IPMU, Nov 10. 2010

Atmospheric neutrinos (mostly results from Super-K)

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Outline

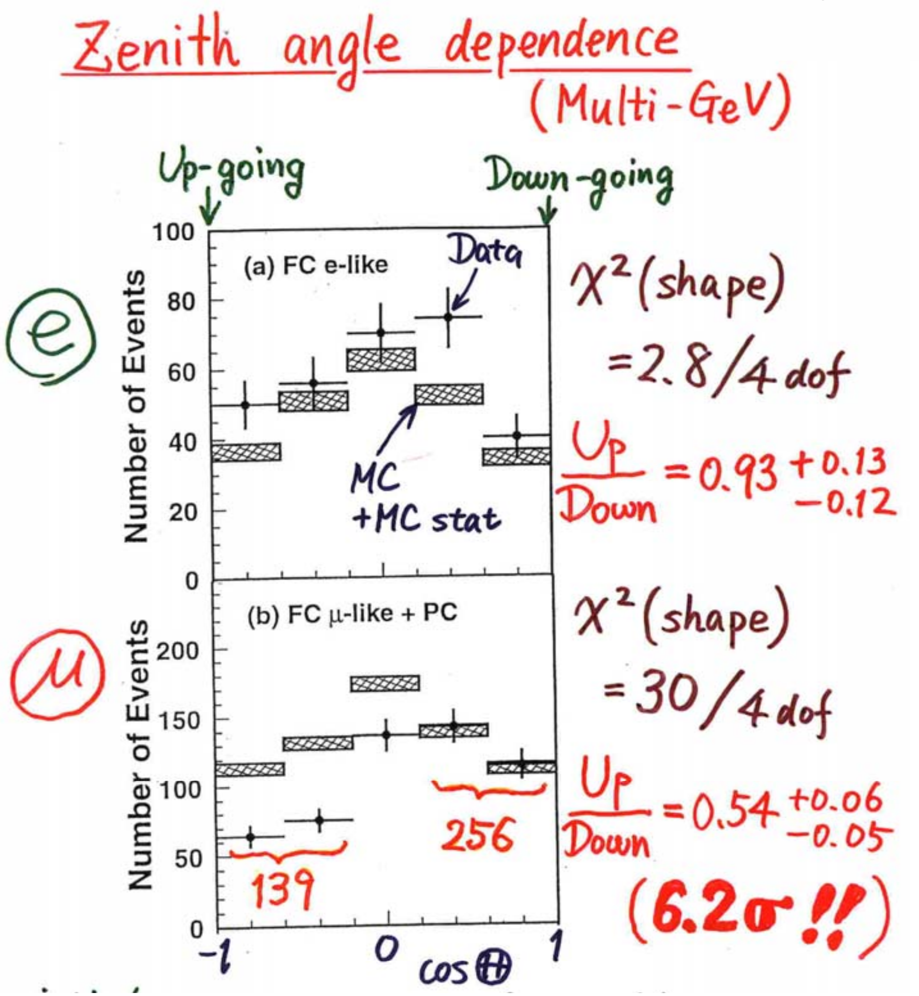
- Introduction
- Flux calculation
- Recent atmospheric neutrino data and (Δm_{23}^2, $\sin^2 2\theta_{23}$)
- 3 flavor oscillation analyses and the future prospects
- Summary

Many thanks: Super-K colleagues and M. Honda

Introduction

Super-K @Neutrino 98

535 day data



Zenith angle dependence (Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

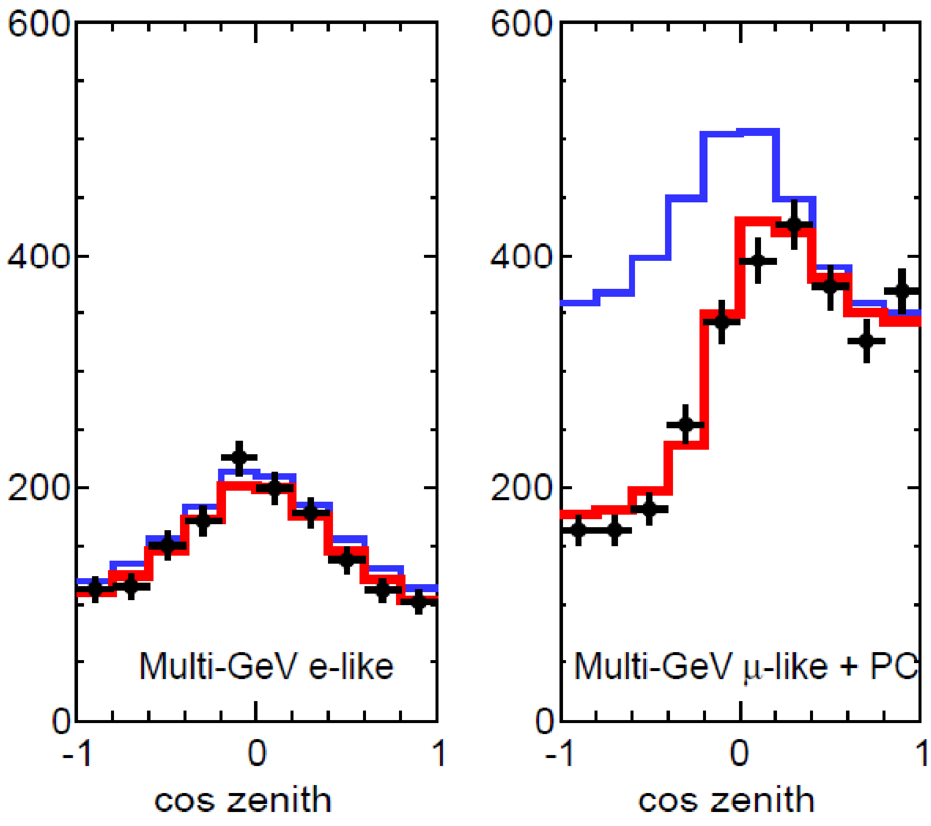
$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ !!)

Super-K 2010

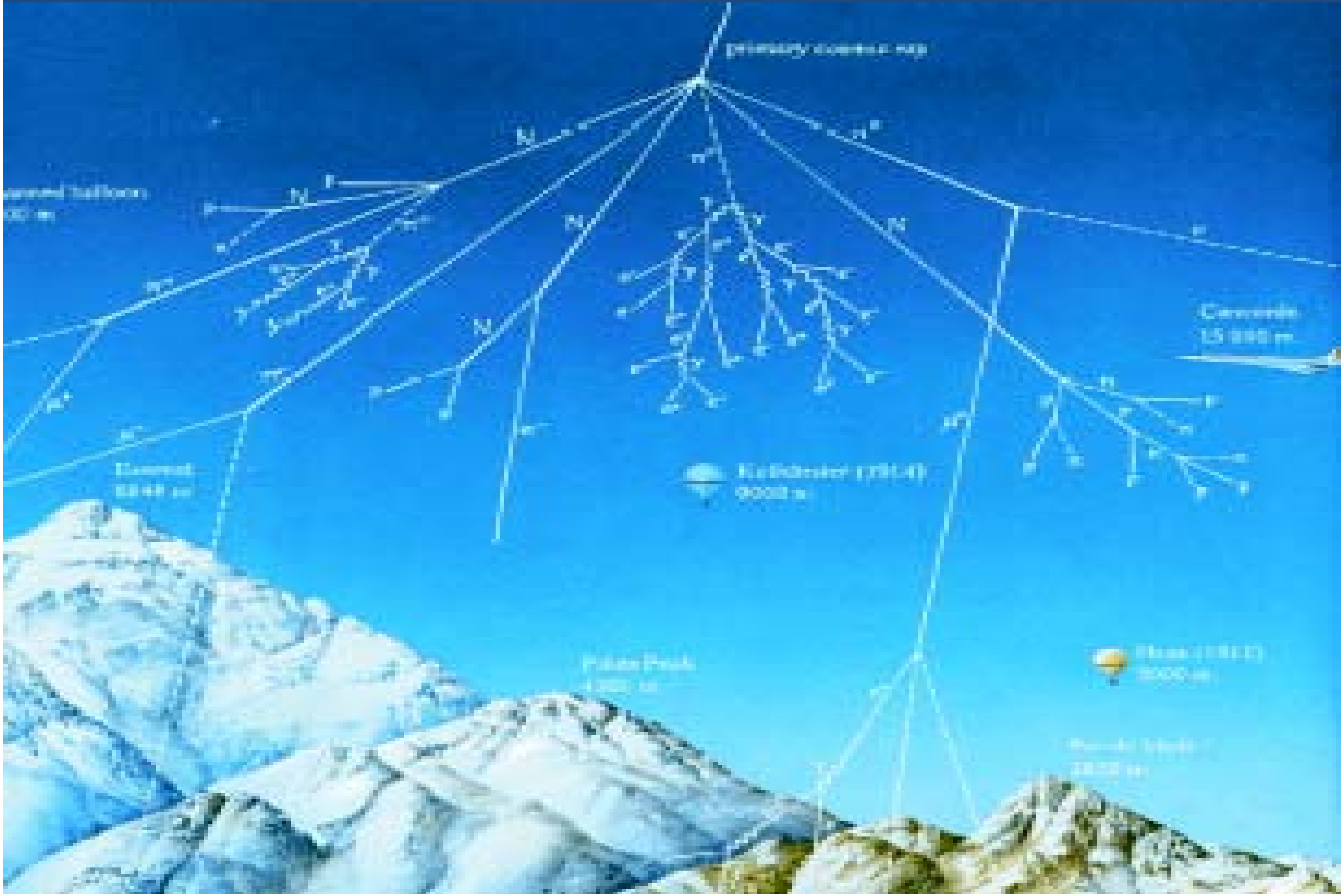
2806 day data

More than factor of 5 higher stat.



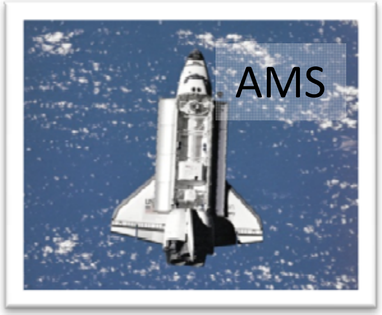
Would like to discuss most updated atmospheric neutrino analysis from Super-K.

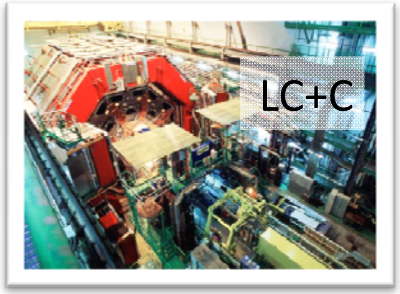
Flux calculation

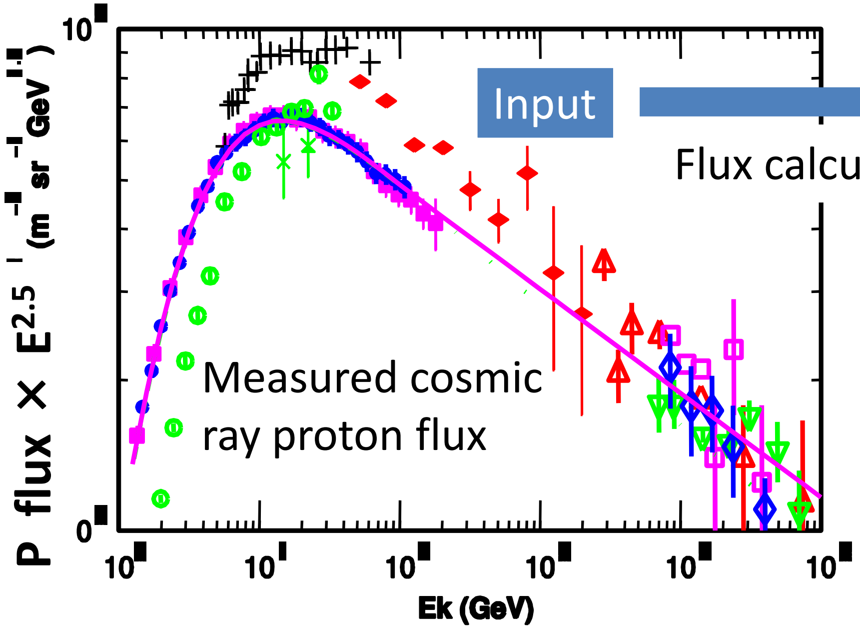


Precise cosmic ray flux measurements and flux calculation

After the discovery of oscillations, experiments have been carried out to accurately measure the cosmic ray flux, which are essential inputs to the flux calculation.



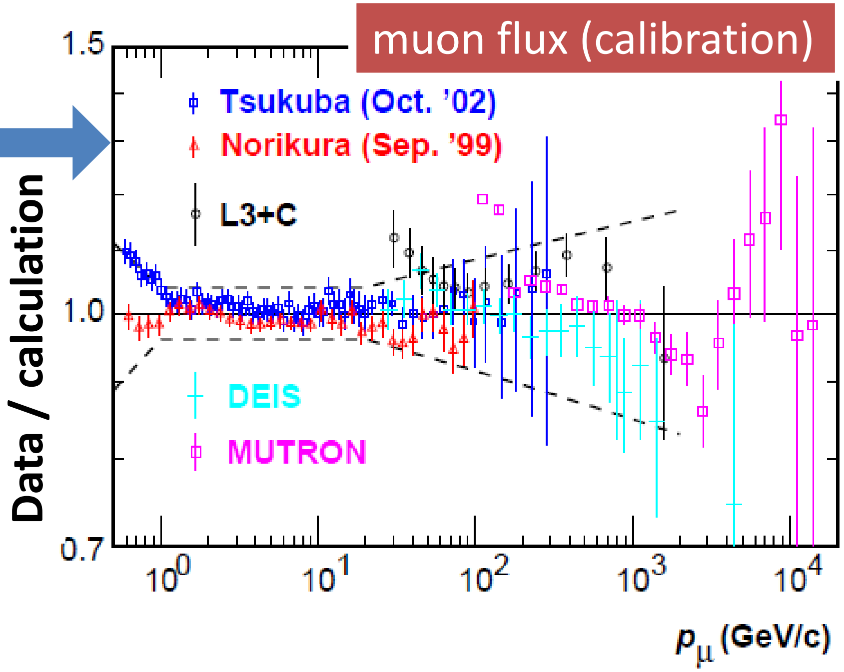




Measured cosmic ray proton flux

Input

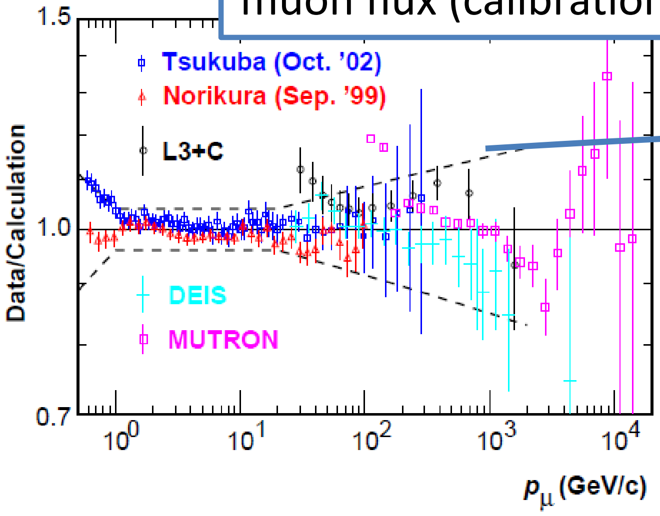
Flux calculation


muon flux (calibration)

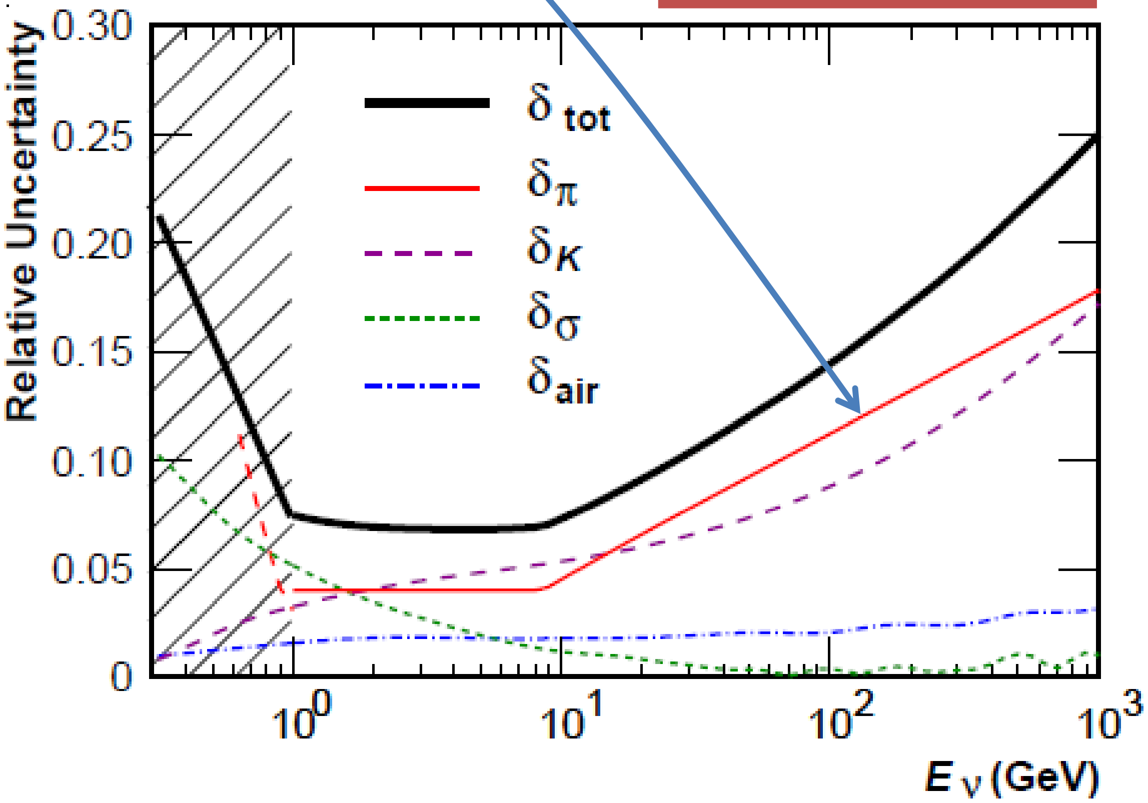
Systematic errors in the absolute flux

Honda et al., astro-ph/0611418

muon flux (calibration)



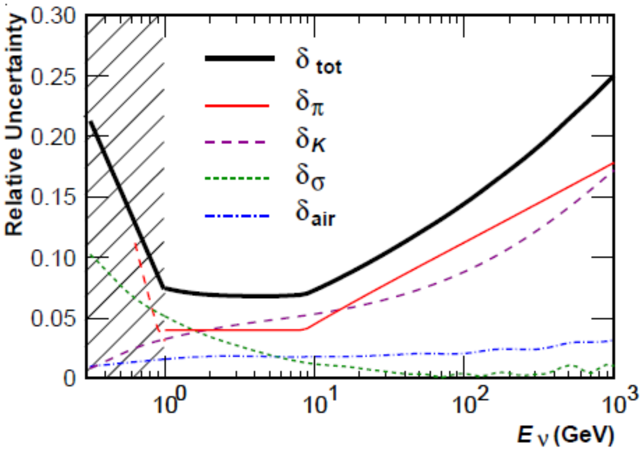
Absolute neutrino flux uncertainty



Better than 10% between
1 and 10 GeV.

Flux calculation update: Motivation

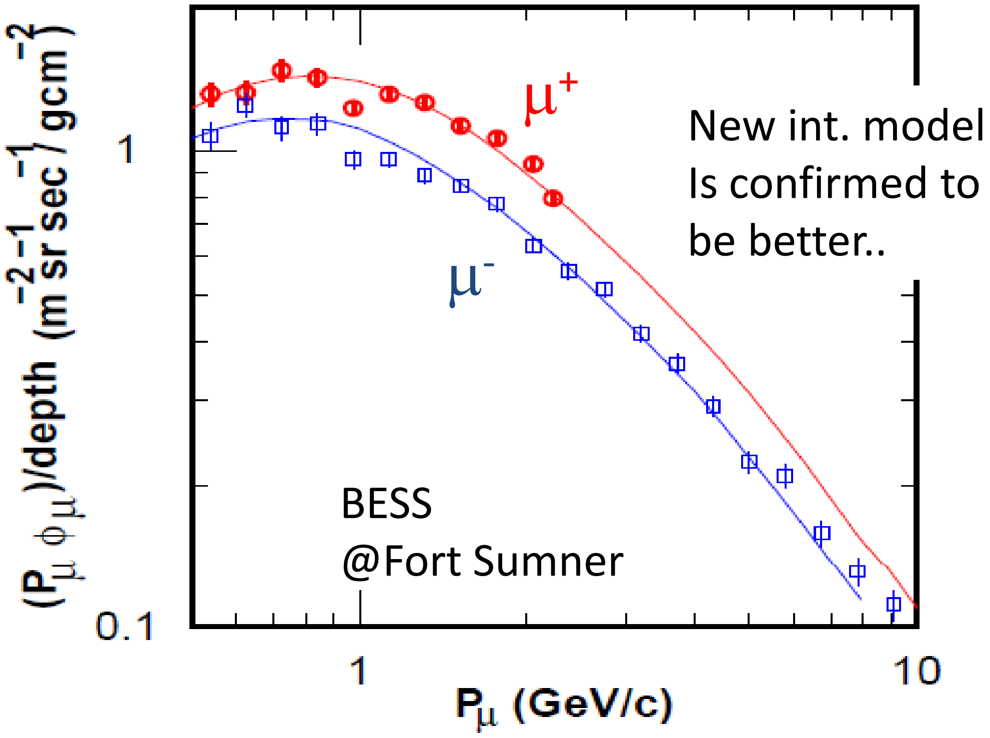
M. Honda et al., work in progress



In the previous calculation, μ flux measurements at ground level and mountain altitude (2770 meters) were used. However, these μ's are not very useful to calibrate the sub-GeV neutrino flux due to the μ energy loss (2GeV) before reaching the ground.

Update 1: Adopting recent hadronic interaction code (JAM) dedicated to the GeV energy range

Update 2: Calibration with balloon altitude muon flux data (5 – 26 g/cm^2)

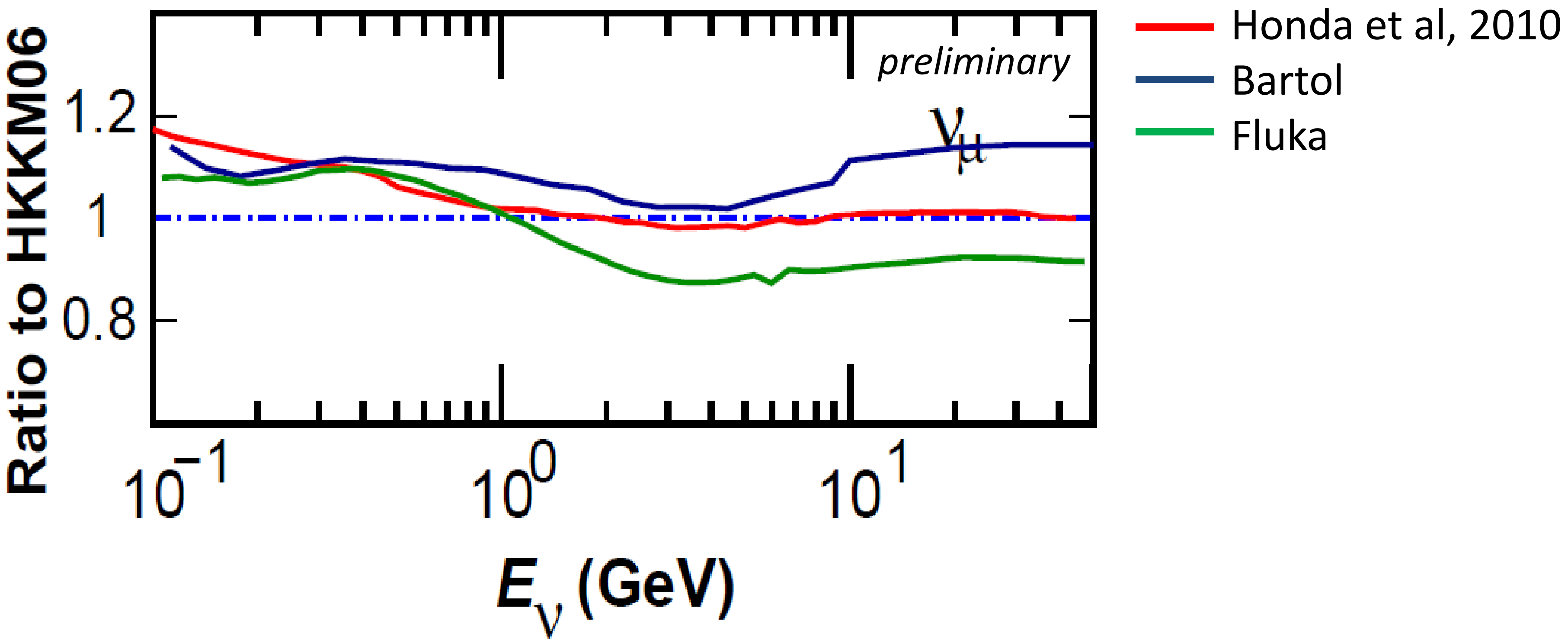


New int. model Is confirmed to be better..

BESS
@Fort Sumner

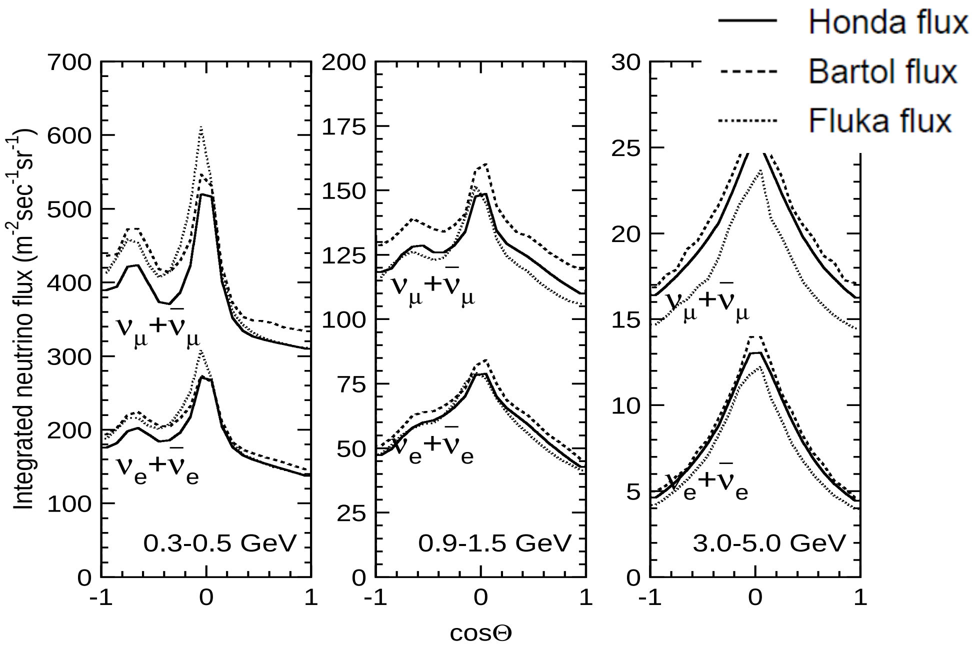
Flux calculation update

M. Honda et al., work in progress



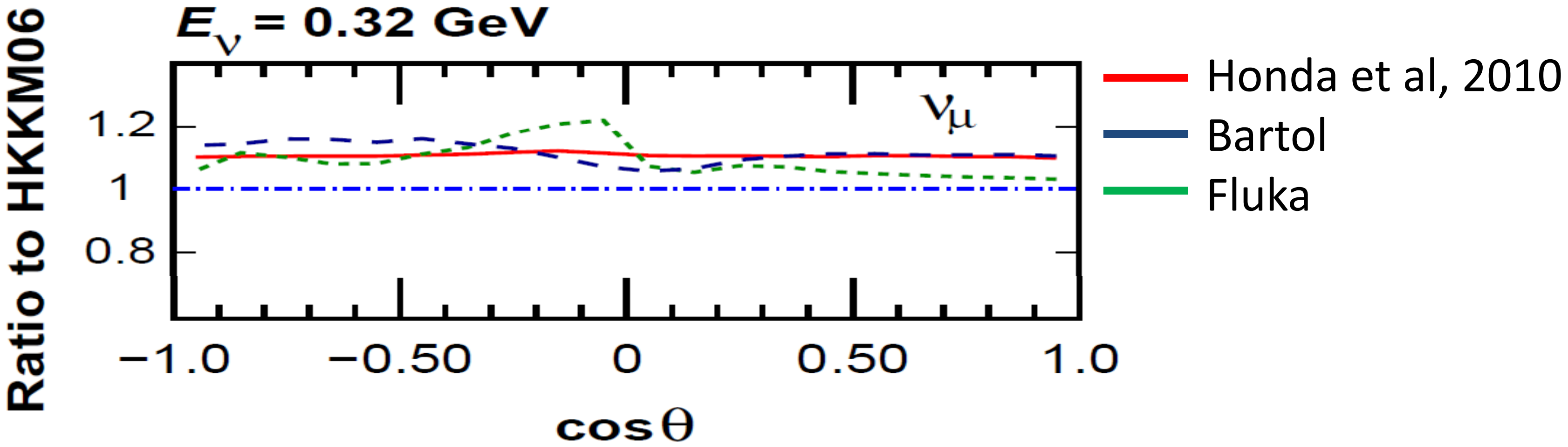
The new flux by Honda et al. is essentially identical to the previous one (as should be).
However, below 1 GeV the new calculation predicts a slightly higher flux.
New syst. error still to be evaluated

Other and more important systematic errors in the flux: zenith angle

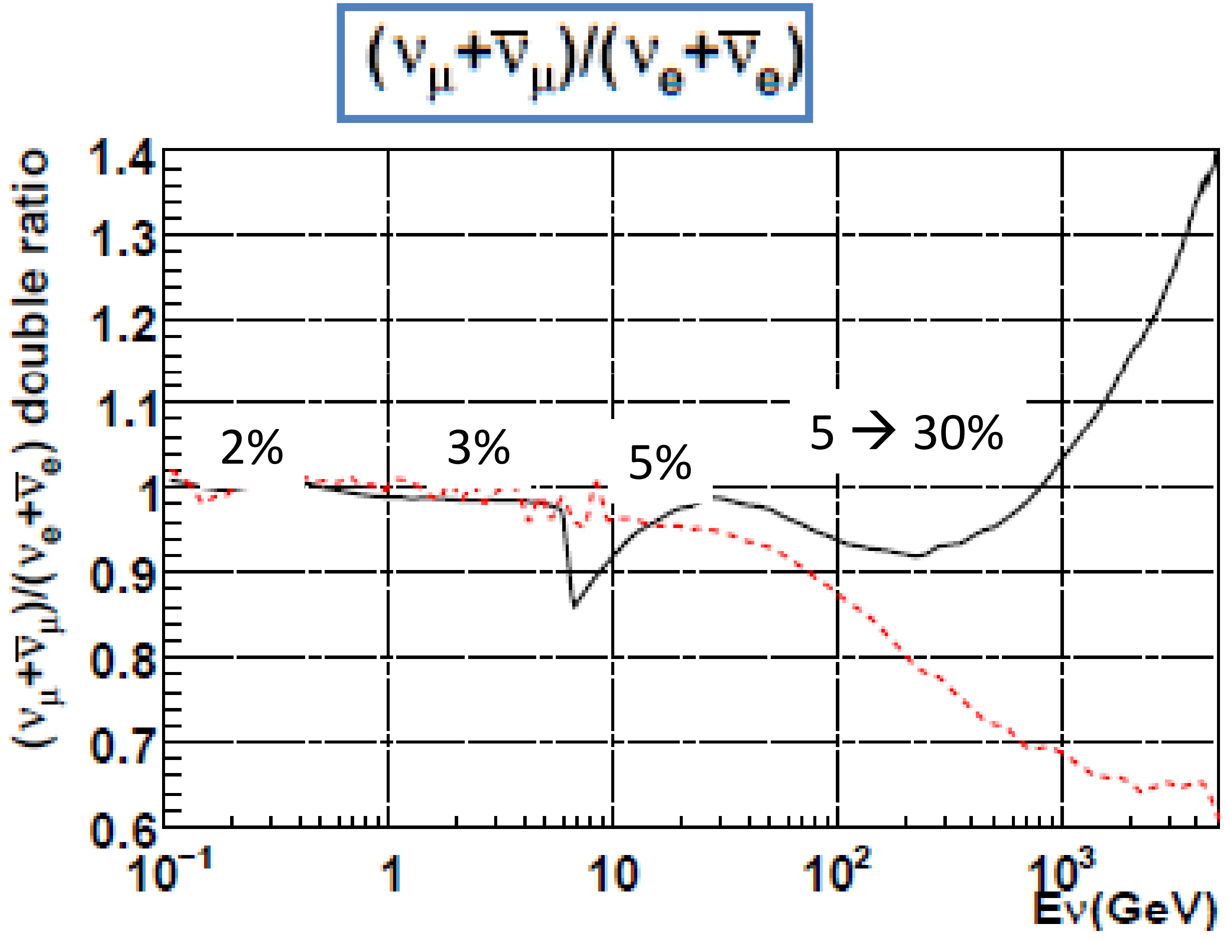


Up/Down uncertainty in the lepton (muon) zenith angle distribution (due to the flux uncertainty):

Energy range (μ-like)	Uncertainty
< 0.4 GeV/c	0.3 %
0.4 – 1.33 GeV	0.5%
> 1.33GeV (fully contained)	0.2%



Other and more important systematic errors in the flux: flavor ratio



2%

3%

5%

5 → 30%

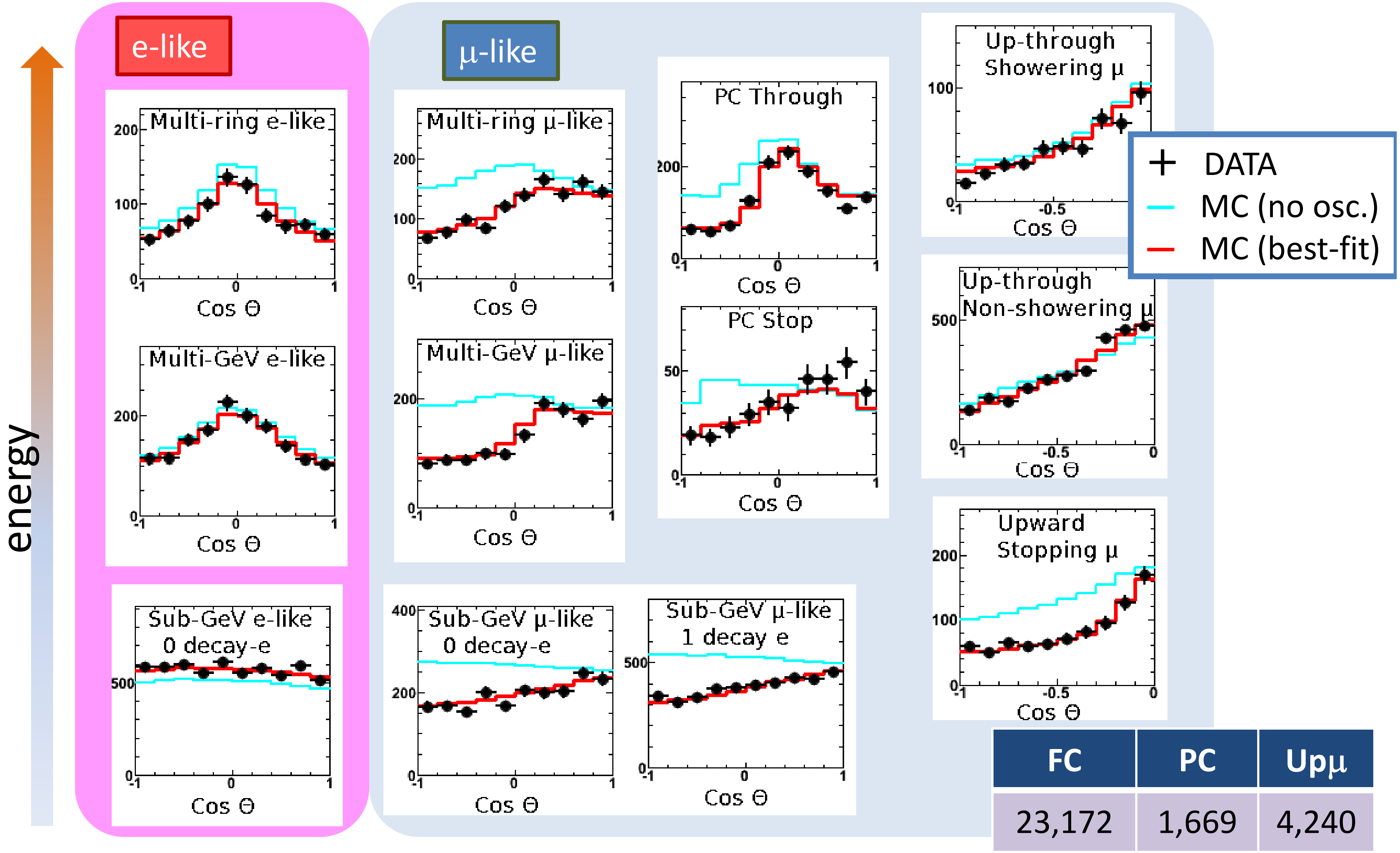
$$\frac{\text{FLUKA}}{\text{Honda et al (2006)}}$$

$$\frac{\text{Bartol}}{\text{Honda et al (2006)}}$$

Recent atmospheric neutrino data and (Δm_{23}^2, $\sin^2 2\theta_{23}$)

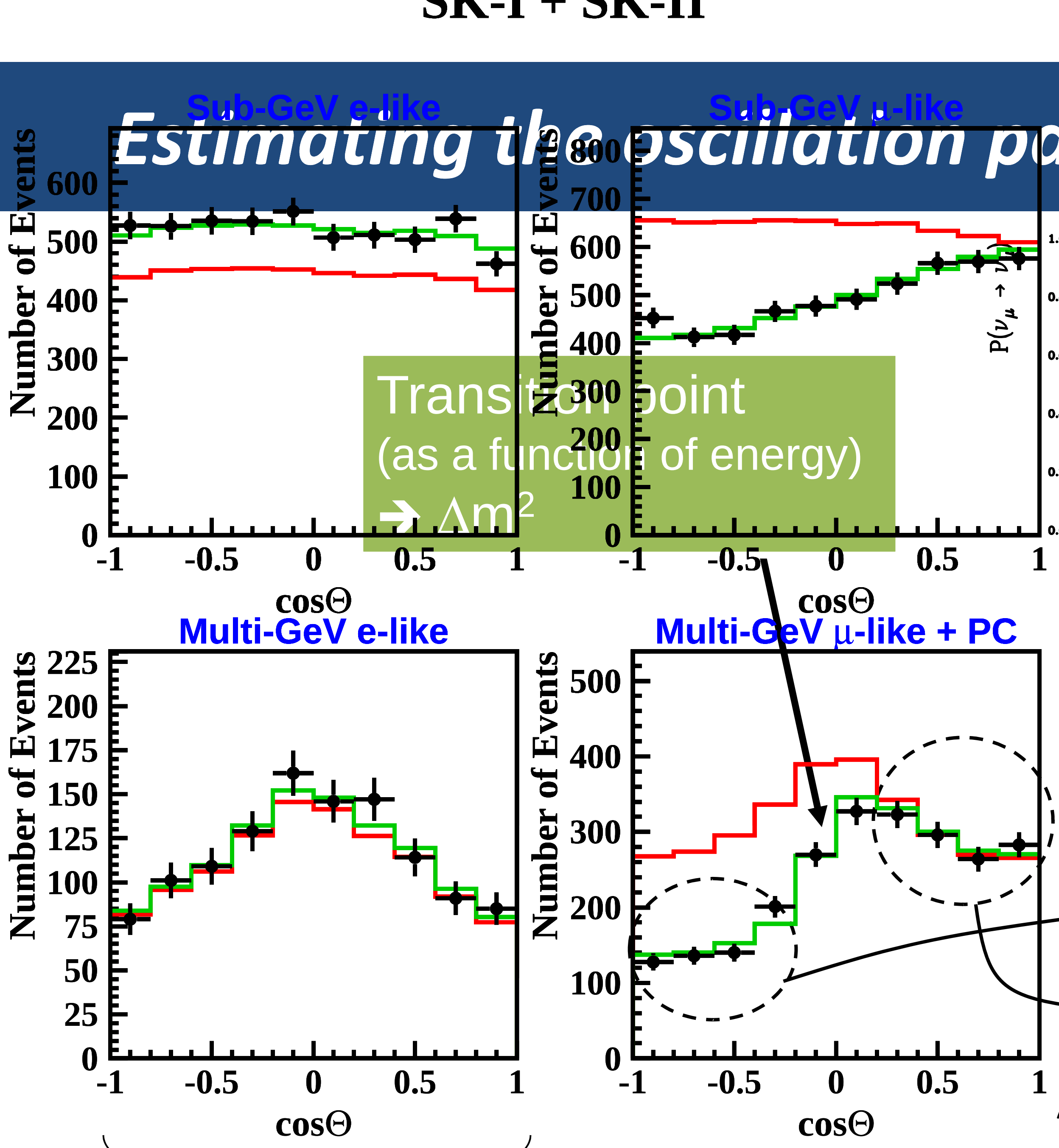
Present Super-K atmospheric neutrino data

Super-K-I+II+III (2806 days (173kton･yr) for FC+PC, 3109 days for up-μ)

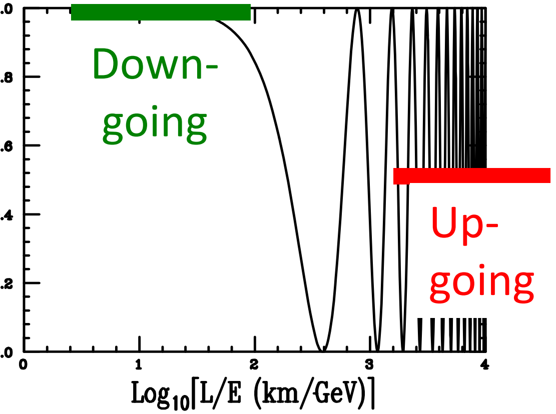


FC	PC	Upμ
23,172	1,669	4,240

Estimating the oscillation parameters



Transition point
(as a function of energy)
➔ Δm^2



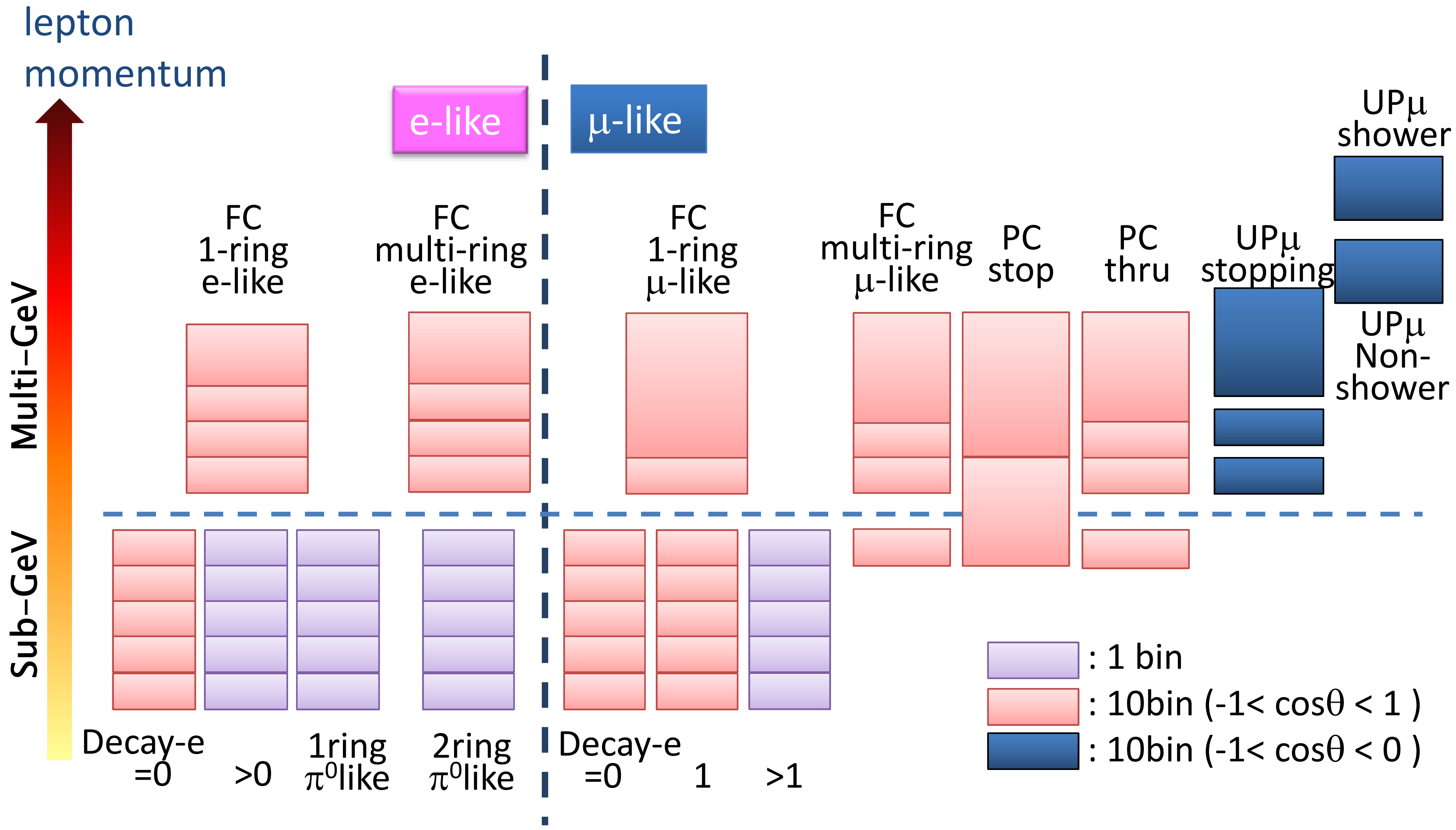
$$\frac{Up}{Down} = 1 - \sin^2 2\theta$$

Accurate measurement possible due to small syst. in up/down (~1%)

Confirmation of non-oscillated flux

Oscillation analysis

(SK-I+II+III combined analysis)



Total Number of bins: 420 x 3 (SK1~3)

Definition of χ^2

Number of data bins (in the final anal.,→420)

Number of syst error terms

$$L\ (N_{\exp}, N_{obs}) = \prod_{n=1}^{1260} \frac{\exp(-N_{\exp}^{n})(N_{\exp}^{n})^{N_{obs}^{n}}}{N_{obs}^{n}!} \times \prod_{i=1}^{123} \exp\left(\frac{-\varepsilon_i^2}{2\sigma_i^2}\right)$$

Poisson with systematic errors

$$\chi^2 \equiv -2\ln\left(\frac{L\ (N_{\exp}, N_{obs})}{L\ (N_{obs}, N_{obs})}\right) = \sum_{n=1}^{1260}\left[2(N_{\exp}^{n} - N_{obs}^{n}) + 2N_{obs}^{n}\ln\left(\frac{N_{obs}^{n}}{N_{\exp}^{n}}\right)\right] + \sum_{i=1}^{123}\left(\frac{\varepsilon_i}{\sigma_i}\right)^2$$

$$N_{\exp} = N_{MC}\cdot P(\nu_\mu \to \nu_\mu\,(for\,CC\,\nu_\mu))\cdot(1+\sum_{j=1}^{70} f_j\cdot\varepsilon_j)$$

N_{obs} : observed number of events

N_{exp} : expectation from MC

ε_i : systematic error term

σ_i: sigma of systematic error

χ^2 minimization at each parameter point (Δm^2, $\sin^2 2\theta$, …).
Method (χ^2 version): G.L.Fogli et al., PRD 66, 053010 (2002).

Syst. error terms

ν_{atm} flux
ν interaction
Reconstruction
Others

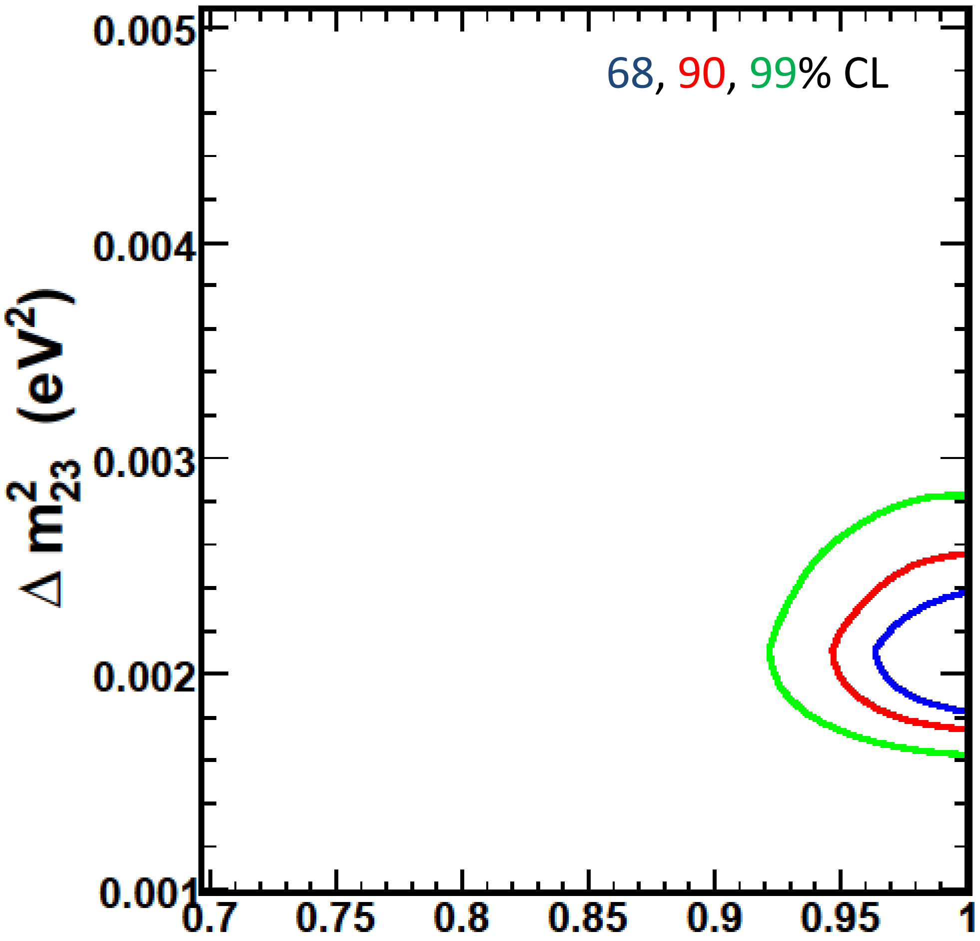
33~61 parameters are evaluated for each SK period.

Total = 123 terms

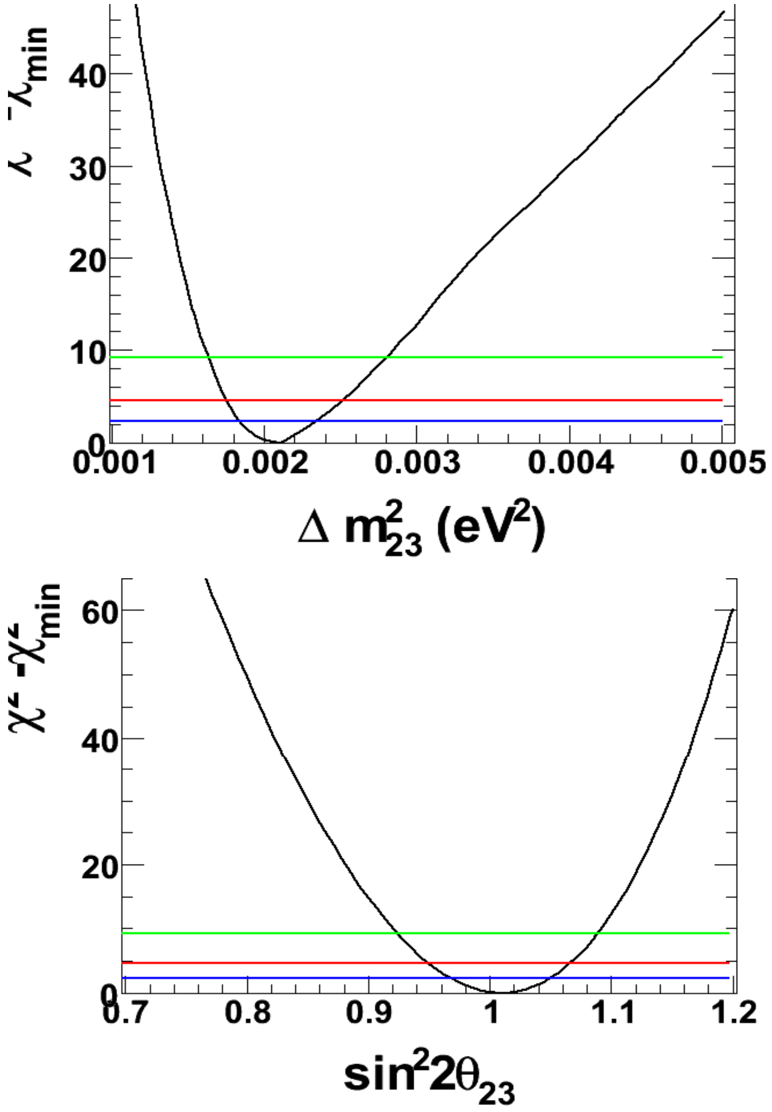
1. absolute normalization (<1GeV)
2. absolute normalization (>1GeV)
3. (ν_μ+anti-ν_μ)/(ν_e+anti-ν_e) (E_ν<1GeV)
4. (ν_μ+anti-ν_μ)/(ν_e+anti-ν_e) (1<E_ν<10GeV)
5. (ν_μ+anti-ν_μ)/(ν_e+νanti-$_e$) (E_ν>10GeV)
6. ν_e/anti-ν_e (E_ν<1GeV)
7. ν_e/anti-ν_e (1<E_ν<10GeV)
8. ν_e/anti-ν_e (E_ν>10GeV)
9. ν_μ/anti-ν_μ (E_ν<1GeV)
10. ν_μ/anti-ν_μ (1<E_ν<10GeV)
11. ν_μ/anti-ν_μ (E_ν>10GeV)
12. up/down
13. horizontal/vertical
14. K/π
15. L_ν (production height)
16. sample-by-sample FC Multi-GeV
17. sample-by-sample PC + UPstop ⌠
18. M_A in CCQE, single-π
19. CCQE (model dependence)
20. CCQE (anti-ν/ν)
21. CCQE (μ/e)
22. single-π (cross section)
23. single-π (anti-ν/ν)
24. single-π(π0/π+↕)
25. DIS(model dependence)
26. DIS (cross section)
27. coherent π (cross section)
28. NC/CC
29. nuclear effect in ^{16}O
30. nuclear effect (pion spectrum)
31. CCν interaction cross section
32. hadron sim. (NC contami. in FC)
33. Solar activity
34. FC reduction
35. PC reduction
36. UPμ reduction
37. FC/PC separation
38. Normalization of PC stop/thru(top)
39. Normalization of PC stop/thru(barrel)
40. Normalization of PC stop/thru(bottom)
41. non-⎨ BG (flasher)
42. non-⎨ BG (cosmic-ray μ)
43. BG subtraction of Upthru (shower) μ
44. BG subtraction of Upthru (non-shower) μ
45. BG subtraction of UPstop μ
46. UPμ stop/thru separation
47. UPμ non-shower/shower separation
48. ring separation
49. PID for single-ring
50. PID for multi-ring
51. energy calibration
52. energy cut for UPstop μ
53. up/down symmetry of energy calib.
54. non-ν_e BG in Multi-GeV 1-ring electron
55. non-ν_e BG in Multi-GeV m-ring electron
56. Likelihood of Multi-GeV m-ring e-like
57. Efficiency for 2-ring π^0
58. number of event for 1-ring π^0
59. Decay electron tagging
60. Fiducial volume
61. Up thru ⌠ length cut
62. Decay electron tagging from pi+
63. Matter effect
64. Low-q2 for DIS W<2GeV
65. Low-q2 for DIS W>2GeV

$\nu_\mu \rightarrow \nu_\tau$ 2 flavor analysis (zenith angle)

SK-I+II+III



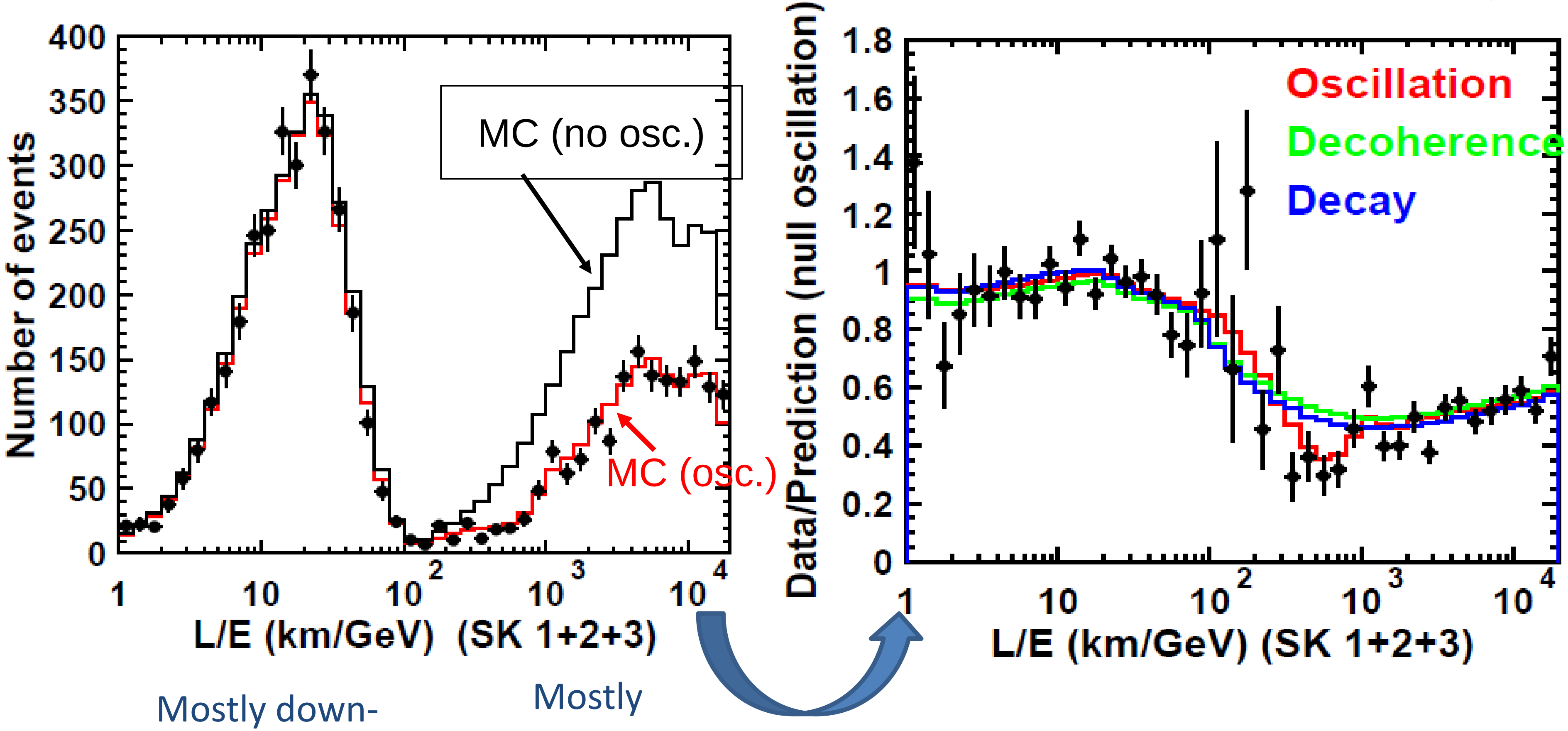
$\Delta\chi^2$ distributions



1.7×10^{-3} eV^2 < Δm^2 < 2.6×10^{-3} eV^2
$\sin^2 2\theta > 0.94$ at 90% CL

L/E distribution update with SK-I+II+III

Preliminary



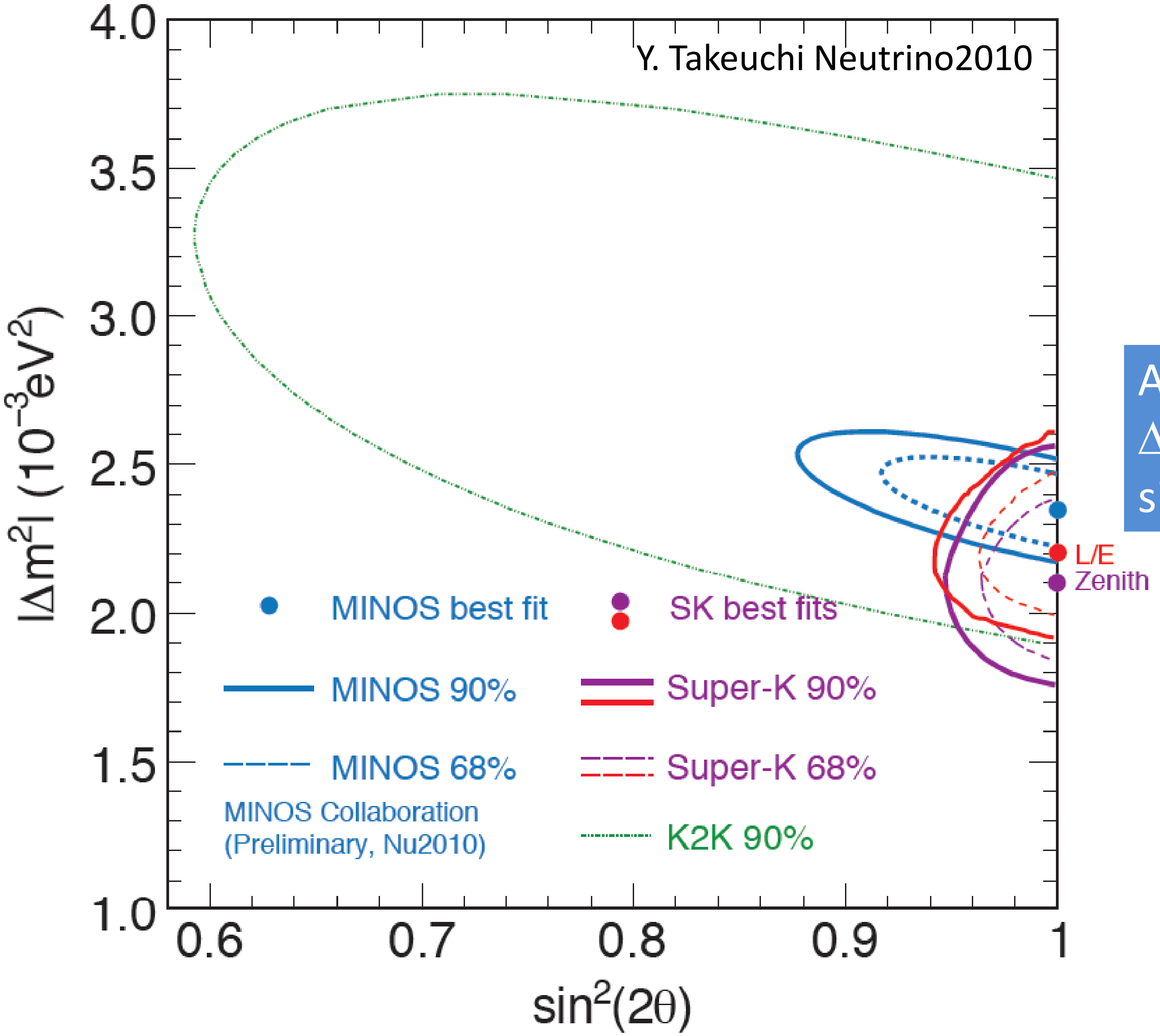
Mostly down-going

Mostly up-going

Neutrino decay disfavored (4.4σ)

Neutrino decoherence disfavored (5.4σ)

Allowed parameter regions from atmospheric and long baseline experiments

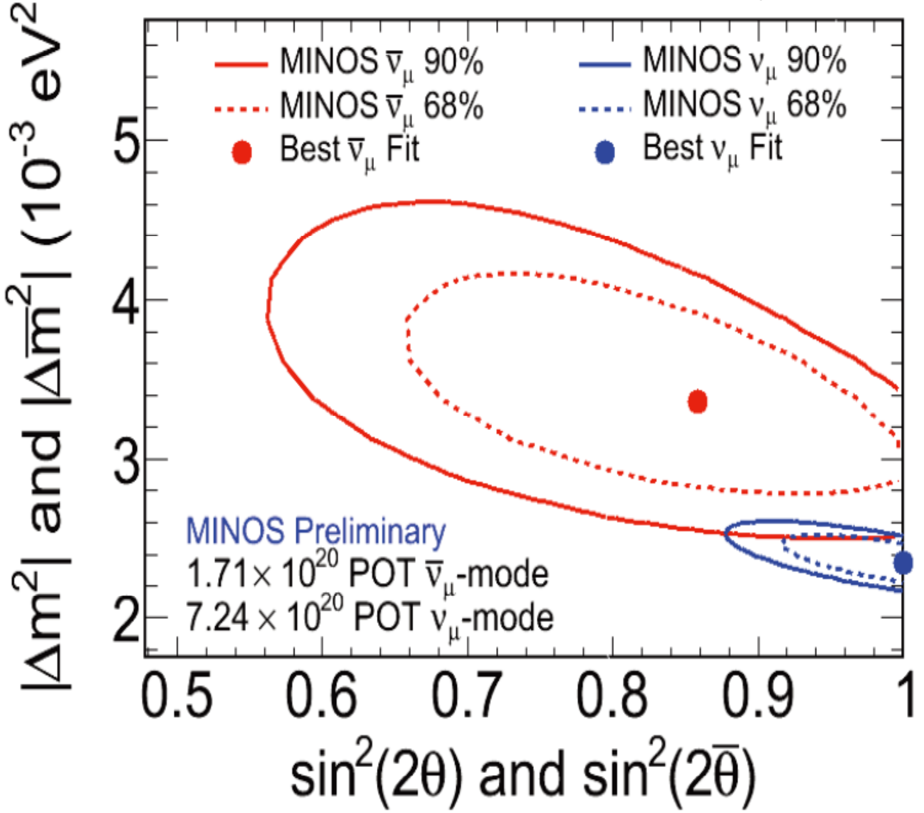


Accuracy:
Δm^2: LBL,
$\sin^2 2\theta$: still atm.

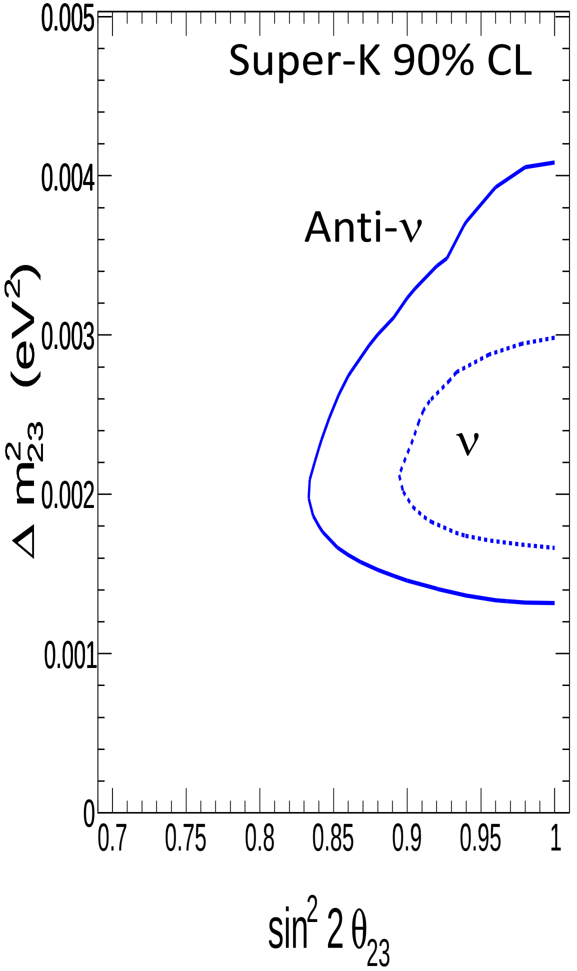
Consistent with maximal mixing!

(Δm_{23}^2, $\sin^2 2\theta_{23}$) for ν's and anti-ν's ?

MINOS (P. Vahle @Nu2010)



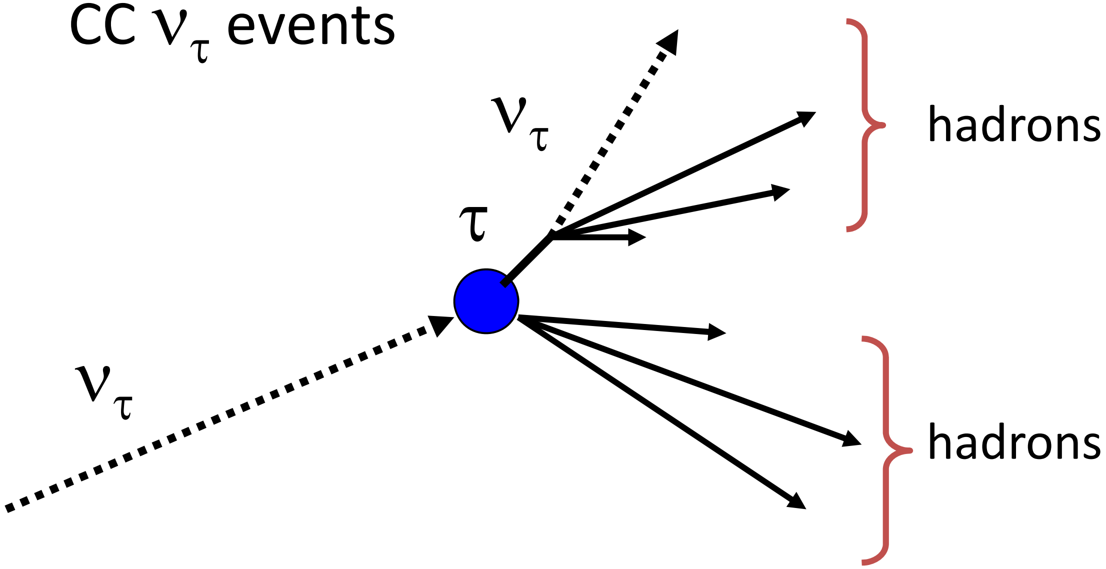
An oscillation analysis with (Δm_{23}^2, $\sin^2 2\theta_{23}$, $\overline{\Delta m_{23}^2}$, $\overline{\sin^2 2\theta_{23}}$) with the zenith angle data.



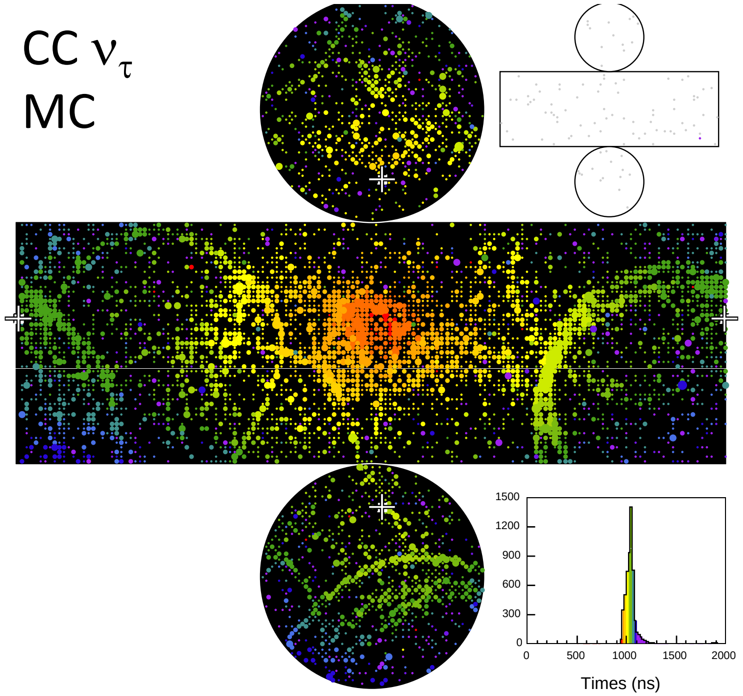
Seach for CC ν_τ events

Search for CC ν_τ events (SK-I)

CC ν_τ events



CC ν_τ
MC



- ● Many hadrons . . . .

(But no big difference with other (NC) events.)

BAD ⟹ τ- likelihood analysis

- ● Upward going only

GOOD ⟹ Zenith angle

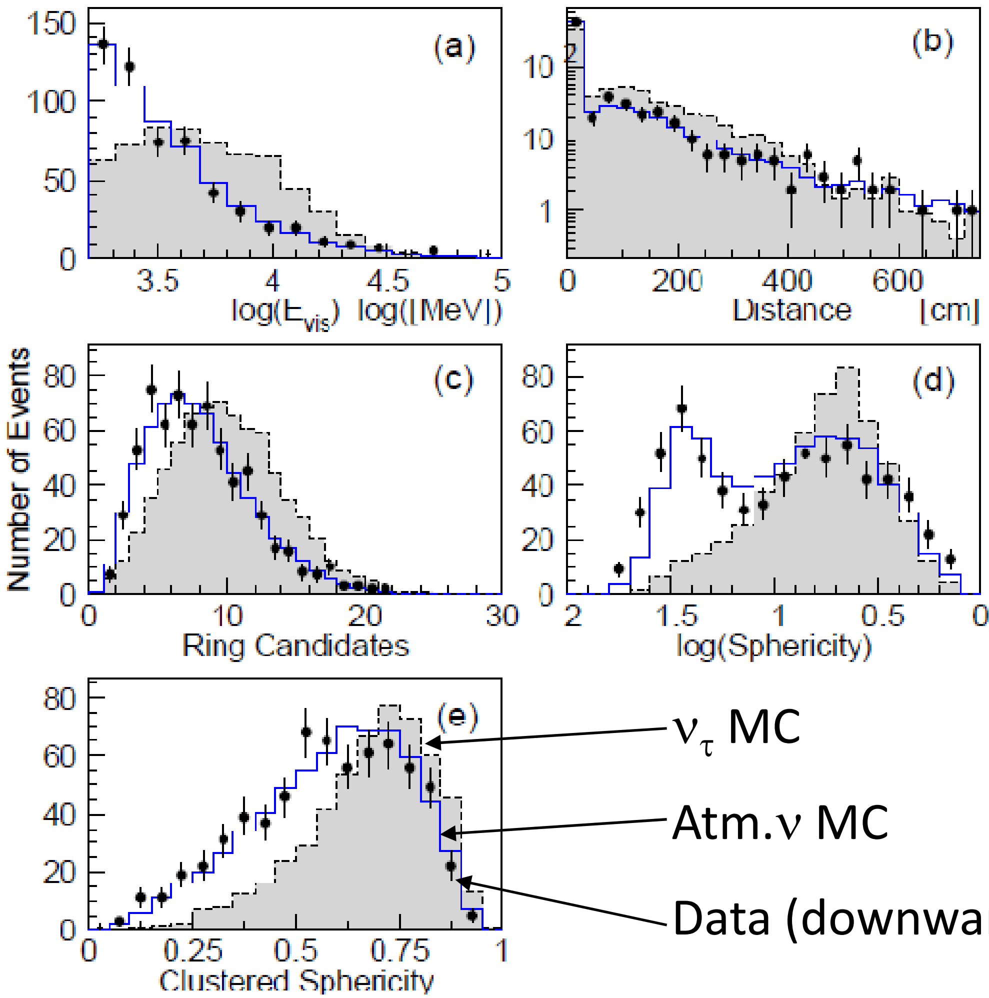
Only ～ 1.0 CC ν_τ
FC events/kton▪yr

⇕

(BG (other ν events)
～ 130 ev./kton▪yr)

Selection of ν_τ events

Pre-cuts: E(visible) >1,33GeV, most-energetic ring = e-like



E(visible)

Max. distance between primary vertex and the decay-electron vertex

Number of ring candidates

Sphericity in the lab frame

Sphericity in the CM frame

ν_τ MC

Atm.ν MC

Data (downward-going)

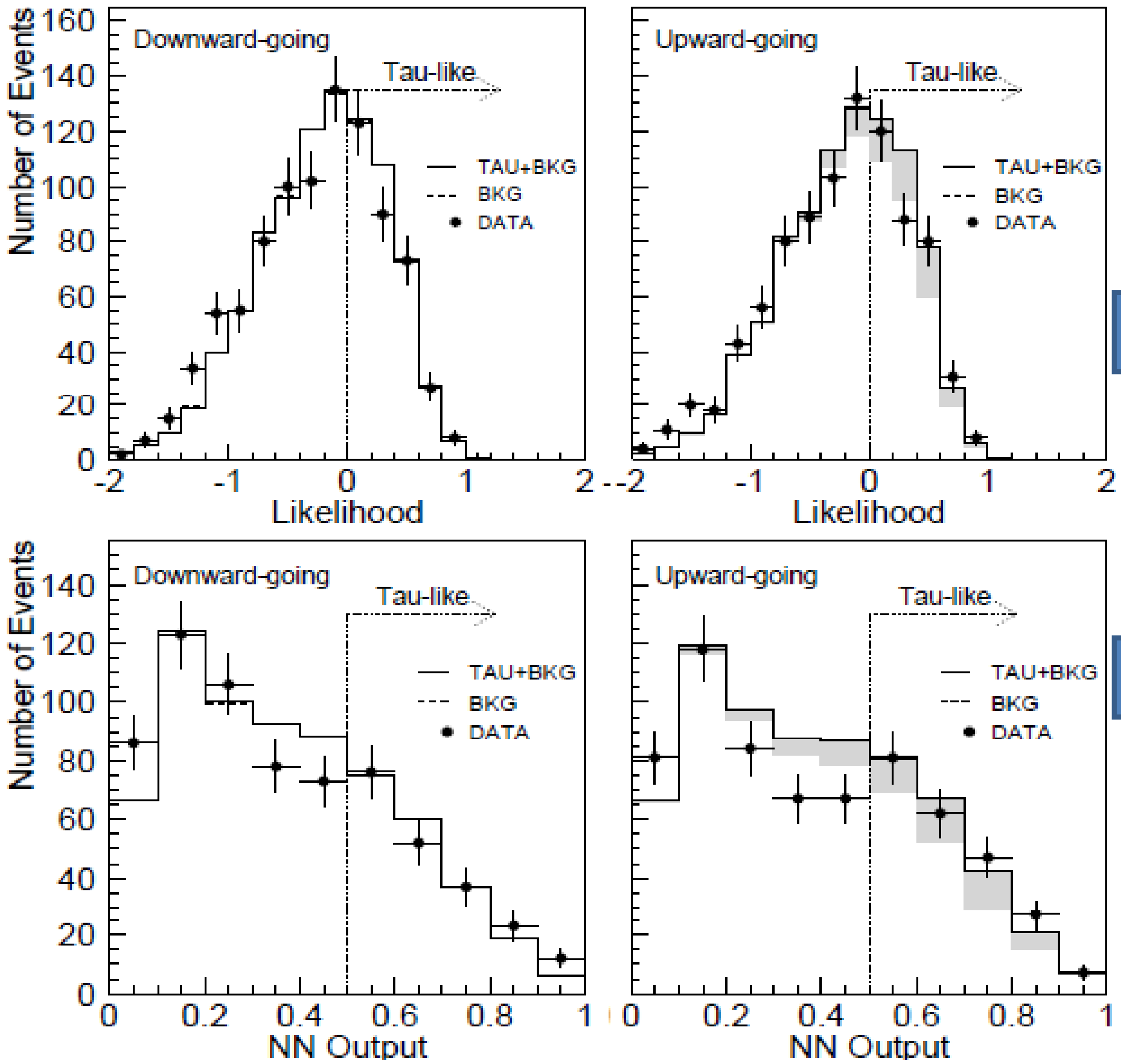
Likelihood / neural-net distributions

Down-going (no ν_τ)

Up-going

Likelihood

Neural-net

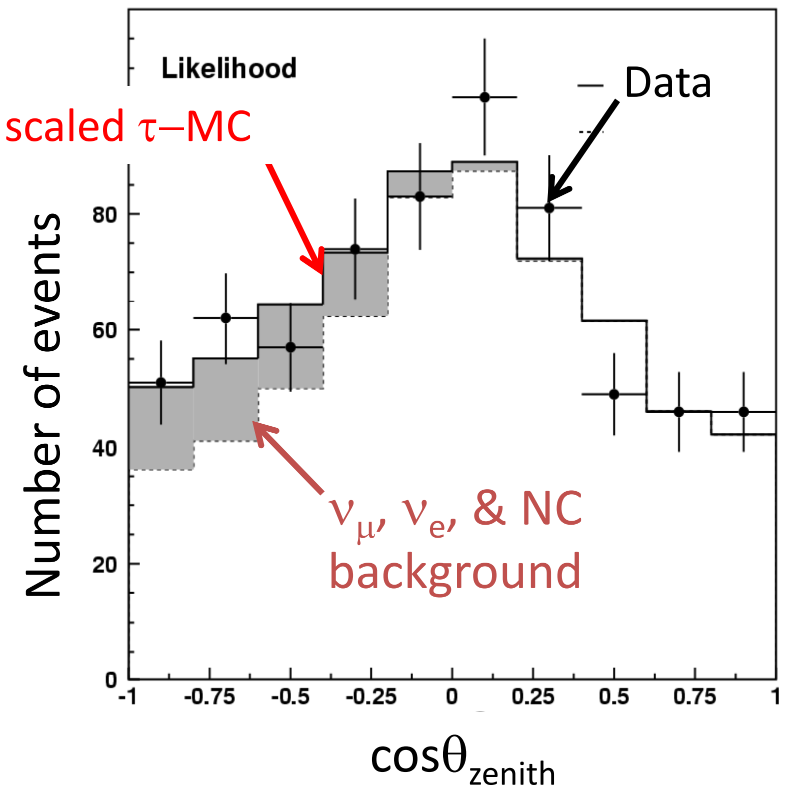


Zenith angle

Zenith angle distributions and fit results

Hep-ex/0607059

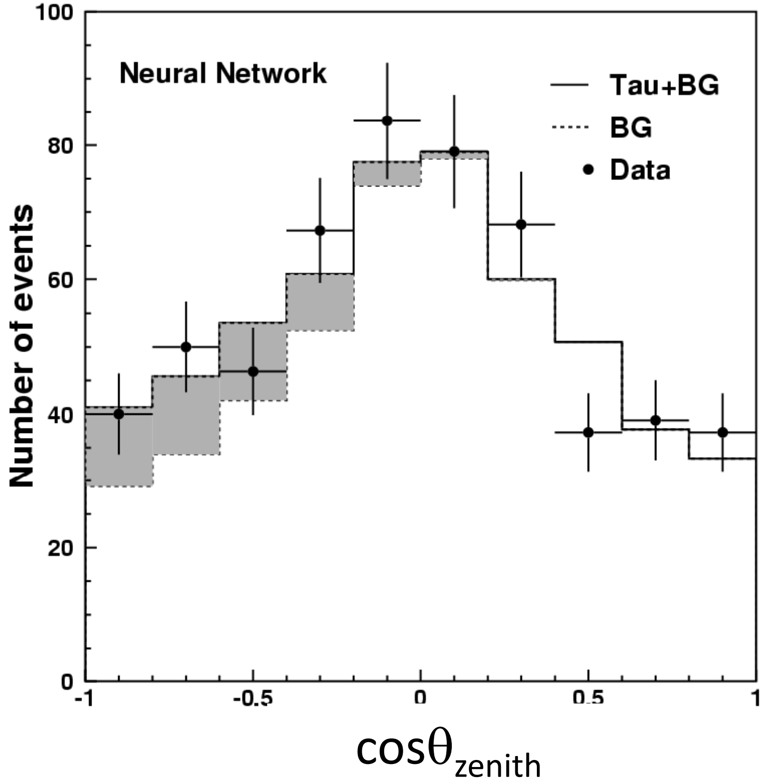
Likelihood analysis



scaled τ–MC

ν_μ, ν_e, & NC background

NN analysis

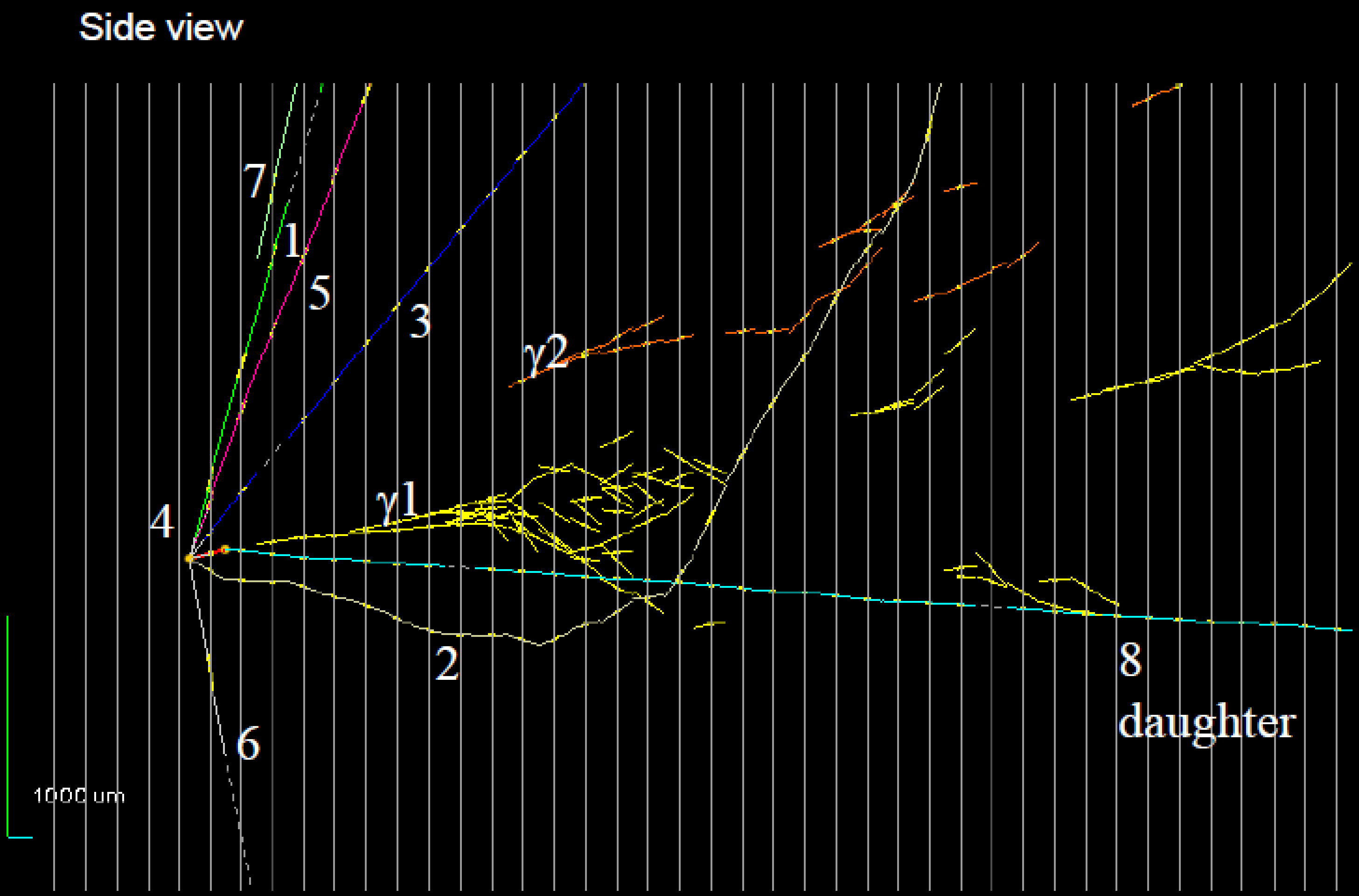


Fitted # of τ events	138±48(stat) +15 / -32(syst)	134±48(stat) +16 / -27(syst)
Expected # of τ events	78±26(syst)	78±27 (syst)

Zero tau neutrino interaction is disfavored at 2.4σ.

OPERA first ν_τ candidate

Event topological features (side view)



Super-K is also trying to update the analysis

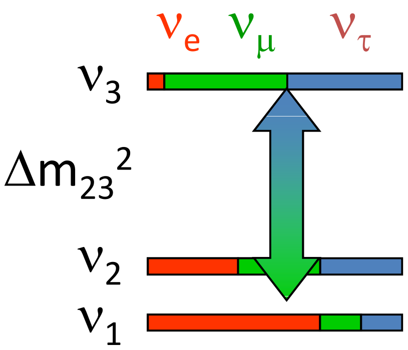
3 flavor oscillation analyses

3 flavor oscillation: framework

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

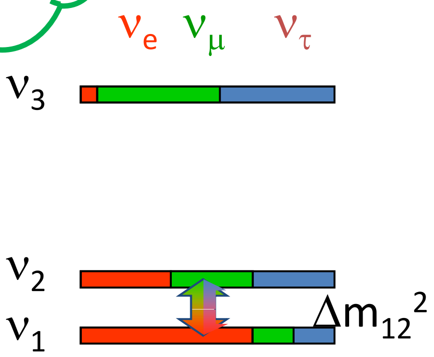
Can atmospheric neutrinos tell something?

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



Atmospheric
LBL

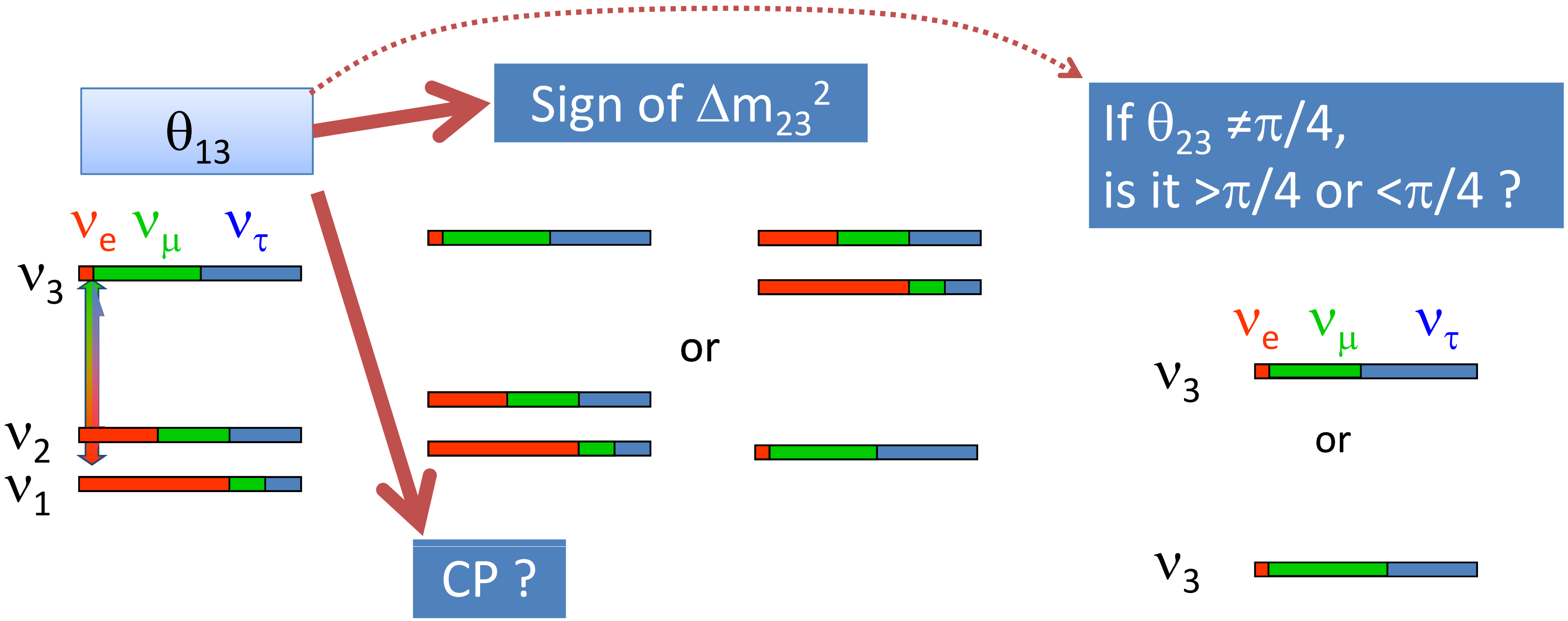
Solar
KamLAND



Sub-leading oscillations

$\sin^2\theta_{12}$, $\sin^2 2\theta_{23}$, Δm_{12}^2, $|\Delta m_{23}^2|$ ···· Already measured.

Next step: measure the unknown mixing angle θ_{13}



θ_{13}

Sign of Δm_{23}^2

If $\theta_{23} \neq \pi/4$,
is it $>\pi/4$ or $<\pi/4$?

CP ?

These are extremely important parameters to be measured.
Question: How can we measure these parameters with ν_{atm} ?

3 flavor oscillation analyses (1)

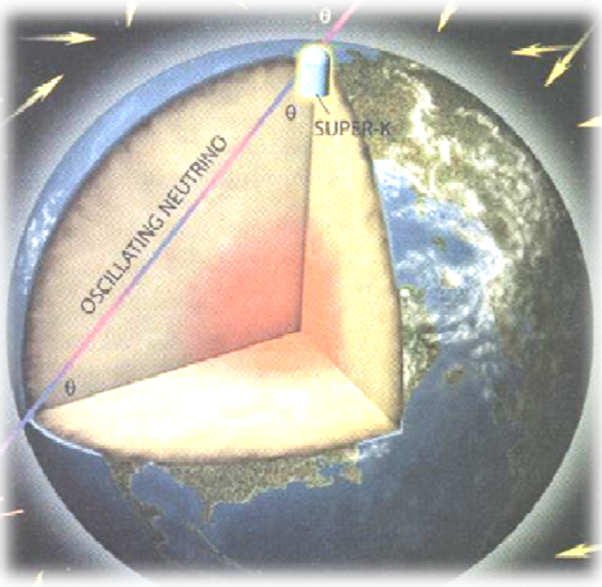
- Study of θ_{13} -

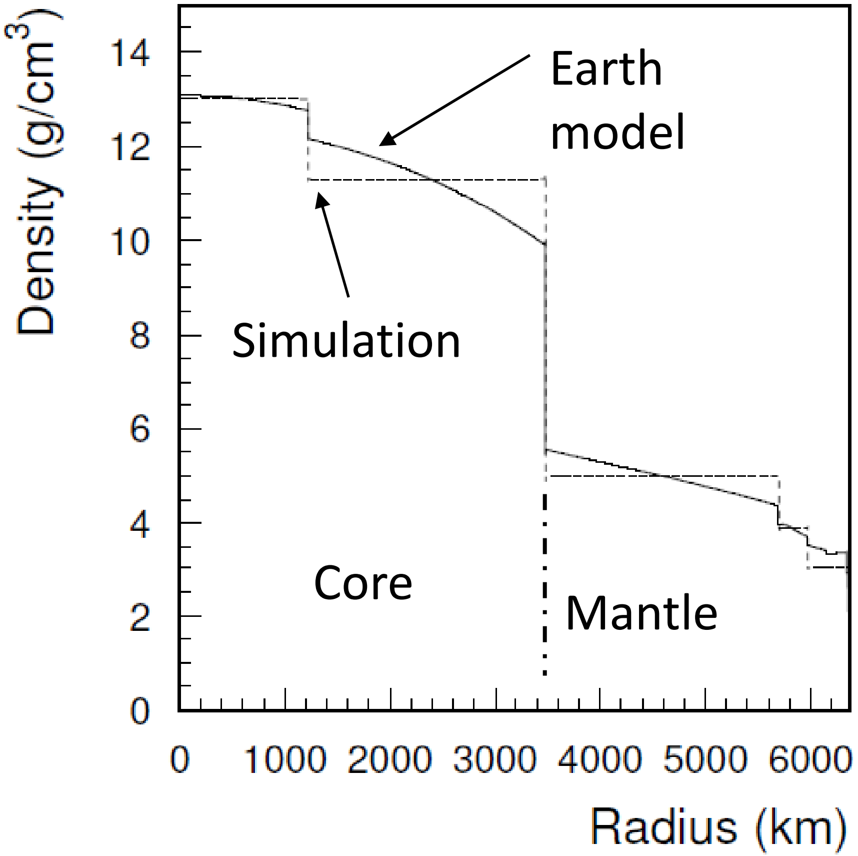
Search for non-zero θ_{13} in atmospheric neutrino experiments

$$P(\underline{\nu_\mu \to \nu_e}) = \sin^2\theta_{23} \cdot \sin^2 \underline{2\theta_{13}} \cdot \sin^2\left(\frac{1.27\Delta m_{23}^{\ 2} L}{E}\right)$$

($\Delta m_{12}^2=0$ and vacuum oscillation assumed)

Since ν_e is involved, the matter effect must be taken into account.

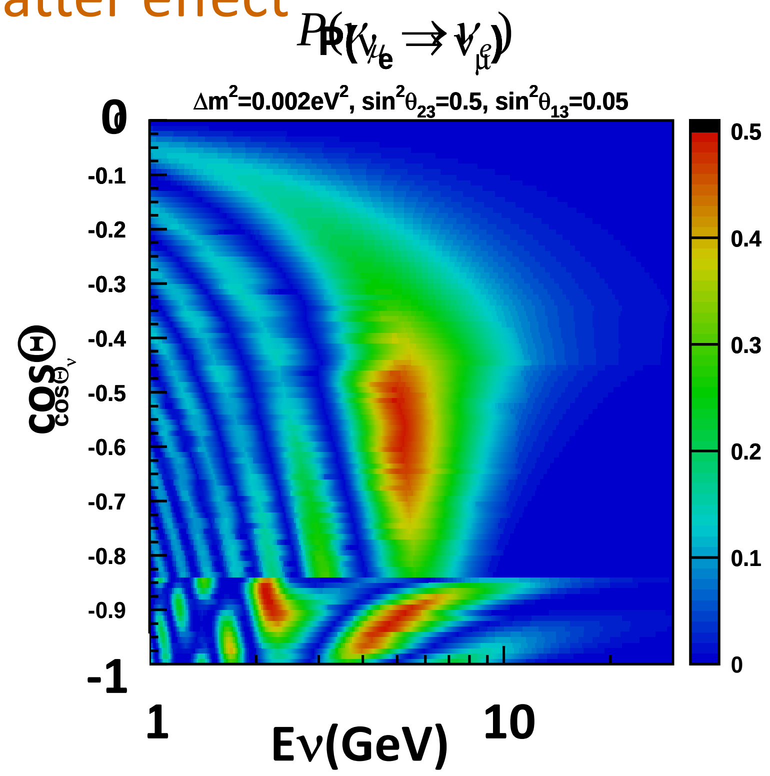


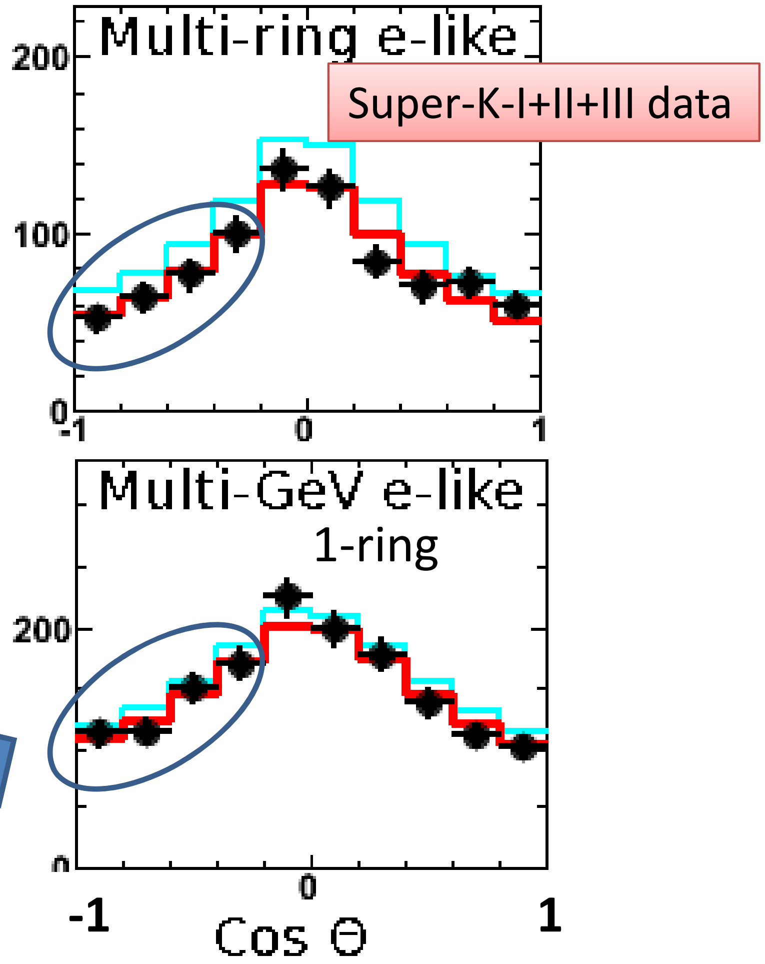


Study of θ_{13}

(One mass scale dominance ($\Delta m_{12}^2=0$) assumed)

Matter effect





➔Electron appearance in the multi-GeV upward going events. (and some effects in ν_μ disappearance probability as well.)

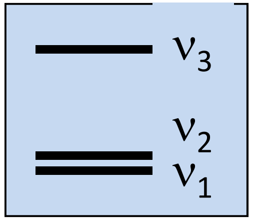
No evidence for electron appearance.

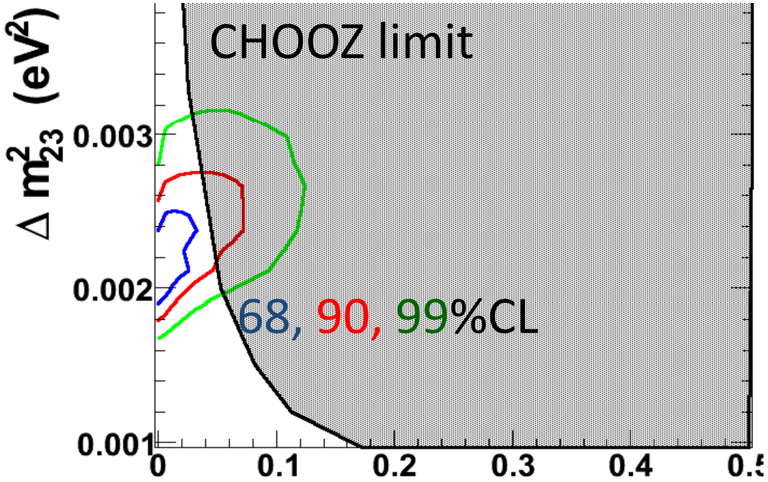
➔ osci. analysis with all data.

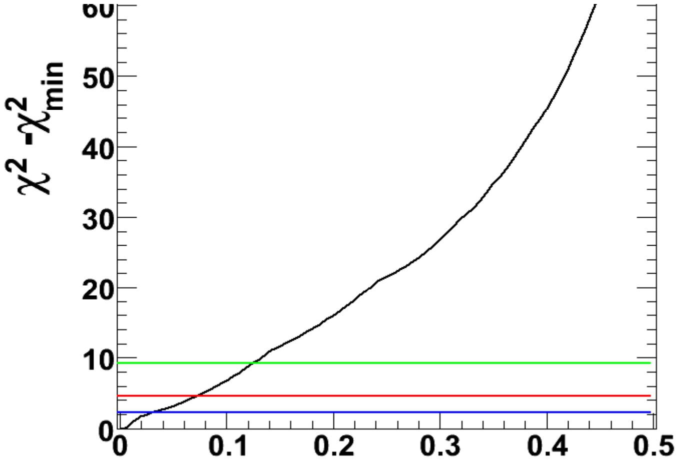
Allowed θ_{13} region from SK atmospheric

SK PRD 81, 092004 (2010)

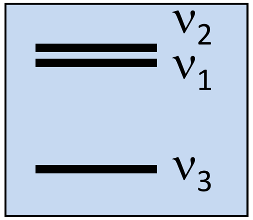
Normal

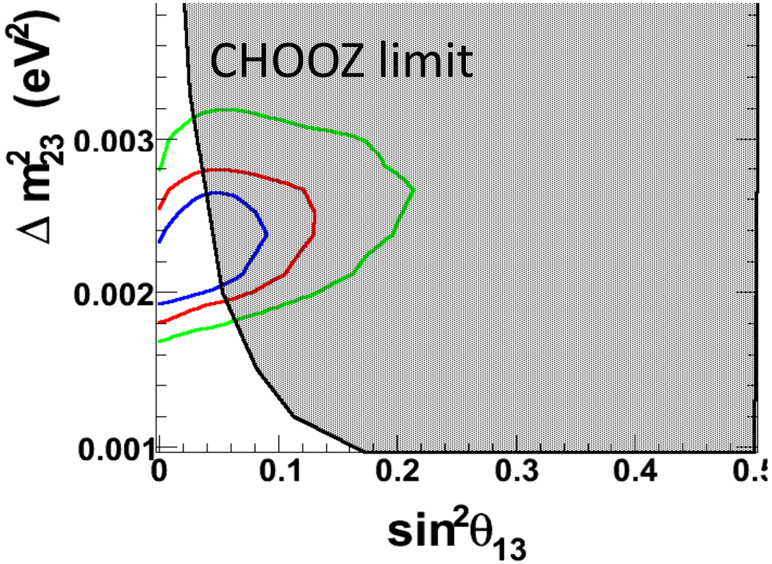


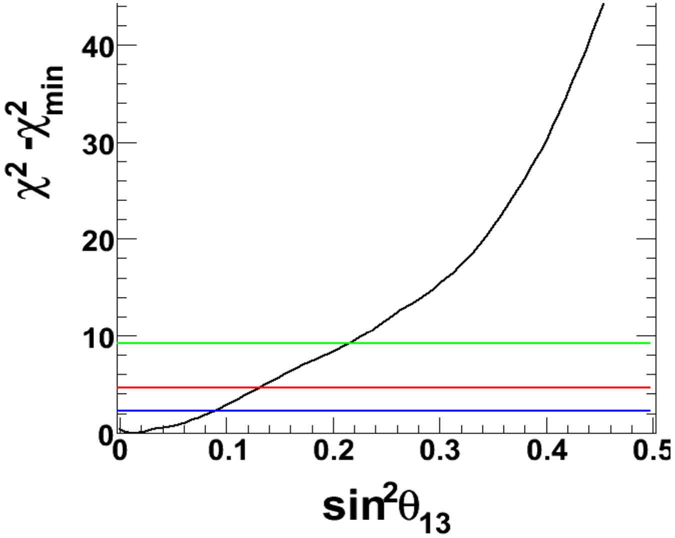




Inverted

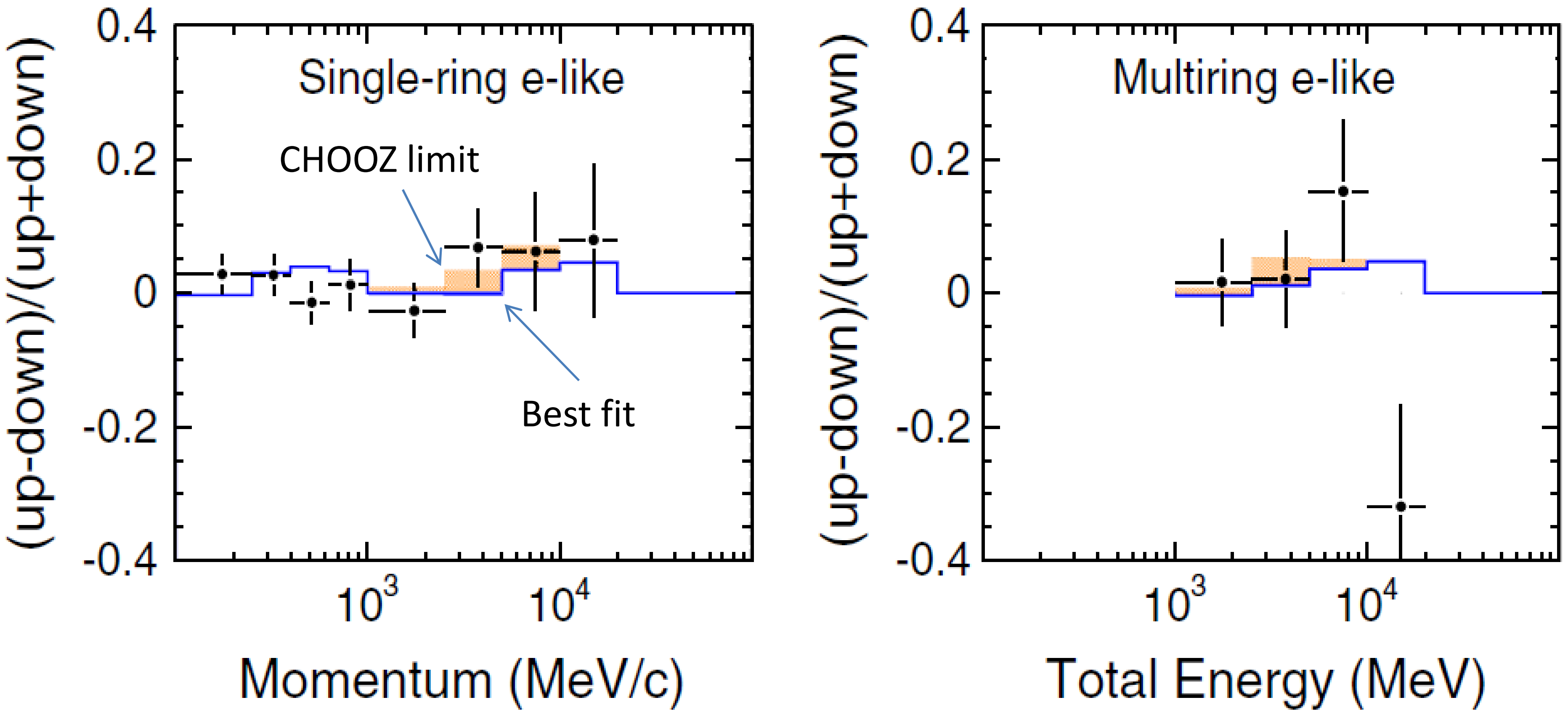






No evidence for non-zero θ_{13} with an analysis that assumed $\Delta m_{12}^2=0$.

Up-down asymmetry

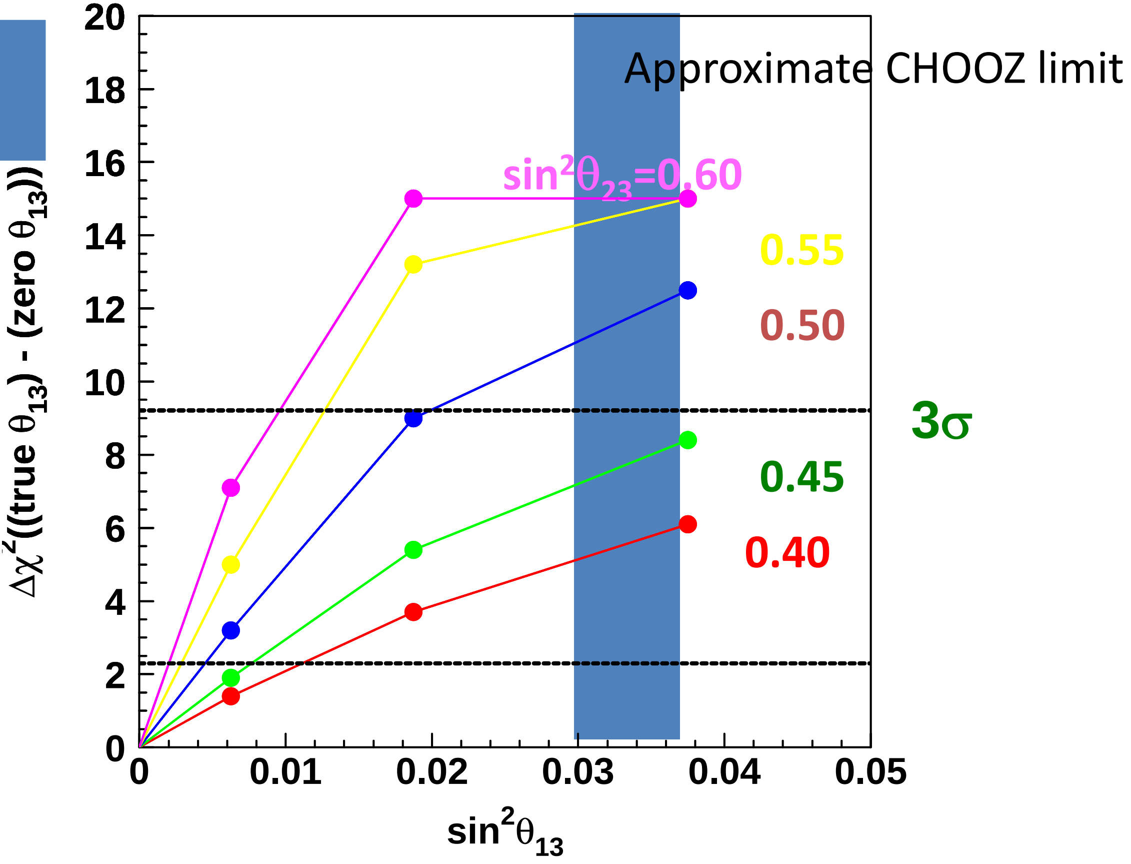


Future sensitivity to non-zero θ_{13}

M.Shiozawa et al., RCCN workshop (2004)

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m_{23}^2 L}{E}\right)$$ (vacuum)

20yrs SK
(450kton･yr)



$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.40 \sim 0.60$
$s^2\theta_{13}=0.00 \sim 0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=+2.5\times10^{-3}$

Positive signal for nonzero θ_{13} can be seen if θ_{13} is near the CHOOZ limit and $\sin^2\theta_{23} > 0.5$

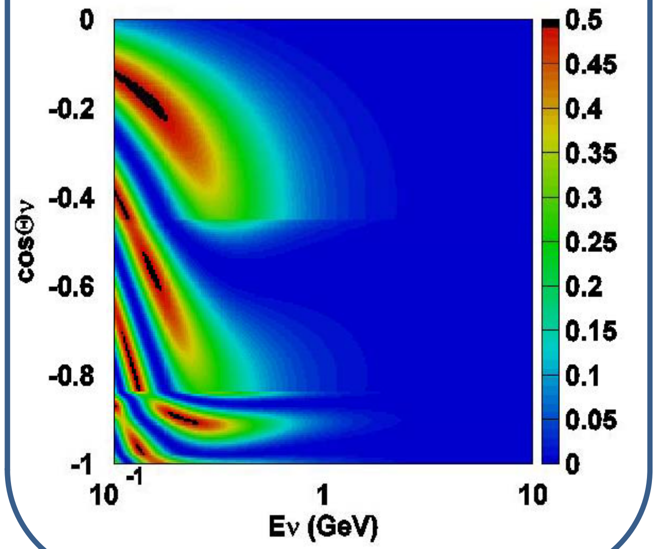
But probably after T2K/Nova/ reactor…

3 flavor oscillation analyses (2)

- Solar term effect and octant of θ_{23} -

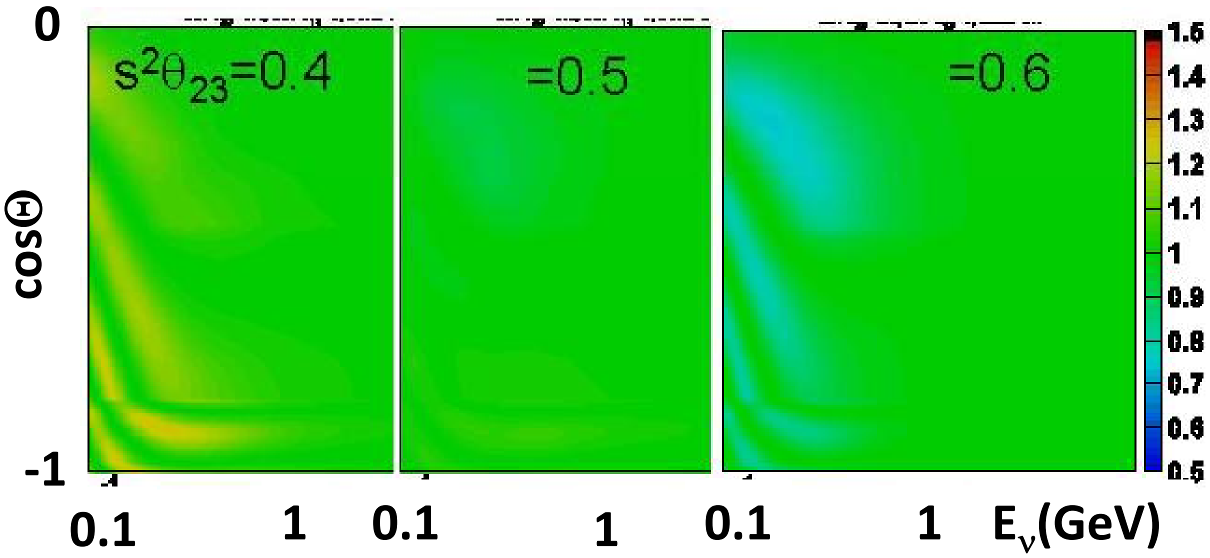
Solar term effect and octant of θ_{23}
(θ_{13}=0 assumed)

P(ν_μ → ν_e) by solar oscillation parameters



However, due to the cancellation between ν_μ→ν_e and ν_e→ν_x, the change in the ν_e flux is small.

$$\frac{\nu_e \ \ flux(osc)}{\nu_e \ \ flux(no\ osc)}$$

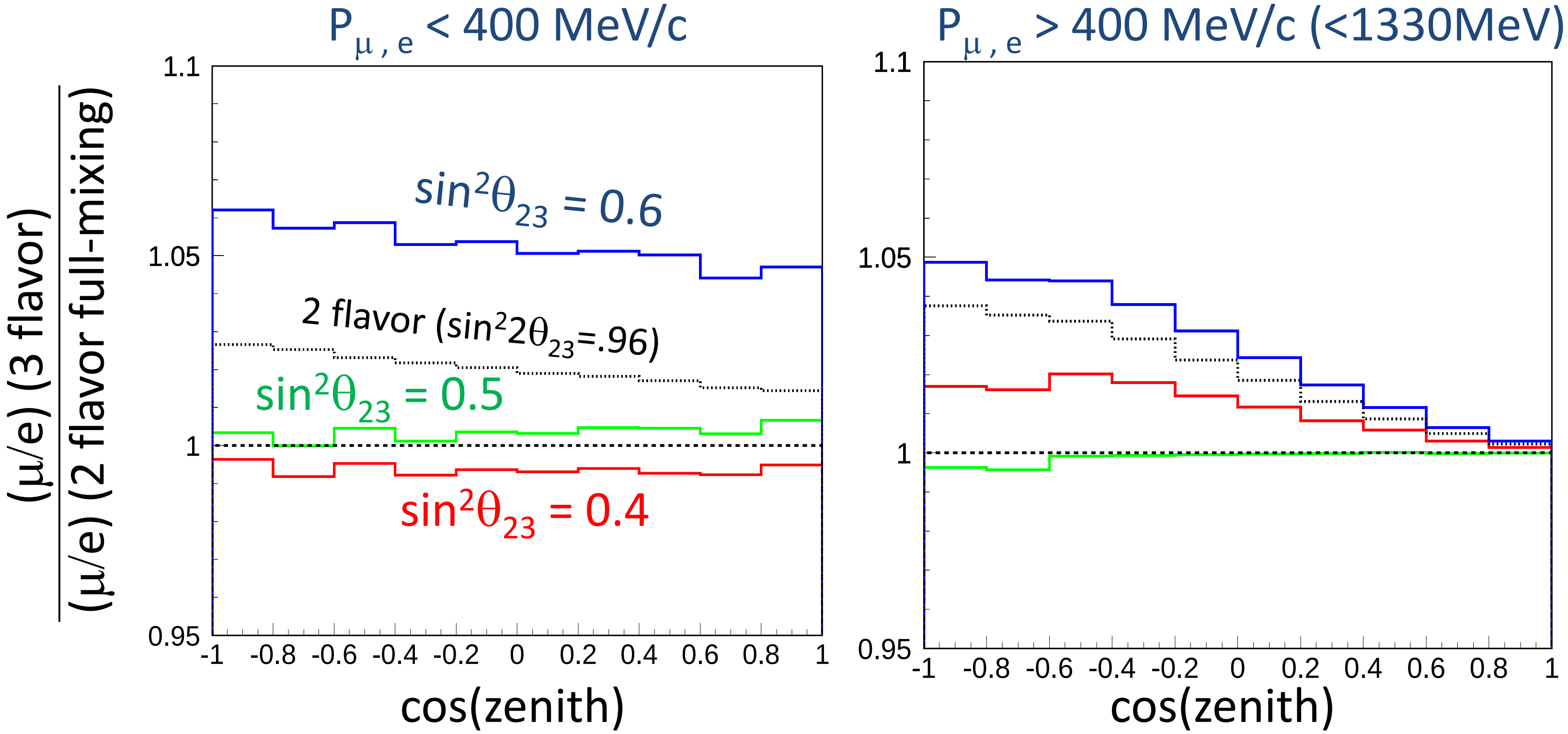


Oscillation probability is different between $s^2\theta_{23}$=0.4 and 0.6

→ discrimination between $\theta_{23} > \pi/4$ and $< \pi/4$ might be possible by studying sub-GeV atmospheric ν_e and ν_μ events.

Effect of the solar terms to the sub-GeV μ/e ratio (zenith angle dependence)

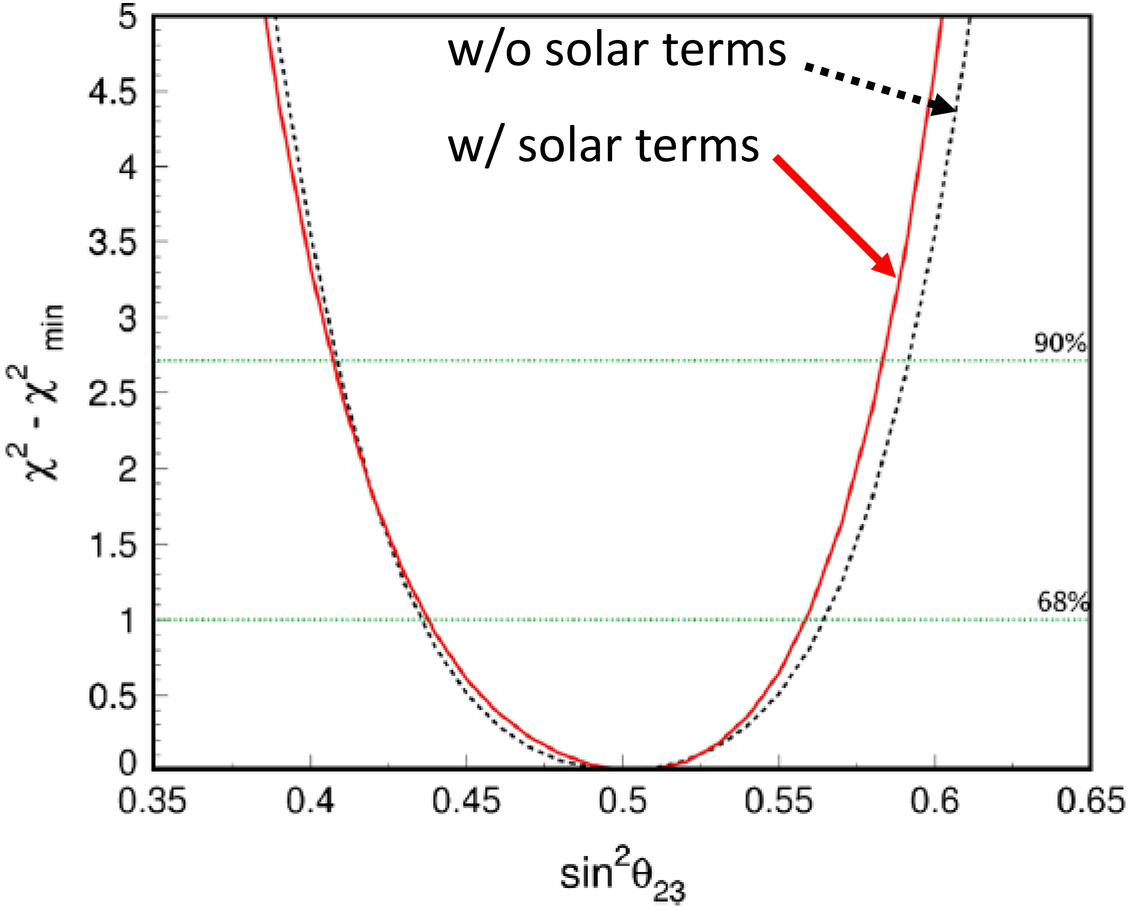
$\Delta m^2_{12} = 8.3 \times 10^{-5}$ eV^2
$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2
$\sin^2 2\theta_{12} = 0.82$
$\sin^2\theta_{13} = 0$



It could be possible to discriminate the octant of θ_{23}, if $\sin^2\theta_{23}$ is significantly away from 0.5.

Constraint on $\sin^2\theta_{23}$ with and without the solar terms

SK PRD 81, 092004 (2010)



Solar terms off :

best-fit : $\sin^2\theta_{23} = 0.50$

Solar terms on :

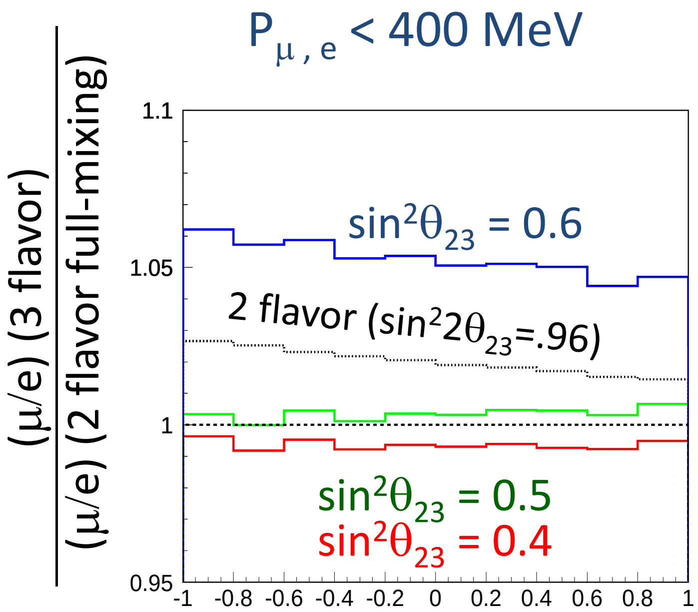
best-fit : $\sin^2\theta_{23} = 0.50$

Still the maximum mixing is most favored.

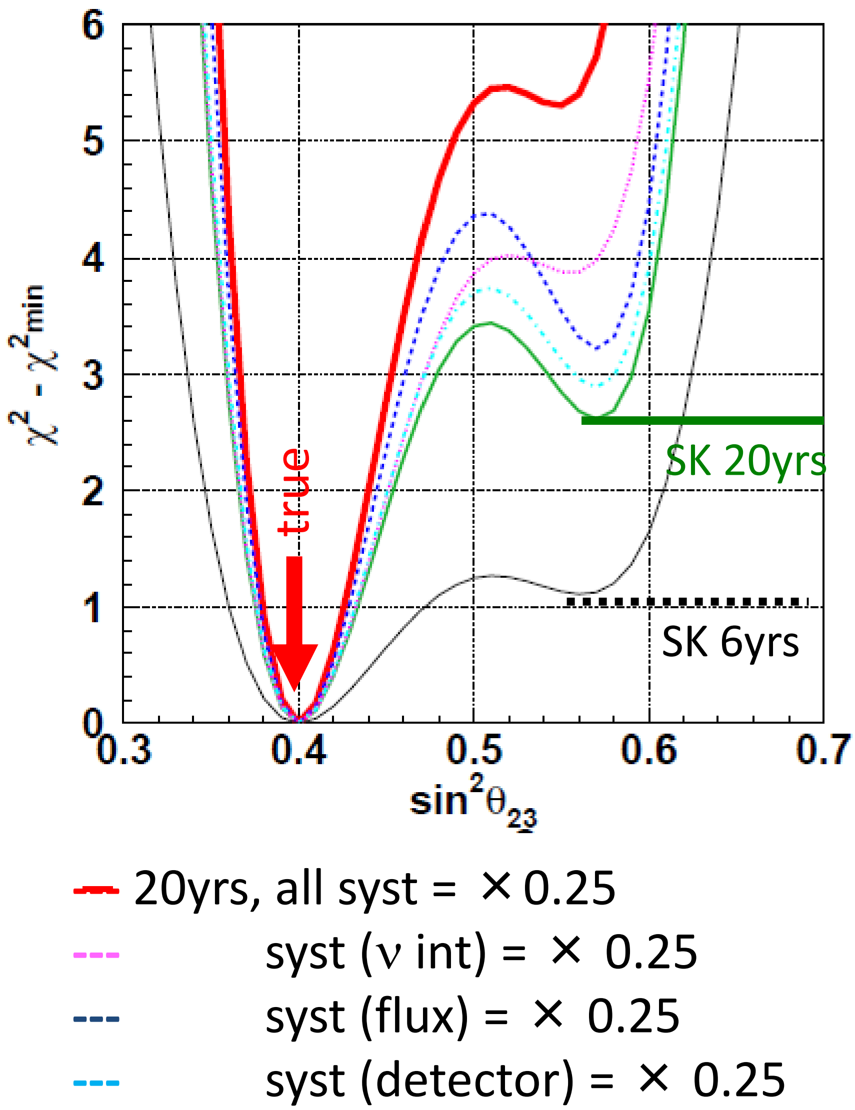
Future θ_{23} octant sensitivity and syst. errors

$\Delta m^2_{12} = 8.3 \times 10^{-5}\ \mathrm{eV}^2$
$\Delta m^2_{23} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$
$\sin^2 2\theta_{12} = 0.82$
$\sin^2\theta_{13} = 0$

0.45 Mtonyr = SK 20yr



Y. Takenaga, PhD thesis (2008)



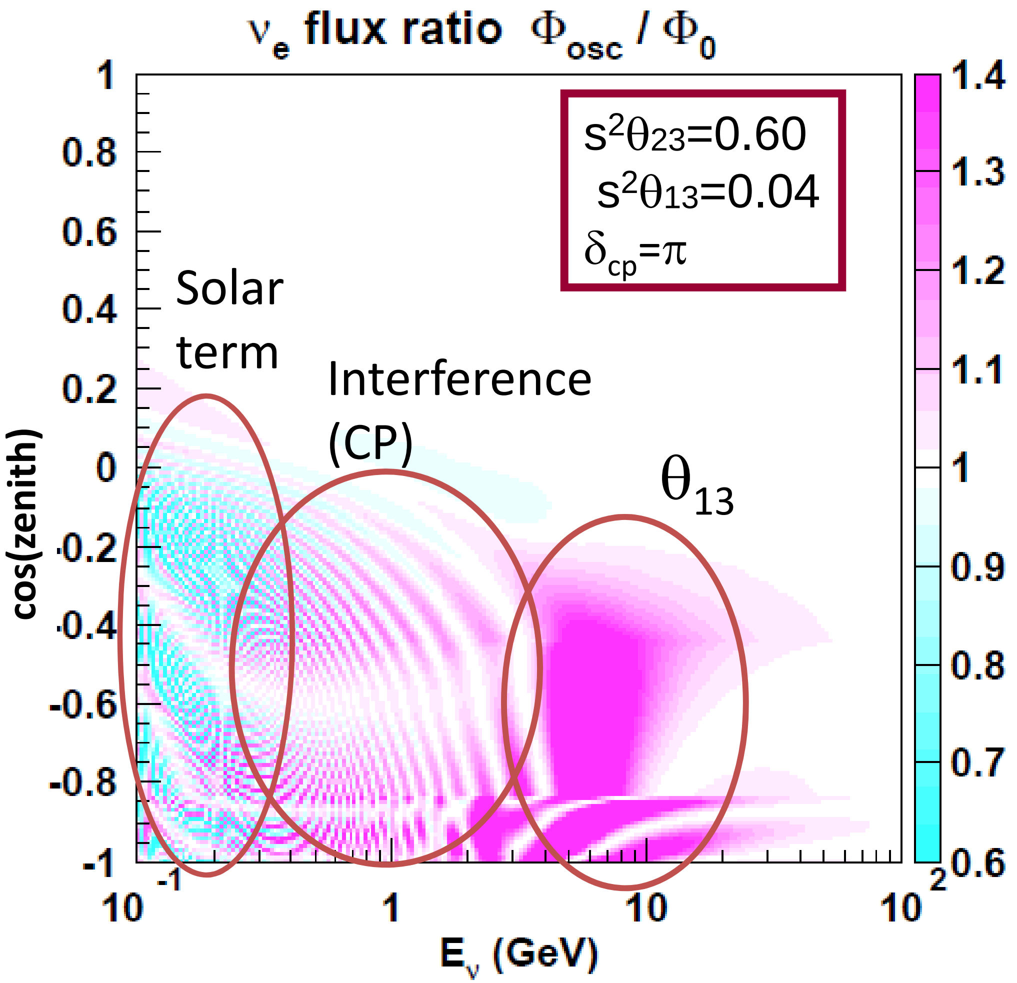
3 flavor oscillation analyses (3)

- Full 3 flavor analysis -

Full 3 flavor analysis of the atmospheric ν data

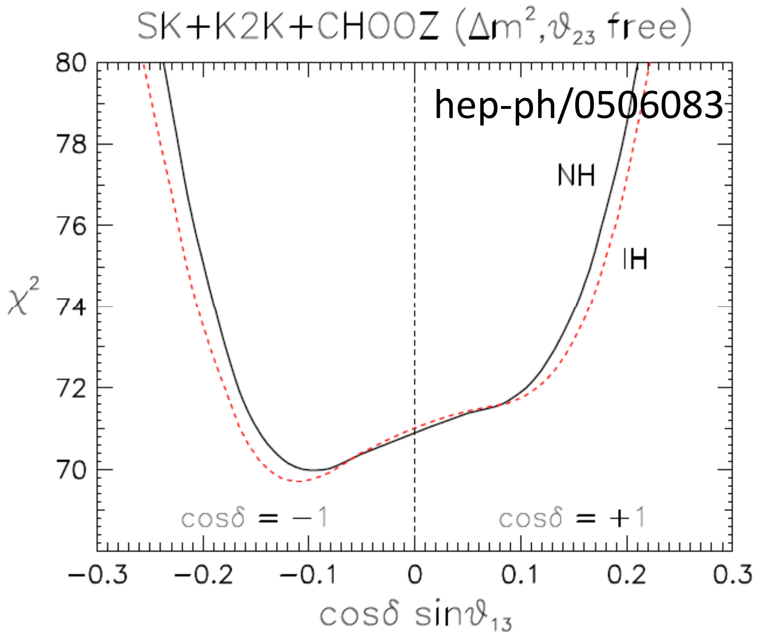
◆Super-K-I+II+III searched for non-zero θ_{13} based on the 1 mass scale dominance model. No evidence for non-zero θ_{13} has been found.

◆However, the solar term effects are relevant in atmospheric neutrino exp's.



◆Therefore, the interference term (CP term) may play an important role.

◆In fact, analyses in hep-ph/0506083 and others indicate the potential importance of the full 3 flavor analysis.



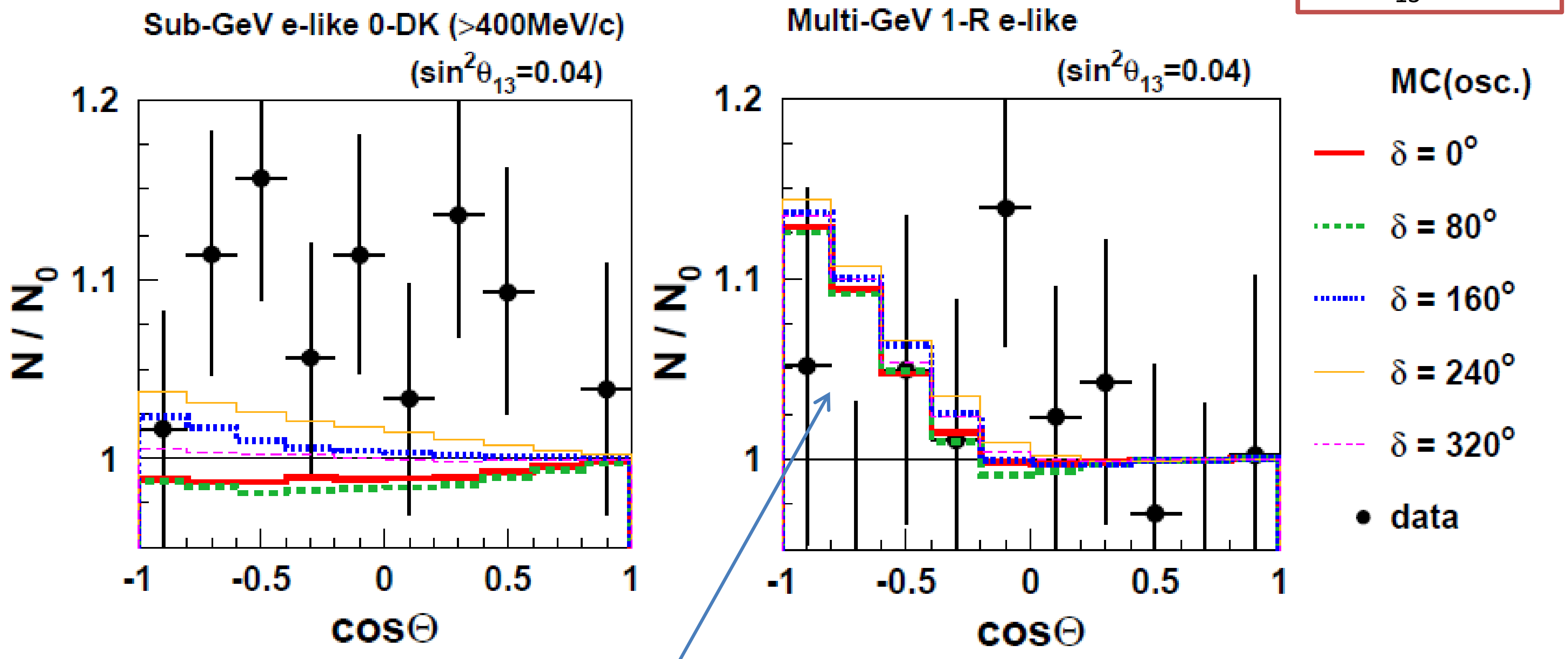
Expected δ_{CP} effect on zenith angle dist.

C.Ishihara, PhD thesis (2010)

$\sin^2\theta_{23}=0.55$
$\Delta m_{23}{}^2=0.0021$
$\sin^2\theta_{13}=0.04$

(below 1.33GeV)

(above 1.33GeV)



Overall excess: θ_{13} effect

Full 3-flavor oscillation results

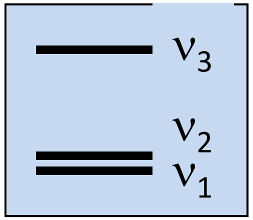
Fitted: Δm_{23}^2, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ_{CP} and sign of (Δm_{23}^2)

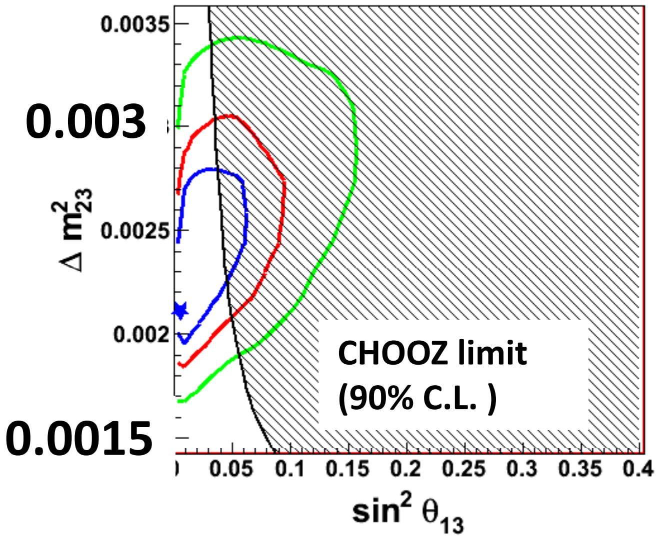
Super-K-I+II+III

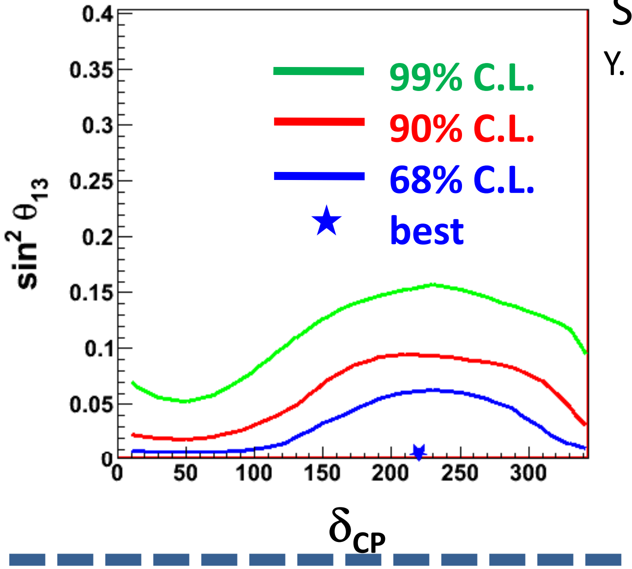
Y. Takeuchi Nu2010

Preliminary

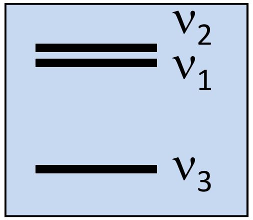
Normal

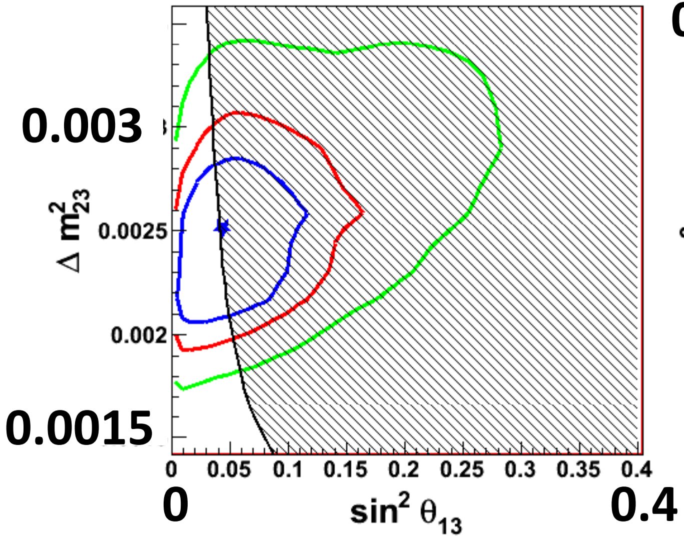


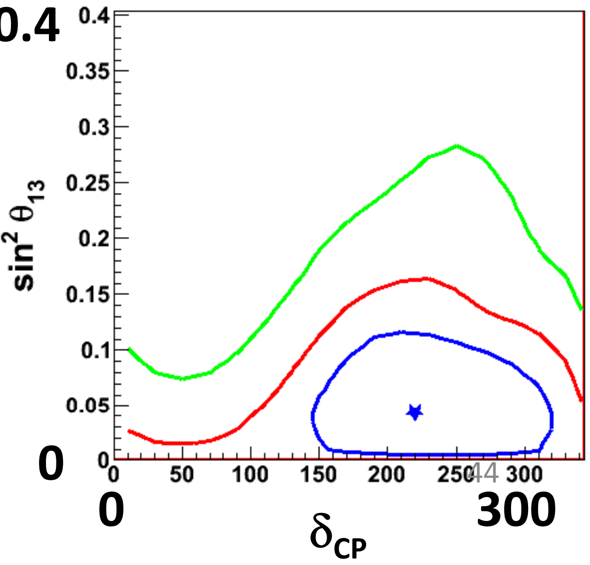




Inverted

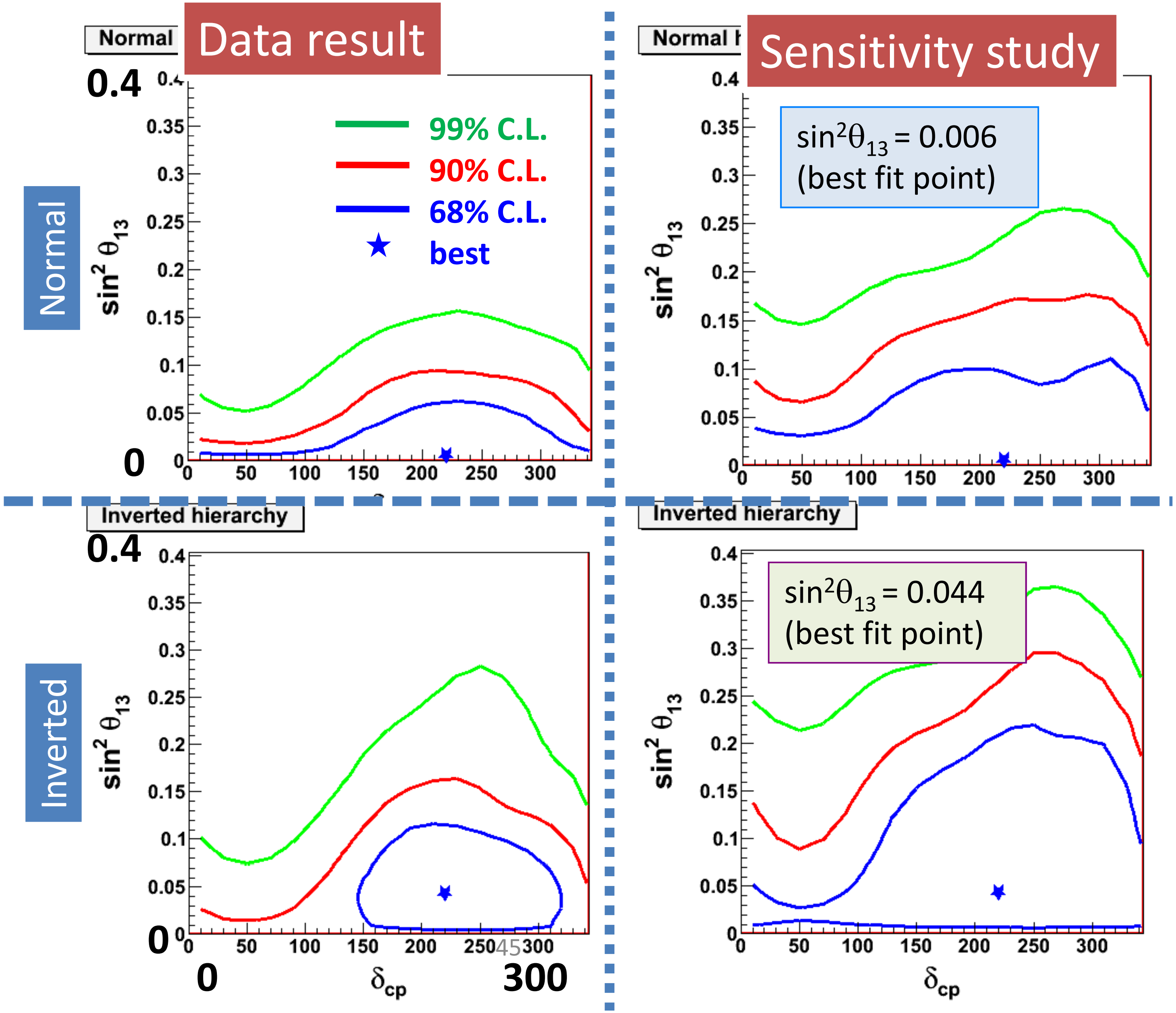






indicating some CP sensitivity

Results versus sensitivity



Data result

Sensitivity study

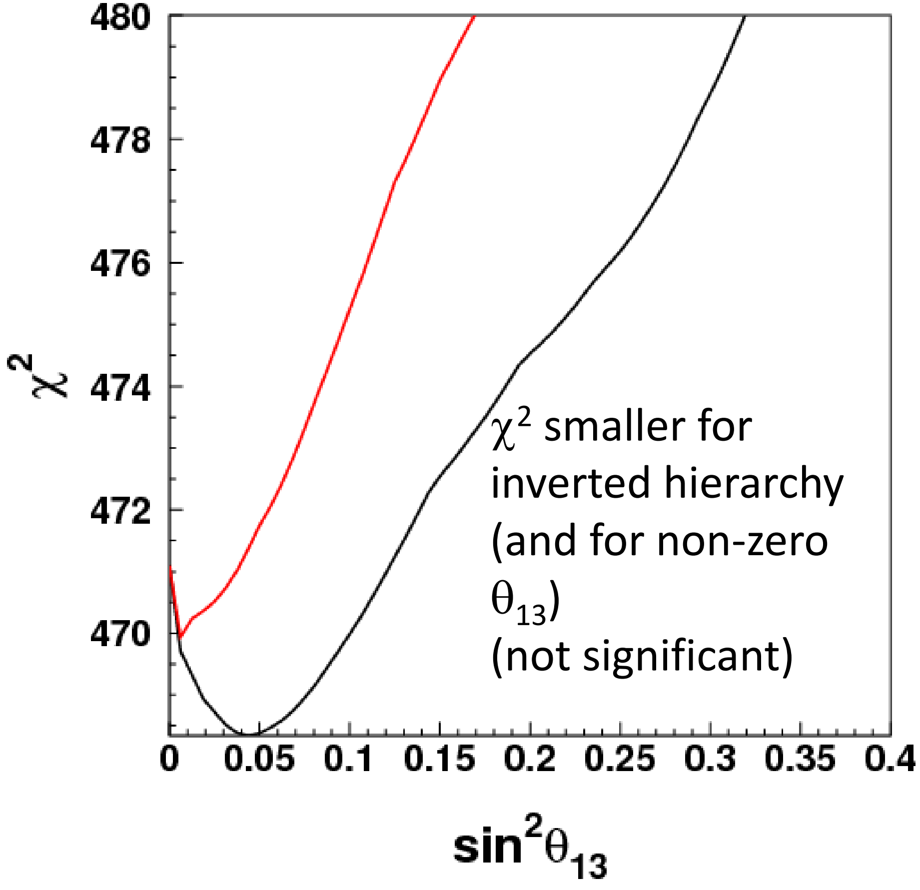
$\sin^2\theta_{13} = 0.006$ (best fit point)

$\sin^2\theta_{13} = 0.044$ (best fit point)

For the assumed oscillation parameters, the results from the data are slightly better than those by the sensitivity study (based on MC).

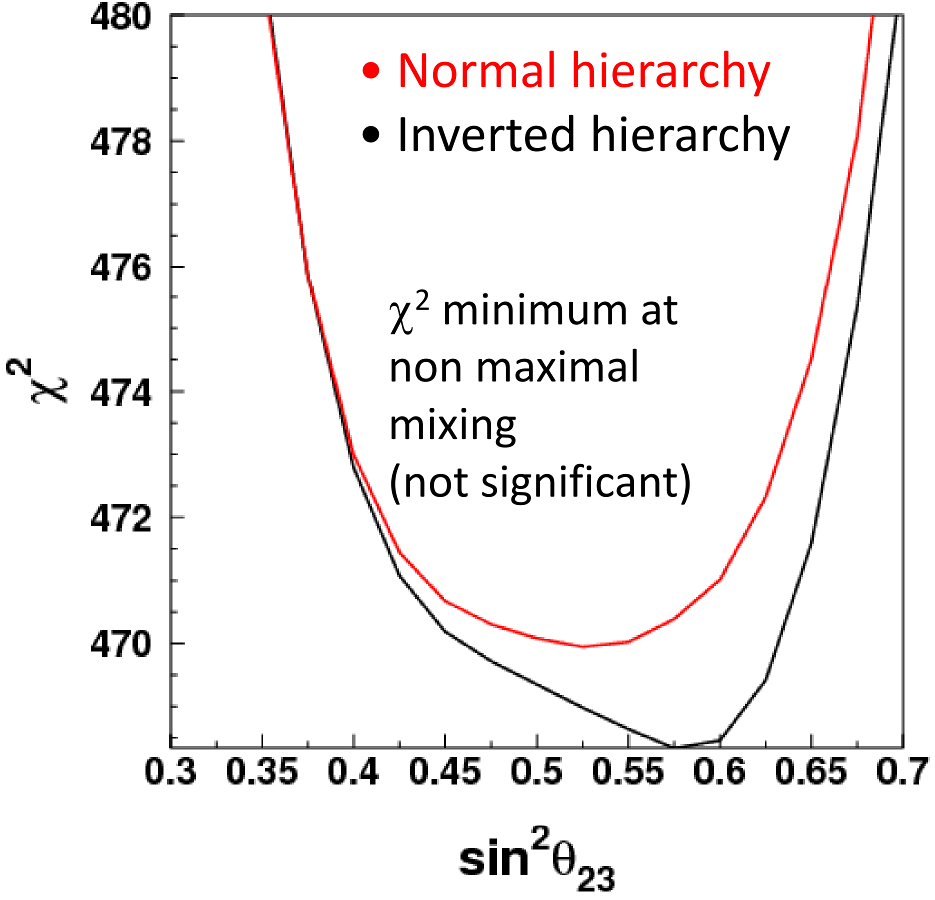
The results suggest that atmospheric neutrino experiments have some sensitivity to CP violation.

χ^2 distributions



χ^2 smaller for inverted hierarchy (and for non-zero θ_{13})
(not significant)

Preliminary Super-K-I+II+III



χ^2 minimum at non maximal mixing
(not significant)

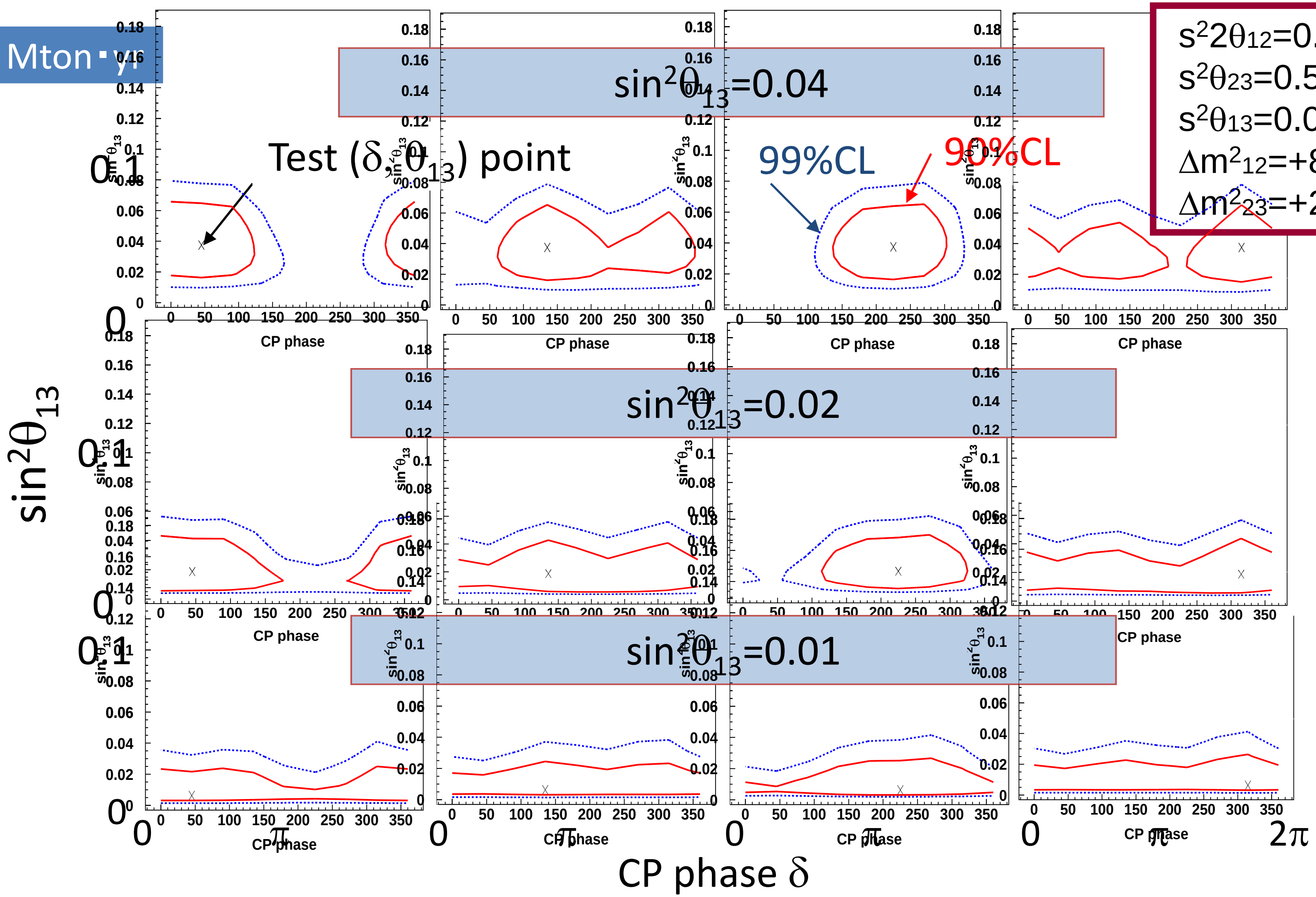
There is no clear evidence for the sub-leading effects. However, the data indicate that future atmospheric neutrino experiments might be a powerful tool for studying sub-leading effects.

Sensitivity: a future ν_{atm} experiment

M.Shiozawa et al., RCCN workshop (2004)

1.8 Mton･yr

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.5$
$s^2\theta_{13}=0.01\sim0.04$
$\Delta m^2_{12}=+8.3\times10^{-5}$
$\Delta m^2_{23}=+2.5\times10^{-3}$



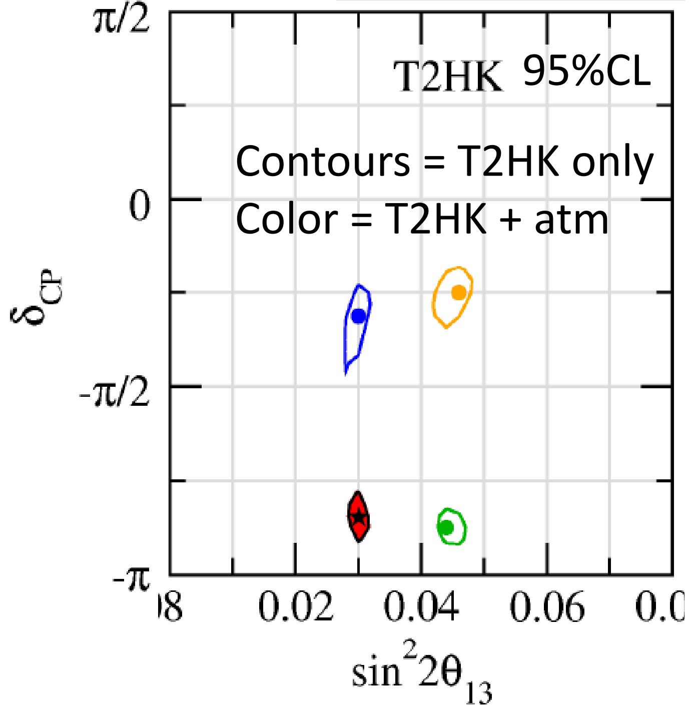
CP phase could be studied if θ_{13} is close to the CHOOZ limit.

Synergies with long baseline experiments

Future long baseline experiments have high sensitivities to δ_{CP} ….
However, in some experiments (especially with relatively short baseline (~300km)), a problem of parameter degeneracy is expected.

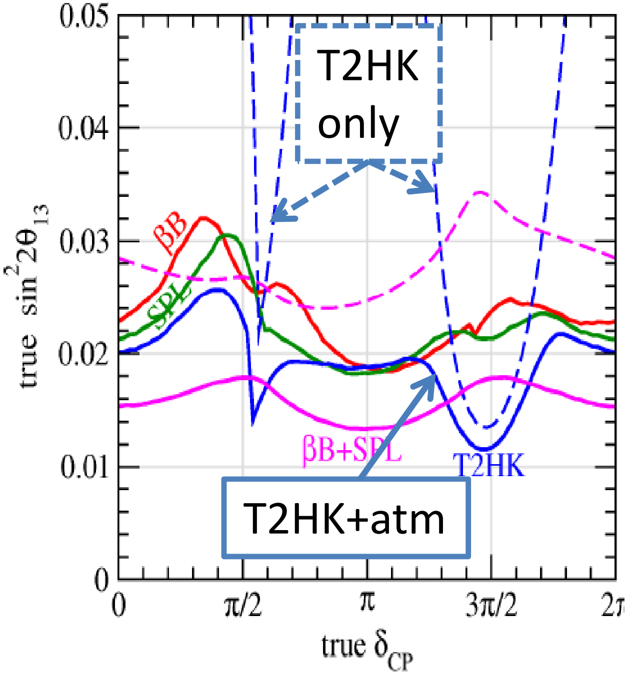
M.Maltoni arXiv: 0707.1218

$\sin^2\theta_{23}=0.6$
$\sin^2 2\theta_{13}=0.03$
$\delta_{CP}=-0.85\pi$


T2HK 95%CL

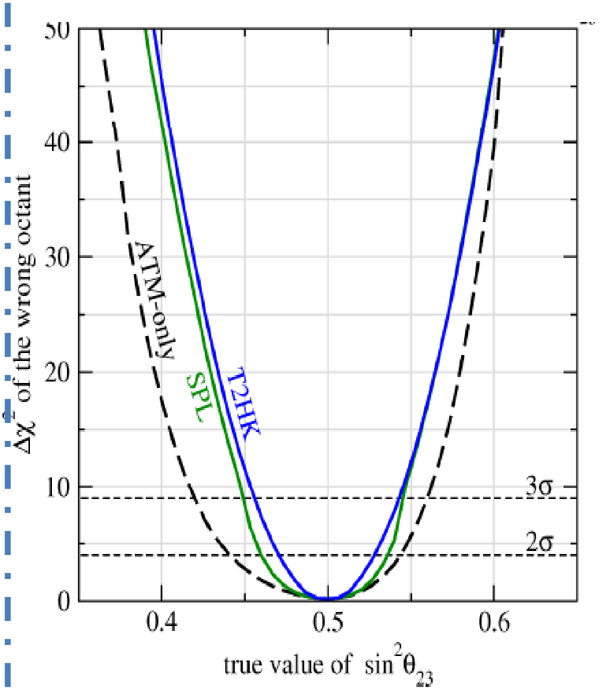
Contours = T2HK only
Color = T2HK + atm

2σ sensitivity to mass hierarchy (true =normal)


T2HK only

T2HK+atm

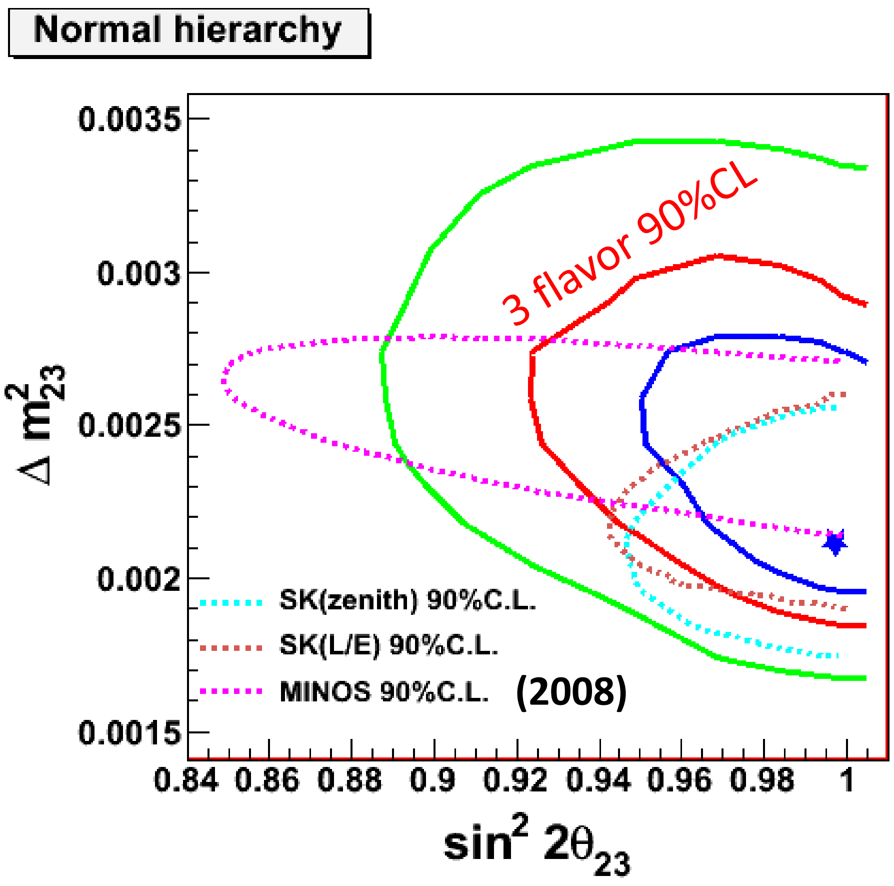
Sensitivity to octant of θ_{23} (θ_{13}=0)

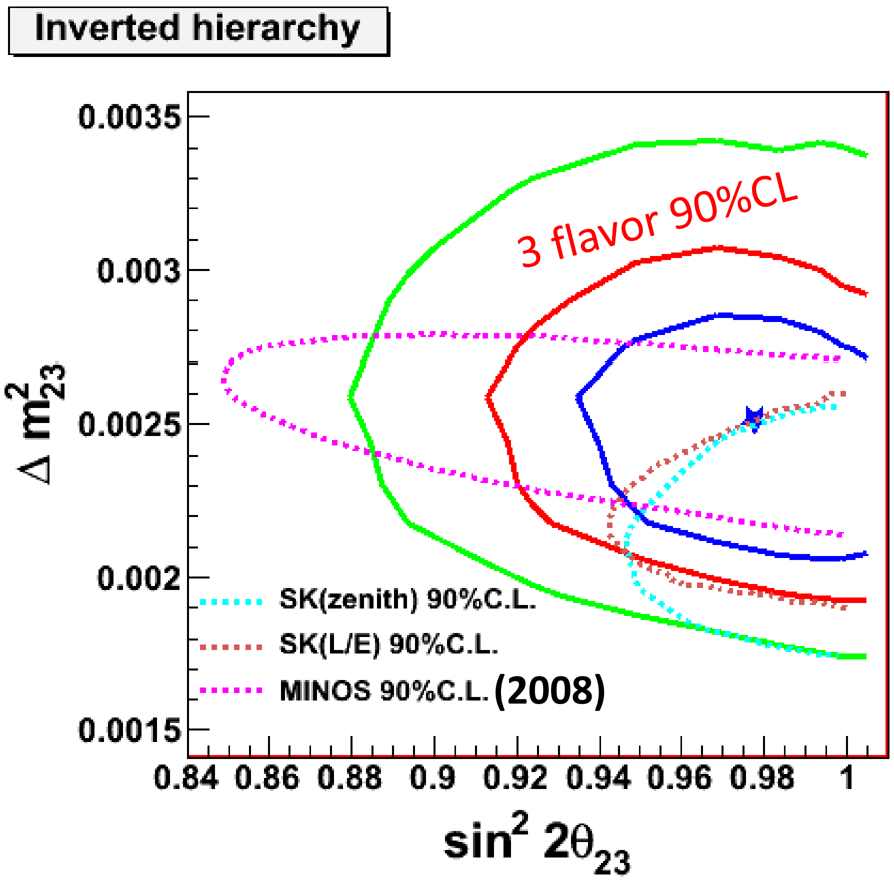


Atmospheric neutrinos (which are available freely) will help future LBL experiments!

Possible importance of the full 3-flavor oscillation analysis (1)

Preliminary Super-K-I+II+III

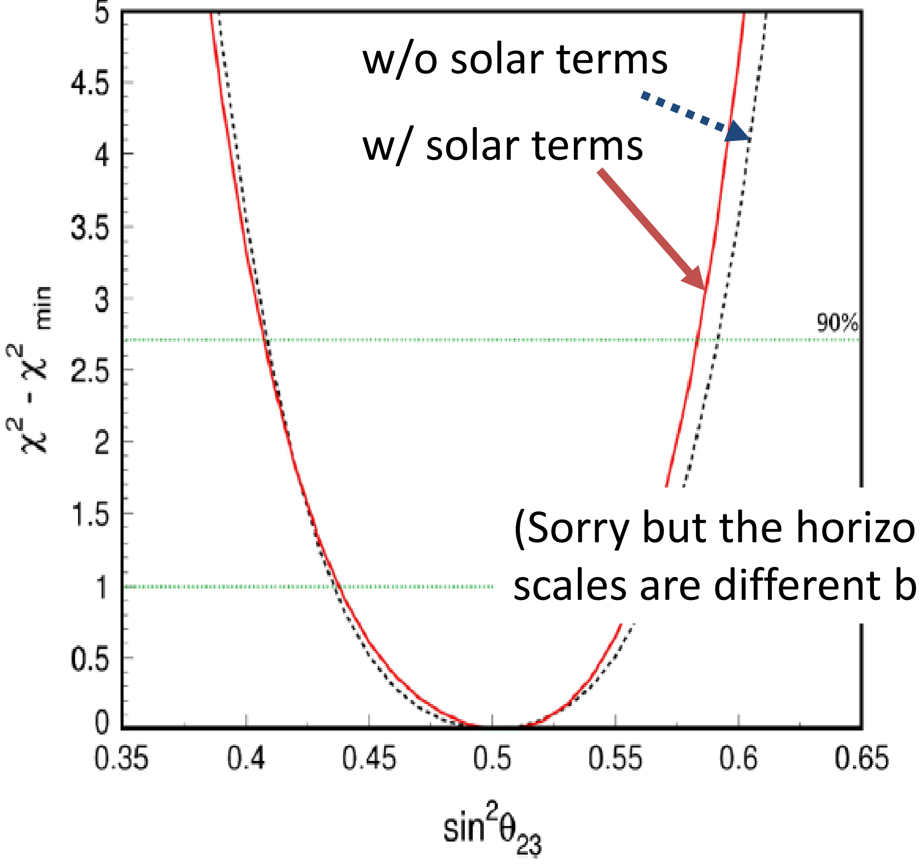




Possible importance of the full 3-flavor oscillation analysis (2)

Preliminary

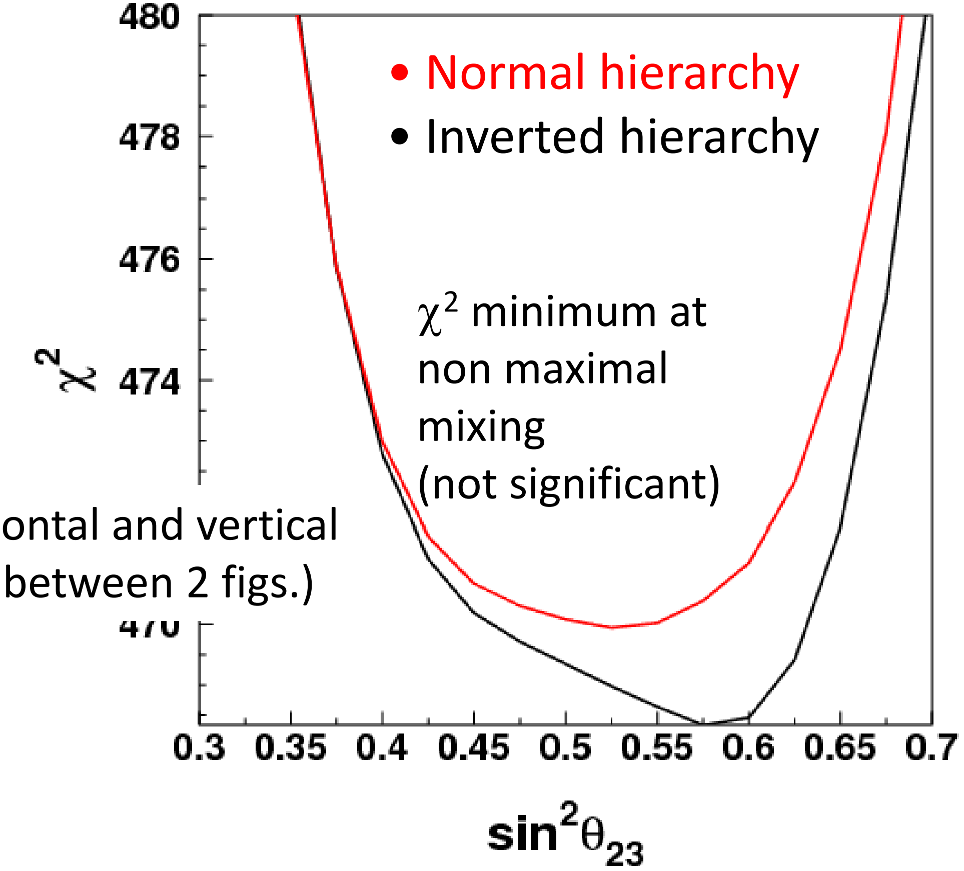
θ_{13} = 0 assumed



w/o solar terms

w/ solar terms

Full 3 flavor



- Normal hierarchy
- Inverted hierarchy

χ^2 minimum at non maximal mixing (not significant)

(Sorry but the horizontal and vertical scales are different between 2 figs.)

These distributions suggest that "full 3 flavor oscillation analysis" is important in estimating the oscillation parameters accurately.

Summary

- With the improved atmospheric neutrino data, the calculation of the neutrino flux is also improving.
- The present data are consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillation with the maximal mixing.
- The full 3 flavor oscillation analysis has been carried out, suggesting that atmospheric neutrino experiments are sensitive to sub-leading effects. In particular, future atmospheric neutrino experiments with high statistics are sensitive to CP violation, if θ_{13} is large.
- Even for estimating ($\Delta m_{23}{}^2$, $\sin^2\theta_{23}$), a full 3 flavor oscillation analysis might be required to accurately estimate the allowed parameter regions.
- Atmospheric neutrinos could help future LBL experiments in resolving the parameter degeneracy problems.