Atmospheric Neutrino Oscillation

~ Review of Recent Progress and Future Prospect ~

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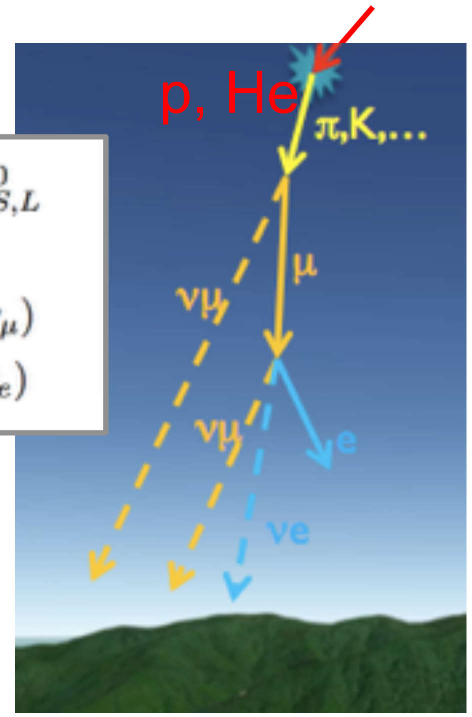
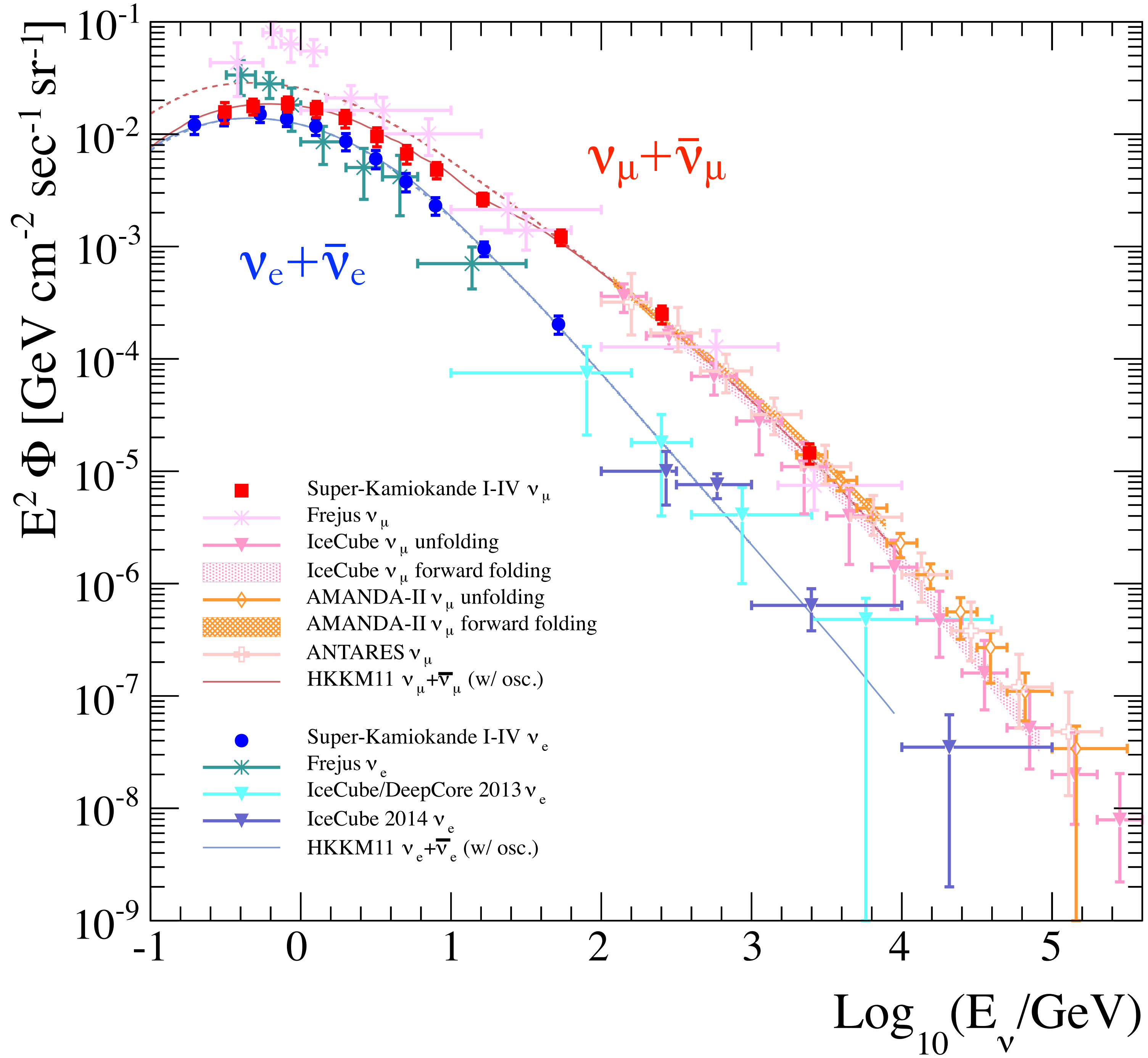
Atmospheric Neutrinos

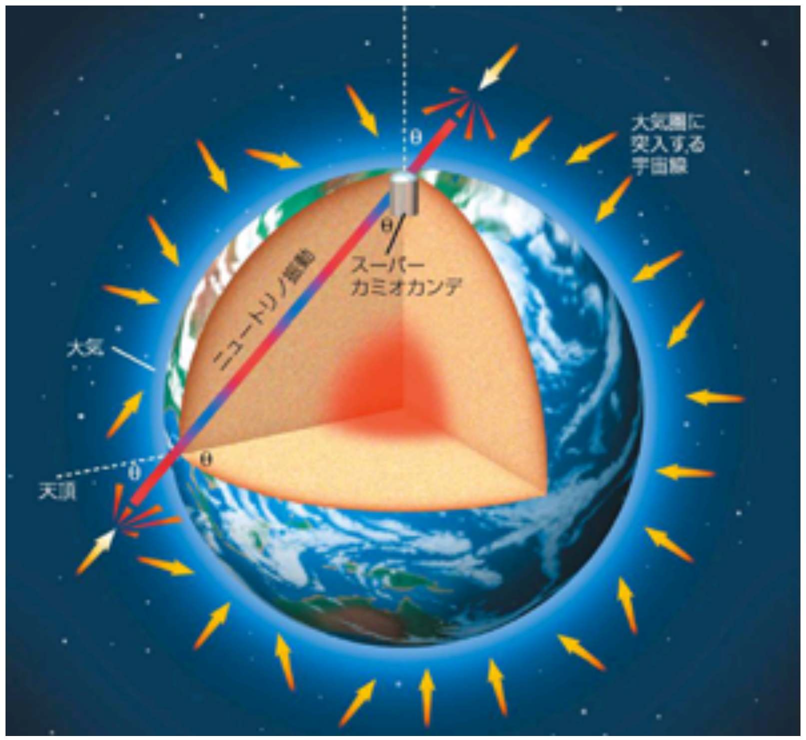
$$p, A + \text{air} \to \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}_{S,L}$$
$$\pi^{\pm}, K^{\pm} \to \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$$
$$\mu^{\pm} \to e^{\pm}\ \nu_e(\bar{\nu}_e)\ \bar{\nu}_{\mu}(\nu_{\mu})$$
$$K^{\pm}, K^{0}_{L} \to [\pi^{\pm}, \pi^{0}]e^{\pm}\nu_e(\bar{\nu}_e)$$

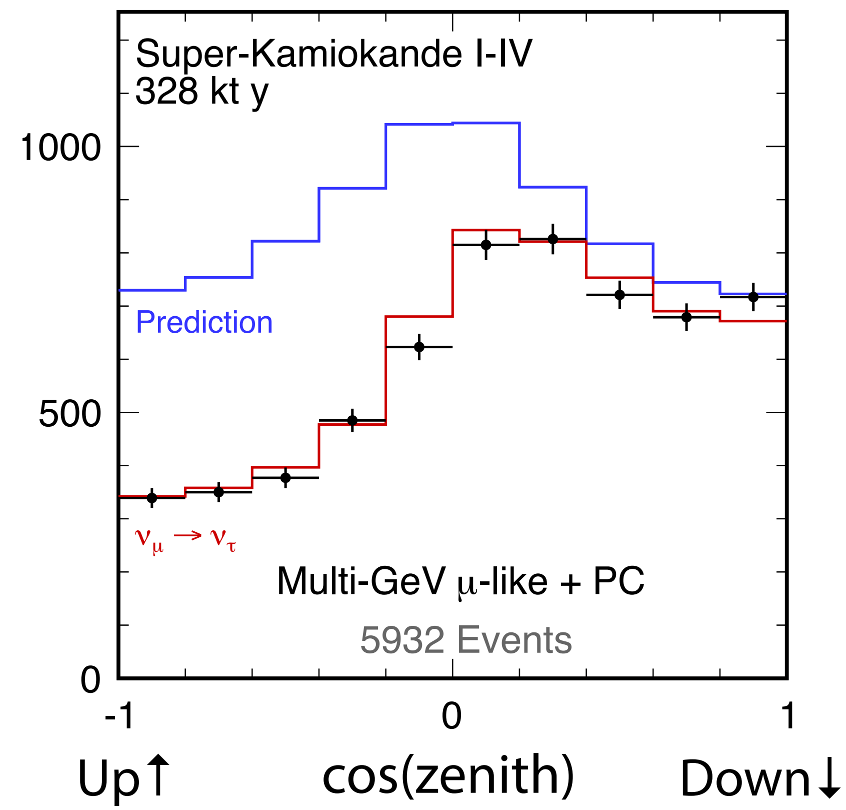


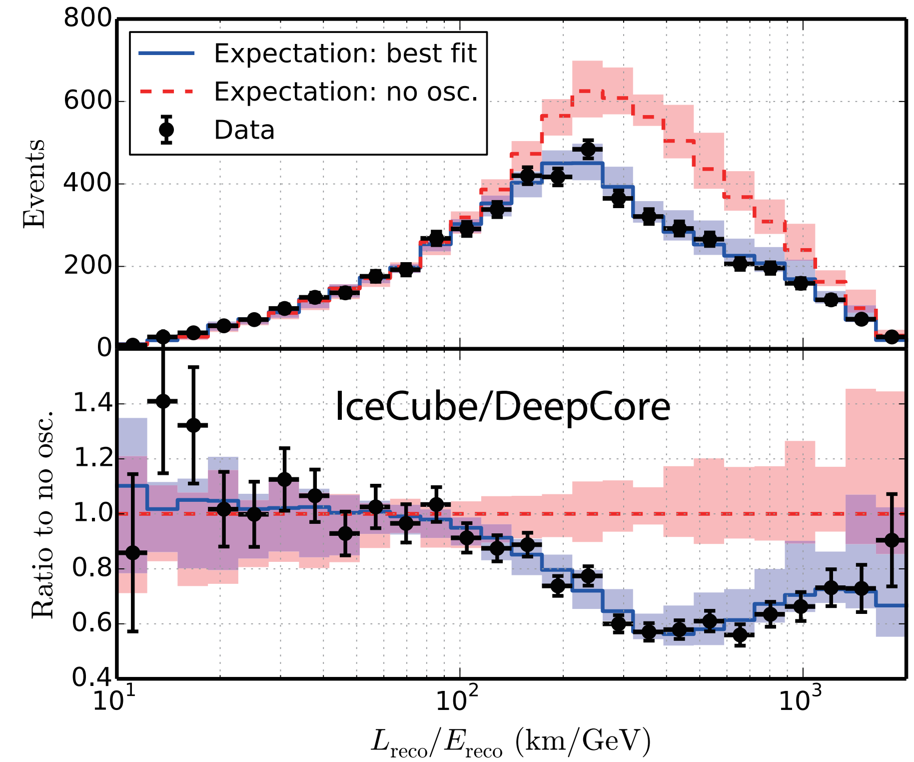


- Decay products of secondaries by cosmic ray interactions with atmosphere
- Power-law spectrum: $\sim E^{-3.7}$
- Affected by rigidity cutoff due to geomagnetic field below 1 GeV
- Spectra modified by neutrino oscillation below O(10) GeV

Muon Neutrino Oscillation







- Large deficits of muon neutrino are observed in upward-going events and at L/E ~ 230 km/GeV
- Pathlength ranges from O(10) km to O(10000) km depending on zenith angle
- Muon neutrino oscillation driven by θ_{23} is dominant channel in atmospheric ν:

$$P_{3\nu}(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1 - \cos^2\theta_{13}\sin^2\theta_{23}\right)\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

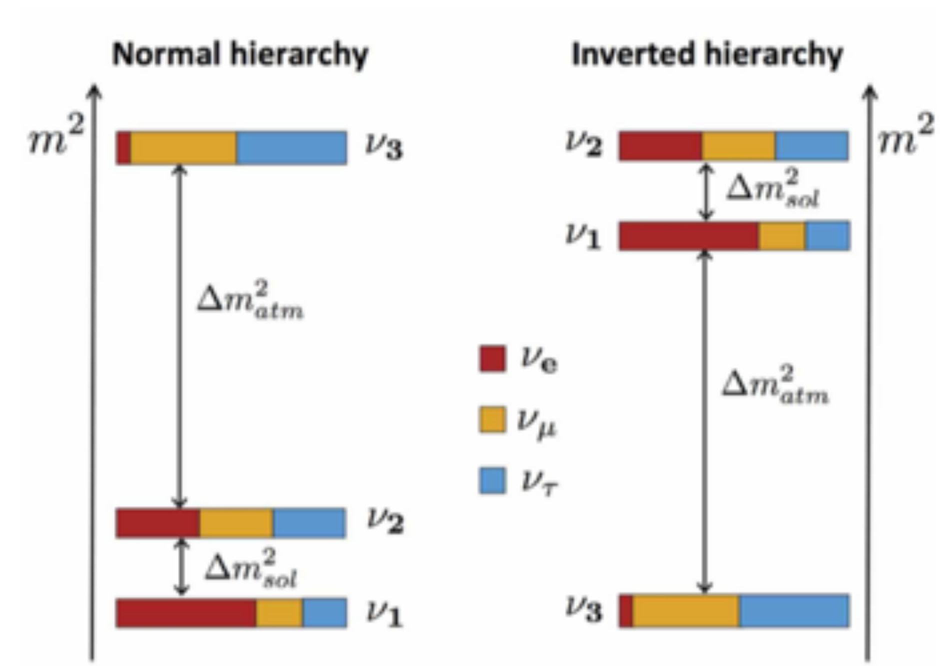
Neutrino Oscillation

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

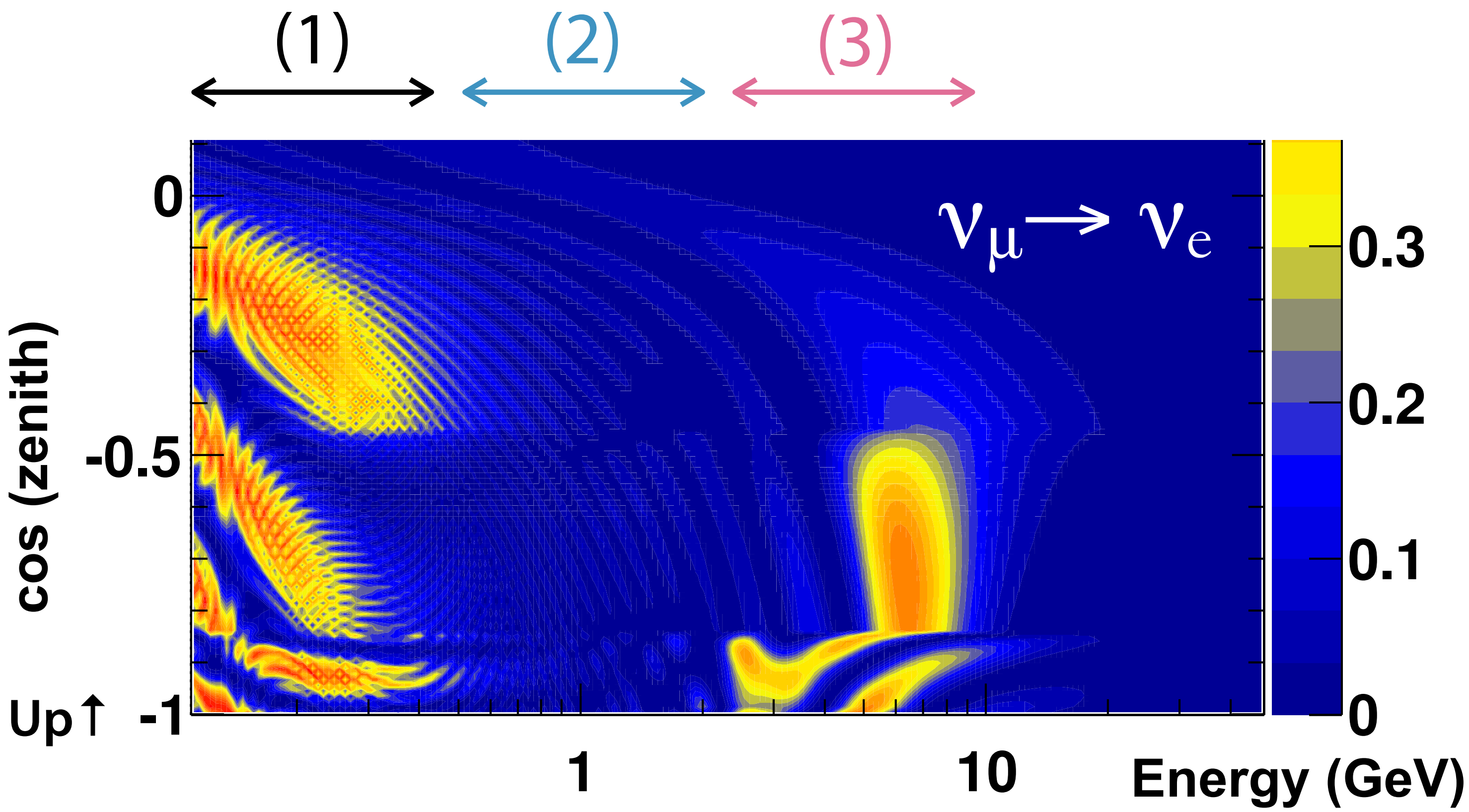
Atmospheric, LBL	Reactor, LBL	Solar, KamLAND
$\Delta m^2_{32} \simeq 2.4 \times 10^{-3}\mathrm{eV}^2$ $\sin^2\theta_{23} = 0.4 \sim 0.6$	$\sin^2\theta_{13} \simeq 0.021$	$\Delta m^2_{21} \simeq 7.5 \times 10^{-5}\mathrm{eV}^2$ $\sin^2\theta_{12} \simeq 0.30$

- Standard 3-flavor oscillation framework are consistent with atmospheric, solar, reactor, accelerator results

- However, still some pieces of neutrino mixing are missing:
  - Mass hierarchy (MH):
    Normal ($\Delta m_{32}^2 > 0$) or Inverted ($\Delta m_{32}^2 < 0$)
  - Leptonic CP phase (δ_{CP}), θ_{23} octant
- Additional verification of 3-flavor oscillation framework:
  - Sterile neutrino
  - Tau appearance from $\nu\mu \rightarrow \nu\tau$ oscillation
- These are explorable with atmospheric neutrinos



Sub-Dominant Effects in $\nu_\mu \rightarrow \nu_e$



Non-zero θ13 and other oscillation parameters cause sub-dominant effect:

(1) solar term oscillation

(2) Interference

(3) Resonance

- $\nu_\mu \rightarrow \nu_e$ resonance is caused by enhancement of θ_{13} mixing by MSW mechanism
- ν_e is affected with forward-scattering potential ($A_{cc} = \pm 2\sqrt{2} G_F E_\nu n_e$) when propagating inside Earth
- Resonance occurs in 2-10 GeV

Effective θ_{13} mixing in matter:

$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\underbrace{\left(\cos 2\theta_{13} - A_{CC}/\Delta m_{32}^2\right)^2}_{\uparrow} + \sin^2 2\theta_{13}}$$

minimum at resonance

Resonance and MH

- Status of MH and ν / $\bar{\nu}$ flips sign of Δm^2 and A_{cc} :

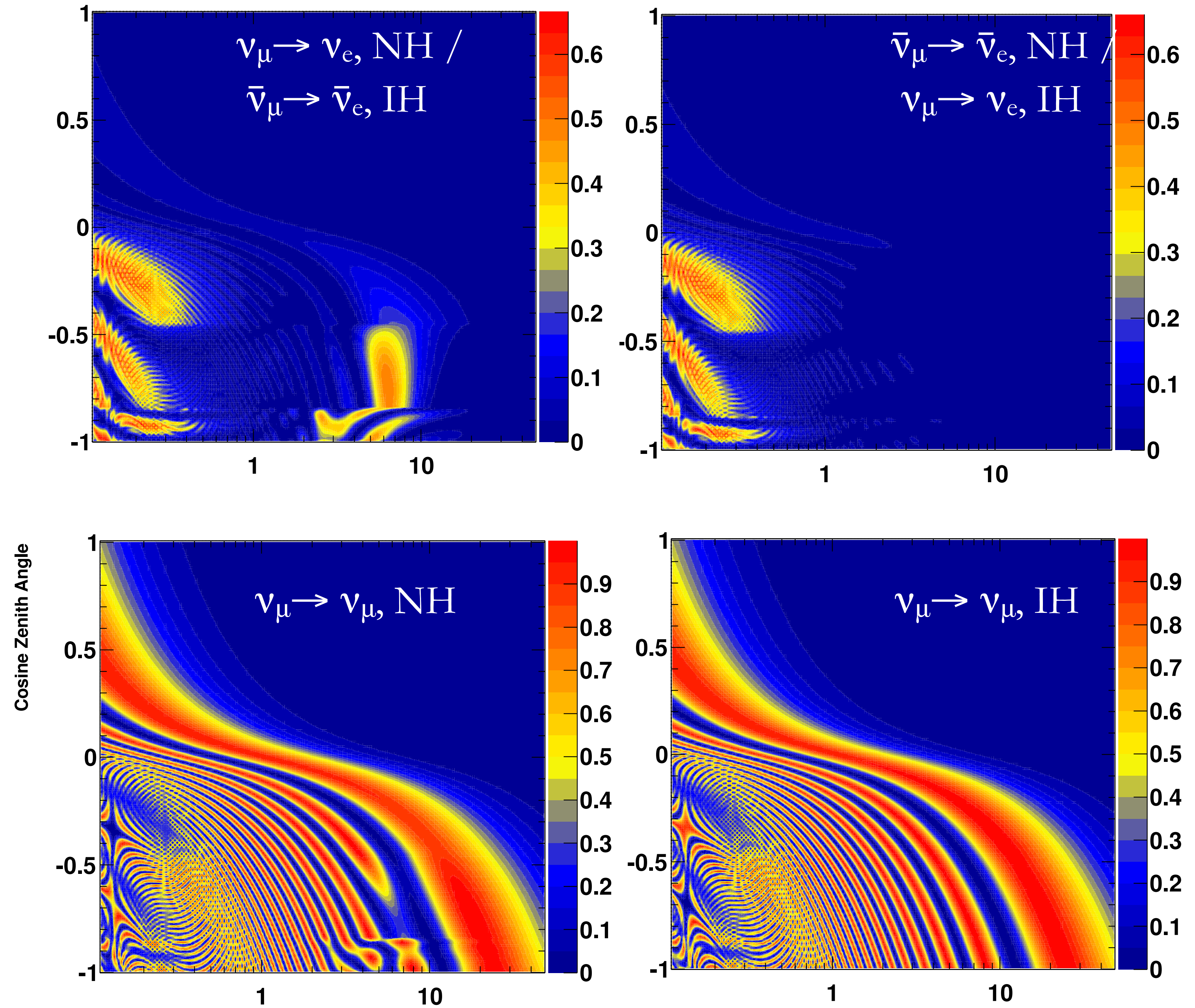
  NM $\rightarrow$ IH ($\Delta m^2 \rightarrow -\Delta m^2$)

  $\nu \rightarrow \bar{\nu}$ ($A_{cc} \rightarrow -A_{cc}$)

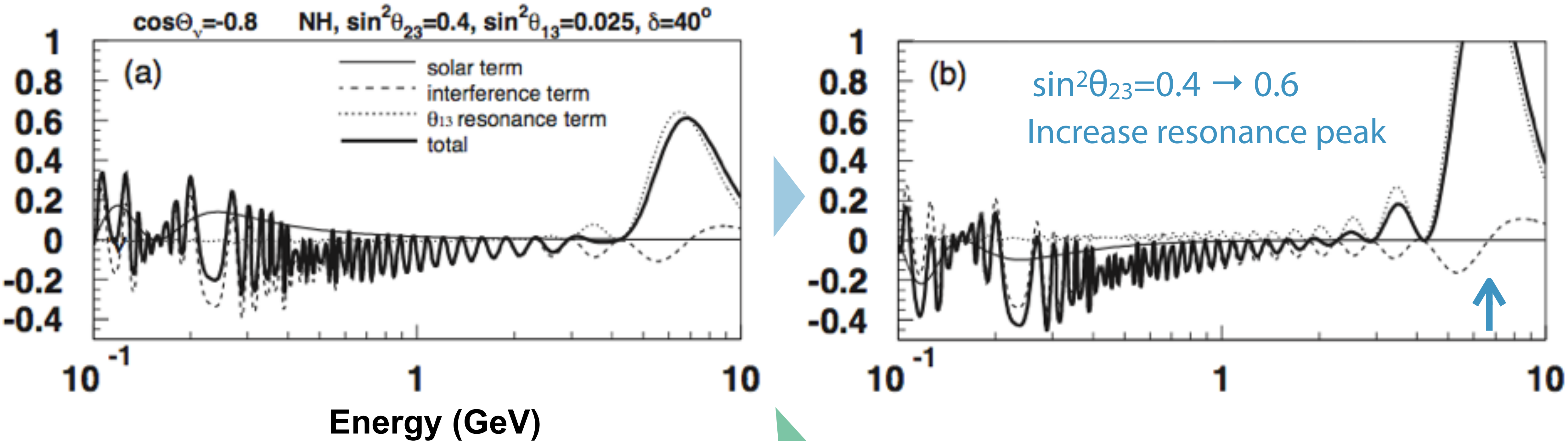
	ν	$\bar{\nu}$
Normal	enhanced (resonance)	surpressed
Inverted	surpressed	enhanced (resonance)

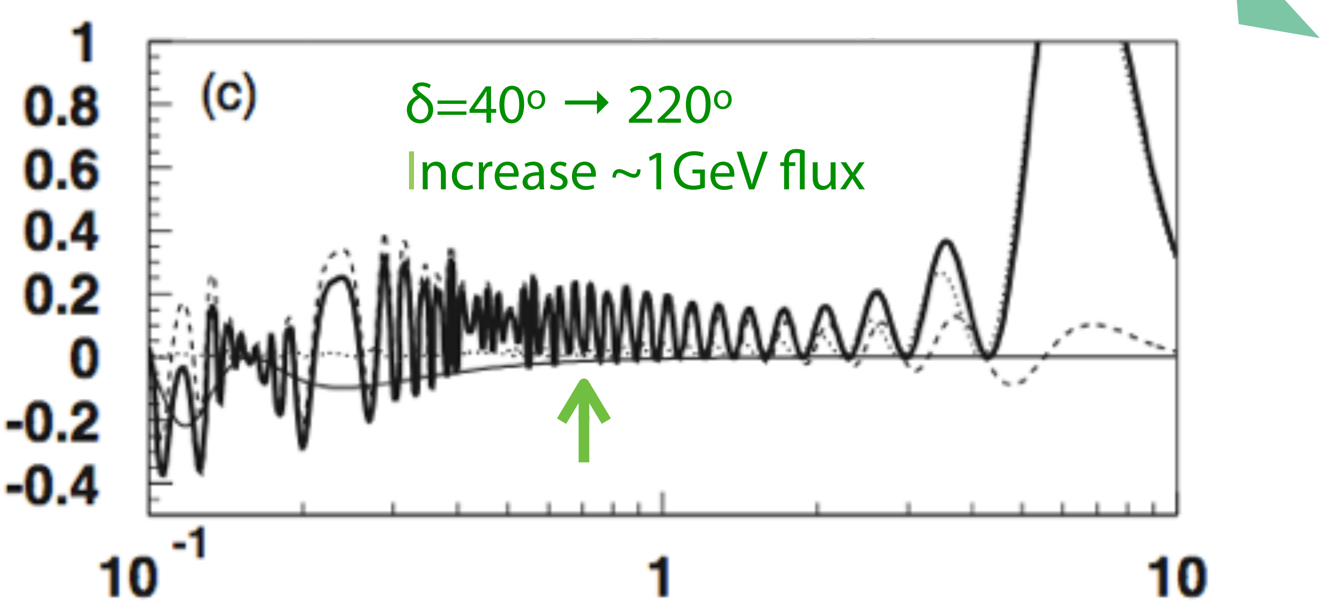
- Matter effect is also seen in $\nu_\mu \rightarrow \nu_\mu$ channel

- resonance condition is similar to $\nu_\mu \rightarrow \nu_e$



Effect of δ_{CP} phase and θ_{23} octant

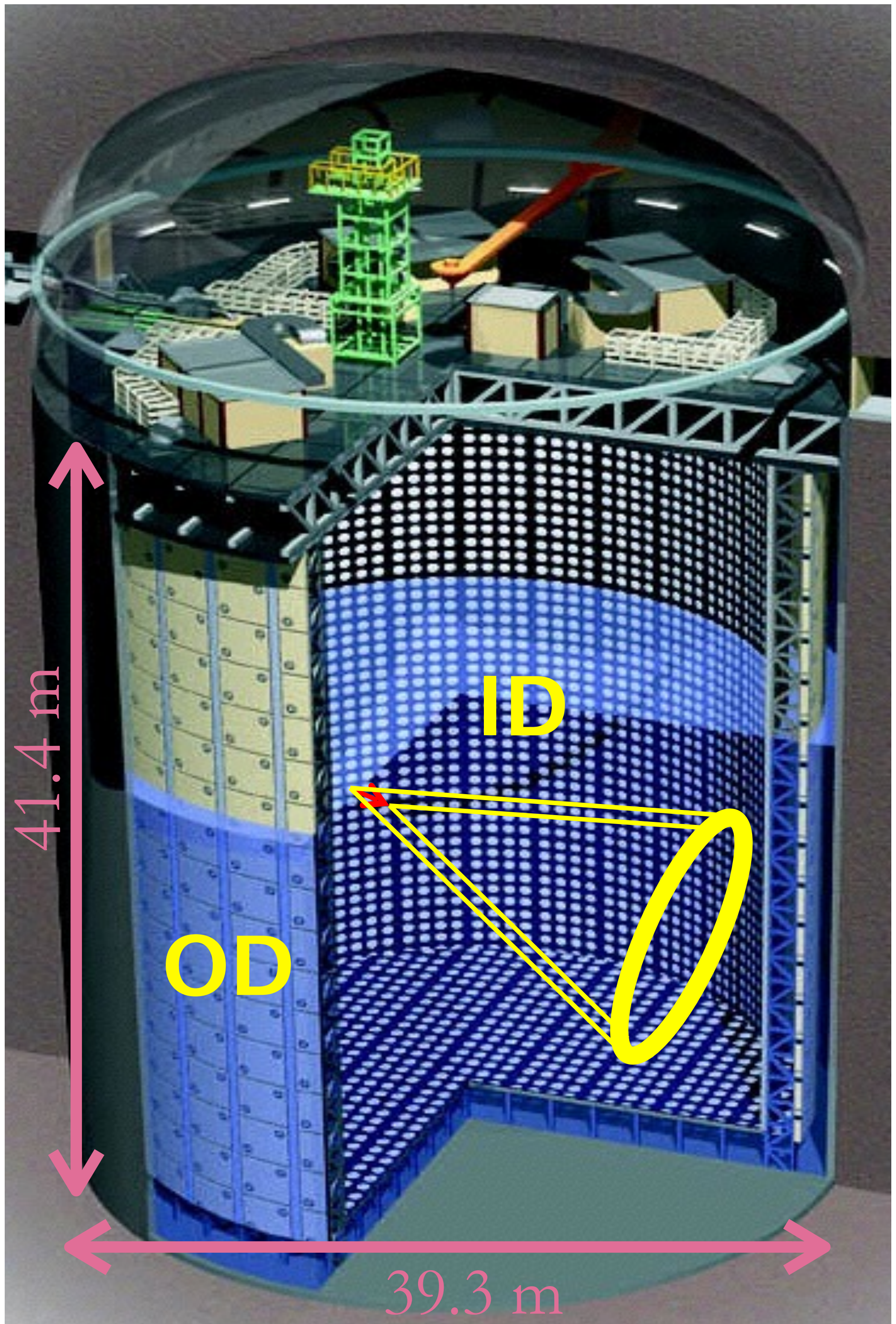




- Figures show fractional change of ν_e flux from zero θ_{13} for cos(zenith) = -0.8
- Atmospheric neutrino are also sensitive to θ_{23} octant and leptonic CP

Recent Progress in Atmospheric Neutrino Oscillation

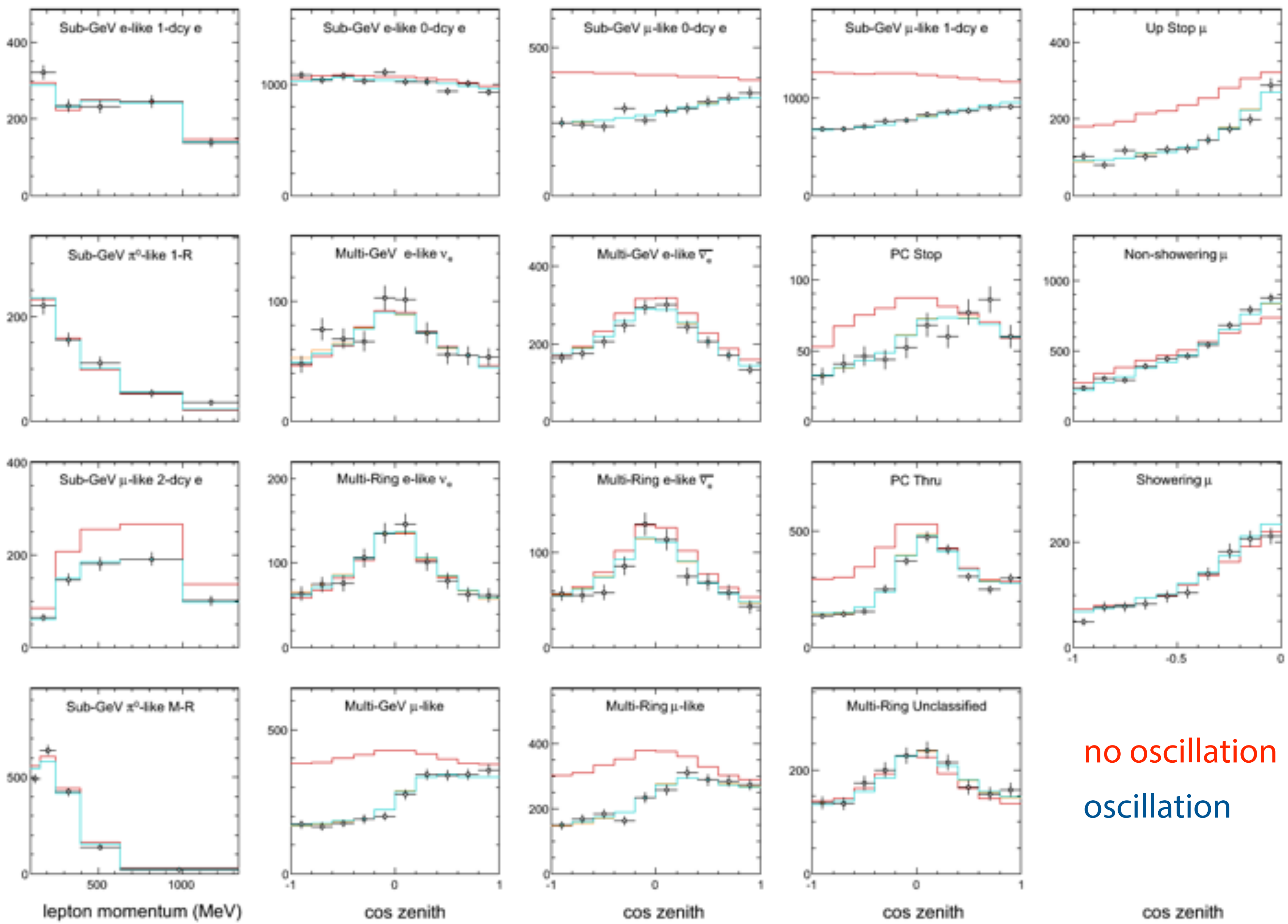
Super-Kamiokande



- Water Cherenkov imaging detector
- 1000 m underground in Kamioka mine
- 50 kton volume (fiducial 22.5 kton)
- 11129 20" PMTs in inner detector (ID) for Cherenkov ring imaging
- 1885 8" PMTs for outer detector (OD)

Phase	Period	# of PMTs
SK-I	1996.4 ~ 2001.7	11146 (40%)
SK-II	2002.10 ~ 2005.10	5182 (20%)
SK-III	2006.7 ~ 2008.8	11129 (40%)
SK-IV	2008.9 ~	

Super-K Updated Data



Data set

- SK-I, II, III, IV: 0.33 Mtyr
- 19 sub-samples
- statistical separations btwn ν and $\bar{\nu}$ for MH

Analysis updates

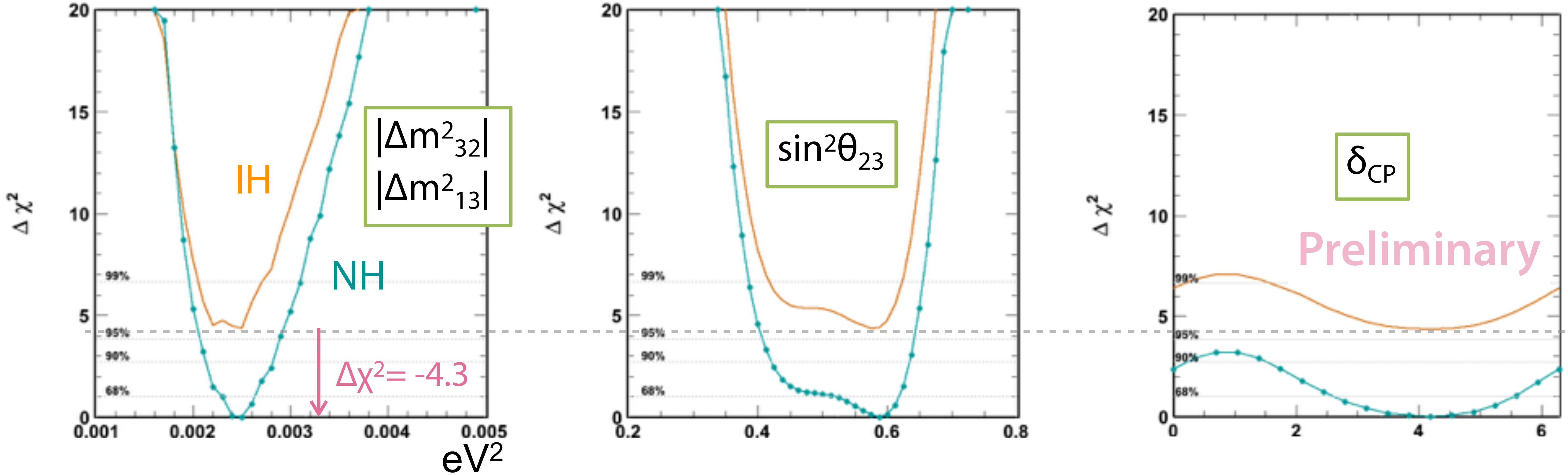
- NEUT update
- Improved calibration
- Systematics

Perform fit by varying

- θ_{23}, Δm_{32}^2, δ_{CP}, and MH
- θ_{13} fixed to reactor

SK Only Parameter Determination

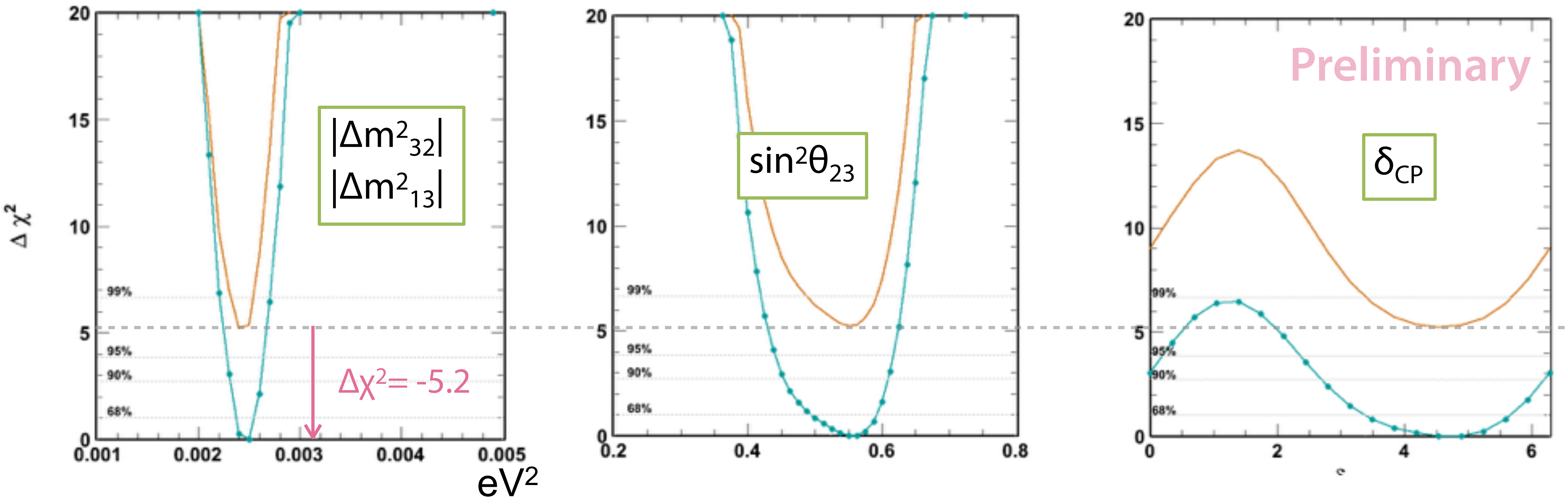
S. Moriyama, Neutrino2016



Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$eV^2
SK (IH)	576.08	0.0219 (fix)	4.189	0.575	2.5x10^{-3}
SK (NH)	571.74	0.0219 (fix)	4.189	0.587	2.5x10^{-3}

- SK only (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH}$= -4.3 (-3.1 expected)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -4.3 or less is 0.031 ($\sin^2\theta_{23}$=0.6) and 0.007 ($\sin^2\theta_{23}$=0.4). Under NH hypothesis, the probability is 0.45 ($\sin^2\theta_{23}$=0.6).

SK+T2K ν_μ, ν_e Parameter Determination

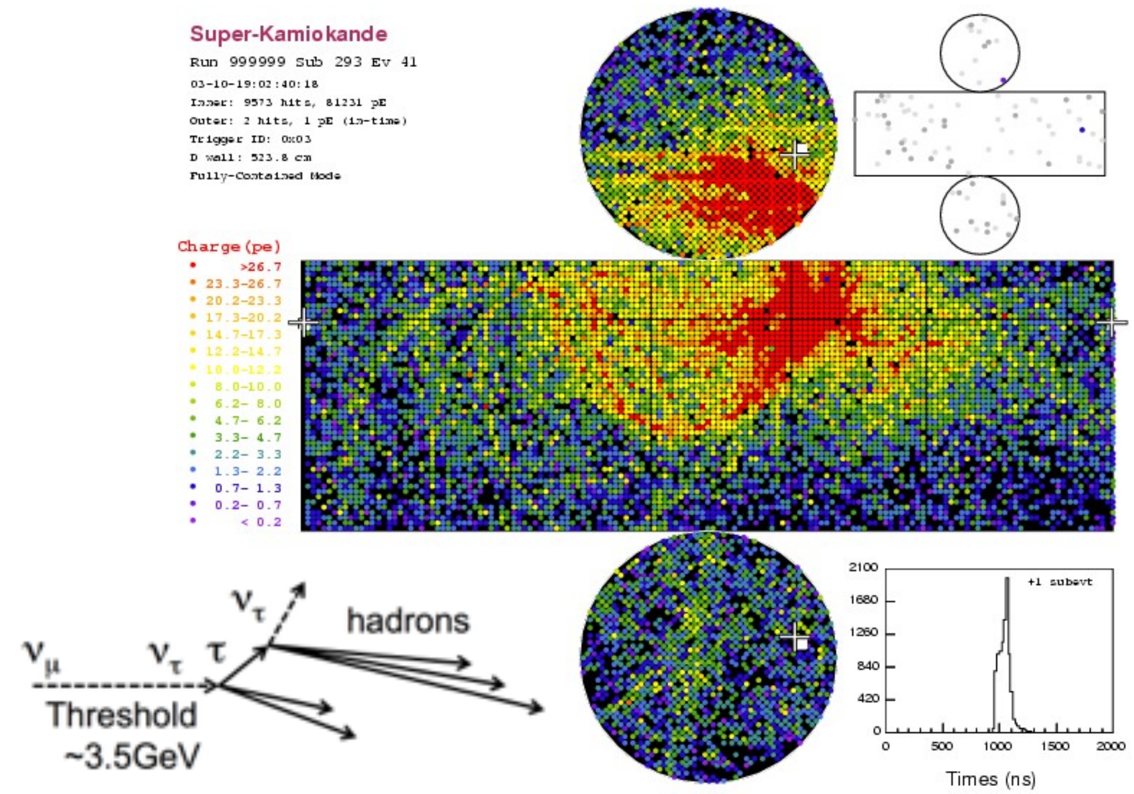


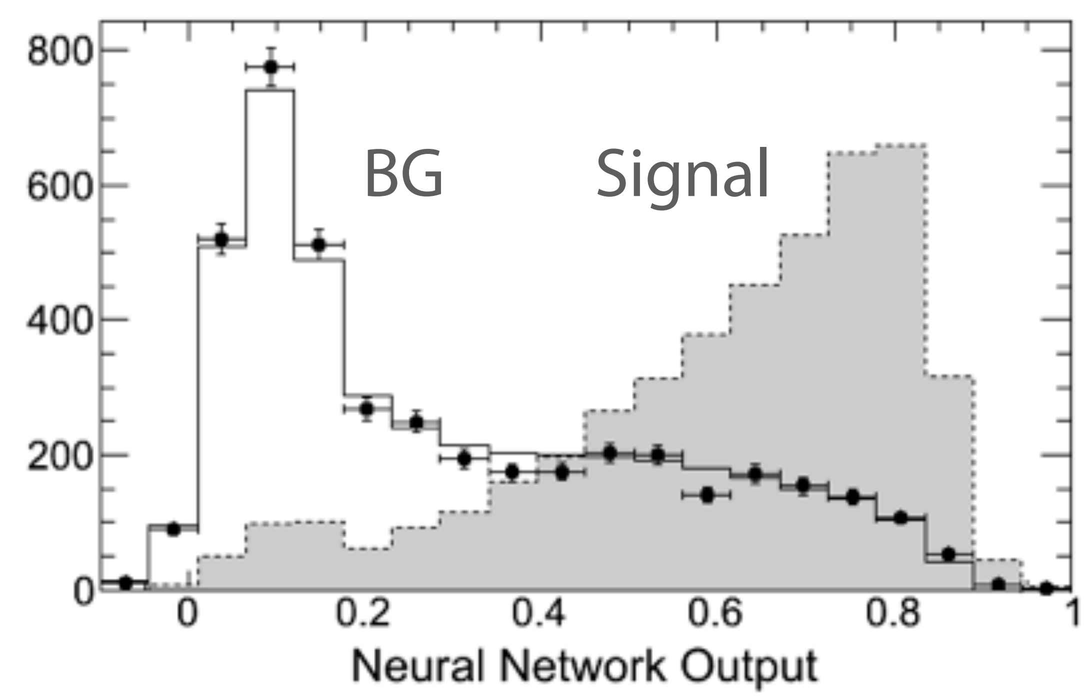
Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ eV^2
SK+T2K (IH)	644.82	0.0219 (fix)	4.538	0.55	2.5×10^{-3}
SK+T2K (NH)	639.61	0.0219 (fix)	4.887	0.55	2.4×10^{-3}

- Introduce additional constraint by publicly available T2K info. Not joint fit.
- SK+T2K (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$ (-3.8 exp. for SK best, -3.1 for combined best)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -5.2 or less is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4). NH: 0.43 ($\sin^2\theta_{23}$=0.6)

Tau Appearance Analysis

- Detection of tau appearance induced by $\nu_\mu \rightarrow \nu_\tau$ oscillation is critical component of verifying 3-flavor mixing
- Expected rate: ~1 event per kt yr at Super-K due to production threshold
- Search for hadronic modes of tau decay (branching ratio: 65%)
- Utilize Neural Network (NN) method to discriminate tau signal from BG





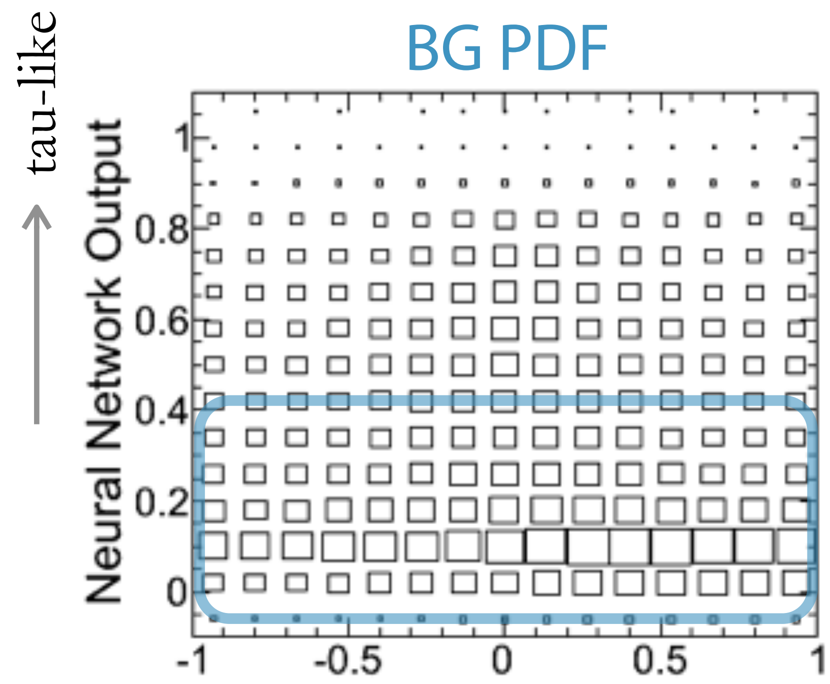
Tau Updated Result

- Perform 2-D un-binned fit with tau signal and BG PDFs :

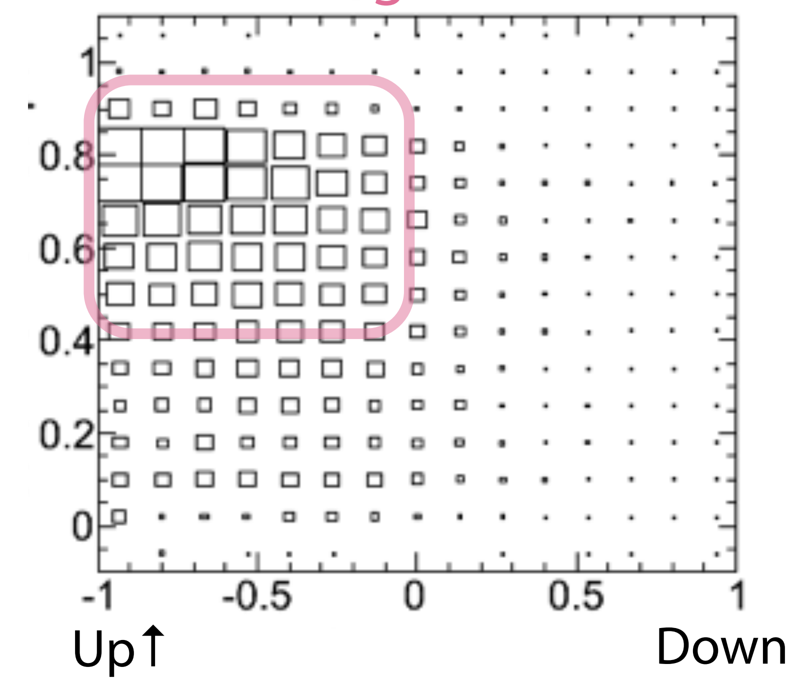
$$N_{ij}^{\mathrm{BG}} + \alpha \times N_{ij}^{\mathrm{Signal}}$$

- Signal is expected in upward direction and large NN output
- Introduce variation of syst. error in fit, and θ_{23}, θ_{13}, Δm^2 uncertainties are taken into account

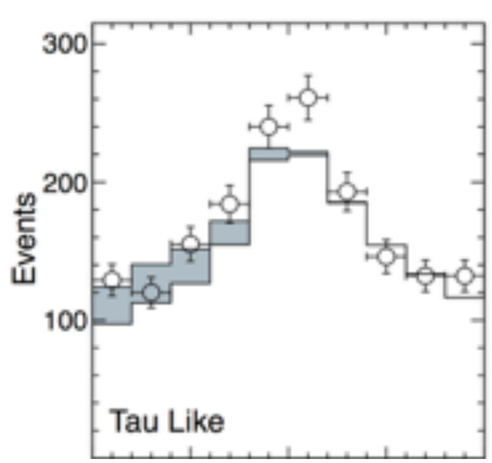
BG PDF



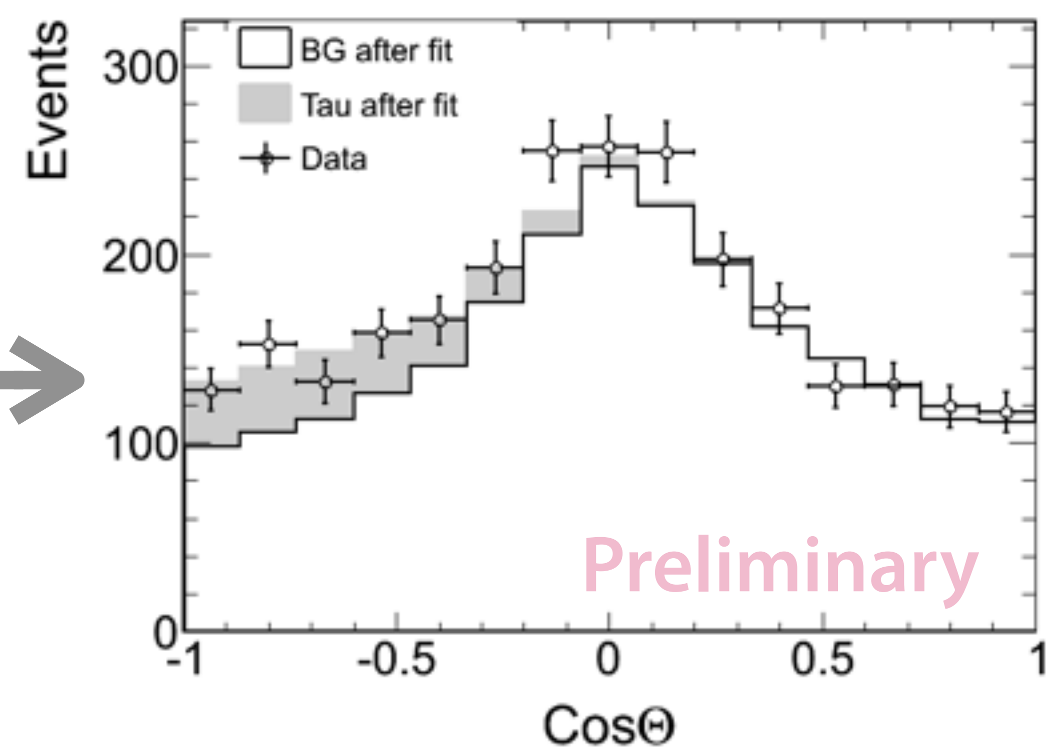
Tau Signal PDF



PRL 110, 181802 (2013)



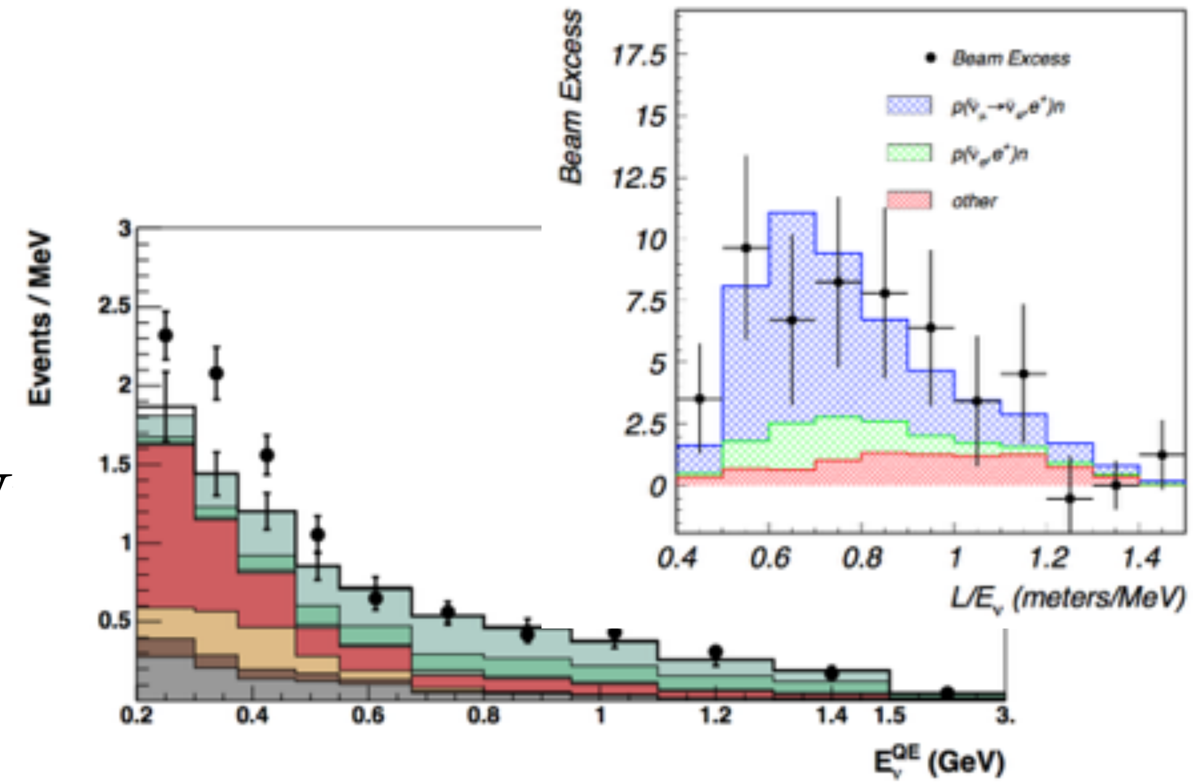
2806 days livetime
α=1.42+/-0.35(stat)+0.14-0.12(sys)
3.8σ (2.7σ expected)

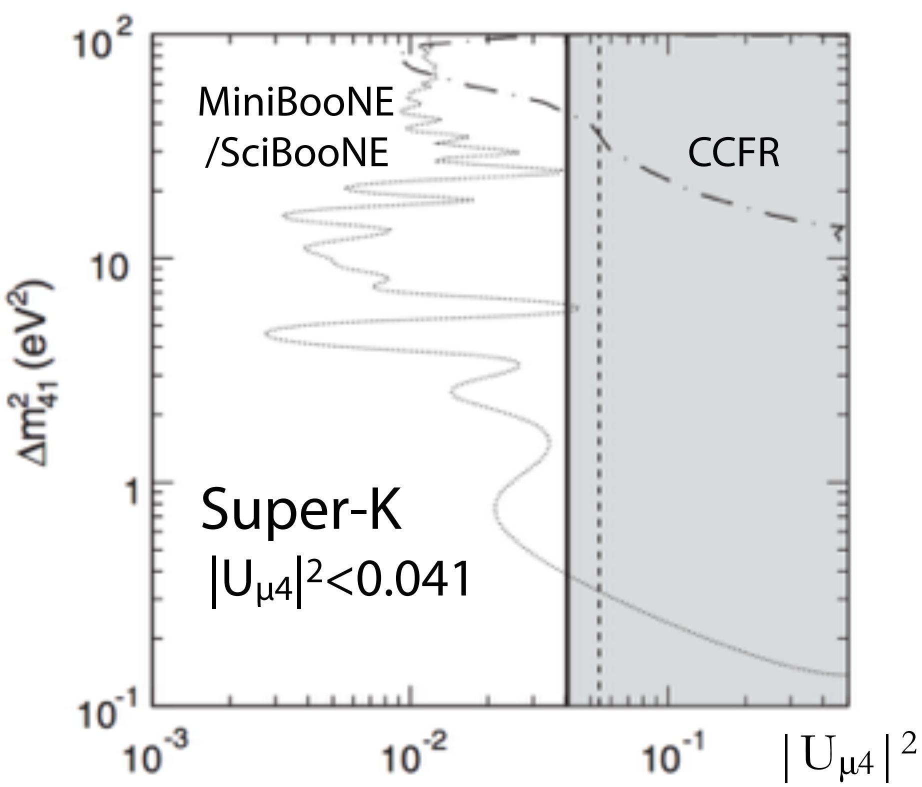


- Fit result:
  - $\alpha = 1.47 \pm 0.32$
  - 4.6σ (3.3σ expected)
- Signal excess becomes more evident, and significance increased

Sterile Analysis in Atmospheric

- Several supporting evidence of sterile neutrino from SBL
- Indicating sterile mass of $\Delta m^2 > 0.1$eV

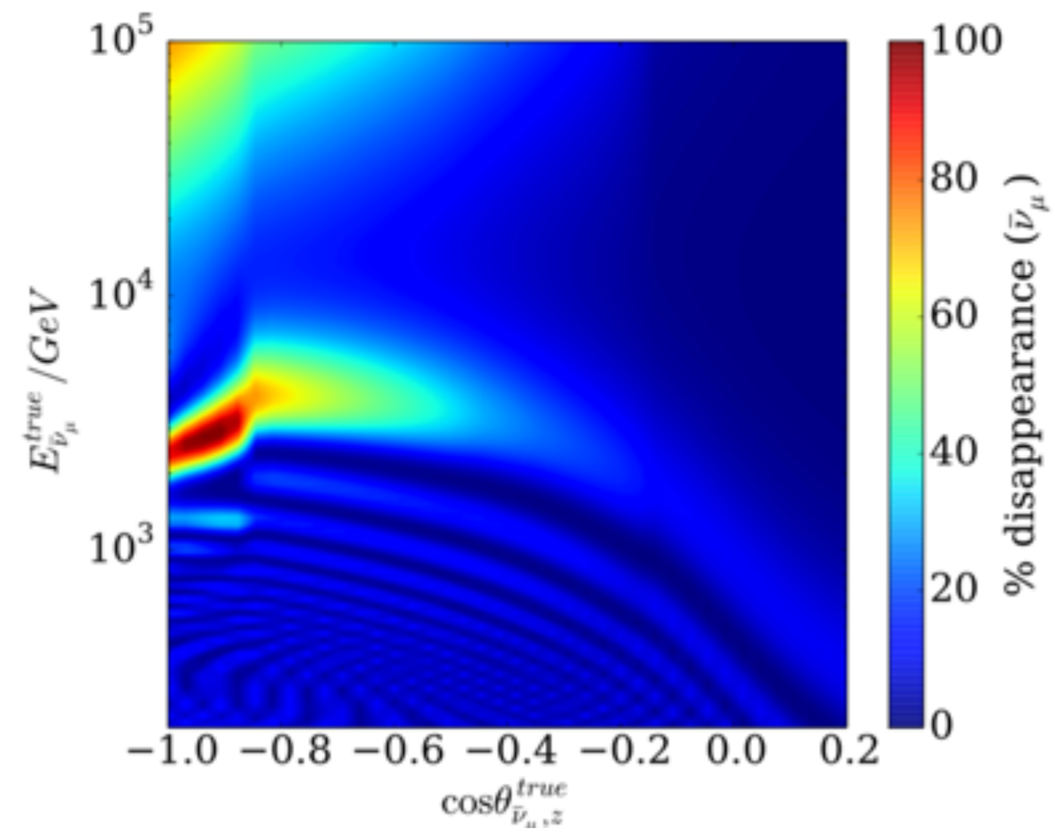


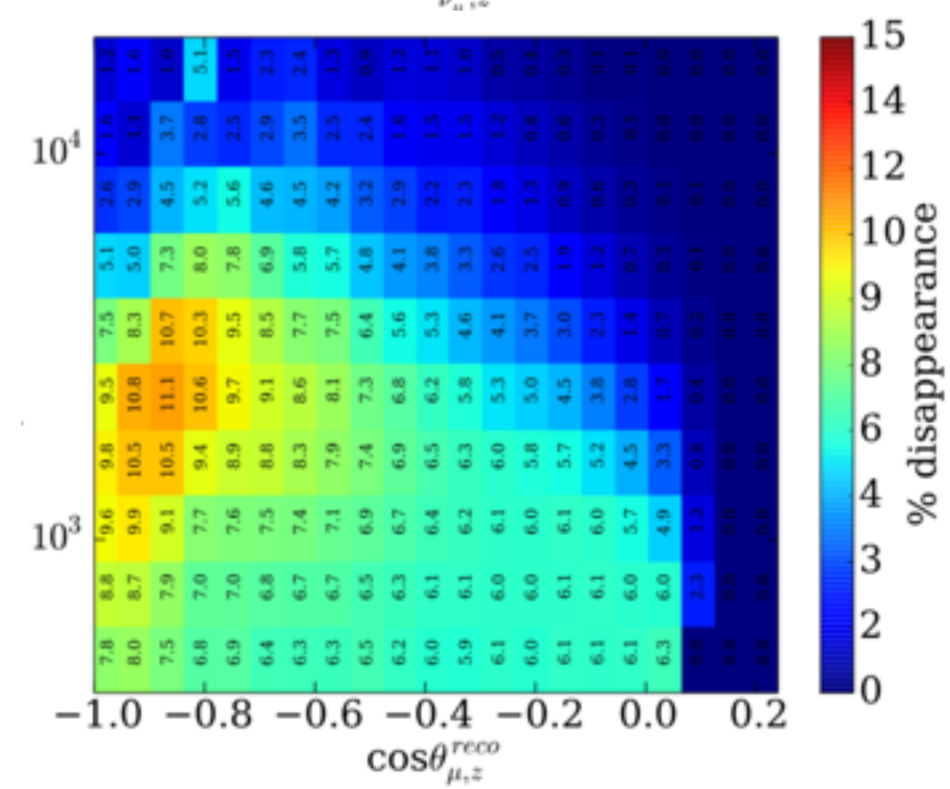


- Possible to probe sterile oscillation with atmospheric neutrinos
- Super-K gave constraint on sterile mixing parameters in 3+1 model ($|U_{\mu4}|^2$, $|U_{\tau4}|^2$) for sterile mass of $\Delta m^2 > 0.1$eV^2
  - Phy. Rev. D91, 052019 (2015)

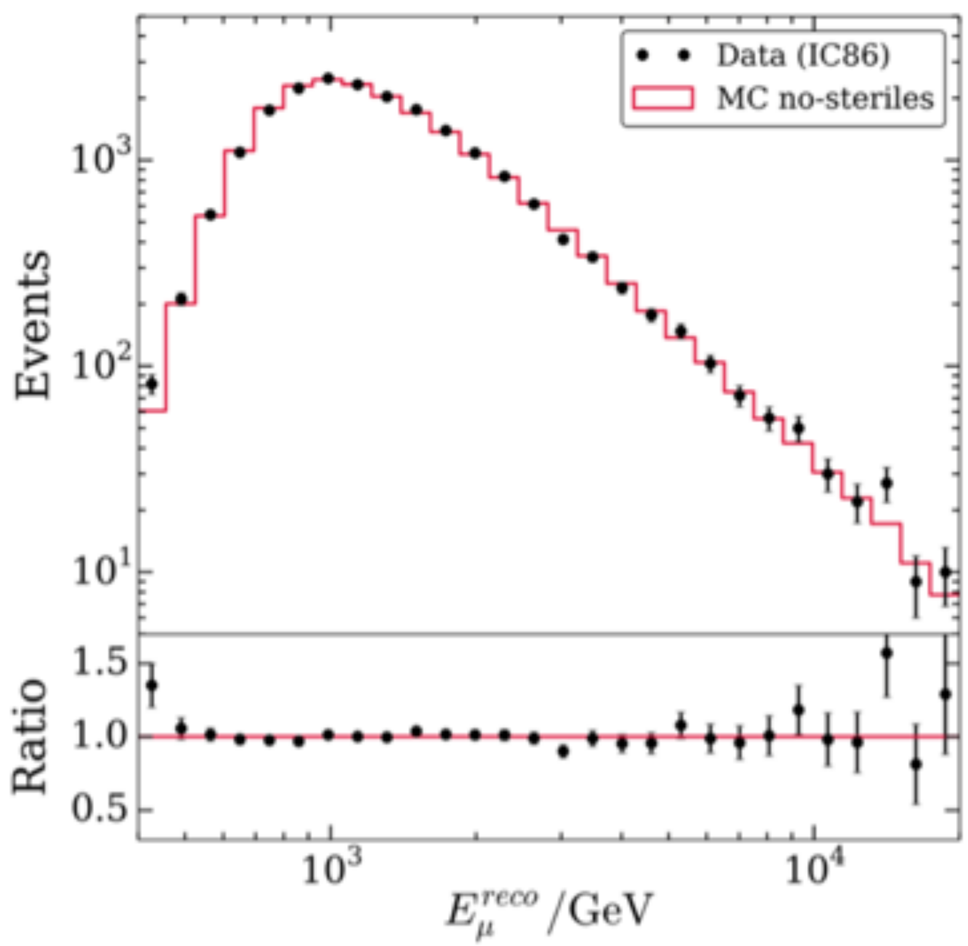
New Sterile Search by IceCube

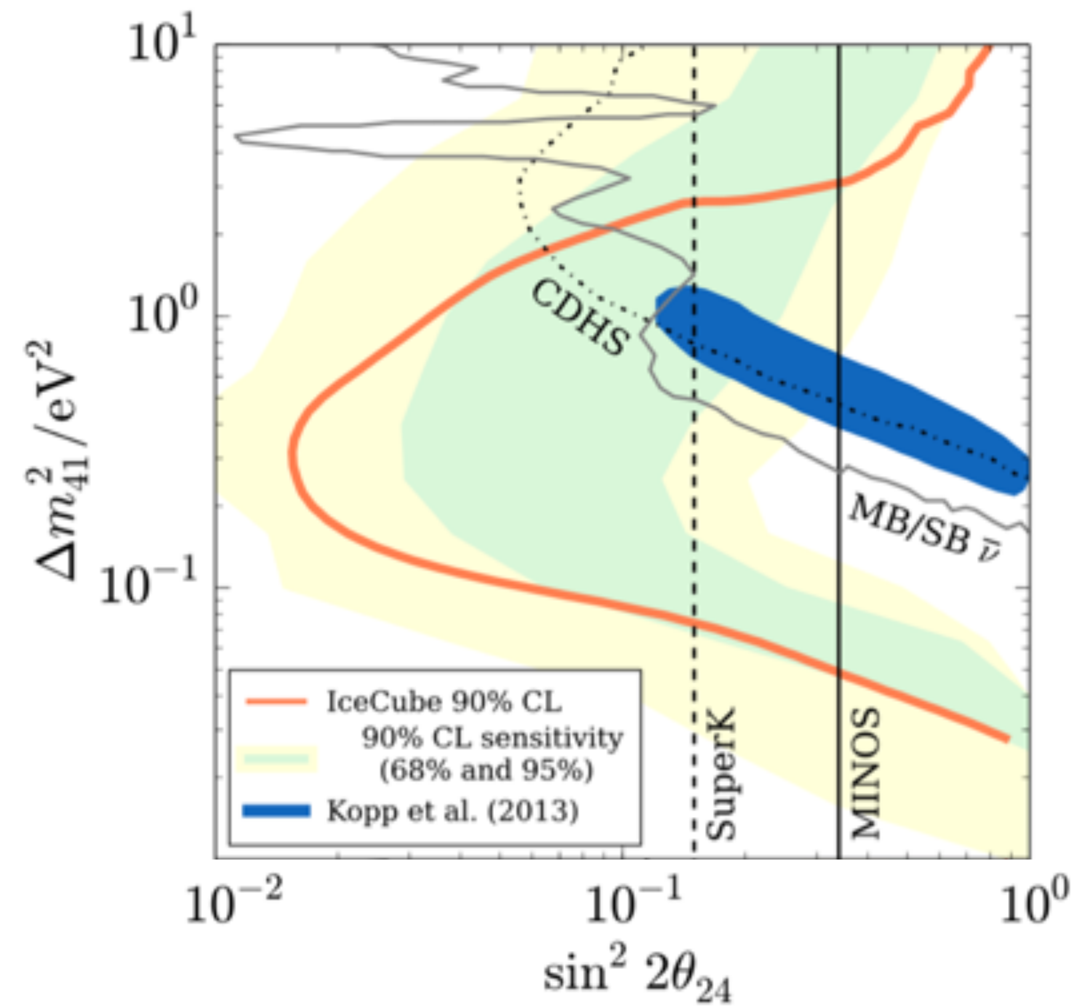
- IceCube performed searches for sterile neutrinos with Δm^2 between 0.1 and 10 eV^2 with help of matter effect
- Sterile has different forward-scattering potential from active ν in matter, and similar resonance to $\nu_\mu \rightarrow \nu_e$ could occur in 320 GeV - 20 TeV depending on sterile Δm^2
- This resonant oscillation would produce distinctive signature in ν_μ energy spectrum
- Resonance appears either for ν or $\bar{\nu}$ depending on sterile mass hierarchy





IceCube Constraint on Sterile





- No significant distortions were seen in muon neutrino spectrum
- Δm^2-dependent constraint on θ_{24} is obtained assuming no other sterile mixing parameters
- Reject allowed region indicated by 3+1 sterile model
  - Phys. Rev. Lett. 117 071801 (2016)
  - See also talk by J-P Yanez

Future Prospect

See also

Hyper-Kamiokande
Talk by T. Feusels, KEK Preprint 2016-21

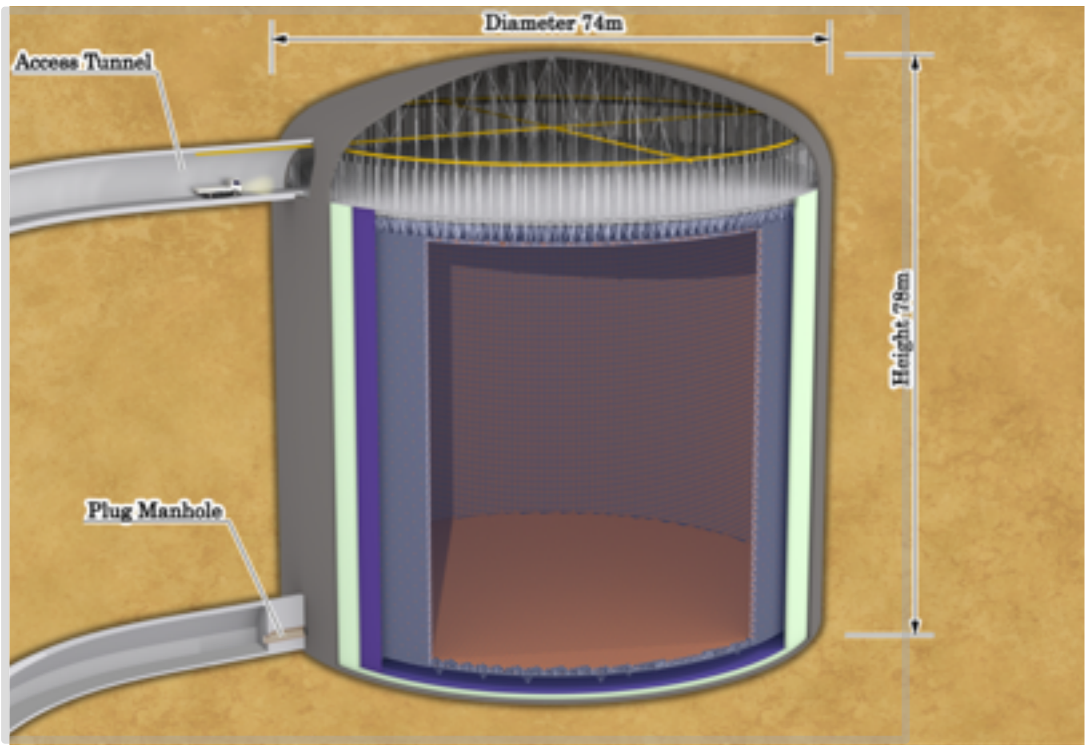
DUNE
Talk by J. Bian, arXiv:1512.06148

INO/ICAL
Talk by N. Majumdar, arXiv:1505.07380

IceCube/PINGU
Talk by J-P Yanez, arXiv:1607.02671

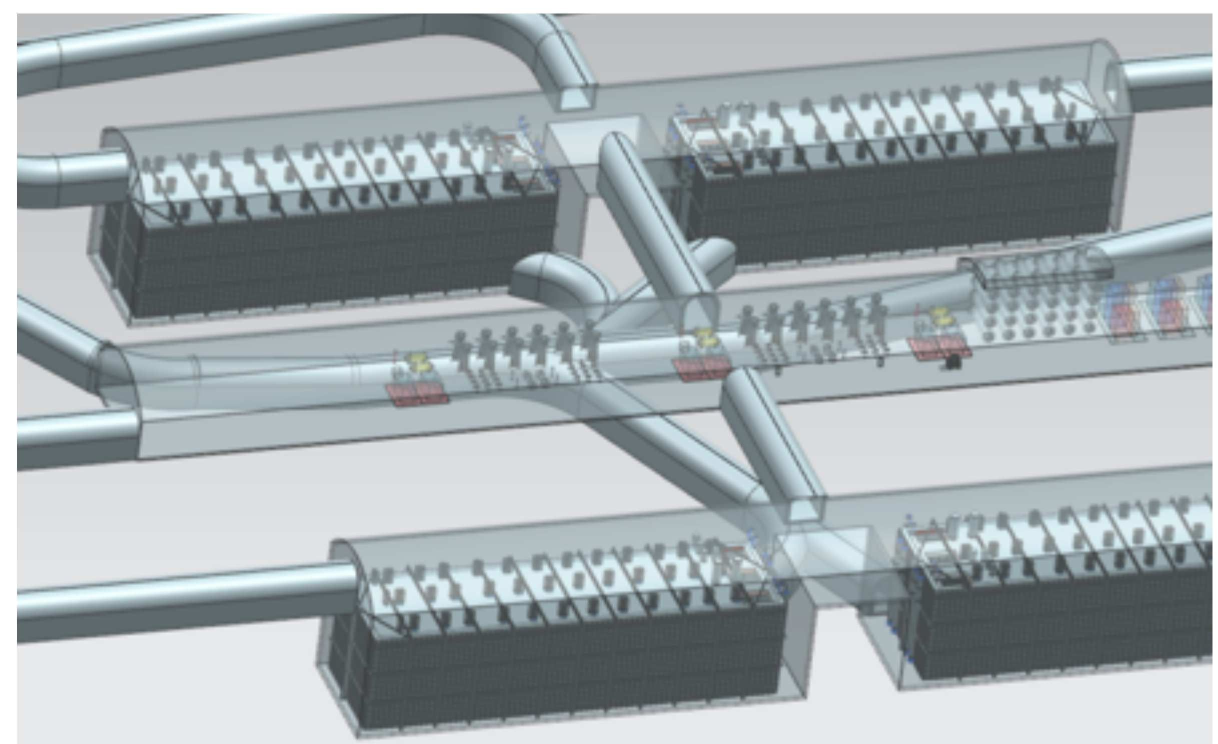
KM3NeT/ORCA
Talk by M. Circella, arXiv:1601.07459

Hyper-K & DUNE

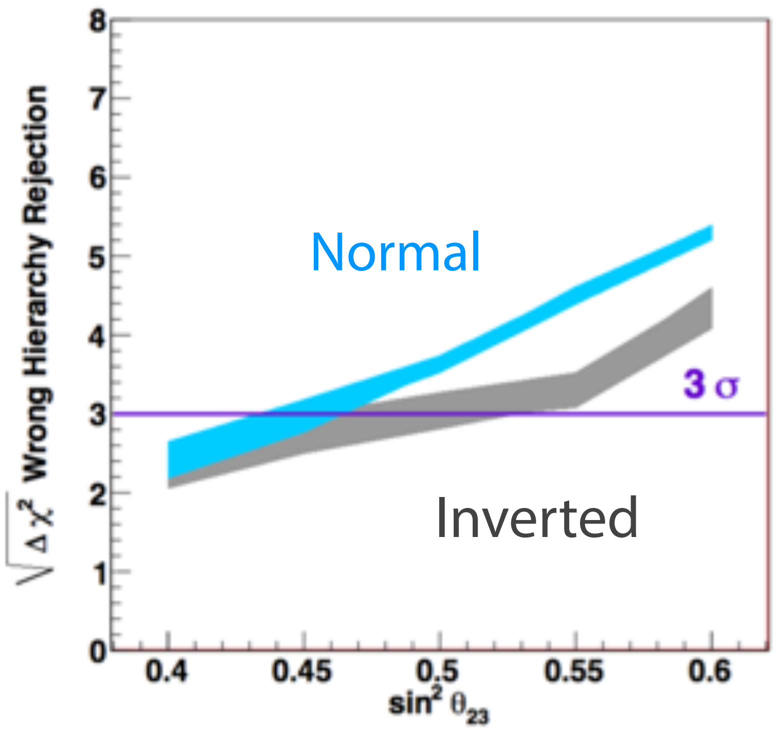


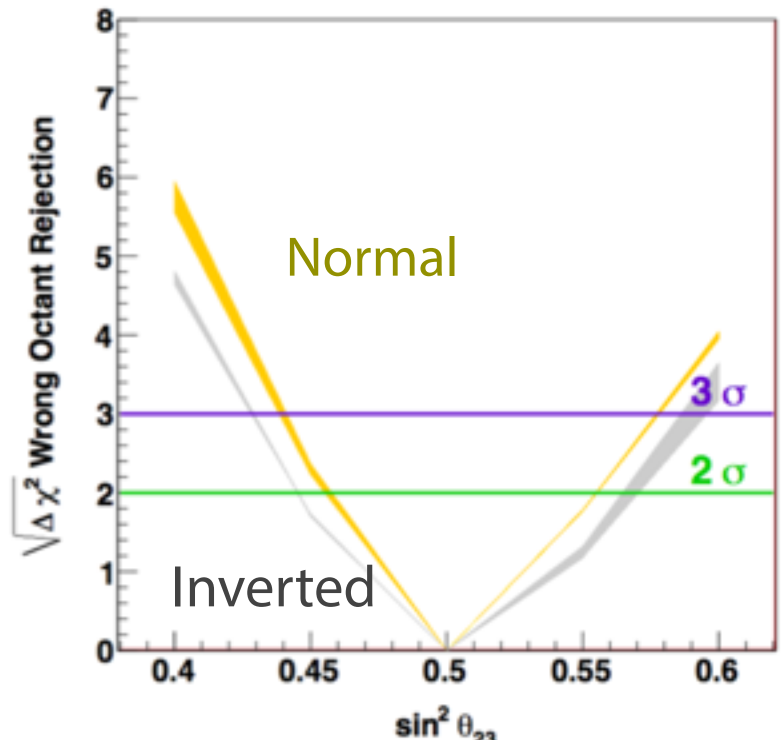
- Hyper-Kamiokande is next generation water Cherenkov detector
- Compared to Super-K, ~25 times atmospheric neutrino rate is expected with 560 kton fiducial volume

- DUNE is liquid argon based time projection chamber
- Though fiducial mass is relatively small, high resolution imaging would offer possibilities to discriminate ν and $\bar{\nu}$



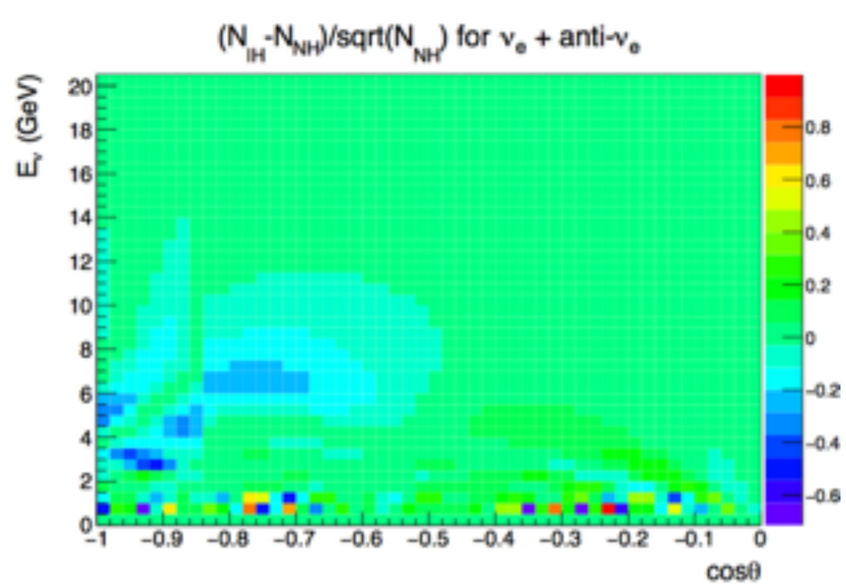
Hyper-K & DUNE Sensitivities

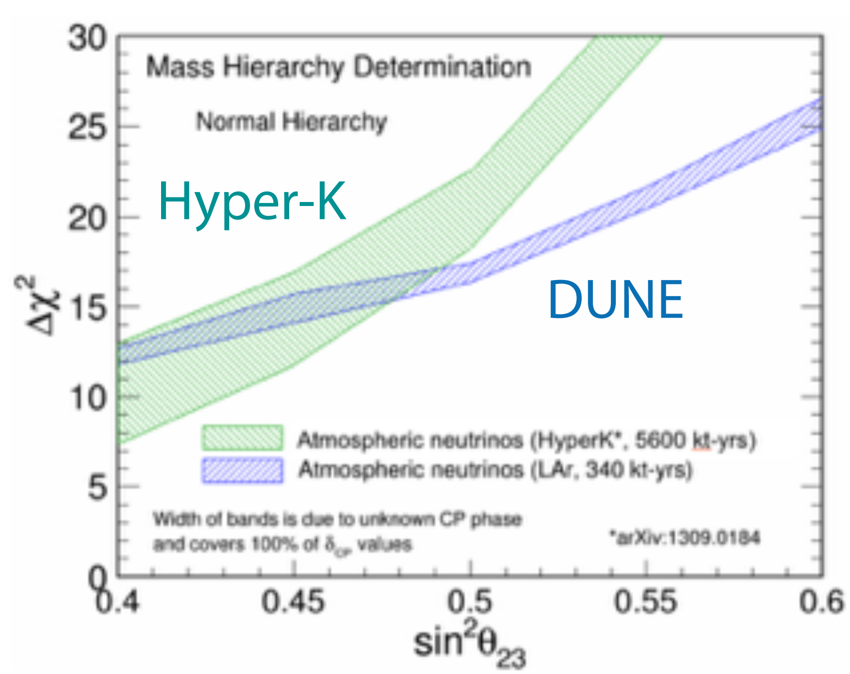




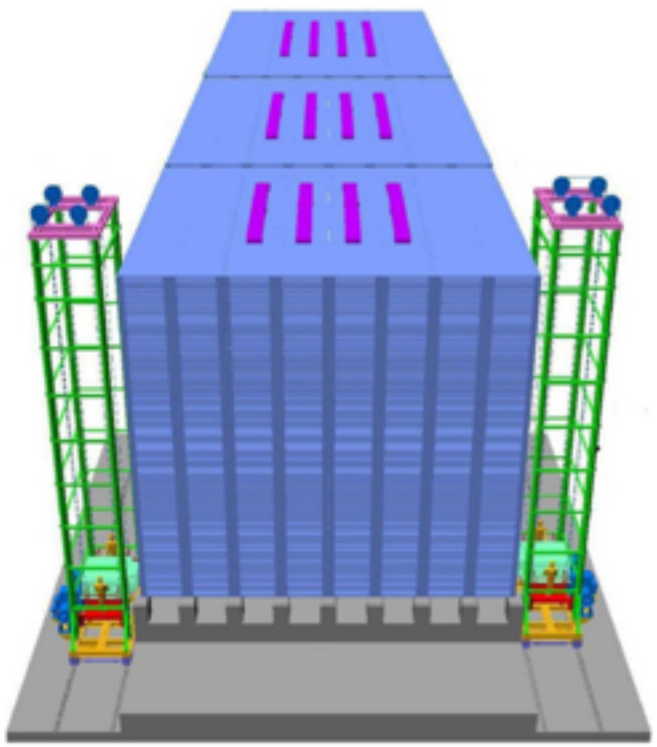
- Hyper-K expects >3σ sensitivity for both MH cases for $\sin^2\theta_{23}$>0.45 with 10yr data (2.6Mtonyr)
- Possible to discriminate θ_{23} octant at >3σ for $|\theta_{23}$-45$|$>4deg

- Despite smaller mass, Dune would have comparable MH sensitivity to Hyper-K due to high detector resolution

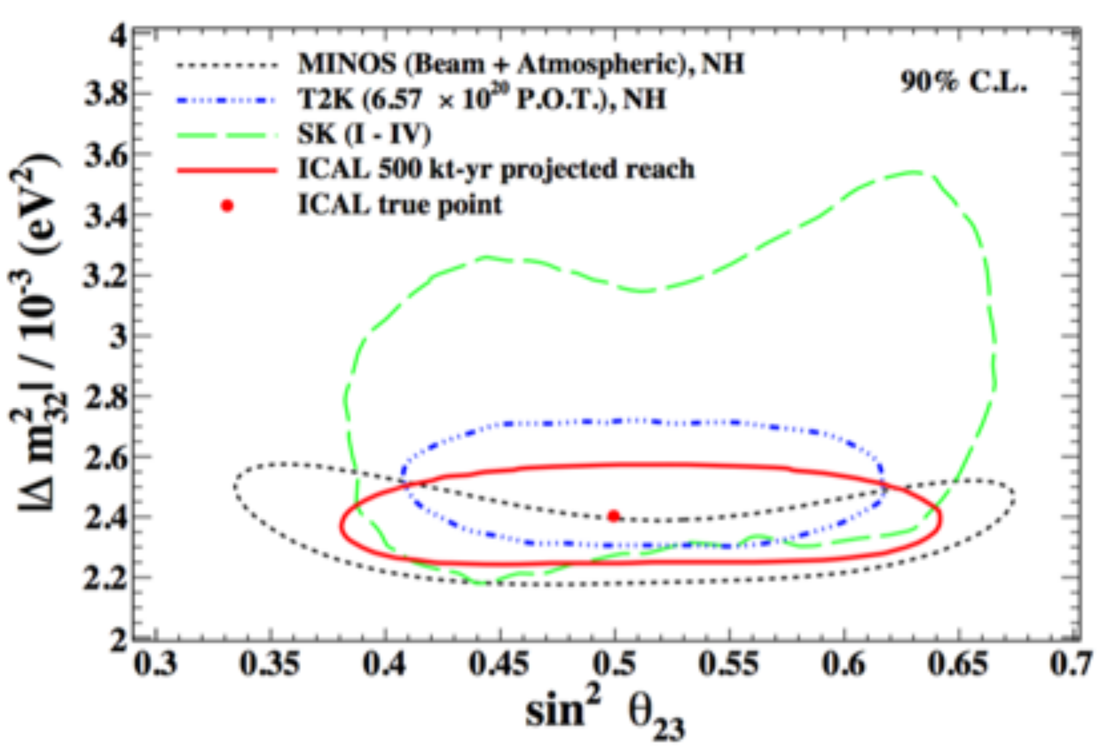


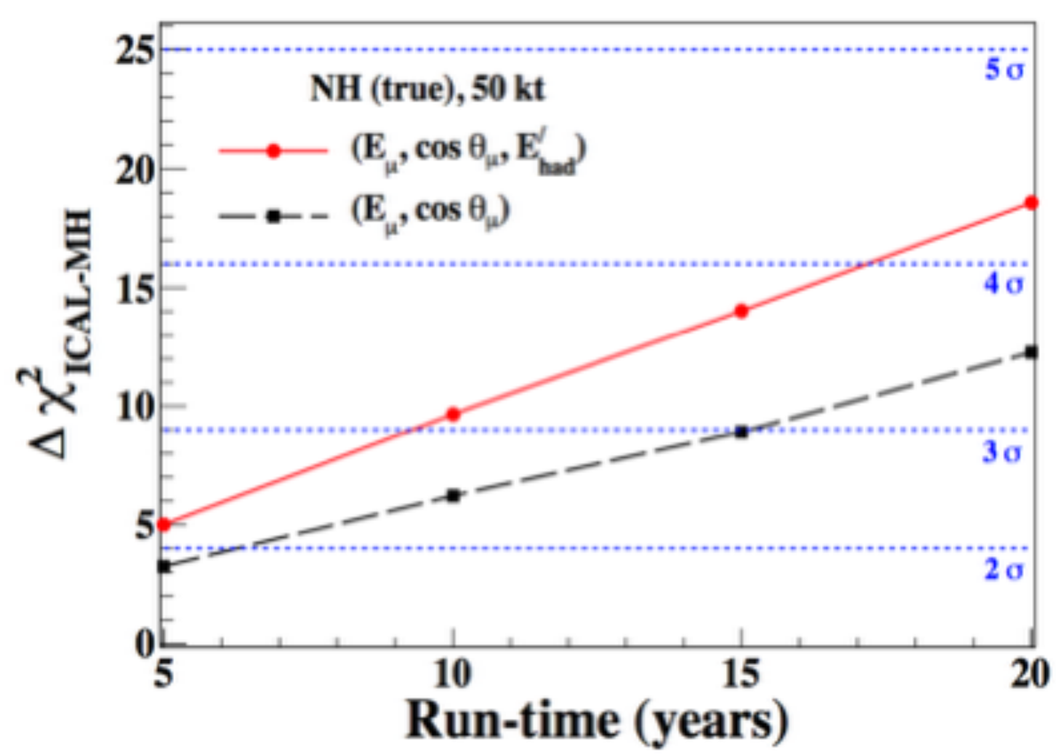


INO / ICAL

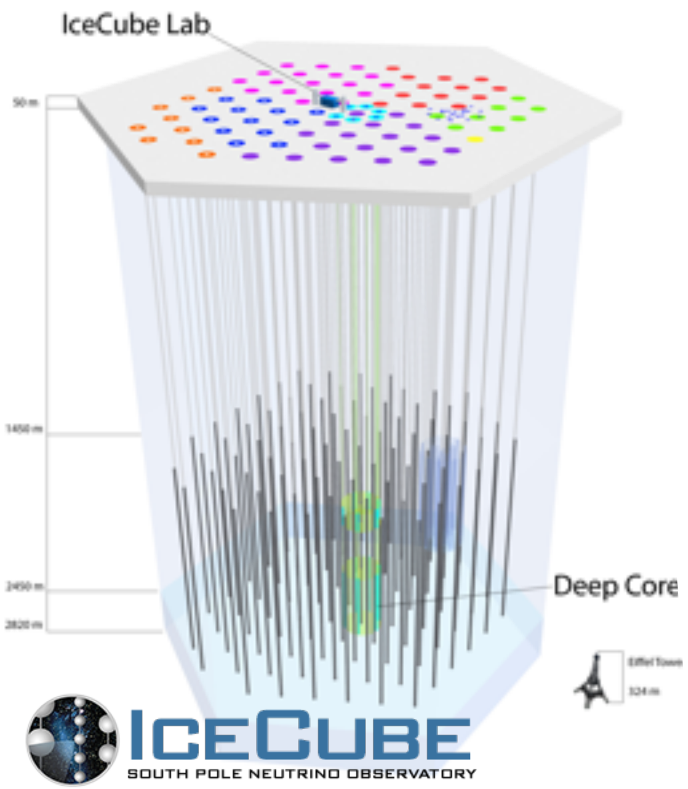


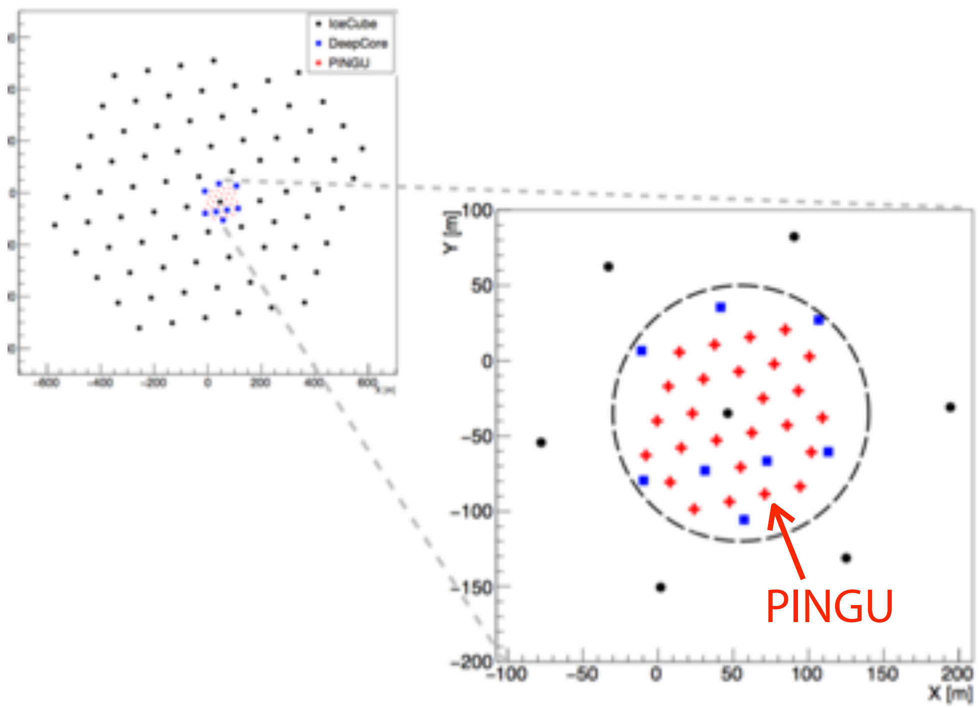
- Magnetized Iron Calorimeter (ICAL) composed of resistive plate chamber (RPC) in India
  - 48x16x14.5 m, 50 kton mass
- ν and $\bar{\nu}$ discrimination by muon charge
- Expect MH determination at 2.2σ using 10 yr data (3σ if hadron information is introduced)





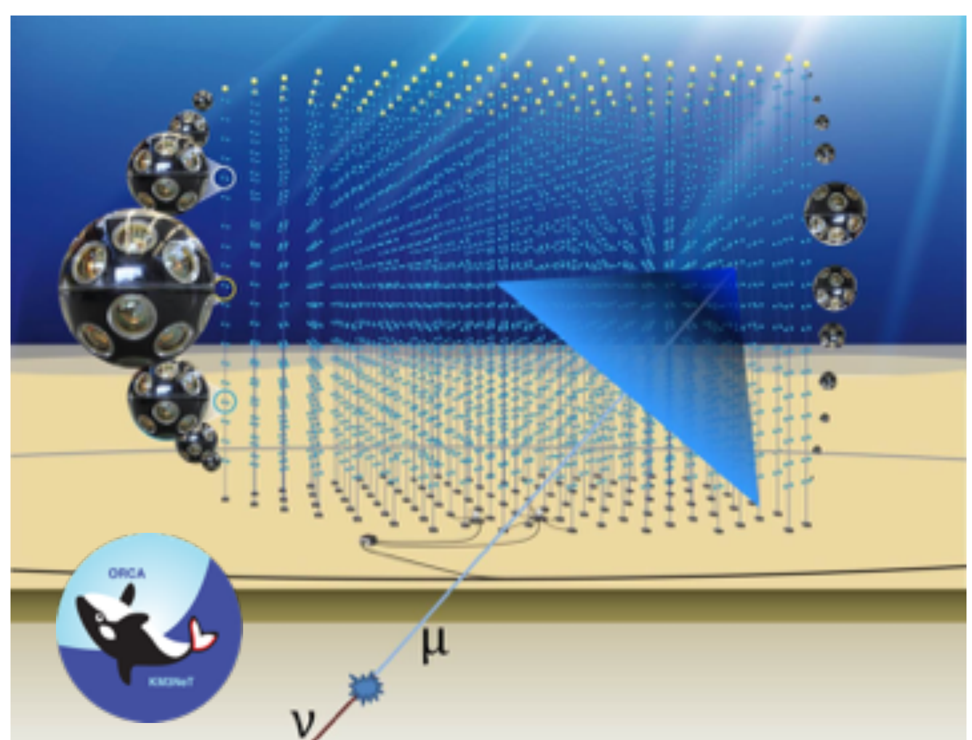
IceCube/PINGU, KM3NeT/ORCA

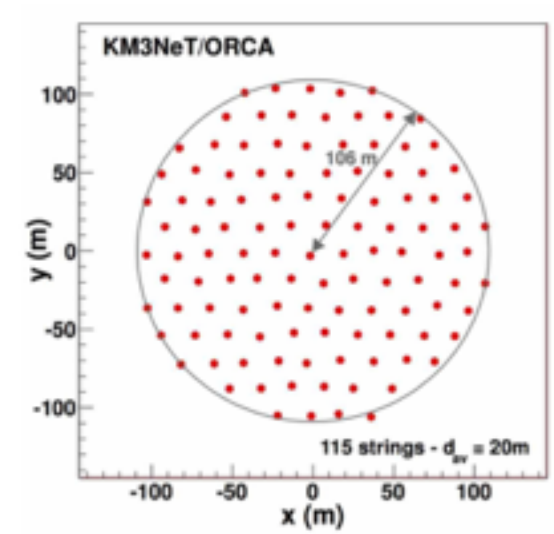




- PINGU is inner detector configuration of IceCube/ DeepCore at South pole
  - 6 Mton effective mass
- Lower threshold below 10 GeV with 22 m spacing of string
- Expect ~60,000 atm. ν event per year

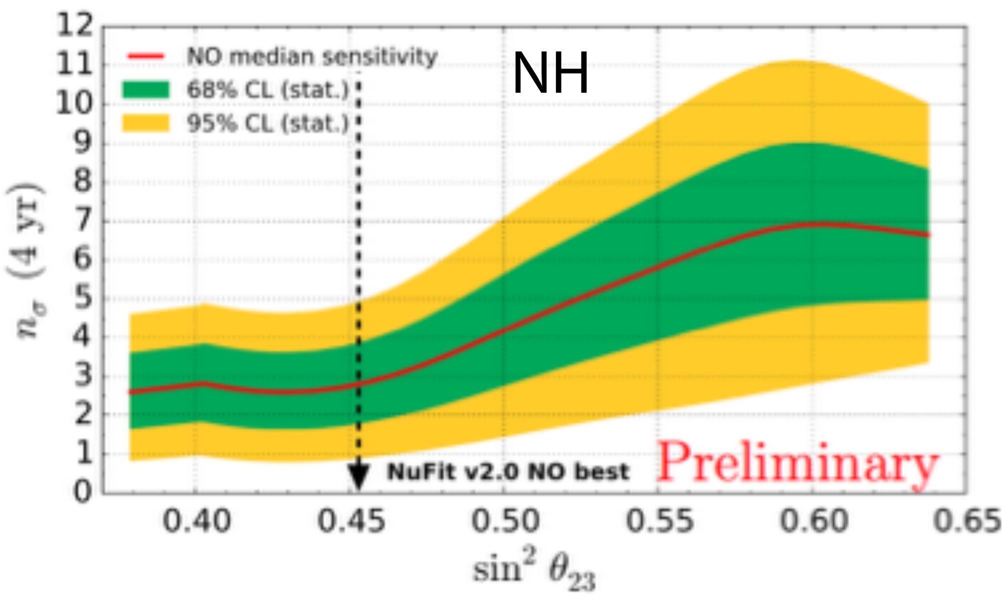
- ORCA is low energy branch of KM3NeT in Mediterranean Sea
- Dense array of multi-PMT digital optical modules (DOMs)

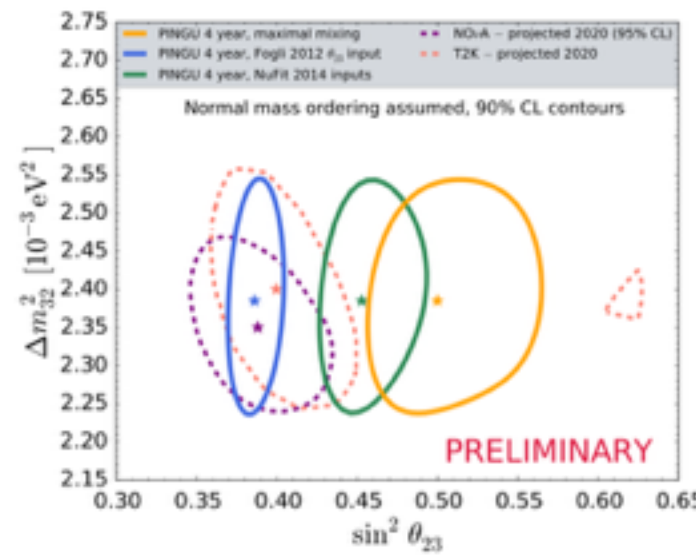


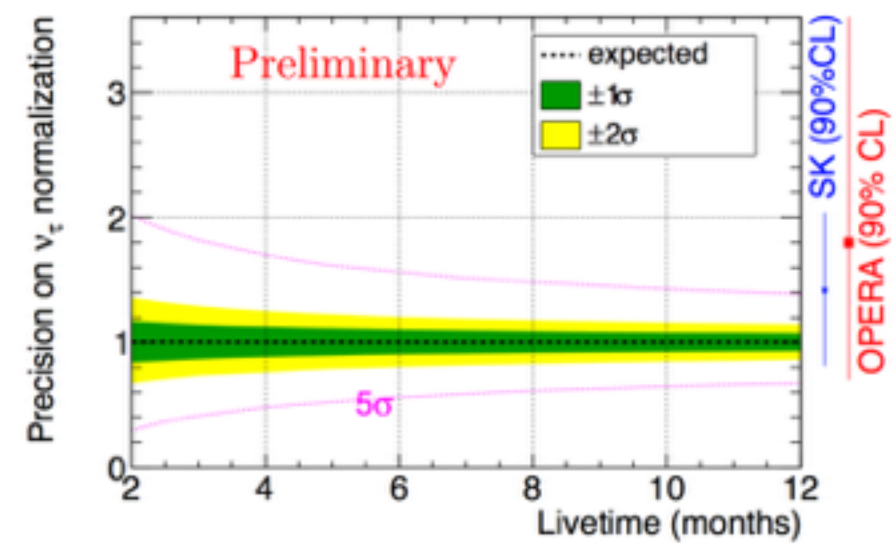


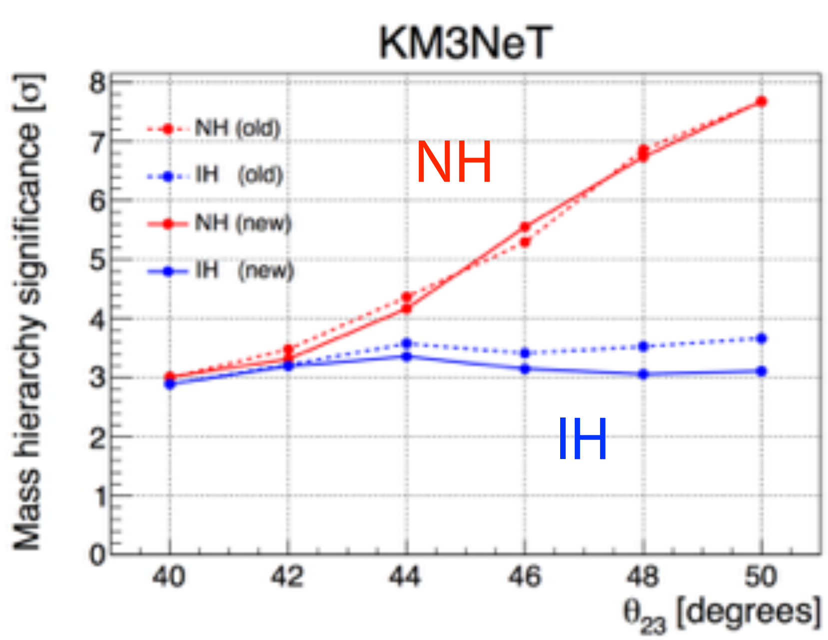
	ARCA	ORCA
Location	Italy	France
String dist. [m]	90	20
DOM spacing [m]	36	6
Volume [10^6 m^3]	~500	~3.8

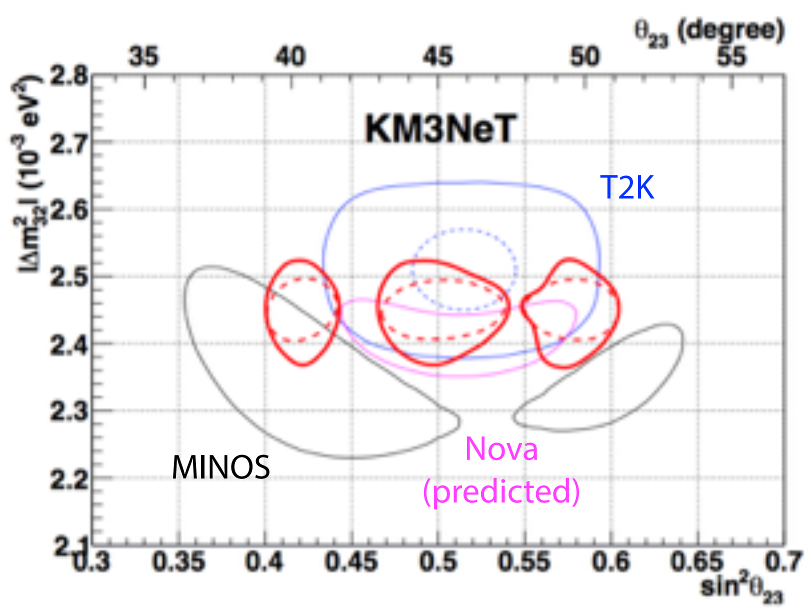
PINGU / ORCA Sensitivities











- Both experiments have similar sensitivity
  - Could reach 3σ for MH within allowed θ_{23} range
- Precise determination of tau appearance is expected for PINGU

Conclusion

- Measurement of atmospheric neutrino oscillation are attractive and effective method to fully understand neutrino oscillation paradigm
- There are several progresses in on-going experiments
  - Significances of mass hierarchy and tau appearance are strengthened in Super-K
  - New sterile constraint is given by IceCube in $\Delta m_{41}^2 >\sim 0.1$ eV^2
- Future projects have enough sensitivities of mass hierarchy and θ_{23} octant determinations

END