Recent results from Super-Kamiokande

~ atmospheric neutrino ~

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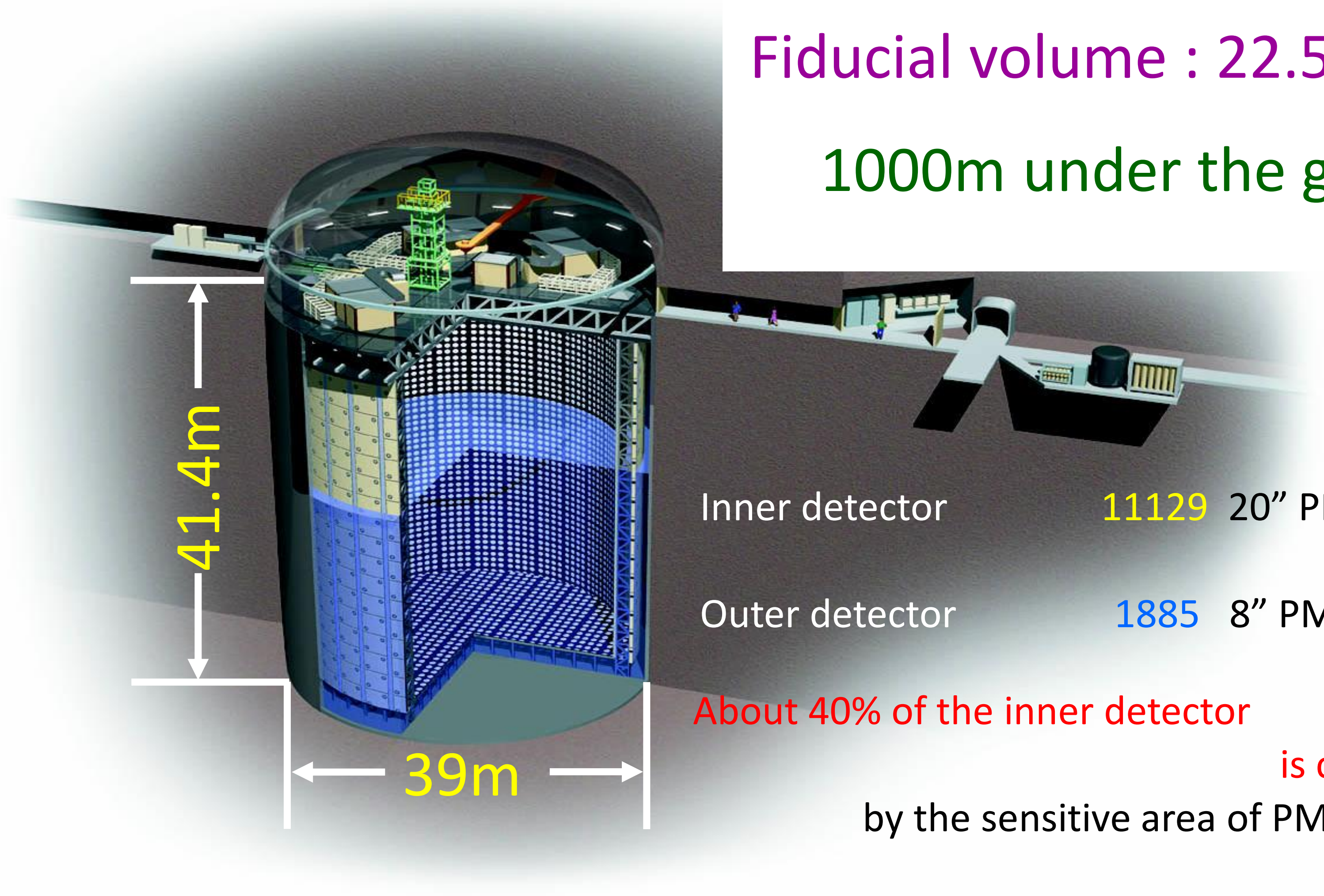
for the Super-Kamiokande collaboration

Super-Kamiokande detector

50000 tons Ring imaging Water Cherenkov detector

Fiducial volume : 22.5 ktons

1000m under the ground



Inner detector	11129	20” PMTs
Outer detector	1885	8” PMTs

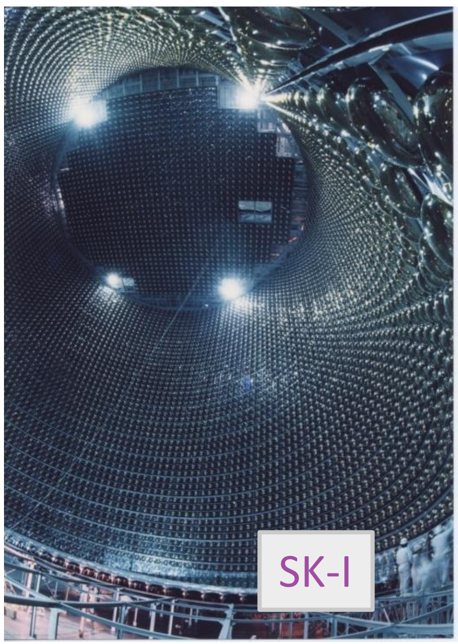
About 40% of the inner detector is covered by the sensitive area of PMT.

Operation started in Apr. 1996.

Super-Kamiokande detector

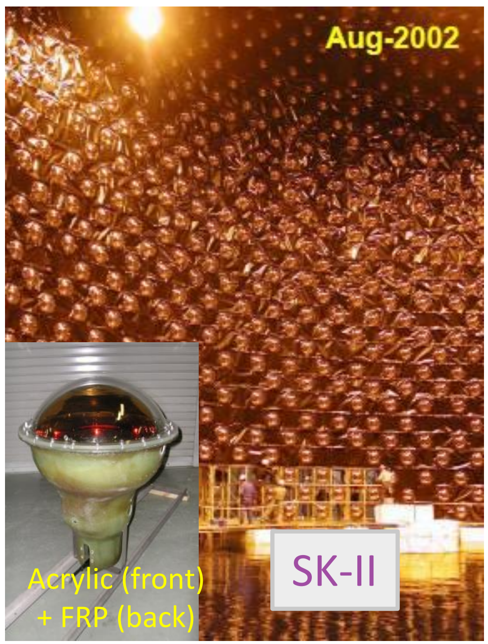
History of the SK detector

SK-I
April 1996
~ June 2001



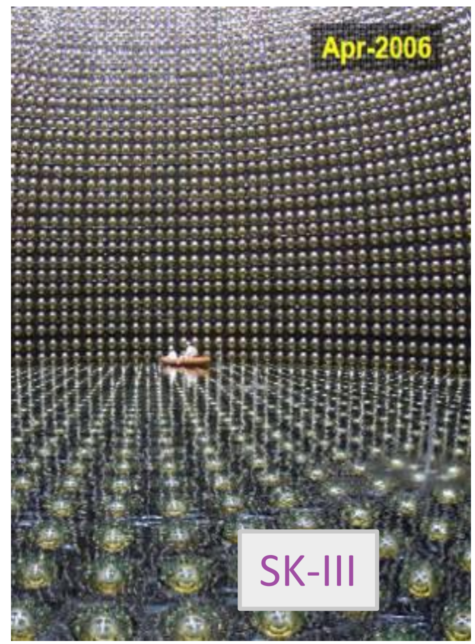
11146 ID PMTs
(40% coverage)

SK-II
October 2002
~ October 2005



5182 ID PMTs
(19% coverage)

SK-III
June 2006
~ September 2008



11129 ID PMTs
(40% coverage)

SK-IV
September 2008
~ running

Electronics
Upgrade

Physics in Super-Kamiokande

Neutrino oscillation

- Accelerator neutrinos
- Atmospheric neutrinos
- Solar neutrinos

GUT

Proton decay

$$p \rightarrow e^{+} + \pi^{0}$$

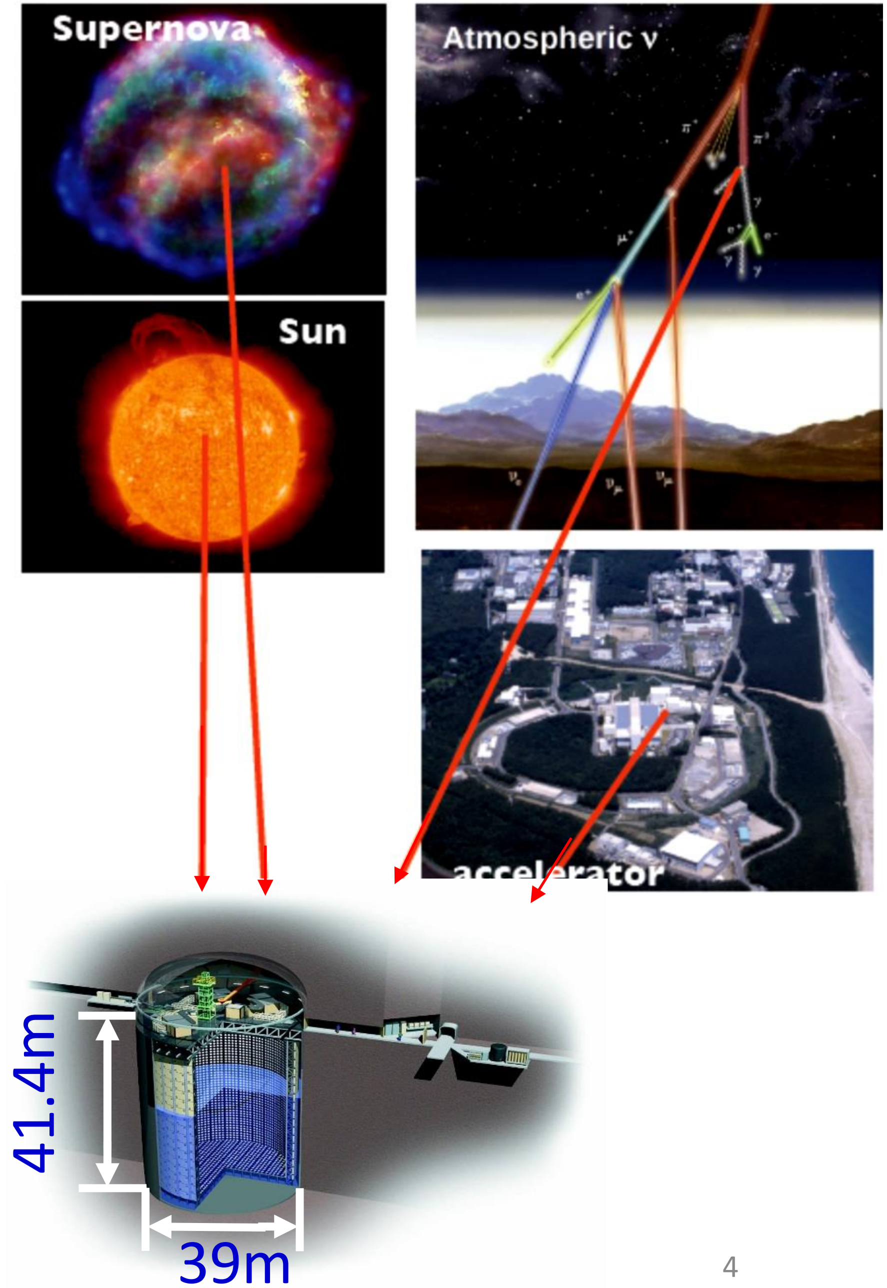
$$p \rightarrow K^{+} + \overline{\nu}$$

New physics

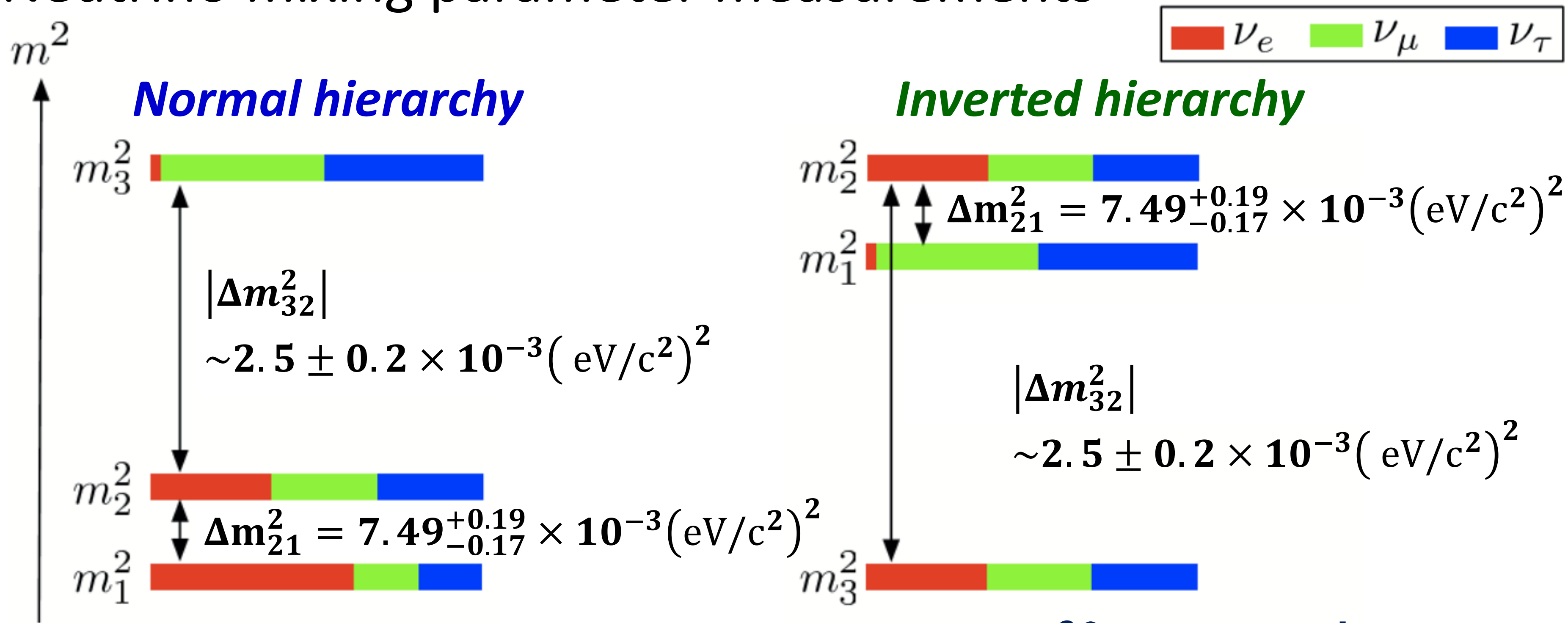
- WIMP search
- n-$\bar{n}$ oscillation
- dinucleon decay etc….

Neutrino astrophysics

- Super nova burst neutrino
- Super nova relic neutrino



Neutrino mixing parameter measurements



$\sin^2\theta_{12} \sim 0.305 \pm 0.013$

$\sin^2 2\theta_{13} = 0.098 \pm 0.013$

Remaining questions

1) θ_{23} is really 45° or < 45° or >45° ?

Current uncertainty of $\sin^2\theta_{23}$ is still large ~ 10% level

$\sin^2\theta_{23} = 0.514 \pm 0.055$ **(T2K 2014)**

2) CP is violated or not ($\delta = 0$ or not) ?

3) Mass hierarchy ~ which is heavier ? ($\Delta m^2_{32} > 0$ or < 0 ?)

Neutrino oscillation probability ~ ν_μ to ν_e oscillation

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = & \; 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

θ_{13} Leading term

CPV

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4E_\nu$$

$$a = 2\sqrt{2} G_F n_e E_\nu$$

For anti neutrinos,

$a \to -a$, $\delta \to -\delta$

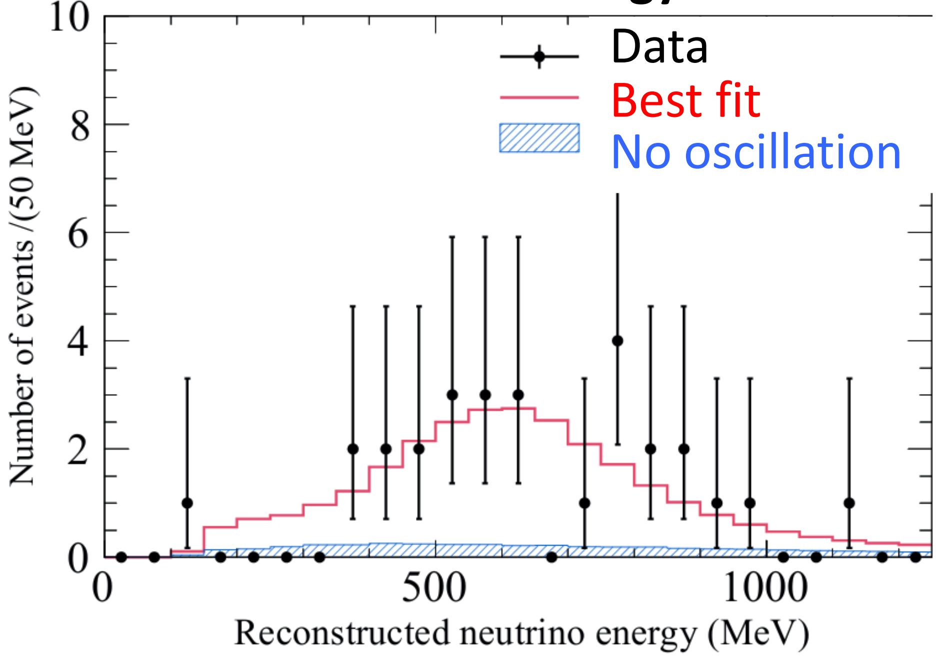
Now, θ_{13} is known to be (quite) large.

There are chances to observe the contributions from ***mass hierarchy*** and ***CPV (δ)*** !

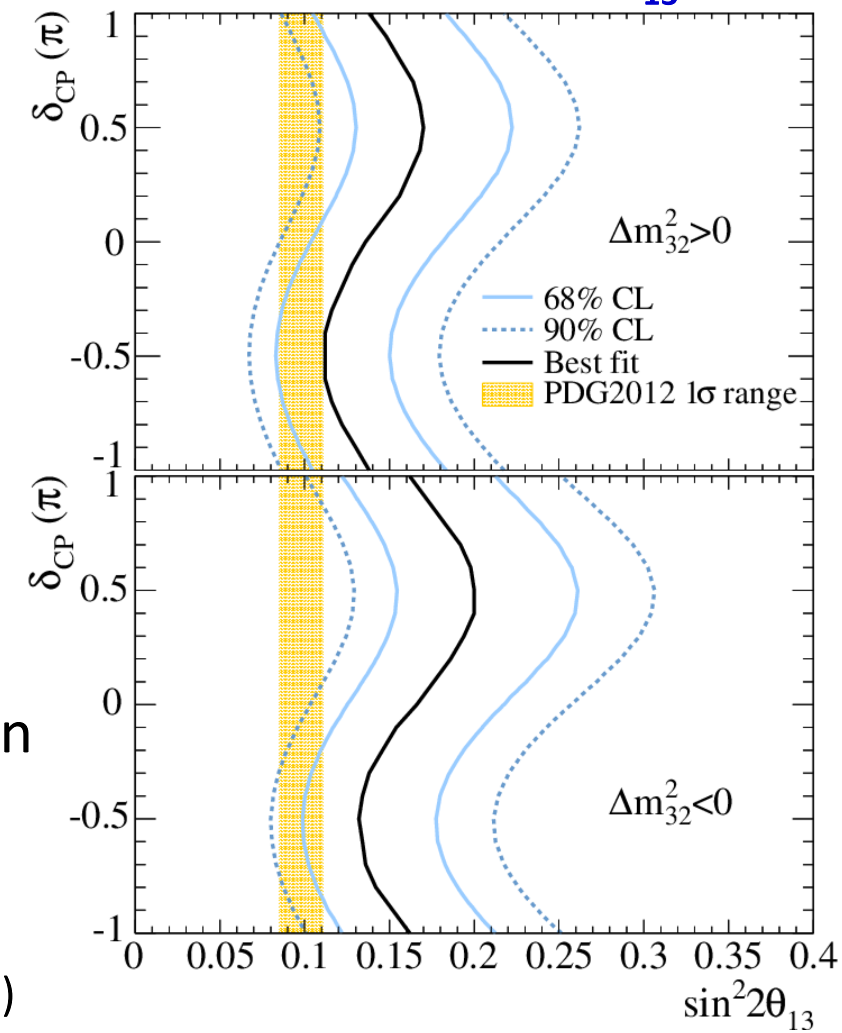
Recent results from Reactor & T2K

ν_e appearance clearly observed in T2K

Reconstructed ν energy



Allowed region of δ_{CP} for each $\sin^2 2\theta_{13}$

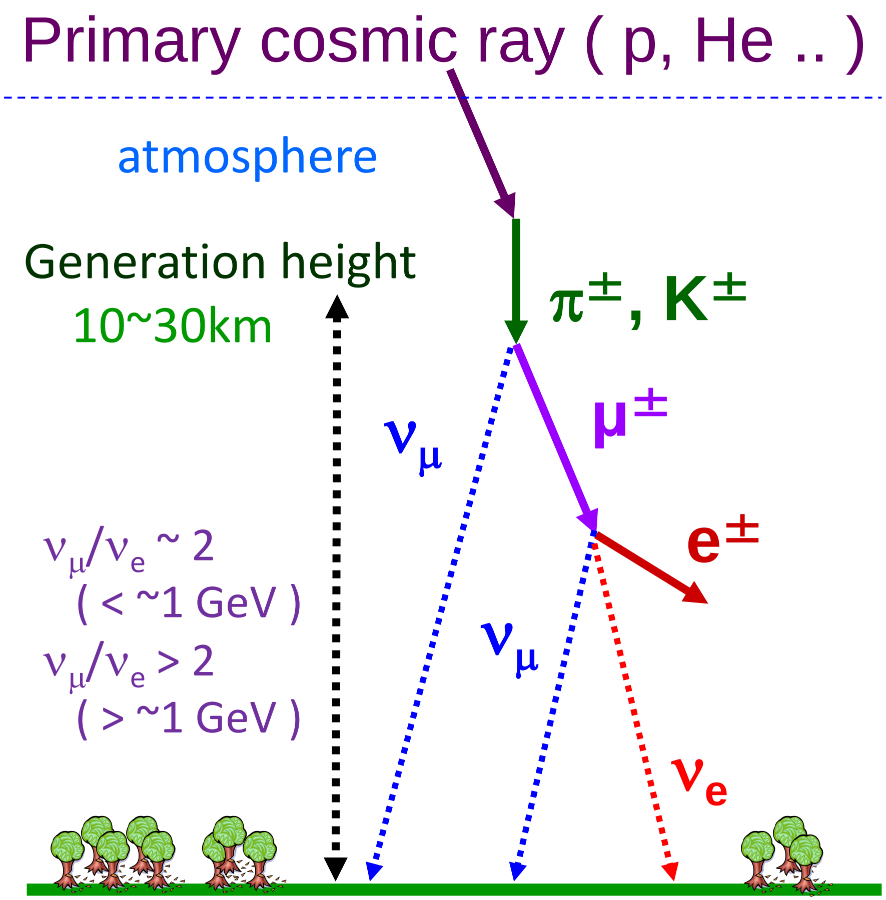


Extracted $\sin^2 2\theta_{31}$ is slightly larger than the ones from reactor experiments

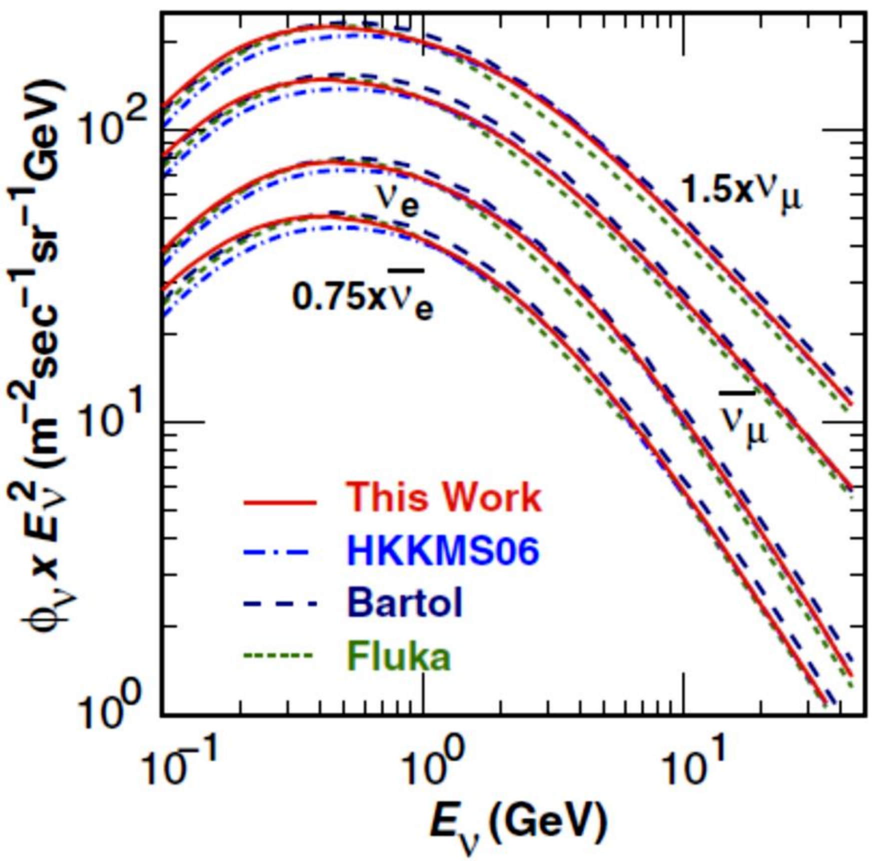
$$\sin^2 2\theta_{13} = \begin{cases} 0.140^{+0.038}_{-0.032} & \text{(normal hierarchy)} \\ 0.170^{+0.044}_{-0.037} & \text{(inverted hierarchy)} \end{cases}$$

Indication of non-zero δ_{CP}?

Characteristics of atmospheric neutrino



Atmospheric ν energy spectrum



Atmospheric neutrino energy spectrum

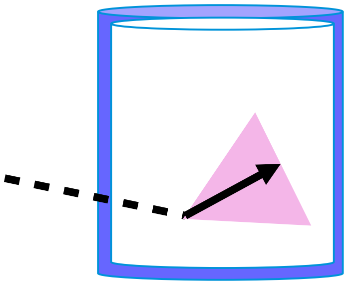
Peaked at ~ several hundreds of MeV, Extended > TeV

Neutrino travel length from ~ 10 km to 13,000 km

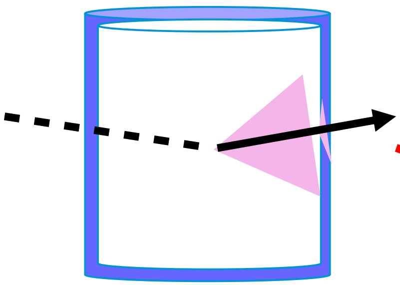
Zenith angle corresponds to travel length of neutrinos.

Atmospheric neutrino ~ event topology in SK

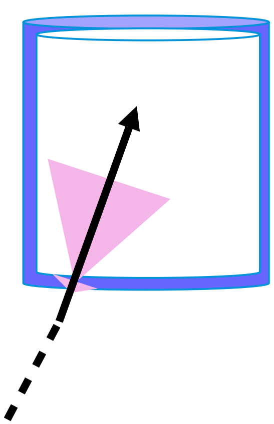
Fully Contained (FC)



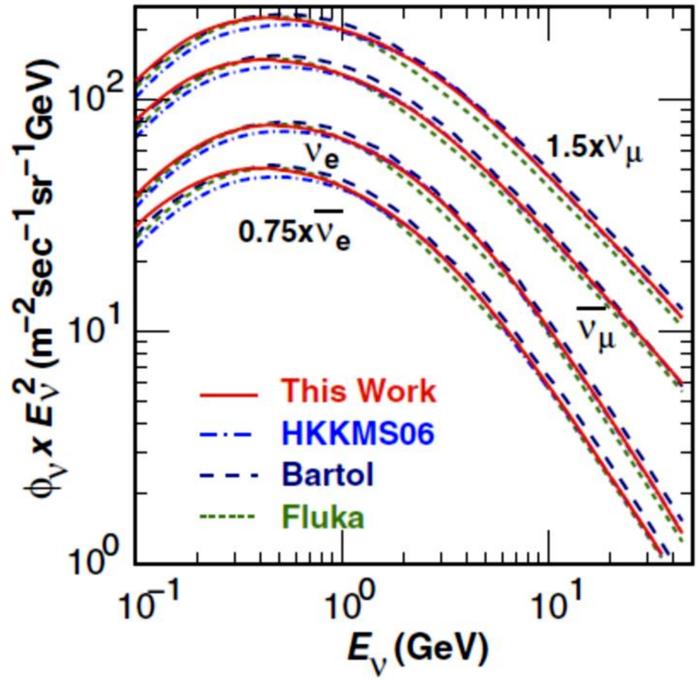
Partially Contained (PC)

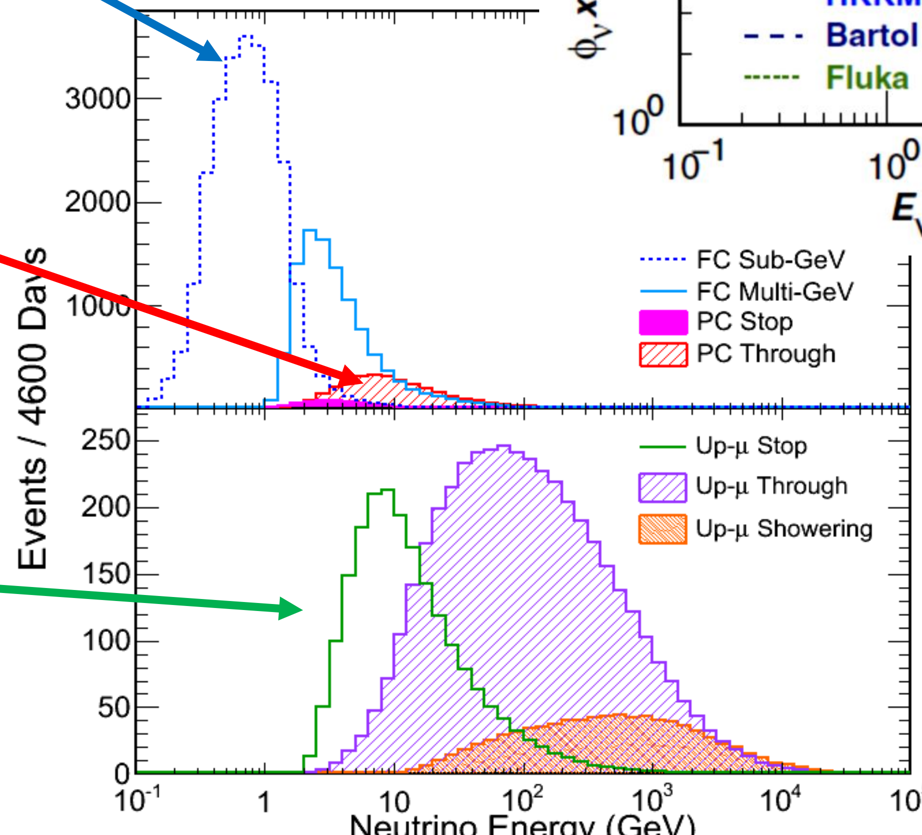


Upward-going Muons (Up-μ)



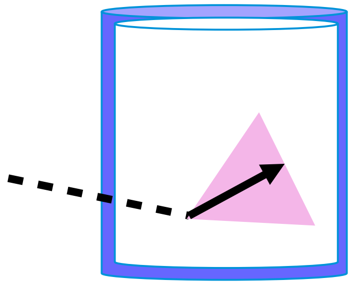
- Average energies
  - FC: ~ 1 GeV
  - PC: ~ 10 GeV
  - UpMu: ~ 100 GeV



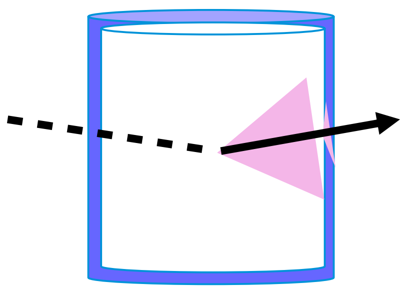


Atmospheric neutrino ~ Analysis samples in SK

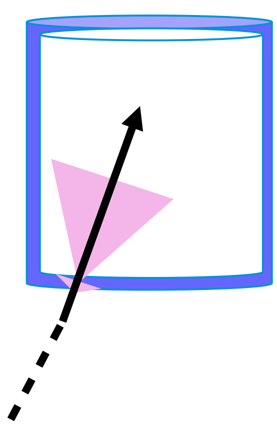
Fully Contained (FC)



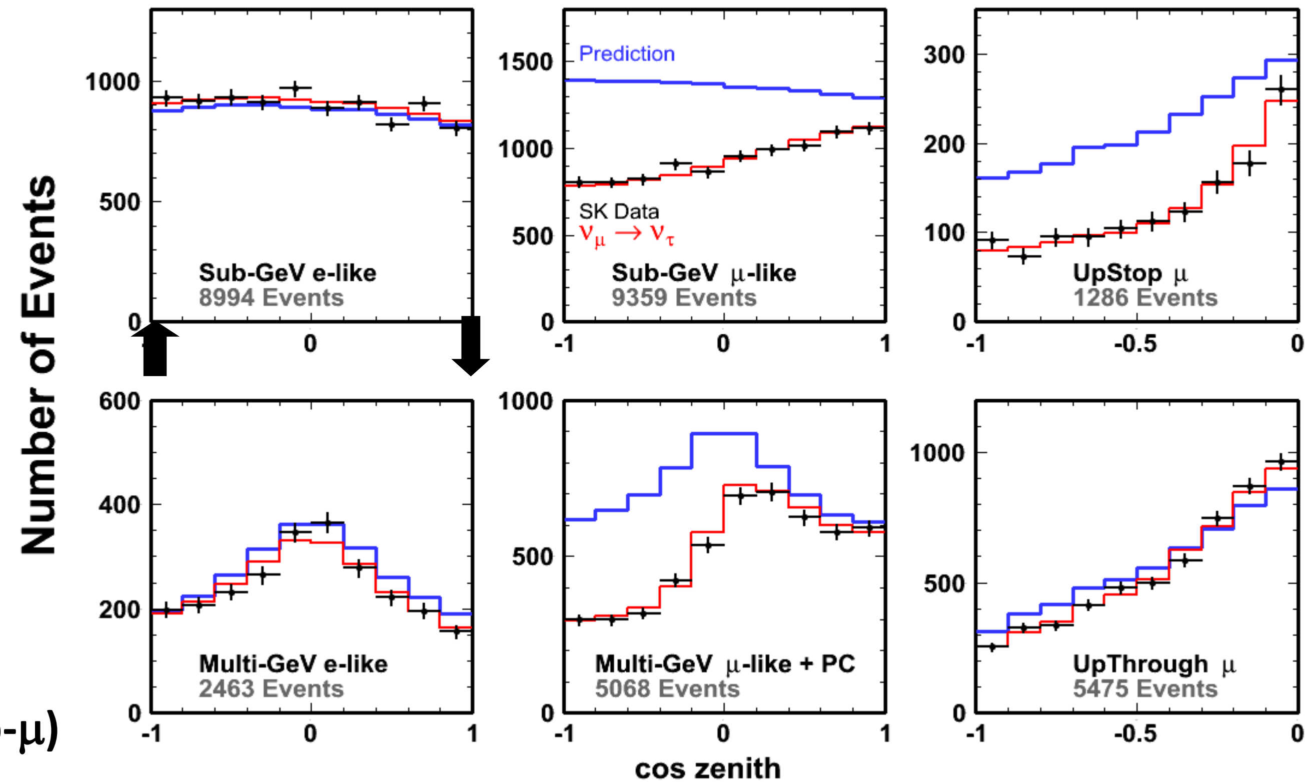
Partially Contained (PC)



Upward-going Muons (Up-μ)



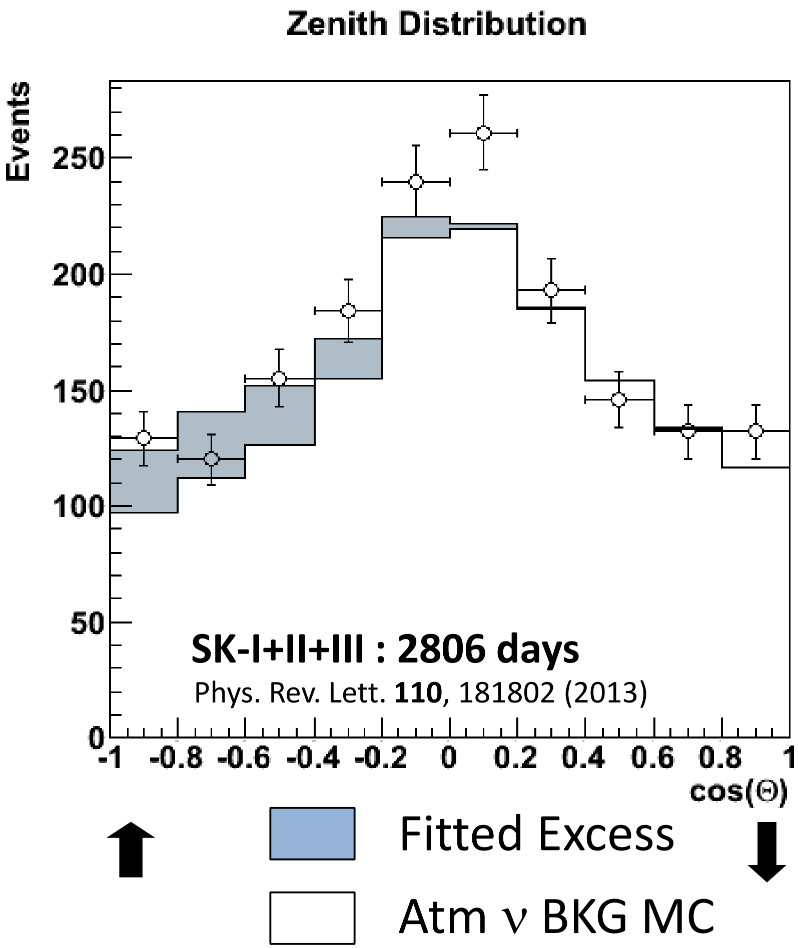
Zenith angle distribution of each sample



- In total 19 analysis samples
  (classified by ν flavors, event topologies, energies, …)
- Fit to the data in bins of $\cos\theta_{zenith}$ and momentum
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Interested in sub-dominant contributions
  - Three-flavor effects, Sterile Neutrinos, LIV, …

Neutrino oscillation studies using atmospheric ν

Evidence for ν_τ Appearance at Super-K



Search for events ~ hadronic decay of τ lepton

Multi-ring e-like events

~ mostly DIS interactions

Actual event selection

performed by neural network

Total efficiency ~ 60%

Negligible primary ν_τ flux

~ ν_τ must be oscillation-induced

Expected only in upward-going

$\beta = 0$: no ν_τ

$$Data = \alpha(\gamma) \times bkg + \beta(\gamma) \times signal$$

Result	Background	DIS (γ)	Signal
SK-I+II+III	0.94 ± 0.02	1.10 ± 0.05	**1.42 ± 0.35**

180.1 $\pm$44.3 (stat) +17.8-15.2 (sys) events

~ **3.8 σ** excess (Expected 2.7 σ significance)

Neutrino oscillation studies using atmospheric ν

High statistics atmospheric neutrino data

~ Possibility in observing small distortion in ν_e

- Matter effect ~ from mass hierarchy

  Possible ν_e enhancement in several GeV passed through the earth core

- Solar term ~ from θ_{23} octant degeneracy

  Possible ν_e enhancement in sub-GeV

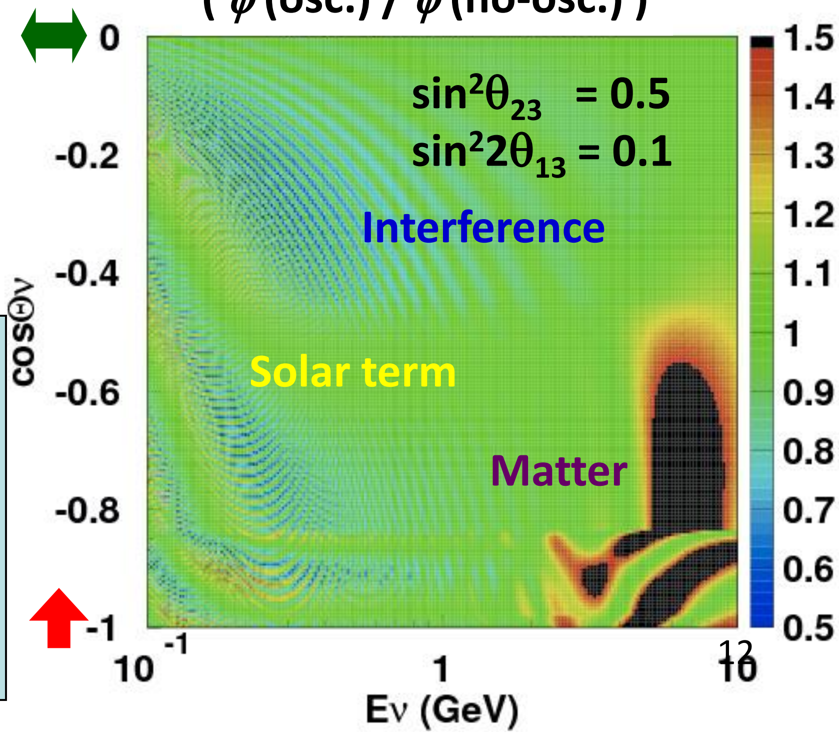
- Interference

  CP phase could be studied.

Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \quad \leftarrow \text{Matter effect}$$
$$+\Delta_2(\Delta m_{12}^2) \quad \leftarrow \text{Solar term}$$
$$+\Delta_3(\theta_{13}, \Delta m_{12}^2, \underline{\delta}) \quad \leftarrow \text{Interference}$$

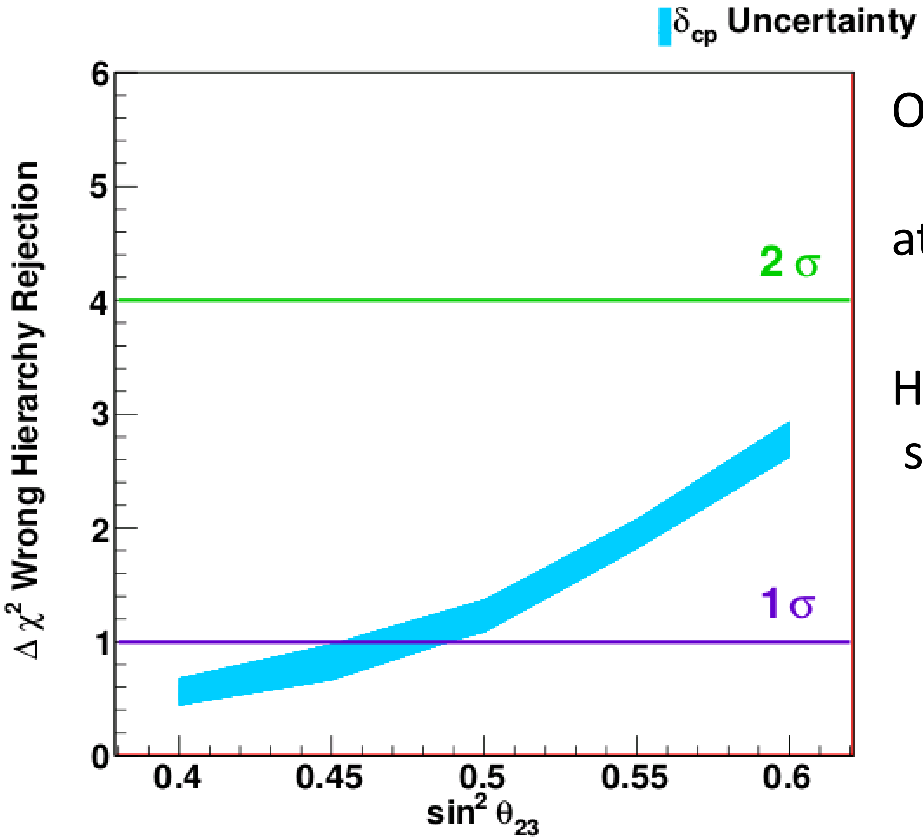
ν_e flux ratio
(ϕ(osc.) / ϕ(no-osc.))



Neutrino oscillation studies using atmospheric ν

Expected Sensitivity

Hierarchy Sensitivity (True : NH)



Owing to the broad energy spectrum and baseline, atmospheric neutrino has sensitivity to the mass hierarchy.

However, sensitivity to the mass hierarchy has rather strong relation with the other oscillation parameters.

As a function of the true value of $\sin^2\theta_{23}$, this plot shows the ability to reject the inverted mass hierarchy hypothesis assuming the normal hierarchy

Neutrino oscillation studies using atmospheric ν

Changes and Updates to Oscillation Analyses

1775 days of SK-IV data: 4581.4 days total (282.2 kton·yrs)

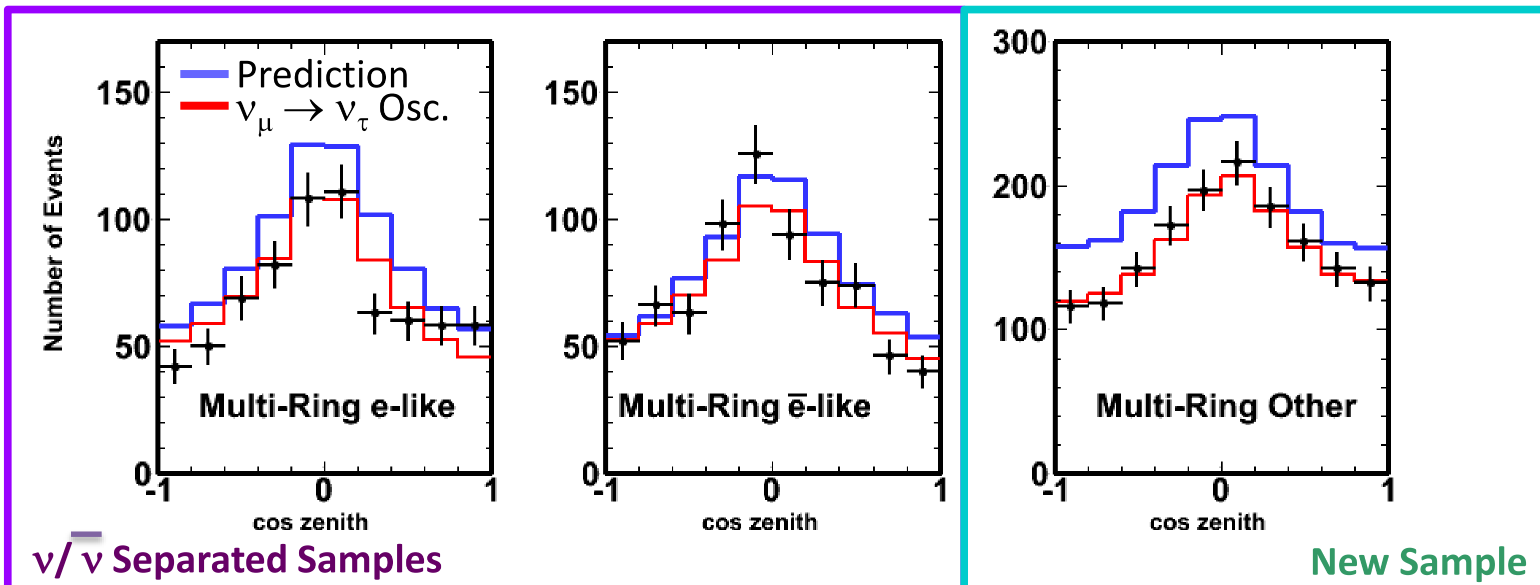
Addition of a new analysis sample

Fully contained Multi-Ring e-like

“other” = not-ν_e & not-$\bar{\nu}_e$

Multi-Ring e-like Sample Purities

Purity	CC ν_e	CCν_μ	CCν_τ	NC
ν-like	72.2%	8.3%	3.2%	16.1%
$\bar{\nu}$-like	75.0%	6.5%	2.8%	15.6%
other	30.9%	33.4%	5.1%	30.5%



Improved systematic error treatments

Updates to cross-section, FSI, detector systematics, 2p-2h (MEC)

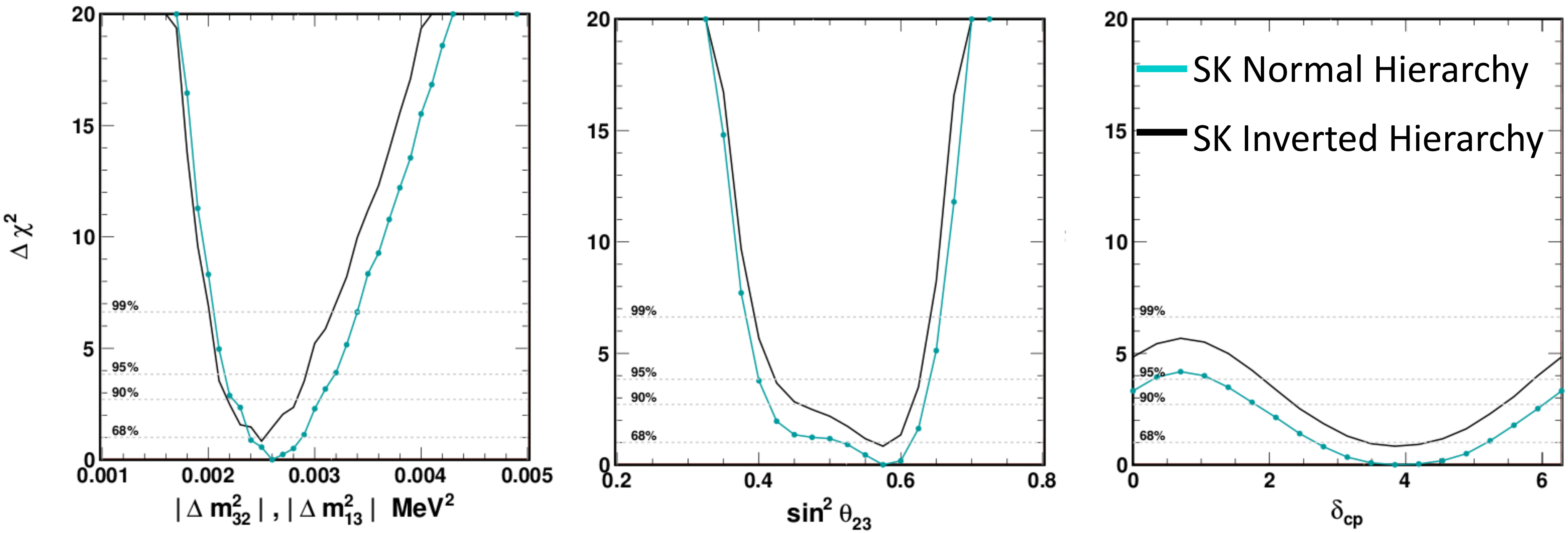
Neutrino oscillation studies using atmospheric ν

θ_{13} **Fixed** Analysis (NH+IH) SK Only

θ_{13} fixed to PDG average

uncertainty is included as a systematic error

Preliminary



Fit (517 dof)	$\chi 2$	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	**559.8**	0.025	3.84	0.57	2.6
SK (IH)	**560.7**	0.025	3.84	0.57	2.5

Offset in these curves shows the difference in the hierarchies

Neutrino oscillation studies using atmospheric ν

θ_{13} Fixed Analysis (NH+IH) SK Only

Normal hierarchy favored

but $\chi^2_{IH} - \chi^2_{NH}$ = **- 0.9**

Not a significant preference

Previous results (2013 Summer) favored inverted hierarchy by $\Delta\chi^2$ ~ **1.5**

Driven by excess of upward-going e-like

consistent with the effects of θ_{13}

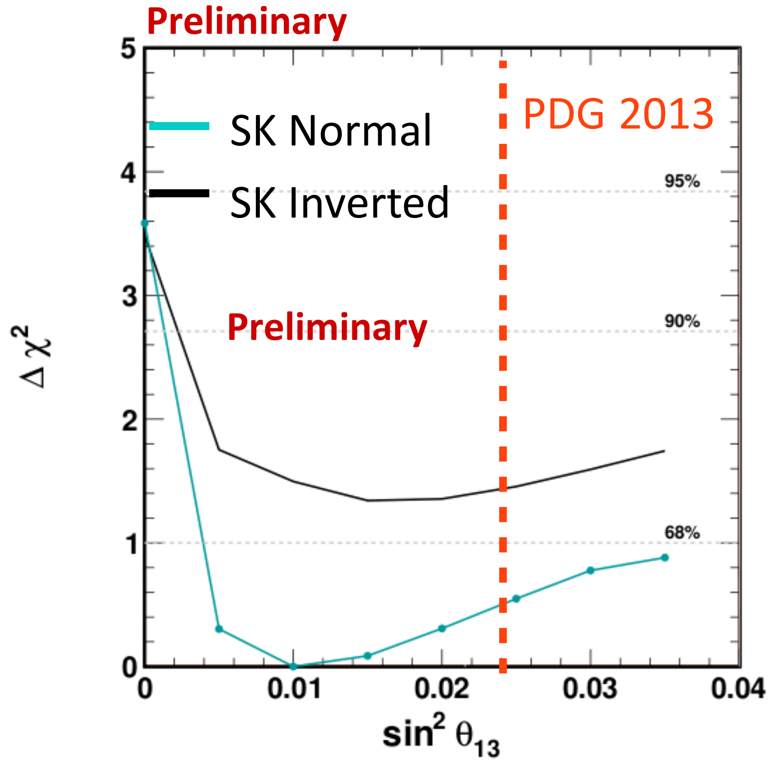
Primarily in SK-IV data

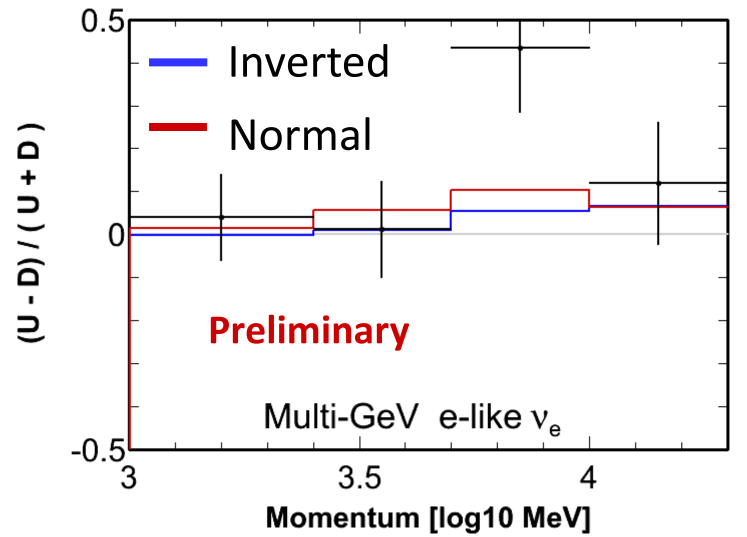
New multi-ring e-like sample also pulls the fit towards the NH

Fit for θ_{13} now weakly favors $\theta_{13} > 0$

Rejection of δ_{cp} ~ 60° driven by excess in Sub-GeV electron events

Constraint is consistent with sensitivity

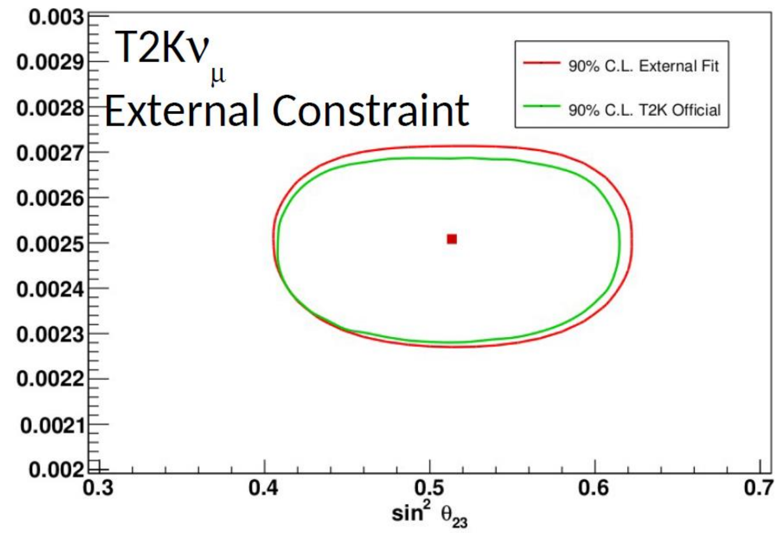




Neutrino oscillation studies using atmospheric ν

Introduction of External Constraint

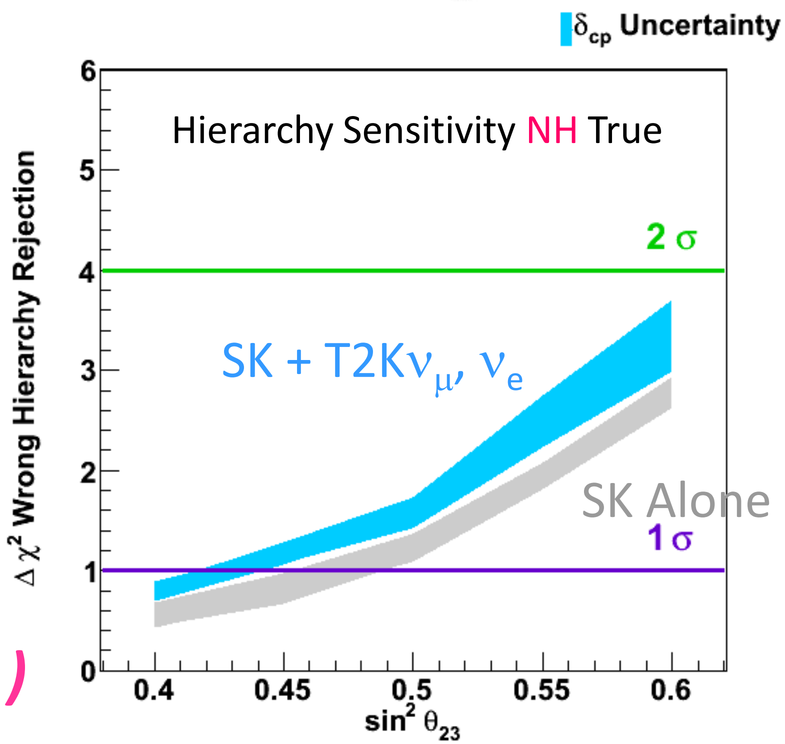
Constraints from the other experiments,
(especially, Δm^2 and $\sin^2\theta_{23}$) ,
make it possible to improve
sensitivity to mass hierarchy.



Fit the T2K ν_μ and ν_e data sets
with SK atmospheric neutrino data.

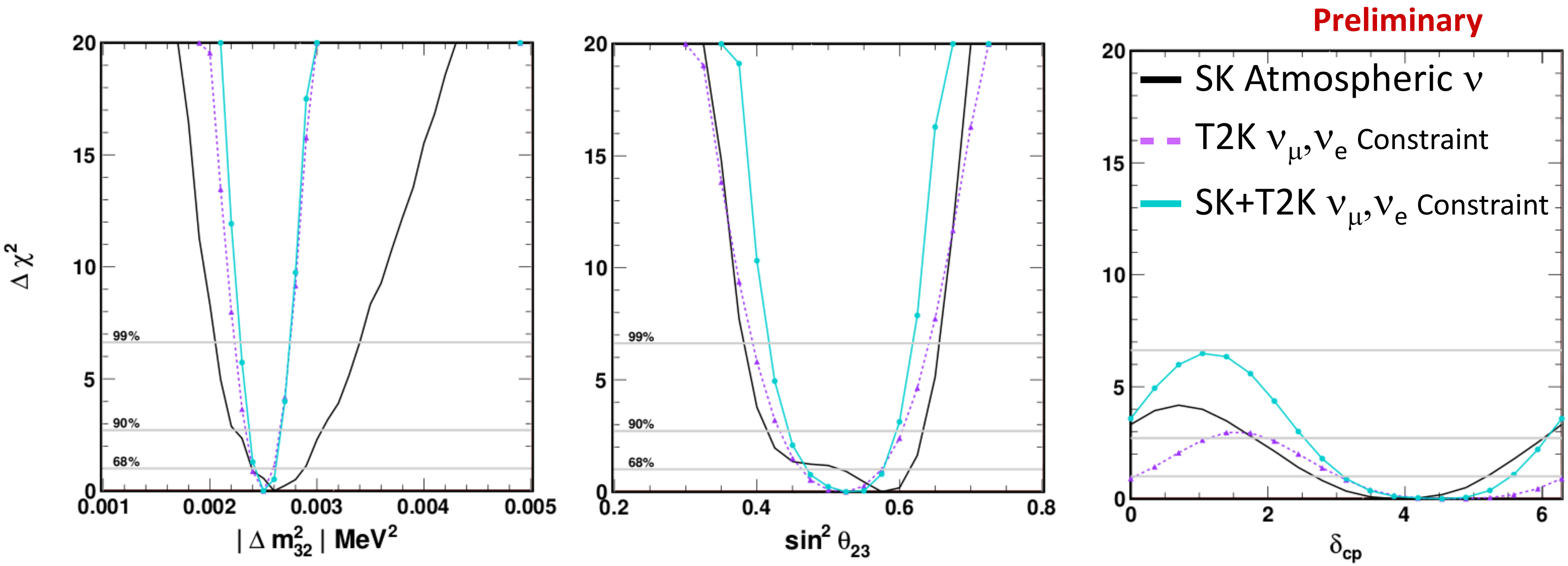
Use **publicly available**
T2K information and results.

Simulate T2K using SK tools
(not a joint result of
the T2K and the SK collaborations)



Neutrino oscillation studies using atmospheric ν

θ_{13} **Fixed** SK + T2K ν_μ, ν_e (External Constraint) Normal Hierarchy



Fit (543 dof)	χ2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5

$\chi^2_{IH} - \chi^2_{NH}$ = **-1.2** (-0.9 SK only)

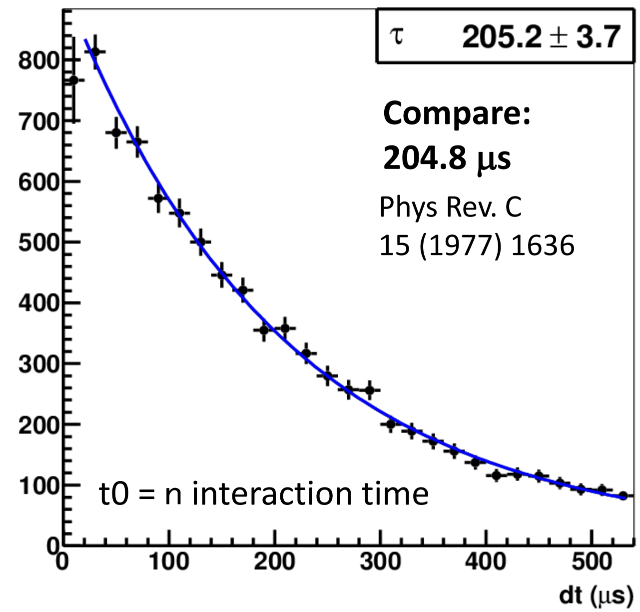
$\sin\delta_{cp}$ = 0 is still allowed at (at least) 90% C.L. for both hierarchies.

Neutron tagging ~ For further improvements ~

Effective neutron tagging make it possible t

1) discriminate ν and $\bar{\nu}$ interactions more efficiently

2) reduce background of proton decay

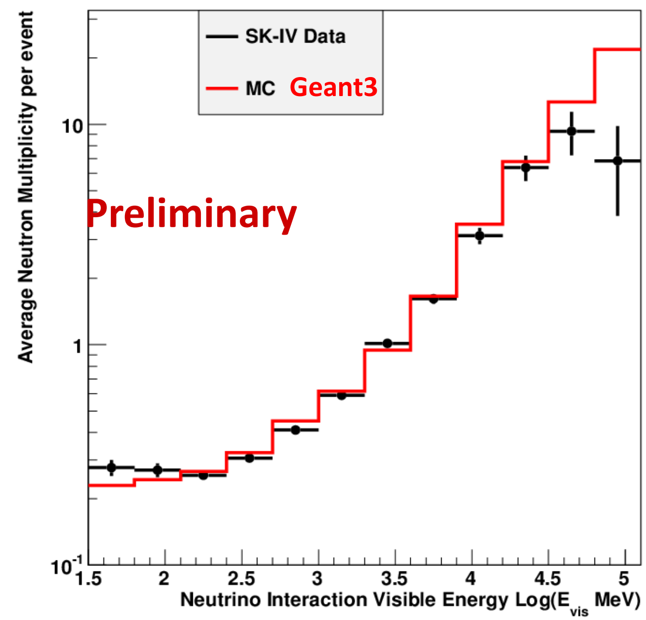


· Electronics in SK-IV store all PMT hits for 500 μsec after a neutrino-like trigger.

· Search for the 2.2 MeV gamma from p(n,γ)d

Actual search is performed with a neural network (16 variables)

· Data and MC show good agreement on atmospheric neutrino sample



2.2 MeV γ Selection	
Efficiency	**20.5%**
Background / Event	**0.018**

Sterile neutrino oscillations in atmospheric neutrino

Sterile Neutrino searches at SK

Independent from

the sterile Δm^2 and

the # of sterile neutrinos.

MNS | Sterile

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

a) 3+1 and 3+N models have the same signatures

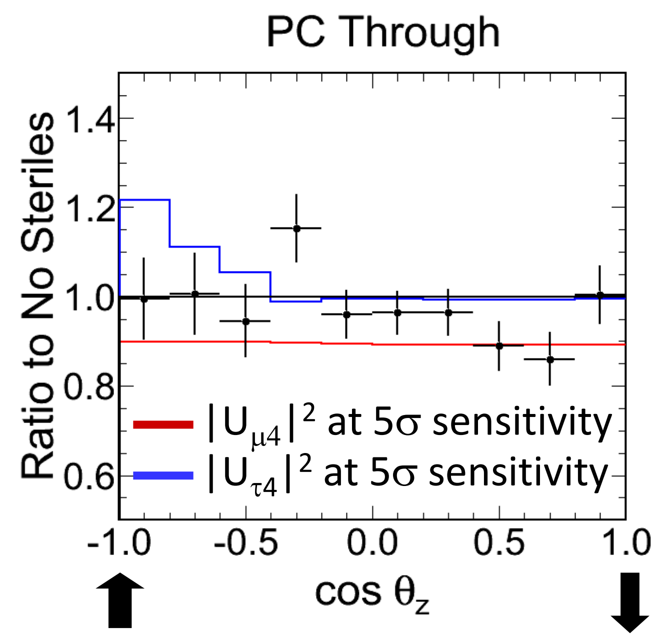
b) For Δm_s^2 ~ 1 eV^2 oscillations appear fast $< \sin 2\, \Delta m^2\, L/E >$ ~ 0.5

$|U_{\mu 4}|^2$

Induces a decrease in event rate of μ-like data of all energies and zenith angles

$|U_{\tau 4}|^2$

Shape distortion of angular distribution of higher energy μ-like data



Limits on sterile neutrino mixing using atmospheric neutrinos in Super-Kamiokande

K. Abe et al., PHYSICAL REVIEW D 91, 052019 (2015)

Sterile neutrino oscillations in atmospheric neutrino

Assuming sterile neutrinos experience vacuum oscillation,

(= turning off sterile matter effects),

while preserving standard three-flavor oscillations

provides a pure measurement of $|U_{\mu4}|^2$

$$P_{ee} = P_{ee}^{(3)},$$

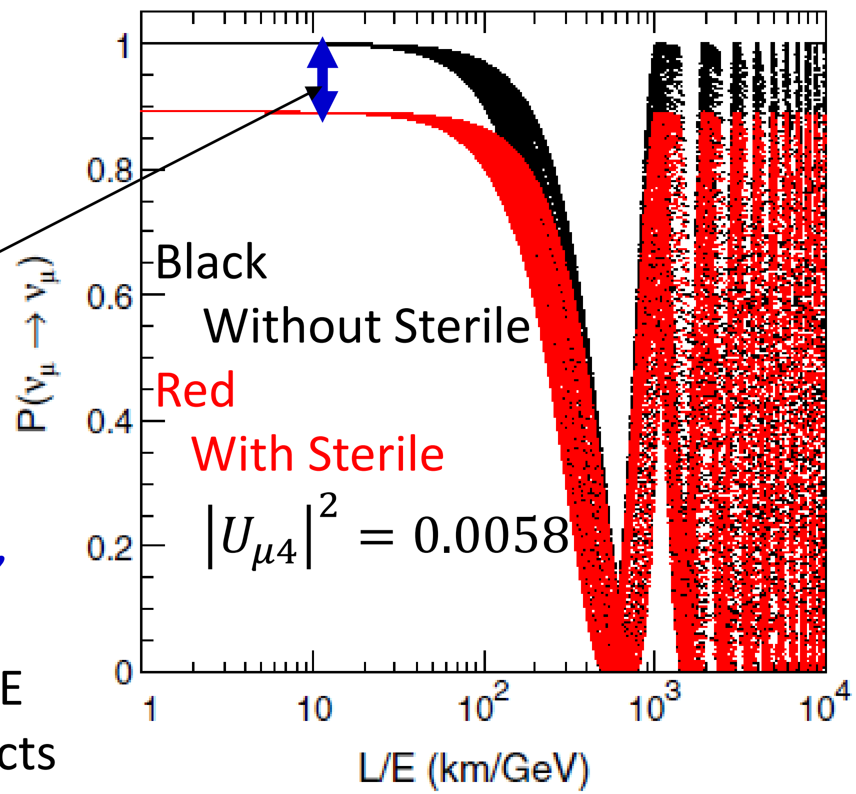
$$P_{e\mu} = \left(1 - |U_{\mu4}|^2\right) P_{e\mu}^{(3)},$$

$$P_{\mu e} = \left(1 - |U_{\mu4}|^2\right) P_{\mu e}^{(3)},$$

$$\boldsymbol{P_{\mu\mu} = \left(1 - |U_{\mu4}|^2\right)^2 P_{\mu\mu}^{(3)} + |U_{\mu4}|^4}$$

Suppression due to existence of sterile ν

μ survival probability

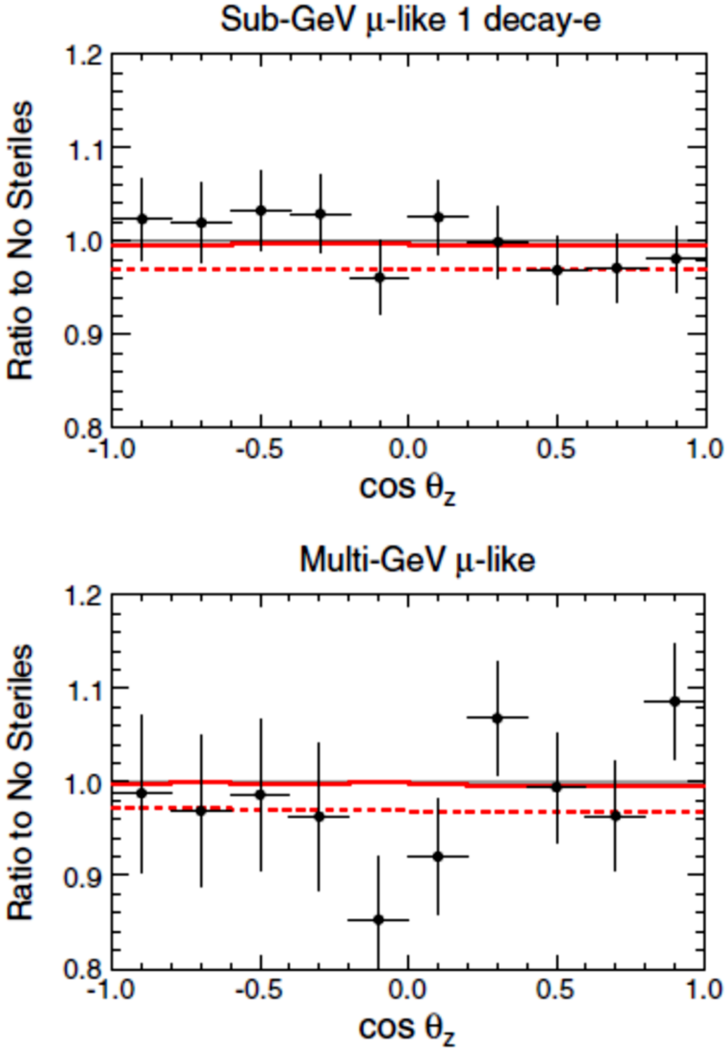


*) Infinite width for same L/E

~ ν_e CC matter effects

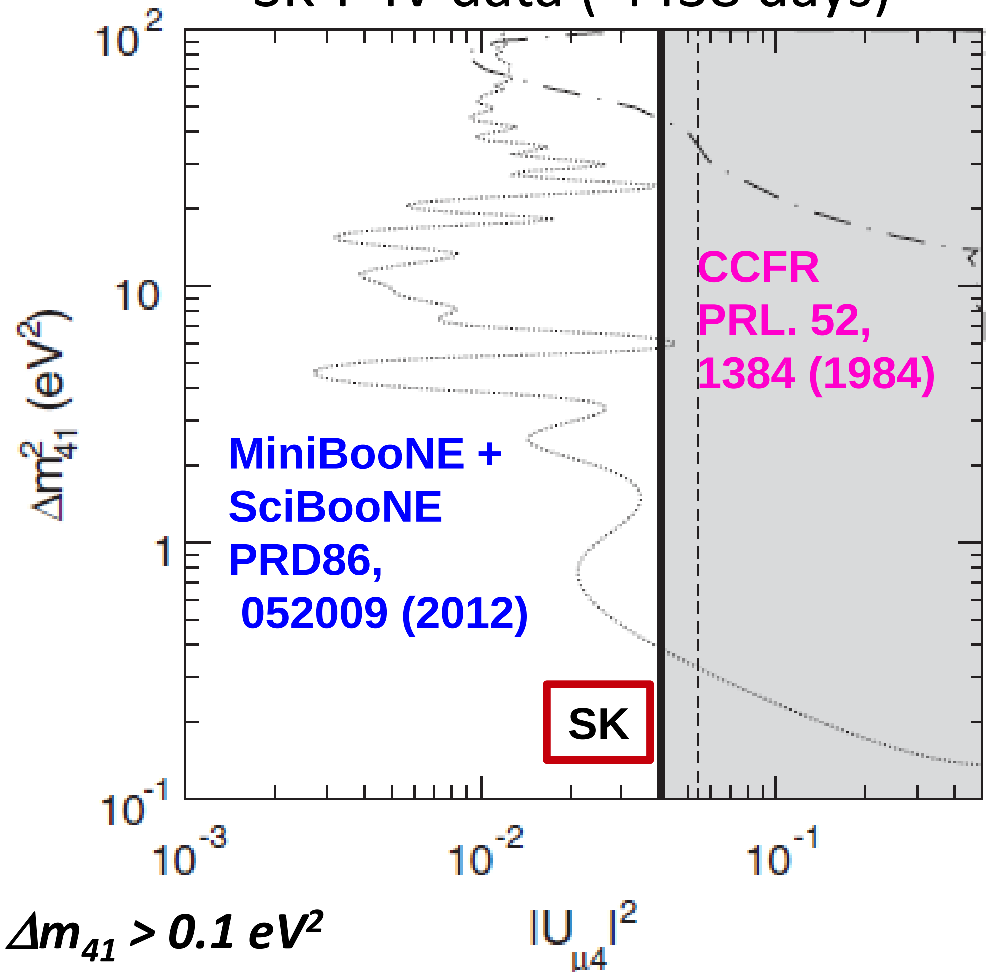
Sterile neutrino oscillations in atmospheric neutrino

Sterile vacuum oscillation



Limits on sterile neutrino mixing using atmospheric neutrinos in Super-Kamiokande
K. Abe et al., Phys. Rev. D 91, 052019 (2015)

$|U_{\mu4}|^2 < 0.041$ at 90% C.L.(*)
SK-I~IV data (4438 days)



(*) Limit is valid for $\Delta m_{41} > 0.1$ eV²

Summary

ν_τ appearance

180.1 ±44.3 (stat) +17.8-15.2 (sys) events(3.8σ)

Three-Flavor neutrino oscillation analysis

Using data from SKI to IV (4538 days),

~1 σ preference for the NH, and second octant

Neutron tagging

Data taken with SK-IV electronics,

we developed new "neutron tagging" analysis tools.

Efficiency ~ 20.5 %

Will be used for atmospheric neutrino oscillation analyses and proton decay search.

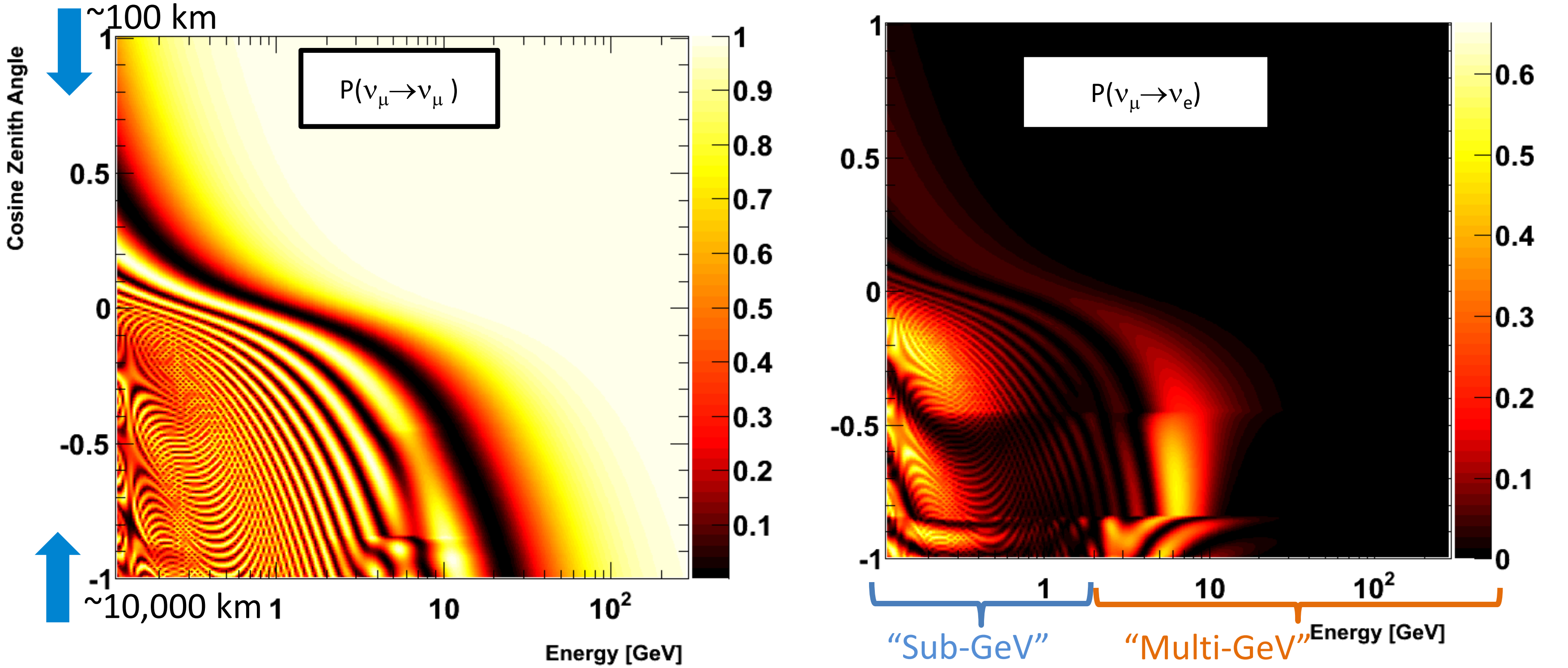
No indication of oscillations into sterile neutrinos

For 3+N models $|U_{\mu 4}|^2 < 0.041$ at 90% C.L.

fin.

Neutrino oscillation studies using atmospheric ν

Searching for Three-Flavor Effects: Oscillation probabilities



Resonant oscillations between 2-10 GeV **(Multi-GeV region)** for ν or $\bar{\nu}$ depending upon MH,

No oscillations from downward-going neutrinos above ~5 GeV

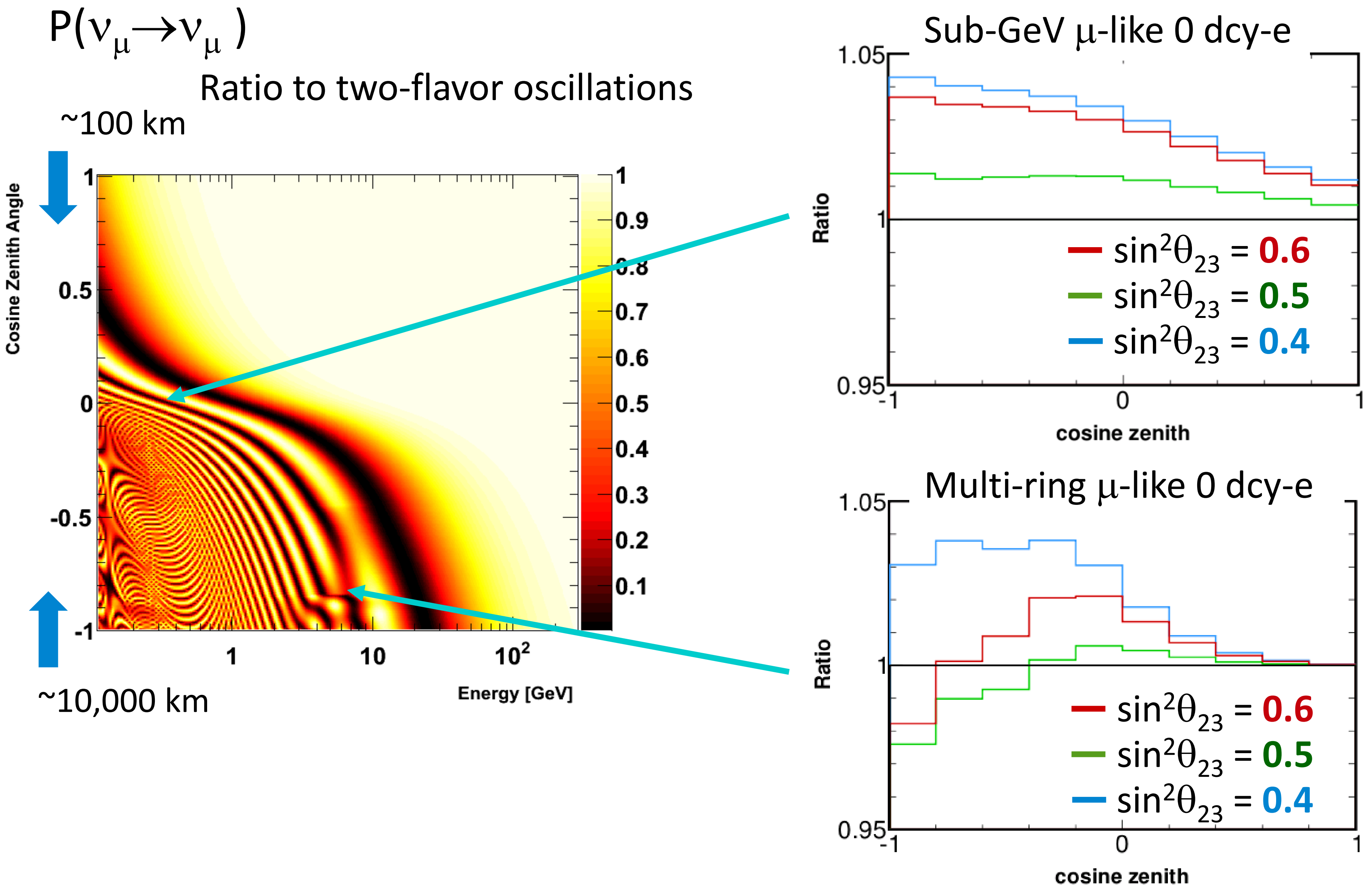
No oscillations above 200 GeV ,

No $\nu_\mu \rightarrow \nu_e$ appearance above ~20 GeV,

Expect effects in most analysis samples, largest in upward-going ν_e

Neutrino oscillation studies using atmospheric ν

Oscillation Effects on Analysis Subsamples

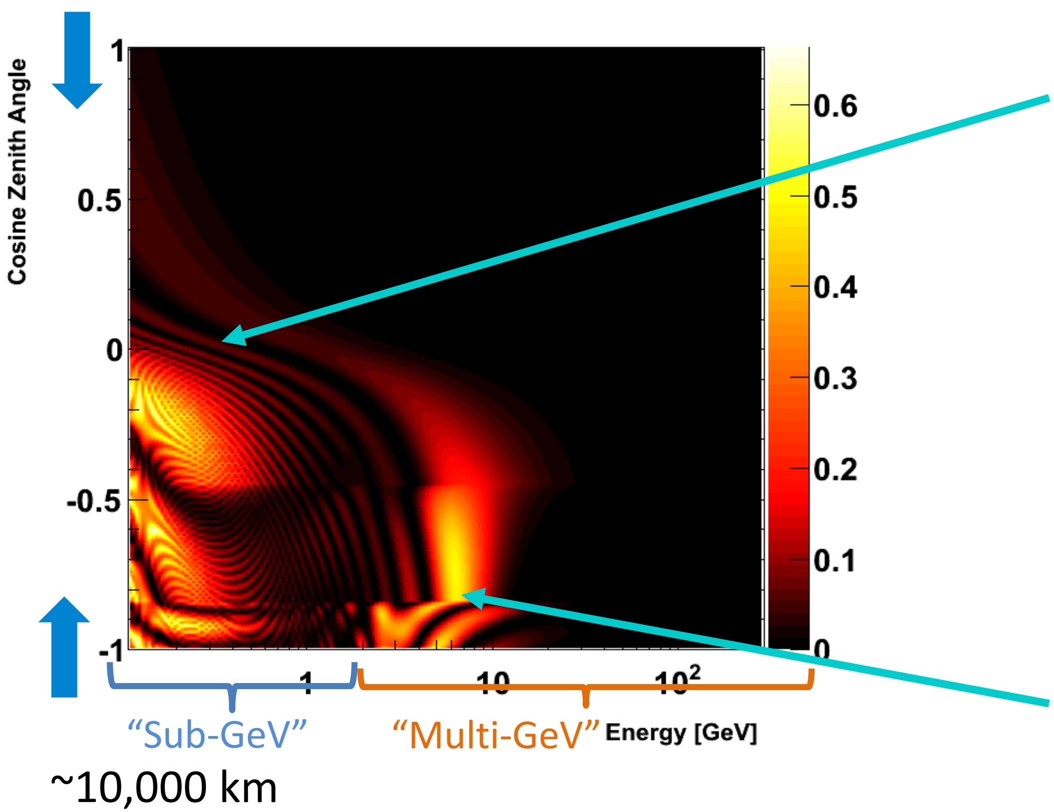


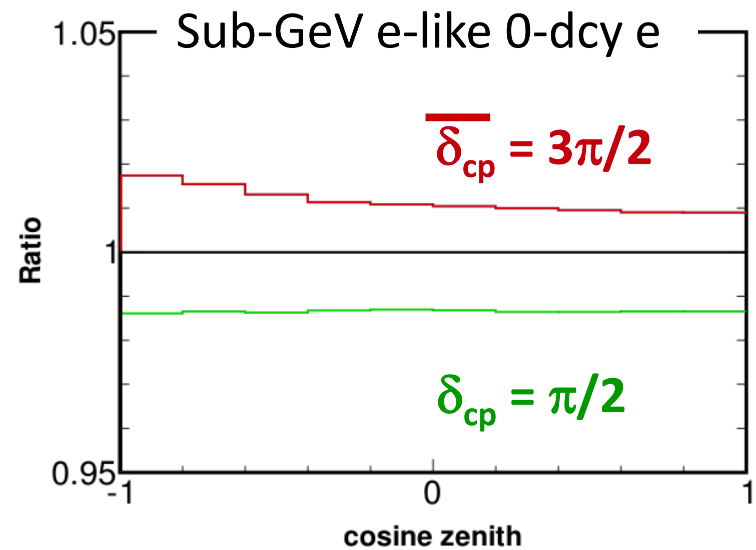
Neutrino oscillation studies using atmospheric ν

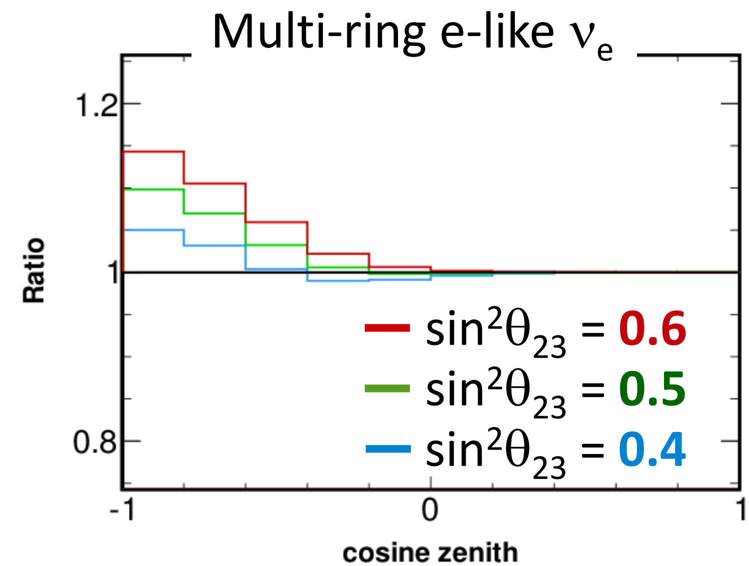
Oscillation Effects on Analysis Subsamples

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

Ratio to two-flavor oscillations







Appearance effects are roughly halved for the inverted hierarchy.

Atmospheric neutrino ~ Analysis samples in SK

FC
- Sub-GeV
  - 1-ring
    - e-like
      - 0 decay electron
      - 1 decay electron
      - π^0 like
    - μ-like
      - 0 decay electron
      - 1 decay electron
      - 2 decay electron
  - 2-rings π^0 like
- Multi-GeV
  - 1-ring
    - e-like
      - 0 decay electron
      - with decay electron
    - μ-like
  - multi-ring
    - e-like
      - ν_e -like
      - $\bar{\bar{\nu}}_e$-like
      - others
    - μ-like

Atmospheric neutrino ~ Analysis samples in SK

PC	OD stopping
	OD through going
Up-going m	Stopping
	Through going showering
	Through going non-showering

Sterile neutrino oscillations in atmospheric neutrino

Assuming $\theta_{13} = \theta_{12} = 0$,

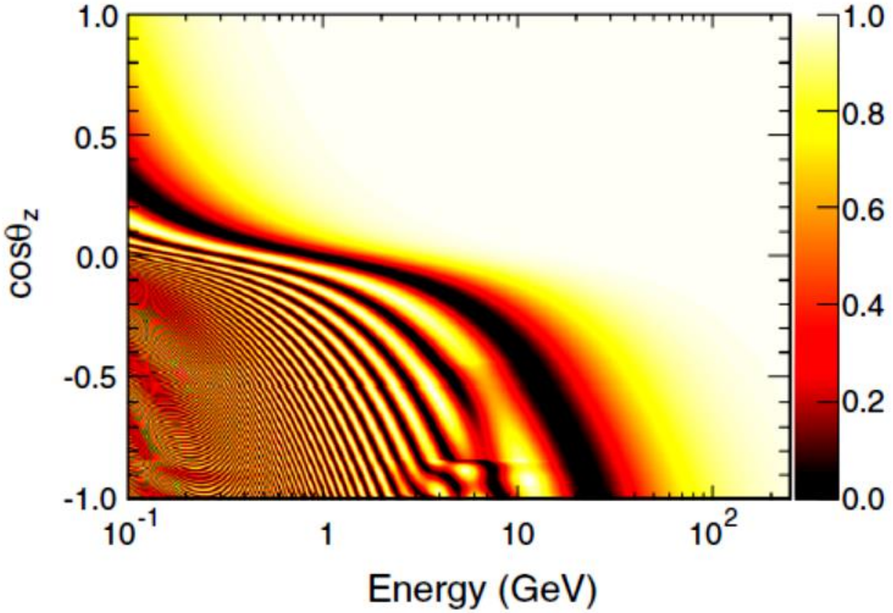
$$P_{\mu\mu} = \left(1 - |U_{\mu 4}|^2\right)^2 \left(1 - \sin^2(2\theta_m)\sin^2(E_m L)\right) + |U_{\mu 4}|^4,$$

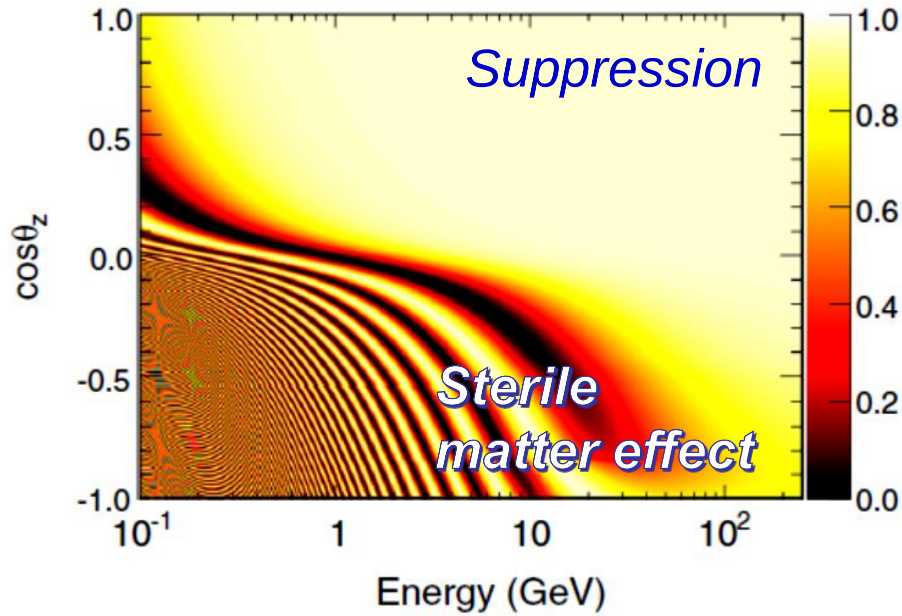
$$E_m^2 = \left(\frac{\Delta_{32}^2}{4E}\right)^2 + A_s^2 + 2A_{32}A_s\cos(2\theta_{23} - 2\theta_s),$$

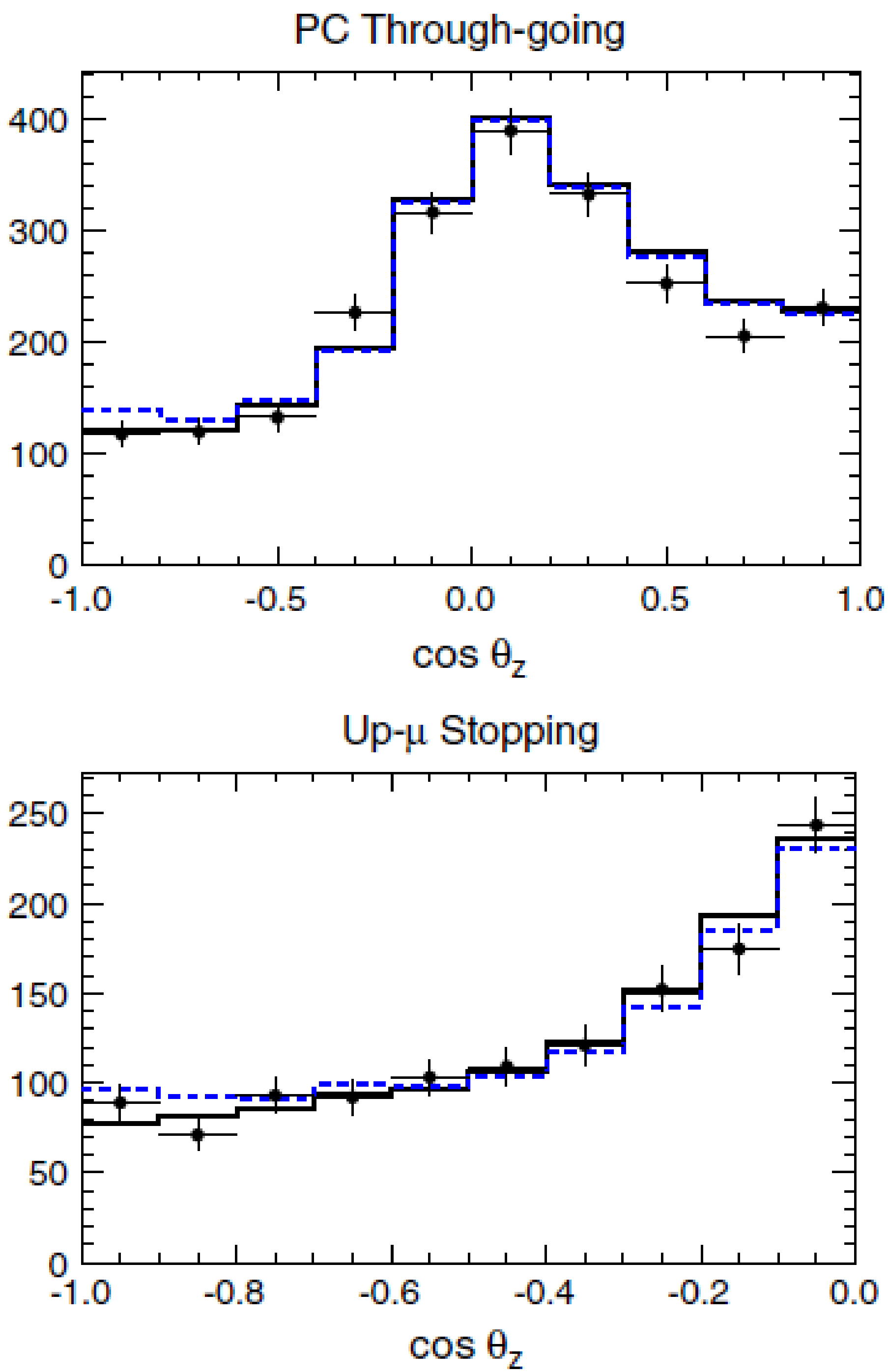
$$sin\theta_m = \frac{A_{32}\sin(2\theta_{23}) + A_s\sin(2\theta_s)}{E_m}, A_s = \frac{\left(|U_{\mu 4}|^2 + |U_{\tau 4}|^2\right)}{2}$$

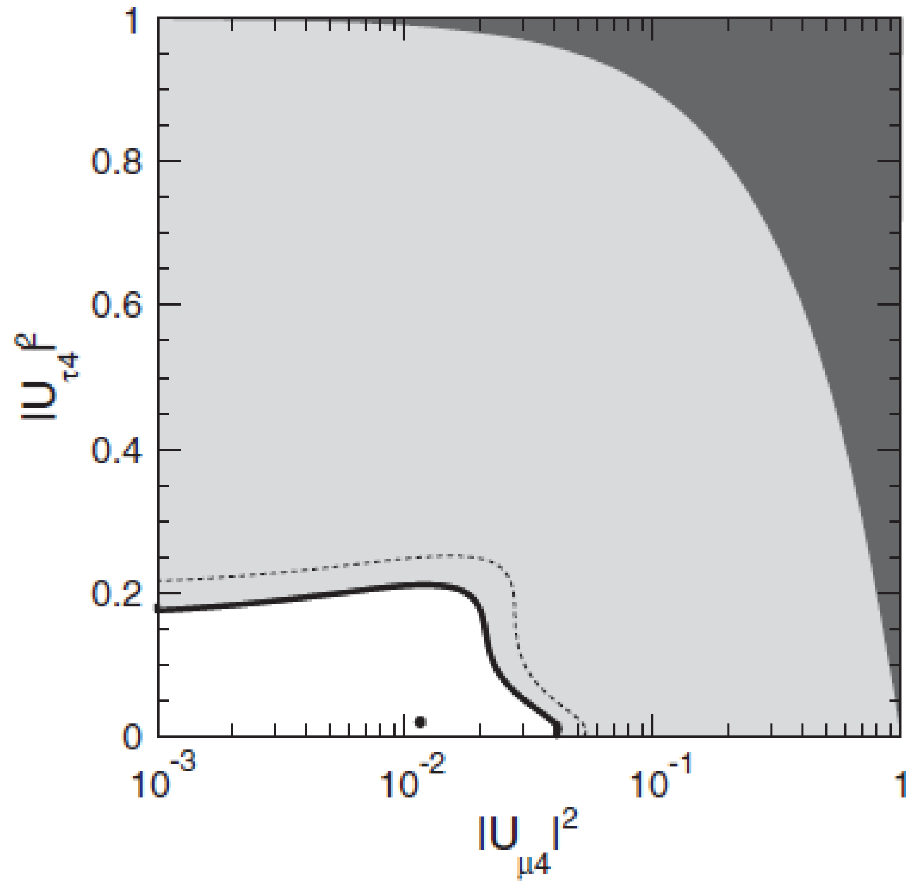
μ survival probability

$|U_{\mu 4}|^2 = 0.0018, |U_{\tau 4}|^2 = 0.33$









of freedom. We limit $|U_{\tau 4}|^2$ to less than 0.18 at 90% and less than 0.23 at 99%. These limits are independent of the new Δm^2 above 0.1 eV^2 (see Appendix B 3). The contours in $|U_{\tau 4}|^2$ vs $|U_{\mu 4}|^2$ can be seen in Fig. 5. The $|U_{\mu 4}|^2$ best fit point and limit are discussed in the next section in the analysis which focuses on that parameter.