Atmospheric Neutrinos: Overview and Opportunities

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Neutrino Telescopes 2013
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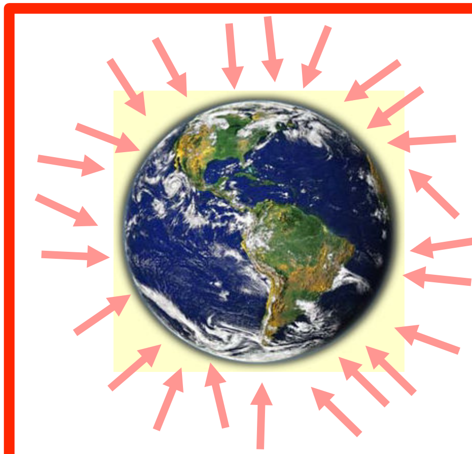
Outline

- Introduction
- Types of detectors and samples
- Fits and systematic errors
- Atmospheric neutrinos in the three-flavor era
- Future prospects and lessons for the future



Protons hitting the atmosphere

RELAX

The Good - The Bad
(all neutrinos are beautiful)

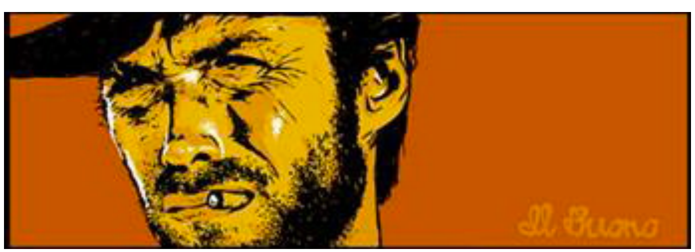
The Good

- Δm^2, $\mathrm{Sin}^2 2\theta_{23}$, Octant, $\mathrm{Sin}^2 2\theta_{13}$, δ_{CP} etc..
- Mass Hierarchy
- Non-standard oscillations
- CC Tau interaction physics
- Complimentary to beam / resolve degeneracies
- FREE!

The Bad

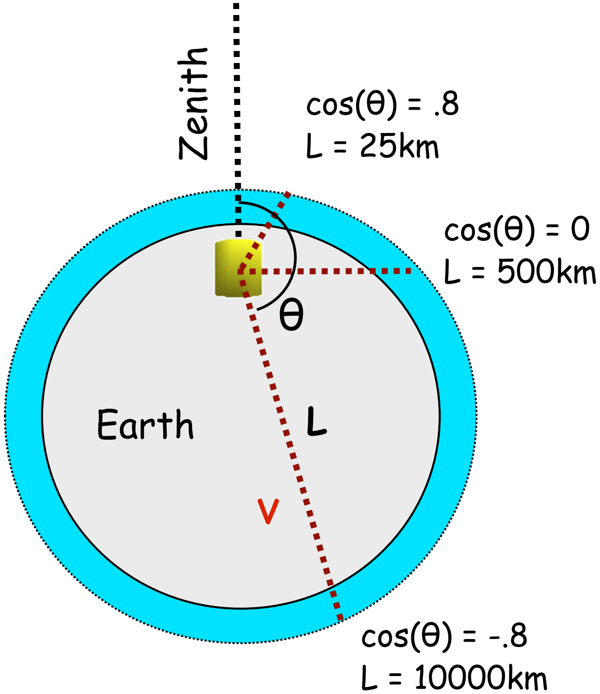
- Proton Decay
- Astrophysical neutrinos
  - GRBs
  - Solar Flares
  - AGNs
  - Etc
- Indirect dark matter

Must understand as a background!

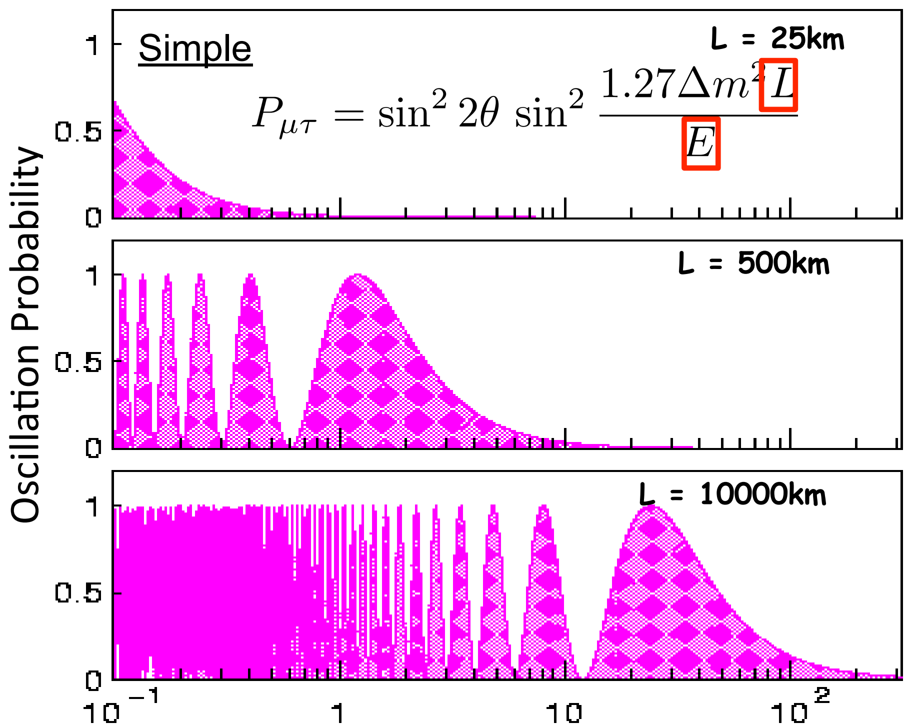


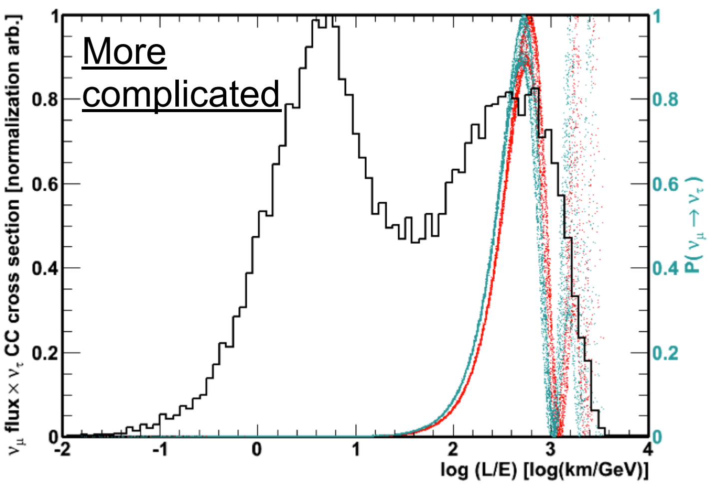
Atmospheric Neutrino Oscillations

Spans huge **path-length** range: **10 – 10,000 km**
Spans enormous **energy** range: **~100 MeV – 1 PeV**
Mixed **neutrino** and **anti-neutrino** and **Numu** and **nue**
But: direction not known and threshold for production

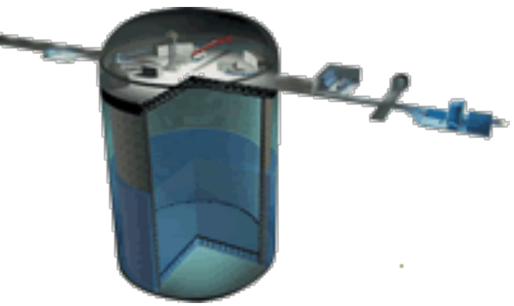
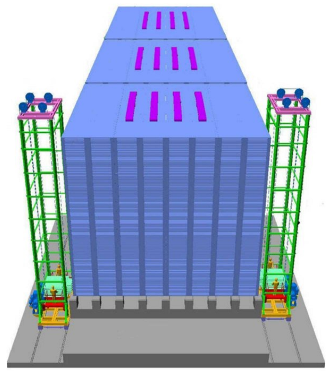
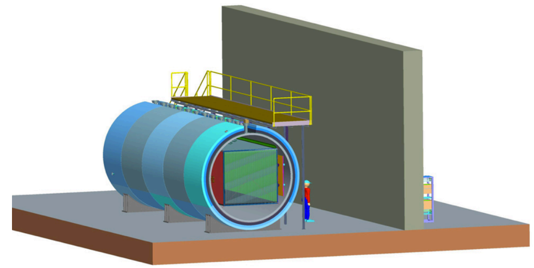
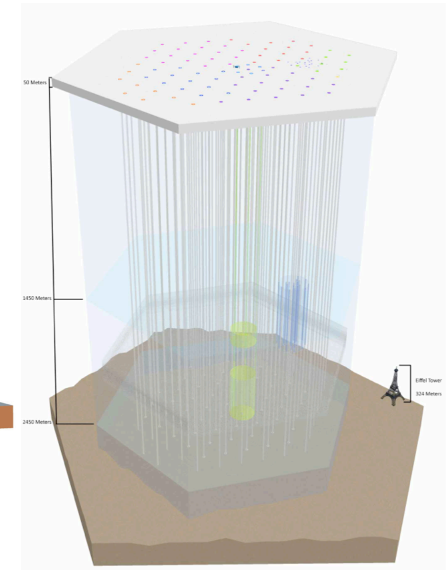


Δm^2 = .003 eV^2 sin^2(2Θ) = 1.0





Types of Detectors

Water Cherenkov

- Super-K -> Hyper-K
- Cheap / Well understood
- Huge Mass
- Has Cherenkov threshold

Iron Calorimeter:

- Soudan -> MINOS -> ICAL
- Charge separation
- Good tracking
- High threshold
- Good for muons/less for electrons

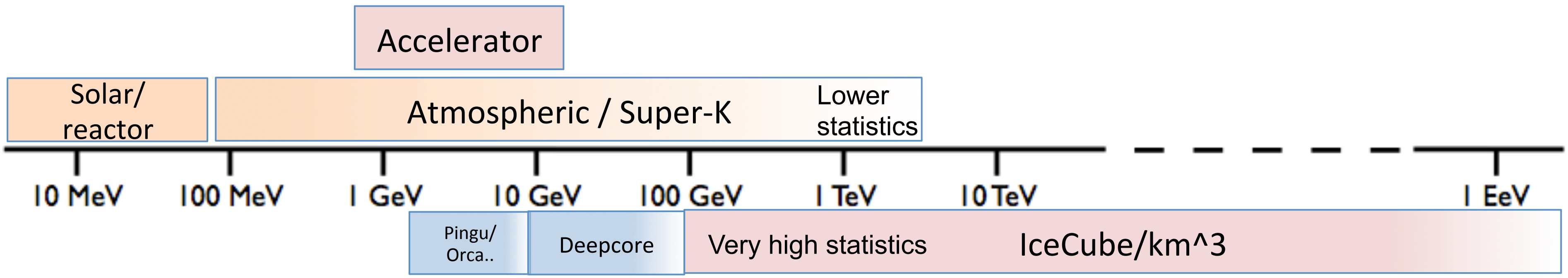
Liquid Argon

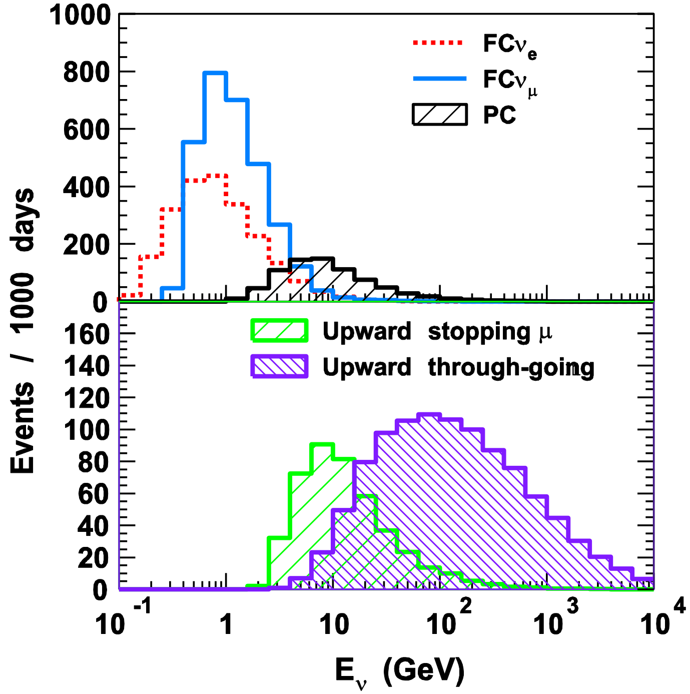
- Icarus ->Microboone ->Glacier/LBNE
- Electronic bubble chamber
- Resolution/BG rejection excellent
- Can see low energy particles
- Scaling/cost not yet proven

Water/Ice Telescopes:

- Enormous mass
- Can contain very high energy events
- Challenging reconstruction/systematics

Event types and neutrino energy



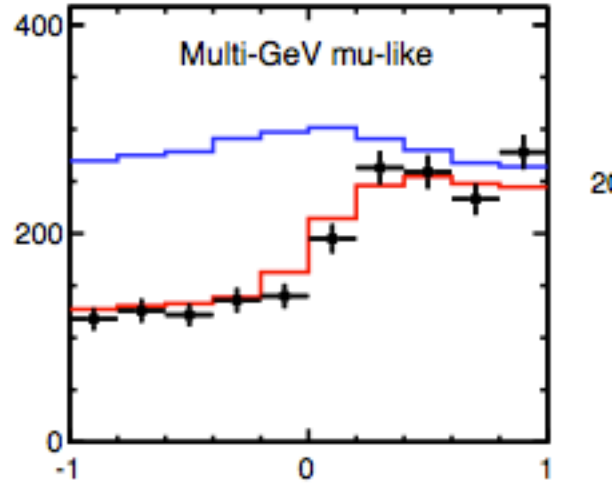


By pushing down the thresholds of the ice/ocean detectors we might greatly increase the statistics in interesting oscillation regions.

An example of using data in a fit

Multi-GeV Muon - Like

Data is put into sub-samples that maximizes the various oscillation effects.
Note: only a projection also binned in momentum.



Angle wrt/zenith

Includes variables related to:

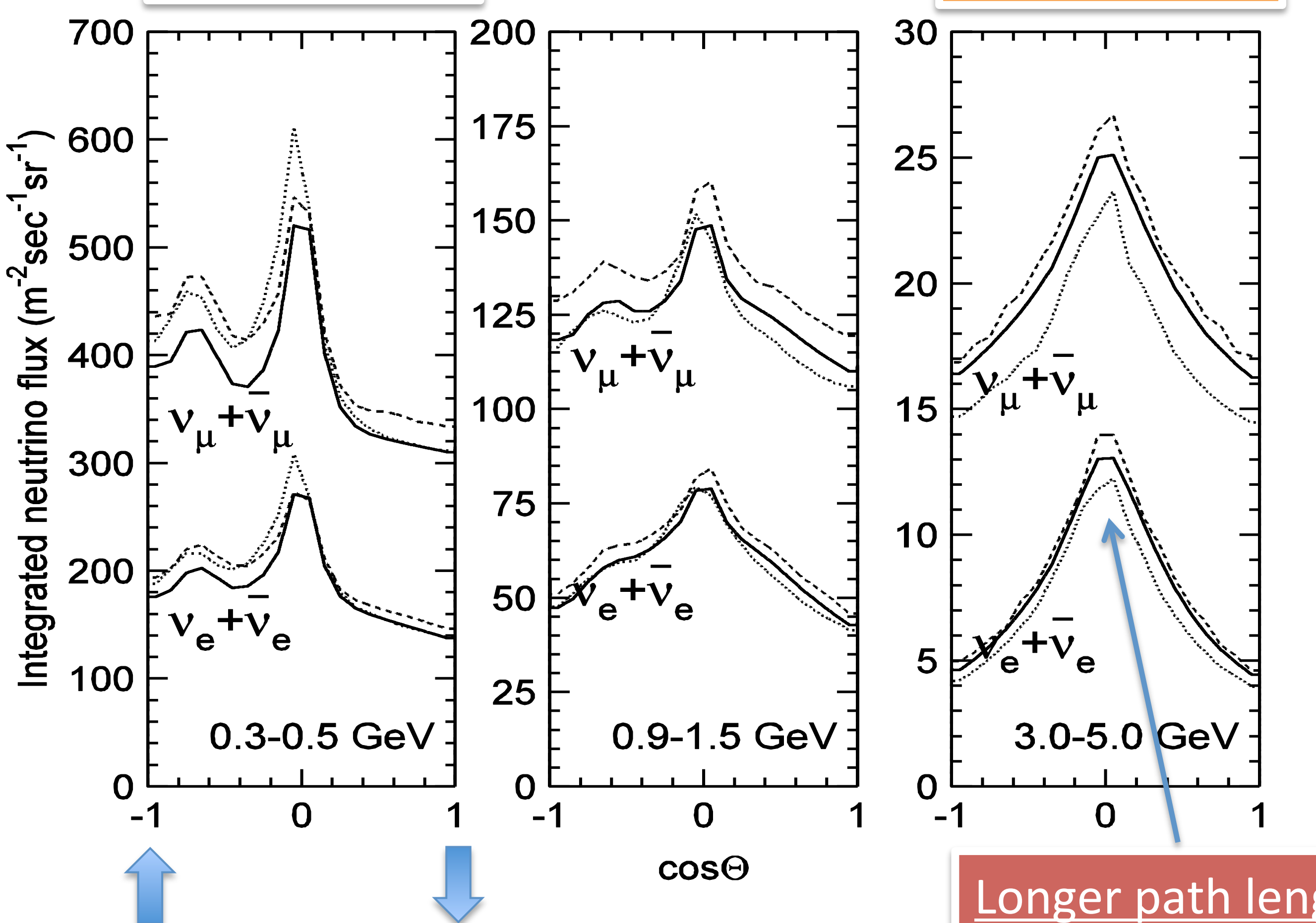
- L (direction)
- E (Energy)
- ν type (PID)

Uncertainties in the predictions and resolution effects can limit the ability to extract precision physics.

Flux uncertainties

Lower Energy

Higher Energy



Measure primary cosmic ray flux then:

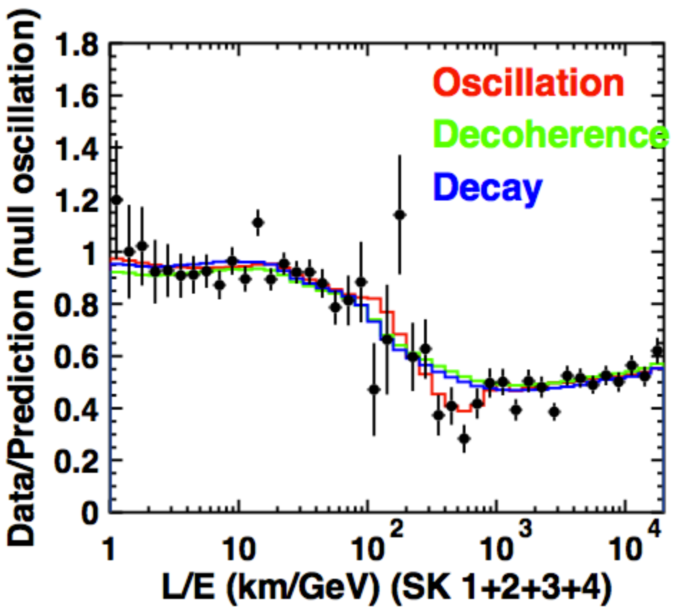
- Model interactions
- Model pi/K decay
- Geomagnetic fields….

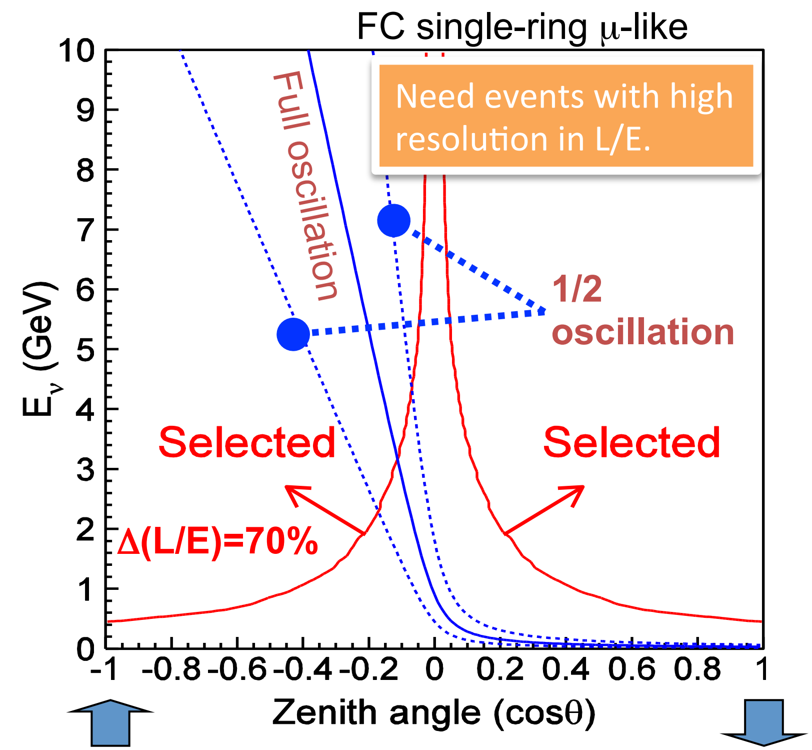
At high energy the up/down ratio is near 1 and known to 1% or better.

In general ratios in flux and flavor are much better known

Longer path length through low density atmosphere

Need to well measure L and E





For L:

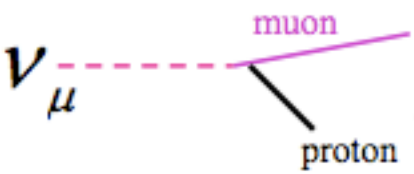
Lepton doesn't follow neutrino well at low energies. Unless you can see the proton (Maybe in LAr) you must use the lepton direction itself.

For L:

Near the horizon tiny mistakes in angle correspond to large differences in L. Also there is a distribution of production heights in the atmosphere.

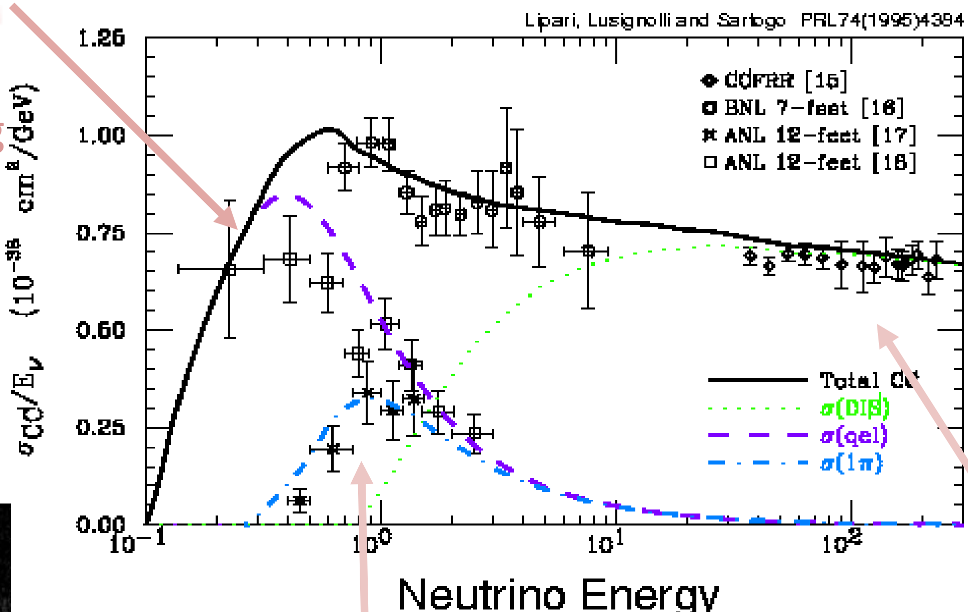
Neutrino interactions: more uncertainties

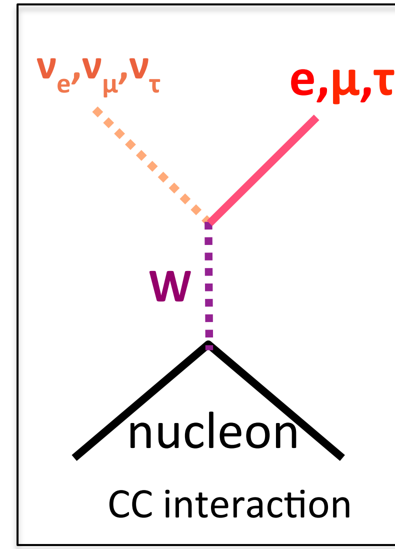
Use external measurements and regions with no oscillation

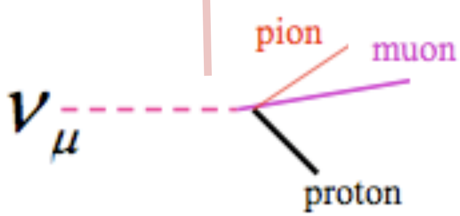


Quasi-Elastic Scattering

(E <~ GeV)

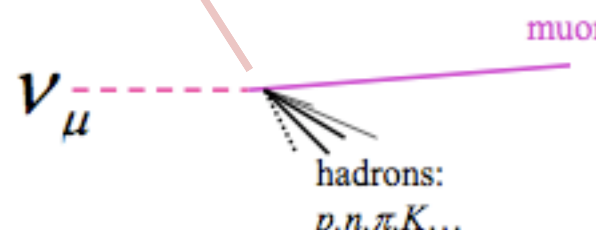






Single Pion Production

E ~ GeV



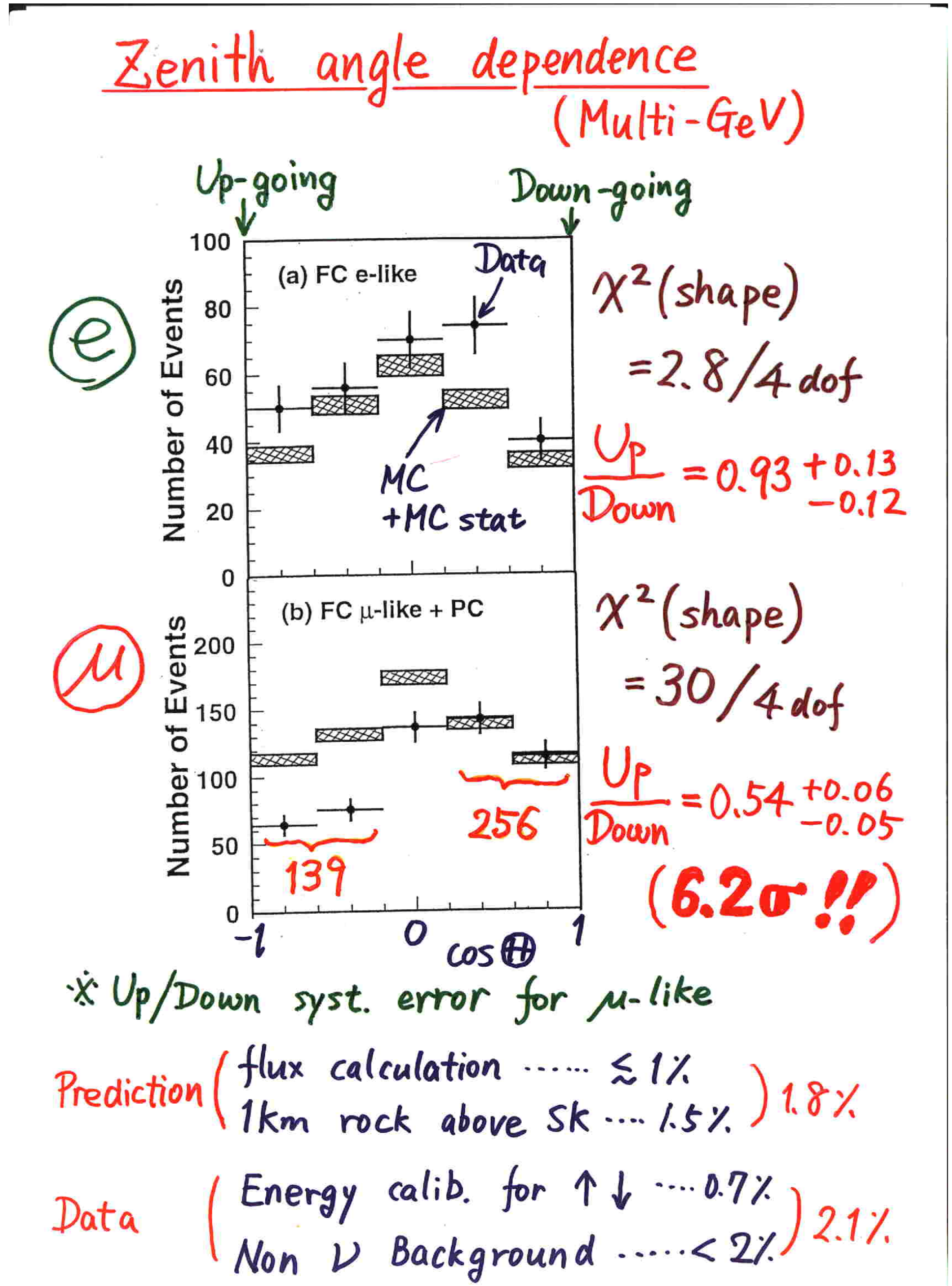
Multi-Pion Production +

Deep inelastic scattering

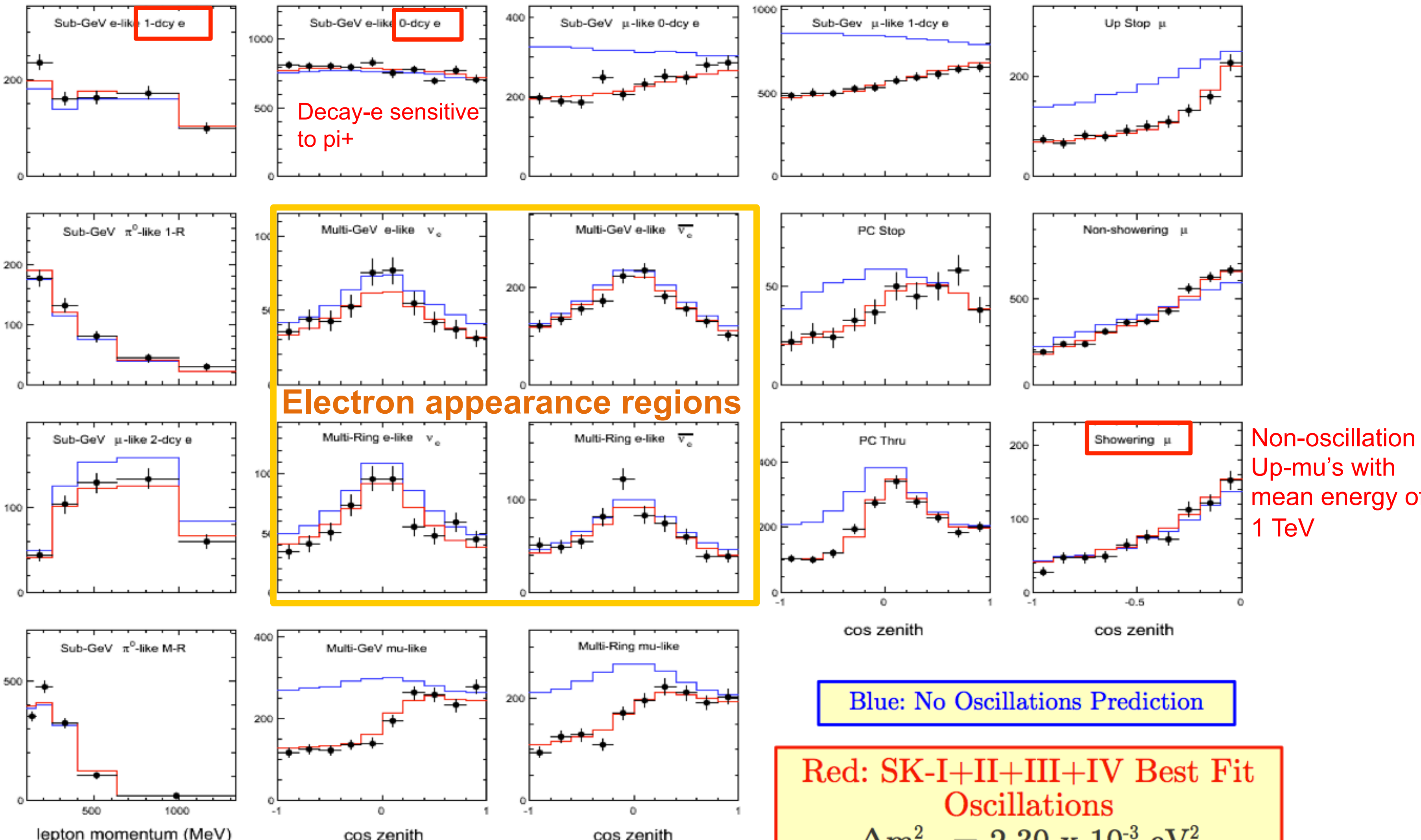
E > many GeV

Analysis Techniques

T. Kajita - Neutrino 98
"*The announcement of the discovery of neutrino oscillations*"



What does that data look like today?



Blue: No Oscillations Prediction

Red: SK-I+II+III+IV Best Fit Oscillations

$$\Delta m^2_{23} = 2.30 \times 10^{-3}\ eV^2$$

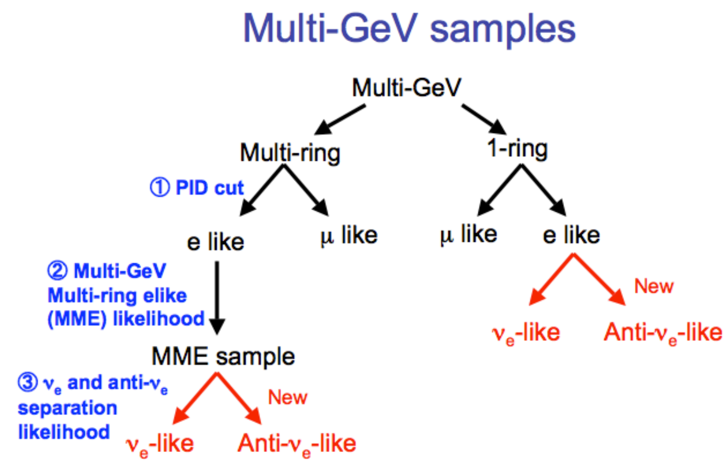
$$\sin^2 2\theta_{23} = 0.99$$

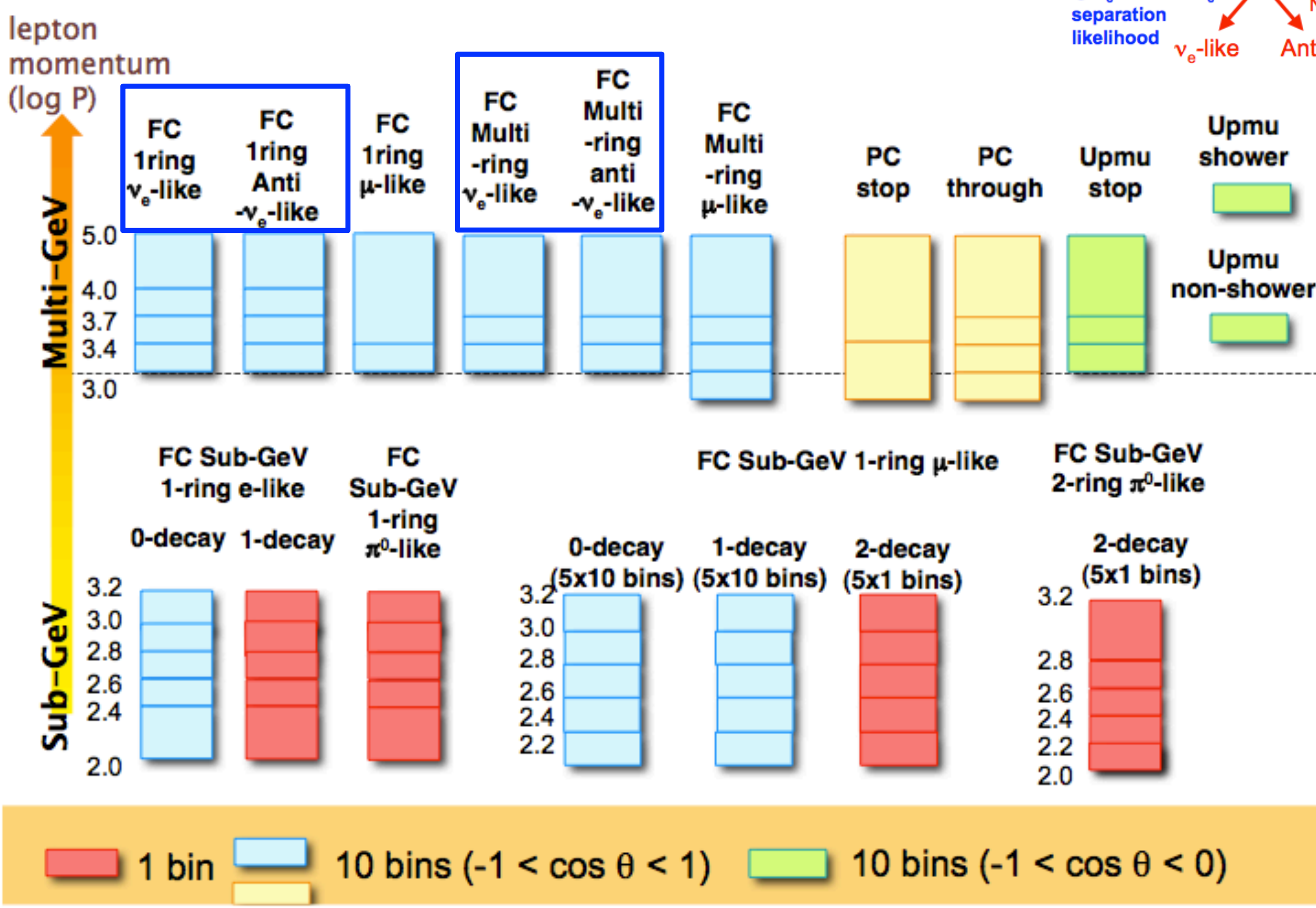
Categories designed for separating signal and control regions.

Now: more categories

Try to separate neutrino and anti-neutrino and isolate electron appearance regions

480 bins in angle and momentum



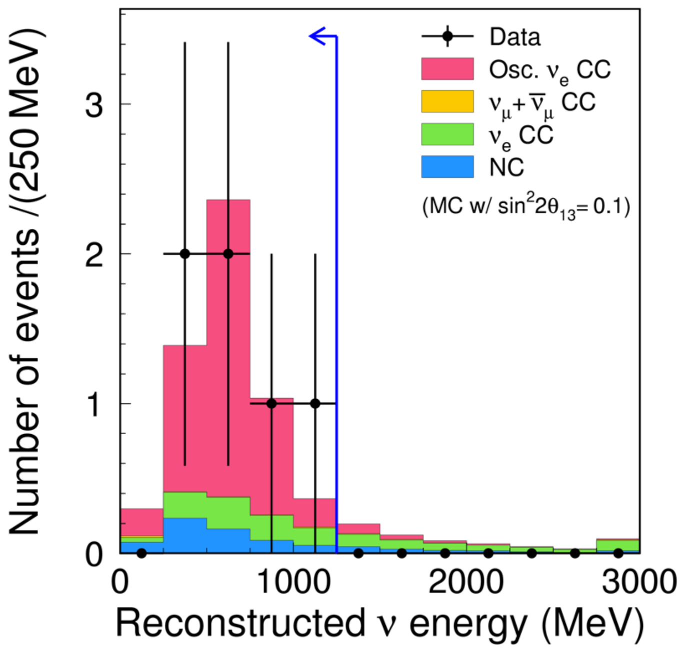


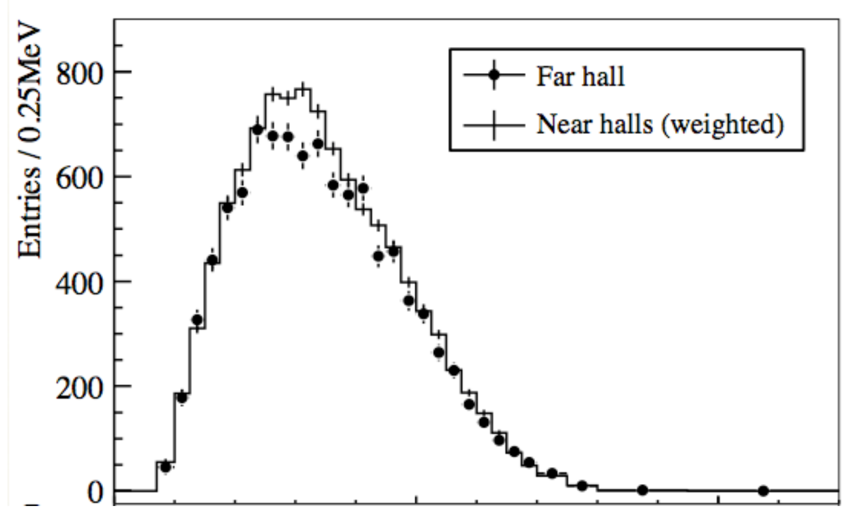
What systematics are important for the expectations? (an example from an oscillation analysis is shown here.)

- Flux
- Interaction
- Reconstruction
- Others
- Many (33-59) evaluated separately for each run periods.

1. absolute normalization (<1GeV)
2. absolute normalization (>1GeV)
3. $(\nu_\mu+\nu_\mu)/(\nu_e+\nu_e)$ $(E_\nu<1\text{GeV})$
4. $(\nu_\mu+\nu_\mu)/(\nu_e+\nu_e)$ $(1<E_\nu<10\text{GeV})$
5. $(\nu_\mu+\nu_\mu)/(\nu_e+\nu_e)$ $(E_\nu>10\text{GeV})$
6. ν_e/ν_e $(E_\nu<1\text{GeV})$
7. ν_e/ν_e $(1<E_\nu<10\text{GeV})$
8. ν_e/ν_e $(E_\nu>10\text{GeV})$
9. ν_μ/ν_μ $(E_\nu<1\text{GeV})$
10. ν_μ/ν_μ $(1<E_\nu<10\text{GeV})$
11. ν_μ/ν_μ $(E_\nu>10\text{GeV})$
12. up/down
13. horizontal/vertical
14. K/π
15. L_ν (production height)
16. sample-by-sample FC Multi-GeV
17. sample-by-sample PC + UPstop μ
18. M_A in CCQE, single-π
19. CCQE (model dependence)
20. CCQE (anti-ν/ν)
21. CCQE (μ/e)
22. single-π (cross section)
23. single-π (anti-ν/ν)
24. single-π ($\pi 0/\pi{+-}$)
25. DIS(model dependence)
26. DIS (cross section)
27. coherent π (cross section)
28. NC/CC
29. nuclear effect in ^{16}O
30. nuclear effect (pion spectrum)
31. $CC\nu_\tau$ interaction cross section
32. hadron sim. (NC contami. in FCμ)
33. Solar activity
34. FC reduction
35. PC reduction
36. UPμ reduction
37. FC/PC separation
38. Normalization of PC stop/thru(top)
39. Normalization of PC stop/thru(barrel)
40. Normalization of PC stop/thru(bottom)
41. non-ν BG (flasher)
42. non-ν BG (cosmic-ray μ)
43. BG subtraction of Upthru (shower) μ
44. BG subtraction of Upthru (non-shower) μ
45. BG subtraction of UPstop μ
46. UPμ stop/thru separation
47. UPμ non-shower/shower separation
48. ring separation
49. PID for single-ring
50. PID for multi-ring
51. energy calibration
52. energy cut for UPstop μ
53. up/down symmetry of energy calib.
54. non-ν_e BG in Multi-GeV 1-ring electron
55. non-ν_e BG in Multi-GeV m-ring electron
56. Likelihood of Multi-GeV m-ring e-like
57. Efficiency for 2-ring π^0
58. number of event for 1-ring π^0
59. Decay electron tagging
60. Fiducial volume
61. Up thru μ length cut
62. Decay electron tagging from pi+
63. Matter effect
64. Low-q2 for DIS W<2GeV
65. Low-q2 for DIS W>2GeV

Oscillations in the three-flavor era

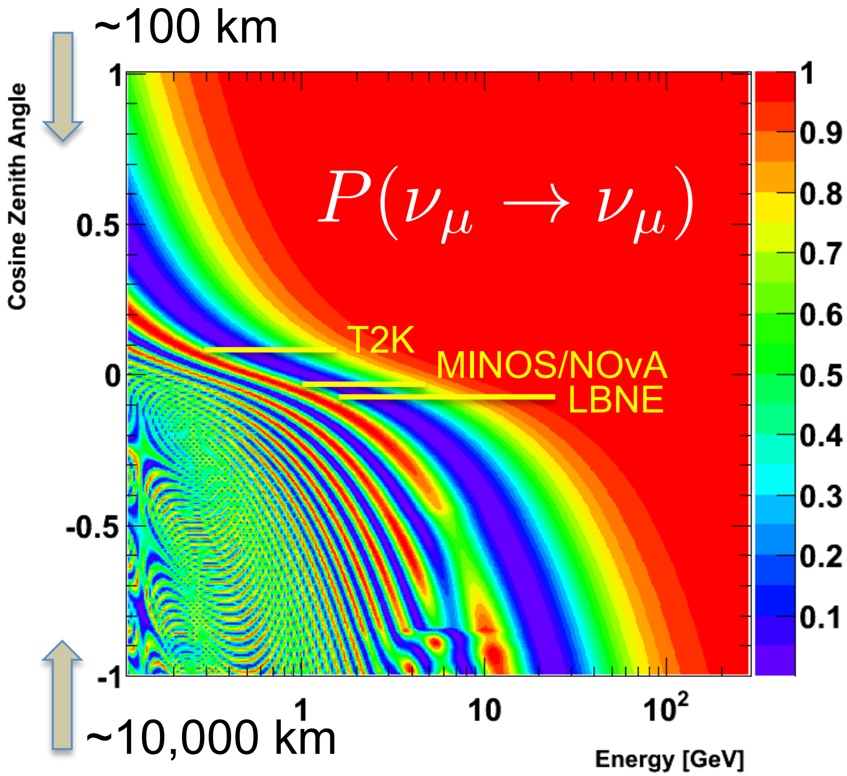




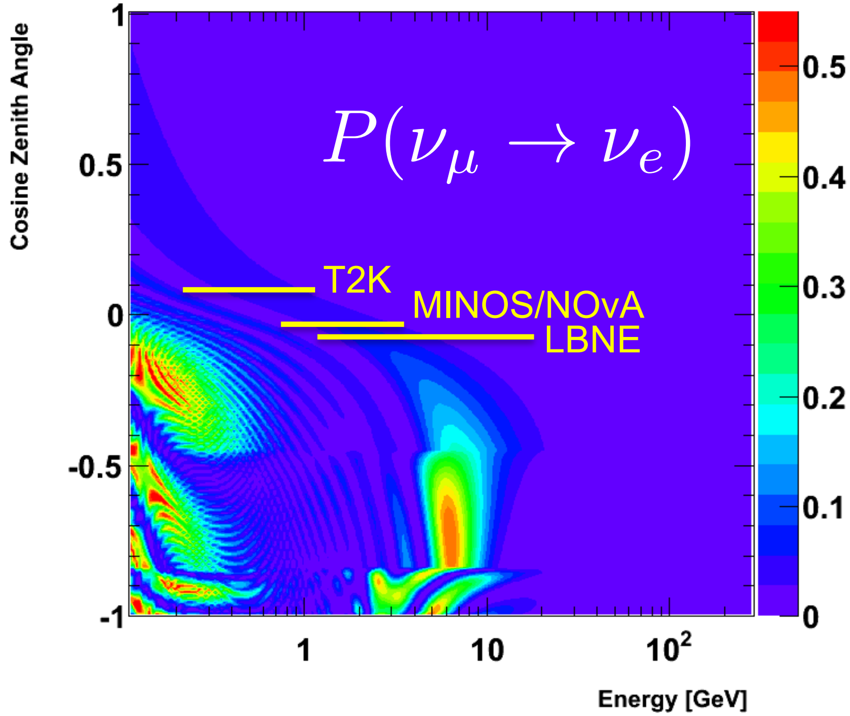
This year we learned the value of θ_{13}. How does that change things?

Before we were looking for θ_{13} and that uncertainty made it difficult to look for other effects. Now we can use this knowledge to look for the other unknowns.

Oscillograms: a very useful tool



Both modes are useful.



Plot equal probabilities of oscillation for energies and angles.

Smirnov el al..

http://arxiv.org/abs/hep-ph/0612285
http://arxiv.org/abs/0804.1466

Using the earth to untangle oscillations

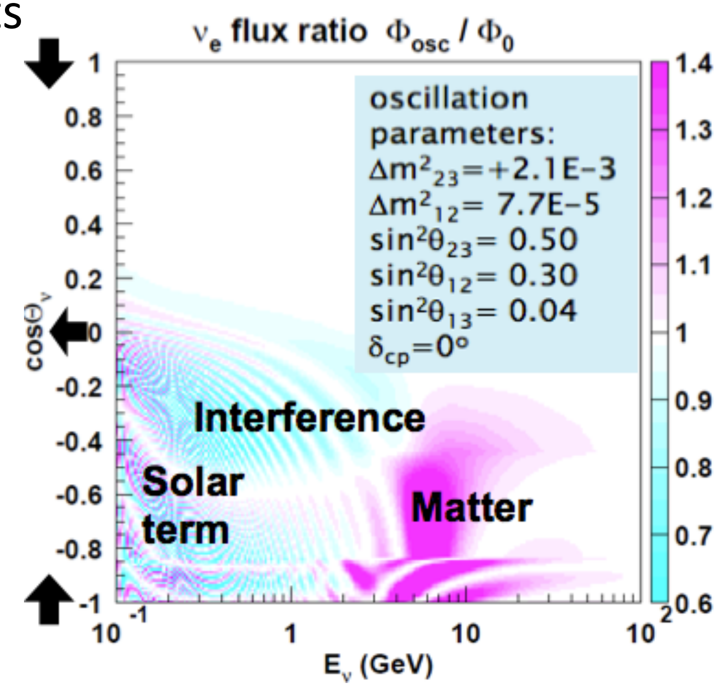
With big detectors and many years of running we have huge statistics. So we can look for *sub-leading* effects. We can concentrate on small modifications to ν_e

- Mass hierarchy: matter effect causes enhancement in high energy upward going ν_e going through the core.
- Octant of oscillations: Solar term causes low energy enhancement of ν_e.
- δ_{CP}: Interference between these two effects

Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \leftarrow \text{Matter effect}$$
$$+\Delta_2(\Delta m_{12}^2) \leftarrow \text{Solar term}$$
$$+\Delta_3(\theta_{13}, \Delta m_{12}^2, \delta) \leftarrow \text{Interference}$$

(The ν_μ flux difference is also expected.)

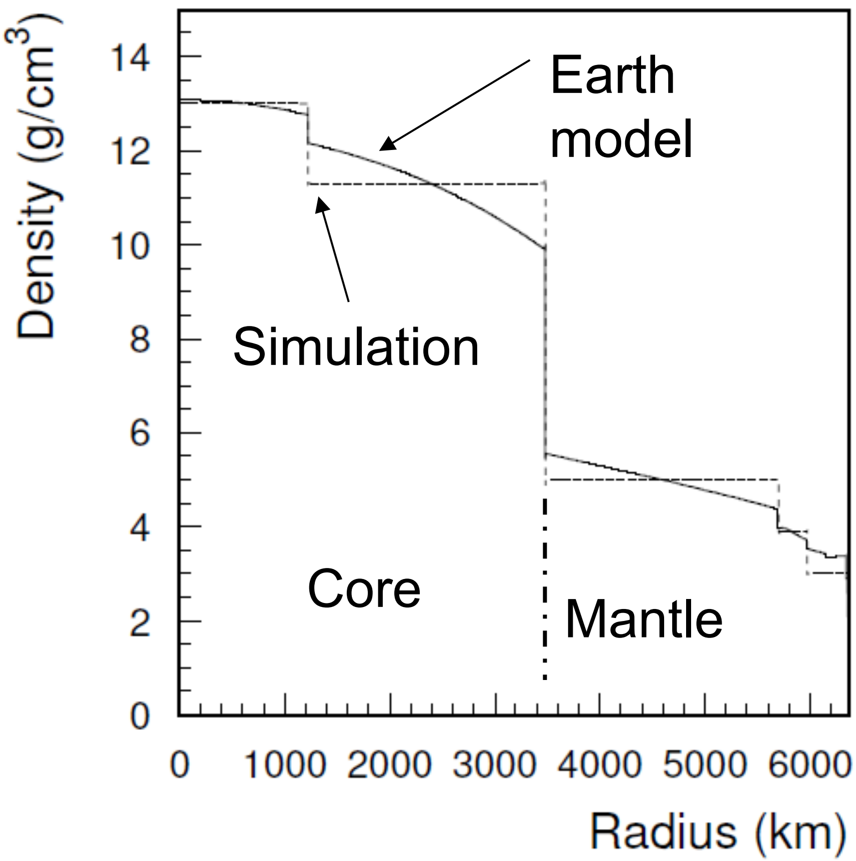


The Effect of θ_{13} (up-going electrons)

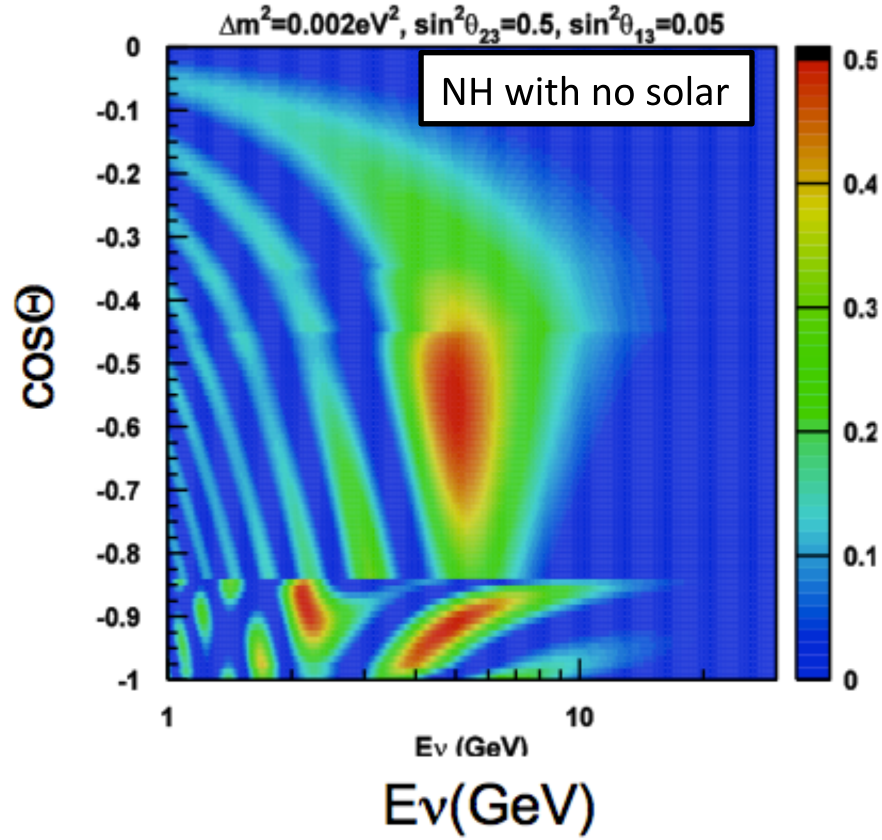
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E_\nu} + \textit{sub-leading terms}$$

$$\sin^2 2\theta^m_{13} = \frac{\sin^2 2\theta_{13}}{(A/\Delta m^2_{23} - \cos 2\theta_{13})^2 + \sin^2 2\theta_{13}}$$

The "PREM" Model



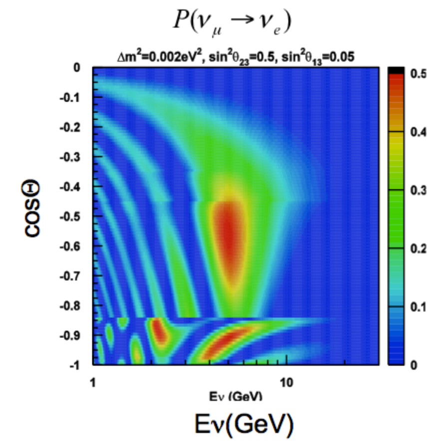
$$P(\nu_\mu \rightarrow \nu_e)$$



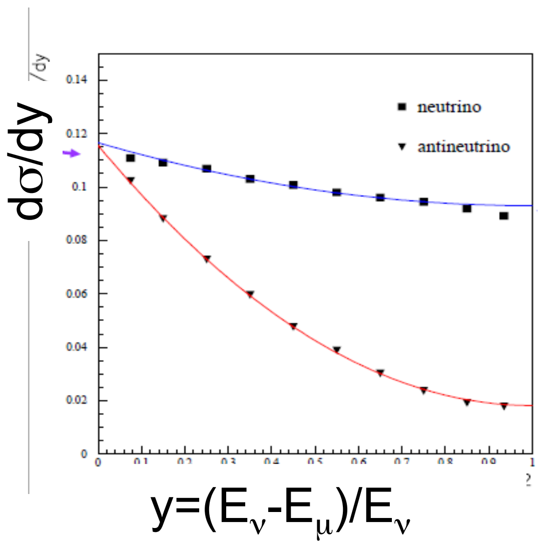
Mass Hierarchy?

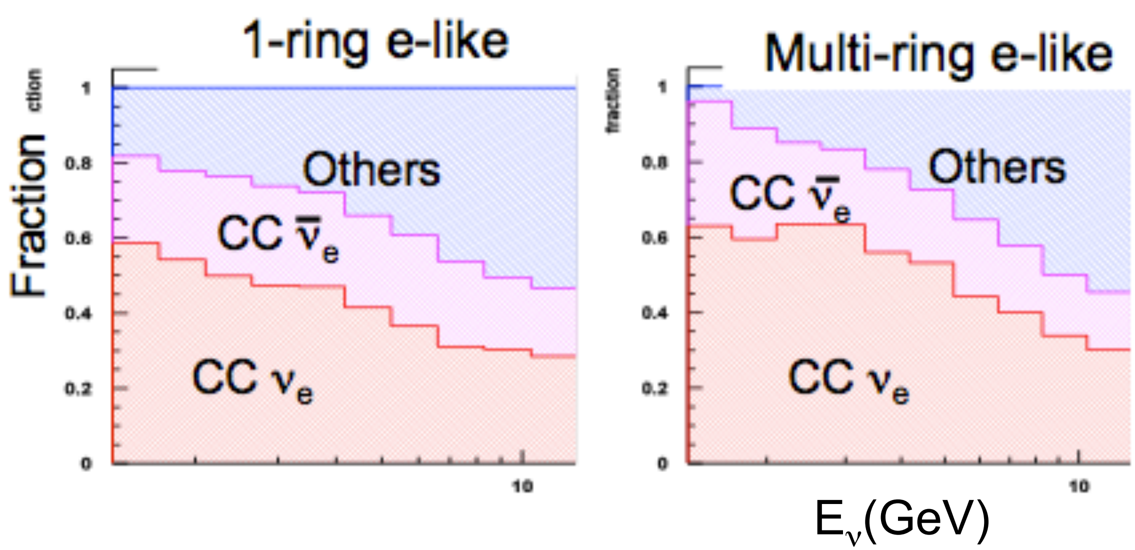
Normal: Resonance happens for neutrinos
Inverted: Resonance happens for anti-neutrinos

Cross-sections are also different for neutrino and anti-neutrinos



We can try to make samples that have different fractions of ν and anti-ν
Technique depends on detector



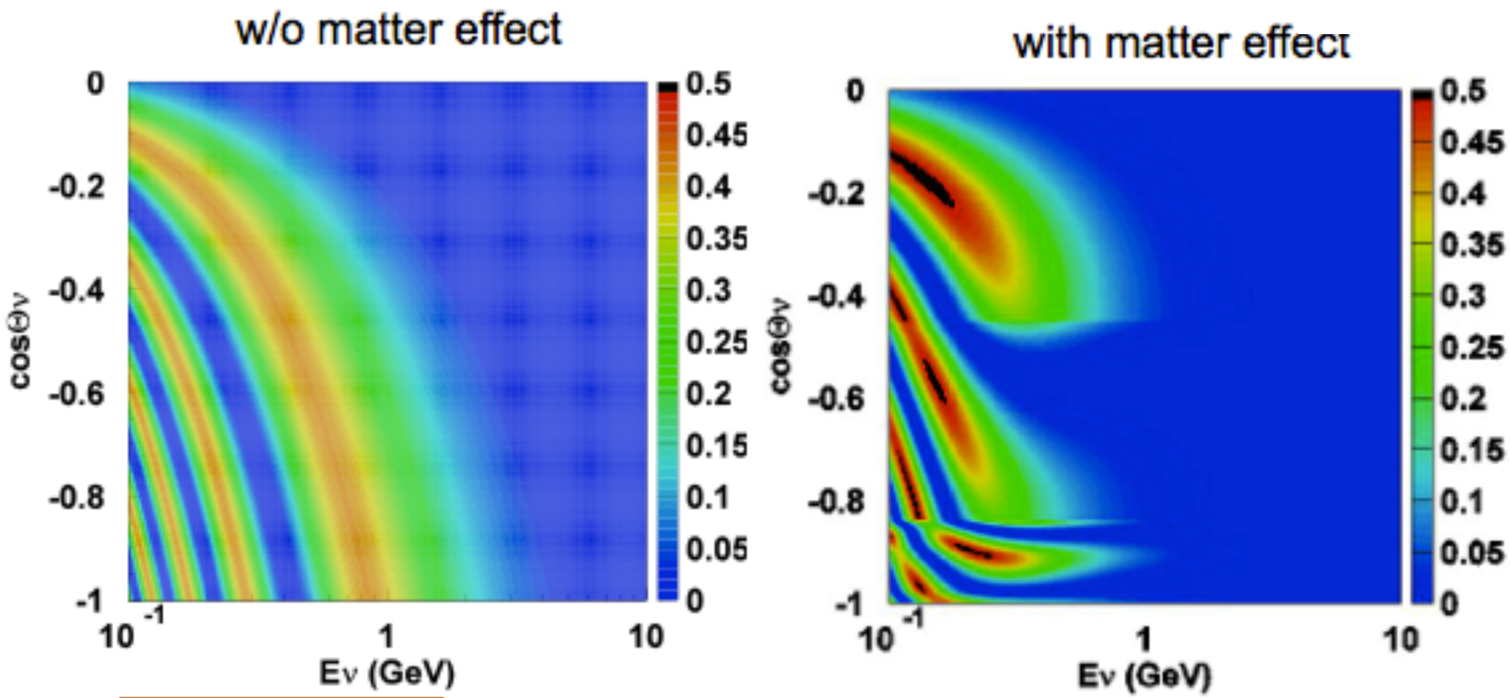


Only solar mixing effect

Peres & Smirnov NPB 680 (2004) 479

$s^2 2\theta_{12}=0.825$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$
$\sin^2\theta_{13}=0$

$$P(\nu_\mu \rightarrow \nu_e)$$



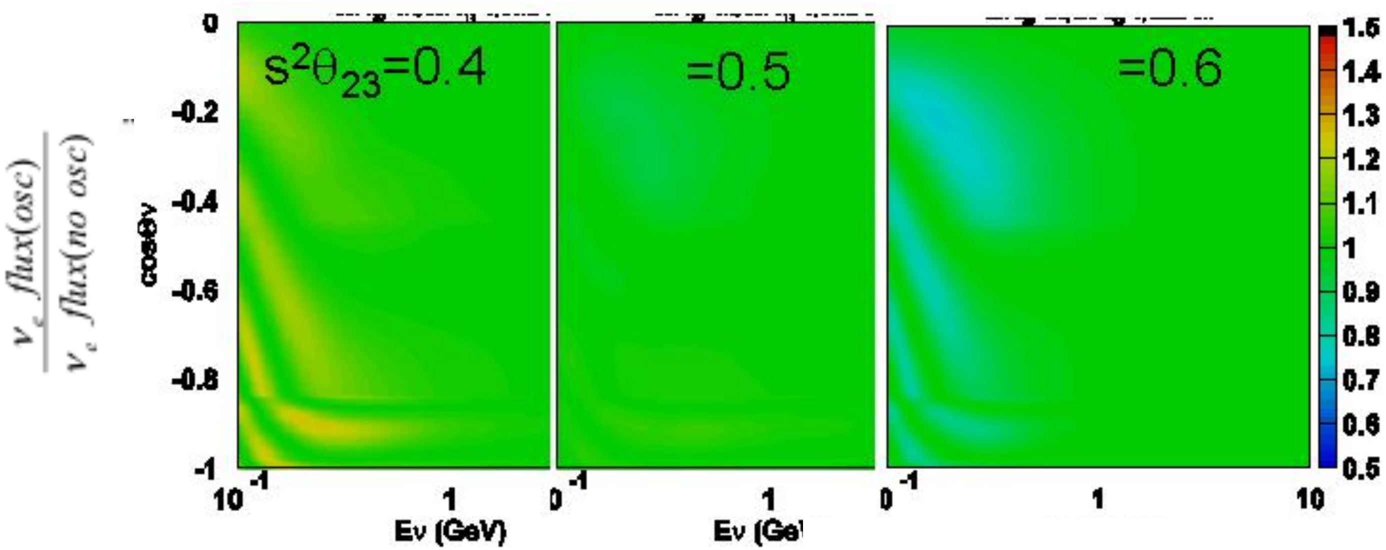
Note: Low Energy!

Solar term also depends on θ_{23}!

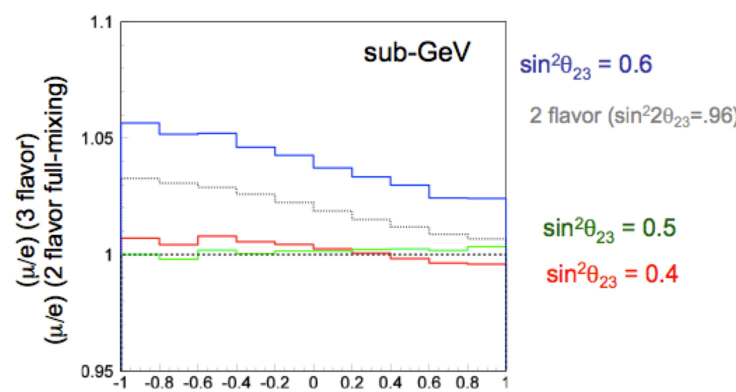
But ν_e also goes to ν_μ and ν_τ so a small effect

NOT

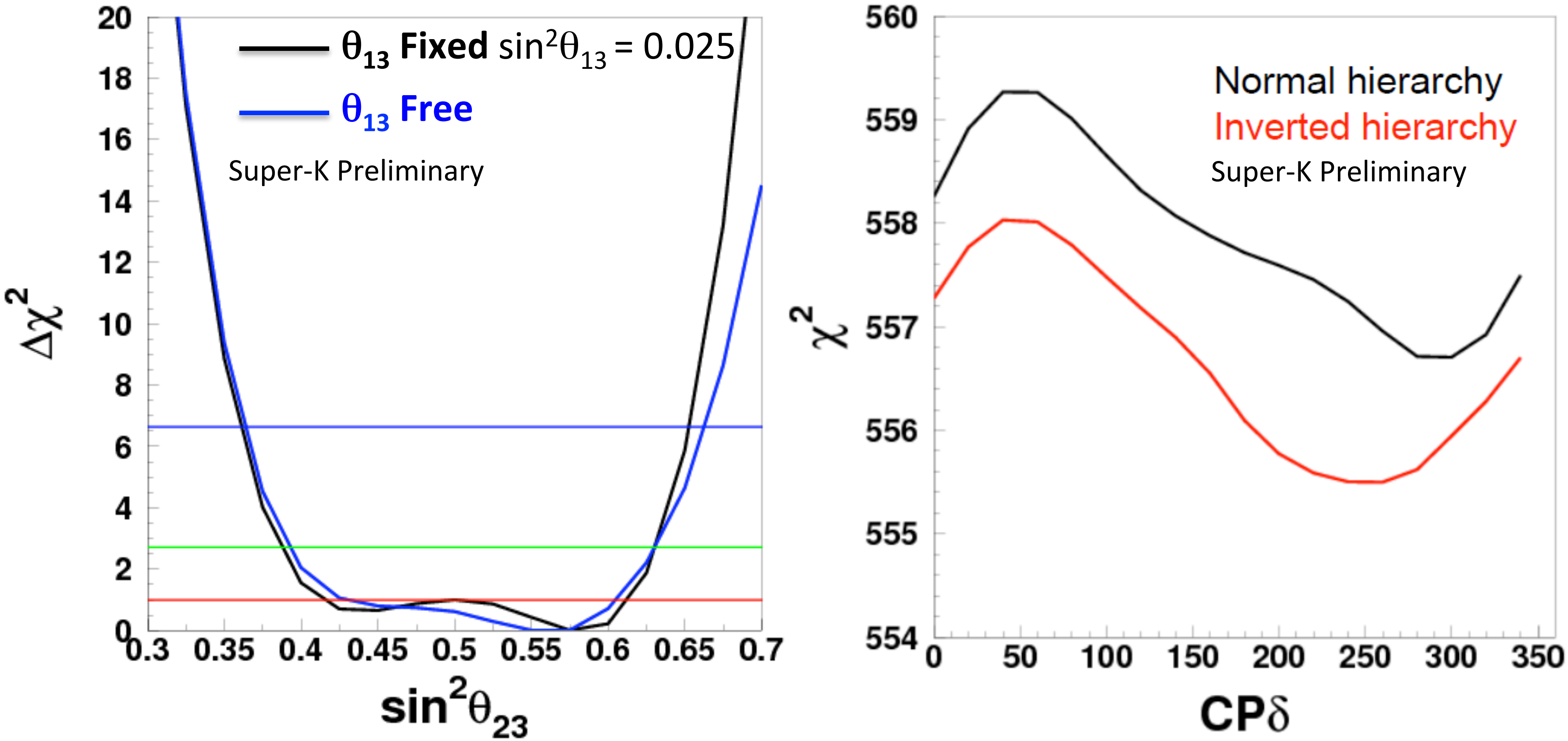
$2\theta_{23}$



Example in WC:
Need to control
Systematics!



Recent Super-K results



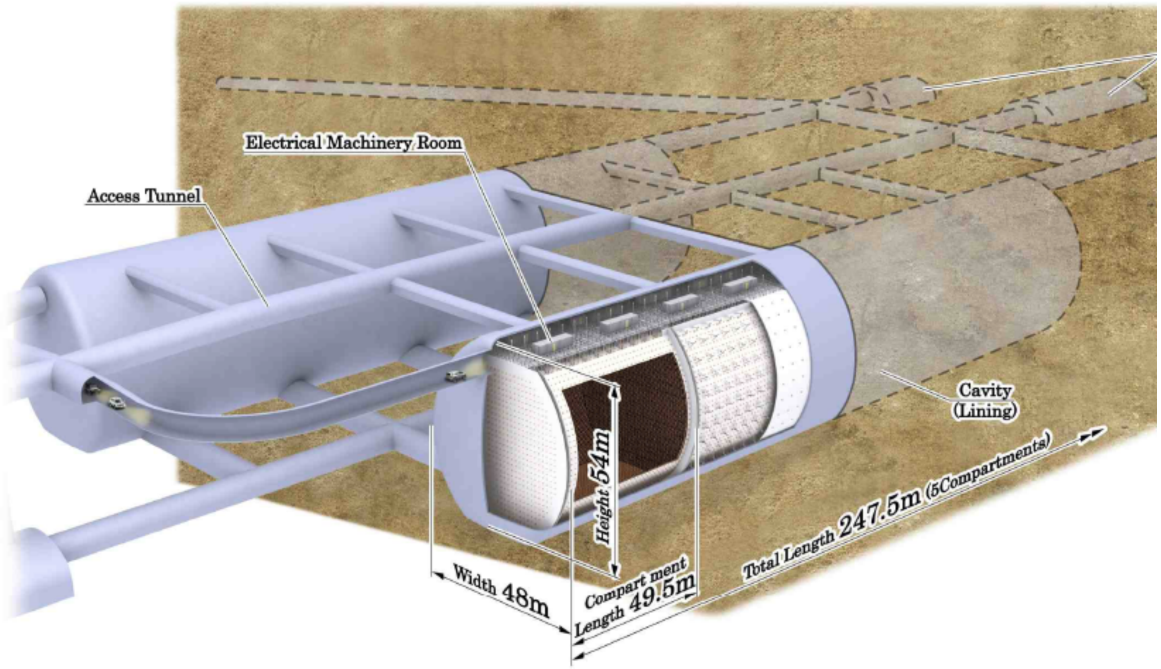
- Both free and constrained fits prefer 2nd octant
- 1.2σ preference for inverted hierarchy
  sensitivity is 0.9σ

} Not significant!

Future Prospects

http://arxiv.org/abs/1109.3262v1

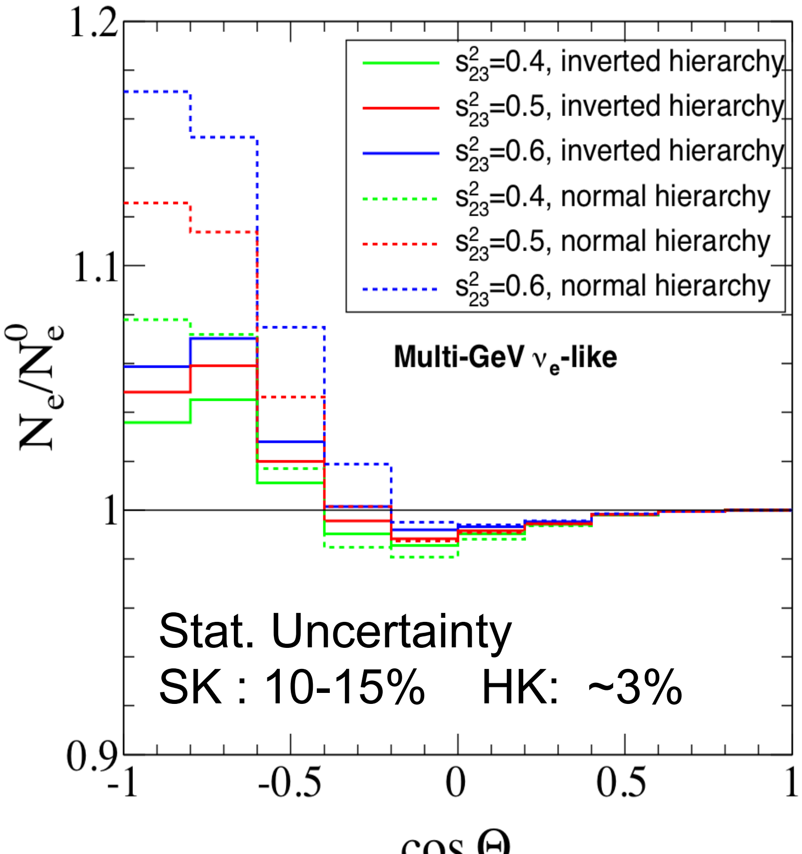
Hyper-Kamiokande

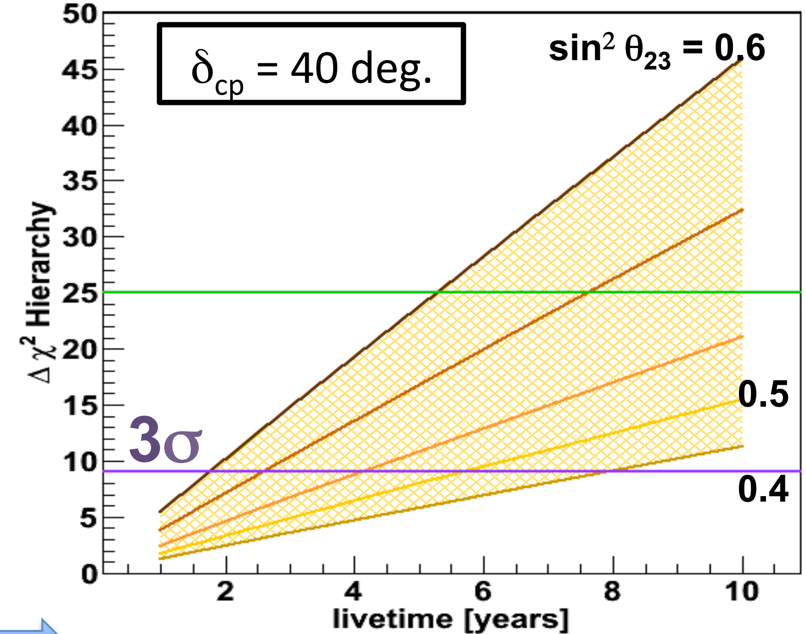


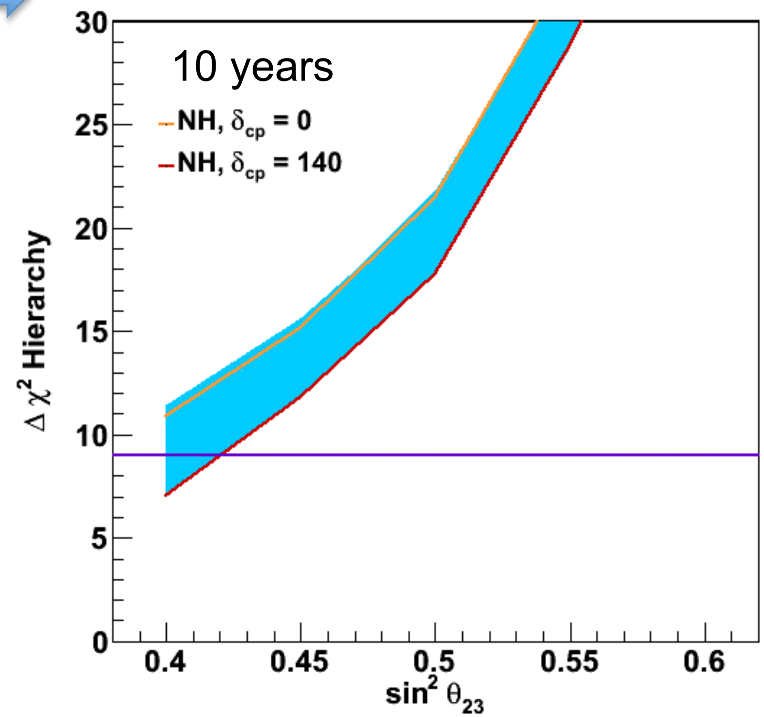
- 560 kton fiducial mass
- 99000 PMTs 20% coverage
- Outer veto detector

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

HK MH Sensitivity

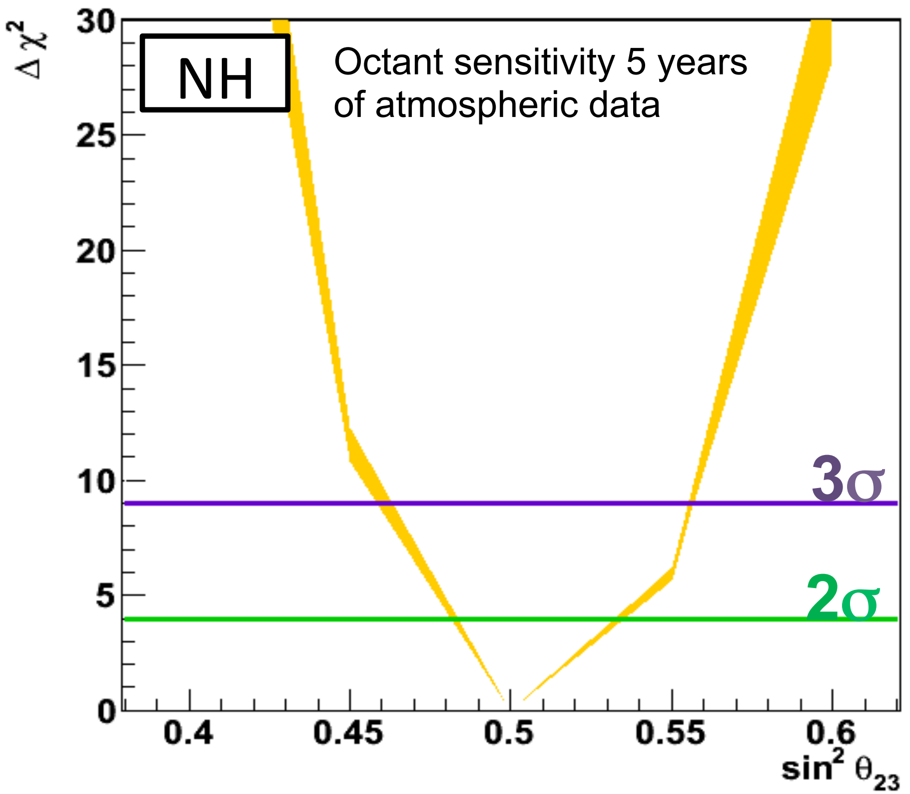


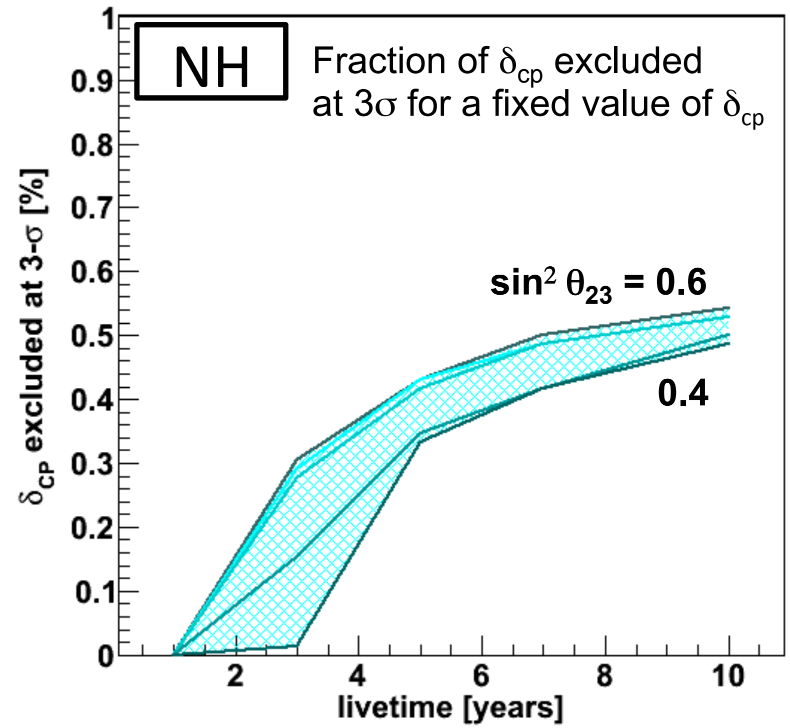




The sensitivity depends on θ_{23}, δ, and slightly on the MH itself.

Octant and δ_{cp} sensitivity

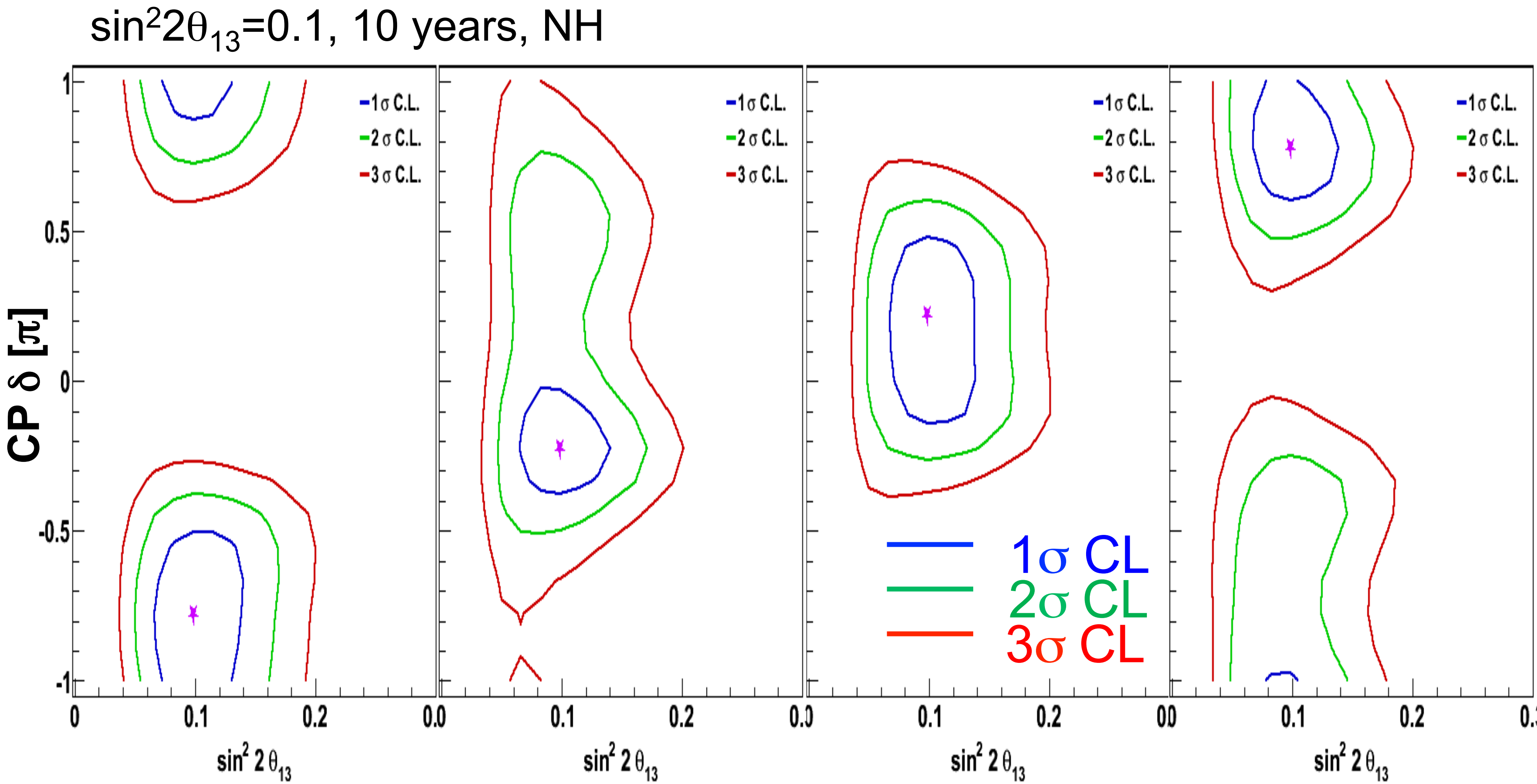




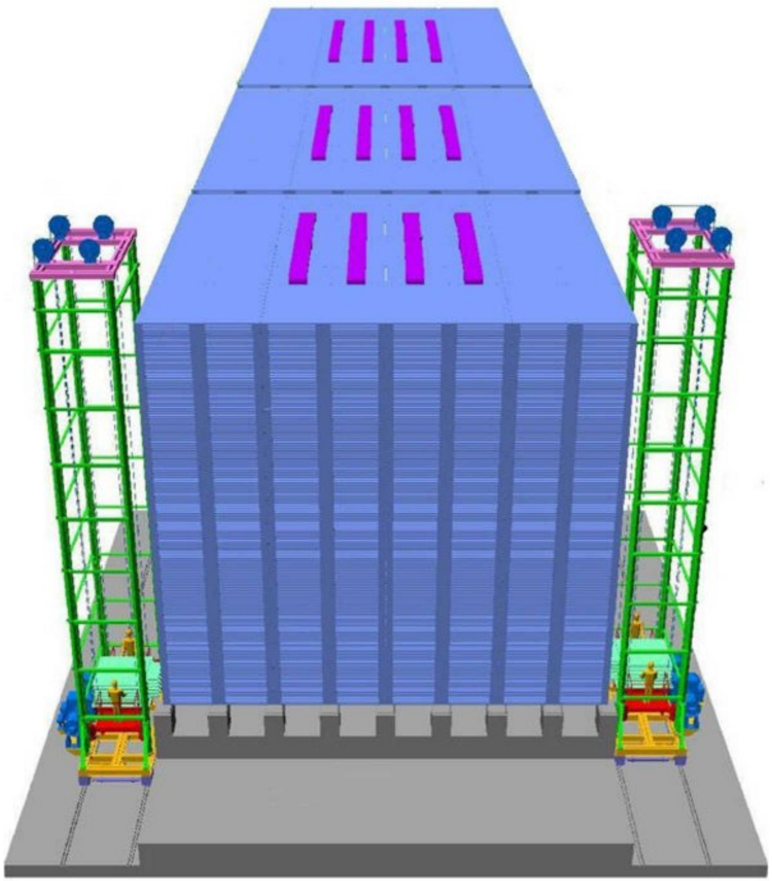
- Thickness of the band corresponds to the uncertainty from δ_{cp}
- Best value of δ_{cp} = 40 degrees
- Worst value of δ_{cp} = 140 (260) degrees, for 1st (2nd) octant

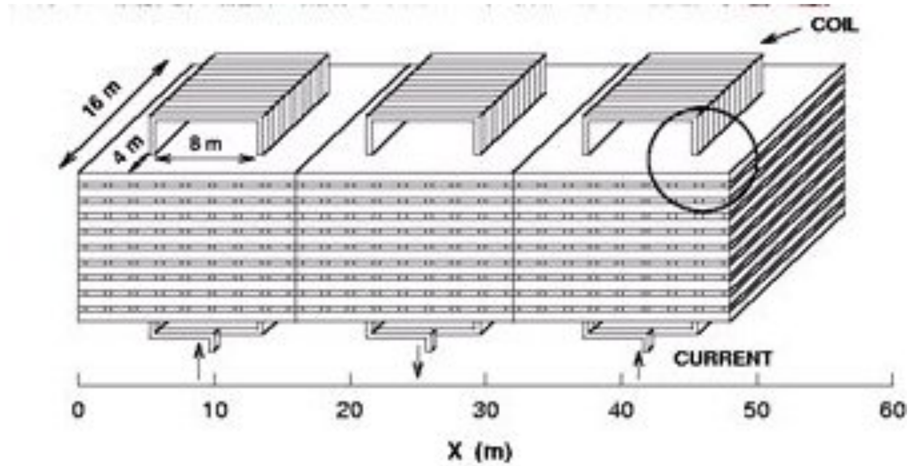
- With 1 year of data 2σ sensitivity to the hierarchy for all values of δ_{cp} and either hierarchy assumption.

HK sensitivity for CP δ and $\sin^2 2\theta_{13}$



INO@ICAL 50kton magnetized calorimeter

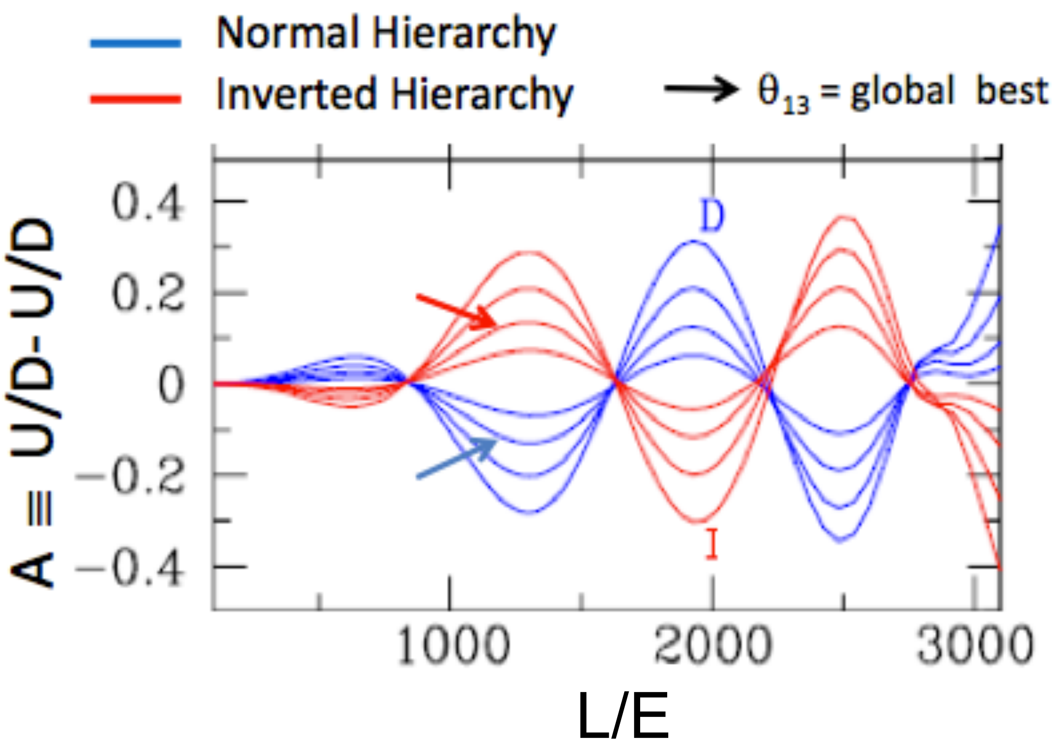




- Very good L/E resolution
- Charge separation

Note: this is using MUONS

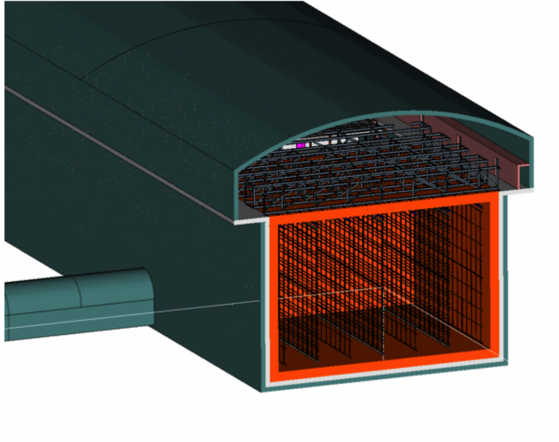
Mass Hierarchy in ICAL using μ

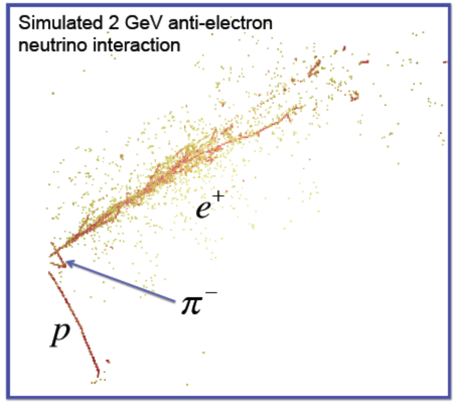


~3 sigma determination of the MH in ~ 10 years.

- Make use of asymmetric matter effects between ν_μ and $\bar{\nu}_\mu$ to discriminate hierarchy
- Sensitivity to hierarchy $> 2\sigma$ if $\sin^2 2\theta_{13} > 0.05$
- 1 Mton • yr exposure

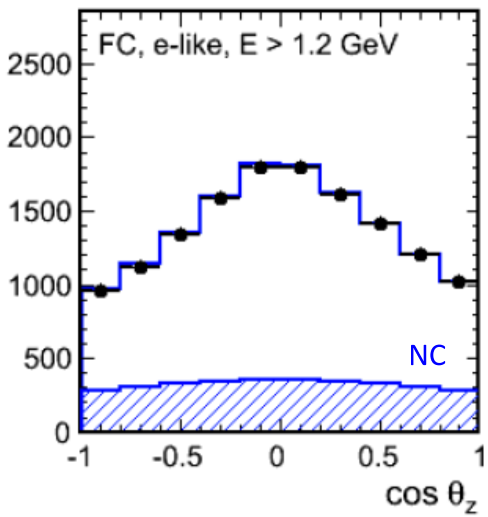
Liquid Argon (LBNE/Glacier/LBNO)

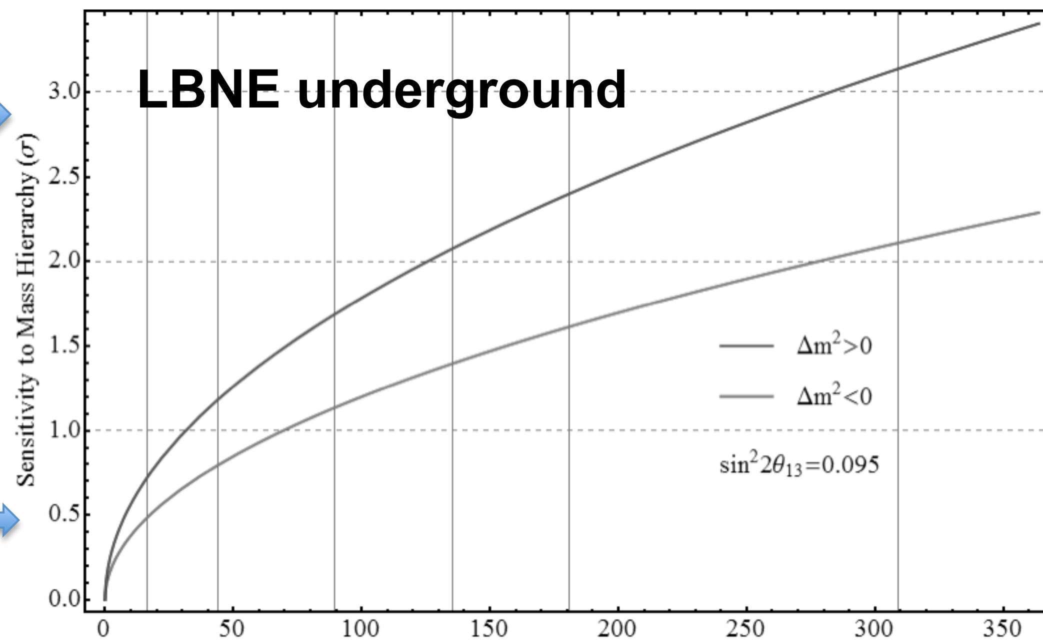




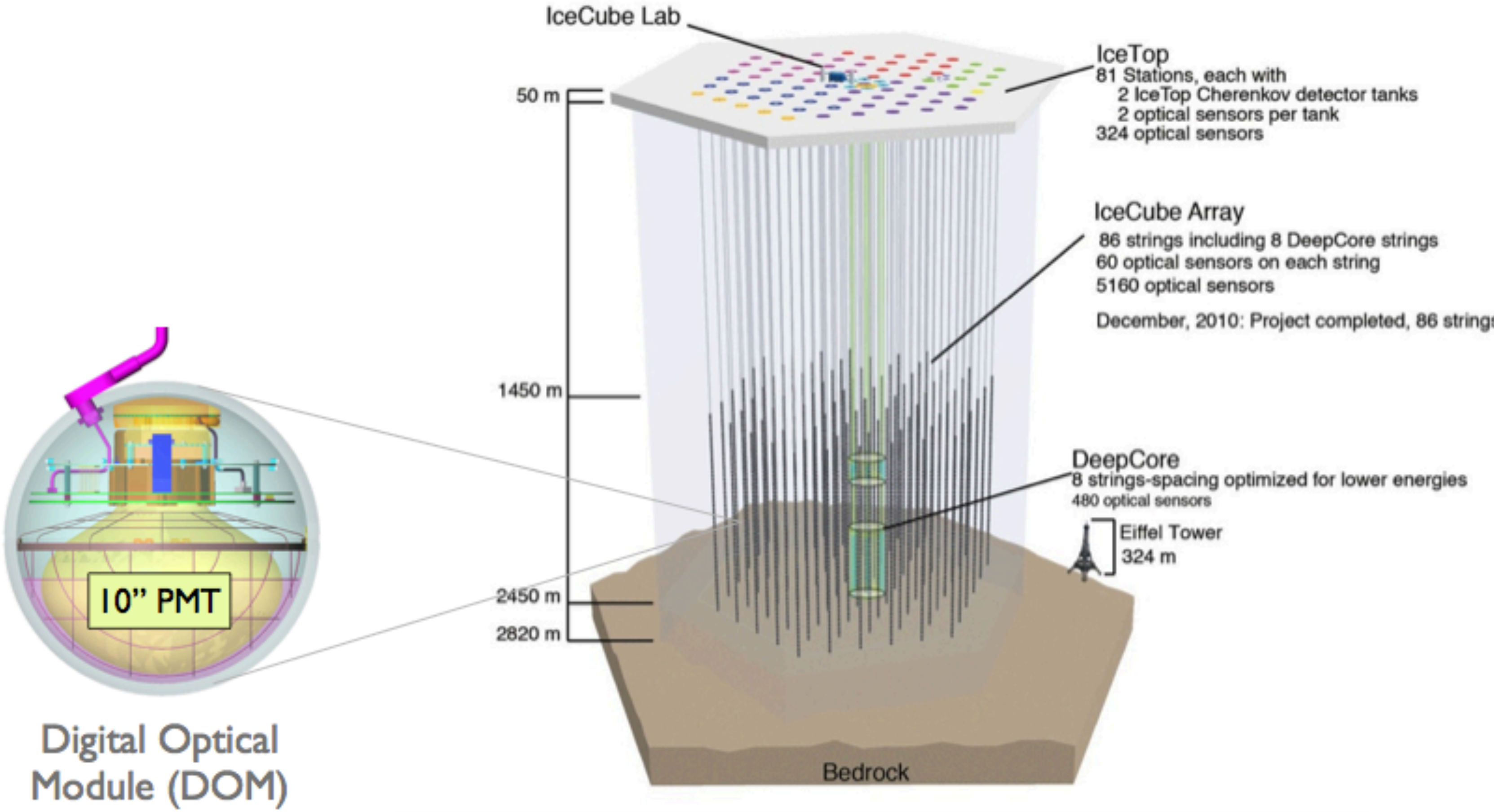
- High resolution:
- NC BG rejection
- Direction/energy (see all charged)
- ν/anti-ν handles
- Above are needed to compensate for modest mass
- Magnetize?

Example from LBNE using performance estimation.





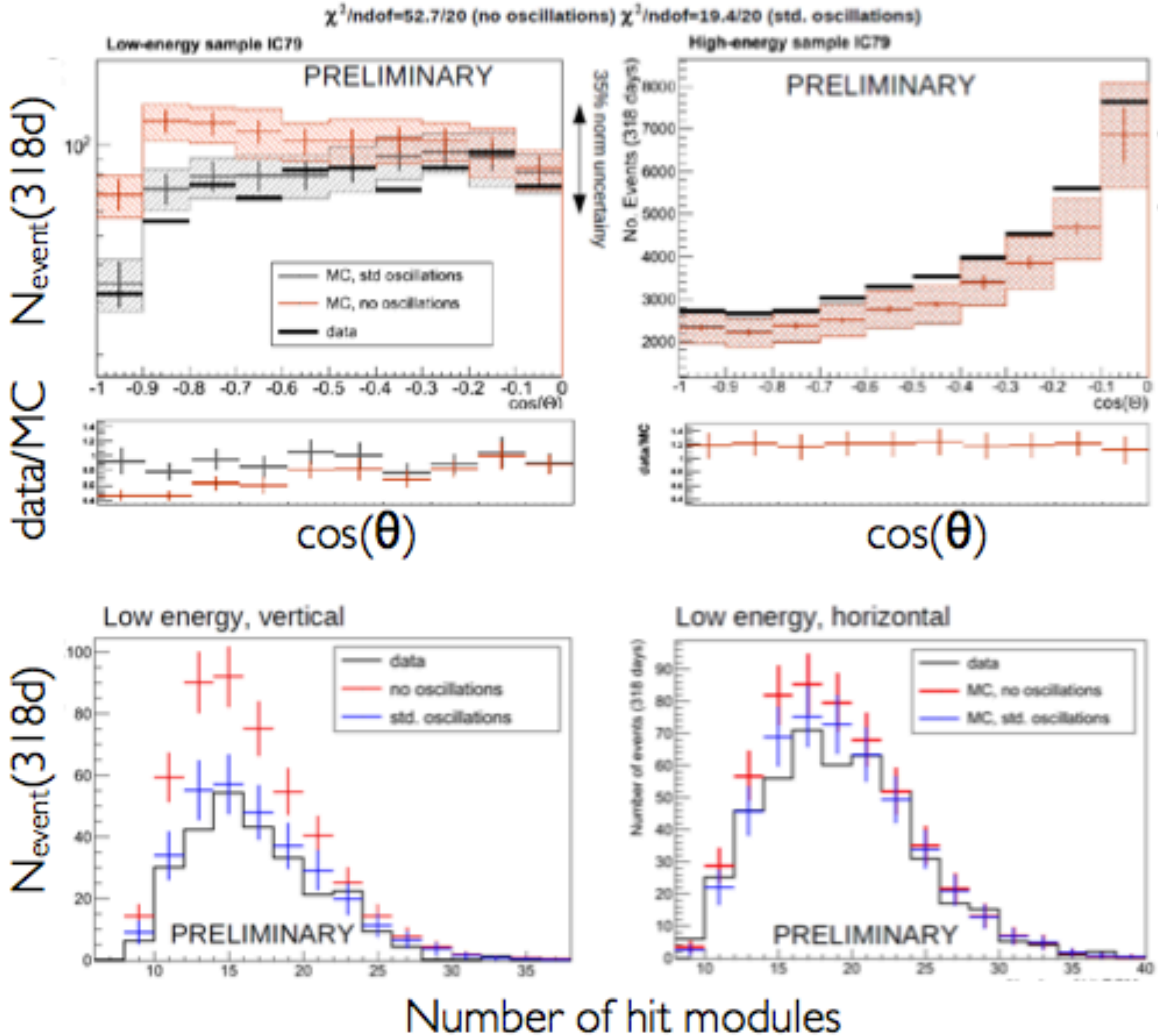
IceCube -> Deep Core



Deep Core is a array of more densely instrumented strings to lower the threshold to ~10 GeV so they can see atmospheric neutrinos.

First observation of oscillations with deep core

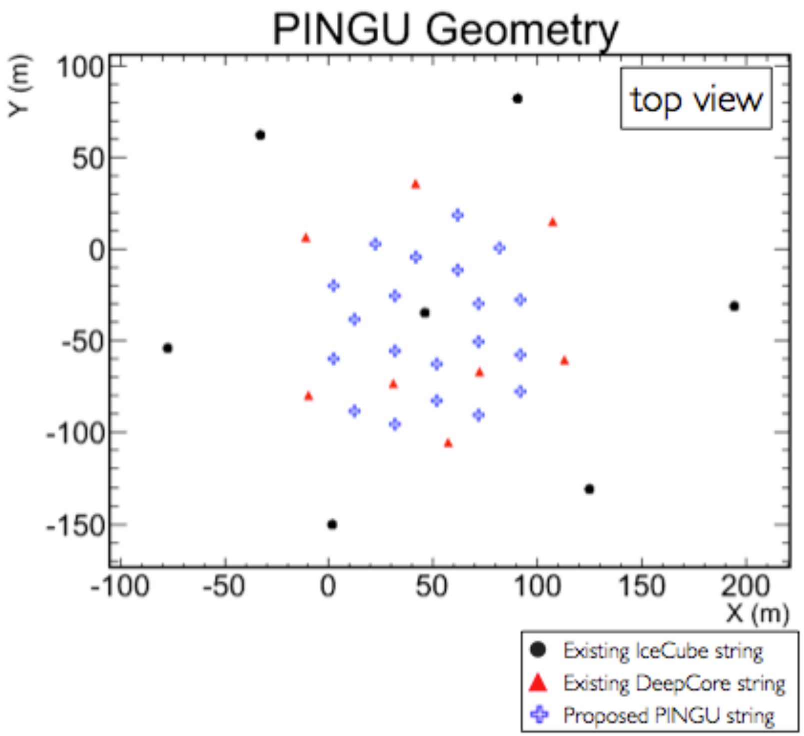
Note: Error bar for MC



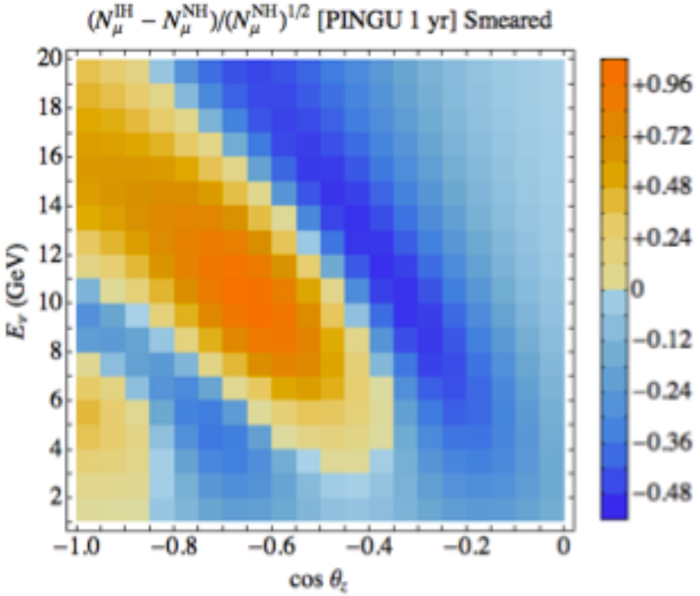
Note: from horizontal to upward going

© [2011] The Pygos Group

PINGU or ORCA:
Even lower threshold



http://arxiv.org/abs/1205.7071



Multi-Megatons of mass. Possible 3-10 sigma measurement of the MH in 5 years. But remember the lessons: push/design to constrain systematics (can downward going events be utilized?)

Conclusions

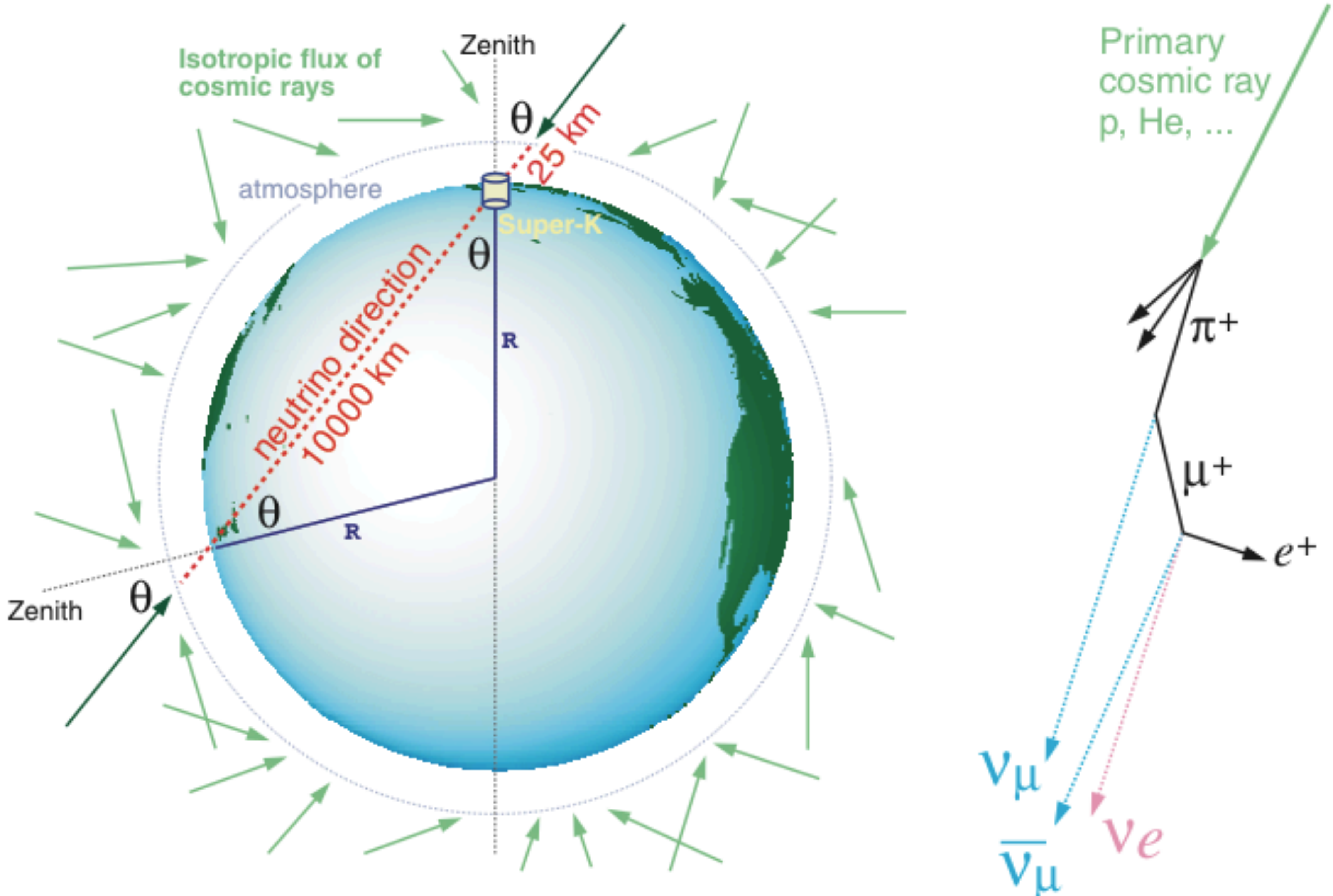
- Please relax and enjoy atmospheric neutrinos!
- We can still learn a lot from them.
- Large experiments like HK and INO and future LAr detectors will do precision oscillation physics and contribute to the measurements of sub-leading effects.
- The large water/ice experiments carry the promise of a big impact in mass hierarchy and maybe other precision measurements. But, the systematics must be understood and mitigated.

Backup

Flux

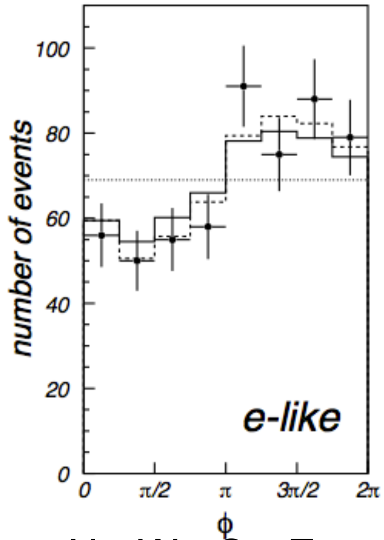
"Artist's impression of a cosmic ray shower over London" (!)

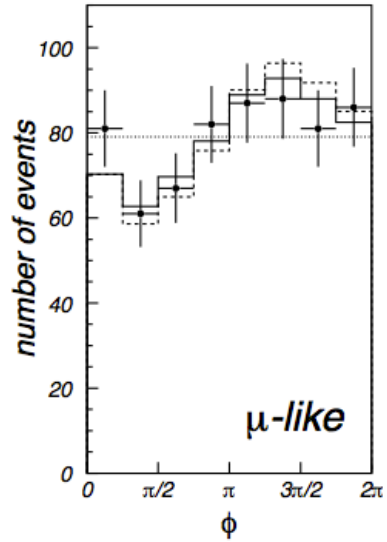
The νs come from all around the earth!



Same number coming up as going down.

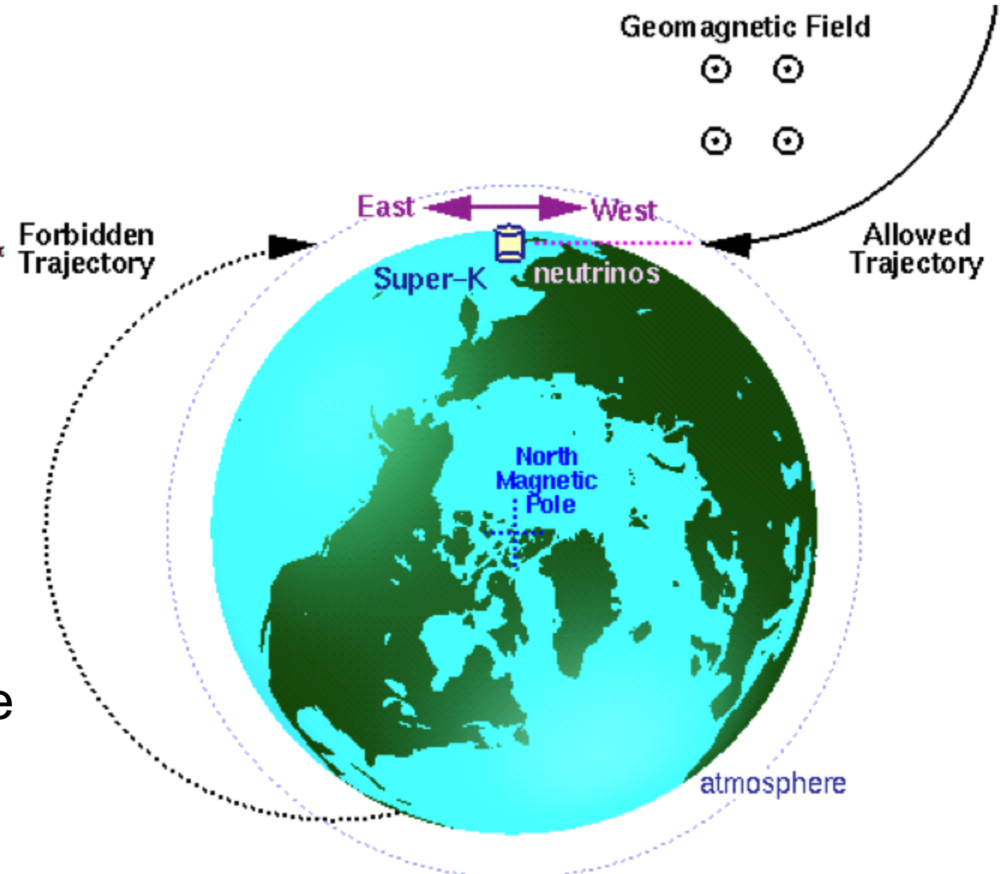
East-West Effect





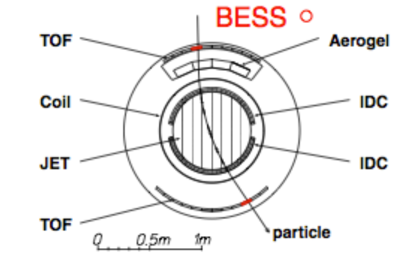
N W S E

1-Ring
abs(cosθ) < 0.5
400 < p < 3000 MeV

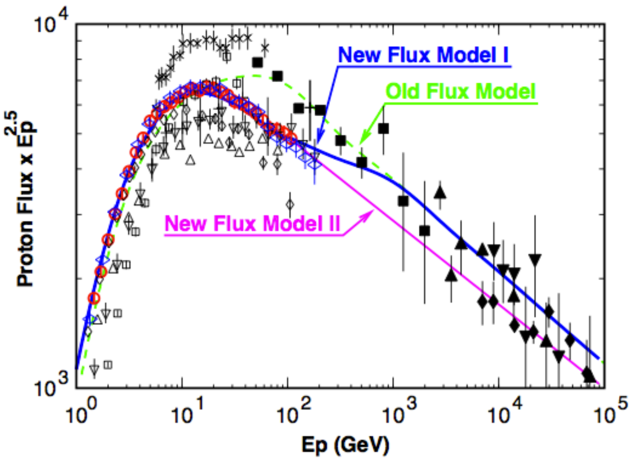


First seen in cosmic rays in the 30s! Repeated with neutrinos.

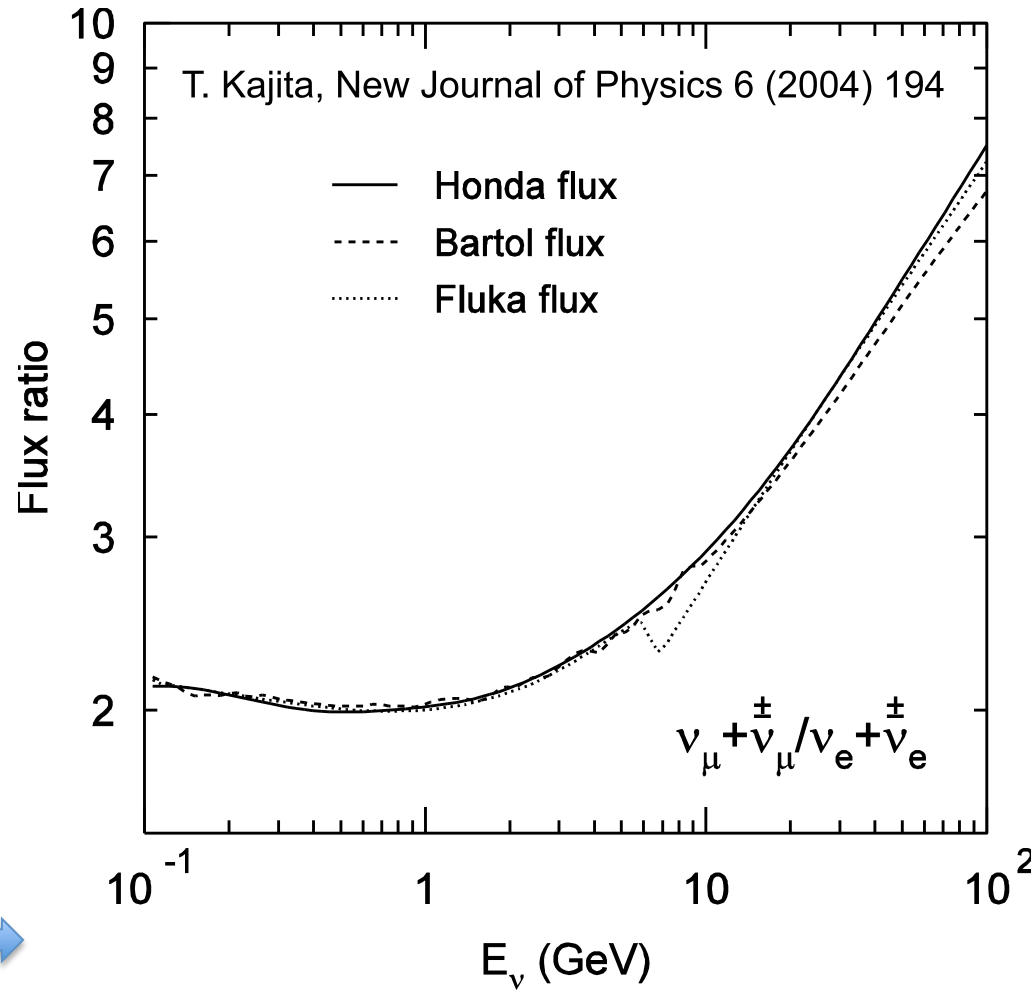
The Flux Model



SPACE and BALLOON Detectors



Honda et al. PRD64(2001)053011



Measure primary cosmic ray flux then:

- Model interactions
- Model pi/K decay
- Geomagnetic fields….

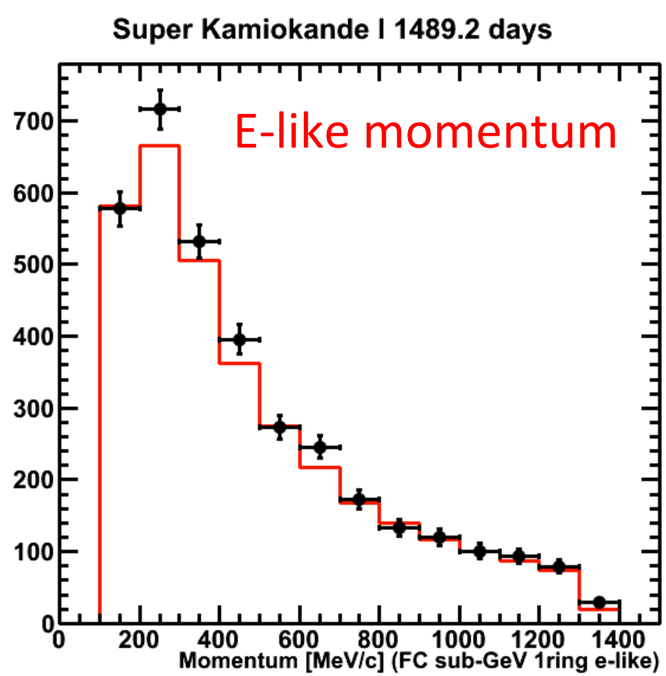
ν_μ/ν_e ratio is ~2, but increases with energy. Known to about 3% below ~5GeV.

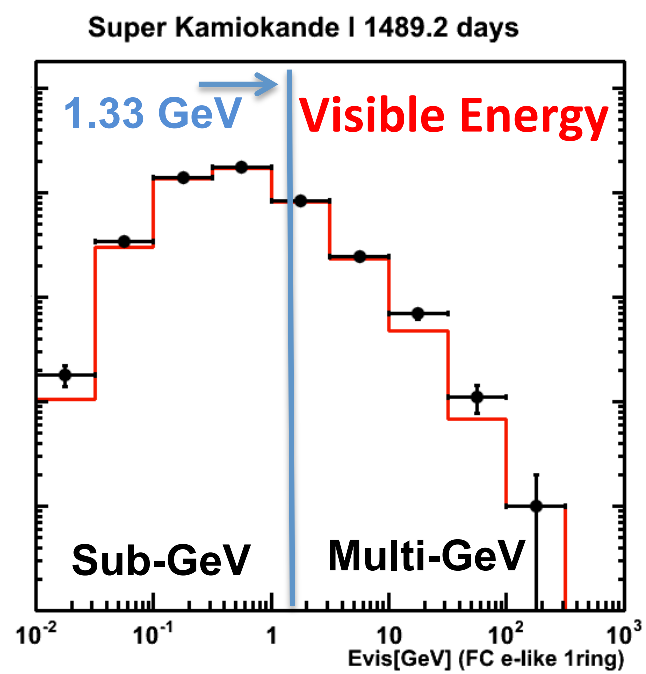
We typically don’t plot neutrino energy.

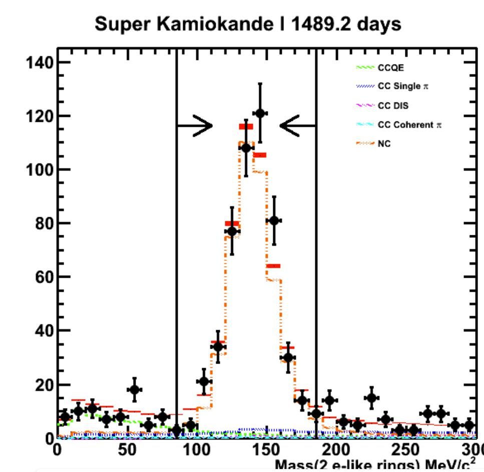
We don’t know the beam direction and if we can’t see the proton can’t do a kinematic reconstruction. So we usually compare expected and reconstructed momentum and related quantities.

Need a way to compare energy of all types of particles. →

__Visible Energy__: The energy of an electron that would produce the observed number of Cherenkov photons.





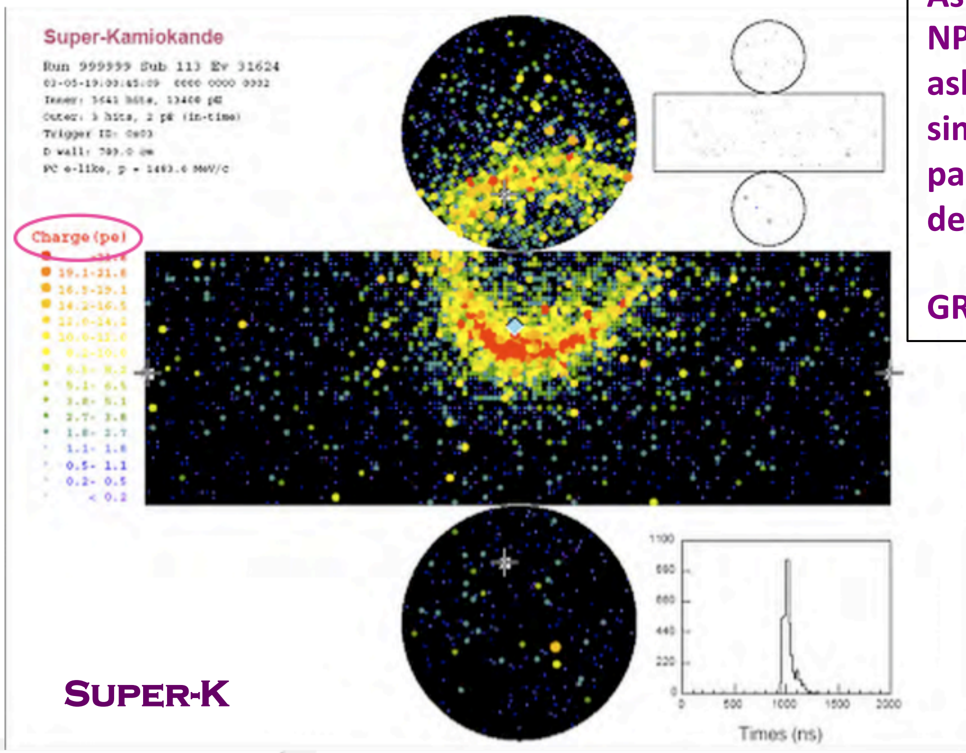


Use control samples like pizeros to control the energy scale.

Same Particles: Different Detectors

E. KEARNS – NPSS07

LIQUID ARGON

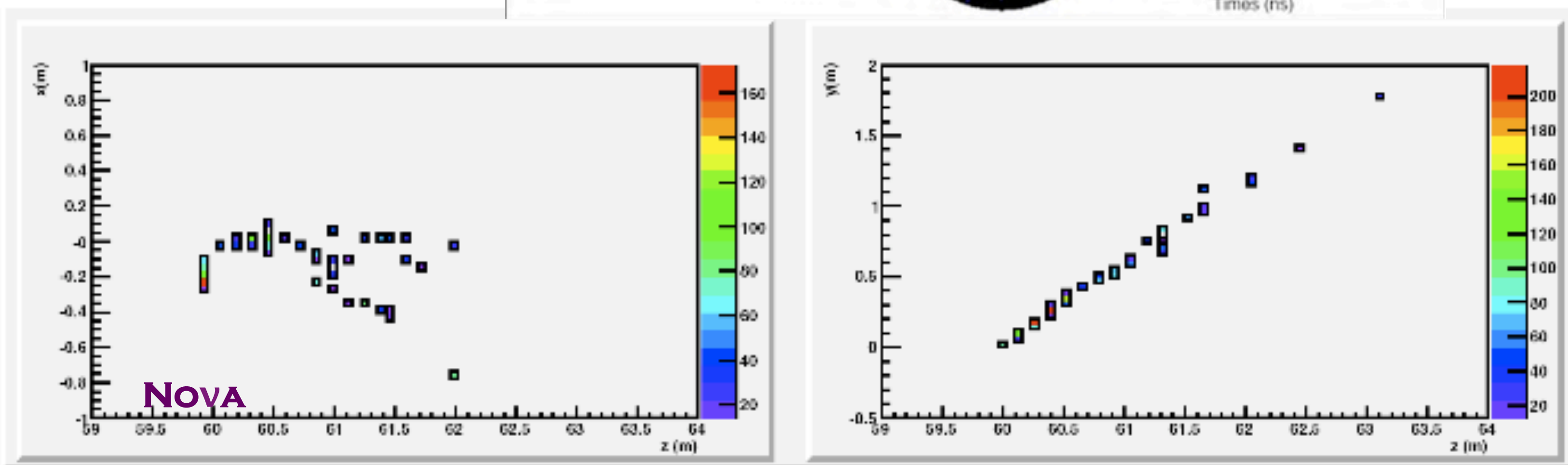


SUPER-K

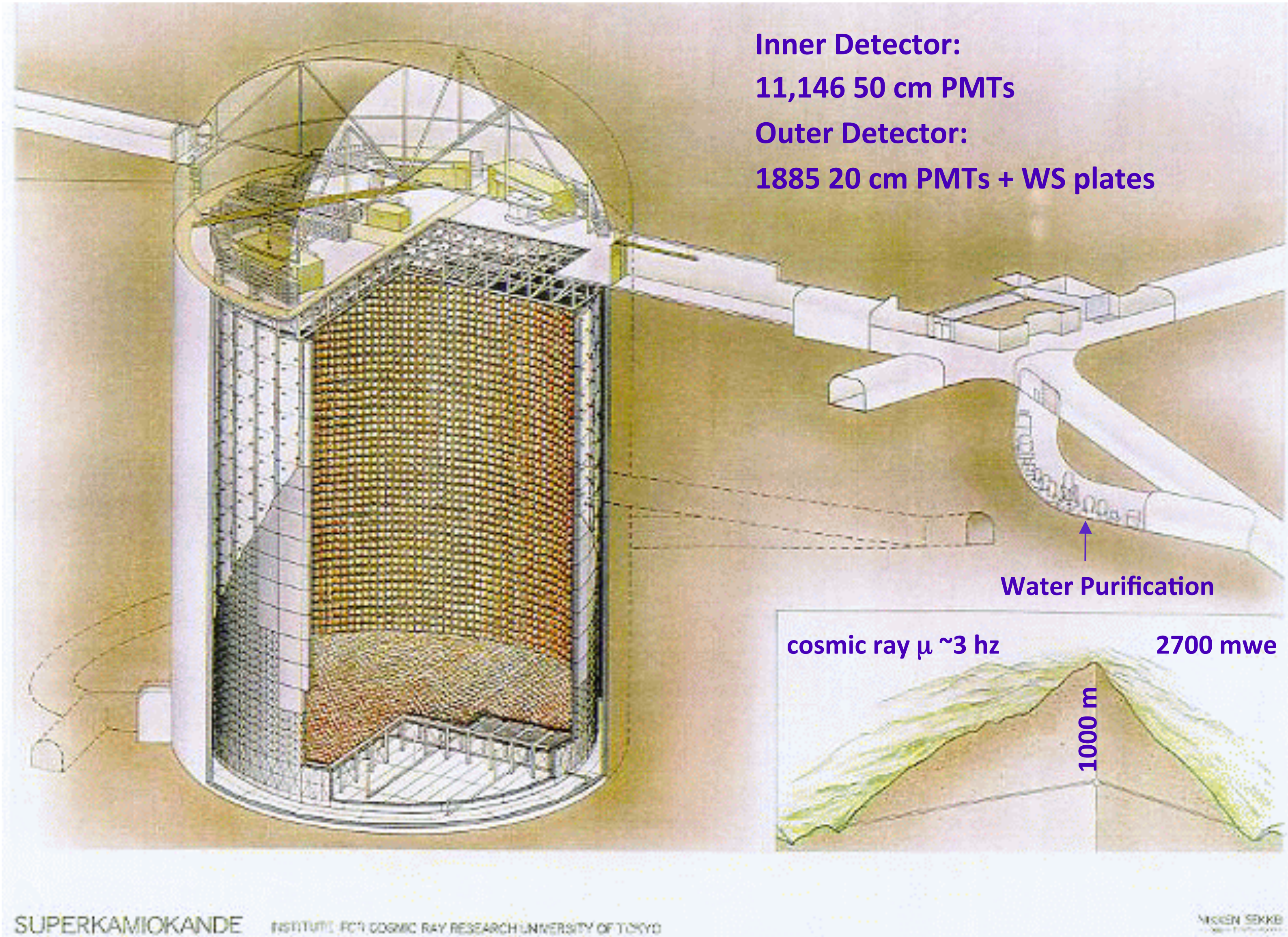
As an exercise for NPSS07. Ed Kearns asked three groups to simulate the same particles in their detectors.

GREAT!

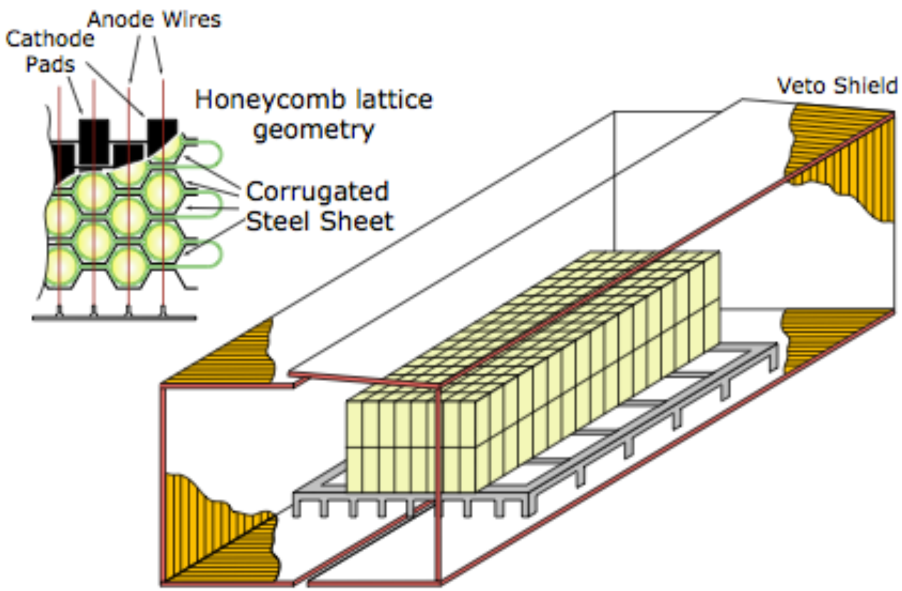
Monte Carlo Vectors	
proton	691 MeV/c
pi0	1442 MeV/c
gamma	245 MeV/c
gamma	1204 MeV/c

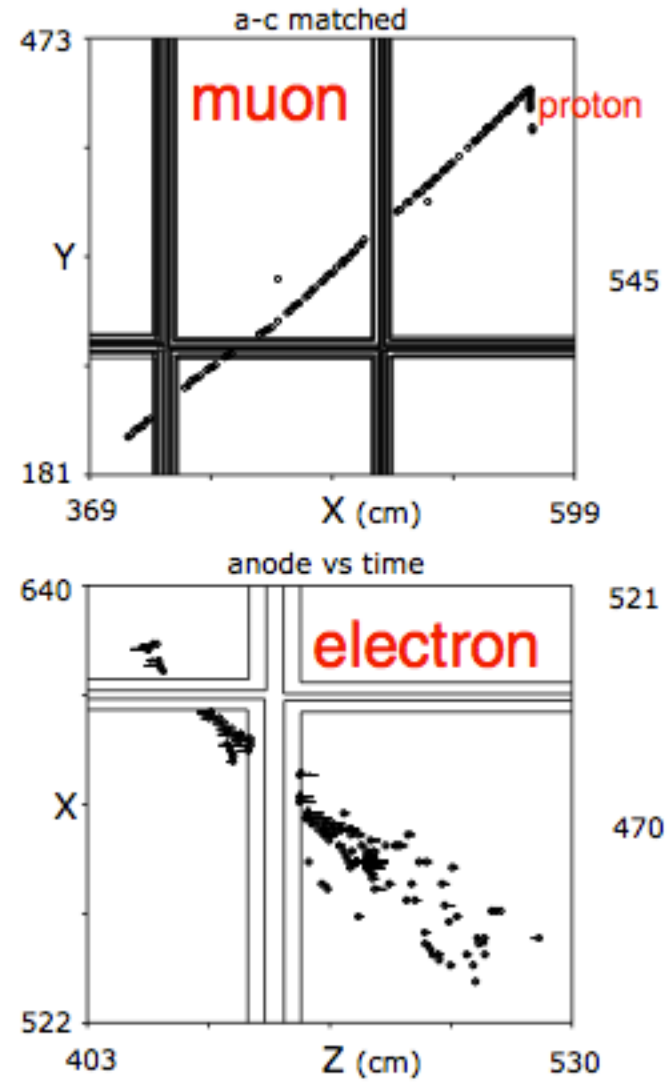


Super Kamiokande Detector: 50,000 Ton Water Cherenkov Detector



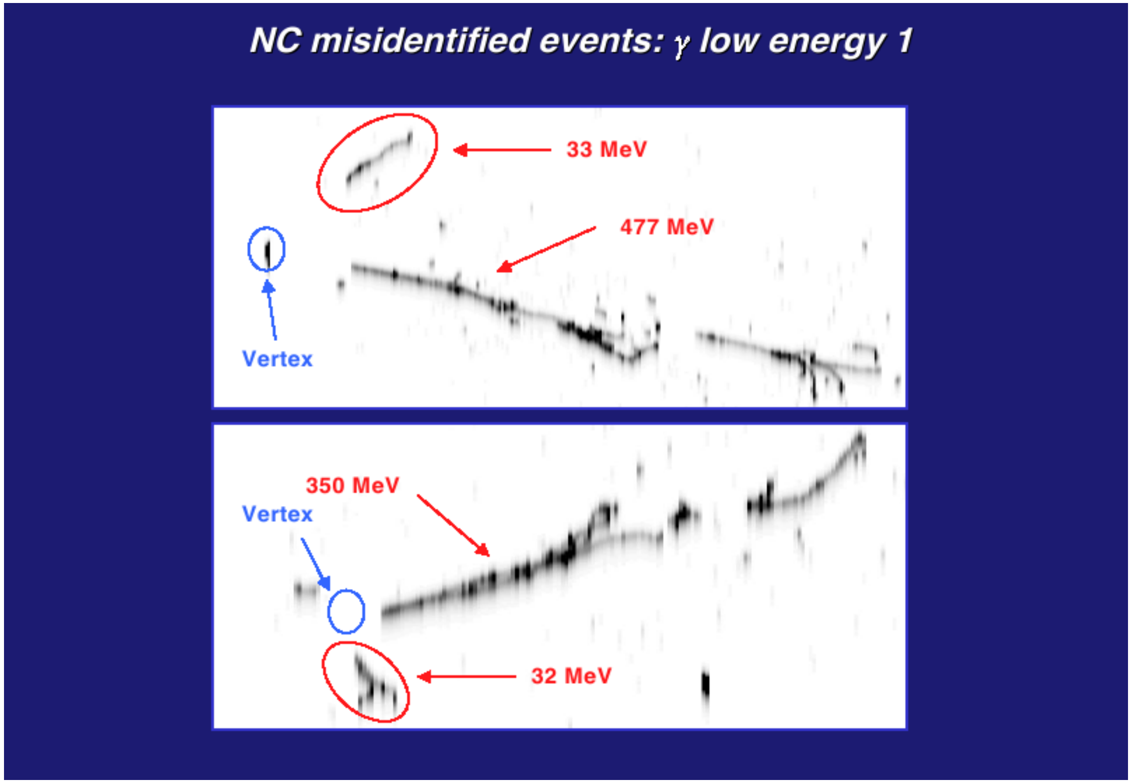
Soudan: an Iron tracking calorimeter

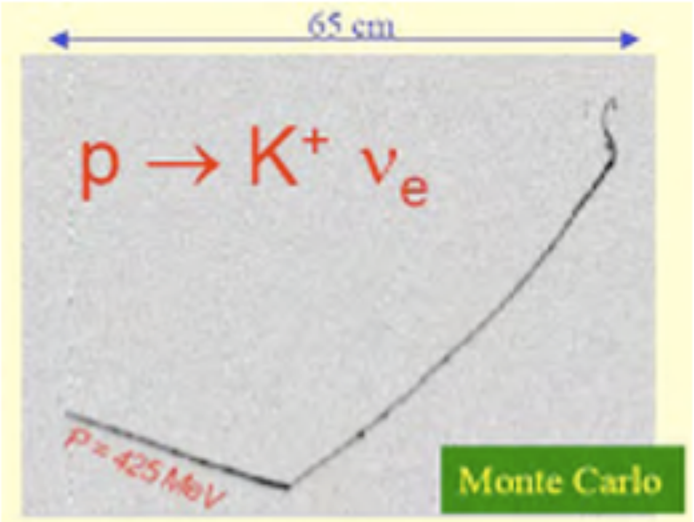




960 tons. Can see all particles.

Liquid Argon TPC – An electronic bubble chamber



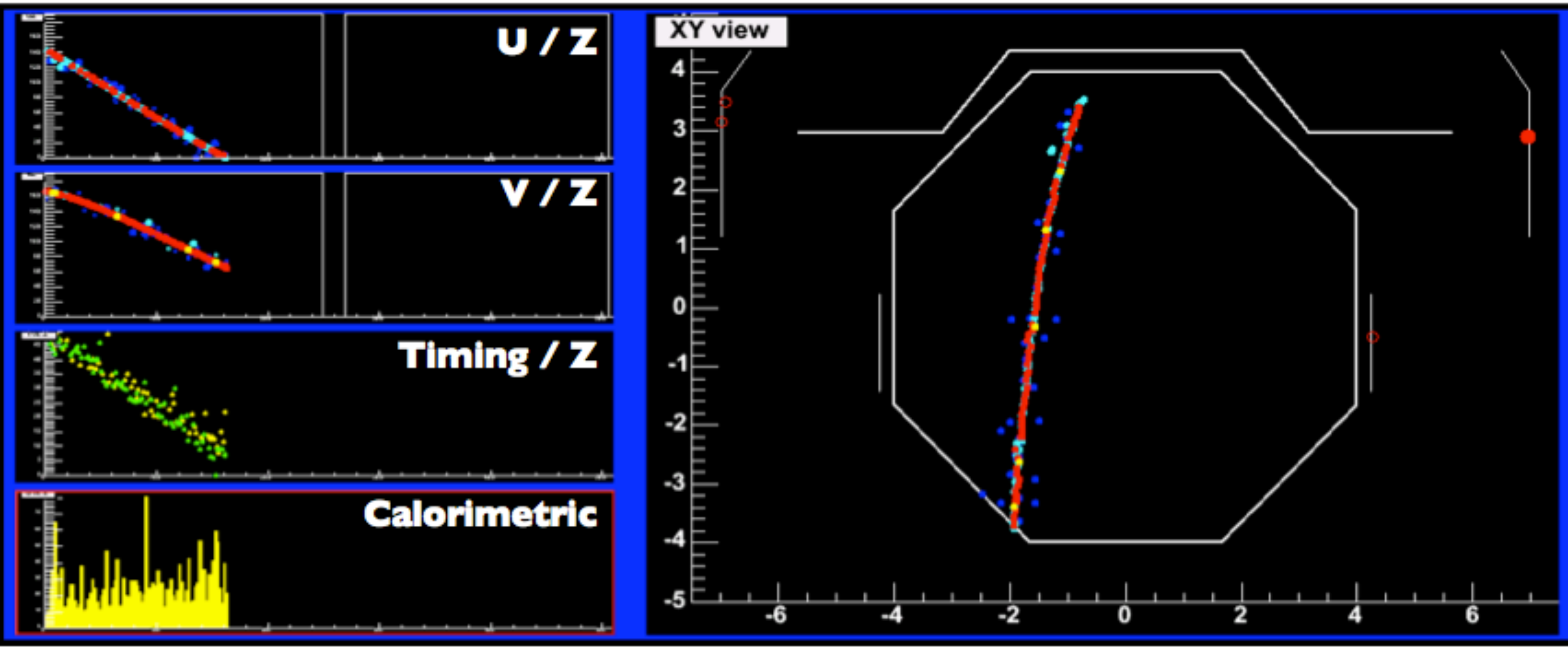


All particles are seen in LAR. In this proton decay the kaon would be below Cherenkov threshold.

Backgrounds missed in WC can be seen in LAR. Example from T2K 2KM studies: *Vectors of NC BG in a WC detector simulated in LAR.*

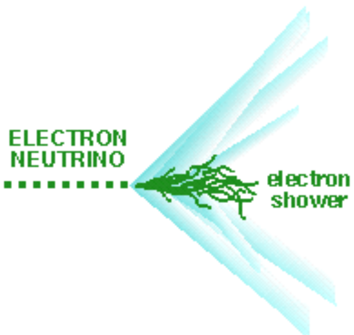
Resolution given by wire spacing ~ 3mm
(comparable to Gargamelle bubble size)

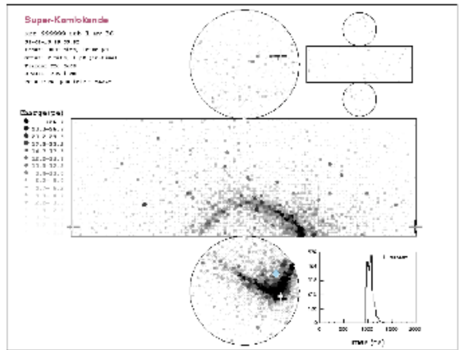
Can we tell ν from anti-ν?

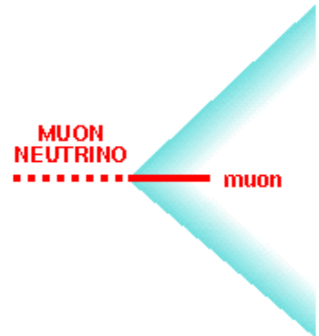


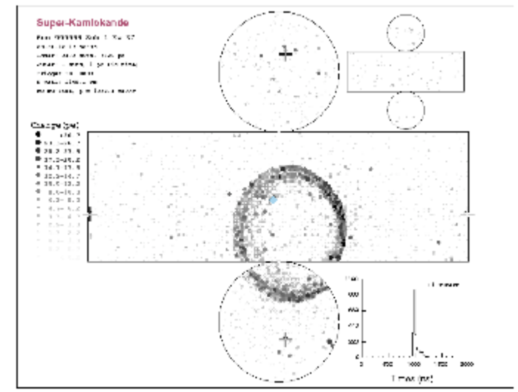
This is a picture from MINOS which has a magnetic field.
This is upward going from timing and curvature tells us it is a μ^+
INO/ICAL will be able to do this with ~50ktons!
Non-magnetic detectors need other tricks.

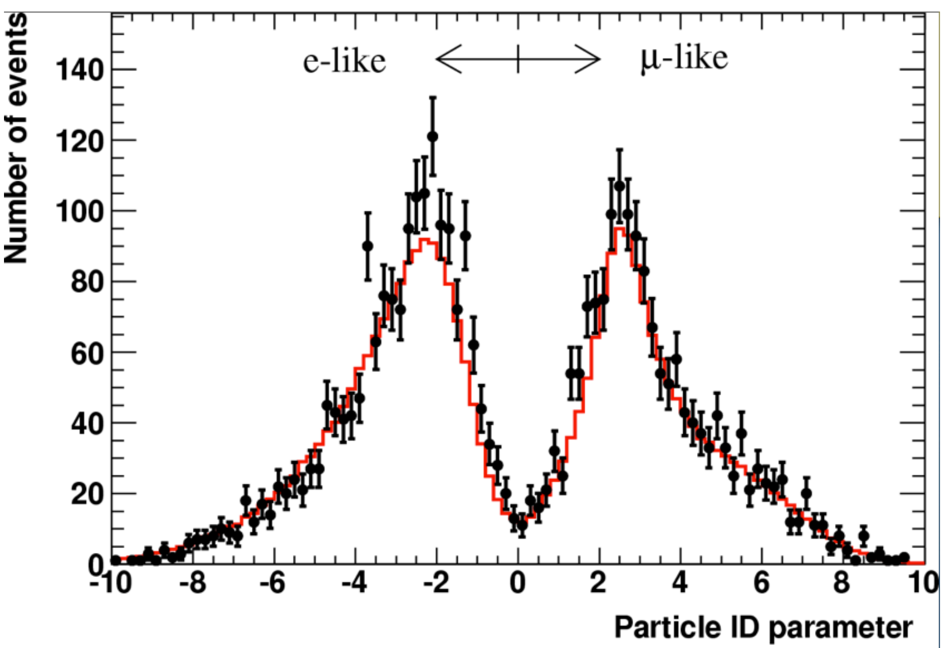
Telling Electrons from Muons





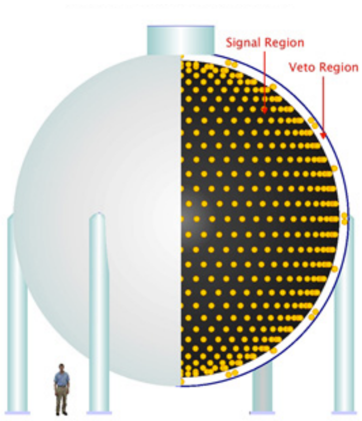


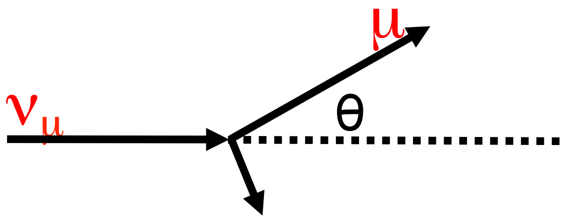




SK-IV atmospheric neutrino data.
mis-id ≤~ 1%

E_ν Reconstruction (assuming QE)





$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos(\theta_\mu)}$$

In Cherenkov detectors not every particle is above Cherenkov threshold. Luckily, in a Quasi-Elastic reaction, even if only the muon is visible we can reconstruct the neutrino energy!

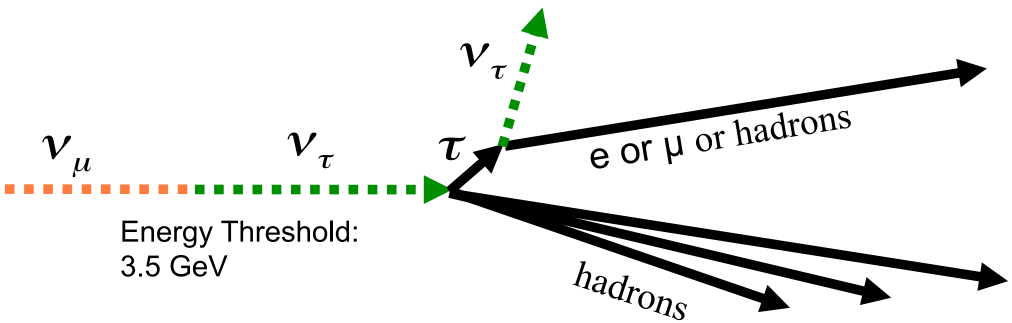
[Case for most events in T2K/MiniBooNE Energies]

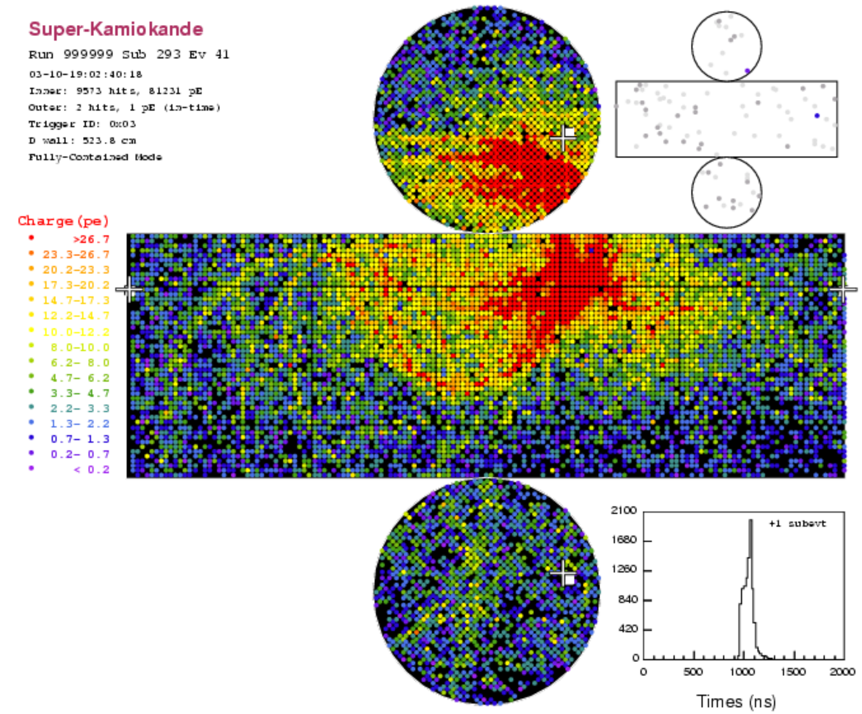
$$m_N = \text{Neutron Mass}$$
$$E_\mu = \text{Muon Energy}$$
$$m_\mu = \text{Muon mass}$$
$$p_\mu = \text{Muon momentum}$$
$$\theta_\mu = \text{Muon angle wrt beam}$$

If the interaction is non Quasi-Elastic then the reconstructed energy will be incorrect.

Tau Leptons in Super-K

A search for another smoking gun of neutrino oscillation:
tau *neutrino appearance*.



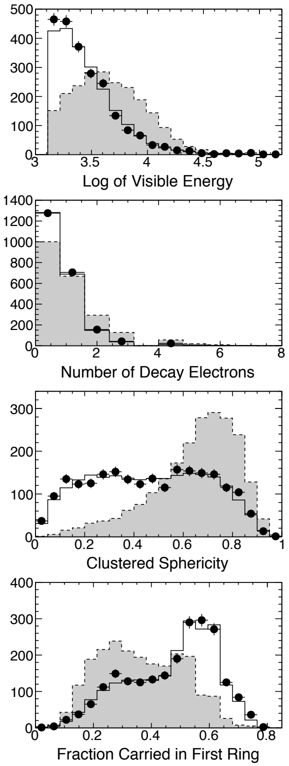


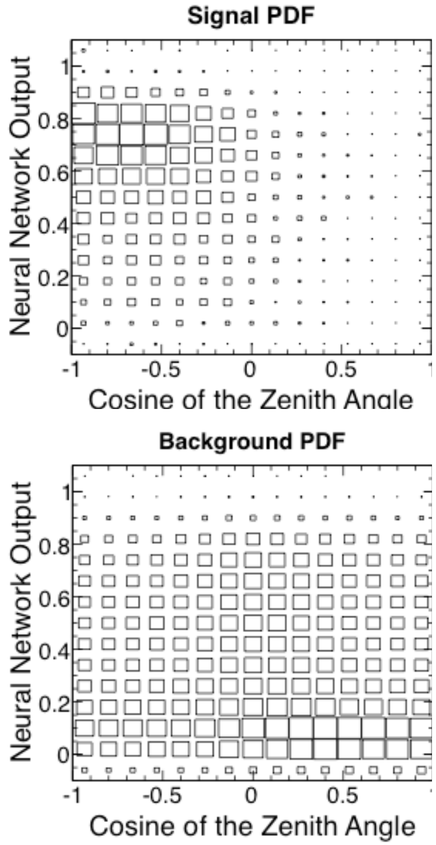
Signal: high energy, extra pions from tau decay,
more spherically symmetric due to decay of heavy tau.

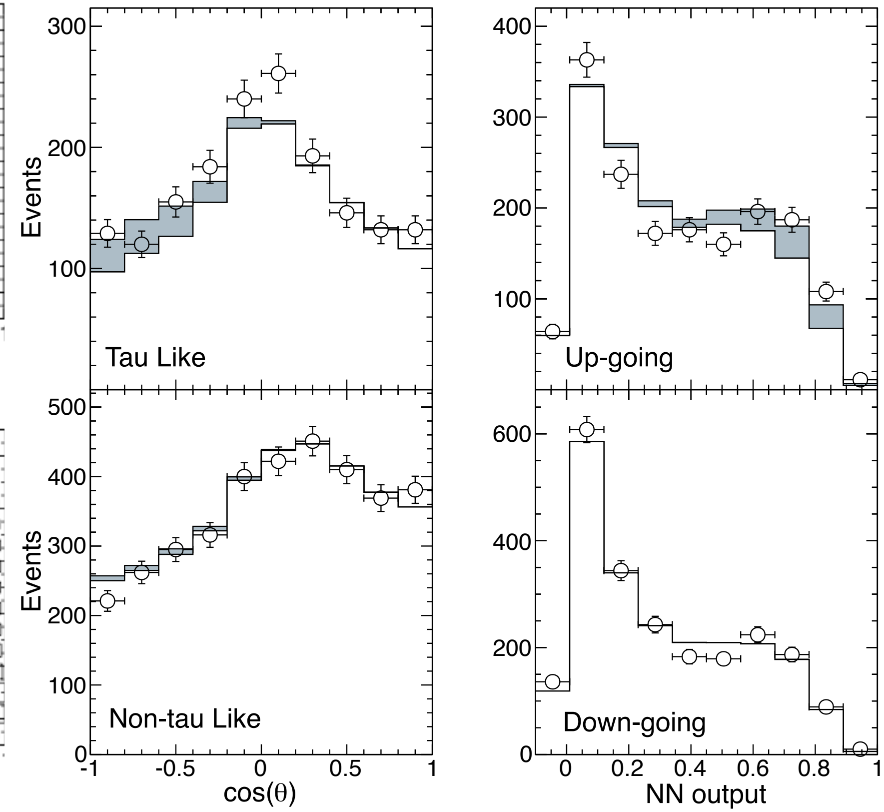
Super-K Evidence for Tau Appearance

New data + perform 2D un-binned likelihood fit of signal and background.

http://arxiv.org/1206.0328 (submitted to PRL)







$$\text{Norm}_{Tau} = 1.42 \pm 0.35_{(stat)} \; {}^{+0.14}_{-0.12} \; (sys)$$

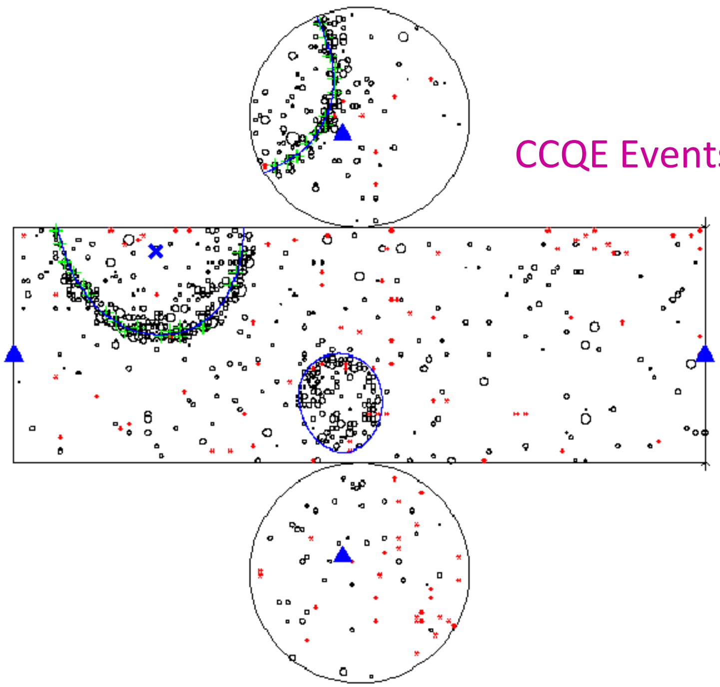
➔ We can reject the no-appearance hypothesis.

P-Value: 6.16×10^{-5} = **3.8 sigma**

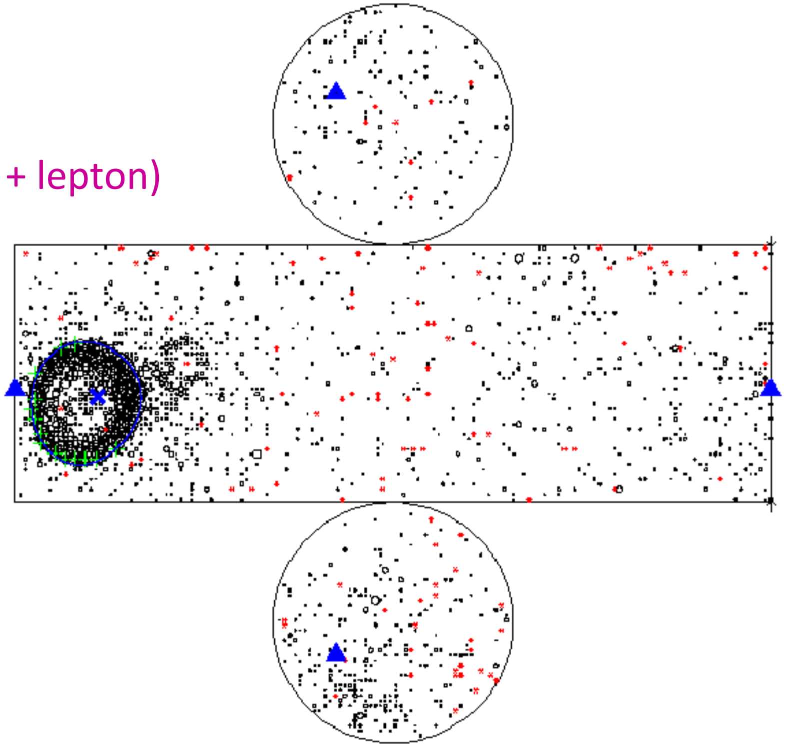
Corresponds to observed signal:

180.1 +- 44.3 (stat) +17.8 -15.2

Neutrino events with a proton



CCQE Events (proton + lepton)



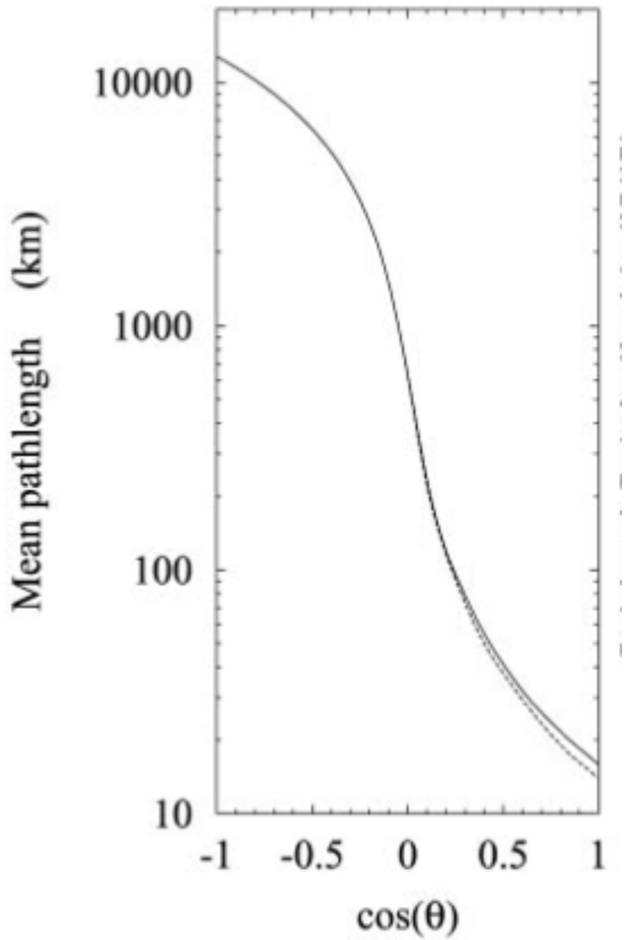
- CCQE events ($\nu + p \rightarrow p + l$) can be fully reconstructed because all kinematics are constrained.
- CC events with a visible proton come only from neutrinos.

Don´t need to know the direction of the beam!

This is very difficult in WC and Iron. LAr can do it.

What is L?

Every angle corresponds to a distribution of lengths.



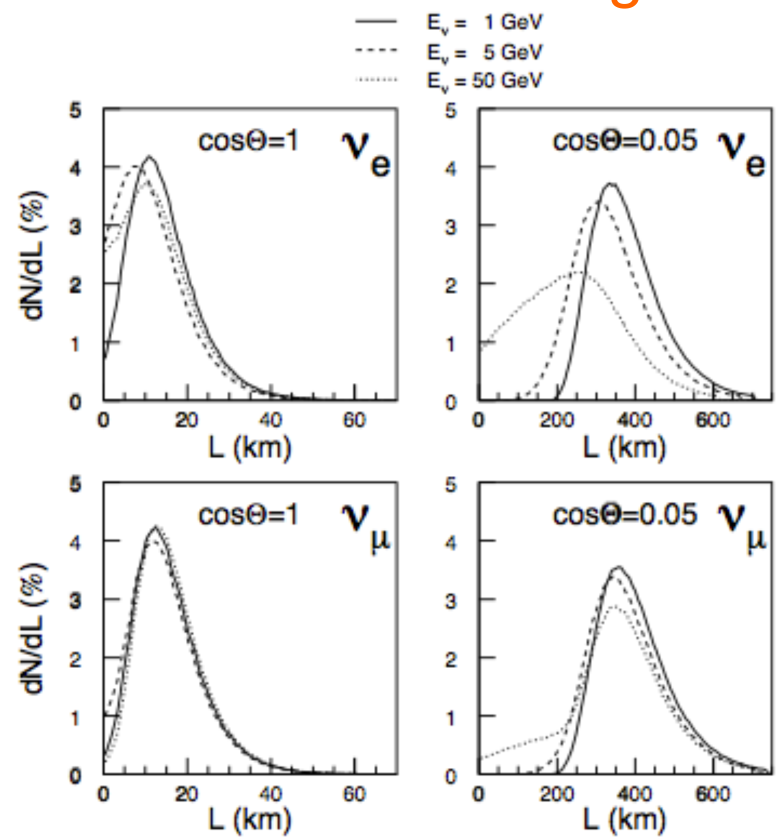


Figure 8.3: The distribution of neutrino production heights for E_ν=1, 5, and 20 GeV for neutrinos from overhead ($\cos\Theta = 1$) and near the horizon ($\cos\Theta = 0.05$).

M. Messier, Thesis 1999

Incorporating errors in fit to a model or hypothesis

$$\chi^2 \equiv \sum_{n=1}^{N_{Bins}} \left[2(N^n_{\exp} - N^n_{obs}) + 2N^n_{obs} \ln\left(\frac{N^n_{obs}}{N^n_{\exp}}\right)\right] + \sum_{i=1}^{N_{Errors}} \left(\frac{\varepsilon_i}{\sigma_i}\right)^2$$

$$N_{\exp} = N_{MC} \cdot P(\nu_\mu \rightarrow \nu_\mu (for\, CC\, \nu_\mu)) \cdot (1 + \sum_{j=1}^{70} f_j \cdot \varepsilon_j)$$

As you change the systematic errors you penalize your χ^2 and modify your expectation.

N_{obs} : observed number of events
N_{exp} : expectation from MC
ε_i : systematic error term
σ_i: sigma of systematic error
f_{ij}: coupling to each bin

This is a Poissonian χ^2 (see the PDG)
(careful about meaning of absolute χ^2)

χ^2 minimization at each parameter point (Δm^2, $\sin^2 2\theta$, …).
Method (χ^2 version): G.L.Fogli et al., PRD 66, 053010 (2002).

In SK we solve a system of equations iteratively instead of using MINUIT. It's faster with lots of errors. It's also possible to mix with minimizer.

http://arxiv.org/abs/1205.7071

What about the other channels?

Are muons also distorted by the resonance?

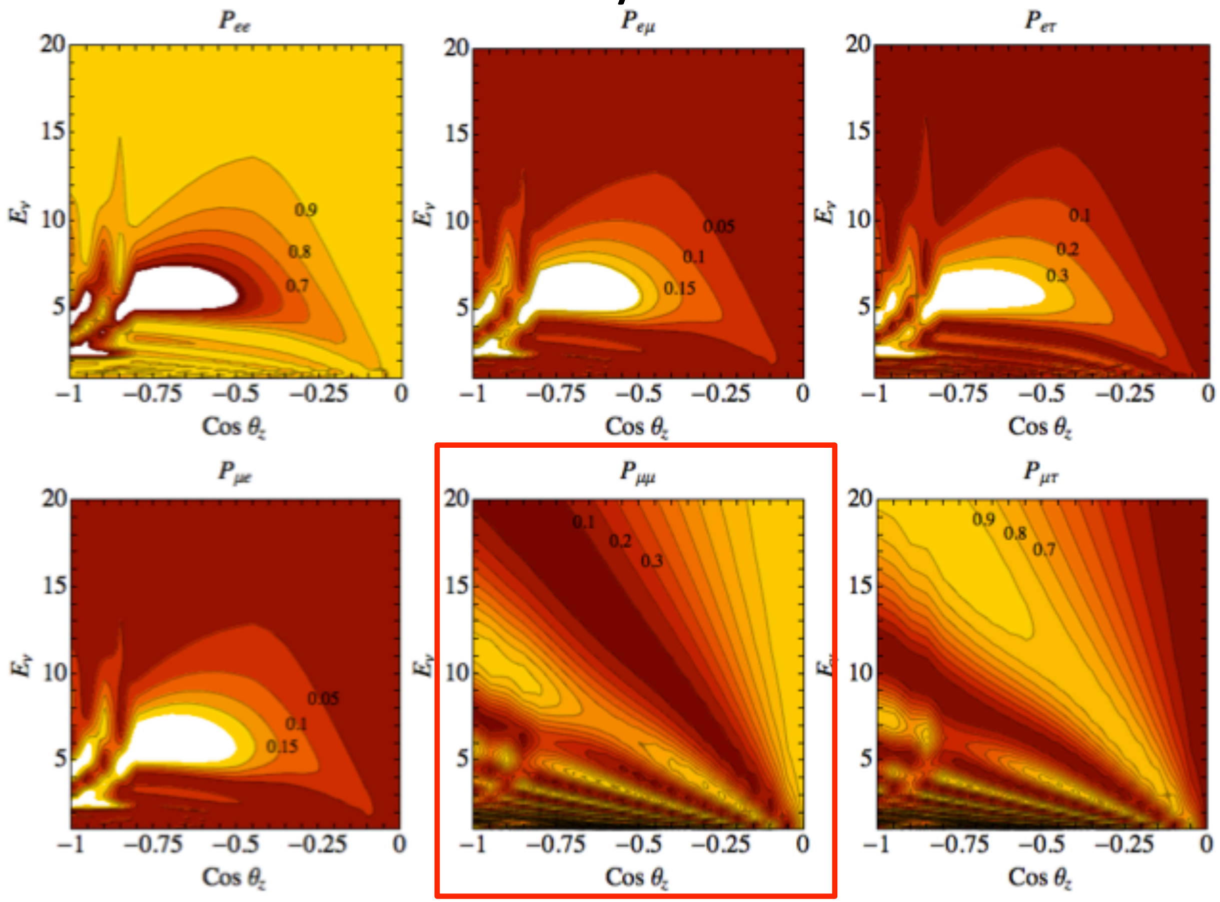
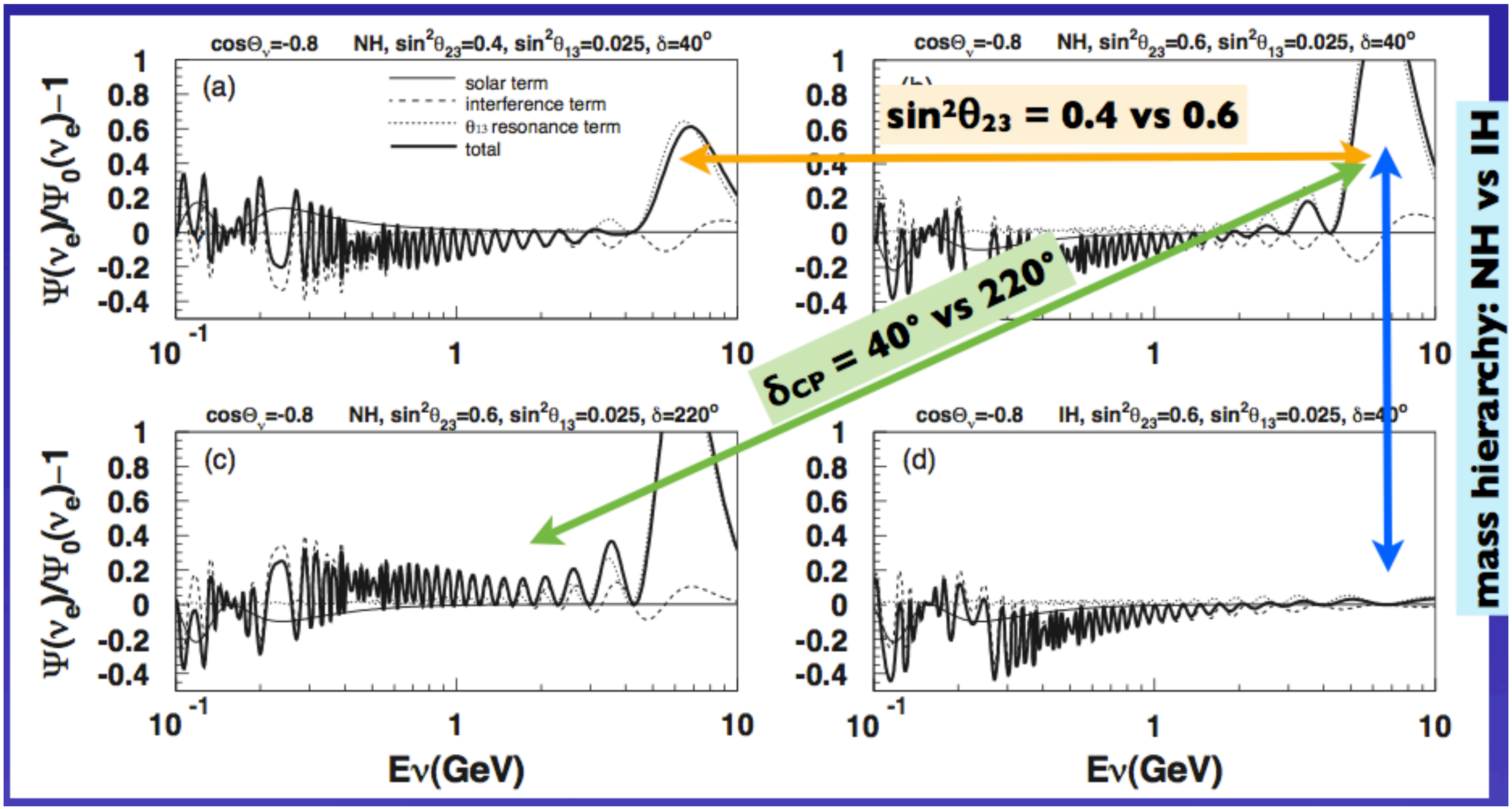
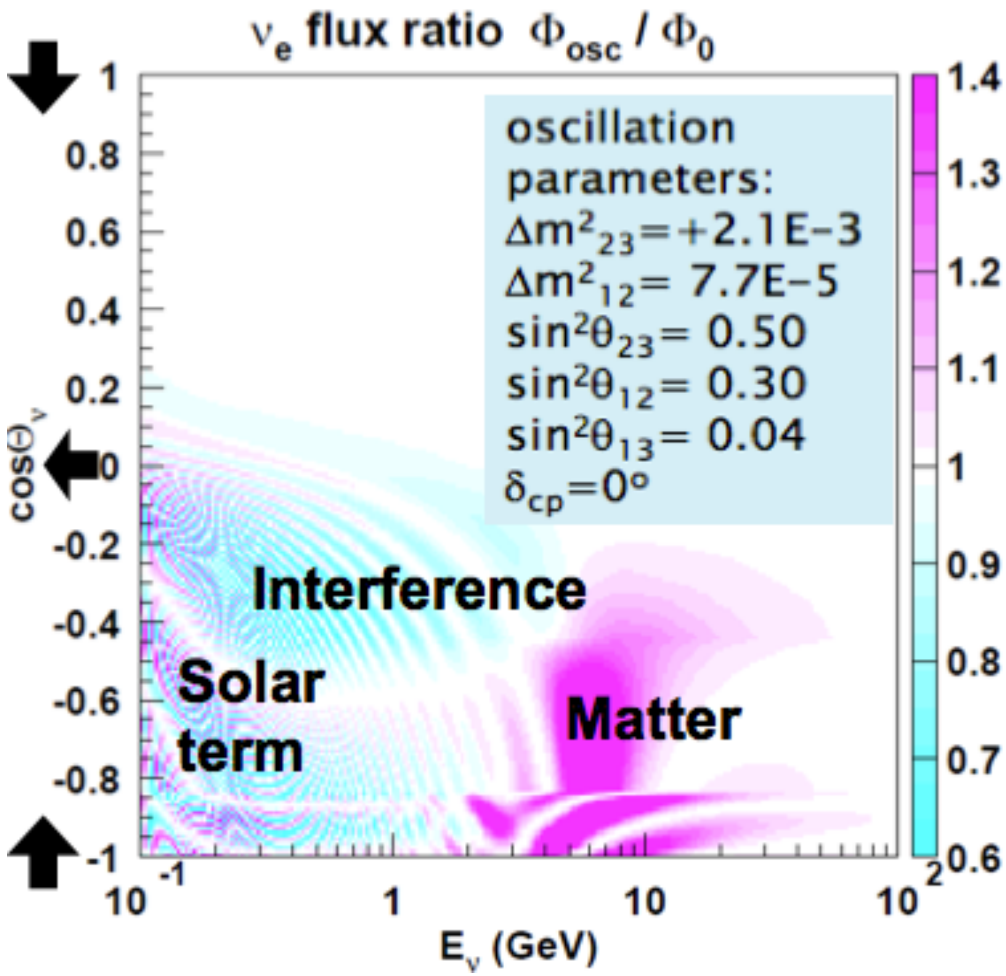


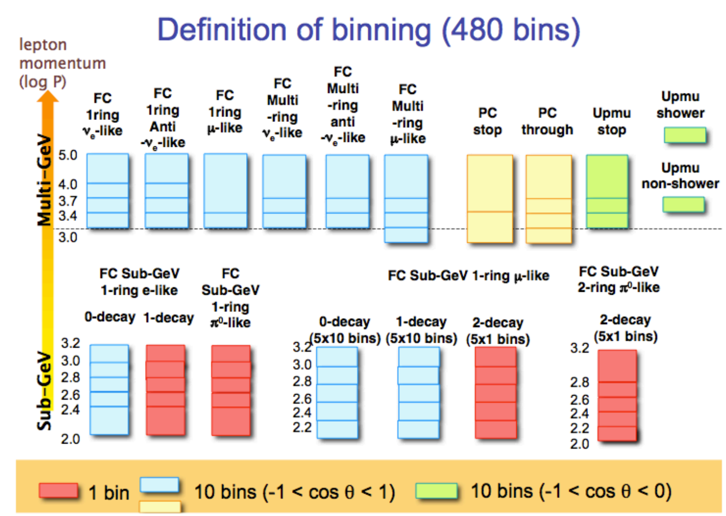
FIG. 2: Neutrino oscillograms of the Earth (lines of equal probabilities in the $E_\nu - \cos\theta_z$ plane) for different oscillation channels for the normal mass hierarchy and the values of the oscillation parameters indicated in the text.


cosΘν=-0.8 NH, sin²θ23=0.4, sin²θ13=0.025, δ=40°
(a)
solar term
interference term
θ13 resonance term
total
cosΘν=-0.8 NH, sin²θ23=0.6, sin²θ13=0.025, δ=40°
sin²θ23 = 0.4 vs 0.6
δCP = 40° vs 220°
cosΘν=-0.8 NH, sin²θ23=0.6, sin²θ13=0.025, δ=220°
(c)
cosΘν=-0.8 IH, sin²θ23=0.6, sin²θ13=0.025, δ=40°
(d)
mass hierarchy: NH vs IH
Ψ(νe)/Ψ0(νe)−1
Eν(GeV)

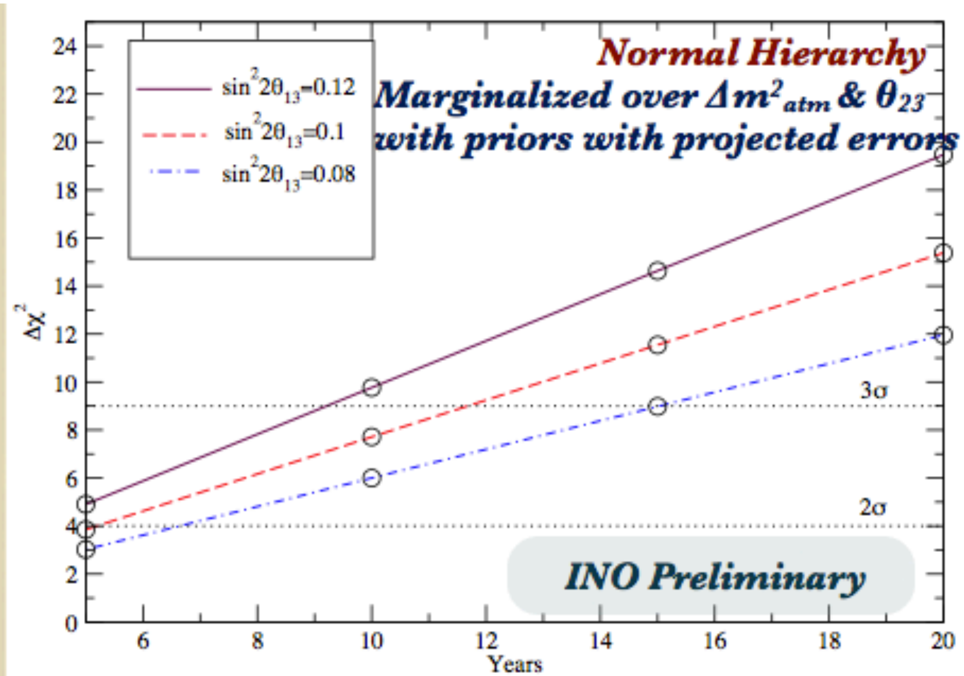
Now put it back together!

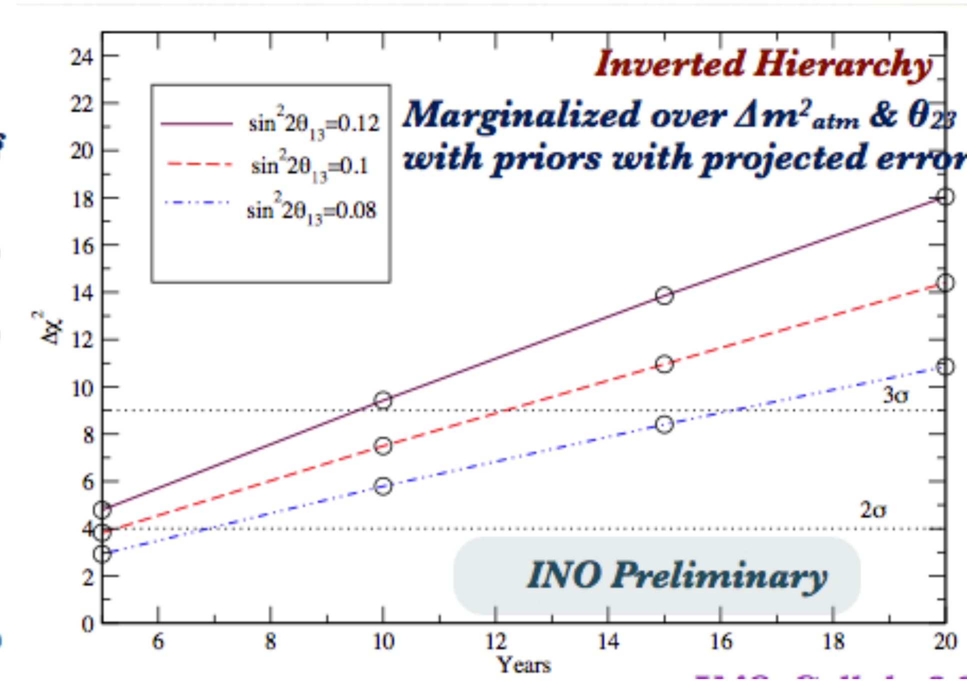


Fit all the data in a way optimized to extract this info



Mass Hierarchy in INO





~3 sigma determination of the MH in ~ 10 years.

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

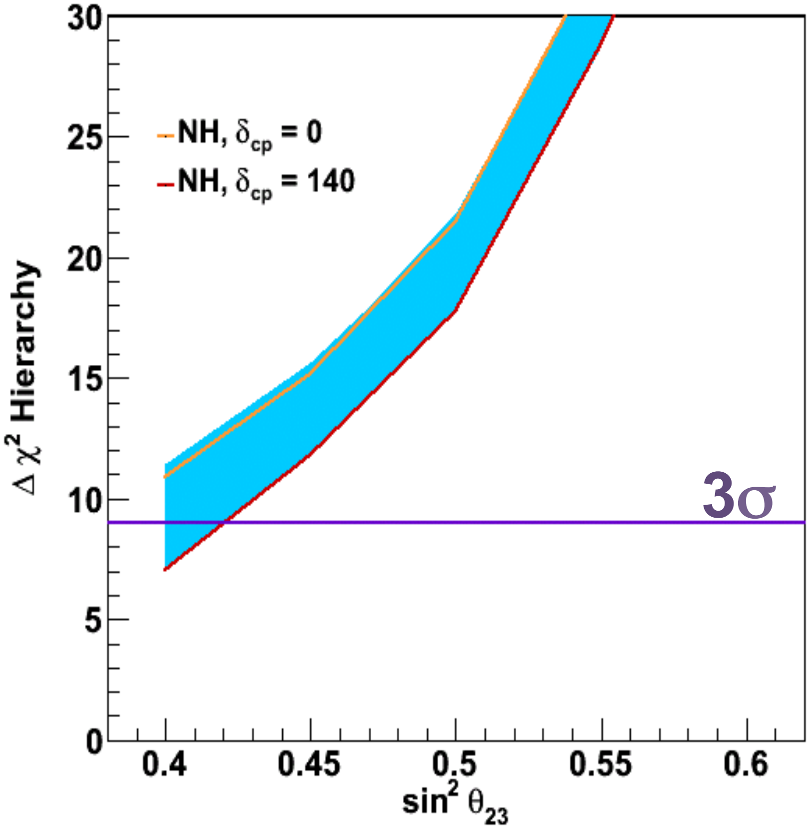
Important Systematic Error Terms for ν_e Appearance (out of 151 considered overall)

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%

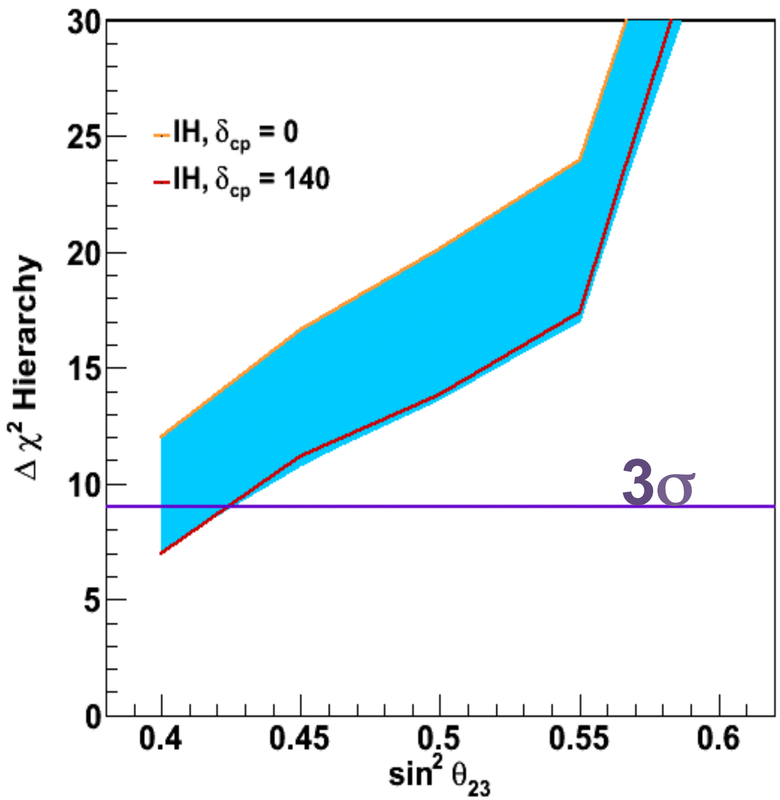
Hierarchy sensitivity, 10 years of Atmospheric neutrino data (Previous meeting)

NH, unknown

θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.10$



IH, Unknown



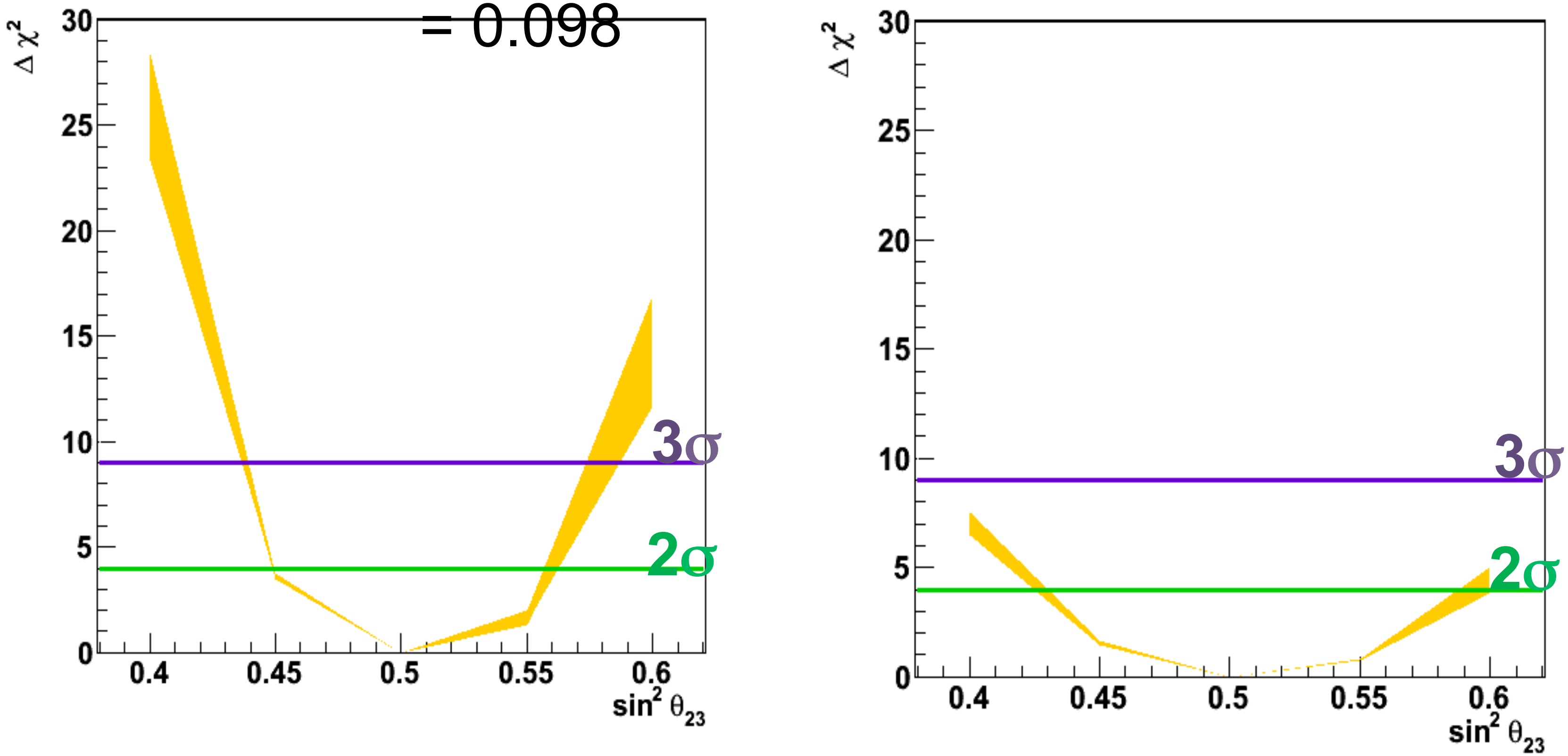
- Thickness of the band corresponds to range of δ_{cp}
- Weakest sensitivity overall in the tail of the first octant

Octant sensitivity, 5 years of Atmospheric data

NH, unknown

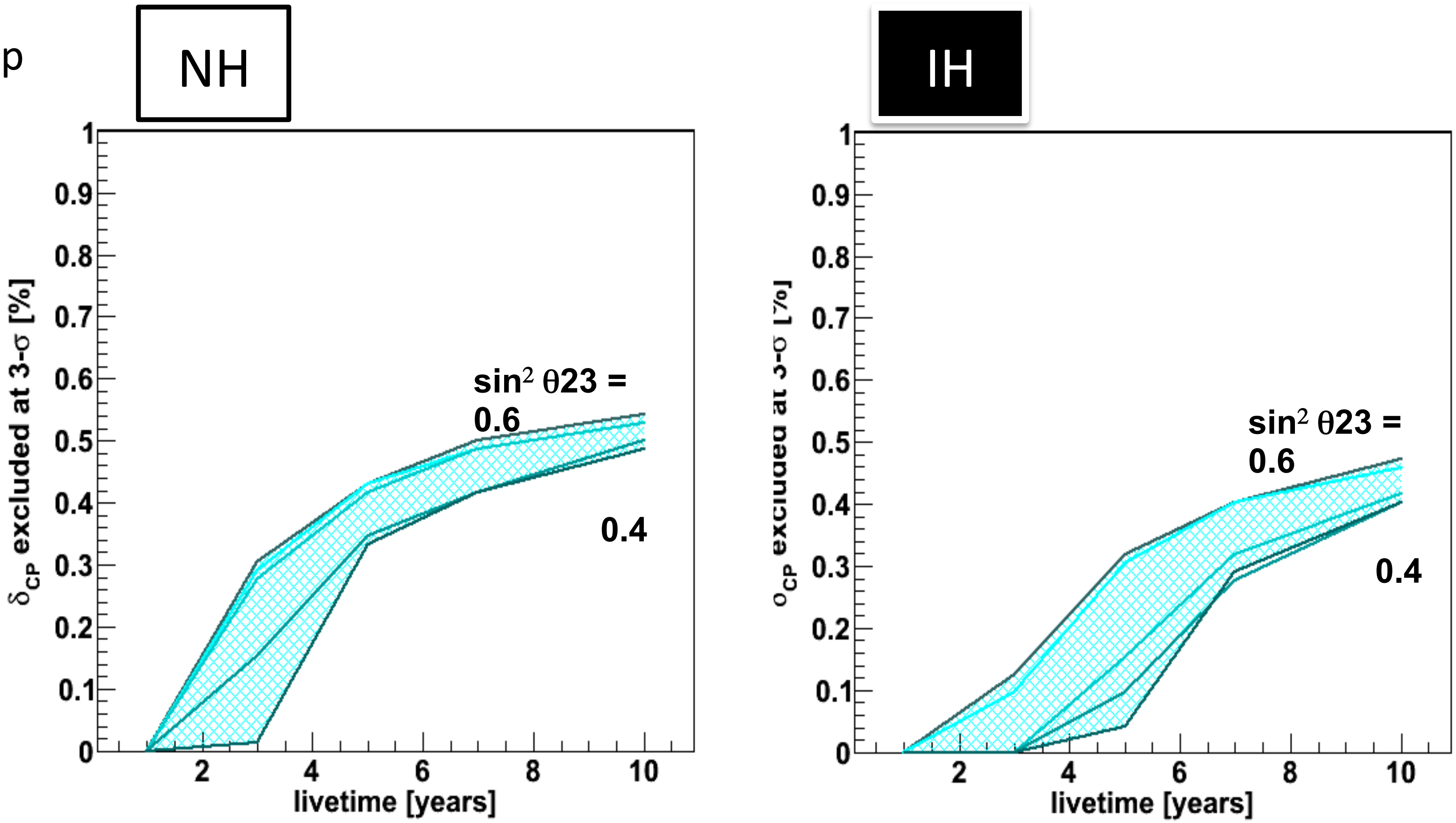
θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.098$

IH, Unknown



- With 1 year of data 2σ sensitivity to the hierarchy for all values of δ_{cp} and either hierarchy assumption
- 3σ sensitivity for the second octant of θ_{23}

Fraction of δ_{cp} excluded at 3σ for a fixed value of δ_{cp}



- For this particular input, the constraint atmospheric neutrinos can place on dcp is about 50%. DCP=40 degrees in this plot.