Number of T2K events at far detector

Number of events in on-timing windows (-2 ~ +10 μsec)

Class / Beam run	RUN-1	RUN-2	Total	non-beam background
POT (x 10^{19})	3.23	11.08	**14.31**	
Fully-Contained (FC)	33	88	**121**	0.023

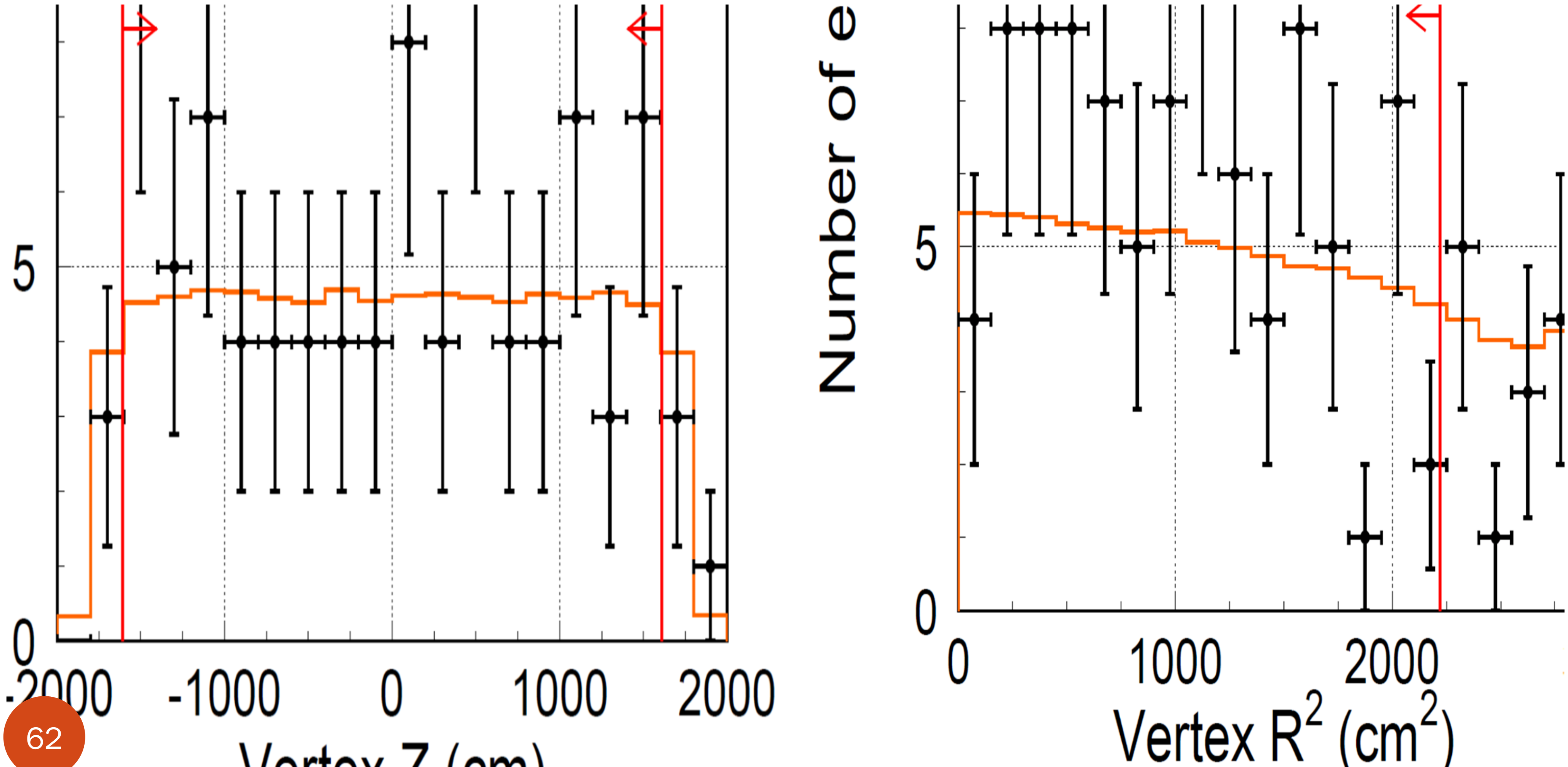
The accidental contamination from atmospheric ν background is estimated using the sideband events to be 0.023

Apply ν_e event selection

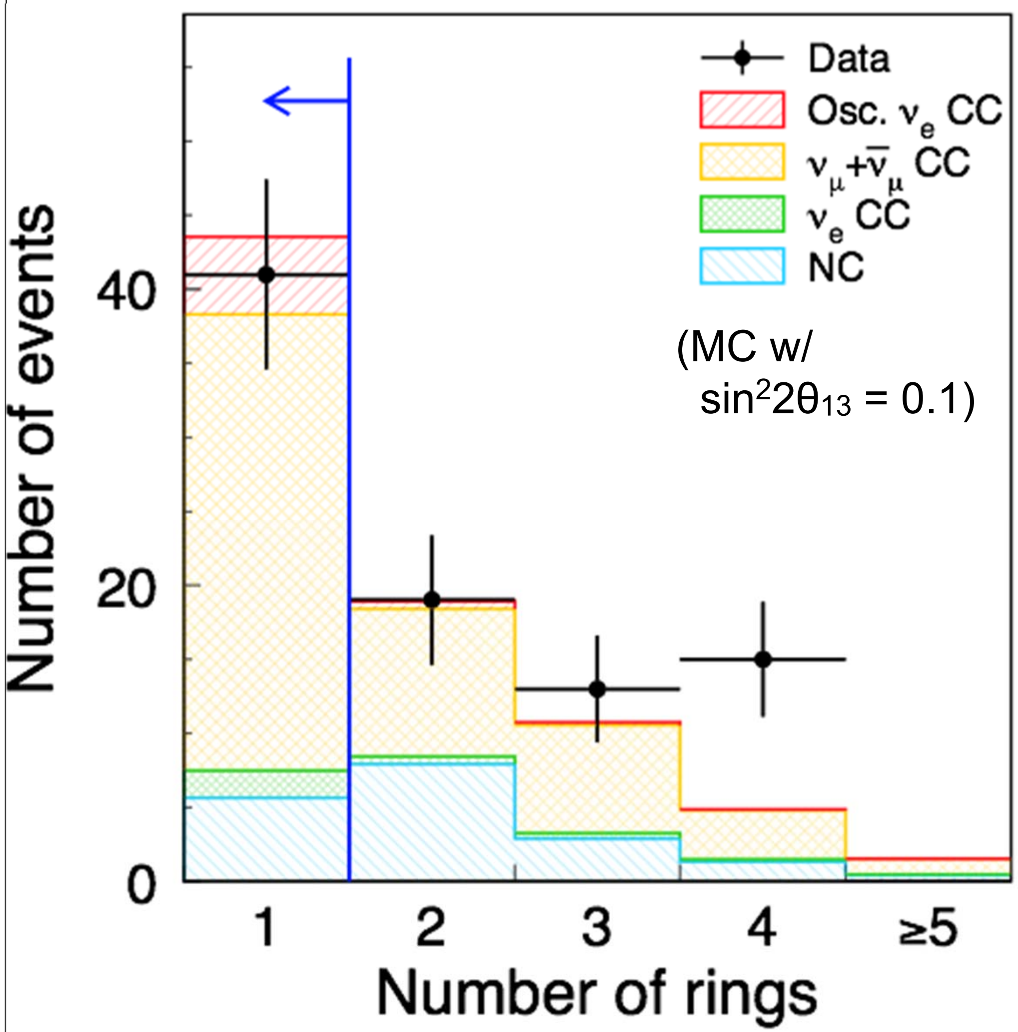
defined before the data collection
6 selection cuts in addition FC cut

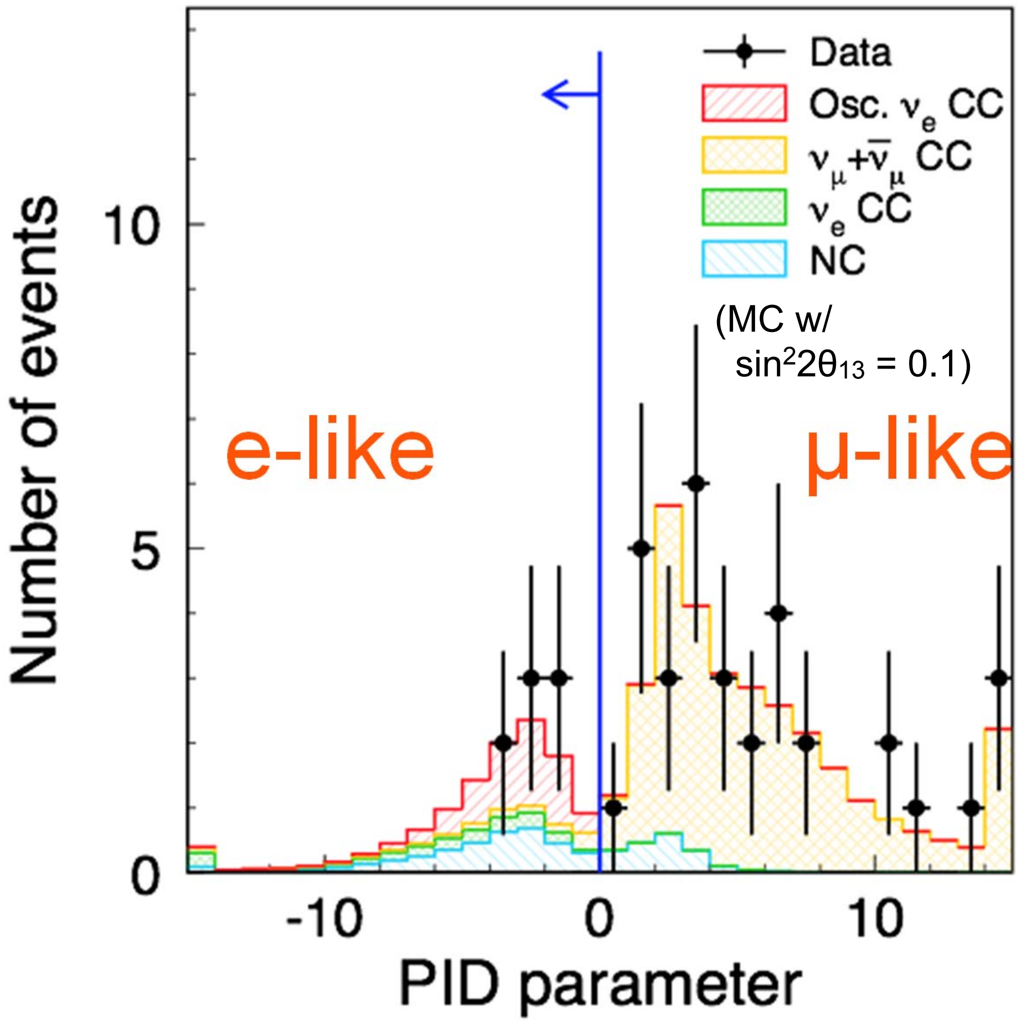
Fiducial volume cut

(distance between recon. vertex and wall > 200cm)

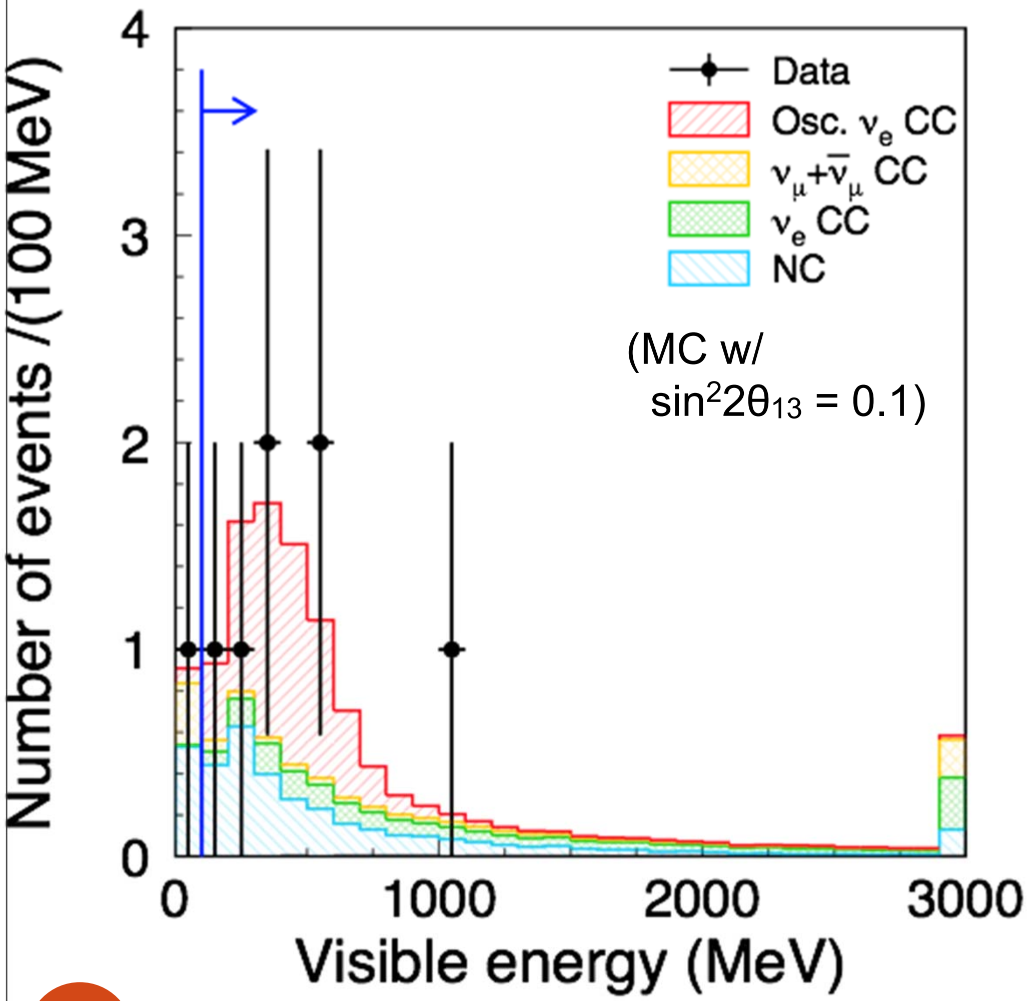


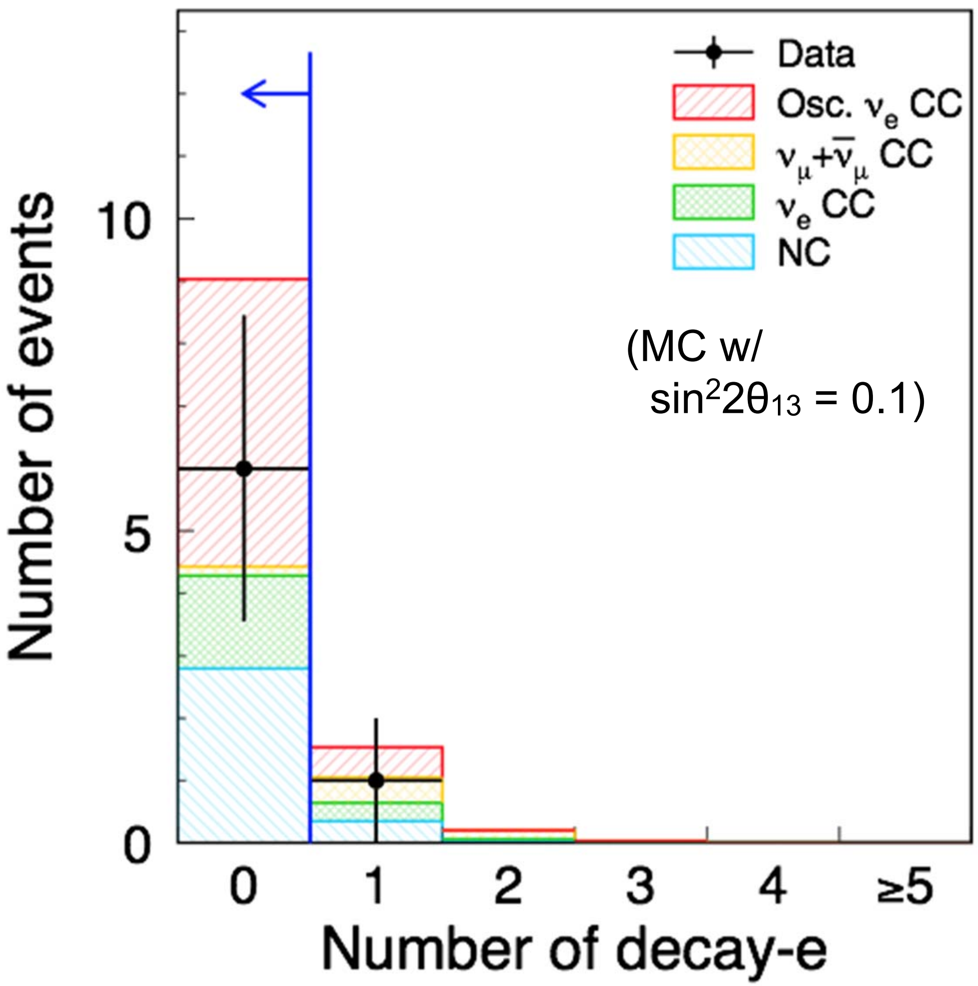
Single electron cut (# of ring is one & e-like)



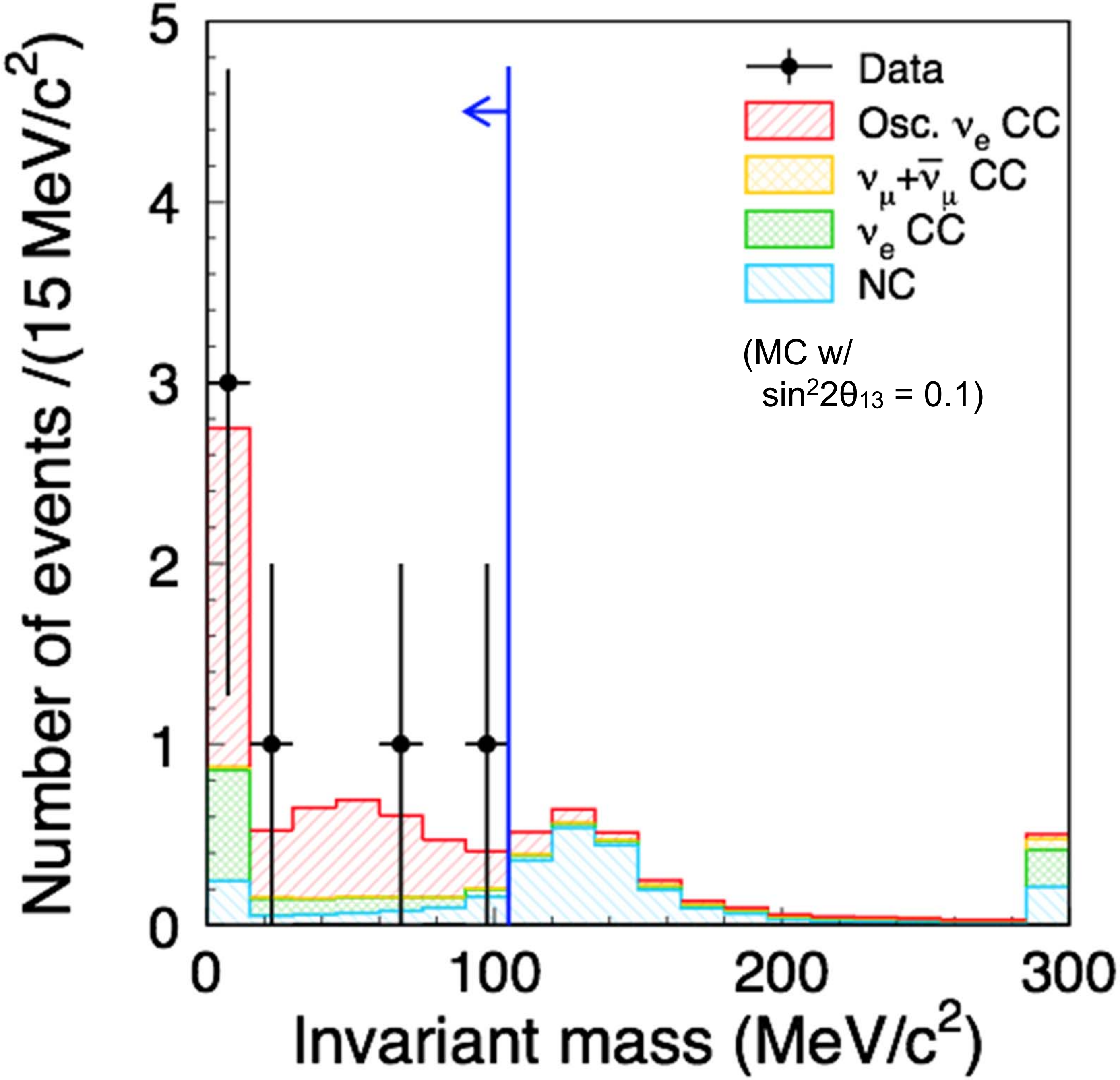


Visible energy > 100 MeV   No decay electron

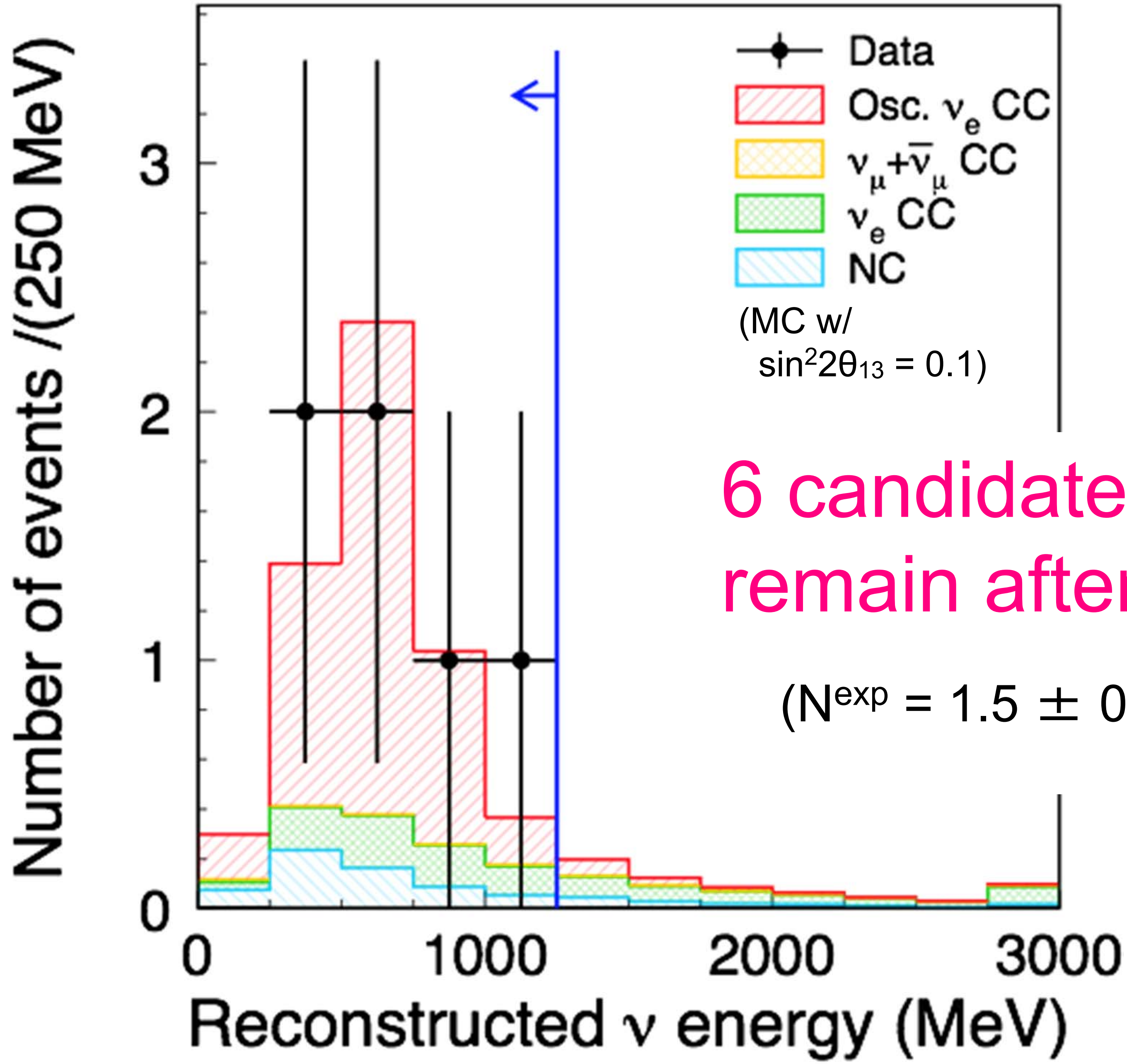




Invariant mass cut (M_{inv} < 105 MeV/c^2)



Reconstructed ν energy cut (E_{rec} < 1250 MeV) : *Final cut*

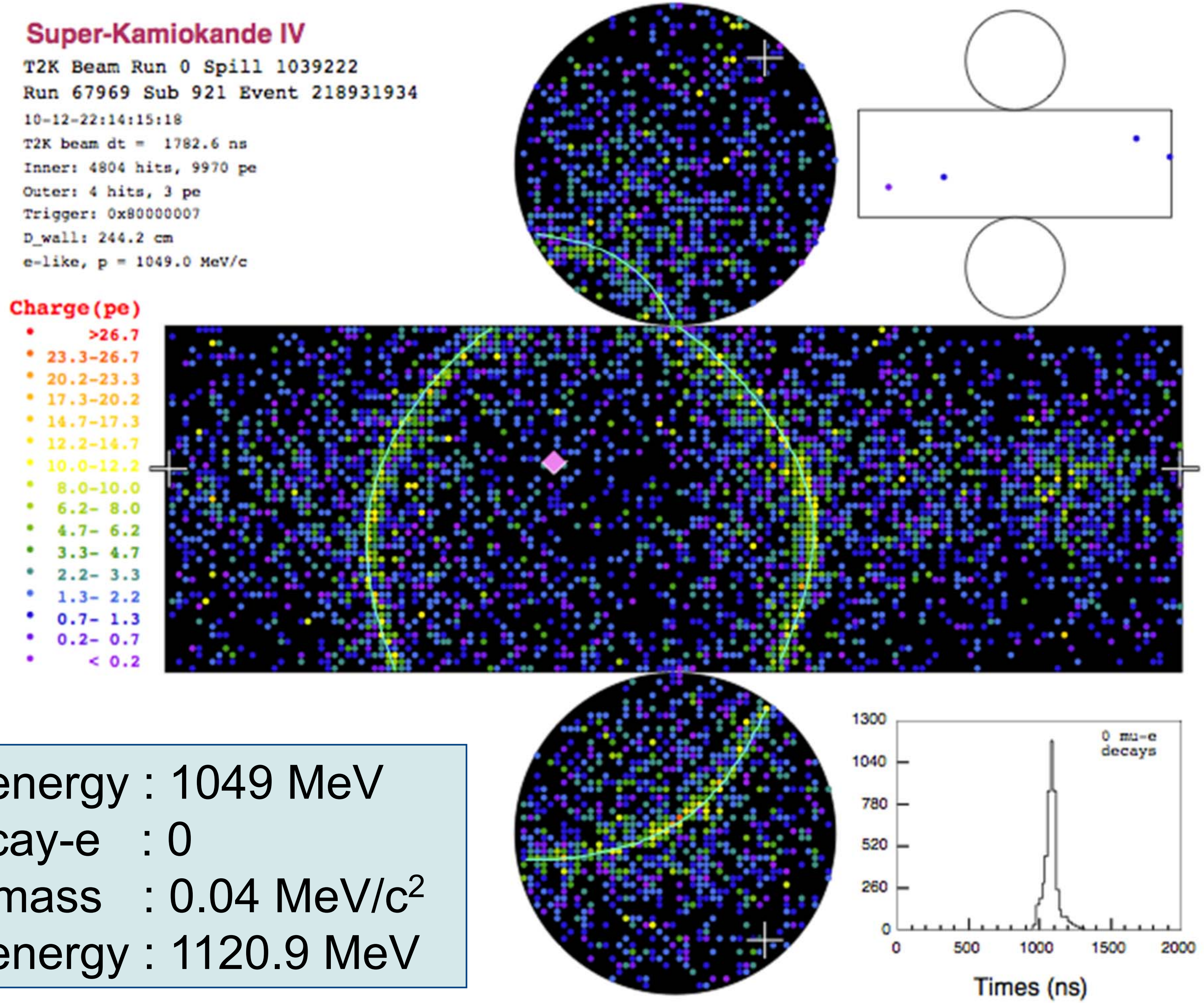


(MC w/ $\sin^2 2\theta_{13} = 0.1$)

6 candidate events remain after all cuts !!

($N^{exp} = 1.5 \pm 0.3$ at $\sin^2 2\theta_{13}=0$)

A ν_e candidate event



visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c^2
on. energy : 1120.9 MeV

Results for ν_e appearance search with 1.43 x 10^{20} p.o.t.

The observed number of events is **6**

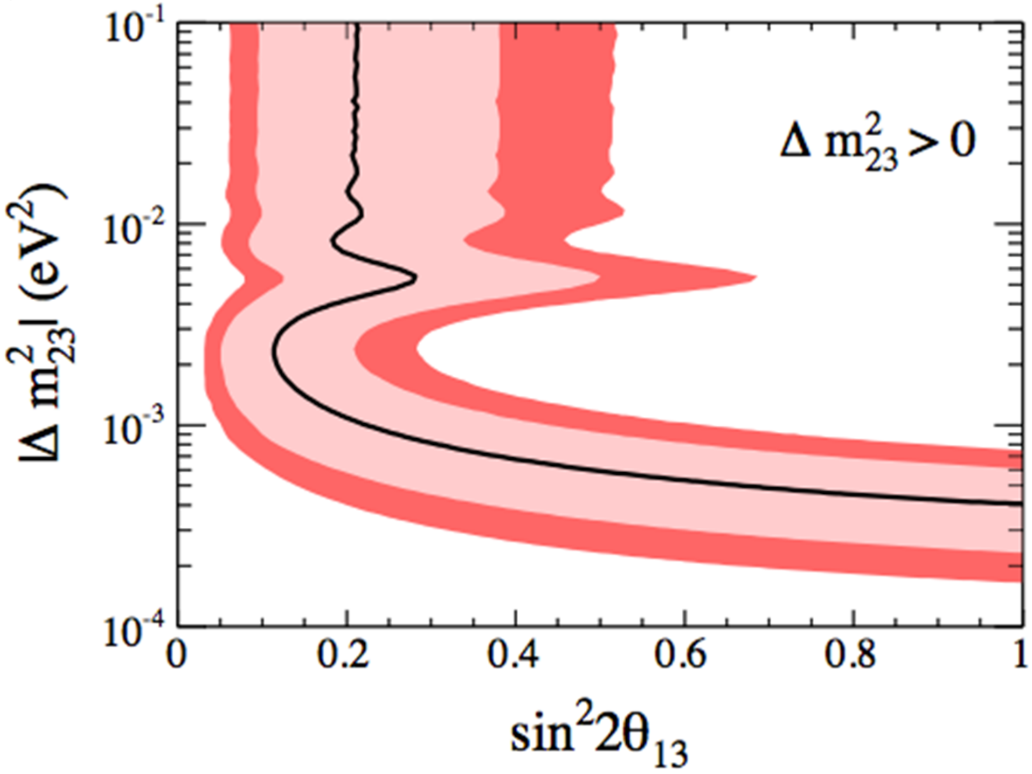
The expected number of events is **1.5 ± 0.3**

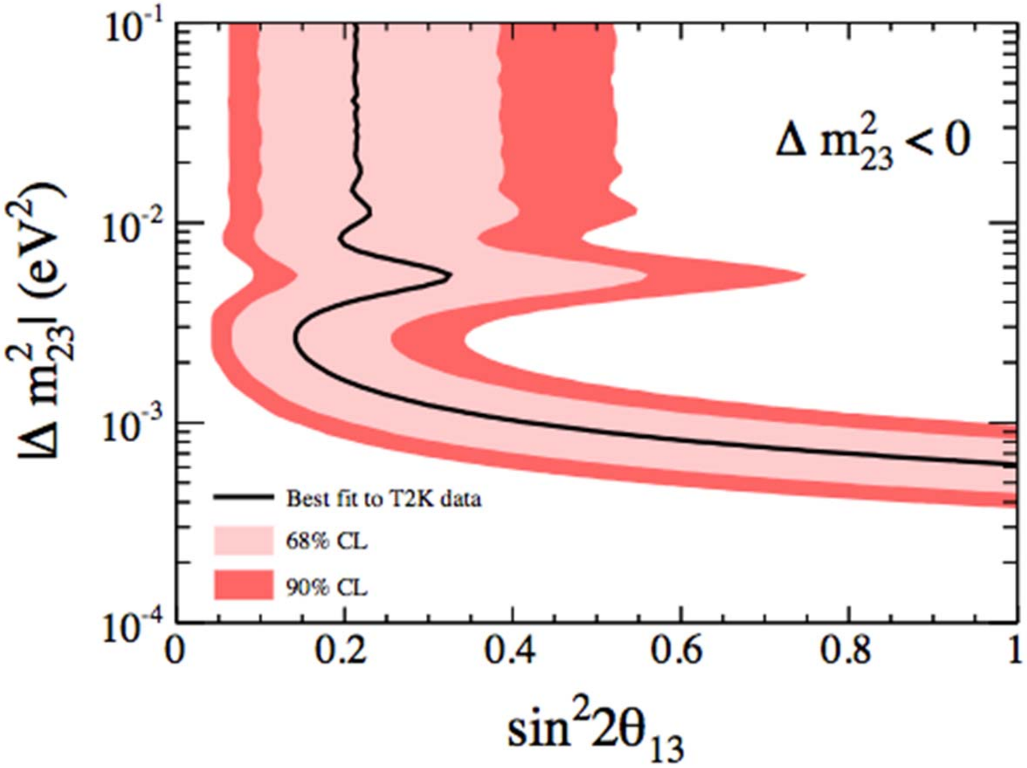
for $\sin^2 2\theta_{13}=0$

Under the $\theta_{13}=0$ hypothesis, the probability to observe six or more candidate events is 0.007 (equivalent to 2.5σ significance)

Allowed region of $\sin^2 2\theta_{13}$ as a function of Δm^2_{23}

(assuming $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

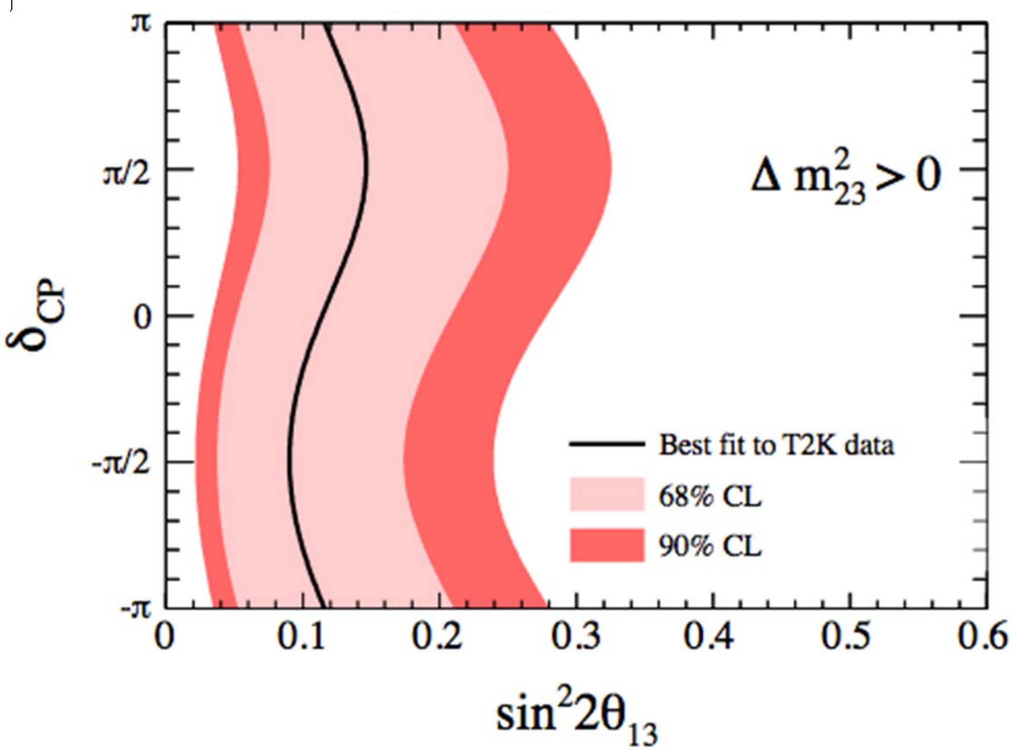


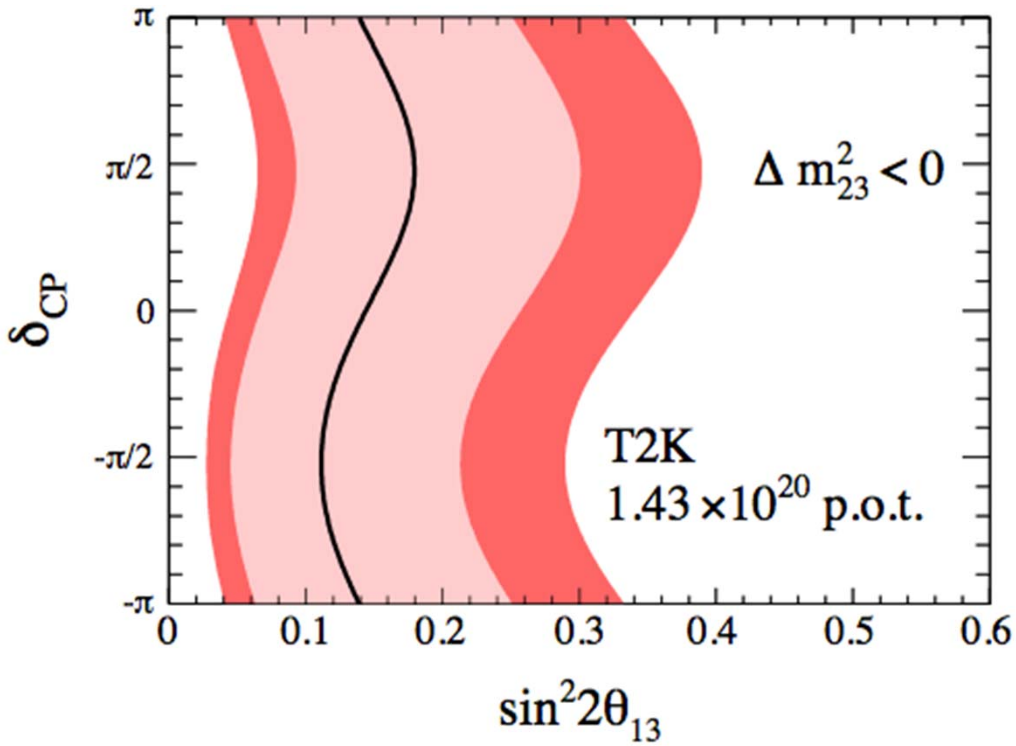


Feldman-Cousins method was used

Allowed region of $\sin^2 2\theta_{13}$ as a function of δ_{CP}

(assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$)





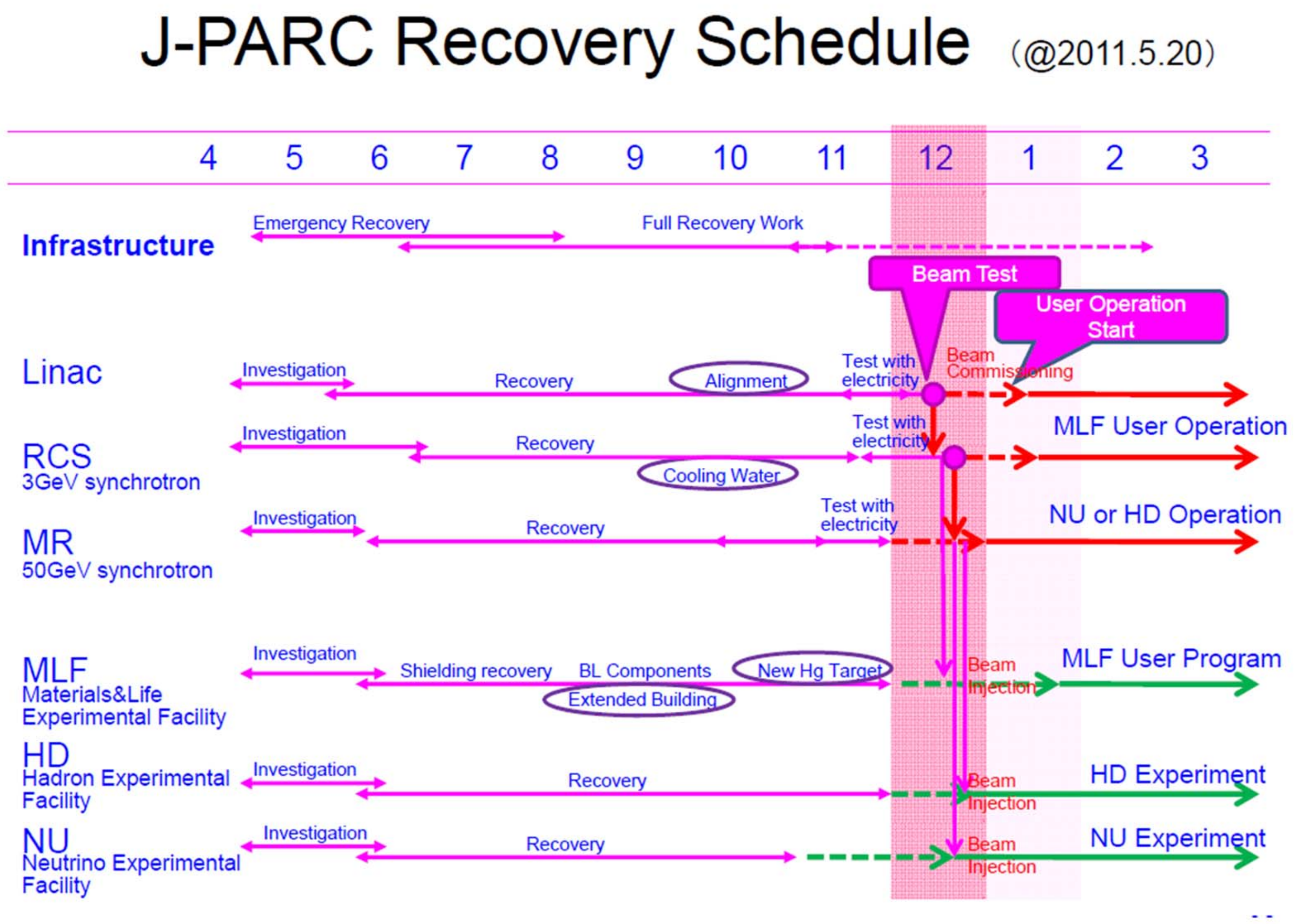
90% C.L. interval & Best fit point (assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

$0.03 < \sin^2 2\theta_{13} < 0.28$ | **$0.04 < \sin^2 2\theta_{13} < 0.34$**

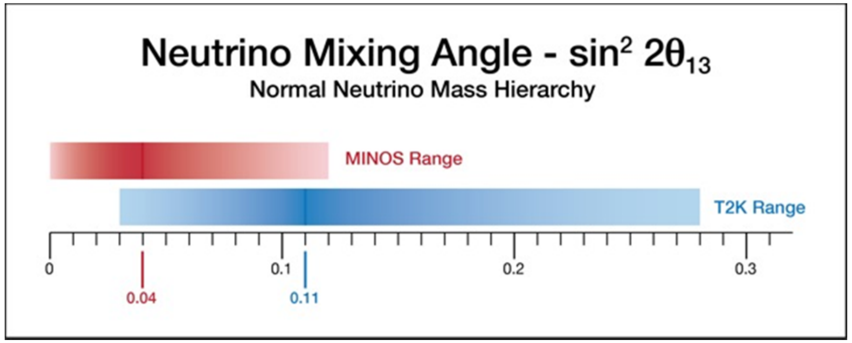
$\sin^2 2\theta_{13} = 0.11$ | **$\sin^2 2\theta_{13} = 0.14$**

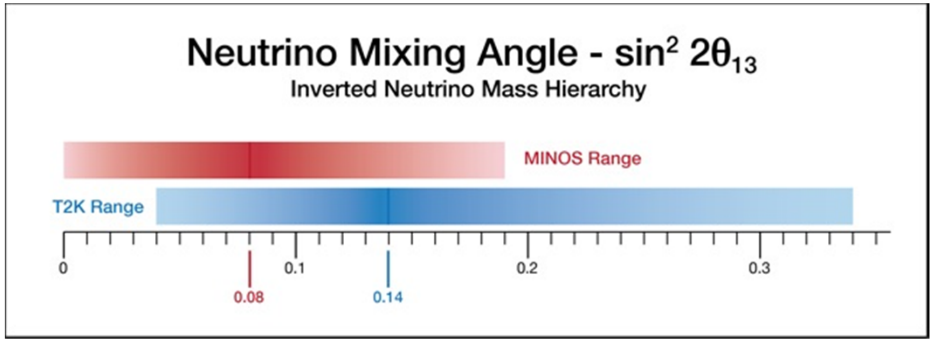
T2K Next steps

Aim for firmly establishing ν_e appearance and better determining the angle θ_{13}



Global fitting with T2K and MINOSdata





From MINOS presentation

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the mass-mixing parameters, assuming old reactor neutrino fluxes. By using new reactor fluxes, the corresponding best fits and ranges for $\sin^2\theta_{12}$ and $\sin^2\theta_{13}$ (in parentheses) are basically shifted by about +0.006 and +0.004, respectively, while the other parameters are essentially unchanged.

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.58	0.306	0.021	0.42	2.35
		(0.312)	(0.025)		
1σ range	7.32 – 7.80	0.291 – 0.324	0.013 – 0.028	0.39 – 0.50	2.26 – 2.47
		(0.296 – 0.329)	(0.018 – 0.032)		
2σ range	7.16 – 7.99	0.275 – 0.342	0.008 – 0.036	0.36 – 0.60	2.17 – 2.57
		(0.280 – 0.347)	(0.012 – 0.041)		
3σ range	6.99 – 8.18	0.259 – 0.359	0.001 – 0.044	0.34 – 0.64	2.06 – 2.67
		(0.265 – 0.364)	(0.005 – 0.050)		

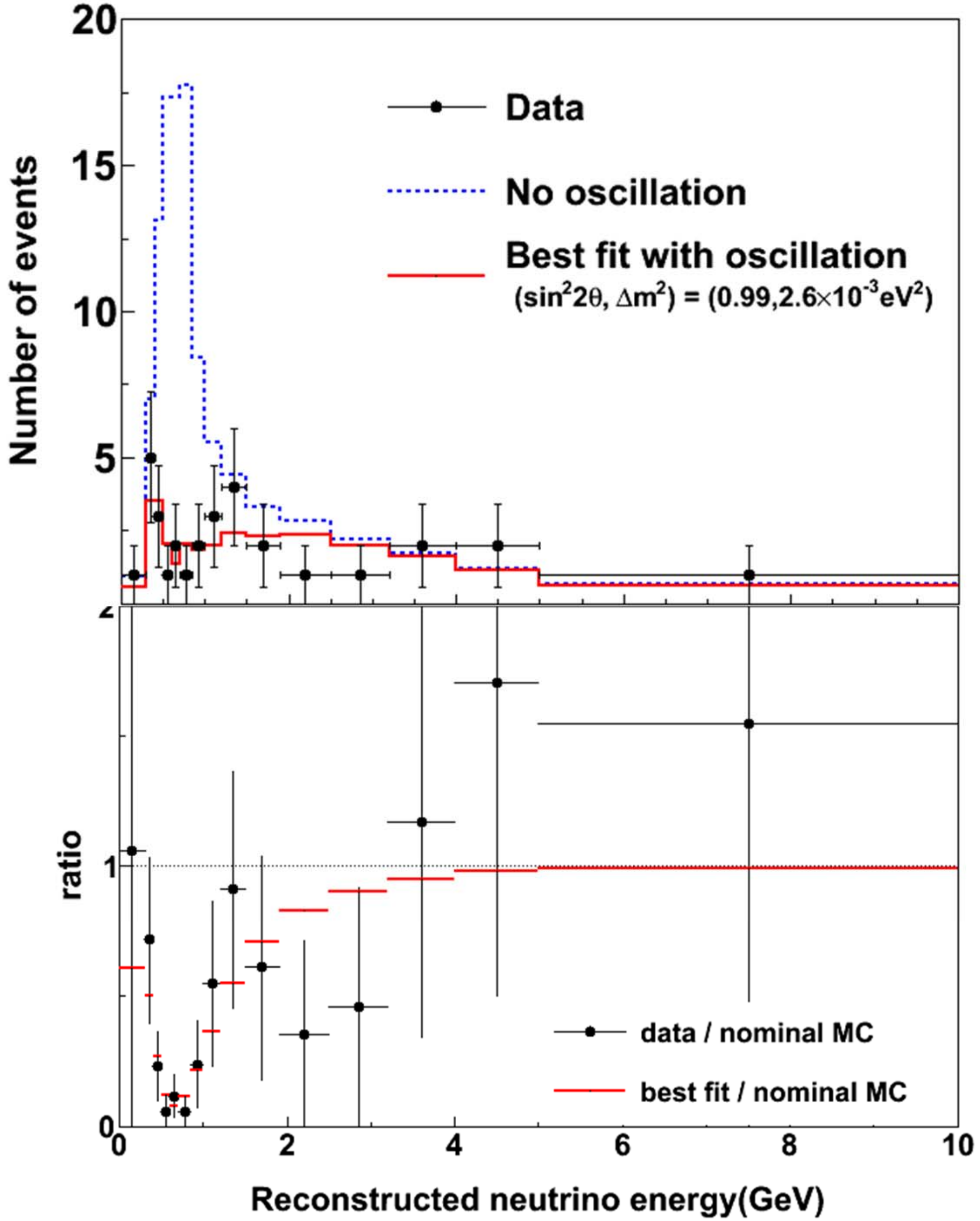
G.L.Fogli, et.al, arXiv:1106.6028v1 [hep-ph]

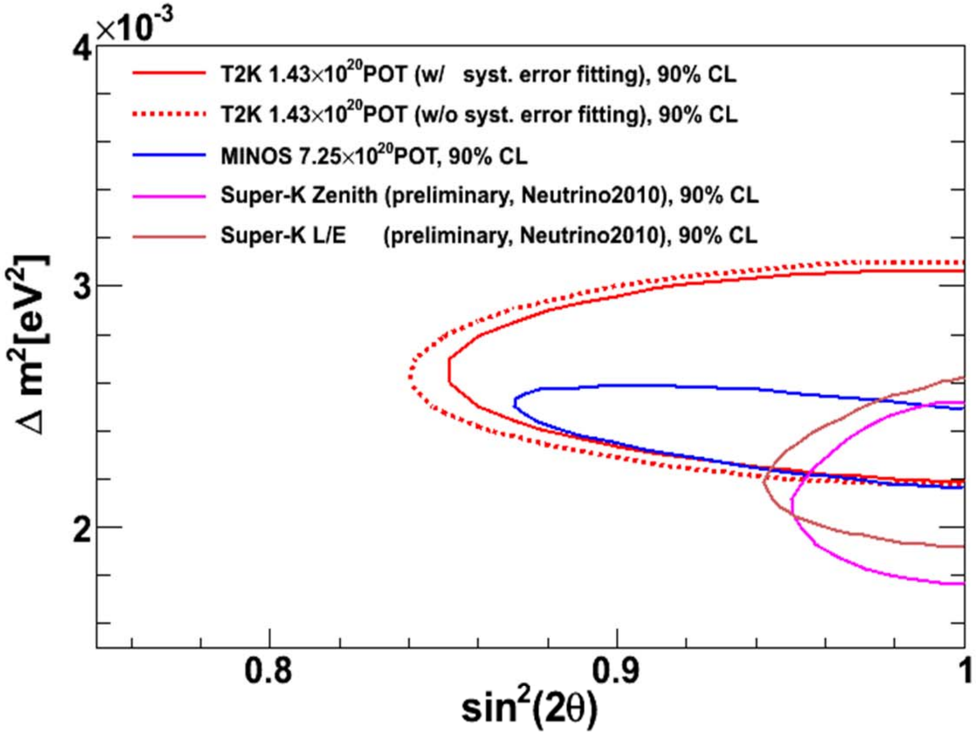
Best fit : $\sin^2\theta_{13}=0.021 \rightarrow \sin^2 2\theta_{13} = 0.084$

BTW, T2K ν_μ disappearance Just published!

	Data	MC w/ 2-flavor oscillation					MC w/o osc.
		Total	ν_μCCQE	ν_μCC non-QE	ν_eCC	NC	
Interaction in FV	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	243
FCFV	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	166
Single-ring	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	120
μ-like	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	112
$P_\mu > 200$ MeV/c	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	111
N(decay-e) ≤ 1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	104

$\sin^2 2\theta_{23}=1.0$, $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2 are assumed


Data
No oscillation
Best fit with oscillation
(sin²2θ, Δm²) = (0.99,2.6×10⁻³eV²)
Number of events
ratio
data / nominal MC
best fit / nominal MC
Reconstructed neutrino energy(GeV)

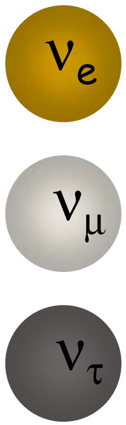

×10⁻³
T2K 1.43×10²⁰POT (w/ syst. error fitting), 90% CL
T2K 1.43×10²⁰POT (w/o syst. error fitting), 90% CL
MINOS 7.25×10²⁰POT, 90% CL
Super-K Zenith (preliminary, Neutrino2010), 90% CL
Super-K L/E (preliminary, Neutrino2010), 90% CL
Δ m²[eV²]
sin²(2θ)

What is the next step?

- CP violation
  - ✓ Fundamental understanding of the origin of lepton mass and mixing
  - ✓ First step to understand the matter dominant universe
- Mass hierarchy
  - ✓ Fundamental understanding of the origin of lepton mass and mixing
  - ✓ Inverted hierarchy is desirable for the discovery of neutrinoless double-beta decay $\rightarrow$ Proof Majorana neutrino and See-Saw mechanism

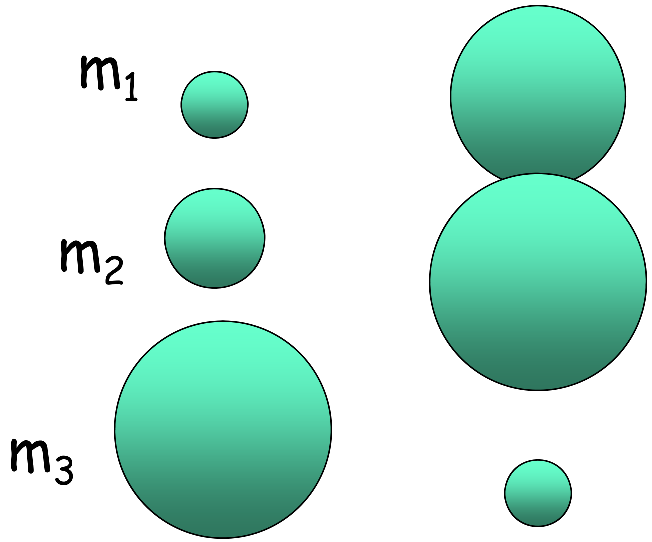
Three Flavor Mixing in Lepton Sector

Weak eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U}_{\mathrm{MNS}} \mathrm{V}_{\mathrm{M}}^{\mathrm{CP}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates



T2K, MINOS and reactor

Solar and reactor neutrino

$$\mathrm{U}_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

Atmospheric neutrino+T2K, MINOS

θ_{12}, θ_{23}, θ_{13}

+ δ (+2 Majorana phase)

Δm_{12}, Δm_{23}, Δm_{13}

ν_e appearance (simplified, δ=0 version)

L is too small, or E is too high for Δm_{12}^2 to oscillate

Oscillation Probabilities when $\Delta m_{23}^2 \frac{L}{4E} \sim \frac{\pi}{2}$

neglect Δm_{12}^2 term because $\Delta m_{12}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2$

- θ_{13}:ν_e appearance

$$P_{\mu\to e} \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\Delta m_{13}^2 L / 4E_\nu\right)$$

ν_e appearance (complete version w/o matter effect)

Leading term at around atm. osciilation maximum

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}$$ θ13

$$+8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$ CPC

$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$ CPV

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21}$$ Solar

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}$$

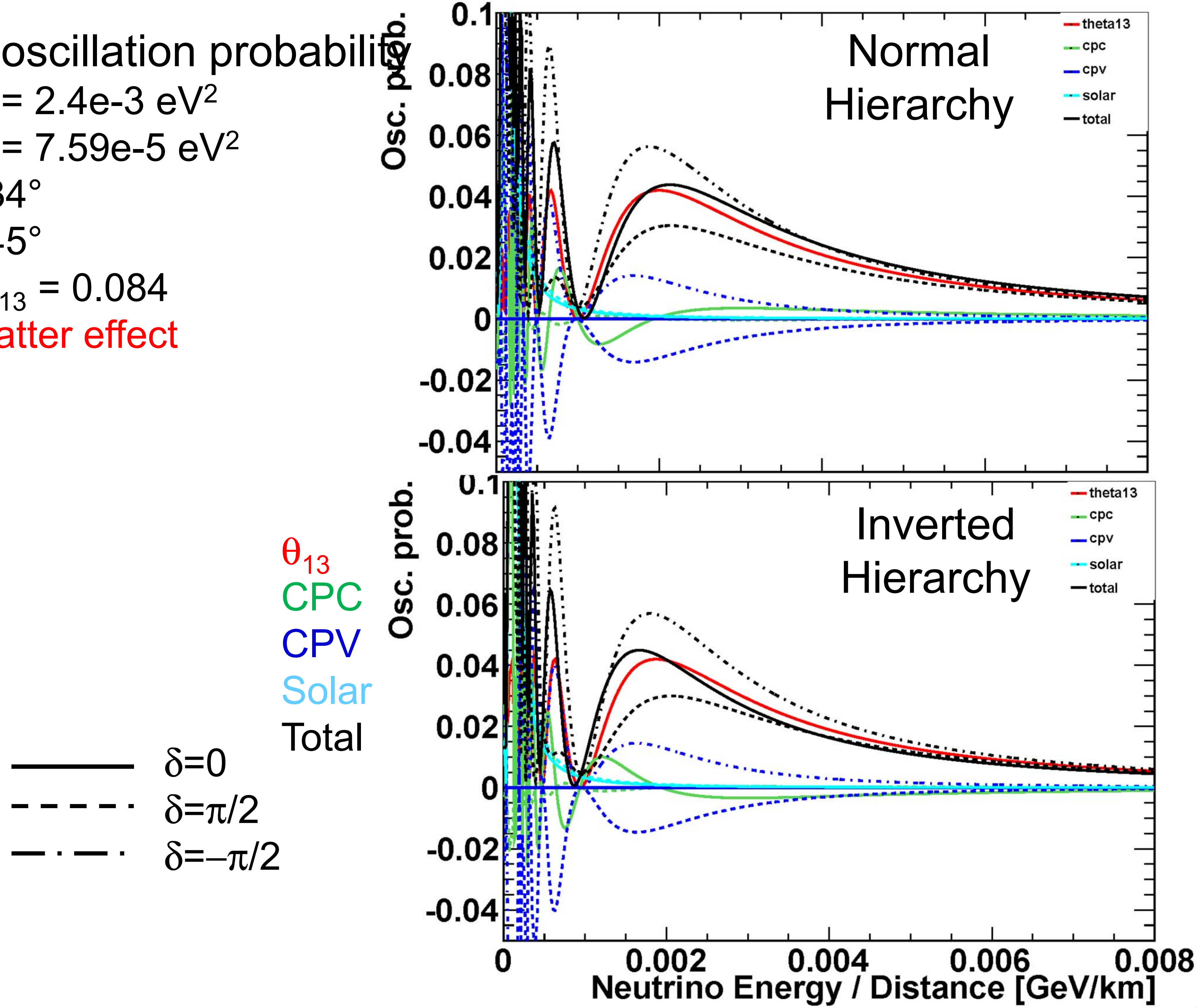
$$\Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

$\delta \to -\delta$ for P(anti-ν_μ → anti-ν_e)

CP violating term introduced by interference btw. θ_{13} and θ_{12}

$\nu_\mu \rightarrow \nu_e$ oscillation probability

- Δm^2_{23} = 2.4e-3 eV^2
- Δm^2_{12} = 7.59e-5 eV^2
- $\theta_{12} = 34°$
- $\theta_{23} = 45°$
- $\sin^2 2\theta_{13} = 0.084$
- w/o matter effect



$\nu_\mu \rightarrow \nu_e$ oscillation probability

- $\Delta m^2_{23} = 2.4\text{e-}3\ \text{eV}^2$
- $\Delta m^2_{12} = 7.59\text{e-}5\ \text{eV}^2$
- $\theta_{12} = 34°$
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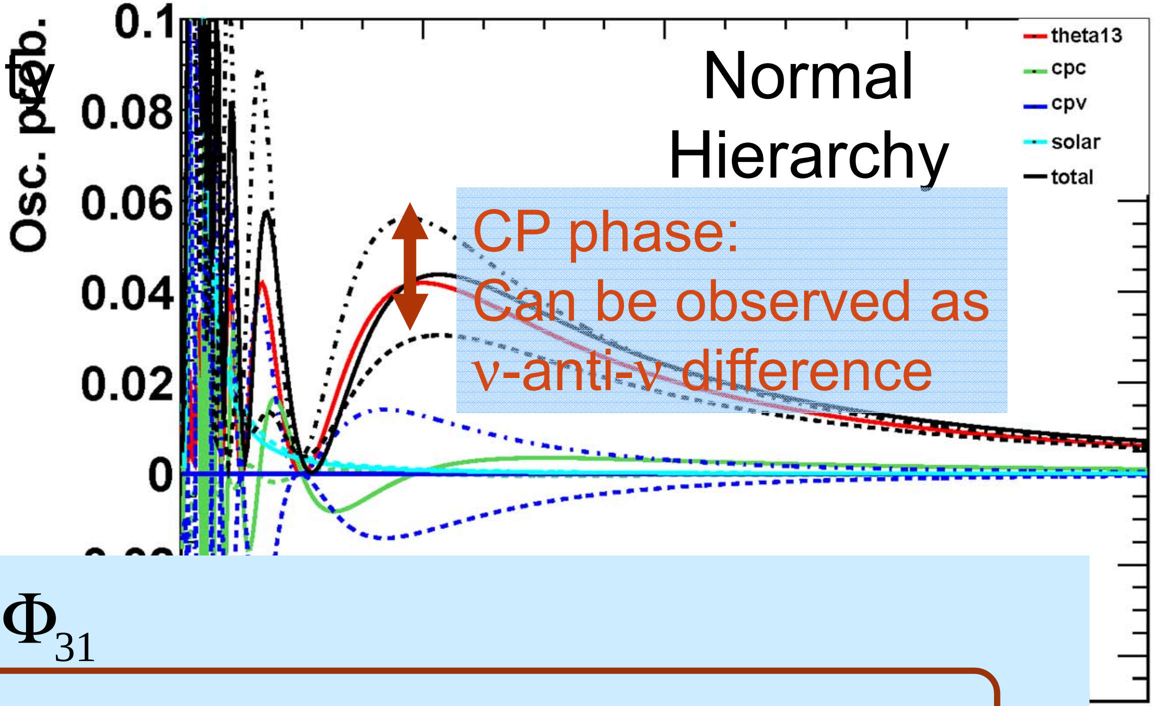
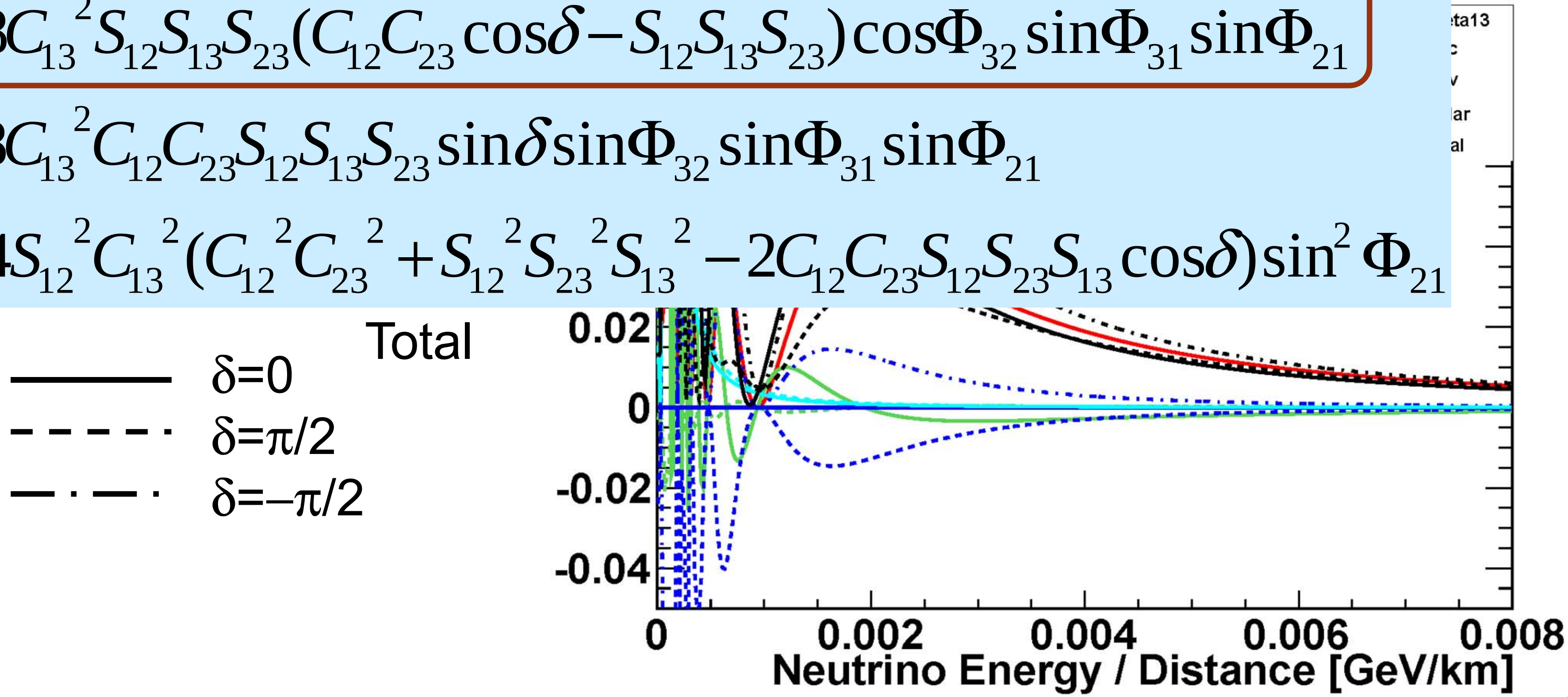


$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}$$
$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$
$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$
$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21}$$



$\nu_\mu \rightarrow \nu_e$ oscillation probability

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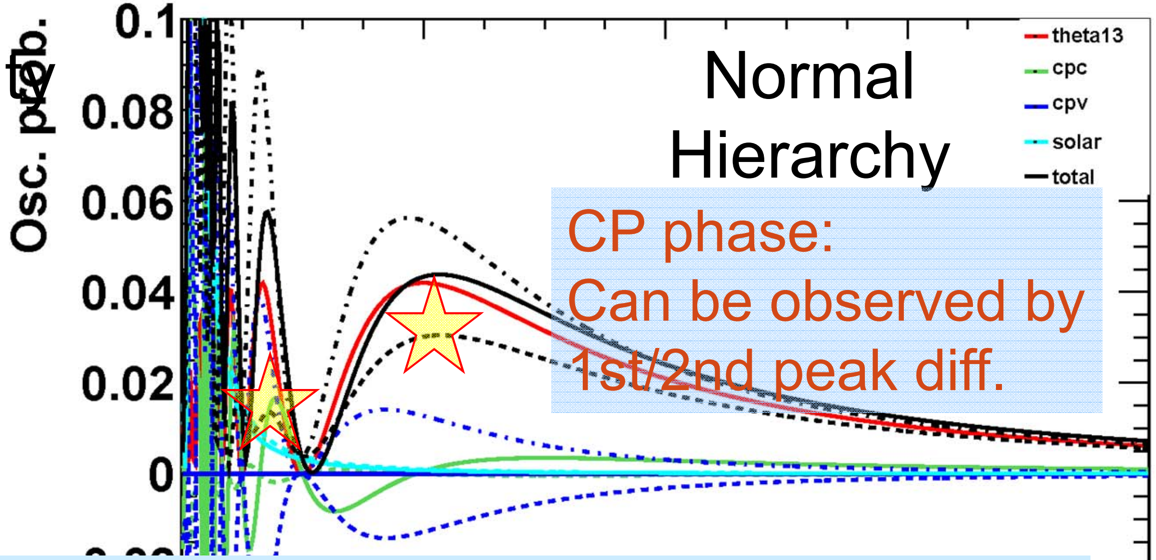
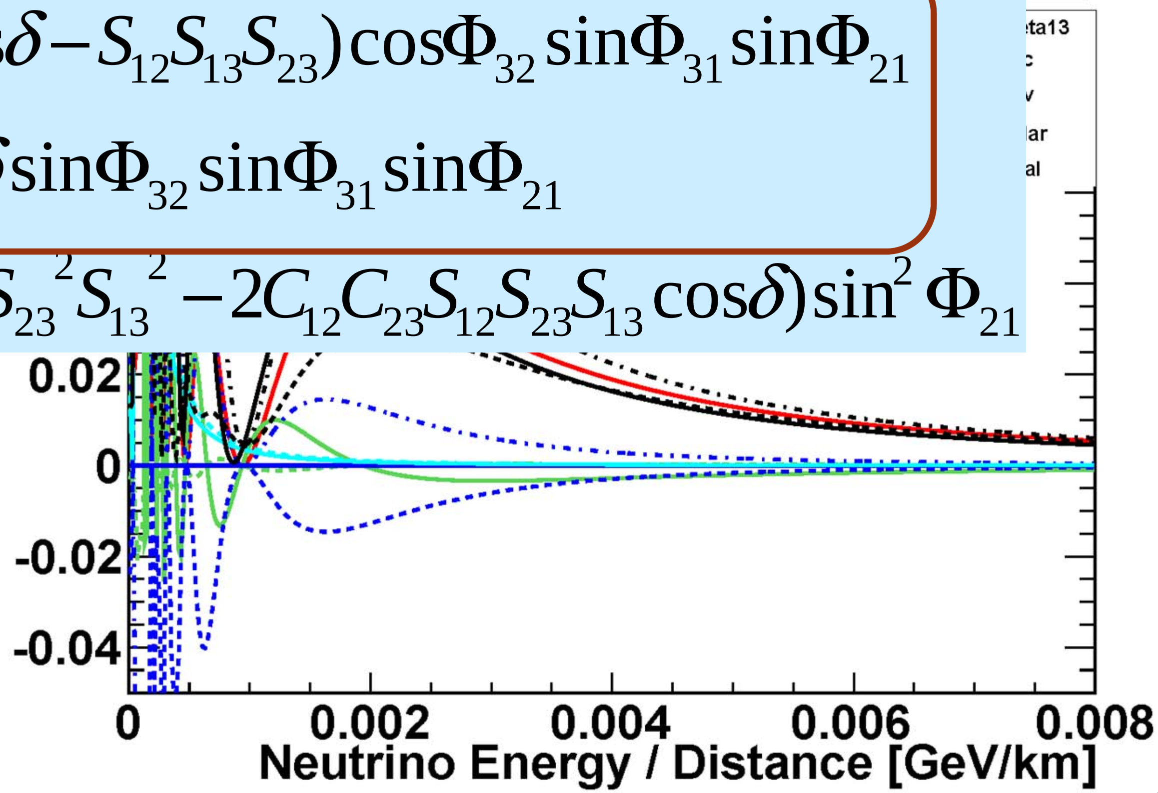


$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31}$$
$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$
$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$
$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21}$$

Total

- δ=0 (solid)
- δ=π/2 (dashed)
- δ=−π/2 (dash-dot)



$\nu_\mu \rightarrow \nu_e$ oscillation probability

- $\Delta m^2_{23} = 2.4\text{e-}3\ \text{eV}^2$
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- $\theta_{12} = 34°$
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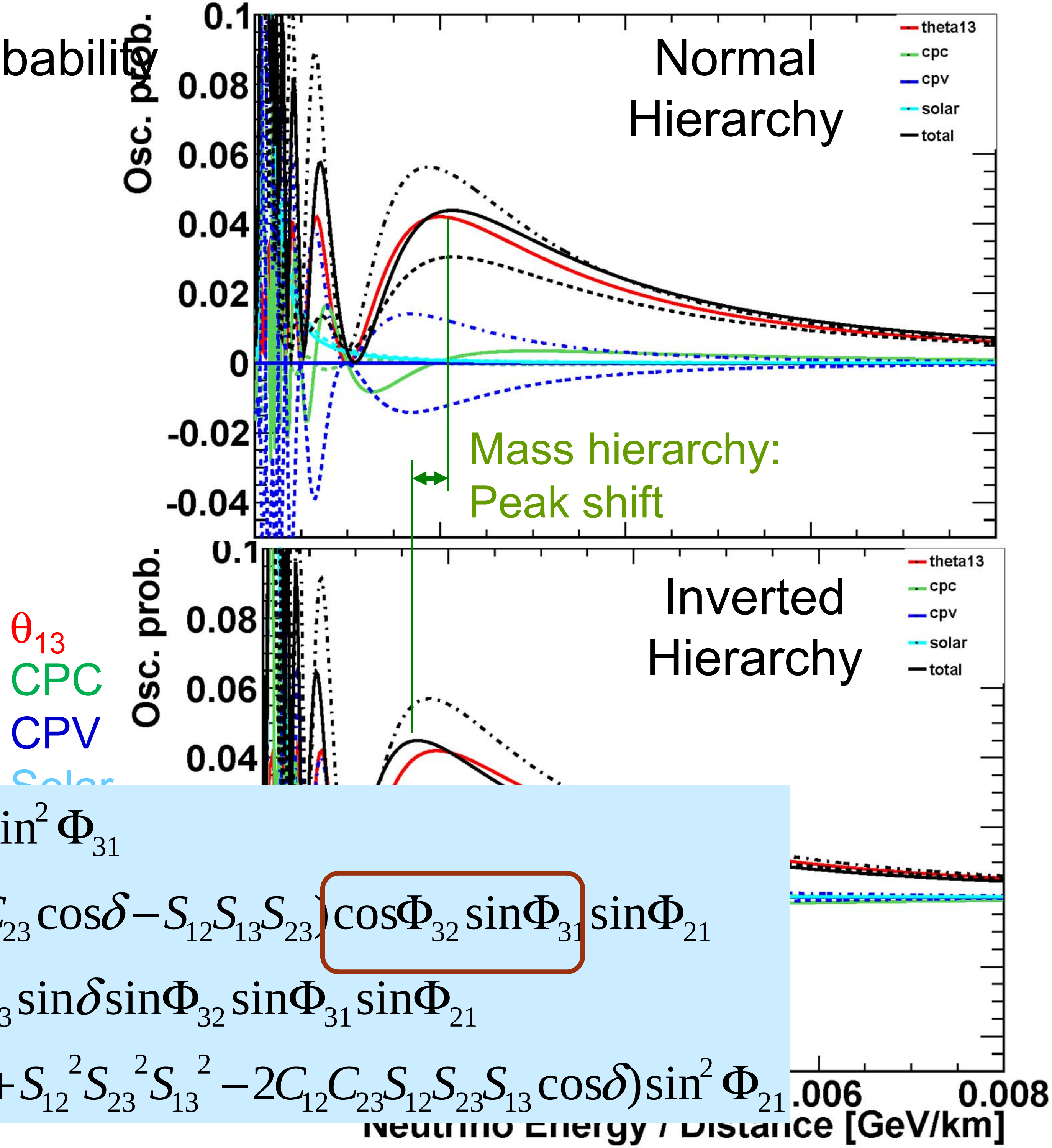


$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^{\ 2} S_{13}^{\ 2} S_{23}^{\ 2} \sin^2 \Phi_{31}$$
$$+8C_{13}^{\ 2} S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$
$$-8C_{13}^{\ 2} C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$
$$+4S_{12}^{\ 2} C_{13}^{\ 2} (C_{12}^{\ 2} C_{23}^{\ 2} + S_{12}^{\ 2} S_{23}^{\ 2} S_{13}^{\ 2} - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21}$$

ν_e appearance (w matter effect)

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2S_{13}^2\right)\right)$$

$$+8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

$$+4S_{12}^2 C_{13}^2(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2(1-2S_{13}^2)\frac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31}$$

θ_{13}

CPC

CPV

Solar

$a \to -a$, $\delta \to -\delta$ for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

L=295km, <E$_\nu$> ~0.6GeV

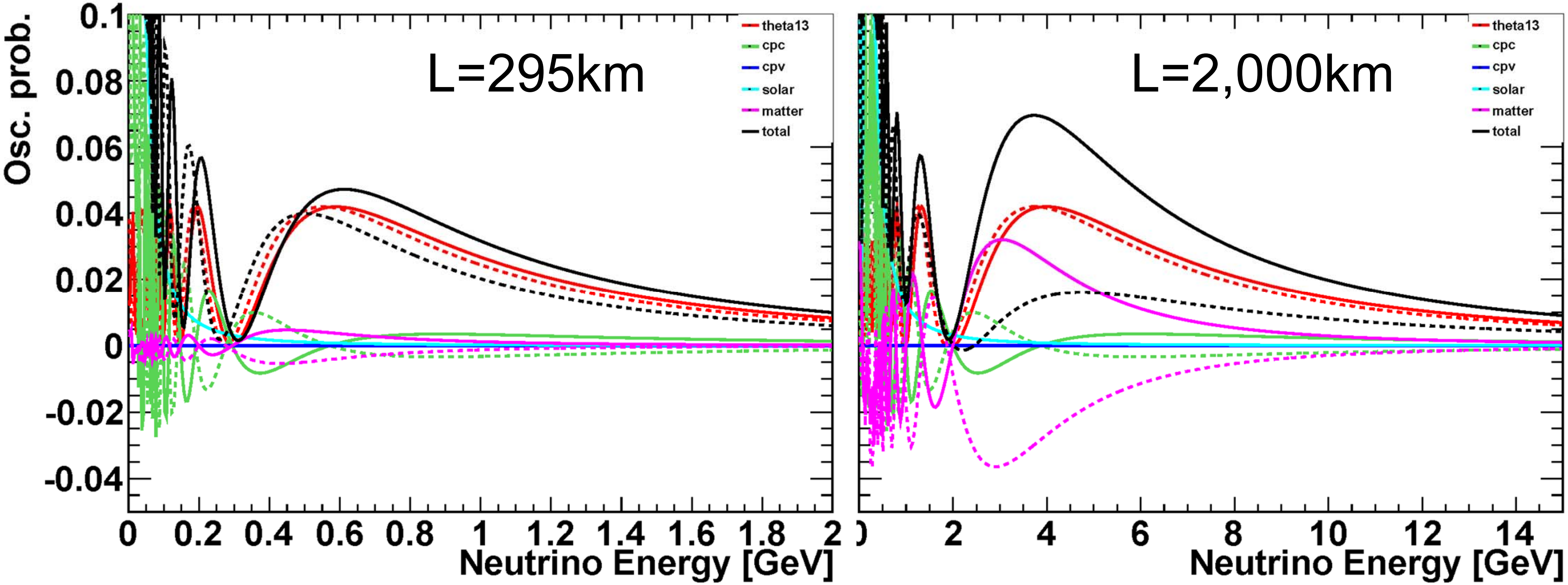
$$a = 7.56\times10^{-5}[\mathrm{eV}^2]\cdot\left(\frac{\rho}{[\mathrm{g/cm}^3]}\right)\cdot\left(\frac{E}{[\mathrm{GeV}]}\right)$$

$\nu_\mu \to \nu_e$ oscillation probability

- $\Delta m^2_{23} = 2.4e\text{-}3\ eV^2$
- $\Delta m^2_{12} = 7.59e\text{-}5\ eV^2$
- $\theta_{12} = 34°$
- $\theta_{23} = 45°$
- $\sin^2 2\theta_{13} = 0.084$
- w/ matter effect (ρ=2.8 g/cm^3)

θ_{13}
CPC
CPV
Solar
Total

Normal hierarchy (solid line)
Inverted hierarchy (dashed line)



$\nu_\mu \rightarrow \nu_e$ oscillation probability

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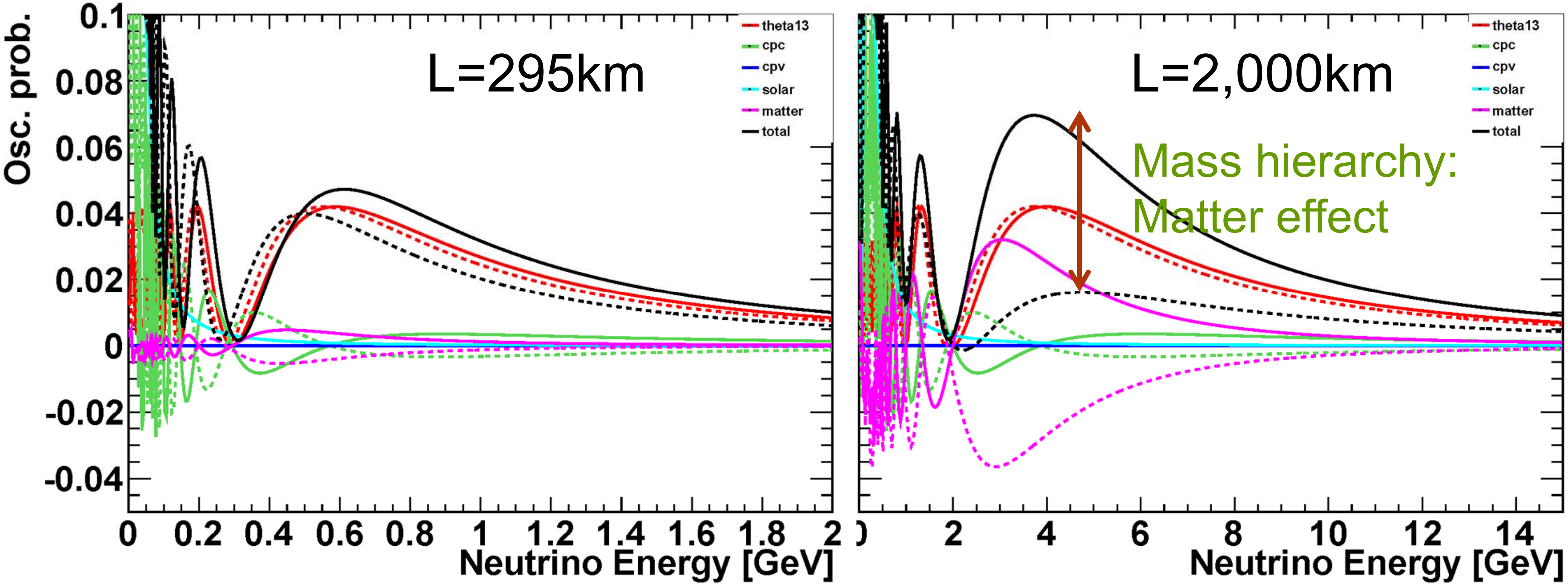
- w/ matter effect (ρ=2.8 g/cm^3)

θ_{13}
CPC
CPV
Solar
Total

——— Normal hierarchy
- - - - Inverted hierarchy



One note

Large θ_{13} is a good news in a sense that,

- ✓ Can be observed
- ✓ S/N is large

But.. CP or matter effect become relatively small

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m_{12}^2 L}{4E_\nu} \bullet \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \bullet \sin\delta$$

$$\approx 0.046 \times \frac{\sin\delta}{\sin\theta_{13}} \text{ @oscillation maximum}$$

So anyway, we need higher statistics, better S/N, smaller systematic error to go further.

How much improvement do we need?

$$\Delta_{stat} A_{CP} = \frac{1 - A_{CP}}{\sqrt{2N_0}}$$

, here N_0 is $\#\nu_e$ or anti-ν_e when $\delta=0$

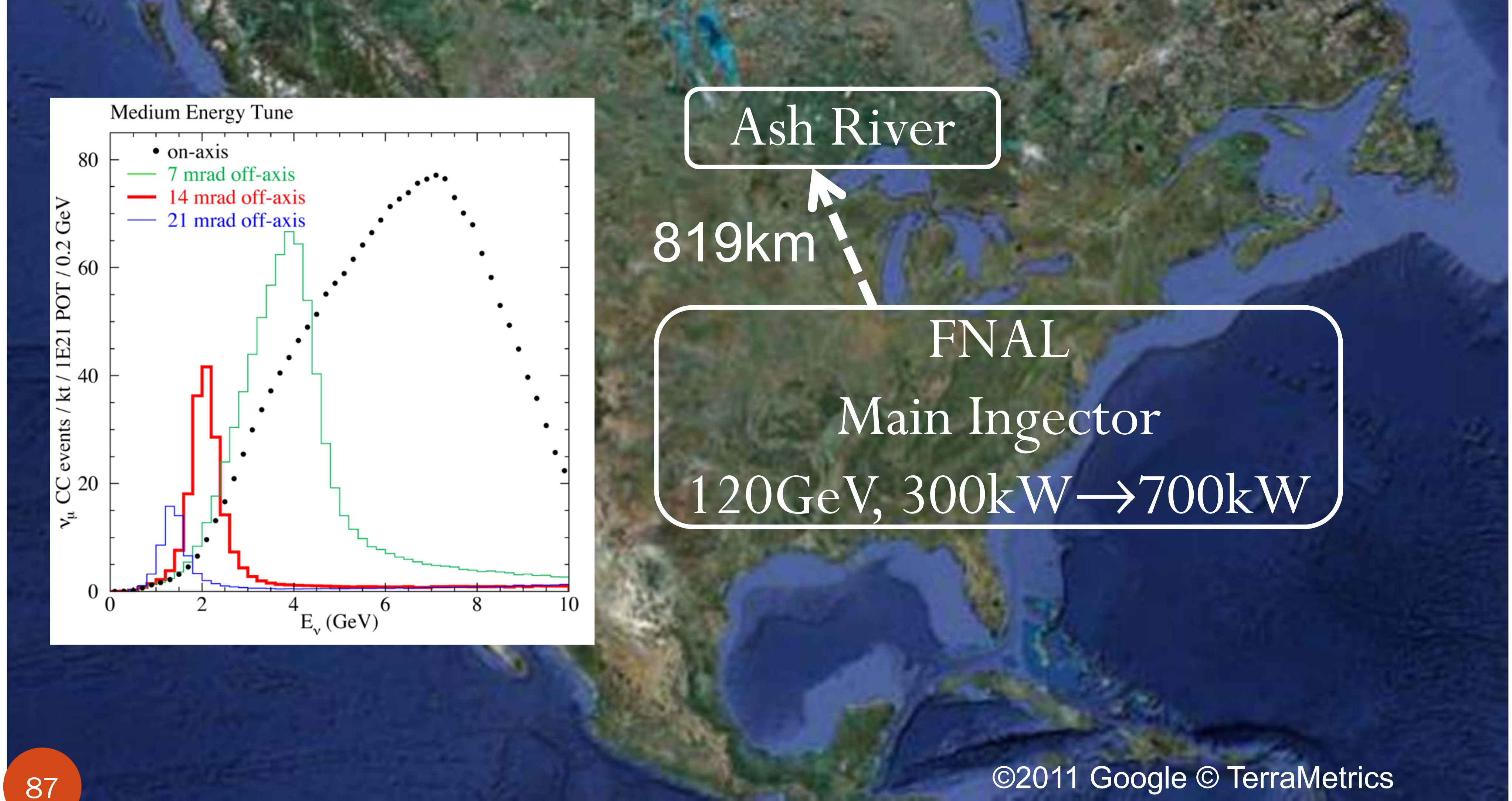
⇒ $N_0 > 10{,}000$ for 3σ $\delta > \pi/5$ discovery when $\sin^2 2\theta_{13} \sim 0.084$

(* anti-ν cross setion ~ 1/3 ν cross section)

NOνA experiment

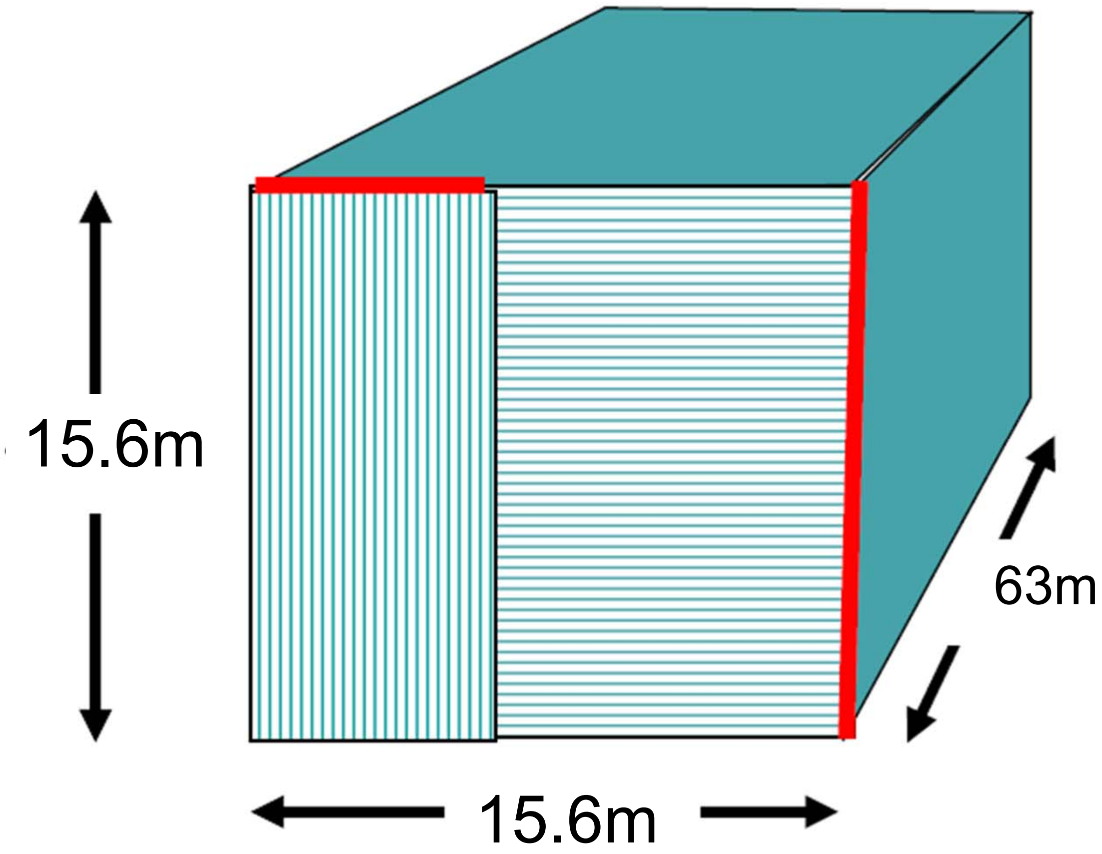
partially start 2011 and Far detector complete in 2013?

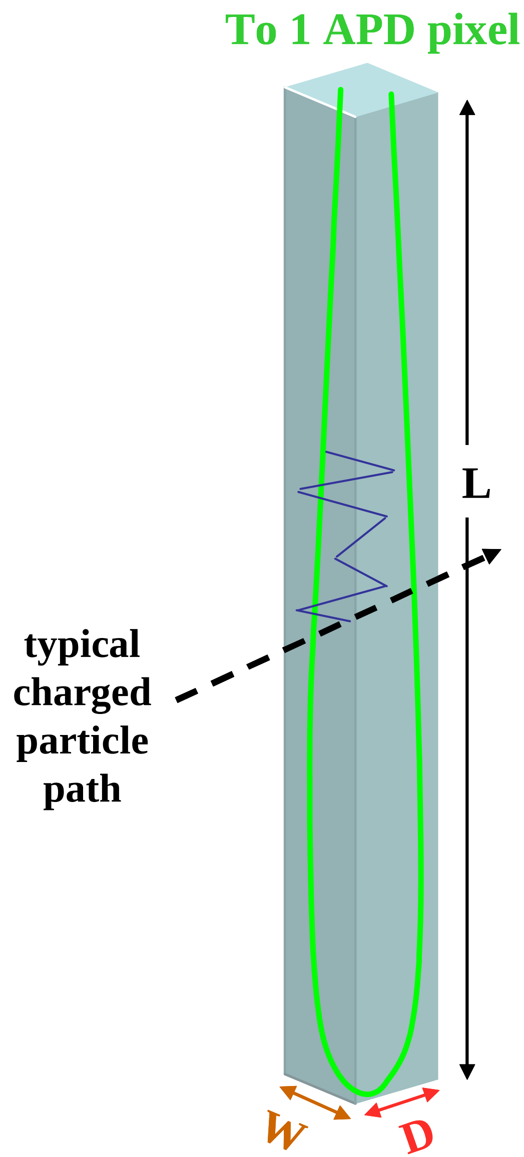
NuMI Off-Axis ν_e Appearance Experiment



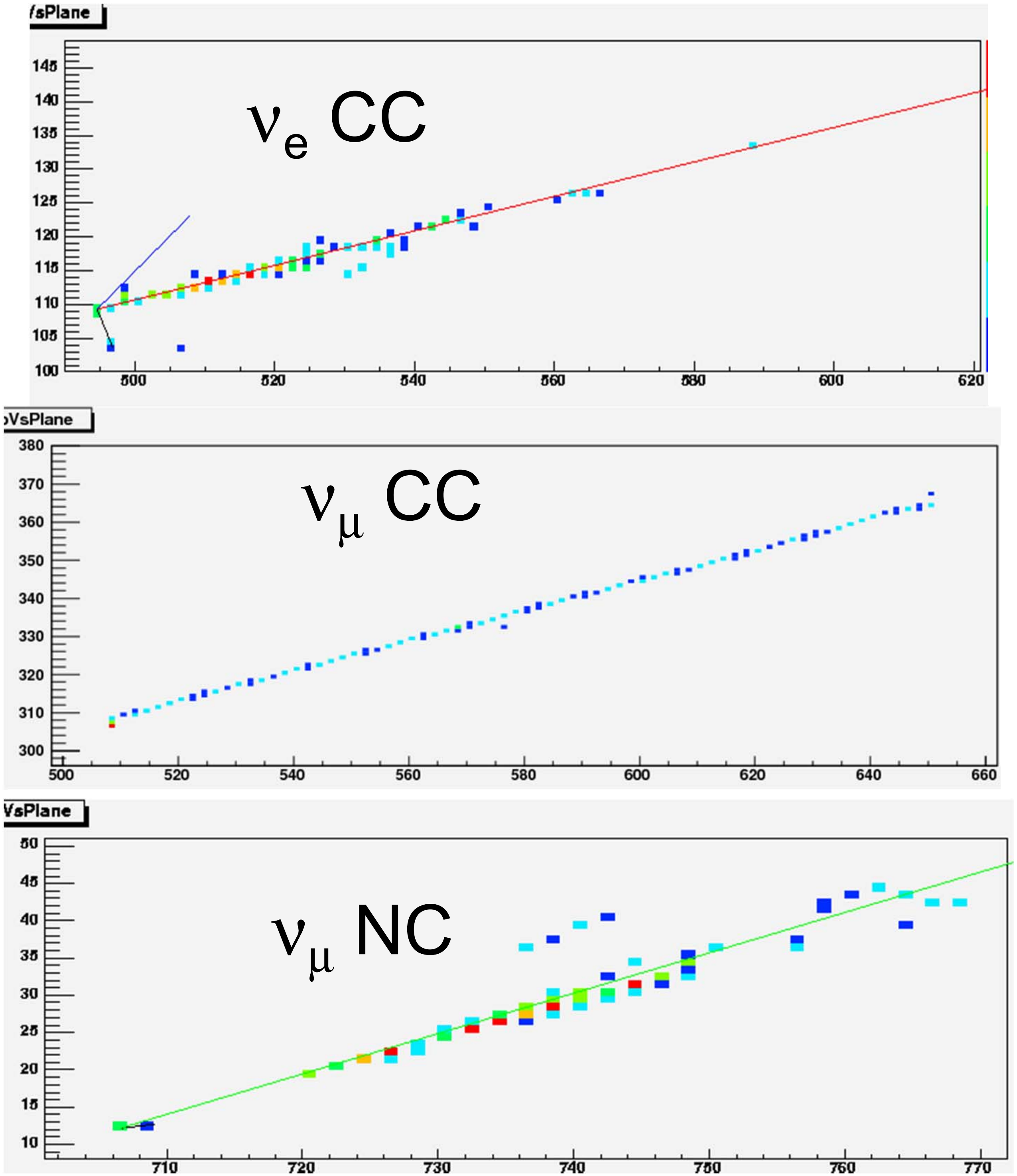
NOνA Far Detector

- 14 ktons
- 930 liquid scintillator planes, (~73% active)
- Scintillator cells 3.8 x 6.0 x 1540 cms
- Expected average signal at far end of 30pe

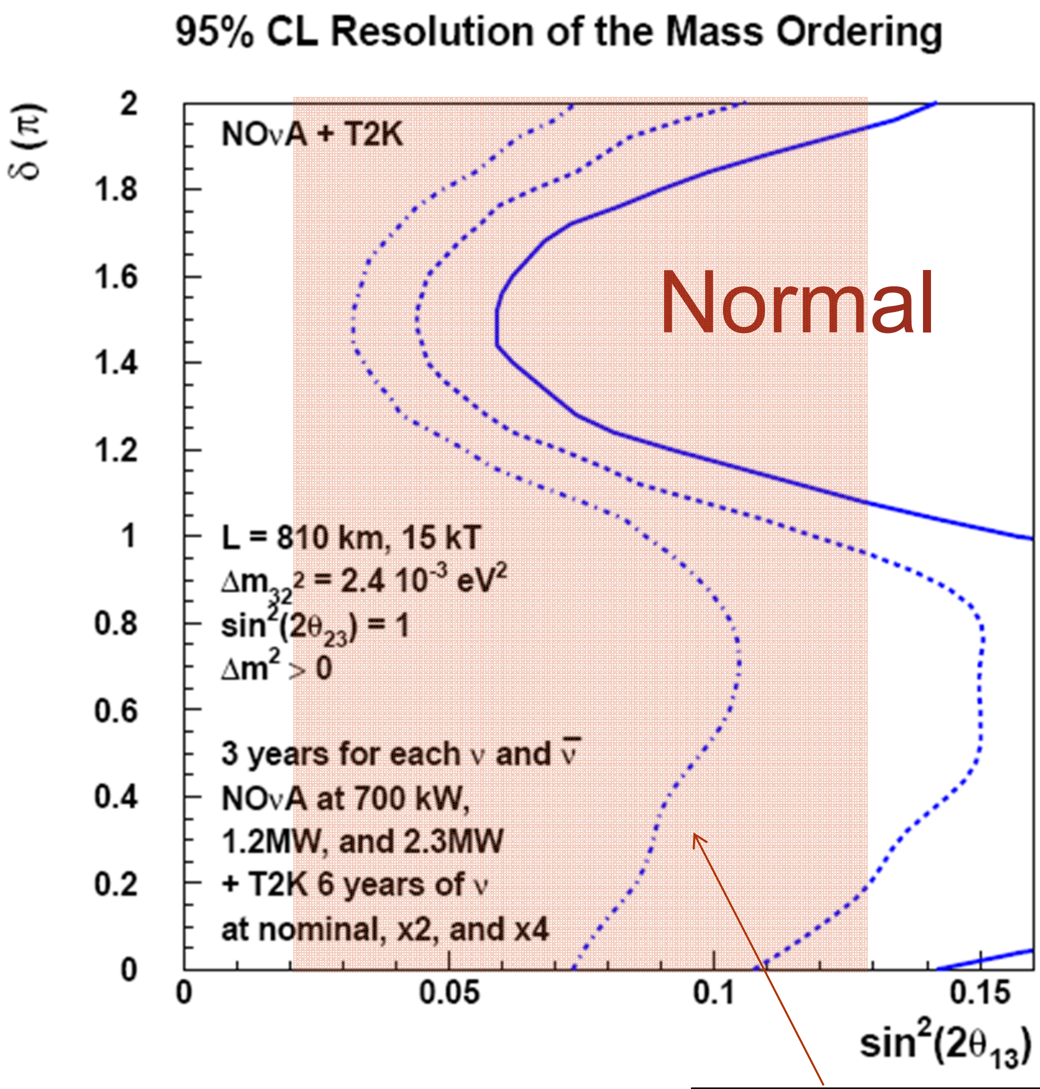


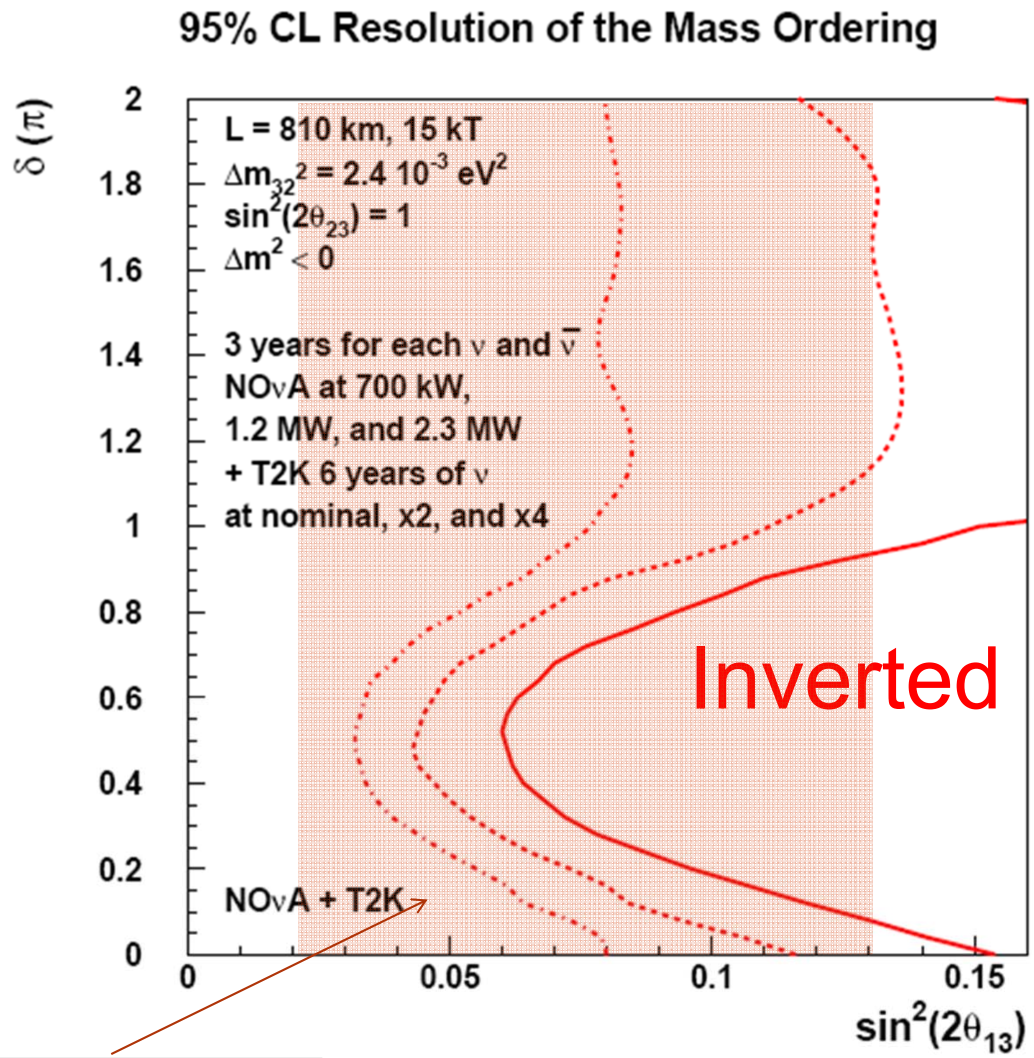


Example event display (MC)



95% CL Sensitivity to the Mass Ordering

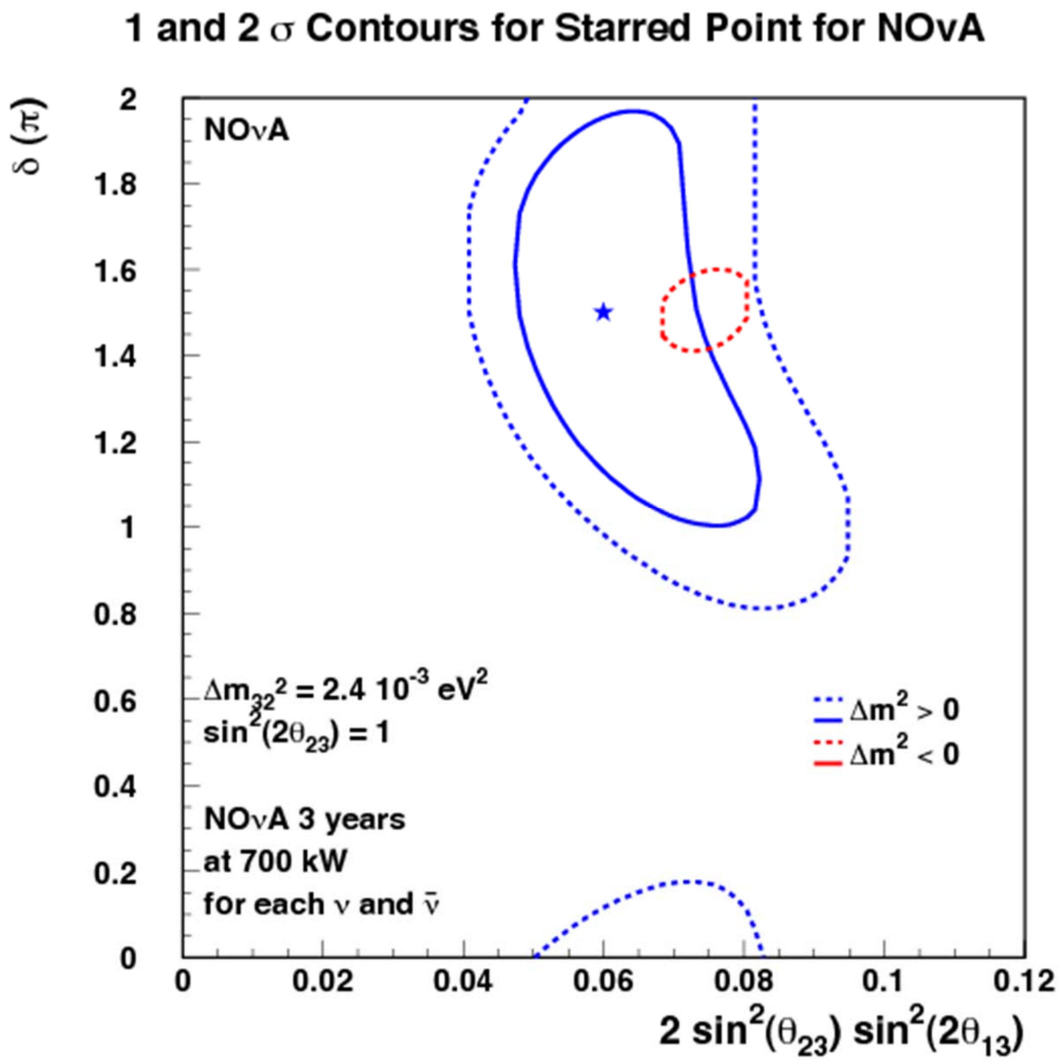




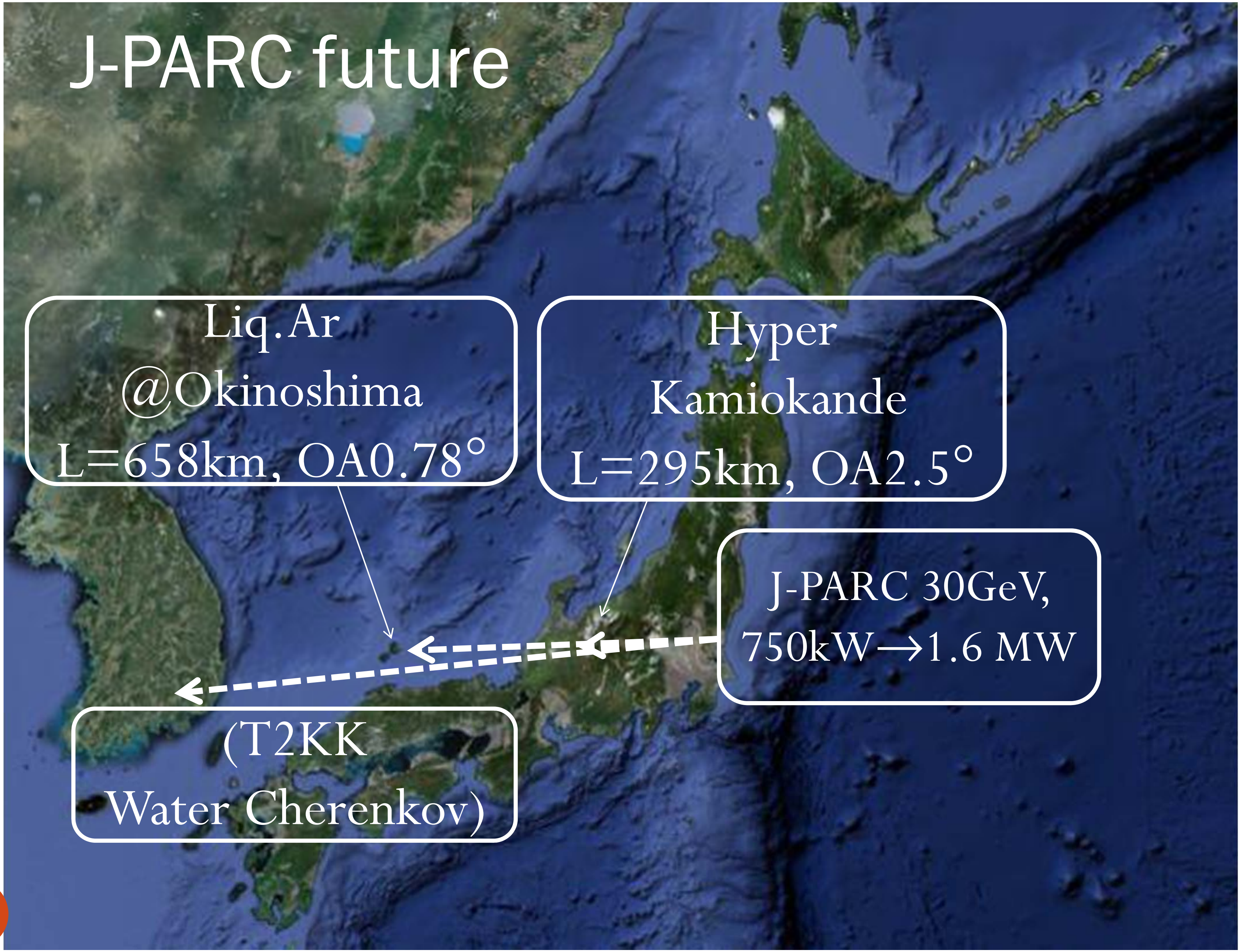
Fogli et al., global fit 3σ region

CP phase

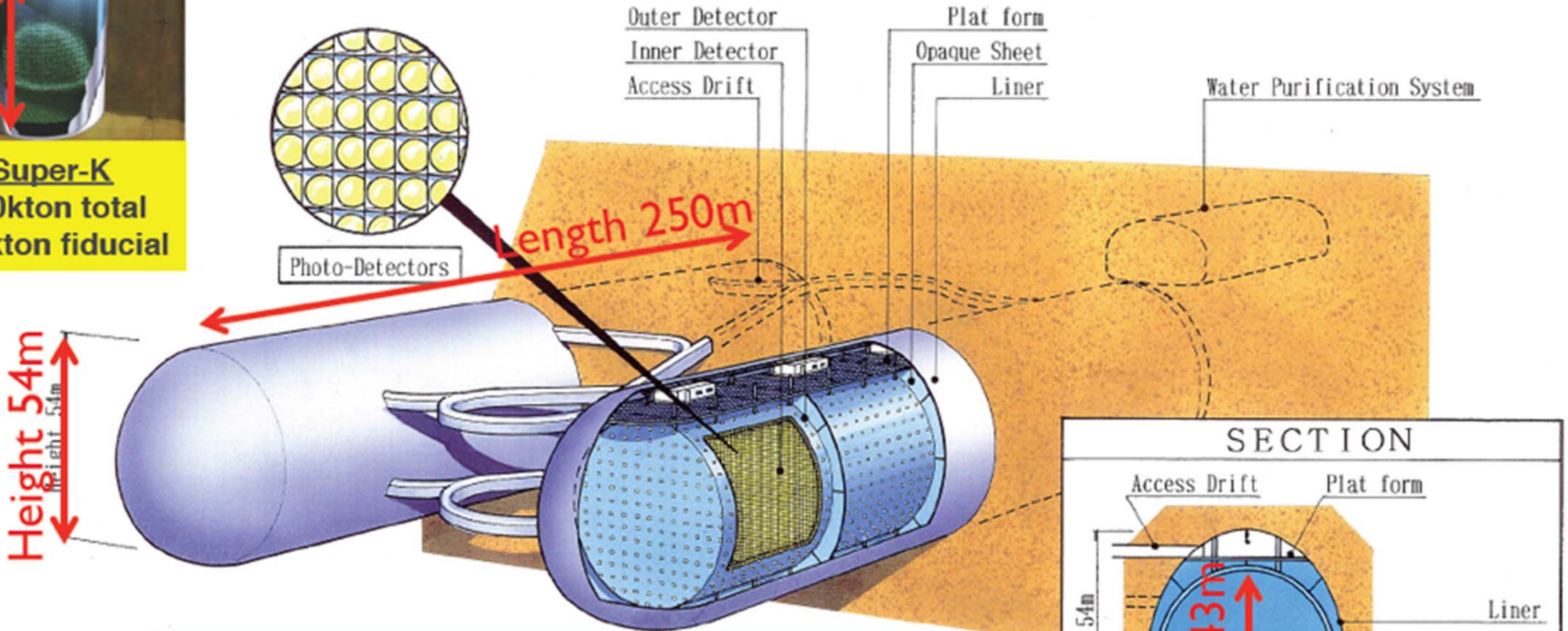
- Assuming a normal hierarchy, and oscillation at the starred point



J-PARC future



Hyper-Kamimokande

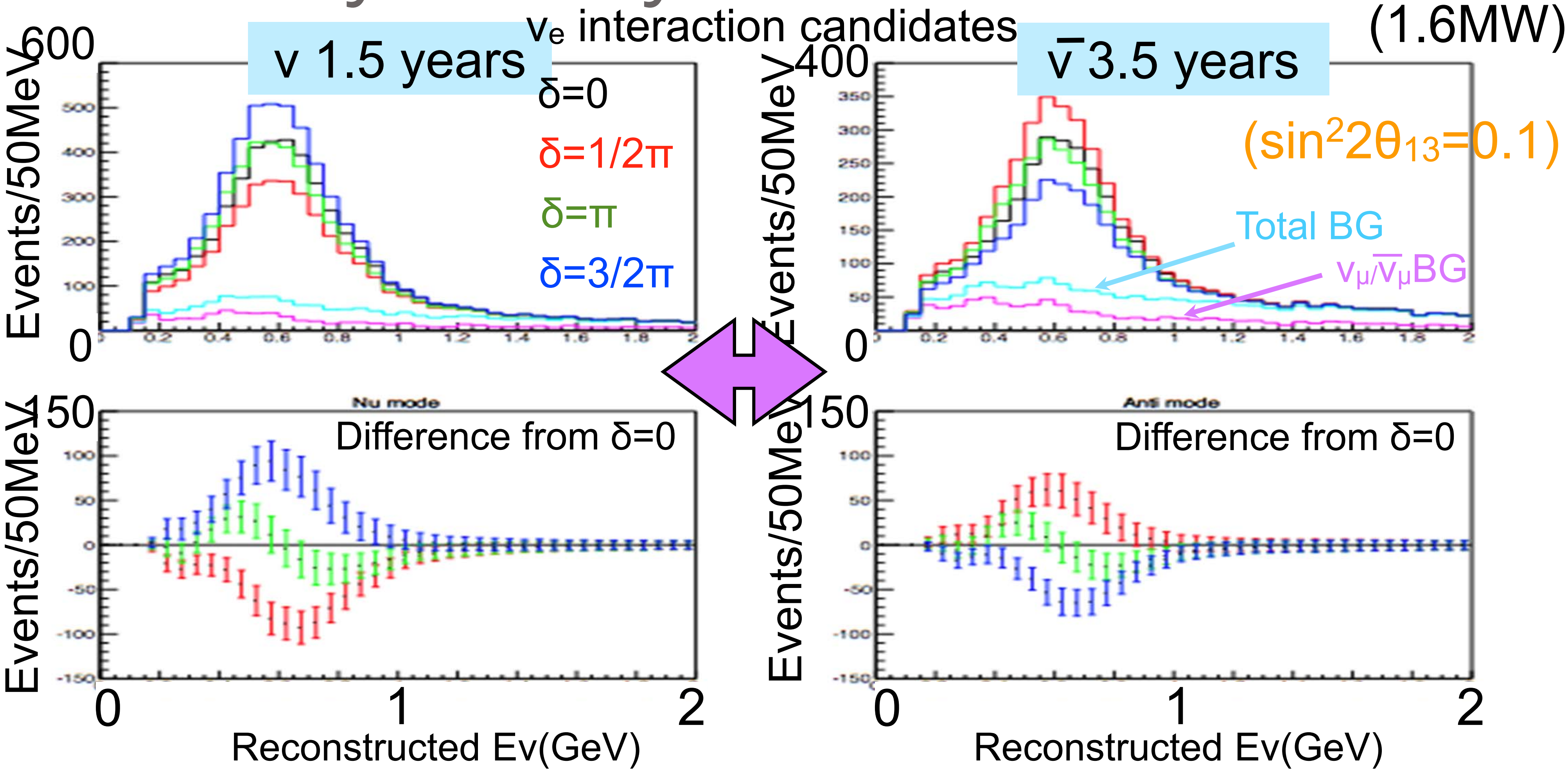


Baseline design

- 1Mton total volume, twin cavity
- ~0.6Mton fiducial volume
- Photo coverage 20% (1/2 x SK)
- 20 inch PMT x 102,000

Aiming to start ~2020

CP asymmetry

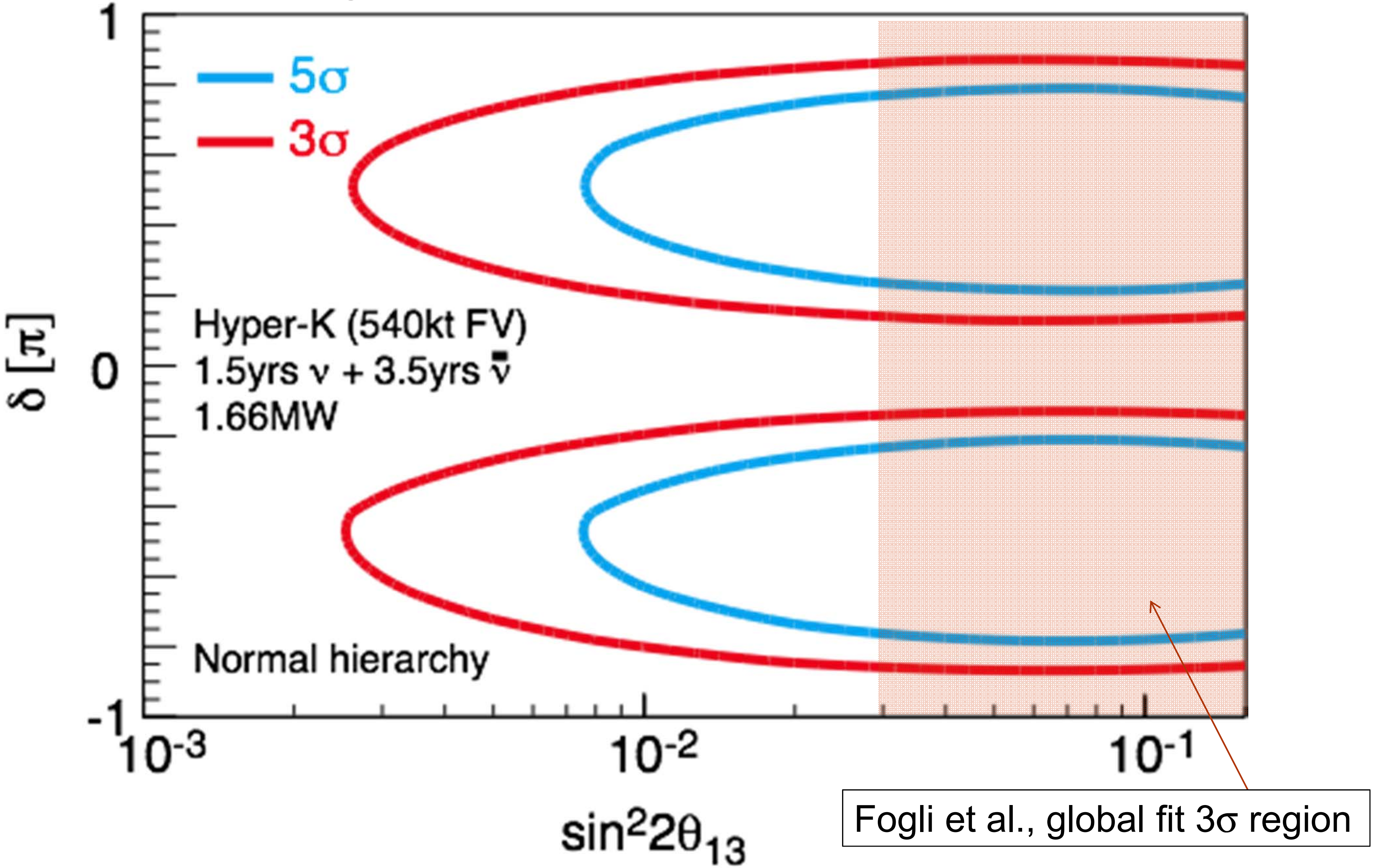


Compare $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\sin\delta \neq 0 \rightarrow$ CP violation!

Full simulation with latest J-PARC / Super-K (20% cov.) MC

Sensitivity to CP violation (sinδ≠0)

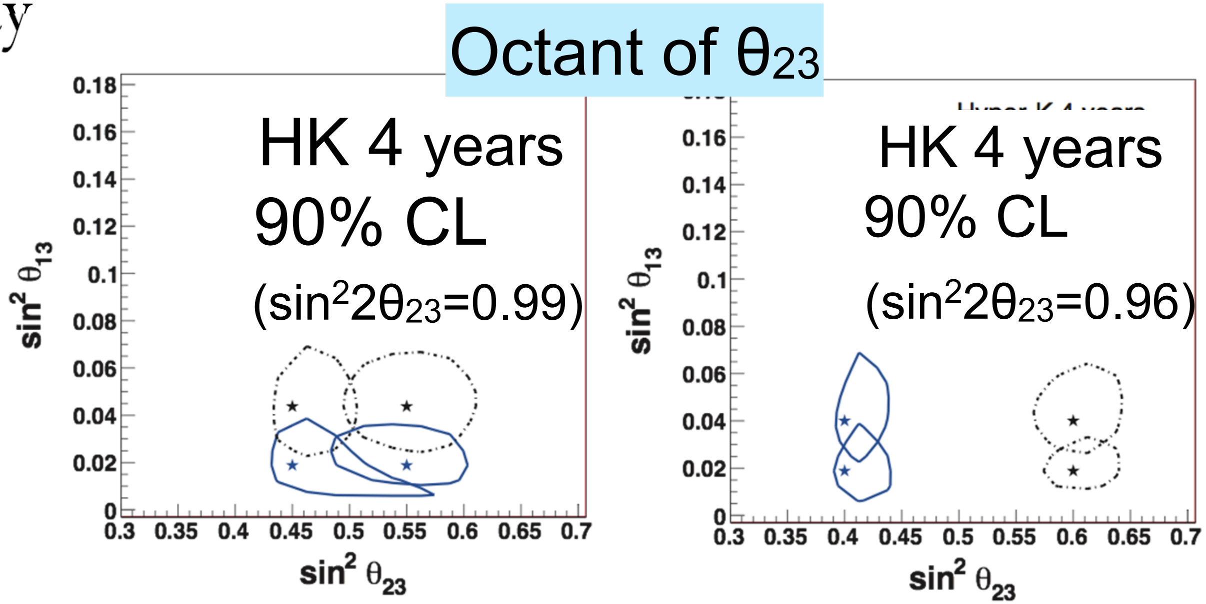


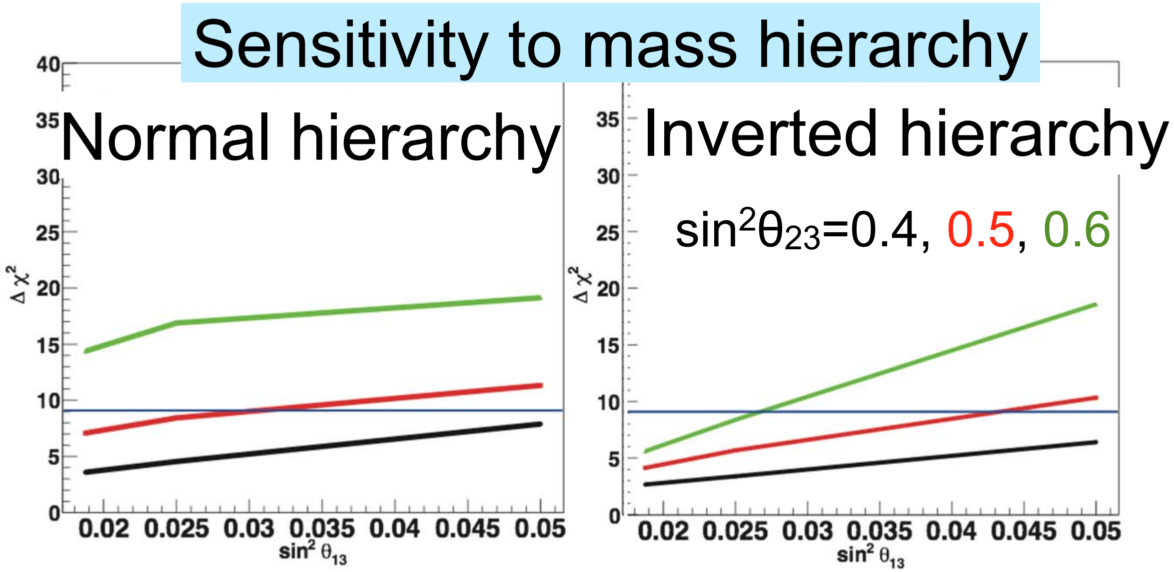
$\sin^2 2\theta_{13} \sim 10^{-2}$ for 5σ, $\sim 3 \times 10^{-3}$ for 3σ

Hyper-Kamiokande project:

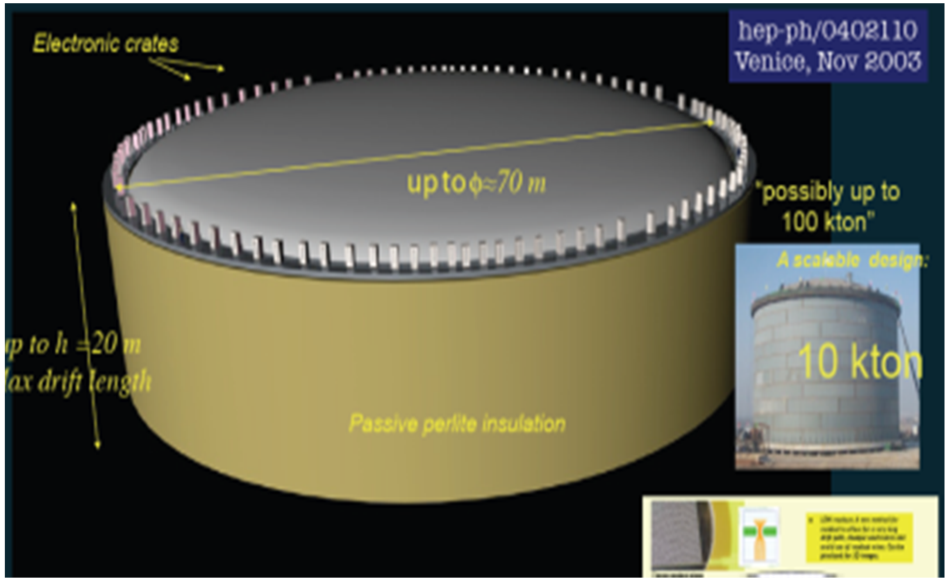
covering a wide range of particle physics/astrophysics

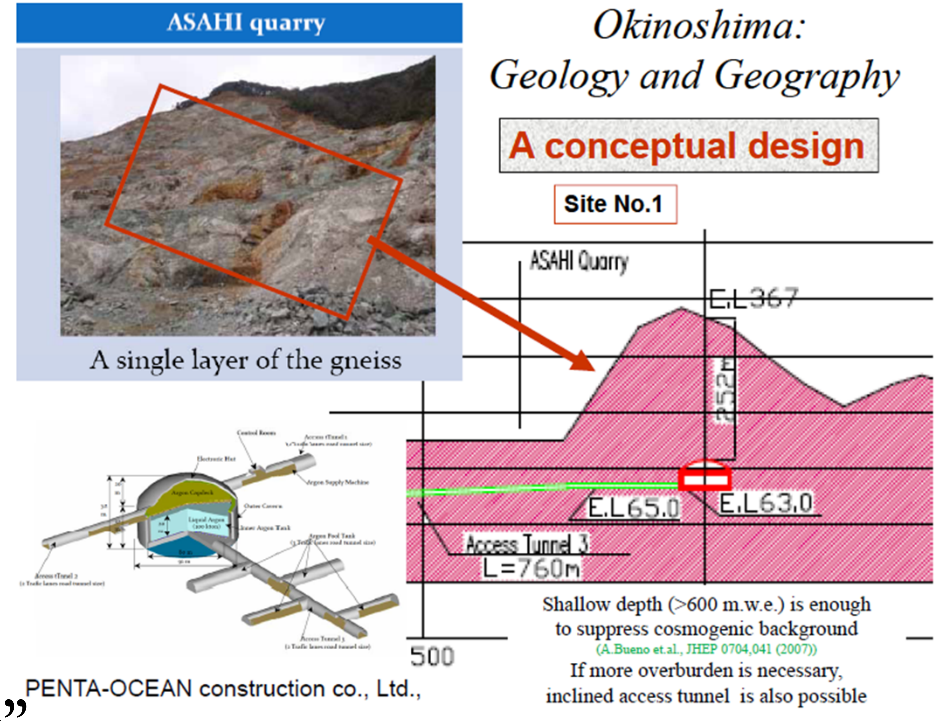
- Search for nucleon decay
  x10 sensitivity
- Atmospheric neutrino
- Solar neutrino
- Supernova neutrino
- WIMP, GRB,
- ….





~100kton Liquid Argon TPC@ Okinoshima

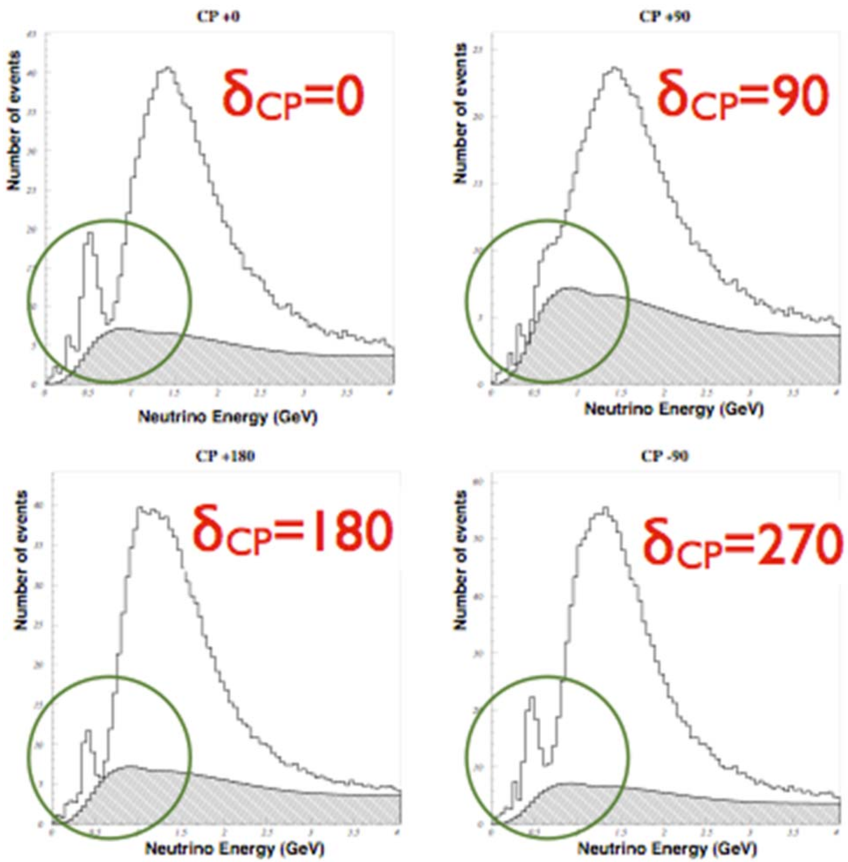




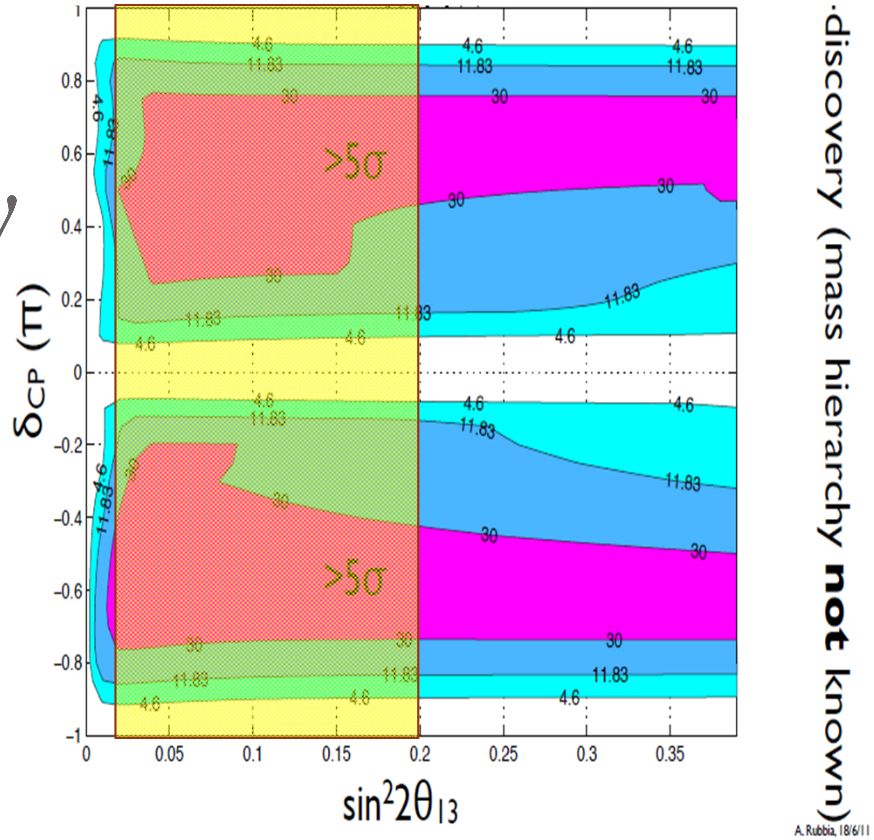
- Electronic "bubble chamber"
  - Can track every charged particle
  - Down to very low energy
- Neutrino energy reconstruction by eg. total energy
- Good PID w/ dE/dx, pi0 rejection
- Realized O(1kton)

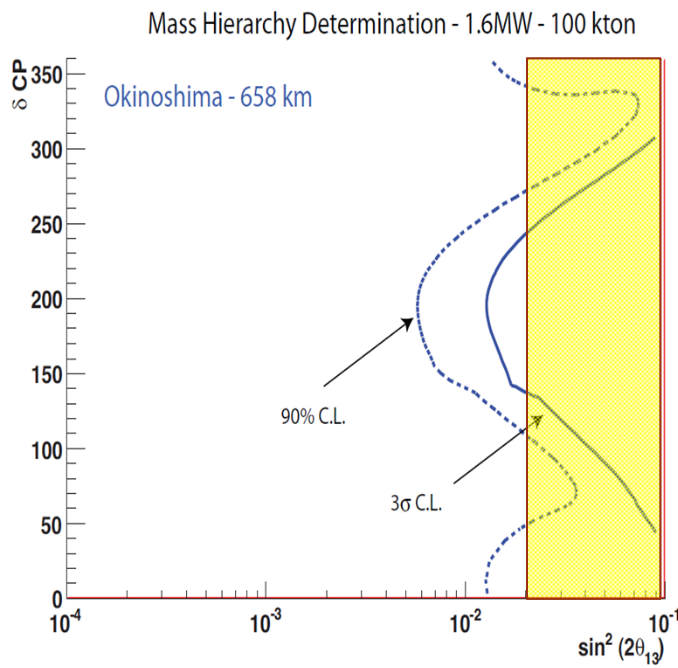
Physics potential

5 years ν and 5 years anti-ν

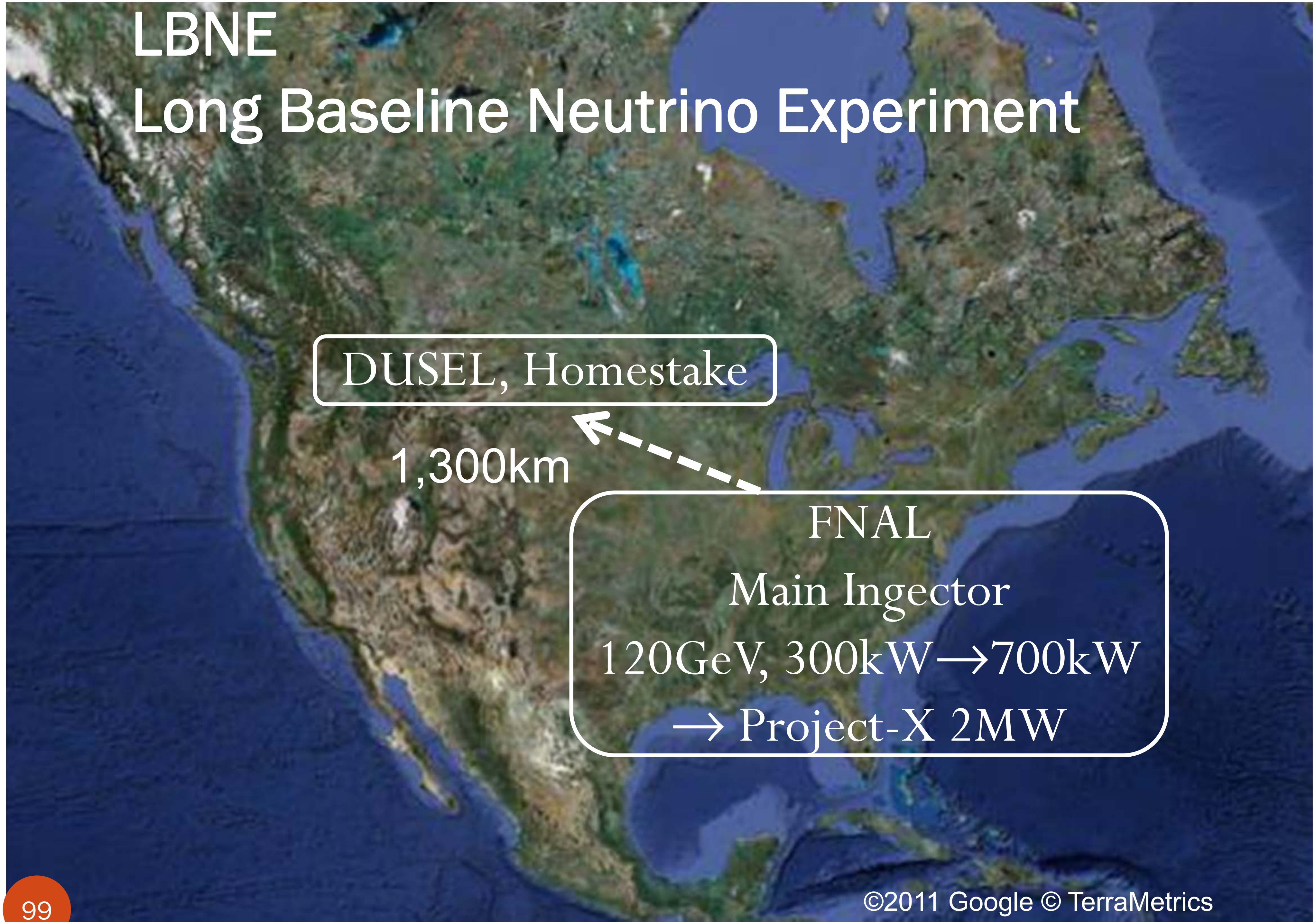


$\sin^2 2\theta_{13}$=0.03 & varying CP phase



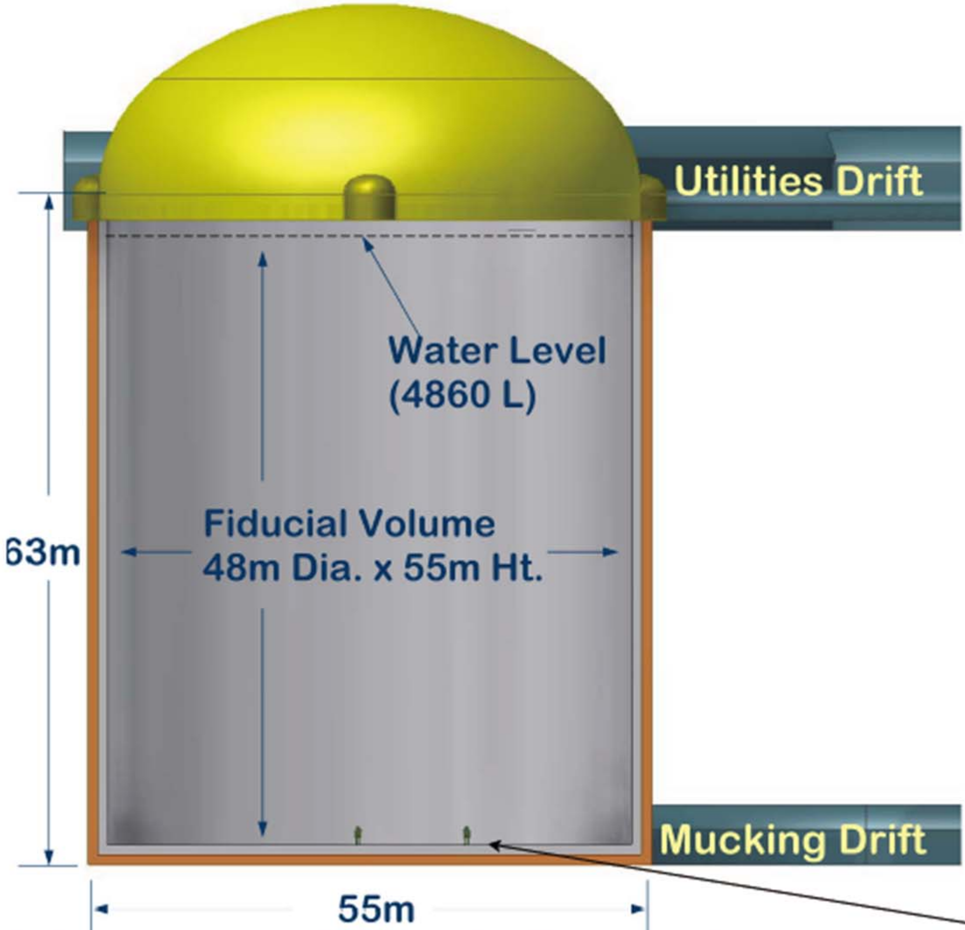


LBNE
Long Baseline Neutrino Experiment

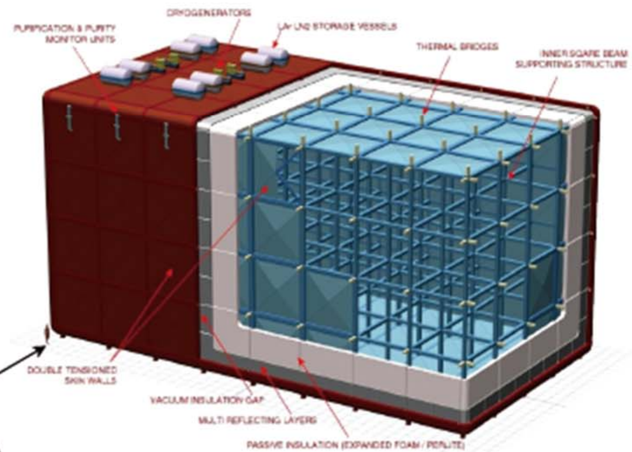


LBNE detectors

Water Cherenkov
100 kt fid. module



Liquid Argon TPC
17 kt fid. module

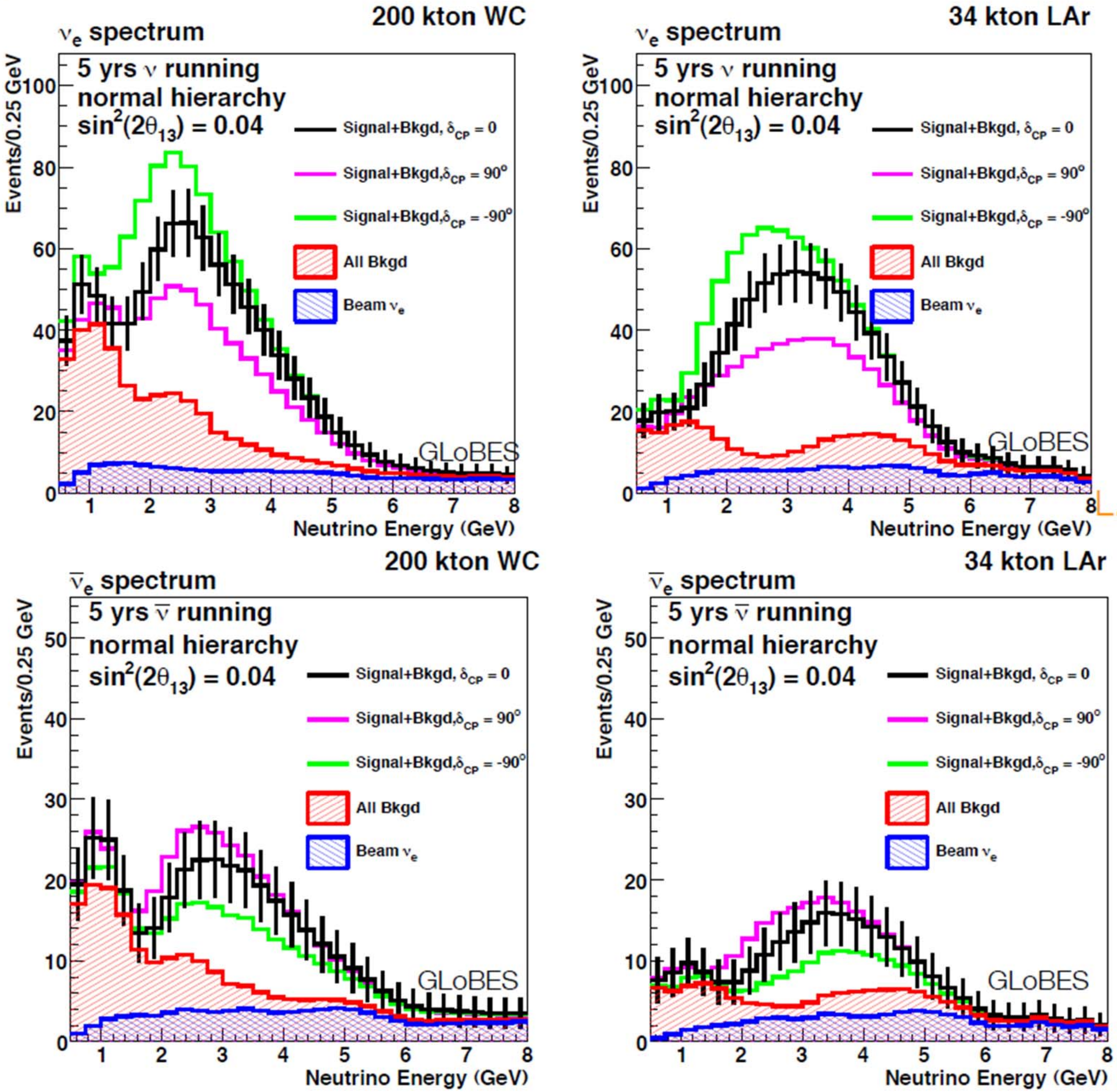


~ 3 (~4) times SuperK (fiducial)

people (!)

Up to 3 modules

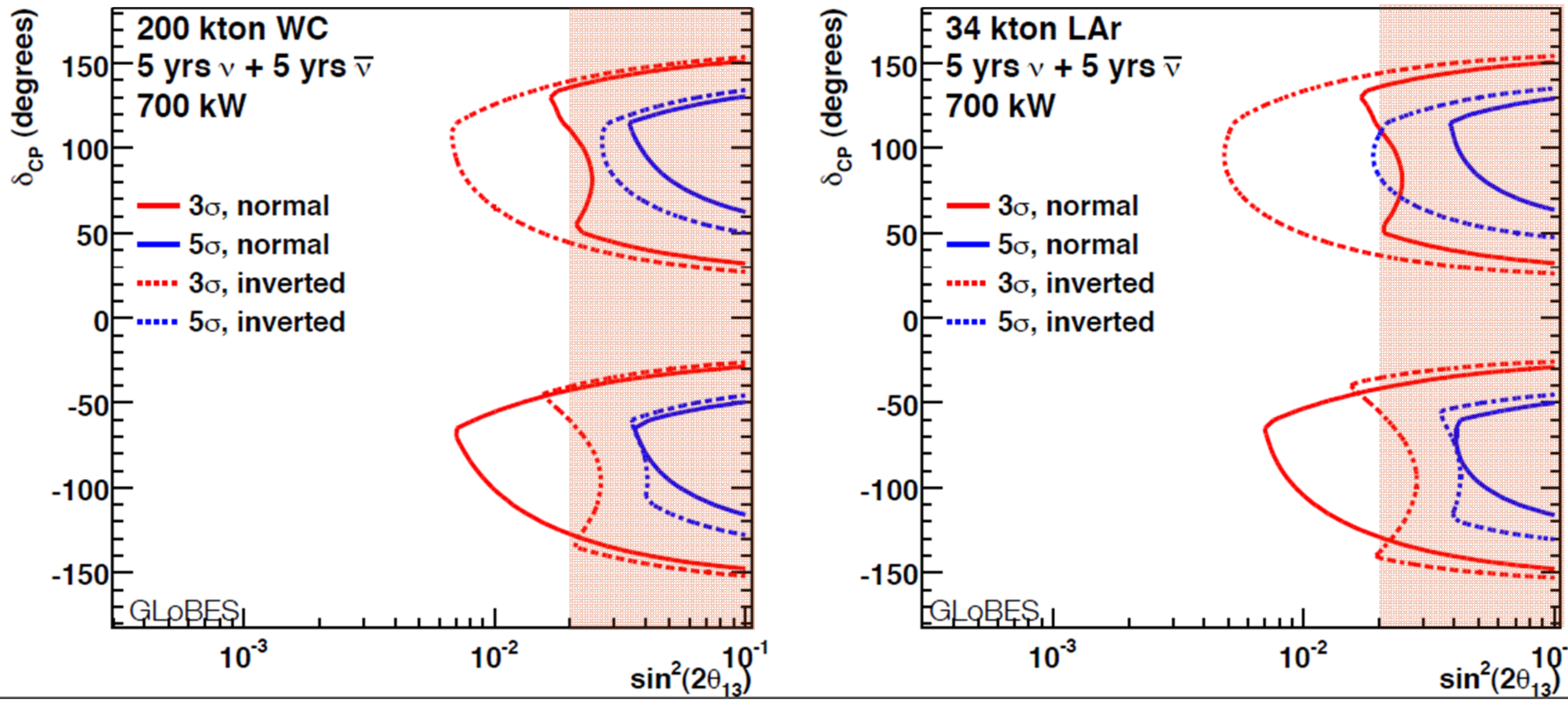
Depending on θ_{13} value the measurement will be more on less precise



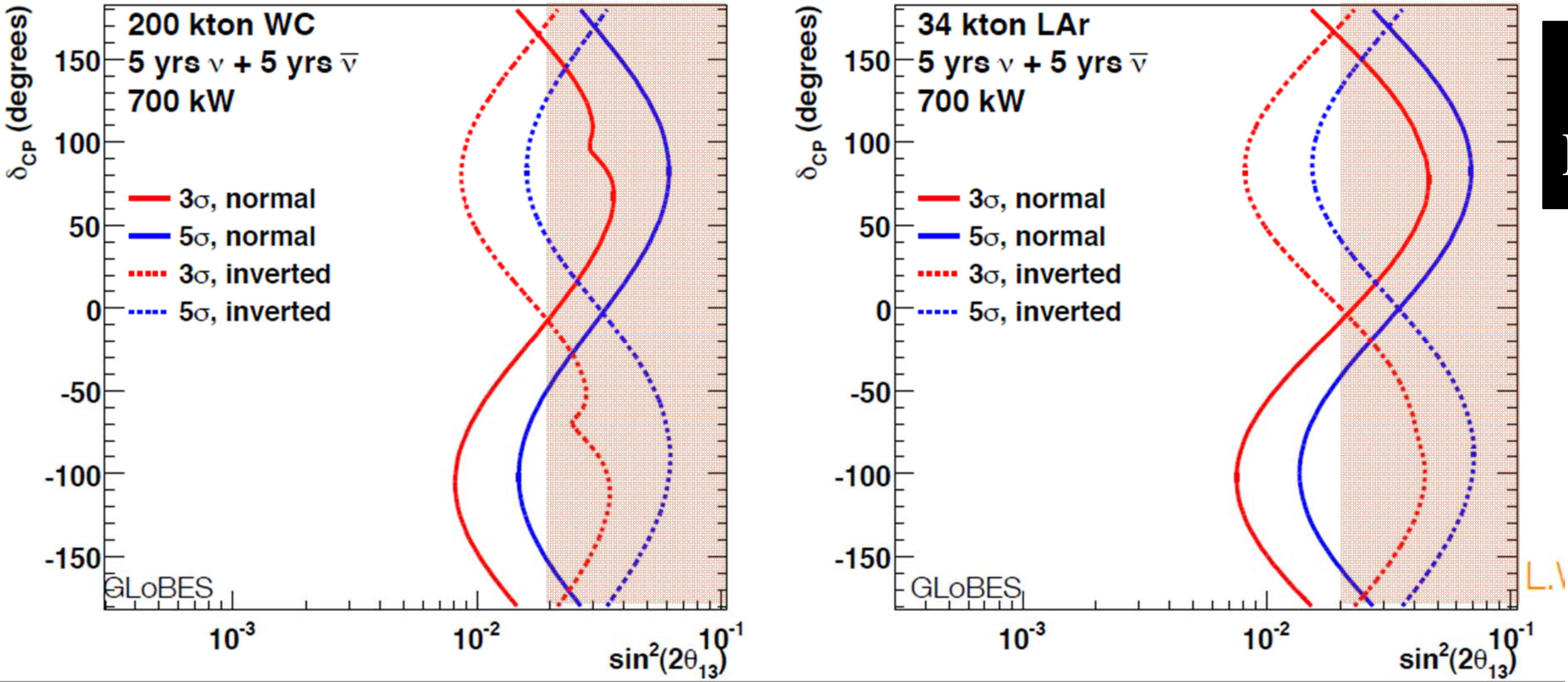
L.Whitehead (BNL)

L.Whitehead (BNL)

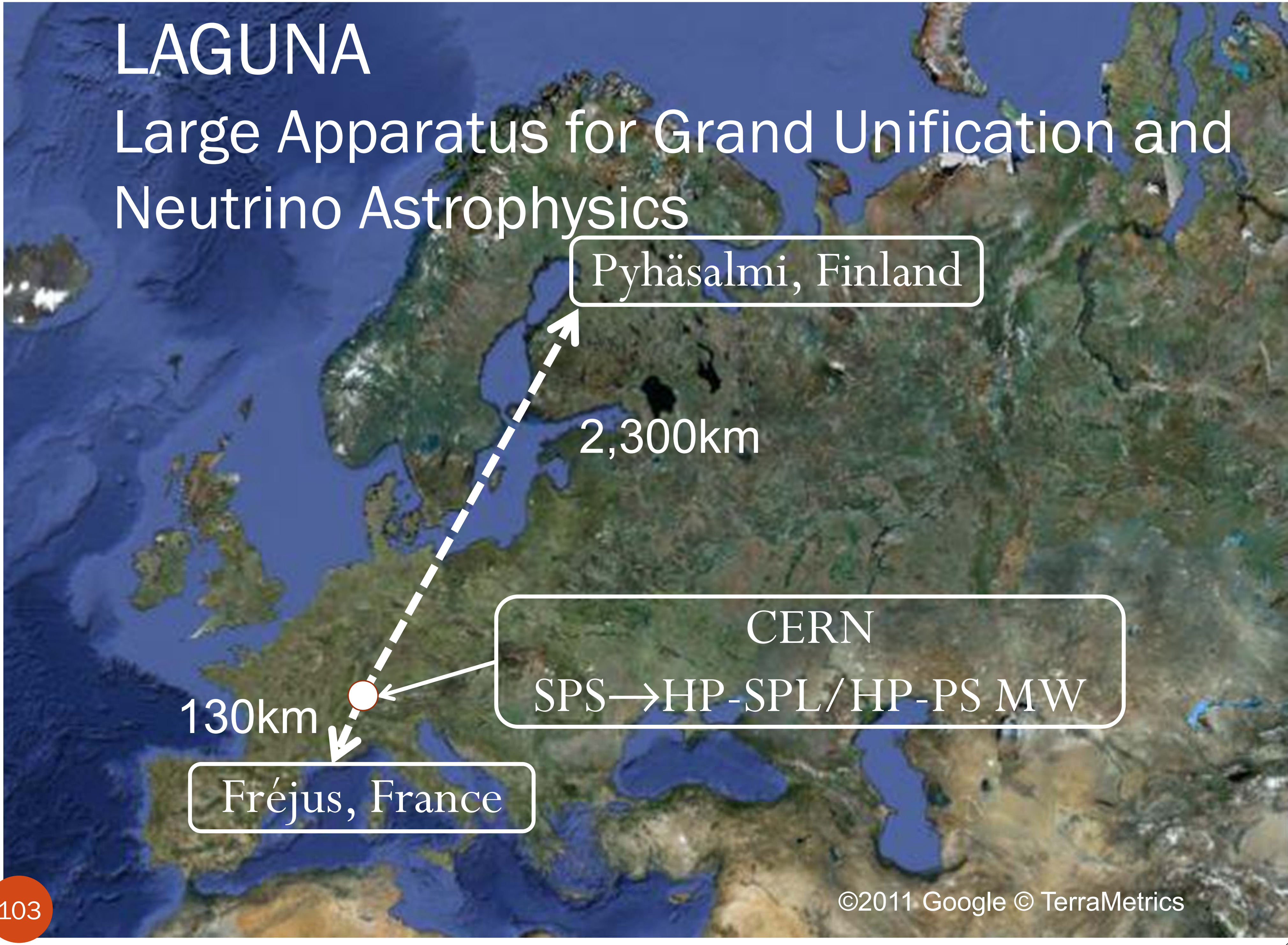
CP



Mass Hierarchy



LAGUNA
Large Apparatus for Grand Unification and Neutrino Astrophysics

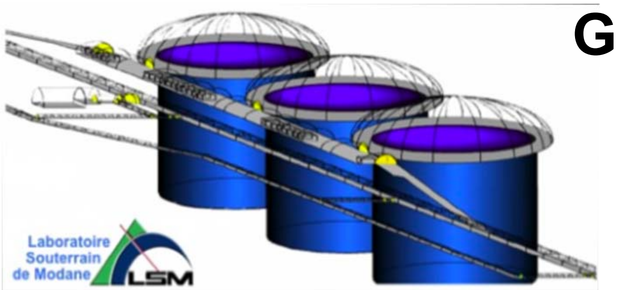


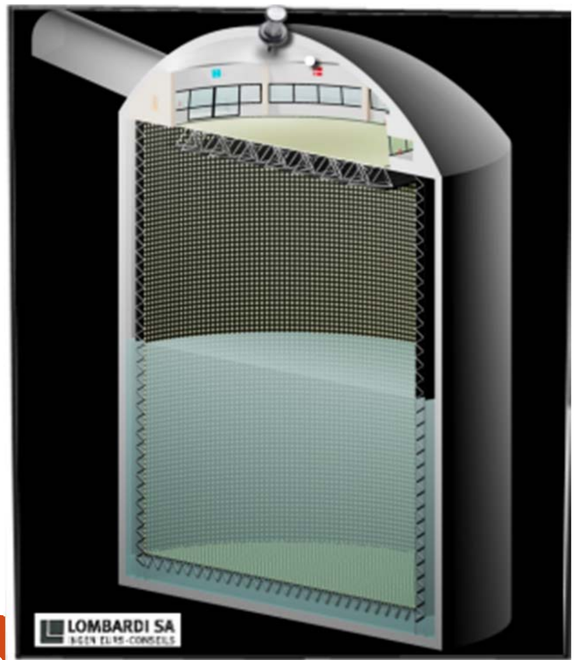
LAGUNA detectors
- three options under discussion-

MEMPHYS

MEgaton **M**ass **PHYS**ics

440kt FV

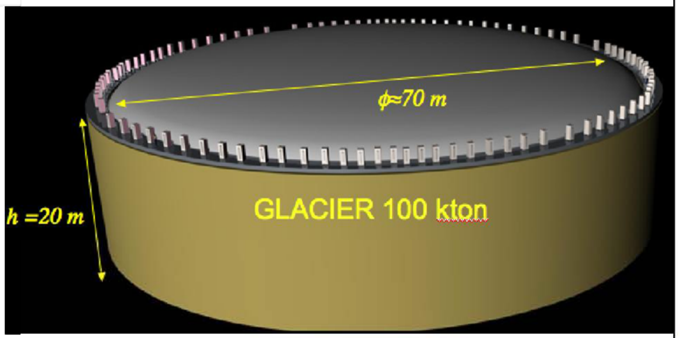


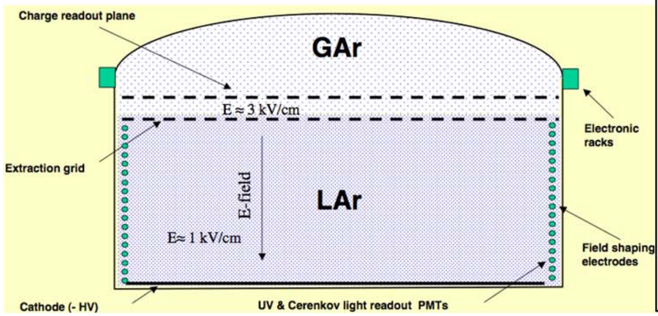


GLACIER

Giant **L**iquid **A**rgon **C**harge **I**maging **E**xpe**R**iment

~100kt

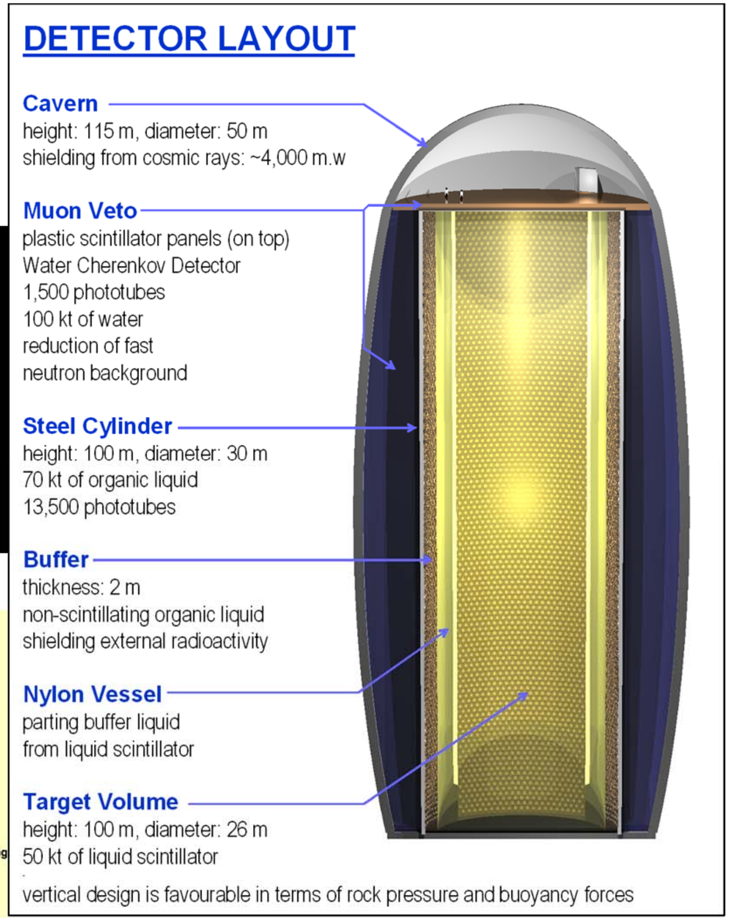




LENA

Low **E**nergy **N**eutrino **A**stronomy

50kt organic scintillator



Water Cherenkov v.s. Liquid Argon -my personal view-

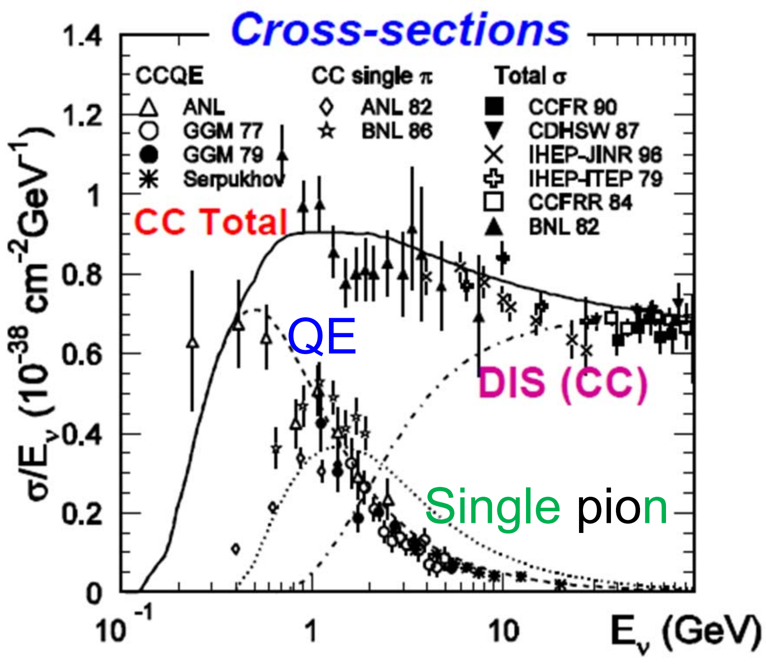
In any case, the sensitivity is not much different.

Water Cherenkov

- ✓ Technology well established
- ✓ Feasible to scale up (Water is easy to get)
- ✓ ν_e selection is good at sub GeV, but bad at >1GeV → ν_e and anti-ν_e run

Liquid Argon

- ✓ Technology need to be established. (600t is maximum so far)
- ✓ ν_e selection and energy measurement are supposed to be good. (Need proof) → 1st & 2nd peaks method



WC : matter of cost?
Liq. Ar : need technology proof

Summary of future ν super beam experiments

already existing or upgrade existing acc/beam-line | construct new one

	Beam Power [MW]	ν beam facility	detector	baseline [km]	ν energy (peak E_{ν})	experimental method
FNAL-Ashriver (NOνA)	0.7	exsiting	14kton Liq.Sincit.	819	NBB (2GeV)	ν and anti-ν
JPARC-Okinoshima	1.66	existing	100kton LArTPC	658	WBB (1.2GeV)	1st, 2nd max
JPARC-Kamioka	1.66	existing	540kton W.C.	295	NBB (0.7GeV)	ν and anti-ν
FNAL-DUSEL	0.7 2.1	need new one	~300kton WC. and/or ~50kton LArTPC	1300	WBB (3GeV)	1st, 2nd max
CERN-Frejus	4 (HP-SPL)	need new one	~440kton W.C.	130	On-axis low energy (0.2GeV)	ν and anti-ν
CERN-Pyhasalmi	1.6 (HP-PS2)	need new one	100kton LArTPC	2300	WBB (3GeV)	1st, 2nd max

Expected Timeline
(purely personal view.
Don't take this too seriously.)

	2012	2013	2014	2015	~	2020	~
Non-zero $\theta_{13}(3\sigma)$	T2K/Reactor						
$\theta_{23}\neq45°$	T2K					→future project	
Mass hierarchy			T2K/NOνA			→future project	
CP phase				T2K/NOνA		→future project	
CPT problem	Refute by MINOS/T2K		confirm by MINOS/T2K				
Surprise							