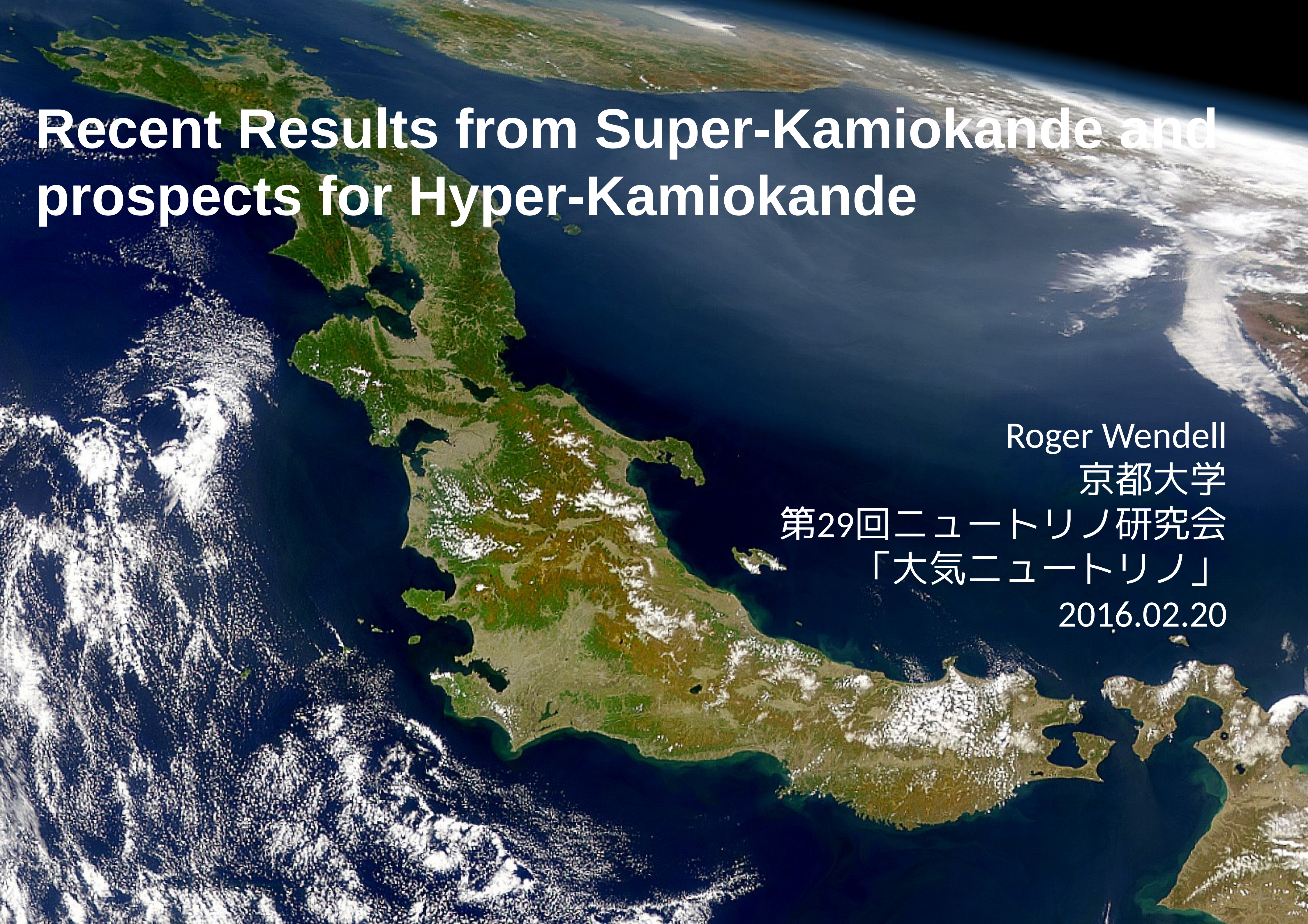


Recent Results from Super-Kamiokande and prospects for Hyper-Kamiokande

Roger Wendell
京都大学

第29回ニュートリノ研究会
「大気ニュートリノ」
2016.02.20

Introduction

- To confirm $\nu\mu \leftrightarrow \nu\tau$ oscillations with Super-K (see previous talk:
  - Rule out disappearence into ν_{sterile} √
  - Oscillatory signature √
  - Appearance of $\nu\tau$ events √
- At the same time several other experiments observed oscillations, in various energy regimes and channels
  - K2K, T2K, MINOS
  - SNO, Super-K (solar), Borexino
  - KamLAND, Daya Bay, RENO, Double Chooz
- We now know that all mixing angles are non-zero
  - Lots left for atmospheric neutrinos:

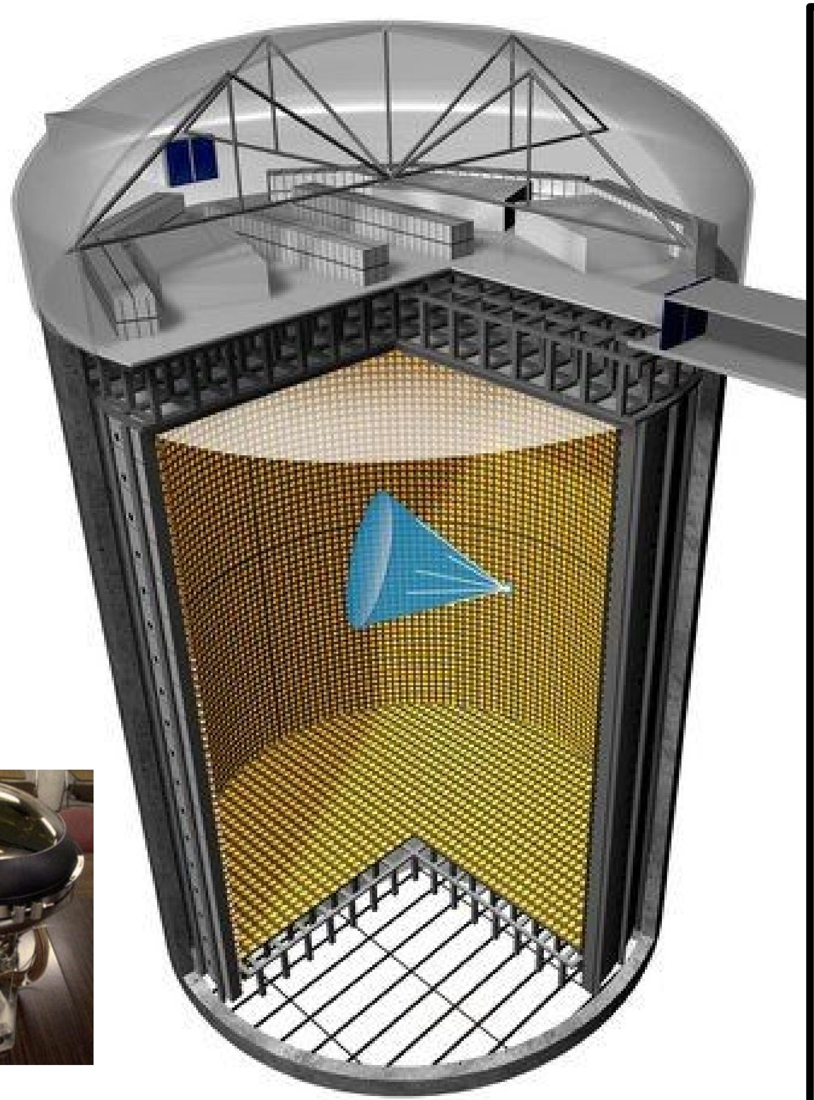
This Talk

- Standard Oscillations
  - Mass Hieararchy, δ_{cp}, θ_{23} octant

Matter effects are key

- Exotic oscillations
  - Search for $\Delta m_s \sim eV^2$ scale sterile neutrinos
  - Search for Lorentz invariance violation
- The near and far future

Super-Kamiokande: Introduction



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

- 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
- Neutrino direction and energy are unknown
  - Hard to reconstruct directly
- Excellent PID between showering (e-like) and non-showering (m-like)
  - ~ 1% MIS ID at 1 GeV

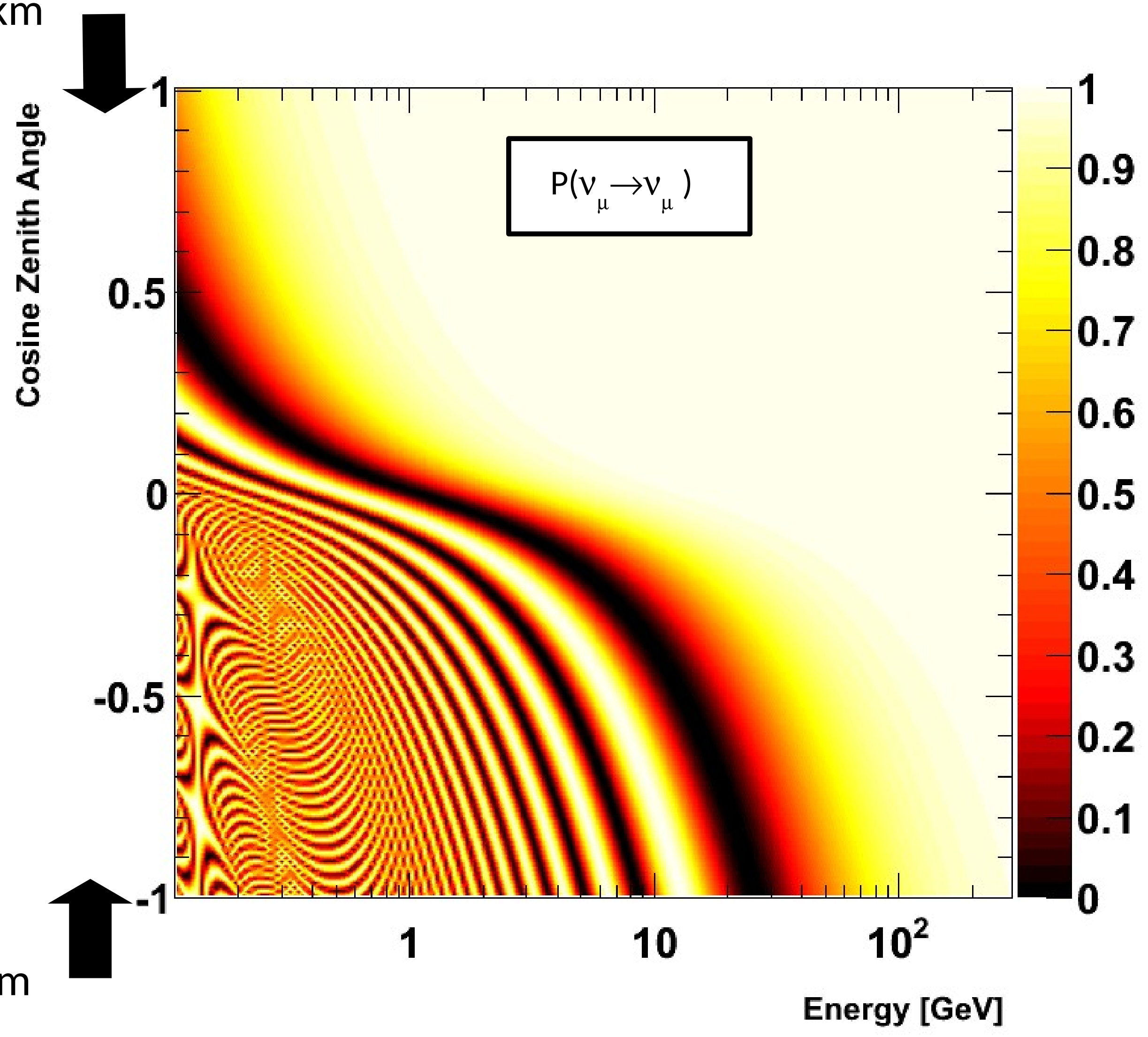
- As of Today: 4972 days of data
  - 51,000 Events
- Multipurpose machine
  - Solar and Supernova Neutrinos
  - Atmospheric Neutrinos (this talk)
  - Nucleon Decay
  - Far detector for T2K

The State of the Art

Up Until 2012

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

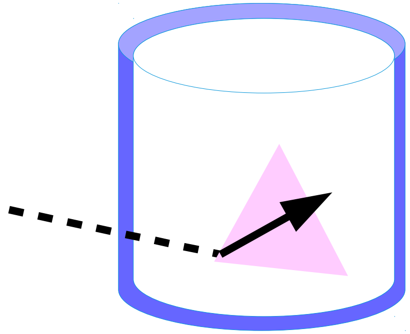
~10 km



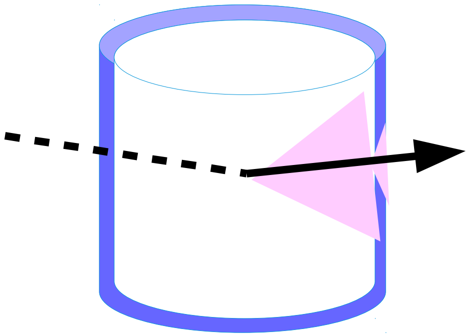
~10,000 km

Super-K Atmospheric ν Analysis Samples

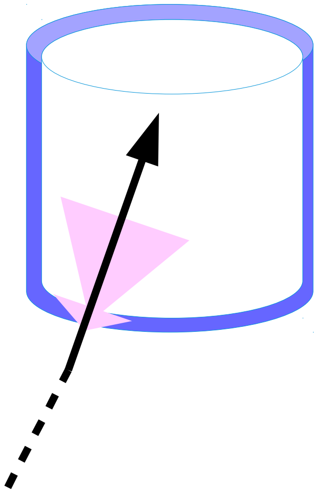
Fully Contained (FC)

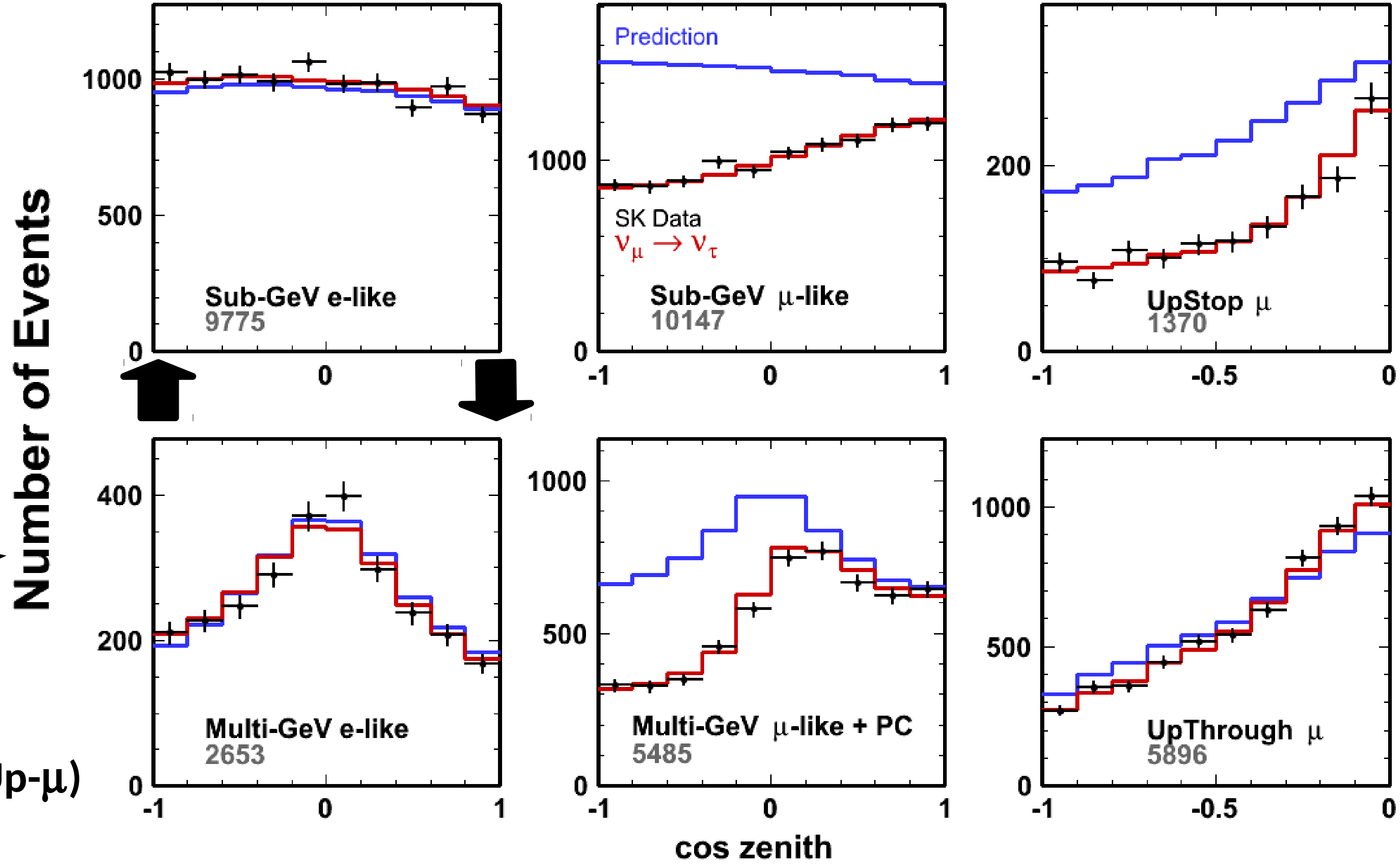


Partially Contained (PC)



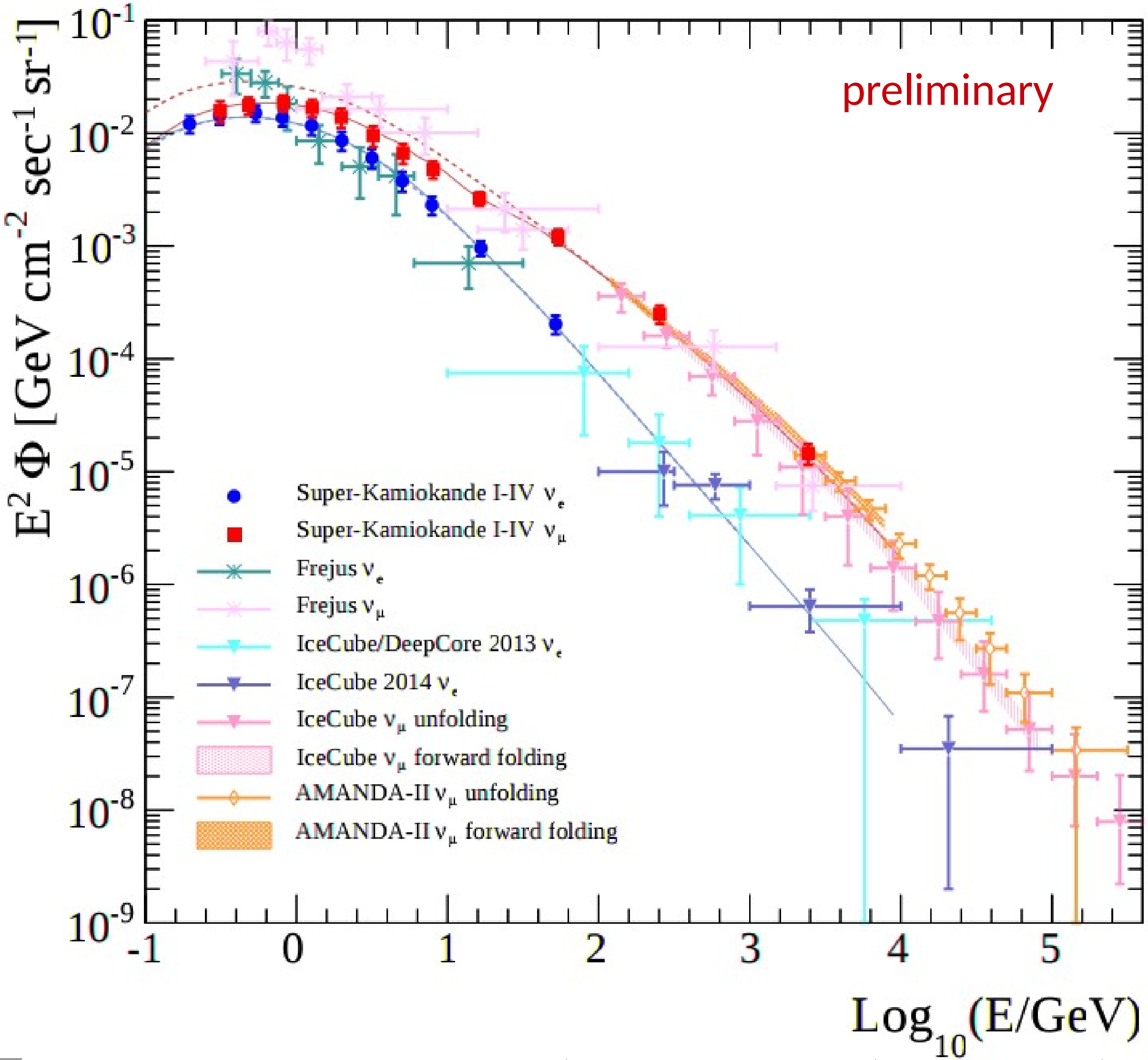
Upward-going Muons (Up-μ)





- In total **19** analysis samples
  - 51,000 Events (x10 more than in 1998)
- Dominated by ν_μ->ν_τ oscillations
- We are now interested in subdominant contributions to this picture : three-flavor effects, Sterile Neutrinos, LIV, etc.

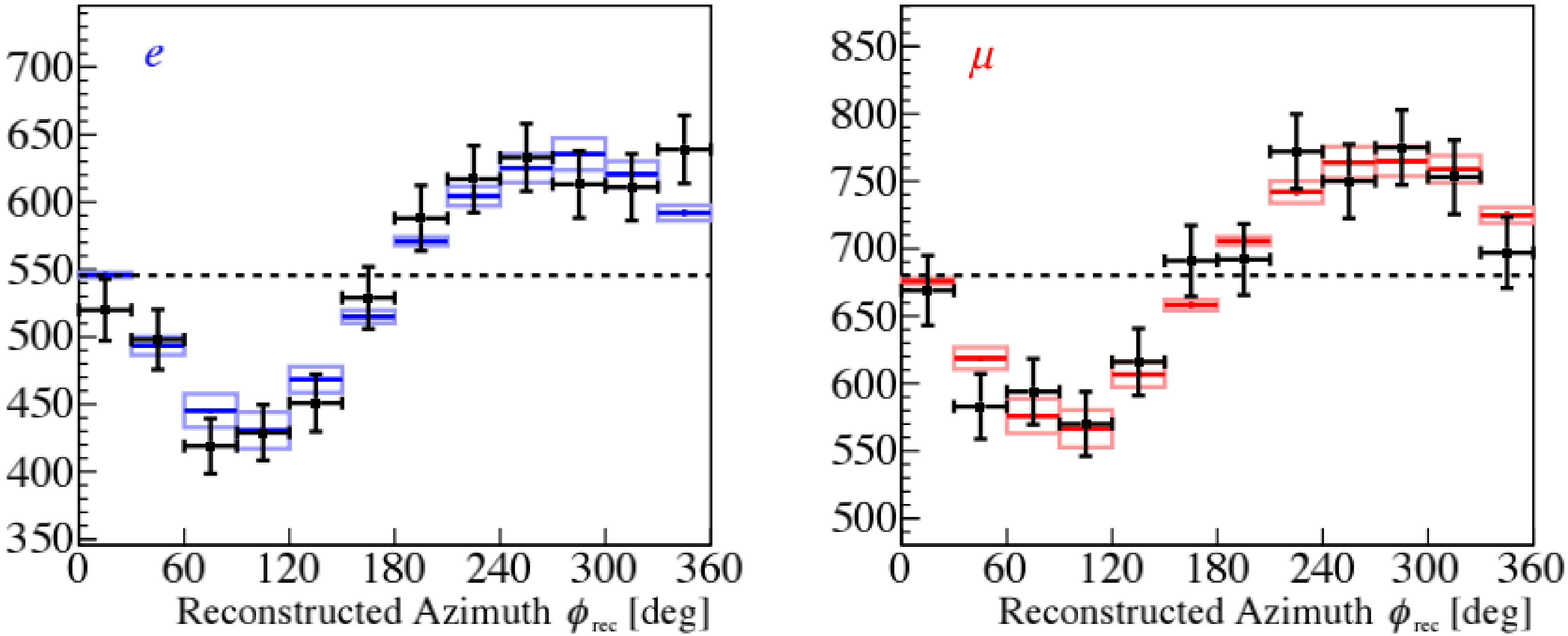
Atmospheric ν Flux Measurement



- Measurement of νe (E < 100 GeV) and νμ (E< 1 TeV) fluxes
  - Good agreement with current models (Honda et. al 2011 shown)
- Dipole asymmetry now confirmed at seen at 6.0σ (μ-like) and 8.0σ (e-like)

Atmospheric ν Flux Measurement

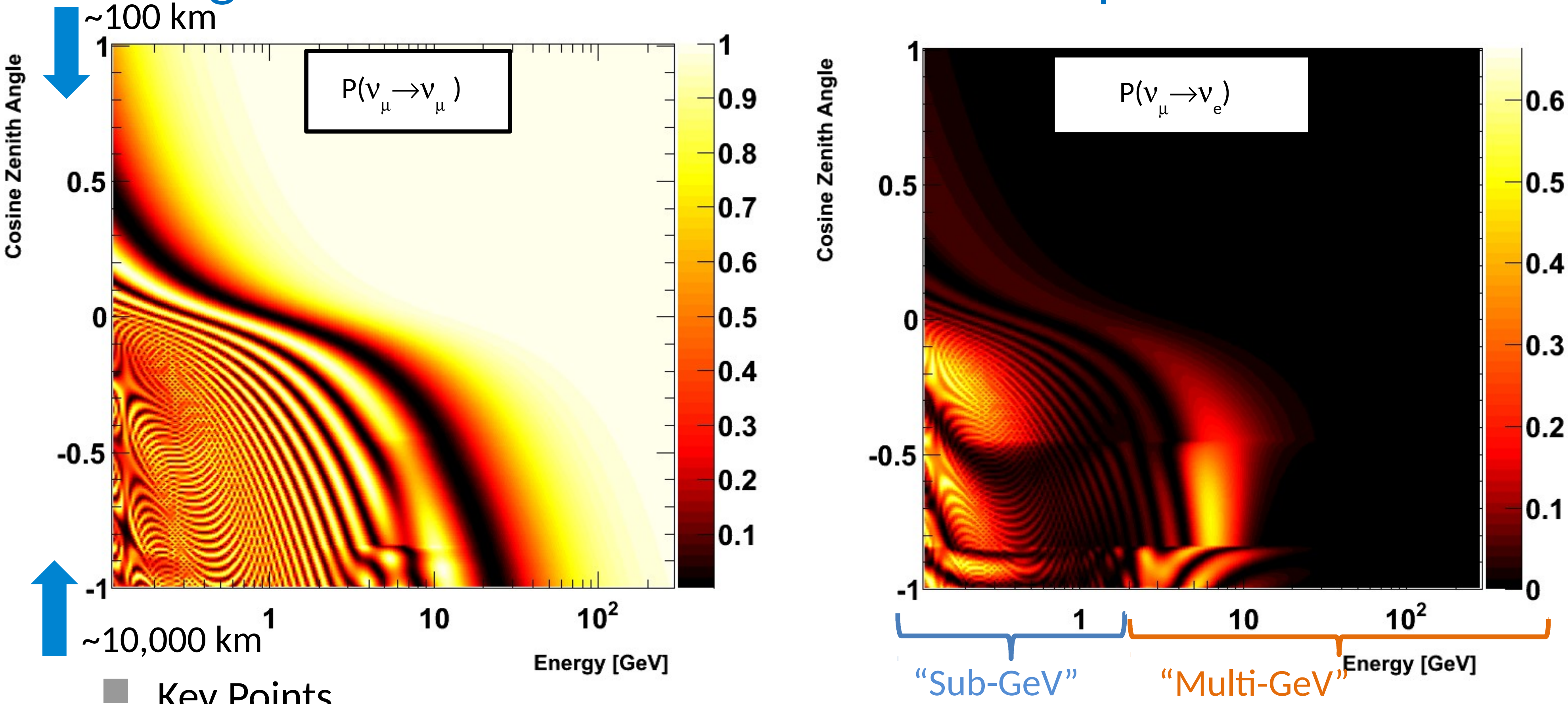
preliminary



S W N E S-going

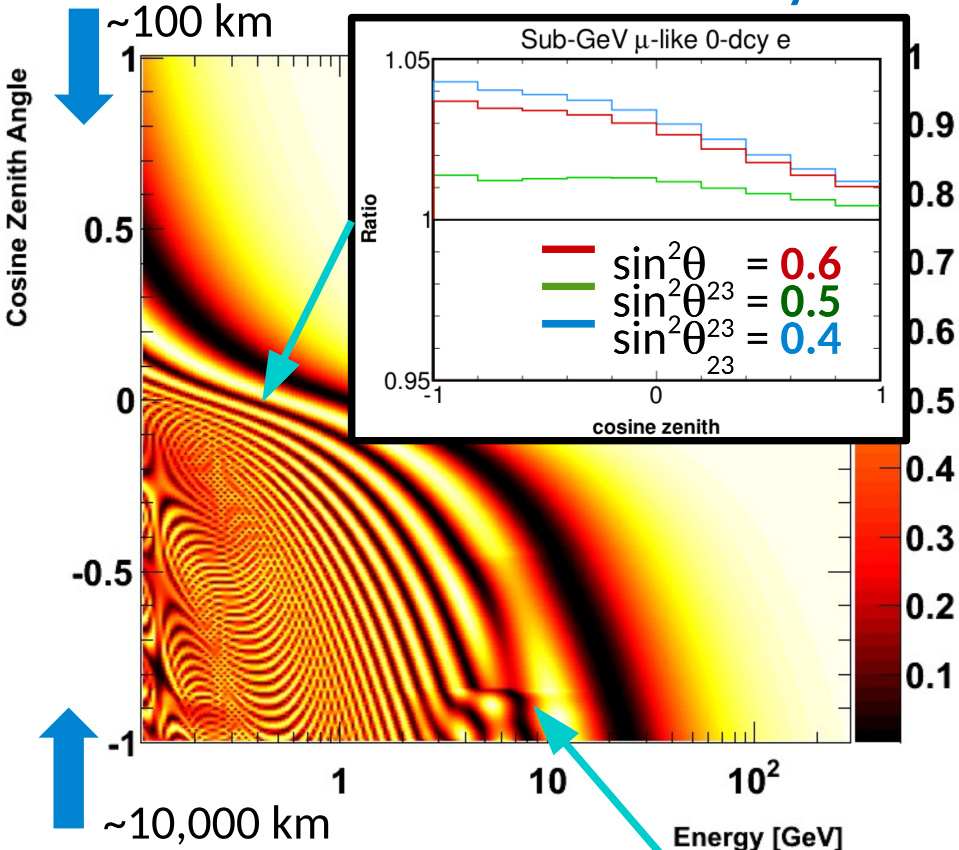
- Measurement of νe (E < 100 GeV) and νμ (E< 1 TeV) fluxes
  - Good agreement with current models (Honda et. al 2011 shown)
- Dipole asymmetry now confirmed at seen at 6.0σ (μ-like) and 8.0σ (e-like)

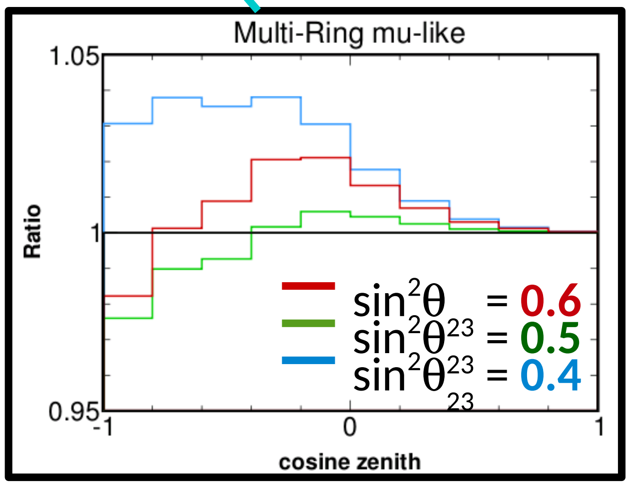
Searching for Three-Flavor Effects: Oscillation probabilities

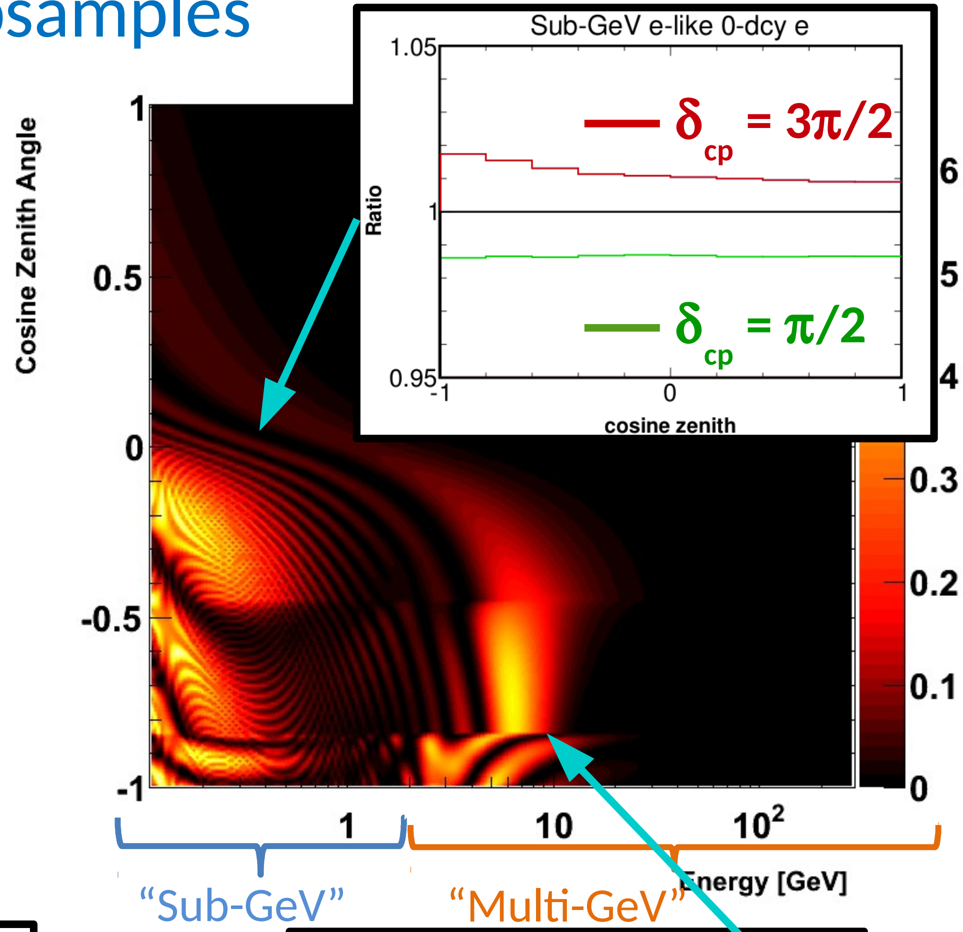


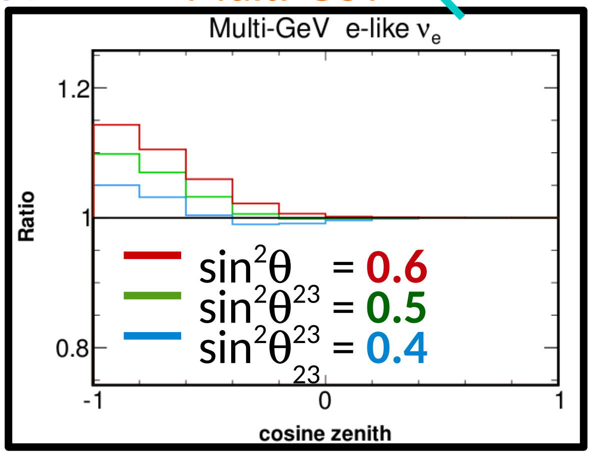
- Key Points
  - No $\nu_\mu \rightarrow \nu_e$ Appearance above ~20 GeV,
  - Resonant oscillations between 2-10 GeV (for ν or $\bar{\nu}$ depending upon MH)
  - No oscillations above 200 GeV
  - No oscillations from downward-going neutrinos above ~5 GeV
  - Expect effects in most analysis samples, largest in upward-going ν_e
  - Sensitive to most of the MNS mixing parameters

Oscillation Effects on Analysis Subsamples







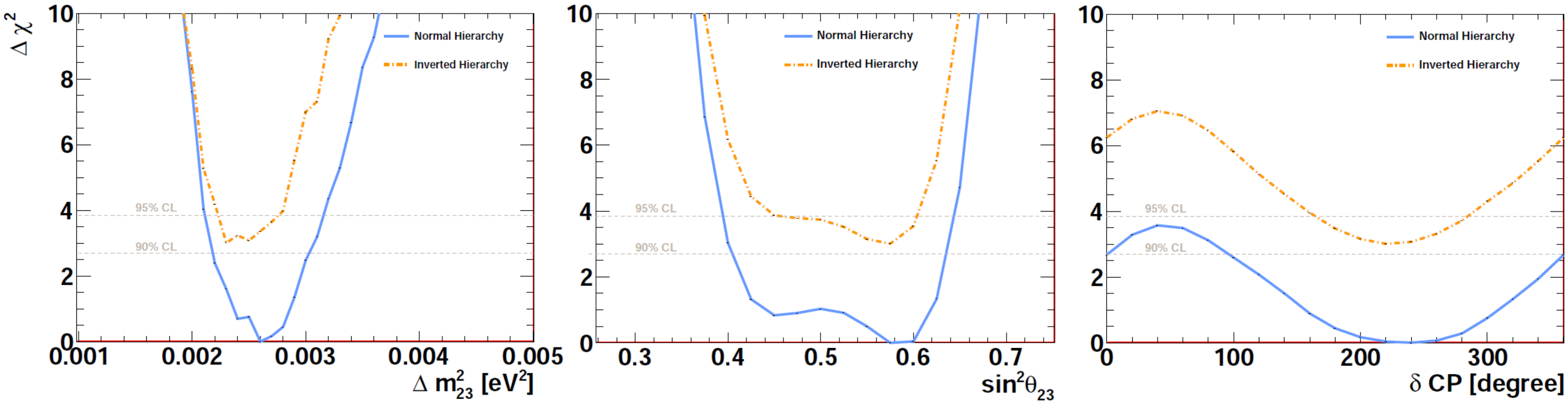


Ratio to two-flavor oscillations

Appearance effects are halved in the IH

θ_{13} Fixed Analysis (NH+IH) SK Only

Preliminary

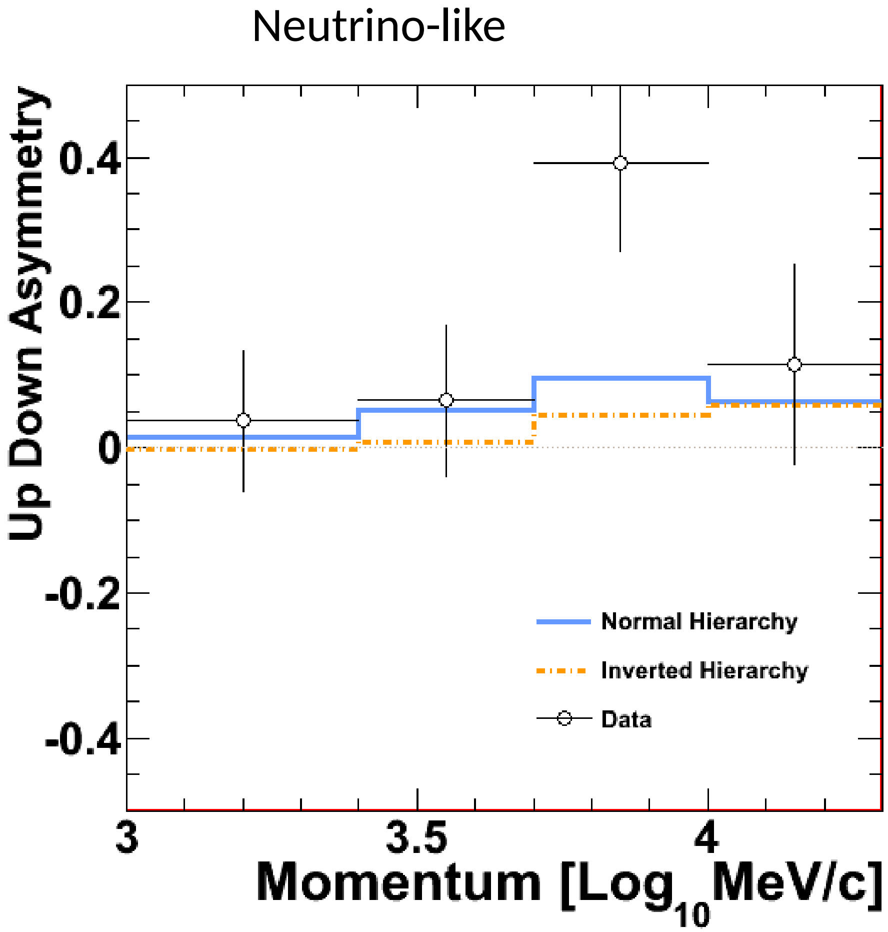


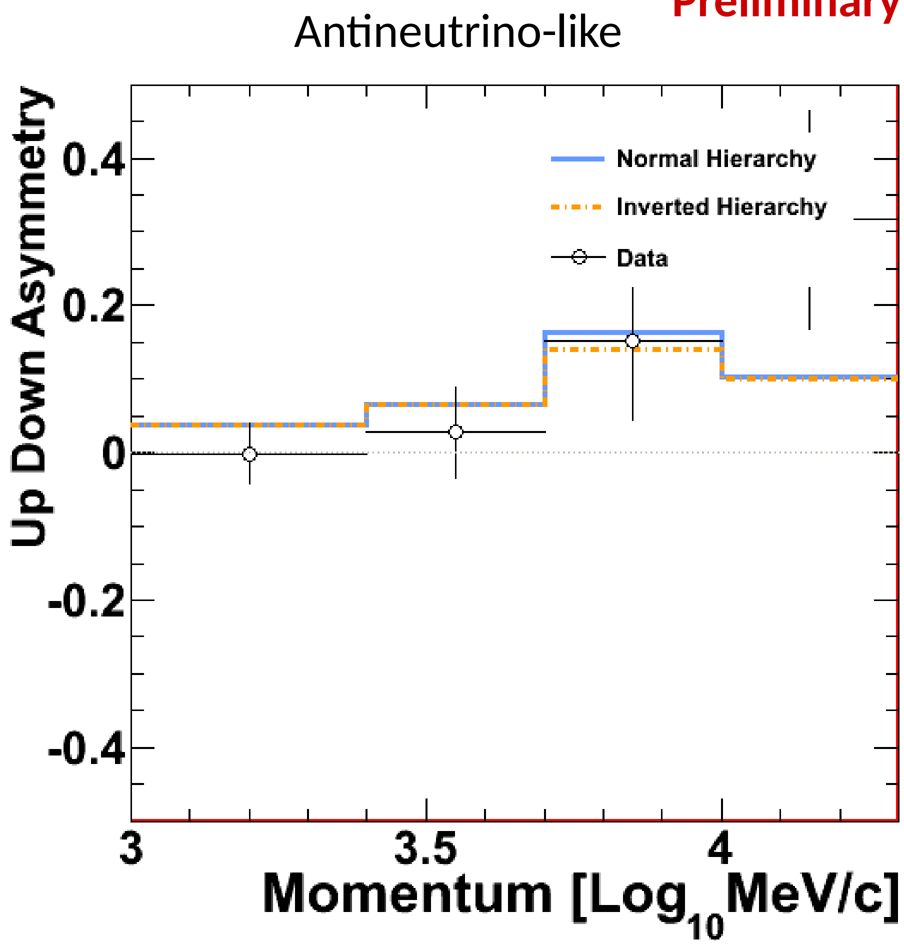
Fit (517 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	582.4	0.0238	4.19	0.575	2.6
SK (IH)	585.4	0.0238	3.84	0.575	2.3

- Offset in these curves shows the difference in the hierarchies
- Normal hierarchy favored at: $\boxed{\chi^2_{NH} - \chi^2_{IH} = -3.0}$, not significant
  - Preference for matter over vacuum oscillations at ~1 σ (82% C.L.)

Single-Ring E-like neutrino-like and antineutrino-like

Preliminary





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- Normal hierarchy favored at: $\boxed{\chi^2_{NH} - \chi^2_{IH} = -3.0}$, not significant
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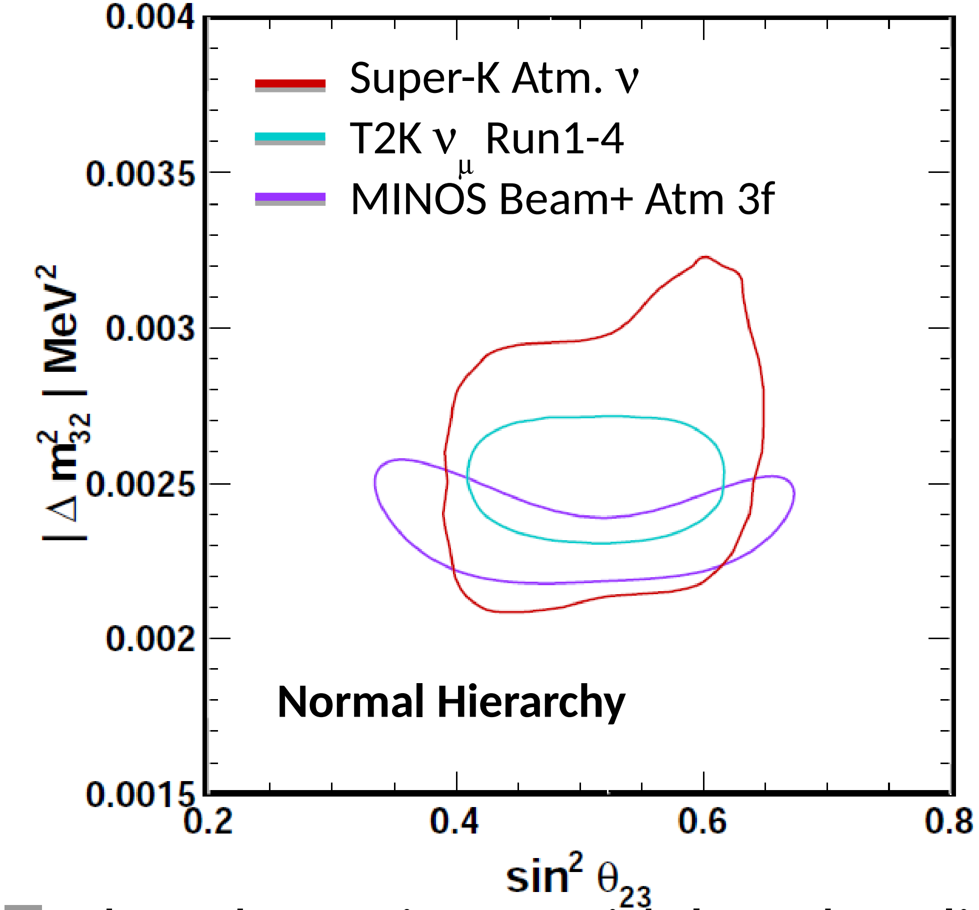
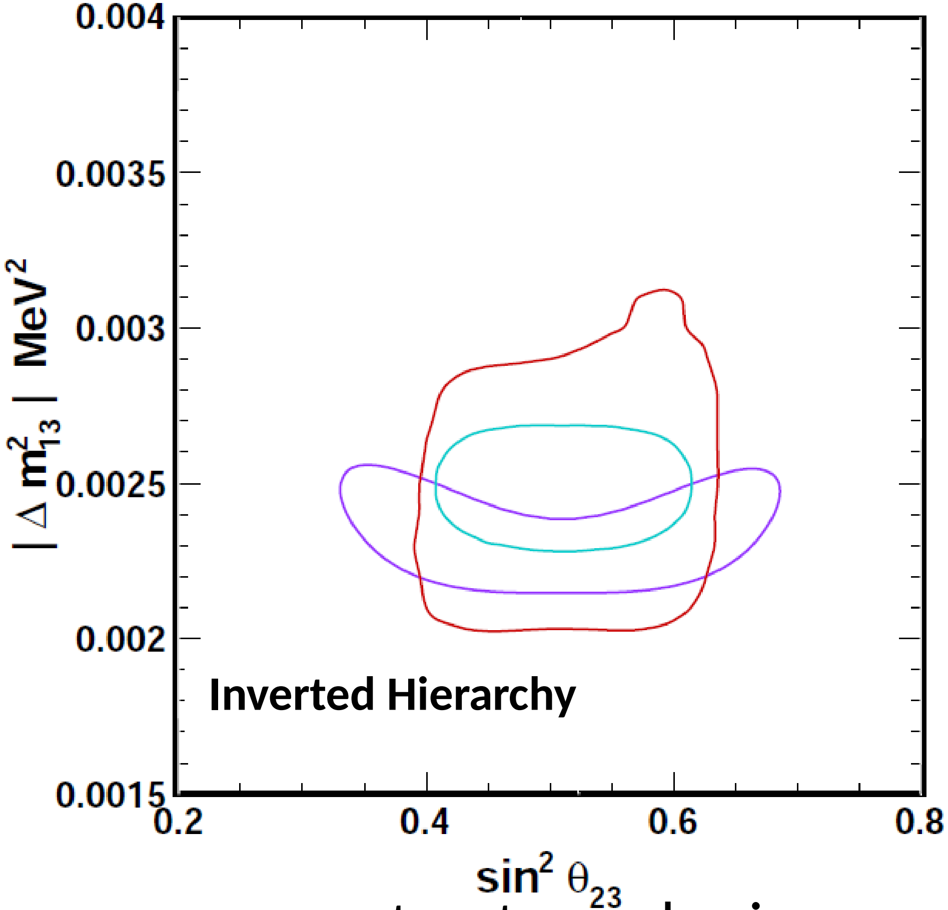
Comparison with Official Results from T2K and MINOS

Preliminary

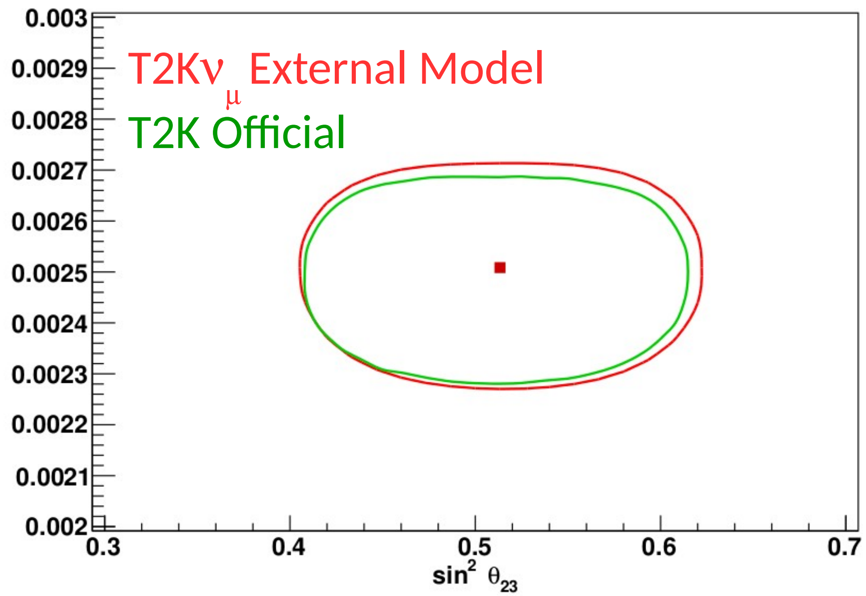




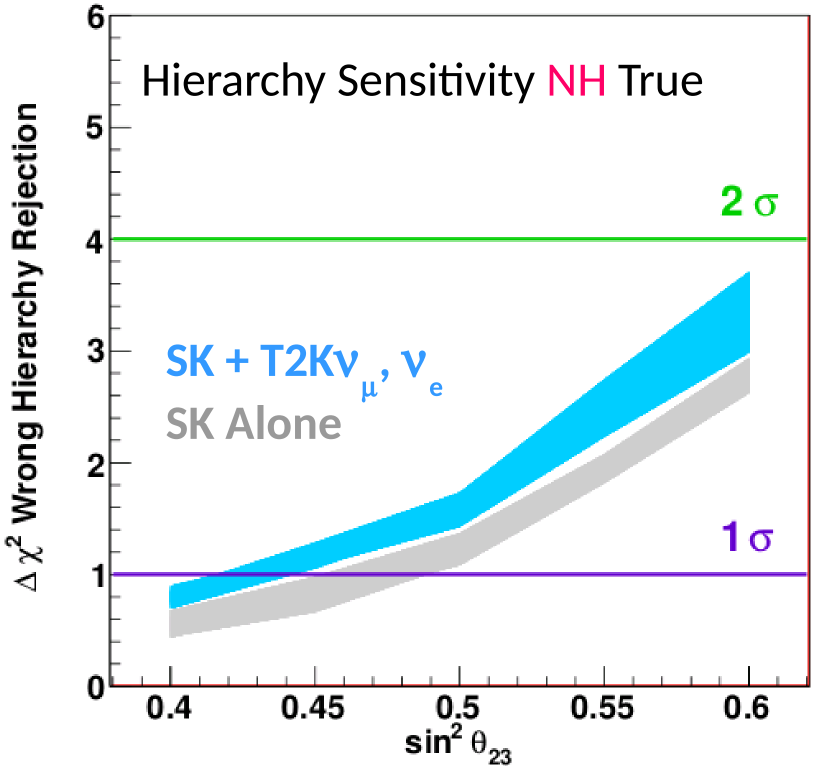
- Though consistent with long-baseline measurements, atmospheric neutrinos allow more of the mixing parameter space
- SK's sensitivity can be improved by incorporating constraints from these measurements

Introduction of External Constraint

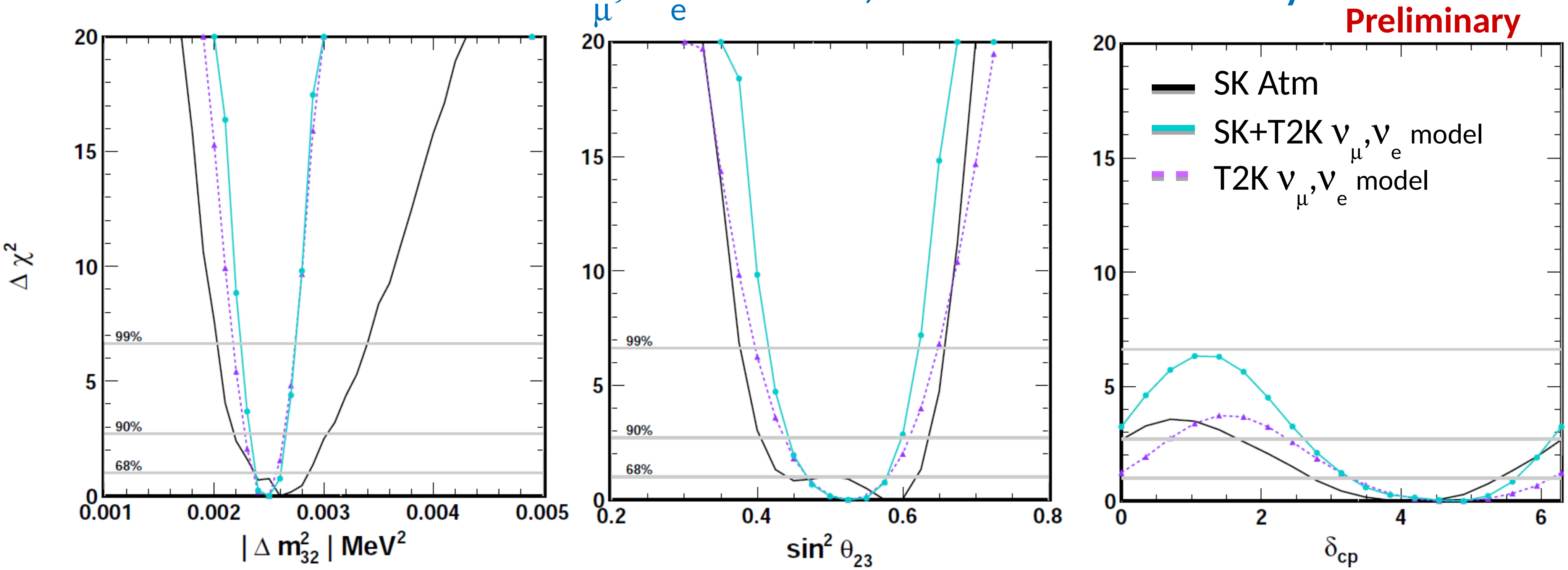
- Restricting the allowed values of Δm^2 and $\sin^2\theta_{23}$ available to the atmospheric neutrino fit can help improve sensitivity to the mass hierarchy
  - Include these constraints as external data sets in the SK fit



- Goal: Fit the T2K ν_μ and ν_e data sets with SK
  - Same detector, generator and reconstruction: systematic error correlations incorporated easily
  - Build external models by reweighting atmospheric neutrino MC to T2K beam
  - Fit is based on **publicly available** T2K information and results
    - Simulate T2K using SK tools
    - (not a joint result of the T2K and SK collaborations)



Theta13 **Fixed** SK + T2K ν_μ, ν_e Model, Normal Hierarchy



Fit (585 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK + T2K (NH)	651.5	0.0238	4.89	0.525	2.5
SK + T2K (IH)	654.7	0.0238	4.19	0.550	2.4

- $\chi^2_{NH} - \chi^2_{IH}$ = **-3.2** (-3.0 SK only)
- CP Conservation ($\sin\delta_{cp}$ = 0) allowed at (at least) 90% C.L. for both hierarchies

Exotic Types of Oscillation

- Because the standard PMNs oscillation parameters are now known very well, its possible to use atmospheric neutrinos to search for other oscillations with more exotic origins

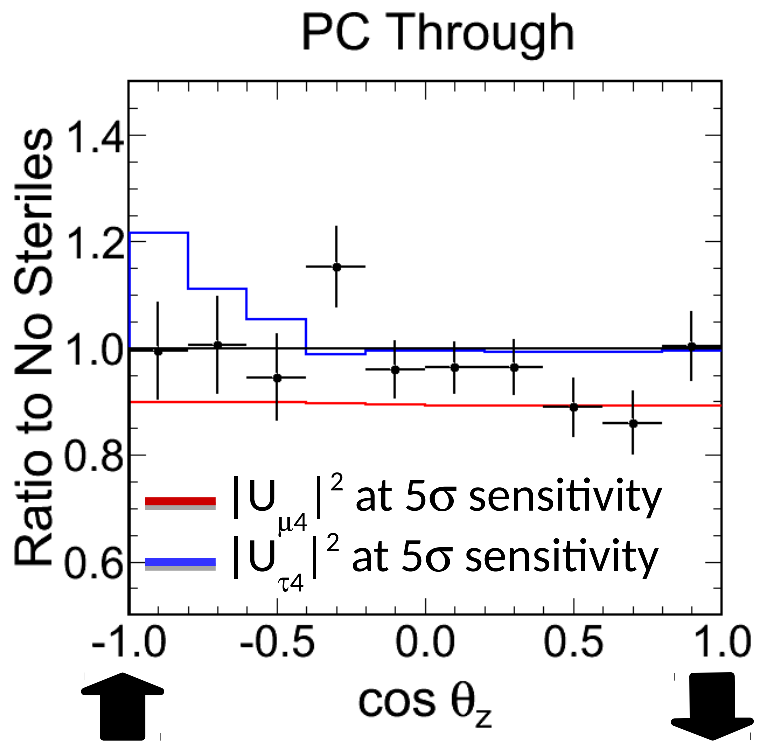
Sterile Neutrino Oscillations in Atmospheric Neutrinos

- Sterile Neutrino searches at SK are independent of the sterile Δm^2 and the number sterile neutrinos
  - 3+1 and 3+N models have the same signatures in atmospheric neutrinos
  - For $\Delta m_s^2 \sim 1$ eV^2 oscillations appear fast:

    $< \sin^2 \Delta m^2 L/E > \sim 0.5$

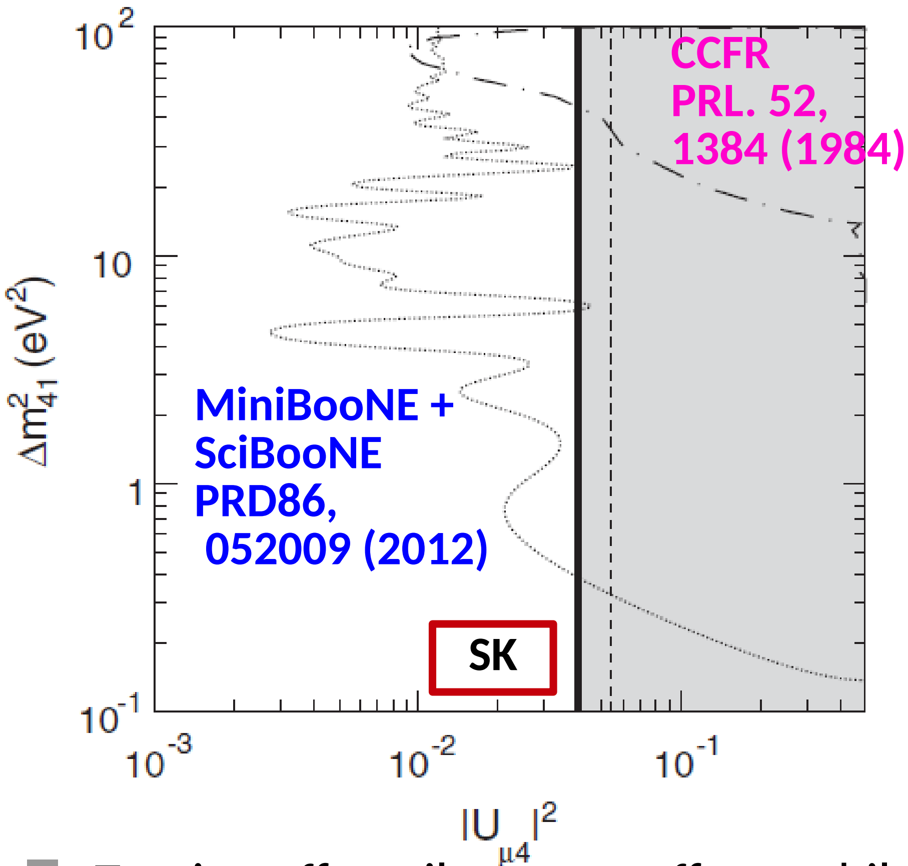
$$U = \begin{array}{c} \begin{array}{ccccc} & \text{MNS} & & \text{Sterile} & \end{array} \\ \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} &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

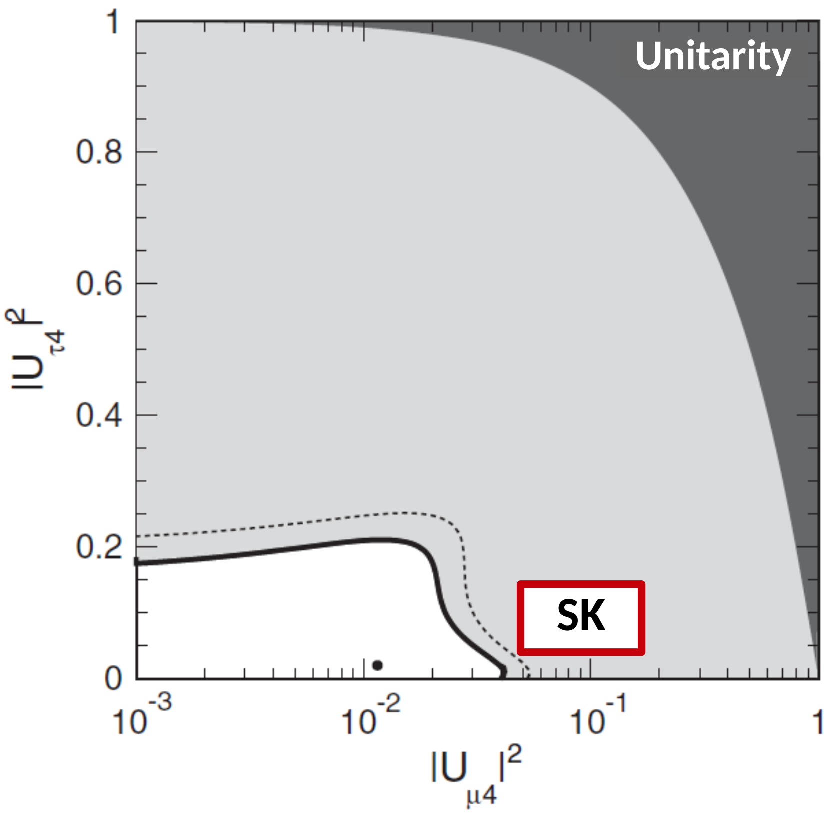
- $| U_{\mu 4} |^2$
  - Induces a decrease in event rate of μ-like data of all energies and zenith angles
- $| U_{\tau 4} |^2$
  - Shape distortion of angular distribution of higher energy μ-like data



Sterile Oscillations Results

PRD.91.052019 (2015)





- Turning off sterile matter effects while preserving standard three-flavor oscillations provides a pure measurement of $|U_{\mu 4}|^2$
- Using sterile matter effects, but decoupling ν_e oscillations provides a joint measurement of $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$, with a slightly biased estimate of the former
- Using SK-I+II+III+IV data (4438 days)
  $|U_{\mu 4}|^2 < 0.041$ at 90% C.L. $|U_{\tau 4}|^2 < 0.18$ at 90% C.L.

Tests of Lorentz Invariance

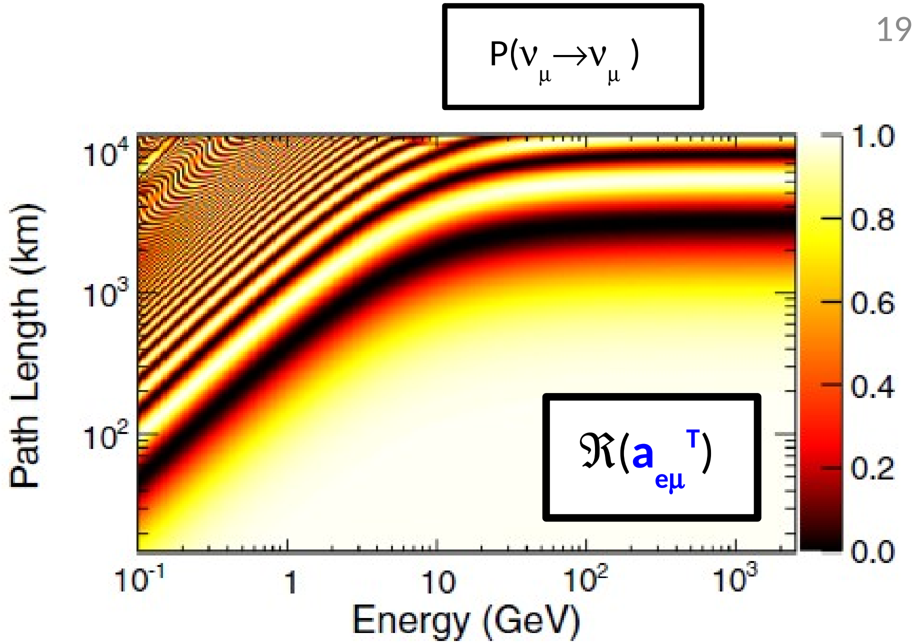
$$H = UMU^\dagger + V_e + H_{LV}$$

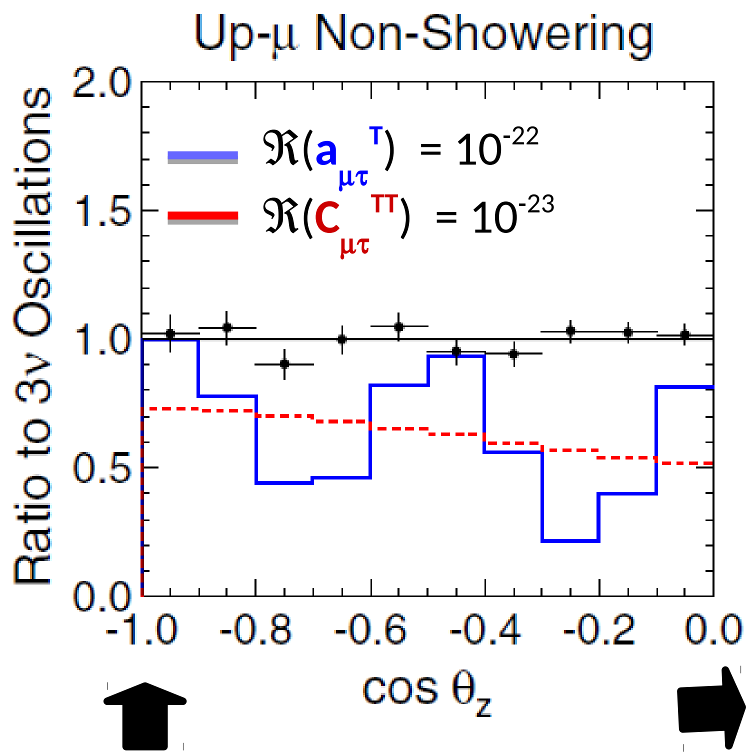
$$\pm \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} - E \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$

- Lorentz invariance violating effects can be probed using atmopsheric neutrinos
  - Focus here on **isotropic** effects
  - (sensitive to sidereal effects as well…)

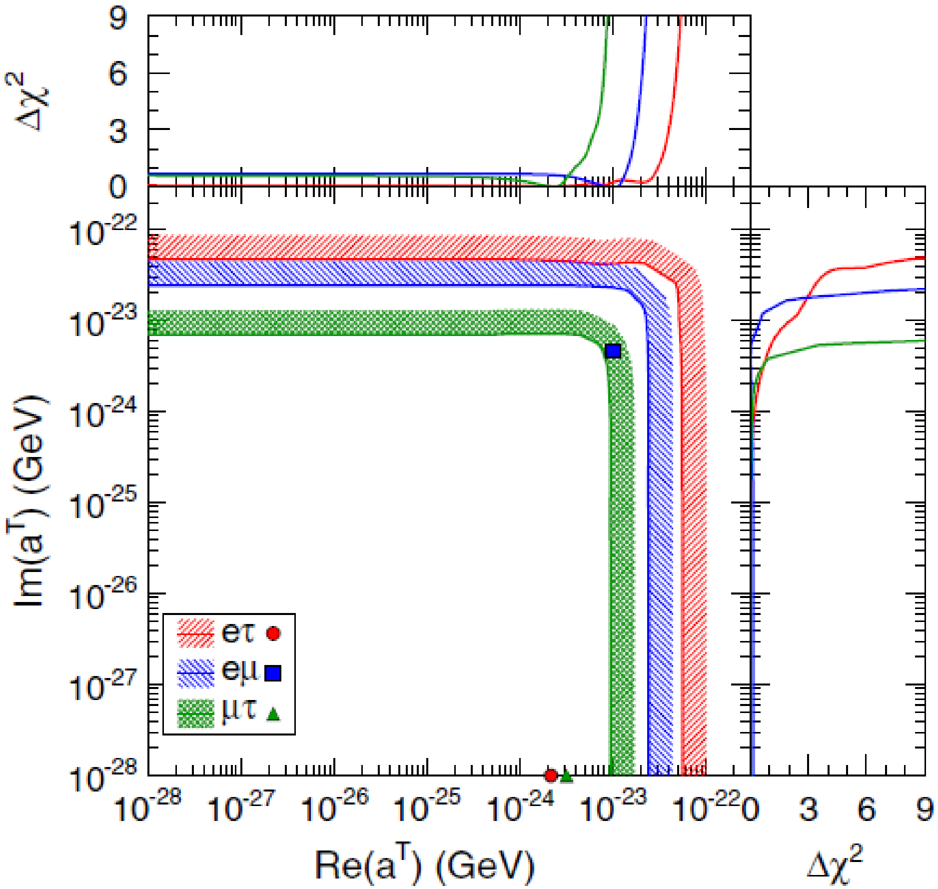
- Analysis using the Standard Model Extension (SME)
  - **Not a perturbative** calculation
  - Effects computed using full solutions of the Hamiltonian

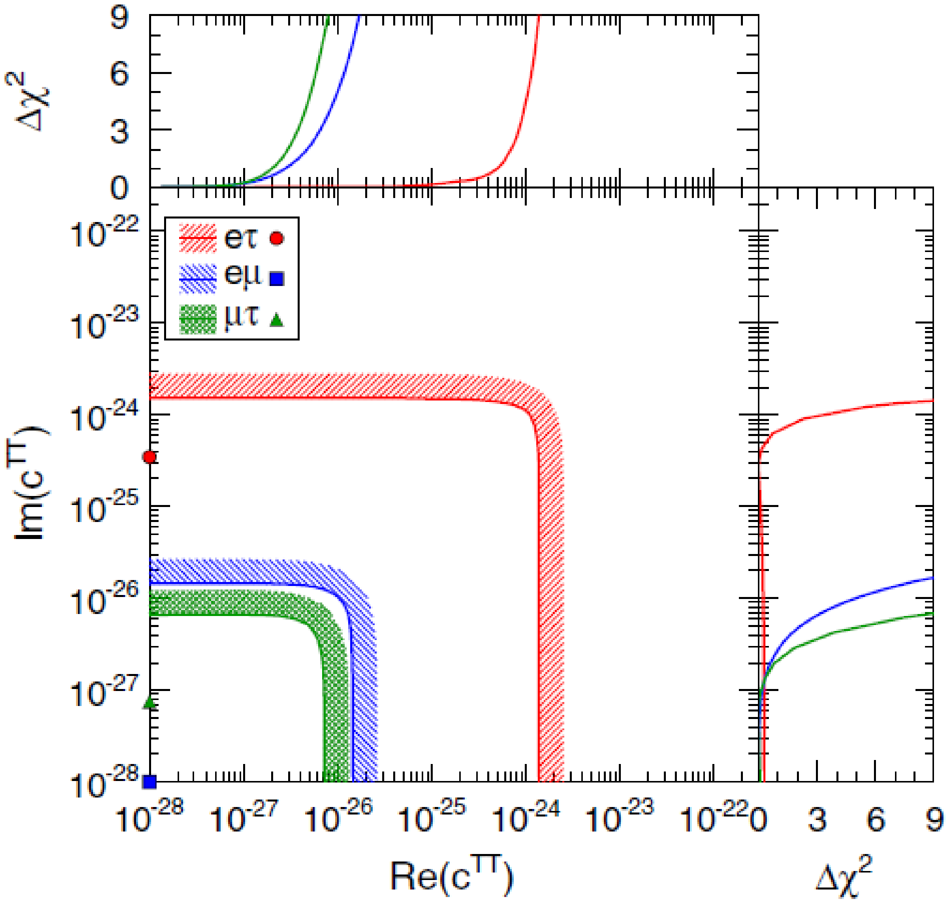
- Effects of LIV controlled by two sets of complex parameters
  - $a^T_{\alpha\beta}$ dim = 3 induces oscillation effects ~ **L**
  - $c^{TT}_{\alpha\beta}$ dim = 4 induces oscillation effects ~ **L × E**





Constraints on Lorentz Invariance Violating Oscillations: **90% C.L.**





PRD.91.052019 (2015)

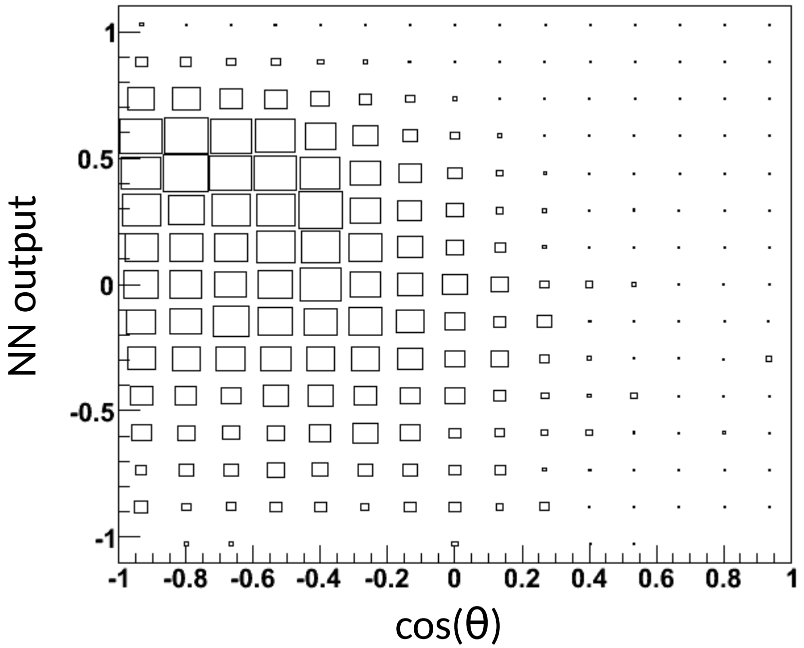
- SK-I+II+III+IV : 4438 days of data
- Perform separate fits on both hierarchy assumptions for each coefficient and each sector : eμ , eτ, μτ
- No indication of Lorentz invariance violation
  - Limits placed on the real and imaginary parts of **6 parameters** $\leq O(10^{-23})$
  - New limits on μτ sector, improvements by **3 to 7** orders of magnitude over existing limits

Future of These Measurements

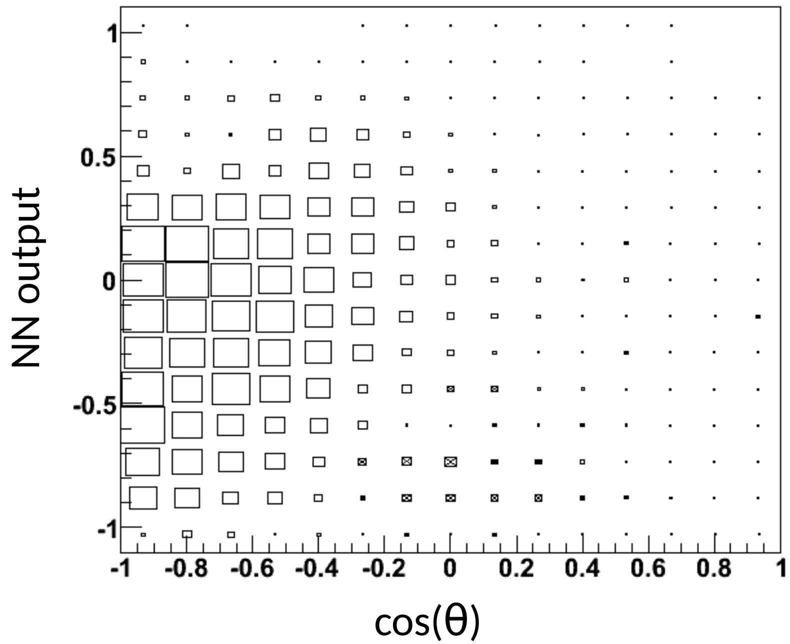
- Several analysis improvements are planned to increase Super-K's sensitivity to the open questions in neutrino physics
- Many of these analyses are predominantly statistics limited, so accumulating more data is essential

Looking Towards the Future

CC $\nu\tau$ Events

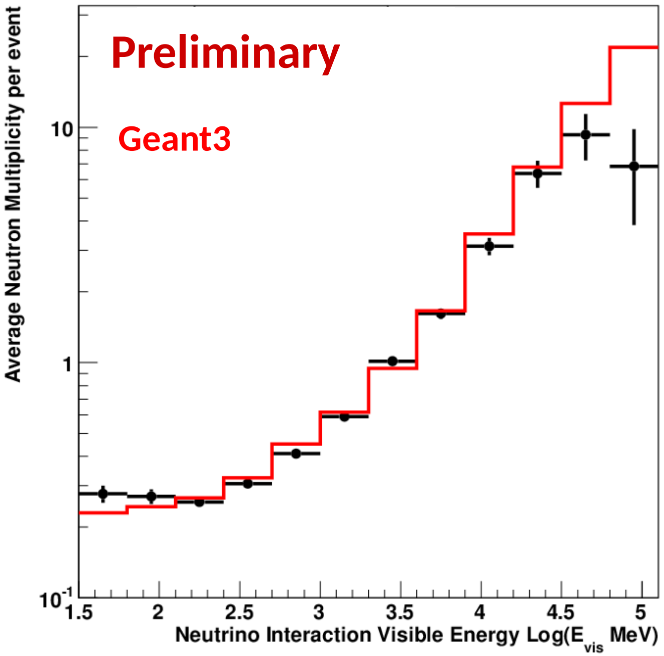


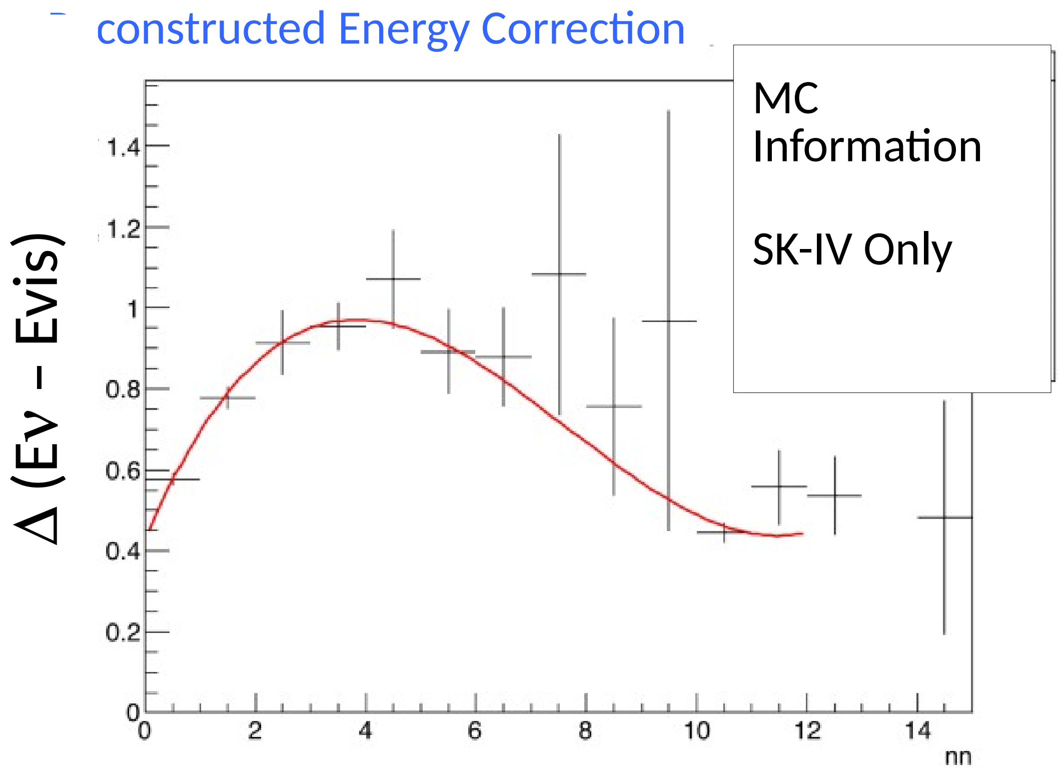
Mass Hierarchy Sensitive ν_e Events



- Expanded fiducial volume
- PID Improvement with advanced reconstruction methods
  - Reject CC$\nu\mu$ and NC backgrounds in e-like samples
- Constrain τ background with NN (see previous talk)
  - Main background to hierarchy search
  - Meausurement of cross section normalization
- n-H / n-Gd neutron tagging
  - Improved energy reconstruction
  - NC background reduction
  - Neutrino / Antineutrino separation

Looking Towards the Future





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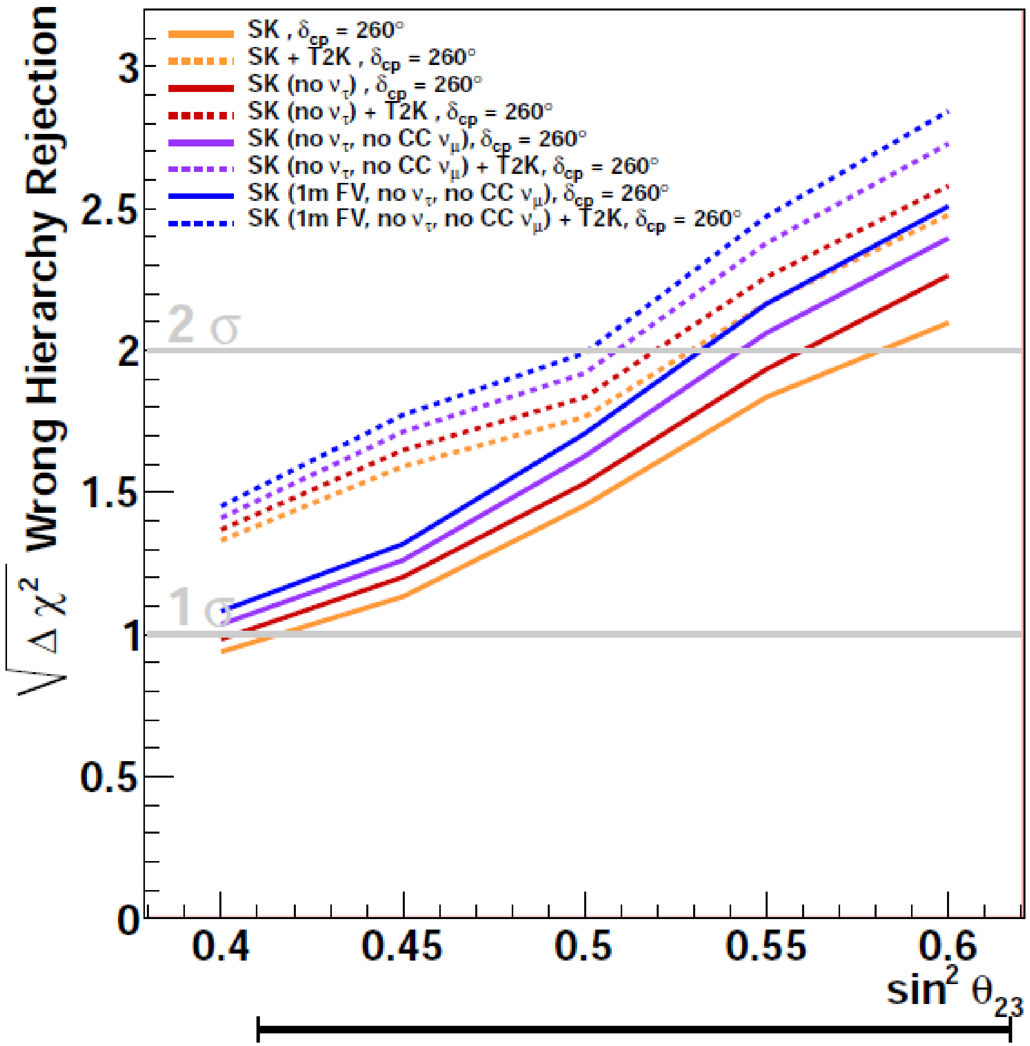
  - NC background reduction
  - Neutrino / Antineutrino separation

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

....More Data is key!

Future Hierarchy Sensitivity

Hierarchy Sensitivity At End of JFY2017

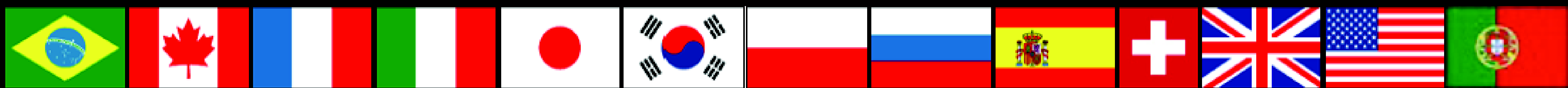


Current T2K Allowed Range (90% C.L.)

Upcoming Analysis Improvements

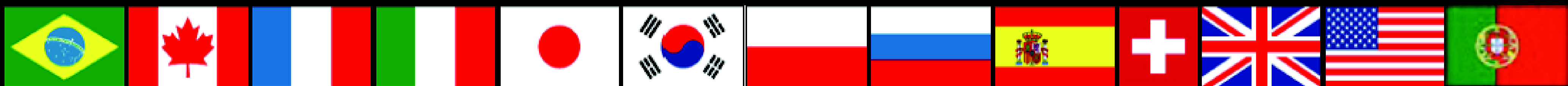
- Expanded fiducial volume
- PID Improvement
  - Better Multi-GeV/-Ring e-like identification
- Constrain τ background with NN
  - Main background to hierarchy search
- n-H / n-Gd neutron tagging
  - Improved energy reconstruction, NC background reduction
  - Neutrino / Antineutrino separation

Hyper-Kamiokande



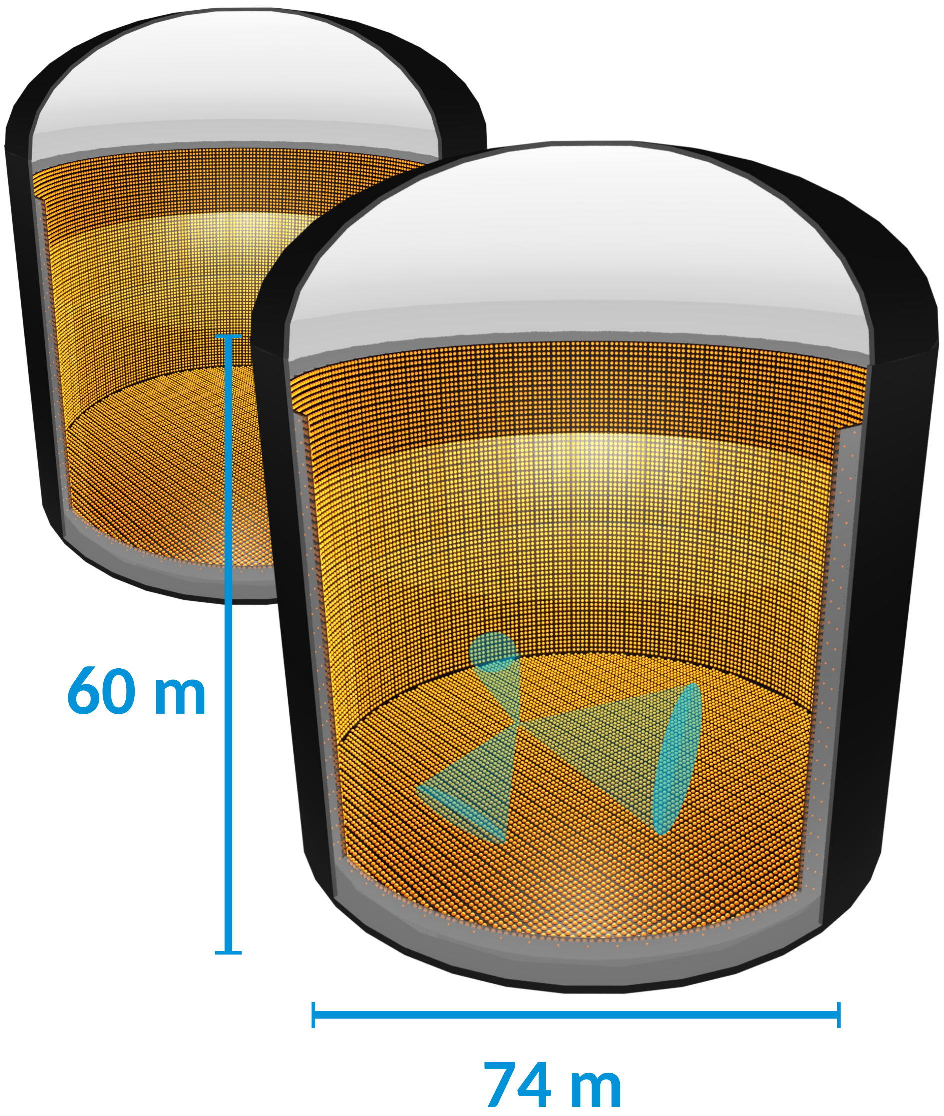
23 countries, 261 people (Oct.2015)

Hyper-Kamiokande



23 countries, 261 people (Oct.2015)

Hyper--Kamiokande: Introduction



Staged design:
186 kton 6 years,372 kton thereafter

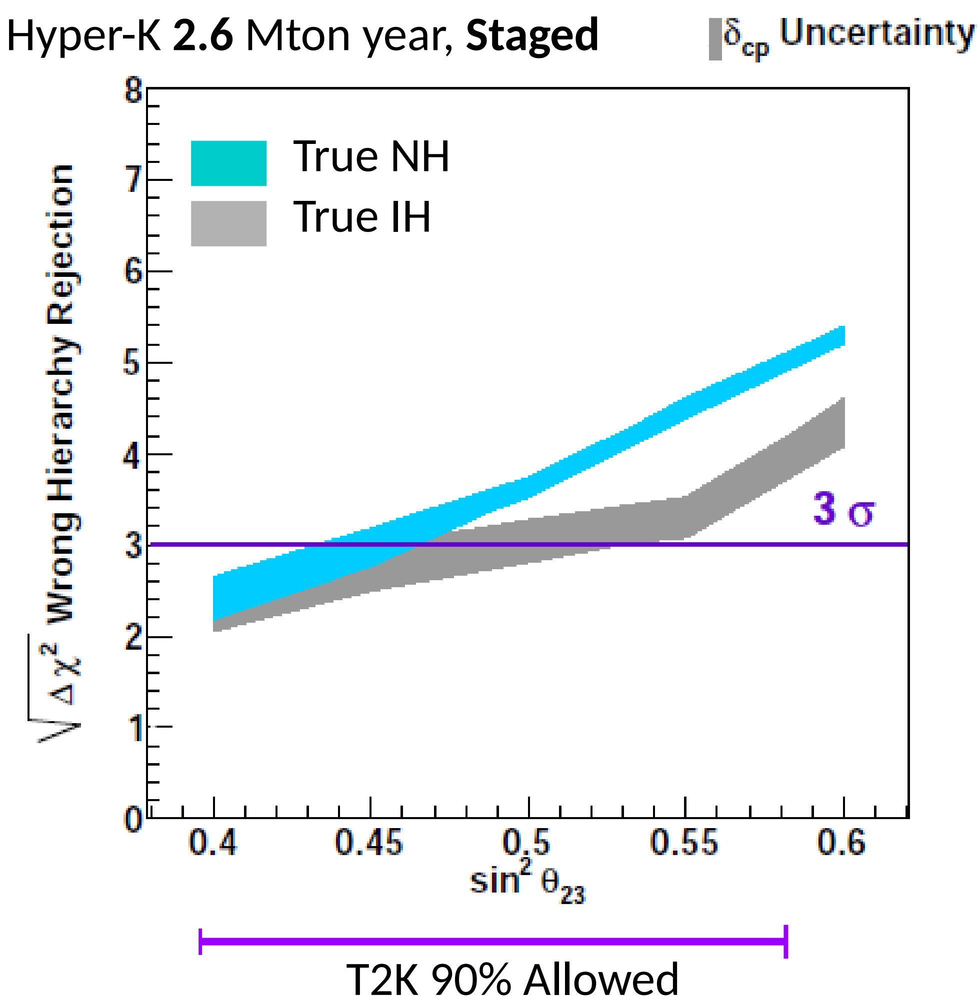
- 186 (×2) kton fiducial volume (2 × 8.3 × SK)
- Optically separated into
  - Inner Detector 40,000 (×2) PMTs (2×4×SK)
    - 40% Coverage (same as SK)
  - Outer Detector 12,000 (×2) PMTs (2×6×SK)
- ID Photosensors will be high QE
  - Single photon detection : 24% (2 × SK)
- Receive 1.3 MW beam from J-PARC
  - Accumulate 2.7×10^{22} POT (3 × T2K)
- Multipurpose machine
  - All of the physics of Super-K and T2K
  - Plus more! Geophysics
    - Accessible only with very large detectors
- Not just a larger version of Super-K
  - Improved performance: photosensors, tank materials

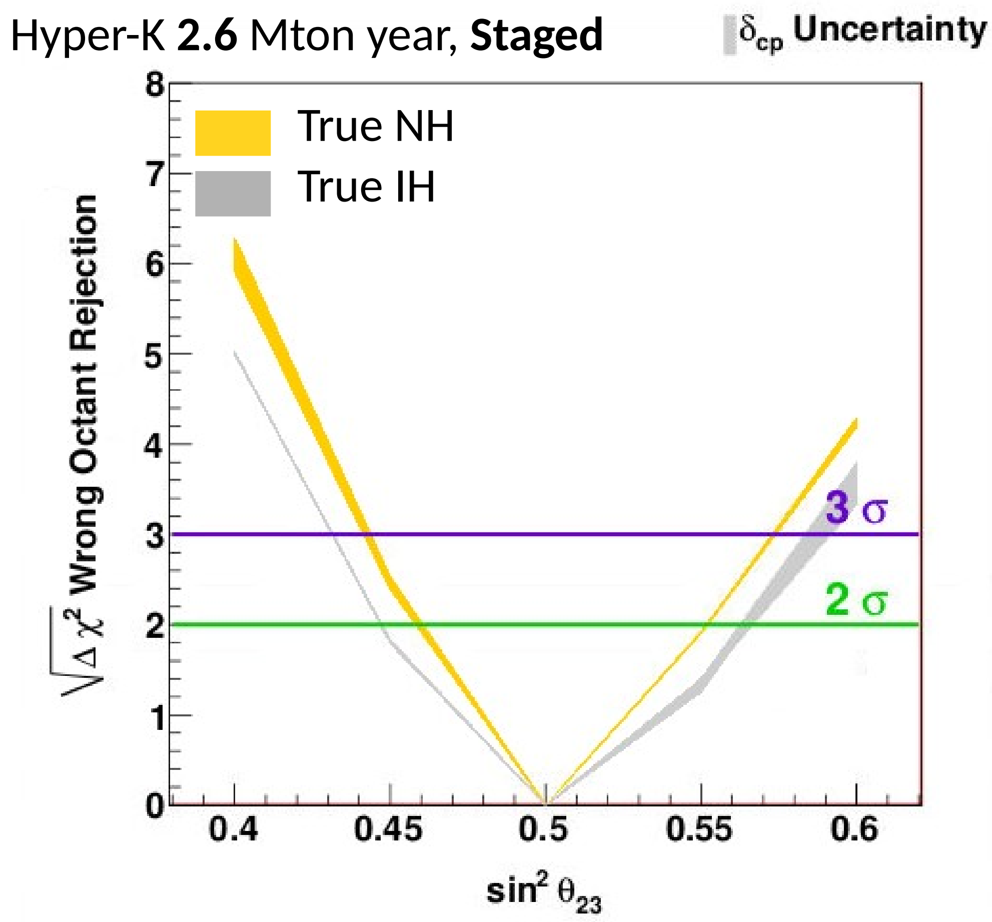
Comparison to Current Super-K Exposure

	Hyper-K HD	SK-IV
Fiducial Vol.	**186 kton**	22.5 kton
Eff. Area	**6,430 m^2**	1500 m^2
Protons	**6.0×10^{34}**	7.5×10^{33}
Neutrons	**5.0×10^{34}**	6.0×10^{33}
Fully Contained μ-/e-like	**246,600**	41,000
Partially Contained μ-like	**21,300**	3,100
Upward-Going μ	**24,300**	7,400

- Hyper-K sensitivity studies are based on Super-K simulation and reconstruction
  - Analyses exposures have been adjusted to account for difference in fiducial volume and effective area between Hyper-K and Super-K
- Event rates compare 10 years of Hyper-K and 12.8 years of SK

Hyper-K Sensitivity 10 Years, Staging Scenario



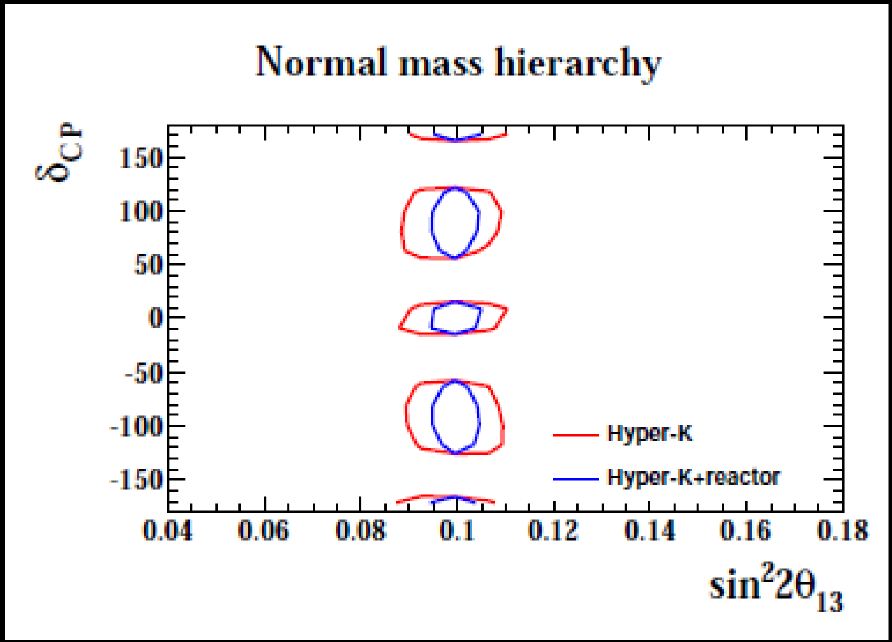


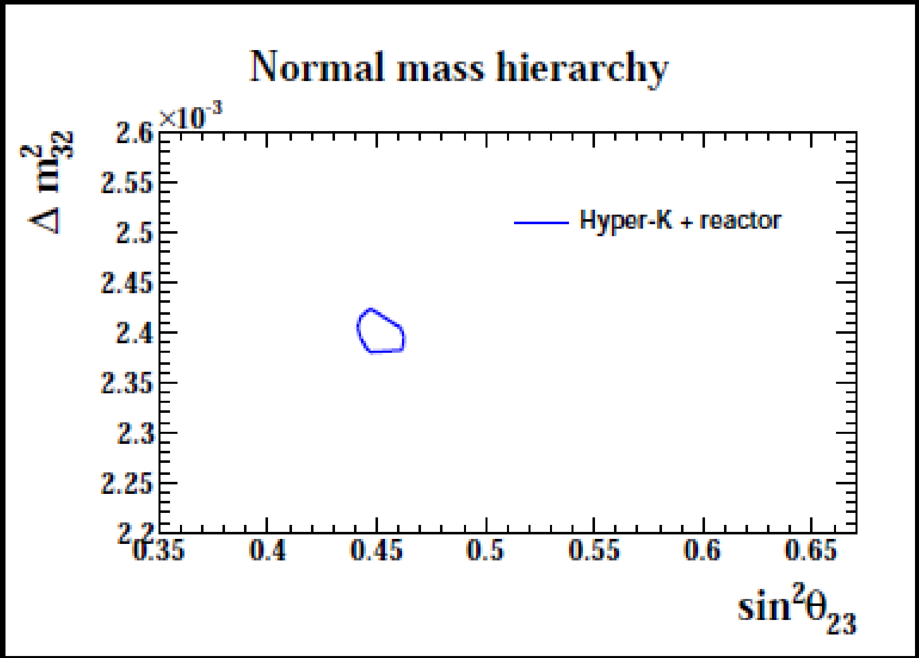
- Expect better than ~3σ sensitivity to the mass hierarchy using atmospheric neutrinos alone
- 3σ Octant determination possible if $|\theta_{23} - 45°| > 4°$

Combination of Beam and Atmospheric Neutrinos

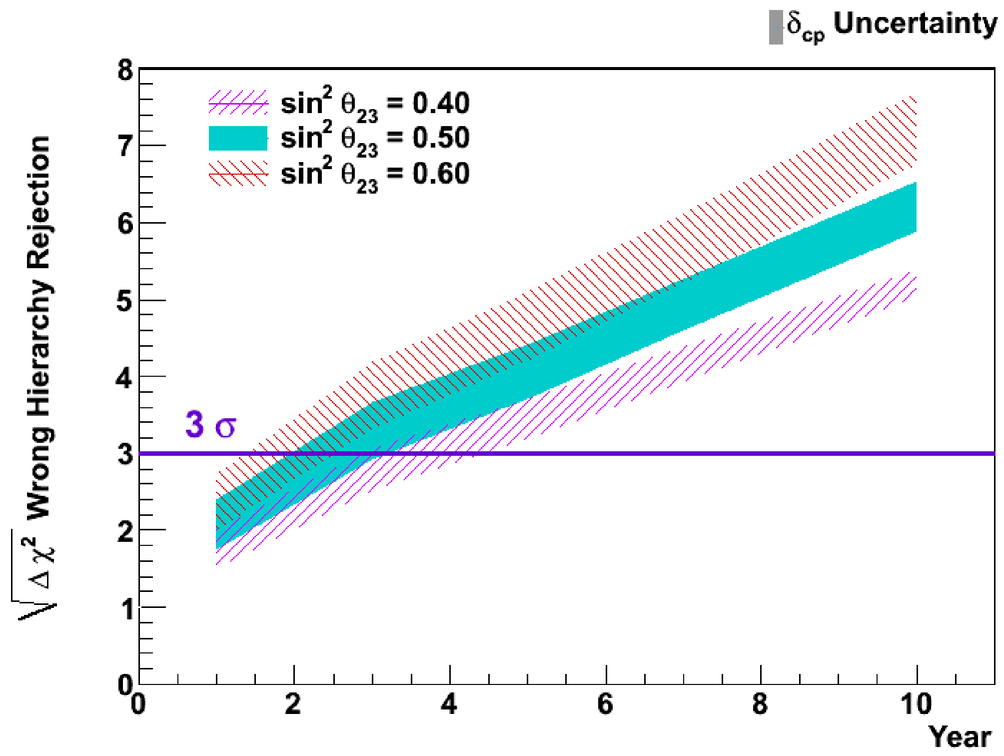
- Beam neutrinos provide tight constraints on mixing parameters that weaken the sensitivity of the (statistics limited) atmospheric neutrino sample to the mass hierarchy for instance

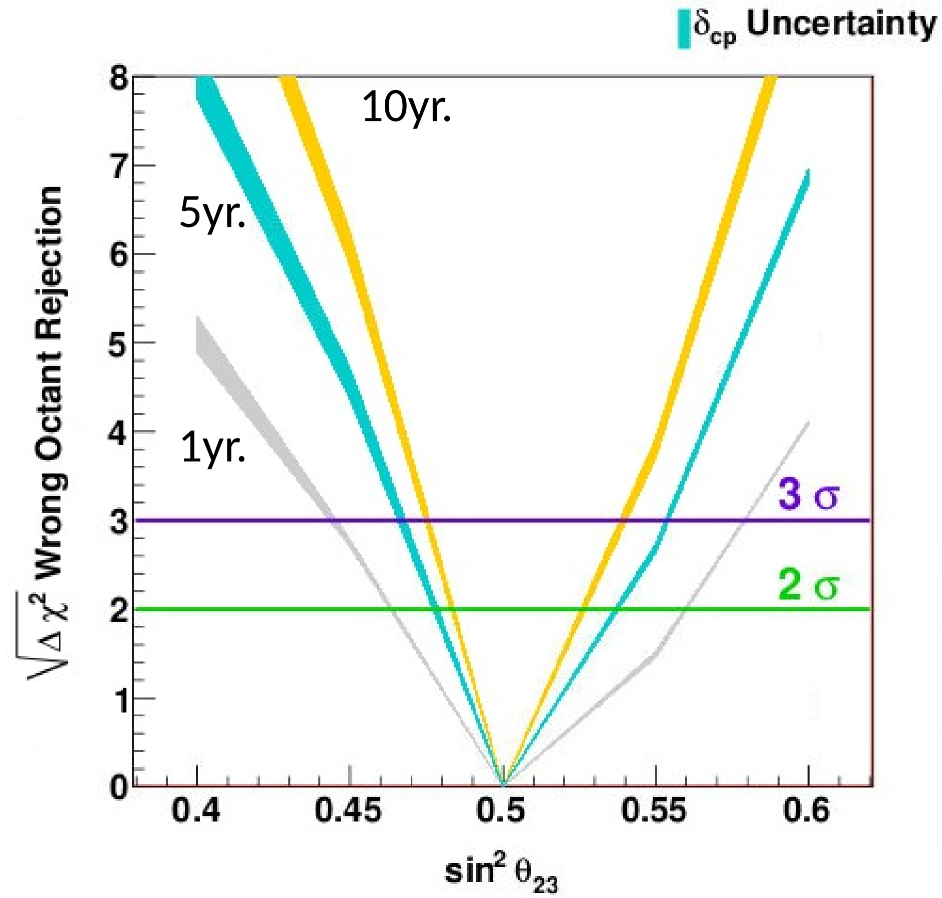
- Sensitivity of the two samples to the CP parameter is largely complementary, such that combined measurement yields better precision.





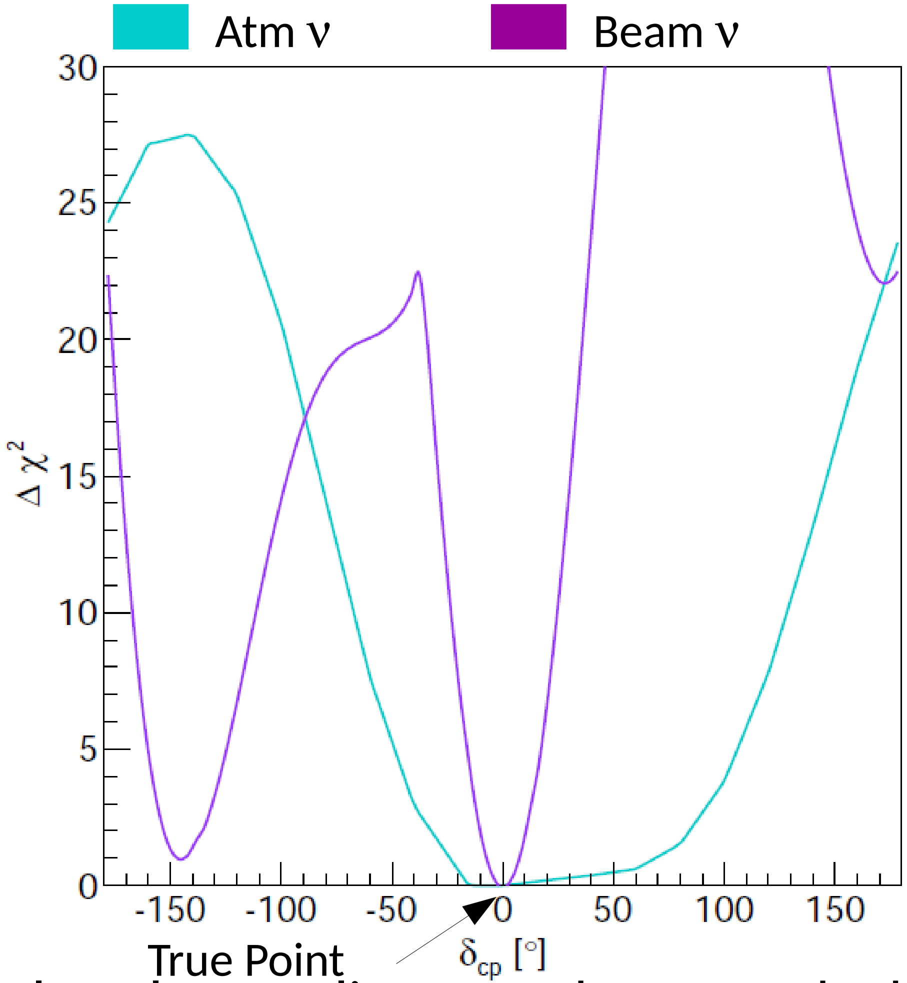
Combination with Beam Neutrinos : Hierarchy and Octant





- For the optimal (worst) set of parameters the combined measurement can determine the mass hierarchy with ~1.5 (4.0) years of data
- Here the beam exposure after 10 years is assumed to be 2.7×10^{22} POT , divided in a 1:3 ratio between neutrinos and antineutrinos
  - POT have been scaled evenly for shorter run periods
- 3σ Octant determination possible if $|\theta_{23} - 45°| > 3°$

Combination with Beam Neutrinos : δcp



- Sensitivity to δ_{cp} is largely complimentary between the beam and atmospheric neutrino samples
- Constraint on δ_{cp} improves with their combination
- Atmospheric ν sensitivity is limited by flux and cross section uncertainties

Other Atmospheric Neutrino Physics

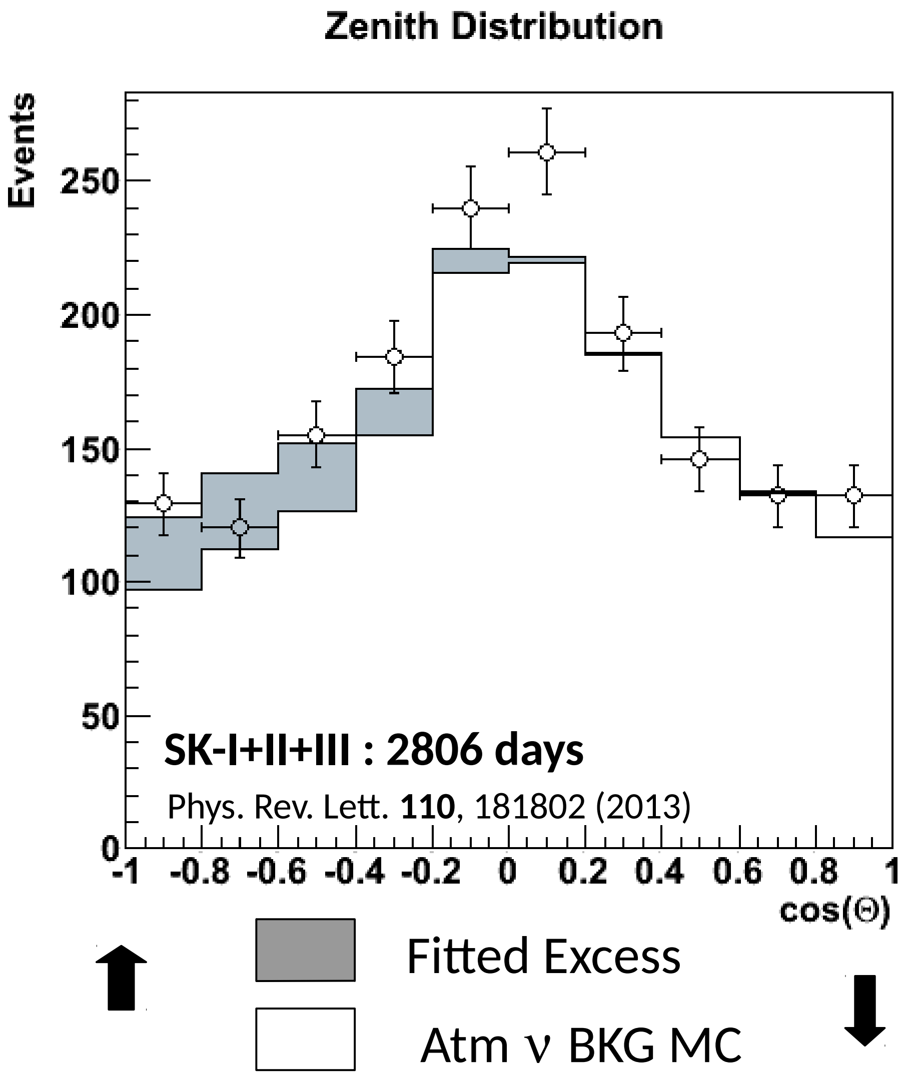
- Just a sampling
- Other studies exist in the backups
  + Sterile neutrino oscillation
  + Lorentz Invariance violating oscillations
  + Indirect dark matter searches

Oscillation-induced ν_τ measurements

- Incorporate t NN information into oscillation analysis

per/ 100 kton yr.	Hyper-K	LAr
Signal CC $\nu\tau$	**40.2**	**28.5**
Background	**448.7**	**44.8**
S /√B , 10 years	**9.6**	**8.5**

- HK Numbers are upward-going event rate
- LAr numbers based on PRD82, 093012



- After 10 years Hyper-K will have O(1,000) $\nu\tau$ events that can be used to study
  - CC ν_τ cross section, leptonic universality, etc.
- Fit for CC ν_τ cross section normalizaton
- After 5.6 Mton years Hyper-K constraint on this parameter would be about 7%

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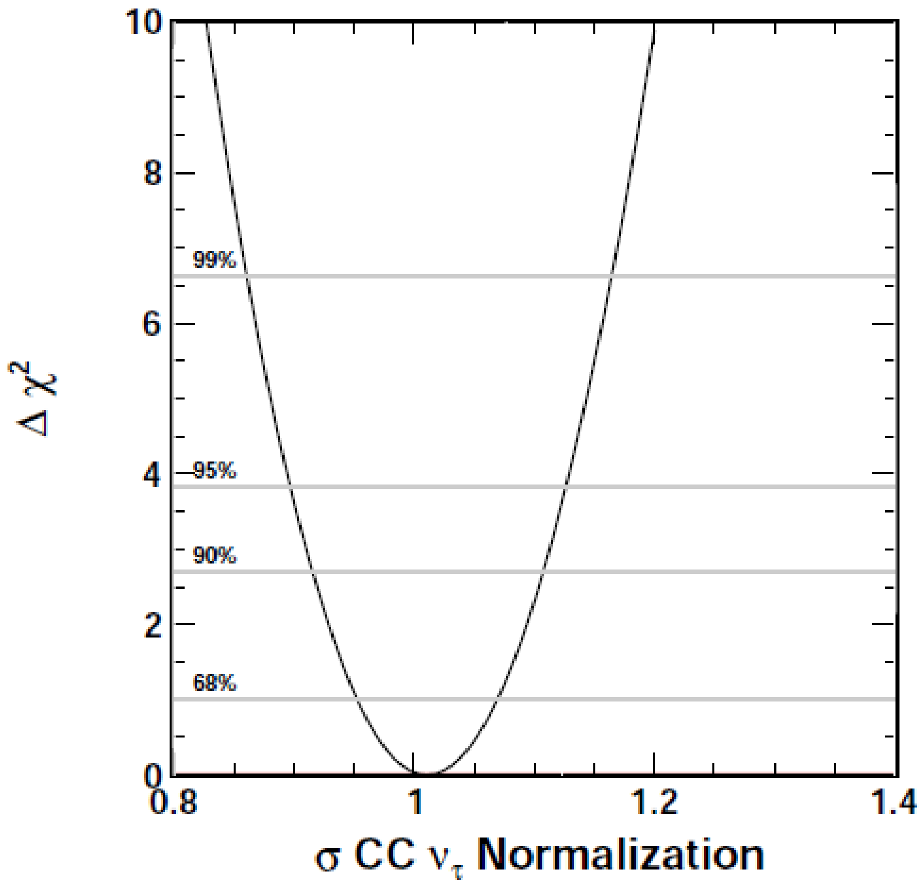

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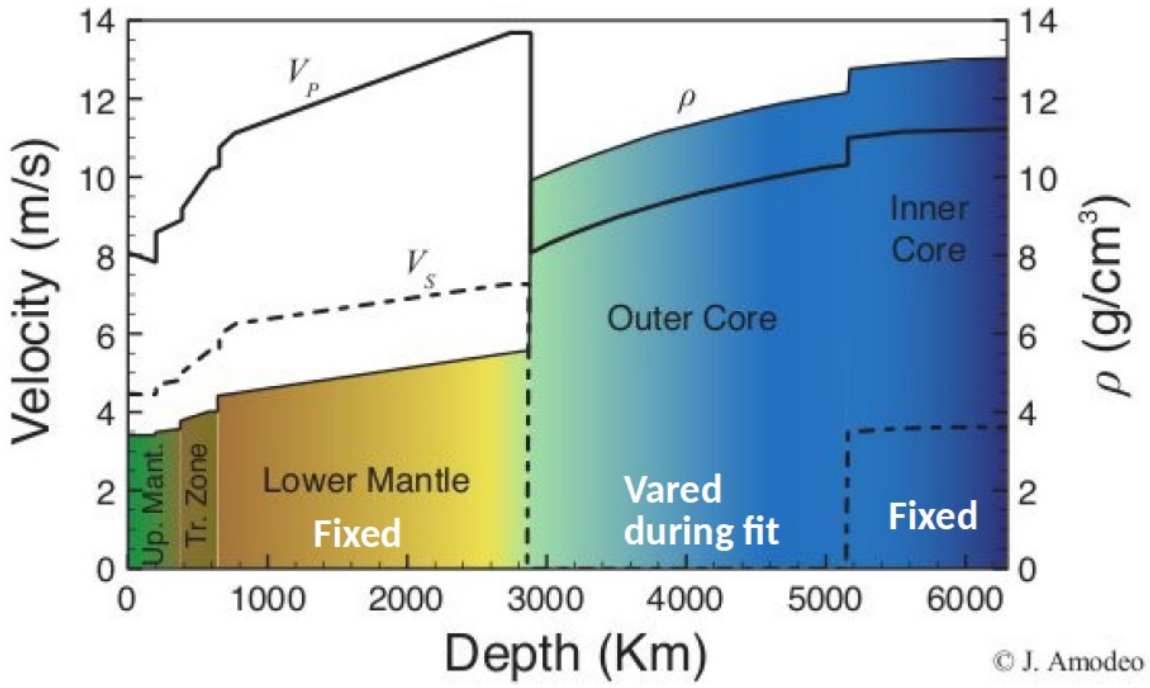
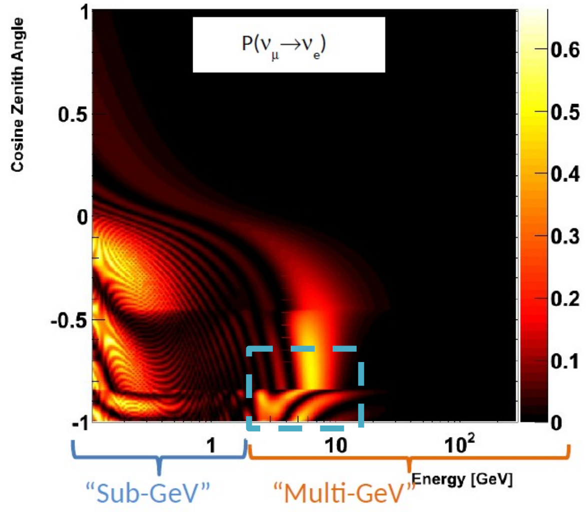
Geophysics: Chemical composition of Earth's Outer Core

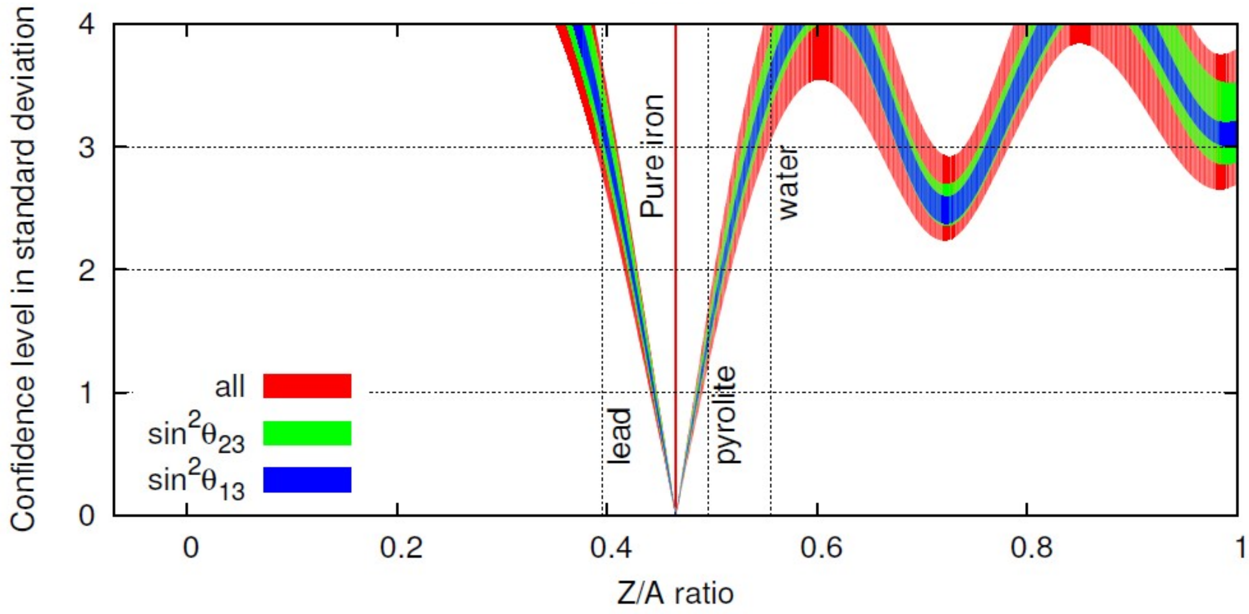


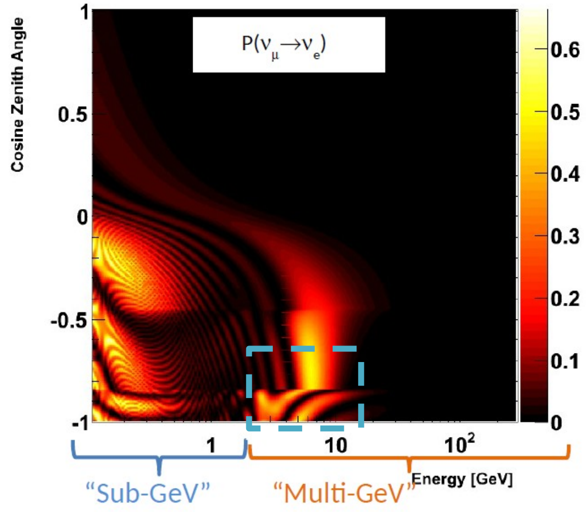


- Density profile of the Earth is well known from seismology
  - Outer core is thoughts to be made of Fe+Ni and some other light element (unknown)
- Chemical composition of the Earth's core (Z/A ratio) is essential to understanding the formation of the Earth and its magnetic field
- Hyper-K can begin making measurements in this as yet unopened field
- <u>Any measurement</u> is of interest to the geophysics community , even if errors are large
- With a 10 Mton year exposure Hyper-K can exclude a lead- and water-based cores
- Technique is complementary to that of large neutrino telescopes

Geophysics: Chemical composition of Earth's Outer Core

Sensitivity to Outer Core Chemical Composition, 10 Mton yr





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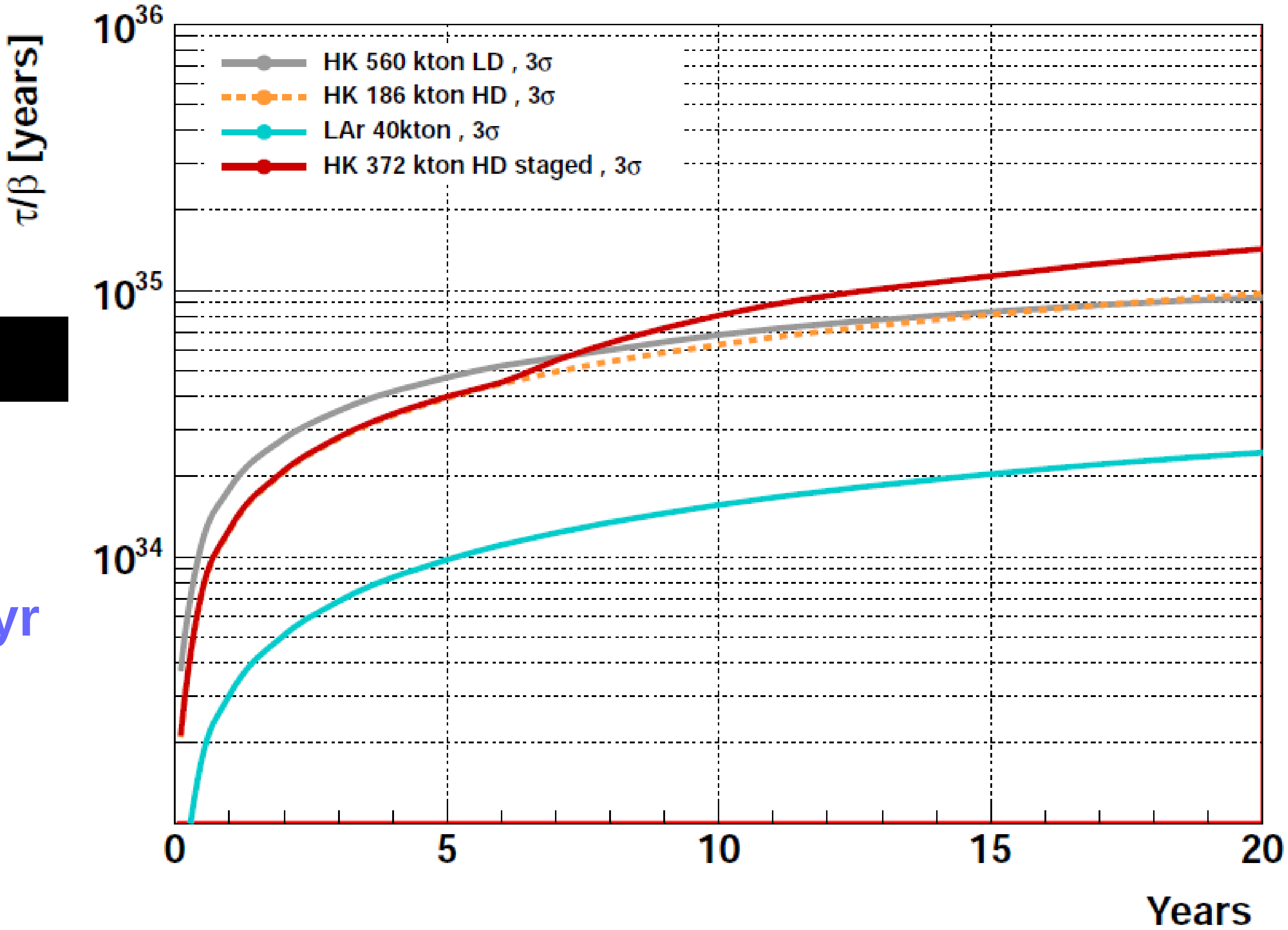
Proton Decay Discovery Potential at Hyper-K: 3σ

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

	Hyper-K
Signal ε	~39%
BG/Mton yr	0.7
90% C.L.	1.0×10^{35} yr



- If proton lifetime is near the current Super-K limit of 1.7×10^{34} years Hyper-K will observe a positive signal at **8.9σ** in 10 years
- 3 σ discovery is possible after 20 years if $\tau < 10^{35}$ yr – Only possible with Hyper-K!

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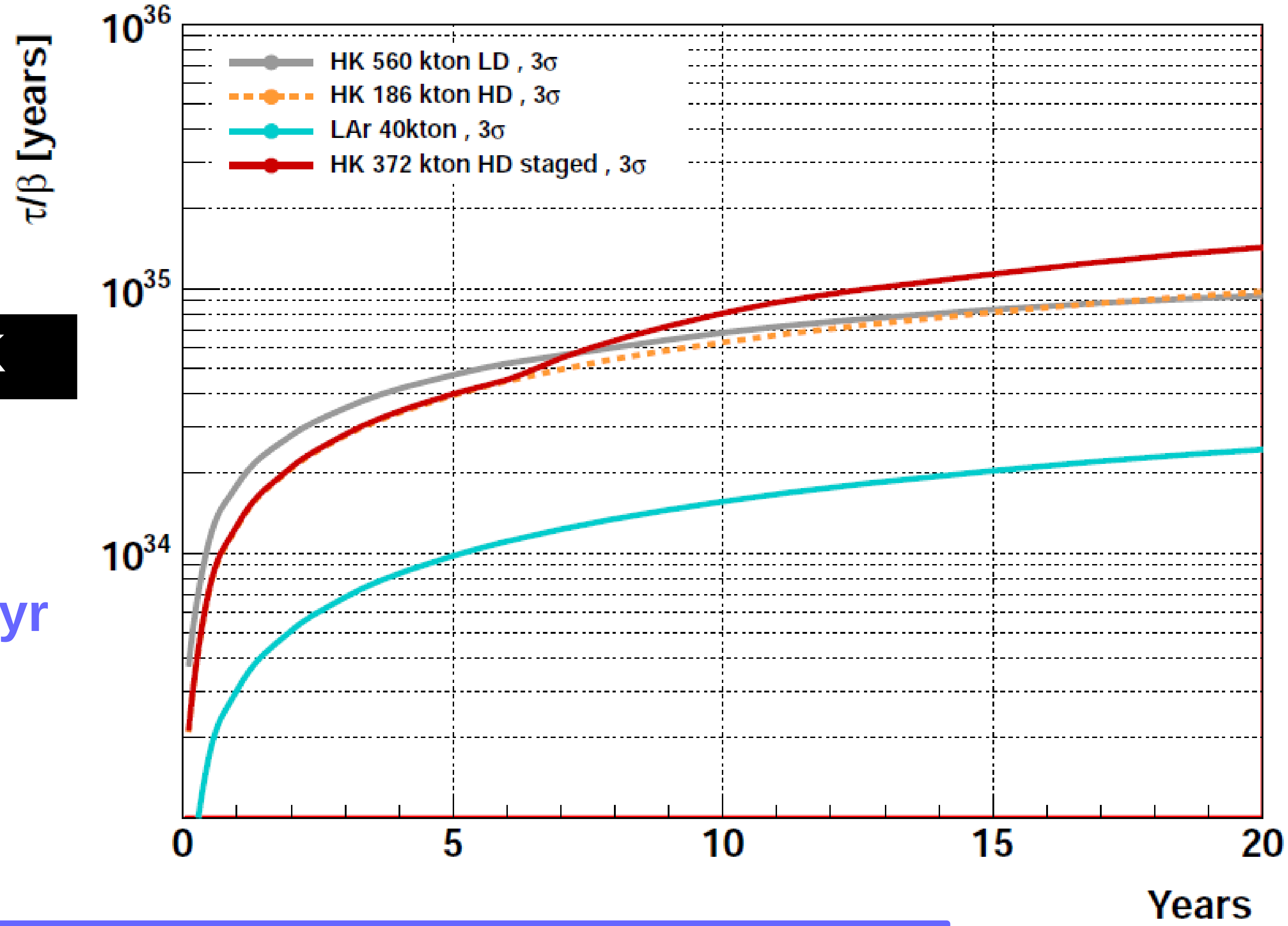


- Recently Super-K has found two candidates in the mode
  - $p \to \mu^+\pi^0$ (BG = 0.87)
- Excellent motivation
  - Reduce backgrounds further!
  - Build a larger detector… like Hyper-K!

Summary

- Atmospheric neutrino physics at Super-K has come a long way since the oscillation discovery in 1998
  - Now exploring sub-dominant three-flavor oscillations with weak hints for the normal hierarchy and second octant
  - Stringent limits on sterile neutrino and Lorentz invariance violating oscillations
- However, statistics remain a limiting factor for Super-K

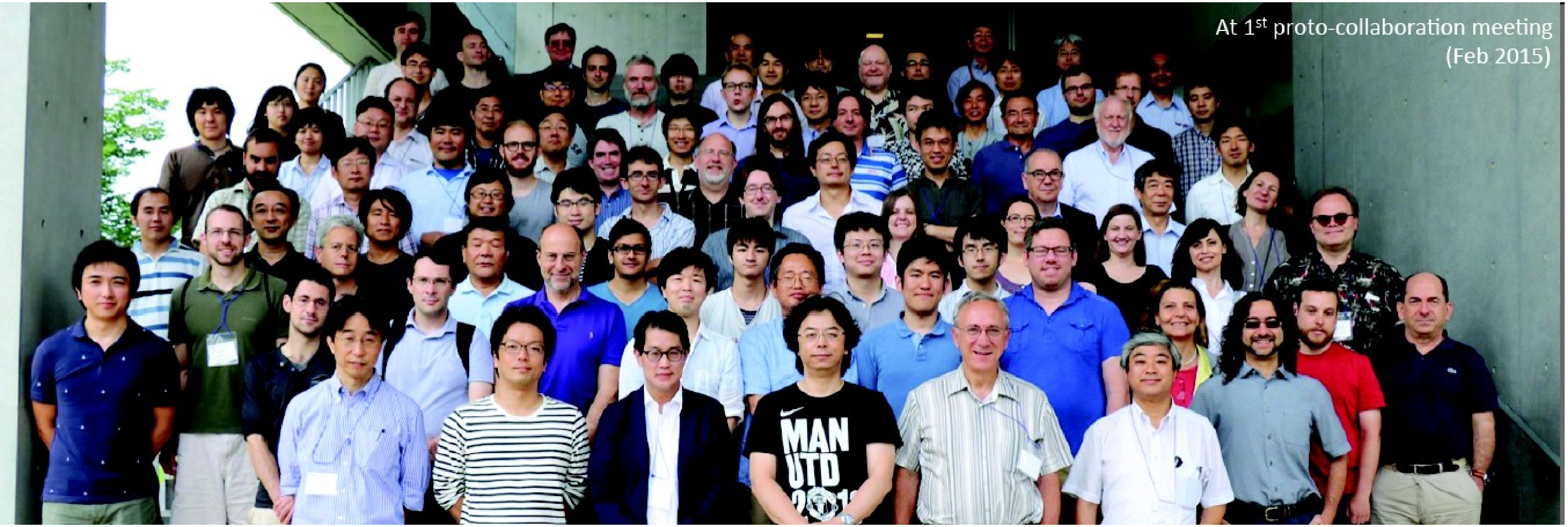
- Hyper-K is expected to be more expansive and precise
  - 3σ+ mass hierarchy and octant determination,within a few years of operation
  - New studies of ν_τ physics, Earth core's chemical composition

- Nucleon decay physics potential is equally promising
  - Sensitivity to $p \rightarrow e^+\pi^0$ at $\tau/B > 10^{35}$ years (only with Hyper-K!)
  - Sensitivity to $p \rightarrow \nu K^+$ at $\tau/B > 10^{34}$ years and beyond
  - Order of magnitude increase in sensitivity in many other modes

- The role of atmospheric neutrinos in our understanding of the natural world will continue to be significant well into the future

Supplements

Hyper-Kamiokande Proto-Collaboration



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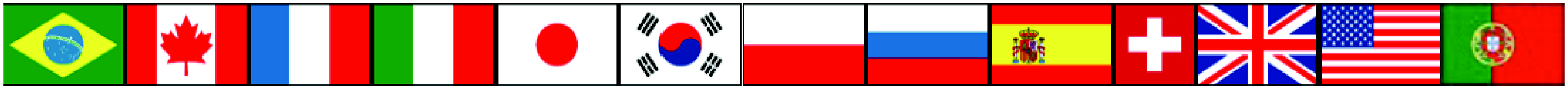
(1st ProtoCollab) http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=67#all.detailed

Still open to new collaborators!



23 countries, 261 people (Oct.2015)