Mass Hierarchy with Atmospheric Neutrinos

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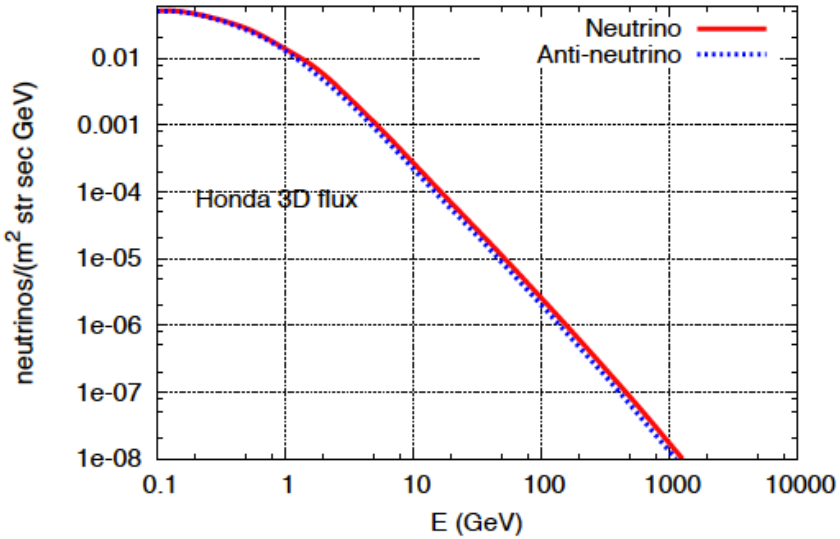
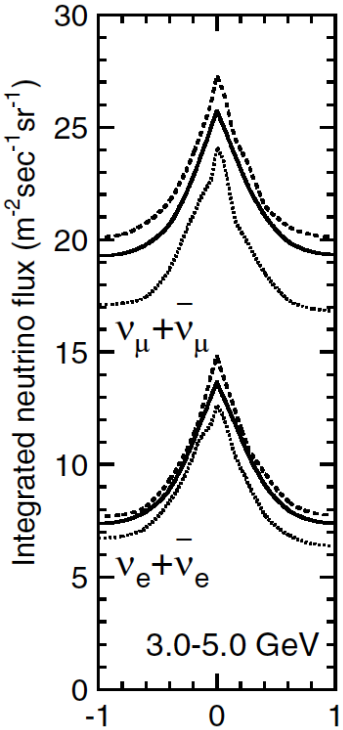
Boston University

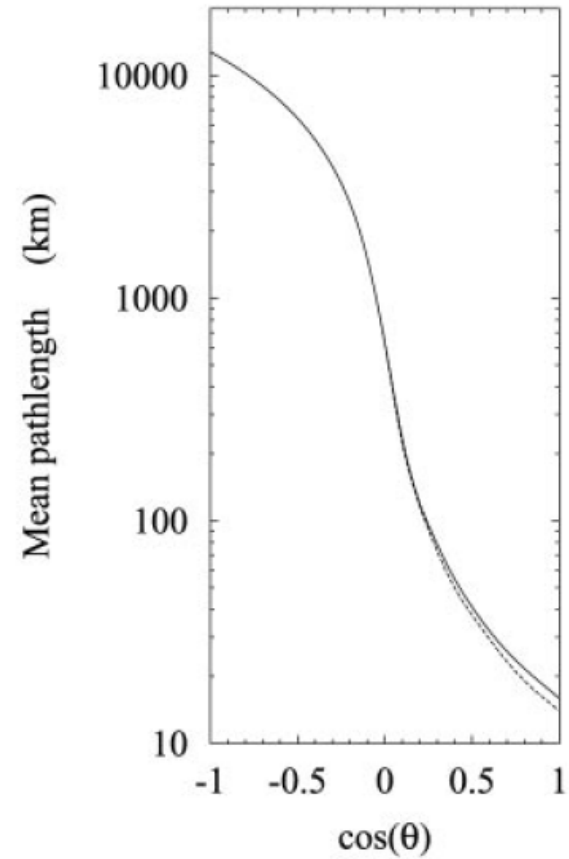
Intensity Frontier
Neutrino Meeting
SLAC – March 6, 2013

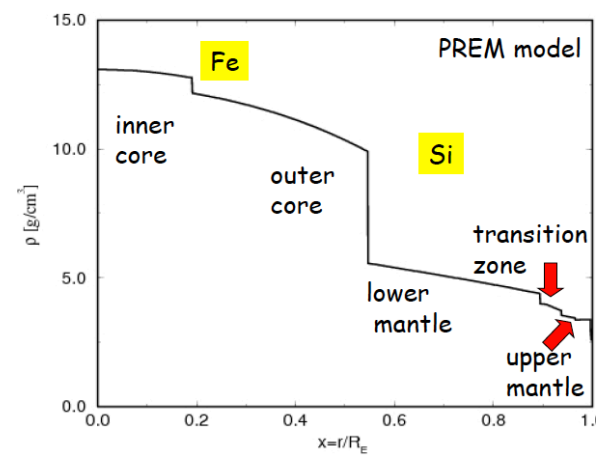




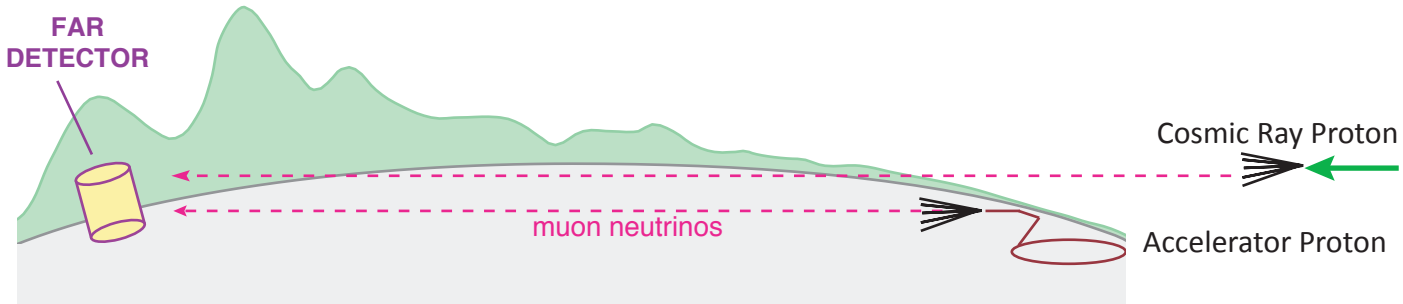
Characteristics of the Atmospheric ν Flux:

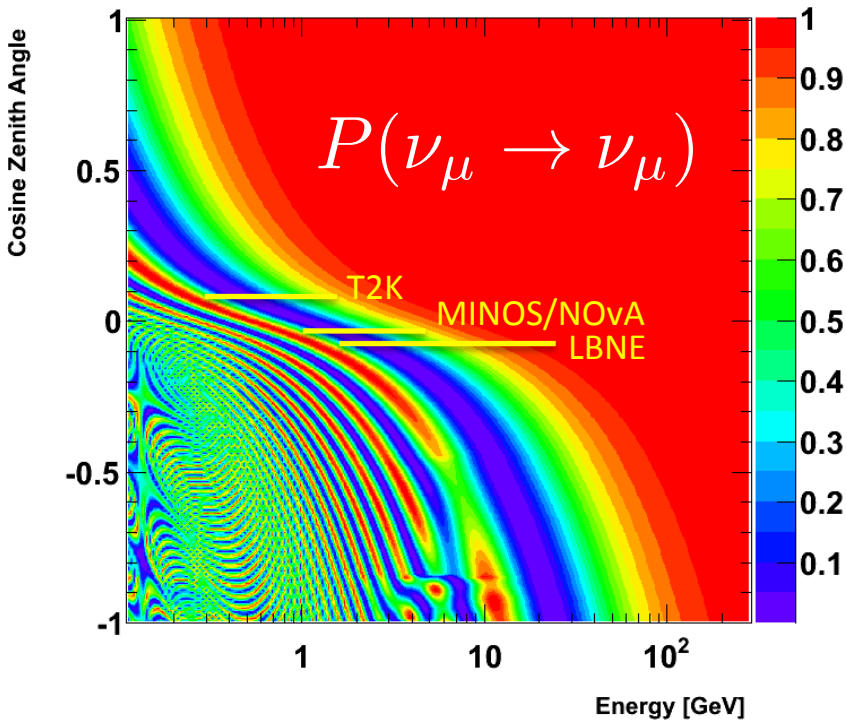
- Exponential energy spectrum
- Flux ratios (well estimated)
- - mu/e
- - up/down
- Pathlength: 15-13000 km
- Varying matter density

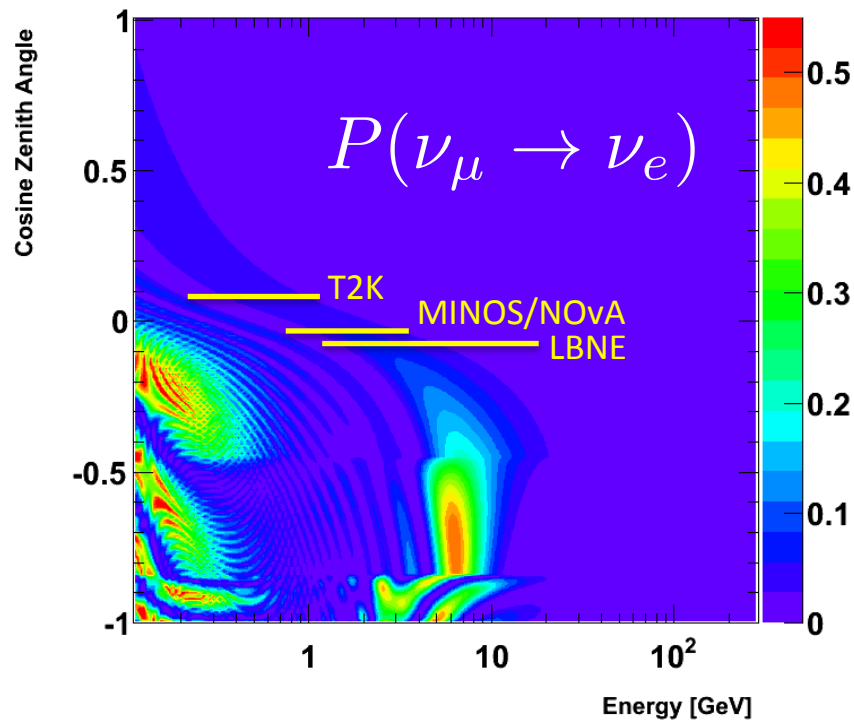




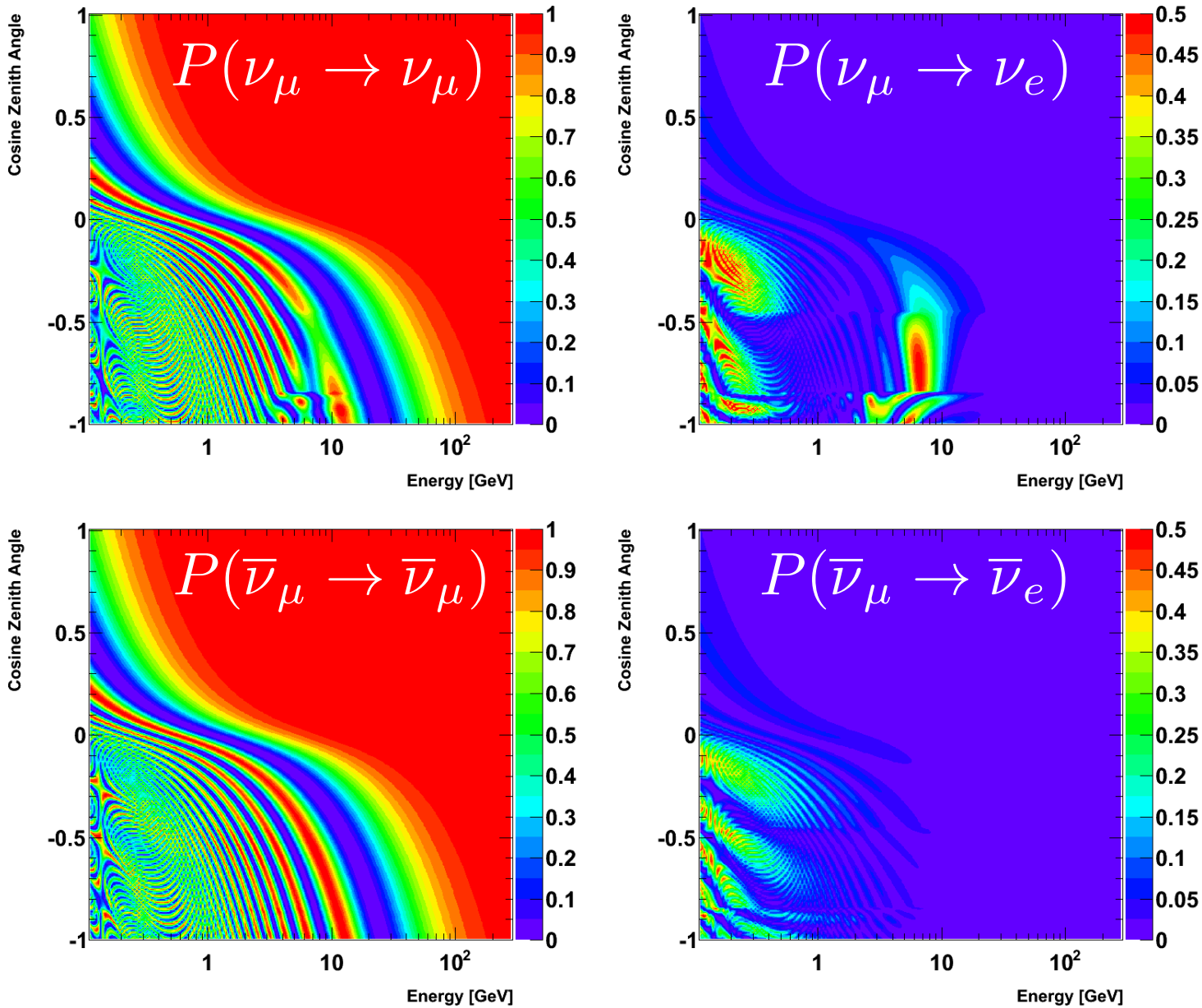
Atmospheric Neutrinos and Long Baseline Neutrinos







Oscillograms: Graphical representations of neutrino mixing probability

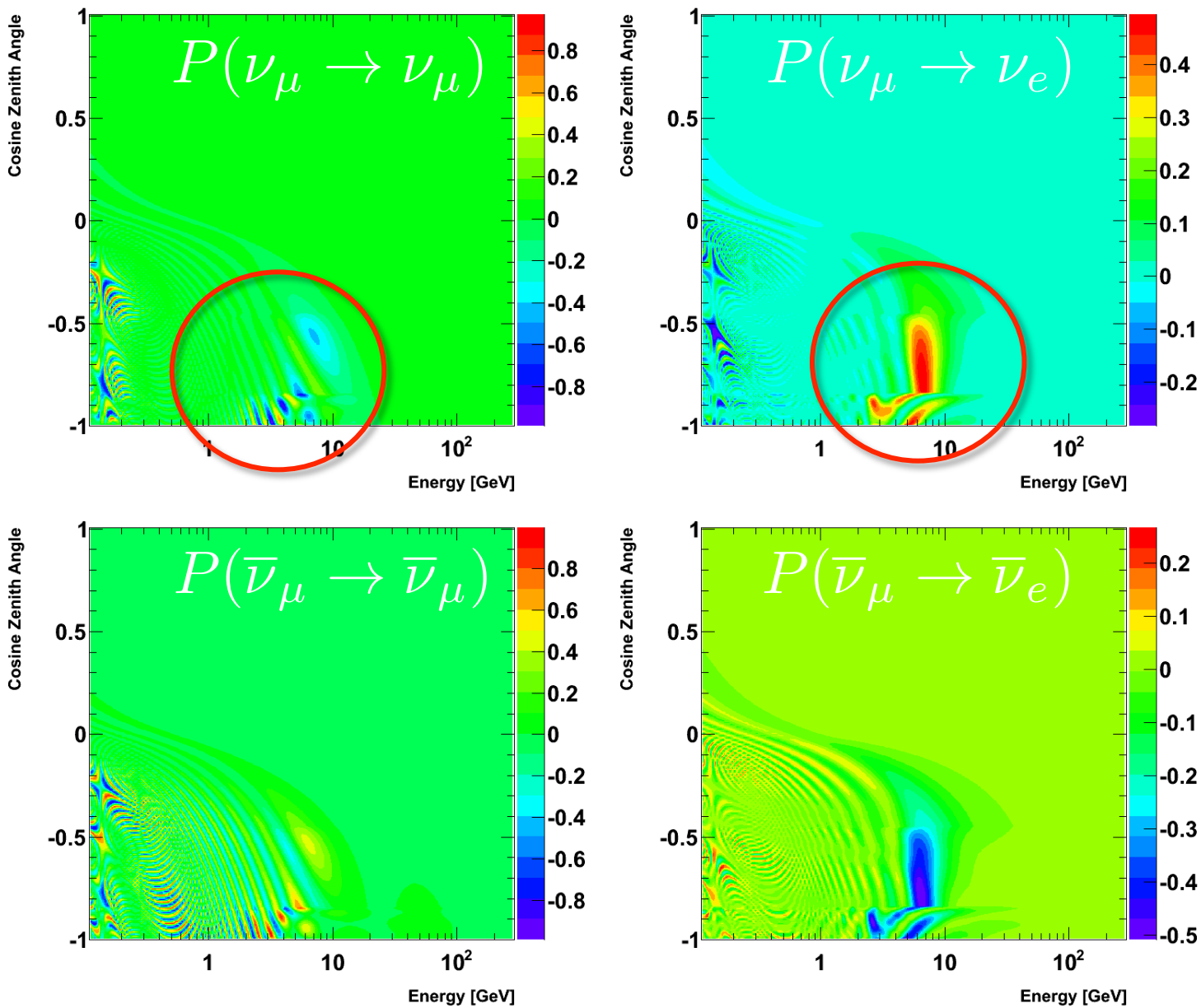


Resonance in ν_μ–ν_e for NH

…

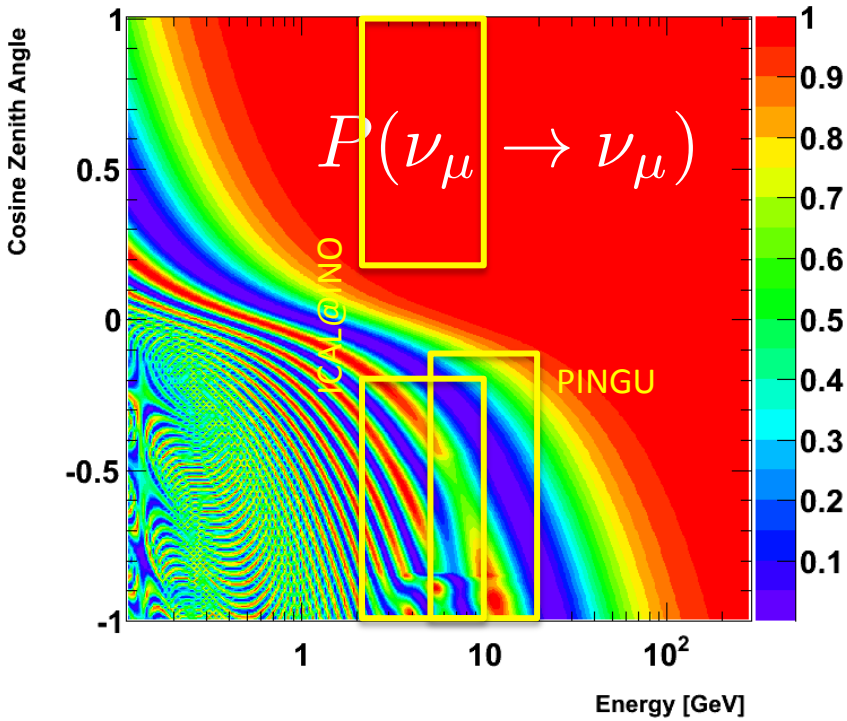
(in antinu for IH)

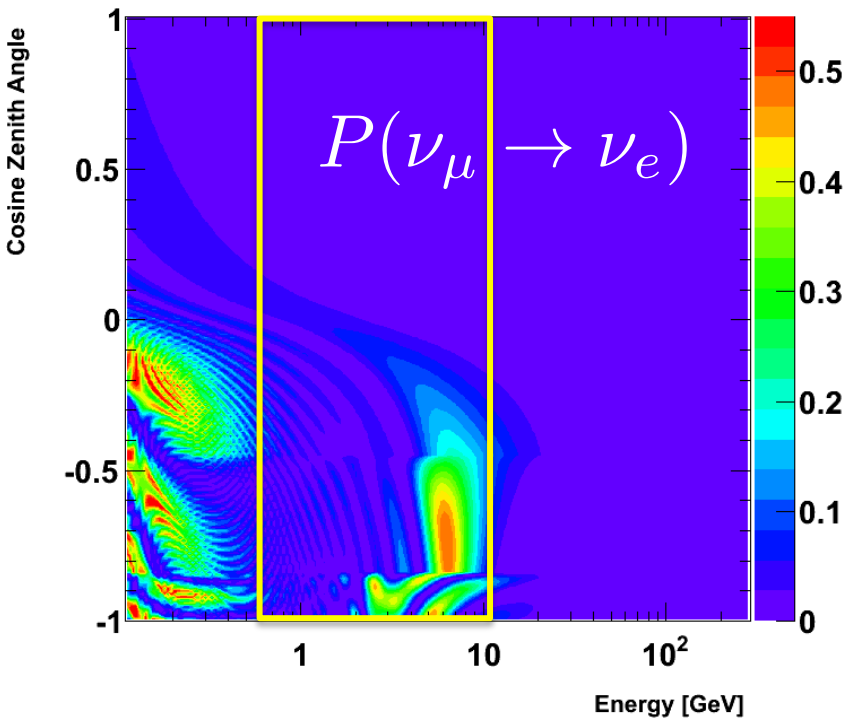
Normal Hierarchy minus Inverted Hierarchy



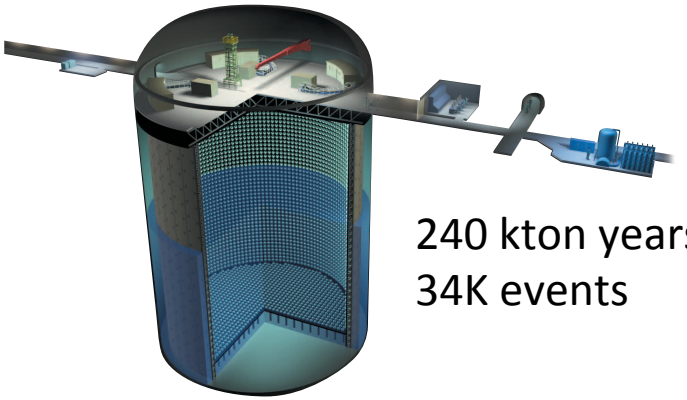
Atmospheric Neutrinos Experiments

Category	Examples	ν_μ–ν_e	ν_μ–ν_μ	ν/*anti*-ν	U/D	Mass
Water Cherenkov	Super-K Hyper-K	Y	Y	Some	Y	22.5 kton 560 kton
Magnetized Iron	ICAL@INO		Y	Good	Y	50 kton
Neutrino Telescope	PINGU ORCA		Y	??		Mton
Liquid Argon TPC	LBNE GLACIER	Y	Y	Good	Y	10-34 kton 20 -100 kton

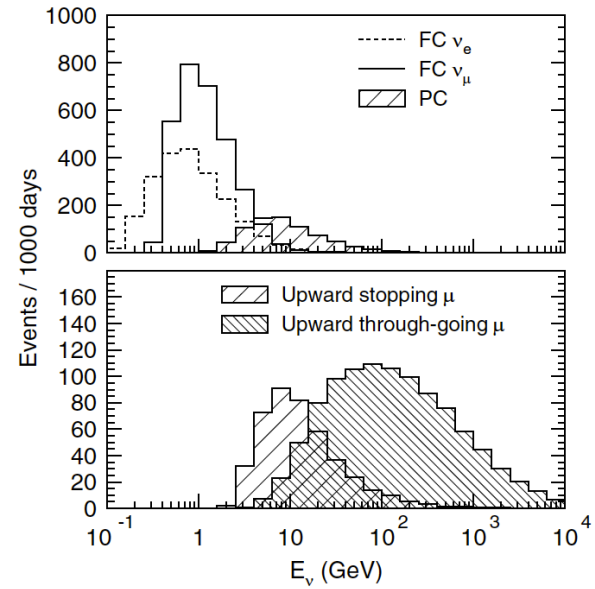


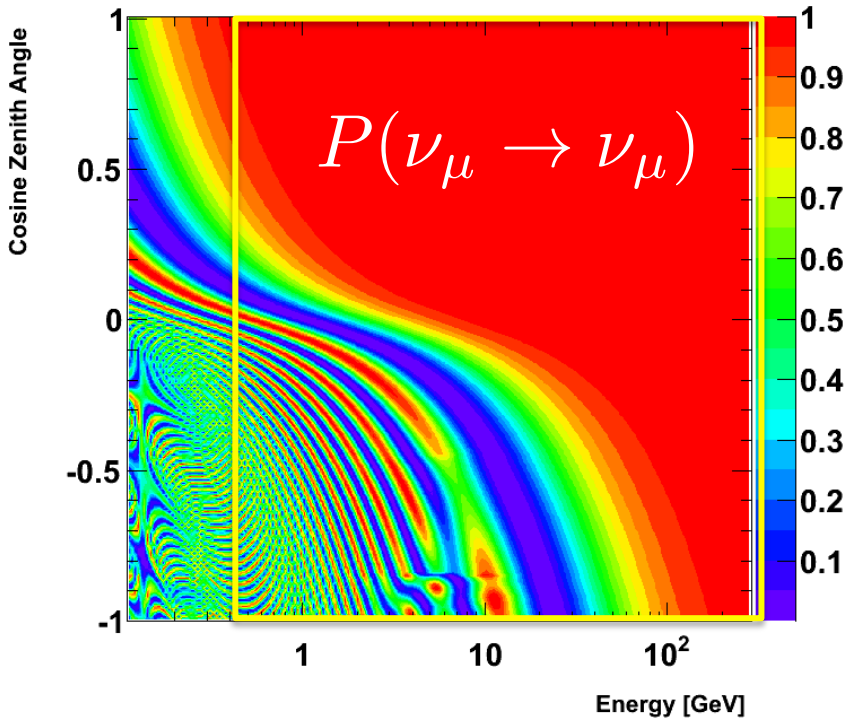


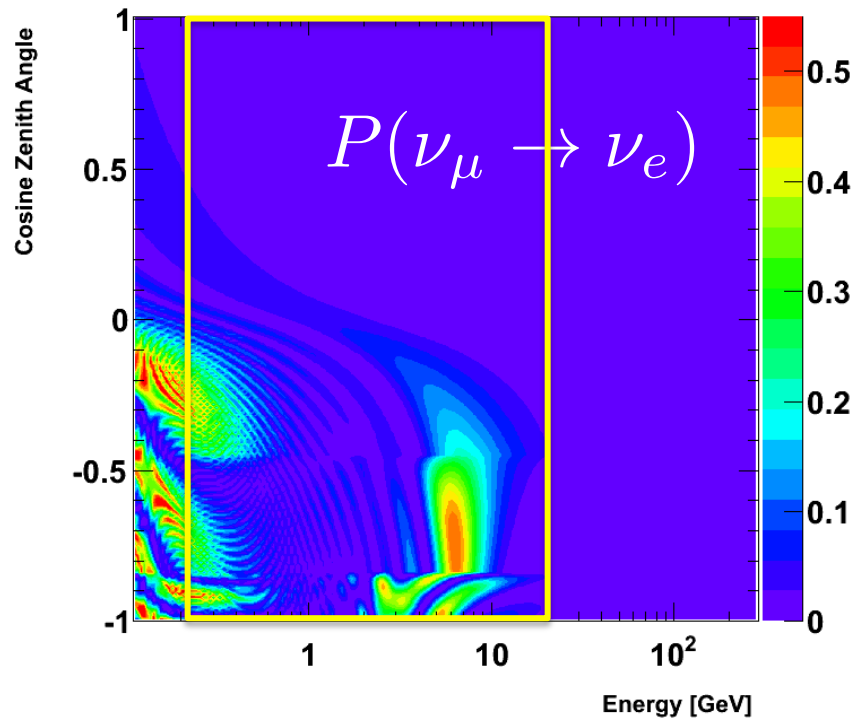
Super-Kamiokande: Current Results



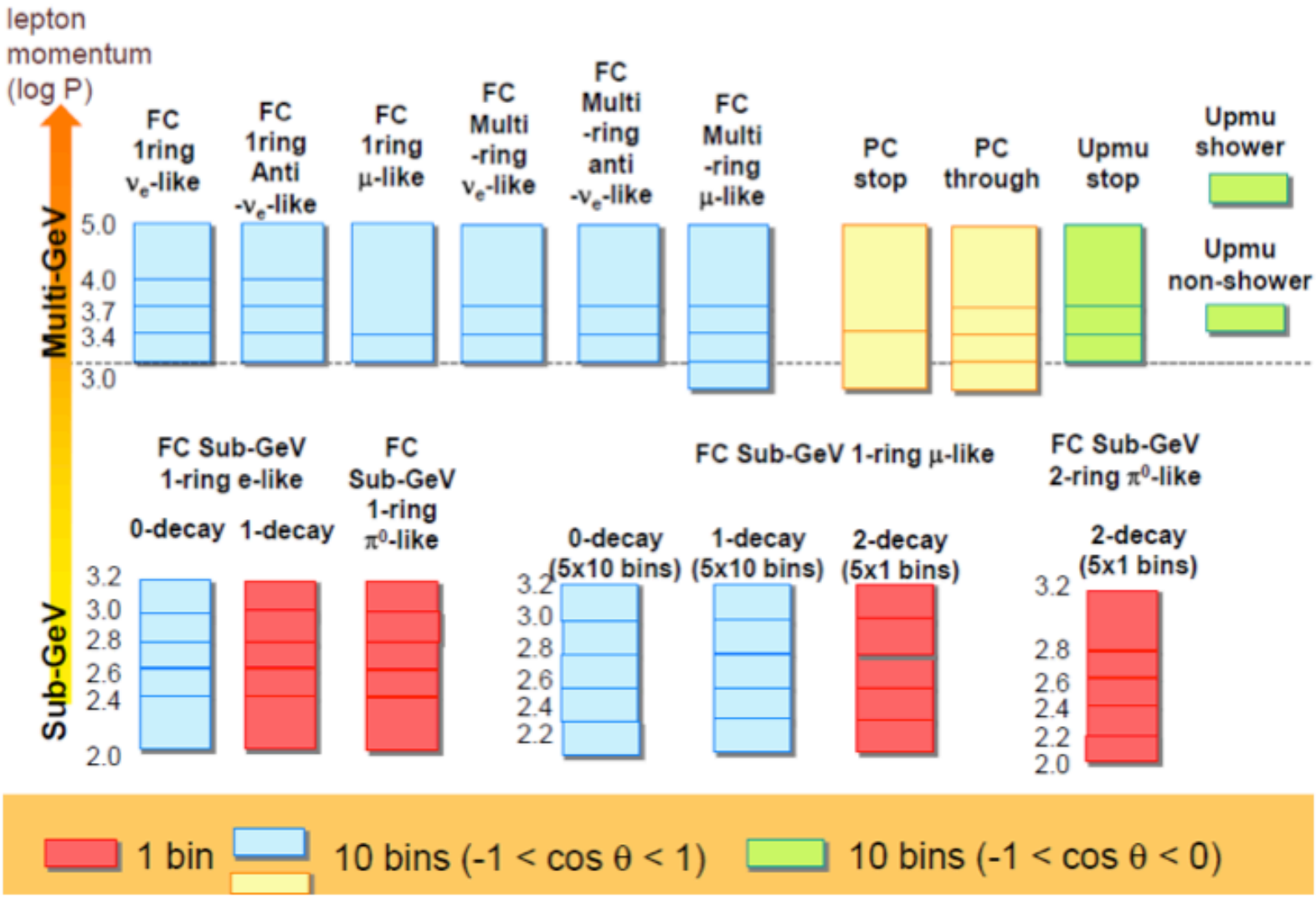
240 kton years
34K events





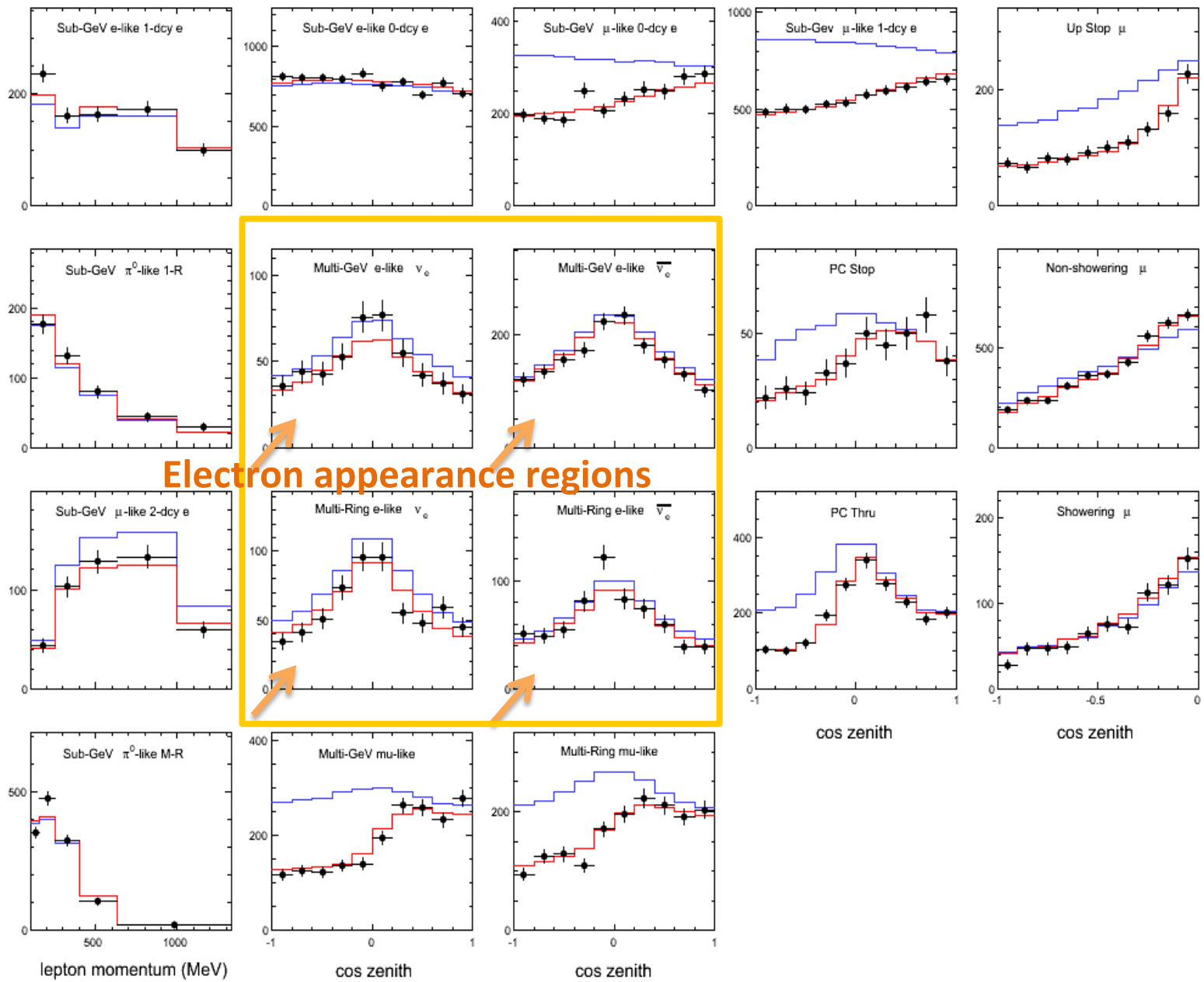


480 Bins in Zenith Angle, Energy, and Event Category



Multi-GeV categories selected by cuts and likelihood functions to enhance CC flavor ID and neutrino/antineutrino fraction

Super-K I+II+III+IV Combined Dataset



Neutrino Sample Composition at Multi-GeV Energies (try to enhance nu vs antinu)

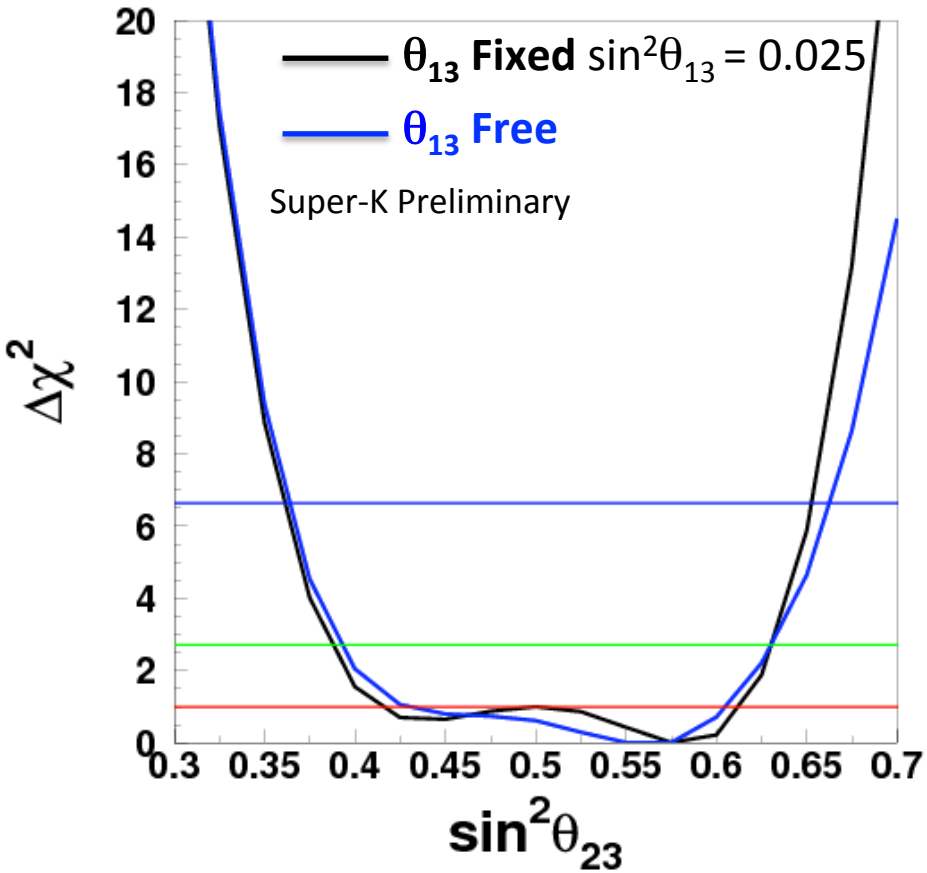
Composition (%)		CC ν_e	CC anti-ν_e	CC ν_μ+anti-ν_μ	NC
ν_e like	1R	60.2	10.6	13.5	14.8
	MR	57.5	17.4	10.7	13.7
Anti-ν_e like	1R	55.7	36.6	1.1	6.4
	MR	51.9	20.7	8.2	19.7

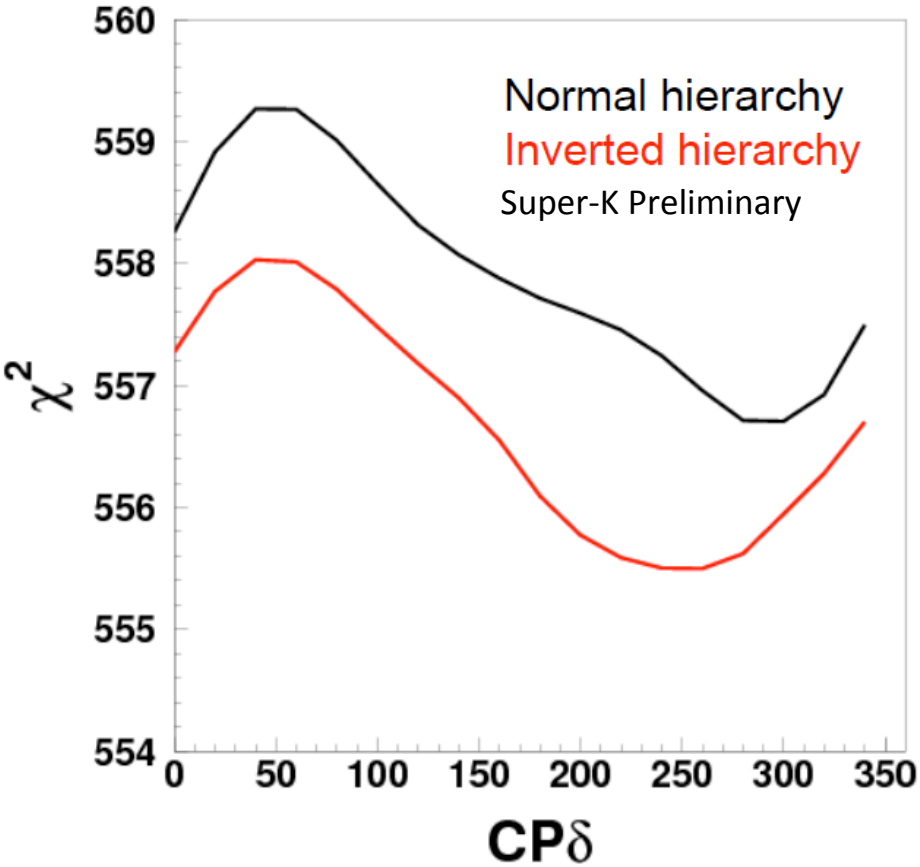
Composition (%)		CC ν_e	CC anti-ν_e	CC ν_μ+anti-ν_μ	NC
ν_μ like	1R	0.2	0.08	98.8	0.2
	MR	2.5	0.3	91.7	4.4

Important Systematic Error Terms for ν_e Appearance (out of 151 considered overall)

Error Source	Uncertainty
ν_e vs. anti-ν_e sample selection	7%
Charged-Neutral Pion Production	40%
Tau Production Cross section	25%
DIS Cross Section	5-10%
NC / CC Ratio	20%
Single-Pion Production	20%
Flux Normalization above 1 GeV	7%
Flux Ratio ν to ν bar above 1 GeV	5-8%

Results: using reactor θ_{13} constraint

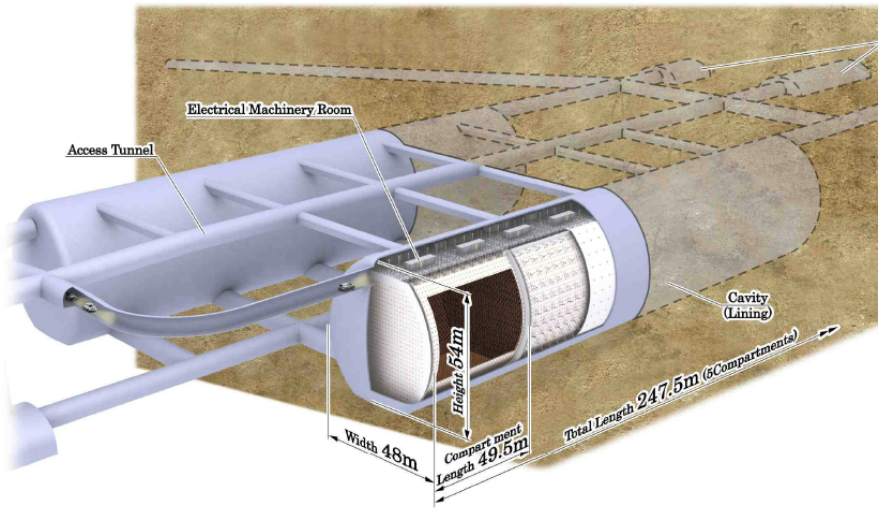




- Both free and constrained fits prefer 2nd octant
- 1.2σ preference for inverted hierarchy
  sensitivity is 0.9σ

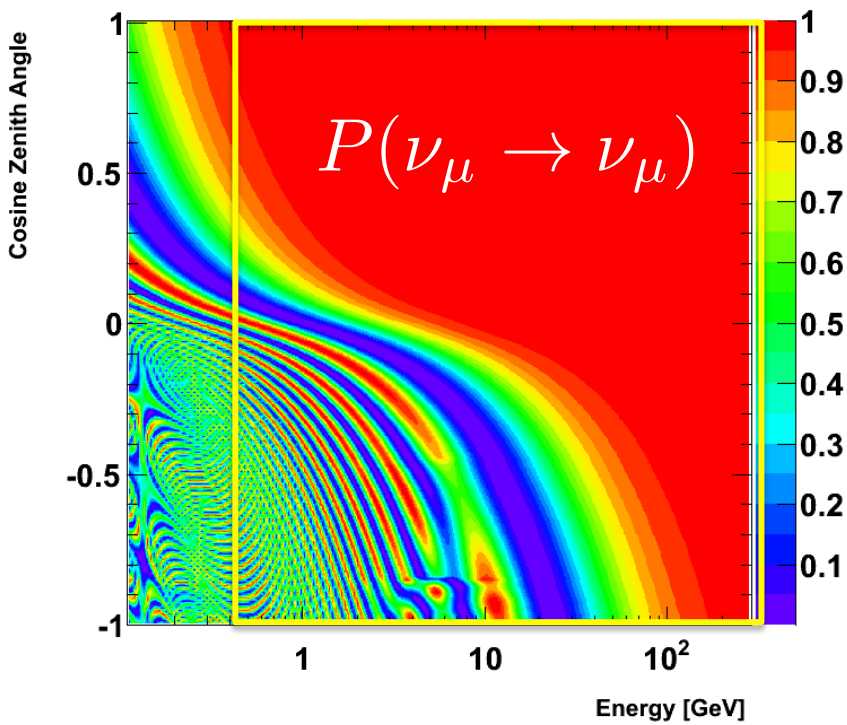
} Not significant!

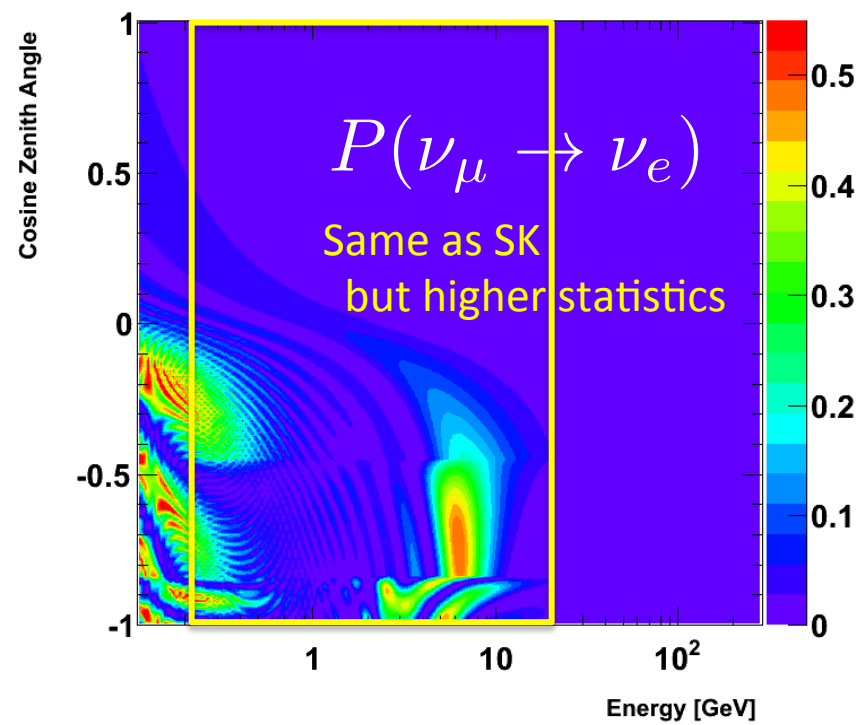
Hyper-Kamiokande



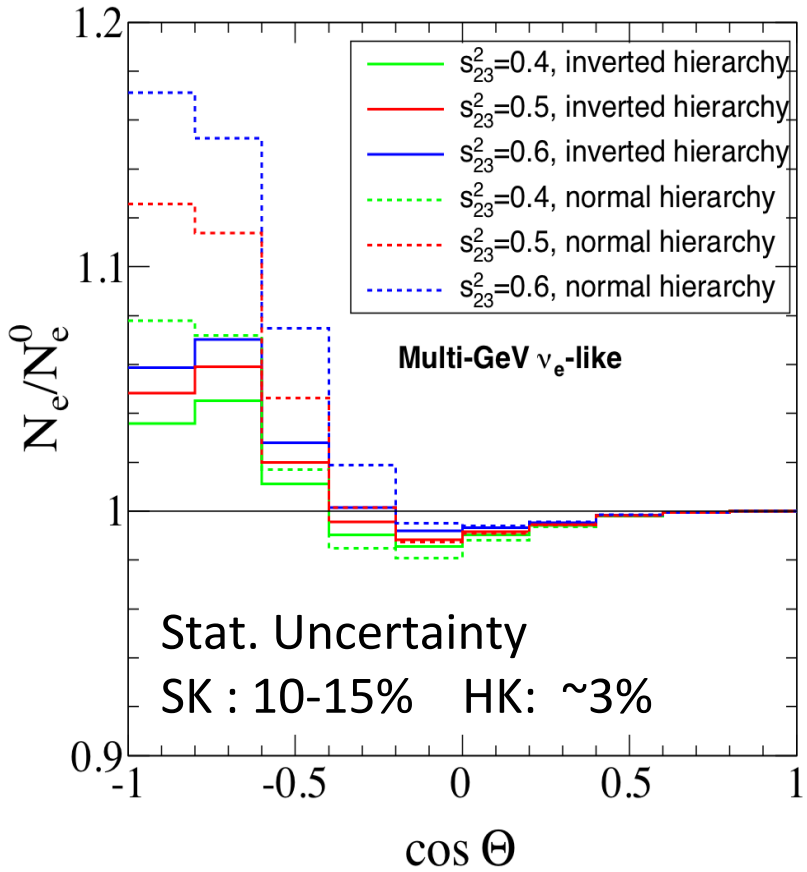
- 560 kton fiducial mass
- 99000 PMTs 20% coverage
- Outer veto detector

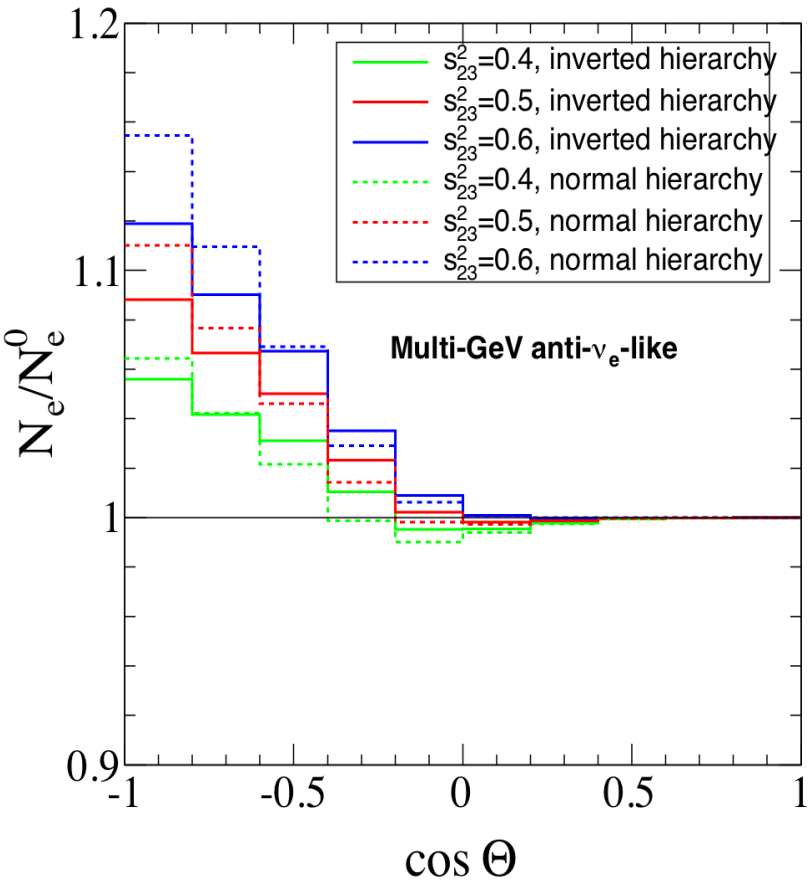
- Sensitivity studies simply scale SK result to large exposure, i.e. assume the same detector performance



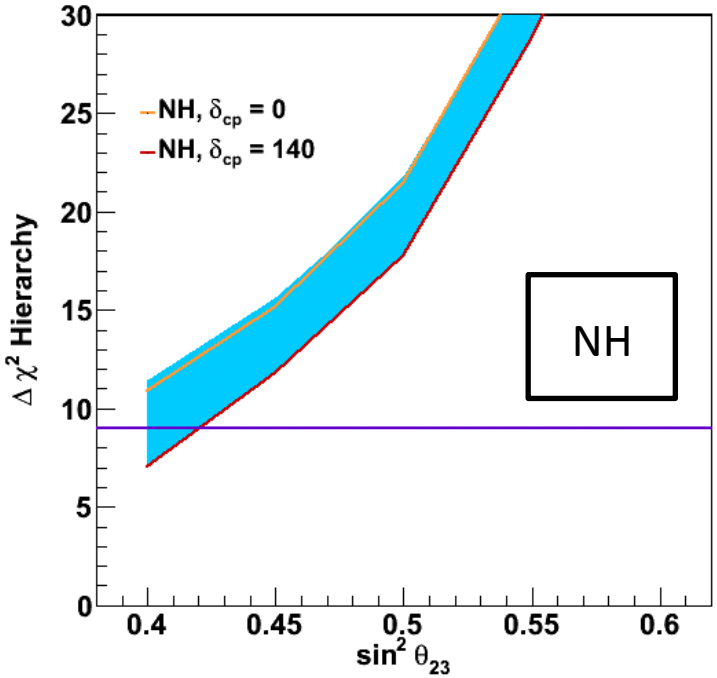


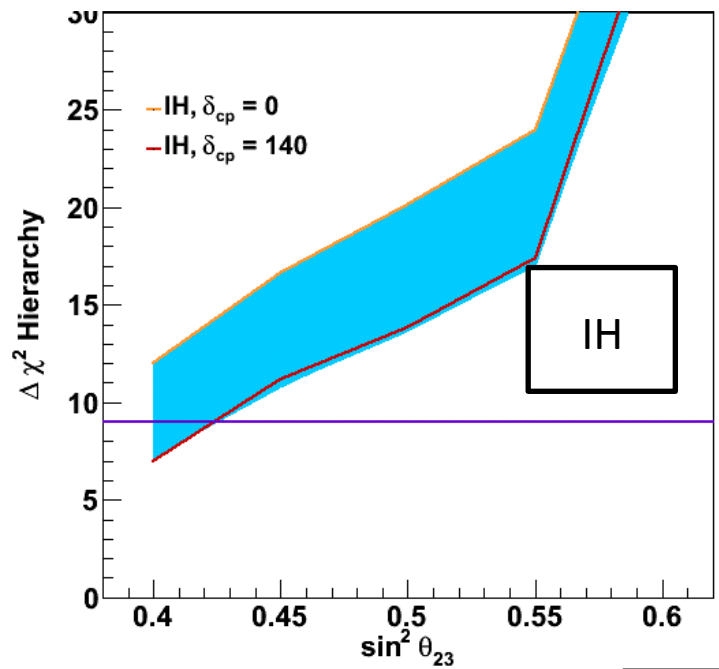
Multi-GeV ν_e-like and anti ν_e-like samples

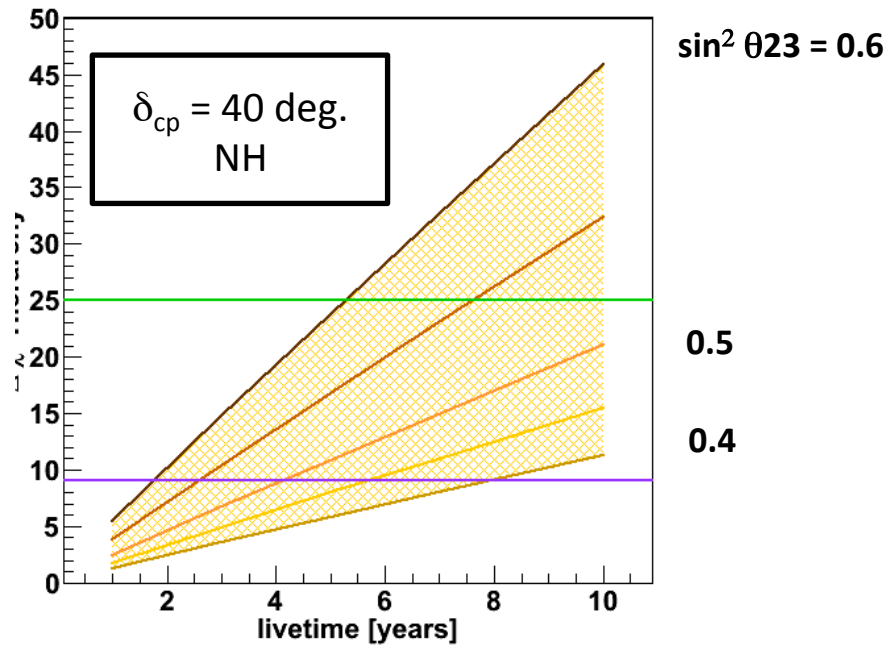




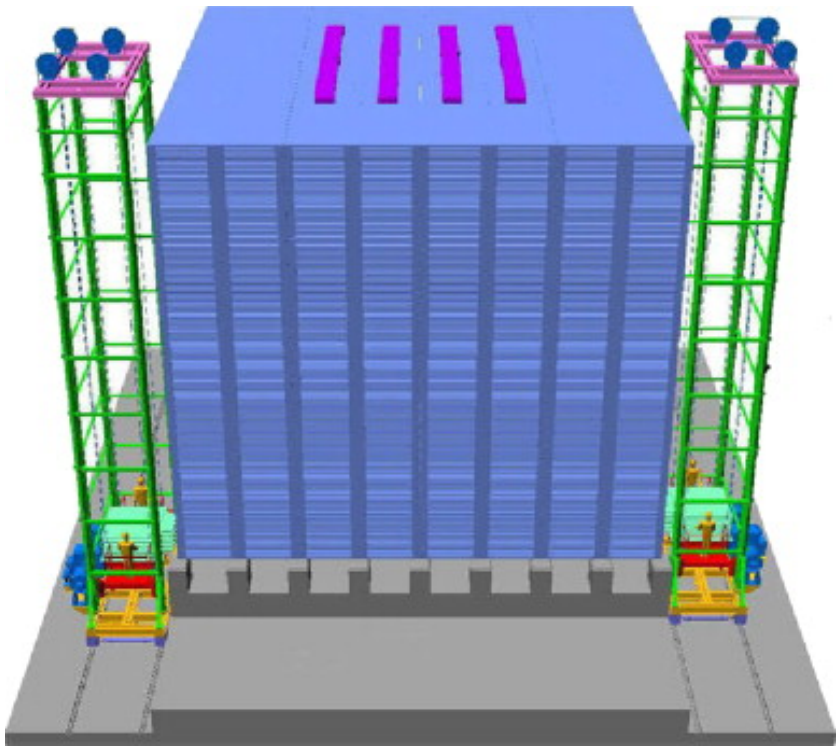
Octant and CP-δ dependency

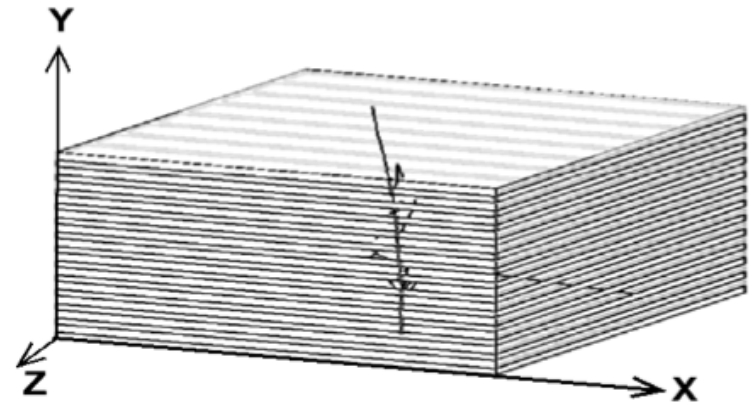


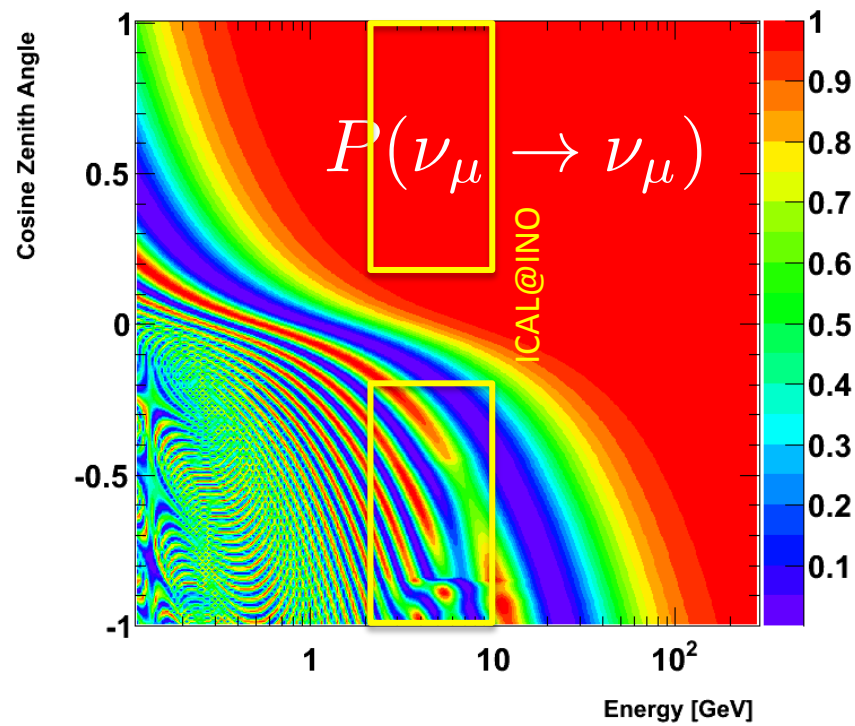




ICAL @ INO (Iron Calorimeter at India-based Neutrino Observatory)





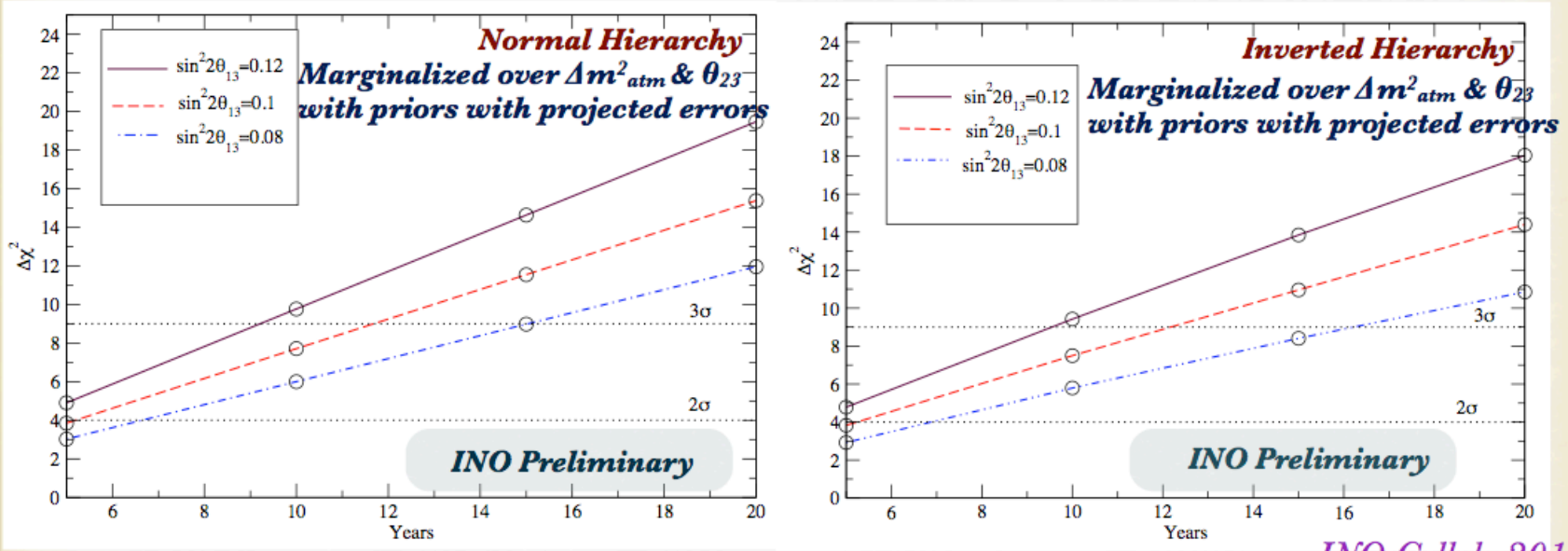


- 50 kton mass
- 29000 RPCs
- 1.3T magnetic field
- Best acceptance for vertical muons
- Charge separation efficiency = ?

http://dx.doi.org/10.1016/j.nima.2012.03.017

MASS HIERARCHY @ INO

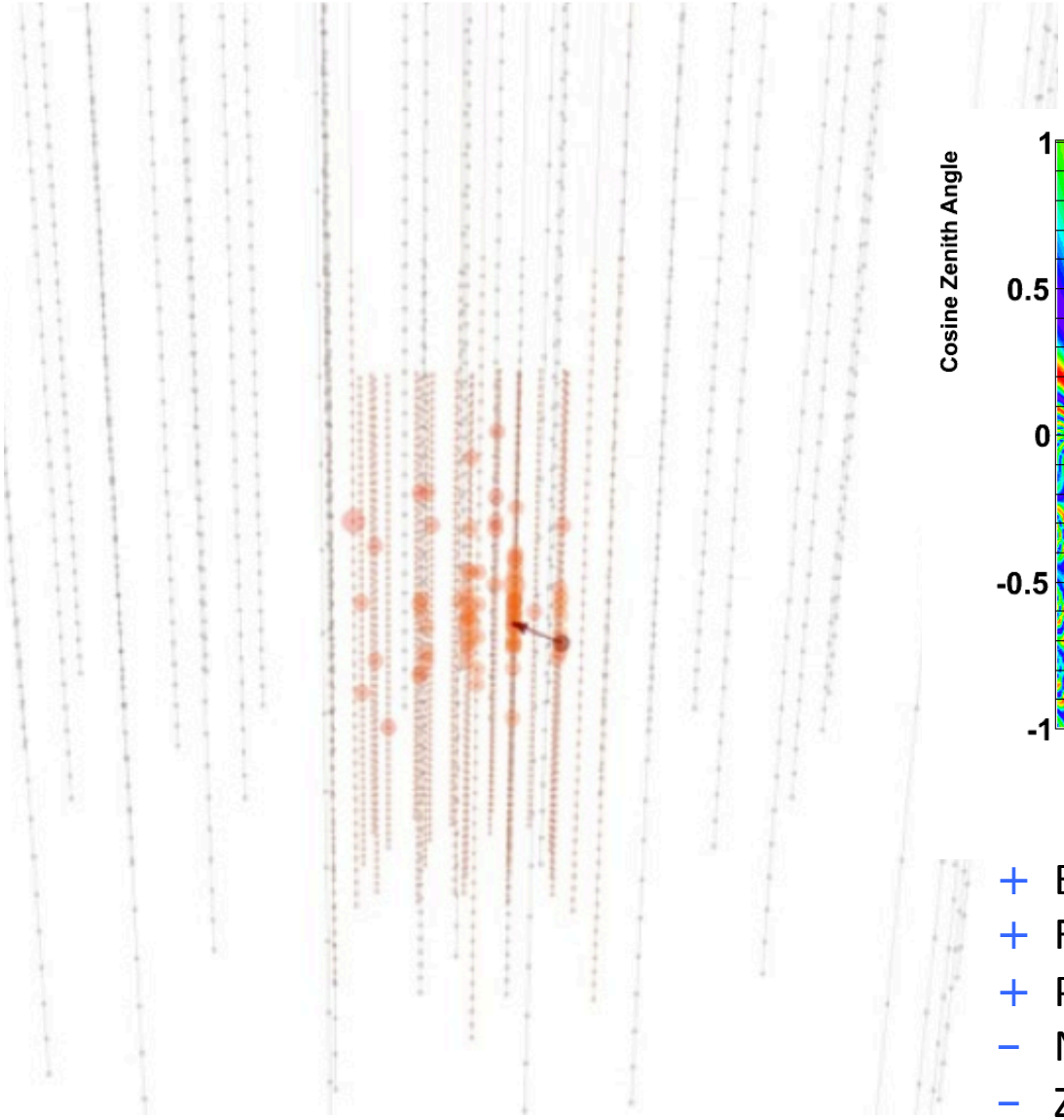
- *Events generated using Nuance and ICAL resoln in E and $\cos\theta_{zenith}$*



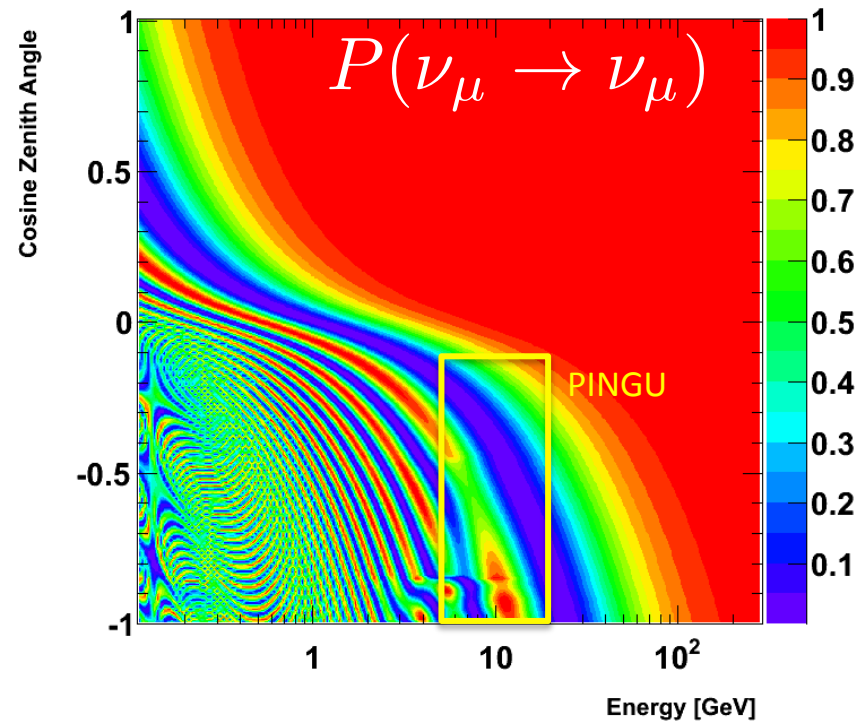
INO Collab, 2012

- *~2σ sensitivity for $\sin^2\theta_{23}$=0.5, $\sin^2 2\theta_{13}$=0.1 by 2022 (5 yrs)*
- *~2.7σ sensitivity for $\sin^2\theta_{23}$=0.5, $\sin^2 2\theta_{13}$=0.1 by 2027 (10 yrs)*

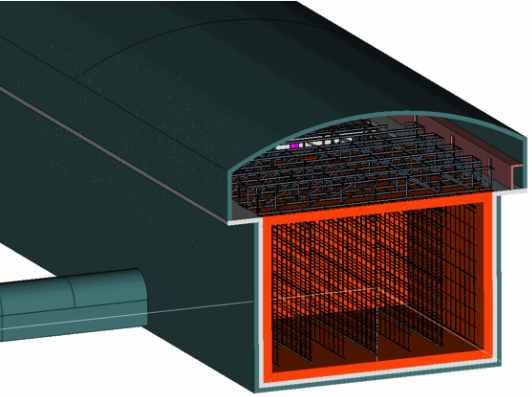
PINGU (Precision IceCube Next Generation Upgrade)



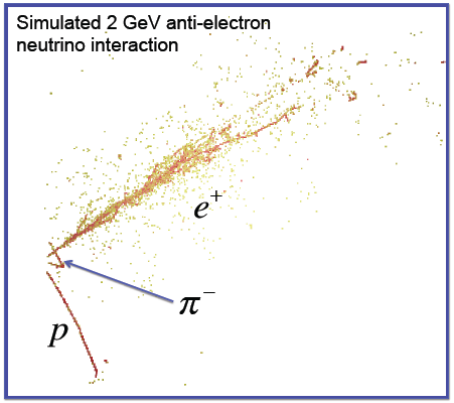
Please see Doug Cowen's talk for details



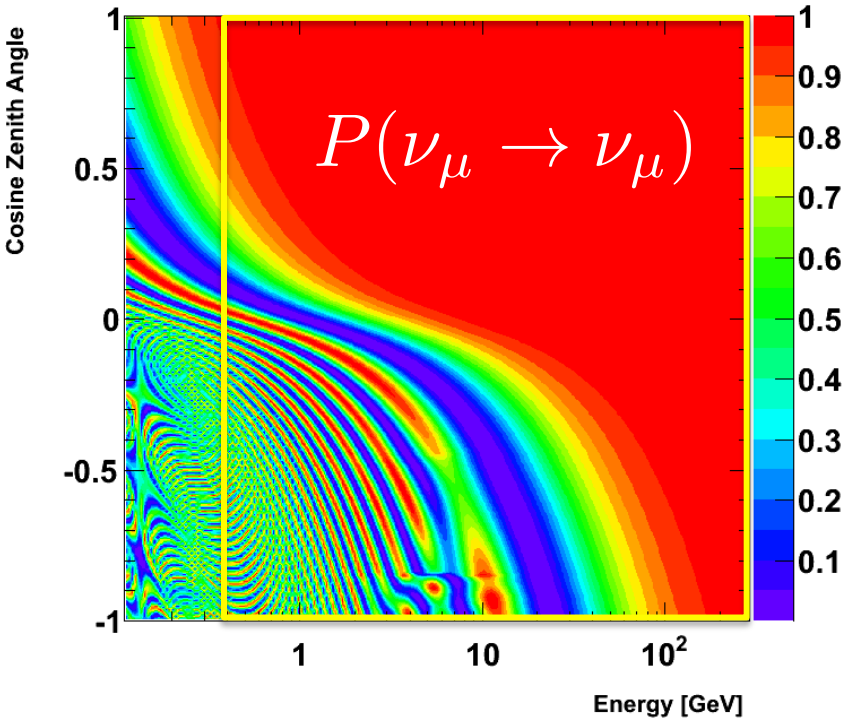
+ Enormous statistics (25K evt/yr)
+ Full containment of 10 GeV νμCC
+ Possible ν/antiν by $d\sigma/dy$ (ArXiv:1303.0758)
− No up/down normalization
− Zenith acceptance & detector response may be challenging to control

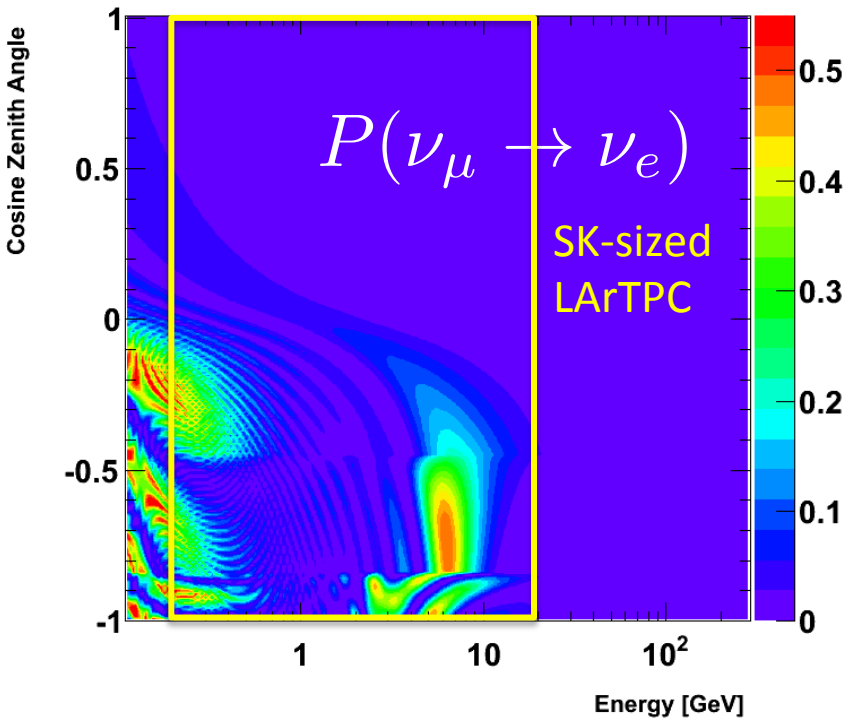


LArTPC (LBNE or GLACIER/LBNO e.g.)



- High resolution:
- NC BG rejection
- Direction/energy (see all charged)
- ν/anti-ν handles
- Above are needed to compensate for modest mass
- Magnetize?

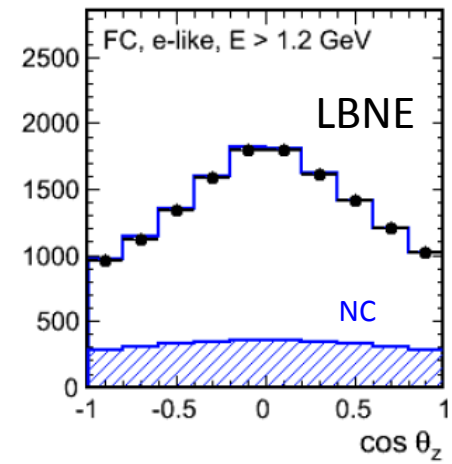




LBNE Sensitivity Studies via Performance Estimates

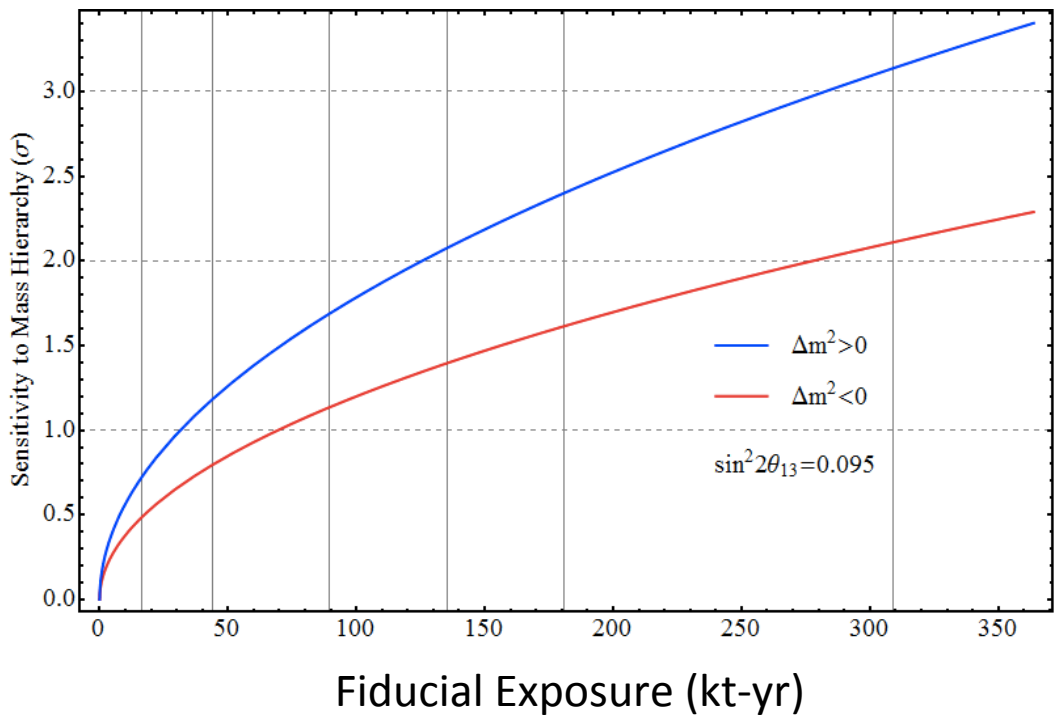
	Lepton (electron)	Lepton (muon)	Hadronic System
Angular Resolution	2°	2°	10°
Energy Resolution	$10\% / \sqrt{E}$	2% (FC) 15% (PC)	$30\% / \sqrt{E}$

A. Guglielmi, Neutrino 2010, Ghandi et al., hep-ph/0807.2759.



LBNE study	Neutrino (true)	Antineutrino (true)	Tag method(s)
ν_e-like	30%	6%	p ID only
Anti ν_e-like	43%	22%	p ID only
ν_μ-like	27% / 57%	5% / 0%	p ID / μ-e decay
Anti ν_μ-like	49% / 19%	19% / 24%	p ID / μ-e decay

MH Determination using LArTPC (by LBNE if underground)



SUMMARY and CONCLUSIONS

- There are several approaches to determining the MH using atmospheric neutrinos
- Few sigma sensitivity is achievable with multi-100 kt-yr esposure
- Super-K currently has ~ 1σ sensitivity. This is a major collaboration project.
- Impact of systematics uncertainty is considerable
  - SK/HK analysis benefits from fully developed approach
  - Other proposed experiments should improve with time and effort

References:

Roger Wendell talk at Vietnus, HK Workshops
Hyper-Kamiokande LOI --- http://arxiv.org/abs/1109.3262
Sandhya Choubey talk at Neutrino 2012
Dasgupta et al., NIMA 678 (2012) 105
Ribordy and Smirnov --- http://arxiv.org/abs/130.0758
Ghosh, et al. --- http://arxiv.org/abs/1212.1305
Blake, Gallagher, and Guennette, Neutrino 2012 Poster

Whitepapers:

Opportunities for Underground Physics with LBNE, R.J. Wilson for LBNE
Hyper-Kamiokande Physics Opportunities [...], T. Nakaya for Hyper-K
Measuring the Neutrino Mass Hierarchy with PINGU, D. Cowen, et al.