Atmospheric Neutrino Experiments

Part-II

Roger Wendell
Kyoto University
CCEPP Summer School on Neutrino Physics
Daya Bay

2017.07.07

Introductory Remarks

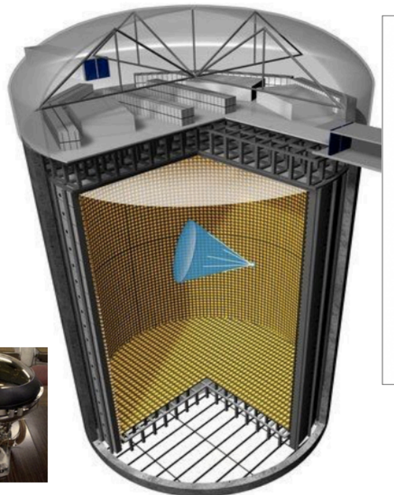
- Lecture organization
  - History of Atmospheric Neutrino Measurements
  - Discovery of Oscillations
  - Three Flavor Oscillations
  - Systematic Errors for Atmospheric Neutrinos
  - Other Types of Oscillation Physics
  - Future for atmospheric neutrino oscillations

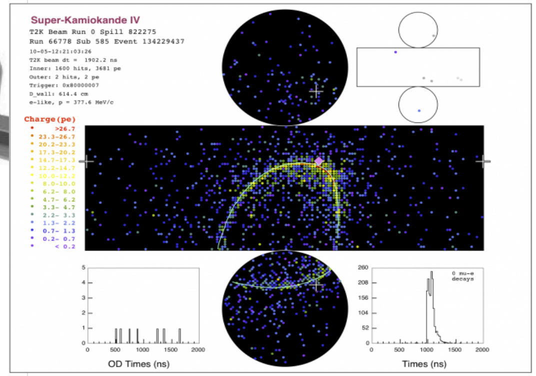
- Bias towards Super-K still present, but better coverage of other experiments

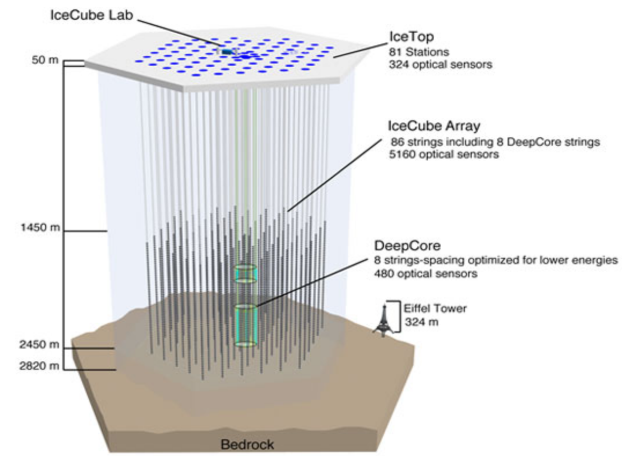
The Three Flavor Era

- Thanks to measurements of reactor neutrinos, θ_{13} is known to be non-zero and there is a connection between the ''solar'' and ''atmospheric'' mixing

Atmospheric Neutrino Experiments:







ICECUBE

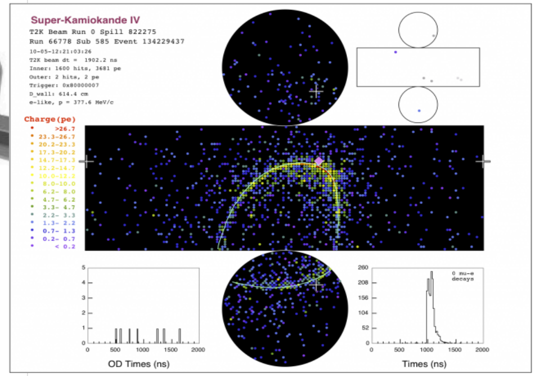
40m

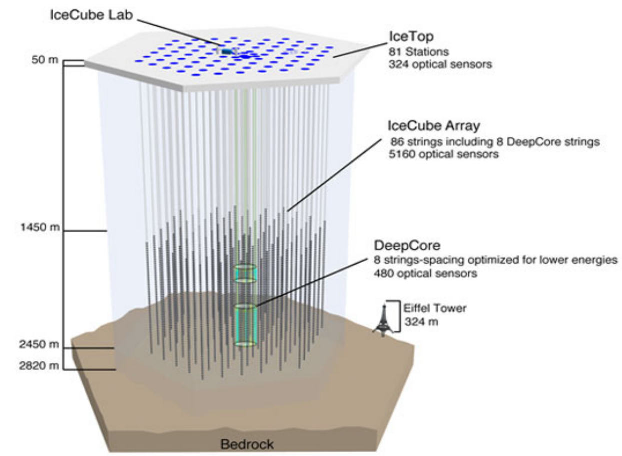
1 km

Super-Kamiokande	IceCube
50,000 Ton Ultrapure Water	1 km^3 of Antarctic *Ice*
11,000 20" PMTs (ID) 1885 8" (OD)	5100 Digital Optical Modules (DOM)
Ring-Imaging	"String" Imaging
40% Cathode Coverage	86 Strings, 17m / 7m DOM Spacing
0.1 ~ 10^3 GeV	10 ~ 10^5 GeV
Excellent e/μ PID, MIS PID 1%	Cascade (e/NC) and Track (μ)

Both are Cherenkov detectors without event-by-event $\nu/\bar{\nu}$ separation

Atmospheric Neutrino Experiments:

40m

ICECUBE

1 km

Super-Kamiokande	IceCube
50,00(	
11,000 2(	)
40%	
Excelle	

A quick aside about systematics:

SK suffers more from flux and cross section errors

IceCube/DeepCore mainly worries about detector systematics

Both are Cherenkov detectors without event-by-event $\nu/\bar{\nu}$ separation

Open Questions in Neutrino Physics

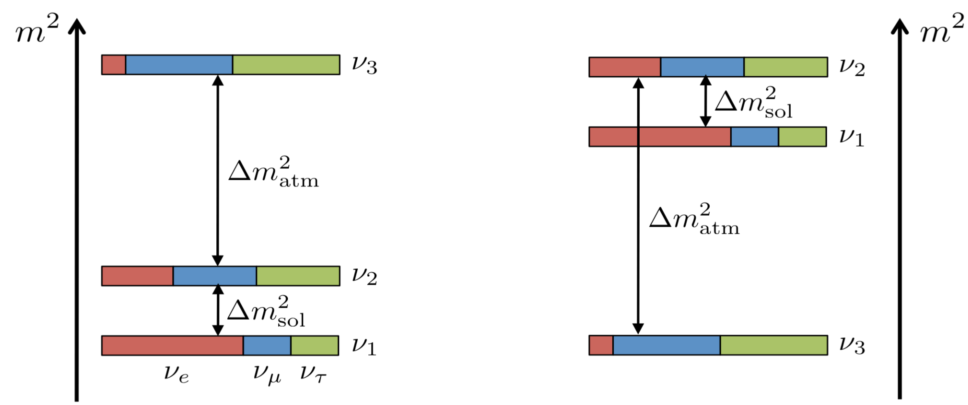
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric   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
  - Neutrino Mass hierarchy

Mass Ordering is Unknown

normal hierarchy (NH)   **inverted hierarchy (IH)**



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

Open Questions in Neutrino Physics

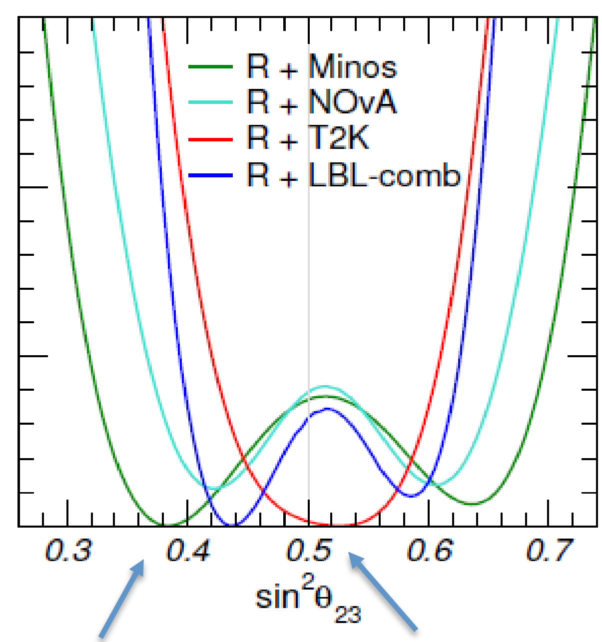
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric

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
  - Maximal Mixing?

Is Atmospheric Mixing Maximal



Open Questions in Neutrino Physics

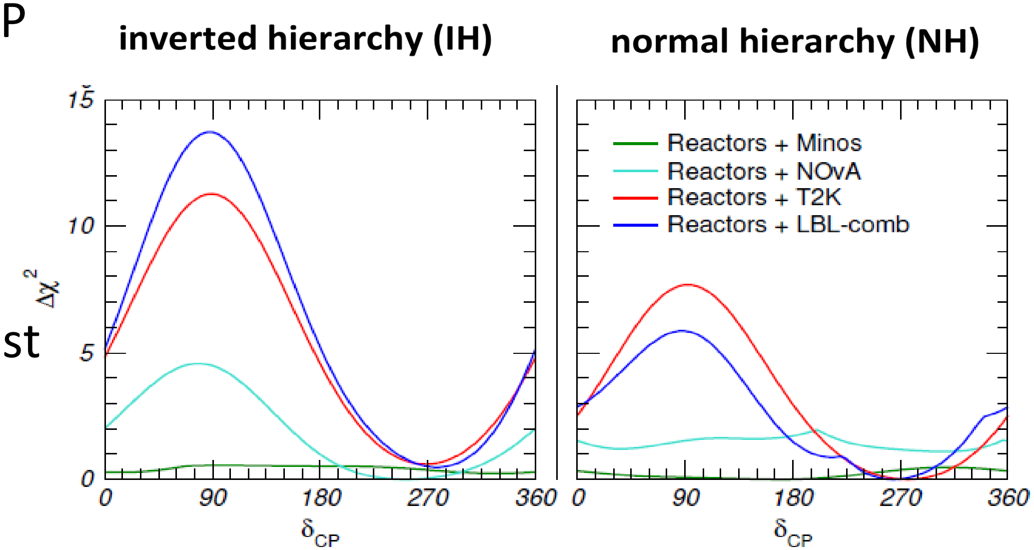
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric   Solar

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

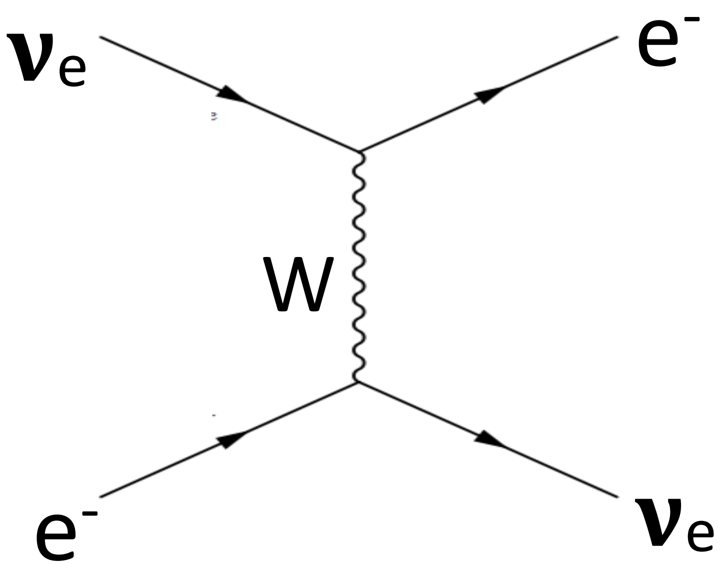
- Currently, ***all*** parameters have been measured, though δ_{cp} is the least well constrained and the topic of much interest
- However, several open questions remain
  - CP violation?

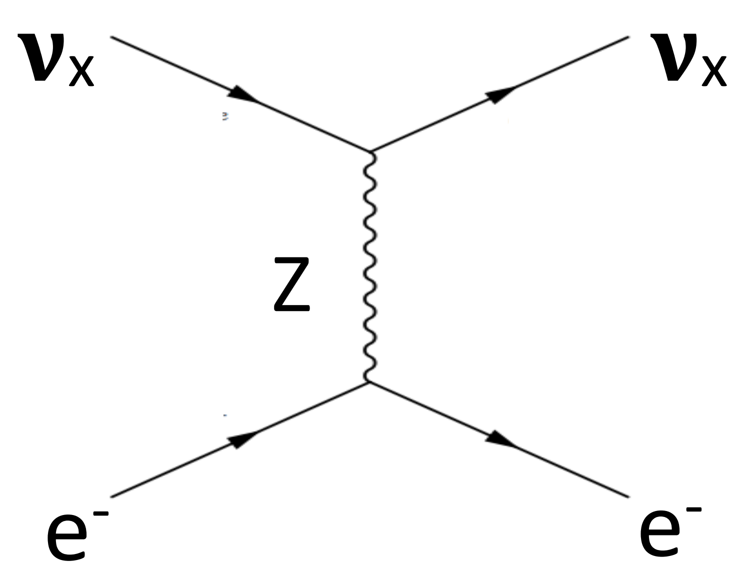
Is CP Violated in Neutrino Mixing?



Esteban, I et al: 1611.01514

Matter Effects Matter





$$V_{cc}^{\nu_e} = \pm\sqrt{2}G_F N_e = \pm 7.56 \times 10^{-14} \left(\frac{\rho}{g/cm^3}\right) Y_e eV$$

G_F is Fermi Constant, N_e is electron density

$\boldsymbol{\rho}$ is matter density

Y_e is electron to nucleon ratio (≈0.5 in Earth)

+ for ν_e, - for $\overline{\nu}_e$

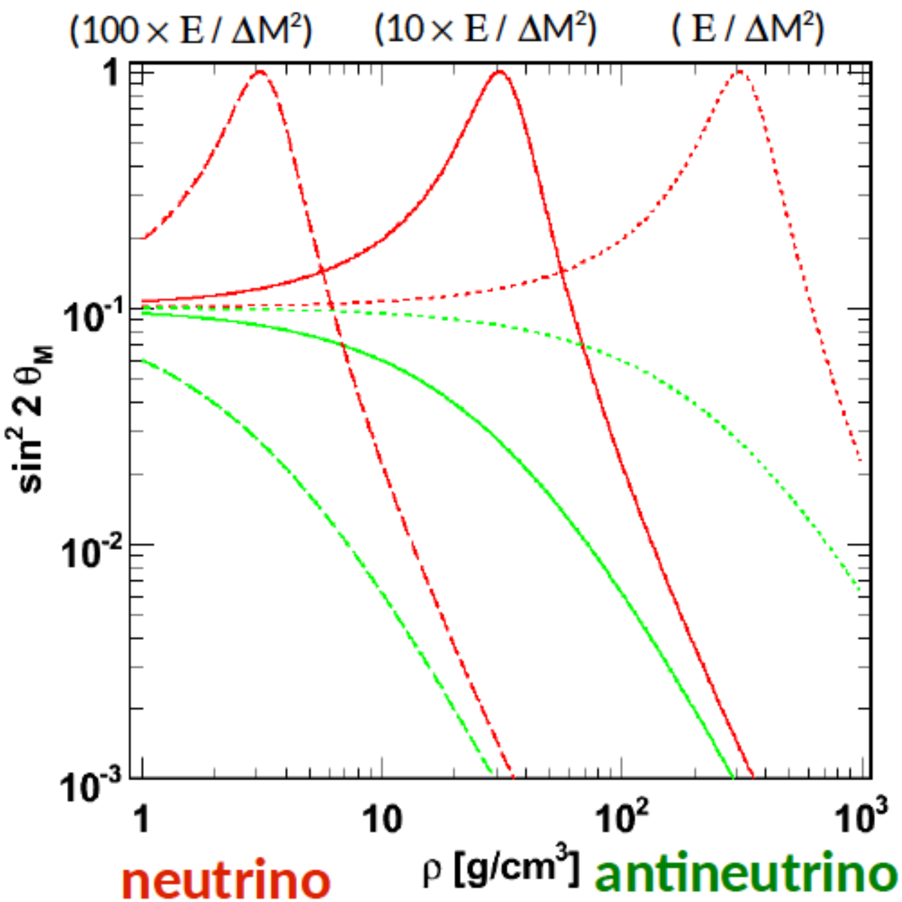
- Hamiltonian of neutrino passing through matter affected by coherent $\boldsymbol{\nu}_e$ CC scattering

Matter Effects Matter

$$P(\nu_e \to \nu_\alpha) = \frac{\sin^2 2\theta}{\sin^2 2\theta - (\pm\sqrt{2}\, G_F\, n_e\, E/\Delta m^2 - \cos 2\theta)^2} \sin^2\left(\frac{1.27 \Delta M^2 L}{E}\right)$$

neutrino (+)
antineutrino (-)

Sign of Δm^2 matters
Ie, hierarchy



$| 2EV/\Delta m^2 | >> | \cos 2\theta |$:
Suppression

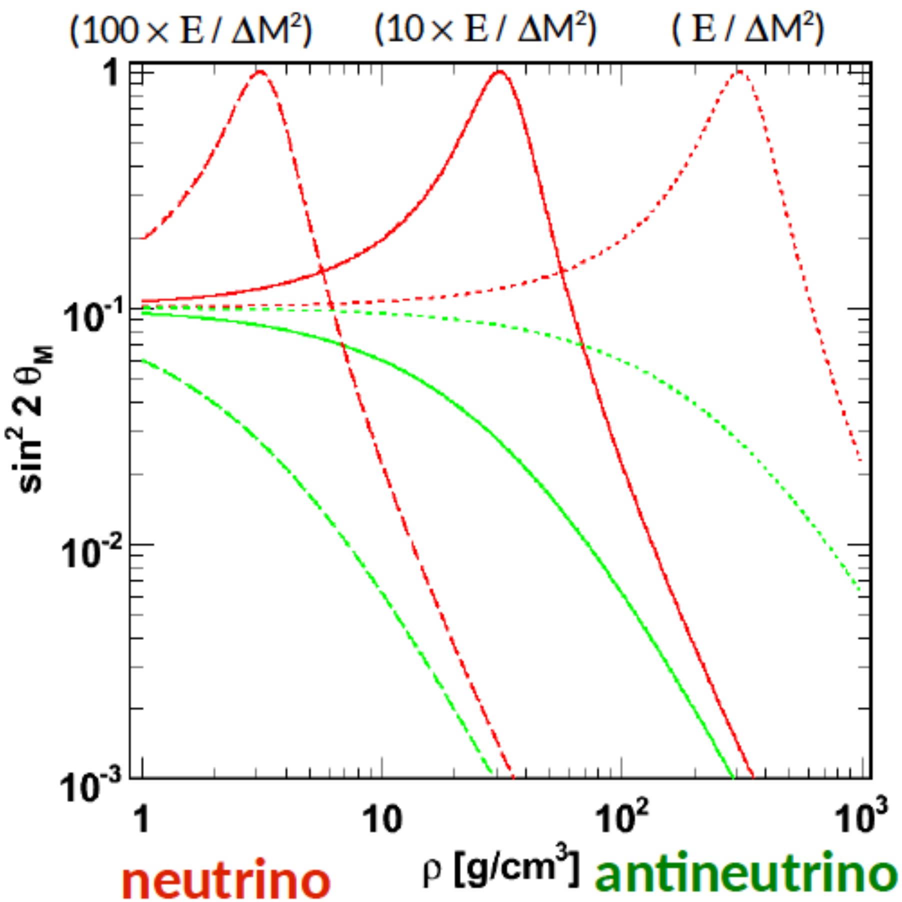
$2EV/\Delta m^2 \approx \cos 2\theta$:
Resonance

Matter Effects Matter

$$P(\nu_e \rightarrow \nu_\alpha) = \frac{\sin^2 2\theta}{\sin^2 2\theta - (\pm\sqrt{2} G_F n_e E/\Delta m^2 - \cos 2\theta)^2} \sin^2\left(\frac{1.27 \Delta M^2 L}{E}\right)$$

neutrino (+)
antineutrino (-)

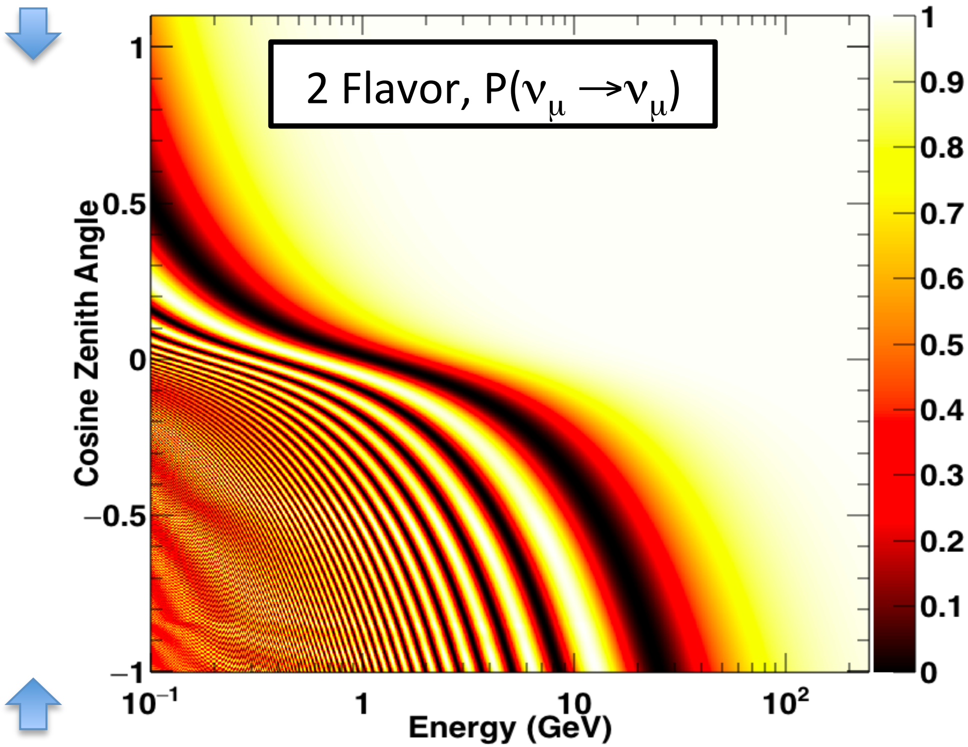
Sign of Δm^2 matters
Ie, hierarchy

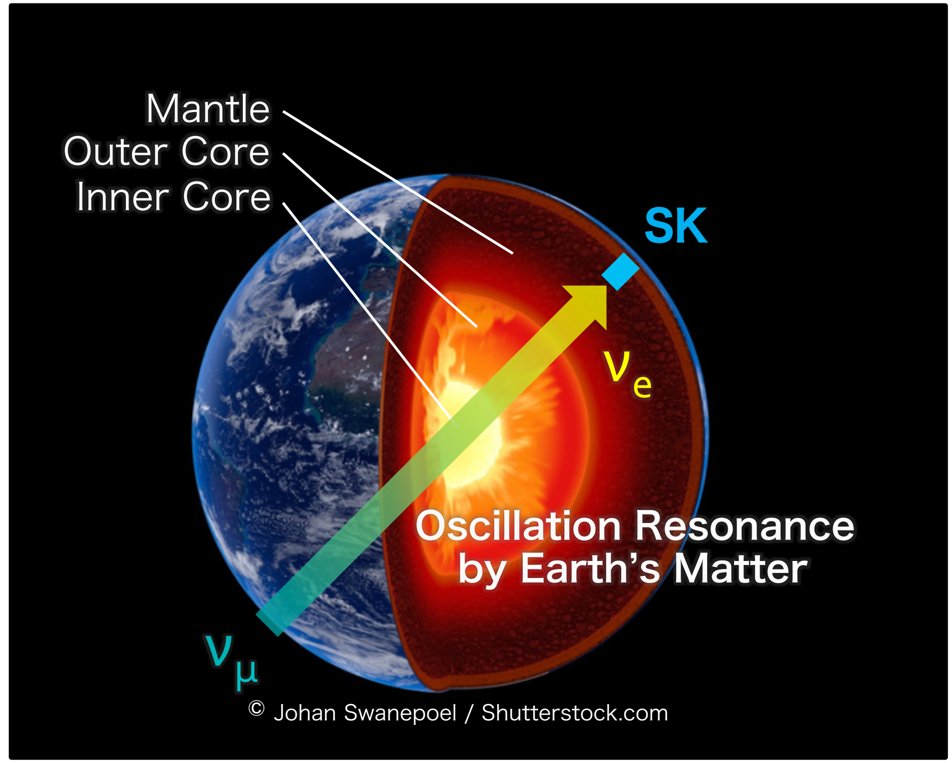


- Additional matter potential gives rise to resonantly enhanced oscillations
- Resonance is for either neutrinos or antineutrinos – not both!
- Depends on the sign of the mass hierarchy
  - Look for this resonance to determine the mass hierarchy!

Mass Hierarchy Determination: Matter-Effects

Normal Hierarchy

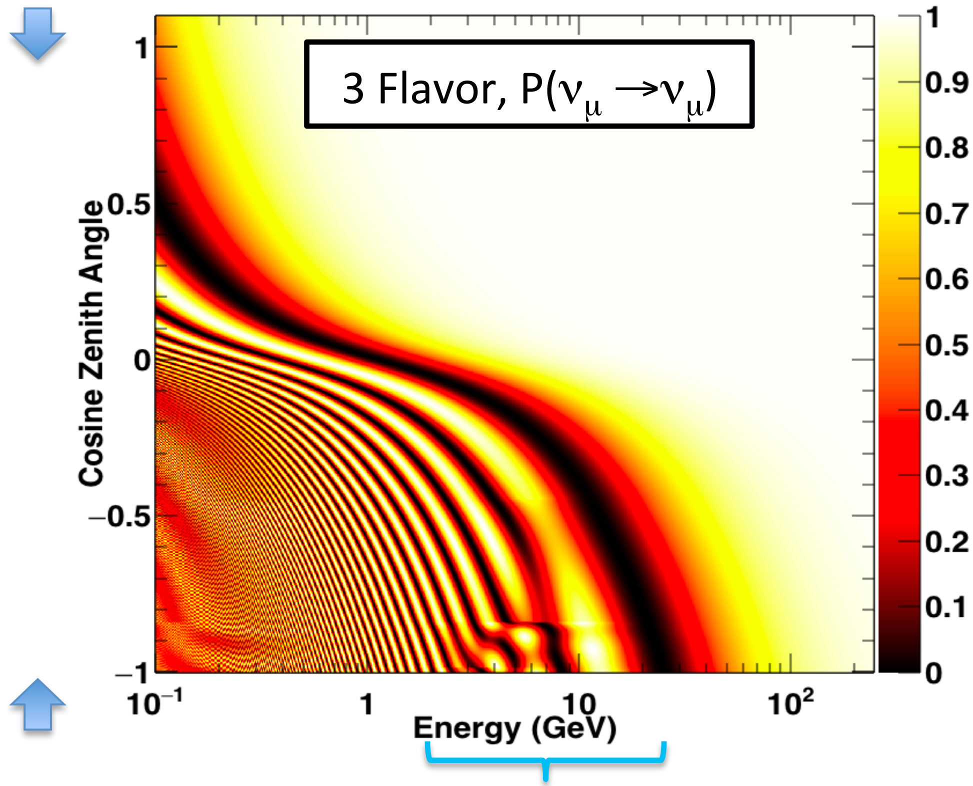




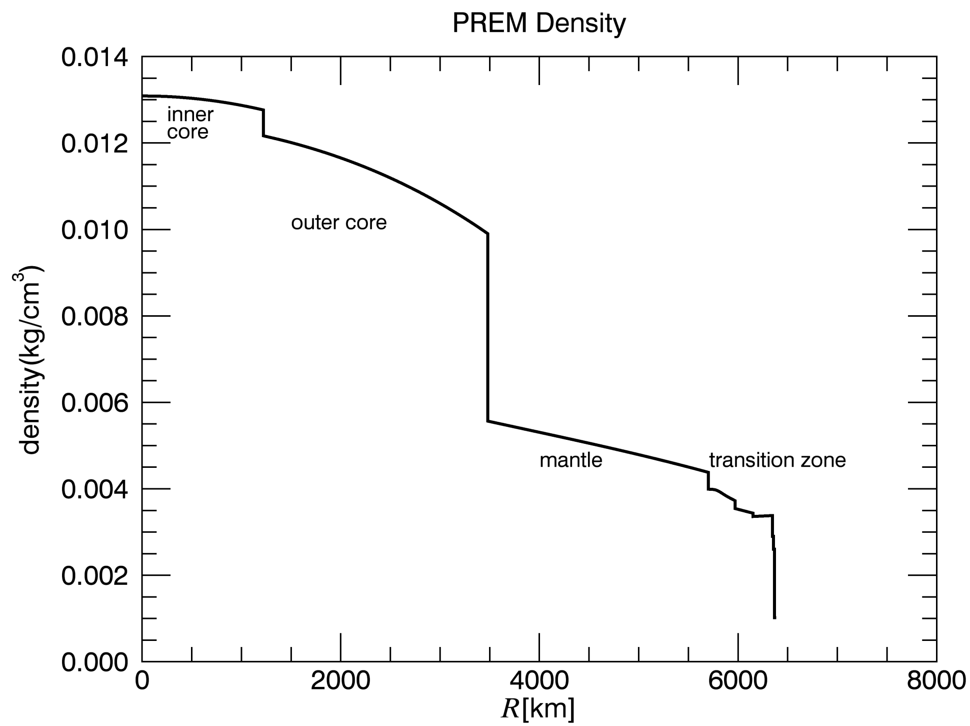
- Presence of electrons (as opposed to muons) induces asymmetric oscillations between electron-type neutrinos and antineutrinos

Mass Hierarchy Determination: Matter-Effects

Normal Hierarchy



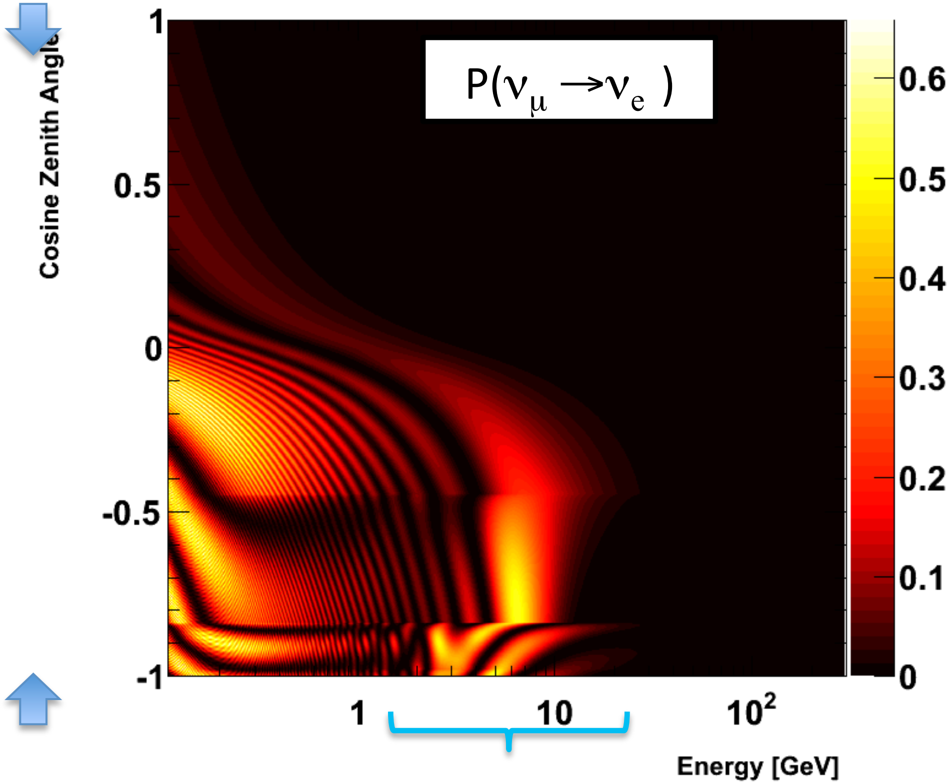
Astrophys.J. 814 (2015) no.2, 122



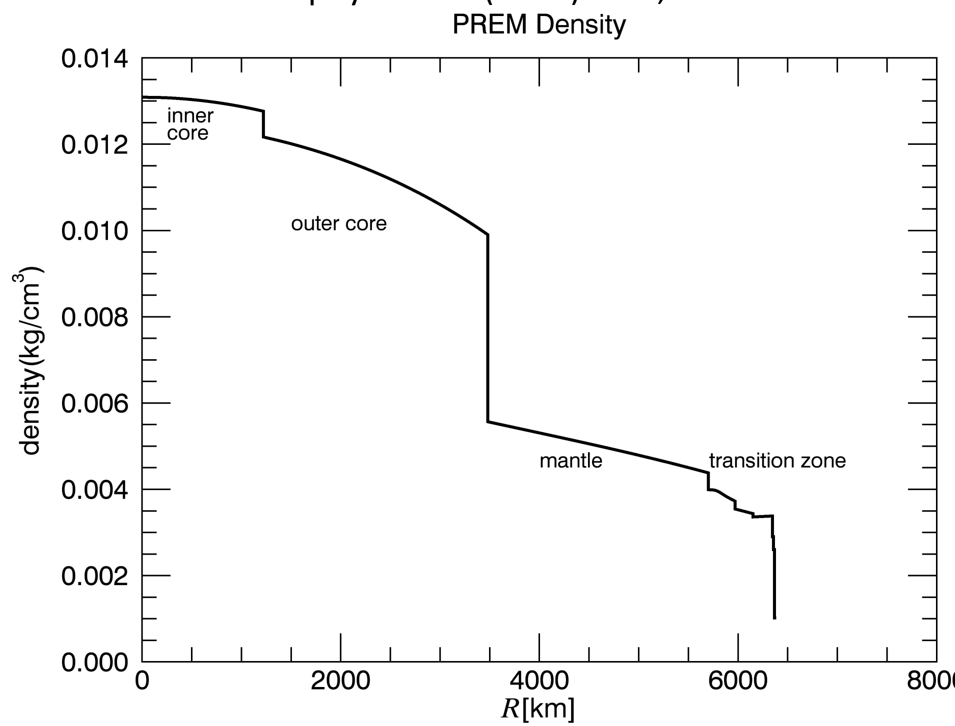
- Earth is not constant density, but density causes resonant oscillations
- Expect slightly *more* muon neutrino disappearance for neutrinos travelling through the core of the earth

Mass Hierarchy Determination: Matter-Effects

Normal Hierarchy



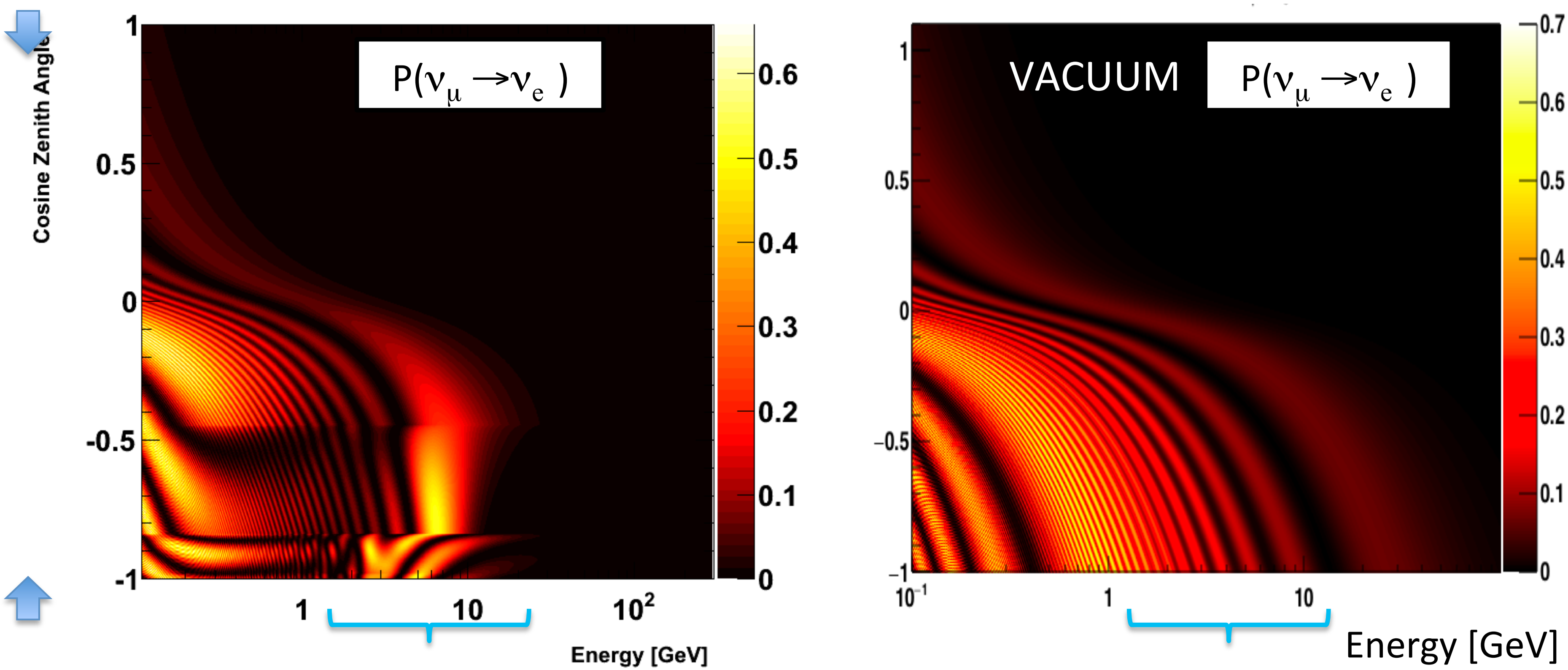
Astrophys.J. 814 (2015) no.2, 122



- Resonance effects are expected to enhance the number of upward-going electron neutrinos
- Size of the effect depends on θ_{13}, which has been measured precisely by reactor experiments

Matter Effects Versus Vaccuum

Normal Hierarchy

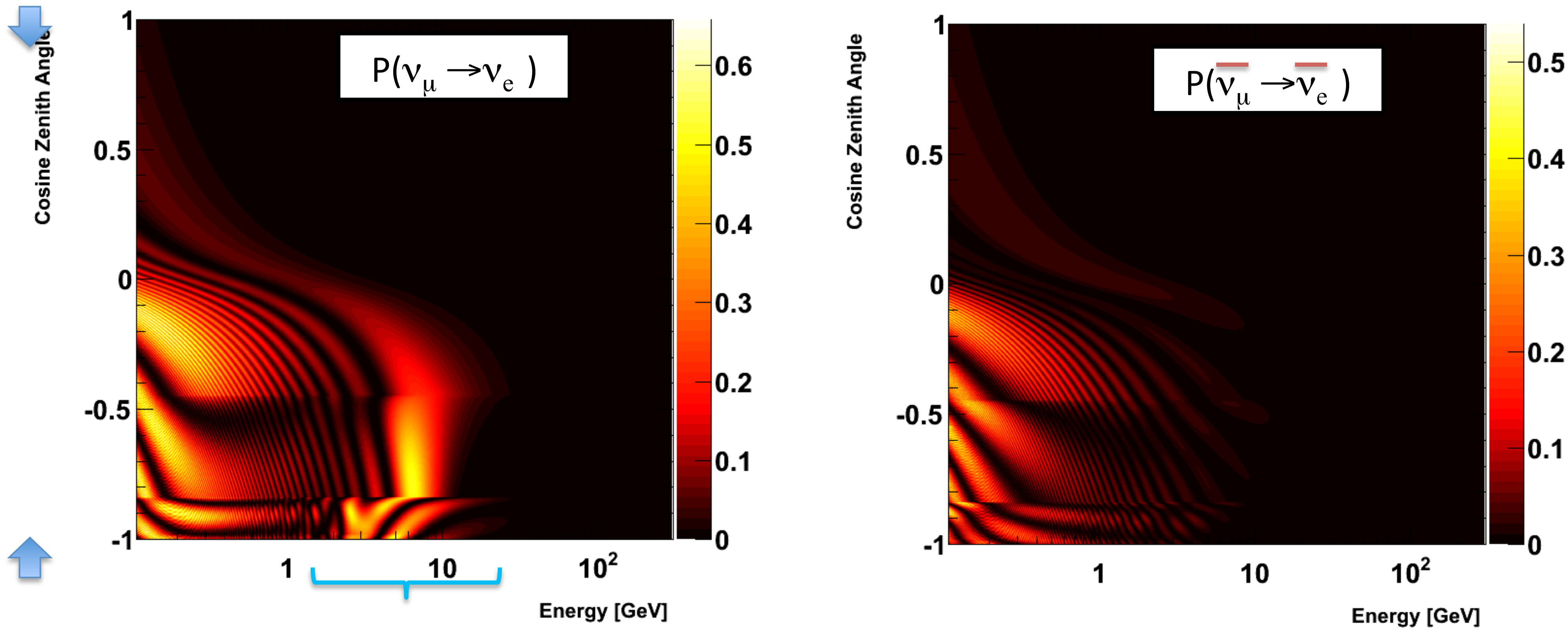


- If we temporarily assume the Earth is made of vacuum (or there were no matter effect) resonance disappears

- Still have oscillations via θ_{12}, Δm^2_{12}, and θ_{13}

Mass Hierarchy Determination: Antineutrinos

Normal Hierarchy

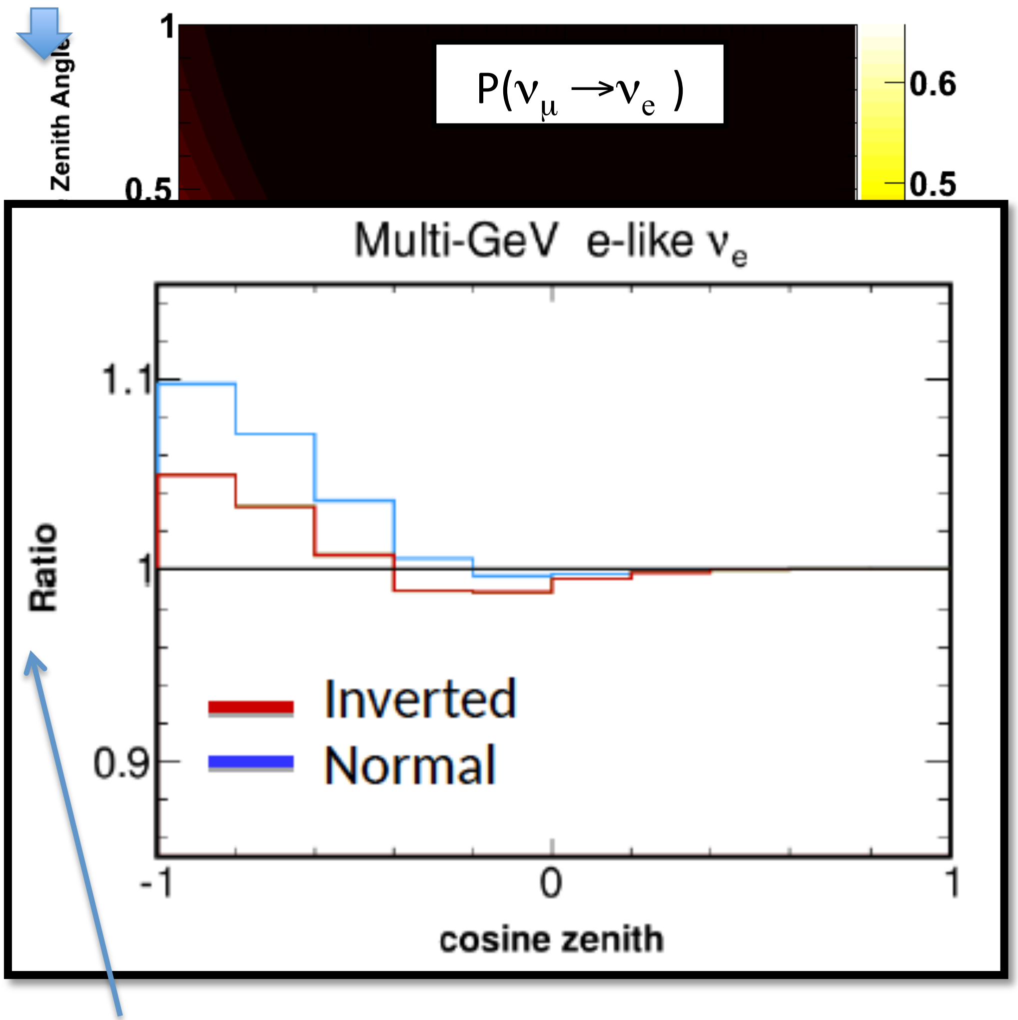


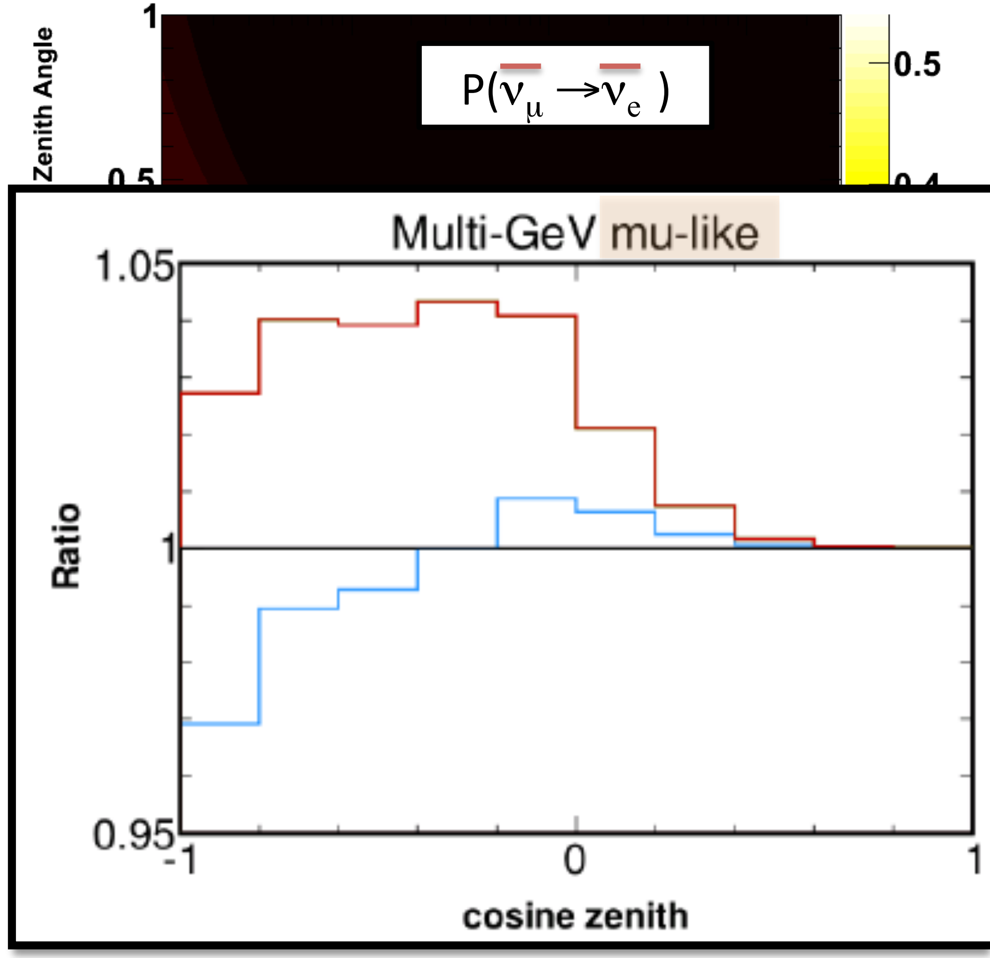
- Resonance effects are expected to enhance the number of upward-going electron neutrinos
- Enhancement expected for antineutrinos if the hierarchy is *inverted*

- *Muon nuetrinos also sensitive (ICAL-INO)*

Mass Hierarchy Determination: Antineutrinos

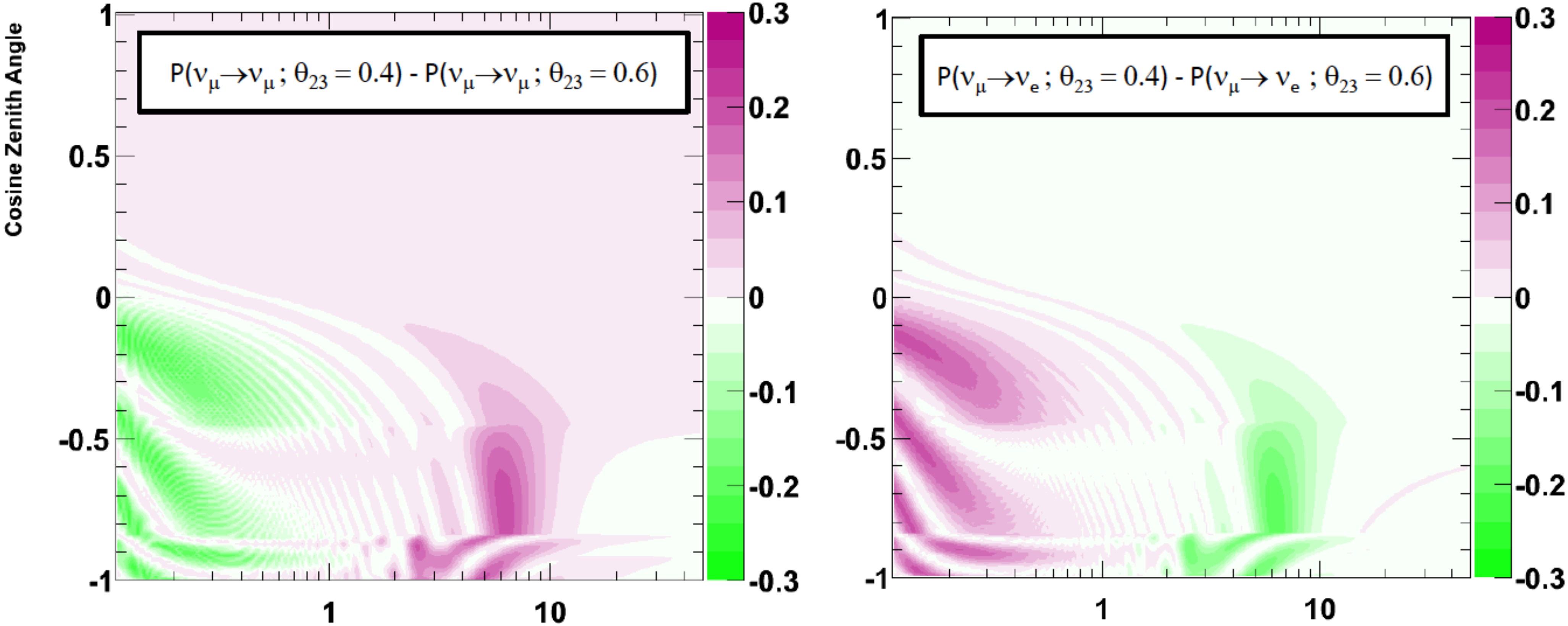
Normal Hierarchy





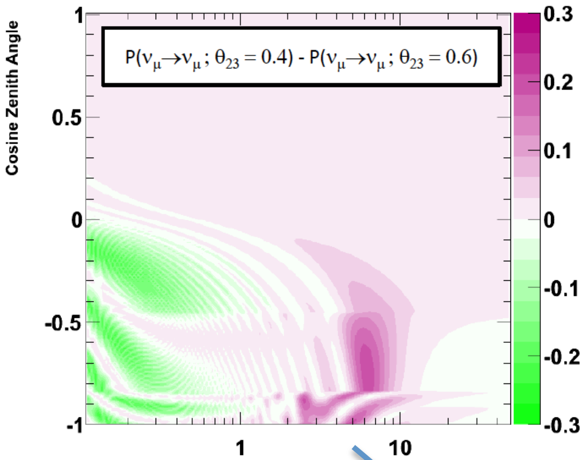
Event rate relative to 2 Flavor oscillation

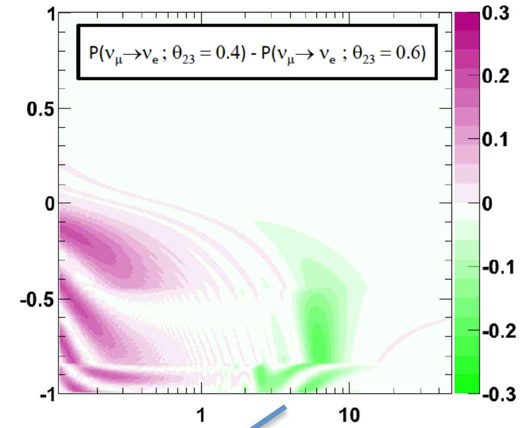
P(1st Octant) - P(2nd Octant)



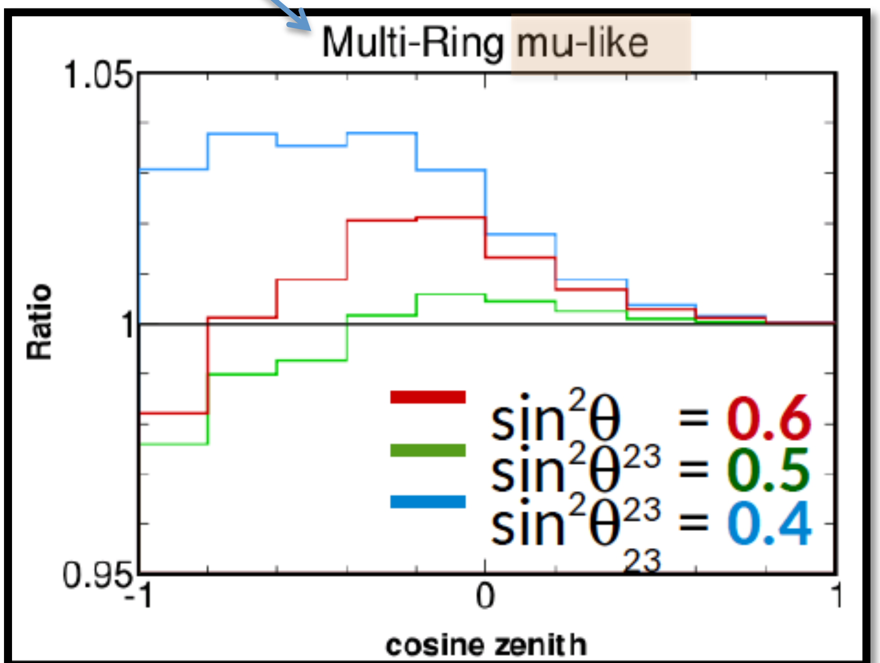
$\sin^2\theta_{23}$ = 0.4 vs 0.6	$P(\nu_\mu \to \nu_\mu)$	$P(\nu_\mu \to \nu_e)$
E ~ Sub-GeV	More disappearance	More appearance
E ~ **Multi**-GeV	Less disappearance	Less appearance

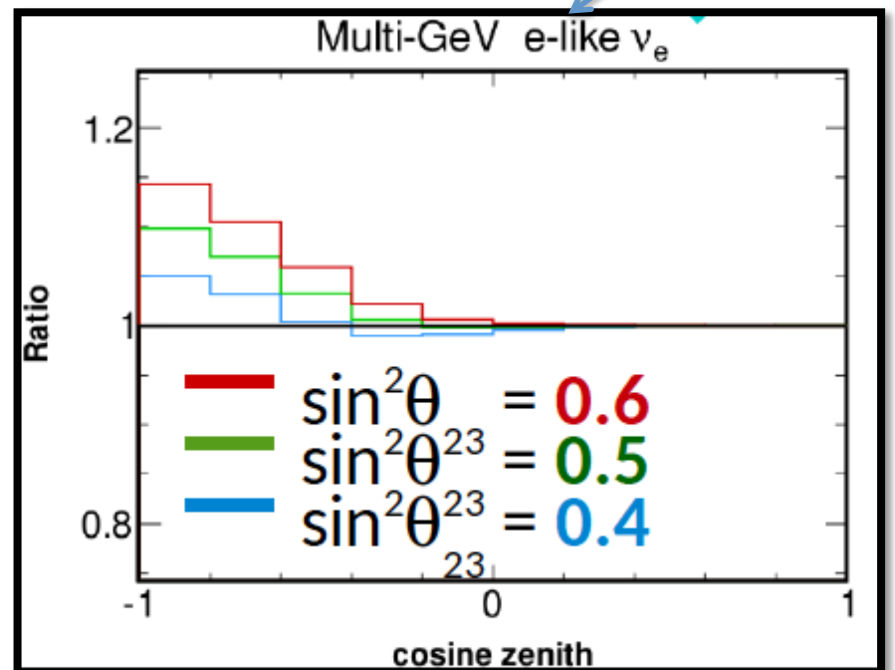
P(1st Octant) - P(2nd Octant)



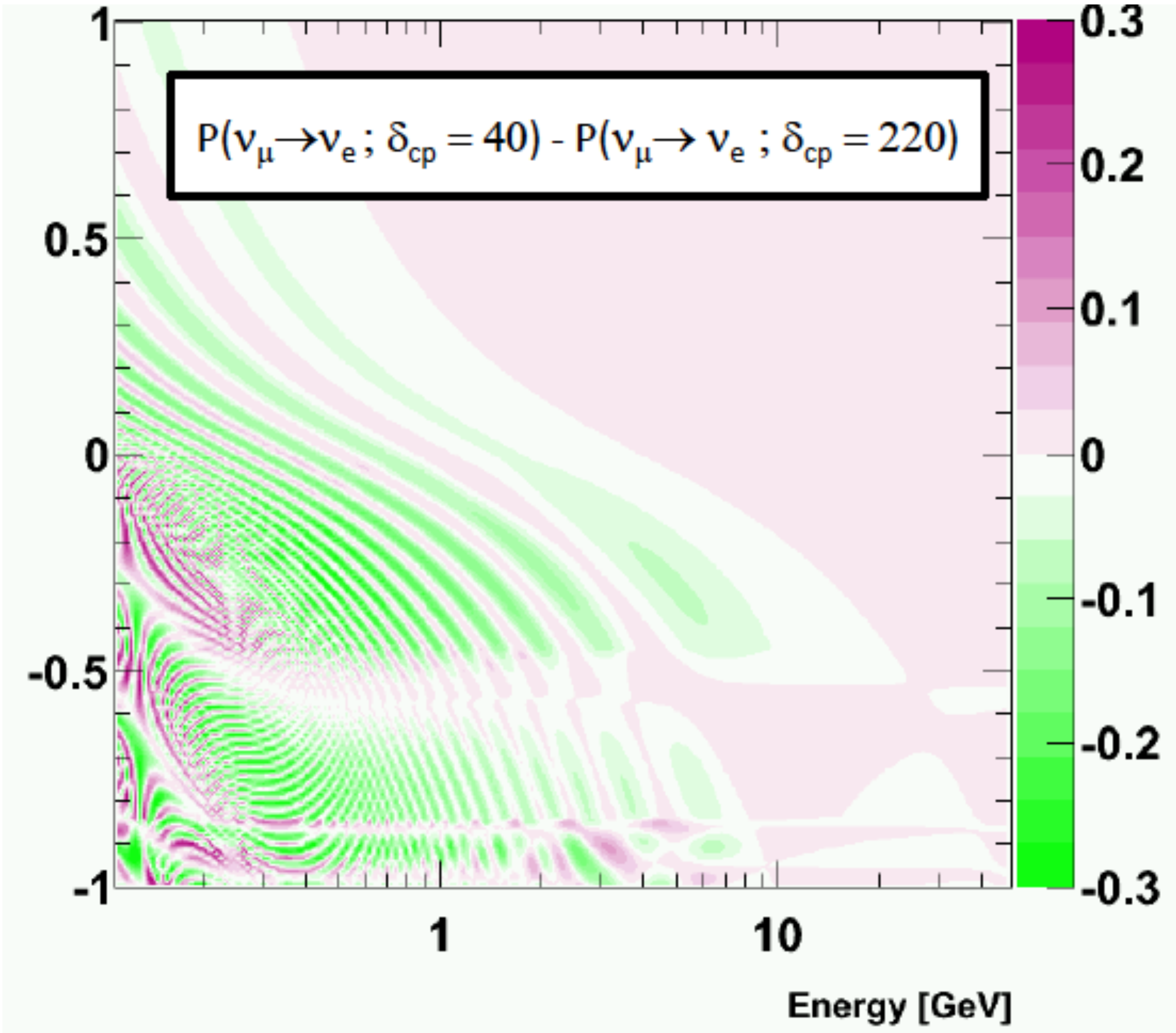


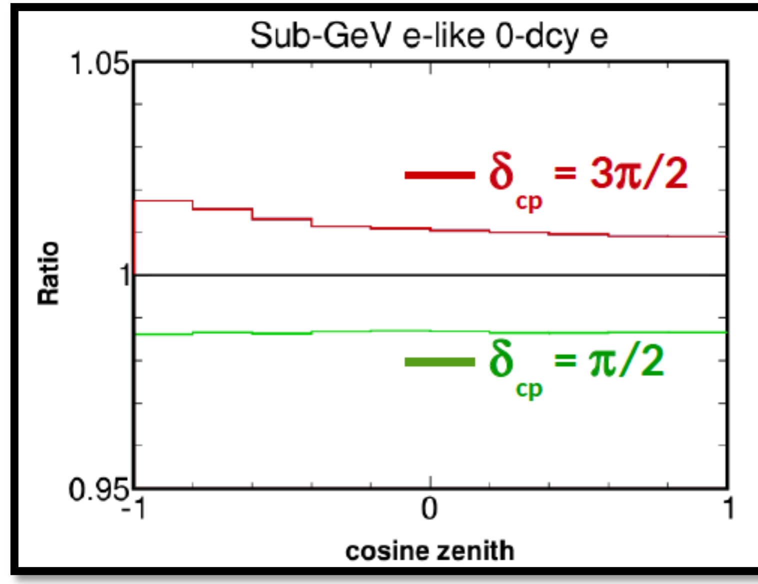
Octant Sensitivity

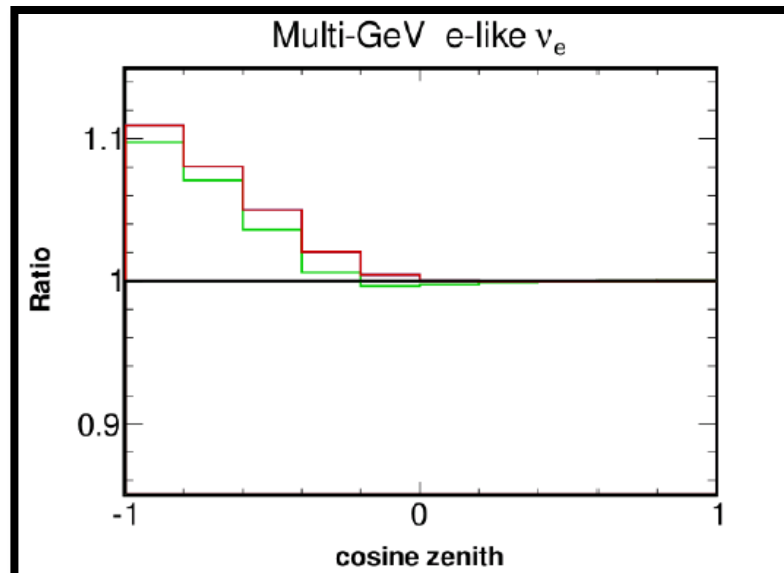




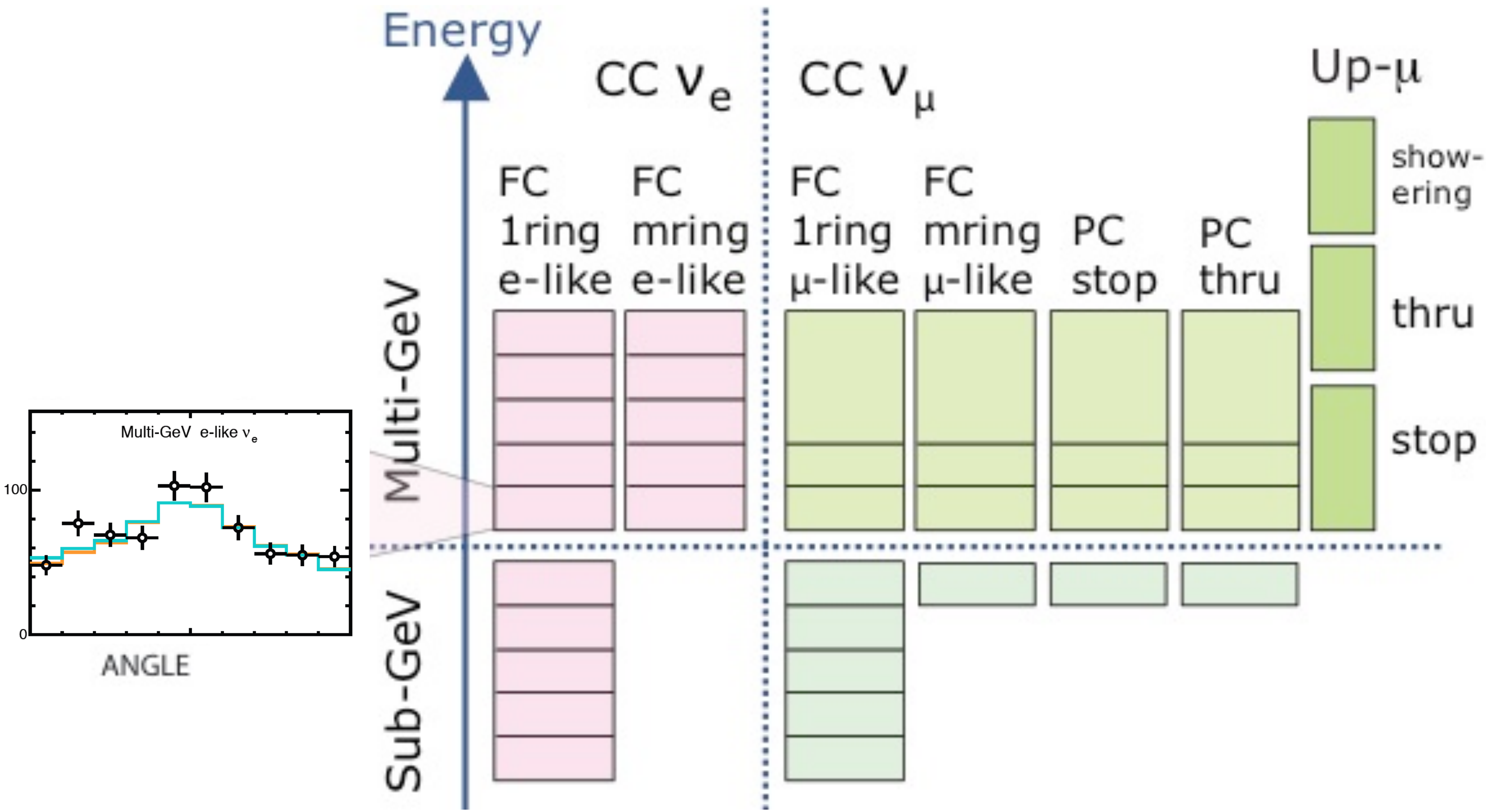
Affect of δ_{cp} giving ~maximum and minimum appearance





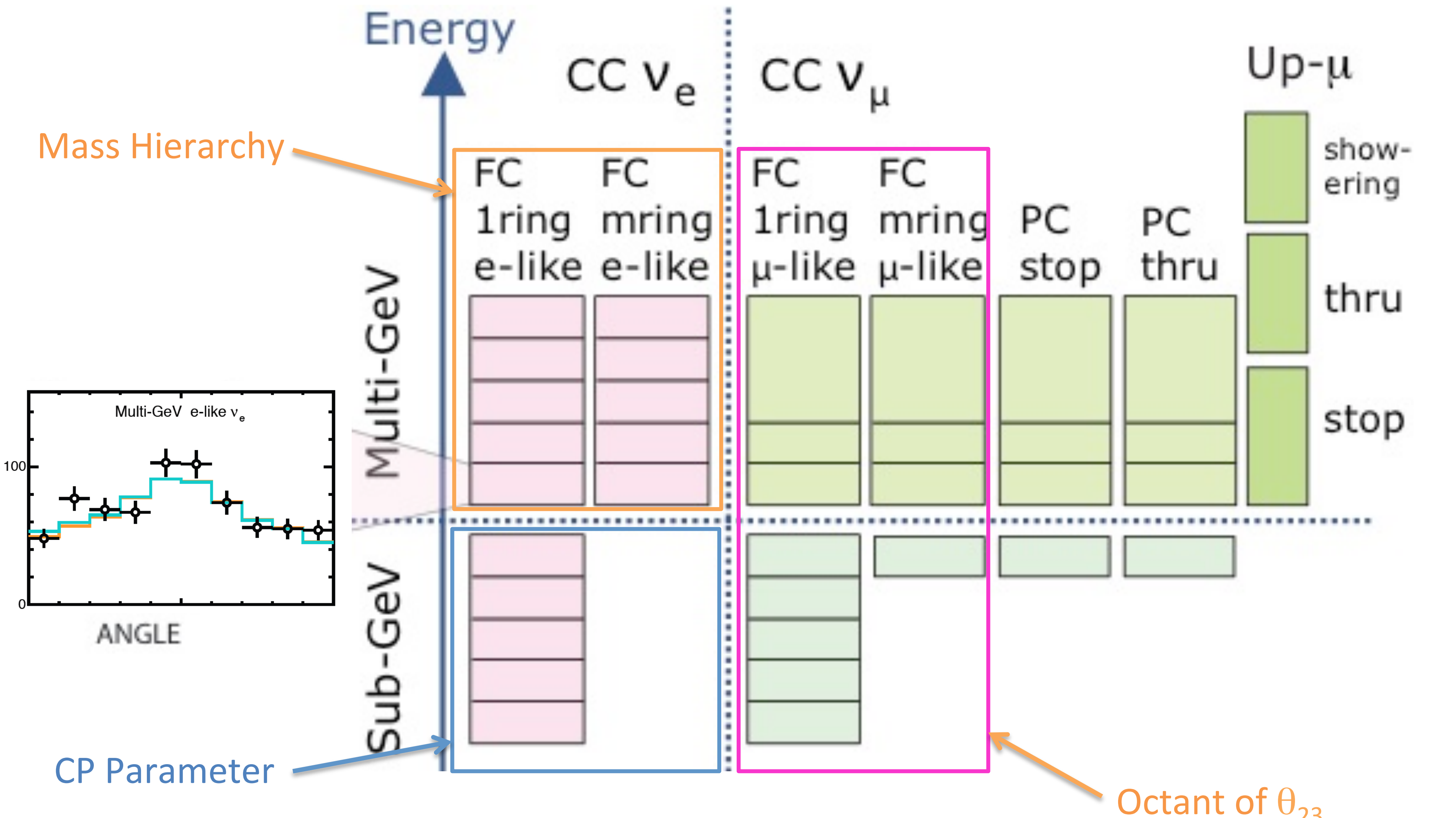


Super-Kamiokande Analysis Samples



- Total of 520 analysis bins
- 154 sources of systematic error (!!)

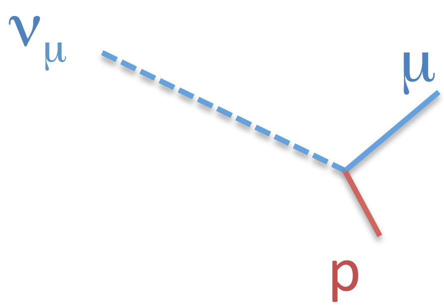
Super-Kamiokande Analysis Samples



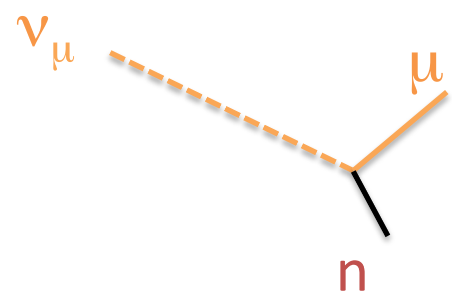
- Total of 520 analysis bins
- 154 sources of systematic error (!!)

Neutrino-Antineutrino Separation

Neutrino Interaction



antineutrino Interaction

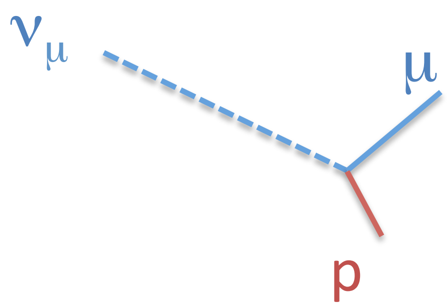


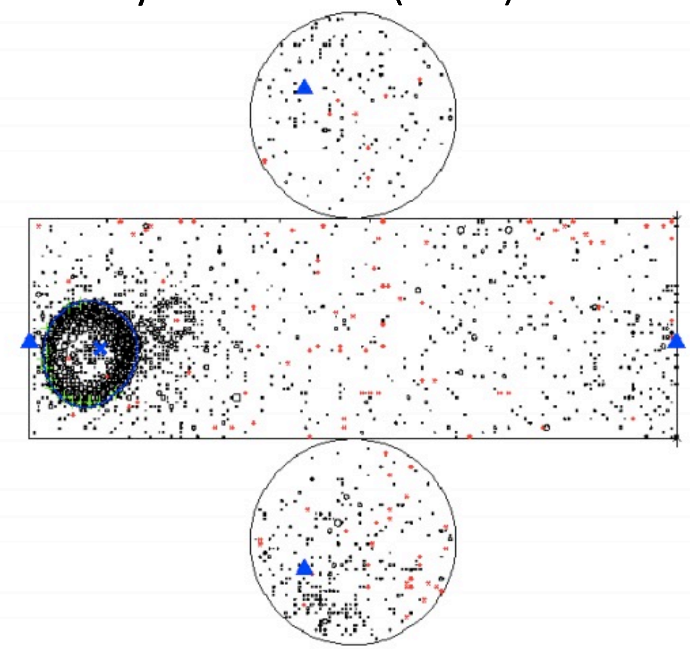
- Tagging the nucleon from a neutrino interaction seems like a great way to separate neutrino and antineutrinos
- In practice this is a difficult problem, with many potentially large systematic errors
- A magnetic field would not* make life easier for Super-K

Neutrino-Antineutrino Separation

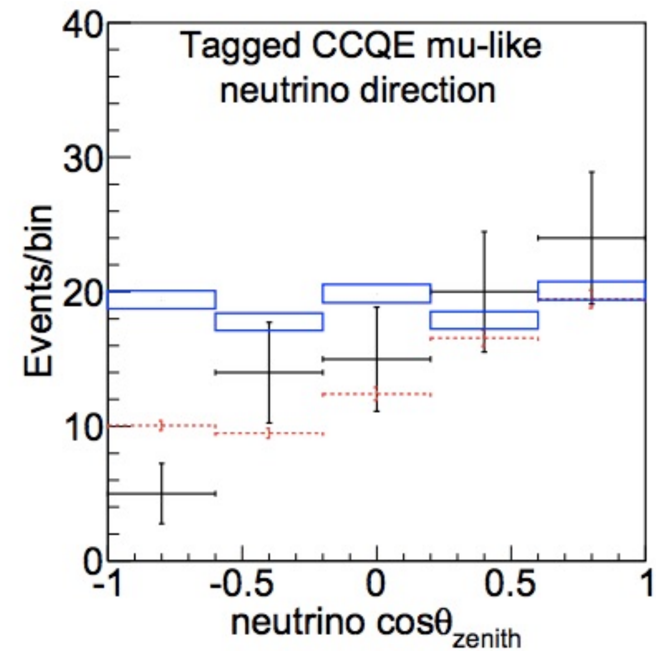
Phys. Rev. D 79 (2009) 112010

Neutrino Interaction

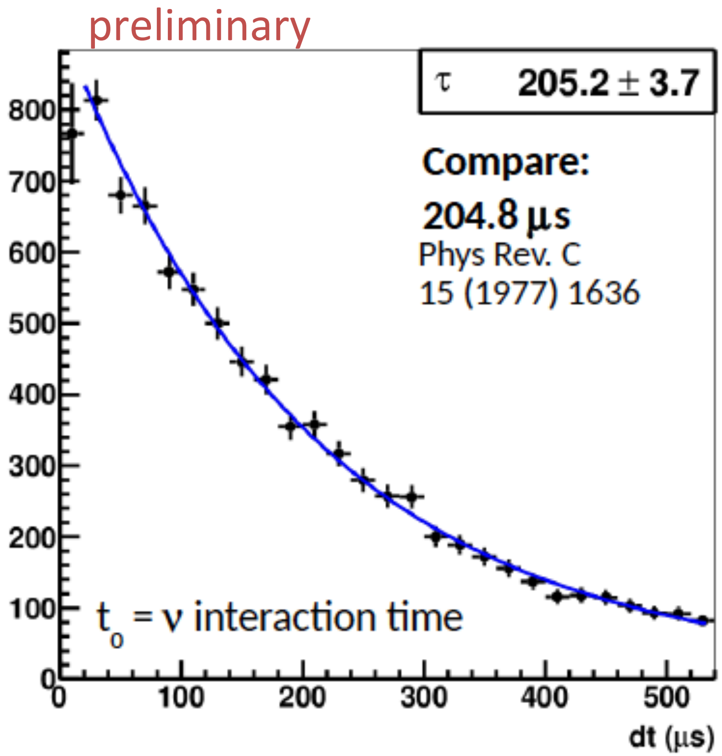




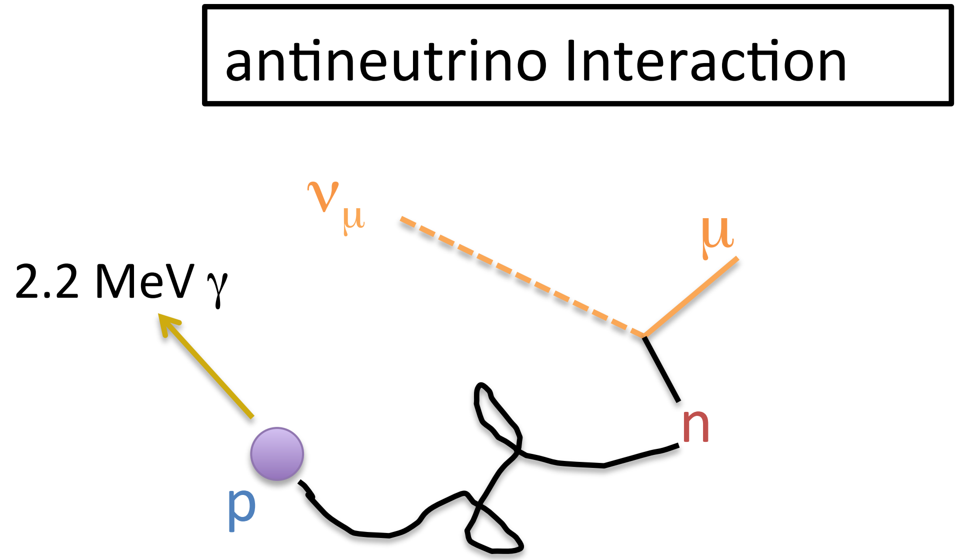
- Proton be seen if momentum > 1.07 GeV
- Hadronic interactions tend to create short tracks with thin cherenkov rings
- Expect only ~ 0.1 events/day with both proton and lepton above threshold



Neutrino-Antineutrino Separation



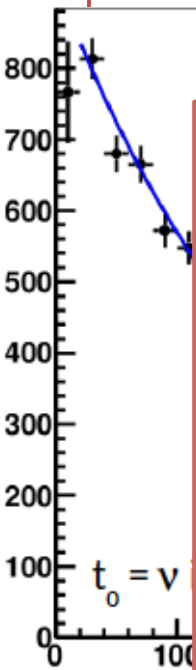
2.2 MeV γ Selection	
Efficiency	20.5%
Background / Event	0.018

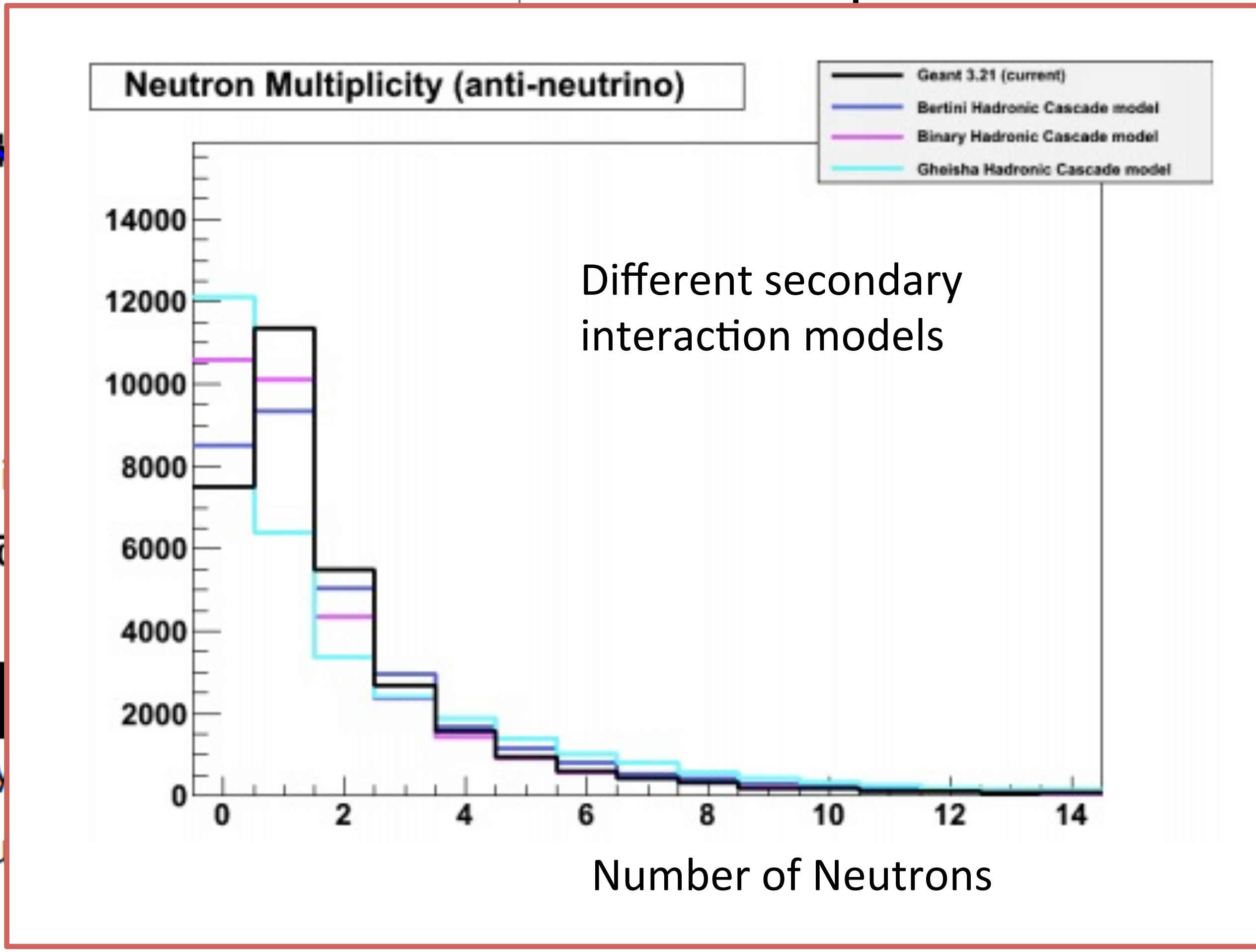


- Neutron tagging in Super-K (without Gd) is possible and has been demonstrated
- Efficiency is low, but could in principle be used for neutrino/antineutrino separation
- Buyer beware! Neutron production uncertainties and secondary interactions

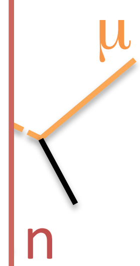
Neutrino-Antineutrino Separation

preliminary





antineutrino Interaction



2.2 MeV

Efficiency

Backgrou

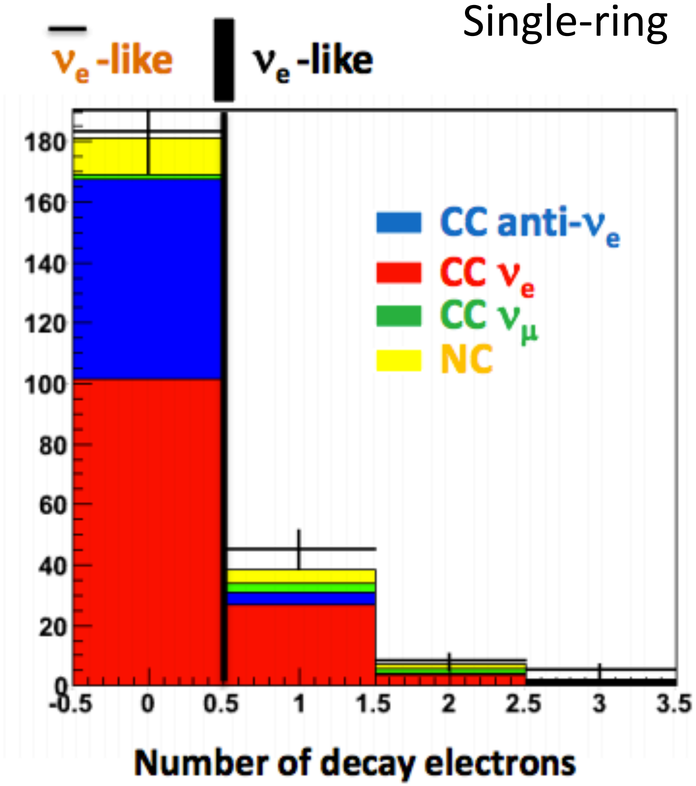
r-K (without Gd) is
emonstrated

ld in principle be
eutrino separation

- Buyer beware! Neutron production uncertainties and secondary interactions

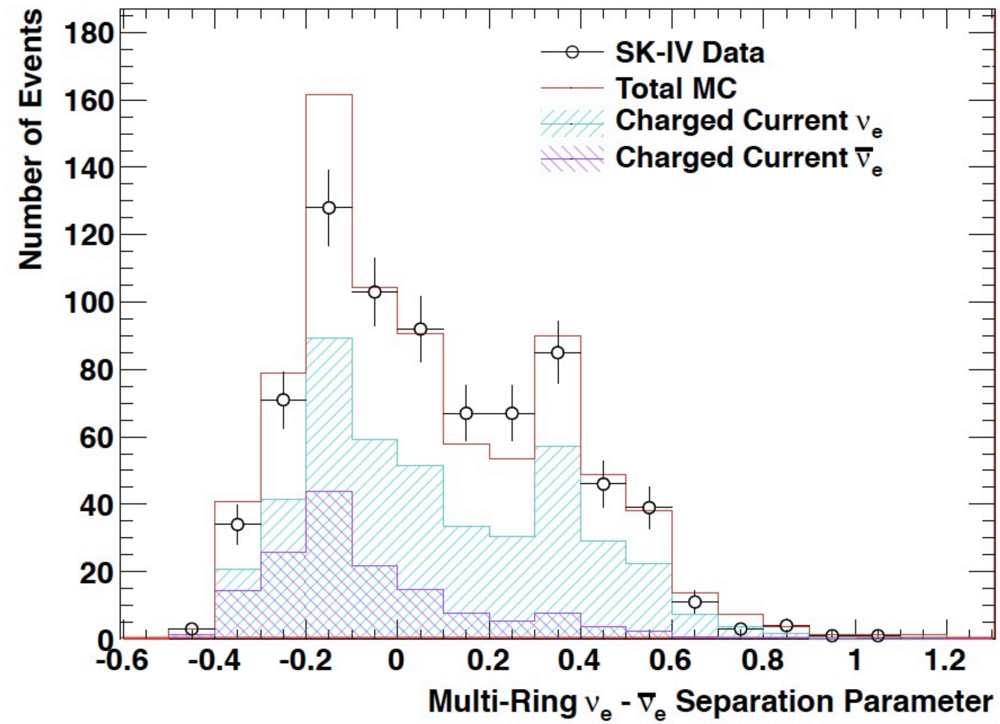
What about neutrino/neutrino separation?

Single-ring

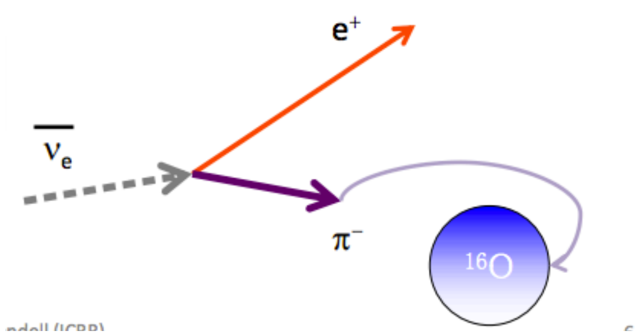


Multi-ring

preliminary

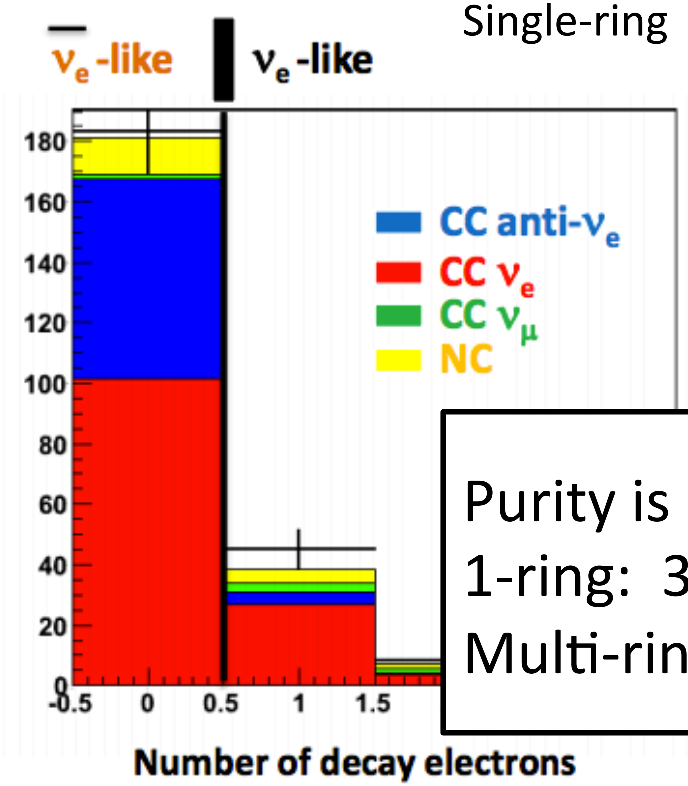


- Counting decay electrons allows for some enhancement due to negative pion absorption
- Try to measure transverse momentum relative to lepton in multi-ring events and build a likelihood

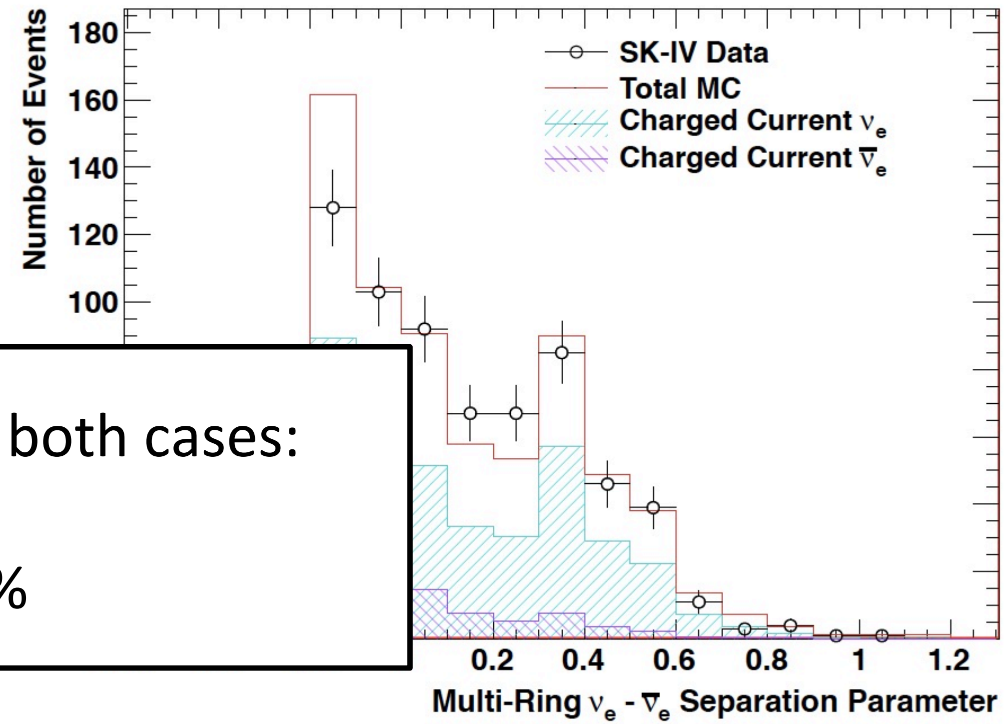


What about neutrino/neutrino separation?

Single-ring



Multi-ring



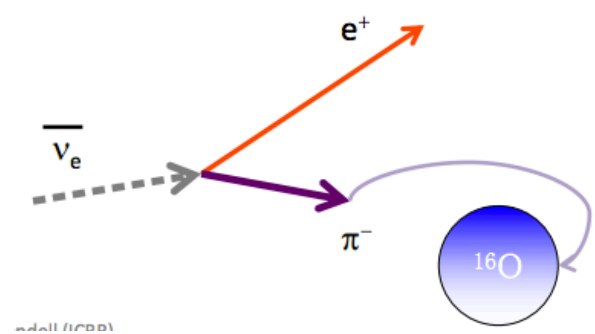
Purity is low in both cases:

1-ring: 37%

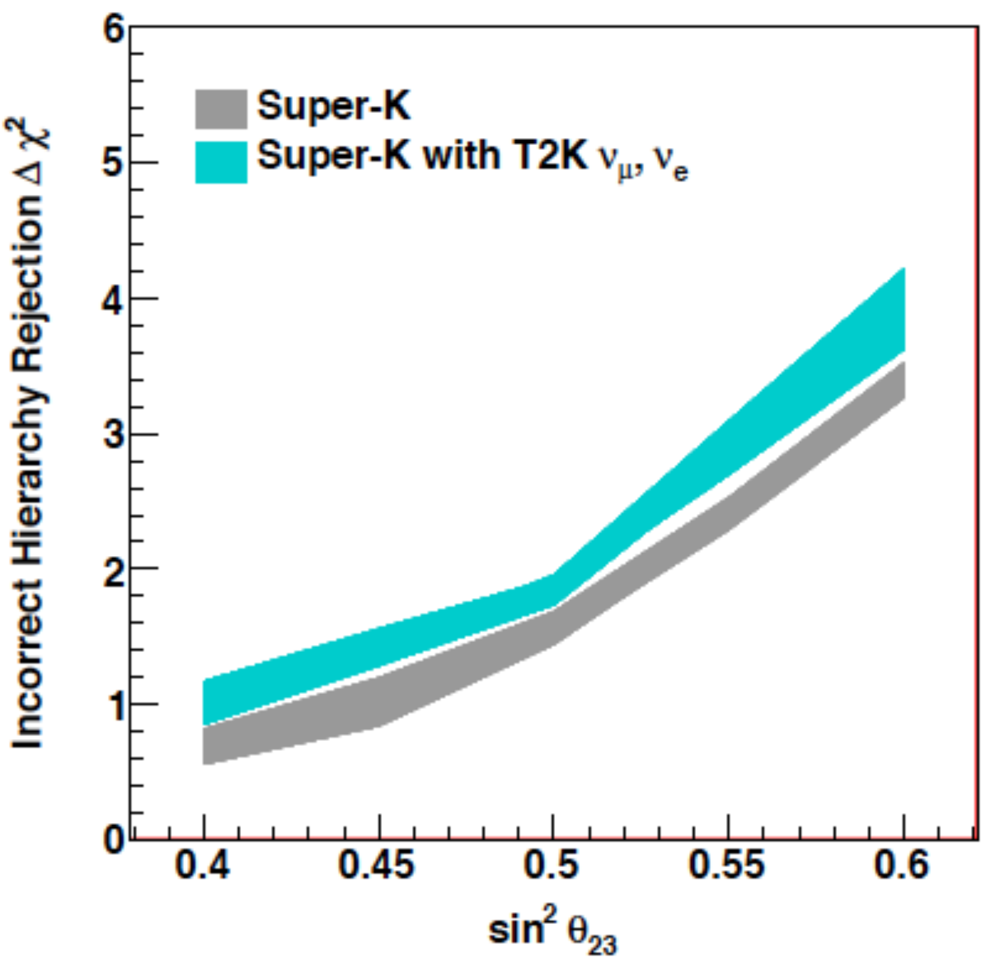
Multi-ring: 30%

- Counting decay electrons allows for some enhancement due to negative pion absorption

- Try to measure transverse momentum relative to lepton in multi-ring events and build a likelihood

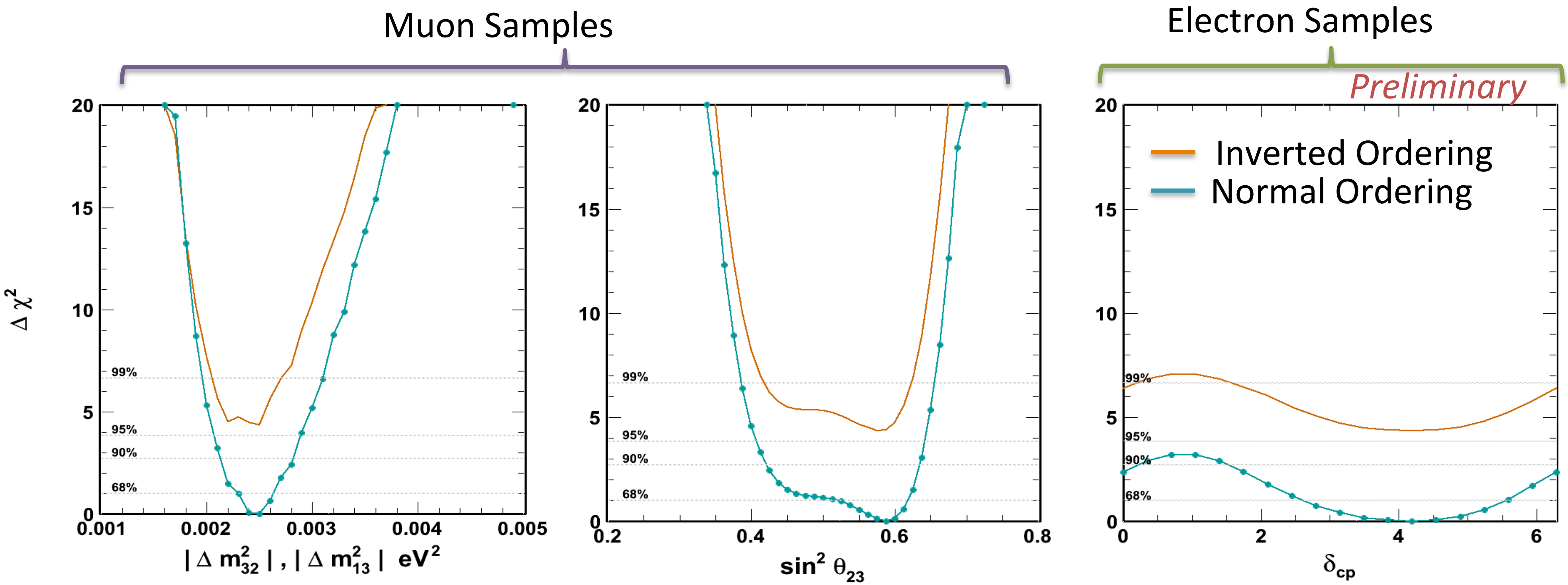


Hierarchy Sensitivity



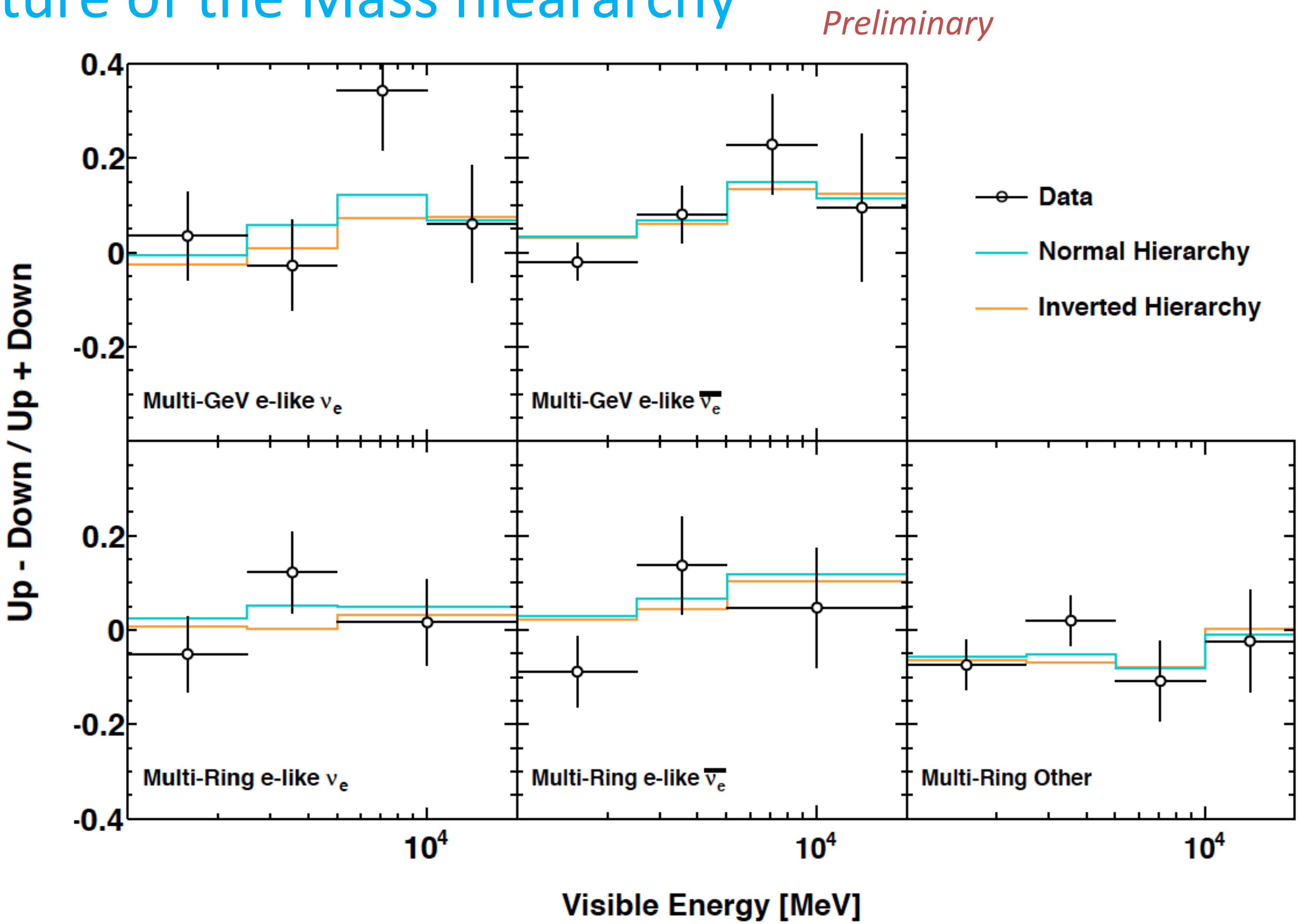
- Mass hierarchy sensitivity depends strongly on the assumed value of θ23
- This effect can be reduced by combining the atmospheric neutrino measurements with constraints on these parameters
- Best if a fit can be done with both beam and atmospheric neutrinos

Atmospheric Mixing + δ_{cp}: Super-Kamiokande



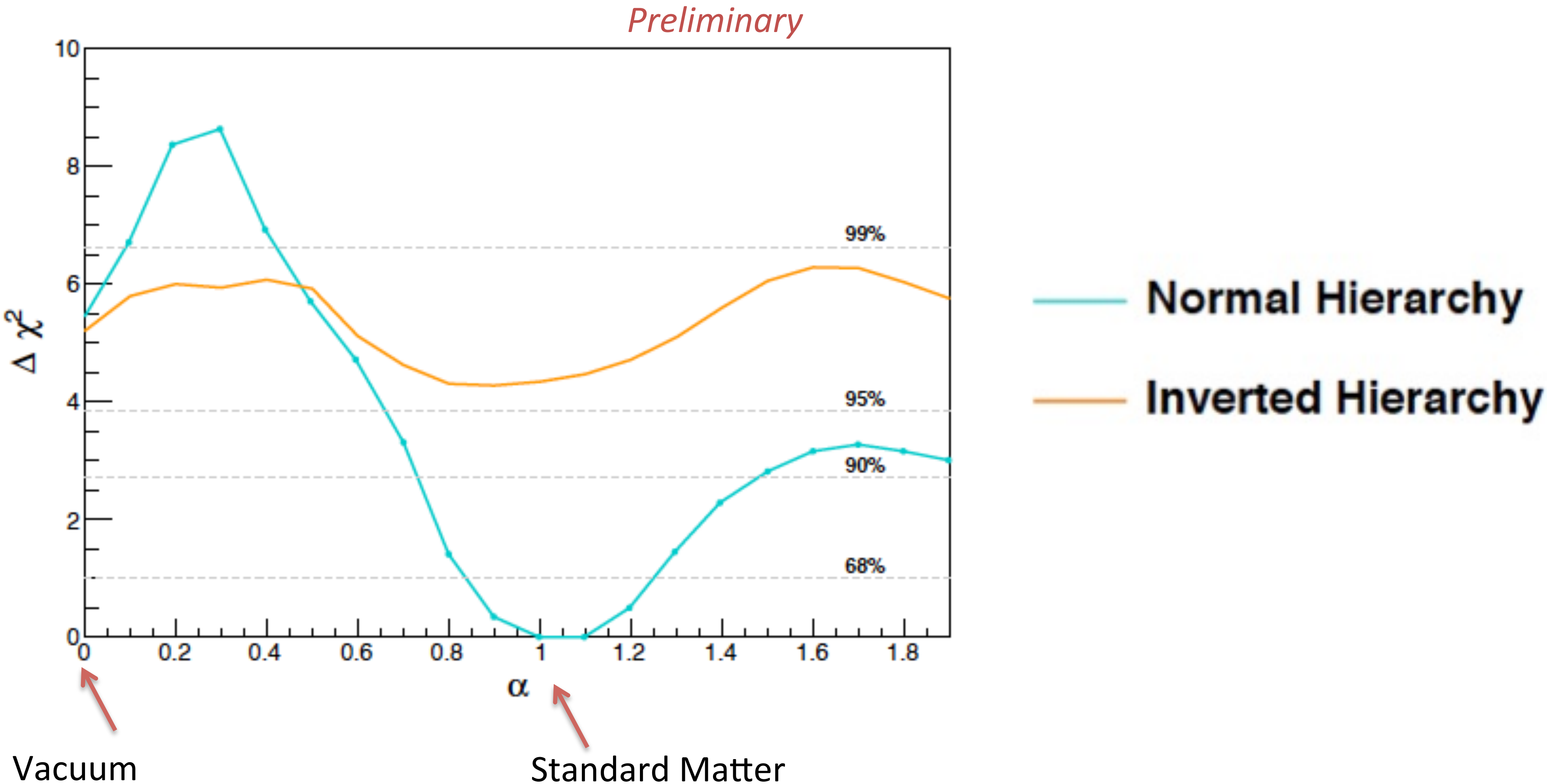
- Comparatively weak constraint on atmospheric mixing
- Observe an excess of upward-going electron neutrino events weakly favoring the *normal hierarchy*
  - $\Delta\chi^2$ (NH – IH) = -4.3
  - P(NH|IH) : 3.1% (depends on assumed value of θ23!)
- Weak hint for δ_{cp} ~1.33π

Signature of the Mass hieararchy



- Some indication of expected upward-going electron neutrino appearance, but not conclusive

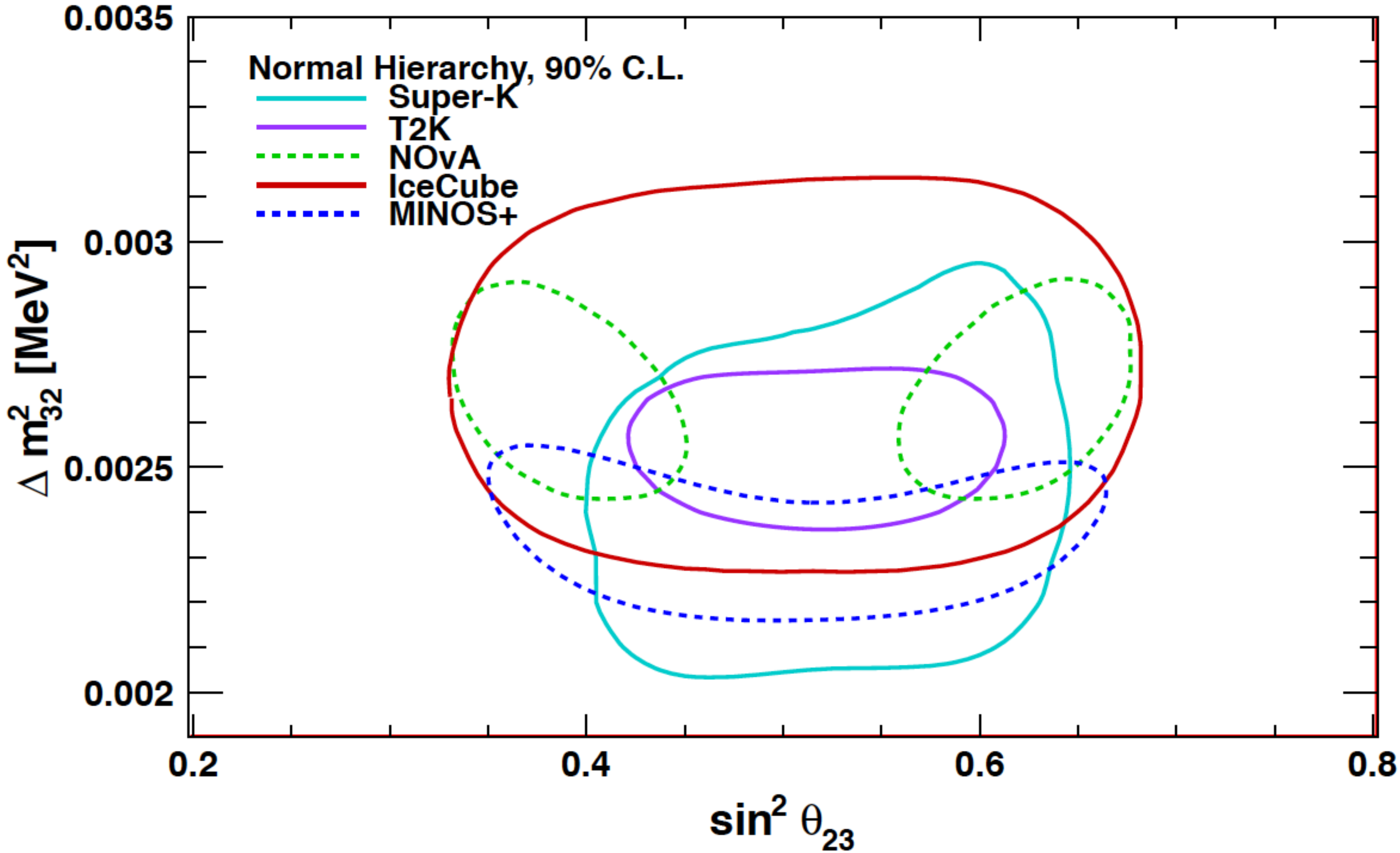
Testing For Matter Effects



- Here θ_{13} is assumed to be reactor value with uncertainties
- Reject no-matter effects at 1.6σ

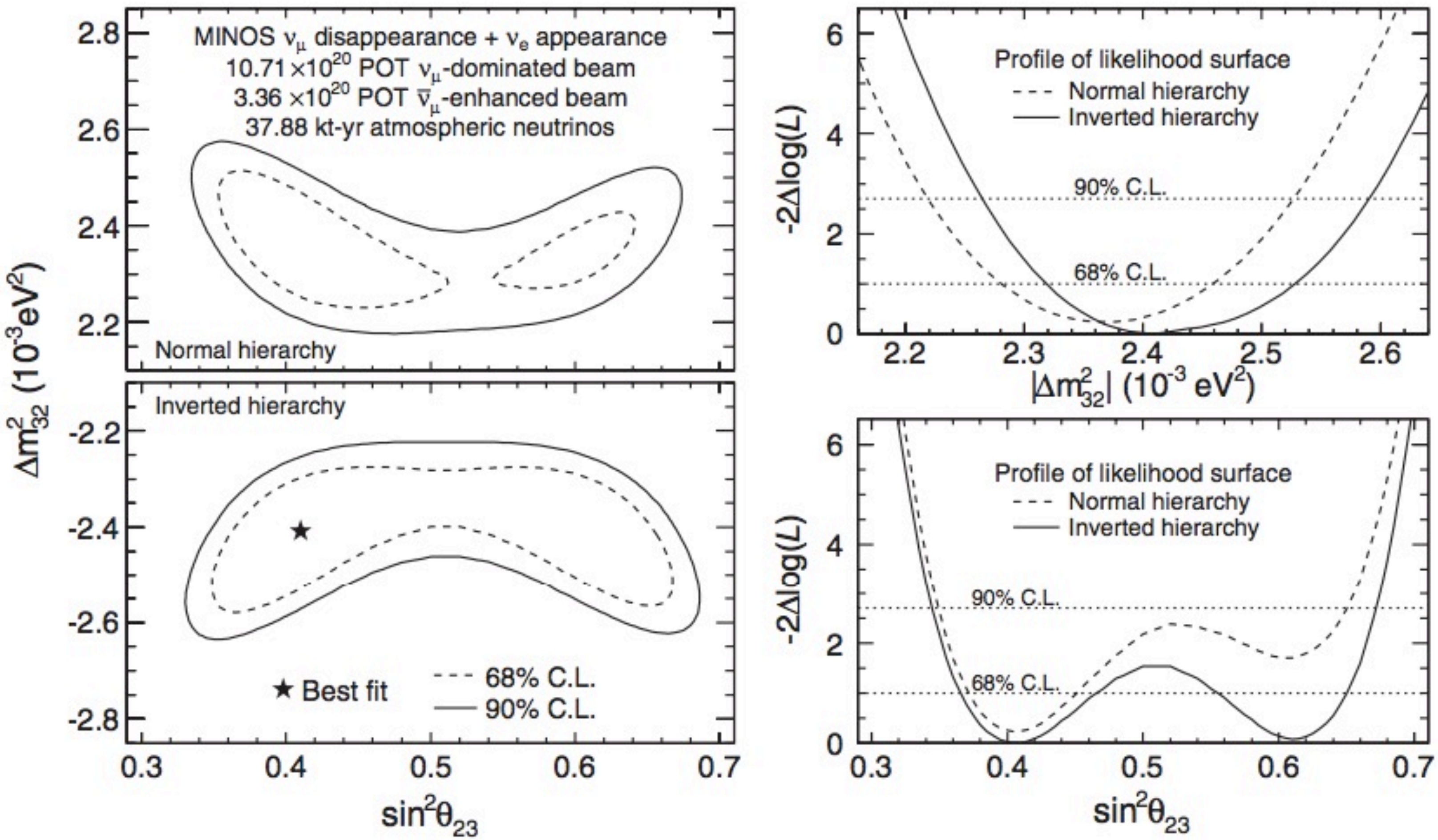
Atmospheric Mixing

Preliminary



MINOS Combined Beam and Atmospheric ν Measurement

PRL 112, 191801 (2014)

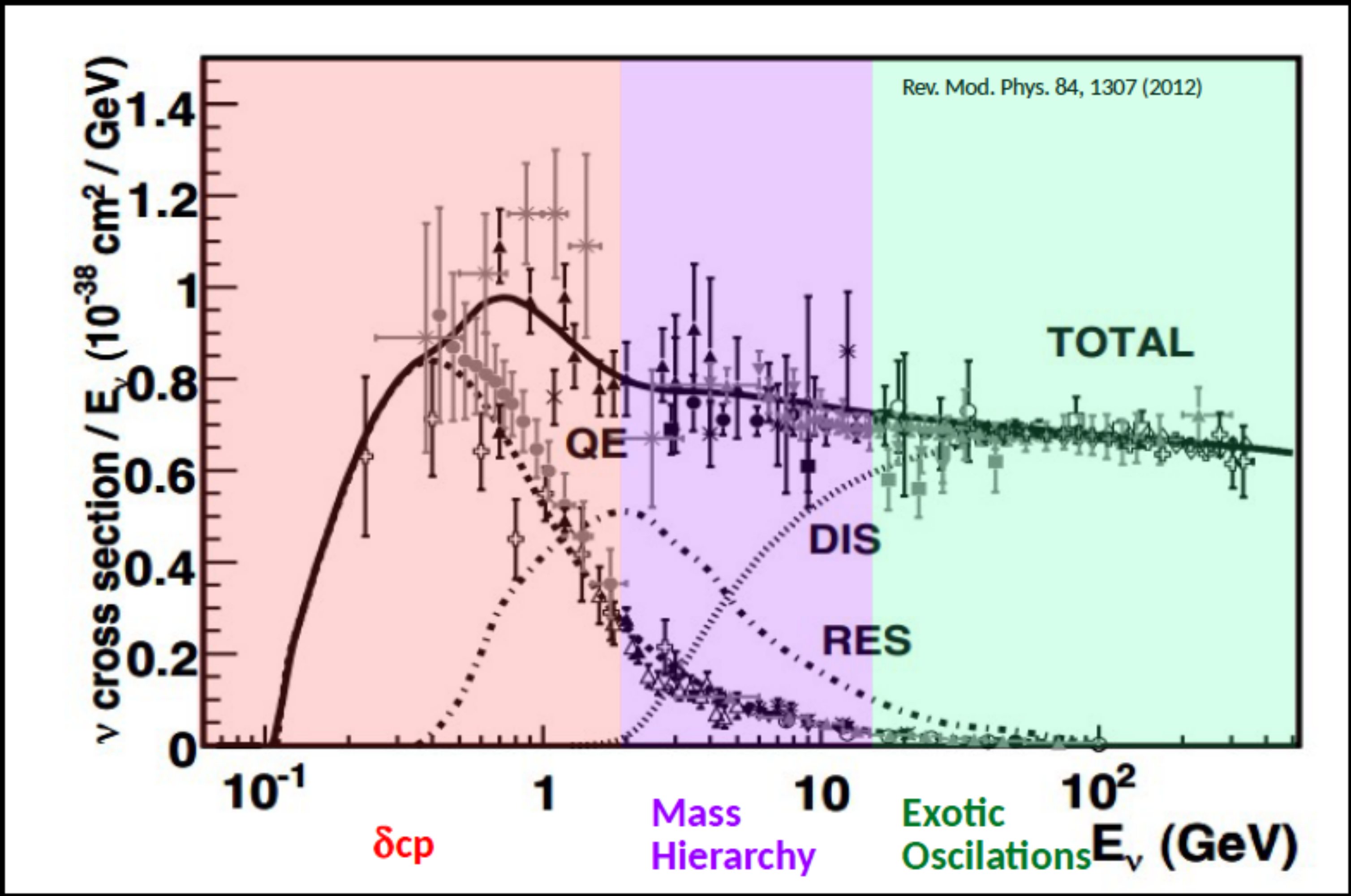


- First experiment to combine atmospheric and beam neutrino data
- Improves hierarchy sensitivity
- This result weakly favors the inverted hierarchy

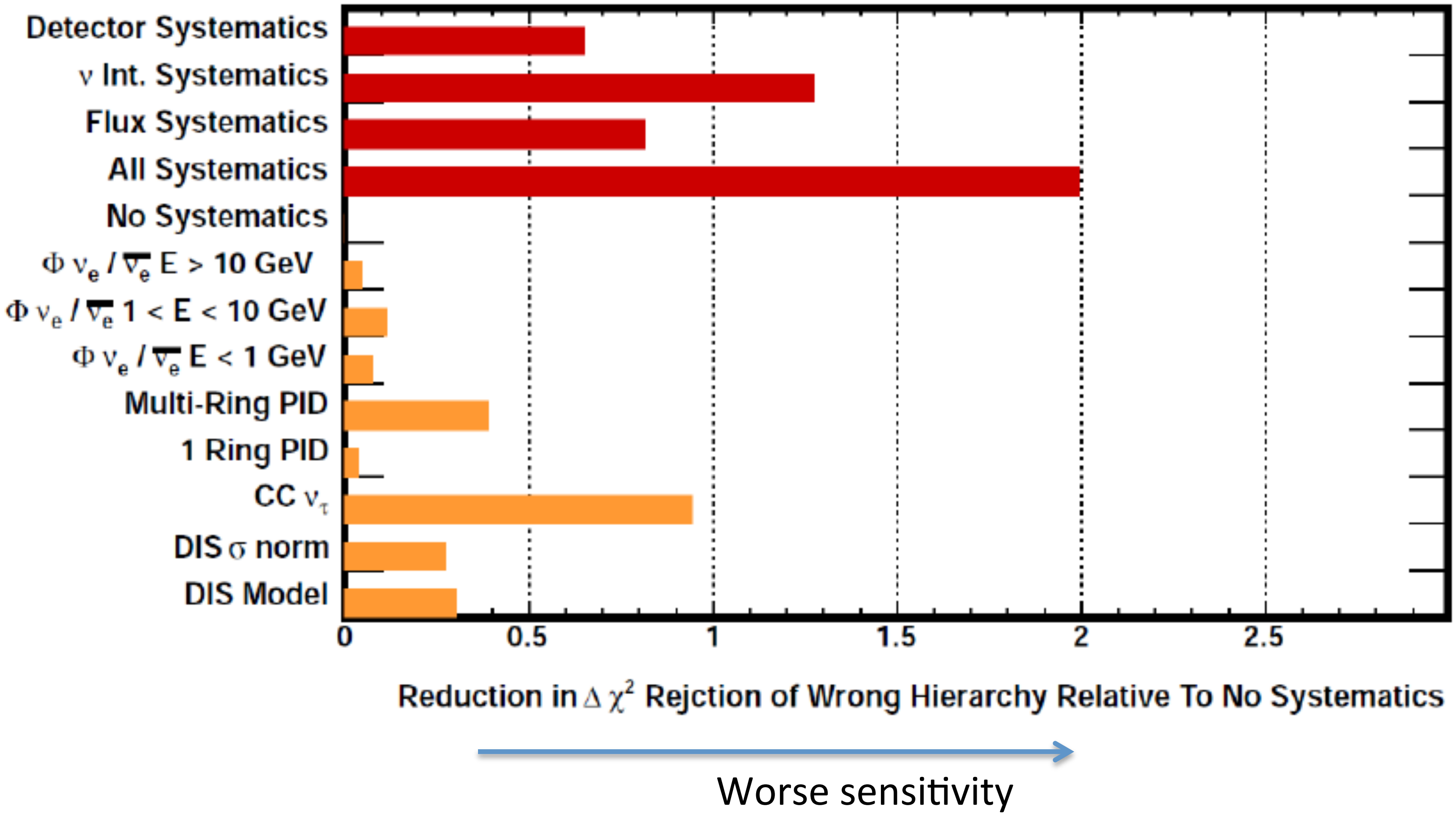
Systematic Errors

- For the hierarchy search in Super-K, statistics are the dominant error but ...

Neutrino Interactions Relevant for Atmospheric Neutrinos

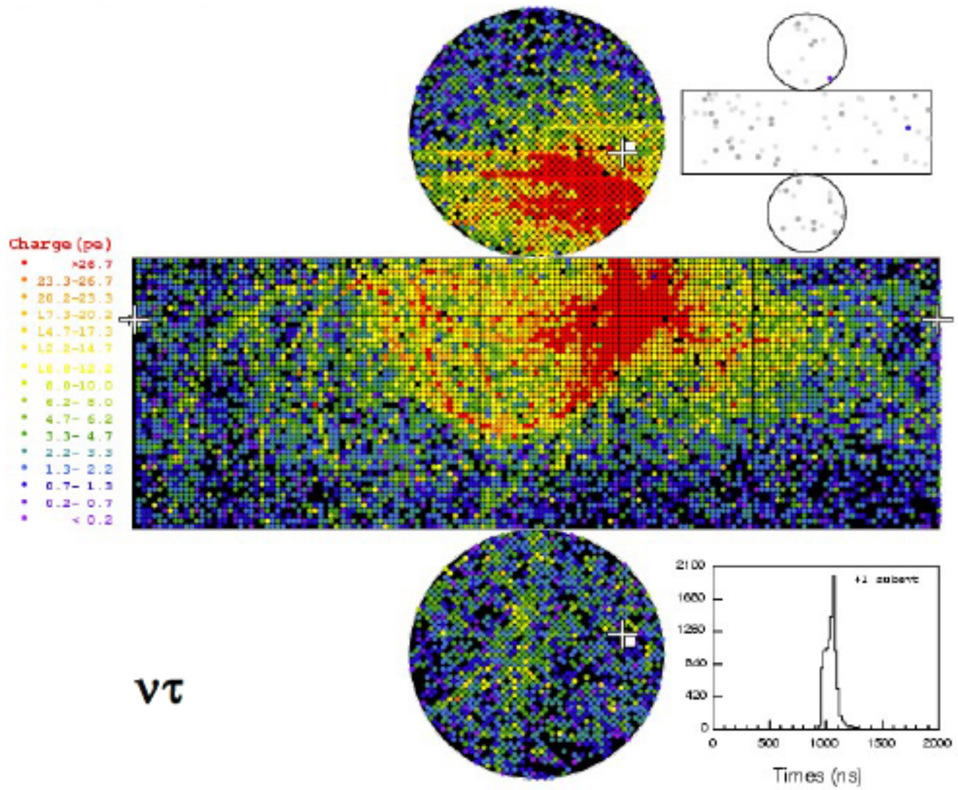


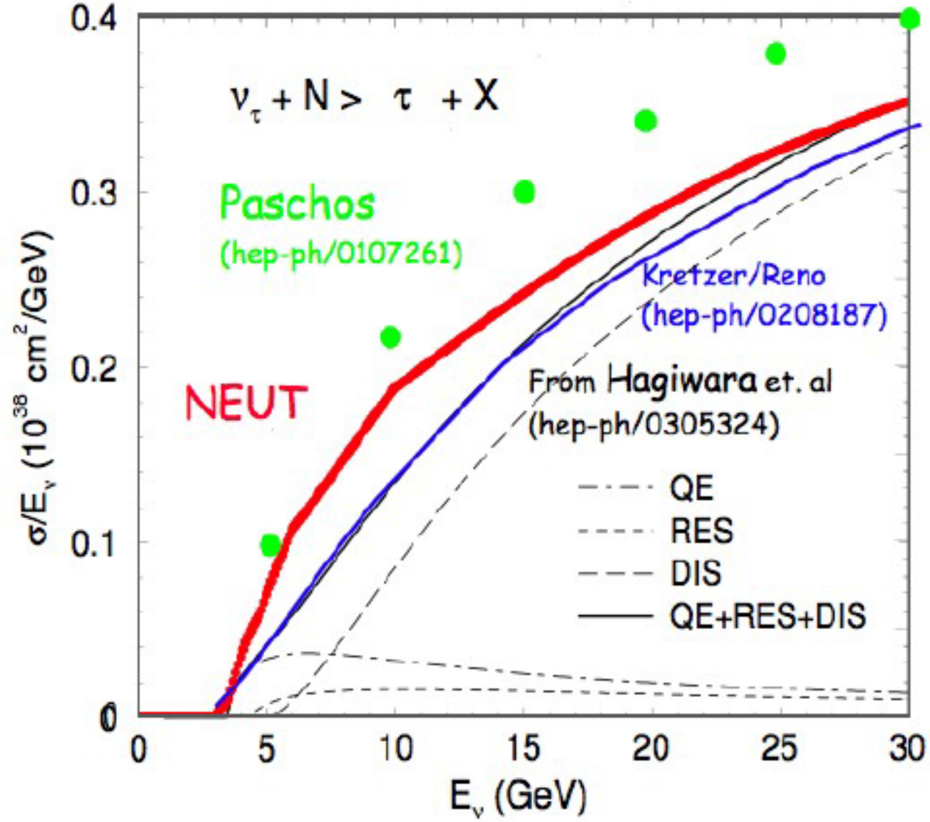
Mass Hierarchy Systematics



- Sensitivity to the hierarchy is largely affected by uncertainties interaction of high energy neutrinos
  - particularly the CC $\nu\tau$ background component

Tau Background for Mass Hierarchy

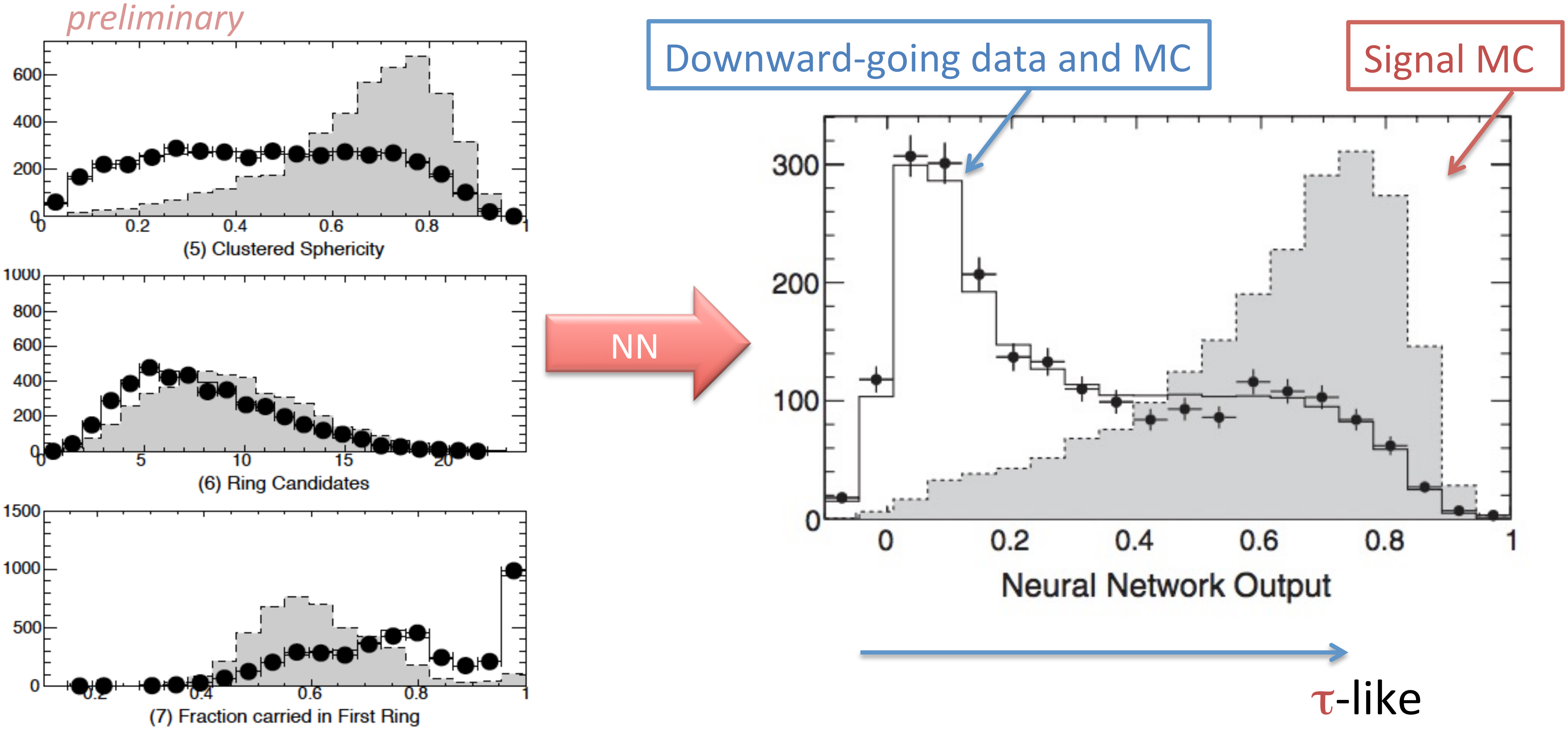




- Tau neutrino events often look electron-like
- Upward-going, so they are the main background for hierarchy

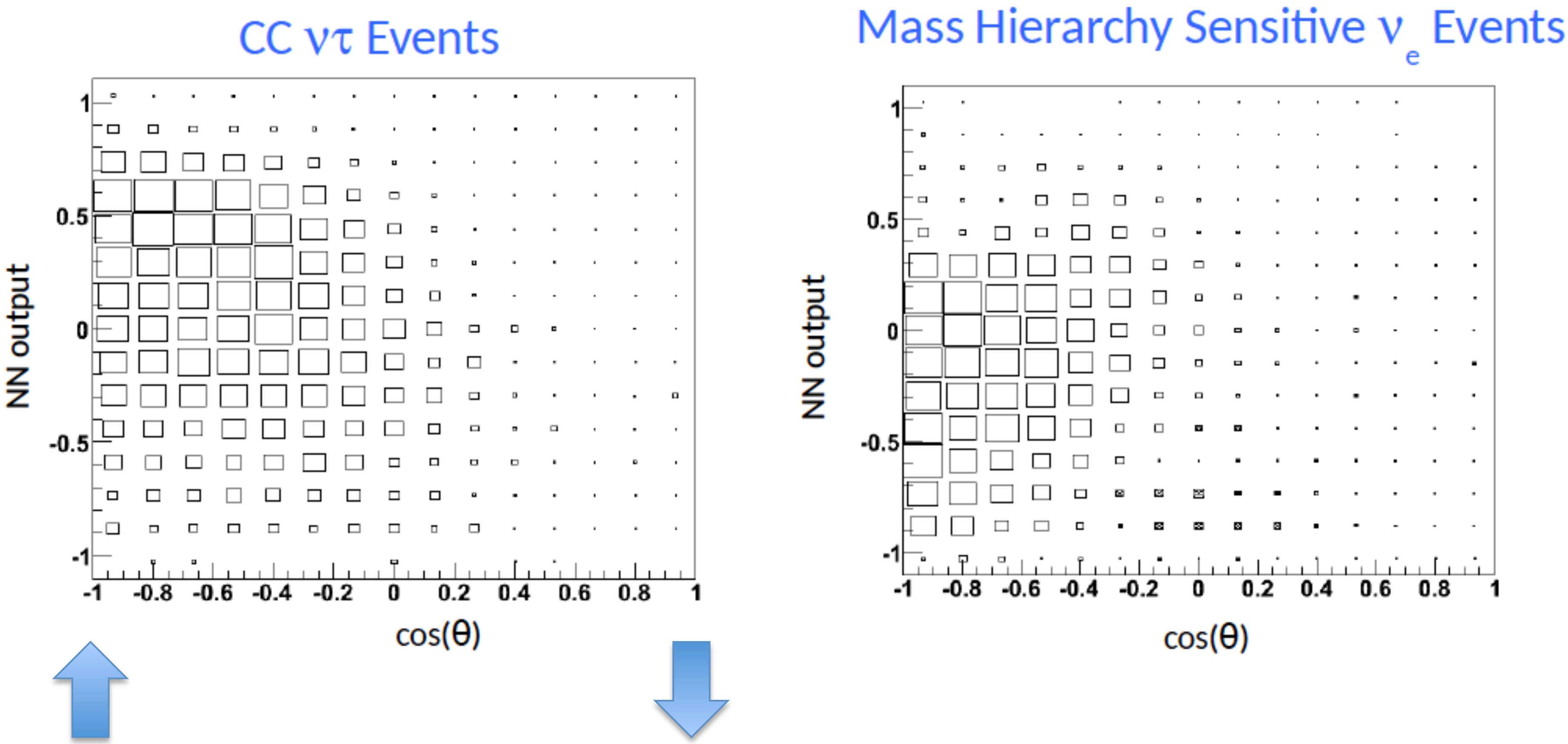
- Tau interaction cross section is not very well known
- Systematic error is taken to be 25% based on differences in models

Mitigating the Background Uncertainty



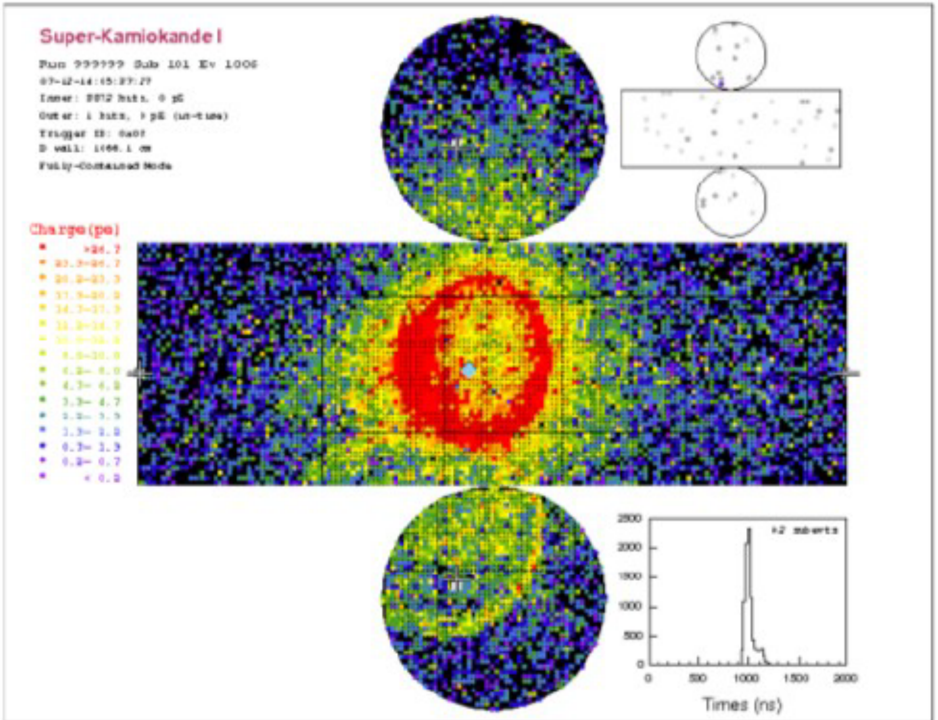
- In principle the neural network used to find tau neutrino interactions can be used to separate those events in the oscillation analysis
- This is an idea that is currently being implemented

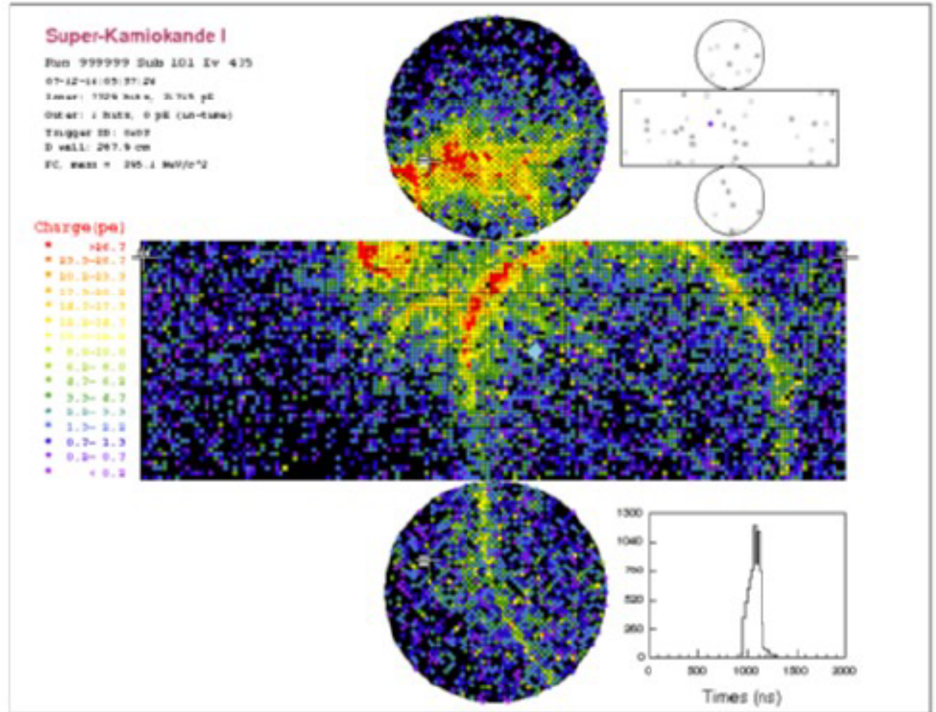
Mitigating the Background Uncertainty



- In principle the neural network used to find tau neutrino interactions can be used to separate those events in the oscillation analysis
- This is an idea that is currently being implemented

Particle ID for Multi-Ring Topologies

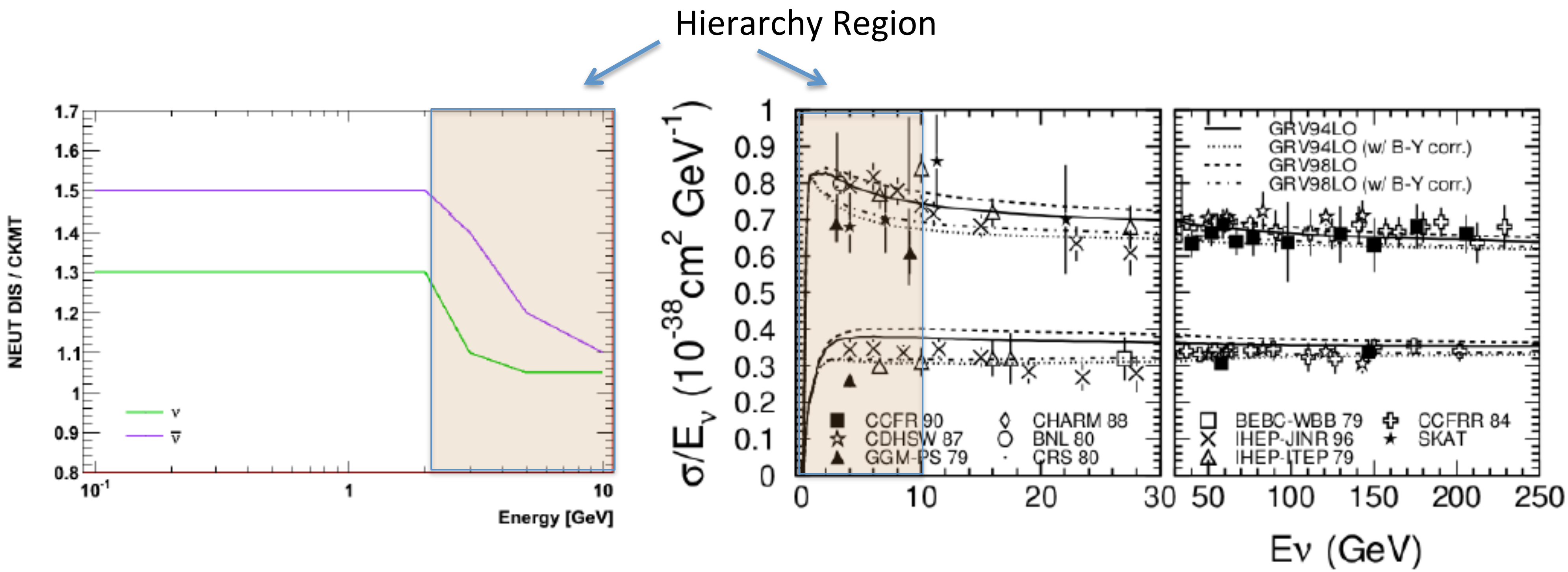




- The largest detector systematic comes from the mis-ID of CC $\nu\mu$ interactions in multi-ring e-like events

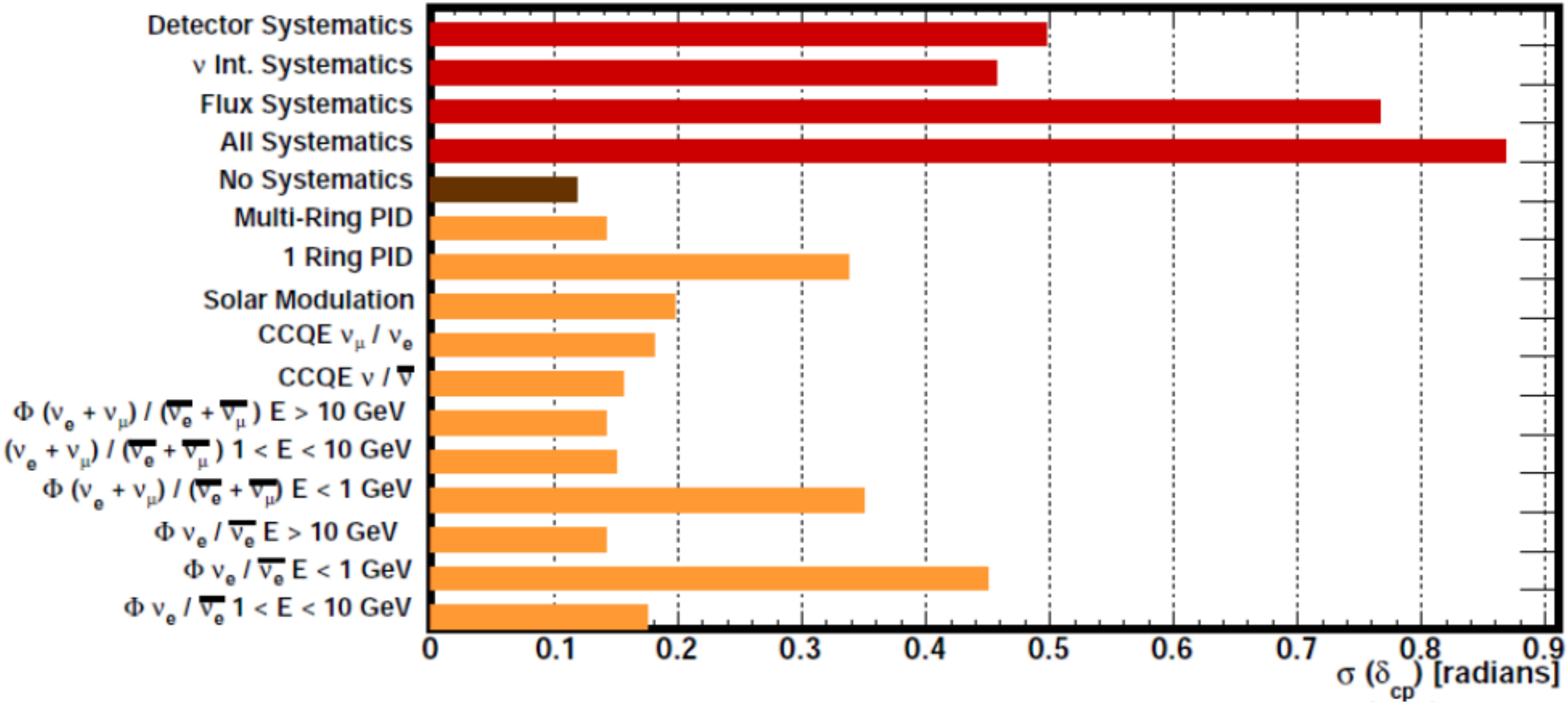
- Difficult to constrain – no genuine control samples
- Data studies suggest the uncertainty is between 4 and 9% depending on the data set

Deep Inelastic Scattering



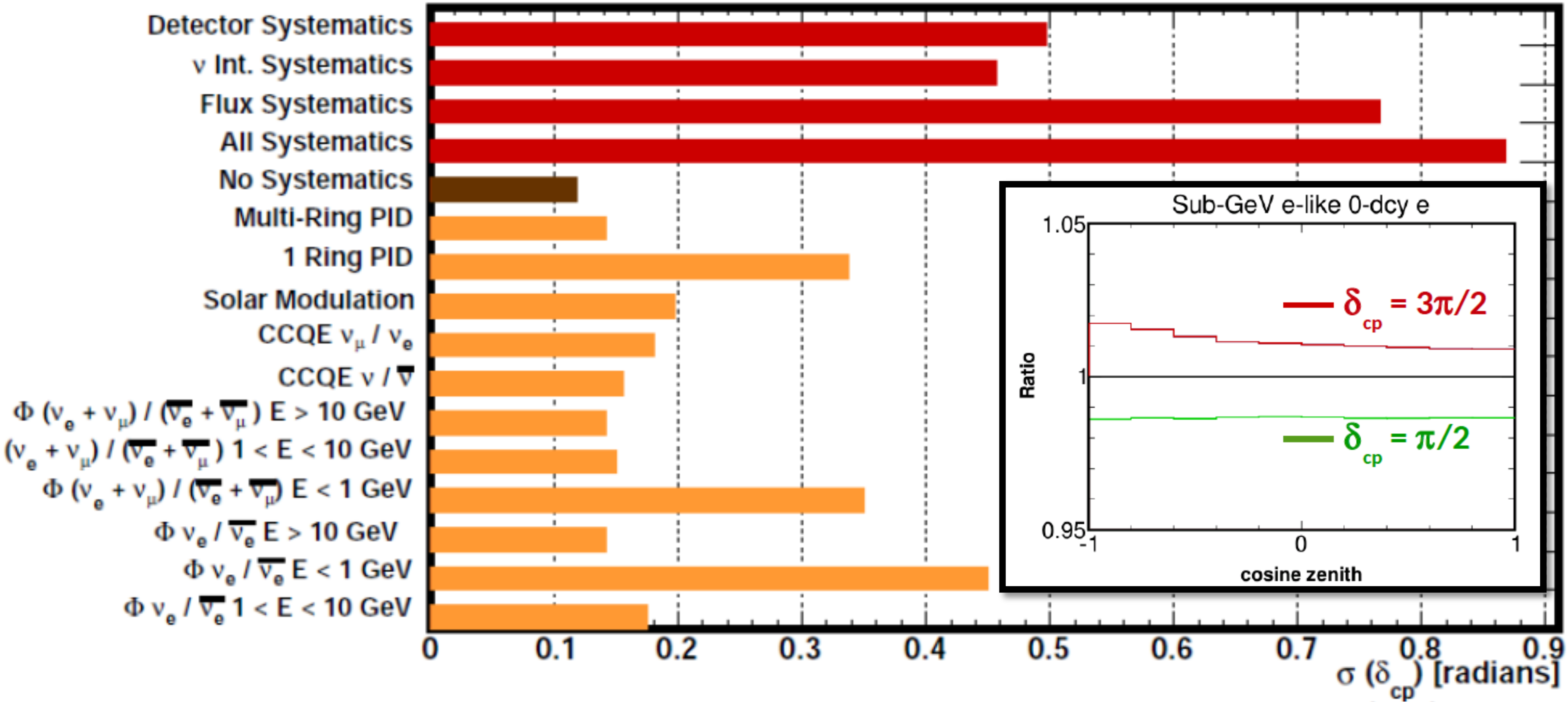
- DIS cross section systematics are taken as model differences
  - Default model with and without CKMT parameterization below
- In addition, a 5% normalization uncertainty is taken from accelerator measurements

Systematics effecting δcp Measurement (Large Stat.)



- Generally sensitivity is affected by systematics in the low energy flux
- Figure shows uncertainty on measurement of δ_{cp} assuming δ_{cp} is $-\pi/2$

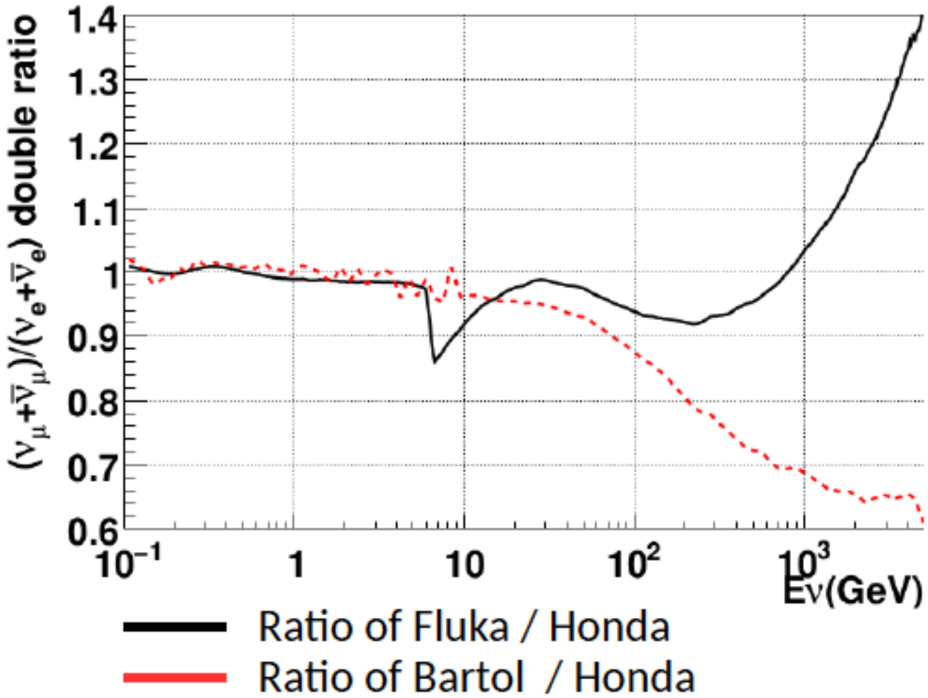
Systematics effecting δcp Measurement (Large Stat.)



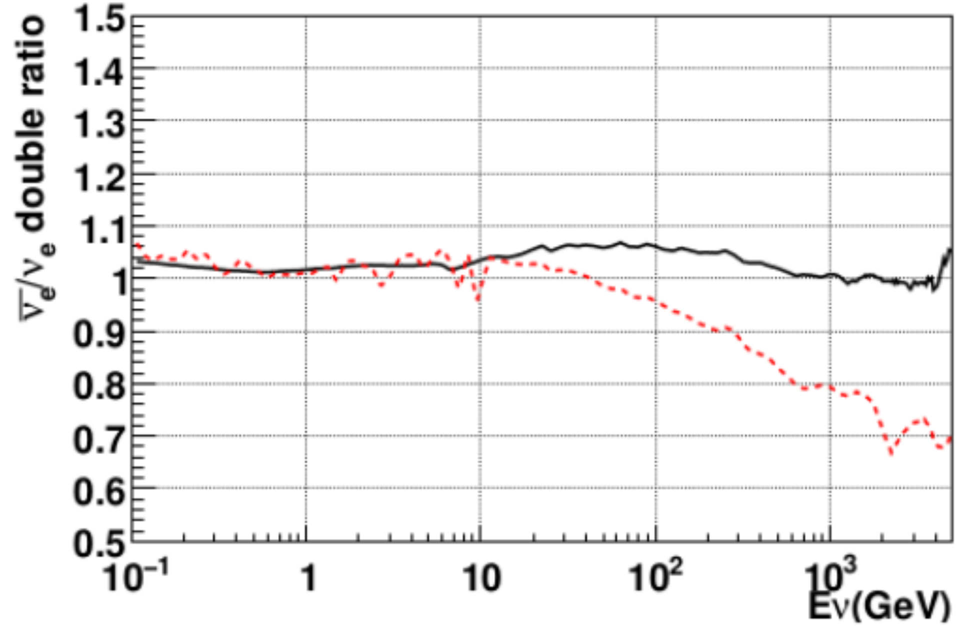
- Generally sensitivity is affected by systematics in the low energy flux
- Figure shows uncertainty on measurement of δ_{cp} assuming δ_{cp} is $-\pi/2$

Atmospheric Neutrino Flux Uncertainties (Honda 2011)

Flavor Ratio Comparison

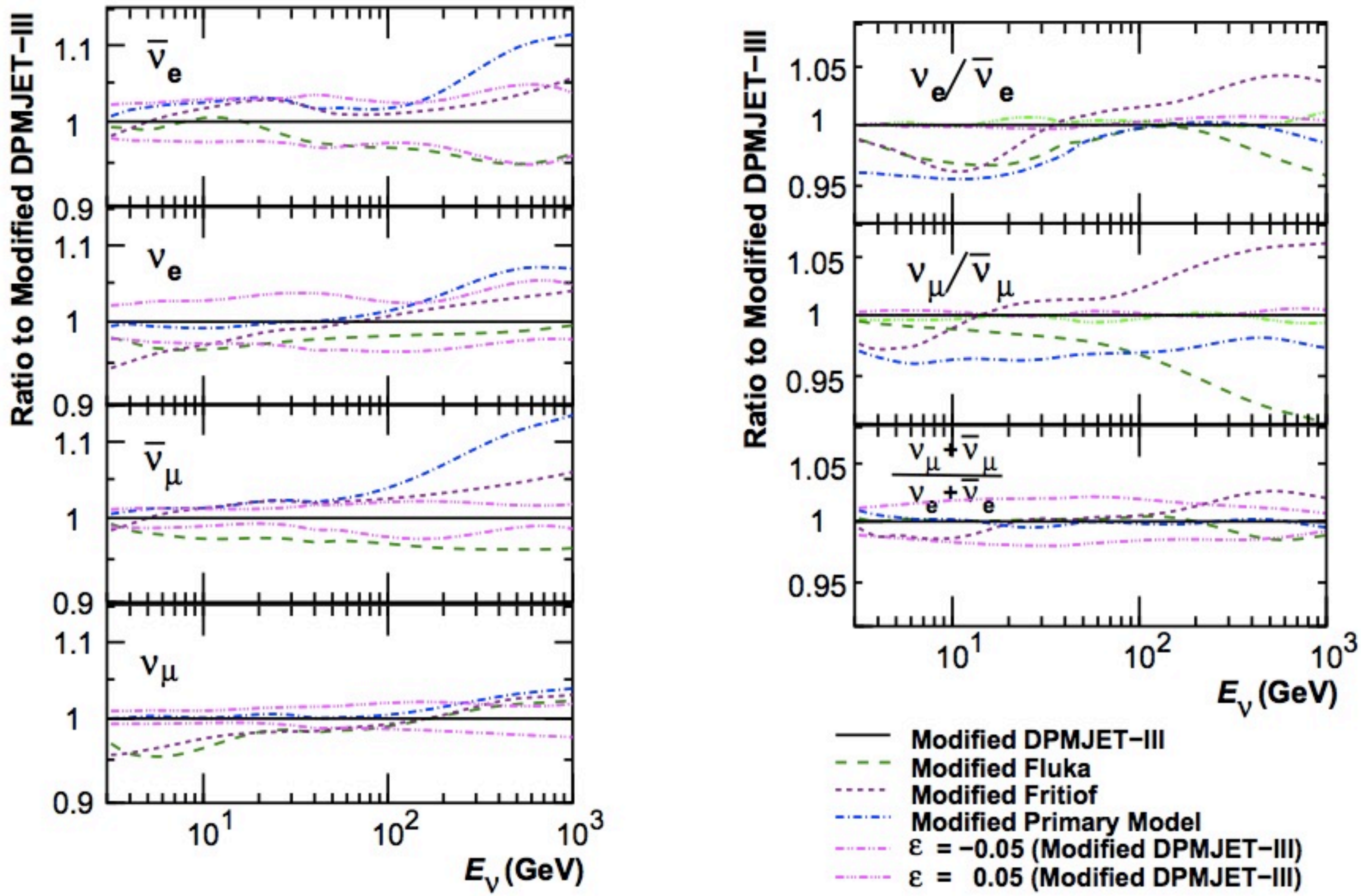


Electron to Antielectron Neurino Ratio



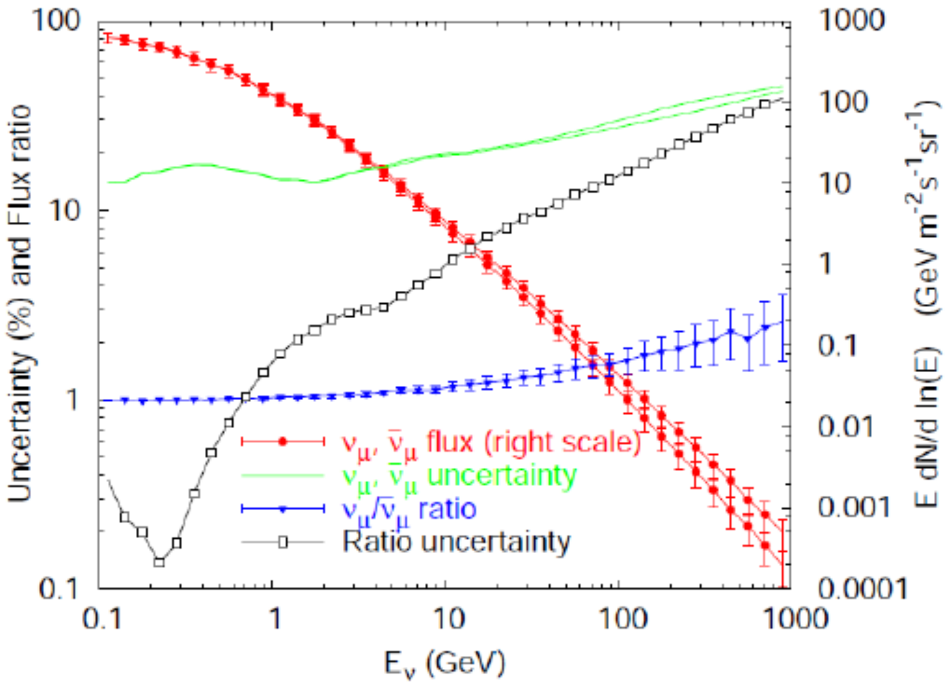
- Systematic Errors on the Neutrino flux at Super-K (Hyper-K) are based on both direct estimates from the authors of the Honda 2011 Flux and by comparisons with other models
  - Flavor Ratio uncertainty is 2% below 1 GeV
  - Electron ratio uncertainty is 5% below 10 GeV

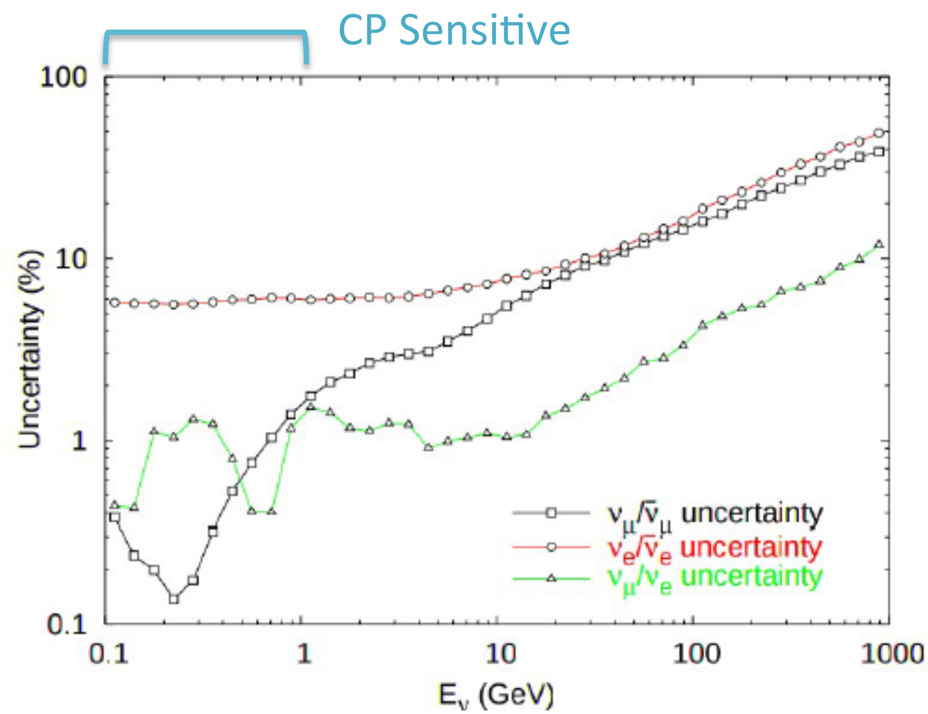
Honda Flux Systematics (HKMMS07)



- Systematic Errors on the Neutrino flux at Super-K (Hyper-K) are based on both direct estimates from the authors of the Honda 2011 Flux and by comparisons with other models
  - Flavor Ratio uncertainty is 2% below 1 GeV
  - Electron ratio uncertainty is 5% below 10 GeV

Other Systematic Error Estimates



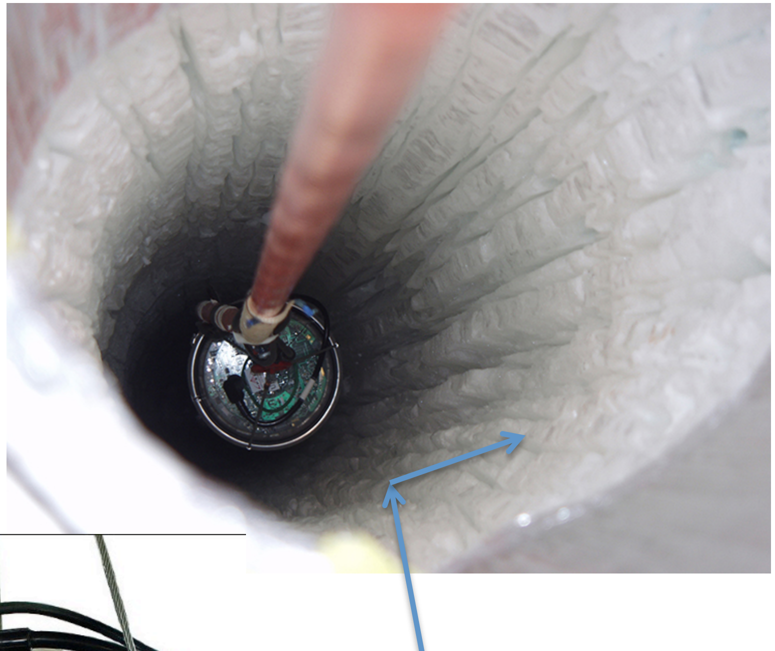


E_i (GeV)	Pions			
<8	10%		30%	
8–15	30%	10%	30%	
15–30	30	10	5%	10%
30–500	30	15%		
>500	30	15%+Energy dep.		
	0	0.5	x_{LAB}	1

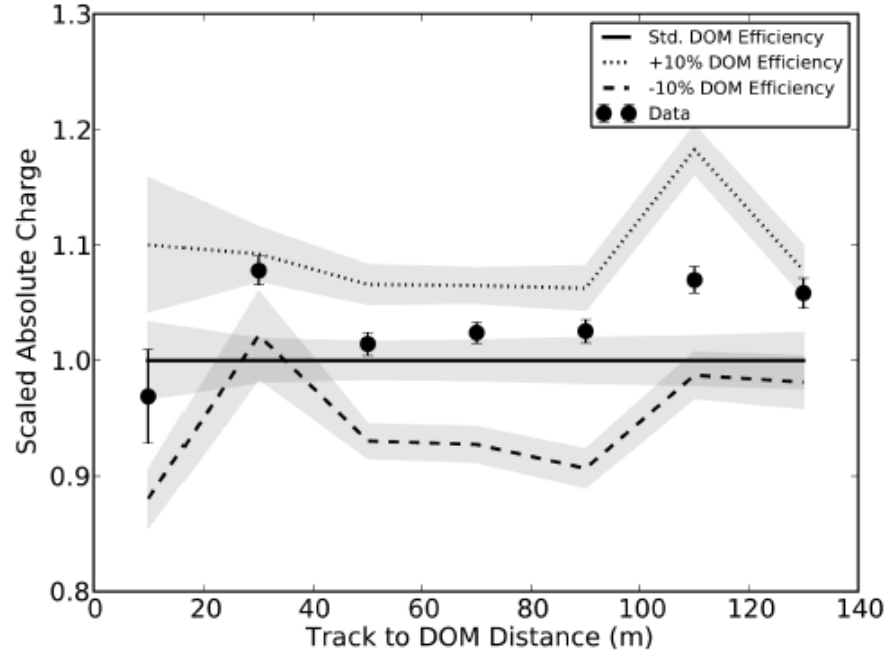
- Systematic errors for the Bartol flux have been estimated using variations in the hadron production model
  - Electron ratio uncertainty between 5% and 7% below 5 GeV
  - Differing approaches with basically consistent results

- Atmospheric neutrino flux models at low can be improved by
  - Better hadron production measurements at low momenta
    - Most 500 MeV ν are produced by cosmic ray protons with between 3 and 30 GeV
  - Better muon measurements at momenta around 500 MeV

IceCube Systematics (Oscillations and Flux)



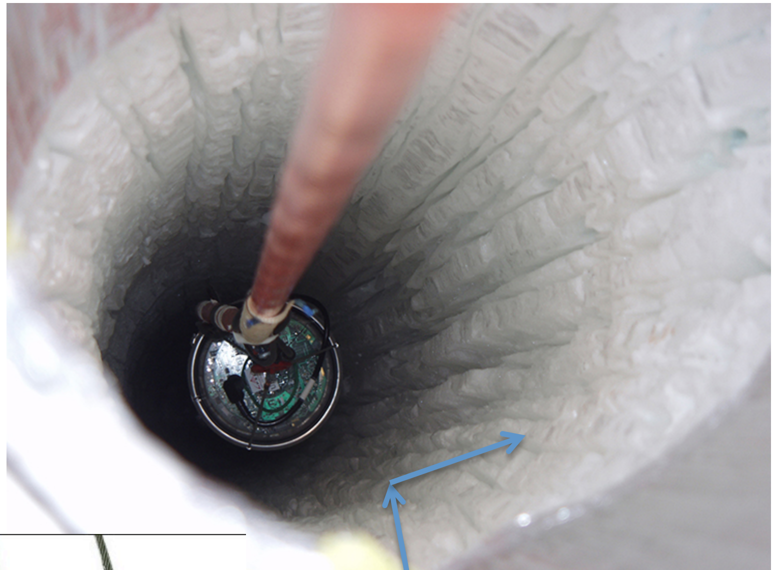
JPS Conf. Proc. **12**, 010014 (2016)

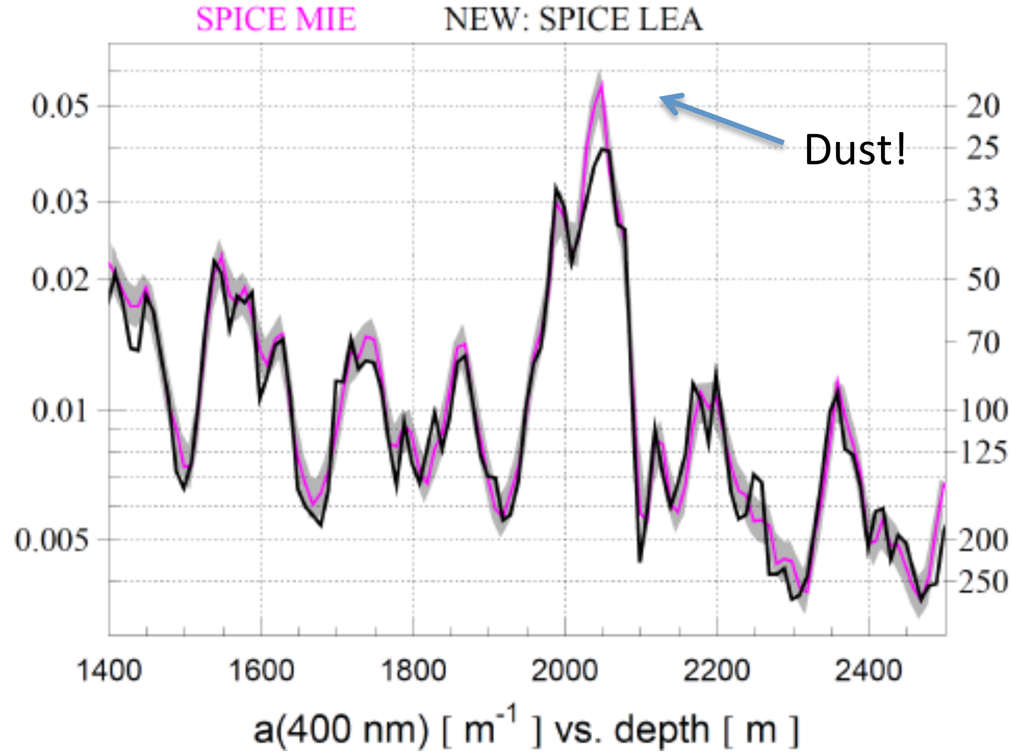


- Dominant source of systematics comes from the detector energy scale
  - Combination of PMT efficiency (σ=7.7%) and muon interaction cross section (σ=4%)
- Uncertainty in scattering and absorption properties of the ice (σ=10%) for both

IceCube Systematics (Oscillations and Flux)

JPS Conf. Proc. **12**, 010014 (2016)





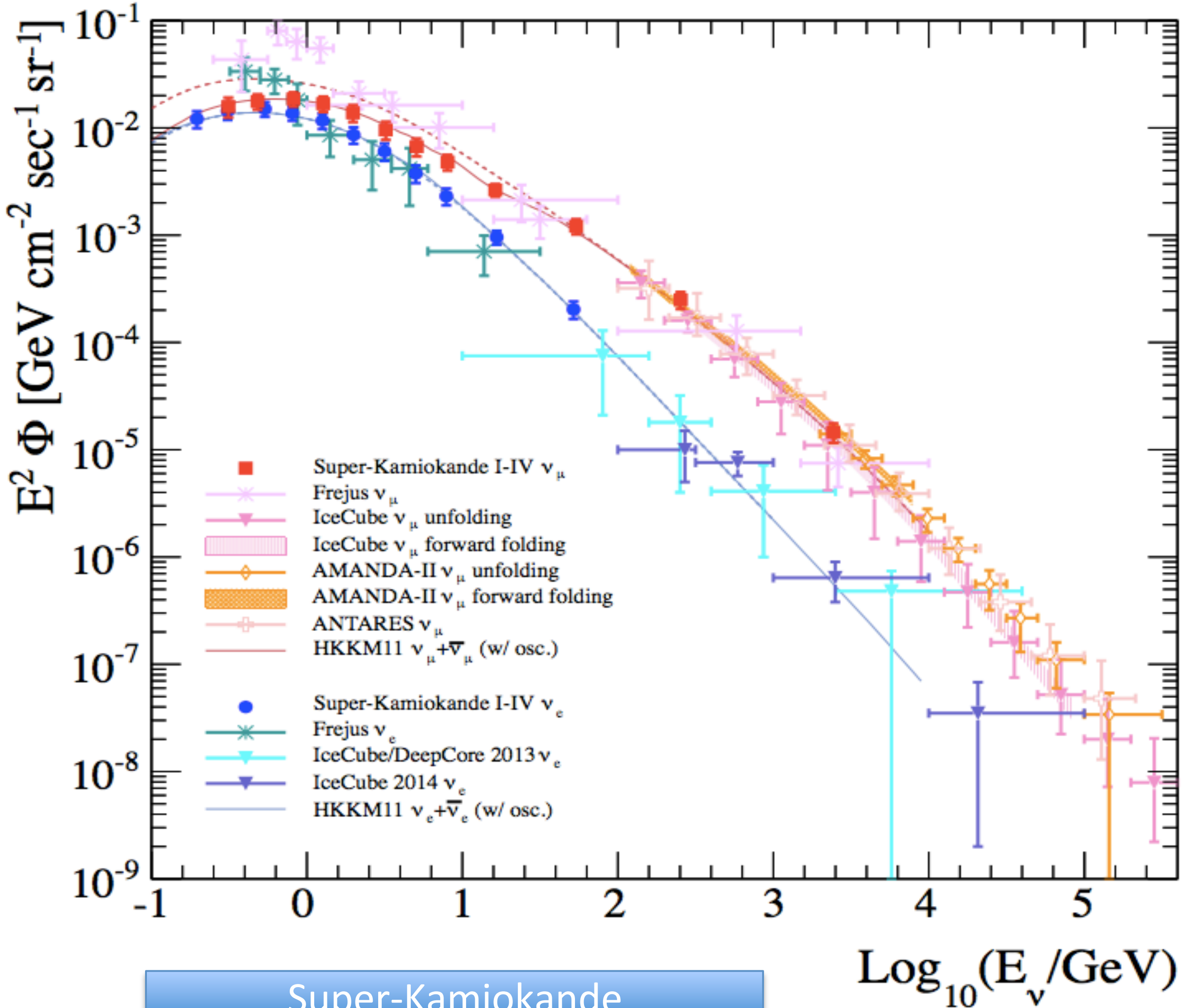
- Dominant source of systematics comes from the detector energy scale
  - Combination of PMT efficiency (σ=7.7%) and muon interaction cross section (σ=4%)
- Uncertainty in scattering and absorption properties of the ice (σ=10%) for both

Flux Measurements

- Atmospheric neutrinos are still the dominant background for many other processes...

Atmospheric Neutrino Flux:

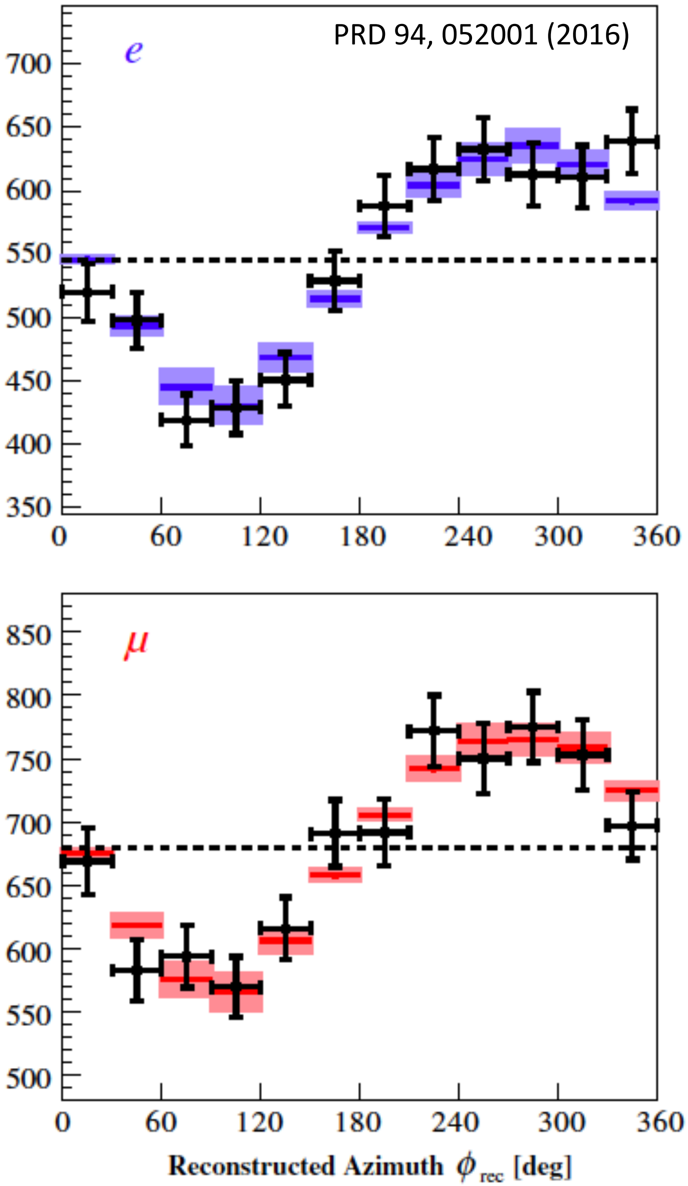
PHYSICAL REVIEW D 94, 052001 (2016)



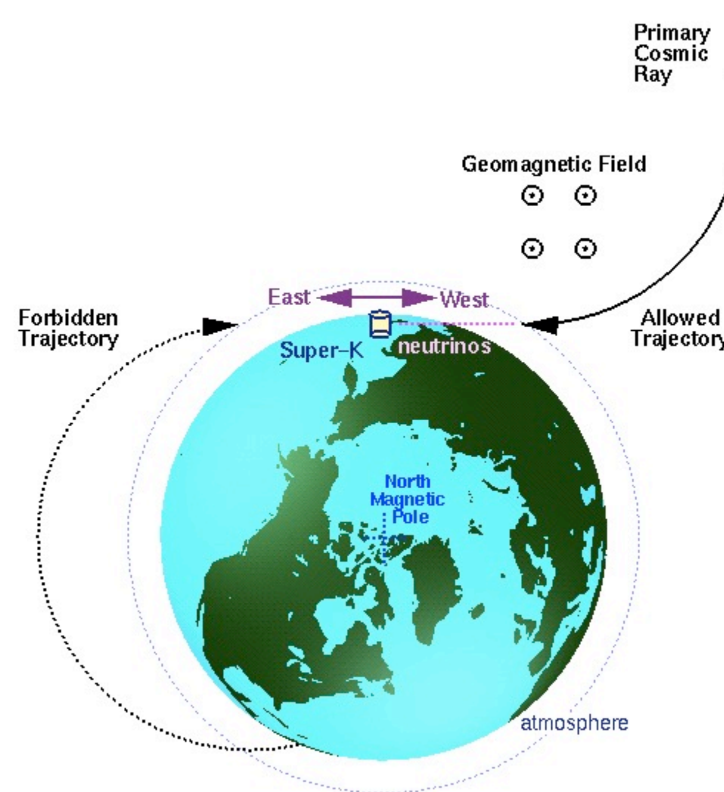
Super-Kamiokande

IceCube/DeepCore

Low Energies (Super-K)



S W N E S

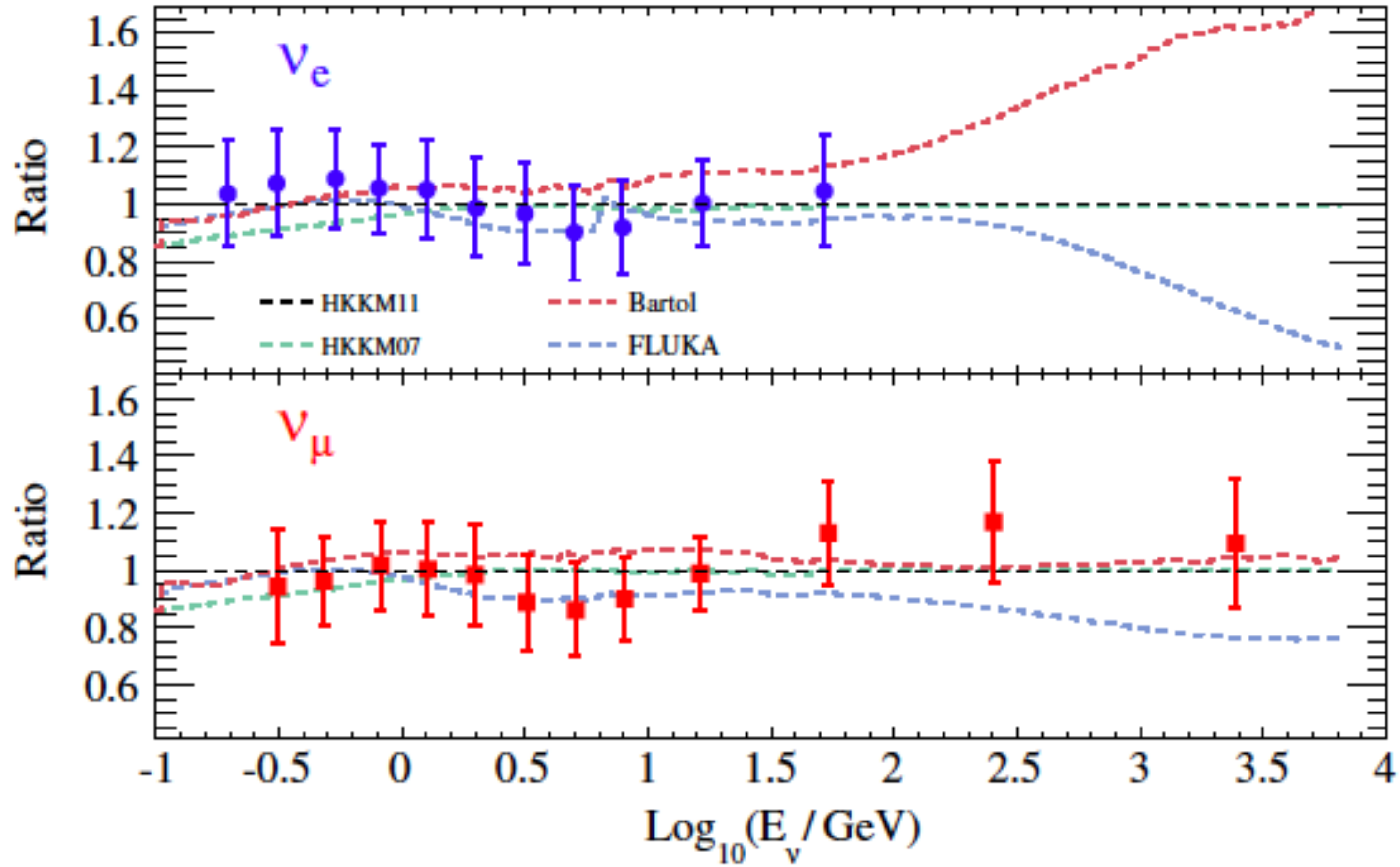


- Predicted asymmetries at low energy due to geomagnetic field observed

← Forward direction of lepton

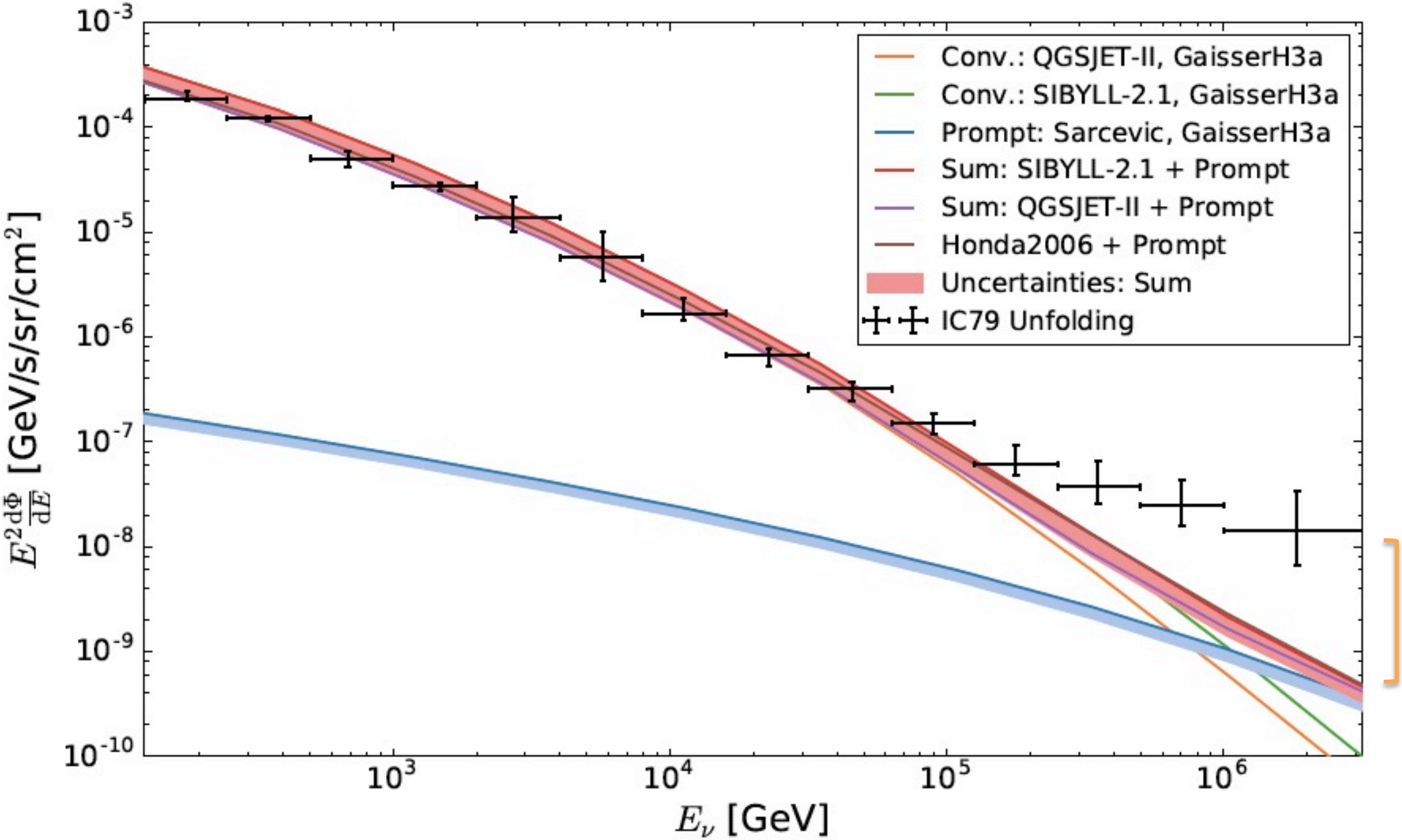
Model Preference?

PHYSICAL REVIEW D 94, 052001 (2016)



- Data are consistent with several flux models
- Dominant systematic errors are from the neutrino interaction model

High Energy Muon Flux at IceCube



- Good agreement with models up until around 60 TeV
- Deviation of data is roughly 2σ, consistent with astrophysical flux

Exotic Oscillations

Sterile Neutrinos

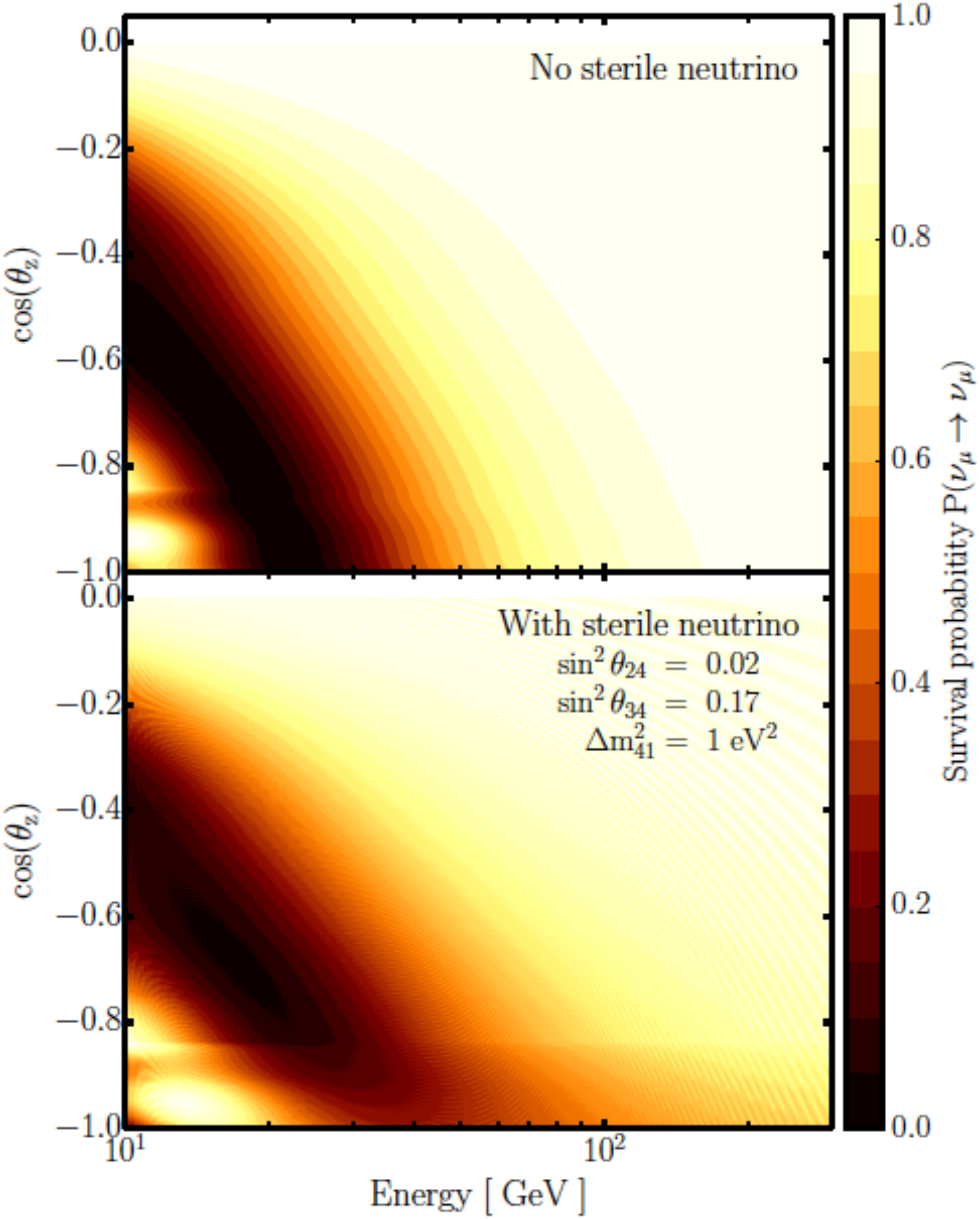
- Indications for the presence of a sterile neutrino state with $\Delta m^2_{43} \sim 1\text{eV}^2$
- For atmospheric neutrinos these oscillations appear "fast"
  - $< \sin^2 \Delta m^2_{43} > = 0.5$
- Also largely insensitive to the number of sterile neutrinos
  - 3+1, 3+N models have basically the same signature

MNS — Sterile

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

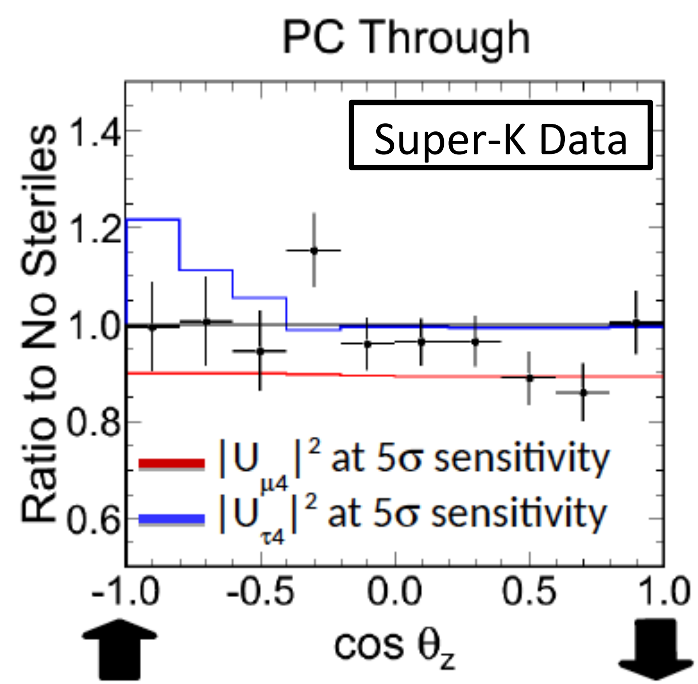
- $| U_{\mu 4} |^2$
  - Induces a decrease in event rate of μ-like data of all energies and zenith angles
- $| U_{\tau 4} |^2$
  - Shape distortion of angular distribution of higher energy μ-like data

Sterile Neutrinos



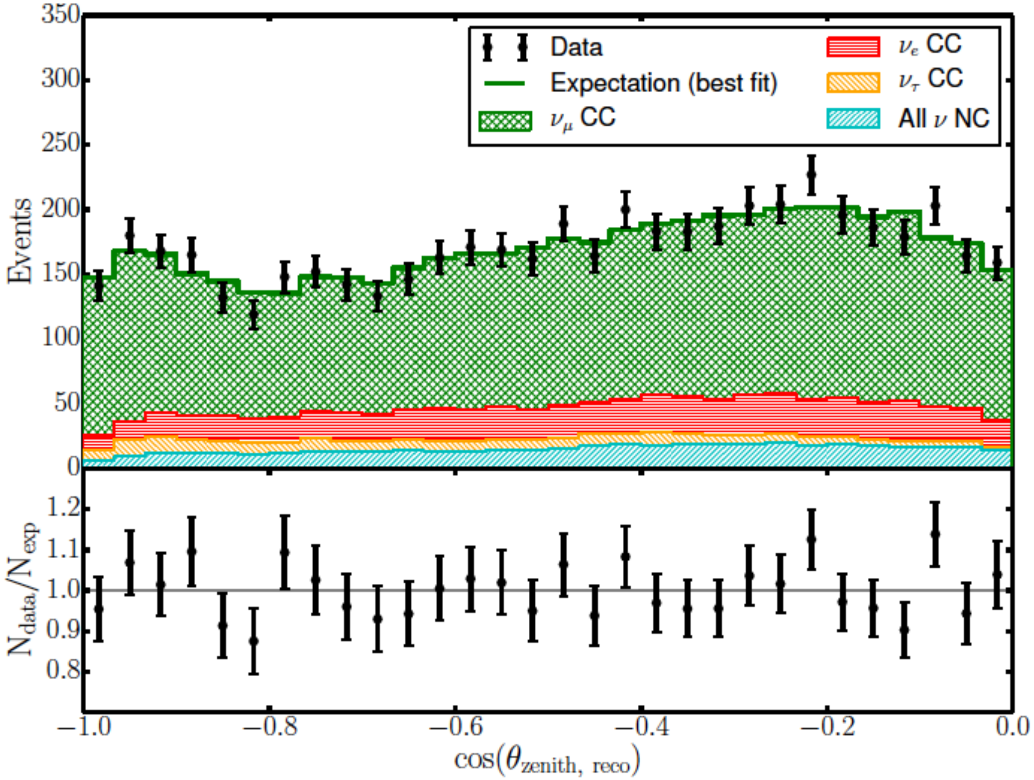
$$\hat{V}_{int} \equiv \pm \frac{G_F}{\sqrt{2}} \text{diag}(2N_e, 0, 0, N_n)$$

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

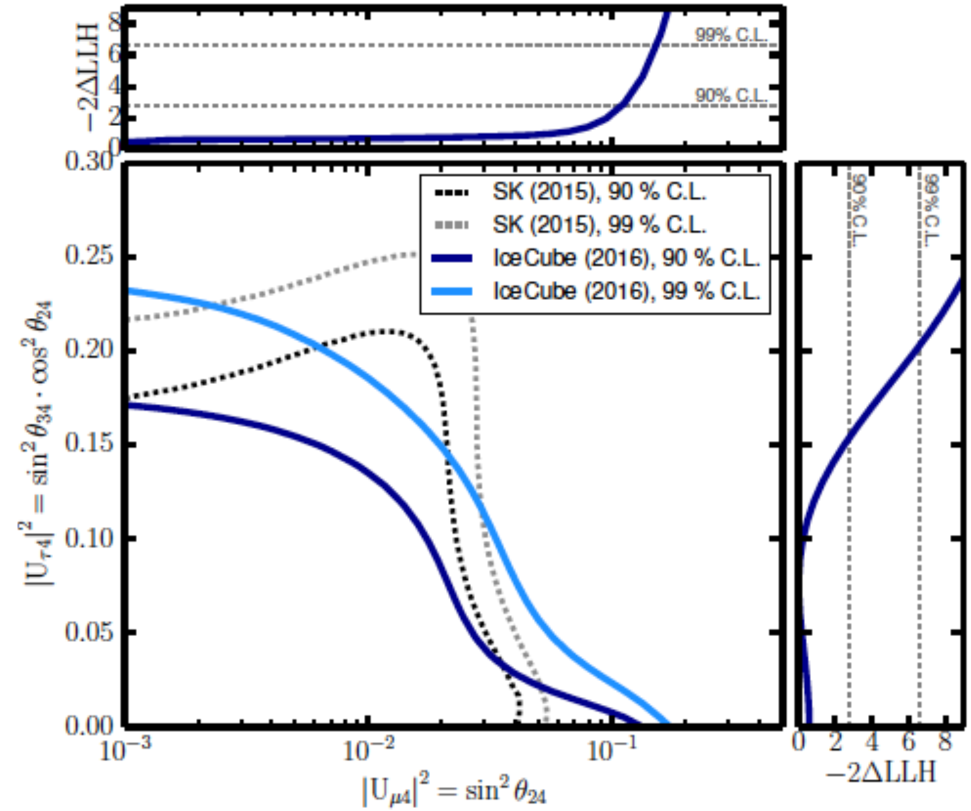


Sterile Neutrinos

Icecube/DeepCore Data



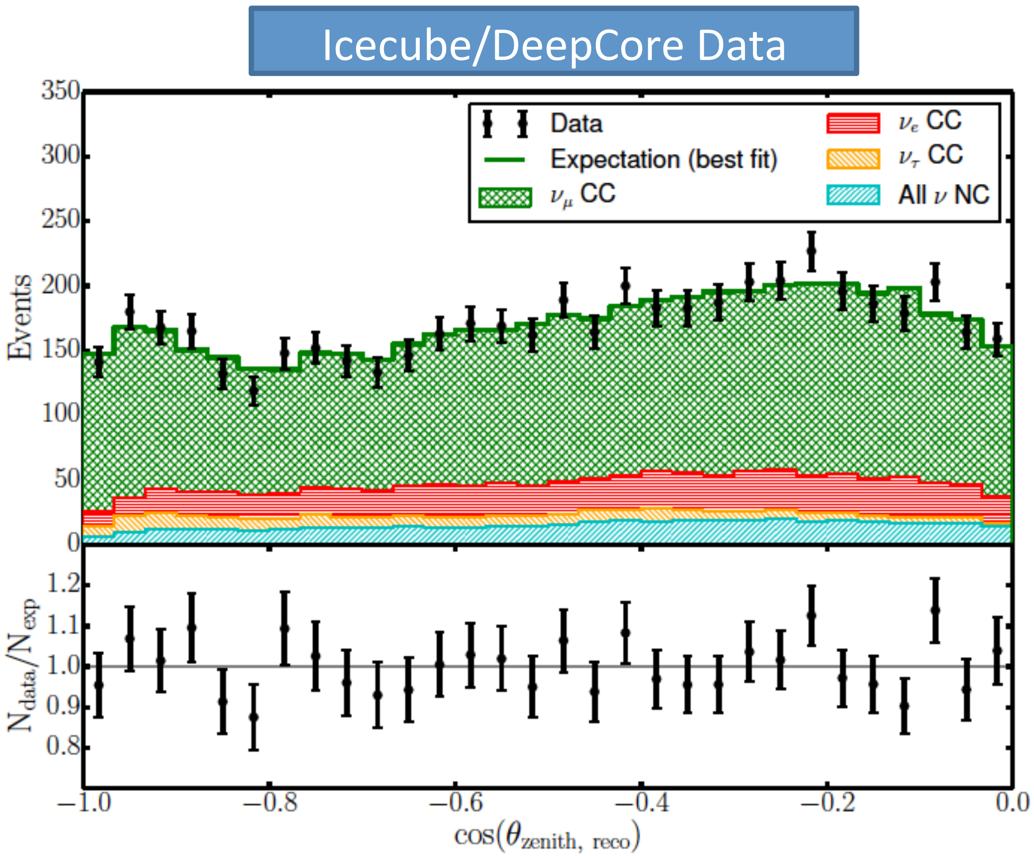
arXiv:1702.05160v1



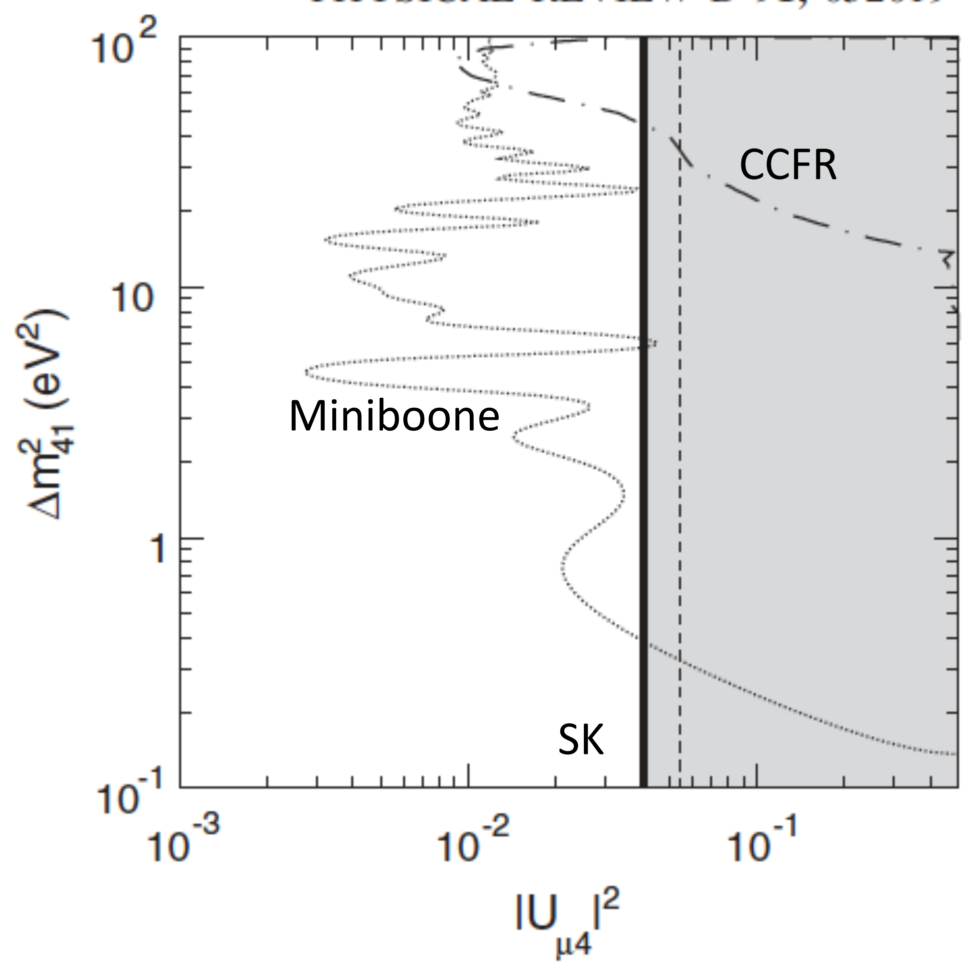
- No indication of a positive sterile signal in either IceCube or Super-K

$$|U_{\mu4}|^2 < 0.11 \text{ (90\% C.L.)}$$
$$|U_{\tau4}|^2 < 0.15 \text{ (90\% C.L.)}$$

Sterile Neutrinos



PHYSICAL REVIEW D 91, 052019



- No indication of a positive sterile signal in either IceCube or Super-K
- For 3+N models constraint on

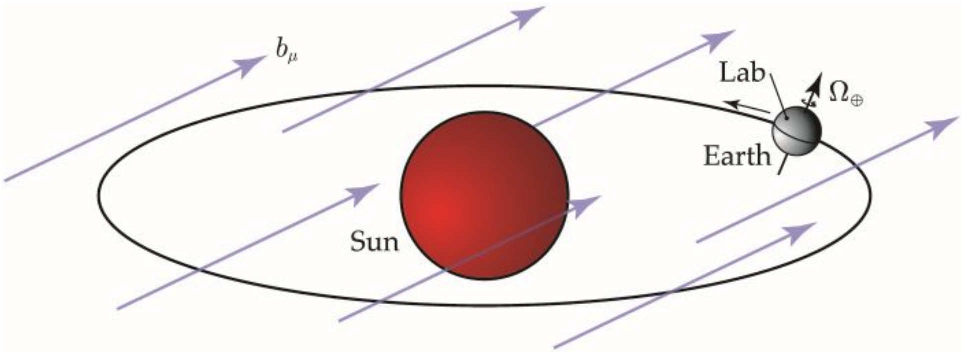
$$|U_{\mu 4}|^2 \longrightarrow d_\mu = \sum |U_{\mu i}|^2$$

Test of Lorentz Invariance

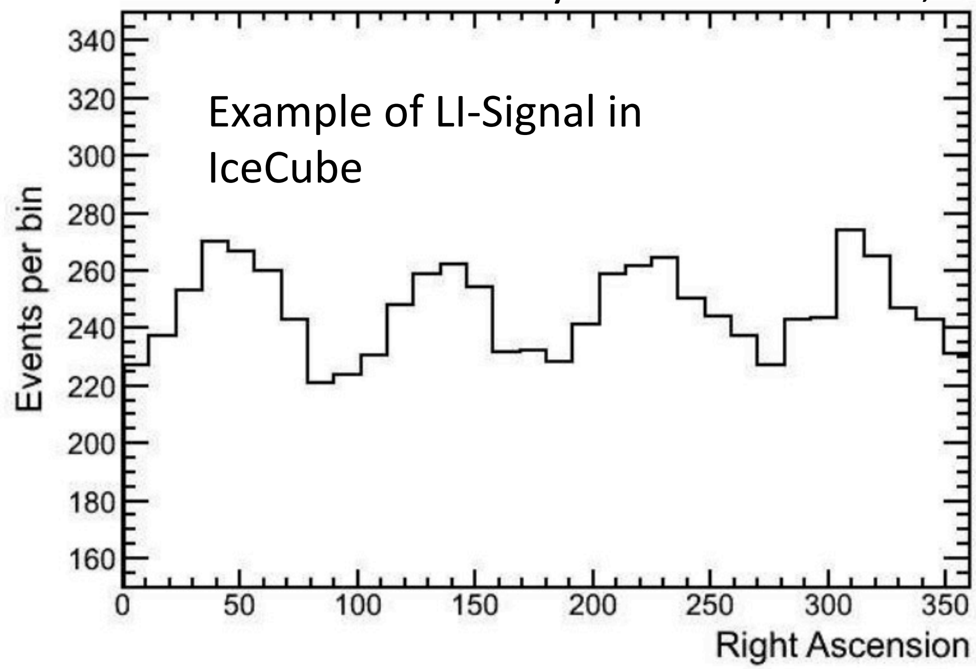
Coefficient	Unit	d	CPT	Oscillation effect
Isotropic				
$a^T_{\alpha\beta}$	GeV	3	Odd	$\propto L$
$c^{TT}_{\alpha\beta}$	…	4	Even	$\propto LE$
Directional				
$a^X_{\alpha\beta}, a^Y_{\alpha\beta}, a^Z_{\alpha\beta}$	GeV	3	Odd	Sidereal variation
$c^{XX}_{\alpha\beta}, c^{YZ}_{\alpha\beta}, \ldots$	…	4	Even	Sidereal variation

- As an interferrometric effect neutrino oscillations can be a very sensitive probe of small effects
- Study Lorentz invariance violating effects within the “Standard Model Extension” (SME)
  - Effective field theory containing the standard model lagrangian and all types of Lorentz- and CPT-violating operators

Test of Lorentz Invariance (LI) : Sidereal Variations



Phys.Rev.D82:112003,2010



- The existence of a "preferred" direction in space could influence neutrinos as they propagate to the detector

- In the absence of such a direction expect a flat event rate as a function

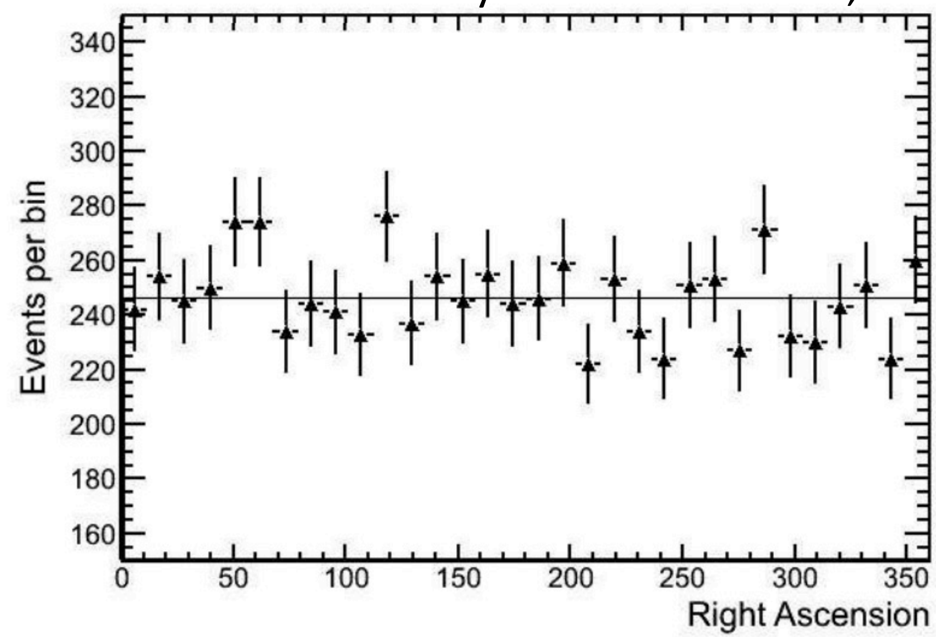
$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 \left(L \left[(A_s)_{\mu\tau} \sin(\alpha + \varphi_0) + (A_c)_{\mu\tau} \cos(\alpha + \varphi_0) \right] \right)$$

Neutrino right ascension

Test of Lorentz Invariance (LI) : Sidereal Variations

- Use track-like sample of muon neutrinos for the analysis
- Event rate is consistent with no lorentz invariance violating signal
- Establish very tight limits on model parameters

Phys.Rev.D82:112003,2010



IceCube

$a_L^X, a_L^Y < 1.8 \times 10^{-23}$ GeV

$c_L^{TX}, c_L^{TY} < 3.7 \times 10^{-27}$

MINOS PhysRevLett.105.151601

Coeff.	Limit	$\mathcal{I}$	Coeff.	Limit	$\mathcal{I}$
$(a_L)^X_{\mu\tau}$	5.9×10^{-23}	510	$(a_L)^Y_{\mu\tau}$	6.1×10^{-23}	490
$(c_L)^{TX}_{\mu\tau}$	0.5×10^{-23}	20	$(c_L)^{TY}_{\mu\tau}$	0.5×10^{-23}	20
$(c_L)^{XX}_{\mu\tau}$	2.5×10^{-23}	220	$(c_L)^{YY}_{\mu\tau}$	2.4×10^{-23}	230
$(c_L)^{XY}_{\mu\tau}$	1.2×10^{-23}	230	$(c_L)^{YZ}_{\mu\tau}$	0.7×10^{-23}	170
$(c_L)^{XZ}_{\mu\tau}$	0.7×10^{-23}	190	–	–	–

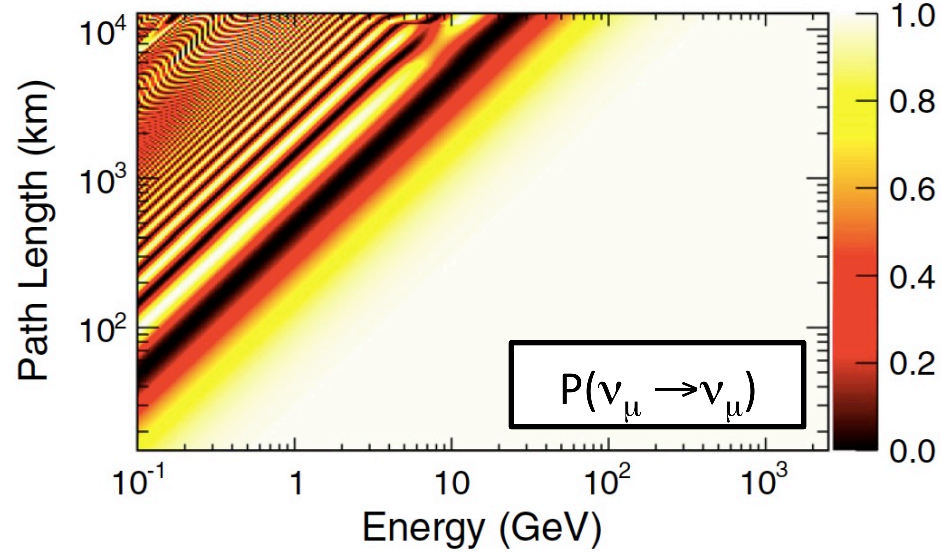
Test of Lorentz Invariance : Isotropic Effects

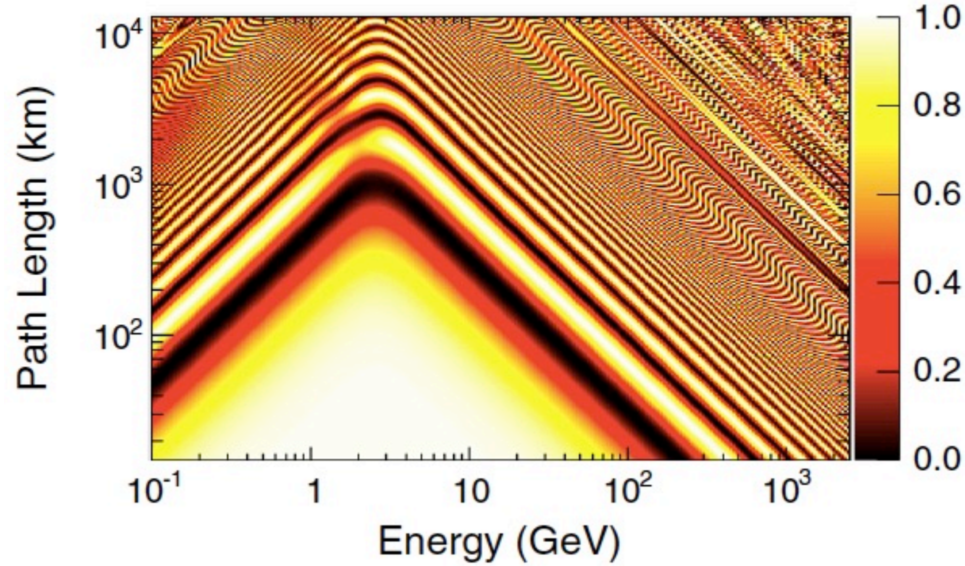
$$H = UMU^{\dagger} + V_e + H_{LV}$$

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

- The effect of "isotropic" parameters from the SME on neutrino oscillations can be very dramatic
- The Super-K analysis uses the full data set to search for effects over all energies

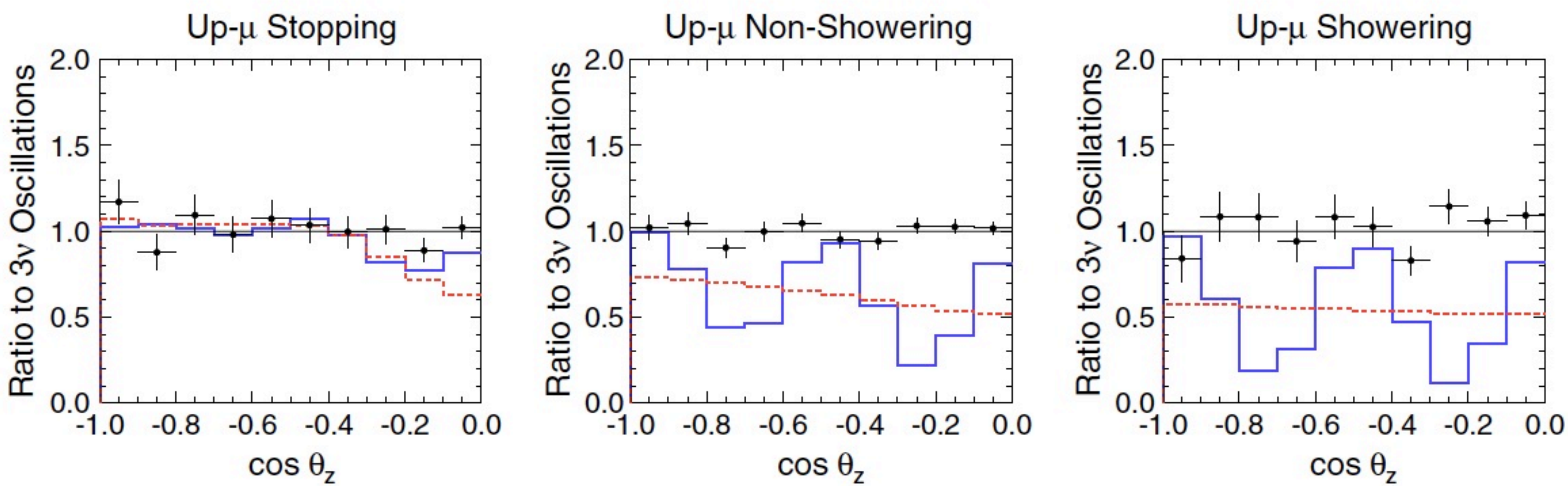
Standard Oscillations





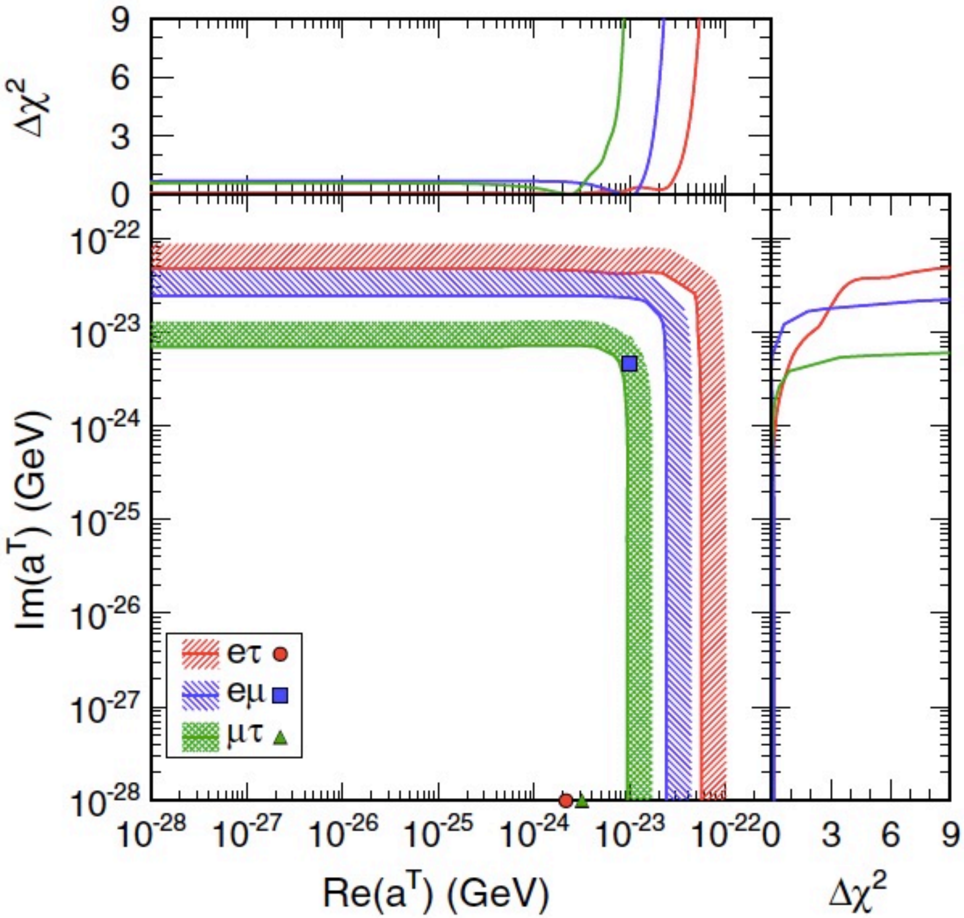
(a) $\nu_\mu \rightarrow \nu_\mu$, $c^{TT}_{e\mu} = 7.5 \times 10^{-23}$

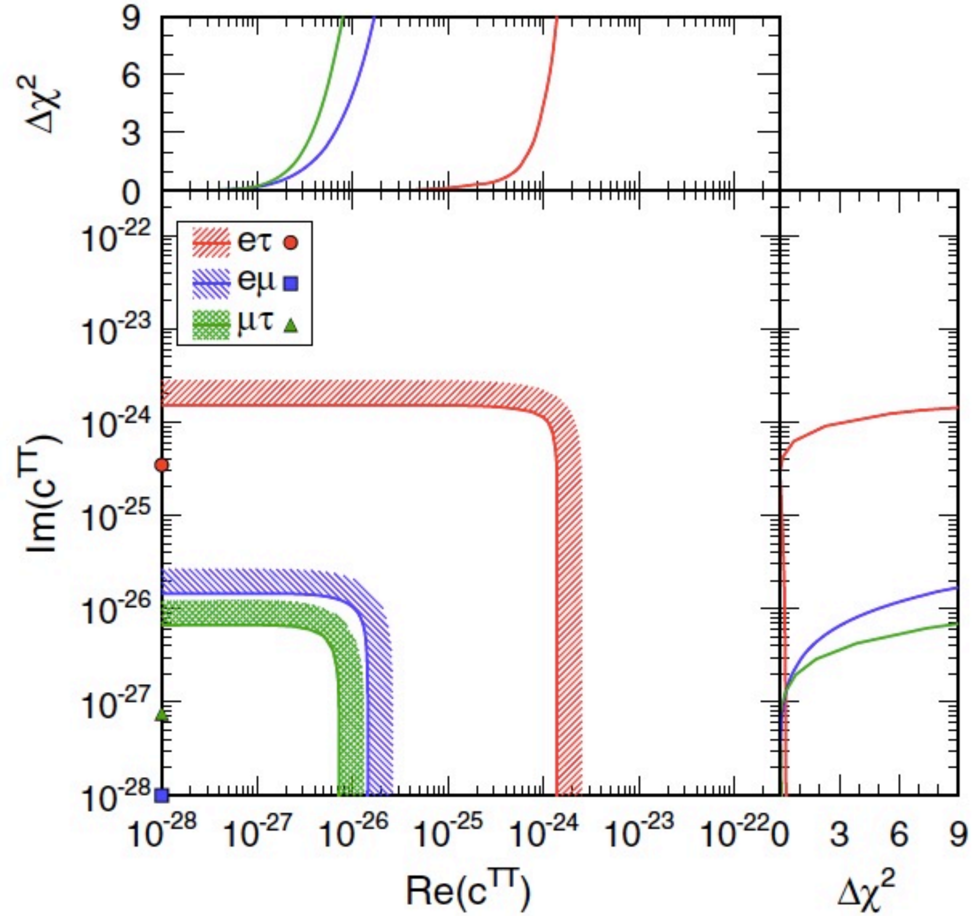
Test of Lorentz Invariance : Isotropic Effects



- 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**

Test of Lorentz Invariance : Isotropic Effects





- Long baselines and high energies of atmospheric neutrinos provide stringent constraints

Test of Lorentz Invariance : Isotropic Effects

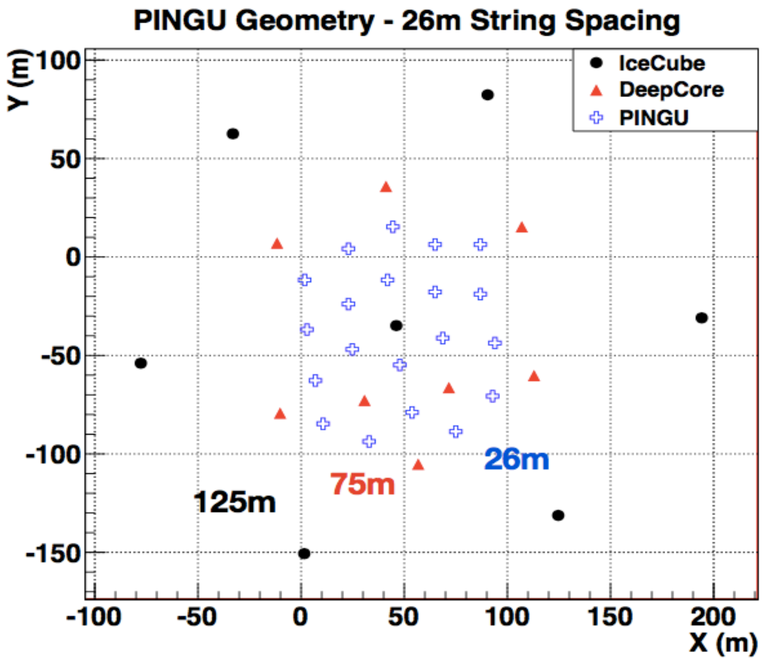
MiniBooNE

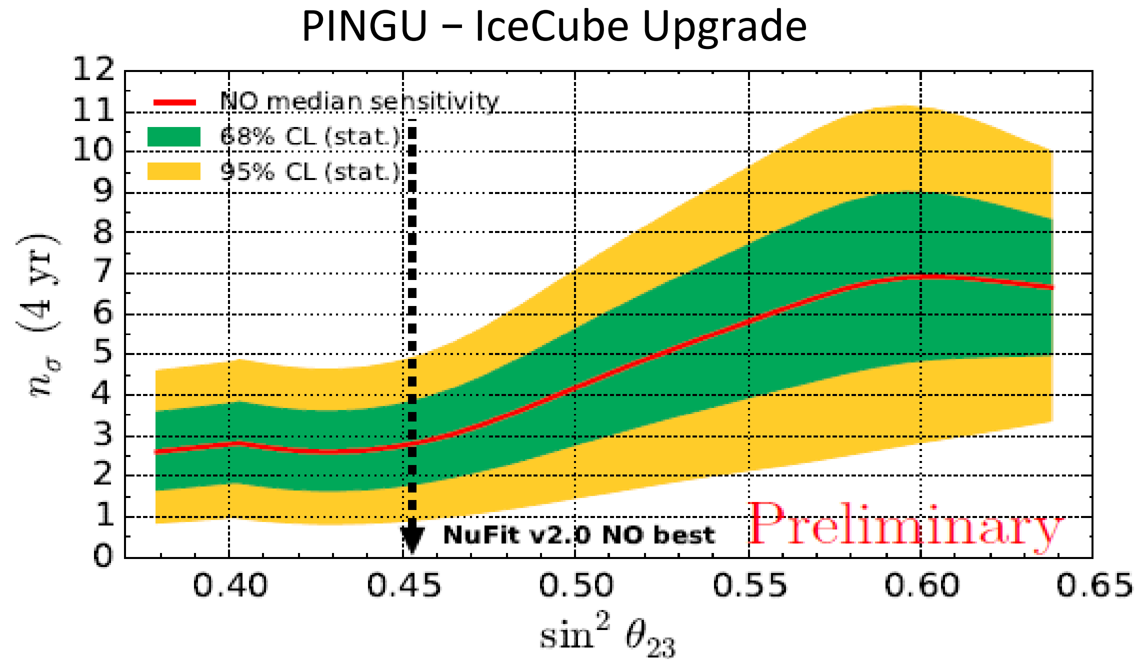
LV parameter		Limit at 95% C.L.	Best fit	No LV $\Delta\chi^2$	Previous limit
$e\mu$	$\mathrm{Re}(a^T)$	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV [61]
	$\mathrm{Im}(a^T)$	1.8×10^{-23} GeV	4.6×10^{-24} GeV		
	$\mathrm{Re}(c^{TT})$	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20} [61]
	$\mathrm{Im}(c^{TT})$	8.0×10^{-27}	1.0×10^{-28}		
$e\tau$	$\mathrm{Re}(a^T)$	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV [62]
	$\mathrm{Im}(a^T)$	2.8×10^{-23} GeV	1.0×10^{-28} GeV		
	$\mathrm{Re}(c^{TT})$	9.3×10^{-25}	1.0×10^{-28}	0.3	1.3×10^{-17} [62]
	$\mathrm{Im}(c^{TT})$	1.0×10^{-24}	3.5×10^{-25}		
$\mu\tau$	$\mathrm{Re}(a^T)$	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	...
	$\mathrm{Im}(a^T)$	5.1×10^{-24} GeV	1.0×10^{-28} GeV		
	$\mathrm{Re}(c^{TT})$	4.4×10^{-27}	1.0×10^{-28}	0.1	...
	$\mathrm{Im}(c^{TT})$	4.2×10^{-27}	7.5×10^{-28}		

- Dramatic improvement in several limits (3 to 7 orders of magnitude)
- New limits on several parameters of the standard model extension

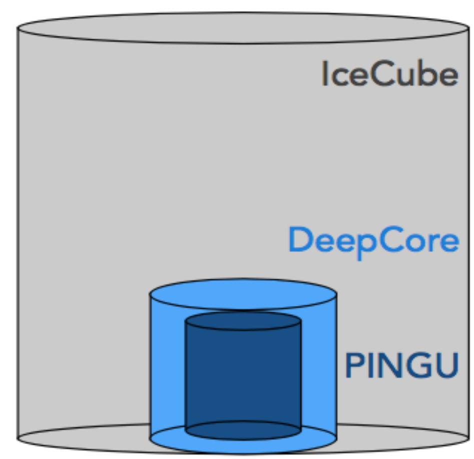
Into the FUTURE

Near Future : Hierarchy with Atmospheric Neutrinos



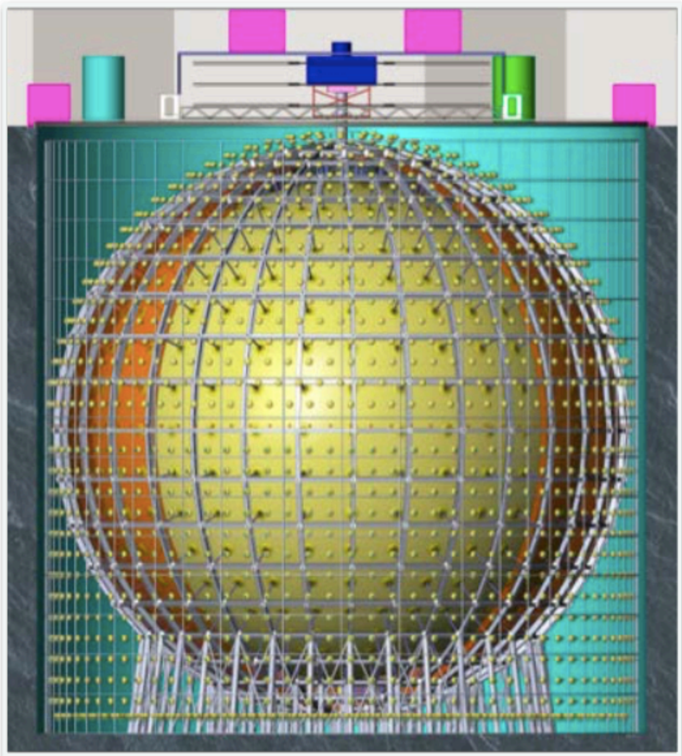


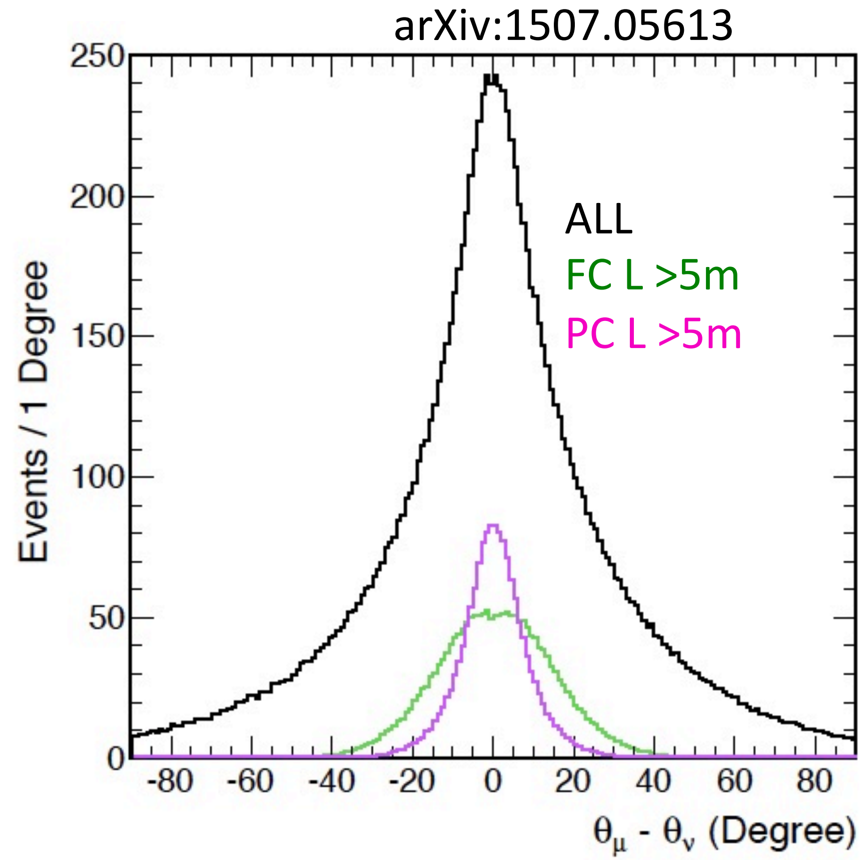
PINGU
Lower energy threshold of DeepCore/IceCube to ~5 GeV, by addition of densely instrumented strings
Improved resolution, PID and sensitivity to electron component of flux
If funded begin data taking with full detector in 2020+



* N.B. : Similar project in mediteranean sear, ORCA, also expects 4σ sensitivity (backup)

Atmospheric Neutrinos with JUNO

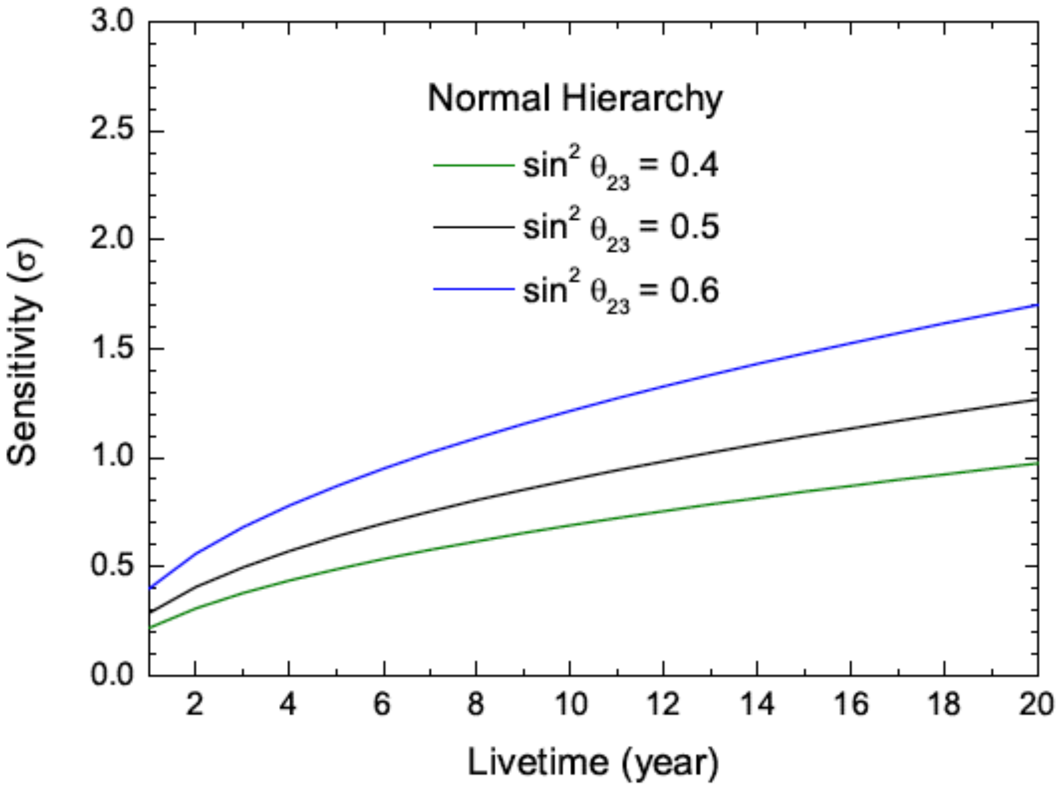




- 20 kton LS detector capable of containing and reconstructing atmospheric neutrinos
- Track reconstruction possible with timing information on the PMTs
  - Relies on information from *Cherenkov* photons in the scintillator

Atmospheric Neutrinos with JUNO

arXiv:1507.05613

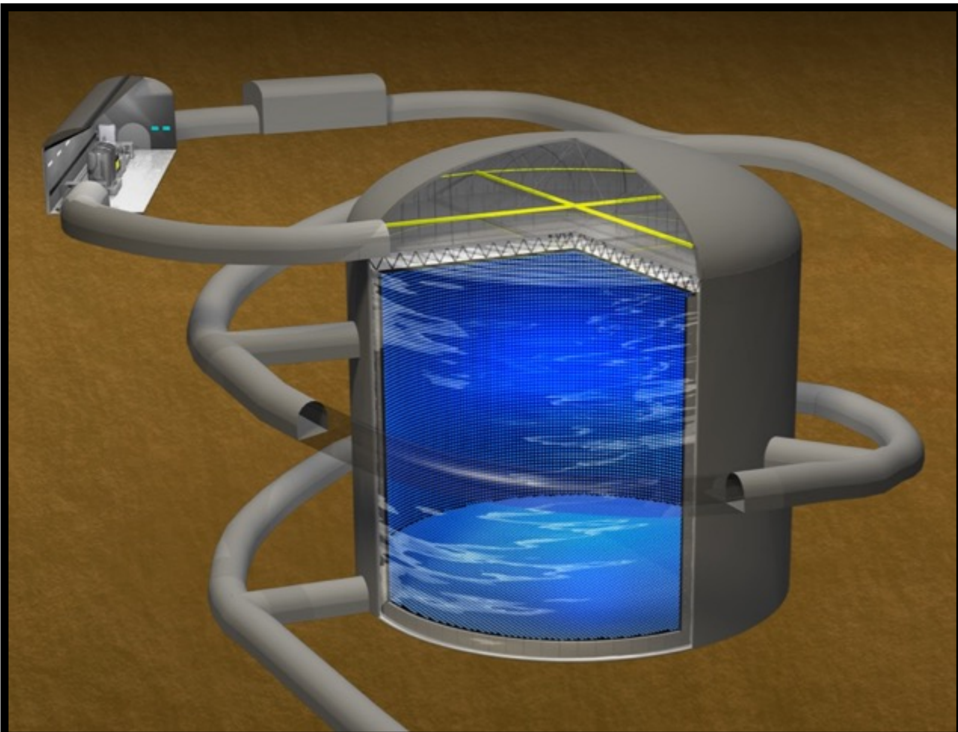


	ν_μ events	$\bar{\nu}_\mu$ events	Total events	ν_μ purity
FC ν_μ-like	656	83	739	88.8%
FC $\bar{\nu}_\mu$-like	652	541	1193	54.6%
PC ν_μ-like	577	166	743	77.7%
PC $\bar{\nu}_\mu$-like	383	384	767	50.0%

- Statistical separation of neutrino-like and antineutrino-like using decay electron and transverse momentum information (hadronic energy deposit)
- First atmospheric+reactor combined measurement?!
- = faster hiearchy sensitivity

Hyper-Kamiokande

Hyper-Kamiokande

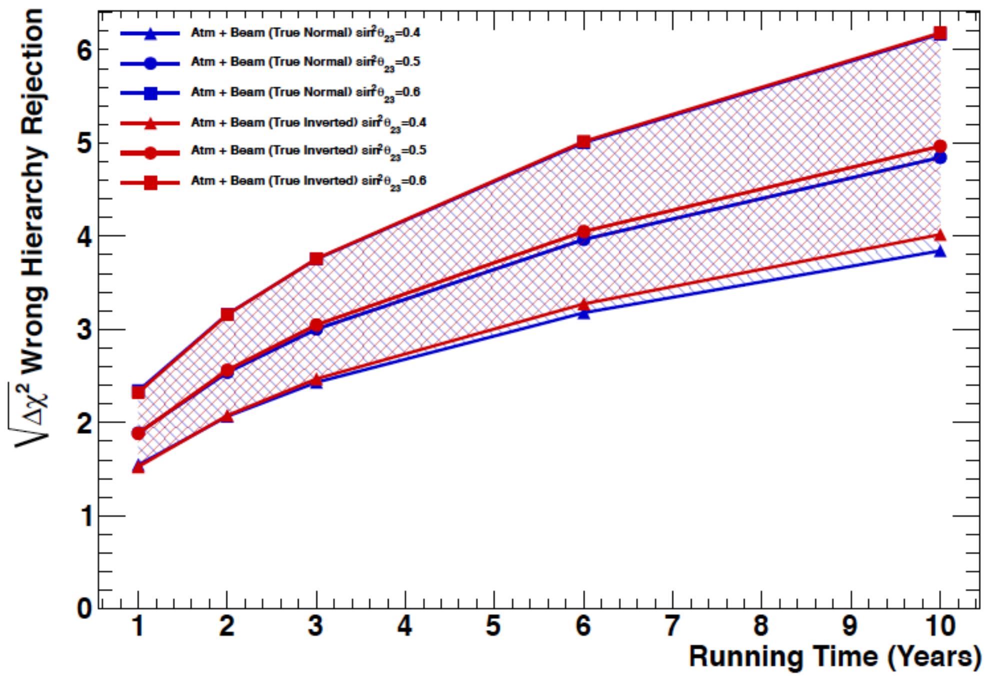


- 186 (×2) kton fiducial volume (2 × 8.3 × SK)
- Optically separated into
  - Inner Detector 40,000 (×2) PMTs (2×4×SK)
    - 40% Coverage (same as SK)
  - Outer Detector 12,000 (×2) PMTs (2×6×SK)
- ID Photosensors will be high QE
  - Single photon detection : 24% (2 × SK)
- Receive 1.3 MW beam from J-PARC
  - 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

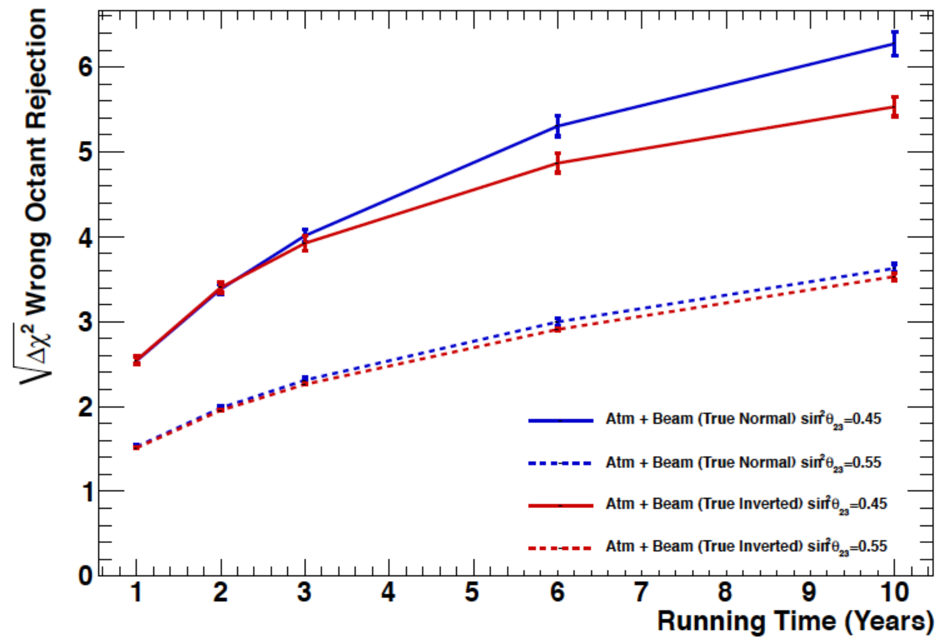
Staged design:
186 kton 6 years,372 kton thereafter

Hyper-Kamiokande Beam+Atmosheric ν Sensitivity

Neutrino Mass Hierarchy



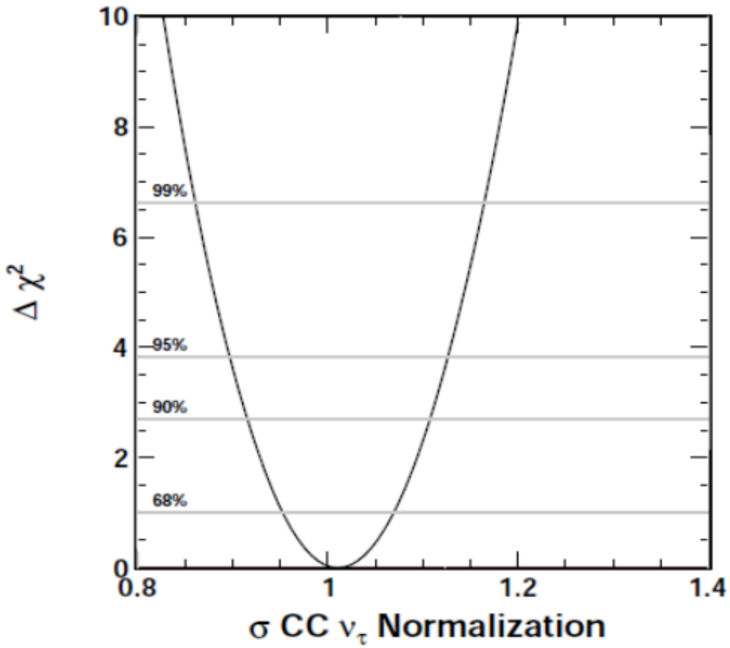
θ_{23} Octant



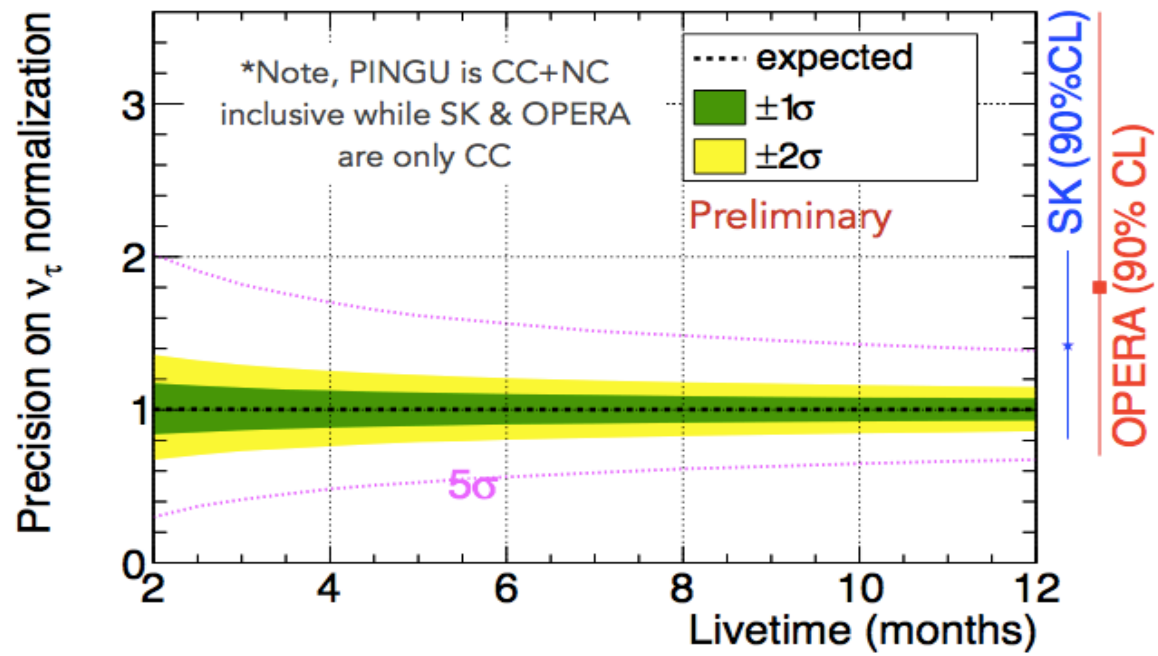
- Combined analysis of beam and atmospheric neutrinos improves sensitivity to mass hierarchy and θ23 octant
  - Matter effects are small with J-PARC beam
  - Beam measurement determines atmospheric mixing parameters

A Word about Tau Neutrinos

Hyper-Kamiokande



PINGU

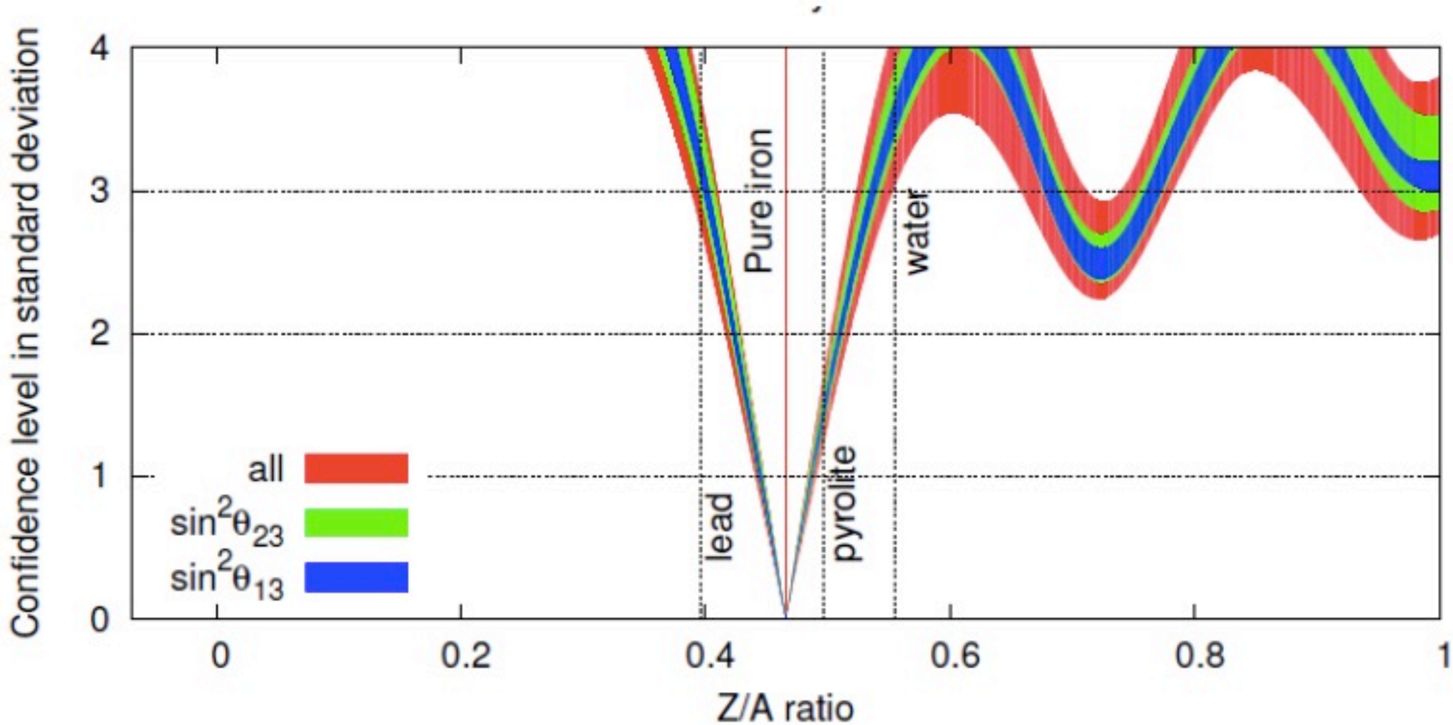


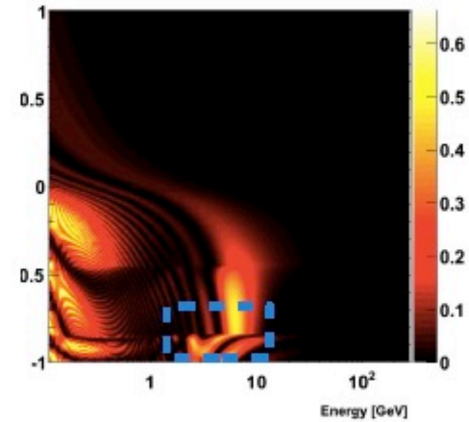
per/ 100 kton yr.	Hyper-K	LAr
Signal CC ντ	40.2	28.5
Background	448.7	44.8
S /√B , 10 years	9.6	8.5

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

- Achieve 7% uncertainty on tau cross section normalization with 560 Mton-year exposure of Hyper-K
- PINGU is similar, but faster
- These samples will be useful for testing cross section modeling as well as providing direct probe of $|U_{\tau 3}|^2$

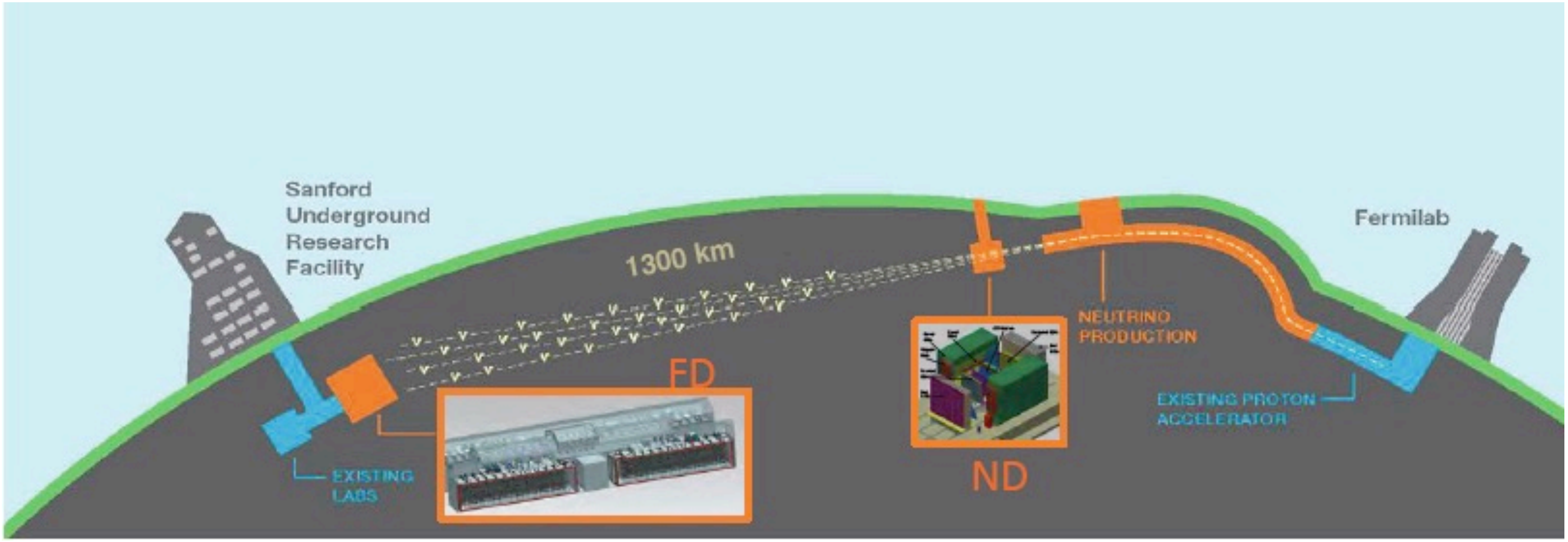
Chemical Composition of Earth's Outer Core (SK 500 years)





- Density profile of the Earth is well known from seismic measurements
  - Outer core is thought to be liquid iron+Ni and another light element (Unmeasured!)
- Z/A ratio is important to understanding formation of Earth and its magnetic field
- With 10 years of data Hyper-K can open the field of Earth Spectroscopy
  - First Z/A measurement, can exclude lead-based and water-based outer core
  - Longer exposures more useful (want to discriminate iron from pyrolite)

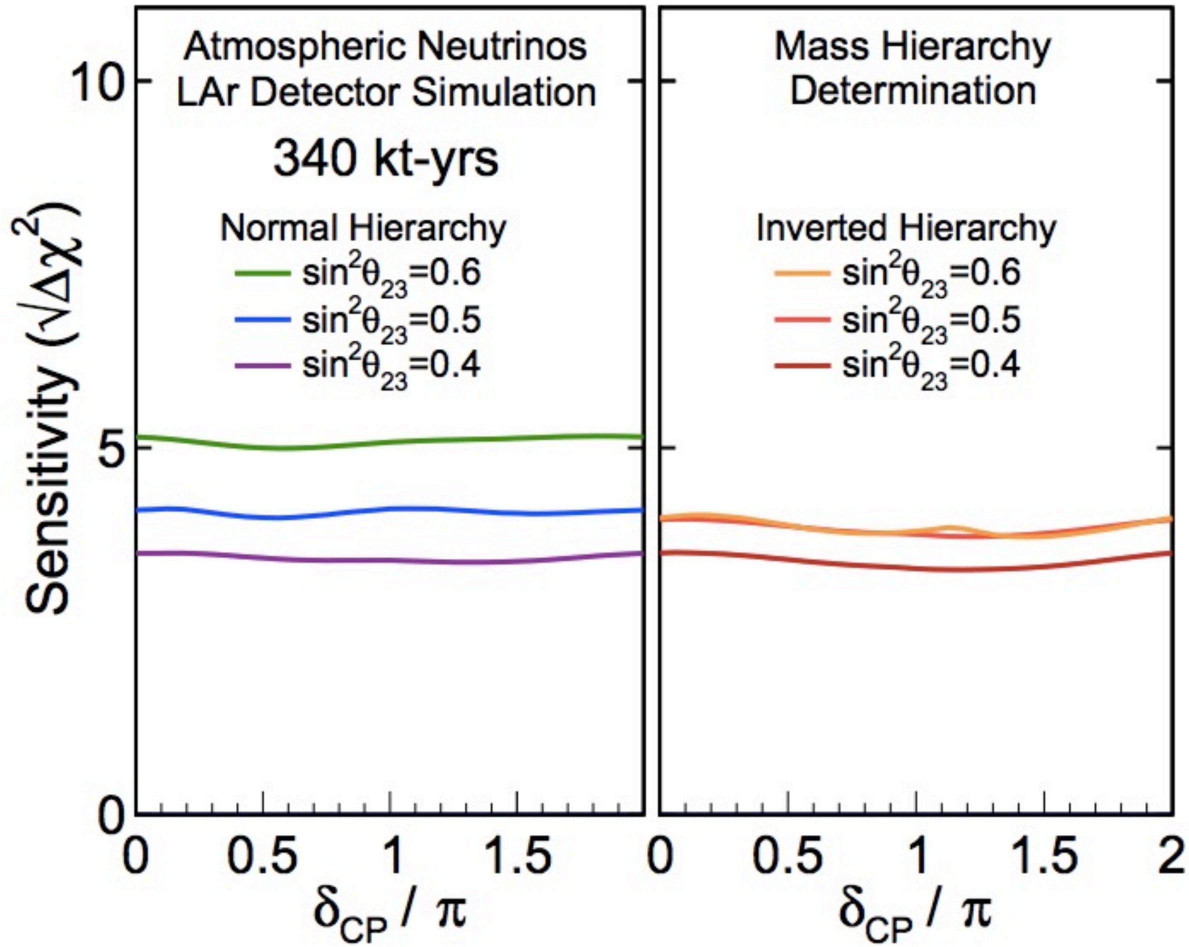
Dune Experiment



- 40 kton liquid argon TPC
- Beam from FNAL to Sanford Lab
- Large enough to observe atmospheric neutrinos
- Exquisite reconstruction of neutrino interactions

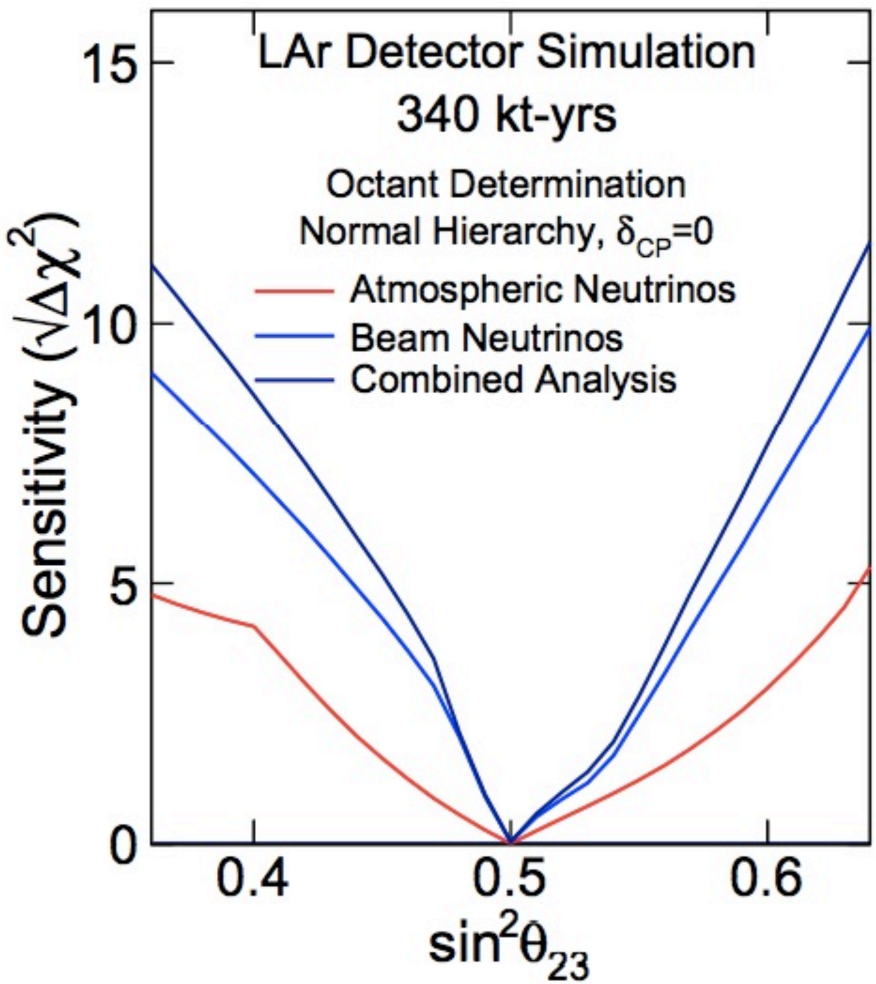
Particle	Resolution
Angular Resolutions	
Electron	1°
Muon	1°
Hadronic System	10°
Energy Resolutions	
Stopping Muon	3%
Exiting Muon	15%
Electron	$1\%/\sqrt{E(GeV)} \oplus 1\%$
Hadronic System	$30\%/\sqrt{E(GeV)}$

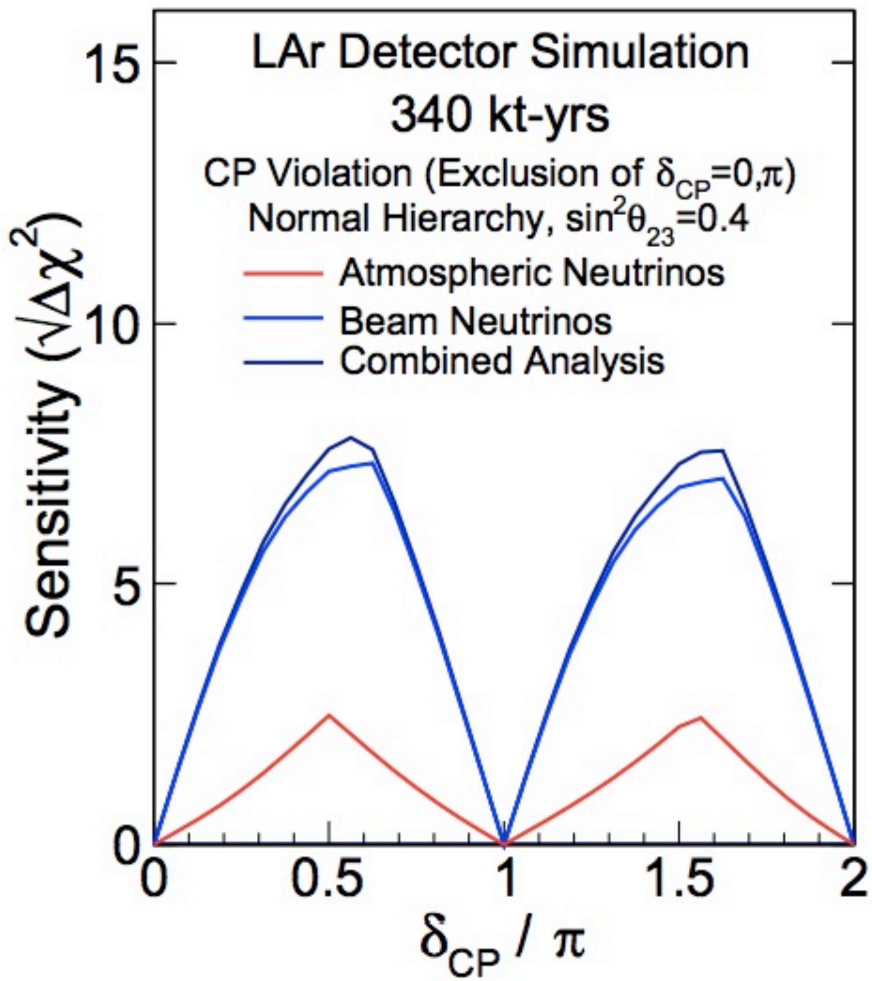
Dune Experiment



- Similar hierarchy sensitivity to Hyper-K despite smaller volume

Dune Experiment: Octant and CP





- Combination of beam and atmospheric neutrinos
- N.B. not much improvement in CP violation sensitivity (true for Hyper-K also)

Mass Hierarchy Sensitivity Summary

- Assuming 2nd octant of θ_{23}

Experiment	2020	2025-6	2030	2035
Super-K	2.5σ	3.0σ		
T2K /-II		~1σ		
NOvA	3.4σ	4.4σ		
KM3NeT	0.5σ	4.0σ		
IceCube (Pingu)		>4.0σ		
JUNO		4.0σ		
ICAL-INO		2.0σ	3.0σ	~4σ
DUNE		3.0σ	5.0σ	~7σ
Hyper-K			4.0σ	~6σ

- Currently , not all are funded but good chance for a determination in 10 years

Main Messages:

- Atmospheric neutrinos are a useful probe many interesting (potential) phenomena because:
  - Wide range of energies
  - Wide variety of their baselines
  - Constant source

- But precision measurements are challenging because:
  - Wide range of energies
  - True neutrino direction is unknown
  - Constant source
    - Form a background for many other interesting phenomena

	Large lAr or H_20 Cherenkov	Iron Calorimeter	ν Telescope
"Atmospheric" and Neutrino Oscillations			
— Δm^2	■	■	■
— $\mathrm{Sin}^2\theta_{23}$, octant	■	■	
— $\mathrm{Sin}^2\theta_{13}$	■	■	■
— δ_{cp}	■		
— Mass Hierarchy	■	■	■
— Exotic Scenarios	■	■	■
— τ Appearance	■	■	■
Earth Radiography	■		■
Resolution of Parameter Degeneracy (+ beam)	■	■	■
Measurement of prompt flux			■

Large lAr or H_20 Cherenkov
Iron Calorimeter
ν Telescope

Summary

- Due to their range of both path lengths and energies atmospheric neutrinos have proven a useful probe of standard and exotic oscillation physics

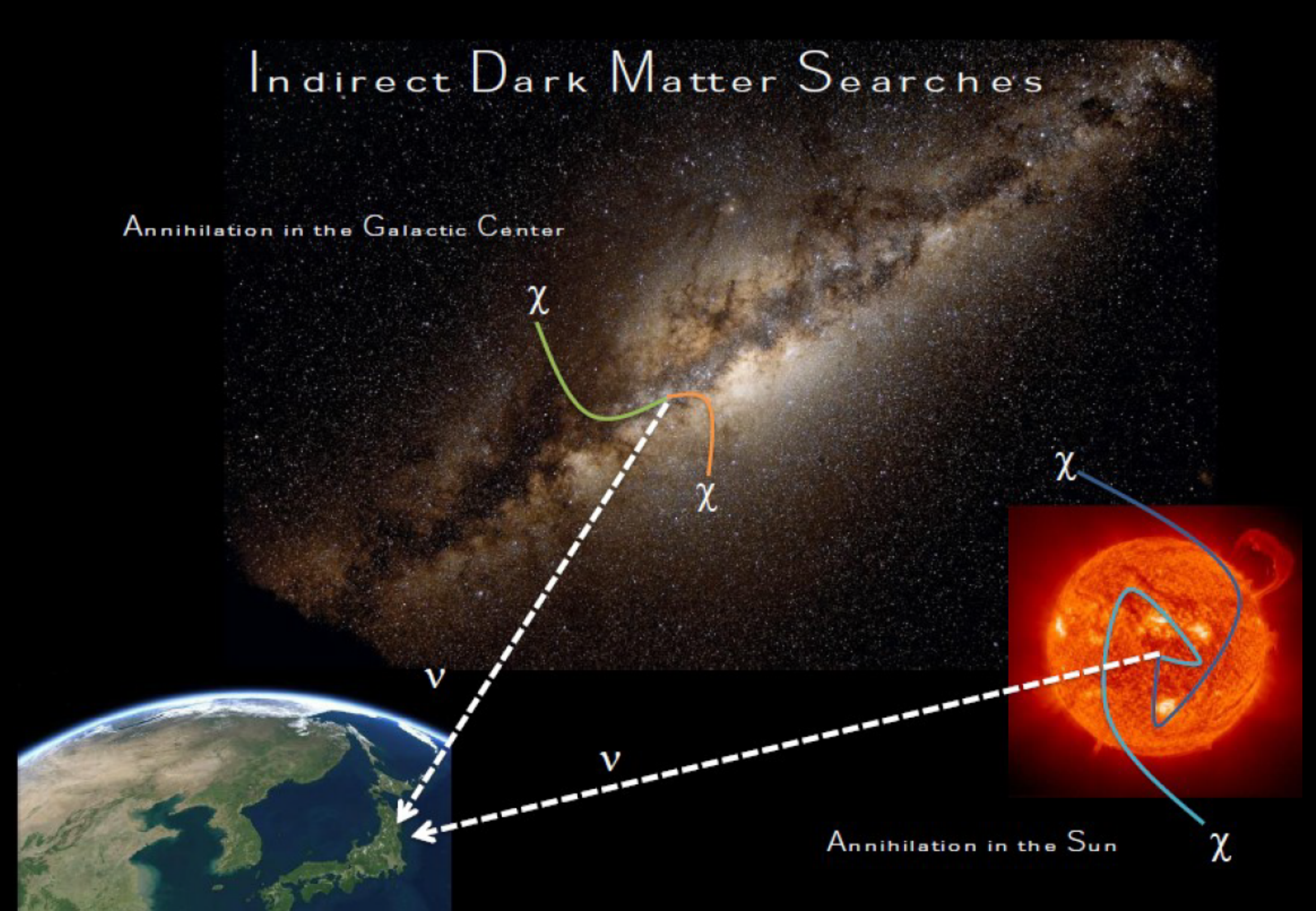
- Currently flux and cross section systematics are the main challenges for detectors trying to use them to study CP violation and the mass hierarchy

- The flux is increasingly well known but as the search for increasingly rare phenomena (relic neutrinos, proton decay), more work will be needed

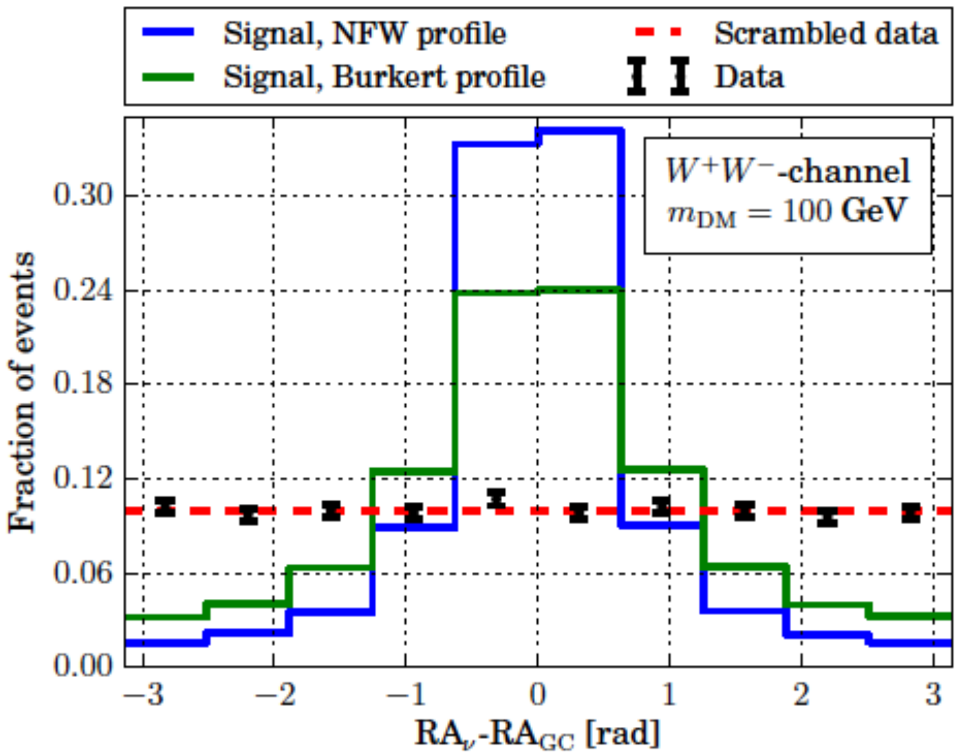
- They can be expected to complement precision measurements at future facilities

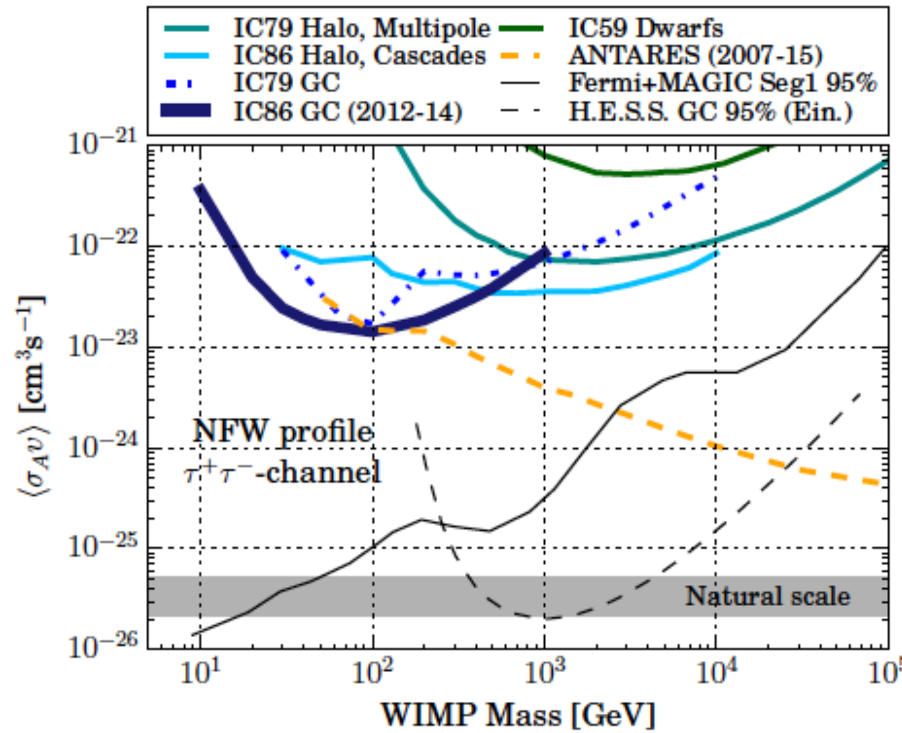
Supplements

Atmospheric Neutrinos as Background


Indirect Dark Matter Searches
Annihilation in the Galactic Center
χ
χ
ν
χ
ν
χ
Annihilation in the Sun

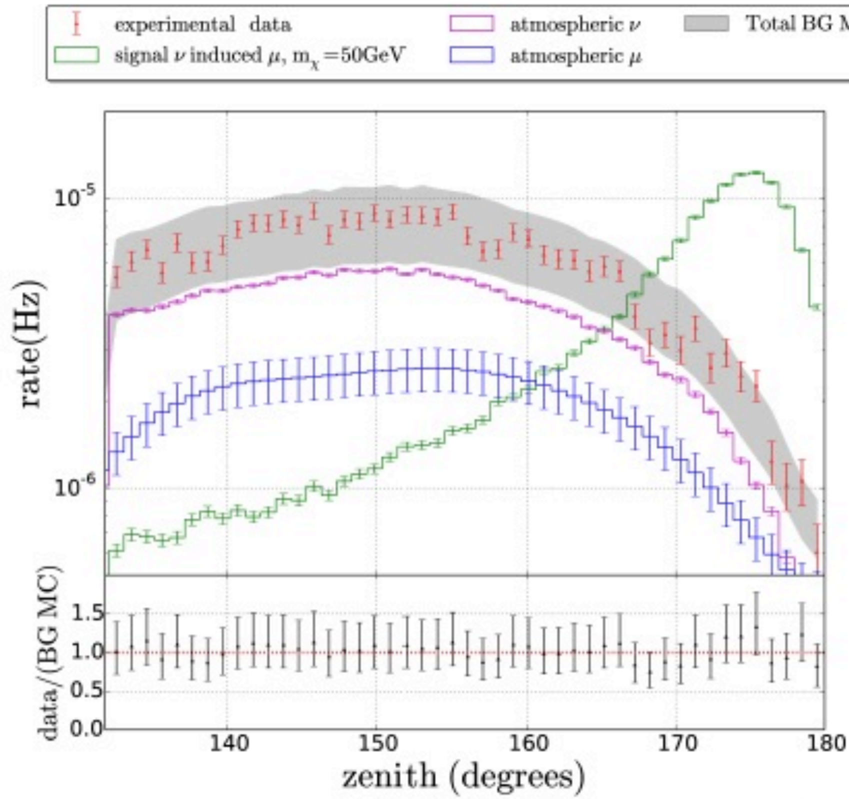
Indirect Dark Matter Searches (Galactic Center)

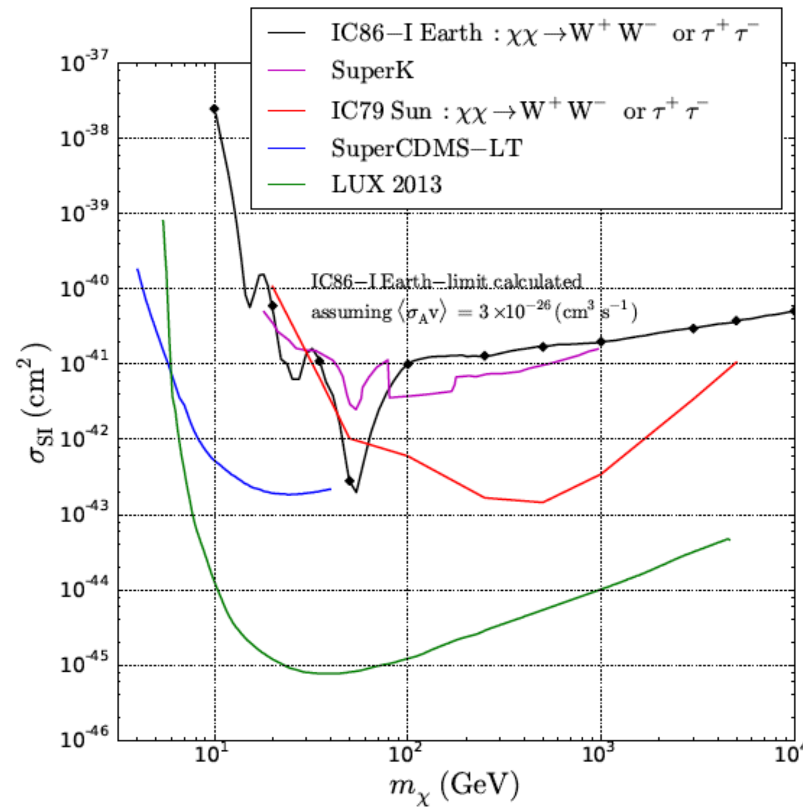




- Look for excess of neutrinos in the direction of the galactic center as a signature of WIMP self-annihilation

Indirect Dark Matter Searches (Earth)

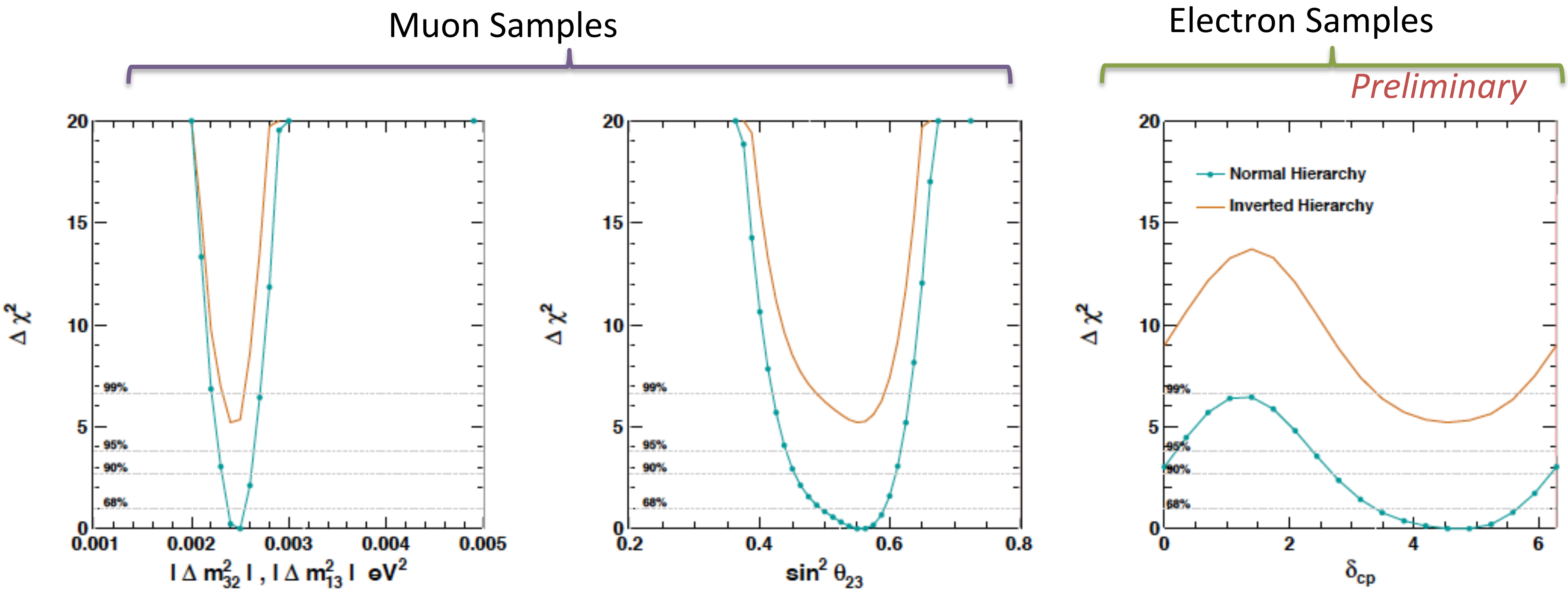




- Look for excess of neutrinos from the center of the Earth as a signature of WIMP self-annihilation

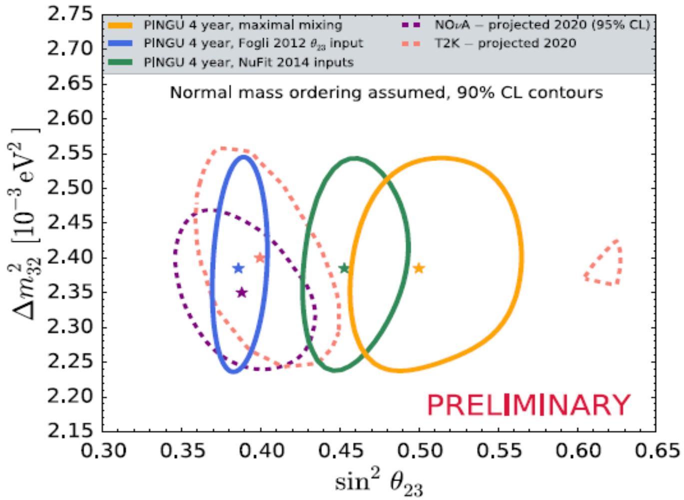
Supplements

Atmospheric Mixing + δ_{cp}: Super-Kamiokande+T2K Model

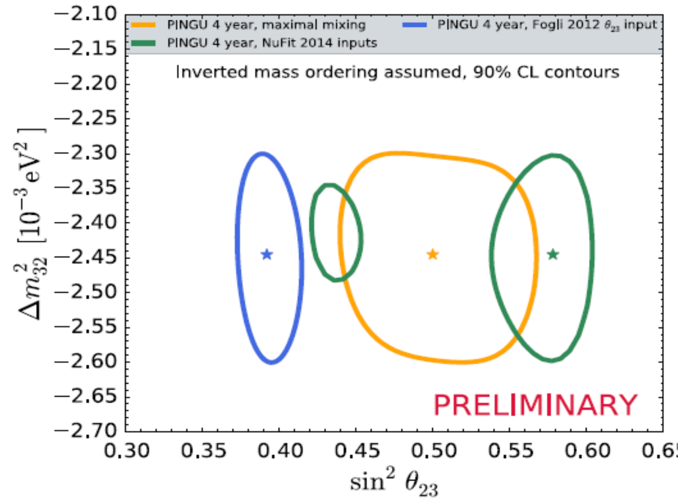


- Introducing a model of T2K (not a two-collaboration fit!)
- Significance of electron neutrino excess increases still favoring the *normal hierarchy*
  - $\Delta\chi^2$ (NH – IH) = -5.2 (SK only: -4.3)
  - P(NH|IH) : 2.8% (depends on assumed value of θ23!)
- Weak hint for δ_{cp} ~1.33π

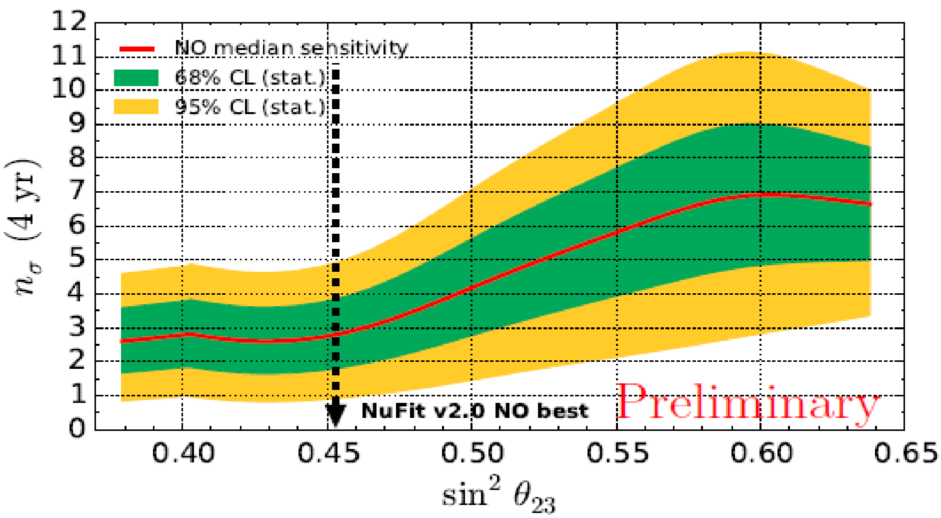
Pingu



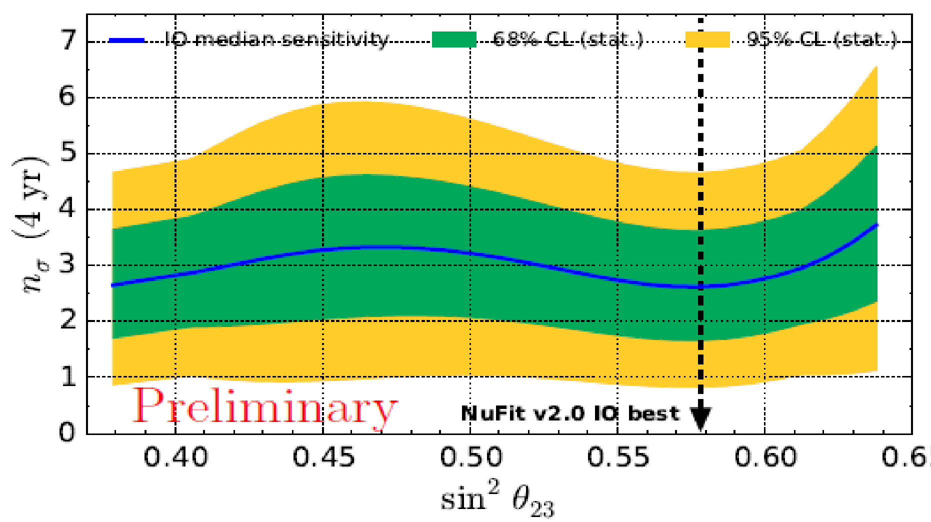
(a) Normal neutrino mass ordering assumed.



(b) Inverted neutrino mass ordering assumed.

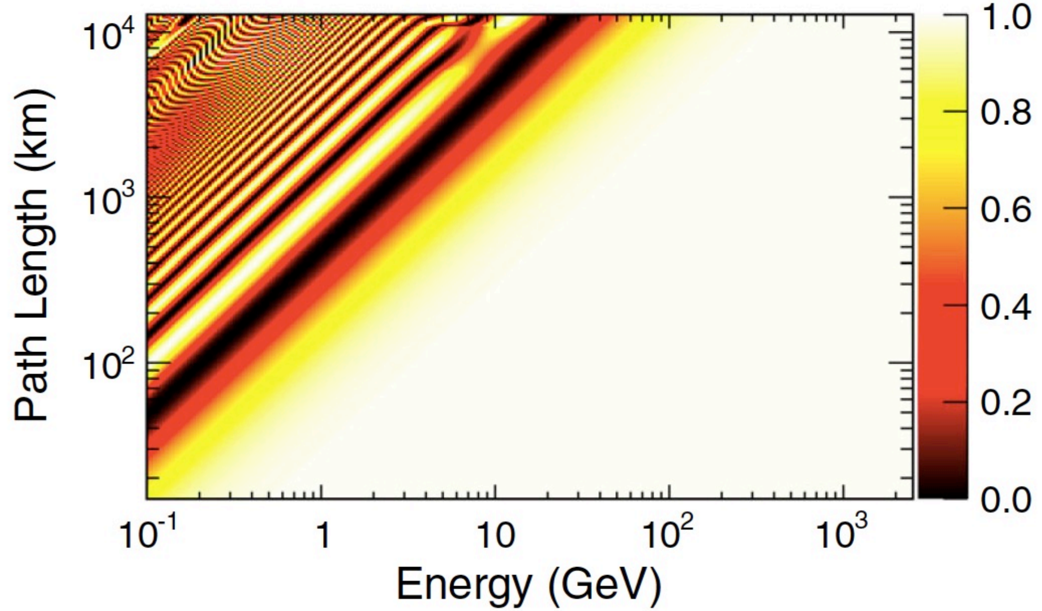


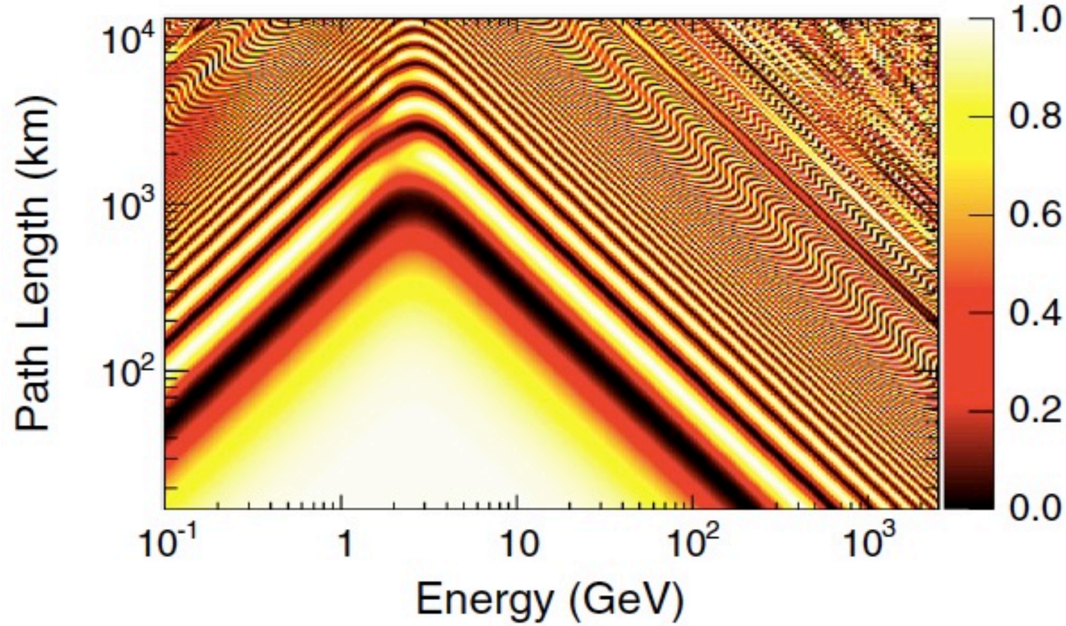
(a) Normal neutrino mass ordering assumed.



(b) Inverted neutrino mass ordering assumed.

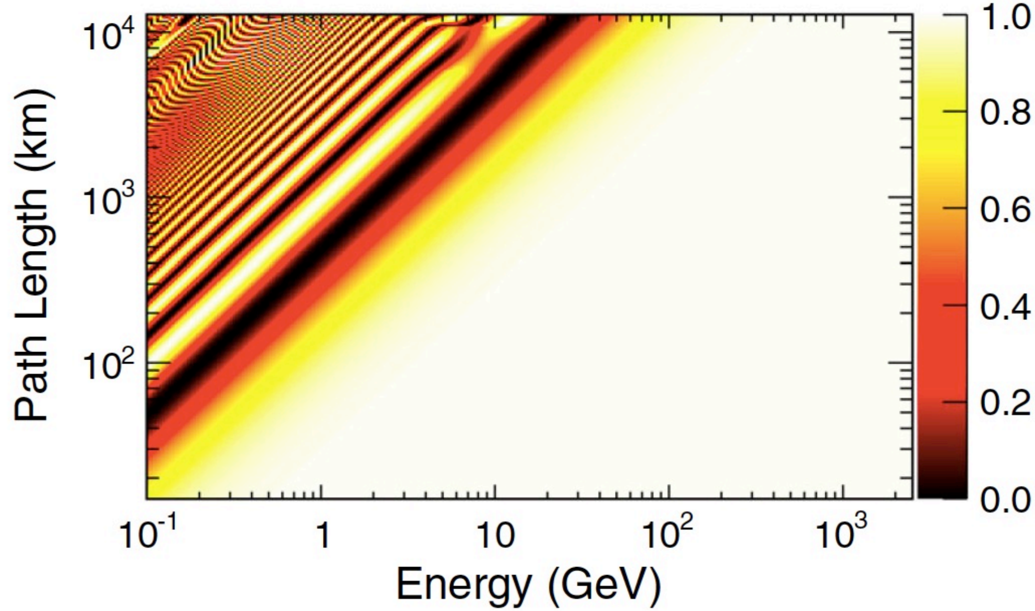
Coefficient	Unit	d	CPT	Oscillation effect
Isotropic				
$a^{T}_{\alpha\beta}$	GeV	3	Odd	$\propto L$
$c^{TT}_{\alpha\beta}$	...	4	Even	$\propto LE$
Directional				
$a^{X}_{\alpha\beta}, a^{Y}_{\alpha\beta}, a^{Z}_{\alpha\beta}$	GeV	3	Odd	Sidereal variation
$c^{XX}_{\alpha\beta}, c^{YZ}_{\alpha\beta}, \ldots$	...	4	Even	Sidereal variation

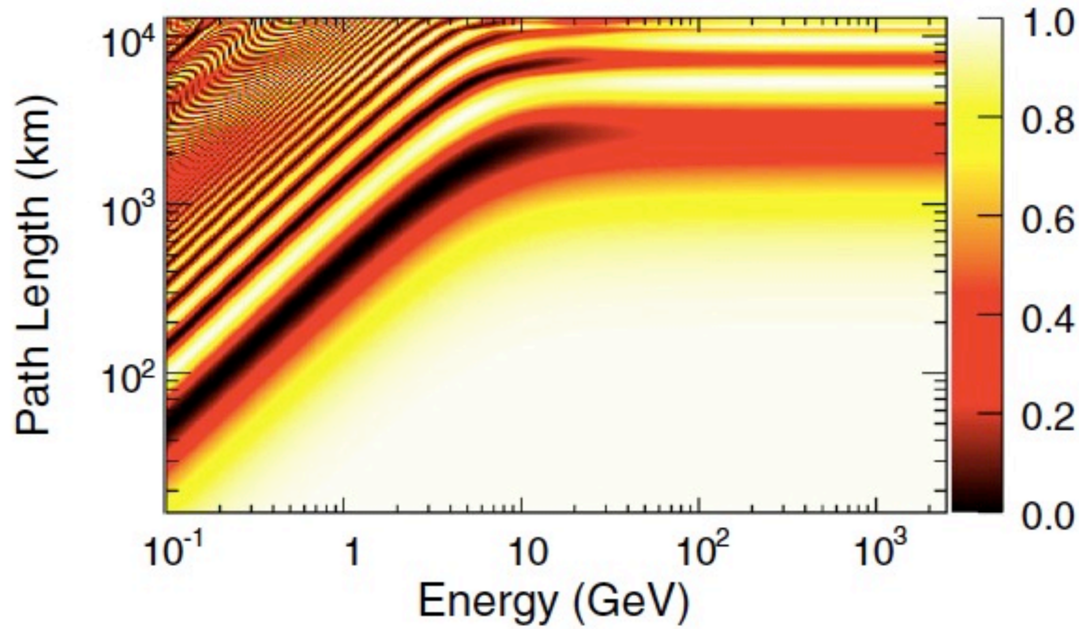




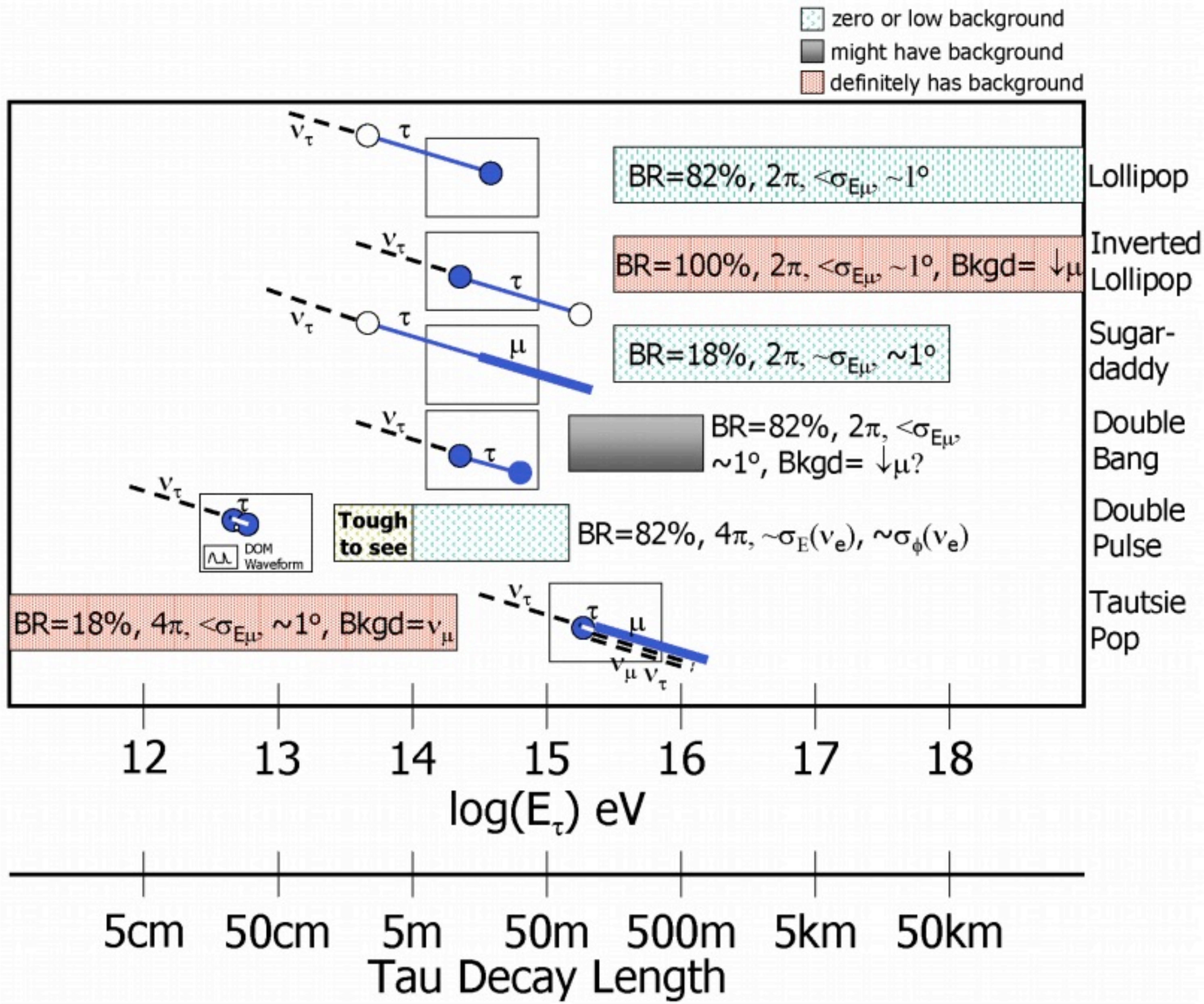
(a) $\nu_\mu \rightarrow \nu_\mu$, $c^{TT}_{e\mu} = 7.5 \times 10^{-23}$

Coefficient	Unit	d	CPT	Oscillation effect
Isotropic				
$a^{T}_{\alpha\beta}$	GeV	3	Odd	$\propto L$
$c^{TT}_{\alpha\beta}$	...	4	Even	$\propto LE$
Directional				
$a^{X}_{\alpha\beta}, a^{Y}_{\alpha\beta}, a^{Z}_{\alpha\beta}$	GeV	3	Odd	Sidereal variation
$c^{XX}_{\alpha\beta}, c^{YZ}_{\alpha\beta}, \ldots$	...	4	Even	Sidereal variation



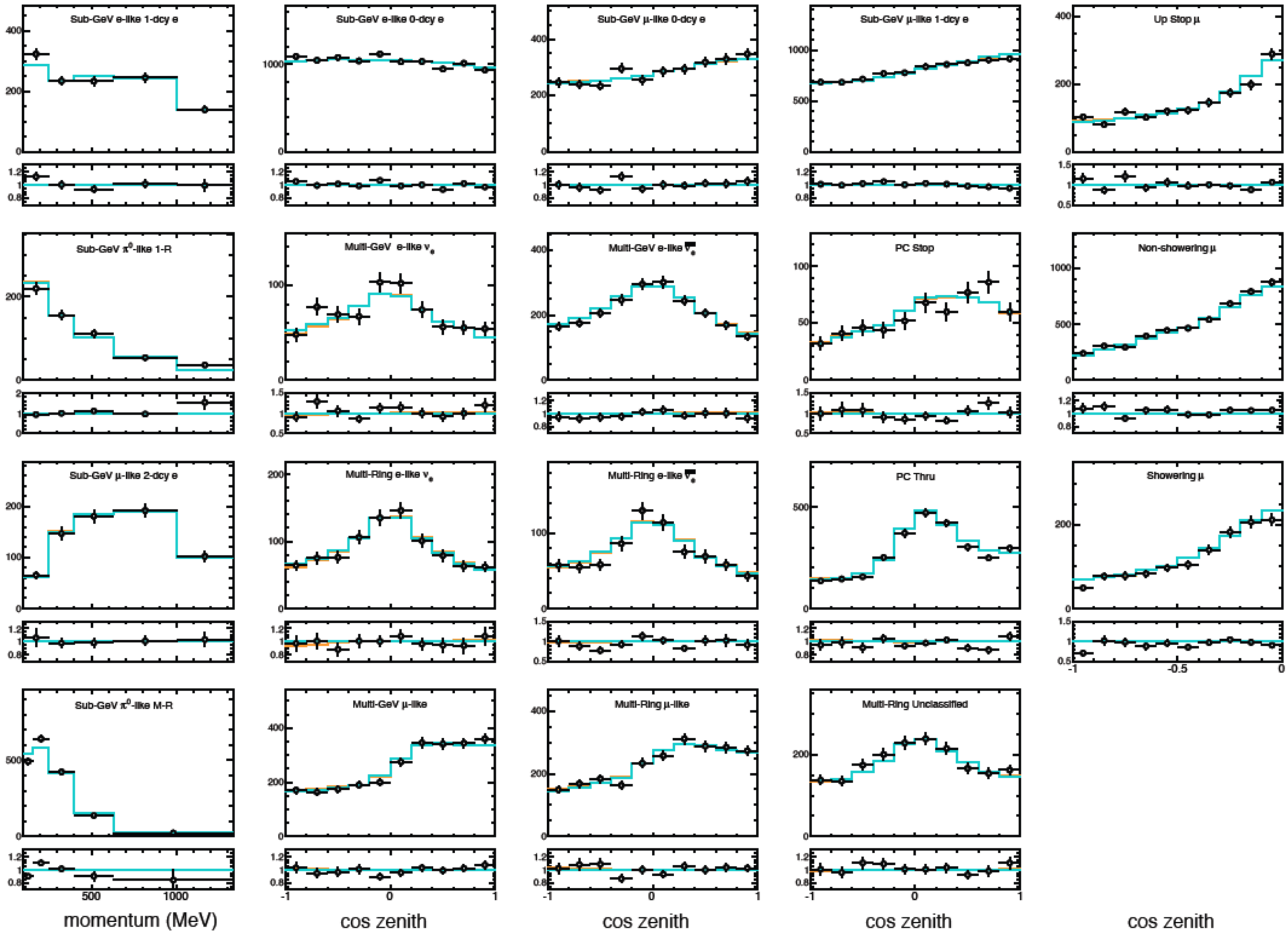


(a) $\nu_\mu \to \nu_\mu$, $a^T_{e\mu} = 10^{-22}$ GeV

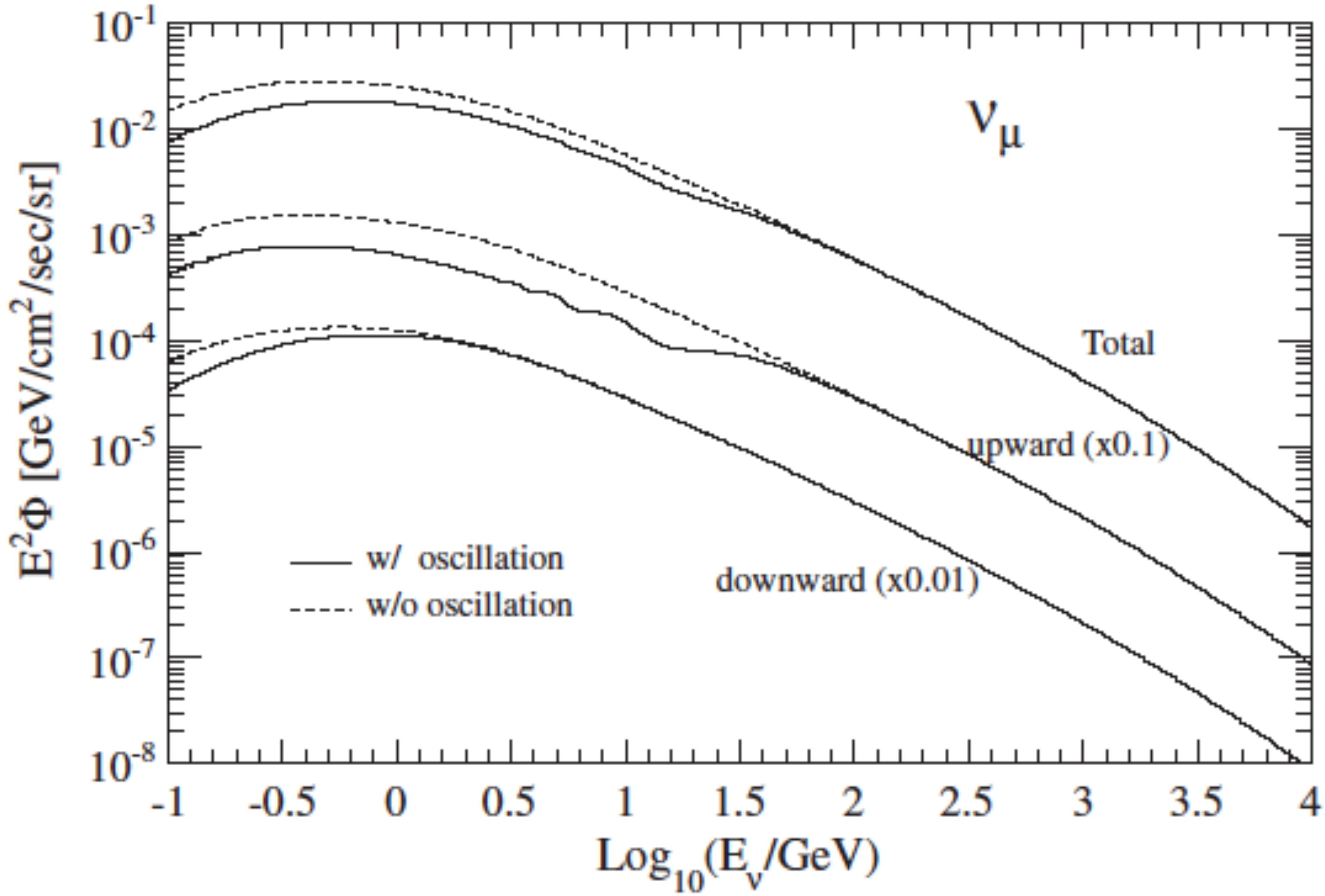


zero or low background
might have background
definitely has background
BR=82%, 2π, <σEμ, ~1°
Lollipop
BR=100%, 2π, <σEμ, ~1°, Bkgd= ↓μ
Inverted Lollipop
BR=18%, 2π, ~σEμ, ~1°
Sugar-daddy
BR=82%, 2π, <σEμ, ~1°, Bkgd= ↓μ?
Double Bang
Tough to see
BR=82%, 4π, ~σE(νe), ~σφ(νe)
DOM Waveform
Double Pulse
BR=18%, 4π, <σEμ, ~1°, Bkgd=νμ
Tautsie Pop
ντ
τ
μ
νμ
12
13
14
15
16
17
18
log(Eτ) eV
5cm
50cm
5m
50m
500m
5km
50km
Tau Decay Length

Zenith Angle Distributions



PHYSICAL REVIEW D 94, 052001 (2016)



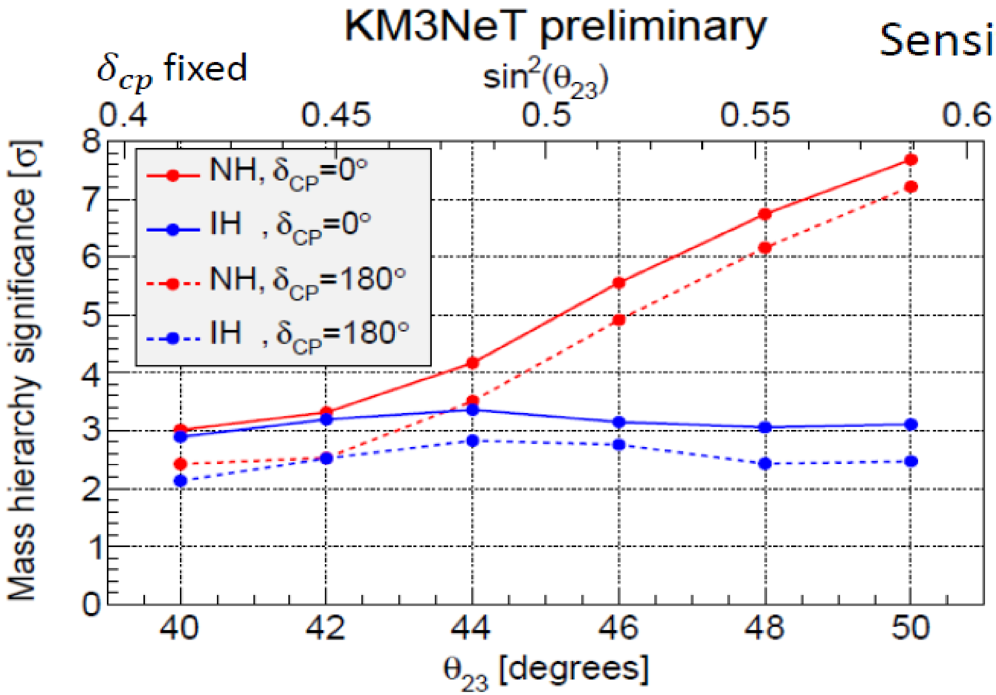
Farther Future: Next Generation Experiments

	Hyper-K	DUNE
Location	Japan / J-PARC	U.S.A. / FNAL
Proton Energy	30 GeV	120 GeV
Beam Power	1.2 MW	1.2MW
Baseline Length	295 km	1300 km
Near Detector	Tracker: FGD, TPC	FGT, STT, Pl. Sci.
Target	Carbon, Water	Ar, C, Fe
Far Detector	360 kton WC	40 kton Lq. Ar TPC
Target	Water	Argon
Off-axis Angle	2.5 deg / 44 mrad	0 deg (on-axis)
Peak ν Energy	~600 MeV	2.5 GeV
Neutrino Data	2025~26	2025~26

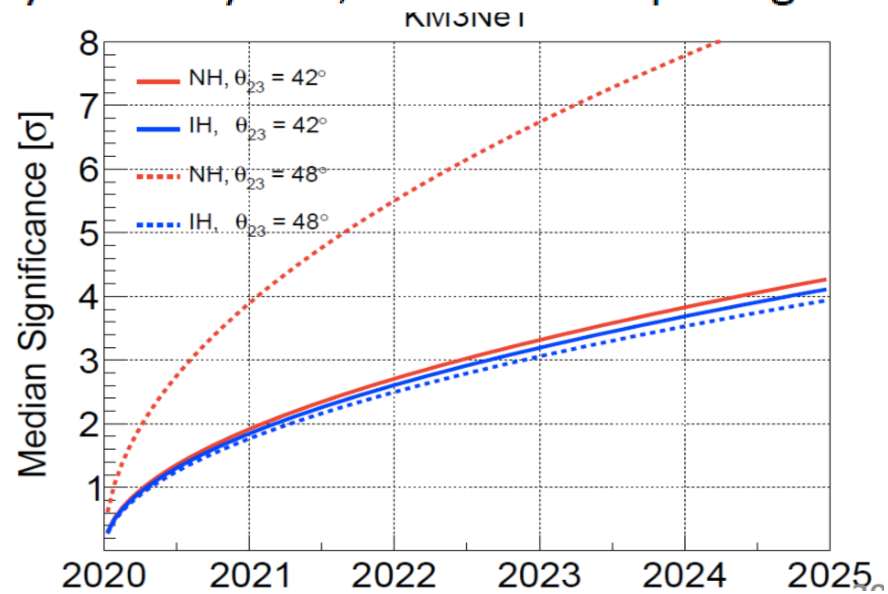
- N.B. Both projects are more than oscillation experiments
  - Nucleon Decay, Astrophysical neutrinos, precision cross section

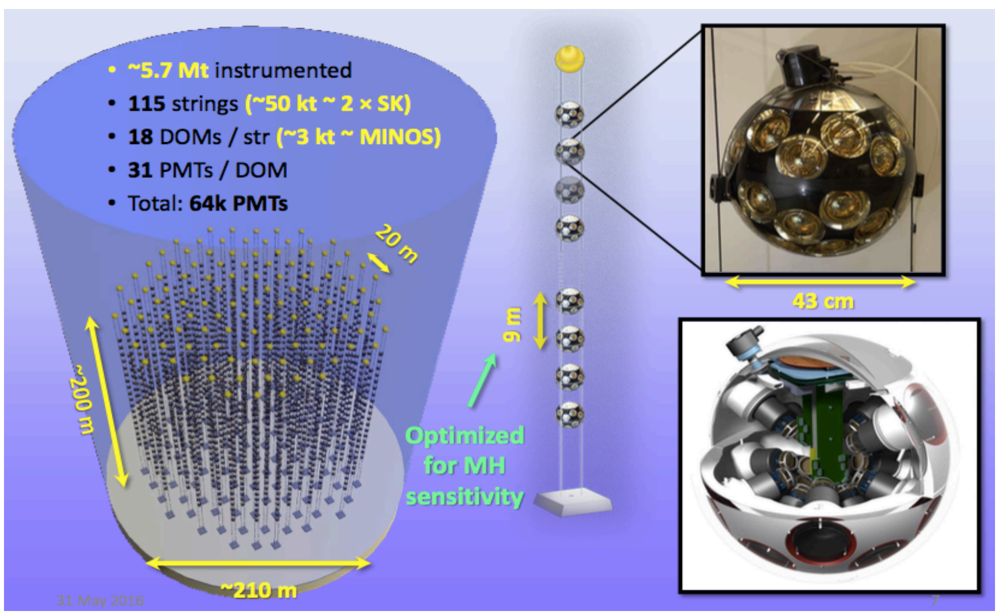
Orca/KM3NeT

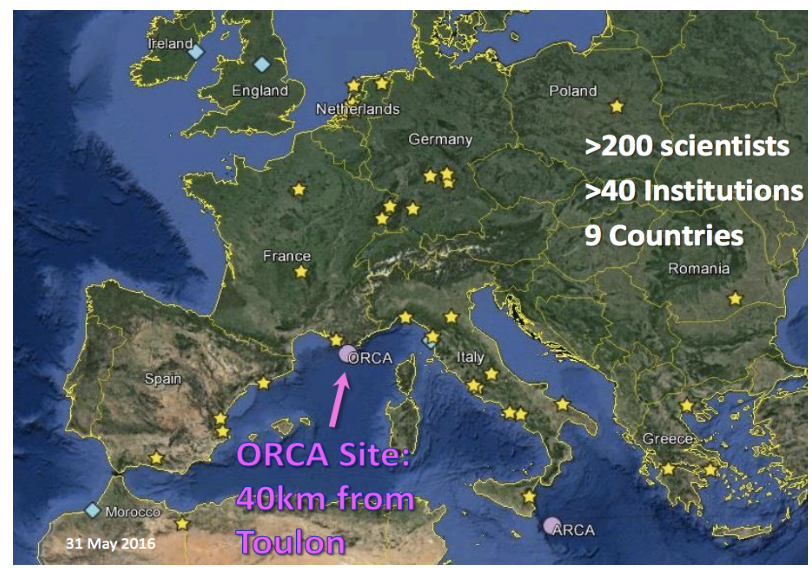
- **7 strings funded** for ORCA
- **Total ORCA cost: 40 M€**



Sensitivity after 3 years, 9m vertical spacing







IceCube Oscillation Systematics

Source of Uncertainty		Nominal Value	Uncertainty
Experimental Uncertainty	DOM absolute efficiency	Muons and flashers [16, 18]	±10%
	DOM angular acceptance	Flashers and laser [16]	±10% to ±30%
	Bulk ice model	Flashers [16]	Models in [16] [17]
Atmospheric flux [1]	Overall scaling	Honda 2015 [25]	Free
	Spectrum index		$E^{\pm 0.04}$
	$\nu/\bar{\nu}$ flux ratio		±20%
	ν_e/ν_μ flux ratio		±3%
Neutrino Interaction	Total cross section scaling	GENIE model [20]	Free
	Energy dependence		$E^{\pm 0.03}$
	DIS cross section		±5%
	RES axial mass		-15% to +25%
	QE axial mass		±20%

High Energy Electron Flux at IceCube/DeepCore