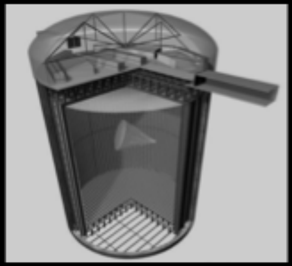
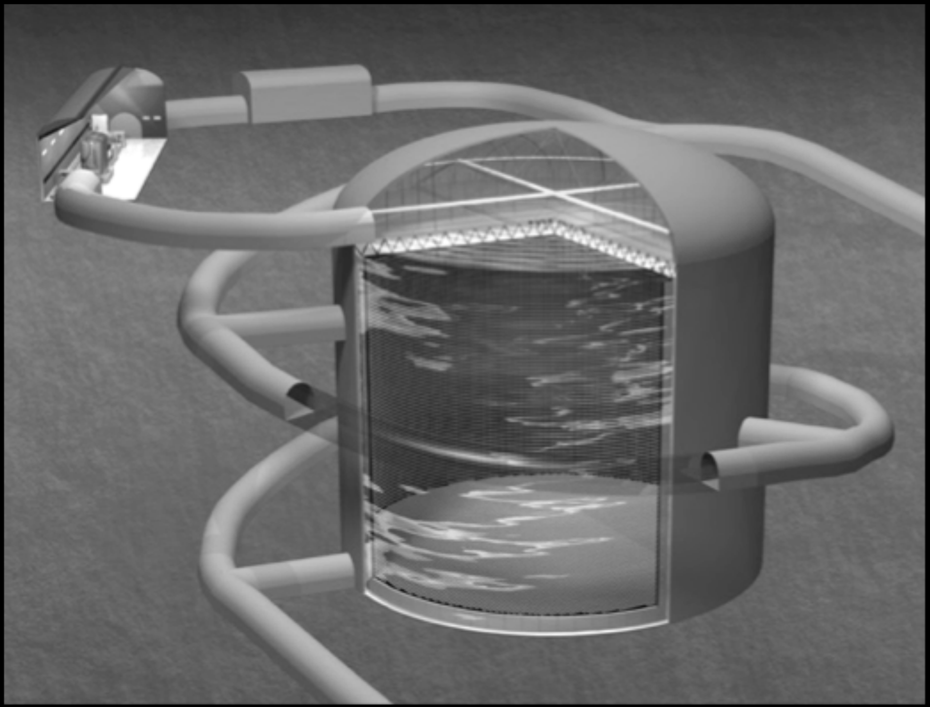
SK results on Atmospheric Neutrinos and Prospects with HK





Roger Wendell
Kyoto University
Prospects of Neutrino Physics
Kashiwa, Kavli-IPMU
2019.04.09

Introduction :

- Super-K has been studying atmospheric neutrino oscillations for more than 20 years
  - Statistical uncertainties are still dominant for the majority of those analyses

- Hyper-K is expected to have even greater sensitivity, especially when its accelerator and atmospheric neutrinos are used together

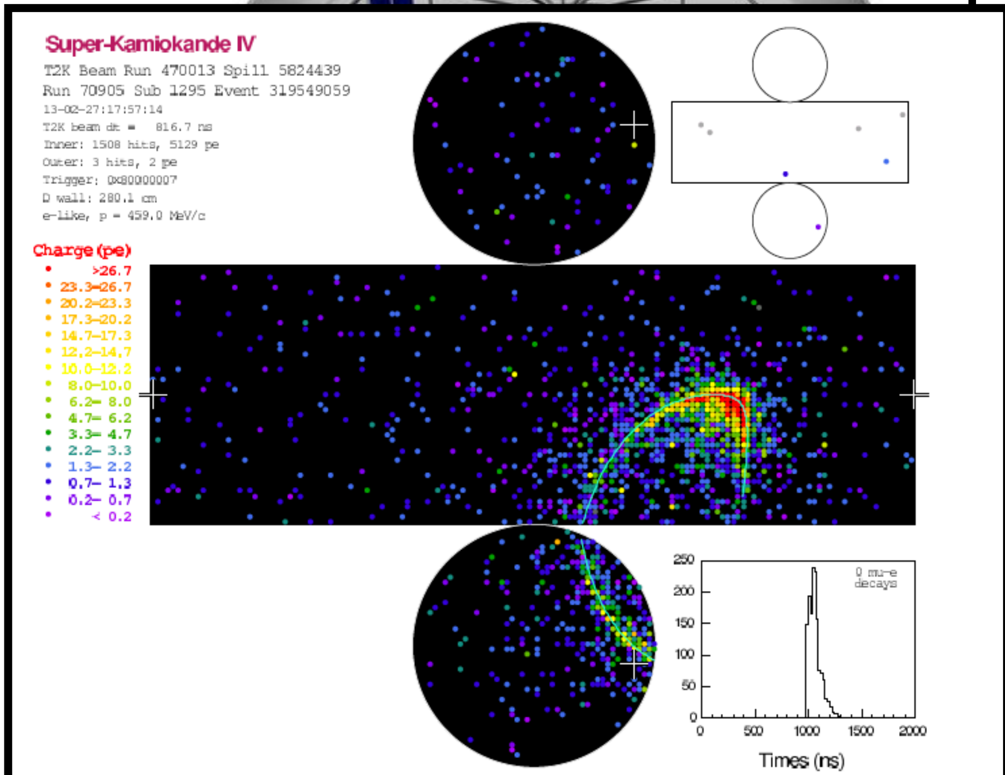
- This talk presents recent analysis results from Super-K as well as expected sensitivities at Hyper-K and comments on the impact of systematic errors

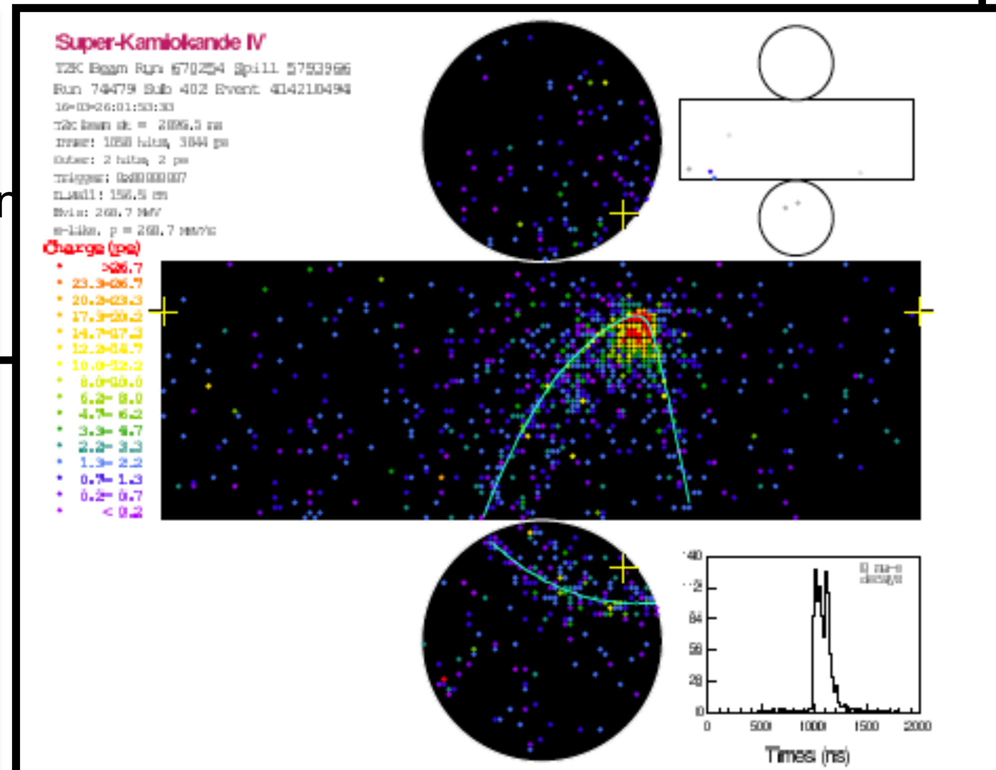
Topics

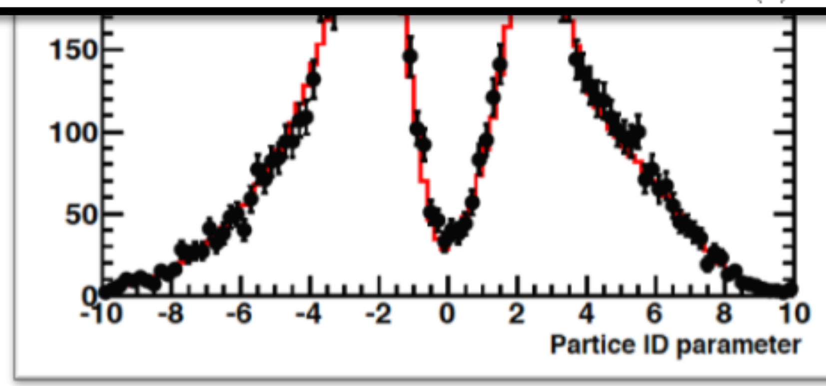
- Present
  - Atmospheric Oscillation analysis
  - Search for Tau Neutrinos
  - Improved Oscillation analysis in SK-IV
- Future
  - Hyper-Kamiokande Sensitivities
  - Prospects with Improved Systematic Uncertainties

Super-Kamiokande: Introduction

Neutrino, Antineutrino?



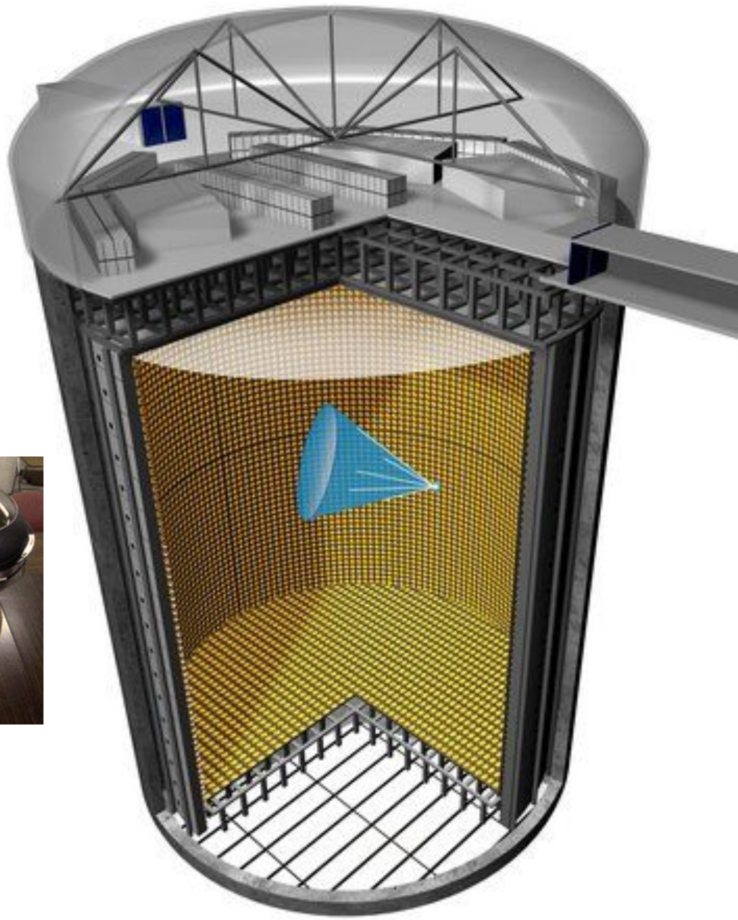




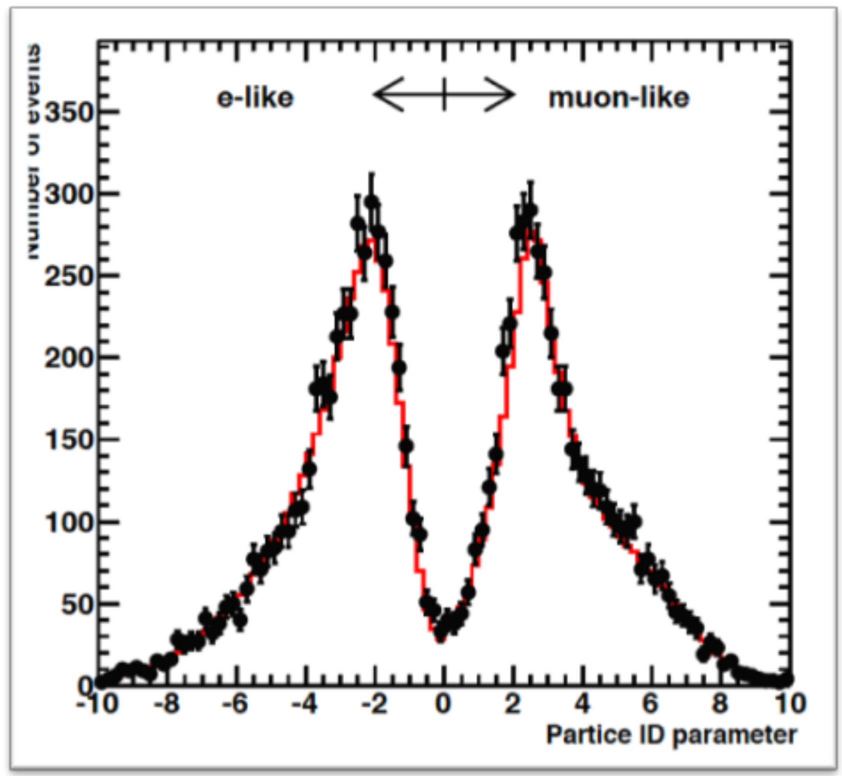
Four Run Periods:
SK-I (1996-2001) SK-II (2003-2005)
SK-III (2005-2008) SK-IV (2008-2018)

Upgrade Complete Now operating as SK-V !!

Super-Kamiokande: Introduction



- 22.5 kton fiducial volume
- Optically separated into
    - Inner Detector 11,146 20” PMTs
    - Outer Detector 1885 8” PMTs
- No net electric or magnetic fields
- Excellent PID between showering (e-like) and non-showering (μ-like)
    - < 1% MIS ID at 1 GeV
- Multipurpose detector



Four Run Periods:

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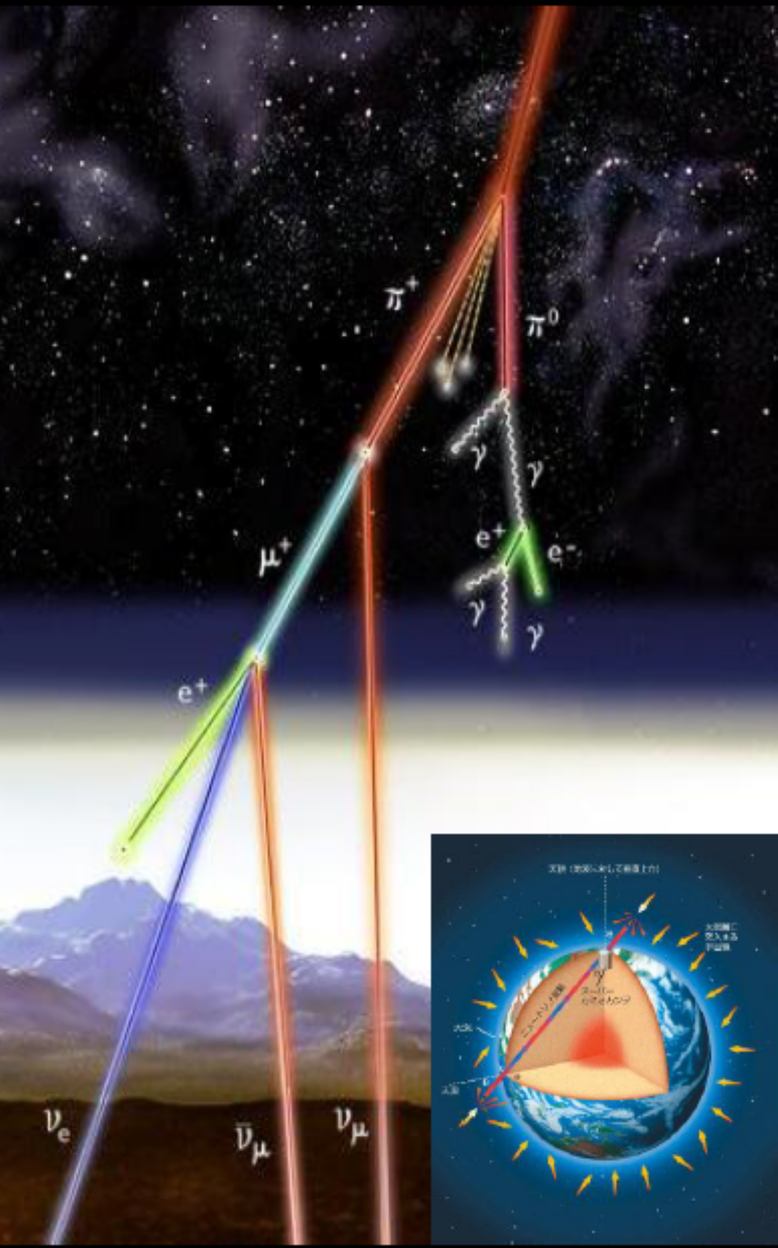
Upgrade Complete Now operating as SK-V !!

About the Atmospheric Neutrino Flux



- Cosmic rays strike air nuclei and the decays of the out-going hadrons produce neutrinos

$$P + A \rightarrow N + \pi^+ + x$$

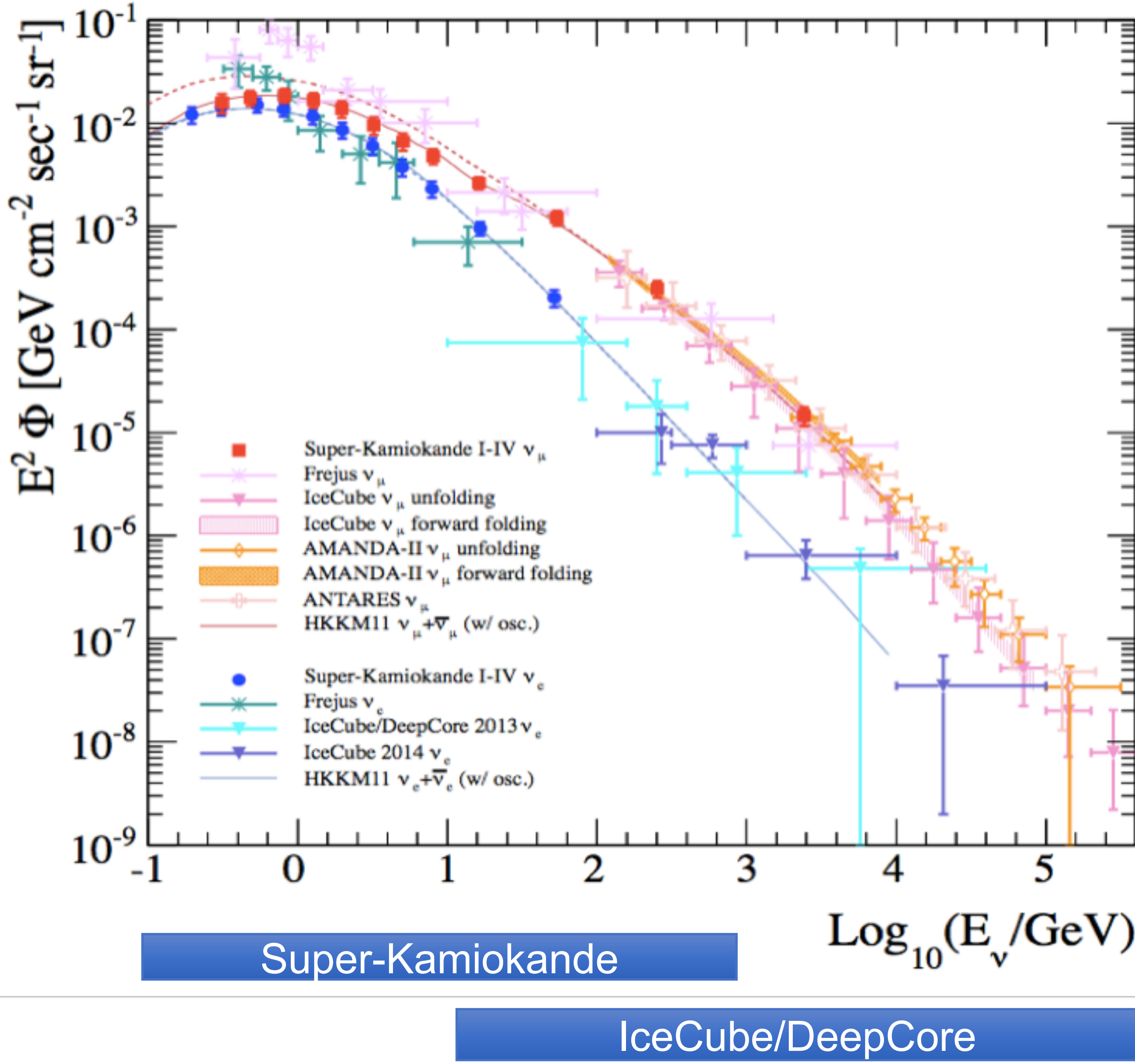
$$\hookrightarrow \mu^+ + \boxed{\nu_\mu} \rightarrow e^+ + \boxed{\nu_e} + \boxed{\bar{\nu}_\mu}$$

- Isotropic about the Earth
  - Path length to the detector spans 10 – 10,000 km

- Spans many decades in energy ~100 MeV – PeV$^+$

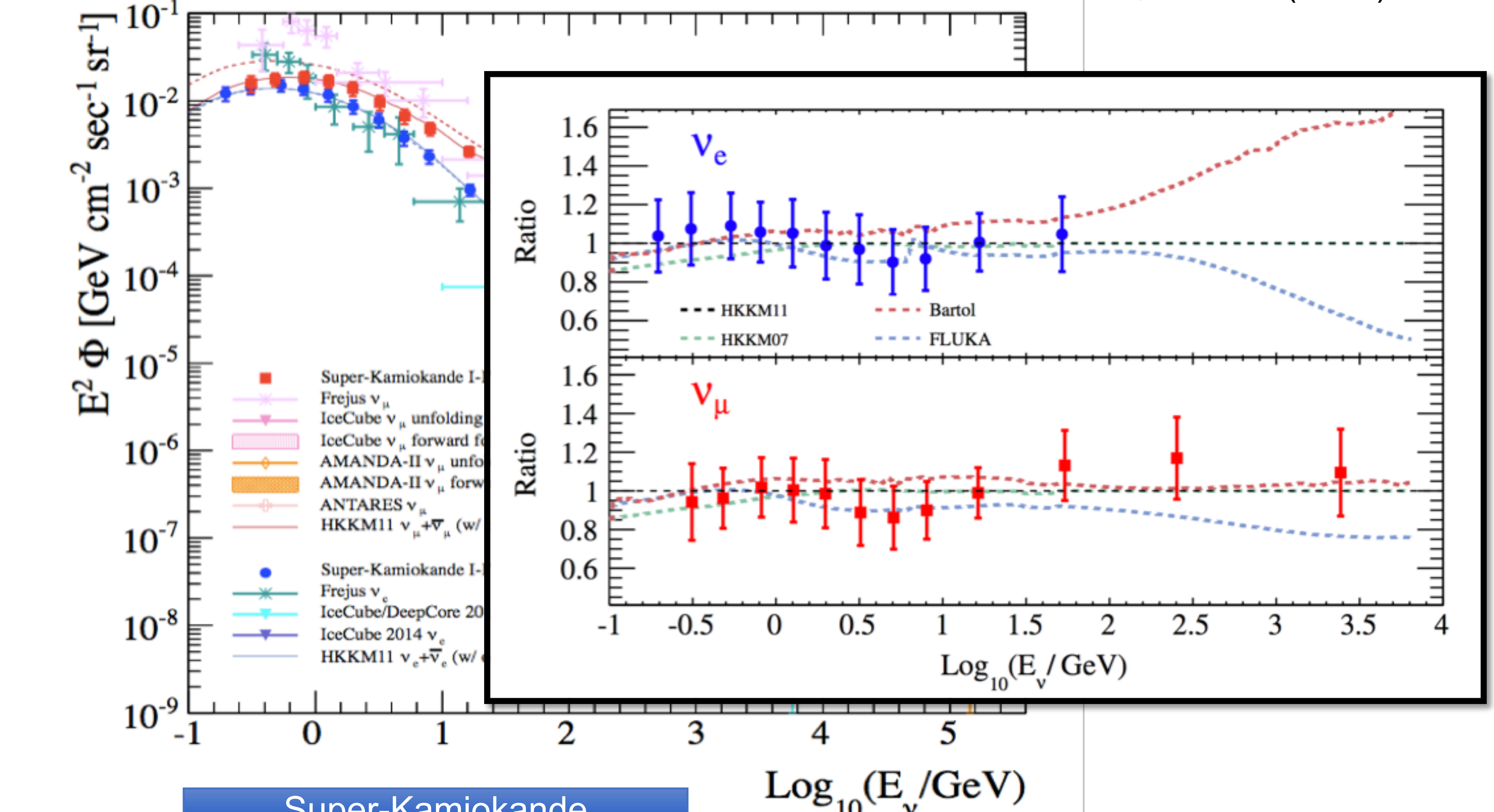
Atmospheric Neutrino Flux:

PHYSICAL REVIEW D 94, 052001 (2016)



Atmospheric Neutrino Flux:

PHYSICAL REVIEW D 94, 052001 (2016)

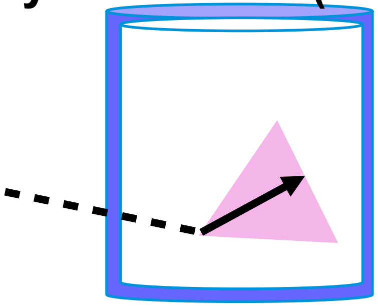


Super-Kamiokande

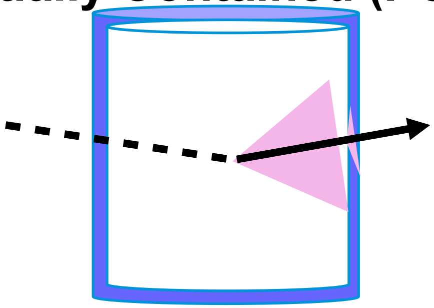
IceCube/DeepCore

Super-K Atmospheric ν Analysis Samples

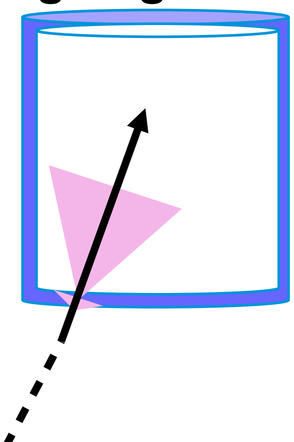
Fully Contained (FC)

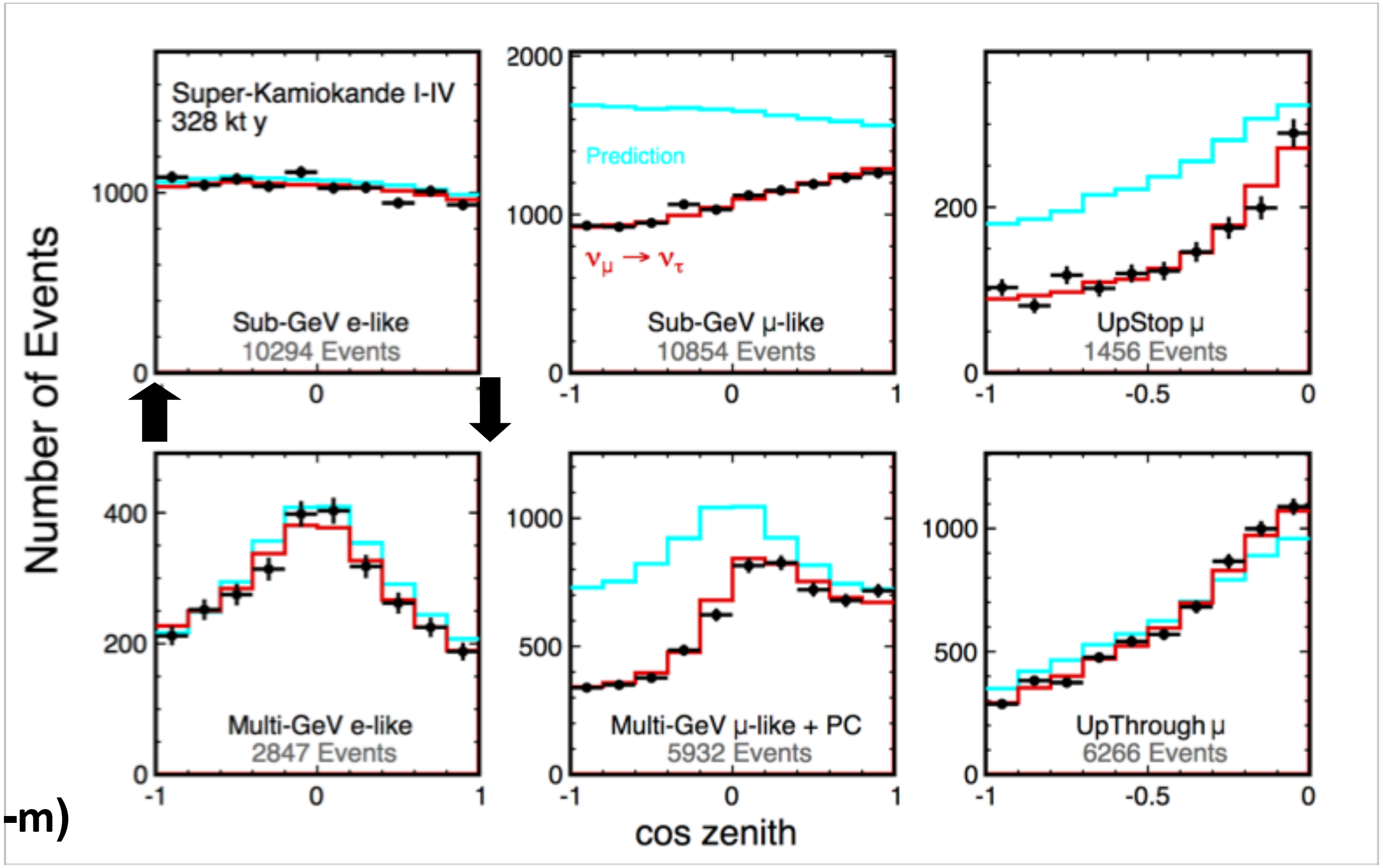


Partially Contained (PC)



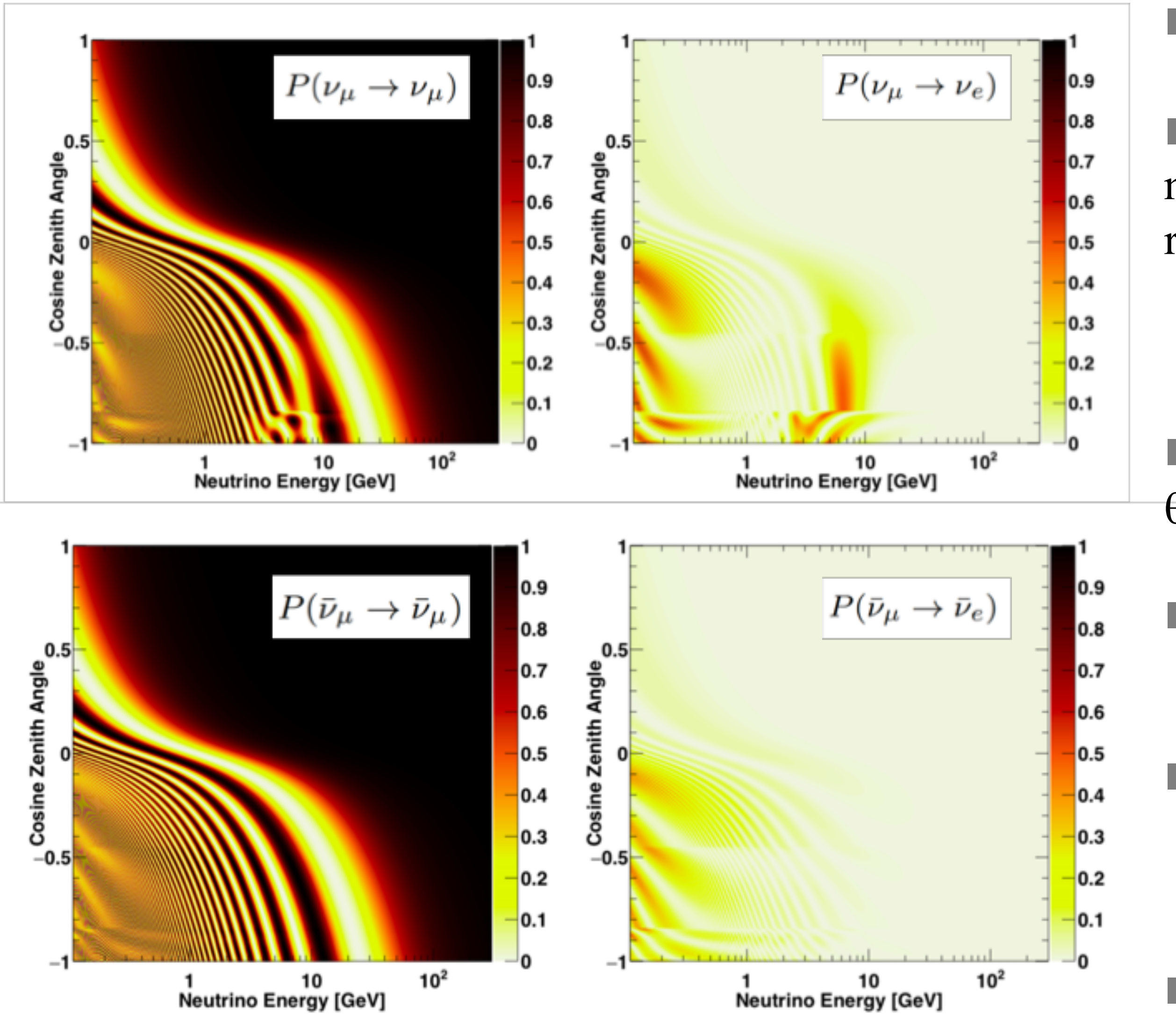
Upward-going Muons (Up-m)





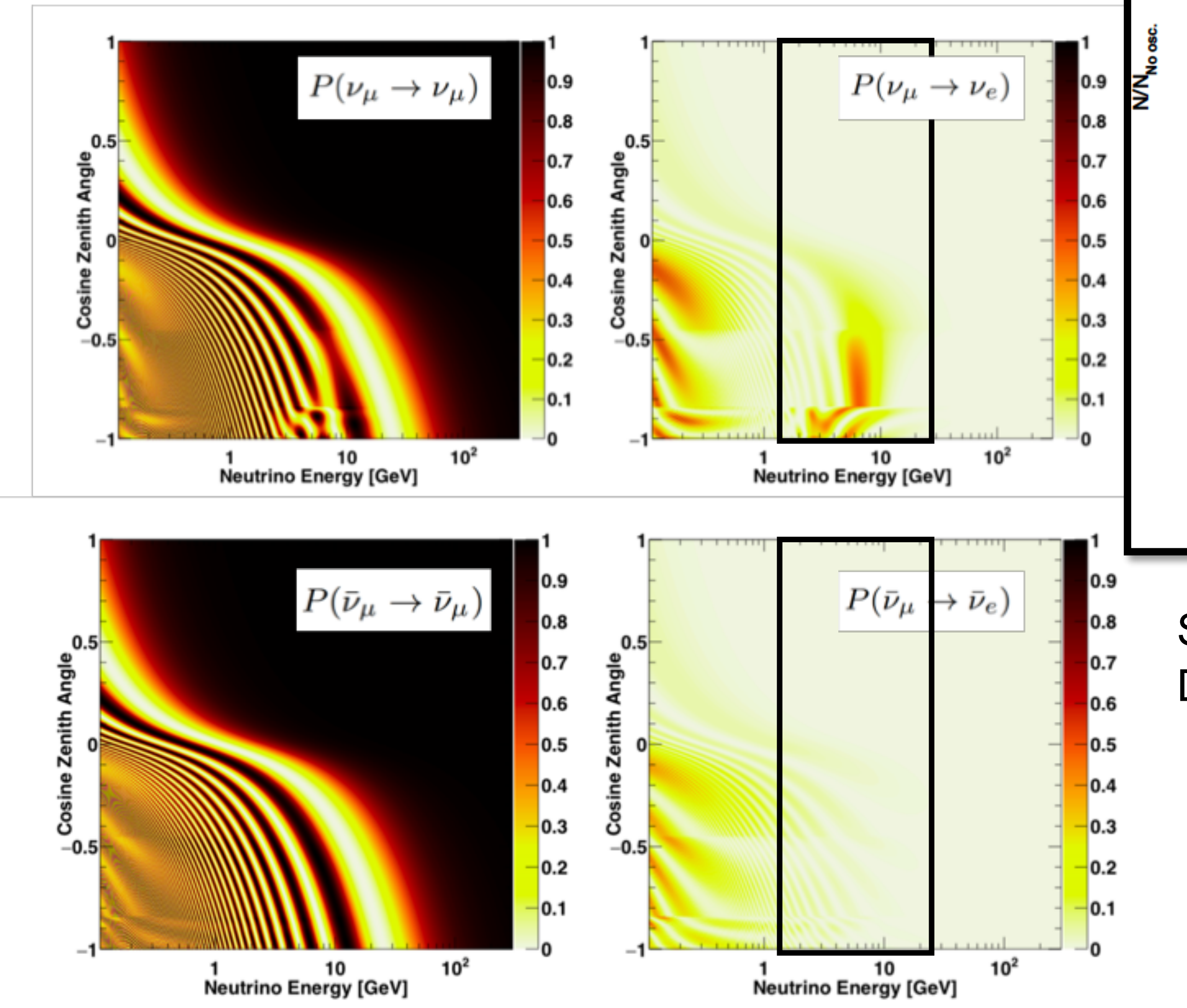
- In total **19** analysis samples: multi-GeV e-like samples are divided into ν-like and ν-bar-like subsamples (p, cos θ) binning
- 5,300 days (328 kton-yr) data set
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Interested in subdominant contributions to this picture
  - Ie three-flavor effects, Sterile Neutrinos, LIV, etc.

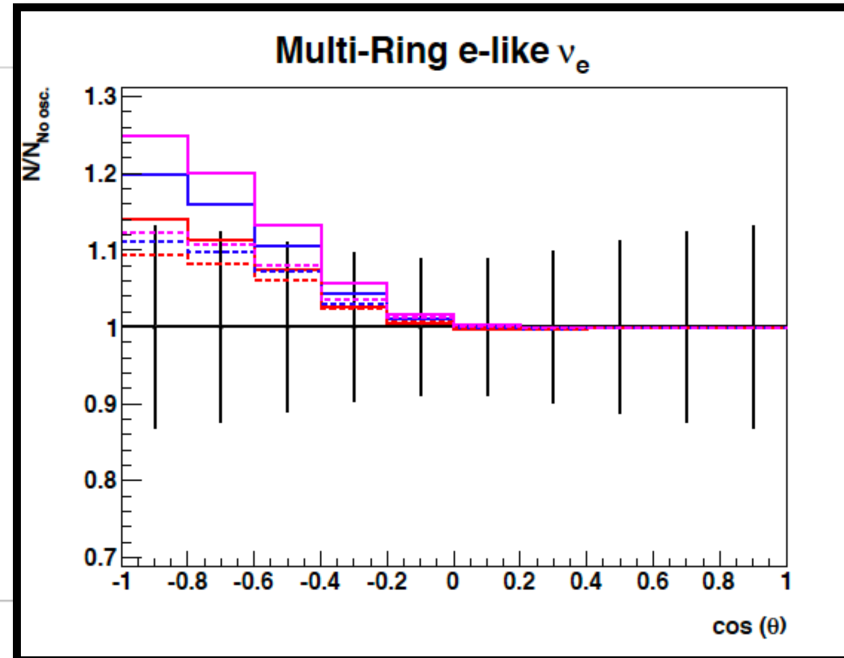
Atmospheric Neutrino Oscillations :



- Plots assume the Normal Hierarchy
- Under the inverted hierarchy the neutrino and antineutrino plots reverse roles
  - Resonance effects in the antineutrino channels
- Size of matter effects depends on θ_{13}, θ_{23}, δ_{CP} (in order of importance)
- Mass hierarchy sensitivity:
  - 2 ~ 10 GeV
- CP sensitivity
  - Below 2 GeV , strongest effects (400~600 MeV)
- *Exotic* Scenarios
  - Lorentz-Invariance: > 5 GeV
  - Sterile Neutrinos > 1 GeV

Atmospheric Neutrino Oscillations :





Solid: Normal Hierarchy

Dash: Inverted Hierarchy

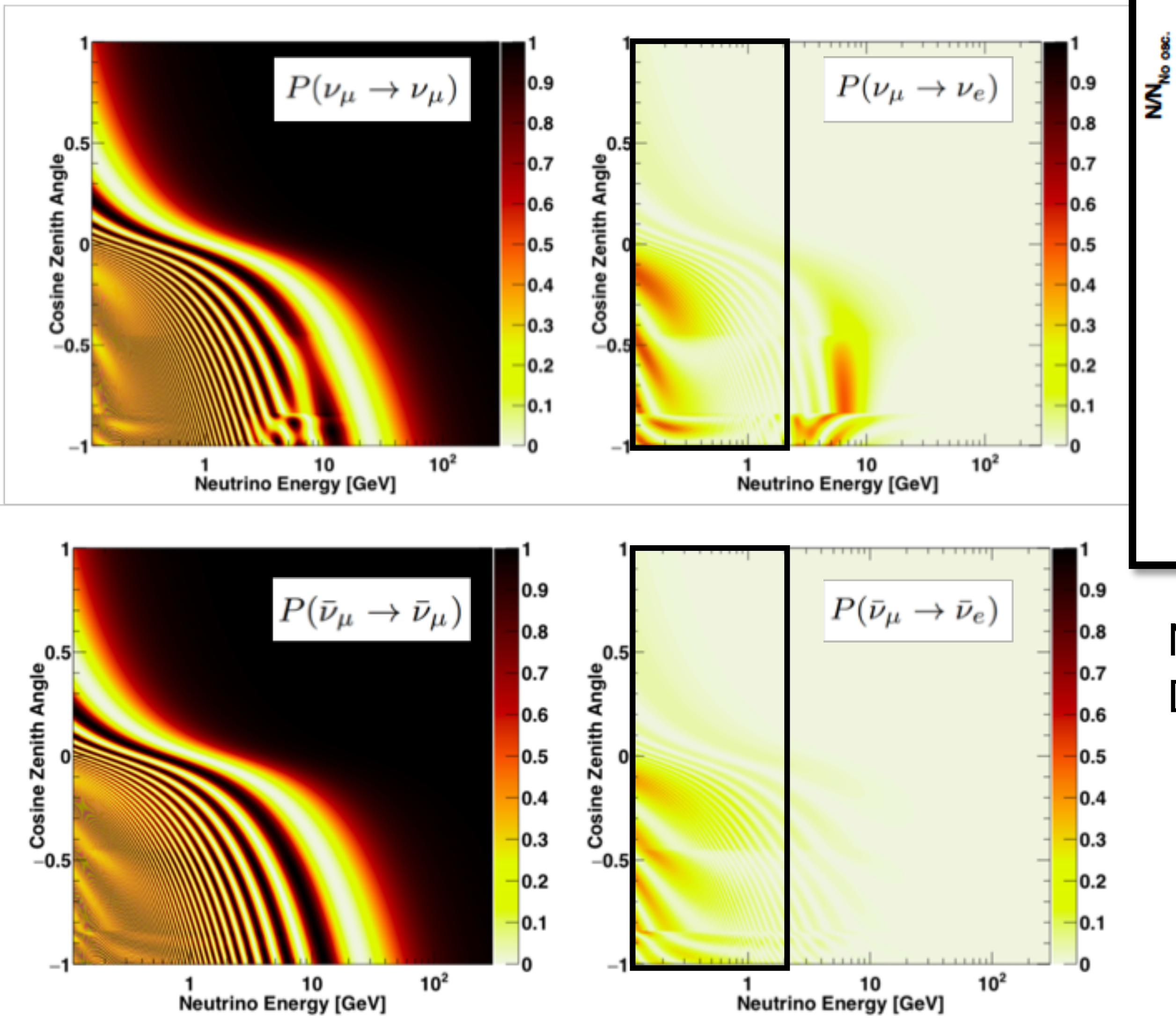
Statistical Error

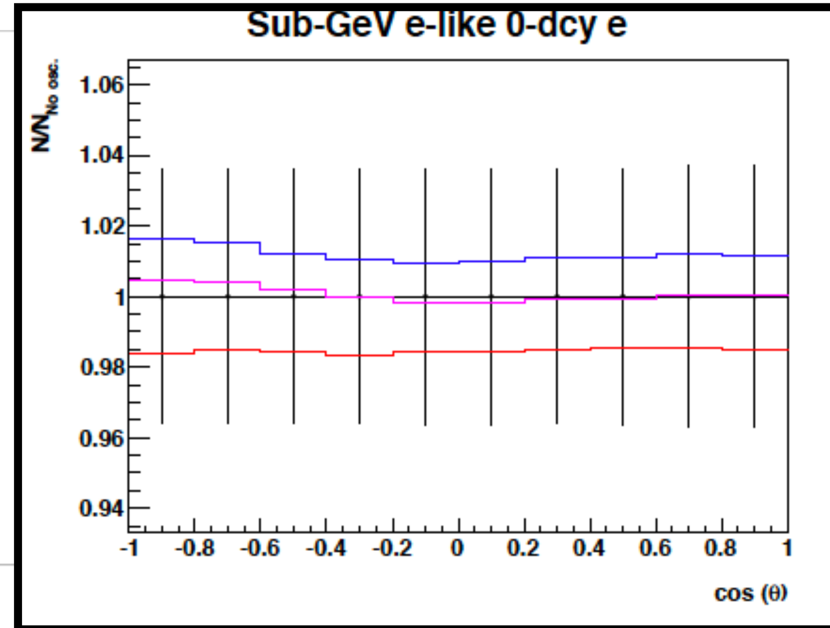
$\sin^2\theta_{23} = 0.4$

$\sin^2\theta_{23} = 0.5$

$\sin^2\theta_{23} = 0.6$

Atmospheric Neutrino Oscillations :



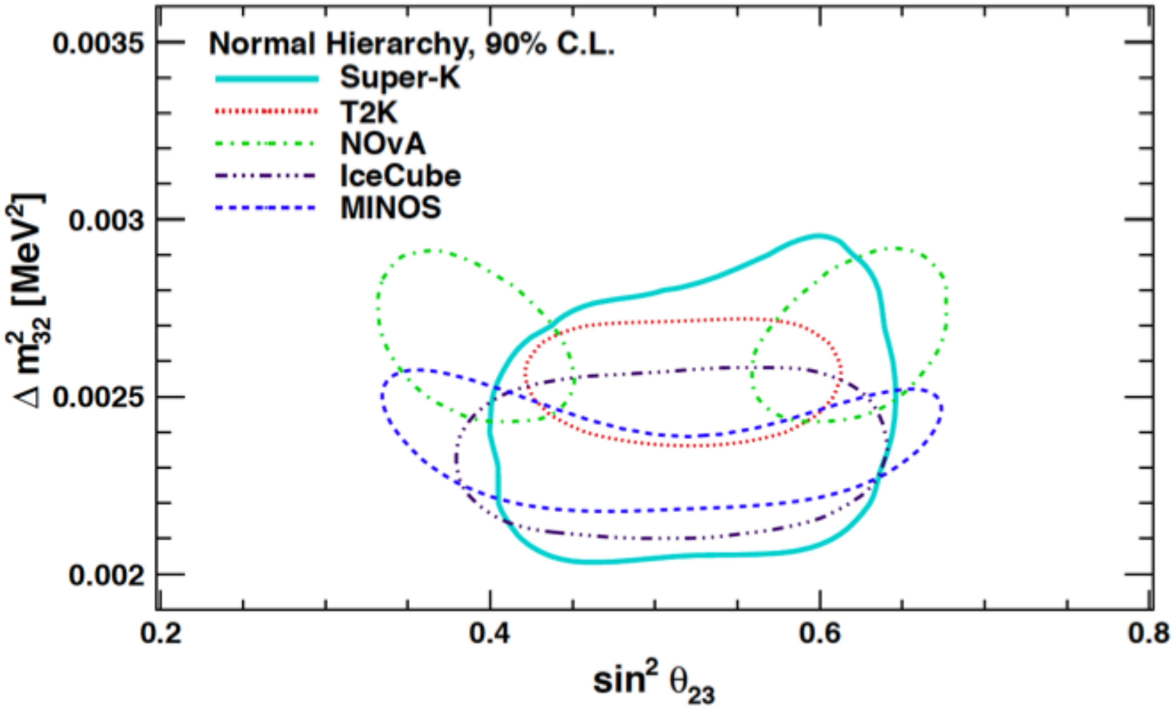


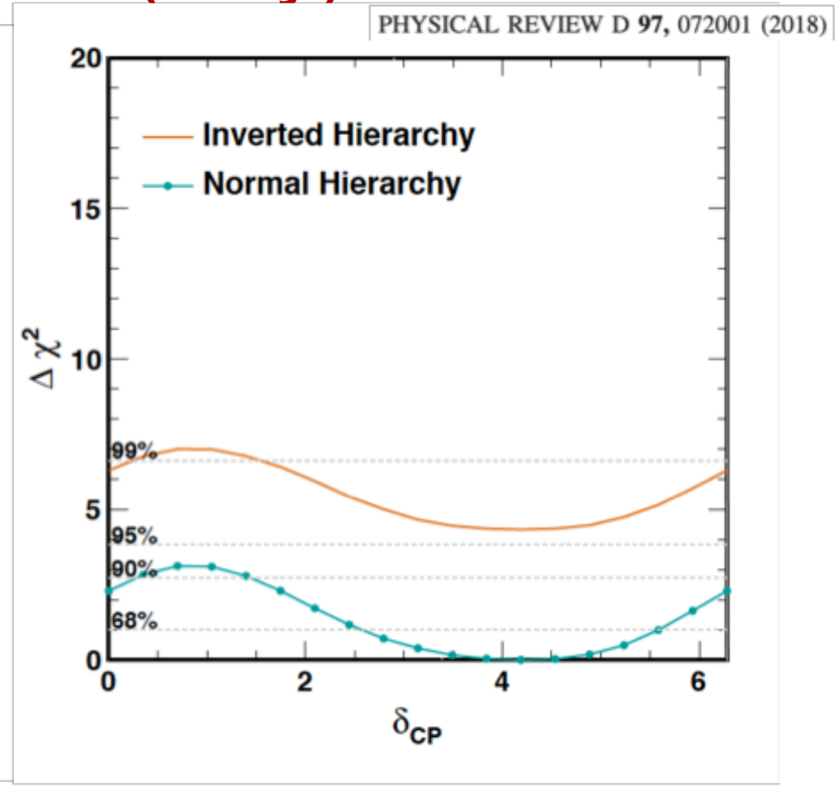
Normal Hierarchy
Dash: Inverted Hierarchy

- Statistical Error
- δ_{CP} = 0°
- δ_{CP} = 80°
- δ_{CP} = 300°

Results from Super-Kamiokande

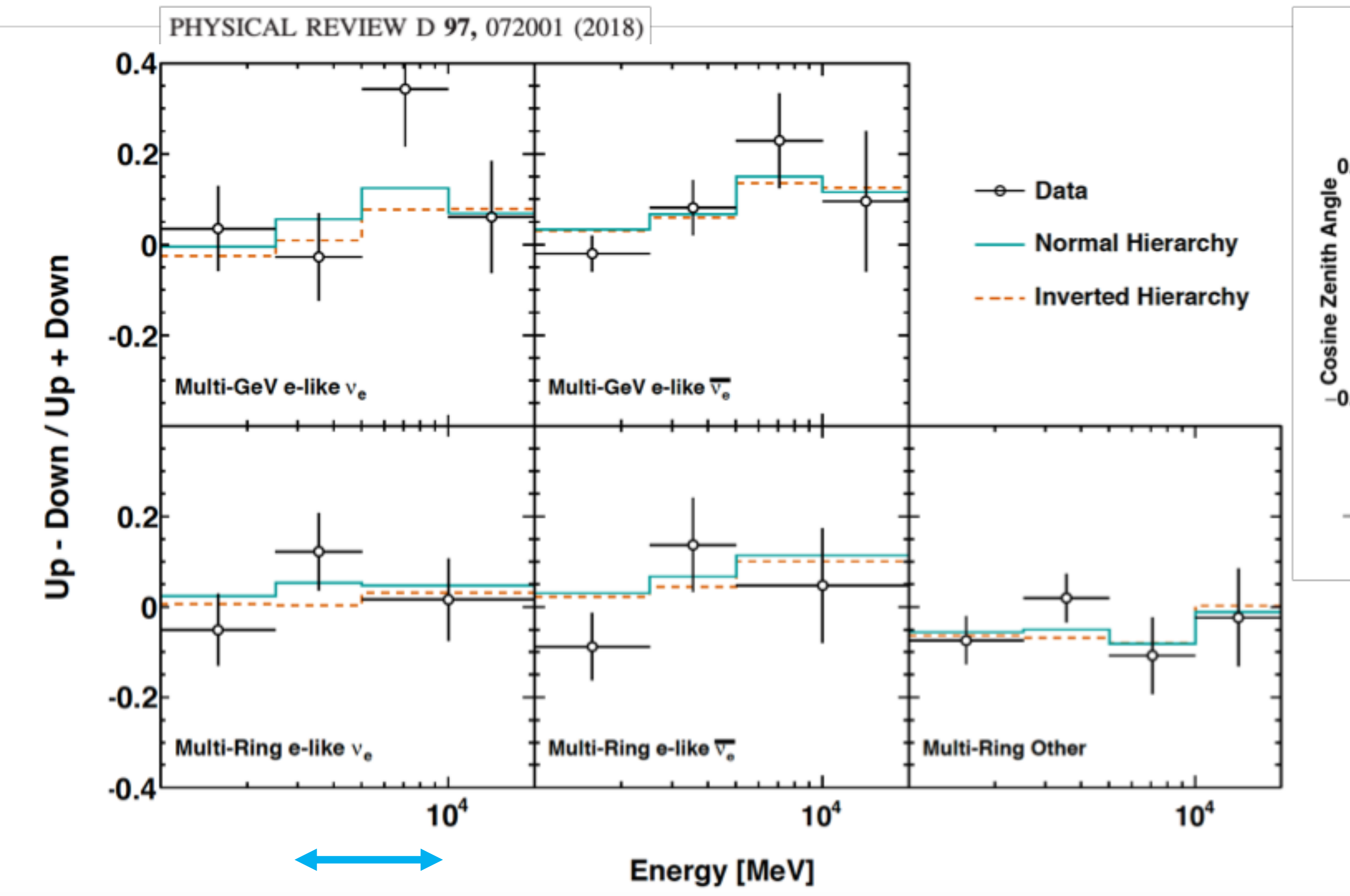
Atmospheric Mixing + δ_{cp}: Super-K (only)

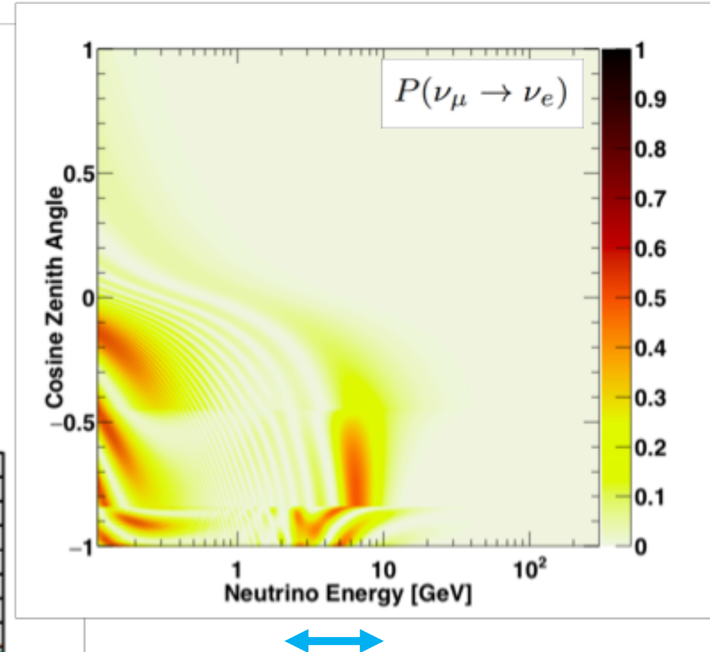




- Atmospheric mixing angles consistent with other experiments, weak preference for second octant ($< 1\sigma$)
  - $\Delta m^2_{32} = 2.5^{+0.13}_{-0.20} \times 10^{-3}$ eV^2
  - $\sin^2\theta_{23} = 0.588^{+0.031}_{-0.064}$
- *Normal hierarchy* preference : $\Delta\chi^2$ (NH – IH) = -4.33
- δ_{cp} ~1.33π

Atmospheric Mixing + δ_{cp}: Super-K (only)





- Normal hierarchy favored by slight data excesses at energies consistent with resonantly-enhanced oscillations

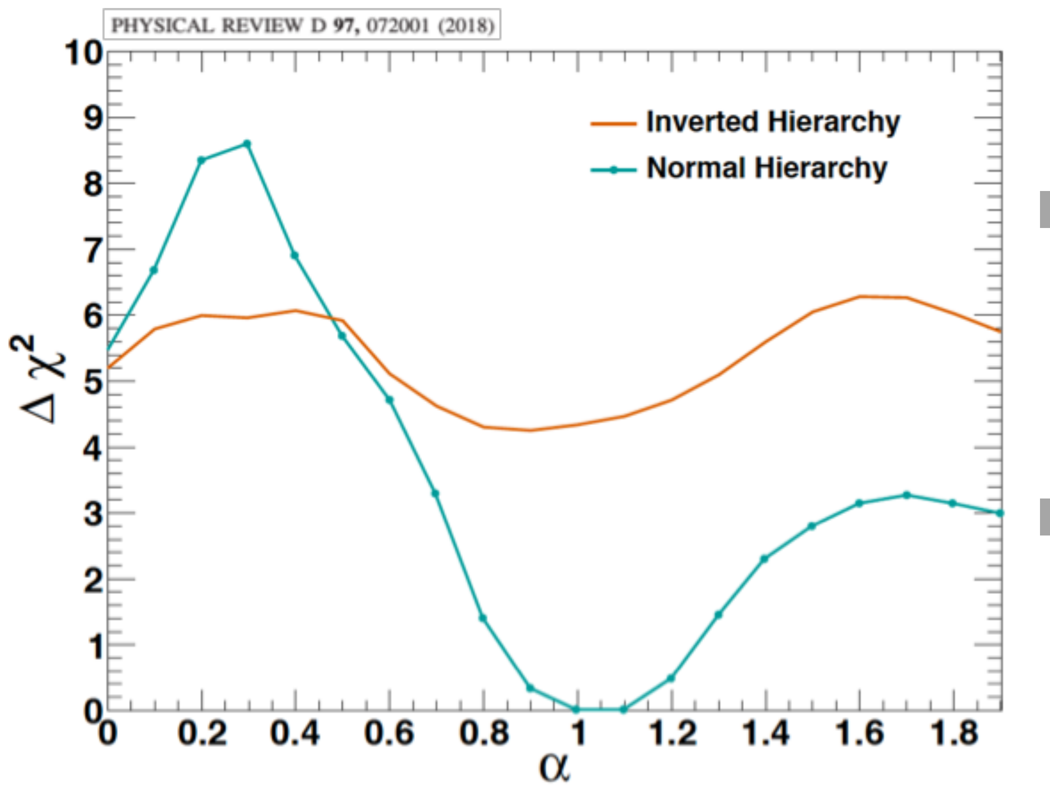
Test for Evidence of Matter Effects

$$H_{\mathrm{matter}} = \begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{pmatrix} + U^\dagger \begin{pmatrix} a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} U$$

$$a = \pm\sqrt{2}\, G_F\, N_e$$

$$\downarrow$$

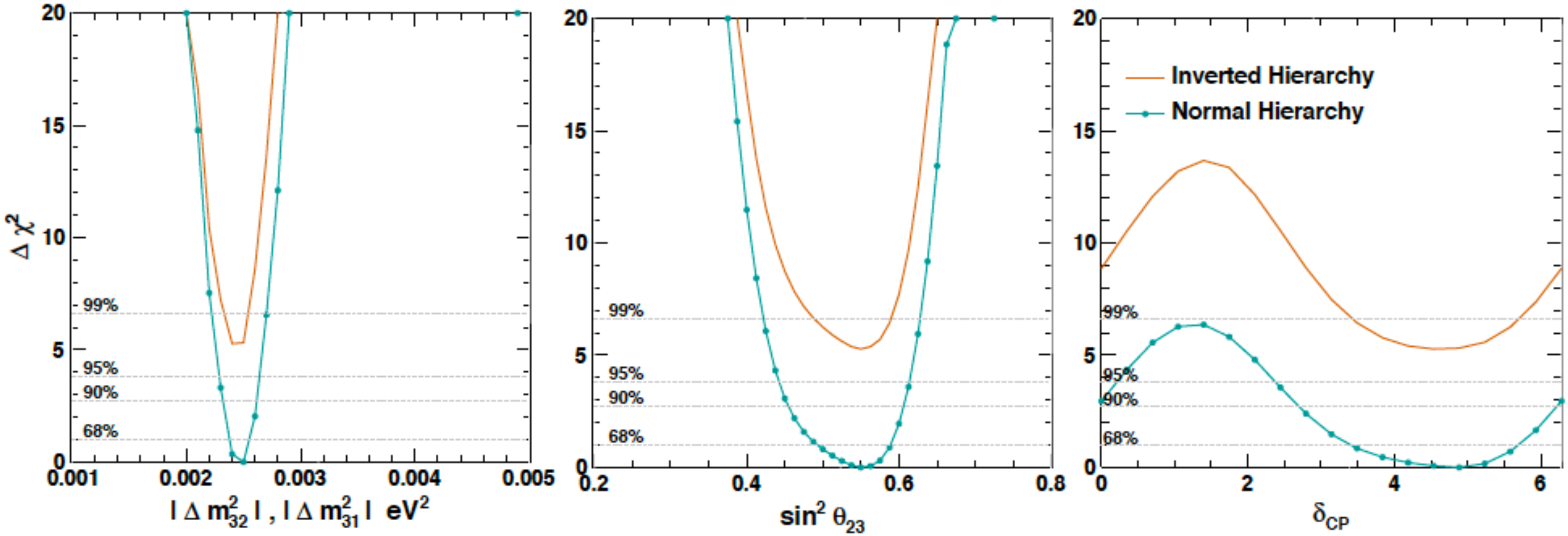
$$a = \pm\, \alpha \sqrt{2}\, G_F\, N_e$$



- Best fit consistent with standard matter density and normal hierarchy ($\alpha = 1$)
- Vacuum oscillations ($\alpha = 0$) rejected at 1.6 σ

Atmospheric Mixing + δ_{cp}: SK+T2K Model

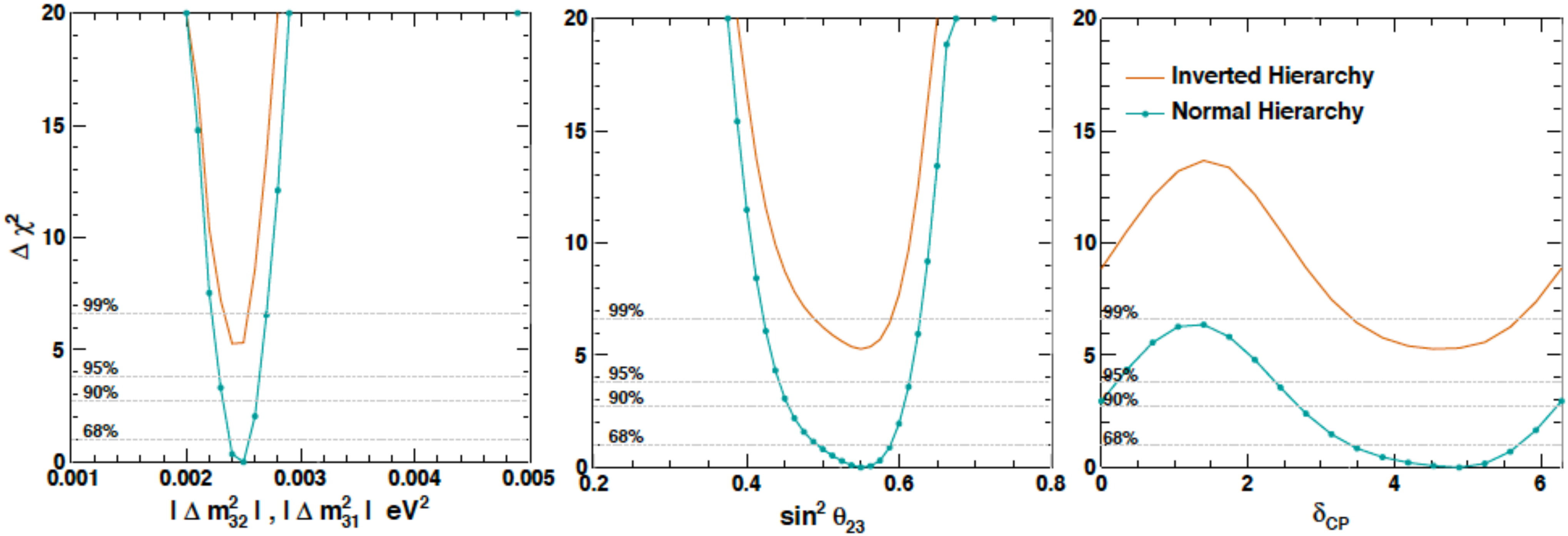
PHYSICAL REVIEW D 97, 072001 (2018)



- Fit atmospheric data with a *model* of T2K (6.57×10^{20} POT, nu mode)
  - T2K has collected 3.16×10^{21} POT
- Atmospheric mixing dominated by T2K Model
- *Normal hierarchy* hint strengthens :
  - $\Delta\chi^2$ (NH – IH) = -5.27 (SK only: -4.33)
- As does preference for δ_{cp} ~1.33π

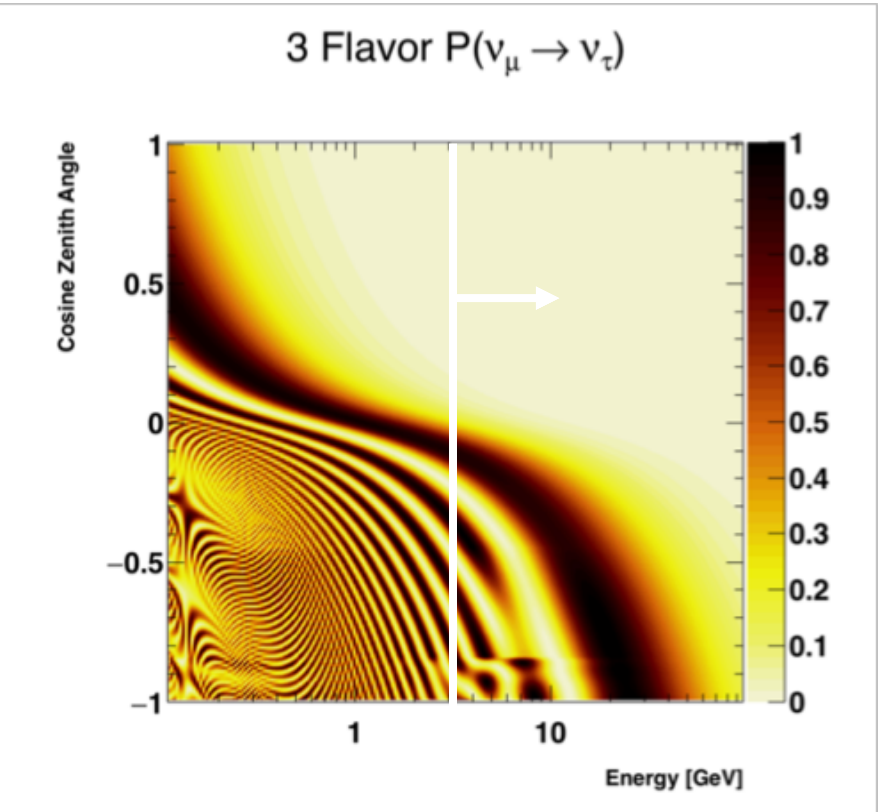
Atmospheric Mixing + δ_{cp}: SK+T2K Model

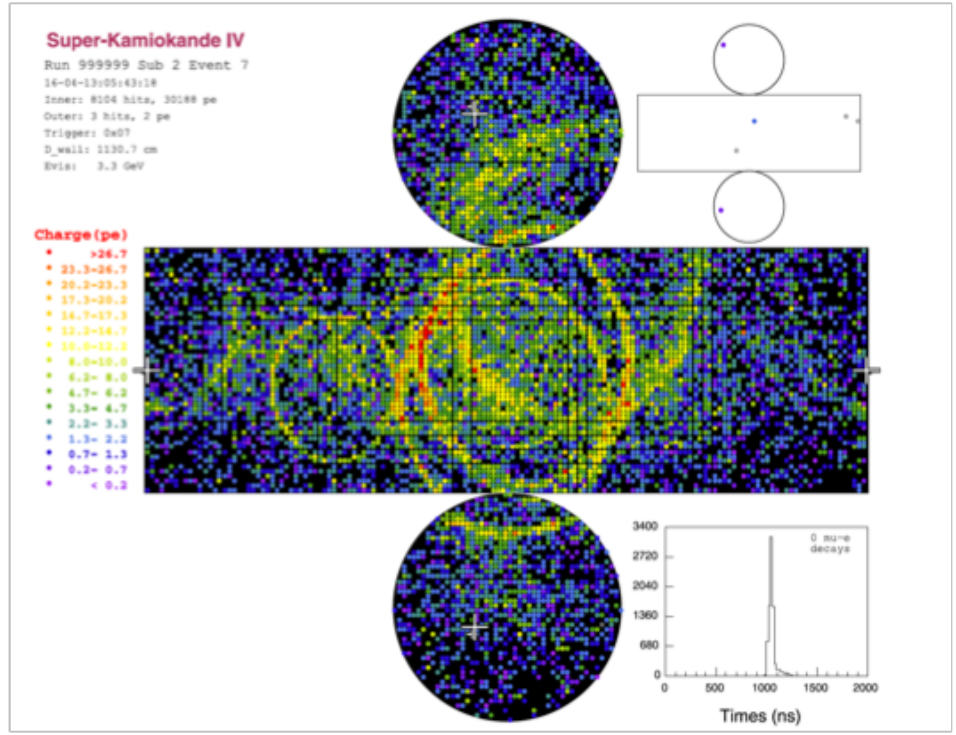
PHYSICAL REVIEW D 97, 072001 (2018)



Hierarchy Significance			
NH Preference	Lower Oct.	Best Fit	Upper Oct.
SK Only	82.9%	93.0%	96.7%
SK+T2K Model	91.9%	92.5%	94.4%

Search for Tau Neutrinos at SK

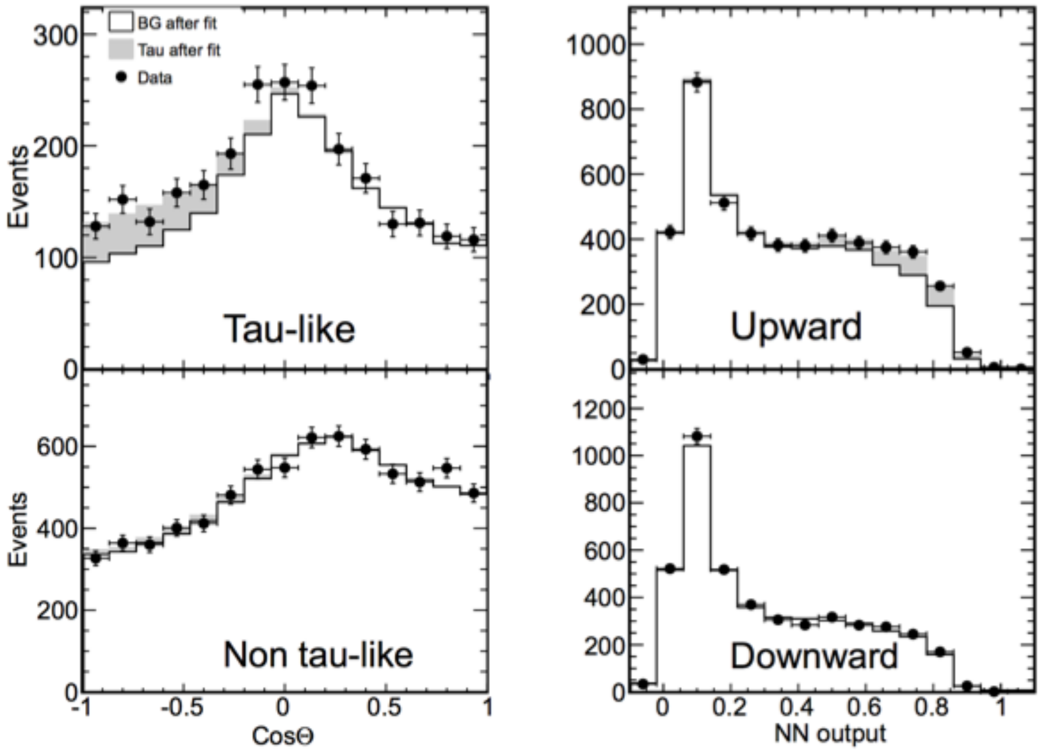




- Tau neutrinos are not in atmospheric flux below 10^5 GeV but can be induced by oscillations
  - Important for ν_τ cross section studies, tests of unitarity, background to mass hierarchy search, etc.
- Complicated event topologies due to hadronic tau decay, search using neural network-based method

Search for Tau Neutrinos at SK :

PHYS. REV. D **98,** 052006 (2018)



$$\text{Data} = \text{PDF}_{\text{BG}} + \alpha \times \text{PDF}_{\text{tau}} + \sum \epsilon_i \times \text{PDF}_i$$

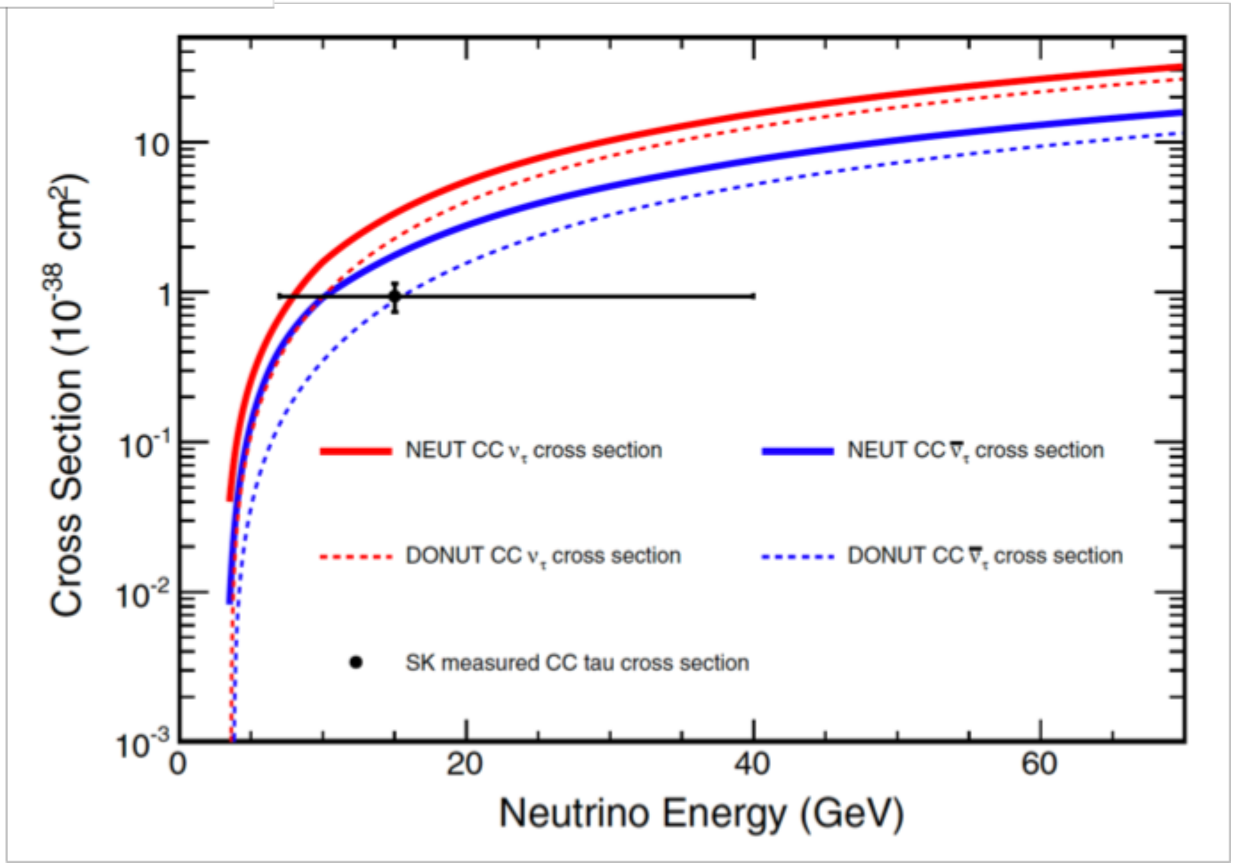
$\alpha = 1.47 \pm 0.32$ (stat+syst)

4.6σ rejection of no τ appearance

- Fit 2-dimensional PDFs (cos θ, Neural Network), while simultaneously varying systematic error templates
- Uses 328 kton-yr exposure (SK-I ~ SK-IV)

Systematic Errors in Search for Tau Neutrinos

PHYS. REV. D **98,** 052006 (2018)



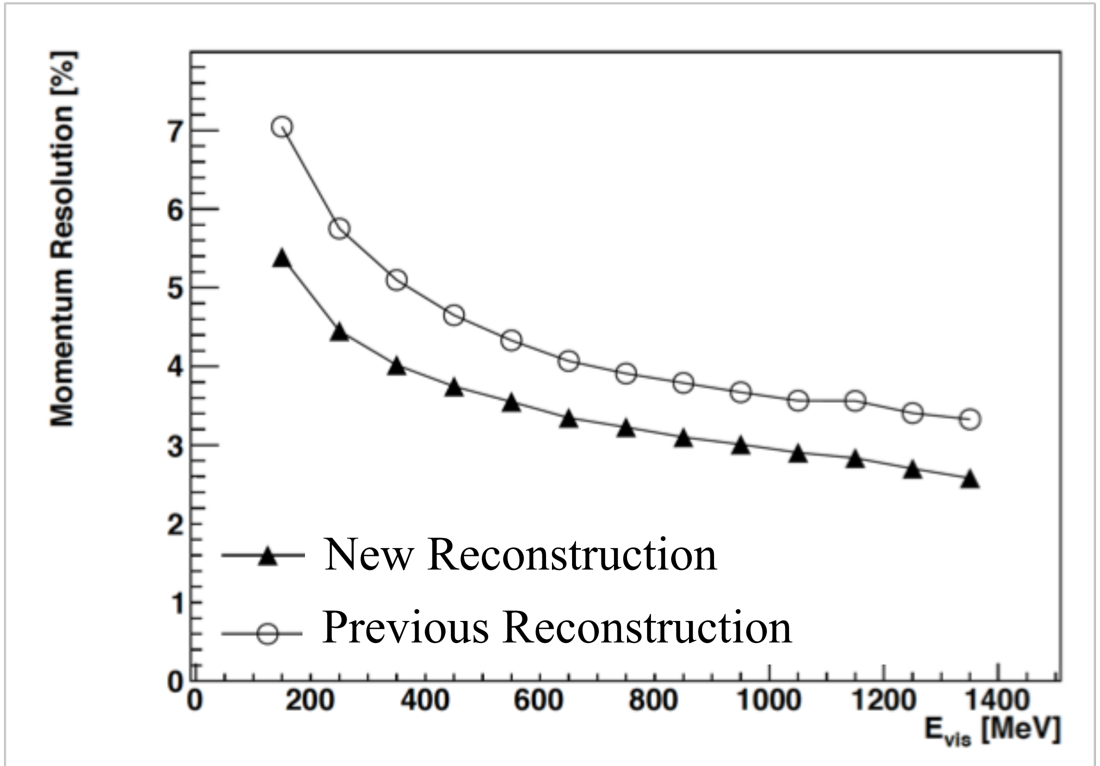
- Flux-averaged cross section:

$$\sigma_{measured} = (1.47 \pm 0.32) \times \langle \sigma_{theory} \rangle$$
$$= (0.94 \pm 0.20) \times 10^{-38}\ \mathrm{cm}^2$$

Stat+Syst.

Present and Near Future Prospects

New Reconstruction Algorithm : Performance



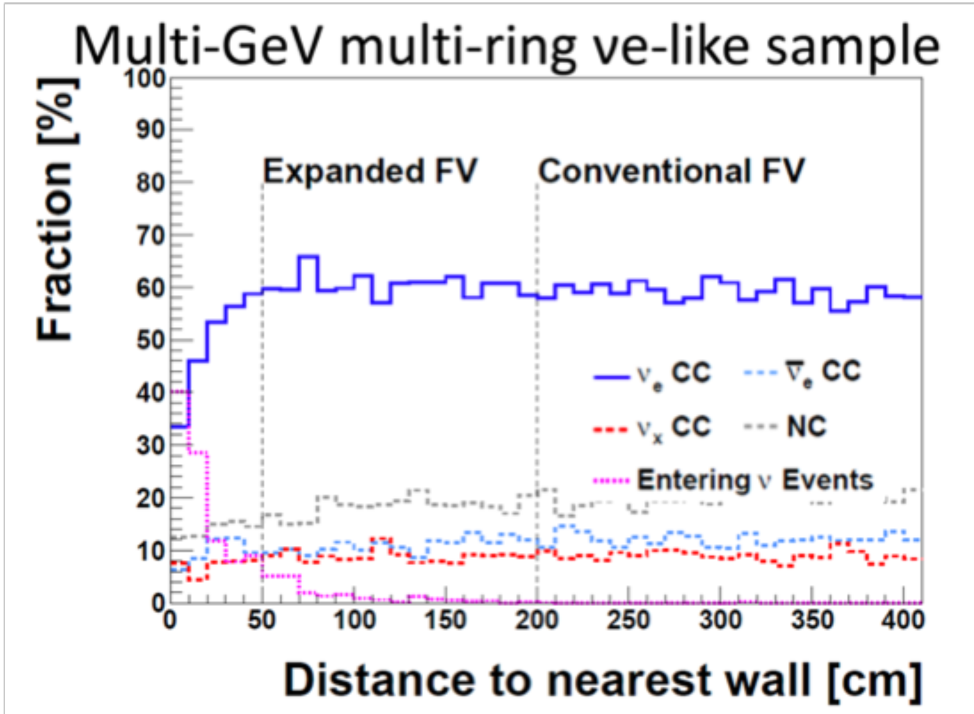
Reconstruction	New	Previous
True CCQE ν_e sample		
Vertex Resolution	20.6 cm	24.9 cm
Direction Resolution	1.48°	1.68°
Momentum Bias	0.43%	0.63%
Momentum Resolution	2.90%	3.56%
Mis-PID rate	0.02%	0.50%
True CCQE ν_μ sample		
Vertex Resolution	15.8 cm	17.3 cm
Direction Resolution	1.00°	1.28°
Momentum Bias	-0.18%	0.54%
Momentum Resolution	2.26%	2.60%
Mis-PID rate	0.05%	0.91%

https://arxiv.org/abs/1901.03230

- A new likelihood-based event reconstruction has been developed at Super-K, which incorporates more PMT information than the previous algorithm
- Now been applied to atmospheric neutrinos (single- and multi-ring events), but for SK-IV data period only
  - Used at T2K since 2017 (single-ring events only)

- New algorithm outperforms previous one in essentially all metrics

New Reconstruction Algorithm : Fiducial Volume Expansion

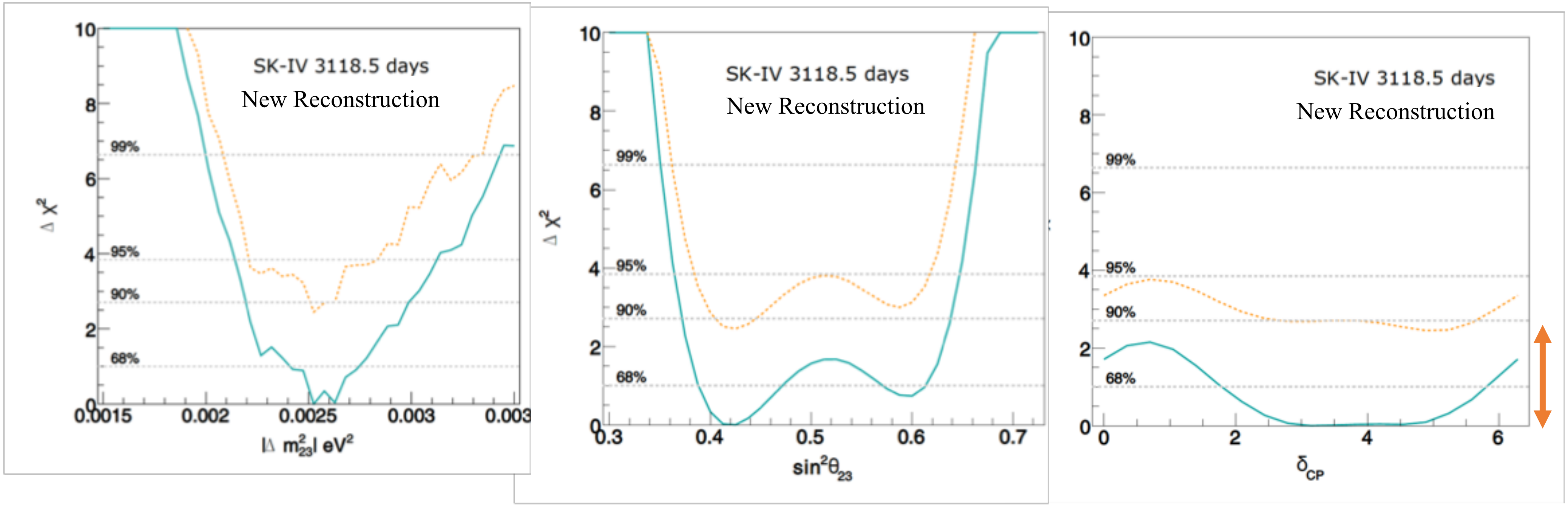


https://arxiv.org/abs/1901.03230

Reconstruction Dwall range	New 50 cm∼200 cm	New > 200 cm	Previous > 200 cm
Particle ID of the brightest ring in multi-ring events			
Sub-GeV			
e-like	-3.19%	-0.72%	4.19%
μ-like	1.31%	0.31%	-1.56%
Multi-GeV			
e-like	$\boxed{1.94\%}$	$\boxed{1.10\%}$	$\boxed{3.33\%}$
μ-like	-1.06%	-0.66%	-1.56%

- Improved performance of the new algorithm has allowed the fiducial volume to be expanded from 22.5 kton to 29.7 kton (~30% increase)
- Analysis of calibration and neutrino data indicate that systematic errors are the same or smaller than those of the previous algorithm, even in the newly-added target region

Oscillation Analysis in Expanded Fiducial Volume : SK-IV



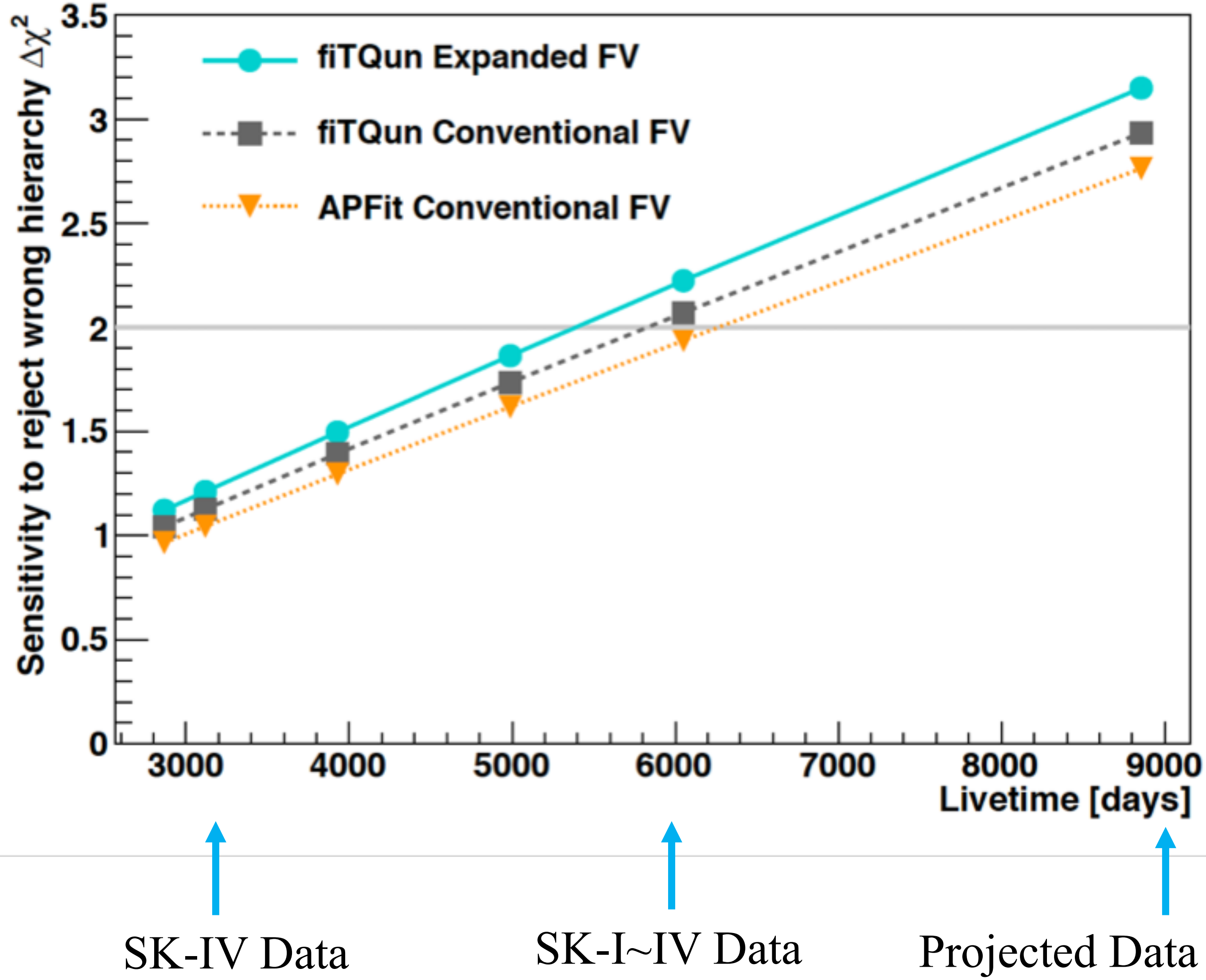
https://arxiv.org/abs/1901.03230

Hierarchy	θ_{13} Constrained NH	IH
χ^2	576.5	579.0
$\sin^2\theta_{13}$	–	–
$\sin^2\theta_{23}$ (1^{st} oct.)	$\boxed{0.425^{+0.046}_{-0.037}}$	$\boxed{0.425^{+0.055}_{-0.036}}$
$\sin^2\theta_{23}$ (2^{nd} oct.)	$0.600^{+0.013}_{-0.030}$	$0.588^{+0.022}_{-0.037}$
$\lvert\Delta m^2_{32,31}\rvert$ [$\times 10^{-3}$ eV^2]	$2.53^{+0.22}_{-0.12}$	$2.53^{+0.14}_{-0.31}$
δ_{CP}	$3.14^{+2.67}_{-1.35}$	$4.89^{+1.51}_{-3.46}$

- Weak preference for the normal hierarchy
- Reject inverted hierarchy at 74% CL (assuming analysis best fit point)

- Similar preference for $\delta_{CP} \sim 3\pi/2$
- Best fit in the first octant (full SK analysis is in second octant)

Prospects : Mass Hierarchy Sensitivity



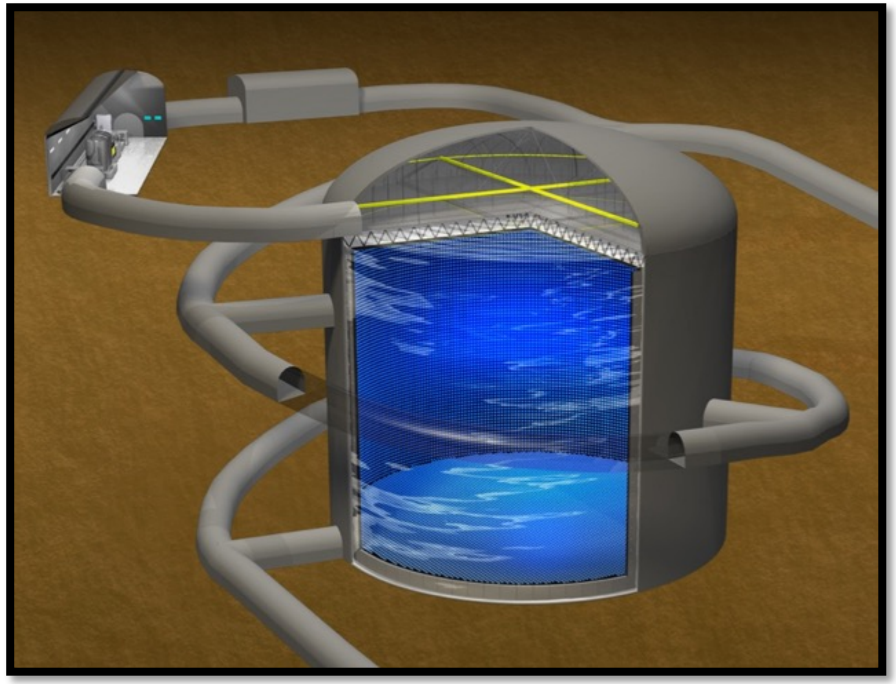
- Median sensitivity is expected to reach ~3σ ($\sin^2\theta_{23}$ = 0.5) by the time Hyper-K starts (assuming $\sin^2\theta_{23}$ = 0.5)

Next-Generation PROSPECTS

Hyper-Kamiokande:

- SK: Atm ν: ~8/day neutron eff. ~20%
- HK: Atm ν: ~80/day neutron eff. >40%
- Nonetheless, statistics are the dominant error for most analyses

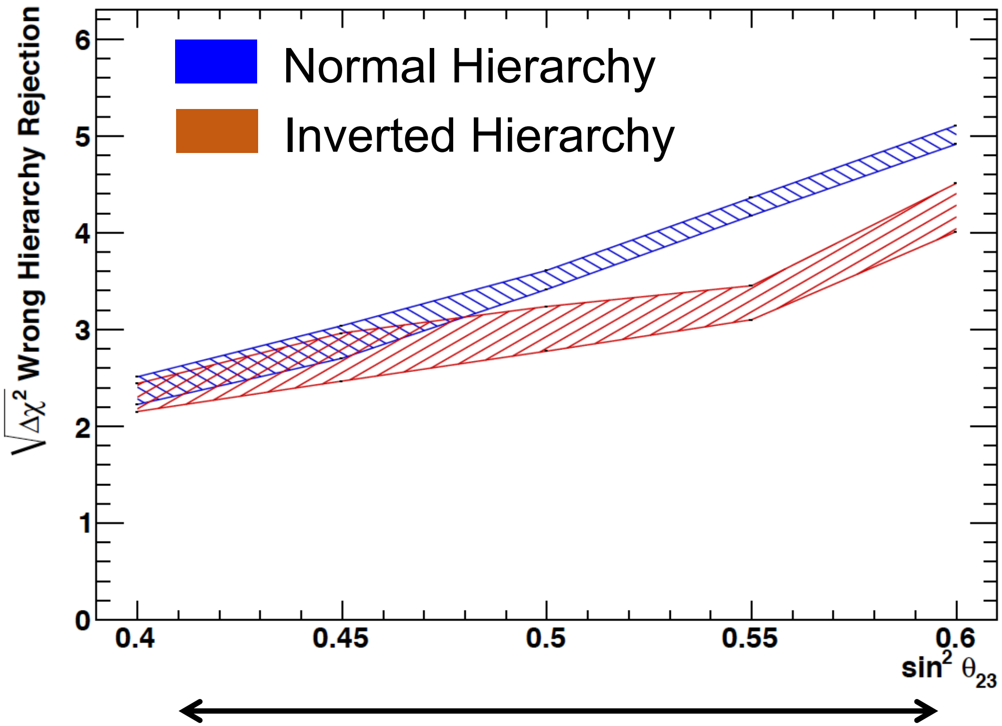
- Additionally Hyper-K analyses use neutrinos from J-PARC beam with effective statistics about 20 times that of T2K

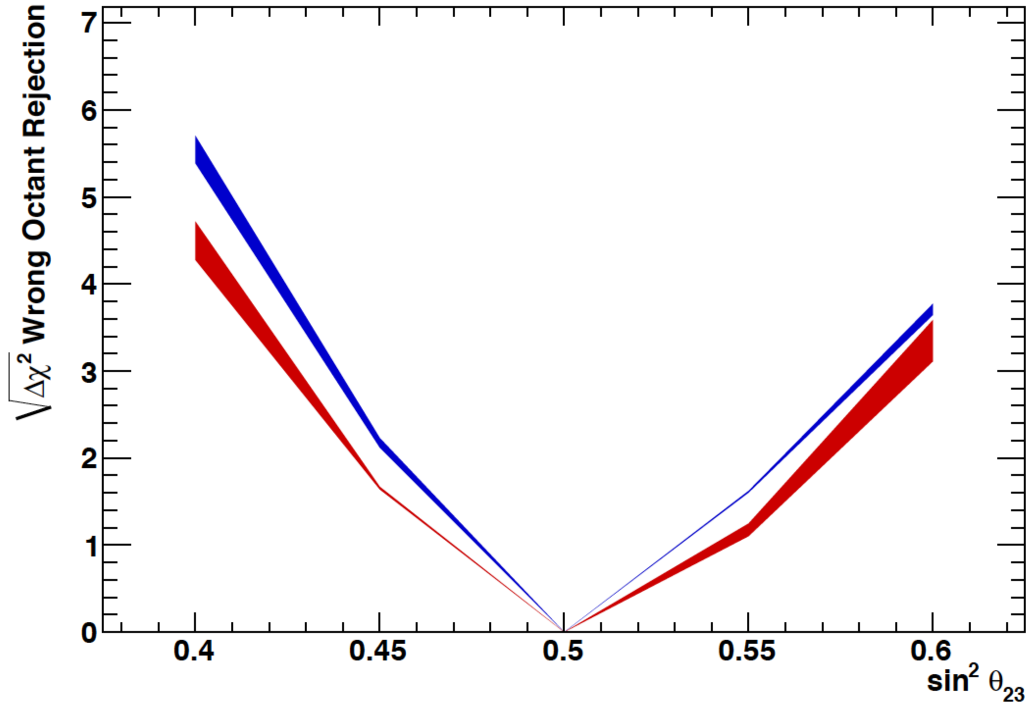


Current Hyper-K analysis uses the same methodology as Super-K above:
HK Studies below assume 1.86 Mton-yr exposure
→ A factor of **~6 times** the current SK data set
→ No improvements in systematic errors assumed

Mass Hierarchy Sensitivity After 10 Years (186 kton)

Atmospheric ν Only



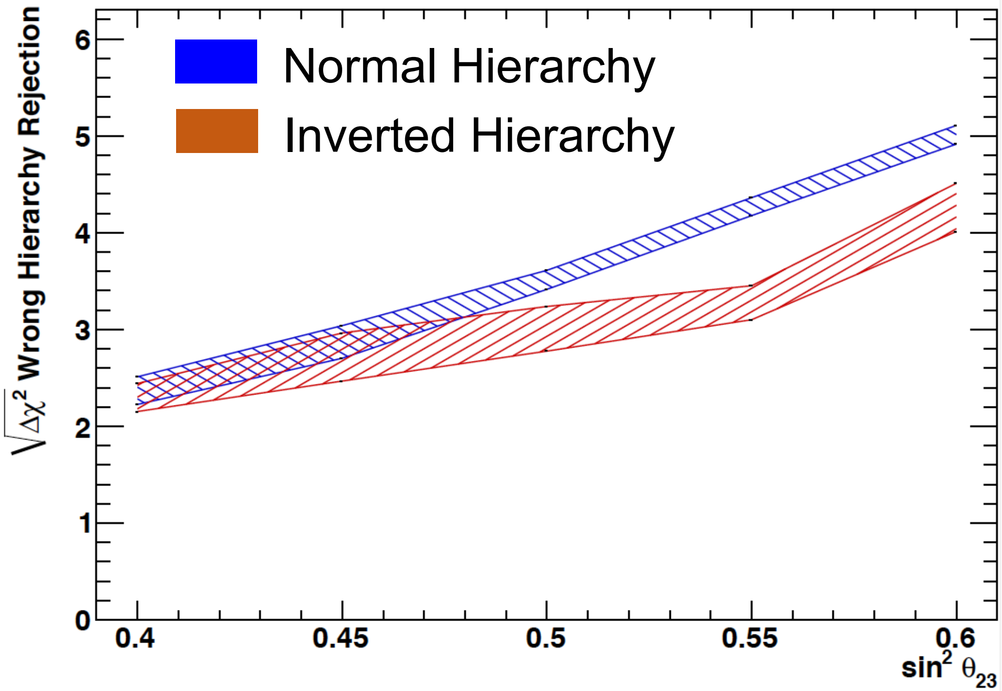


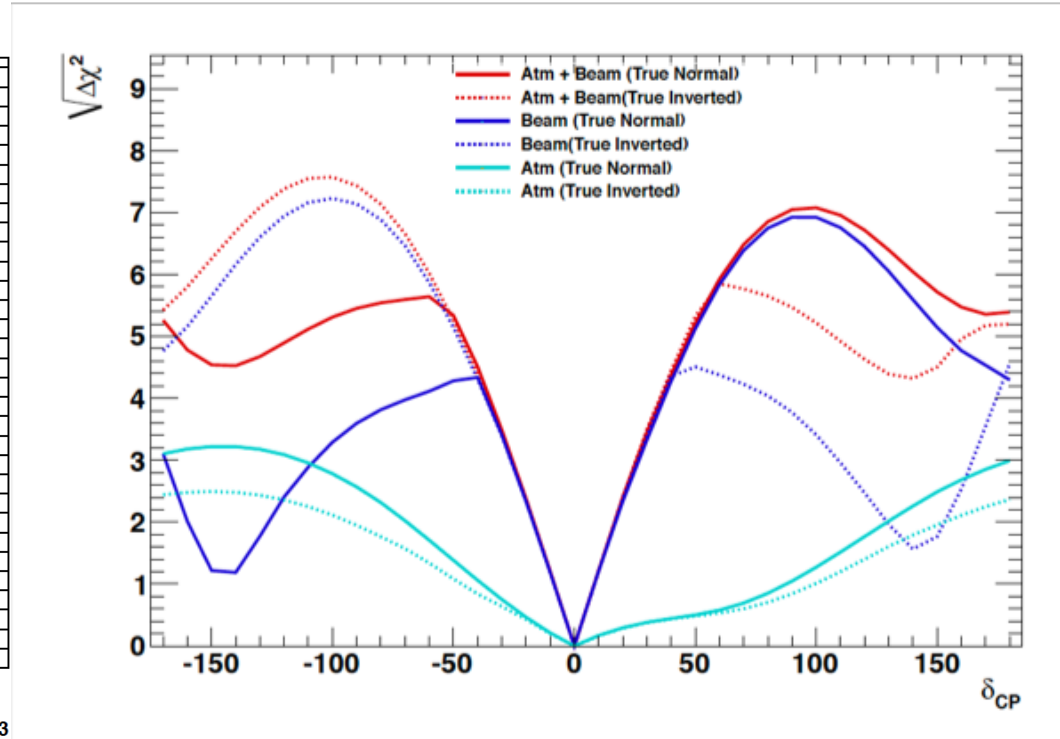
Current Allowed Range

- Mass hierarchy sensitivity $>2\sigma$
  - $>3\sigma$ depending upon hierarchy and true value of $\sin^2\theta_{23}$
- Octant discrimination $>3\sigma$ if $|\theta_{23} - 45| > 4$ degrees
- Error bands denote uncertainty from δ_{CP}
- Precison on δ_{CP} limited by uncertainties

Mass Hierarchy Sensitivity After 10 Years (186 kton)

Atmospheric ν Only





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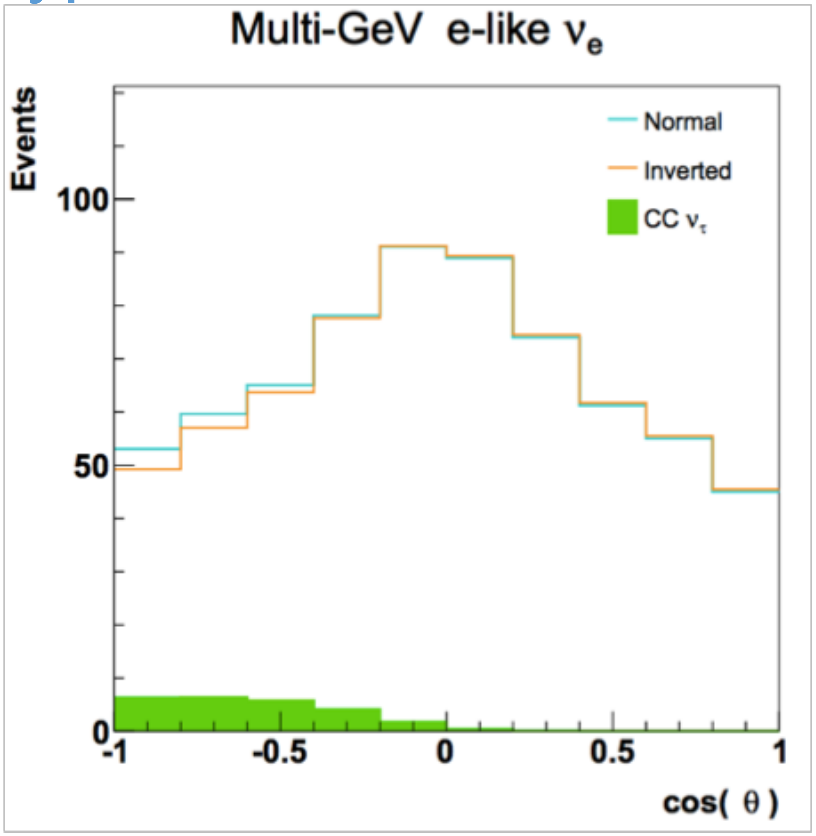
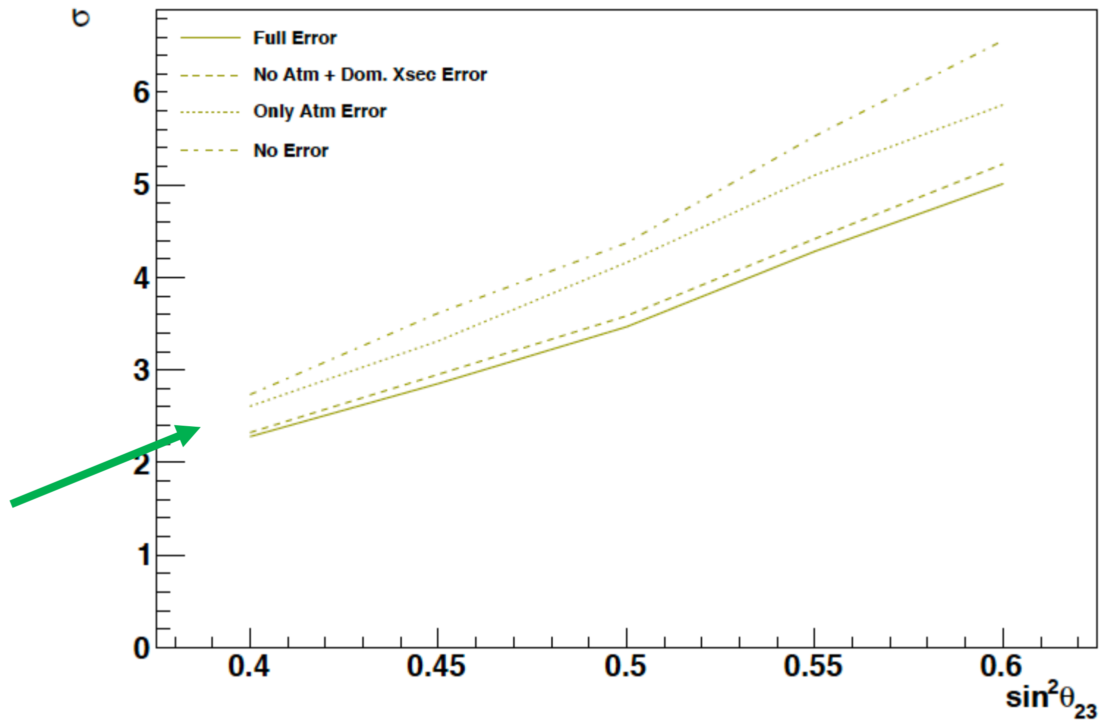
Hyper-Kamiokande : Mass Hierarchy Prospects

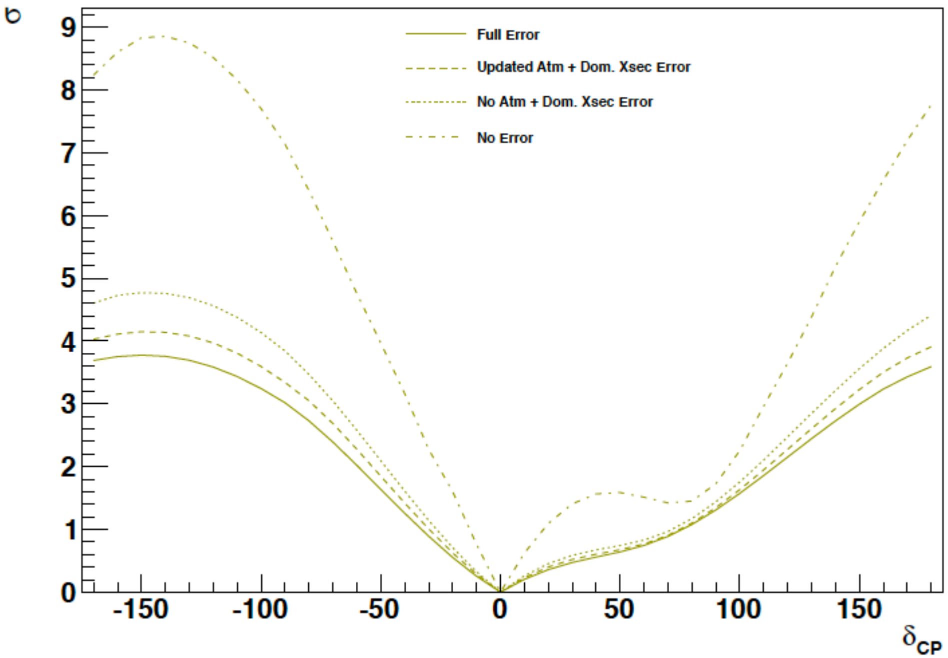




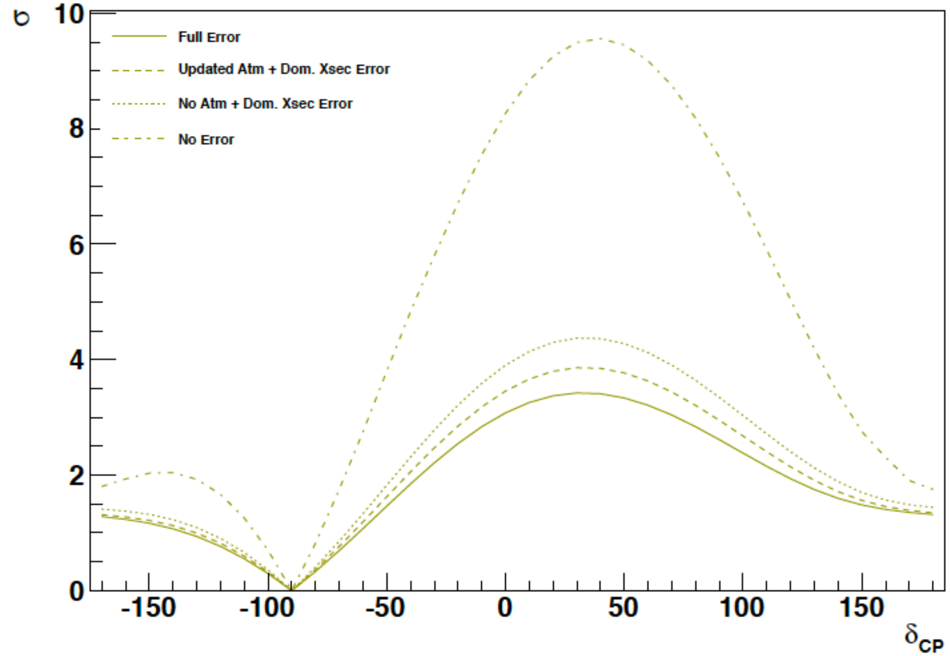
- Tau neutrinos are expected to appear in the same kinematic region as the mass hierarchy signal
- Uncertainty in the tau cross section (currently ~25%) has a large impact

Hyper-Kamiokande : δ_{CP} Measurement

True δ_{CP} = 0



True δ_{CP} = -90



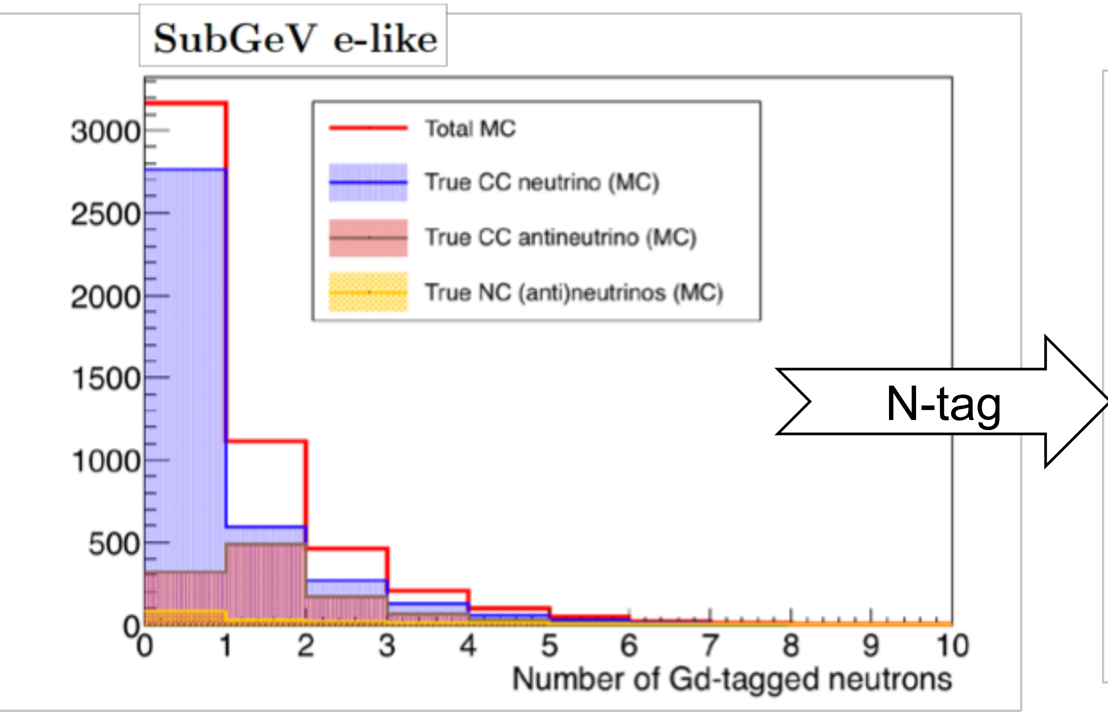
- Plots are for Hyper-K statistics assuming NH
- Legend Explanation:
  - Full error – Current SK errors
  - No Atm. + Dom. X sec – Assume atmospheric flux and dominant xsec errors are zero
  - Updated - Assume 50% reduction in uncertainty
- Impact of flux uncertainties is equal to that from all other sources
  - → Improved flux calculations as well as reduced detector and cross section systematics will have a large impact on Hyper-K's measurements

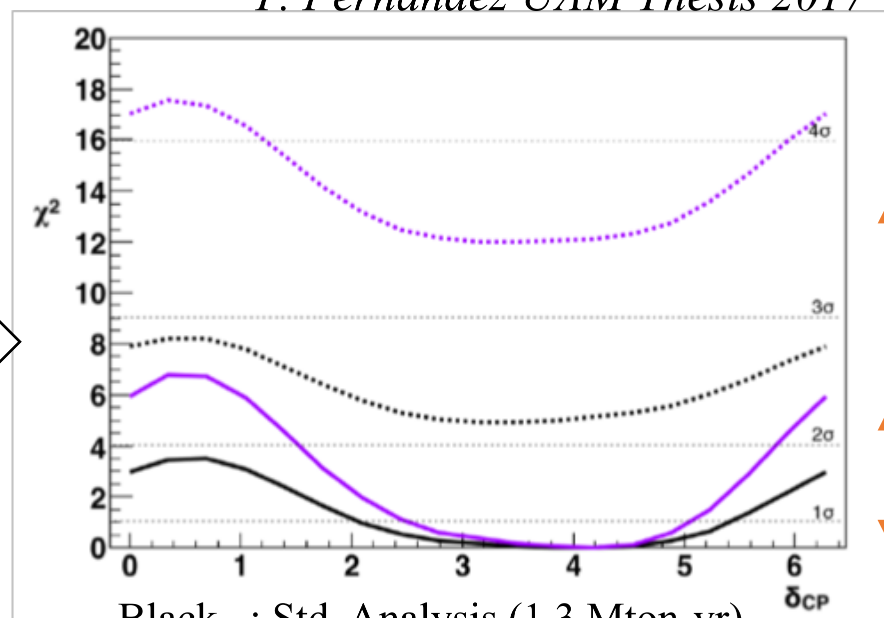
Neutron Tagging: Beneficial for both SK and HK

- SK-Gd will enable high-efficiency neutron tagging
  - Allows for separation of atmospheric neutrinos and antineutrinos and all energies

- Low energy separation improves CP measurement by provided enriched an enriched antineutrino-like sample (with correspondingly better neutrino direction resolution)
- High energy separation will improve hierarchy discrimination
- Studies to test these ideas are underway in SK <u>now</u>

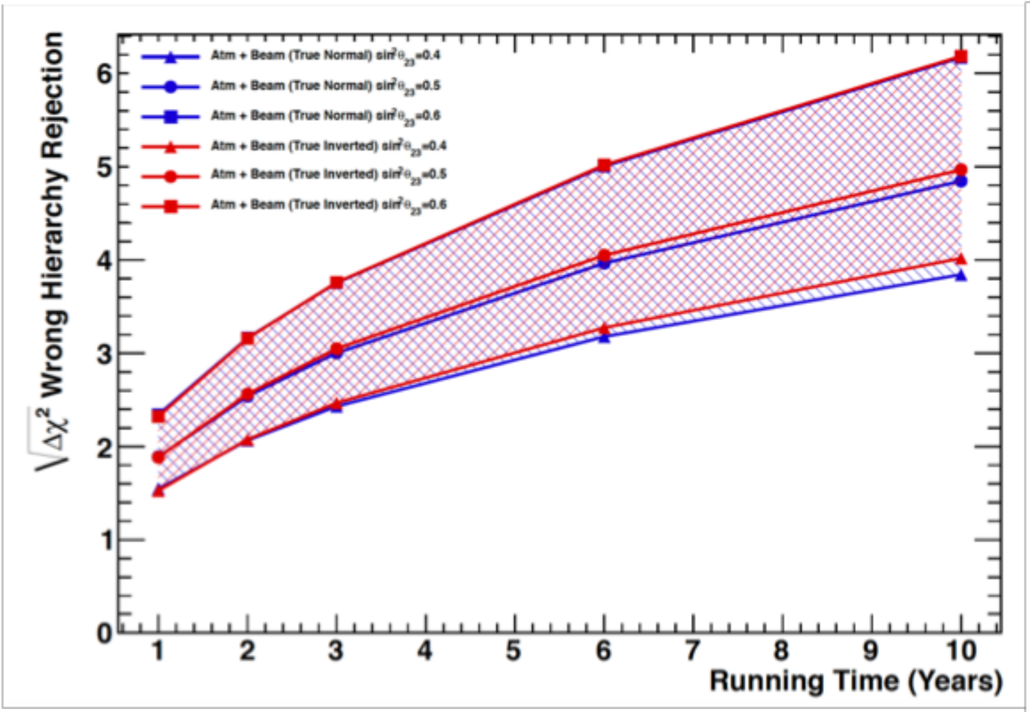
MC Study (no beam ν)
P. Fernandez UAM Thesis 2017

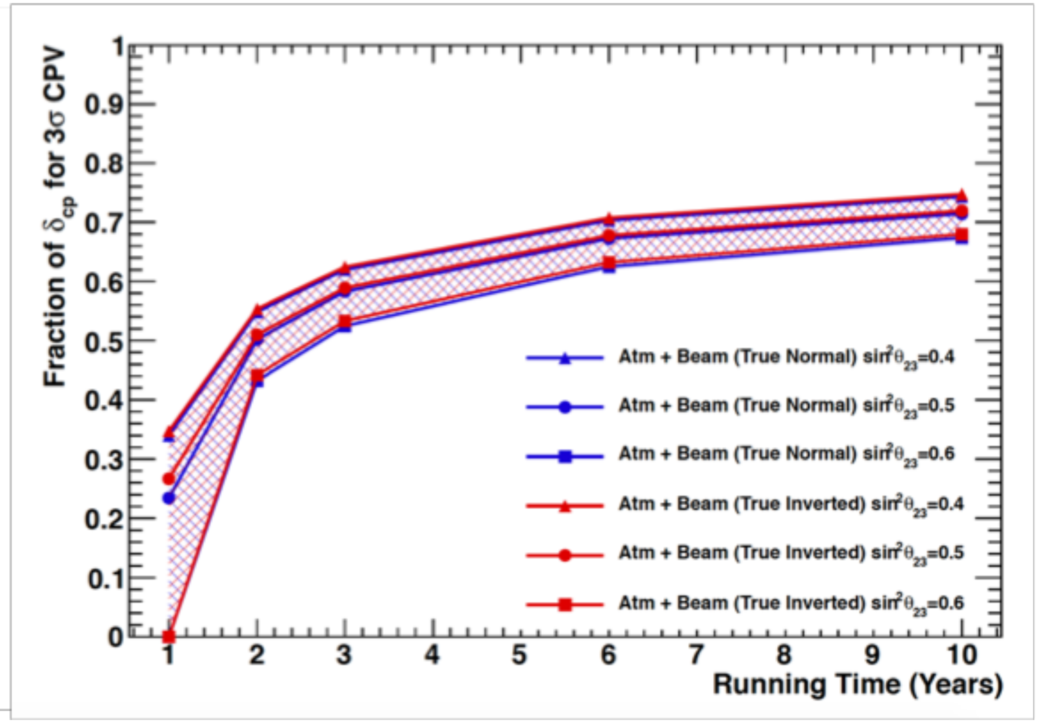




Black : Std. Analysis (1.3 Mton-yr)
Purple : With 70% eff. Neutron tagging
Solid : Normal Hierarchy
Dashed : Inverted Hierarchy

Hyper-K : Beam and Atmospheric Neutrino





- Sensitivity to matter effects (mass hierarchy) increased with improved constraint on atmospheric mixing parameters
- Measurement of CP phase is dominated by accelerator measurement, but parameter degeneracies are broken by atmospheric component, resulting in better sensitivity faster

Summary

- Atmospheric neutrino studies at Super-K presently indicate a weak preference for the normal hierarchy
  - > 90% C.L. including constraints from external experiments (328 kton-yr exposure)
- A similarly weak preference for $\delta_{CP} \sim 3\pi/2$ is found
- Tau neutrinos observed at 4.6σ

- An improved reconstruction algorithm in SK-IV has enabled use of more of the detector target volume
  - 253 kton-year exposure yields similar hierarchy and CP preferences, though weaker
  - Expect to achieve 3σ hierarchy sensitivity in 10 years by applying to full and future data sets

- At Hyper-K mass hierarchy sensitivity with atmospheric neutrinos alone exceeds 2σ for pessimistic parameter assumptions, but reaches 4σ in combination with the beam

- CP sensitivity with atmospheric neutrinos is limited, but complementary

- Improvements in the understanding of the flux, detector, and cross sections important for making the most of this future data set

Backups