Recent results from Super-Kamiokande
~ atmospheric neutrino ~

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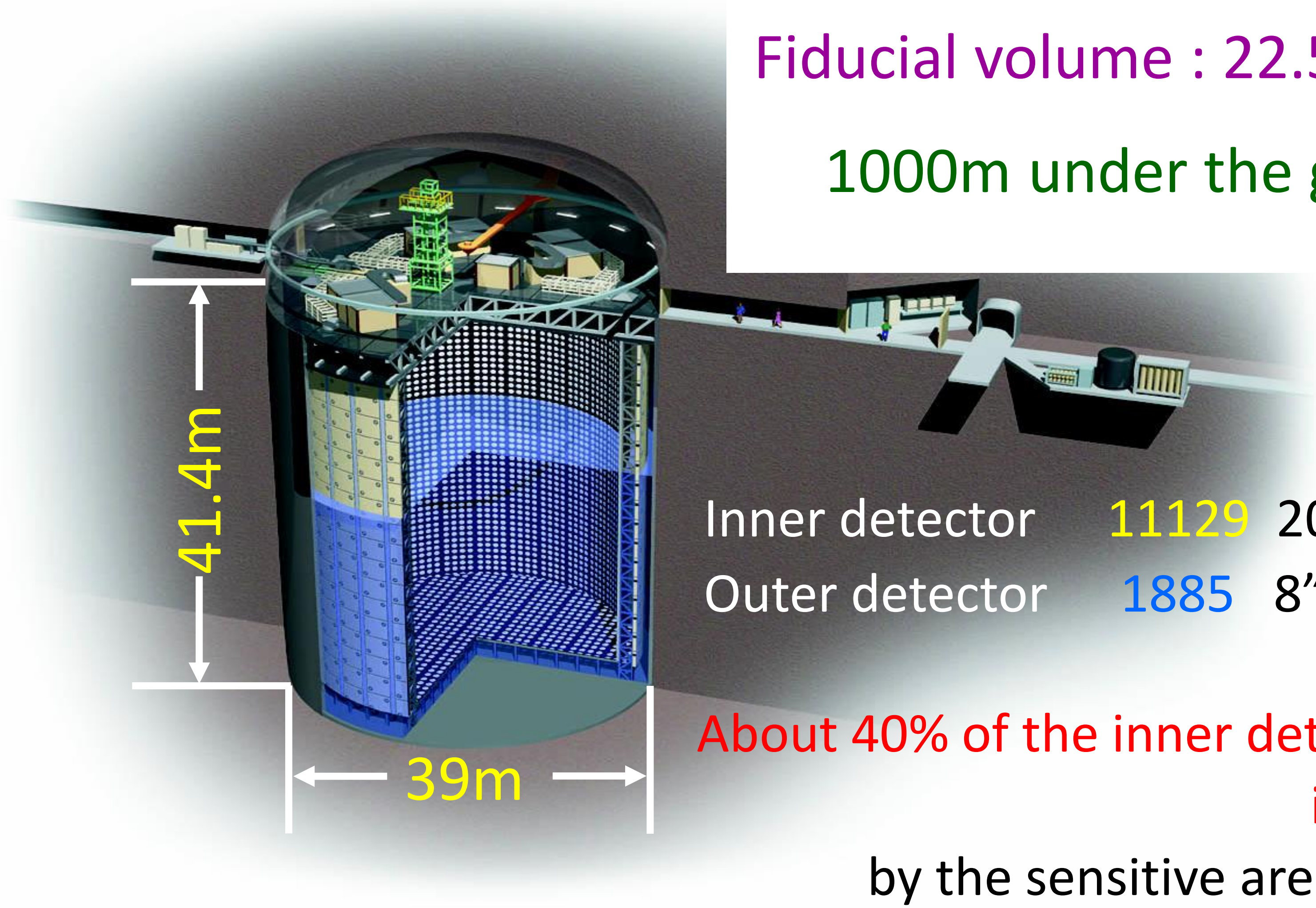
for the Super-Kamiokande collaboration

Super-Kamiokande detector

50000 tons Ring imaging Water Cherenkov detector

Fiducial volume : 22.5 ktons

1000m under the ground



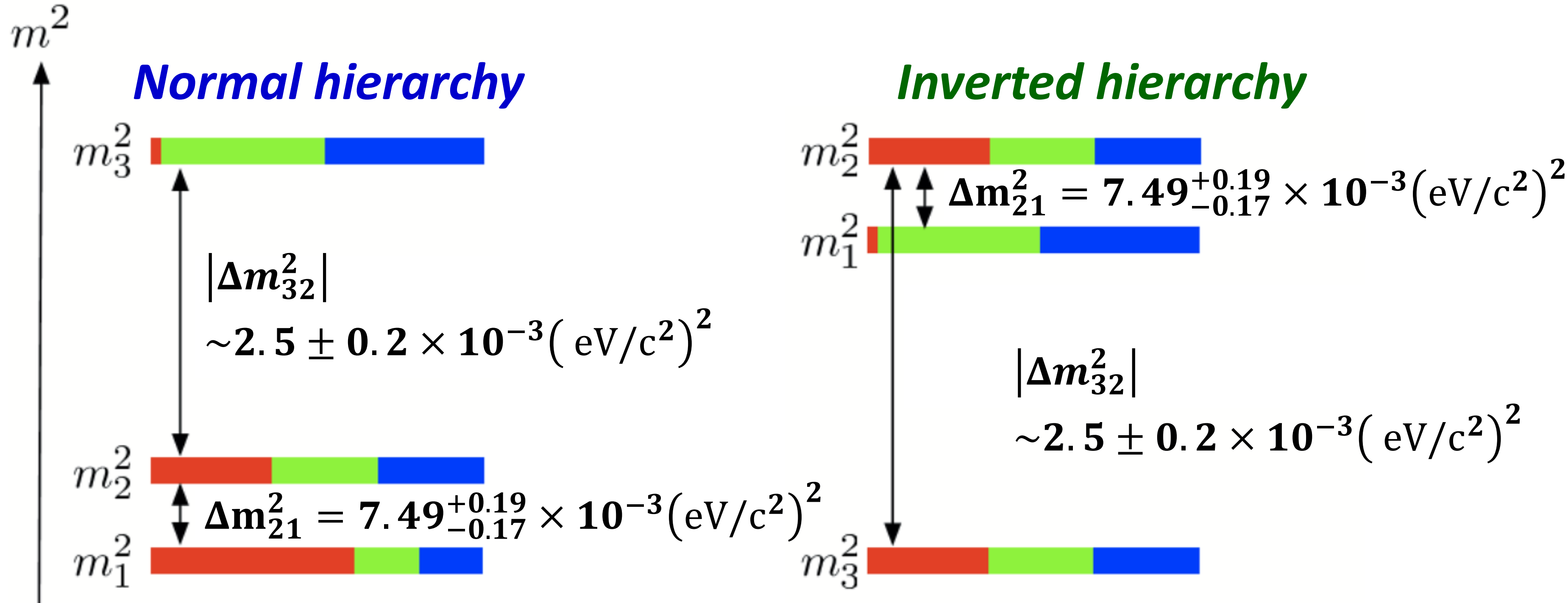
Inner detector 11129 20” PMTs

Outer detector 1885 8” PMTs

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

Operation started in Apr. 1996.

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

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}$$

θ_{13} Leading term

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

CPV

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2\Delta_{21}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2\Delta_{31},$$

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

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

For anti neutrinos,

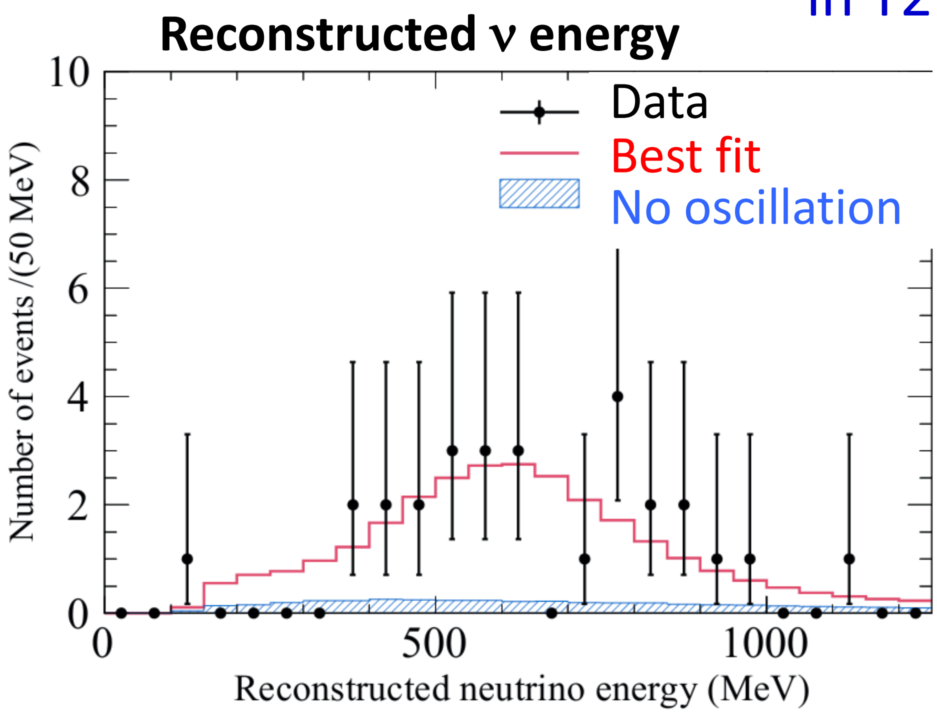
$a \to -a$, $\delta \to -\delta$

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

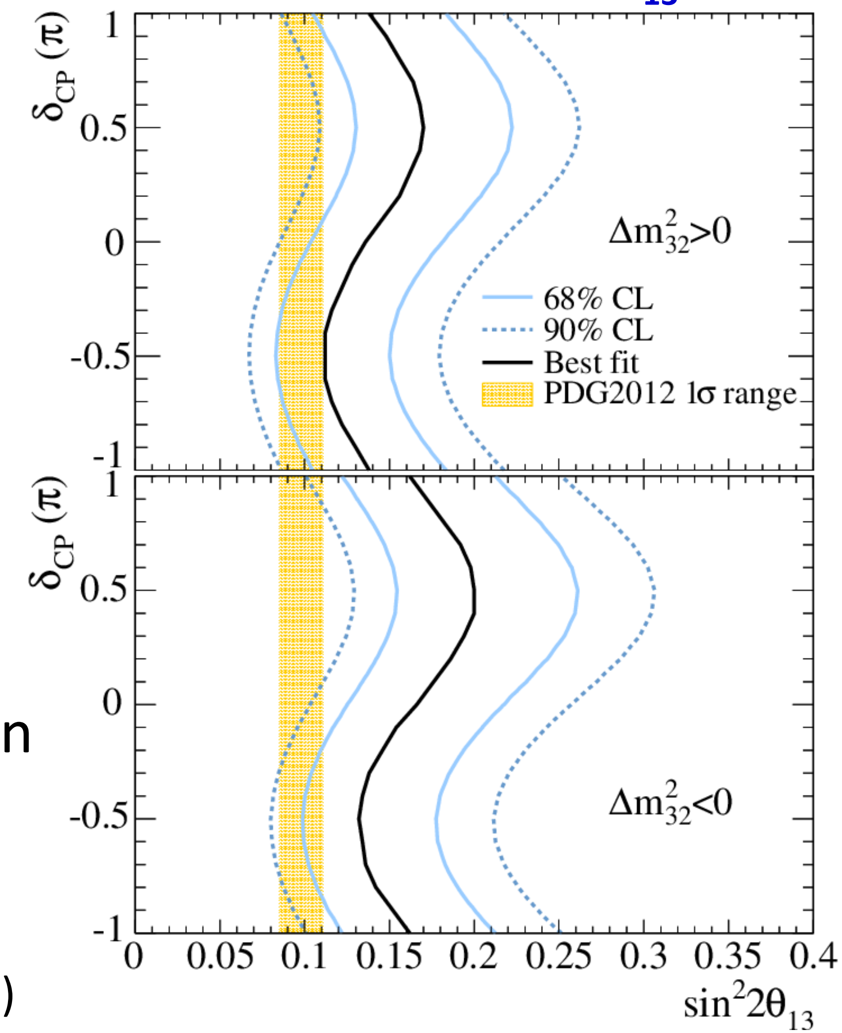
There are chances to observe the contributions from ***mass hierarchy*** and ***CPV (δ)*** !

Recent results from Reactor & T2K

ν_e appearance clearly observed in T2K



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



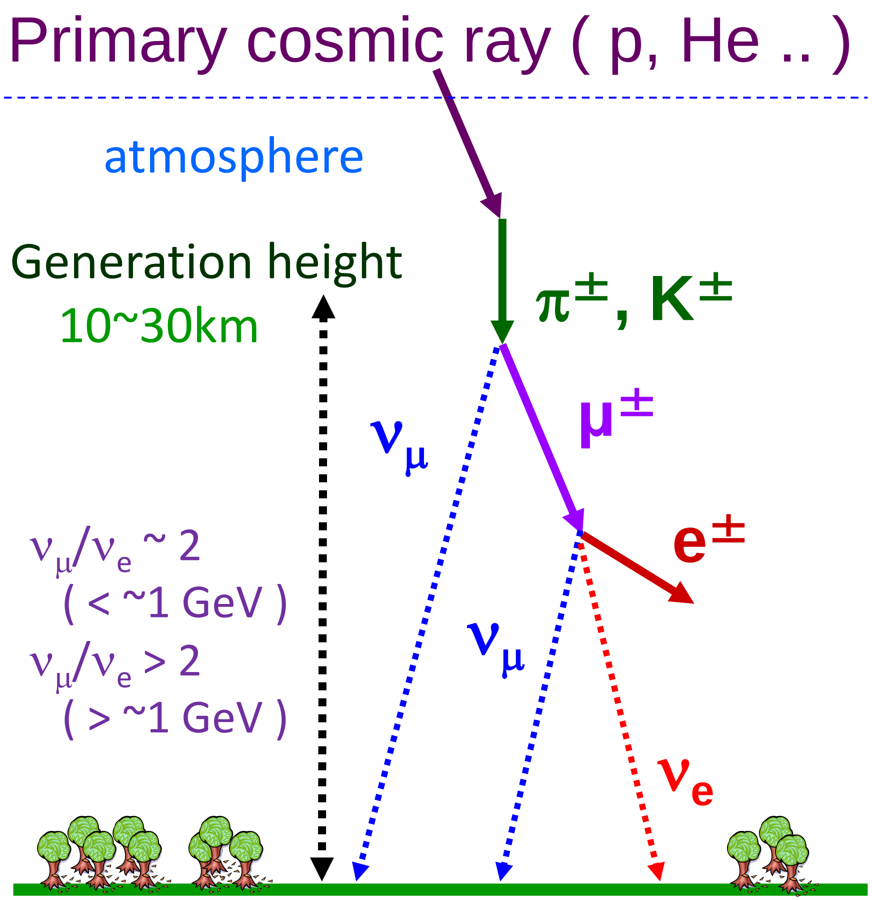
Extracted $\sin^2 2\theta_{31}$ is slightly larger than the ones from reactor experiments

$\sin^2 2\theta_{13} =$ $0.140^{+0.038}_{-0.032}$ (normal hierarchy)

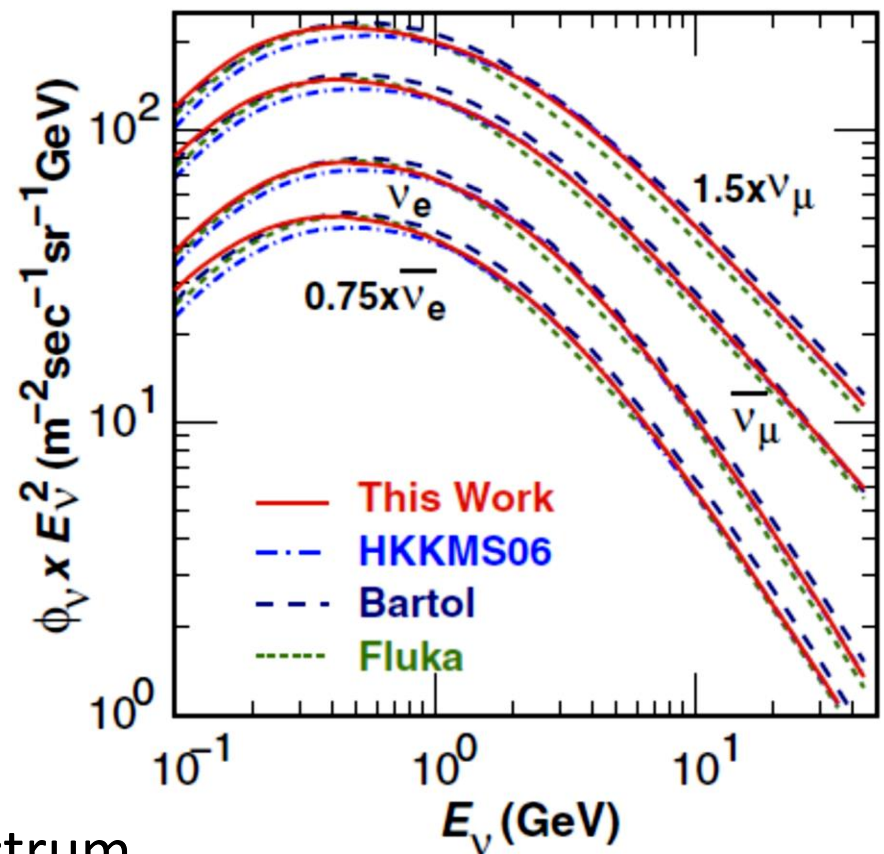
$0.170^{+0.044}_{-0.037}$ (inverted hierarchy)

Indication of non-zero δ_{CP}?

Characteristics of atmospheric neutrino



Atmospheric ν energy spectrum



Atmospheric neutrino energy spectrum

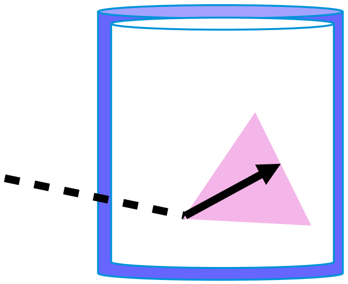
Peaked at ***~ several hundreds of MeV, Extended > TeV***

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

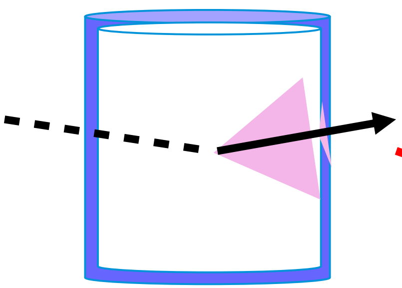
Zenith angle corresponds to travel length of neutrinos.

Atmospheric neutrino ~ event topology in SK

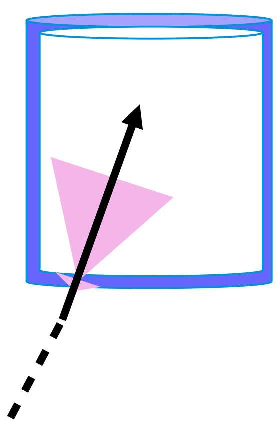
Fully Contained (FC)



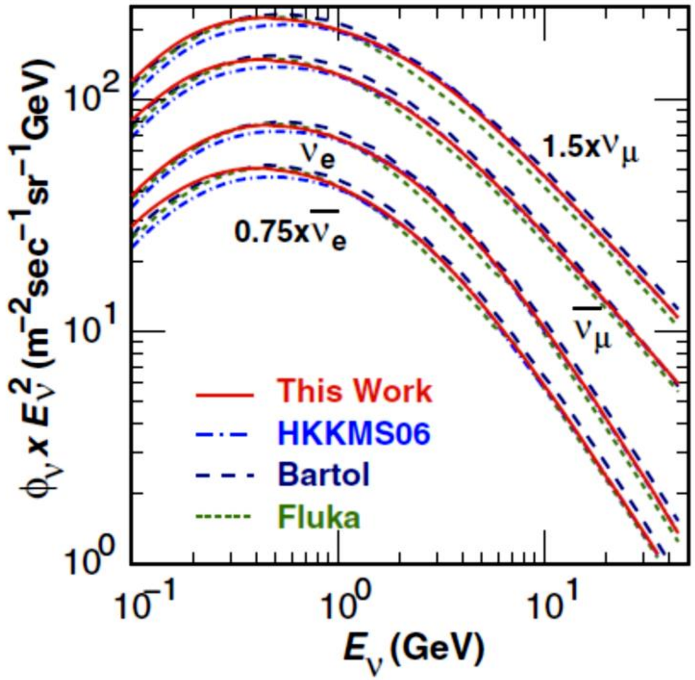
Partially Contained (PC)

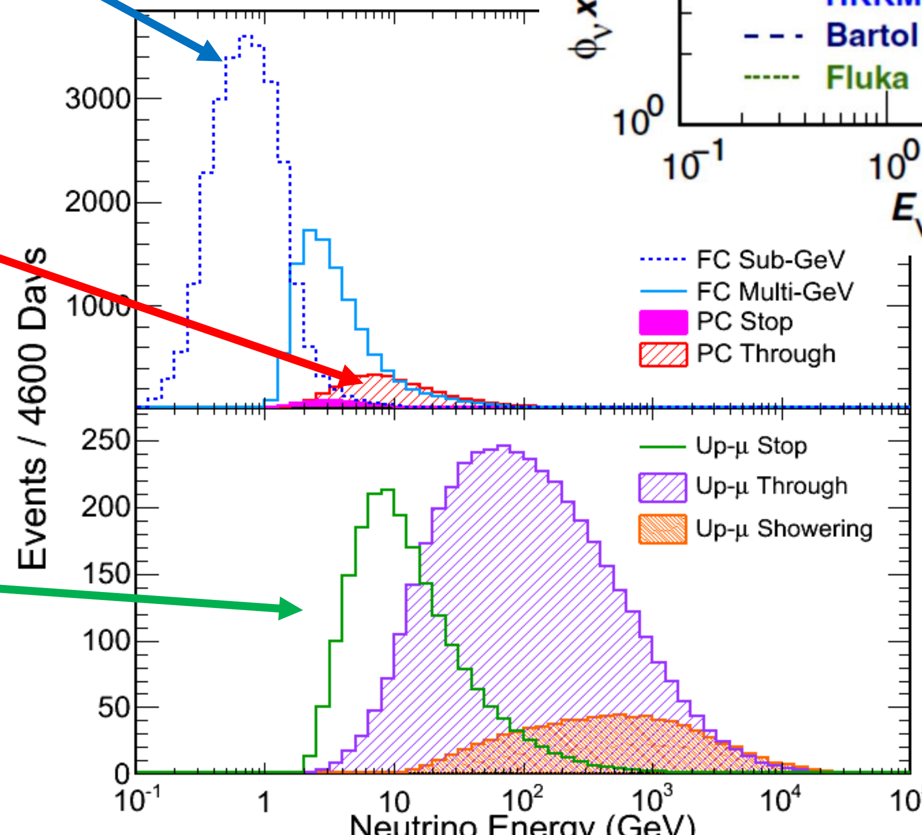


Upward-going Muons (Up-μ)



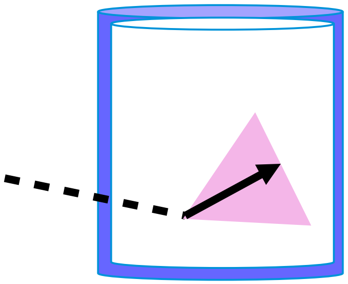
- Average energies
  - FC: ~ 1 GeV
  - PC: ~ 10 GeV
  - UpMu: ~ 100 GeV





Atmospheric neutrino ~ Analysis samples in SK

Fully Contained (FC)



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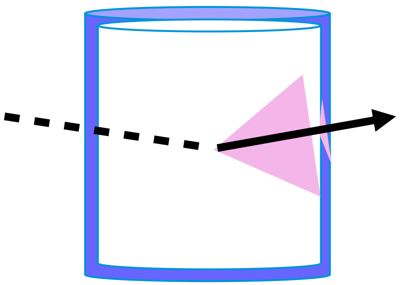
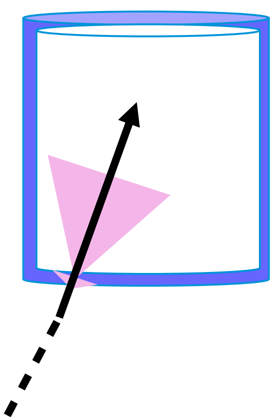
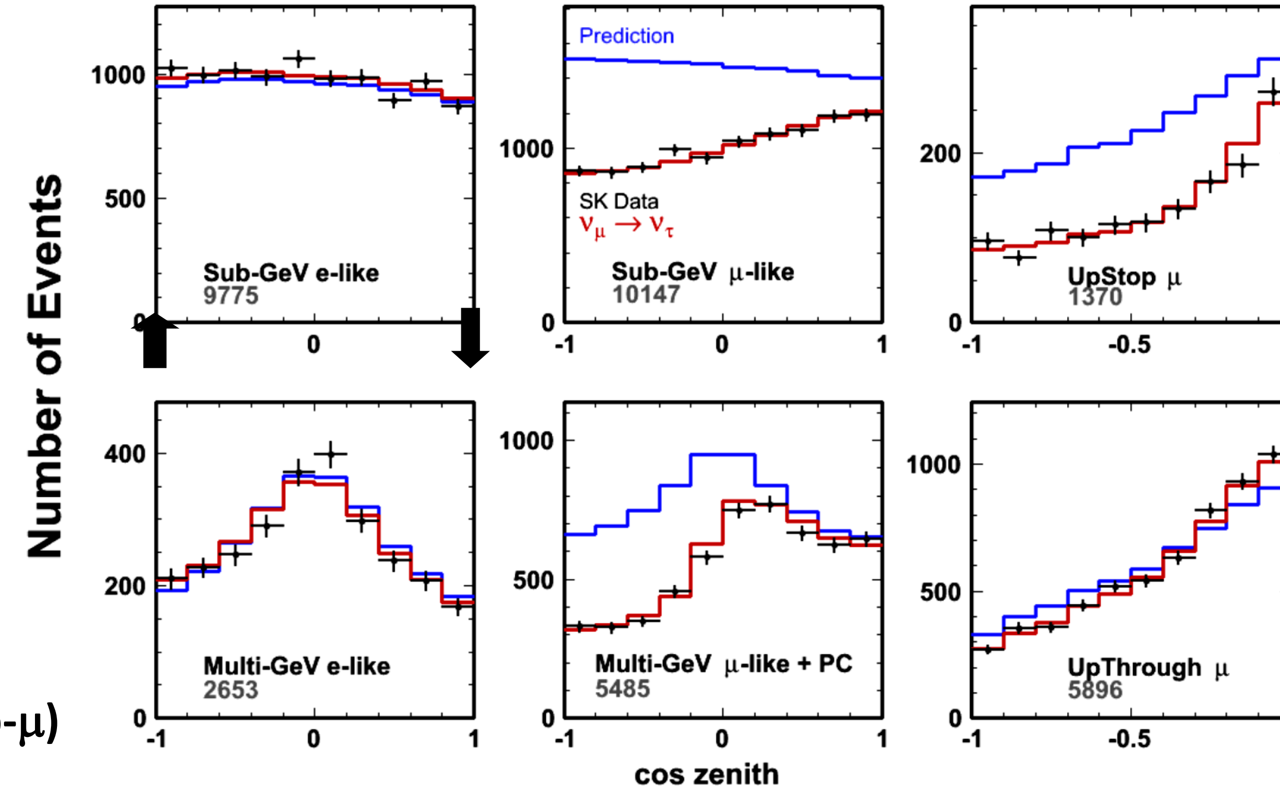


Upward-going Muons (Up-μ)



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

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

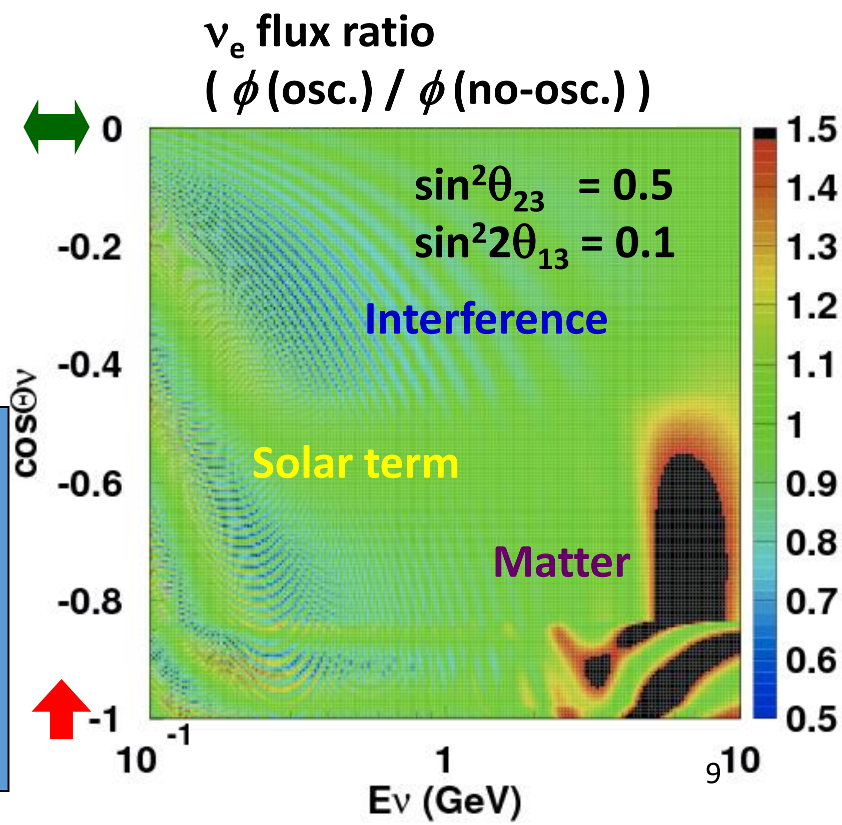
  Possible ν_e enhancement in sub-GeV

- Interference

  CP phase could be studied.

Difference in # of electron events:

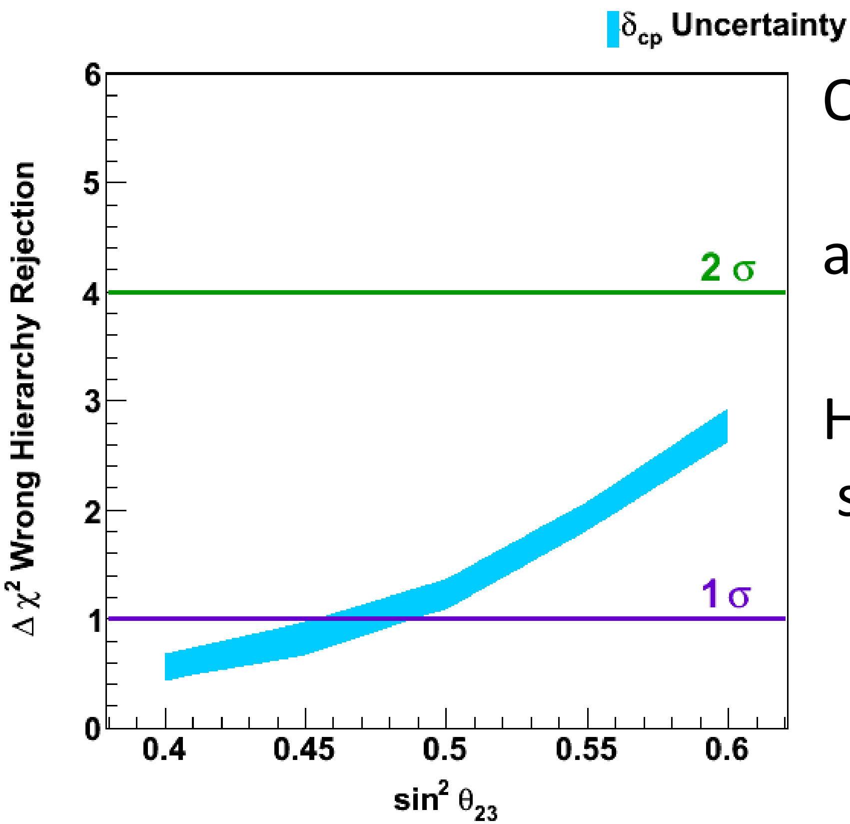
$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \quad \leftarrow \text{Matter effect}$$
$$+\Delta_2(\Delta m_{12}^2) \quad \leftarrow \text{Solar term}$$
$$+\Delta_3(\theta_{13}, \Delta m_{12}^2, \delta) \quad \leftarrow \text{Interference}$$



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

Updates to Oscillation Analyses

2166 days of SK-IV data: 4996 days total (307.7 kton·yrs)

- ***Changes in analysis samples***

  Fully contained Multi-Ring e-like

  ~ subdivide into three

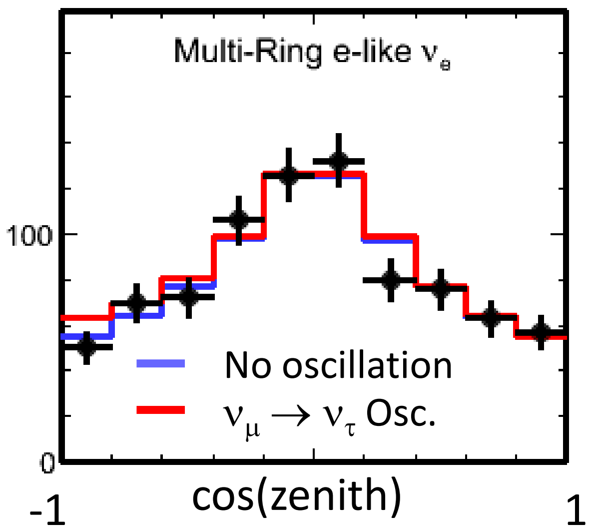
  ν_e-like, $\bar{\nu}_e$-like and

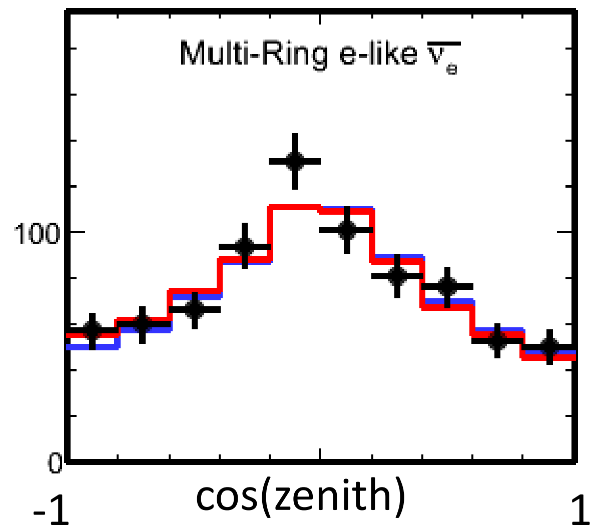
  "other" (= not-ν_e & not-$\bar{\nu}_e$)

Multi-Ring e-like Sample Purities

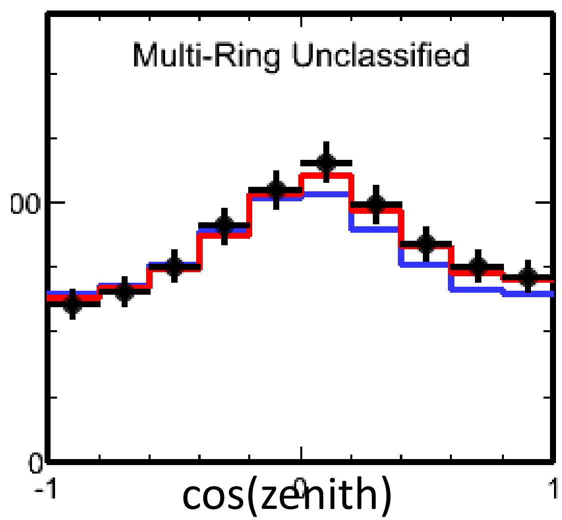
Purity	CC ν_e	CCν_μ	CCν_τ	NC
ν-like	72.2%	8.3%	3.2%	16.1%
$\bar{\nu}$-like	75.0%	6.5%	2.8%	15.6%
other	30.9%	33.4%	5.1%	30.5%

ν_e/ $\bar{\nu}_e$ separated samples





Other



- ***Improved systematic error treatments***

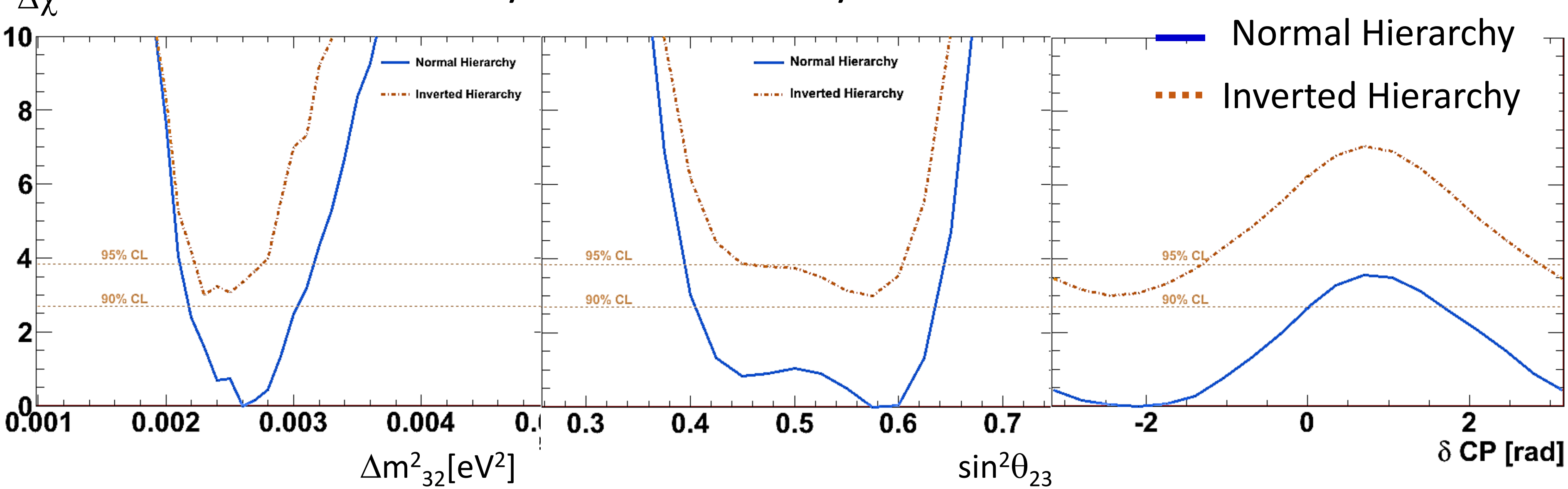
  Updates to cross-section, FSI, detector systematics, 2p-2h (MEC)

Neutrino oscillation studies using atmospheric ν

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

θ_{13} fixed to PDG2014 value ($\sin^2 2\theta_{13}$ =0.093 ±0.08)
uncertainty is included as a systematic error

Preliminary



Fit (517 dof)	$\chi 2$	δ_{cp} (rad)	$\sin^2\theta_{23}$	$\Delta m^2_{32/23}$ ($\times 10^{-3}$eV^2)
SK (NH)	**582.4**	-2.09 (-0.67π)	0.575	2.6
SK (IH)	**585.4**	-2.44 (-0.78π)	0.575	2.3

Offsets in these curves show the absolute χ^2 diff. in the hierarchies.

Normal hierarchy is favored at $\chi^2_{NH} - \chi^2_{IH}$ = -3.0 (not significant still.)

Neutrino oscillation studies using atmospheric ν

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

Normal hierarchy favored

but $\chi^2_{IH} - \chi^2_{NH} = \mathbf{-3.0}$

Not a significant preference

Driven by excess of upward-going e-like

consistent with the effects of θ_{13}

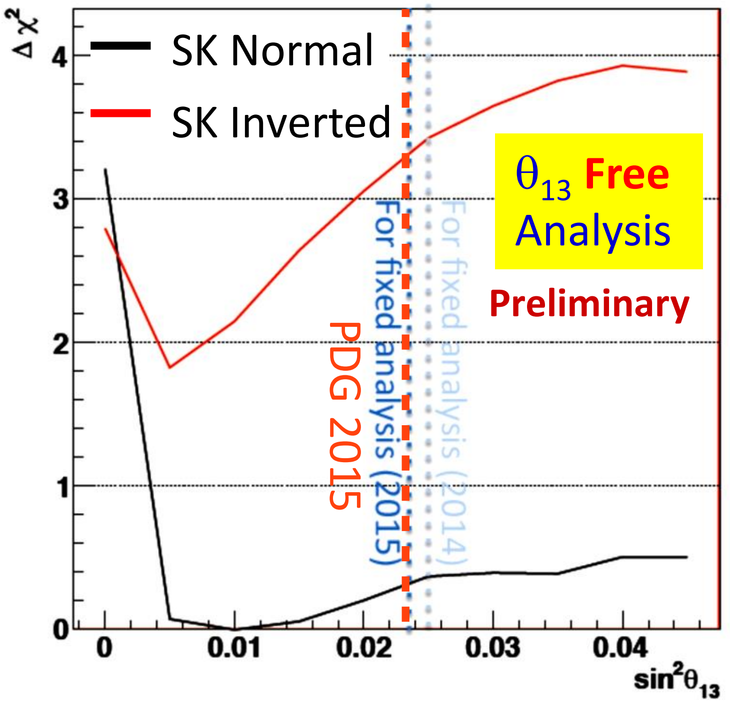
Primarily in SK-IV data

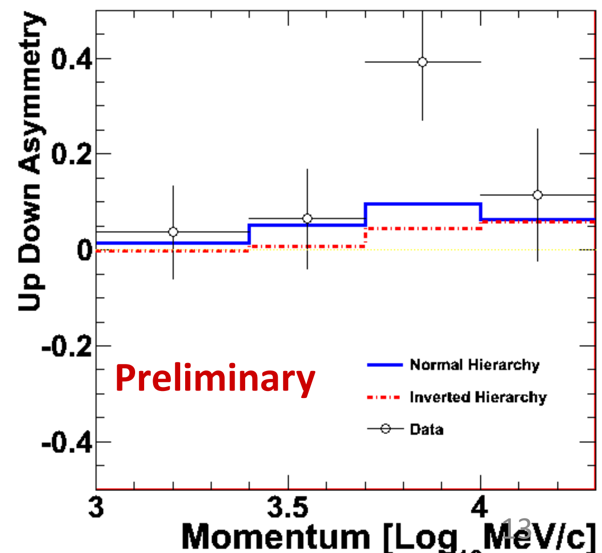
New multi-ring e-like sample also pulls the fit towards the NH

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

Rejection around $\delta_{cp} \sim 0.2\pi$ was driven by excess in Sub-GeV electron events

Constraint is consistent with sensitivity

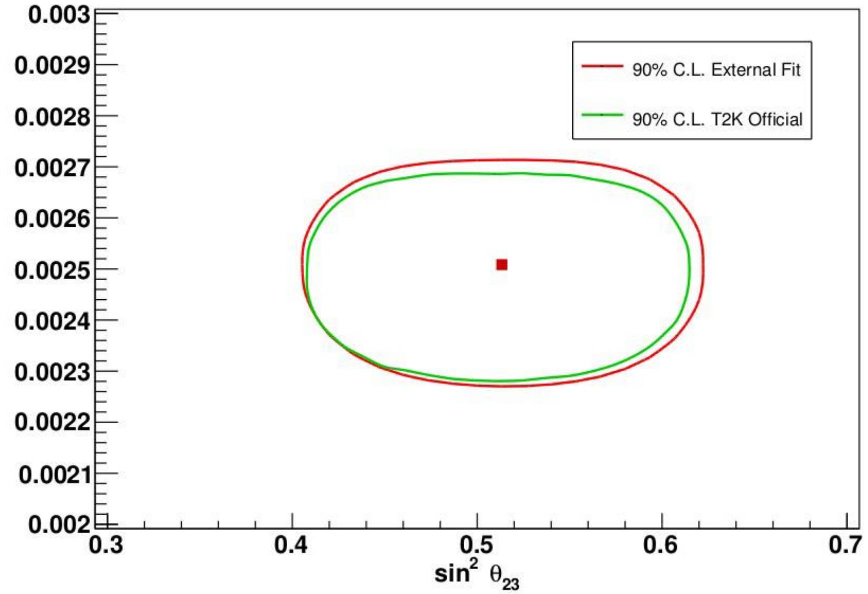




Neutrino oscillation studies using atmospheric ν

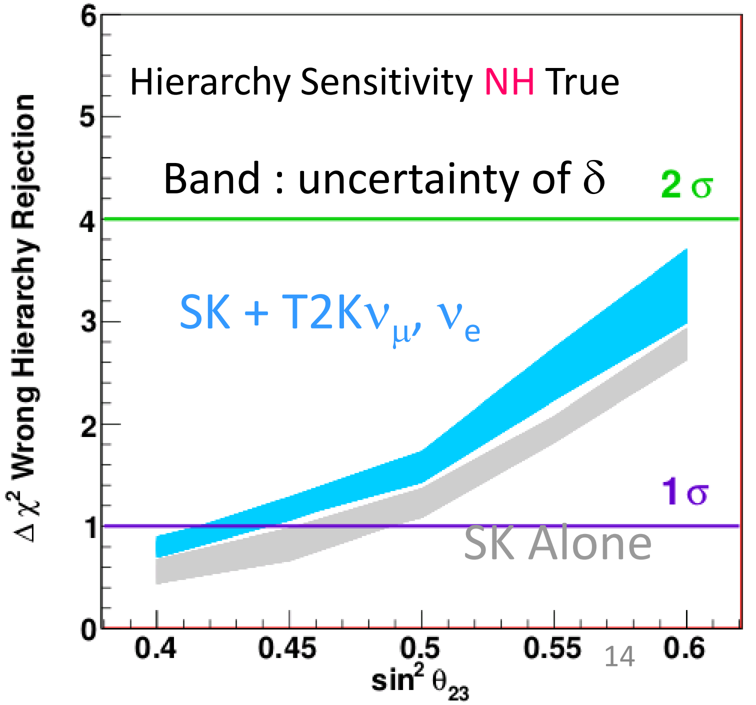
Introduction of External Constraint

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



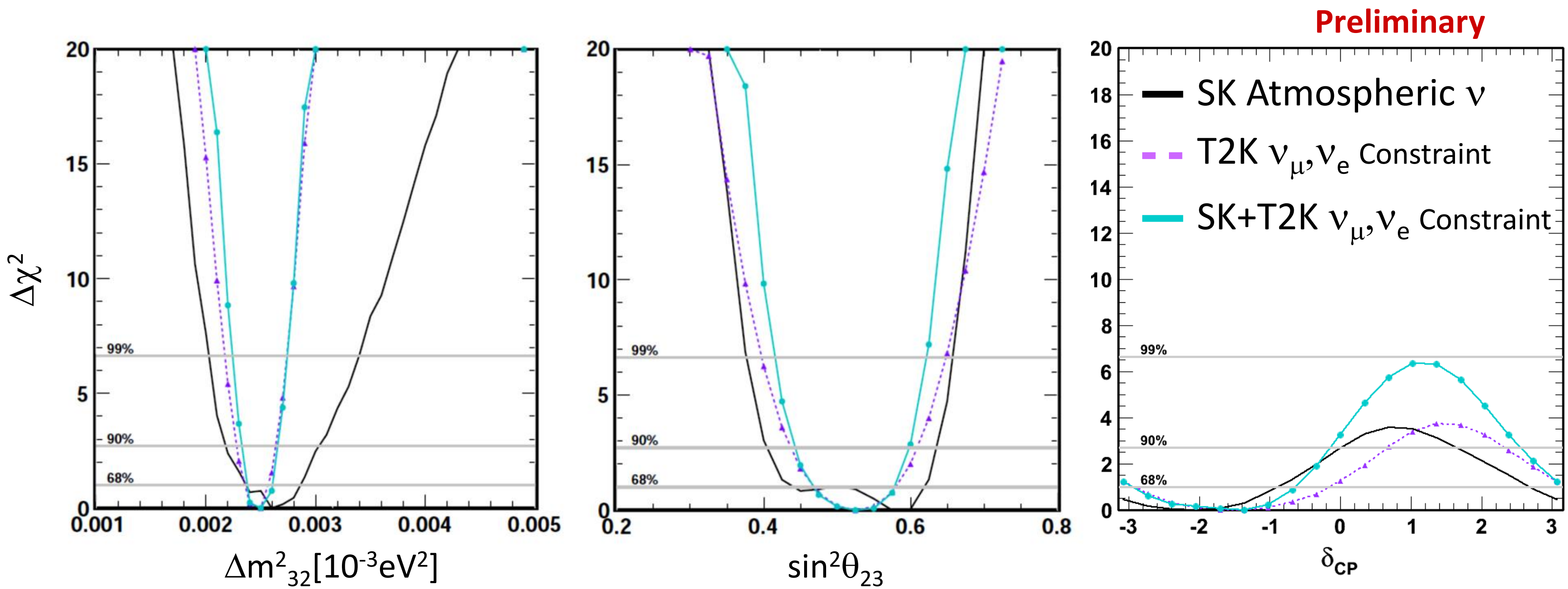
Fit the ***T2K ν_μ and ν_e data sets***
with SK atmospheric neutrino data.

Use ***publicly available information.***
and 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



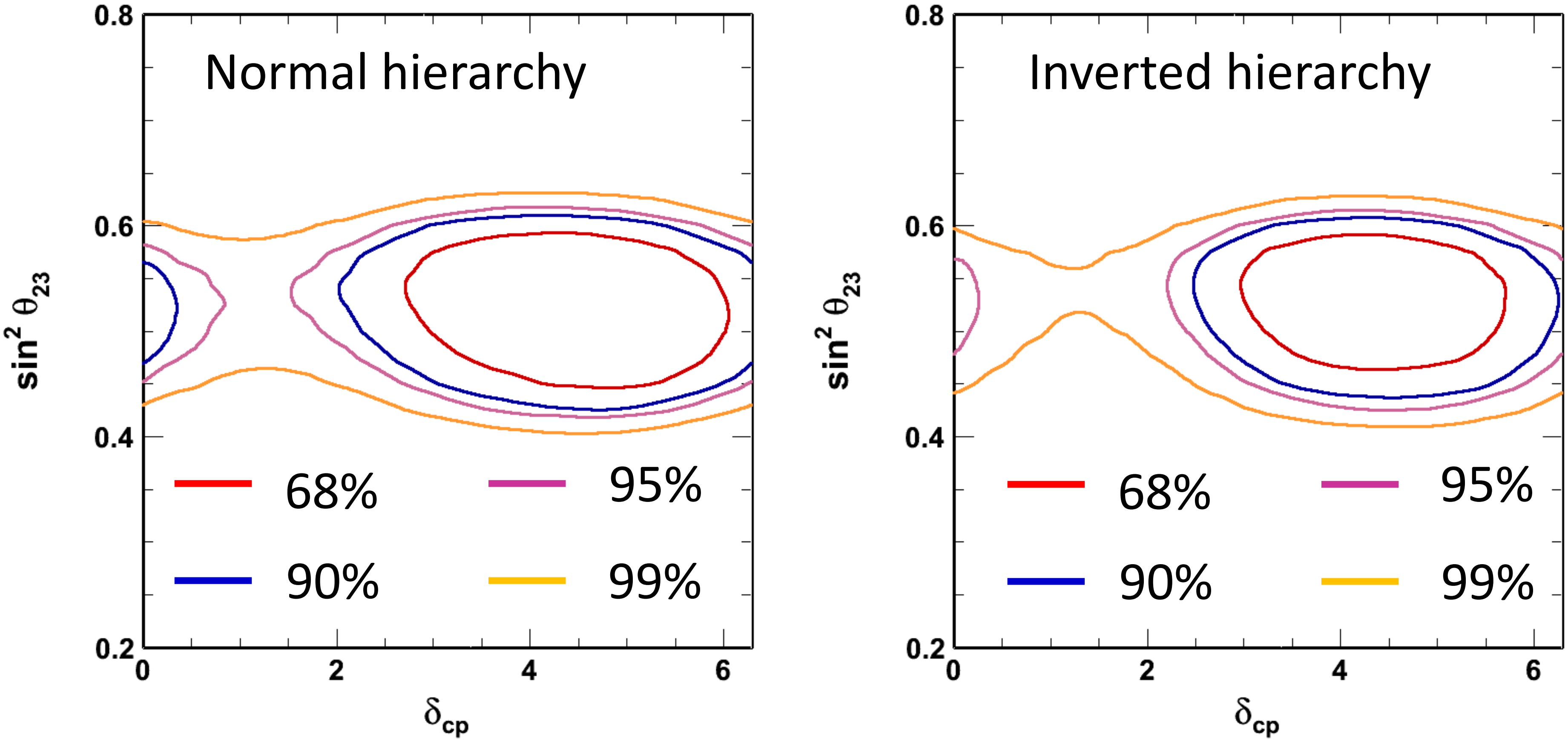
Fit (543 dof)	$\chi 2$	θ_{13}	δ_{cp}	θ_{23}	$\Delta m^2_{32/23}$ ($x10^{-3}eV^2$)
SK + T2K (NH)	651.5	0.0238	-1.39	0.525	2.5
SK + T2K (IH)	654.7	0.0238	-2.09	0.550	2.4

$\chi^2_{IH} - \chi^2_{NH}$ = **-3.2** (-3.0 SK only)

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

Neutrino oscillation studies using atmospheric ν

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



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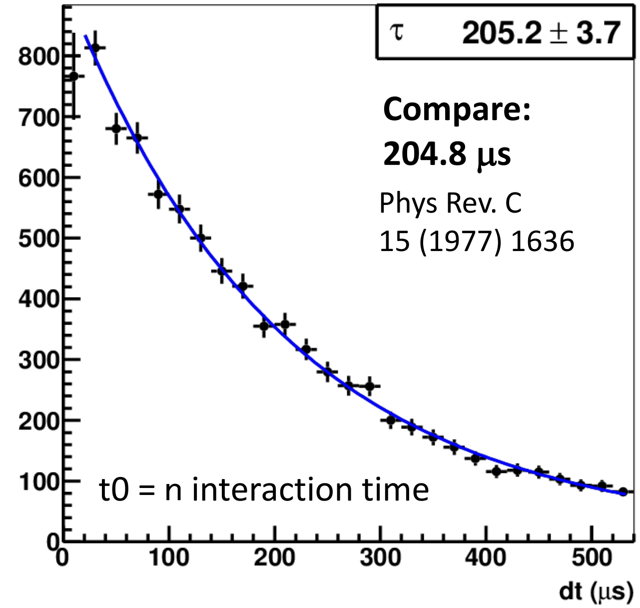
Neutron tagging ~ For further improvements ~

Effective neutron tagging make it possible t

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

2) reduce background of proton decay



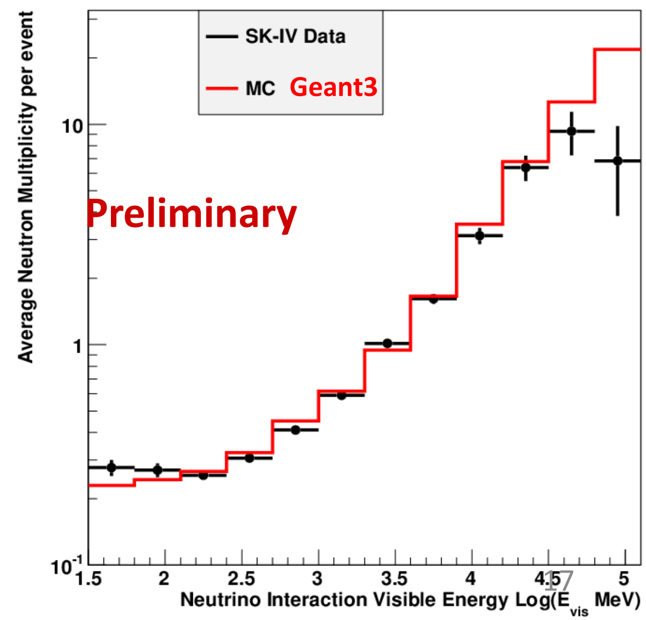
· Electronics in SK-IV store all PMT hits for 500 μsec after a neutrino-like trigger.

· 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.

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

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

MNS Sterile

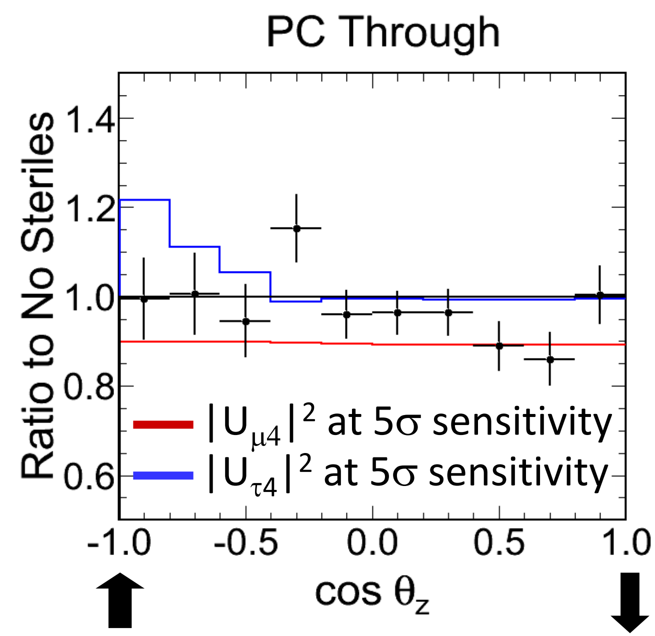
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

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

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 $|U_{\mu4}|^2$

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

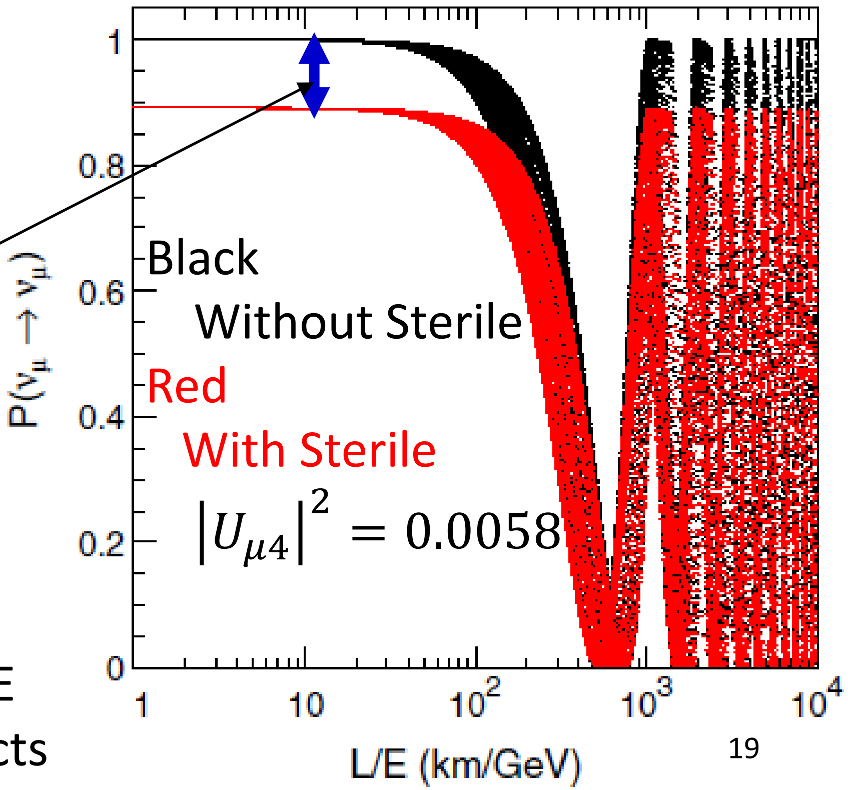
$$P_{e\mu} = \left(1 - |U_{\mu4}|^2\right) P_{e\mu}^{(3)},$$

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

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

Suppression due to existence of sterile ν

μ survival probability

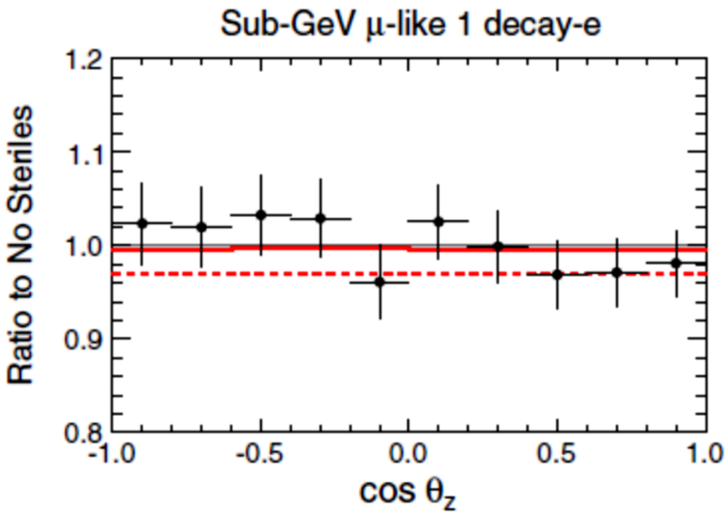


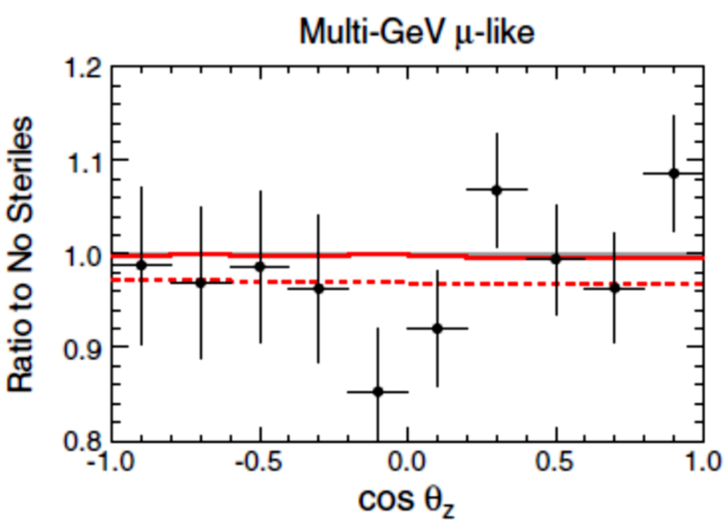
*) Infinite width for same L/E

~ ν_e CC matter effects

Sterile neutrino oscillations in atmospheric neutrino

Sterile vacuum oscillation





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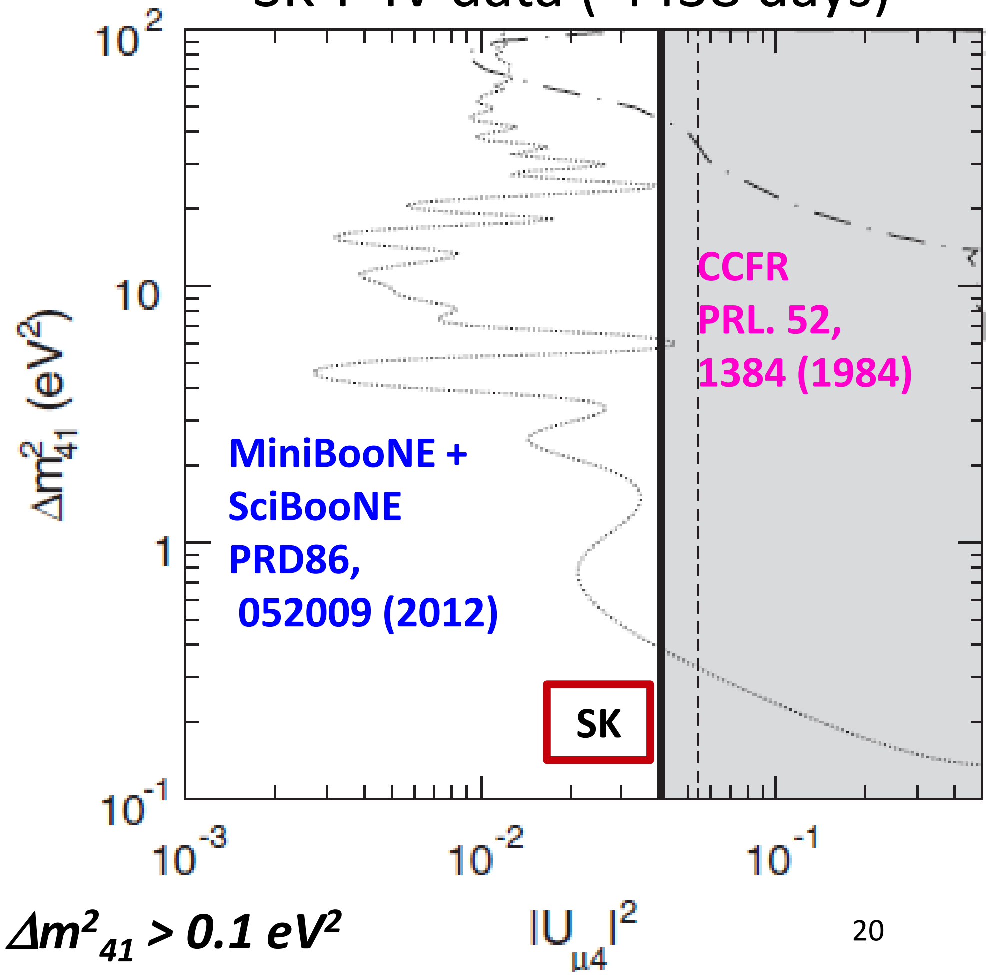
K. Abe et al., Phys. Rev. D 91, 052019 (2015)

$|U_{\mu 4}|^2 < 0.041$ at 90% C.L.(*)

SK-I~IV data (4438 days)



(*) Limit is valid for $\Delta m^2_{41} > 0.1$ eV^2

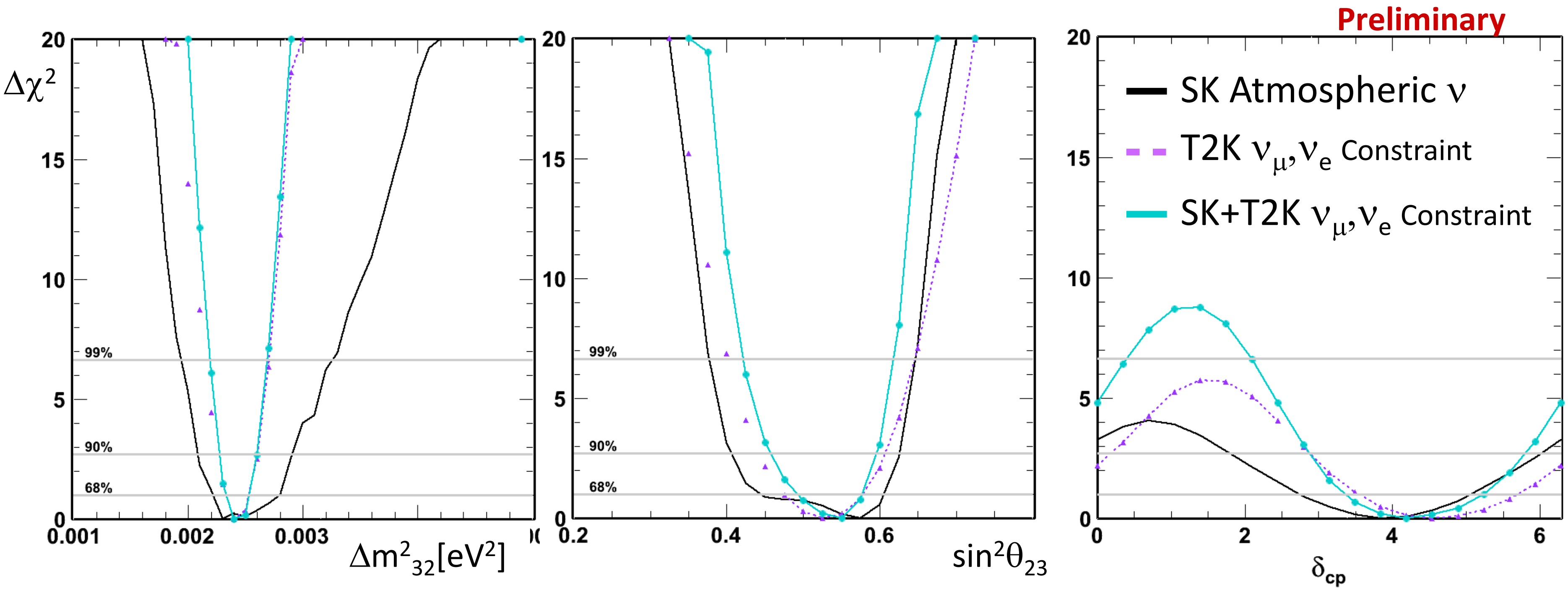
Summary

- Three-Flavor neutrino oscillation analysis
  - Using data from SKI to IV (4996 days),
    - ~1 σ preference for the NH, and second octant
  - Using T2K publicly available data to improve sensitivity
    - Basically, consistent results.
    - ~1 σ preference for the NH
    - $\delta_{CP} = 0$ is allowed at 90% C.L. for both hierarchy.
- 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

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



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