Future of Atmospheric Neutrino Studies

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Kyoto University
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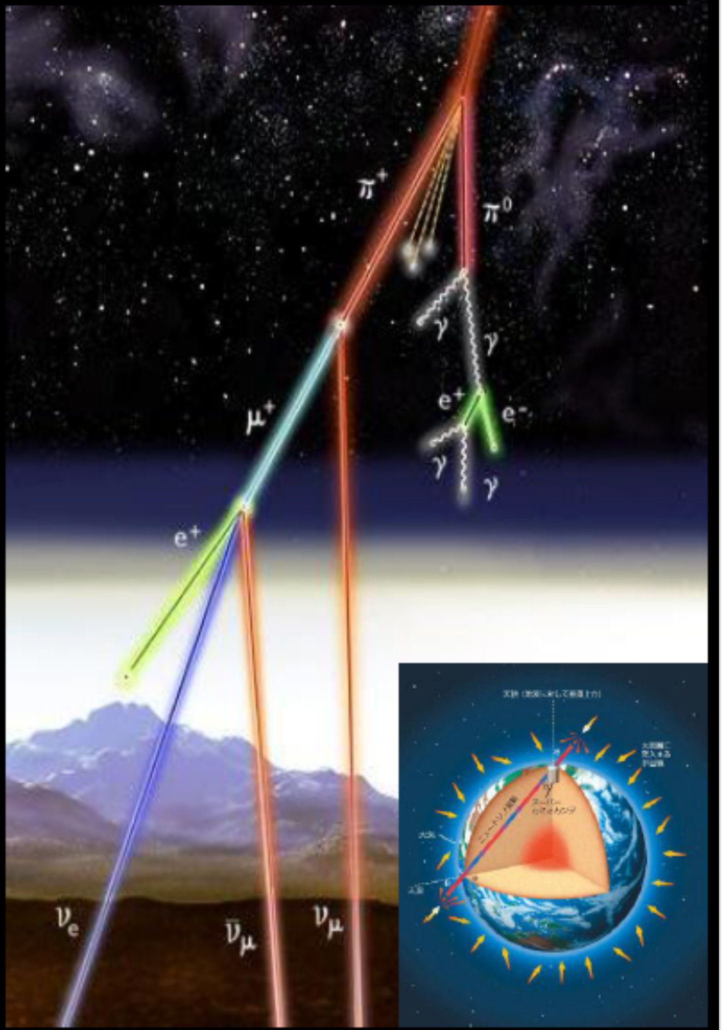
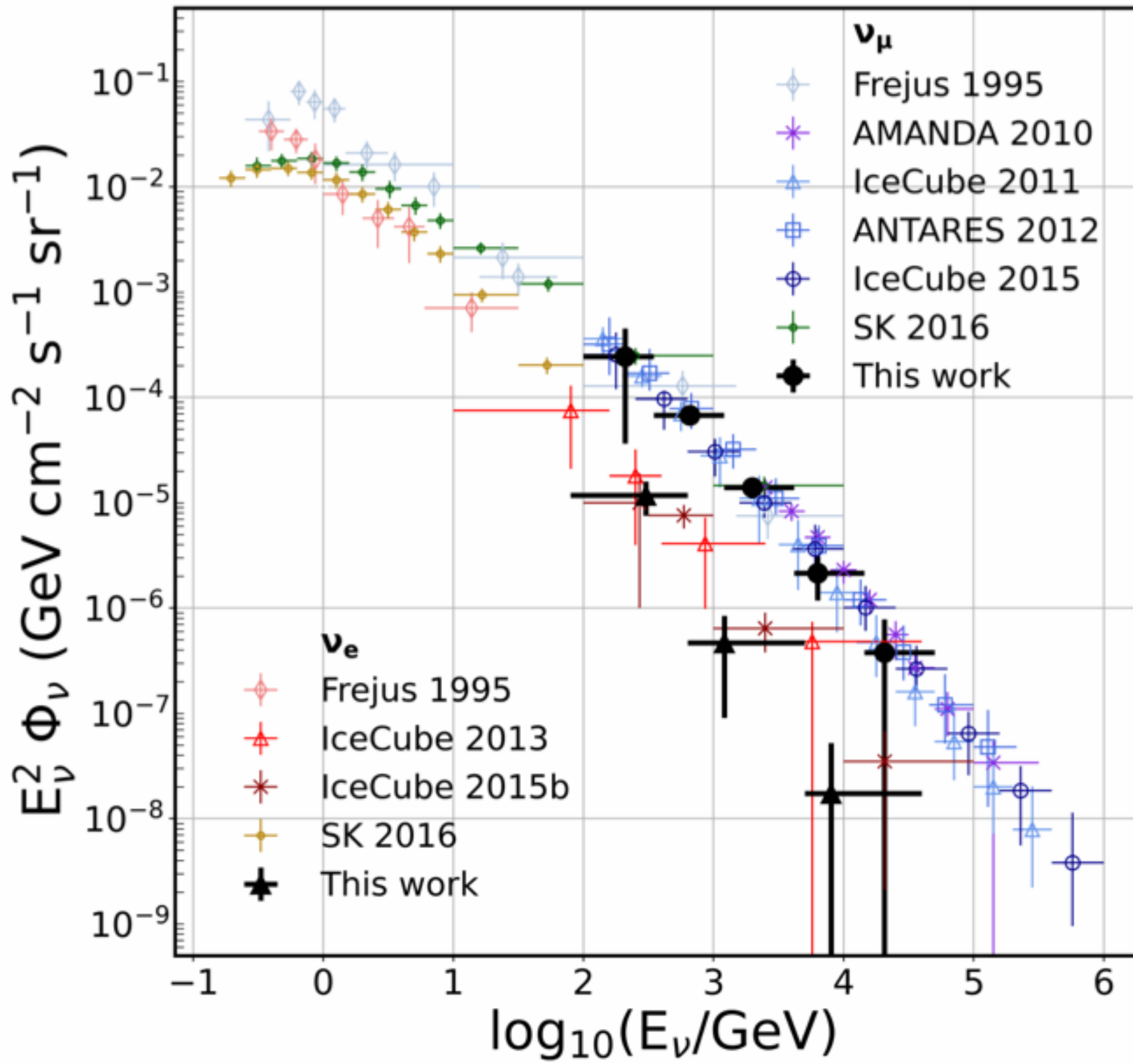
About the Atmospheric Neutrino Flux

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

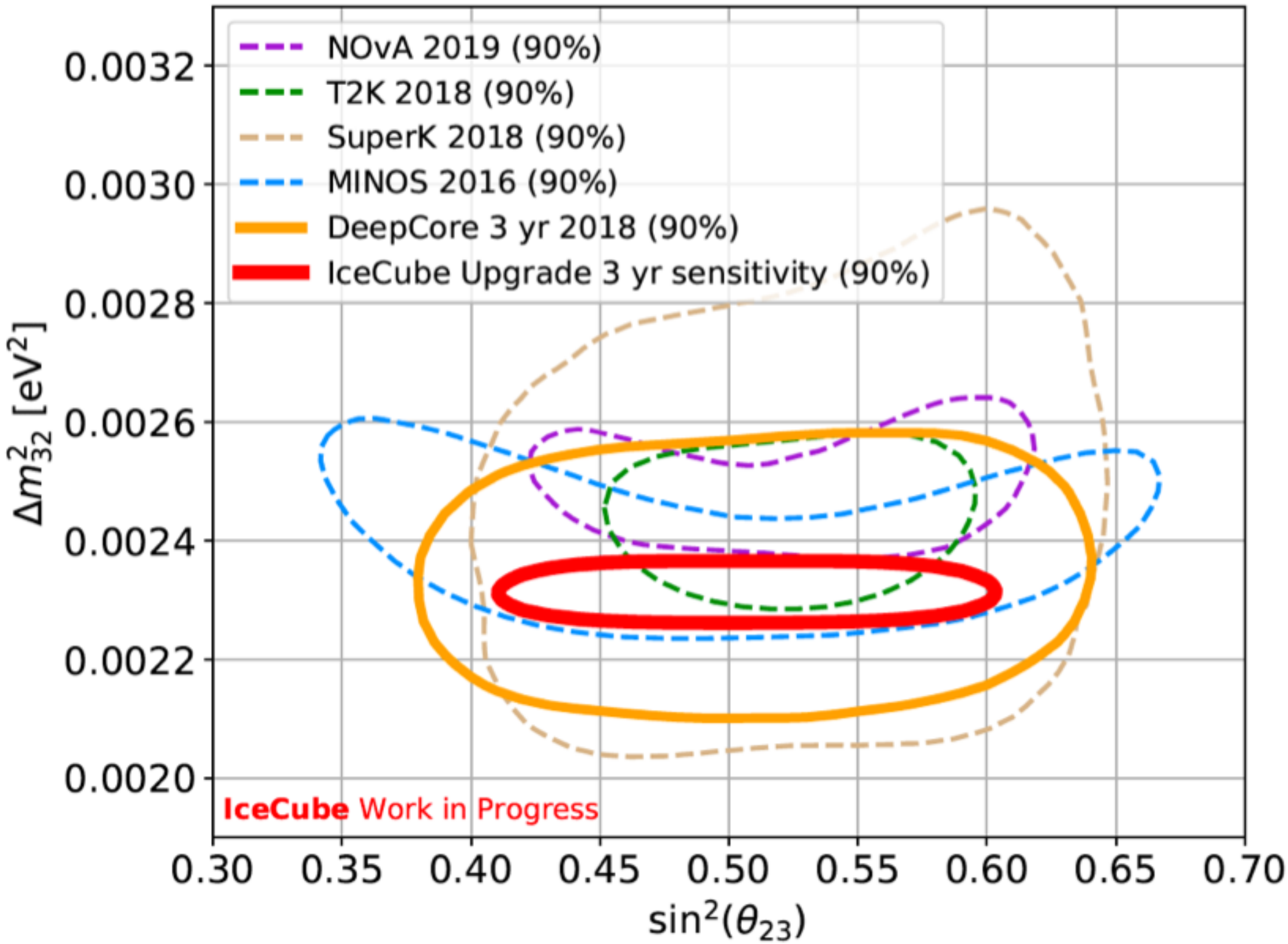
$\hookrightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$



arXiv:2101.12170v1

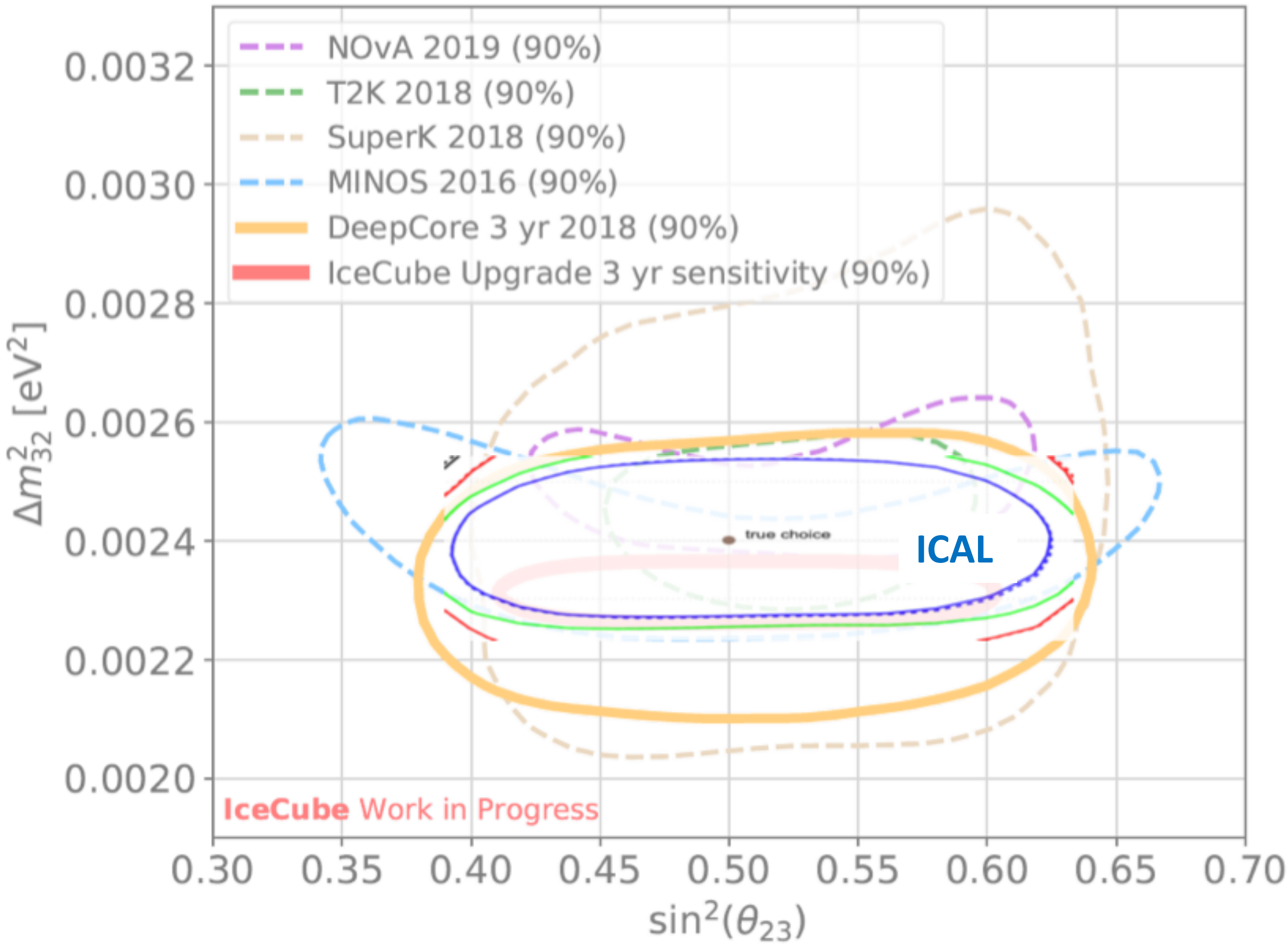


Atmospheric Mixing Parameters: Present and Future



- Atmospheric neutrino oscillation parameter measurements are increasingly dominated by results from accelerator neutrino experiments
- What is left for atmospheric neutrinos ?

Atmospheric Mixing Parameters: Present and Future



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Open Questions and Roles for Atmospheric Neutrinos

Status of Neutrino Oscillations

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

Atmospheric

arXiv:2006.11237v2

Solar

- Three mixing angles, two independent mass differences (Δm^2_{21}, Δm^2_{32}), and a CP violating phase δ_{cp}

- Currently, ***all*** parameters have been measured, though δ_{cp} is the least well constrained and the topic of much interest

- However, several open questions remain

parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\theta_{23}/^\circ$ (NO)	49.26 ± 0.79	47.37–50.71	41.20–51.33
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\theta_{23}/^\circ$ (IO)	$49.46^{+0.60}_{-0.97}$	47.35–50.67	41.16–51.25
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\theta_{13}/^\circ$ (NO)	$8.53^{+0.13}_{-0.12}$	8.27–8.79	8.13–8.92
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
$\theta_{13}/^\circ$ (IO)	$8.58^{+0.12}_{-0.14}$	8.30–8.83	8.17–8.96
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta/^\circ$ (NO)	194^{+24}_{-22}	152–255	128–359
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96
$\delta/^\circ$ (IO)	284^{+26}_{-28}	226–332	200–353

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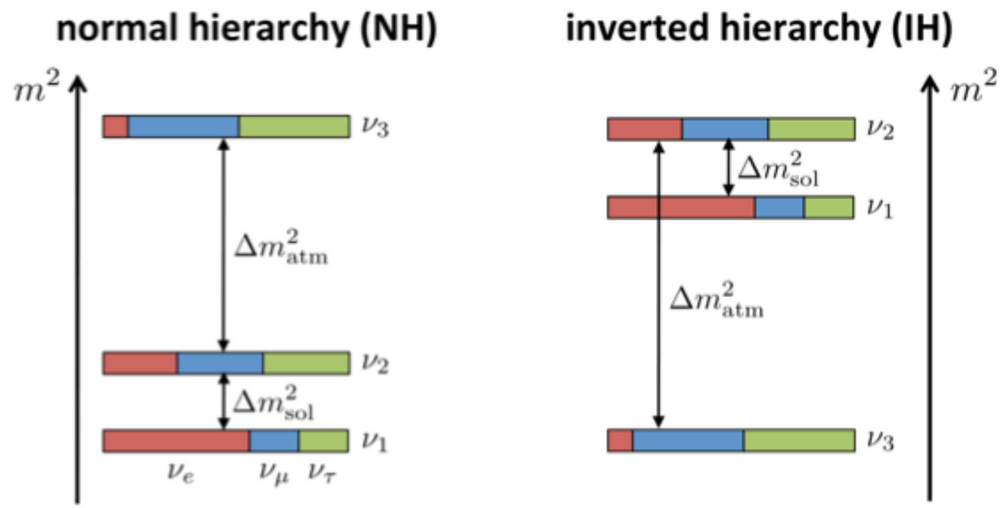
Atmospheric

Solar

Mass Ordering is Unknown

Are the electron-rich states ν_1 & ν_2 **heavier or lighter** than ν_3 ?

- Important implications for
  - GUT Models
  - Neutrinoless double beta decay
  - …



$\Delta m^2_{32} > 0$

$\Delta m^2_{32} < 0$

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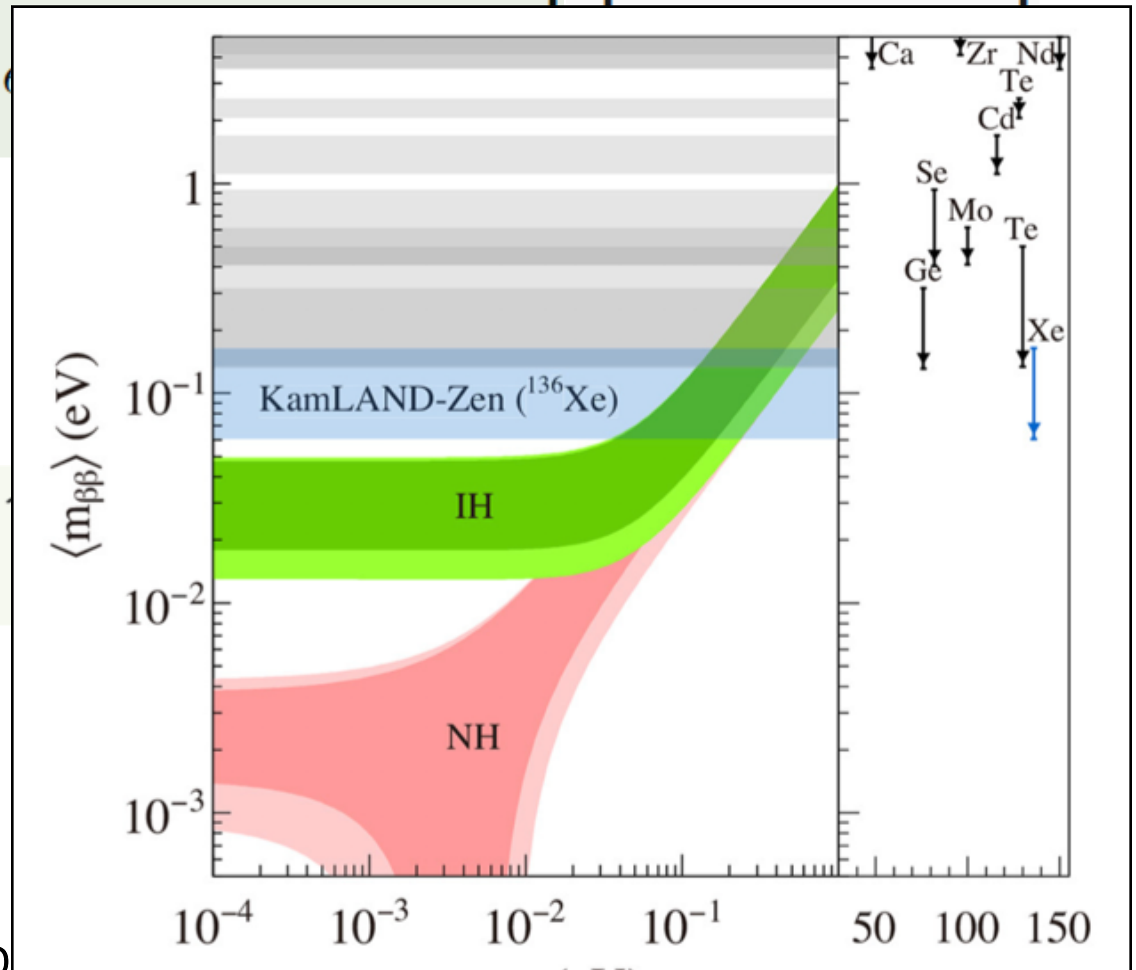
- <u>Atmospheric</u> neutrinos sensitive to MO



Front. Phys., 20 March 2019

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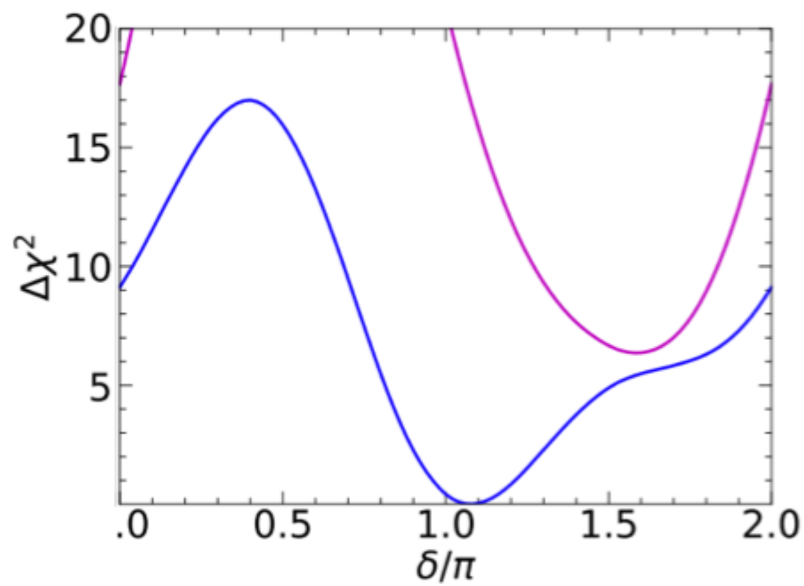
Atmospheric

Solar

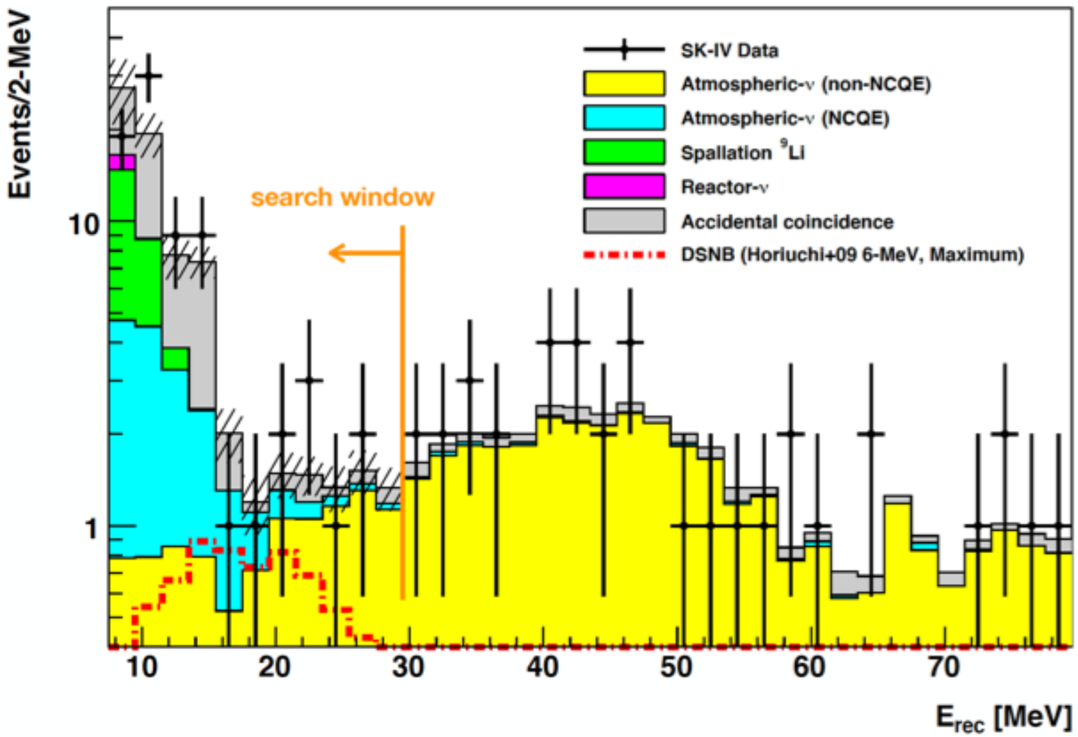
Do neutrino oscillations violate CP?

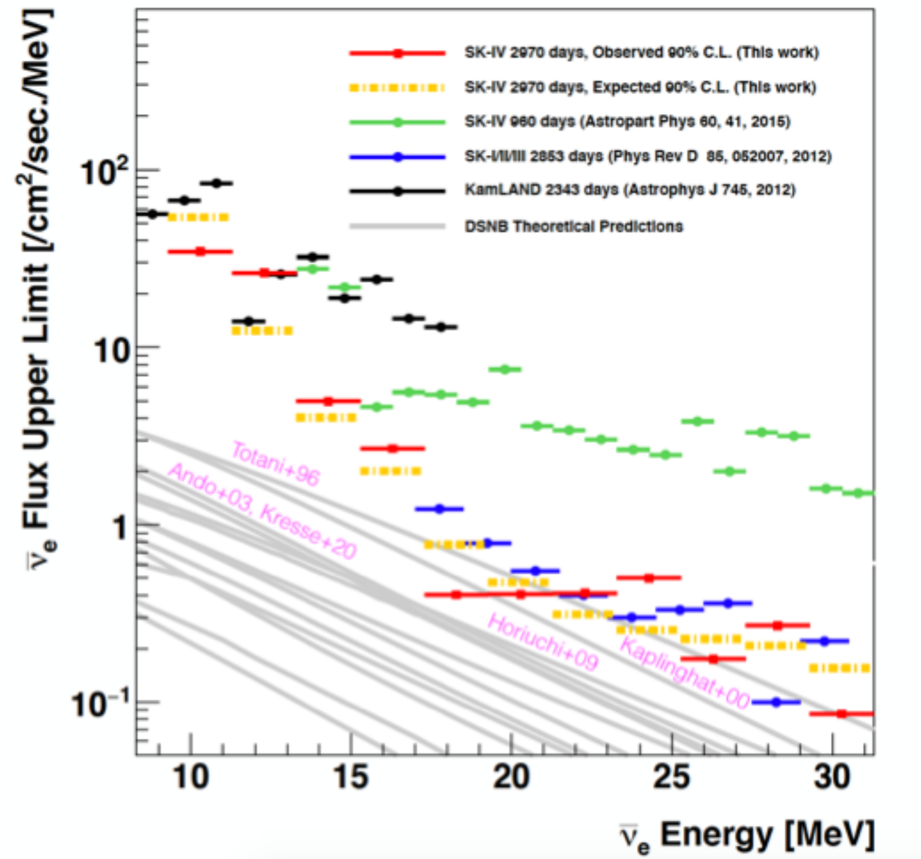
(sin δ ≠ 0 ?)



- New sources of CP violation needed to explain matter dominant universe
- Allowed within νSM
- <u>Atmospheric</u> neutrinos play a role in each of these

Supernova Relic Neutrinos

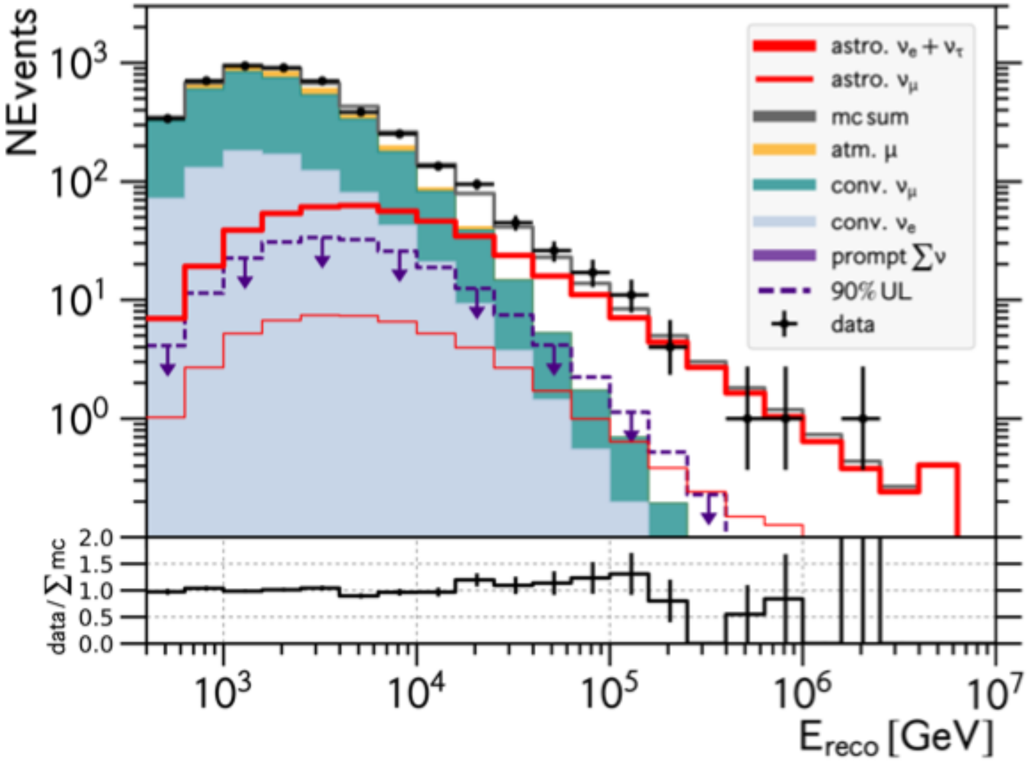




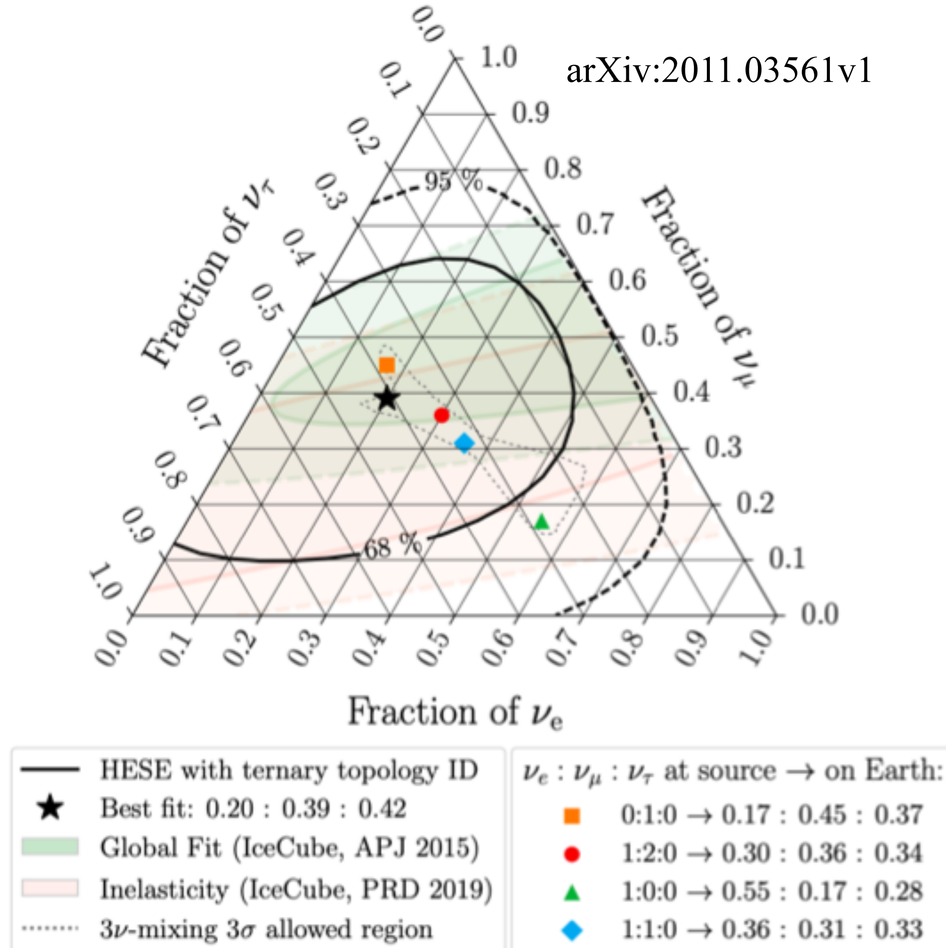
- Expect a cosmic bath of neutrinos from all past supernovae
  - Flux ~ CCSN rate, progenitor mass multiplicity, cosmology
- Estimates of < 5 /cm^2/s → 6-10 ev/year in Super-Kamiokande [22.5kton]
- Backgrounds from atmospheric neutrinos
  - Uncertainties in flux, cross-section, neutron spectra, γ spectra, large or unknown
  - Must be measured and constrained!

Astrophysical Neutrinos

Phys. Rev. Lett. 125, 121104 (2020)



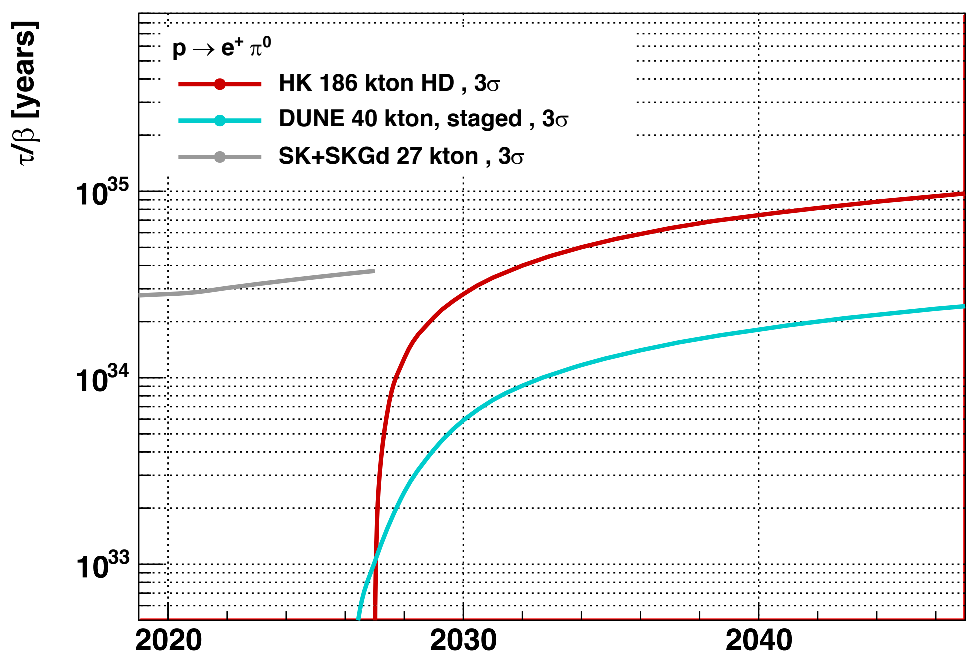
arXiv:2011.03561v1

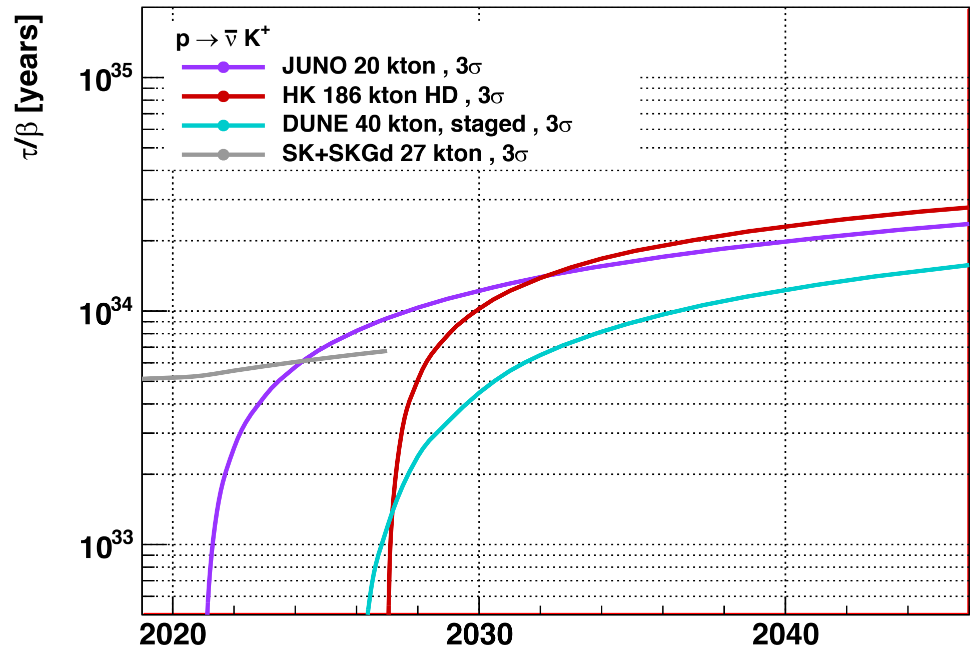


- UHE astrophysical neutrinos have been observed atop atmospheric ν backgrounds
  - What is the power law for UHE ν?
  - Source flavor ratio determines ratio at Earth, what are they?
  - What is the neutrino-antineutrino ratio at Earth?

- Atmospheric neutrino studies can help with these questions

Hyper-Kamiokande Nucleon Decay Discovery Potential





$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20

Prompt γ		$\pi^+\pi^0$	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
12.7 ± 2.4	0.9 ± 0.2	10.8 ± 1.1	0.7 ± 0.2

- Backgrounds to proton decay searchers are exclusively from atmospheric neutrinos
  - Phase space is limited, rare processes unmeasured or come with large uncertainties
  - Neutron tagging can reduce backgrounds, but neutron spectrum in atmospheric neutrino interactions largely unknown

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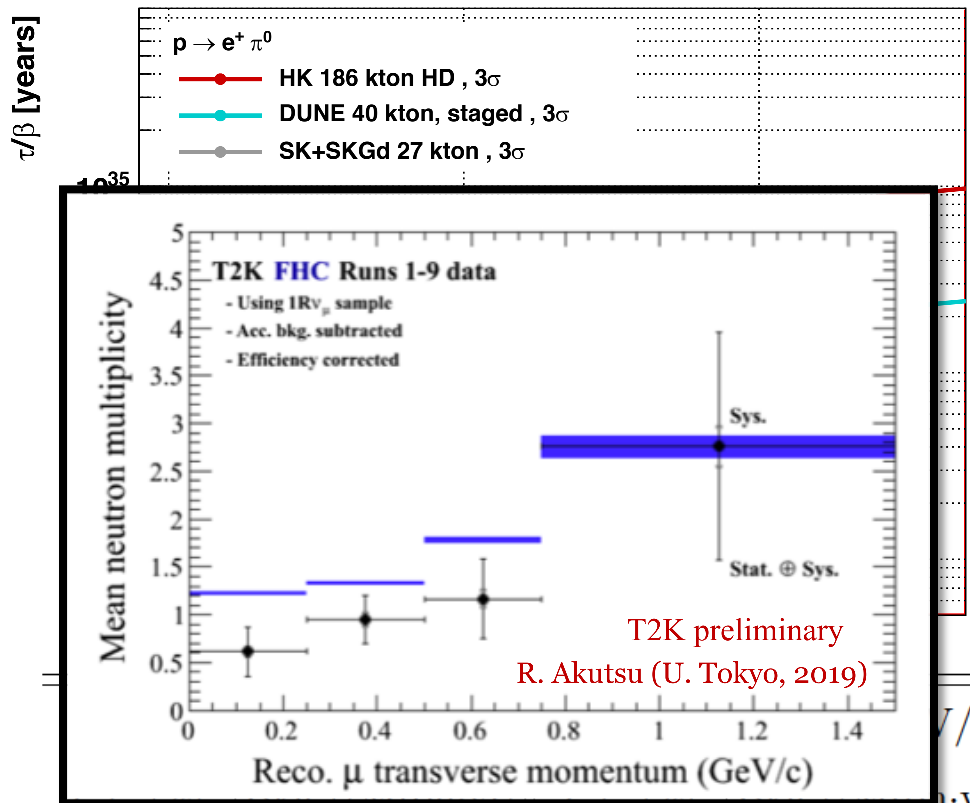

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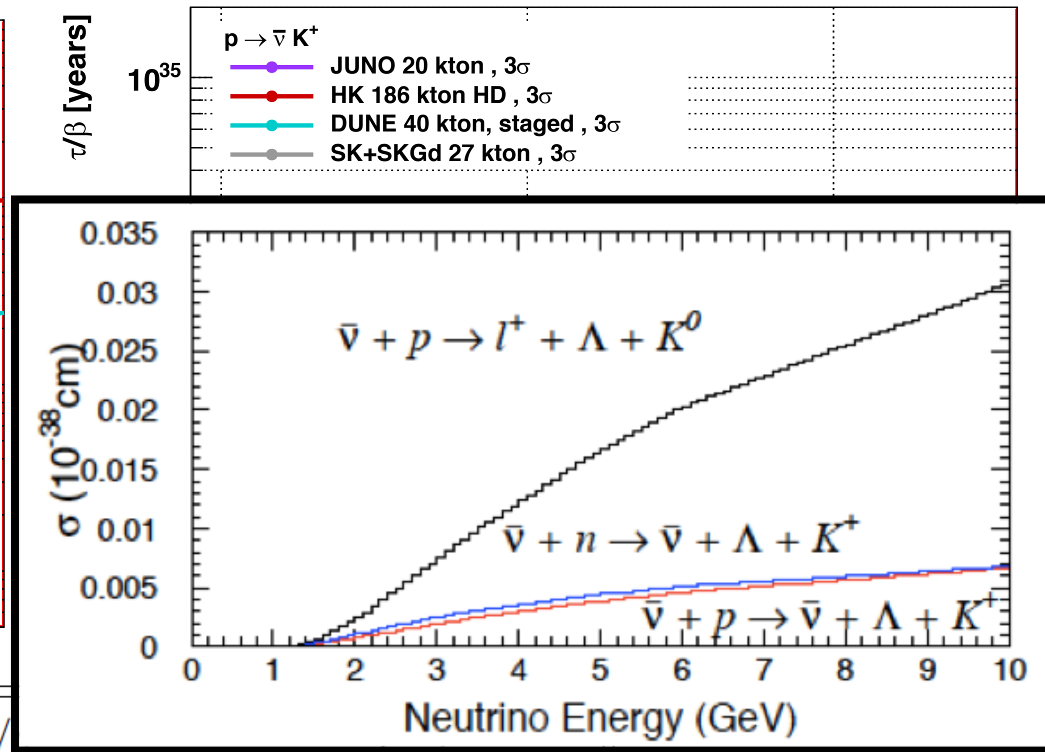

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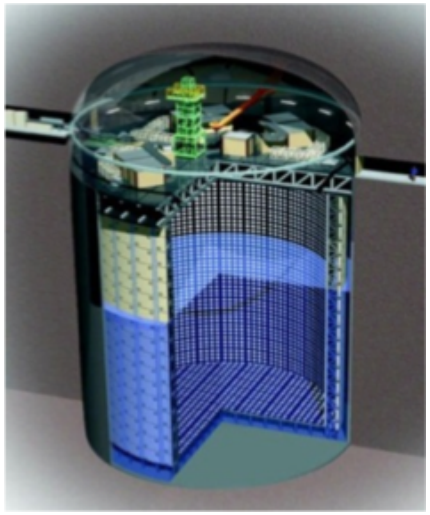
Future of Atmospheric ν Studies: In a word

- Oscillation measurements will benefit directly and indirectly from measurements with atmospheric neutrinos
- Atmospheric neutrino interactions will provide valuable information on backgrounds and expected signals at future facilities
- Improvements in flux and interaction uncertainties over the range of atmospheric neutrino energies will benefit both of the above

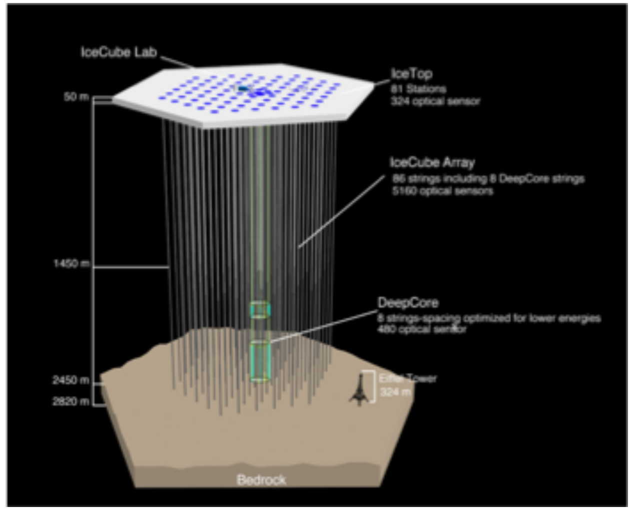
There is a lot of work left to do!

The Major Players

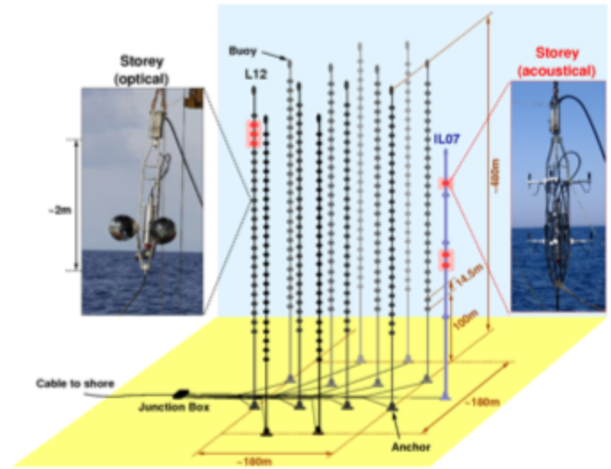
Super-K, Hyper-K



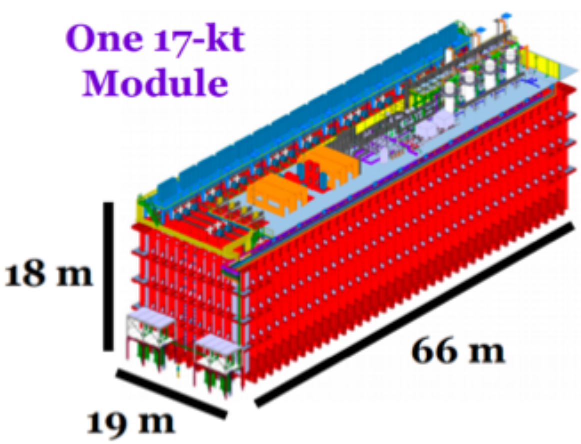
IceCube DC, Upgrade, Gen2



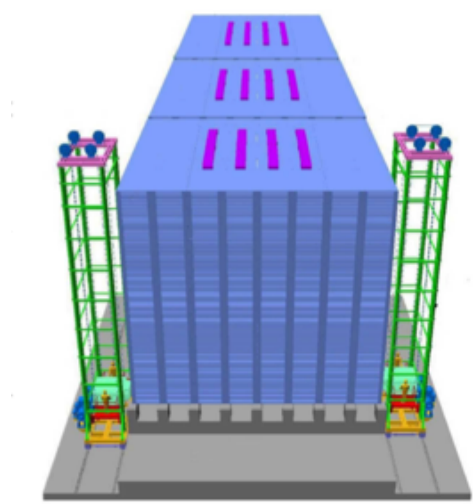
Antares, KM3NeT



DUNE



ICAL



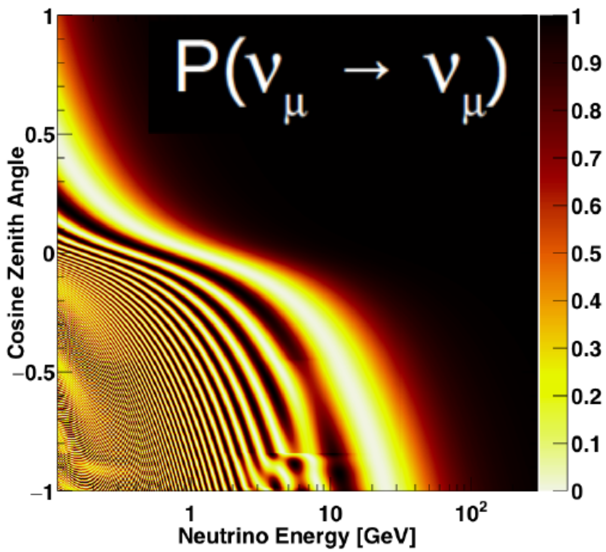
The Major Players

Detector	Target	Size	Threshold	PID	ν/νbar
Super-K	H_2O (lq)	50 kton	5 MeV	e-like / μ-like	Statistical
Hyper-K	H_2O (lq)	290 kton	5 MeV	e-like / μ-like	Statistical
I.C. Deep Core	H_2O (ice)	6 Mton	5 GeV	Casc./Track	---
I.C. Upgrade	H_2O (ice)	1 km^3	3 GeV	Casc./Track	---
I.C. Gen2	H_2O (ice)	8 km^3	~100 GeV	Casc./Track	---
Antares	H_2O (lq)	0.02 km^3	20 GeV	Shower/Track	---
KM3NeT Orca	H_2O (lq)	~10 Mton	1 GeV	Shower/Track	---
KM3NeT Arca	H_2O (lq)	1 km^3	~200 GeV	Shower/Track	---
DUNE	Ar (lq)	40 kton	5 MeV	Charged	Statistical
ICAL	Fe	50 kton	1 GeV	Tracks	Yes

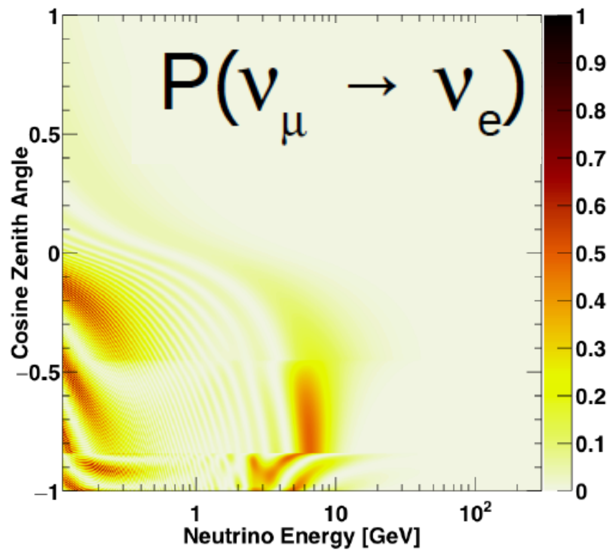
- Most present and future atmospheric neutrino detectors cannot distinguish neutrinos from antineutrinos well
- Many complementary experiments covering complementary energy regions

Mass Hierarchy Determination and the Matter Effect

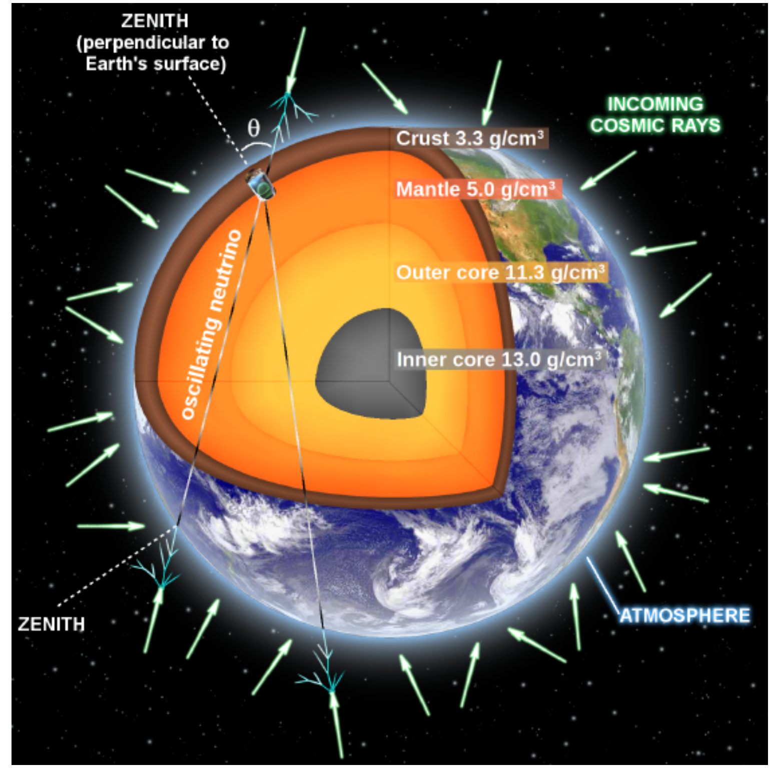
Normal Hierarchy



(a) $P(\nu_\mu \to \nu_\mu)$



(b) $P(\nu_\mu \to \nu_e)$



Neutrino Oscillations

- ν_e traveling through the earth experience resonant-enhanced oscillations which depend on the mass hierarchy
- NH : neutrinos experience the resonance
- IH : antineutrinos experience the resonance
- However the size of the resonance depends on θ_{13}, θ_{23}, δ_{cp} , and the density of electrons in the Earth

Mass Hierarchy Determination and the Matter Effect

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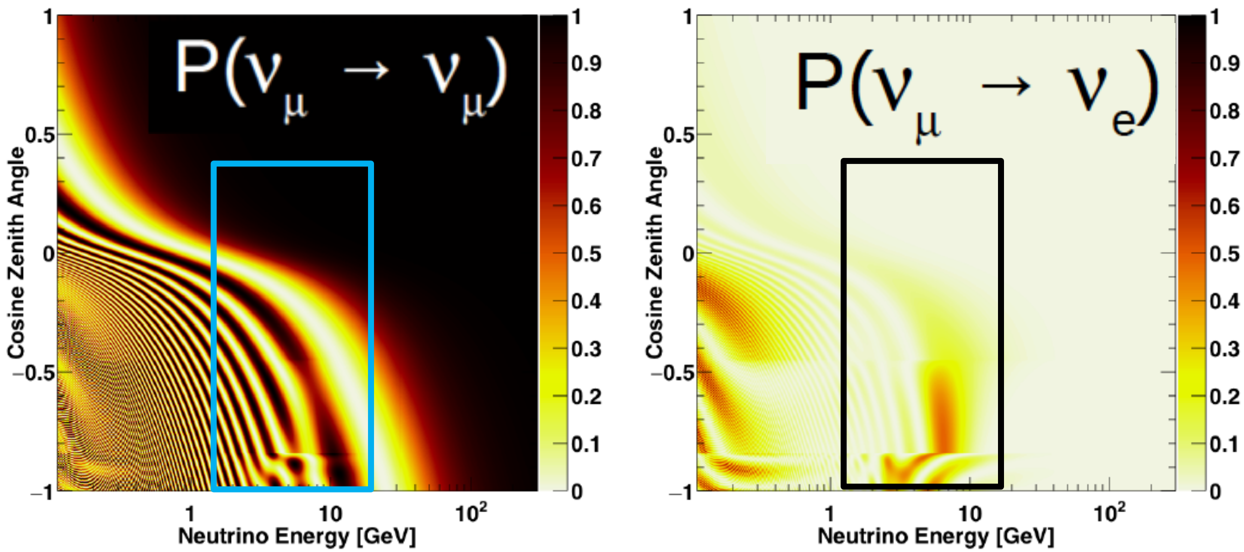
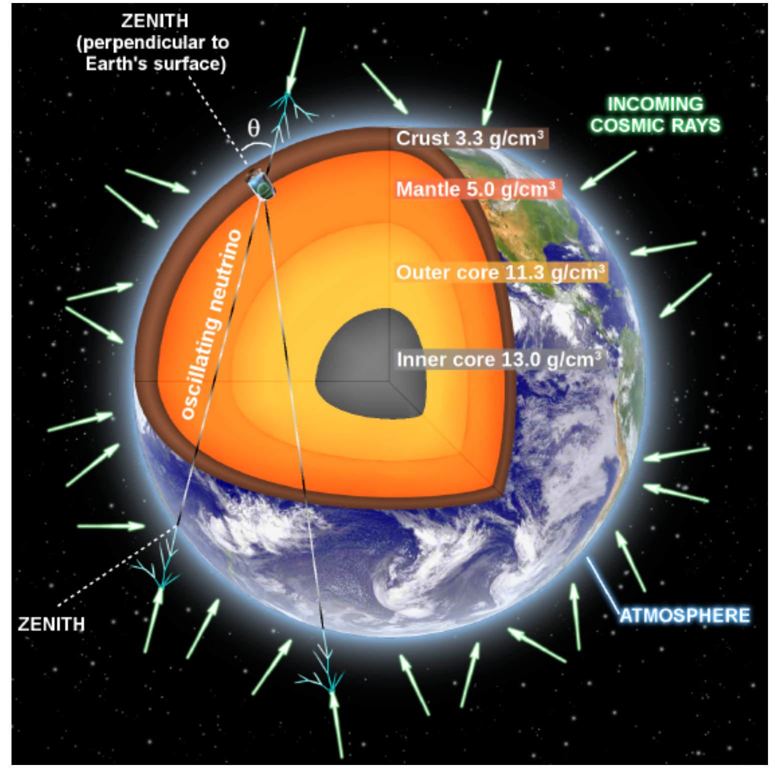


(a) $P(\nu_\mu \to \nu_\mu)$ (b) $P(\nu_\mu \to \nu_e)$



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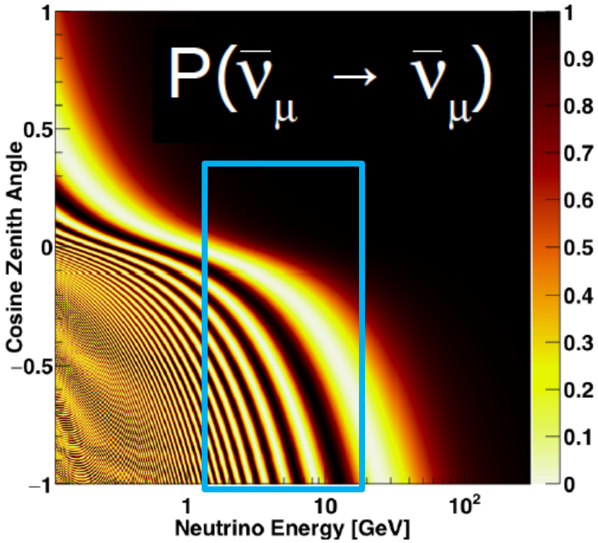
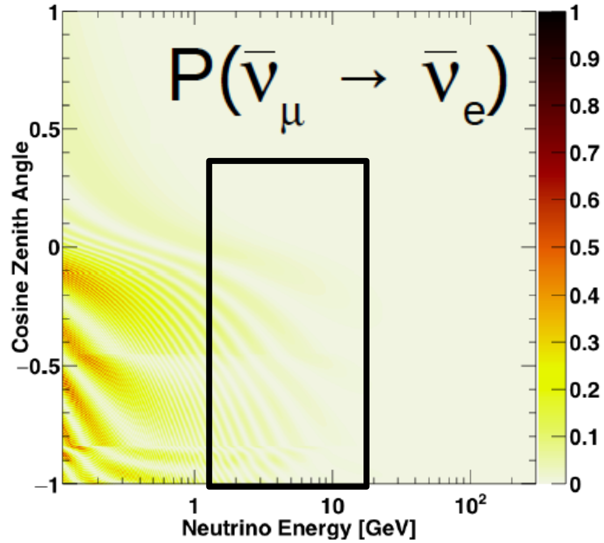
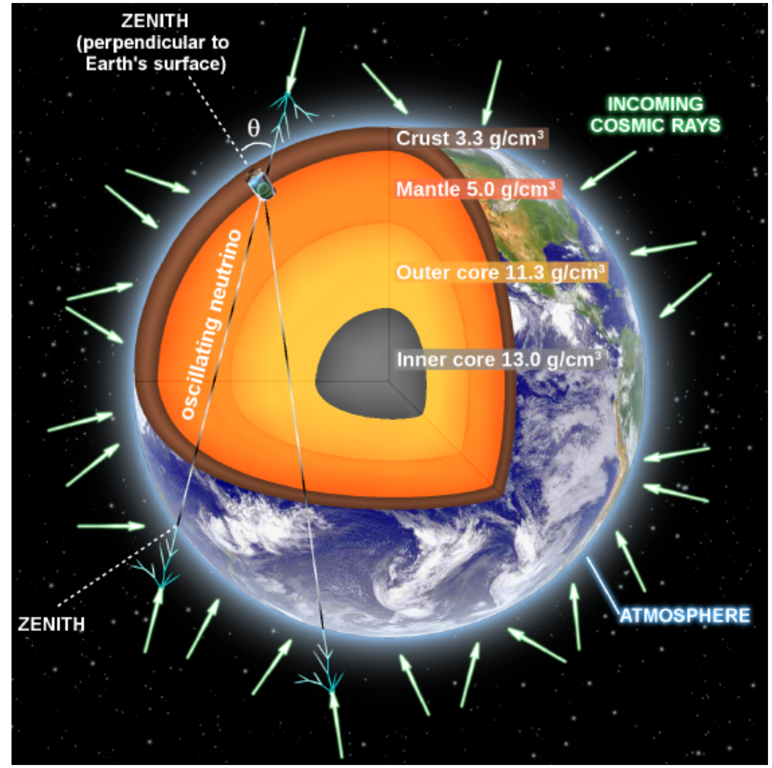


(c) $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$



(d) $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Antineutrino Oscillations



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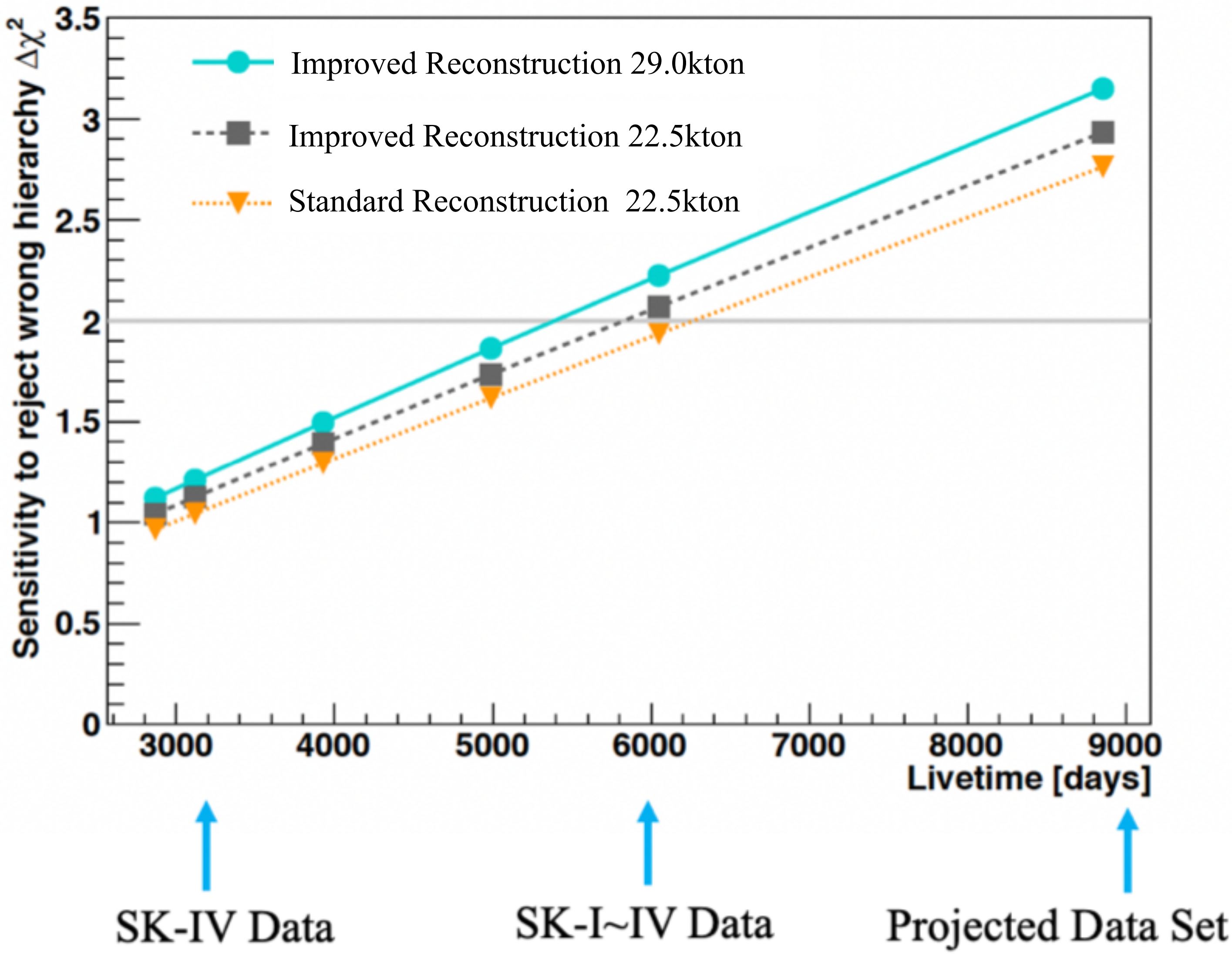
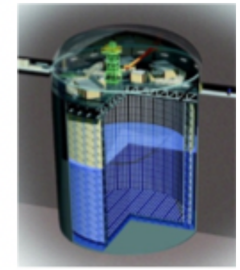
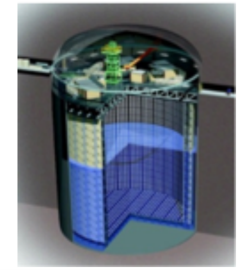
Super-Kamiokande Prospects : Mass Hierarchy Sensitivity

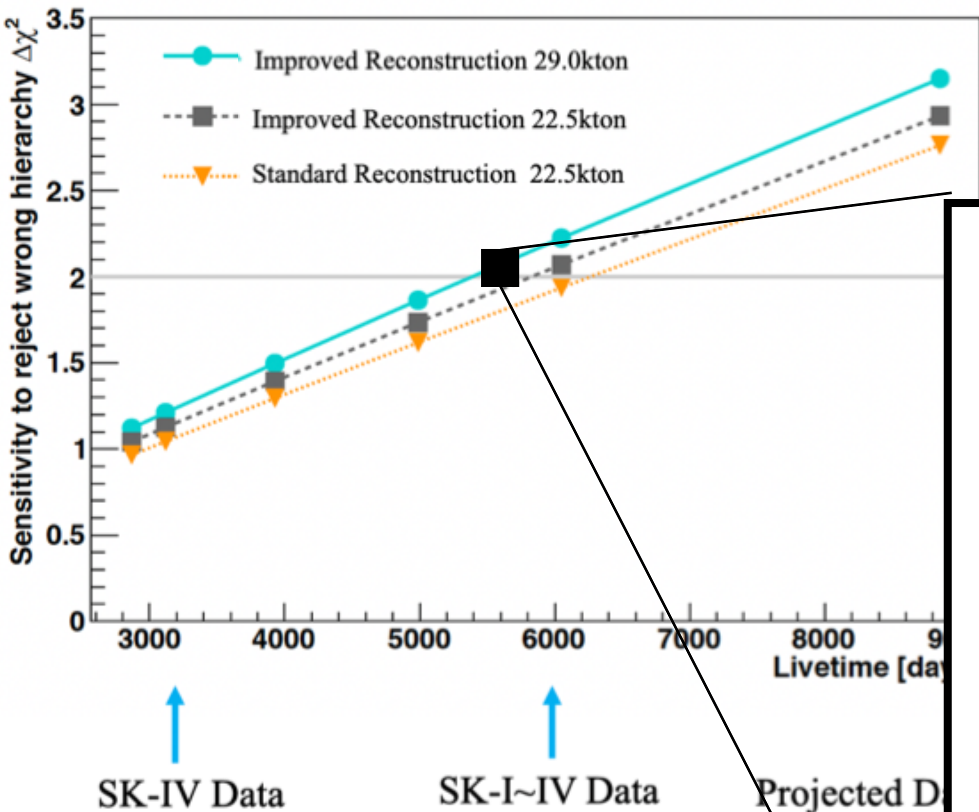


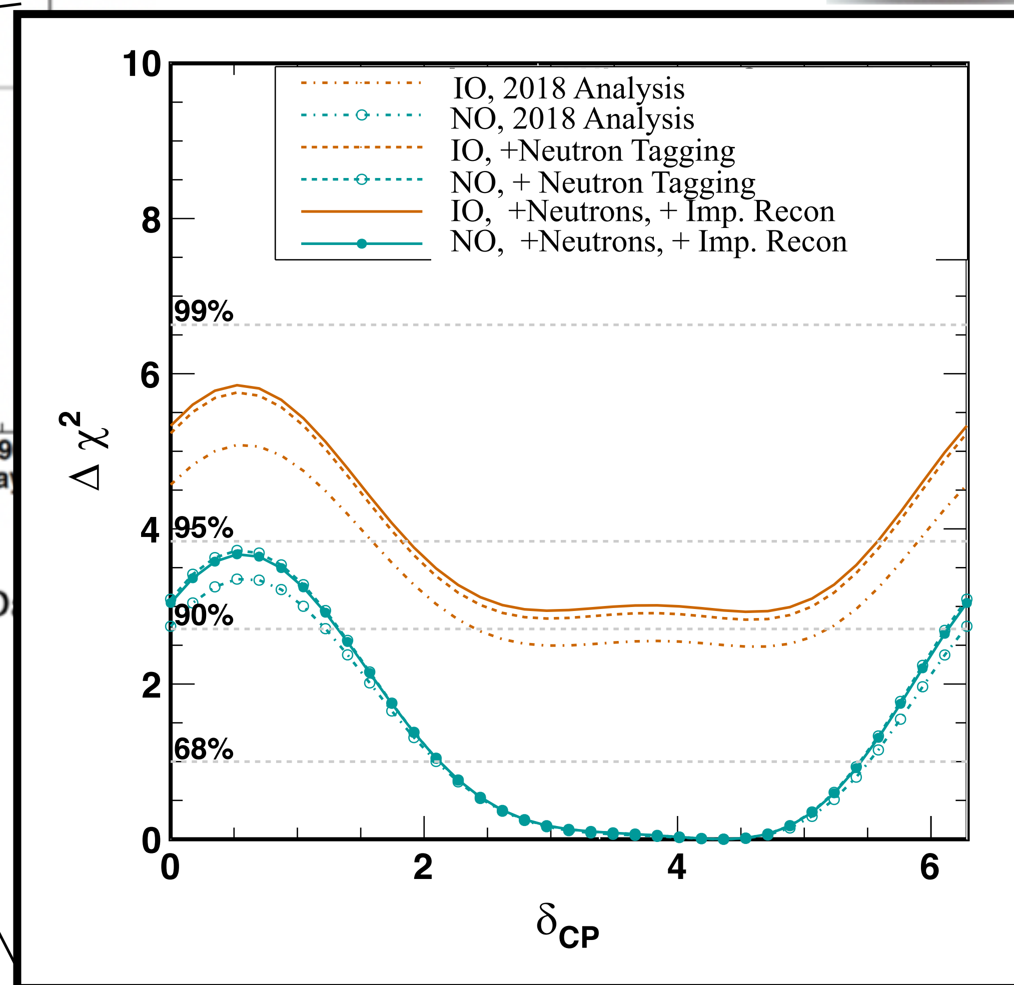


- Modest sensitivity improvement expected with improved reconstruction (“fiTQun”)
  - Reduce νμ and NC backgrounds and allows for expanded

Super-Kamiokande Prospects : Mass Hierarchy Sensitivity







- Improved event selection:
  - Reduced nm background at high energies
  - Neutron Tagging (25% eff) for ν/νbar separation
  - → +15% sensitivity in 2020

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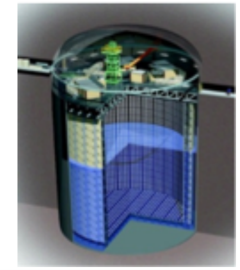

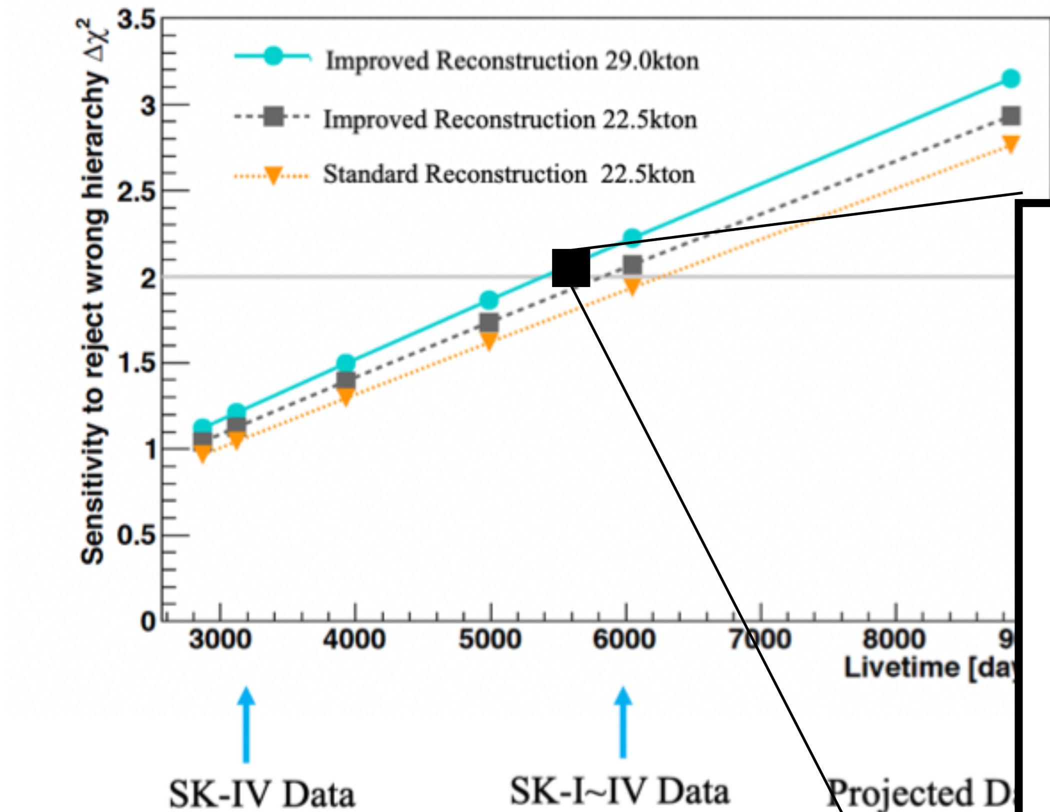

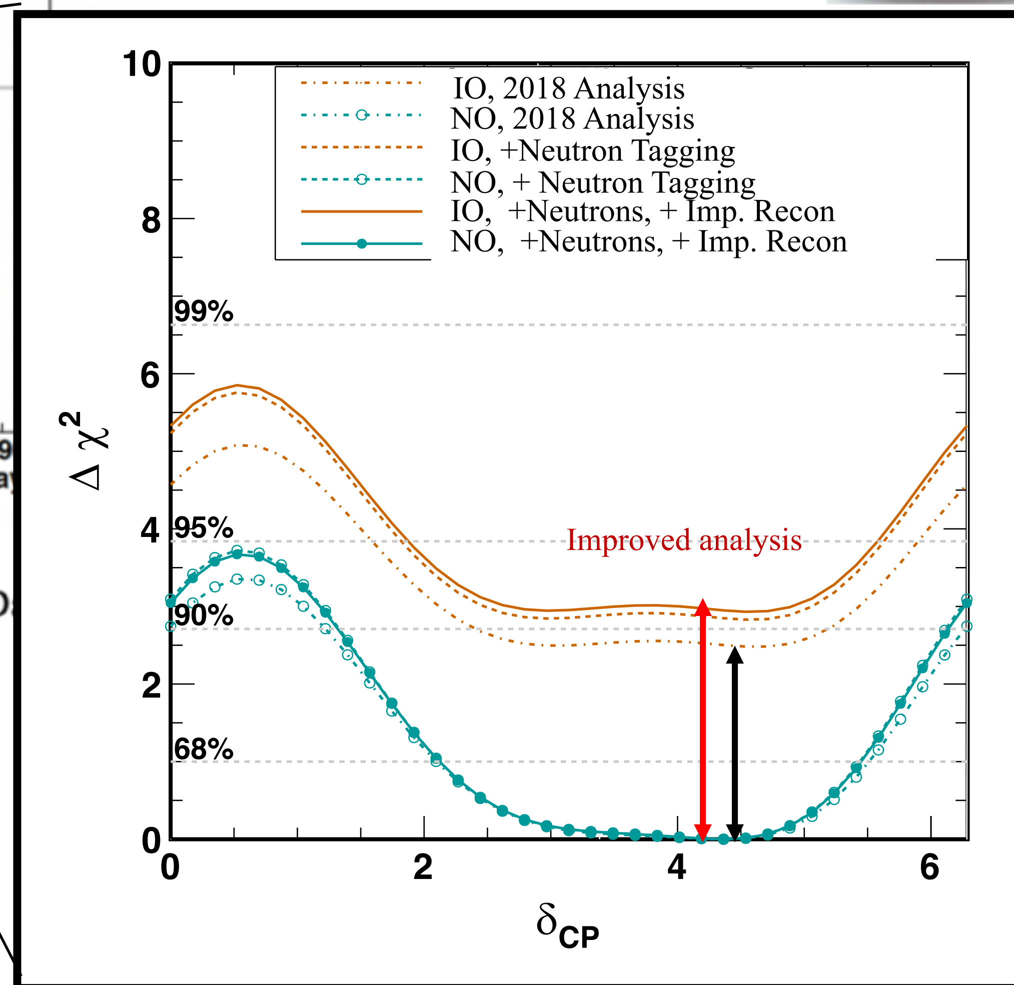

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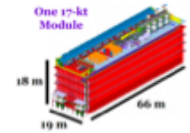
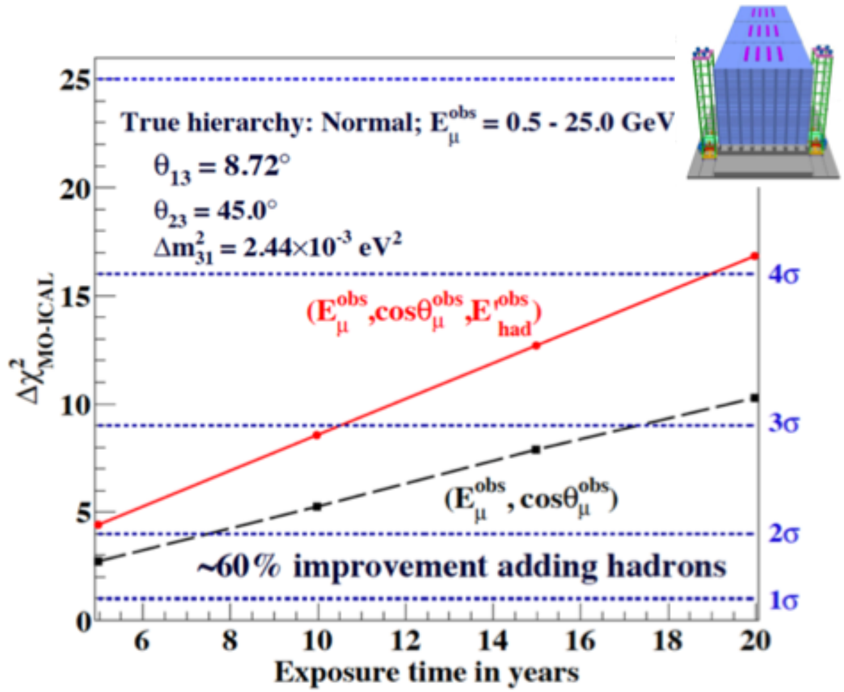
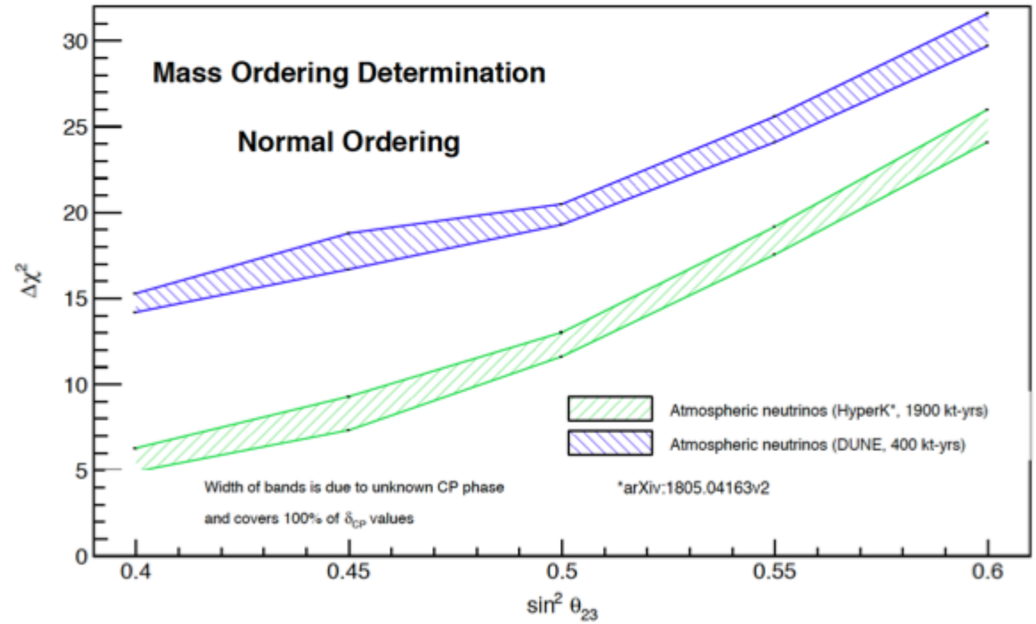
Standalone MO Measurements



arXiv:2002.03005v1





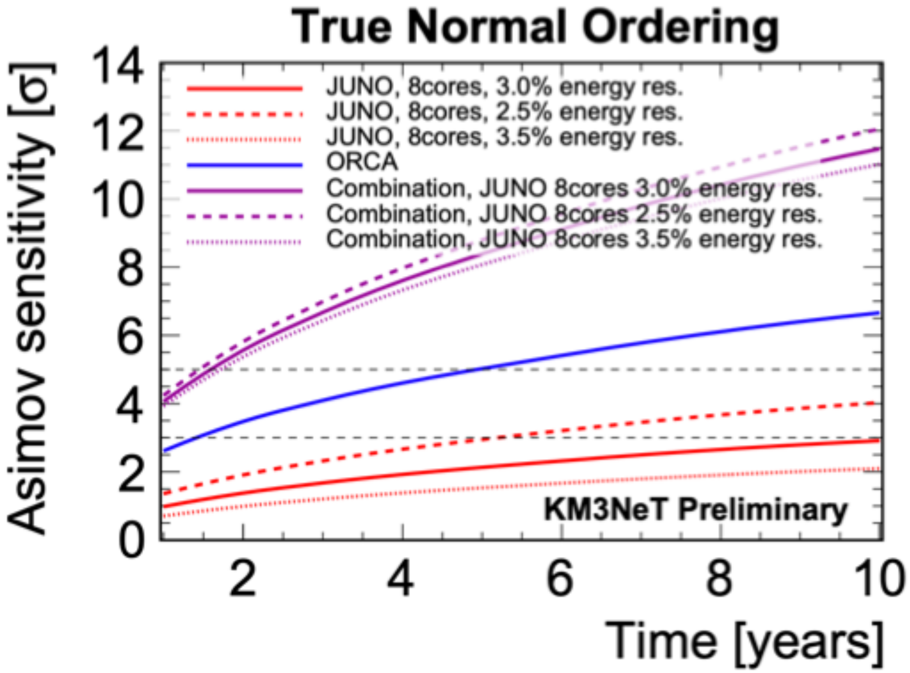
- Measurements with only atmospheric neutrinos should exceed 3σ in all but the most pessimistic cases

- Lots of ideas for improving sensitivity faster:
  - Neutron tagging (Water Cherenkov)
  - Proton-Lepton kinematics (LAr)
  - Magnetization (Fe)

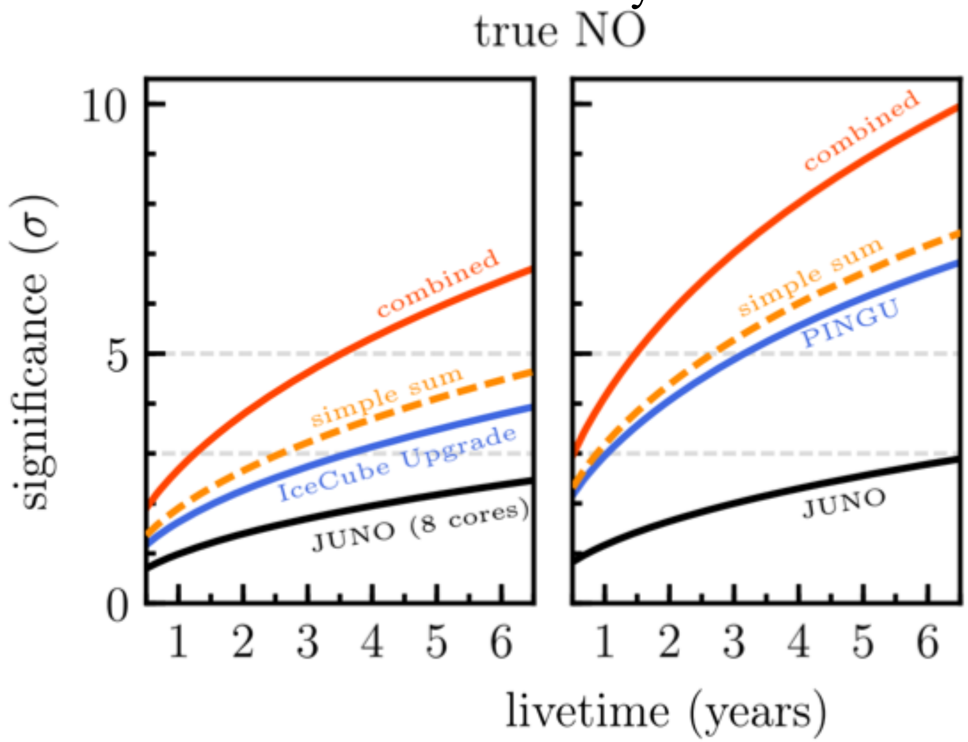
- Expect even further improvement with combined measurements

Cooperative MO Measurements

N. Chau Neutrino 2020

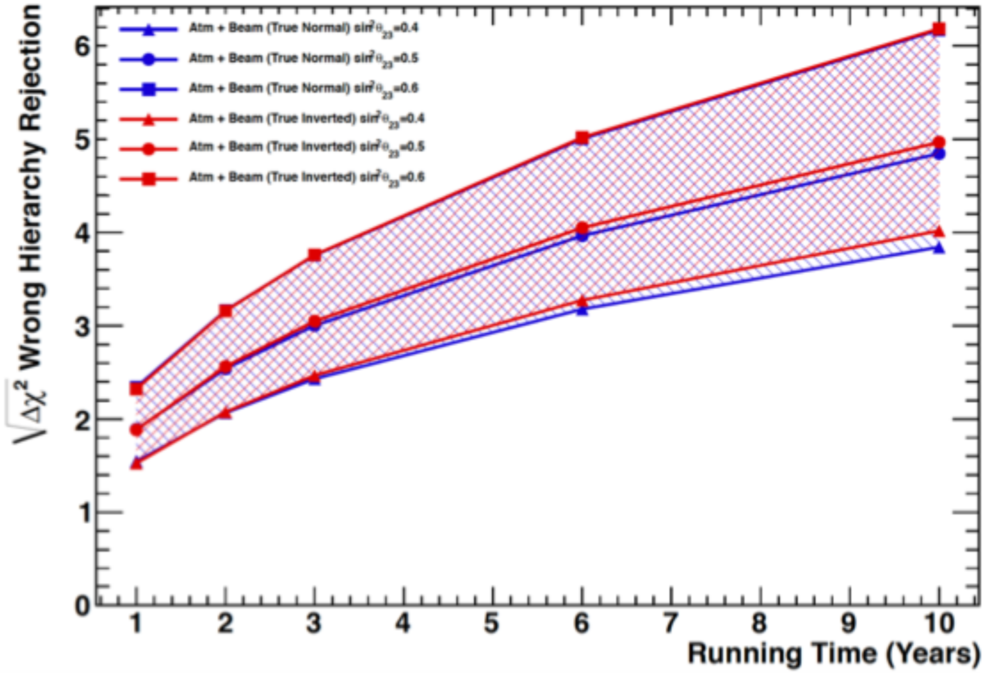


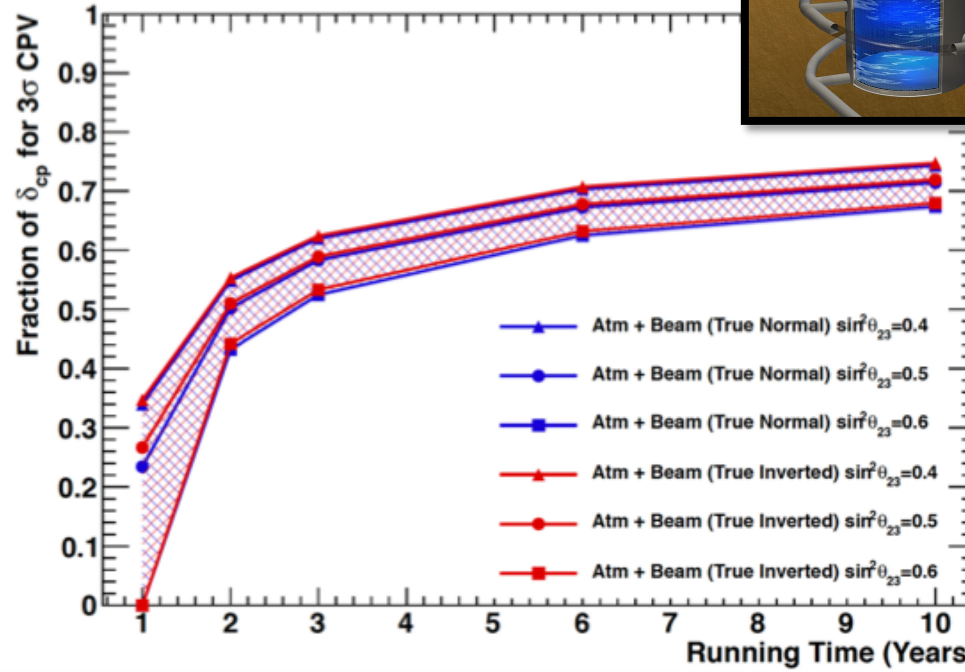
PhysRevD.101.032006

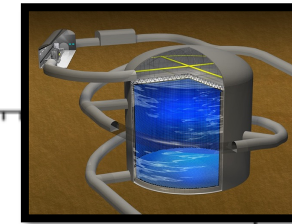


- Combination of JUNO (reactor) and Neutrino Telescopes provides powerful synergistic constraints on the MO
- Conflict of hierarchy+parameter effects in their respective sample allows for stronger constraints than naïve combination of the experiments

Hyper-K : Beam and Atmospheric Neutrino





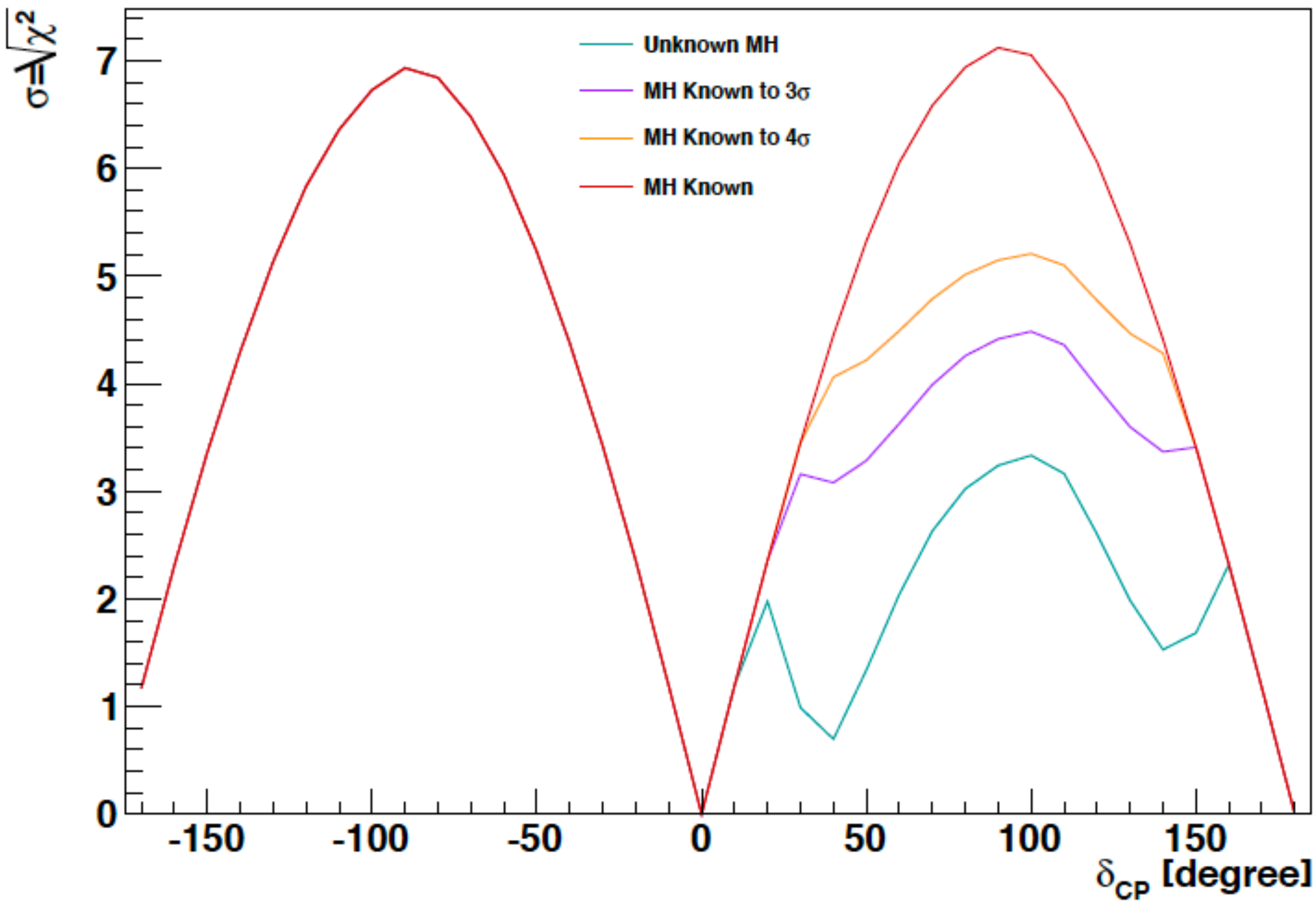


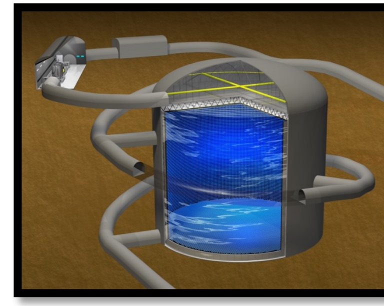
- Sensitivity to matter effects (mass hierarchy) increased with improved constraint on atmospheric mixing parameters
- Measurement of CP phase is dominated by accelerator measurement, but parameter degeneracies are broken by atmospheric component, resulting in better sensitivity faster
- Expect similar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

Mass Ordering Significance by Approximate Date ($\sin^2\theta_{23}=0.6$)

Experiment	2021	2026-7	2031	2036
Super-K	2.5σ	3σ		
T2K /-II		$\sim1\sigma$		
NOvA	3.4σ	4.4σ		
KM3NeT (Orca)		5σ	7σ	
IceCube (Pingu)		$>4\sigma$		
JUNO		3σ		
ICAL-INO		2σ	3σ	$\sim4\sigma$
DUNE		3σ	5σ	$\sim7\sigma$
Hyper-K (+beam)			4σ	$\sim6\sigma$
JUNO+PINGU			10σ	
JUNO+ORCA			10σ	

The Door Swings Both Ways: Combining Beam and Atm ν



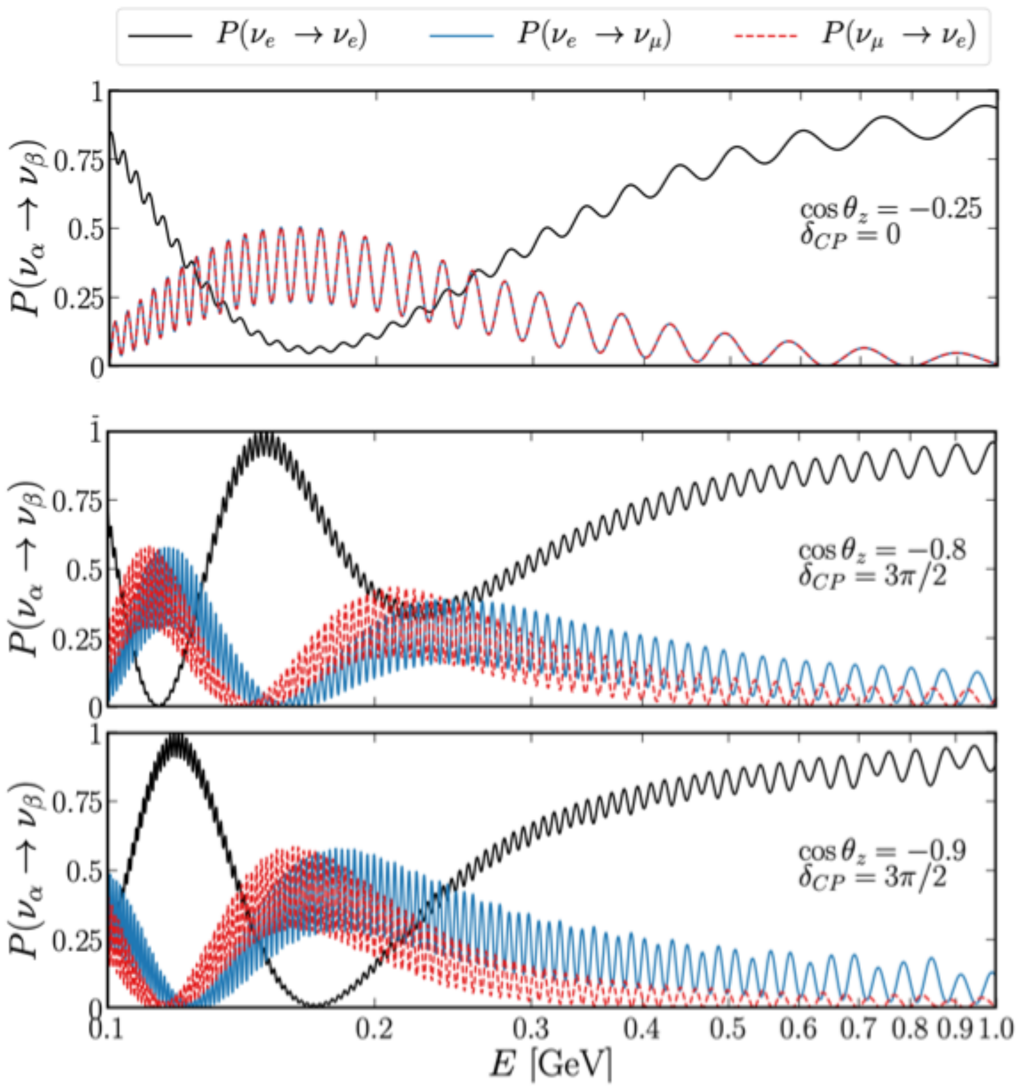


Plot shows the ability to reject sin(δ) = 0 points

Expected sensitivity improves (beam only) when the mass hierarchy is known with high precision

What about CP Measurements with Atmospheric ν?

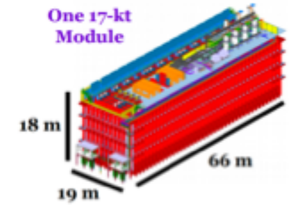
FERMILAB-PUB-19-136-T, NUHEP-TH/19-03

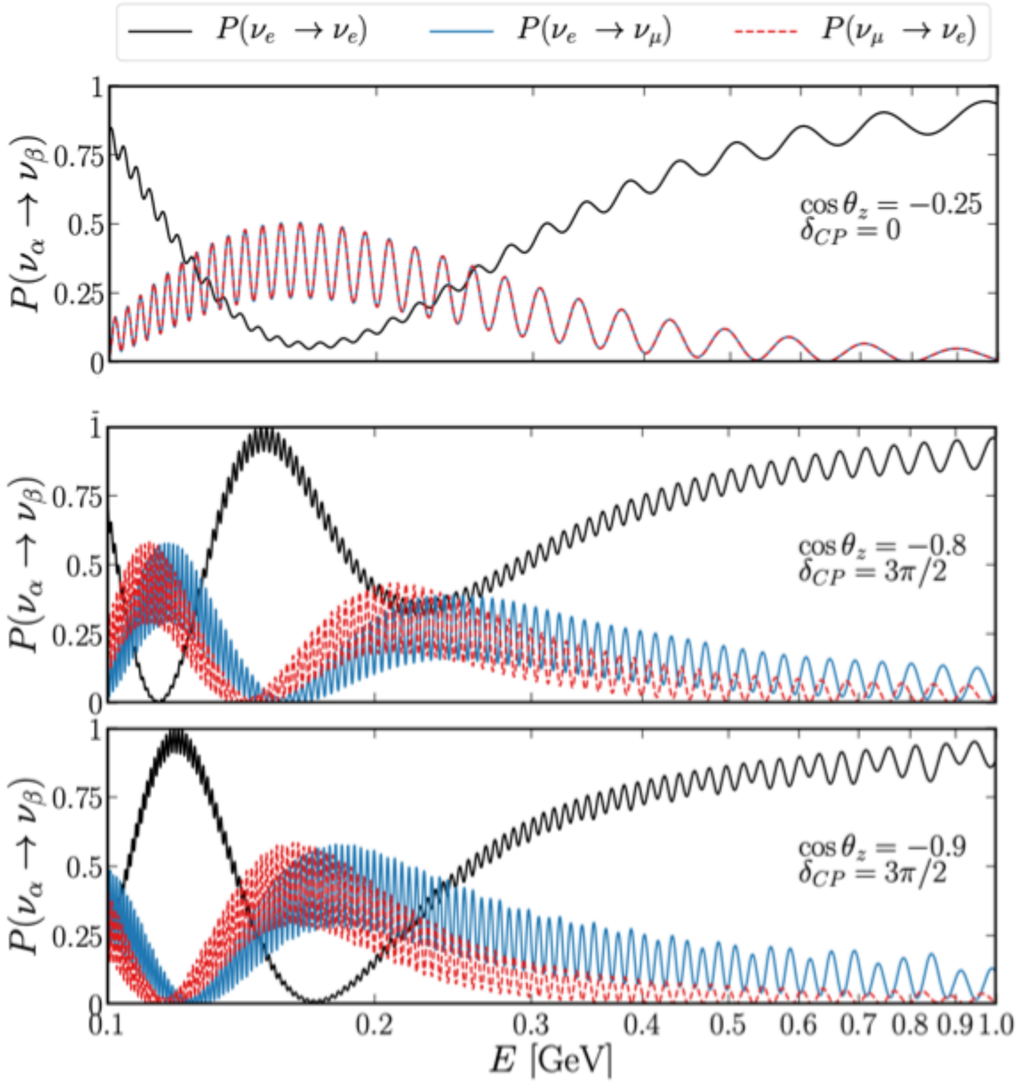


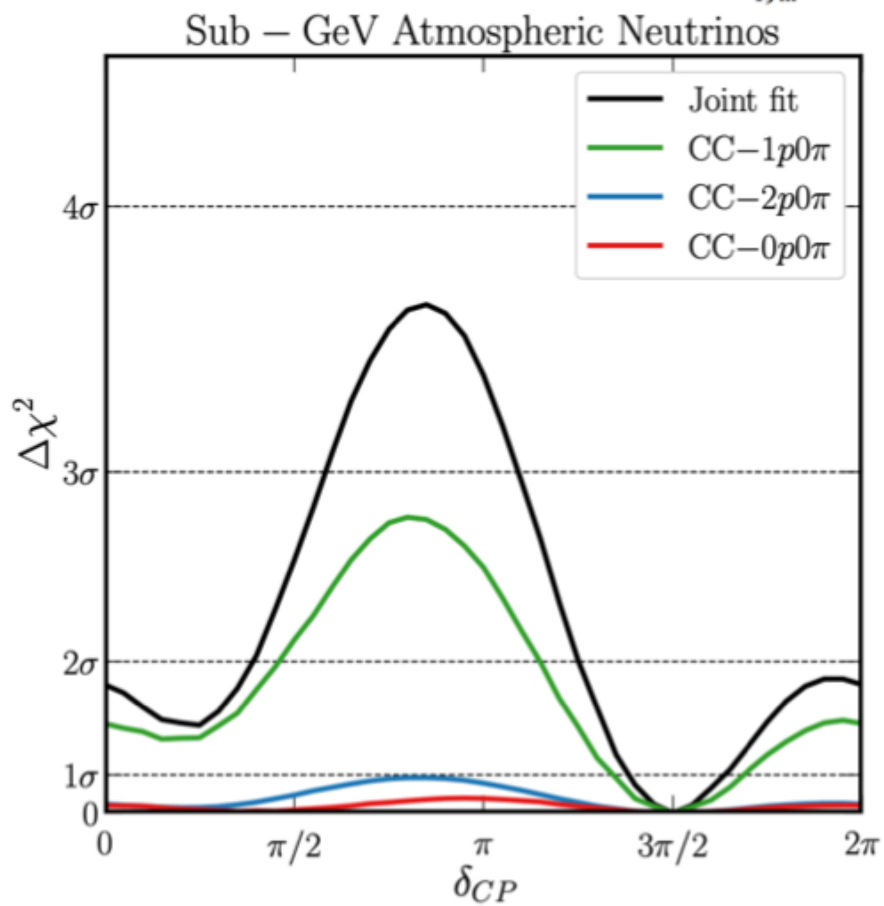
- CP effect largest at low energies, highly complementary to beam measuremests
  - → Many baselines gives acces to cos(δ)
- Flux uncertainties are large
- Dominated by CCQE interactions, poor resolution on neutrino direction without kinematic reconstruction of full final state
- Fast oscillations smear out the CP signal

What about CP Measurements with Atmospheric ν?

FERMILAB-PUB-19-136-T, NUHEP-TH/19-03

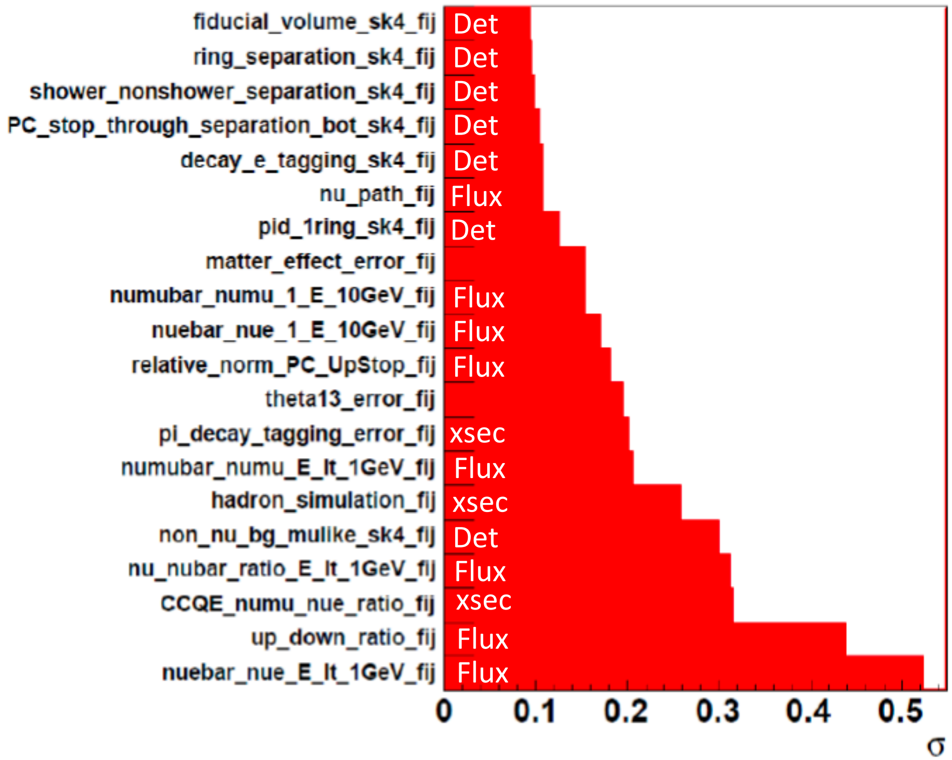




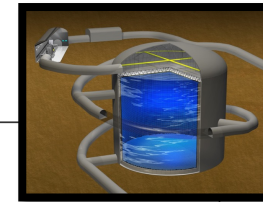


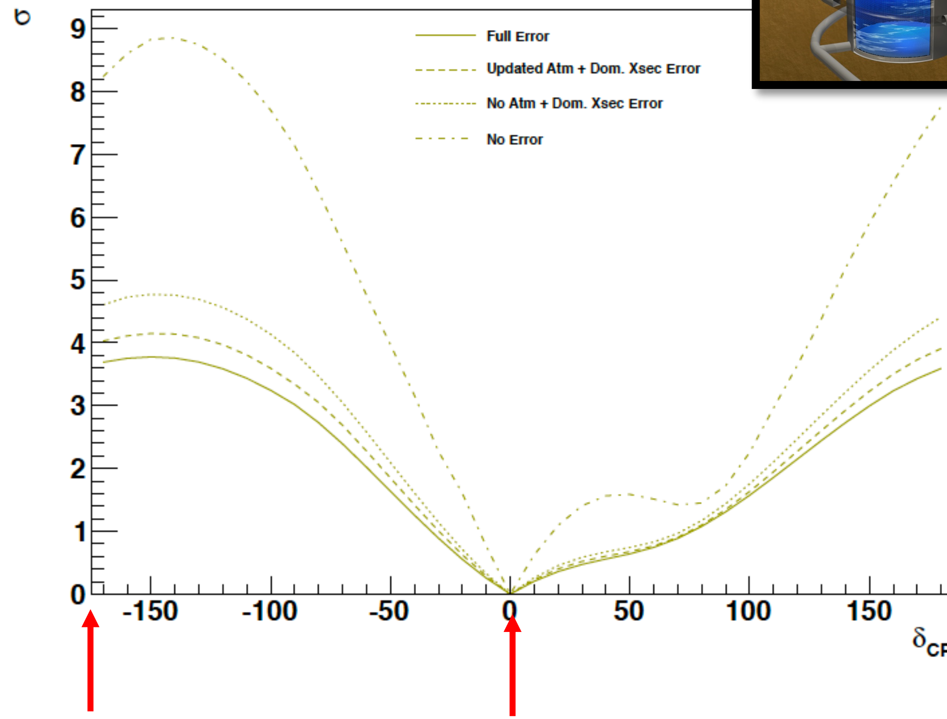
Impact of Various Systematic Error Sources: δ_{CP} Measurement

All Error



True δ_{CP} = 0

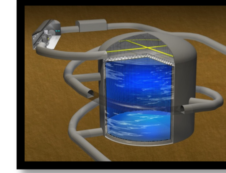


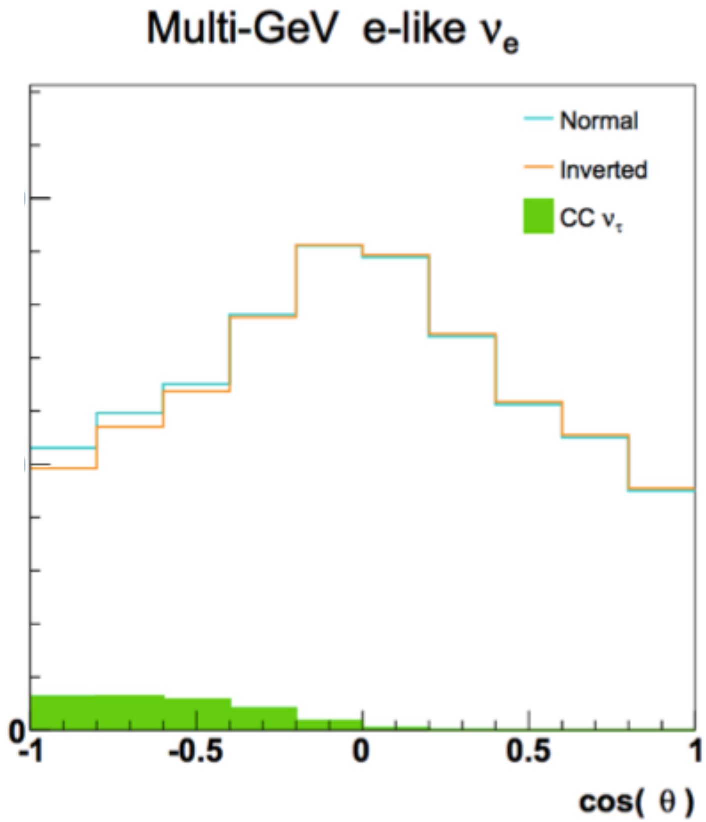


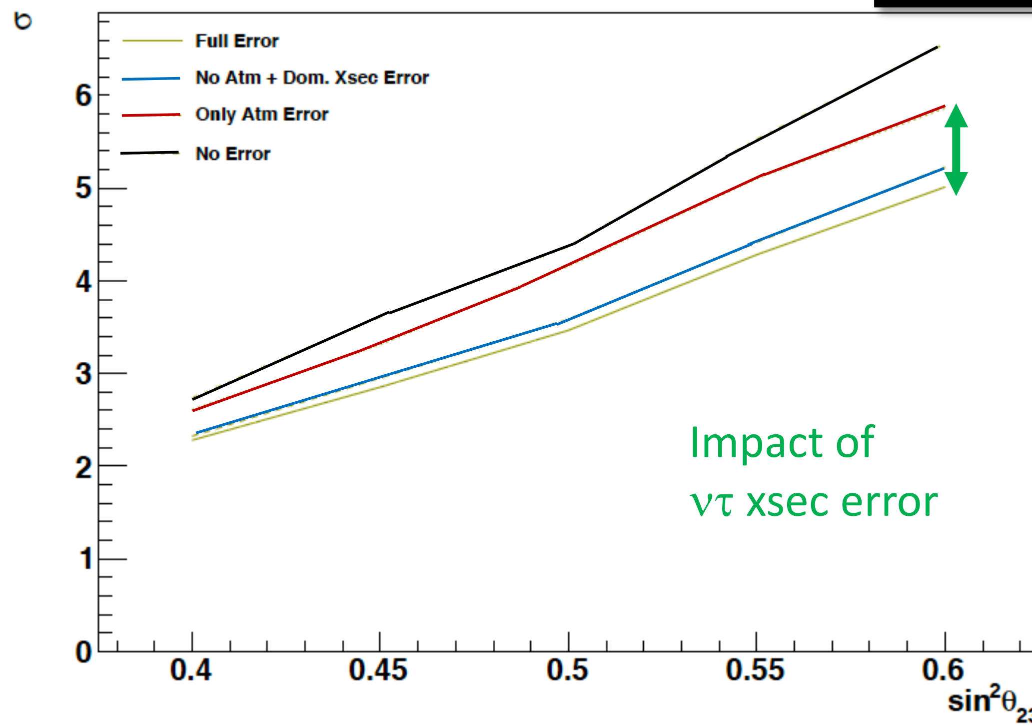
Difference in systematic pulls here

- Without significant improvements in flux and cross section systematic errors it will be difficult for atmospheric neutrinos to compete with acceleratore measurements
  - → Complementary

Hyper-Kamiokande : Mass Hierarchy Prospects



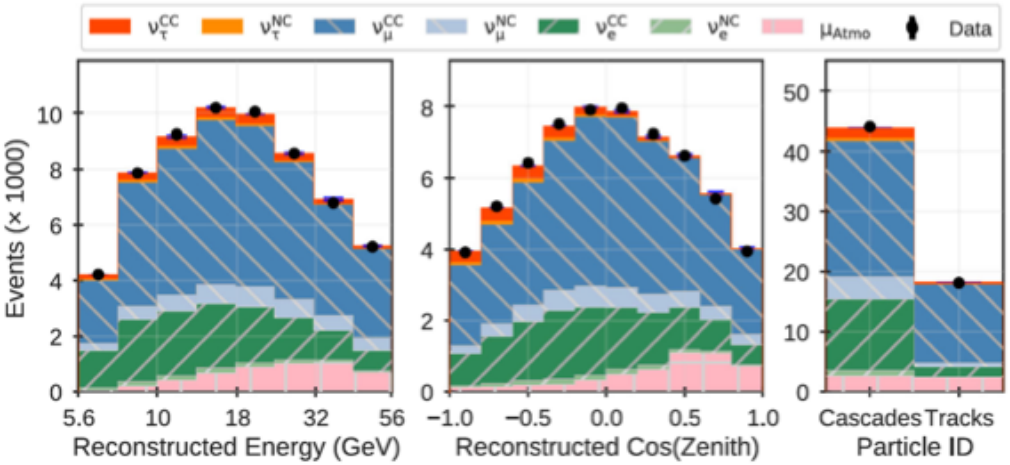


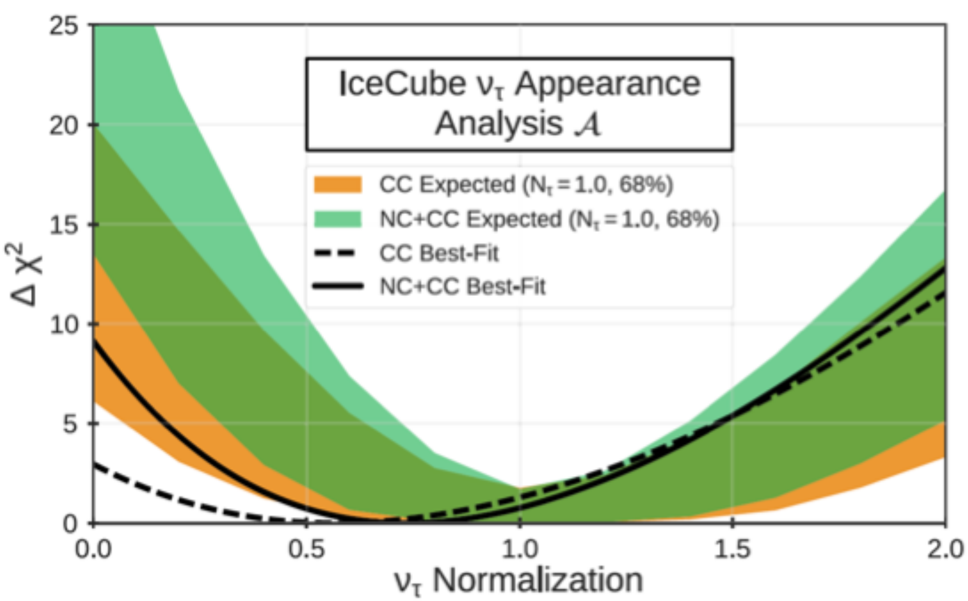


- Tau neutrinos are expected to appear in the same kinematic region as the mass hierarchy signal
- Uncertainty in the tau cross section (currently ~25%) has a large impact on expected sensitivity
- In addition, νμ and NC backgrounds present in signal sample

Search for Tau Neutrinos

PHYS. REV. D 99, 032007 (2019)

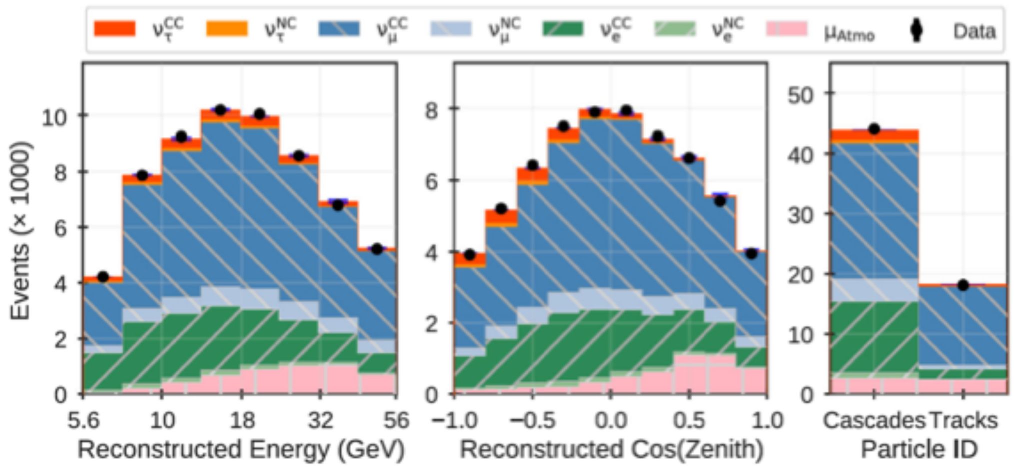


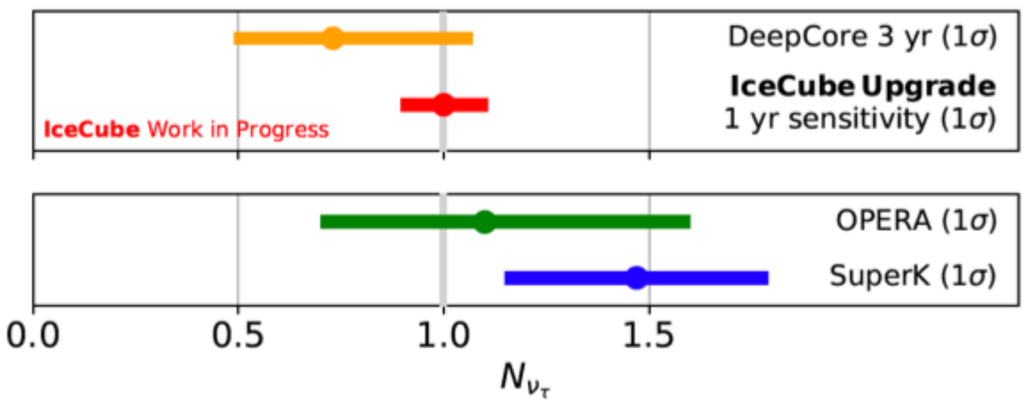


- No ντ in atmospheric flux below 100 TeV
- Search for evidence of oscillation-induced tau interactions
- Appear as increase in number of cascade-like events (hadronic decay of tau)
- Use BDTs to extract signal, incurs large backgrounds, constrained by zenith and energy distributions
- IceCube finds 3.2σ significance for appearance of tau events (CC+NC)
- Complementary to other recent searches
  - 6.1σ from Opera (acc. 2018)
  - 4.6σ from Super-K (atm. 2018)

Search for Tau Neutrinos

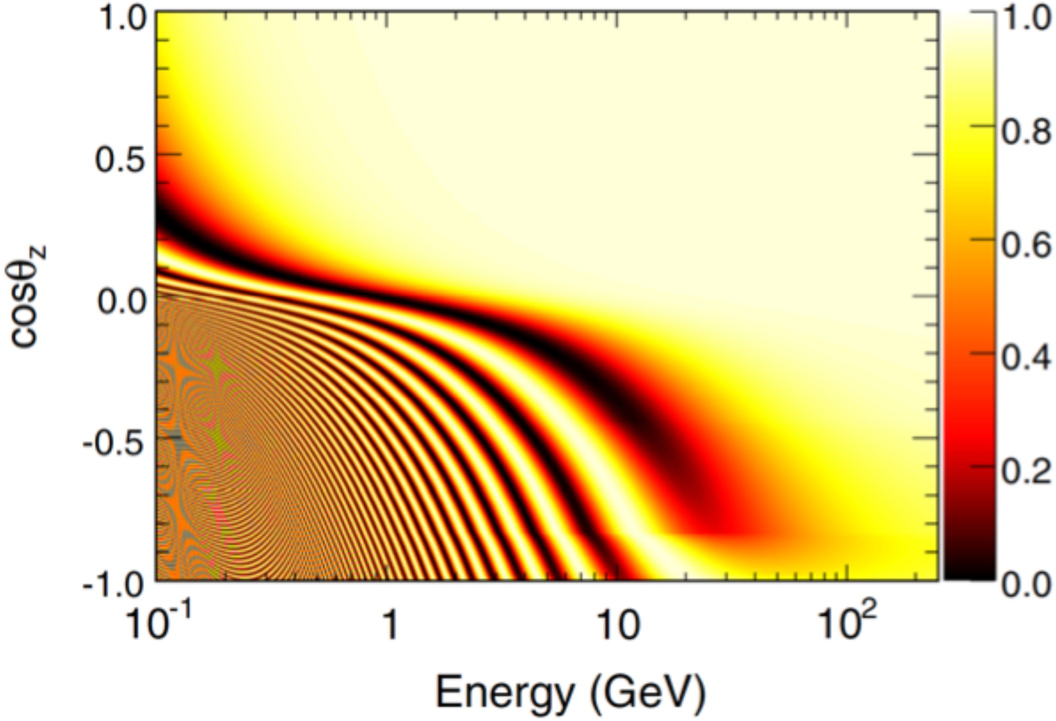
PHYS. REV. D 99, 032007 (2019)



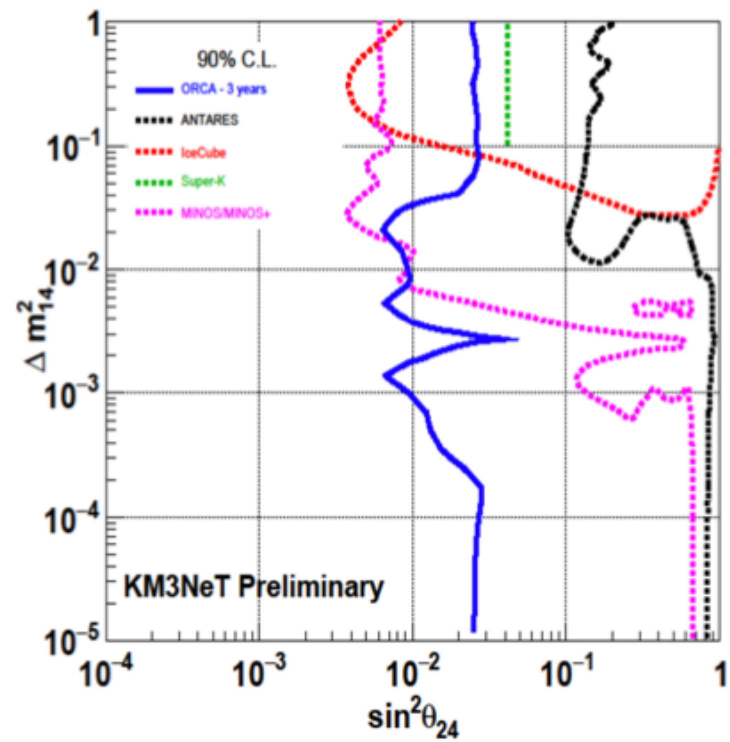


- No ντ in atmospheric flux below 100 TeV
- Search for evidence of oscillation-induced tau interactions
- Appear as increase in number of cascade-like events (hadronic decay of tau)
- Use BDTs to extract signal, incurs large backgrounds, constrained by zenith and energy distributions
- Expect precise measurements of tau normalization at future detector
  - IceCube Upgrade: << 10%
  - Hyper-K : ~10%

Sterile Neutrino Searches:



JHEP06(2019)113



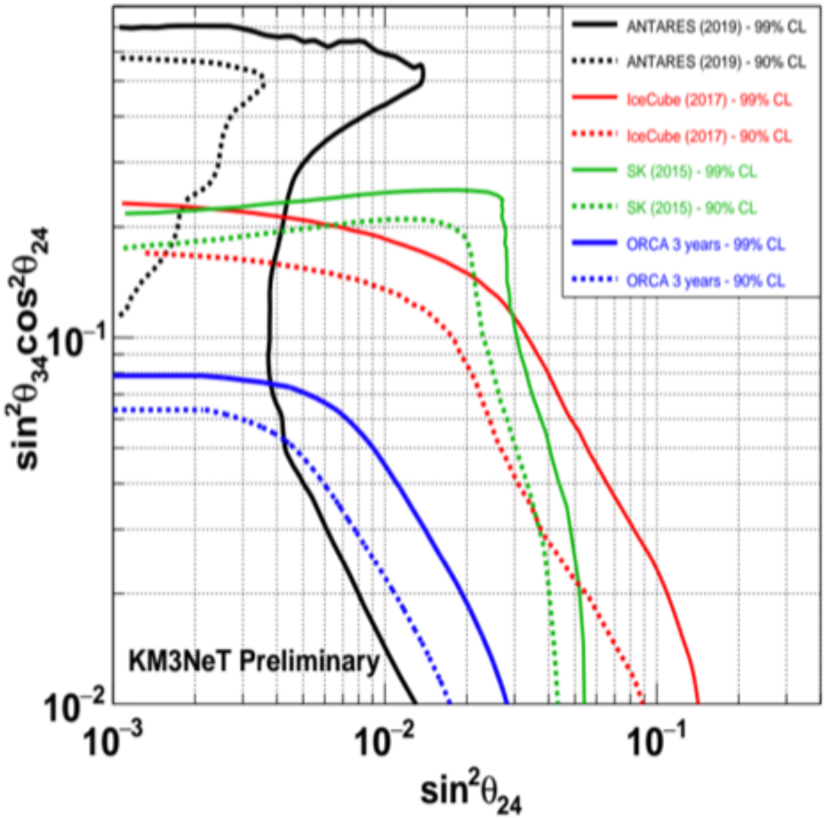
- Add an additional mass state for a neutrino with no weak interactions and expand mixing matrix accordingly

- Track-like events from 20~100 GeV used in Antares study

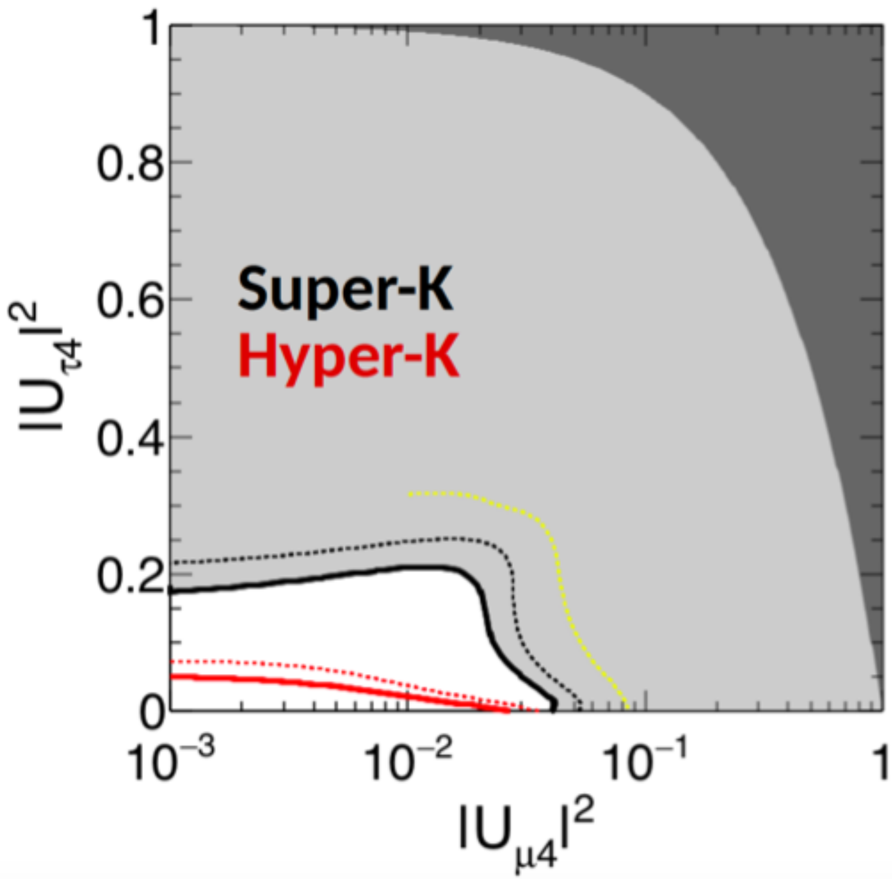
- Present results in the atmospheric mixing community are compatible with pure MNS mixing, but expect improved sensitivity at at future experiments

$$U_{\mu 4} = e^{-i\delta_{24}} \sin\theta_{24} ,$$
$$U_{\tau 4} = \sin\theta_{34} \cos\theta_{24}$$

Sterile Neutrino Searches:



PHYSICAL REVIEW D 91, 052019 (2015)



- Sterile neutrino oscillation sensitivity limited by uncertainties in flux (and cross section) around 1 GeV

- Particularly $U_{\mu 4}$ at water Cherenkov will be difficult

$$U_{\mu 4} = e^{-i\delta_{24}} \sin\theta_{24} ,$$
$$U_{\tau 4} = \sin\theta_{34} \cos\theta_{24}$$

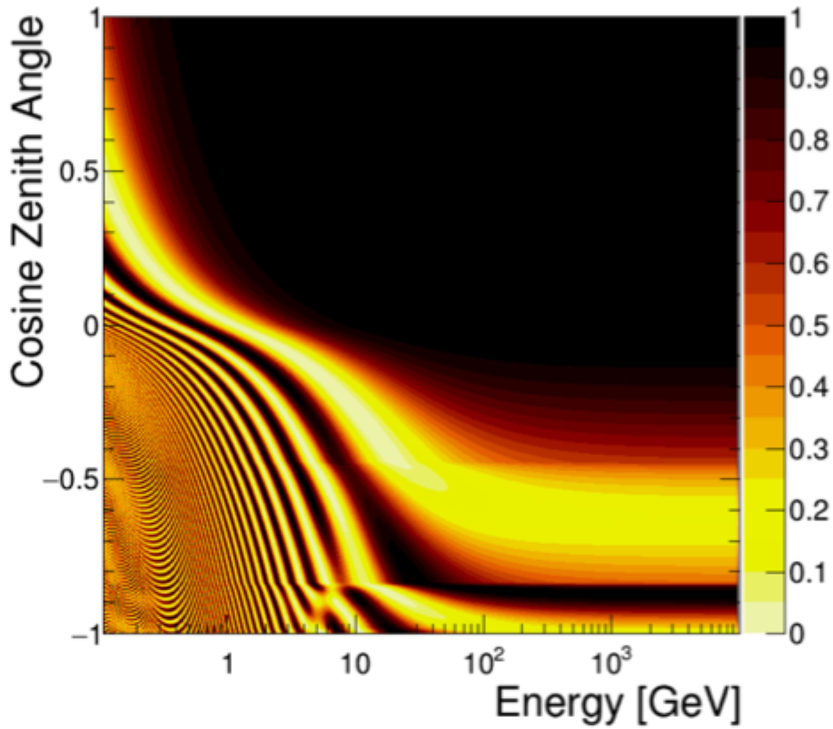
Non-Standard Interactions : μ–τ

Vacuum oscillations | Matter oscillations

$$H_{\alpha\beta} = \frac{1}{2E} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} (U^\dagger)_{k\beta} + V_{\mathrm{MSW}} + \sqrt{2} G_F N_f(\vec{r}) \begin{pmatrix} \varepsilon_{ee} & \varepsilon^*_{e\mu} & \varepsilon^*_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon^*_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Standard oscillations | NSI

$\nu_\mu \rightarrow \nu_\mu$



μ-τ Fit

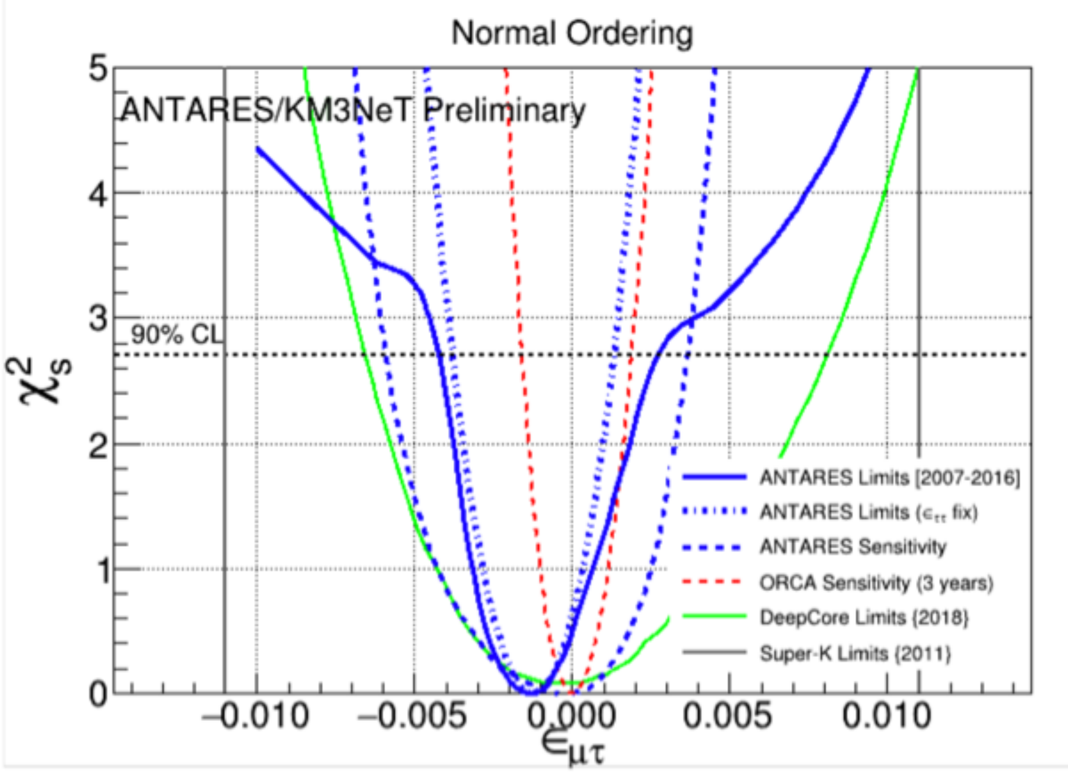
- Fixing other parameters to zero fit only μ–τ parameters
- Current measurements are compatible with no NSI at 90% C.L.
- Several single parameter limits, but expect considerable improvement from high—statistics neutrino telescope data
- Improved sensitivity with ν/νbar

Non-Standard Interactions : μ–τ

Vacuum oscillations | Matter oscillations

$$H_{\alpha\beta} = \frac{1}{2E} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} (U^\dagger)_{k\beta} + V_{\mathrm{MSW}} + \sqrt{2} G_F N_f(\vec{r}) \begin{pmatrix} \varepsilon_{ee} & \varepsilon^*_{e\mu} & \varepsilon^*_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon^*_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Standard oscillations | NSI



N.R.K Chowdhury Neutrino 2020

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Non-Standard Interactions : μ–τ

Vacuum oscillations

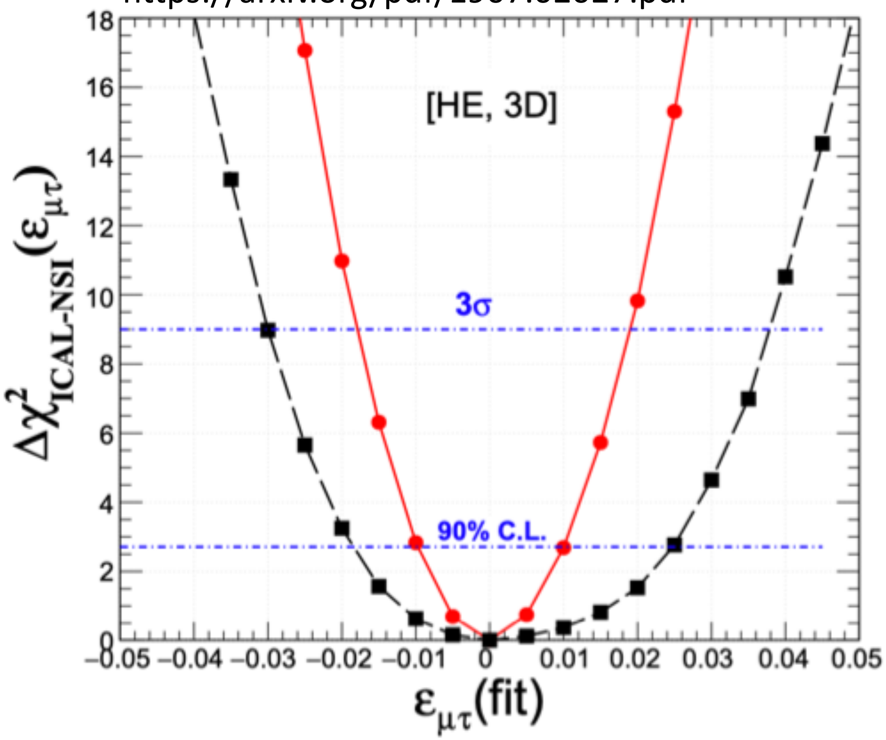
Matter oscillations

$$H_{\alpha\beta} = \frac{1}{2E} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} (U^\dagger)_{k\beta} + V_{\mathrm{MSW}} + \sqrt{2} G_F N_f(\vec{r}) \begin{pmatrix} \varepsilon_{ee} & \varepsilon^*_{e\mu} & \varepsilon^*_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon^*_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Standard oscillations

NSI

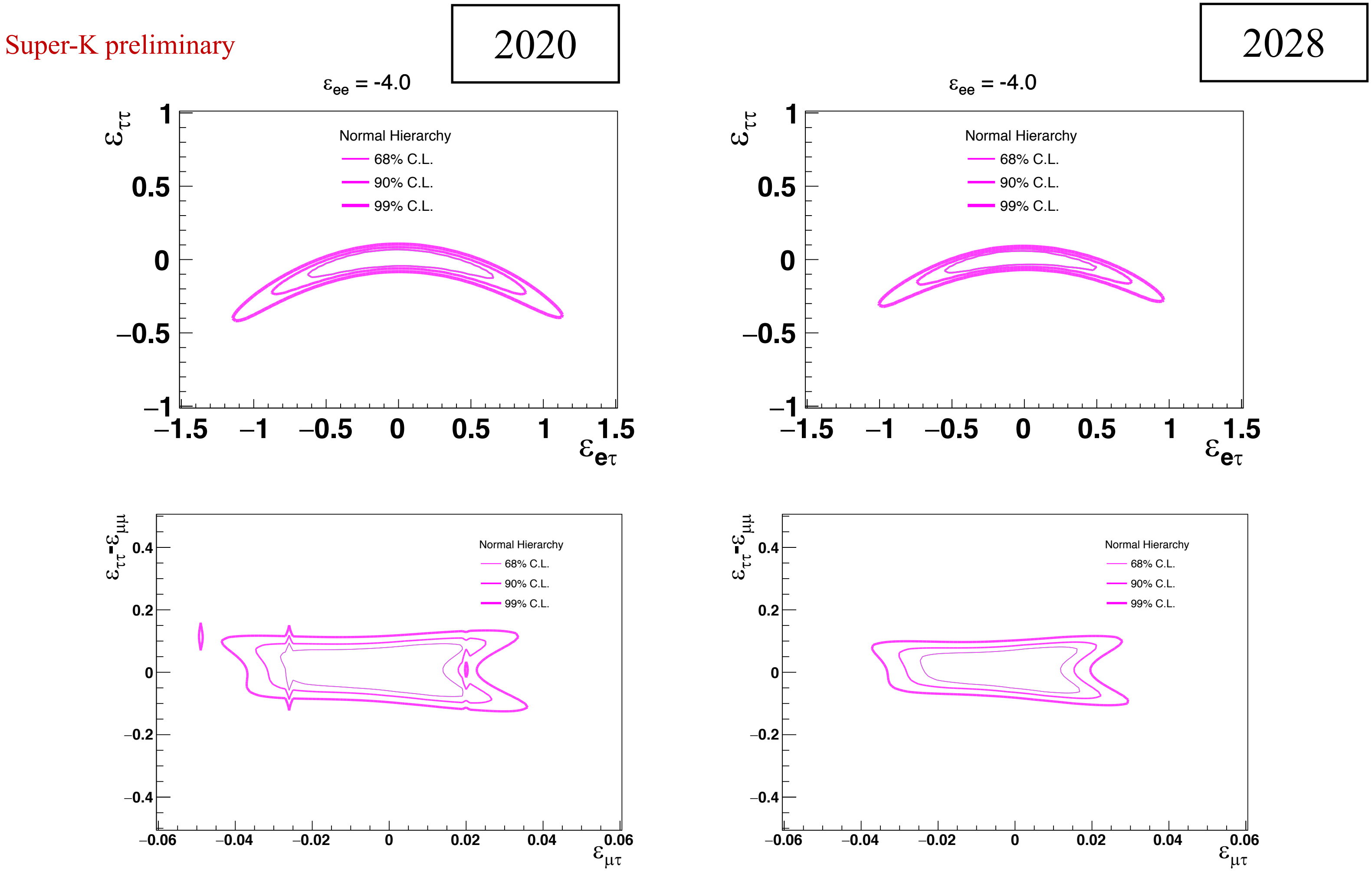
https://arxiv.org/pdf/1907.02027.pdf

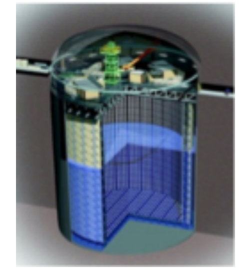


μ-τ Fit

- Fixing other parameters to zero fit only μ–τ parameters
- Current measurements are compatible with no NSI at 90% C.L.
- Several single parameter limits, but expect considerable improvement from high—statistics neutrino telescope data
- Improved sensitivity with ν/νbar

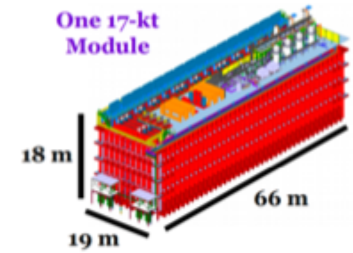
Sensitivity to Non-Standard Interactions : e−τ





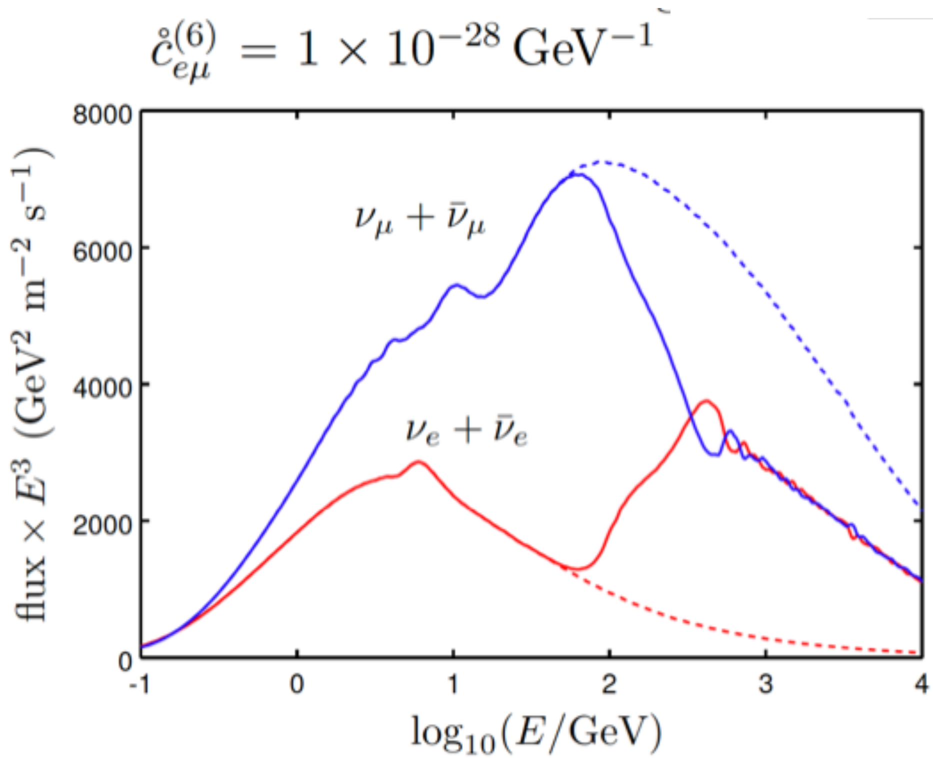
- Modest sensitivity improvements with increased exposure
- Limitations due to flux uncertainties at highest energies for Hyper-K

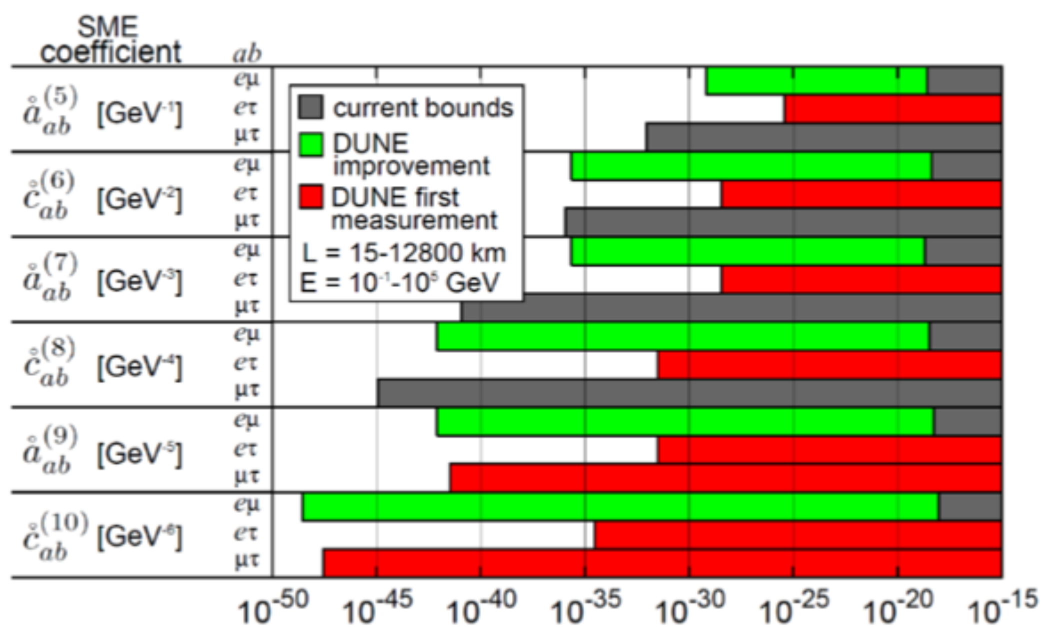
Lorentz-Invariance-Violating Oscillations



$$H_{LV} = \mathring{a}^{(3)} - E\mathring{c}^{(4)} + E^2\mathring{a}^{(5)} - E^3\mathring{c}^{(6)} \cdots$$

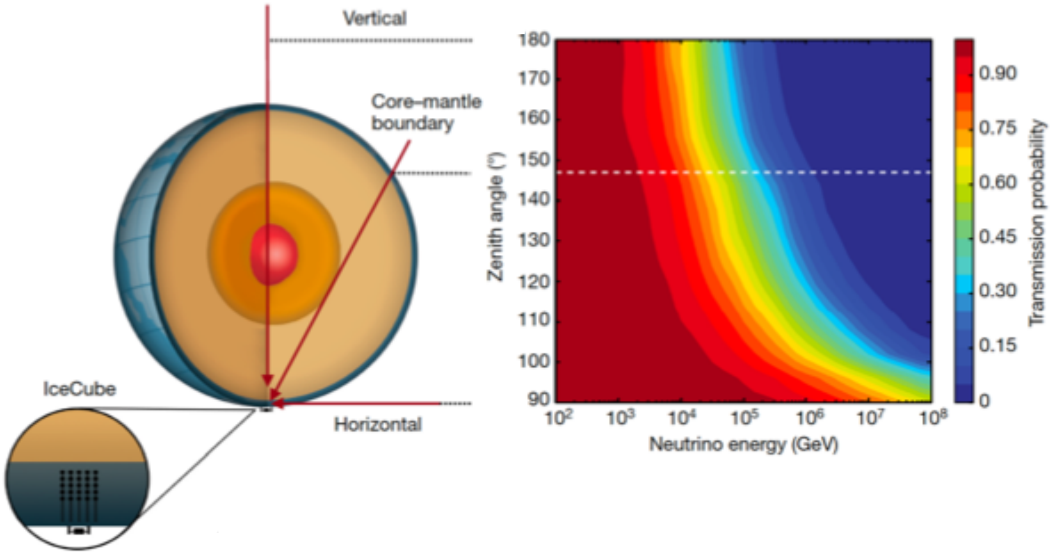
- Include Lorentz-violating operators from effective field theory (Standard Model Extension) , that induce oscillations that are a function of $L \times E^n$
- Present ν limits dominanted by IceCube, Super-K , but expect further constraints from future detectors



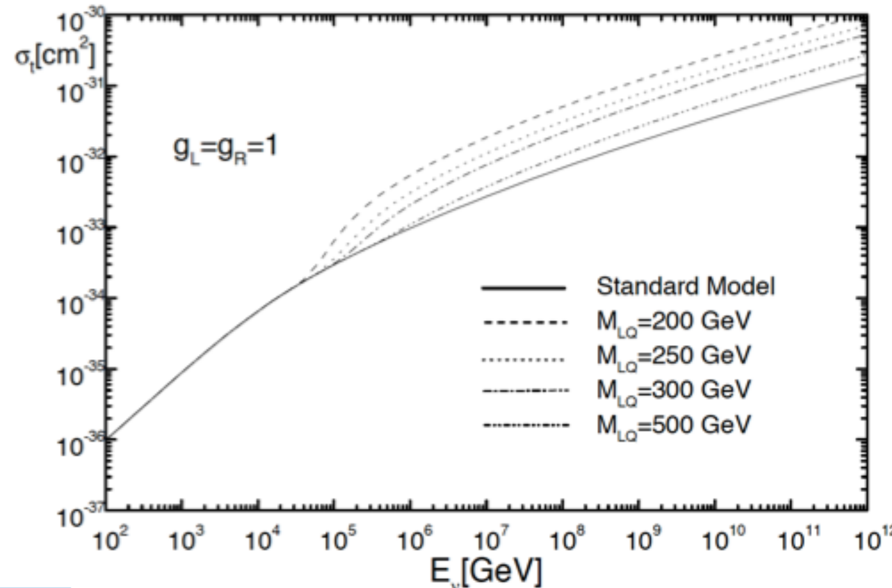


High Energy Neutrino Interaction Cross Section

NATURE 551 (2017)



J. High Energy Phys. 2009, 111 (2009)

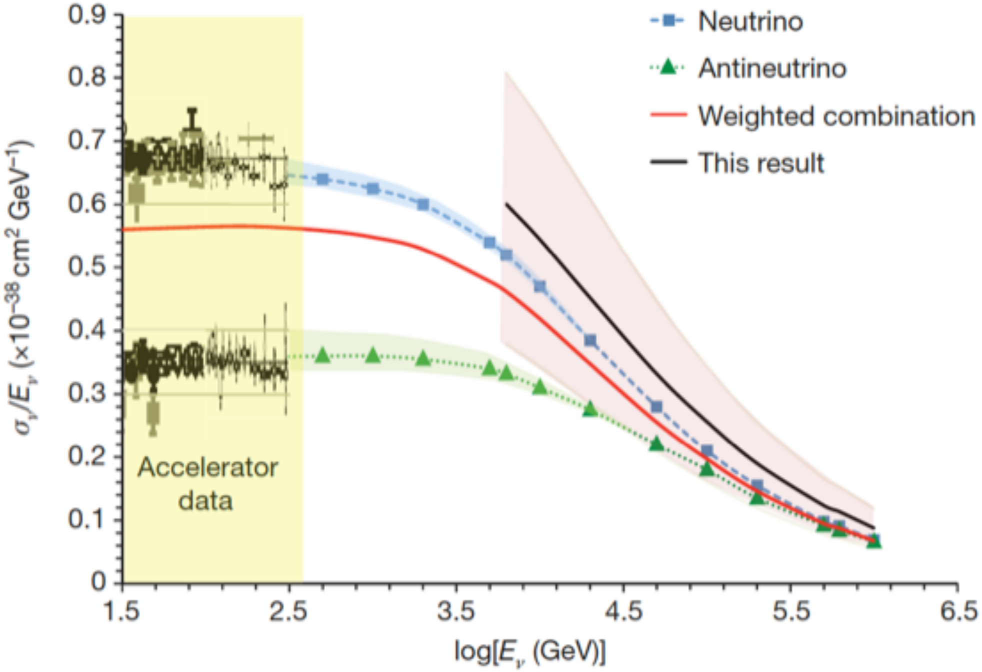


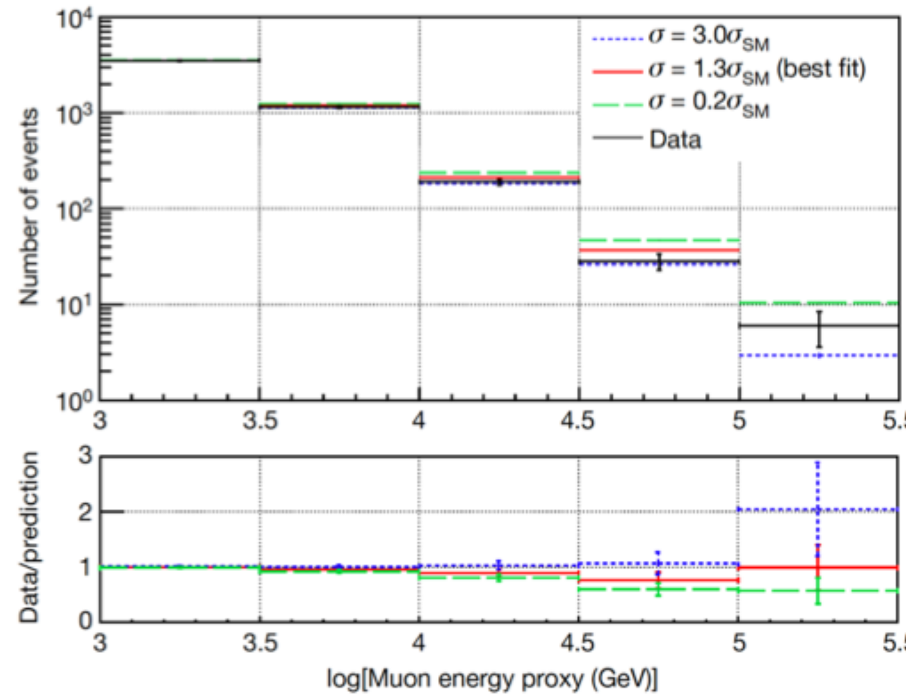
$$\frac{d^2\sigma(\nu_l N \to l^- X)}{dxdy} = \boxed{\frac{2G_F^2 M E}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2}\left[xq(x,Q^2) + x\bar{q}(x,Q^2)(1-y)^2\right]$$

- At TeV energies the Earth becomes increasingly opaque to neutrinos
  - Observable as a depletion in the upward-going neutrino rate
- Interaction cross section is proportional to neutrino energy at low energies
  - For momentum transfer comparable to the weak boson mass, increase with energy slows
  - BSM physics can enhance and supplement the cross section

High Energy Neutrino Interaction Cross Section

NATURE 551 (2017)



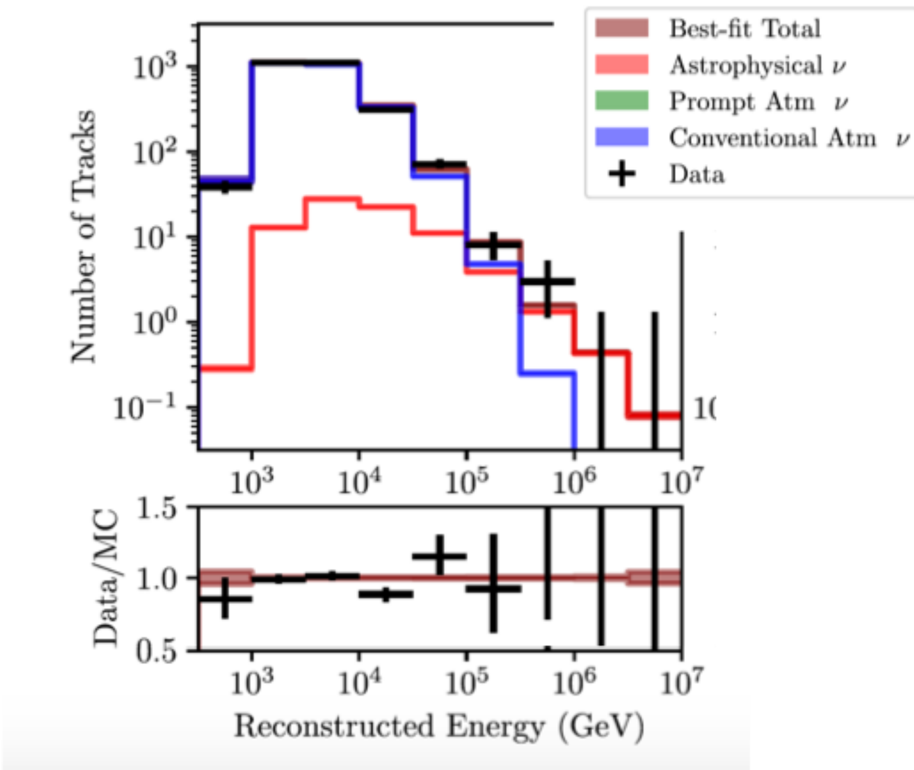


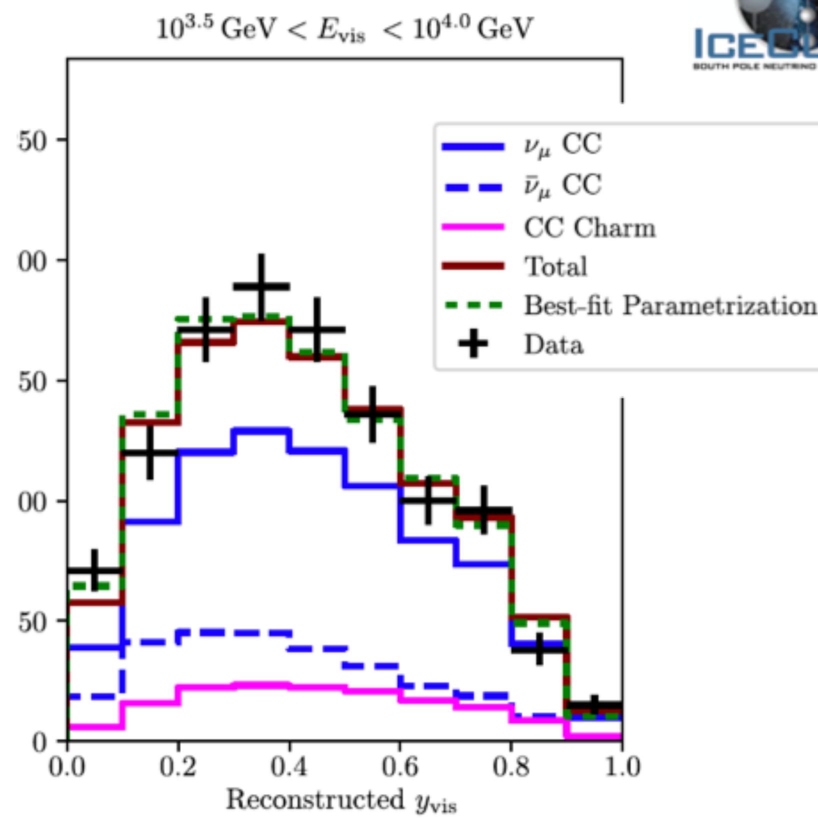
- Analysis uses 10,784 upward-going muons from IceCube-79 data

$$\sigma = 1.30^{+0.21}_{-0.19}(stat)^{+0.39}_{-0.43}(\text{syst.})\ \sigma_{SM}$$

- No indication of deviation from SM
- First measurement about 370 GeV, extensible to higher energies with next-generation detectors with reduced statistical uncertainty

High Energy Neutrino Inelasticity

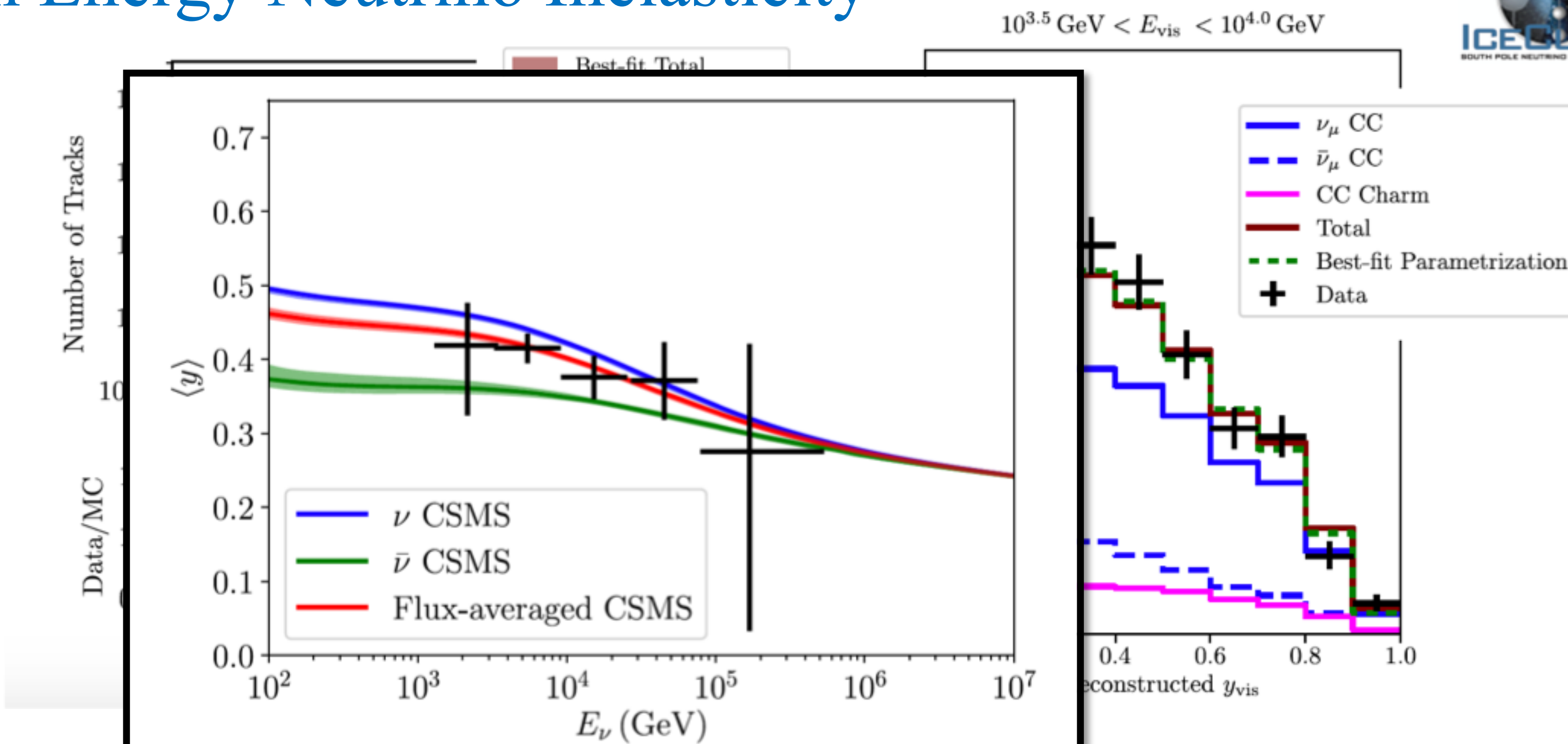




PHYS. REV. D 99, 032004 (2019)

- IceCube has demonstrated ability to measure inelasticity: fraction of energy going to hadrons (y_{vis}) in track-like sample
- Measurement with atmospheric neutrinos at next-generation facilities will have much higher statistics
  - Prospects for n/nbar ratio <10 TeV
  - Constraints on charm production

High Energy Neutrino Inelasticity



PHYS. REV. D 99, 032004 (2019)

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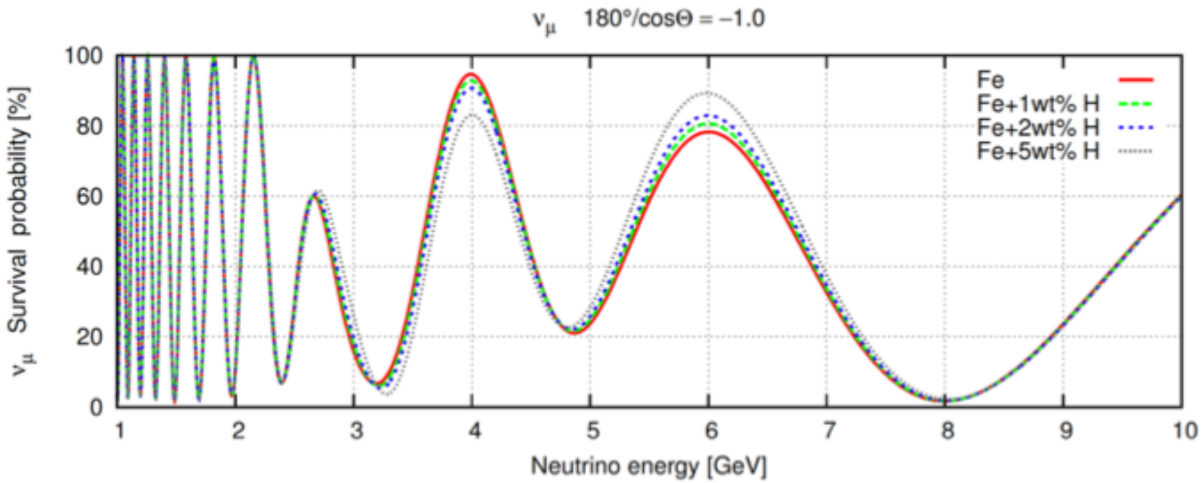
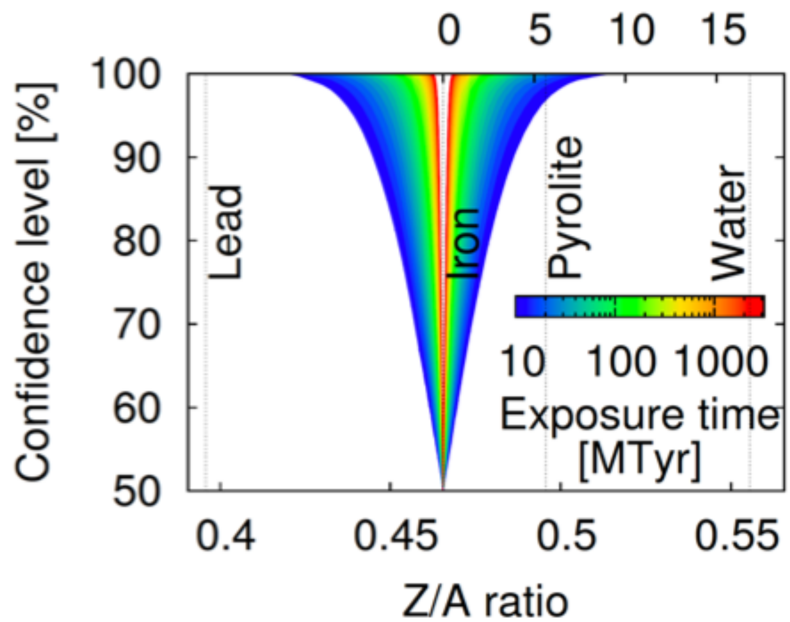
Future : Earth Tomography with Atmospheric Neutrinos

Nature Scientific Reports **volume 5**, 15225 (2015)

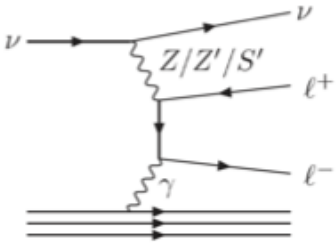




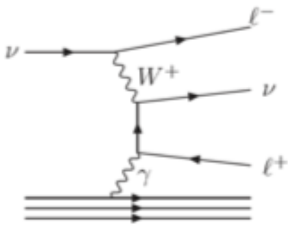
- Core-crossing atmospheric neutrinos can probe electron density of the core via its impact on their oscillations
- High-statistics observations can be used to determine the electron content of the Earth
- Important in geophysics for understanding the origin of the Earth's magnetic field
  - Cannot be done by other means at present and is currently completely unmeasured

Example of tomographical studies with public data here : NATURE PHYSICS 15(2019) 37–40

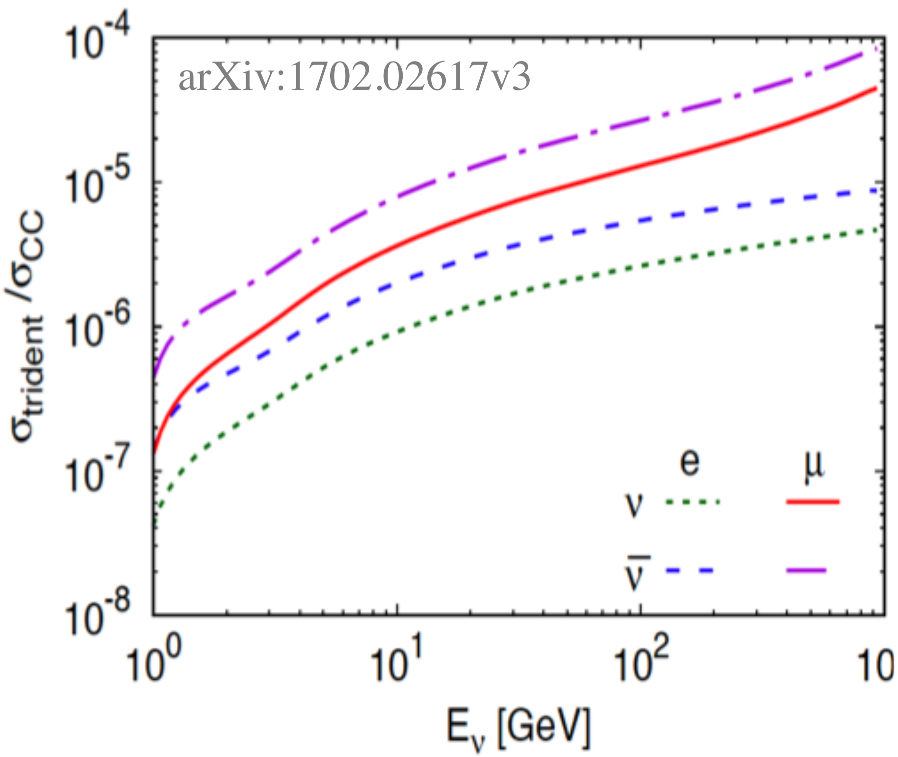
Future : Neutrino Tridents with Atmospheric Neutrinos

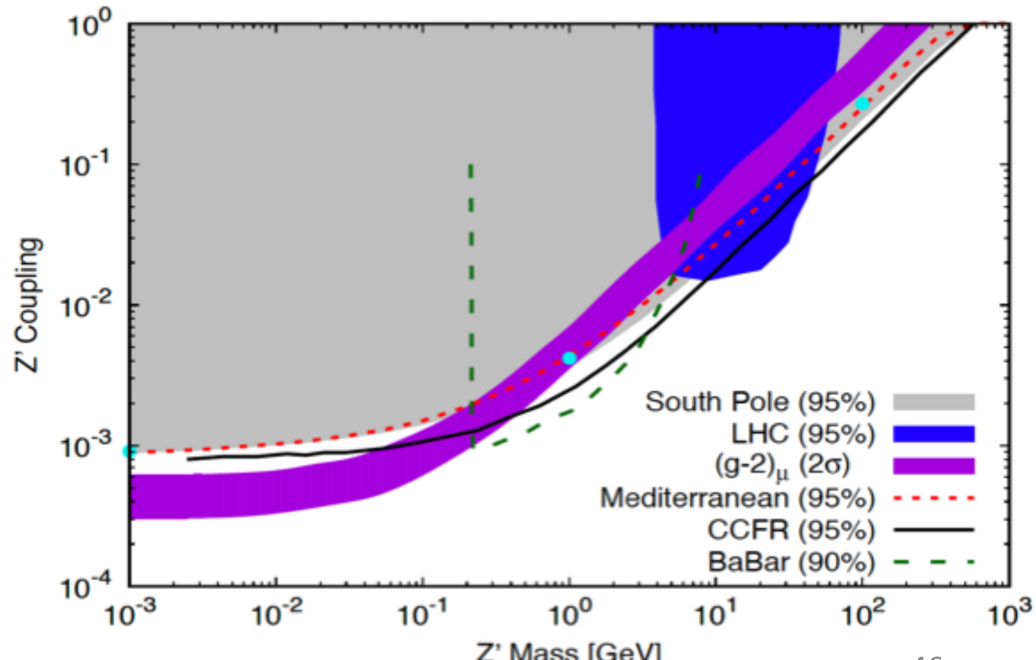


- Standard model predicts neutrino trident production at about 10^{-6} the rate of other CC processes
  - Can also be mediated by exotic scalar (S') or vector (Z') bosons which may enhance the cross section considerably



- Neutrino telescopes using atmospheric neutrino at high energies are a potentially powerful tool for observing these events
  - N.B. reconstruction will be challenging



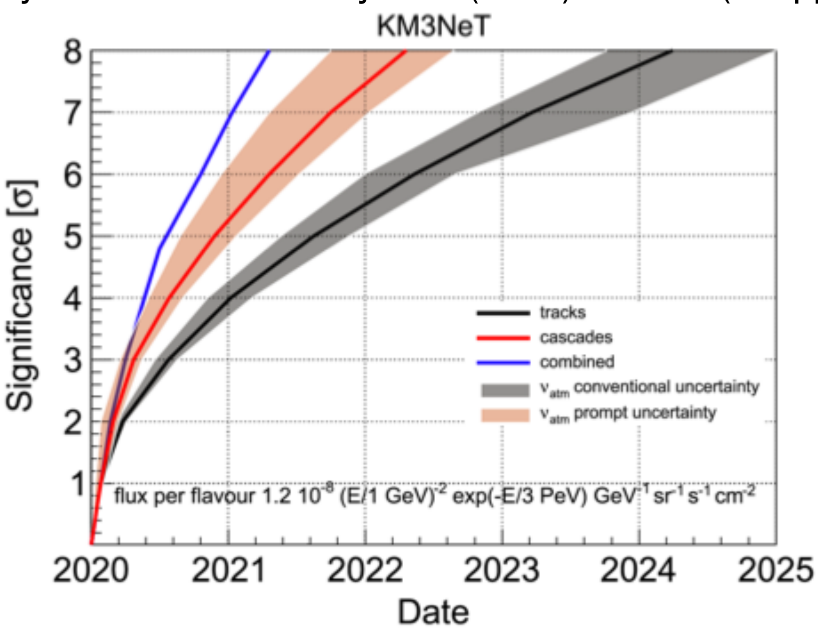


Atmospheric ν Flux and Cross Sections Studies for the Future

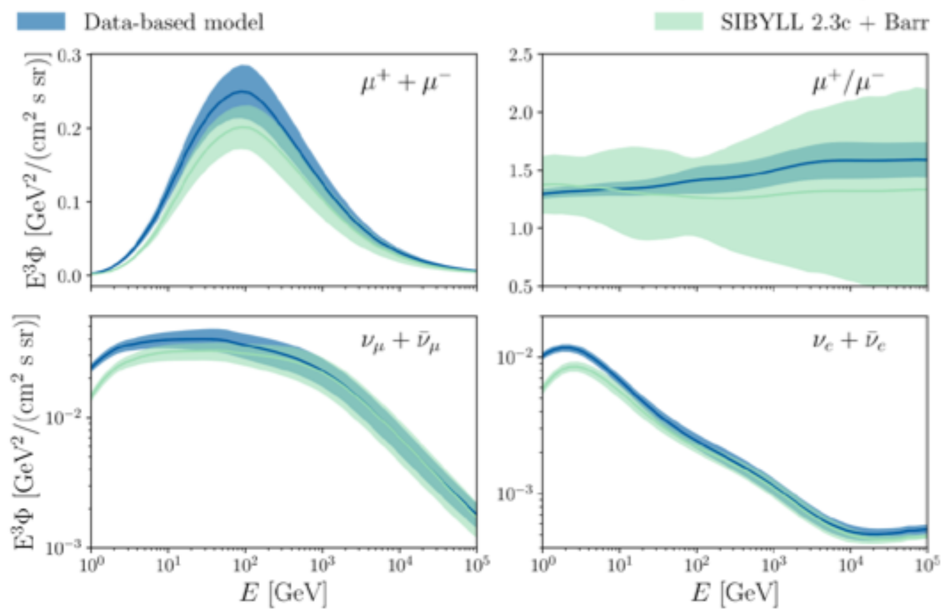
https://indico.cern.ch/event/873509/

- Several efforts are underway to updated and modernize atmospheric neutrino flux calculations across all energies to address uncertainties that will affect future measurements
  - Improved geo-modelling
  - Improved hadron modeling based on accelerator hadron production data
  - Correlations between atmospheric ν and beam ν fluxes, atmospheric μ etc.

J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001 (130pp)



AF et al., ICRC 2017 + Barr 2006, PRD 74



Summary and Conclusions

- Still a lot of work to do with atmospheric neutrinos
  - As signal:
    - PMNS oscillations (MH, Octant, CP)
    - Cross sections (Tau appearance, DIS at high energy, inelasticity)
    - Exotic scenarios (NSI, LV, new bosons, non-unitarity, etc.)
    - Prompt flux
  - As background:
    - Need for better flux and cross section measurements and models to improve discovery potential of many searches (including the above)

- The future seems to be equal parts "low energy" O(1) GeV and "high energy" >1 TeV, but large detectors with large "dynamic range" will be key going forward

- Importantly, these studies have significant ramifications for many other measurements

Supplements