Recent results on neutrino oscillations and CP violation measurement in Neutrinos

M.Nakahata
Kamioka observatory, ICRR,
IPMU, Univ. of Tokyo

CP Violation in Elementary Particles and Composite Systems, Feb.19, 2013, Mahabaleshwar (India)

Contents

- What are neutrino oscillations
- Results and topics from recent measurements
  - θ_{12} and Δm^2_{21} measurements
  - θ_{23} and Δm^2_{32} measurements
  - θ_{13} measurements
- Unknown properties of neutrinos
- Neutrino CP measurement
  - How to measure CP phase
  - Detector for the CP phase measurement
  - Sensitivity

Neutrino oscillations

Weak eigenstates → $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$ ← Mass eigenstates

$$P(\nu_\alpha \to \nu_\beta; L) = \delta_{\alpha\beta} - 4\sum_{j<k} \mathrm{Re}\left(U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k}\right)\sin^2\left(\frac{\Delta E_{jk}L}{2}\right)$$
$$+2\sum_{j<k} \mathrm{Im}\left(U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k}\right)\sin\left(\Delta E_{jk}L\right),$$

where $\Delta E_{jk} \equiv \sqrt{m_j^2+p^2} - \sqrt{m_k^2+p^2} = \Delta m^2_{jk}/2E$

2 flavor case

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Oscillation probability

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$$

$\Delta m^2 = m_2^2 - m_1^2$ (eV^2): mass square difference

L (km): Neutrino travel length

E (GeV): neutrino energy

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

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

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{13}s_{23}e^{-i\delta} & c_{12}c_{23}-s_{12}s_{13}s_{23}e^{-i\delta} & c_{13}s_{23} \\ s_{12}s_{23}-c_{12}s_{13}c_{23}e^{-i\delta} & -c_{12}s_{23}-s_{12}s_{13}c_{23}e^{-i\delta} & c_{13}c_{23} \end{pmatrix}$$

$s_{ij}=\sin\theta_{ij}$、$c_{ij}=\cos\theta_{ij}$

δ : Dirac P phase

$\Delta m_{ij}^2= m_i^2-m_j^2$;Δm_{12}^2, Δm_{23}^2, Δm_{31}^2

Experiments for the oscillation parameters

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{13}s_{23}e^{-i\delta} & c_{12}c_{23}-s_{12}s_{13}s_{23}e^{-i\delta} & c_{13}s_{23} \\ s_{12}s_{23}-c_{12}s_{13}c_{23}e^{-i\delta} & -c_{12}s_{23}-s_{12}s_{13}c_{23}e^{-i\delta} & c_{13}c_{23} \end{pmatrix}$$

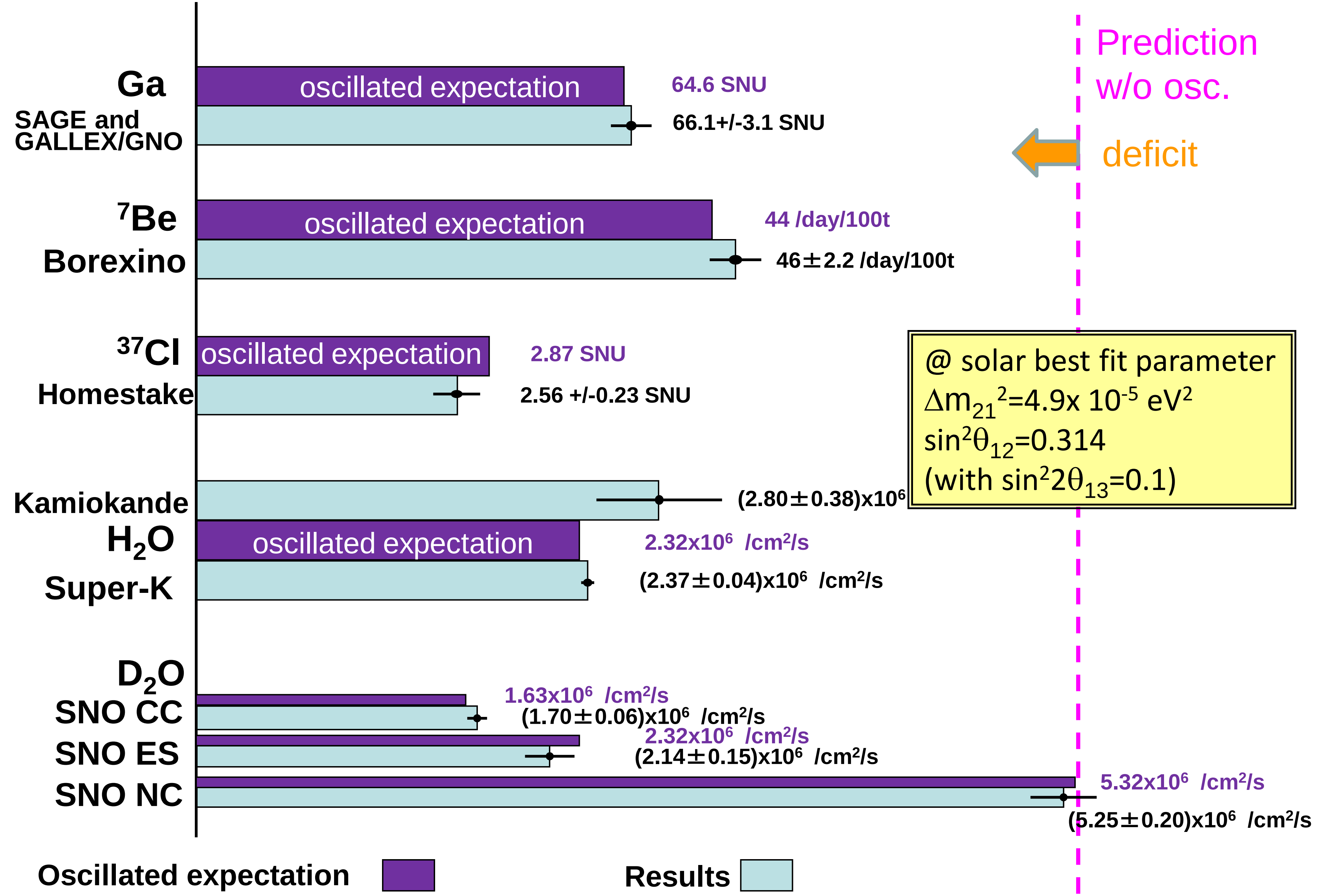
$s_{ij}=\sin\theta_{ij}$、$c_{ij}=\cos\theta_{ij}$

Primarily sensitive to

	Δm_{12}^2	Δm_{23}^2	θ_{12}	θ_{23}	θ_{13}	δ
Solar ν, long BL reactor ν	○		○			
Atm. ν , long BL accelerator ν		○		○	○	
Short BL reactor ν					○	
Future long BL accelerator ν		○ (sign)		○ (=, > or < 45°)		○

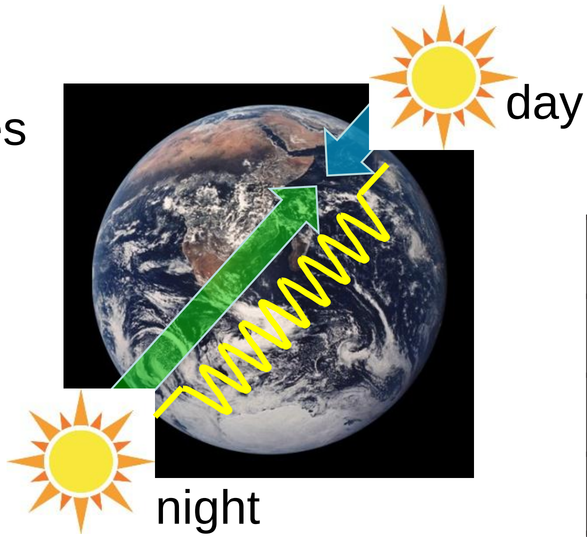
BL=baseline

Measured solar neutrino fluxes



Measurement of Matter effect (Super-K)

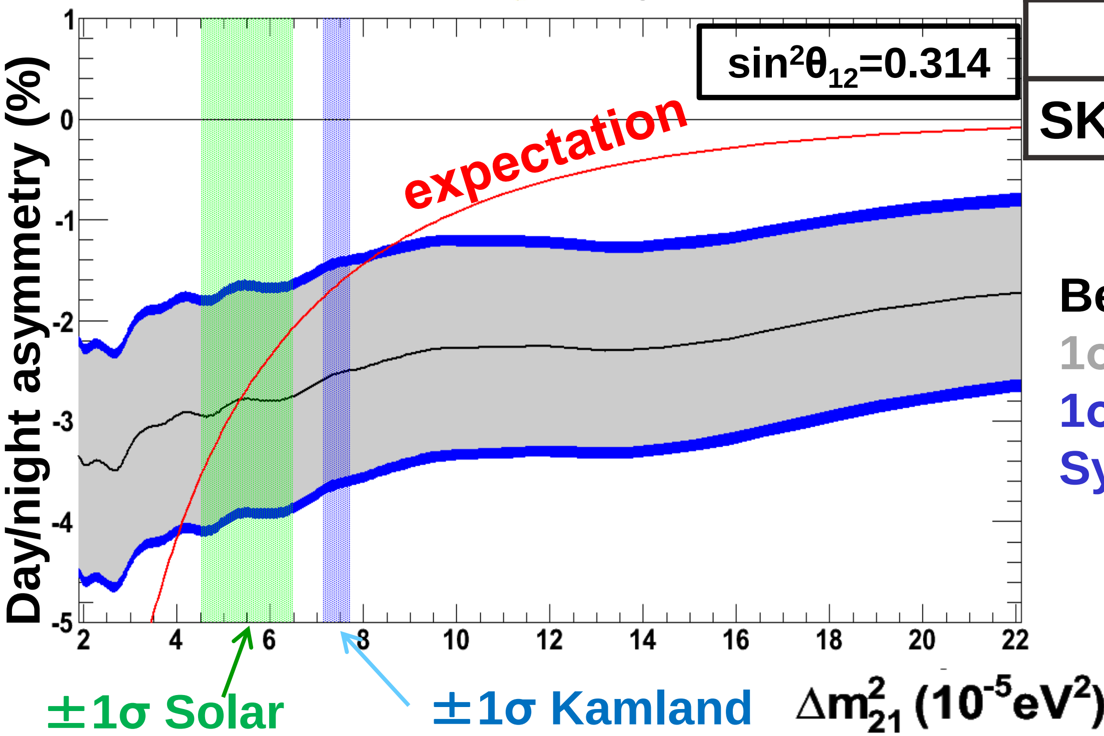
During night, ν_e probability increases due to the earth matter effect.



$$A_{DN} = \frac{\text{Day flux} - \text{Night flux}}{0.5\ (\text{Day flux} + \text{Night flux})}$$

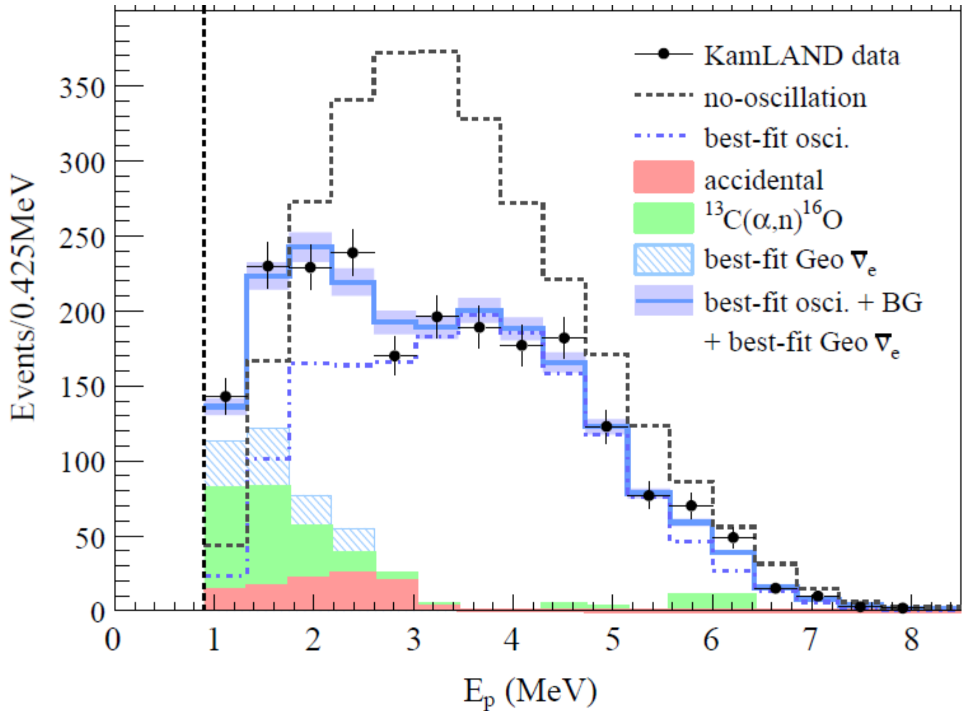
	A_{DN} (±stat.±sys.)
SK-I	-2.0±1.7±1.0 %
SK-II	-4.3±3.8±1.0 %
SK-III	-4.3±2.7±0.7 %
SK-IV	-2.8±1.9±0.7 %
SK combined	-2.8±1.1±0.5 %

2.3 σ away from zero.



Best Fit
1σ Stat.
1σ Stat. + Sys.

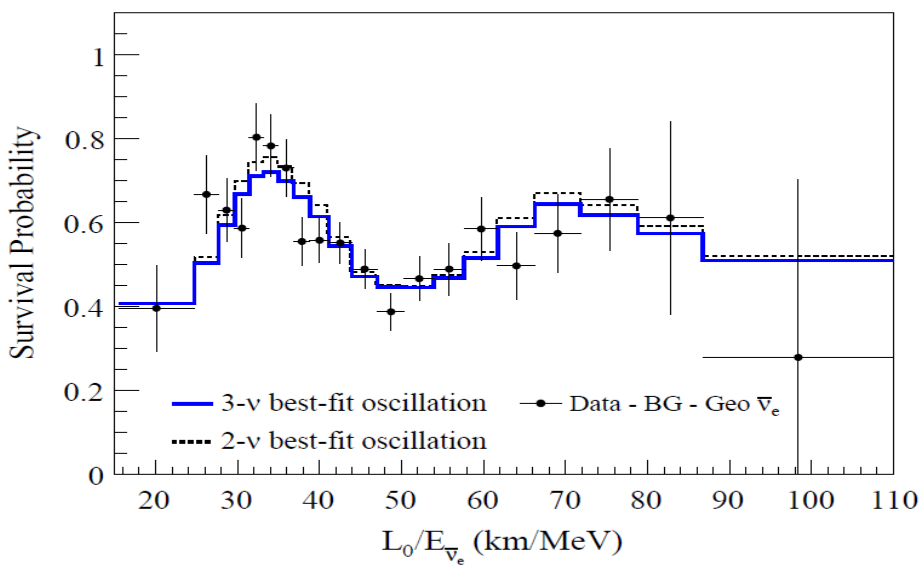
KamLAND reactor neutrino data



Long baseline ~ 180 km

Data from Mar. 2002 to Nov. 2009

Energy spectrum shows clear deficit of reactor neutrinos.



The plot as a function of L/E_ν shows clear oscillatory pattern.

Phys.Rev. D83 (2011) 052002

θ_{12} - Δm_{21}^2 :solar global vs. KamLAND

Solar global:

$\Delta m_{21}^2 = (4.86^{+1.44}_{-0.52})\ [\times 10^{-5} eV^2]$

$\sin^2\theta_{12} = 0.314^{+0.014}_{-0.015}$

KamLAND

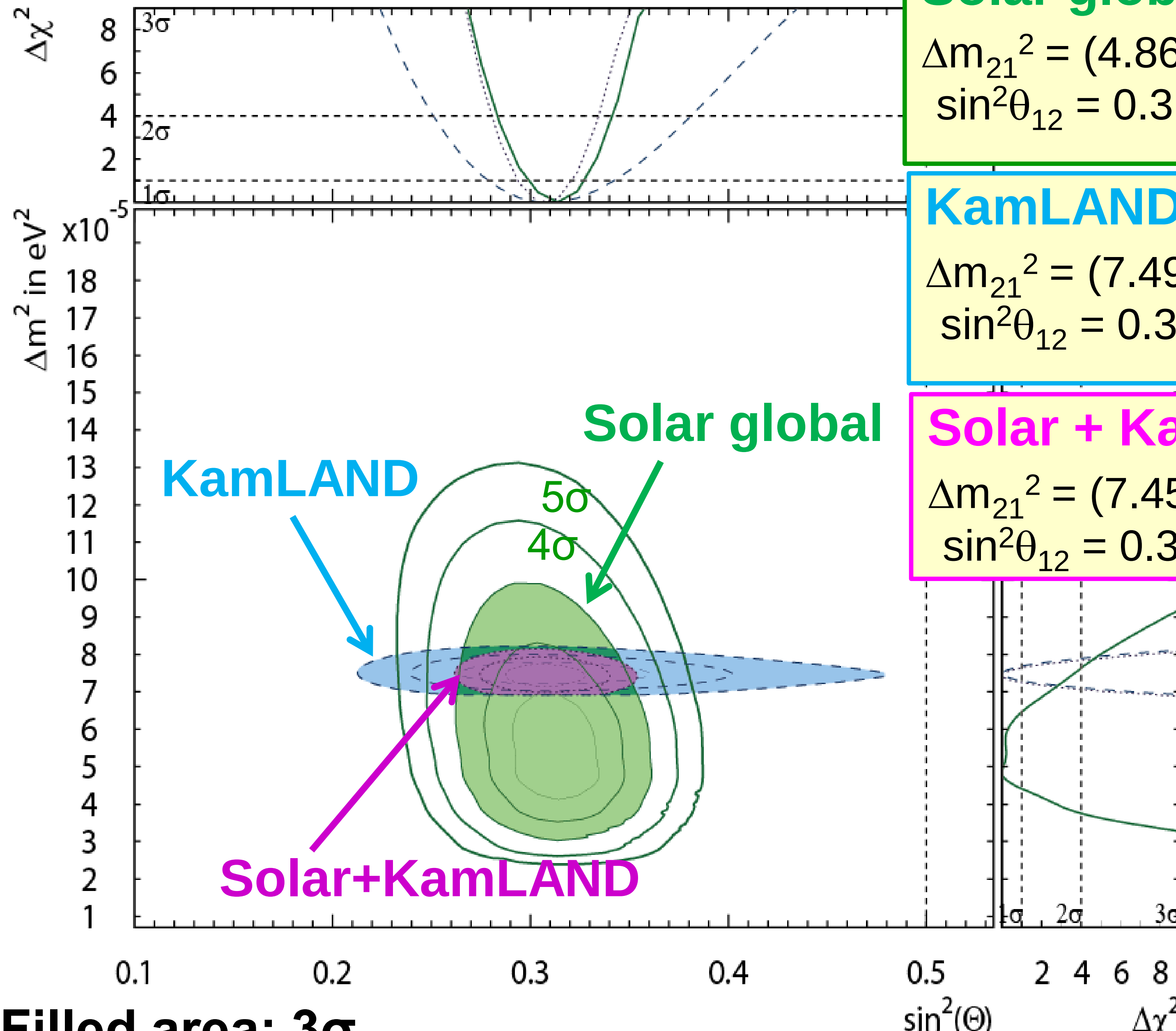
$\Delta m_{21}^2 = (7.49^{+0.20}_{-0.19})\ [\times 10^{-5} eV^2]$

$\sin^2\theta_{12} = 0.309^{+0.034}_{-0.030}$

Solar + KamLAND

$\Delta m_{21}^2 = (7.45^{+0.20}_{-0.19})\ [\times 10^{-5} eV^2]$

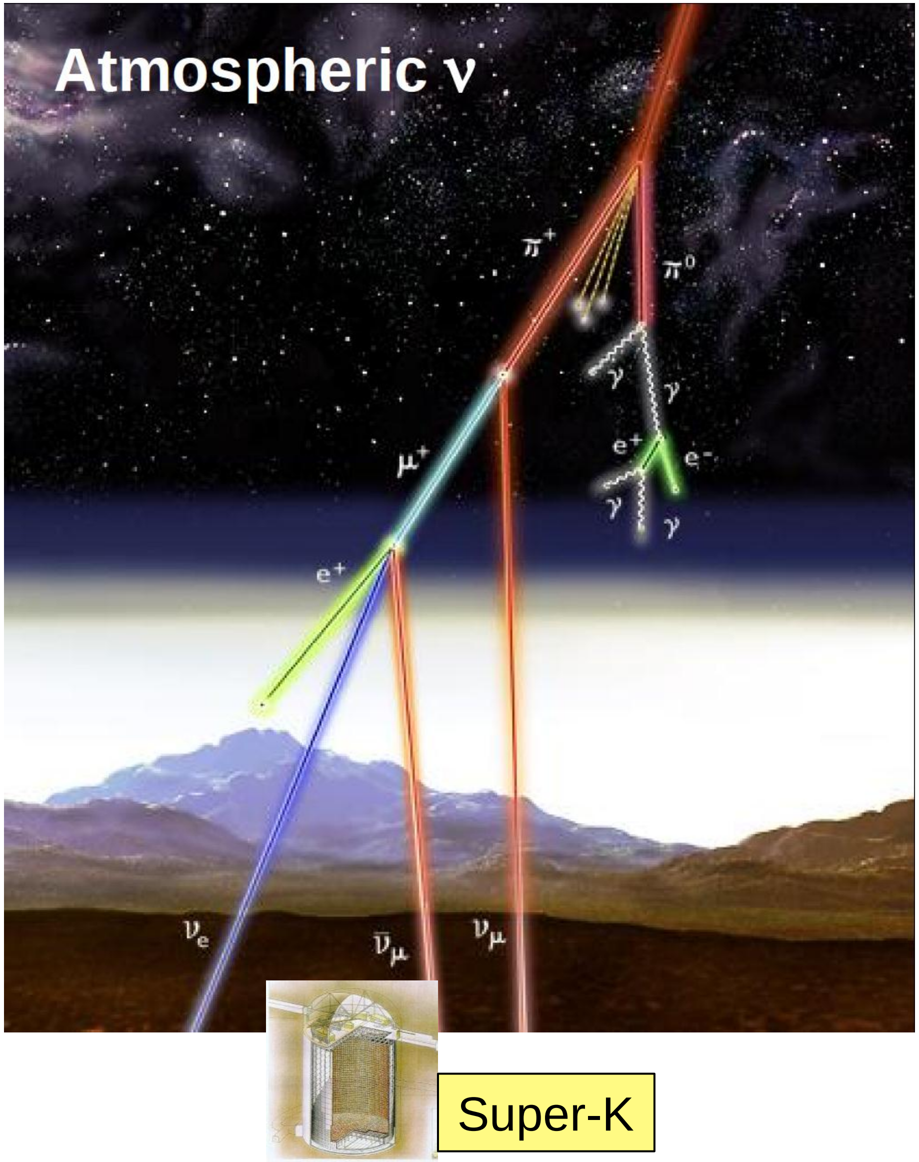
$\sin^2\theta_{12} = 0.307 \pm 0.014$

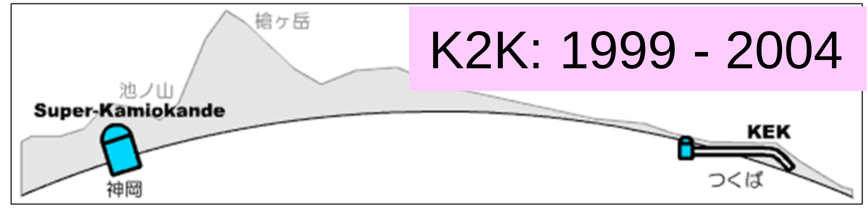


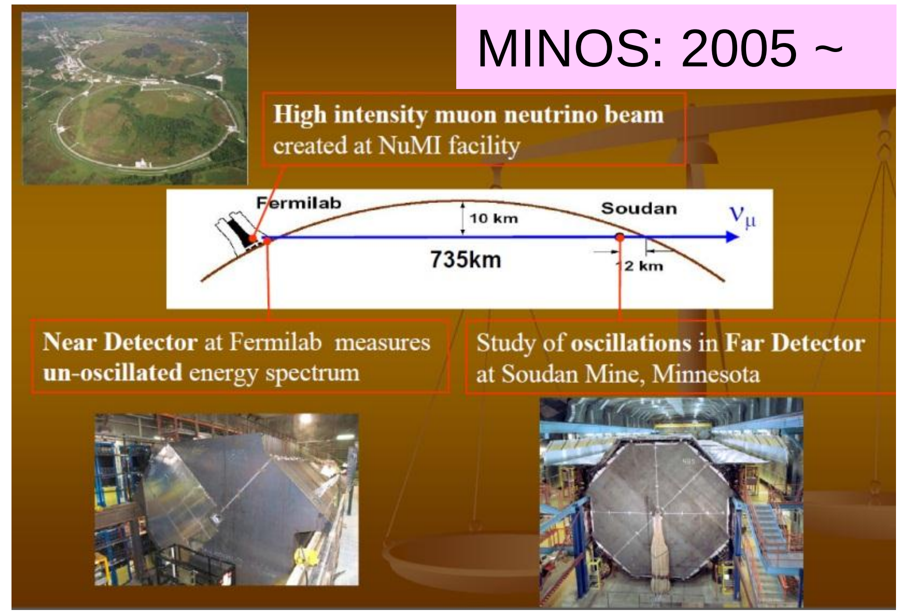
All with $\sin^2 2\theta_{13} = 0.1$

Filled area: 3σ

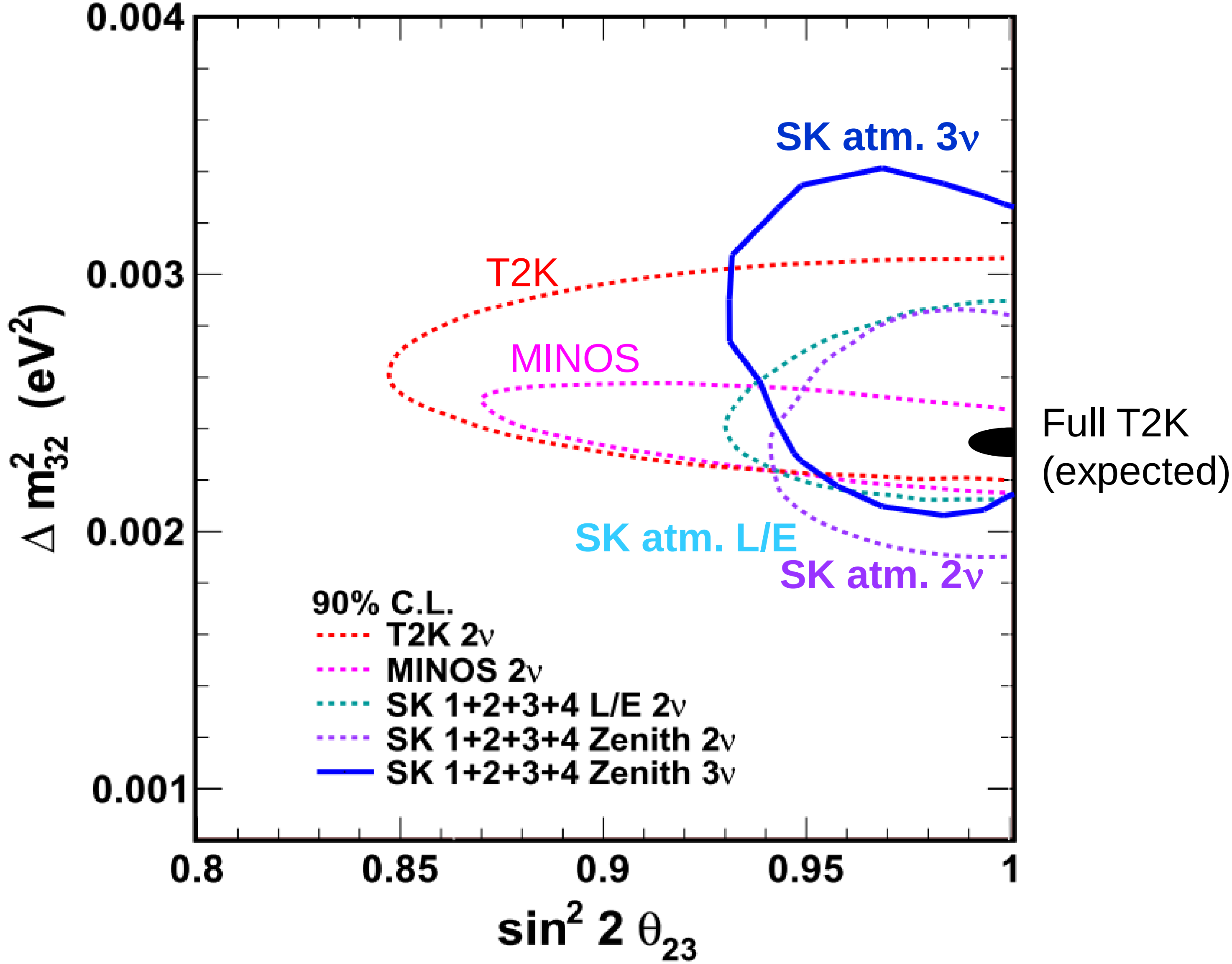
Atmospheric and long BL accelerator ν







θ_{23} –$|\Delta m_{32}{}^2|$: SK atm. and accelerators



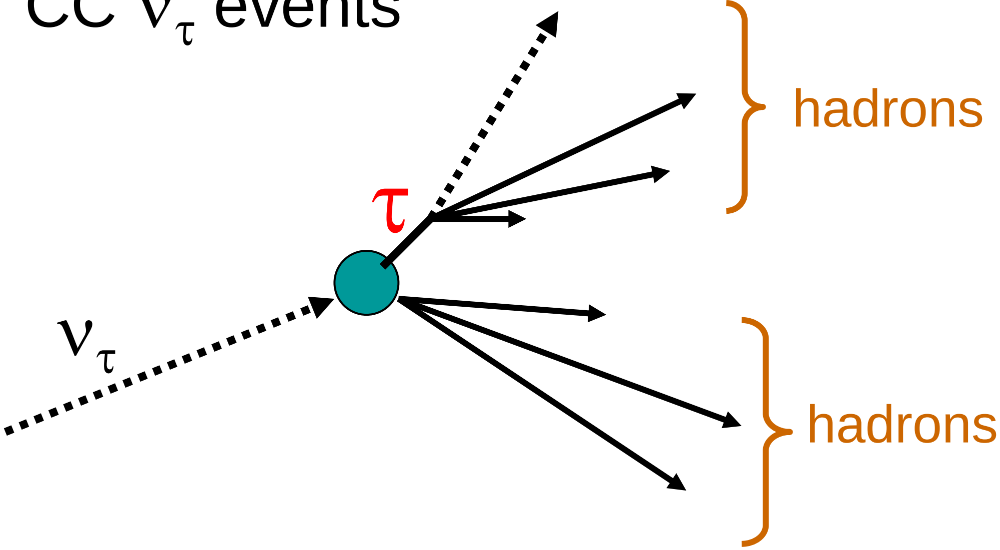
Future: T2K will reach accuracy of $\delta(\sin^2 2\theta_{23})=0.01$ and $\delta(\Delta m^2_{32})=0.0001 eV^2$.

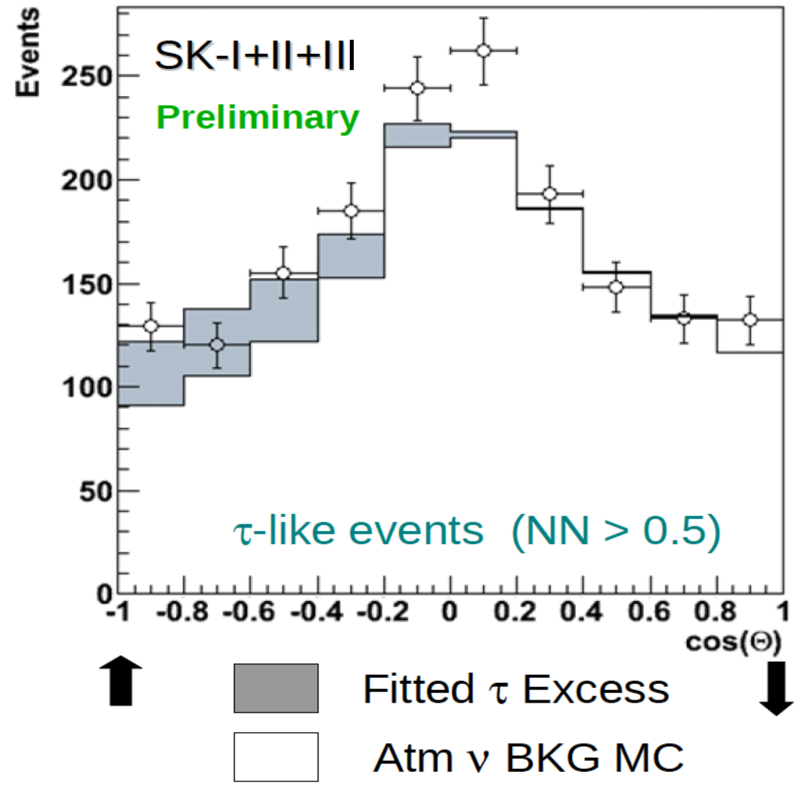
Recent observation at Super-K atmospheric

ν_τ appearance

Zenith angle distribution after seleting CC ν_τ–like events

CC ν_τ events





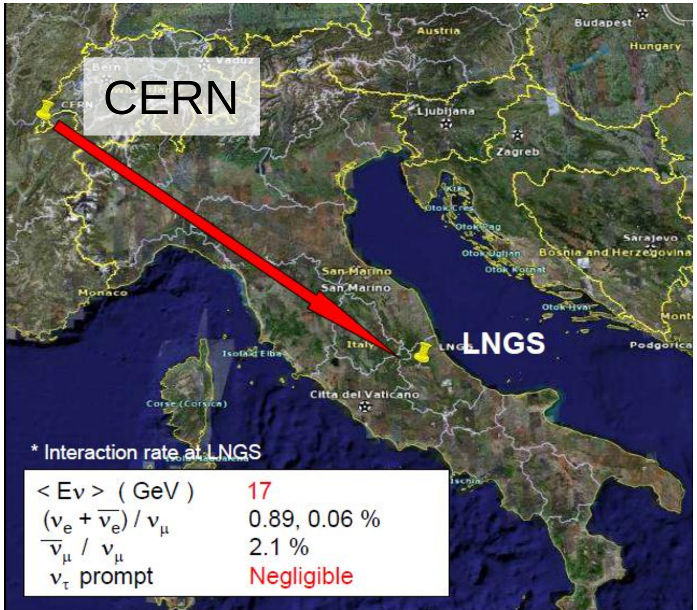
The observed excess is consistent with ν_τ appearance

$$\frac{N_t}{N_{exp}} = 1.42 \pm 0.35(stat.)\ ^{+0.14}_{-0.12}(syst.)$$

3.8 σ level excess.

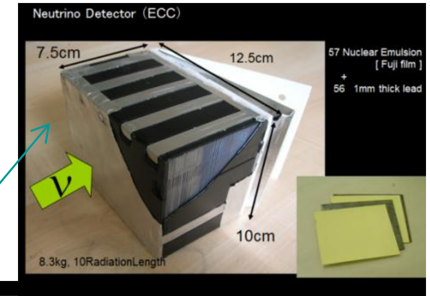
ν_τ events at OPERA

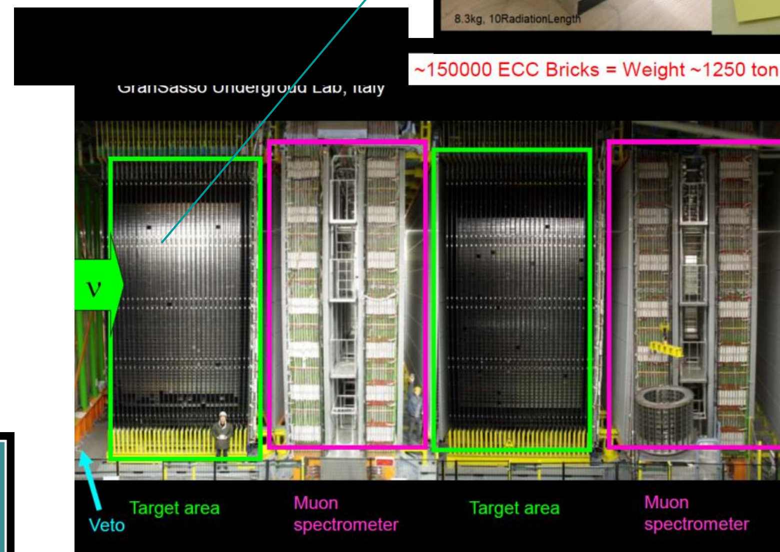
Baseline: 732km, <Eν> = 17 GeV



Detect decay of τ by emulsion chamber

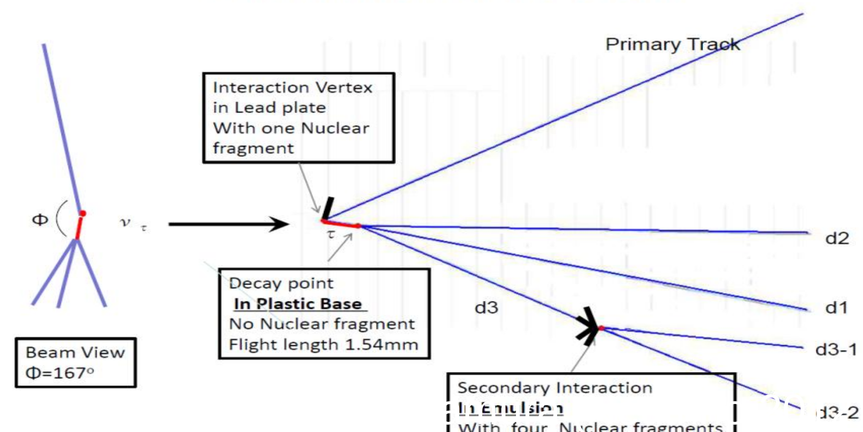
Emulsion chamber





Years	Status	# of events for Decay search	Expected ν_τ (Preliminary)	Observed ν_τ Candidate Events	Expected BG for ν_τ (Preliminary)
2008-2009	Finished	2783		1	
2010-2011	In analysis	1343		1	
2012	Started				
Total		4126	2.1	2	0.2

Schematics of the event



Methods of θ_{13} measurements

- Short baseline reactor: $\bar{\nu}_e$ disappearance

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13})\sin^2(\frac{1.27\Delta m^2{}_{31}L(m)}{E_\nu(MeV)})$$

θ_{13} only

- Long baseline accelerator: ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2(\frac{1.27\Delta m^2{}_{31}L(km)}{E_\nu(GeV)})$$

Leading term

Sub-leading

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

CPC

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

CPV

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

"solar"

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

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2S_{13}^2)\sin^2\Delta_{31}$$

matter

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

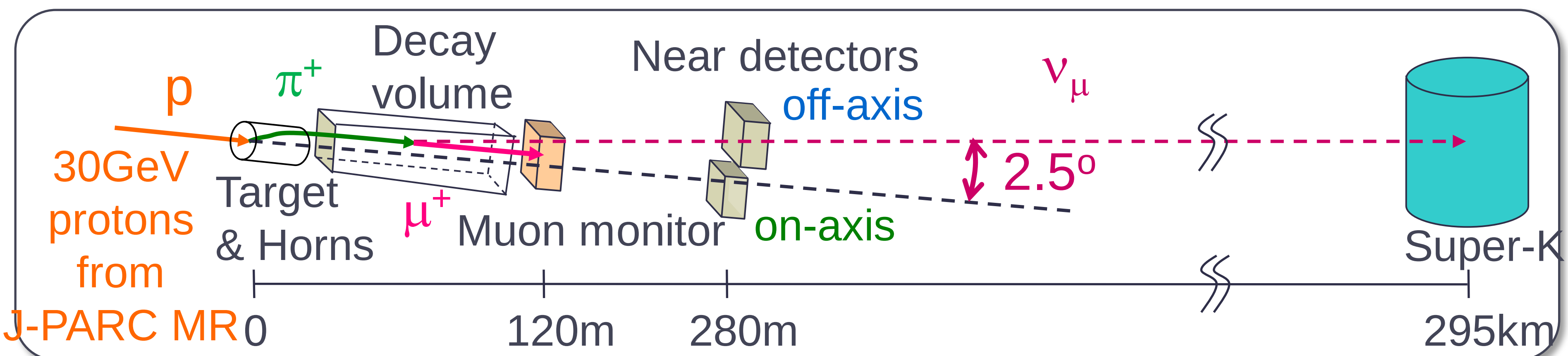
$S_{ij} \equiv \sin\theta_{ij}, C_{ij} \equiv \cos\theta_{ij}$
$\Delta_{ij} \equiv \Delta m_{ij}^2 L / E_\nu$
$a = 2\sqrt{2}G_F.n_e E_\nu$

ν_e appearance: depends on δ and mass hierarchy

T2K（Tokai-to-Kamioka）experiment

Off-axis beam

2.5deg. off-axis in order to make narrow band beam with higher intensity



T2K result (Run 1+2+3) (Data from 2010 - 2012 June)

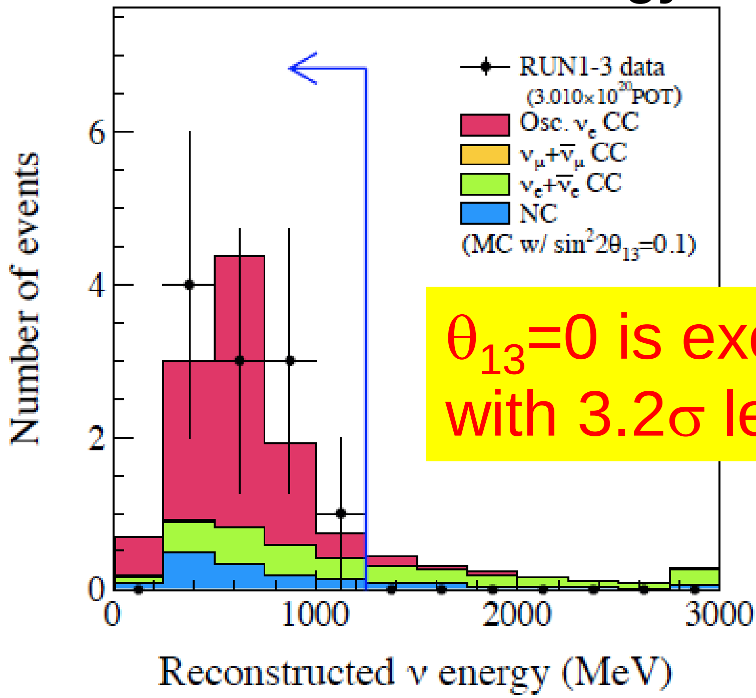
ν_e appearance

Data of 3.01×10^{20} POT (protons on target)
[it is only 5% of designed POT of T2K.]

11 electron neutrinos observed.

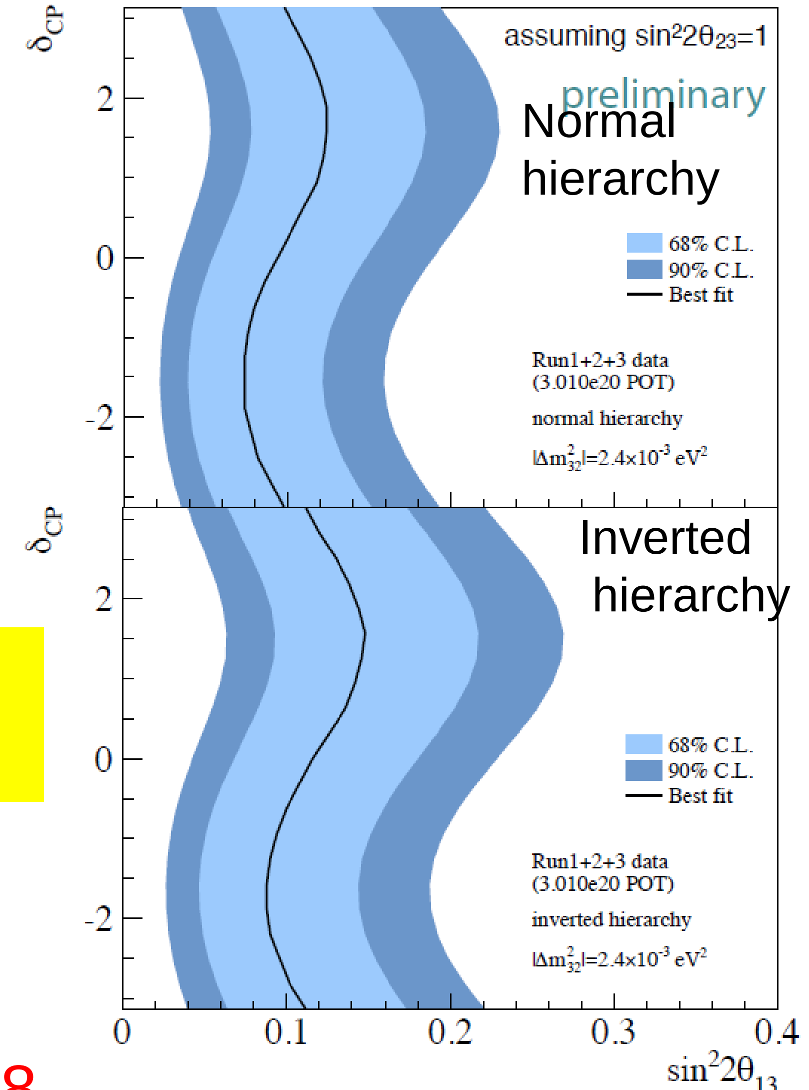
Expected number of background
3.2 ± 0.43 (syst.) for $\sin^2(2\theta_{13})=0$

Reconstructed ν energy



$\theta_{13}=0$ is excluded with 3.2σ level.

Allow region on $\sin^2 2\theta_{13}$ and δ_{CP}



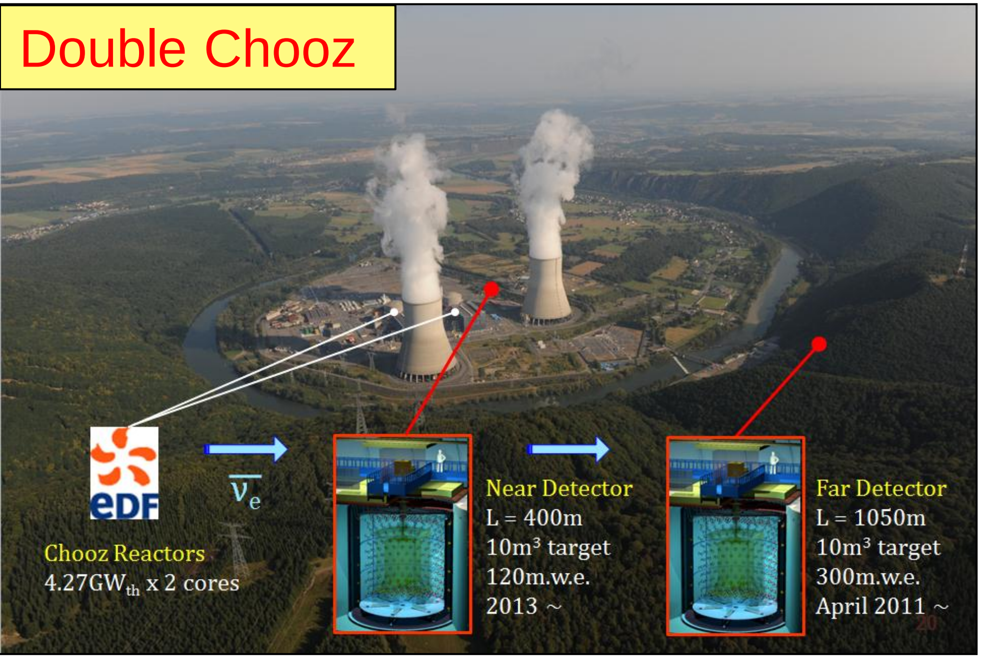
$0.033 < \sin^2 2\theta_{13} < 0.188$

Best fit : $\sin^2 2\theta_{13} = 0.11$

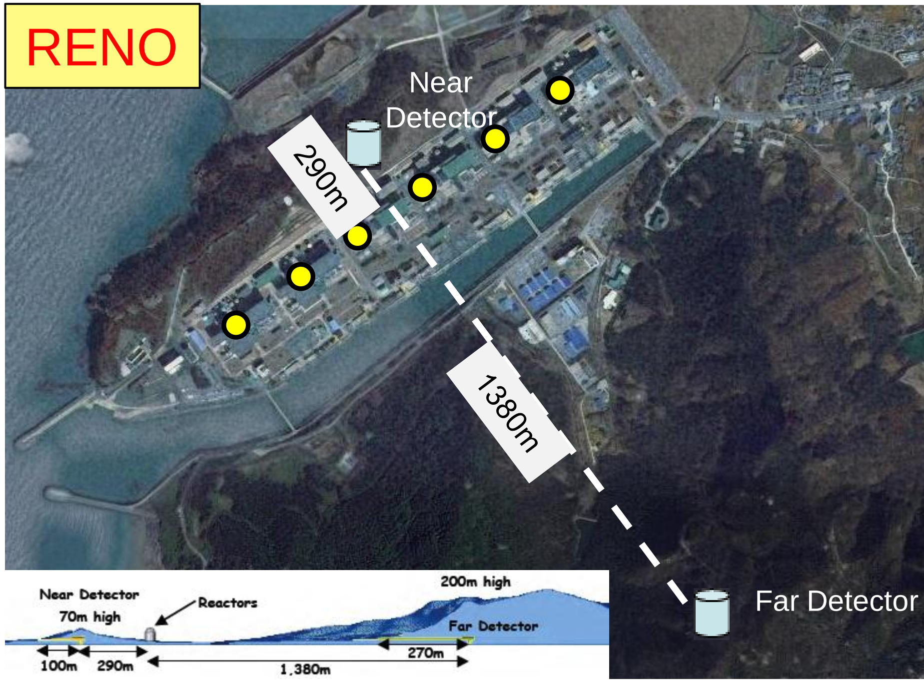
(for $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\delta_{CP}=0$)

Reactor θ13 experiments

Double Chooz



RENO



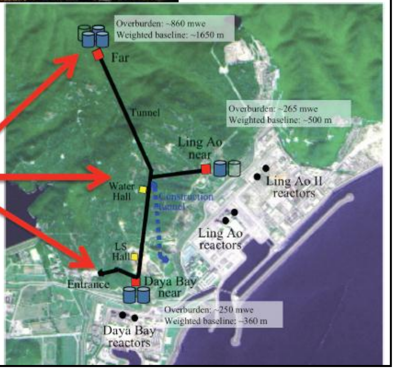
Daya Bay

Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

6 commercial reactor cores with 17.4 GW$_{th}$ total power.

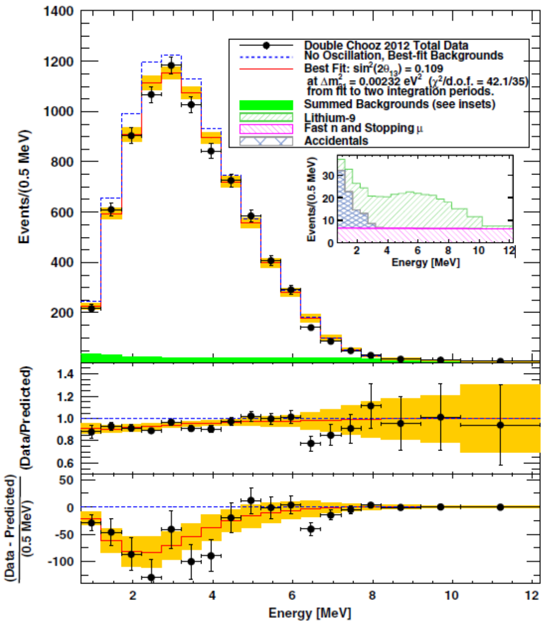
6 Antineutrino Detectors (ADs) give 120 tons total target mass.

Via GPS and modern theodolites, relative detector-core positions known to 3 cm.



Results of reactor θ13 experiments

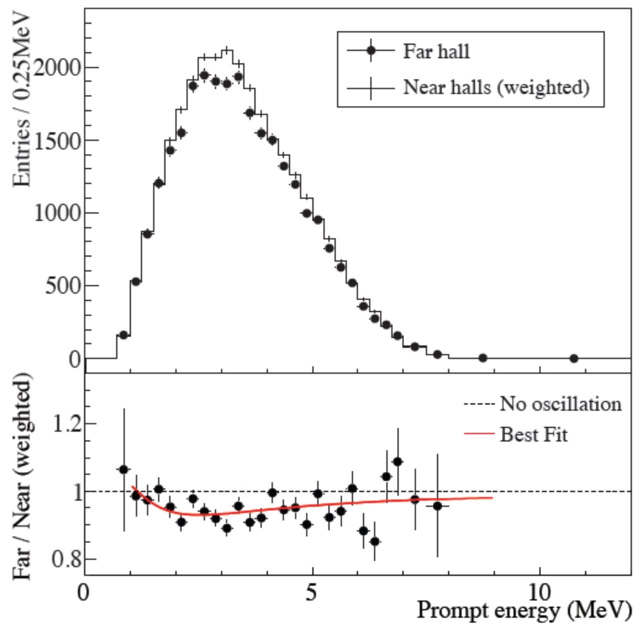
Double Chooz
(Jun. 2012)



$\sin^2 2\theta_{13}$ =
0.109±0.030±0.025
(2.9σ level)

PRD 86, 052008 (2012)

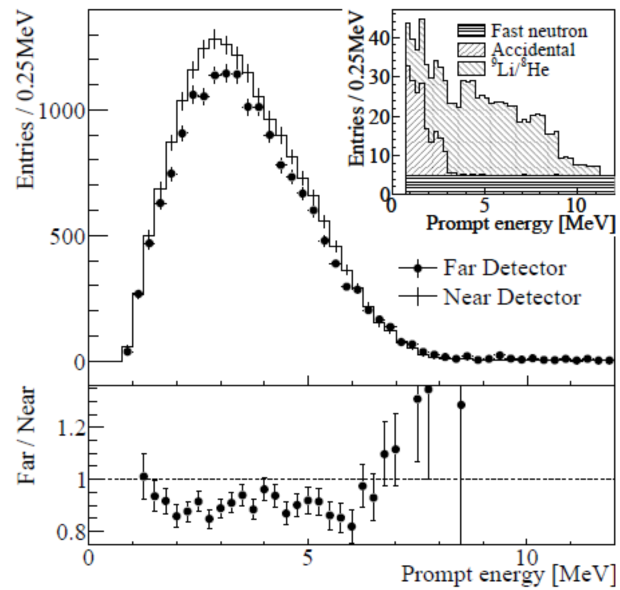
Daya Bay
(Jun. 2012)



$\sin^2 2\theta_{13}$ =
0.089±0.010±0.005
(8σ level)

arXiv:1210.6327 [hep-ex]

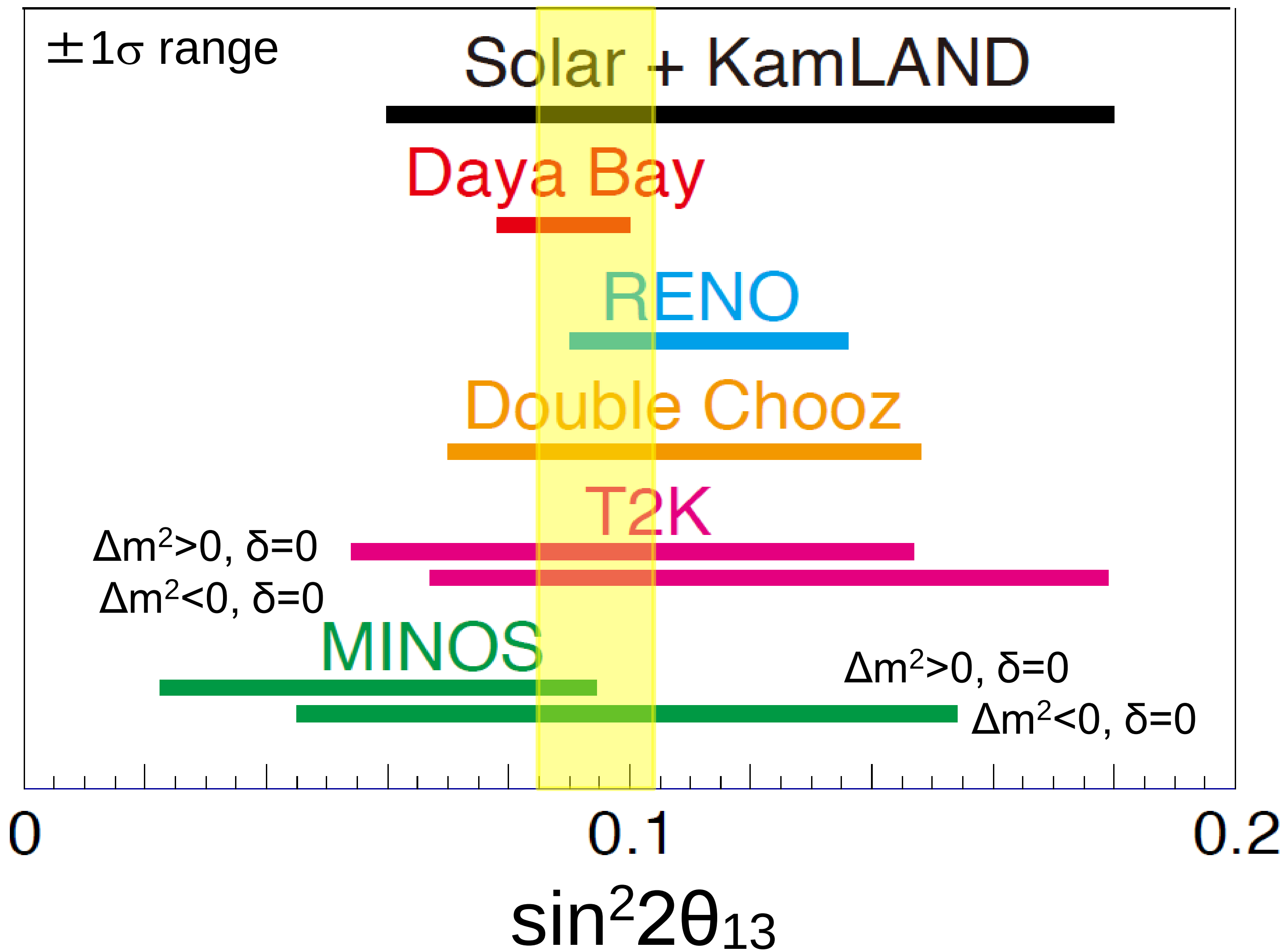
Reno
(April 2012)



$\sin^2 2\theta_{13}$ =
0.113±0.013±0.019
(4.9σ level)

PRL108 (2012) 191802

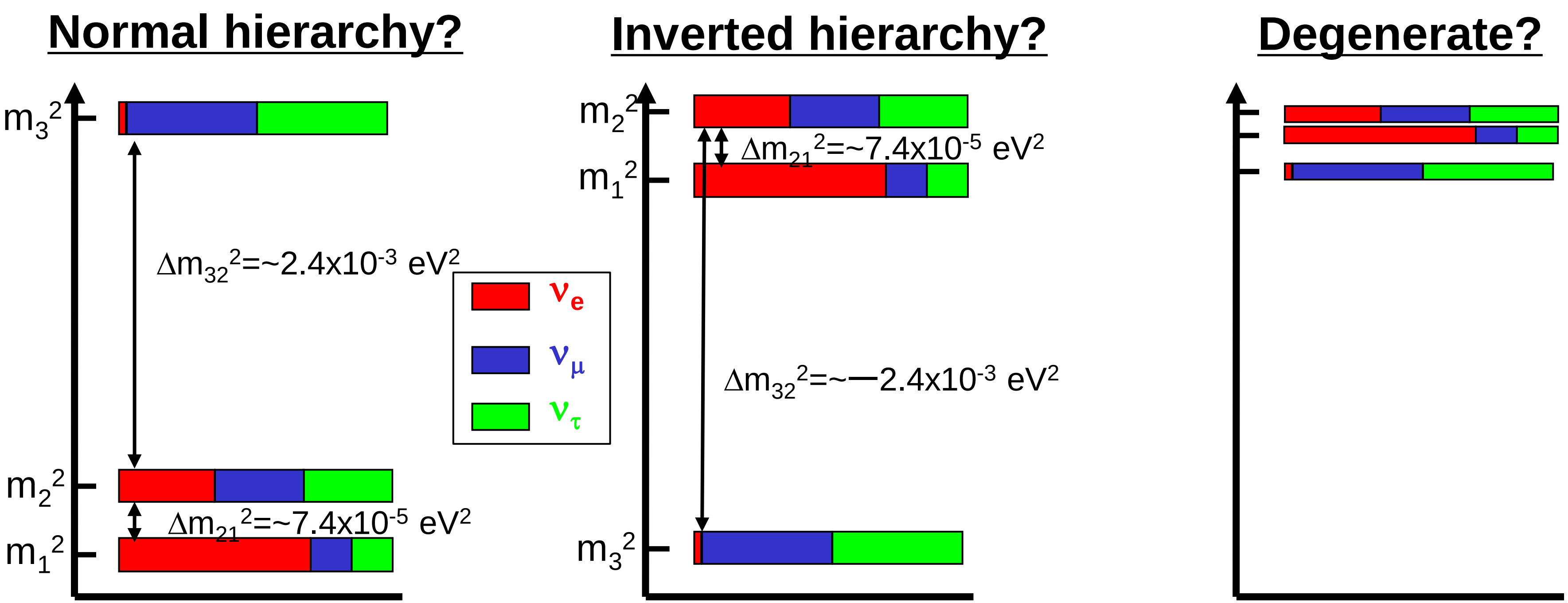
Summary of θ13 measurements



All results are consistent and $\sin^2 2\theta_{13}$ =~0.1.

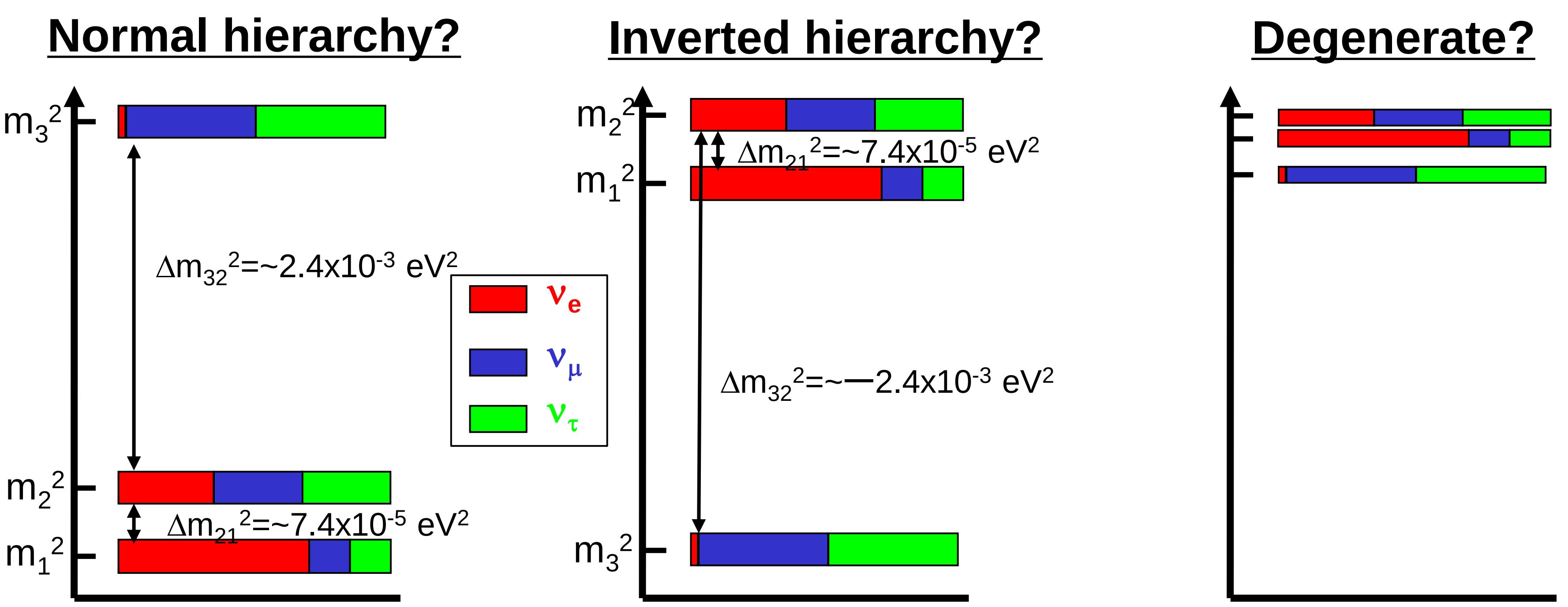
Unknown properties of Neutrinos

- What is the value of CP phase δ ?
- $(\theta_{23} - 45^\circ) = 0?, >0?, \text{ or } <0$?
- Which mass hierarchy ?
- Absolute value of mass ?
- Majorana or Dirac particle ?
- LSND/MiniBooNE, Ga and reactor anomalies ?



Unknown properties of Neutrinos

- What is the value of CP phase δ ?
- $(\theta_{23} - 45^\circ) = 0?,\ >0?,\ \text{or} <0$?
- Which mass hierarchy ?
- Absolute value of mass ?
- Majorana or Dirac mass ?
- LSND/MiniBooNE, Ga and reactor anomalies ?



How to measure CP phase δ

Long baseline accelerator: ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{31}L(km)}{E_\nu(GeV)}\right)$$ Leading term

Sub-leading

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

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

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

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

matter

$$+8C_{13}^2S_{13}^2S_{23}^2\frac{a}{\Delta m_{31}^2}(1-2S_{13}^2)\sin^2\Delta_{31}$$

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

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/E_\nu$$

$$a = 2\sqrt{2}G_F.n_eE_\nu$$

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

Compare $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ for CP phase measurement

Effect of CP violating term in $P(\nu_\mu \rightarrow \nu_e)$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$ Leading

CP violating (flips sign for $\bar{\nu}$)

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

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

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

Matter $\begin{cases} -8C^2_{13}S^2_{13}S^2_{23}\dfrac{aL}{4E_\nu}(1-2S^2_{13})\cos\Delta_{32}\sin\Delta_{31} \\ +8C^2_{13}S^2_{13}S^2_{23}\dfrac{a}{\Delta m^2_{31}}(1-2S^2_{13})\sin^2\Delta_{31} \end{cases}$

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

$\Delta_{ij} \equiv \Delta m^2_{ij}L/E_\nu$

$a = 2\sqrt{2}G_F.n_eE_\nu$

CPV term

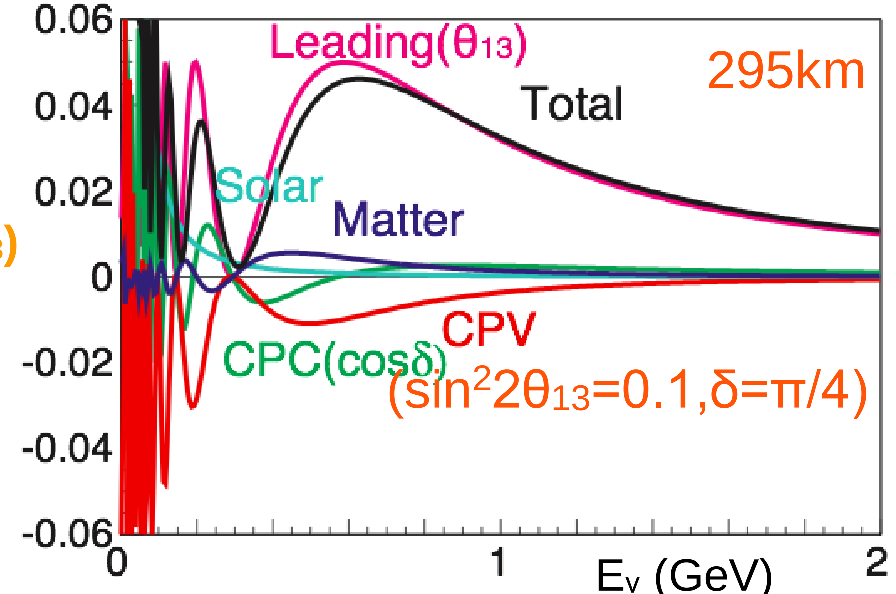
$$\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{21}L}{4E}\sin\delta$$

~0.03 ~11.8 (6.4 from $1/\sin\theta_{13}$)

$$\sim\frac{\pi}{4}\frac{\Delta m^2_{21}}{\Delta m^2_{32}}\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{\sin^2\theta_{23}\sin\theta_{13}}\frac{E_{1st\,max}}{E}[leading]\sin\delta$$

$$\sim 0.27\times[leading]\times\frac{E_{1st\,max}}{E}\times\sin\delta$$

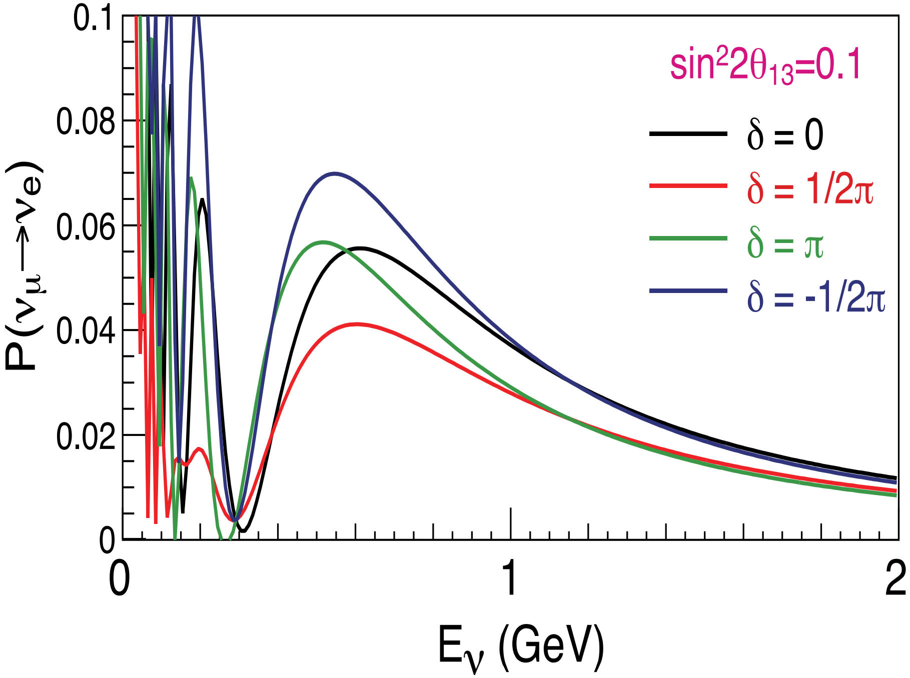
27%



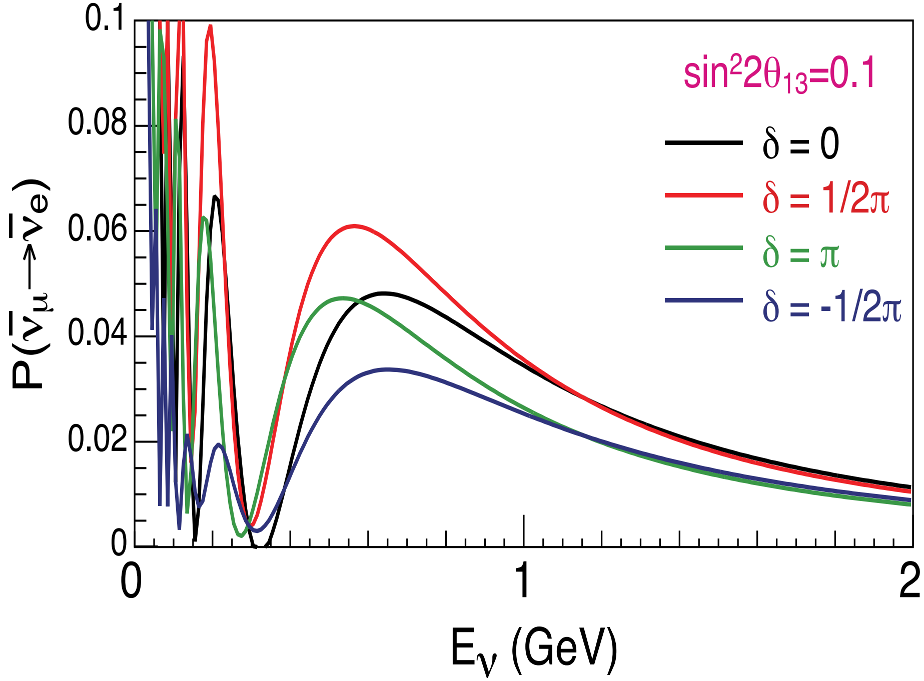
$\nu_\mu \rightarrow \nu_e$ probability (L=295km)

Normal hierarchy

Neutrino case



Anti-neutrino case

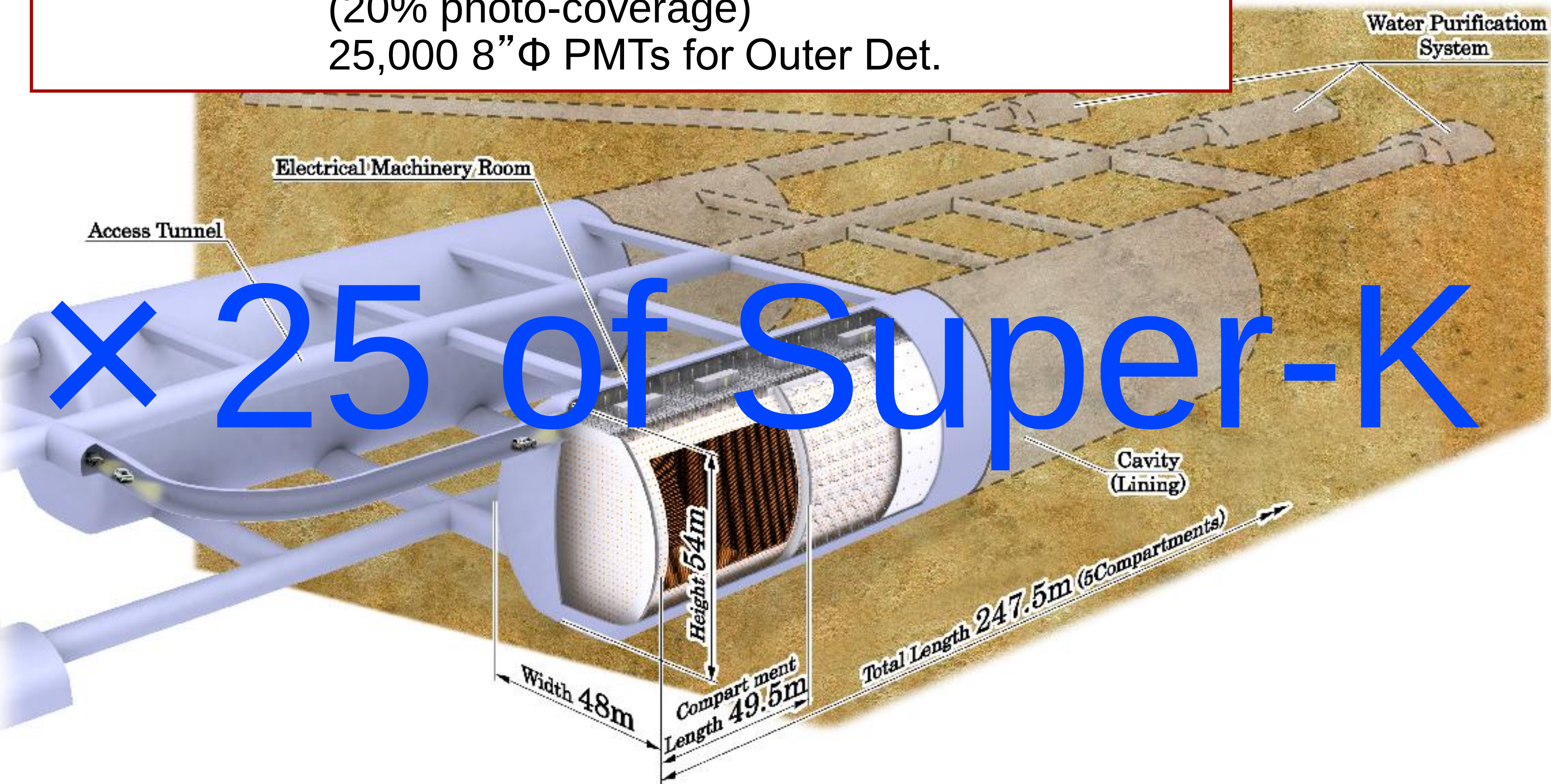


- Comparison between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
    - As large as ~25% from nominal
- It is sensitive also to exotic (non-PMNS) CP violation cases.

We need a larger volume detector for the CP phase measurement.

Hyper-Kamiokande Detectors

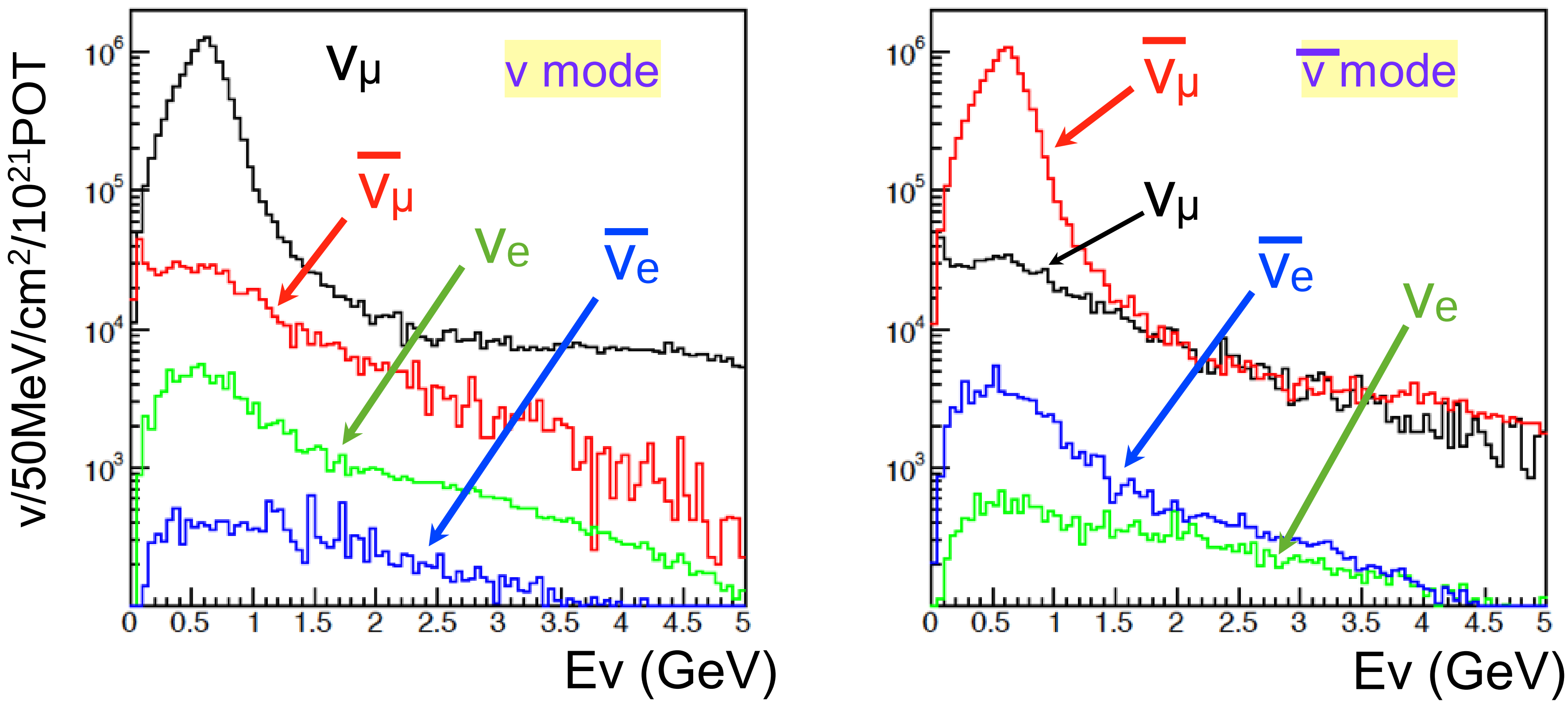
Total Volume 0.99 Megaton
Inner Volume 0.74 Mton
Fiducial Volume 0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume 0.2 Megaton
Photo-sensors 99,000 20”Φ PMTs for Inner Det.
(20% photo-coverage)
25,000 8”Φ PMTs for Outer Det.



Neutrino beam from J-PARC

The ν beam

Expected neutrino flux at Hyper-K (unoscillated)



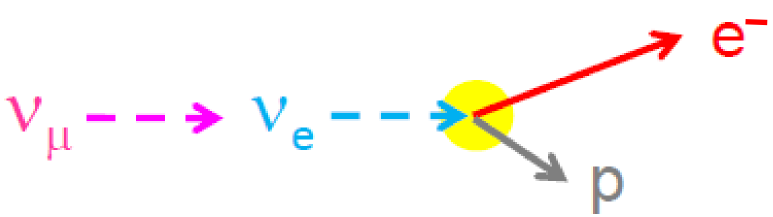
2.5º off-axis beam from J-APRC
Peaked at oscillation maximum
Suppress BG from high energy component.

Signals and backgrounds

Signals

Single electron event by CC interaction of ν_e oscillated from ν_μ

- Mainly CCQE : $\nu_e + n \rightarrow e^- + p$
- Protons mostly have momenta below Cherenkov threshold

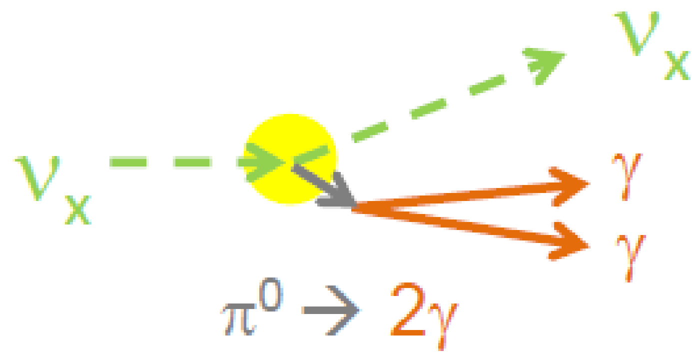


Backgrounds

(1) intrinsic ν_e in the beam (from μ, K decays)

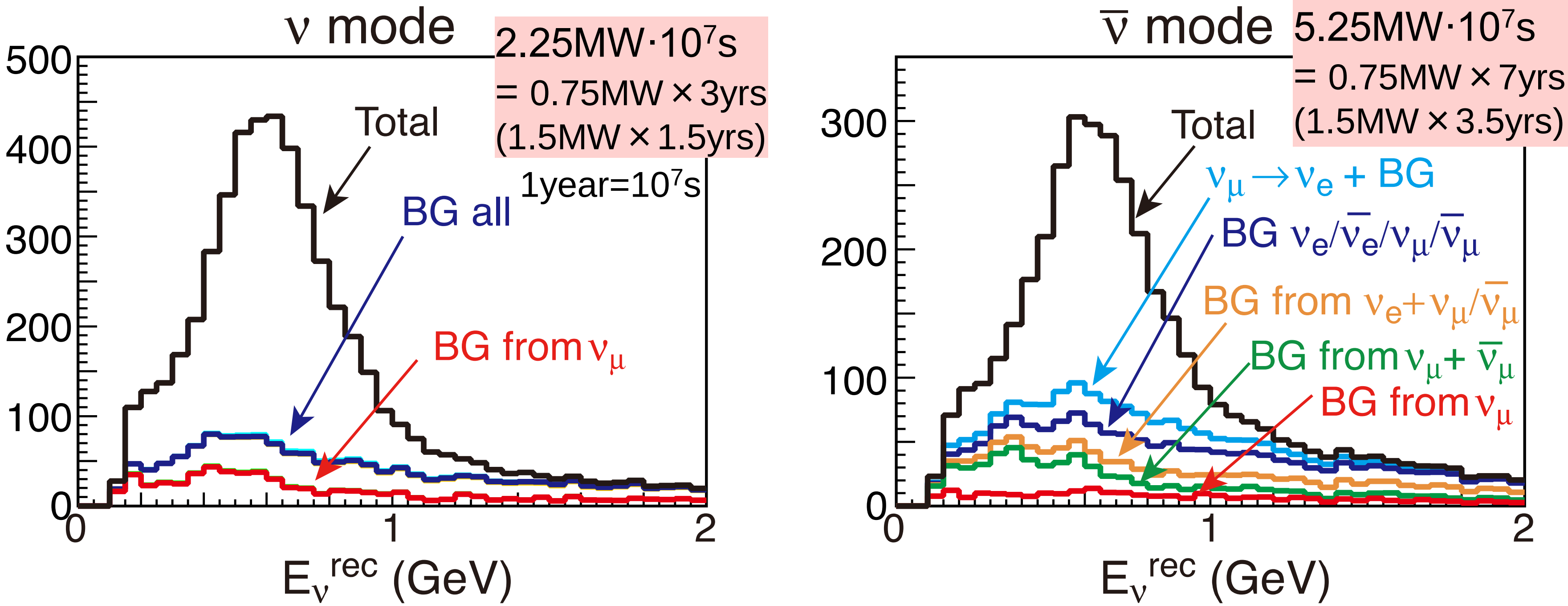
(2) NC single π^0 events

- overlap of 2 γ rings
- asymmetric decay (one of the γ has very low energy)



Expected ν_e candidate events

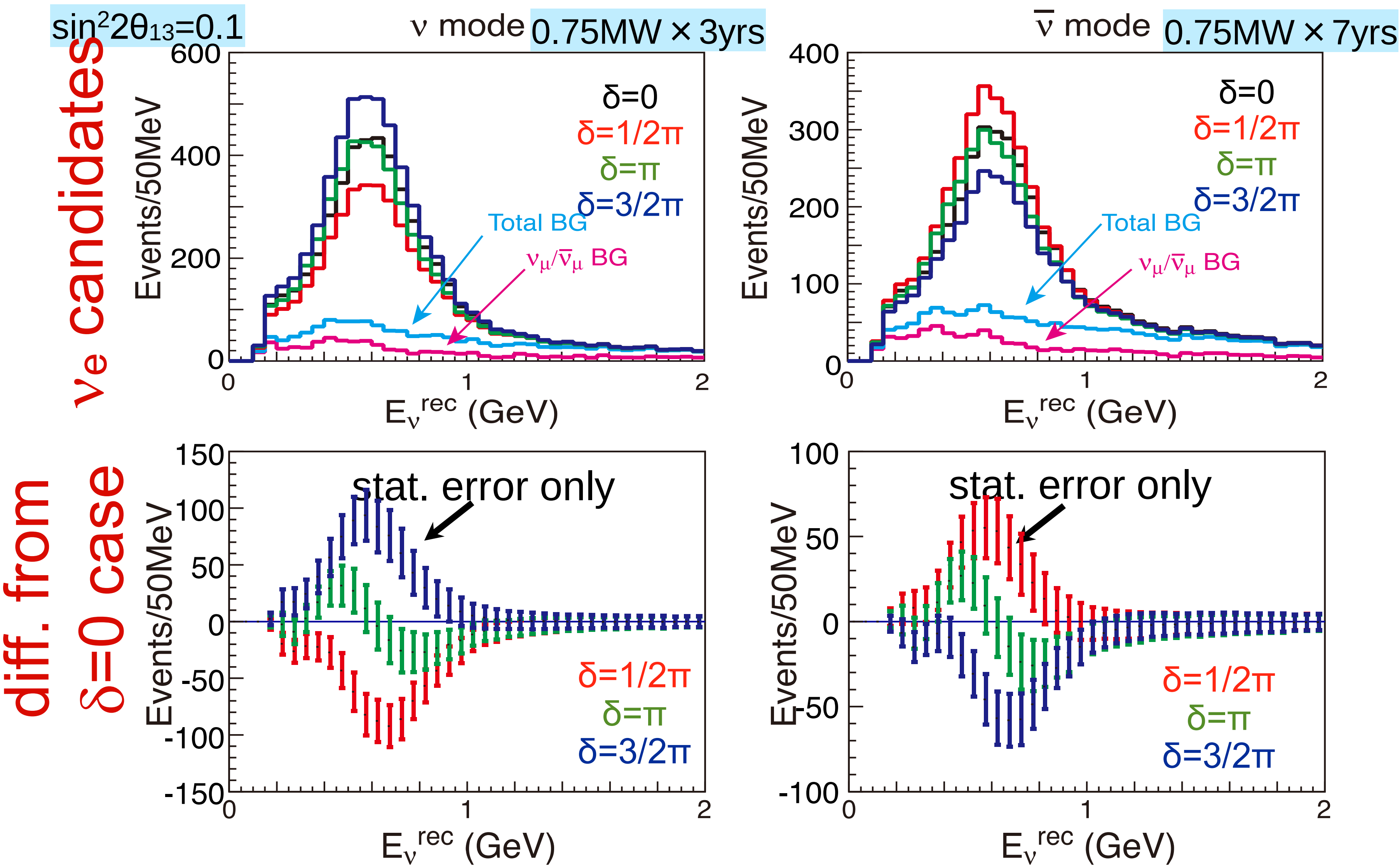
$\sin^2 2\theta_{13}=0.1, \delta=0$, normal MH



	Signal ($\nu_\mu \rightarrow \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν (2.25MW·10^7s)	3,560	46	35	880	649
$\bar{\nu}$ (5.25MW·10^7s)	1,959	380	23	878	678

2000-4000 signal events expected for each of ν and $\bar{\nu}$

Expected ν_e CC candidates



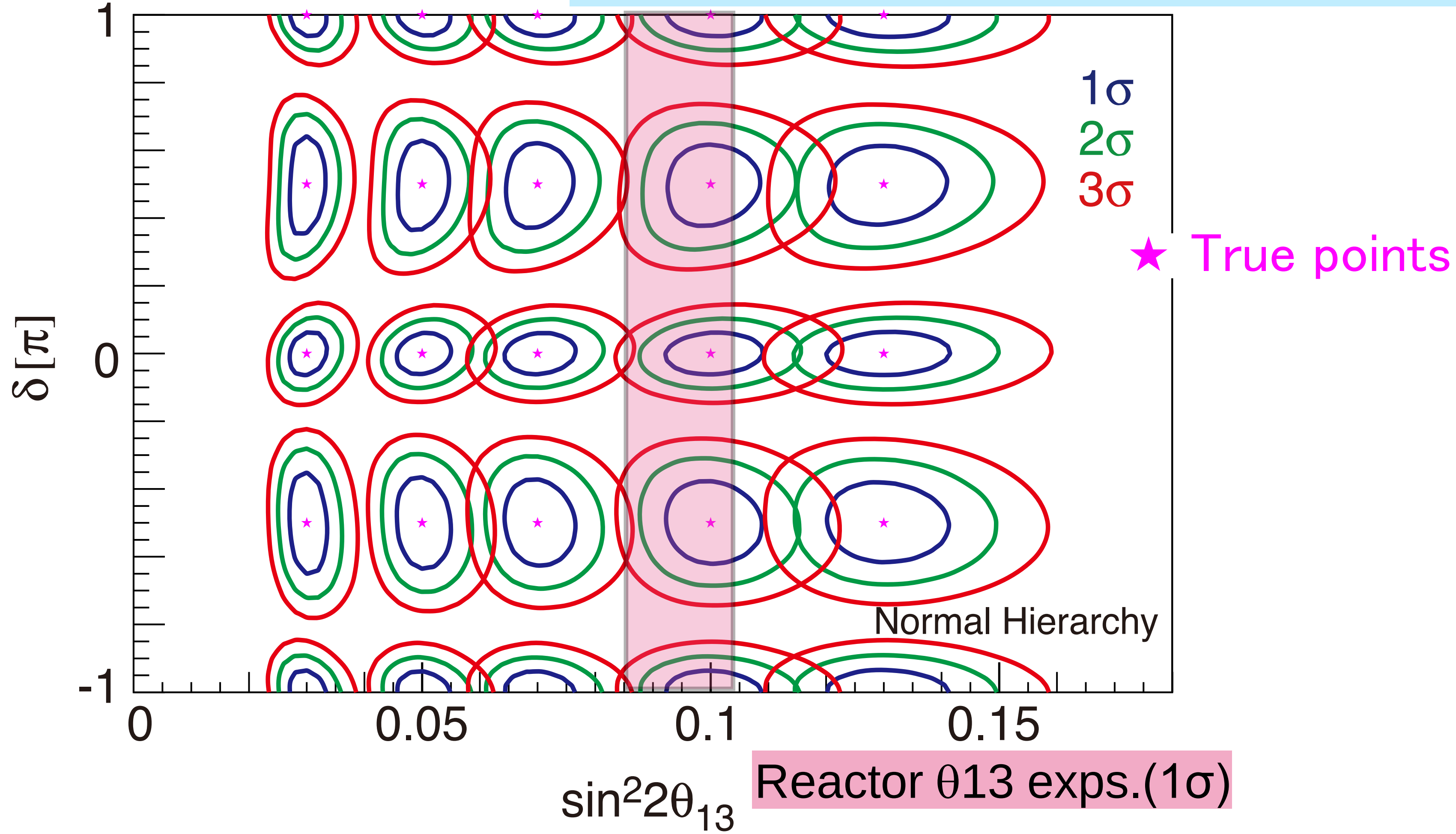
Numbers and shape for CP measurement

Expected Contours

7.5MW・years

Normal mass hierarchy (known)

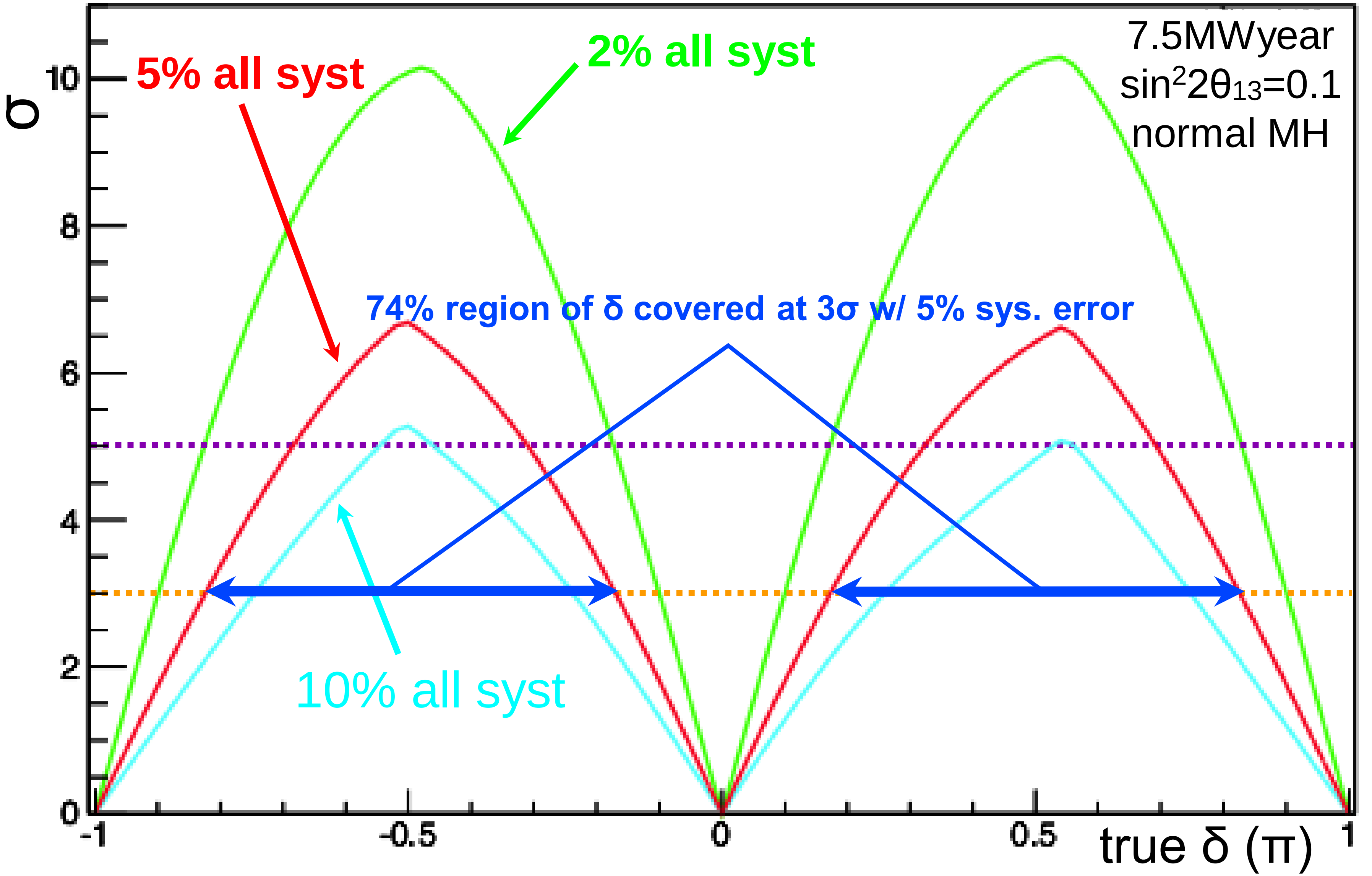
5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



- Good sensitivity for CP δ measurement

CPV Discovery Sensitivity

(w/ Mass Hierarchy known)

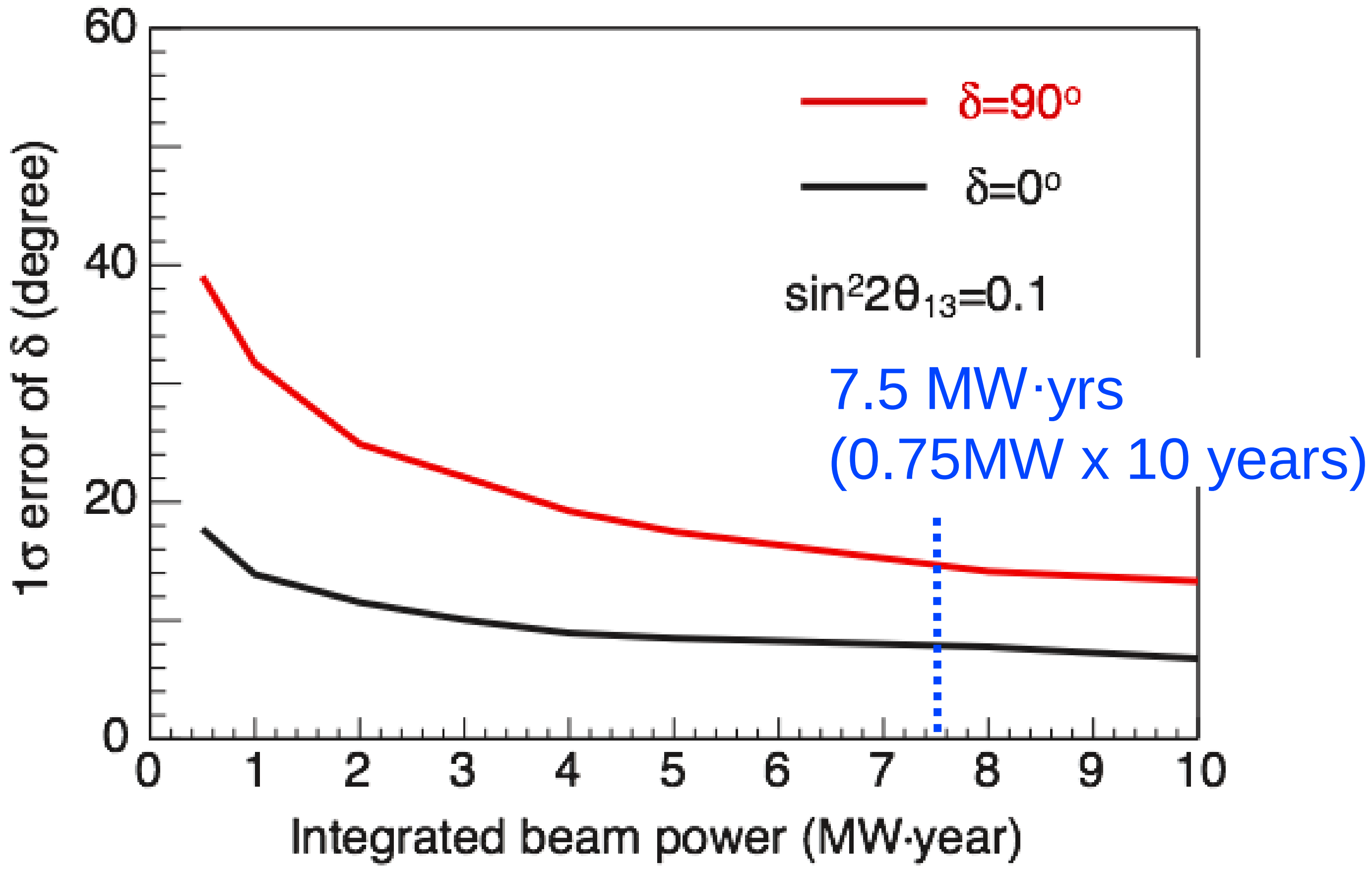


High Sensitivity to CPV w/ <~5% sys. error

δ resolution

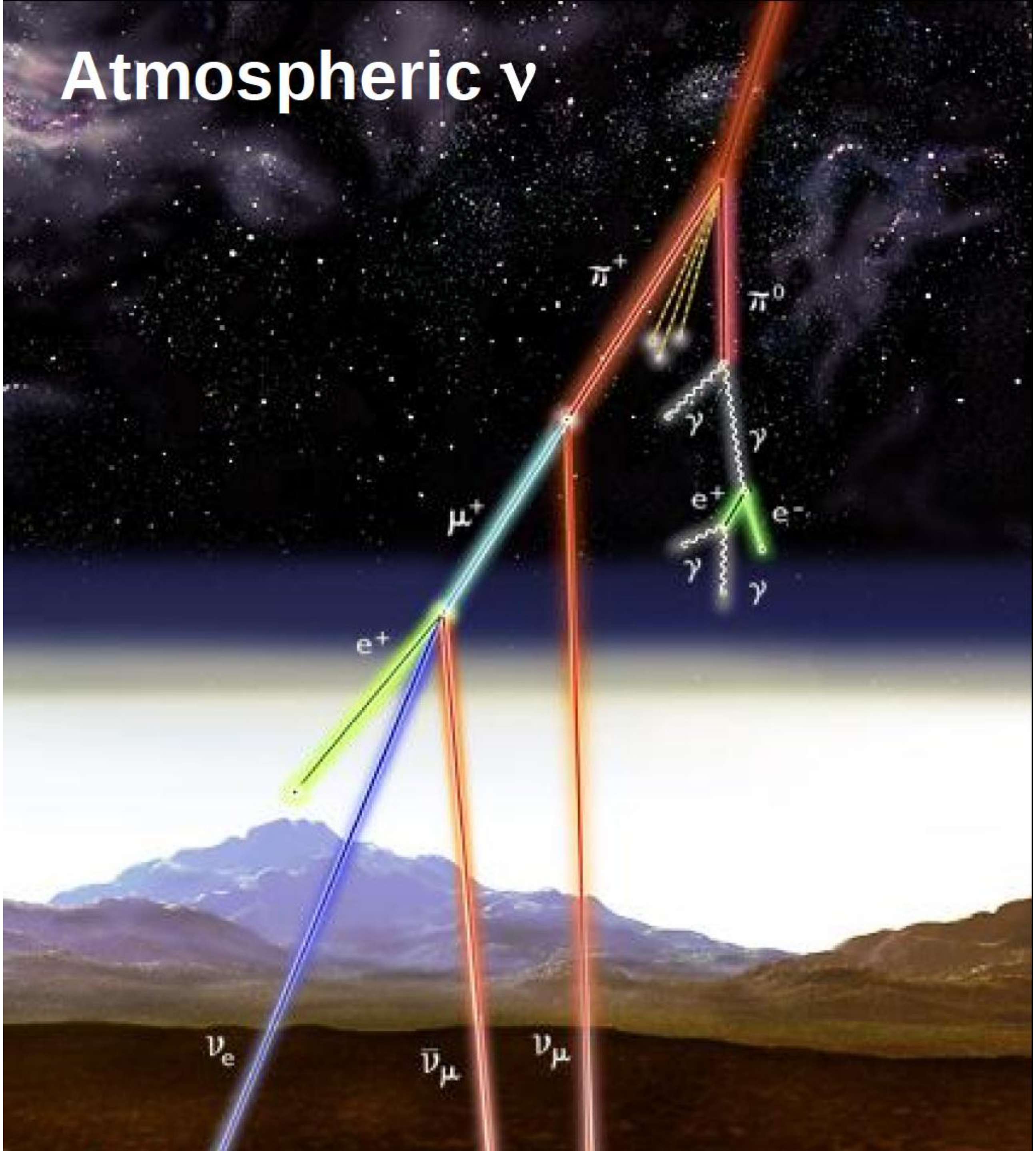
Normal mass hierarchy (known)

$\sin^2 2\theta_{13}=0.1$



- δ precision < 20° (δ=90°)
  < 10° (δ= 0°)
- modest dependence on θ_{13}

Atmospheric ν



ν_e appearance in atmospheric ν

NuclPhysB669,255(2003)

NuclPhysB680,479(2004)

r : μ/e flux ratio (~2 at low energy)

$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter

$R_2 = \mathrm{Re}(A^*_{ee} A_{e\mu})$

$I_2 = \mathrm{Im}(A^*_{ee} A_{e\mu})$

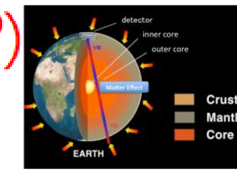
A_{ee} : survival amplitude of the 2ν system

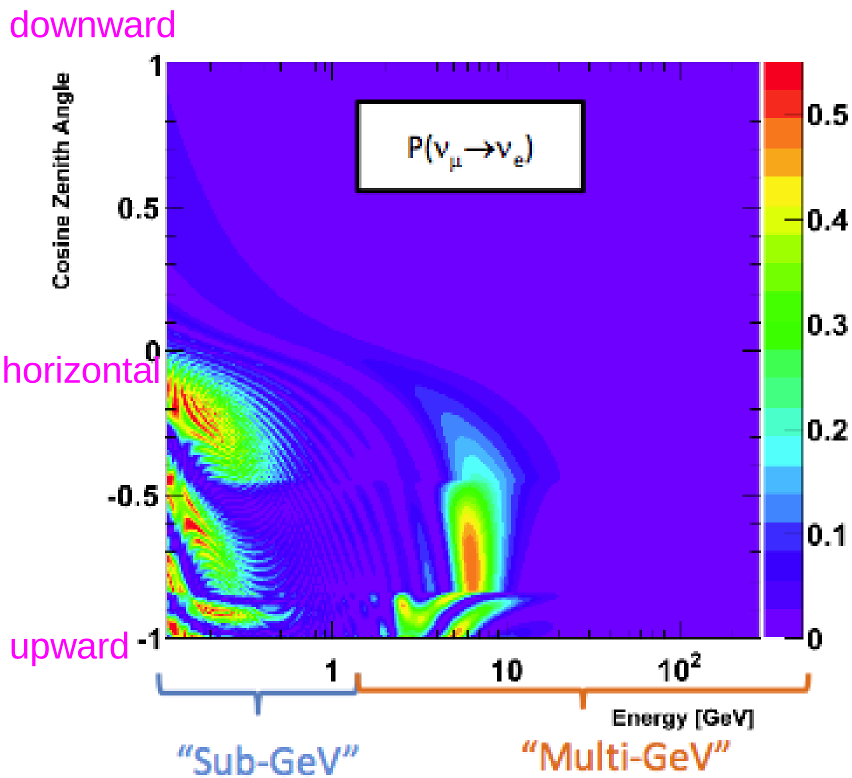
$A_{e\mu}$: transition amplitude of the 2ν system

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2\theta_{23} - 1)$$
Solar term

$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23}(\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$
Interference term (δCP)

$$+2\sin^2\tilde{\theta}_{13}(r \cdot \sin^2\theta_{23} - 1) \qquad (3)$$
θ_{13} resonance term

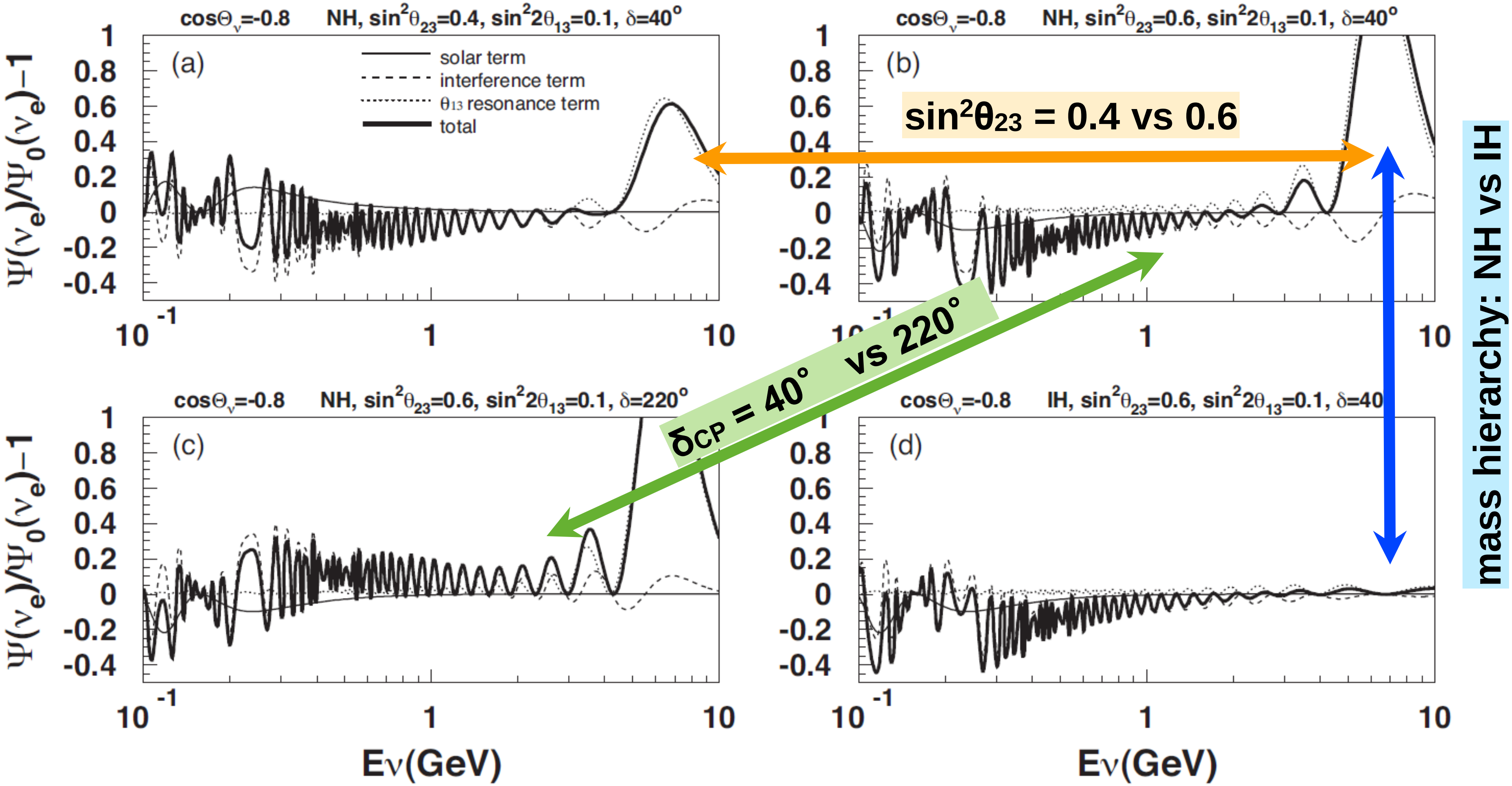




ν_e appearance (and ν_μ distortion) is expected due to MSW effect in the Earth's matter

- happens in ν in the case of normal mass hierarchy
- in anti- ν in inverted mass hierarchy

Large θ_{13} value gives us a good chance to discuss mass hierarchy and CP phase.



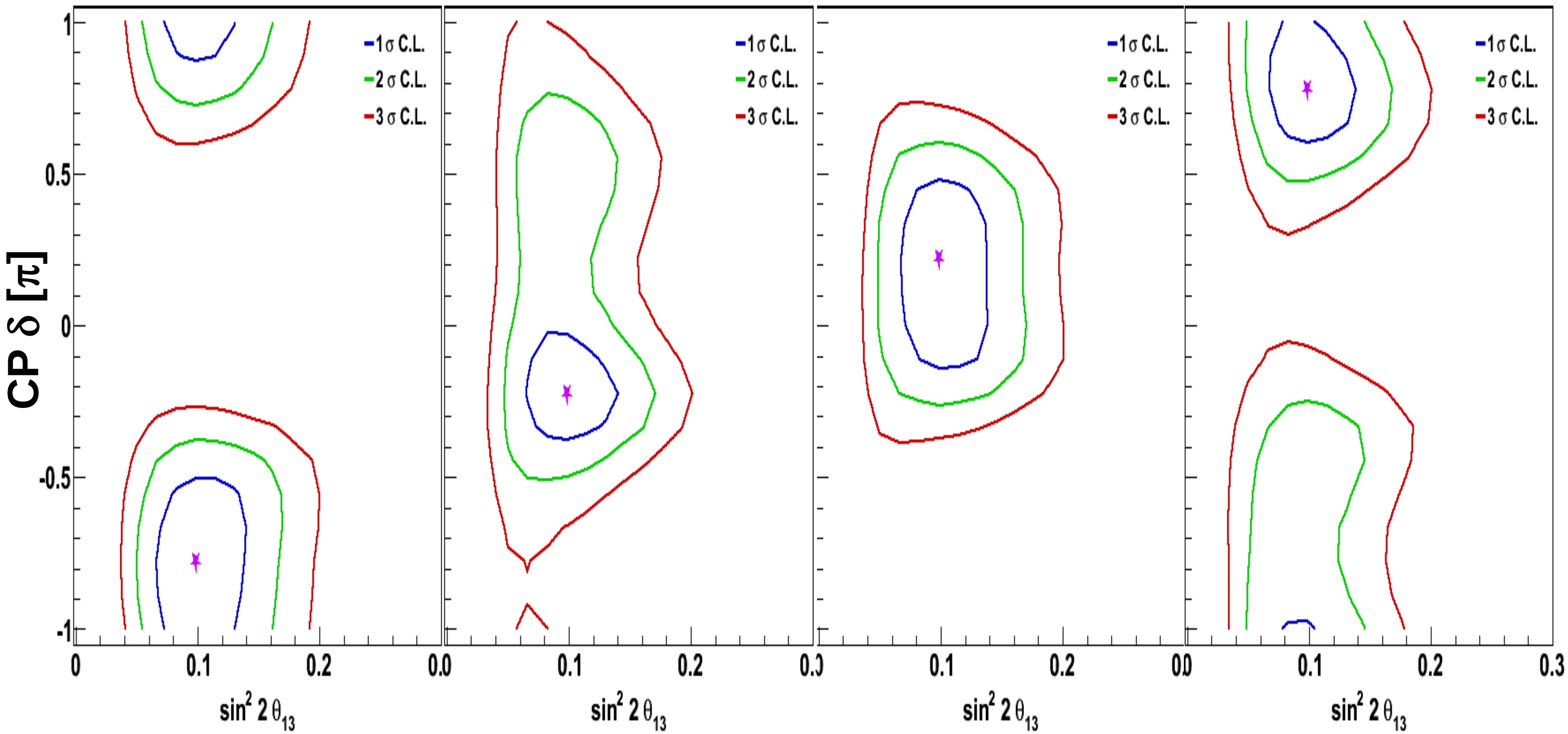
- Through matter effect (MSW), we study
  - Mass hierarchy ⇨ Asymmetry between neutrinos and antineutrinos.
  - Octant of θ_{23} ⇨ Appearance (and $\nu_\mu \rightarrow \nu_\mu$ disappearance) interplay
  - δ_{CP} ⇨ Magnitude of the interference

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

Atmospheric neutrinos of Hyper-K 10 years

1σ CL
2σ CL
3σ CL

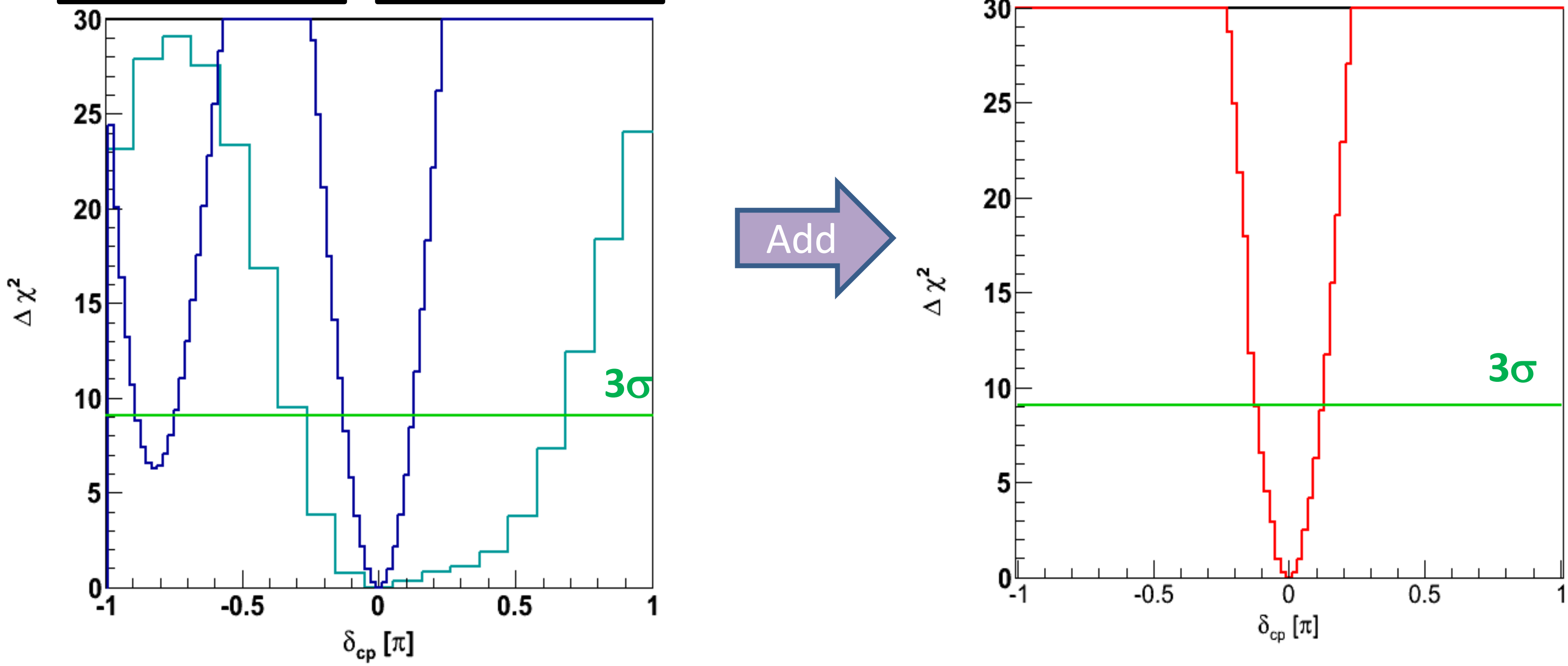
$\sin^2 2\theta_{13}=0.1$



Give supplemental information to the CP study conducted by the J-PARC beam

Combination of Beam and Atmospheric Neutrinos

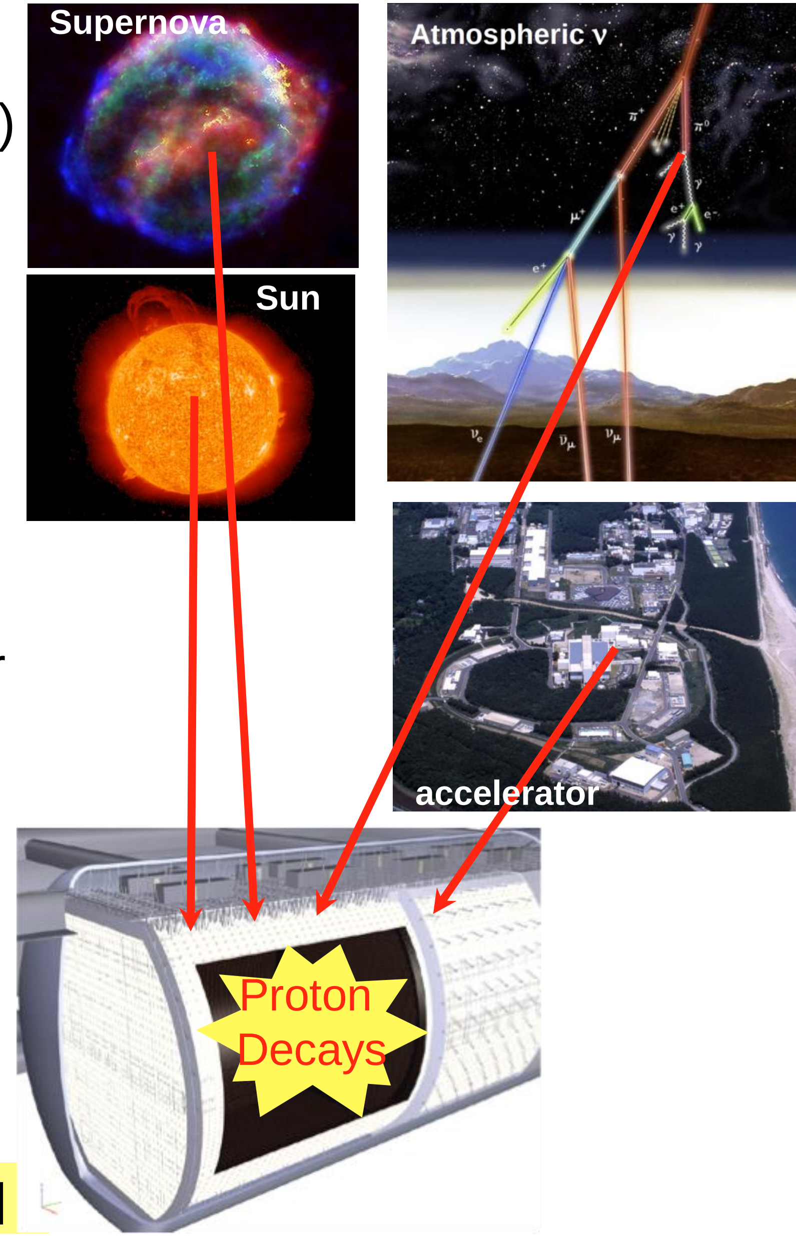
Beam Map | Atm. ν Map | **Allowed δ_{cp} range** | Atm. ν + Beam



- Hierarchy is unknown, but NH is true
- True $\delta_{cp} = 0.0$
- True $\sin^2 2\theta_{13} = 0.10$
- Maximal mixing , $\sin^2 2\theta_{23} = 1.0$
- Degenerate solution exists at 3σ in the beam only case - just add the χ^2 maps
- By adding atmospheric data, single solution is obtained.

Multi-purpose detector, Hyper-K

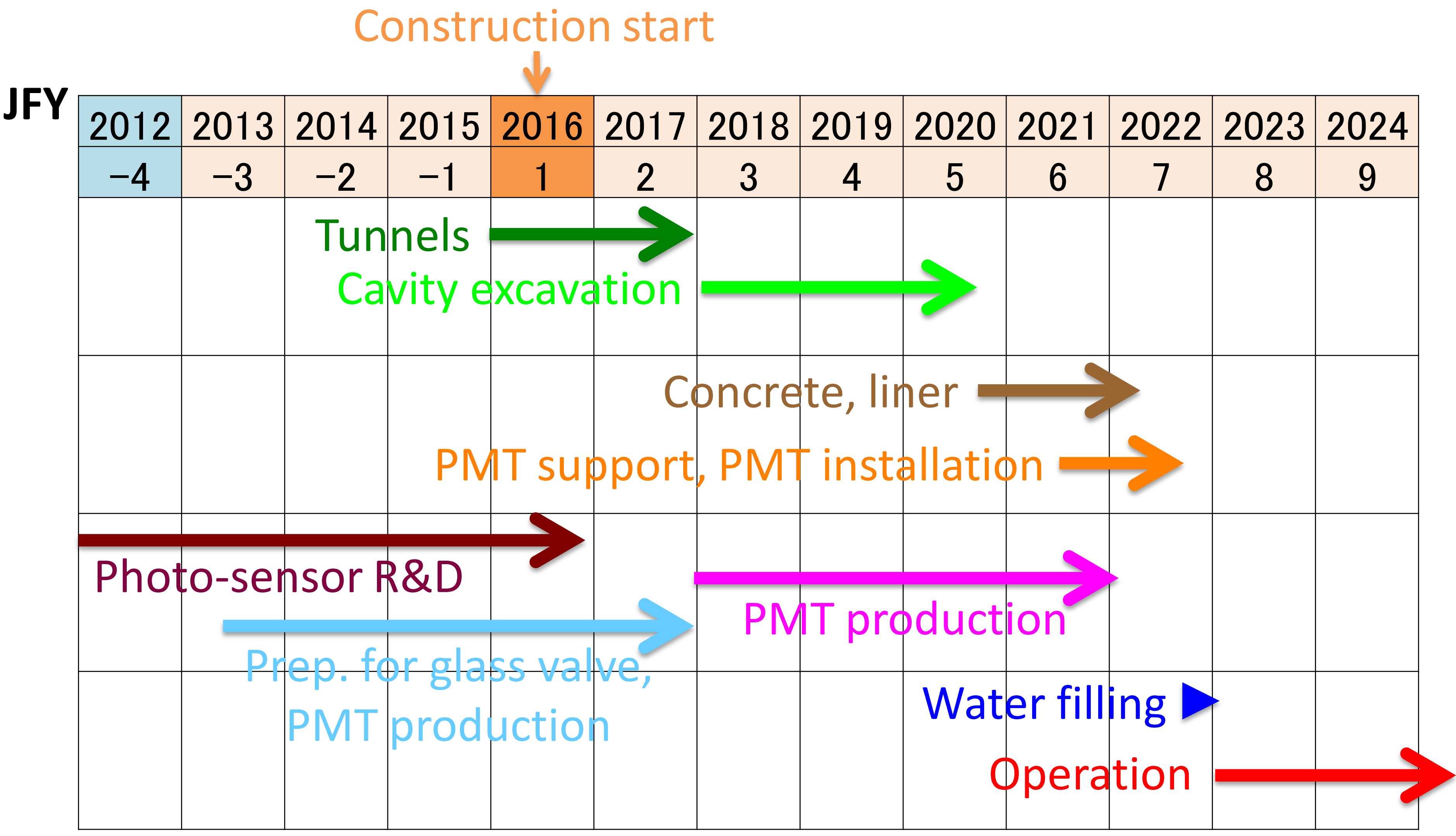
- Explore full picture of neutrino oscillation parameters.
  - Discovery of leptonic CP violation (Dirac δ)
  - ν mass hierarchy determination($\Delta m^2_{32}>0$ or <0)
  - θ_{23} octant determination ($\theta_{23}<\pi/4$ or $>\pi/4$)
- Extend nucleon decay search sensitivity
  - $\tau_{proton}=10^{34}\sim10^{35}$ years
- Neutrinos from astrophysical objects
  - 200 ν's / day from Sun
    - possible time variation, day/night matter effect.
  - 250,000 (50) ν's from Supernova @Galactic-center (Andromeda)
  - ~800 ν's / 10 years (>10MeV) SN relic ν
  - WIMP ν, solar flare ν, etc



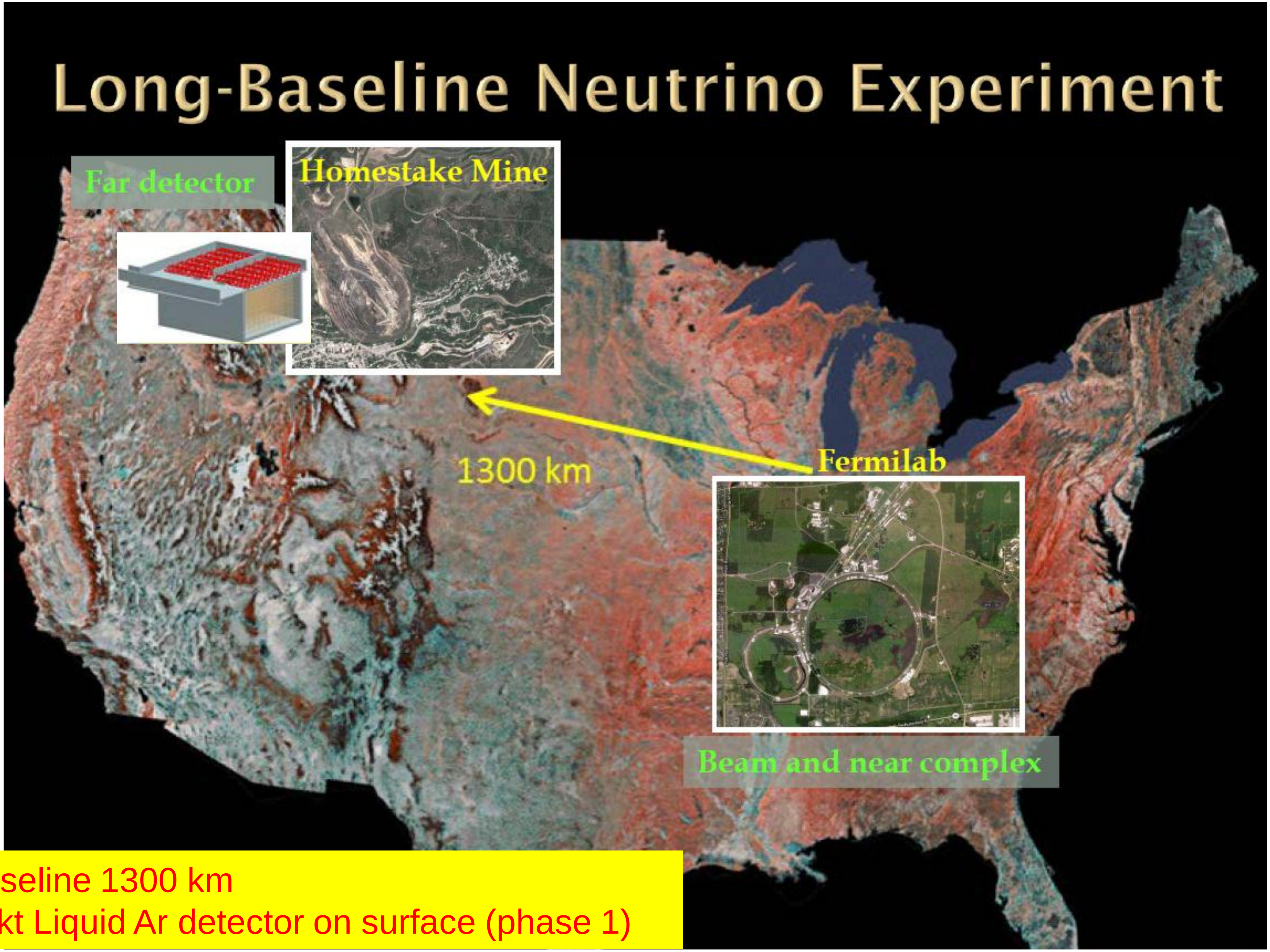
Letter of Intent, Hyper-K WG, arXiv:1109.3262 [hep-ex]

Schedule

assuming budget being approved from JPY2016

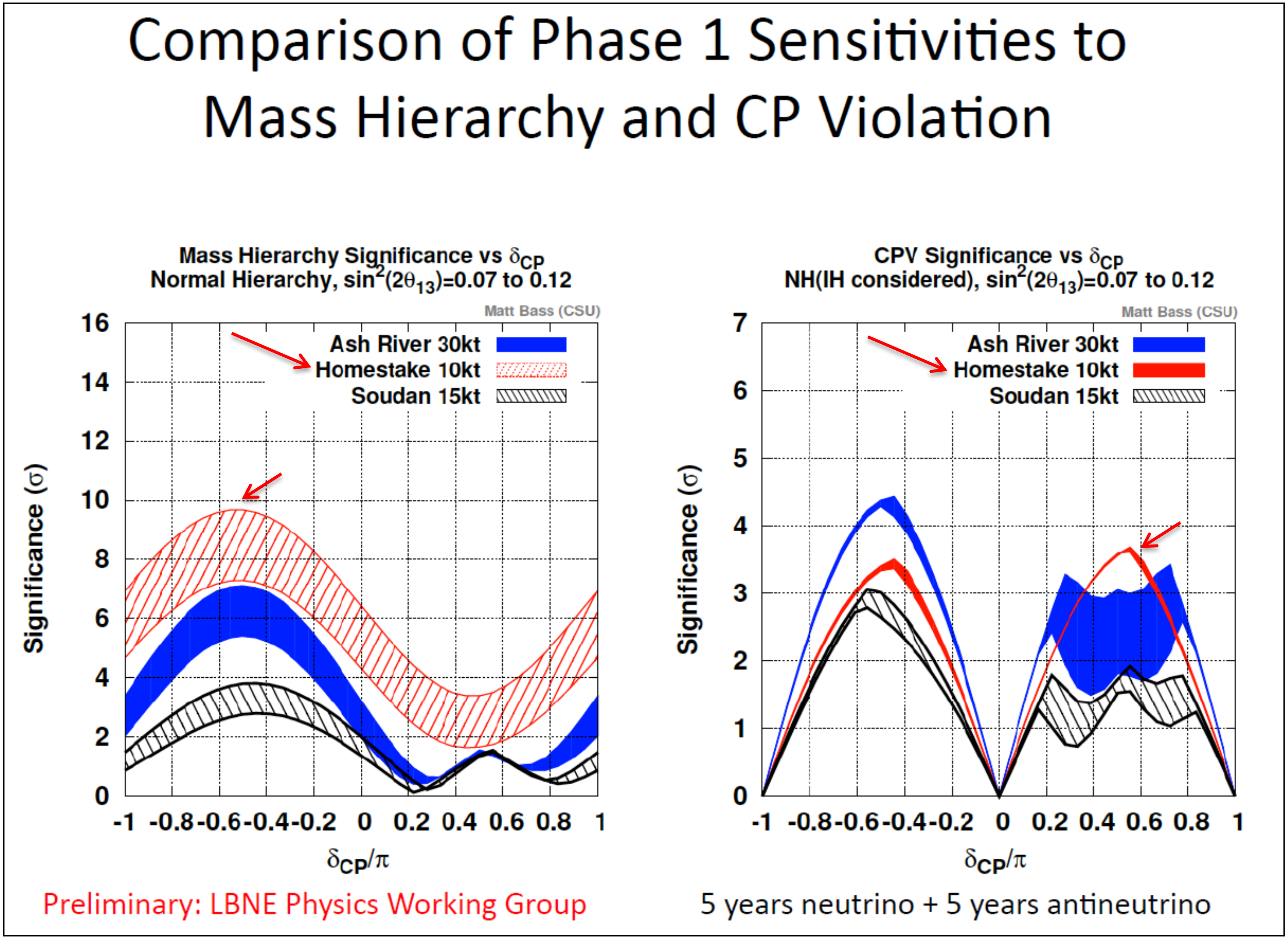


LBNE project in the US



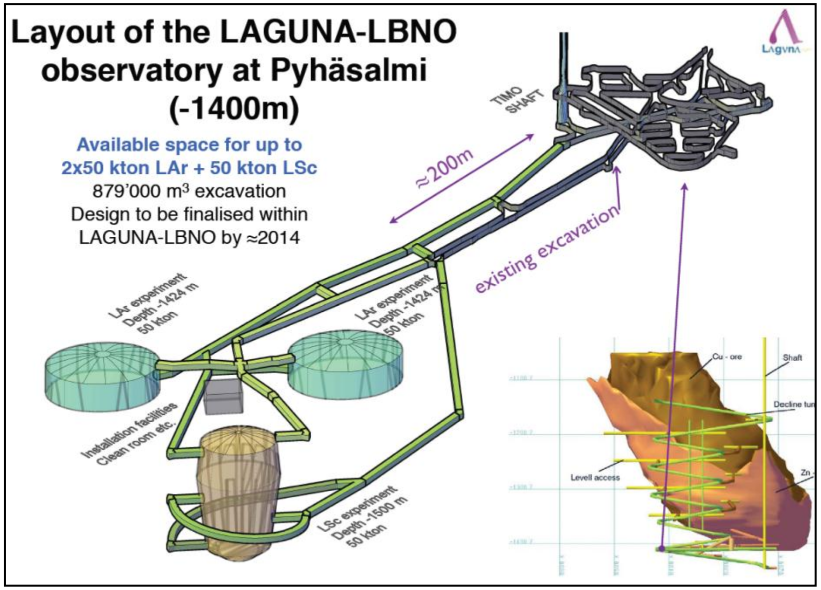
Baseline 1300 km
10kt Liquid Ar detector on surface (phase 1)

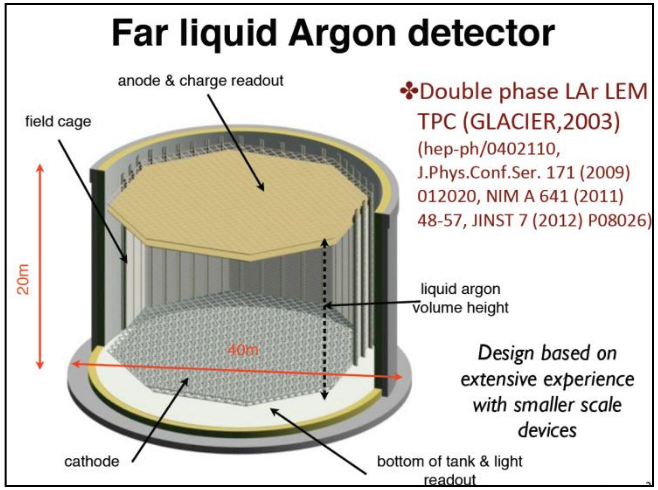
Sensitivity of LBNE



R. Svoboda (Neutrino 2012)

LBNO project in Europe



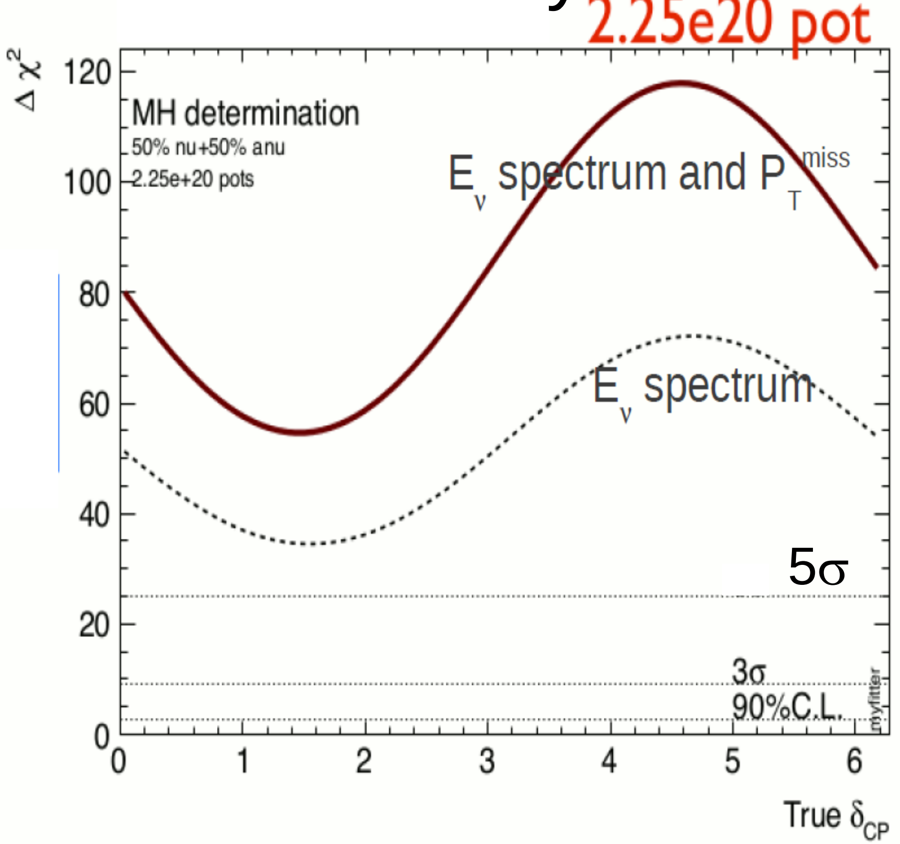


Baseline 2300 km
20kton liquid Ar detector at 1400m underground.

Sensitivity of LBNO

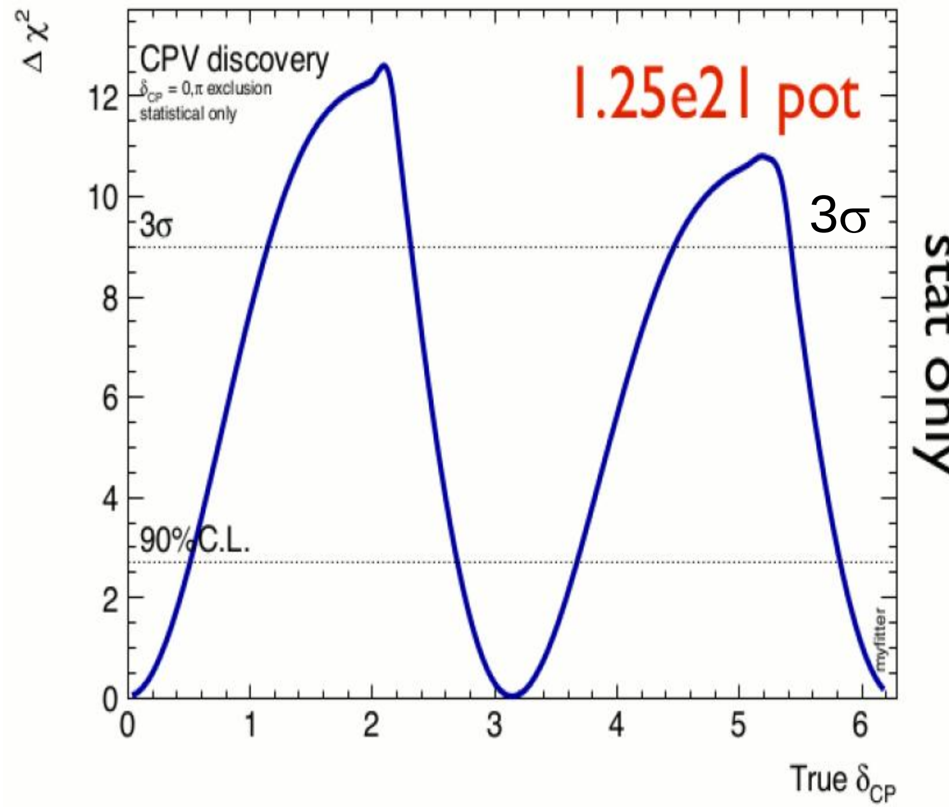
Sensitivity to

Mass hierarchy



Sensitivity to

CP violation



F. Lodovico (NNN2012, Oct.2012)

Summary

- θ_{12}, θ_{23}, θ_{13}, Δm_{21}^2, and $|\Delta m_{32}^2|$ were measured. Remaining unknown parameters are CP phase δ and mass hierarchy.
- Recently, $\theta 13$ was measured to be $\sin^2(2\theta_{13})$=~0.1.
- This large $\theta 13$ enabled us to measure CP phase δ using long baseline accelerator neutrinos in future.
- The proposed Hyper-Kamiokande detector has a high sensitivity for the CP phase measurement.
- Hyper-K is a multiple purpose detector which investigate (discover) also nucleon decays and astrophysical neutrinos.