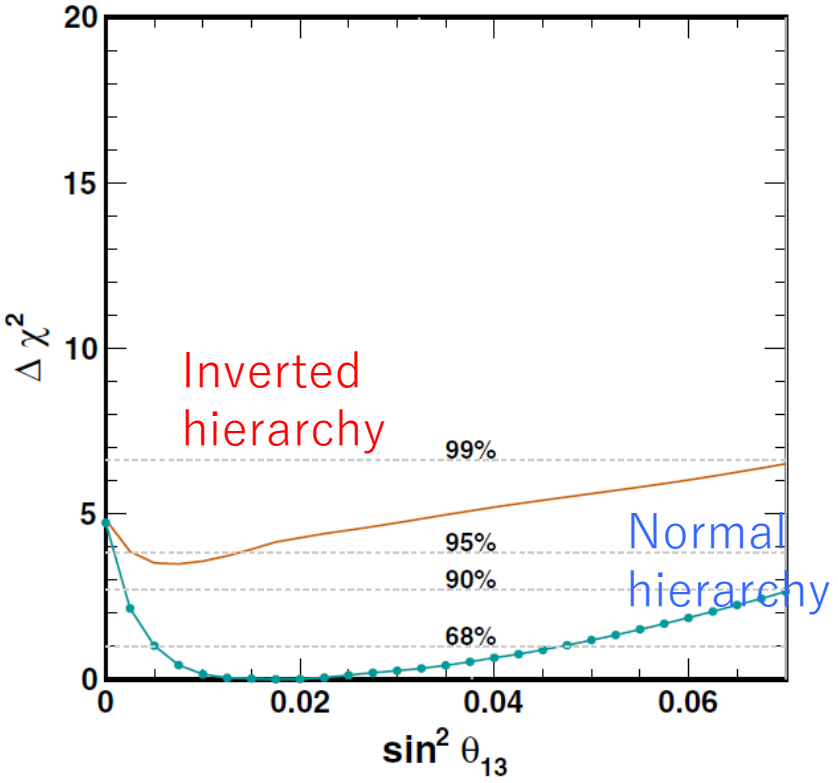
Matter Effect

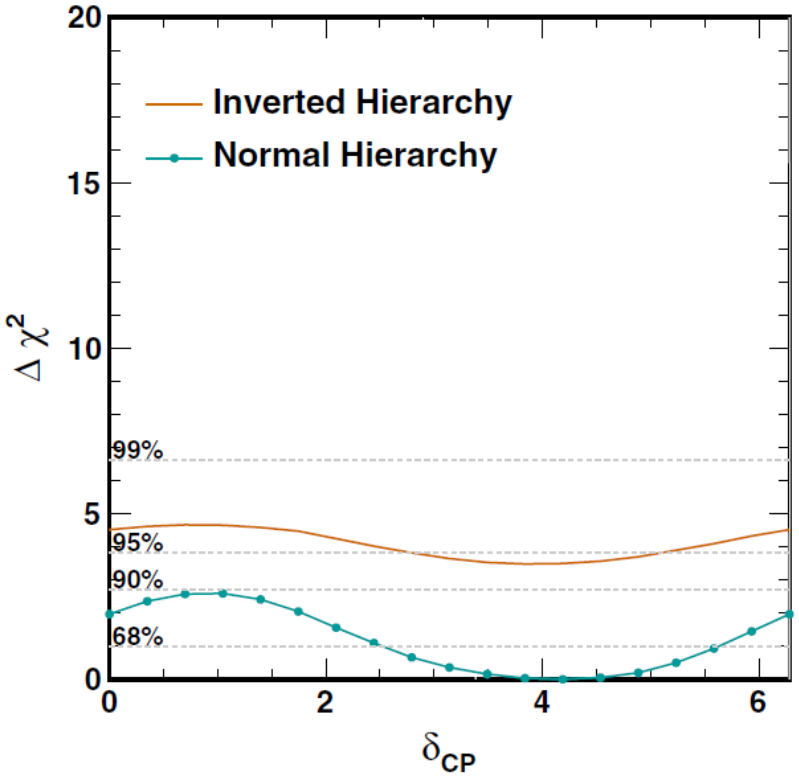




- consistent with standard matter model
- rejecting vacuum model by 1.6 σ

Fitting Results with θ_{13} free



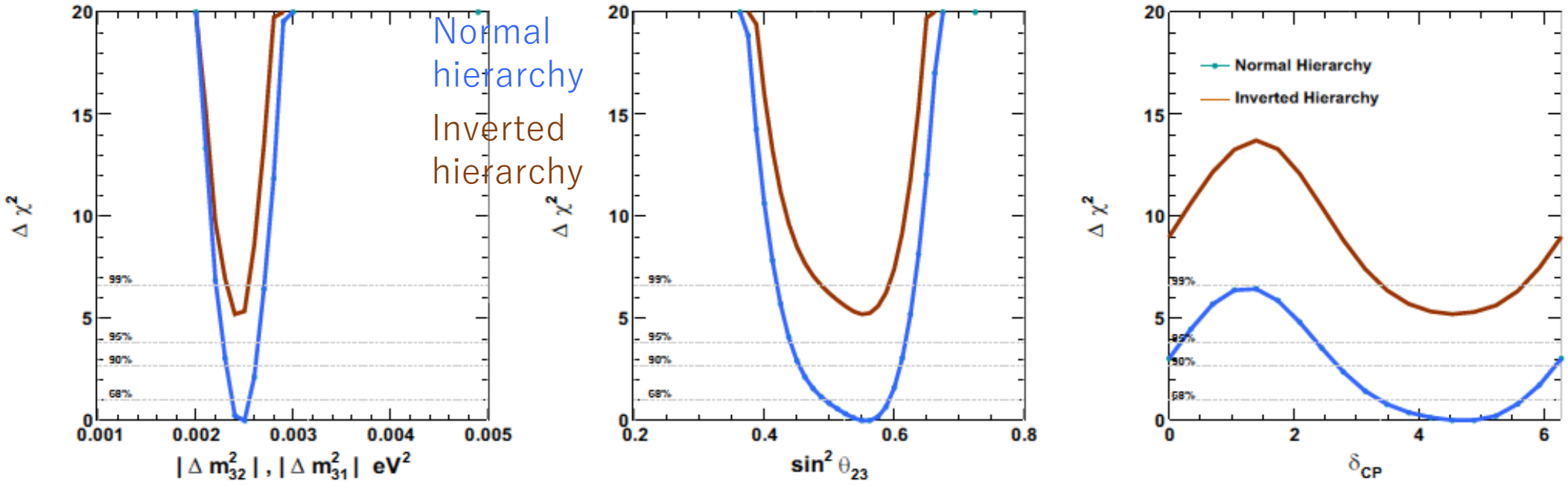


- consistent reactor exp.=0.0219
- rejecting $\sin^2\theta_{13}=0$ in 2 σ
- $\chi 2$(NH-IH) = -3.5, still favor normal hierarchy

- similar behavior (slightly weak)

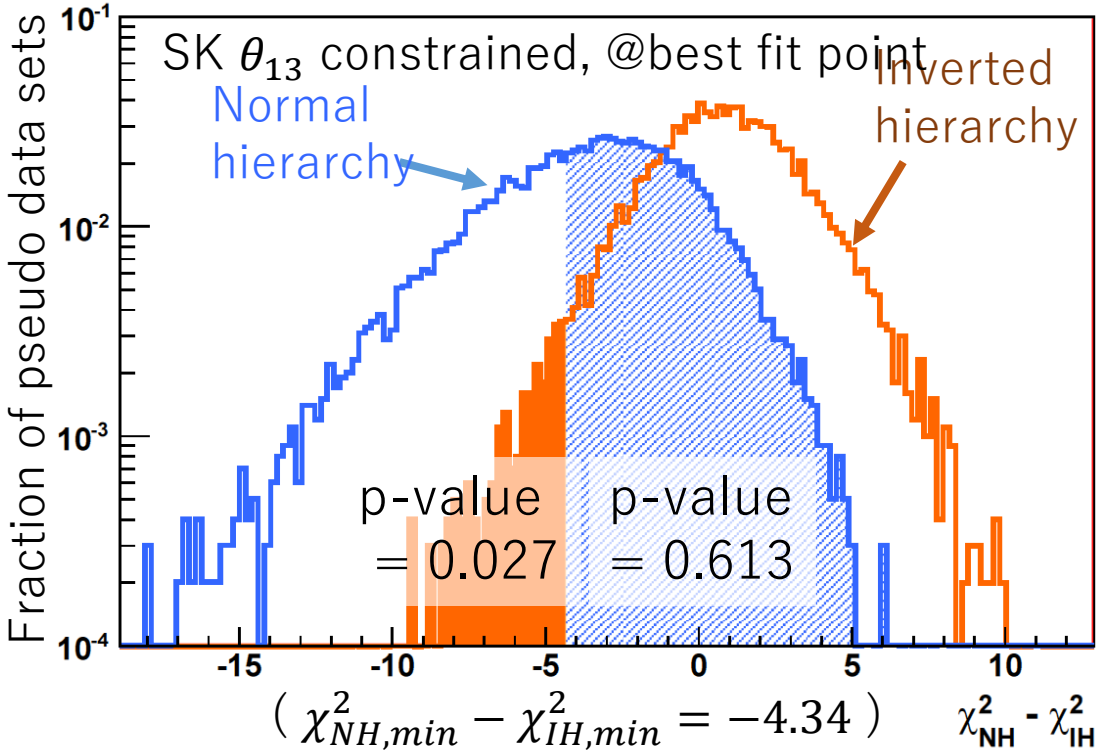
Fitting results with T2K constraint

$(\sin^2\theta_{13} = 0.0219 \pm 0.0012)$



- ($\chi^2_{NH,min} - \chi^2_{IH,min} = -5.2$) stronger than SK-only (-4.3)
- δ_{CP} still favor ~4.9(4.5) with stronger constraint

Interpretation of Hierarchy Determination



- p-values calculated using pseudo-data
- Hypothesis test ~ CL_s method :

$$\mathrm{CL_s(IH\ rejection)} \equiv \frac{p_{0(IH)}}{1-p_0(NH)}$$

- sensitivity depend on $\sin^2\theta_{23}$
  taking smallest and largest $\sin^2\theta_{23}$

IH rejection:

SK only	80.6 ~ 96.7%
SK + T2Kmodel	91.5 ~ 94.5%

Summary

- published atmospheric neutrino results with almost full (88%) data

- updated precise measurement of atmospheric parameter
- favored NH and non-zero δ_{CP}, although statistics is limited

- trying new reconstruction fitQun
  (the performance was shown on Wednesday)
- expanding fiducial volume ~ 20%?