Neutrino Oscillations Quo Vadis?

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Quarks & Leptons
Cosener's House, Abingdon
Nov 2013

Contentus

- Praelocutio
  - Ubi es
  - Quo vadis
- Futurum
  - With reactors
  - With air & ice
  - With accelerators
- Summarium

Neutrino Mixing
The PMNS Matrix

Pontecorvo-Maki-Nakagawa-Sakata

- Assume that neutrinos do have mass:
  - mass eigenstates ≠ weak interaction eigenstates
  - Analogue to CKM-Matrix in quark sector!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

weak
"flavour eigenstates"

Mass eigenstates
m_1, m_2, m_3

Unitary mixing matrix:
3 mixing angles
& complex phases

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle and Δm_{ij}^2 = mass^2 difference

Qui?

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

ν_μ disappearance

Solar neutrino oscillation

ν_e disappearance in ν_μ beam
Or
reactor neutrino experiments

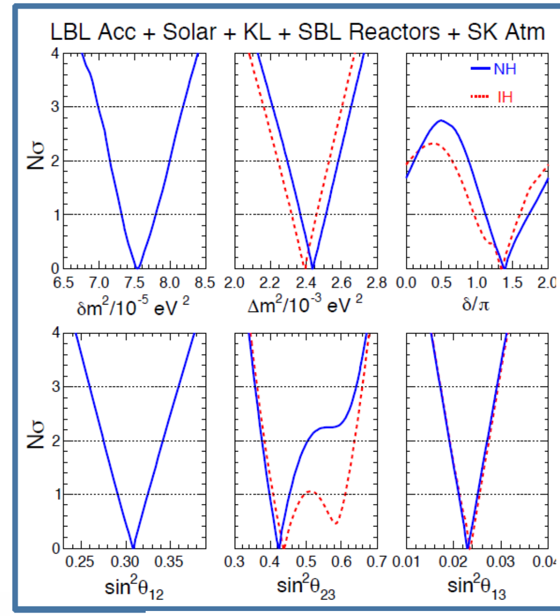
ν –less double beta decay

Ubi es?

$$\Delta m_{21}^2 = 8*10^{-5}\,\mathrm{eV}^2 \quad \left|\Delta m_{32}^2\right| = 2.4*10^{-3}\,\mathrm{eV}^2$$

$$\theta_{12} \approx 34^\circ \qquad \theta_{23} \approx 45^\circ \text{ (or a little smaller)}$$

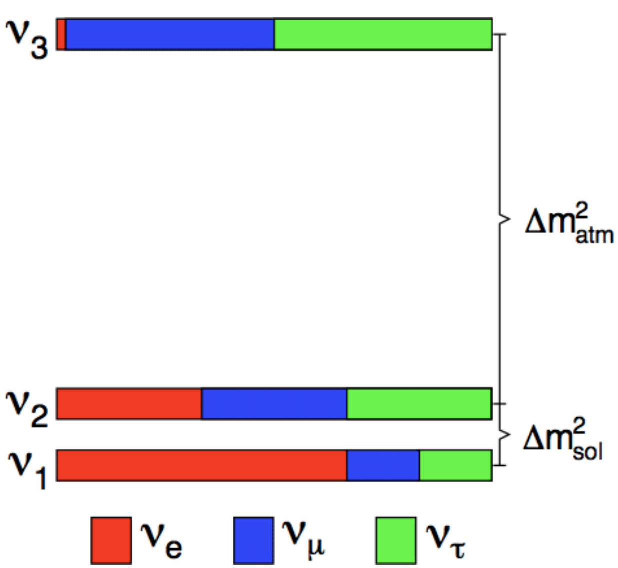
$$\theta_{13} \approx 9^\circ$$

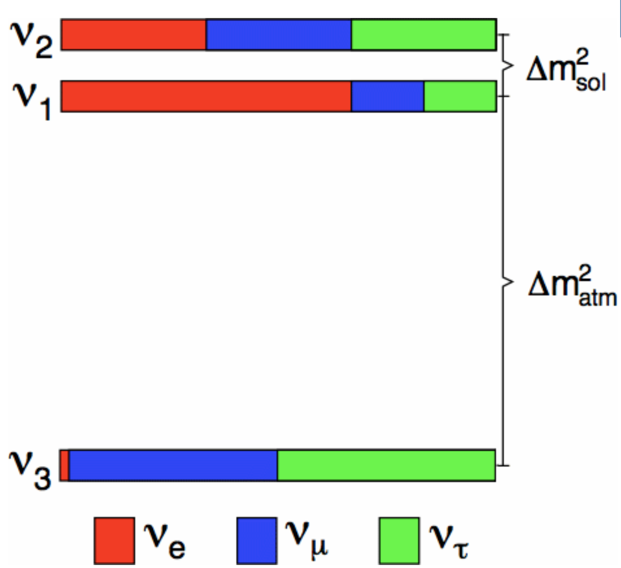


Fogli et al. arXiv:1205.5254

Open questions:

Normal Hierarchy or Inverted Hierarchy?





$$\delta = ?$$

$$\Delta m_{32}^2 > 0\,?$$

Quo vadis?

Juno Goddess of Marriage

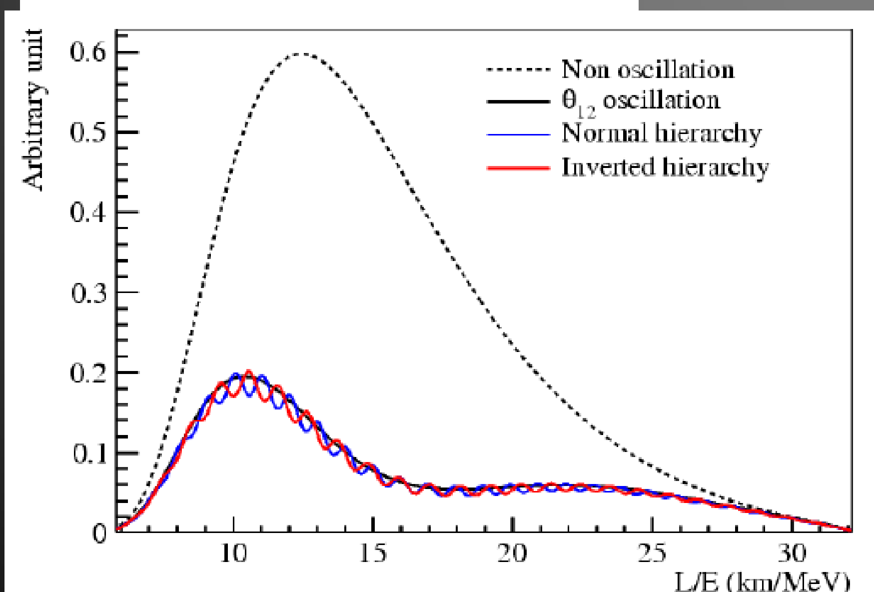
JUNO

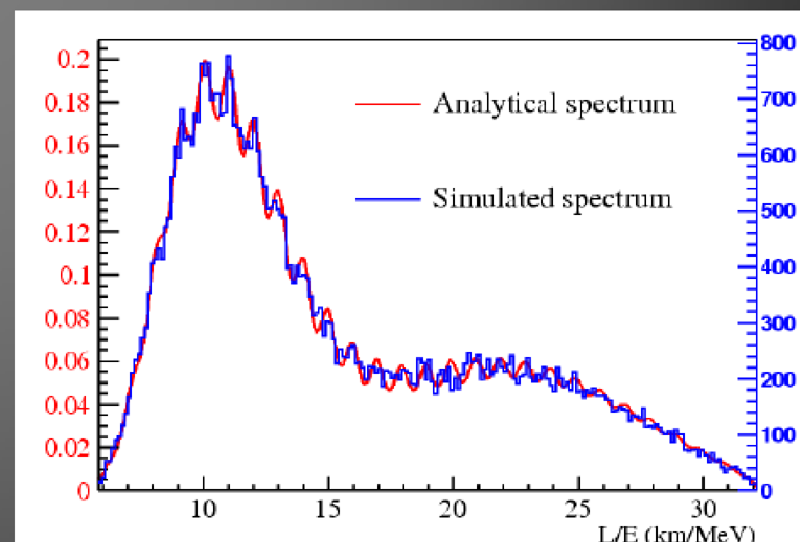
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022 L.

$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\mathrm{IH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
$$

Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009





50000 events

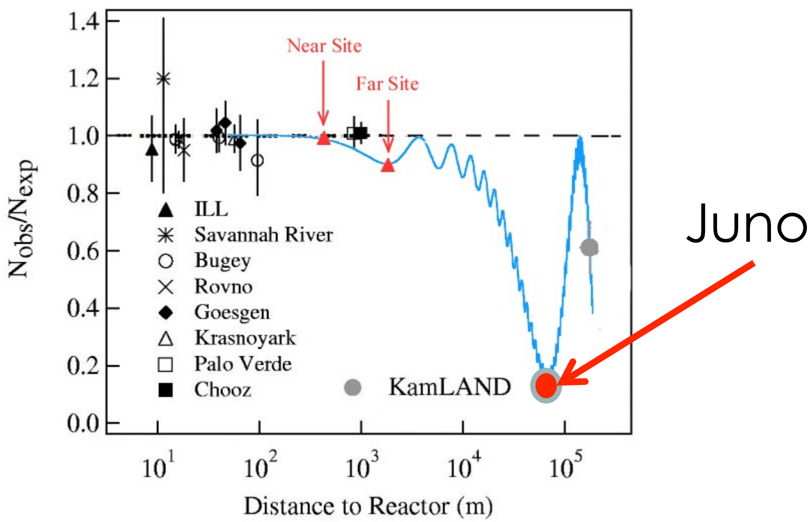
3

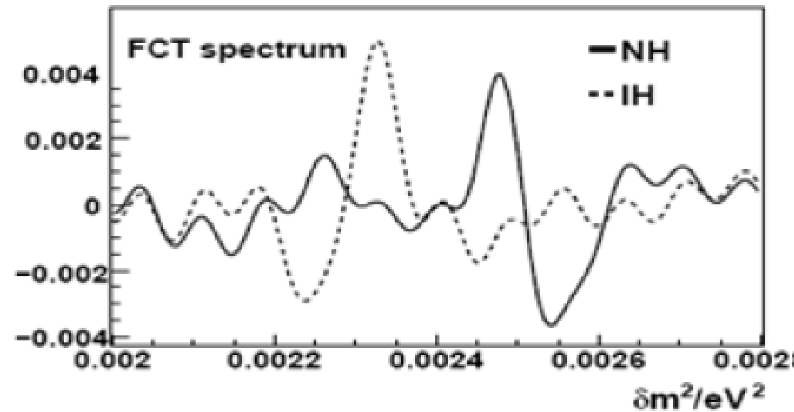
Possible Sites

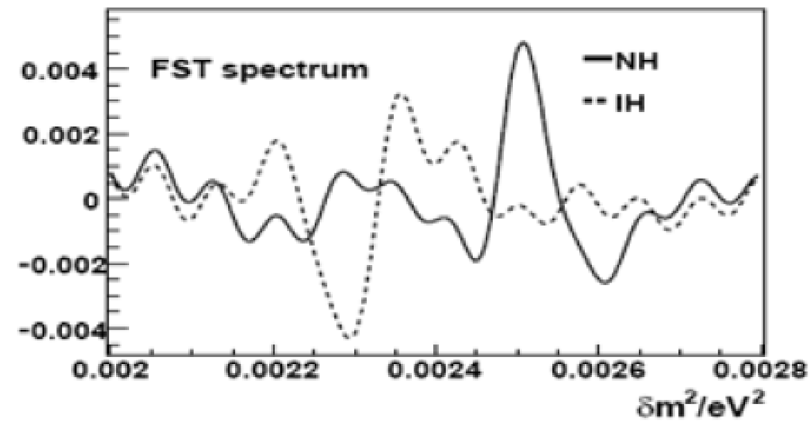
	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

Fourier-Analysis

Optimal Baseline around 50 km





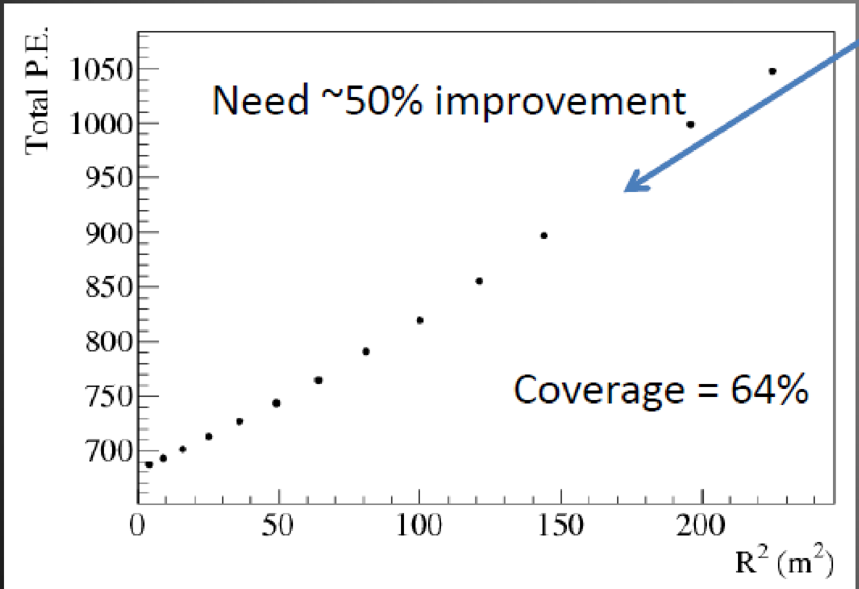


	Current	Daya Bay II
Δm^2_{12}	3%	< 1%
Δm^2_{31}	5%	< 1%
$\sin^2\theta_{12}$	6%	< 1%
$\sin^2\theta_{23}$	20%	-
$\sin^2\theta_{13}$	14% → 5% (Daya Bay in 3 years)	-

Technical Challenges

	KamLAND	Daya Bay II
Detector	~1 kt Liquid Scintillator	20 kt Liquid Scintillator
Energy Resolution	6%/√E	3%/√E
Light yield	250 p.e./MeV	1200 p.e./MeV

How?



- Daya BayII preliminary simulation
  - Use Daya Bay's PMT and LS.
  - Use Daya Bay's result 161 P.E./MeV as normalization.
  - Modify geometry
- Possible improvements > 50%
  - High PMT QE (SBA) or new PMT (MCP-PMT), 20% → 30%
  - Other options
    - Coverage: 64%→75%
    - More transparent LS
    - Low temperature scintillator

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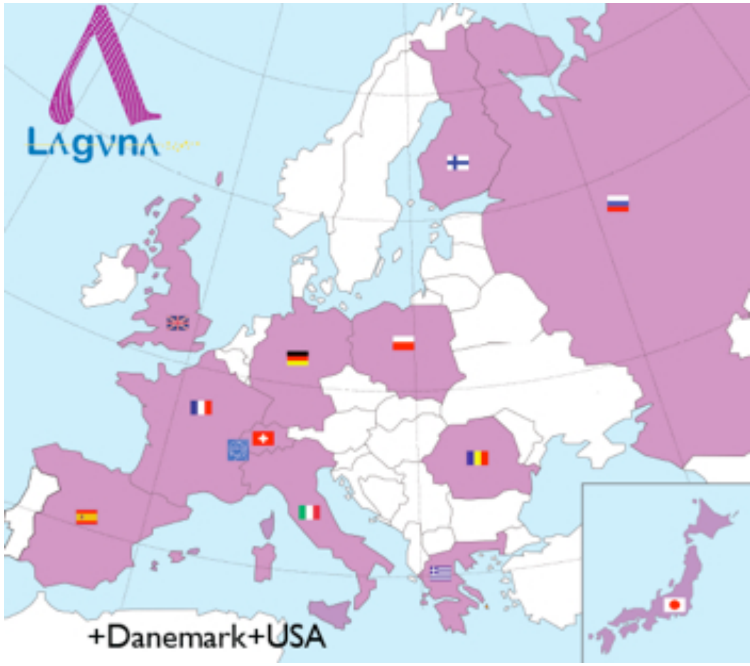
LAGUNA-LBNO

Large **A**pparatus for **G**rand **U**nification and **N**eutrino **A**strophysics

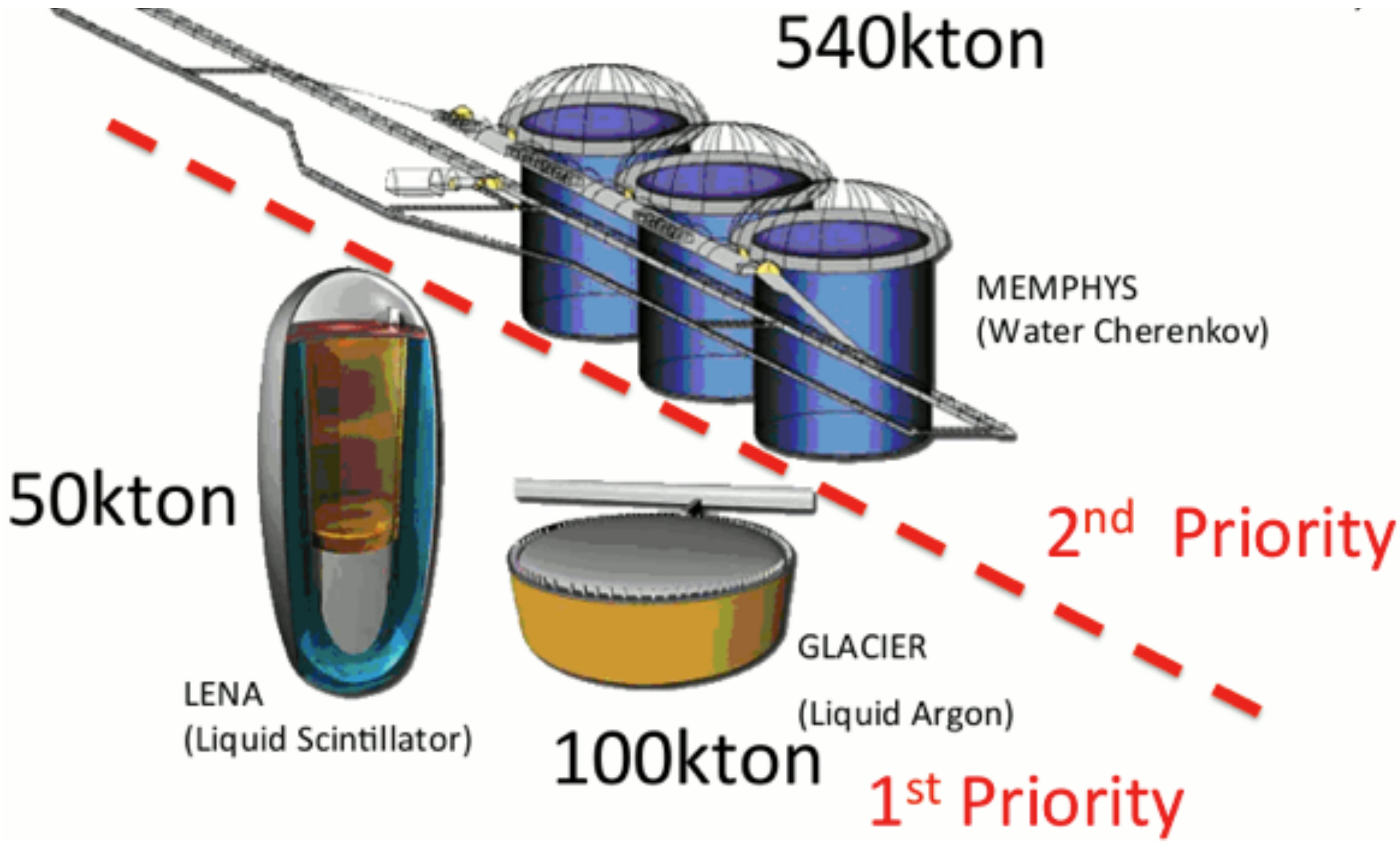
Long **B**aseline **N**eutrino **O**scillations

- **LAGUNA DS** (FP7)
  - 2008 – 2011
  - ~100 members; 10 countries
  - 3 detector technologies ⊗ 7 sites, different baselines (130 → 2300km)
- **LAGUNA-LBNO**
  - 2011 – 2014
  - ~300 members; 14 countries, >40 Institutions
  - Down selection of sites & detectors

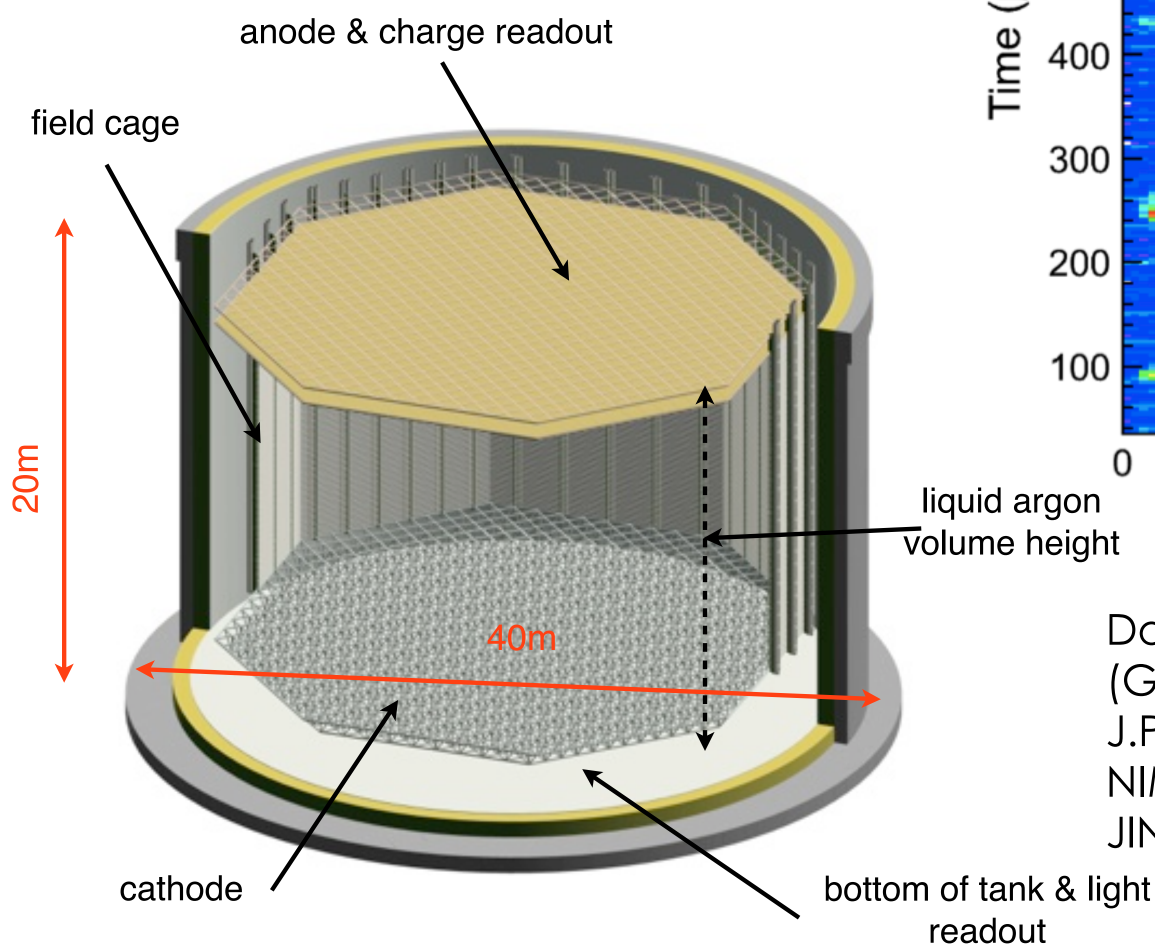


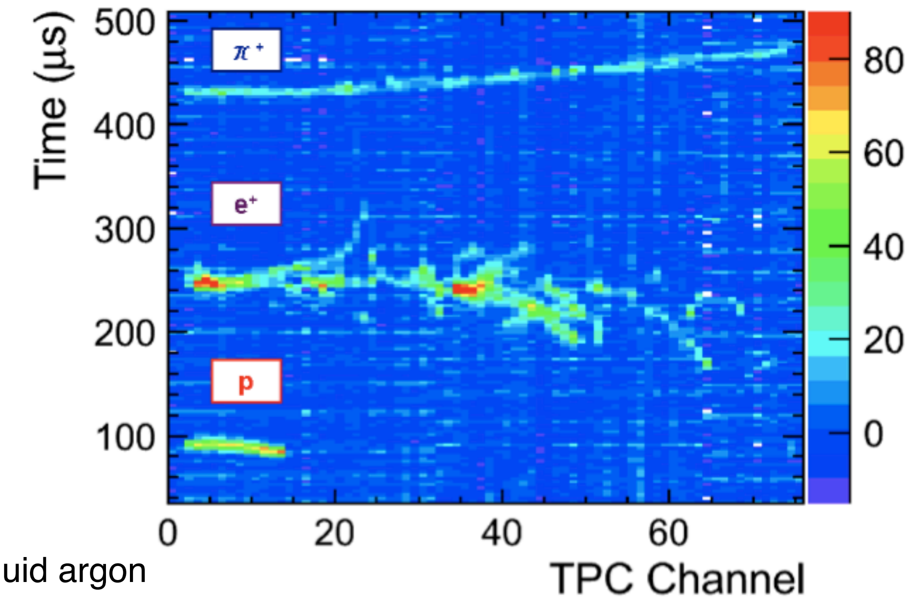
Detector Options

- Prioritisation for neutrino oscillations in light of large θ_{13}
  - 2300 km baseline: Liquid Scintillator/Argon
  - 130 km baseline: Water-Cerenkov



LAr-GLACIER

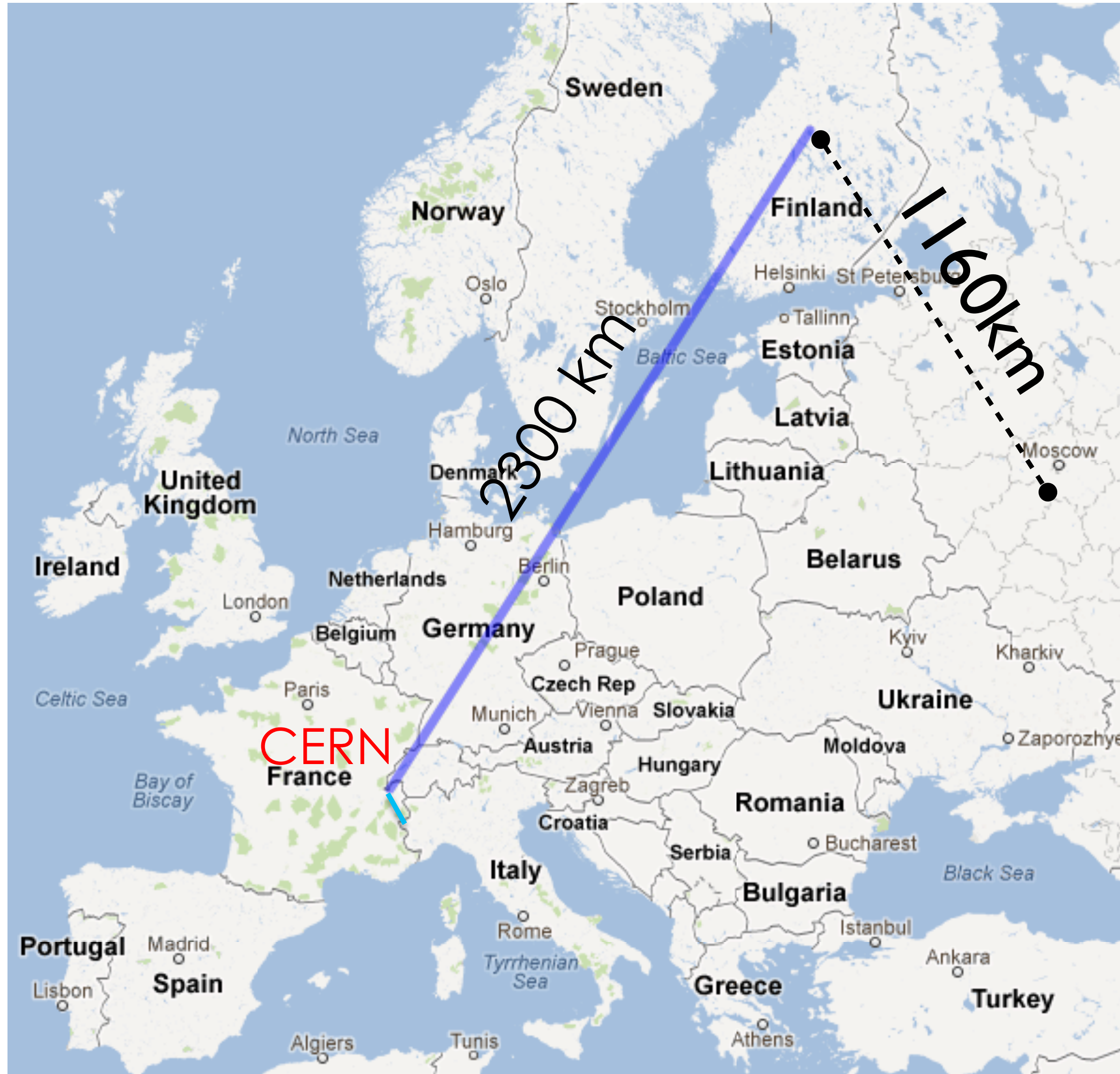




Double phase LAr LEM TPC
(GLACIER,2003) (hep-ph/0402110,
J.Phys.Conf.Ser. 171 (2009) 012020,
NIM A 641 (2011) 48-57,
JINST 7 (2012) P08026)

Several Sites

- Primary site
  - Pyhäsalmi
  - Traditional high energy broadband neutrino (super-) beam
- Secondary site
  - Frejus
  - Beta beam at low energy



Mathematic

- Electron neutrino disappearance

$$P(\nu_\mu \to \nu_e) \sim \frac{1}{2}\sin^2 2\theta_{13} \times \sin^2 \Delta$$

$$\begin{aligned}
P(\nu_\mu \to \nu_e) \sim \quad & \sin^2 2\theta_{13} && \times \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} && (\equiv P_0) \\
& -\alpha \sin 2\theta_{13} && \times \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} && (\equiv P_1) \\
& +\alpha \sin 2\theta_{13} && \times \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} && (\equiv P_2) \\
& +\alpha^2 && \times \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} && (\equiv P_3)
\end{aligned}$$

M. Freund, Phys.Rev. D64 (2001) 053003

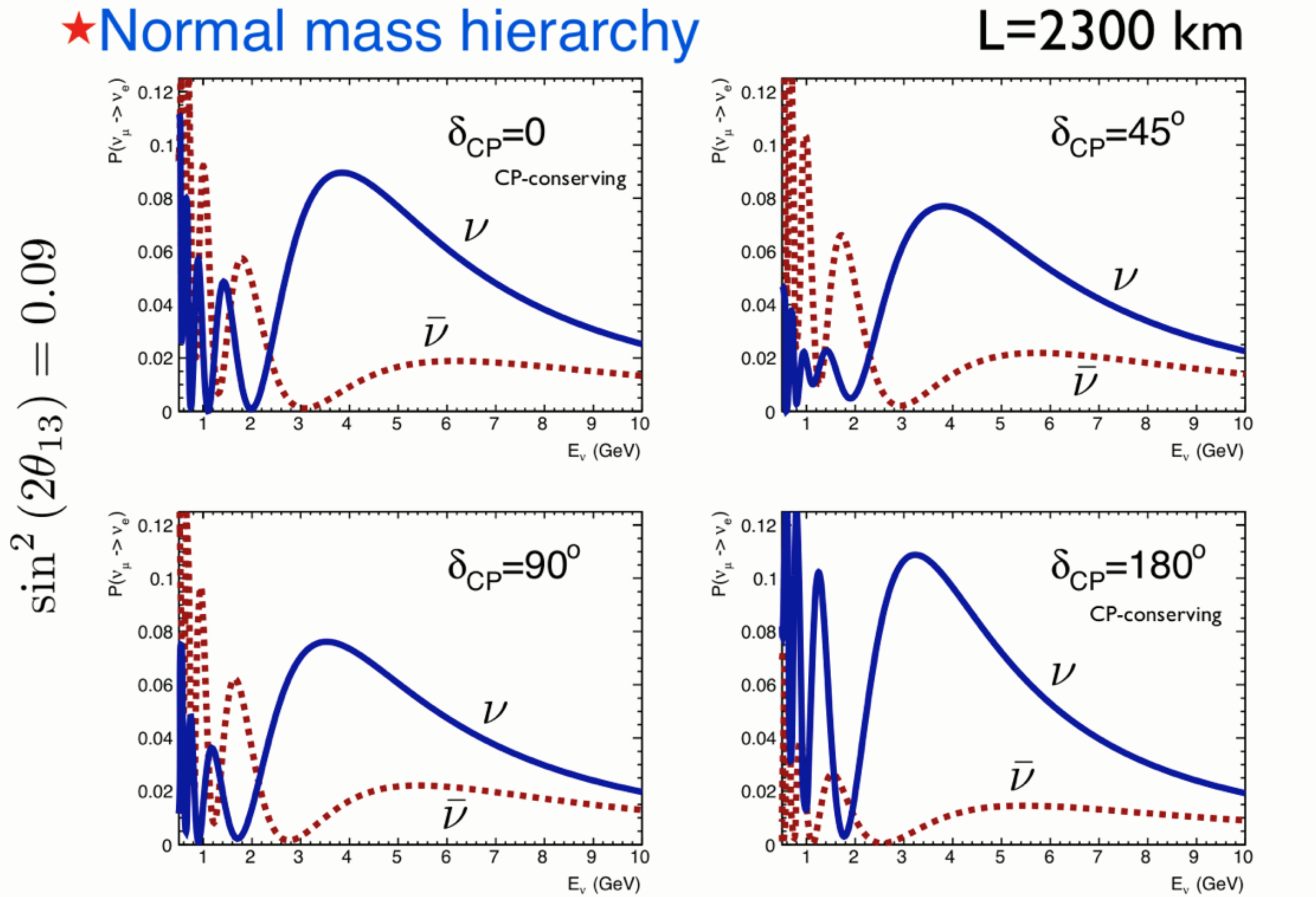
$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

- Muon neutrino appearance

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \times \sin^2 \Delta$$

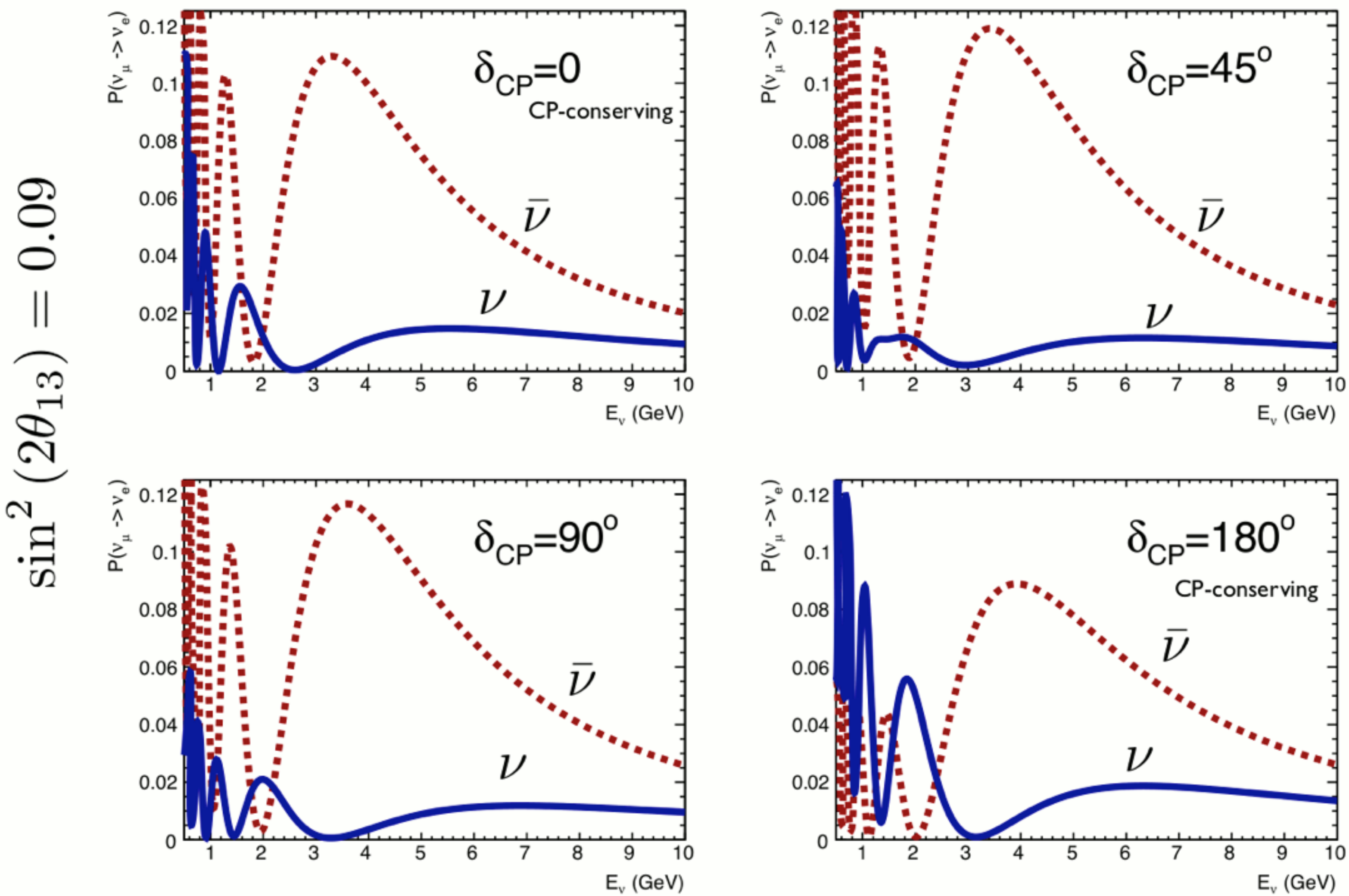
$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\cos^4\theta_{13}\ \sin^2 2\theta_{23} + \sin^2 2\theta_{13}\ \sin^2\theta_{23}\right) \sin^2 \Delta$$

Appearance Signal NH



Appearance Signal IH

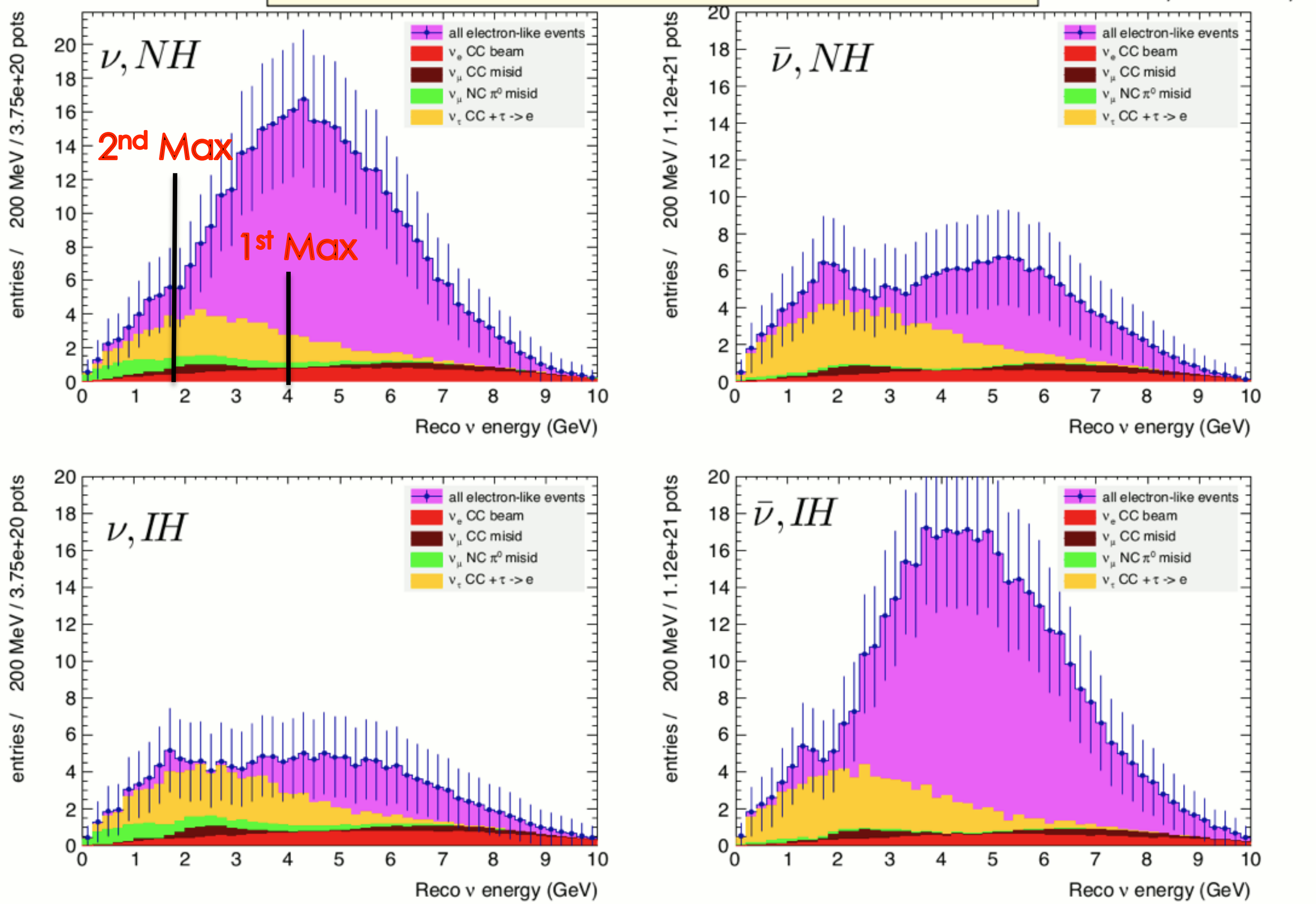
★Inverted mass hierarchy L=2300 km



Signal

Detector response and resolution included

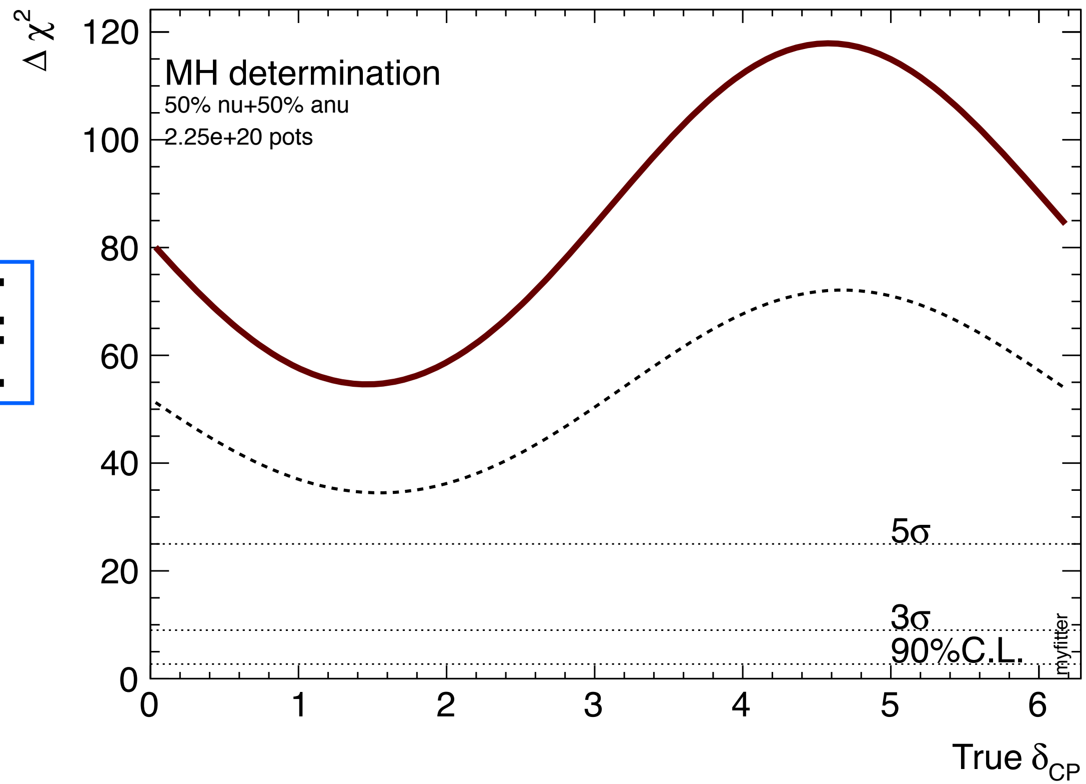
Running mode:
ν/anti-ν:25%/75%



Mass Hierarchy

2.25e20 pot

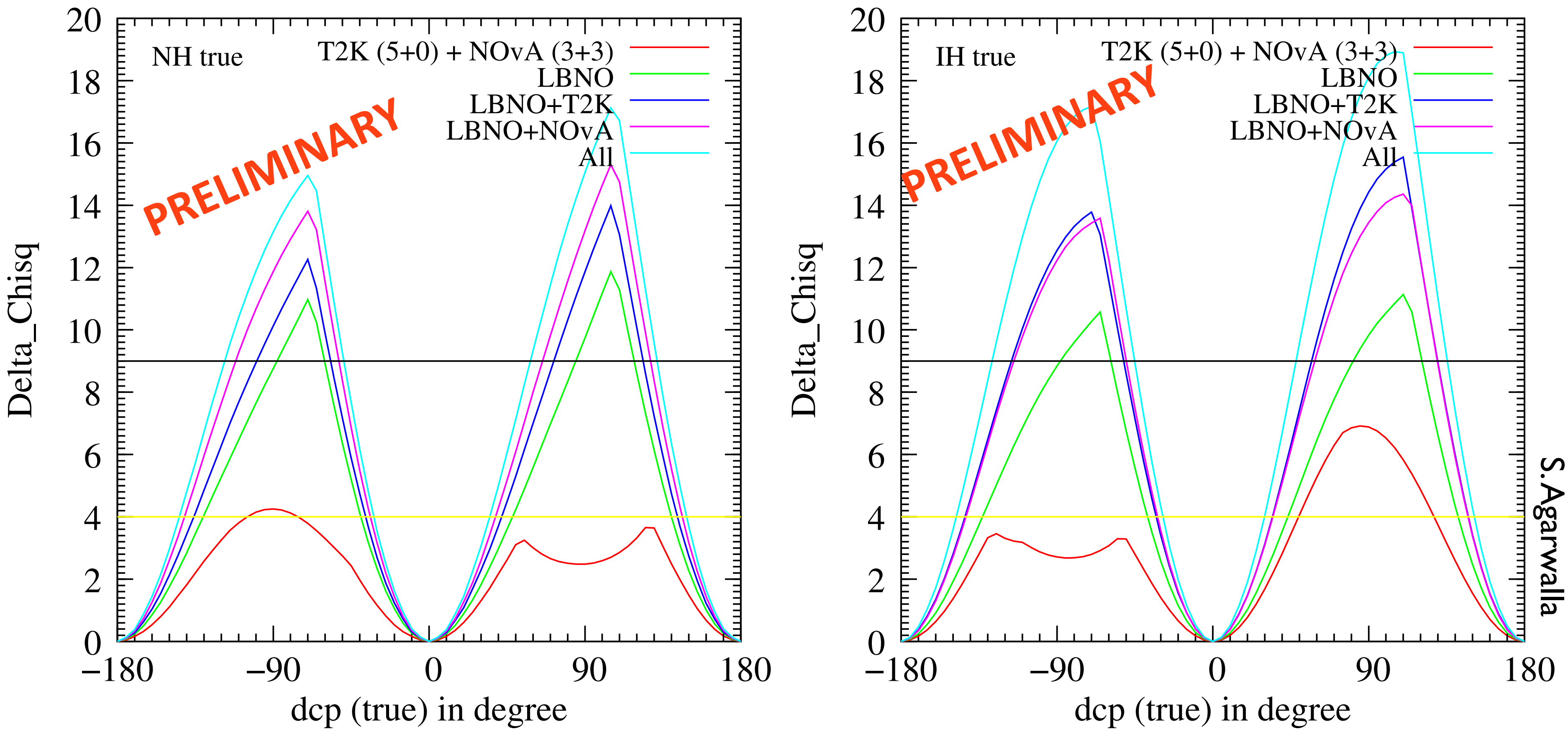
MH



Provide a >5σ direct determination of MH for all values of δ_{CP} within 2.5 years of running

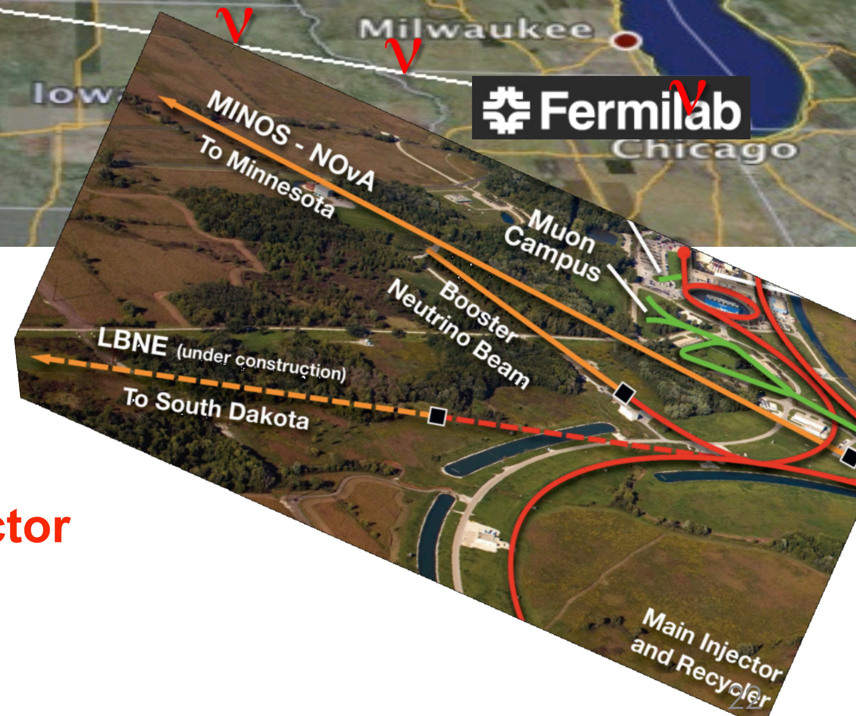
CP Sensitivity

Sensitivity combining T2K(295km), NOvA(810km) and LBNO(2300km)



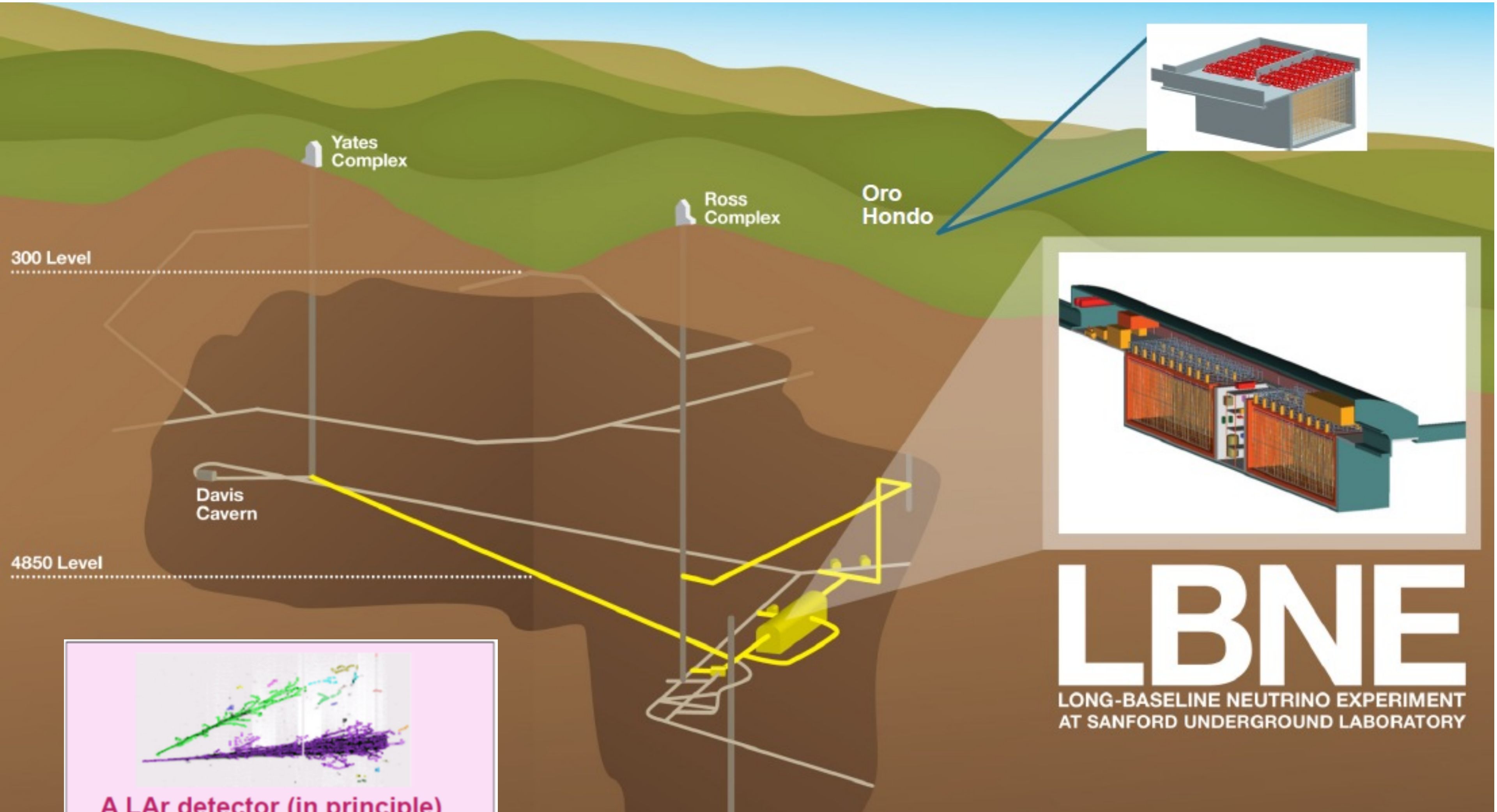
The power of combining several different baselines L:
LBNO 20kton(5+5) + T2K(5+0) + NOvA(3+3) ≈ 40-45% CPV at >3σ C.L.

LBNE



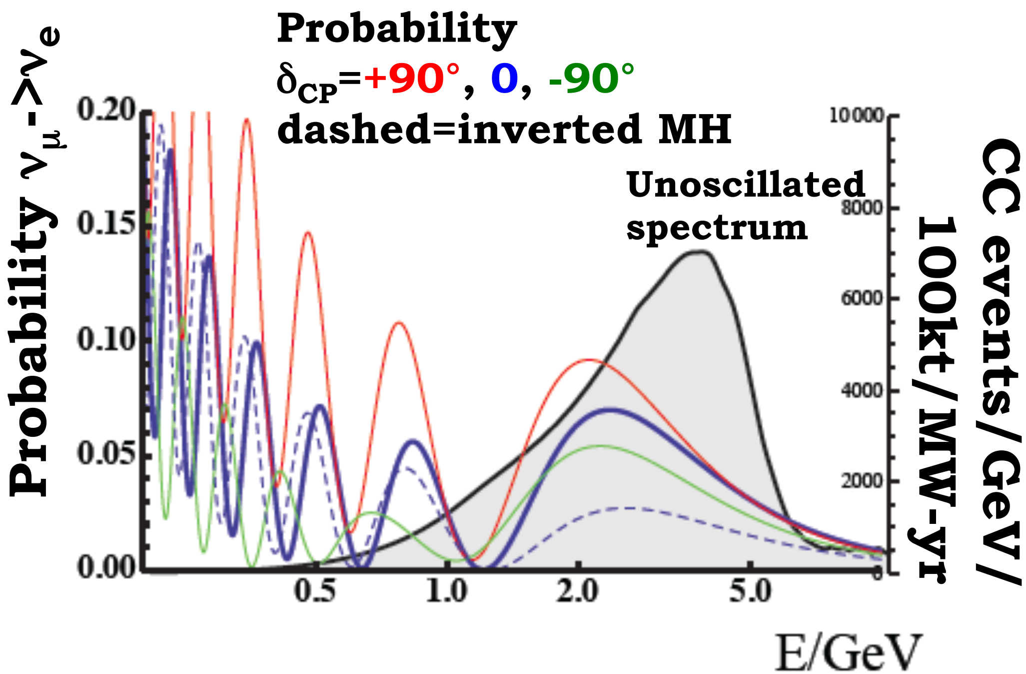
- A new neutrino beamline over 1300 km
- Proton beam power assumption
  - 700 kW → 1.2 MW → 2.3 MW
- A highly-capable near detector system
- A ≥10 kt fiducial mass LAr TPC far detector underground at SURF
- A cavern for a full 34 kt detector system

LBNE Detector



A LAr detector (in principle) reconstructs everything

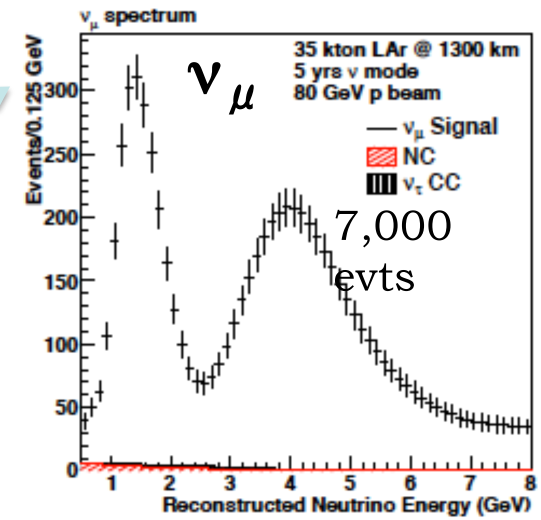
Experimental Technique

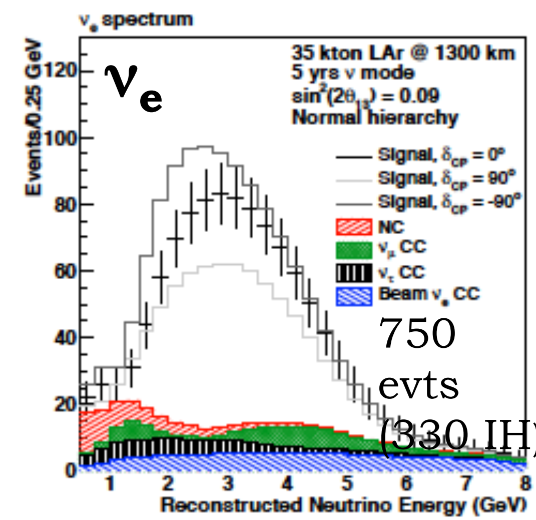


disappearance

appearance

700 kW beam





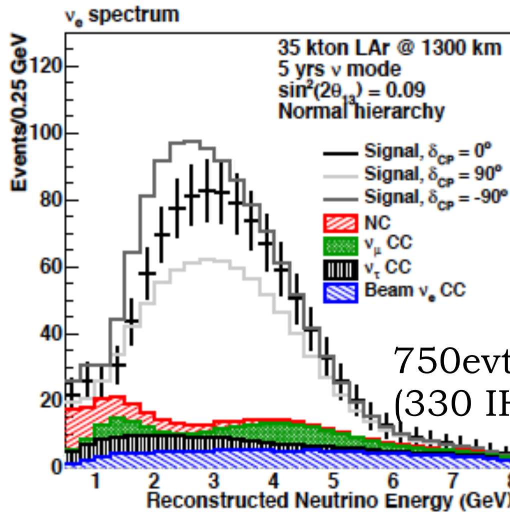
- Produce a pure wide band ν_μ muon-neutrino beam with energy spectrum matched to the 1st and 2nd oscillation maximum
- Measure spectrum of ν_μ and ν_e at a distant detector

C. Adams *et al. arXiv:*1307.7335

LBNE 35kt

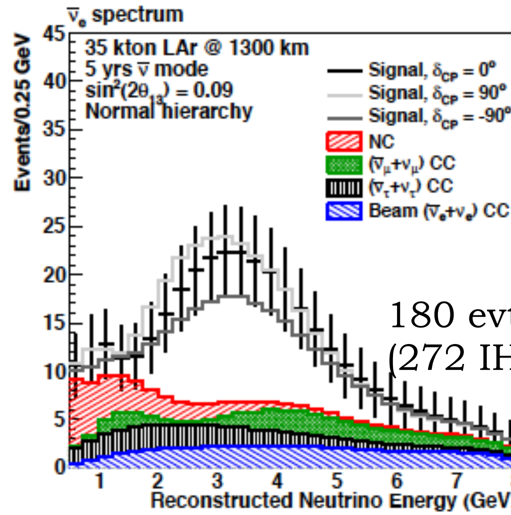
Appearance

$\nu_\mu \rightarrow \nu_e$



750evts
(330 IH)

ν (5 yrs)

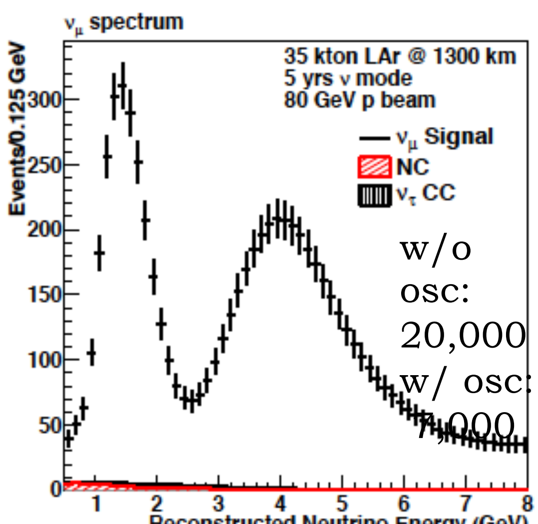


180 evts
(272 IH)

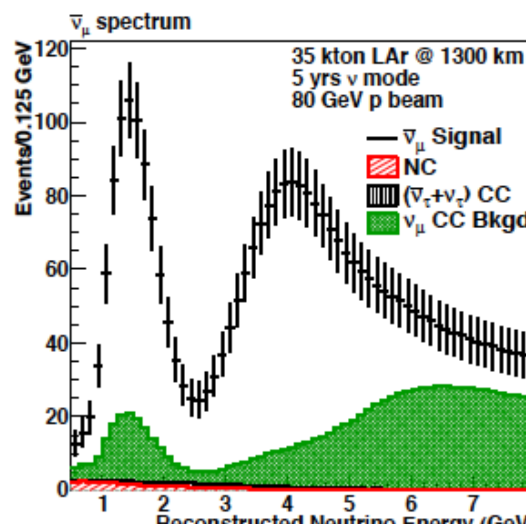
$\bar{\nu}$ (5 yrs)

Disappearance

$\nu_\mu \rightarrow \nu_\mu$



w/o osc: 20,000
w/ osc: 7,000

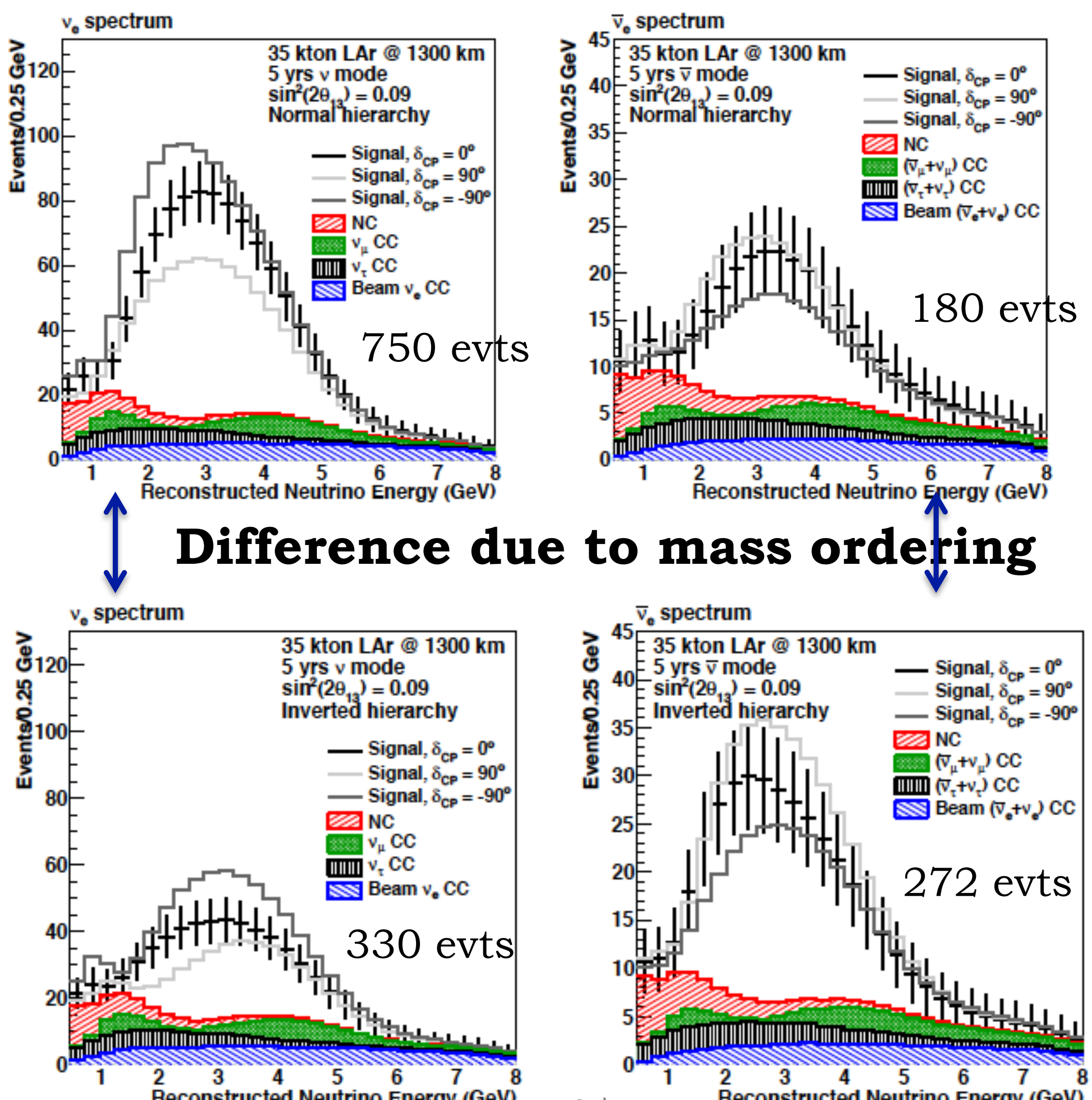


w/o osc: 6,700
w/ osc: 2,200

LBNE Mass-Hirarchie

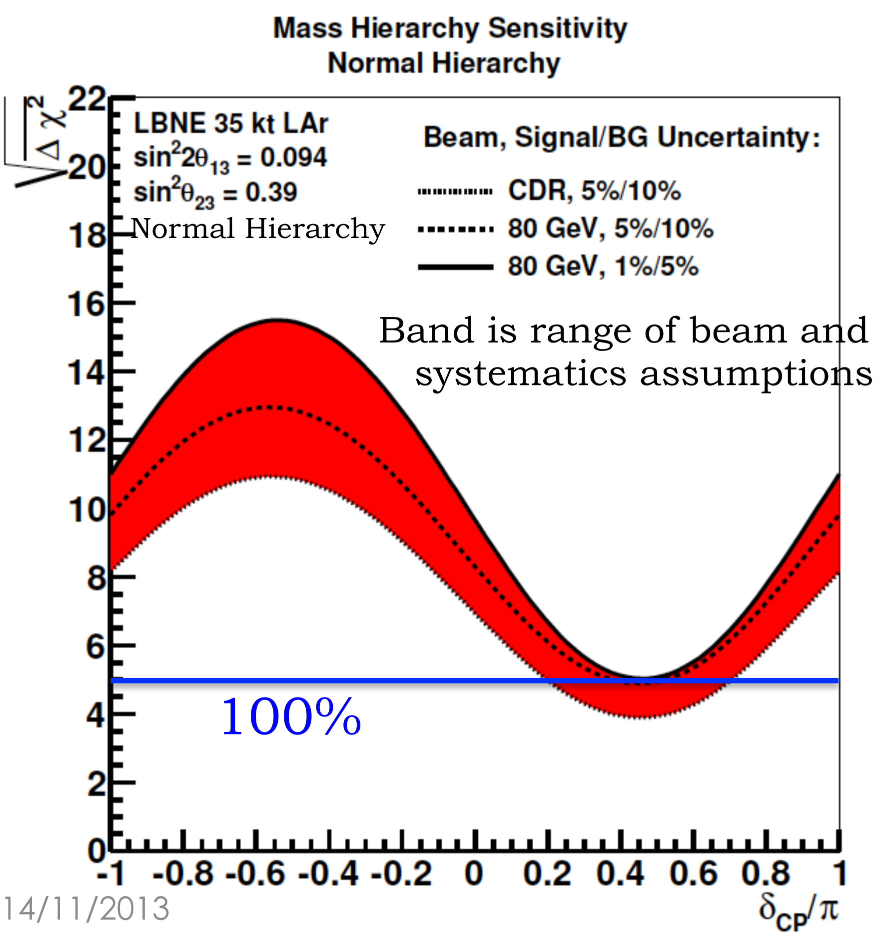
Normal

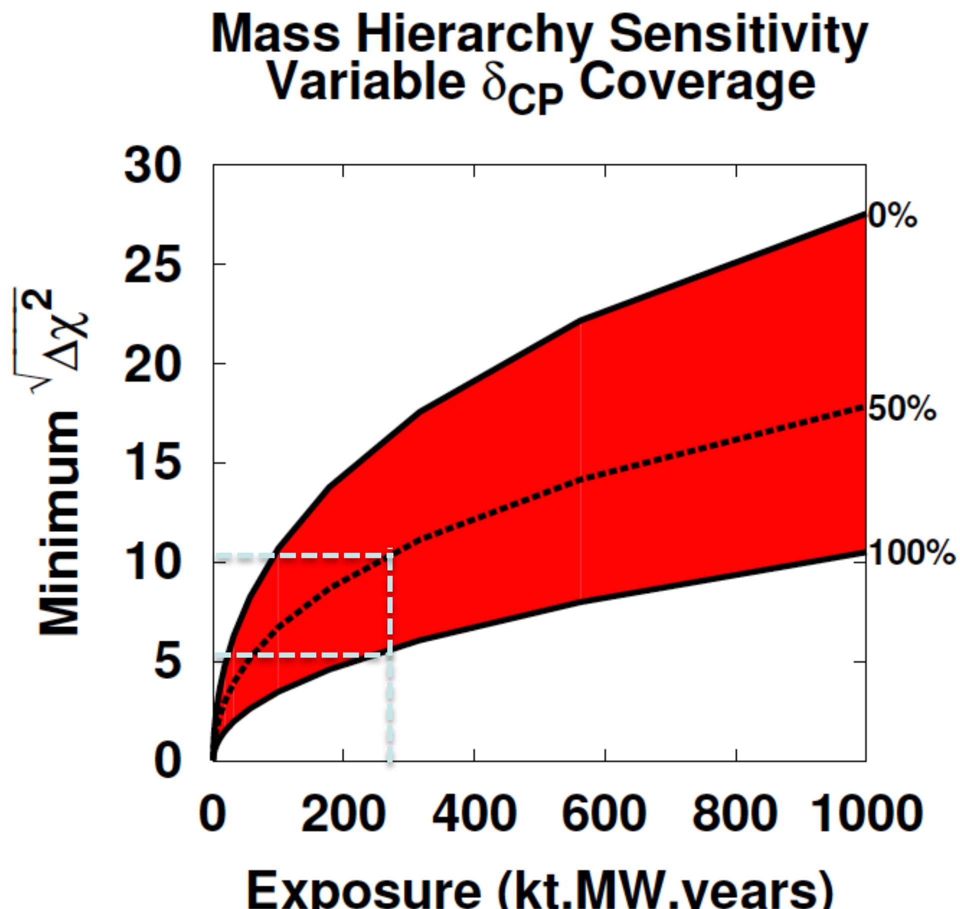
Inverted



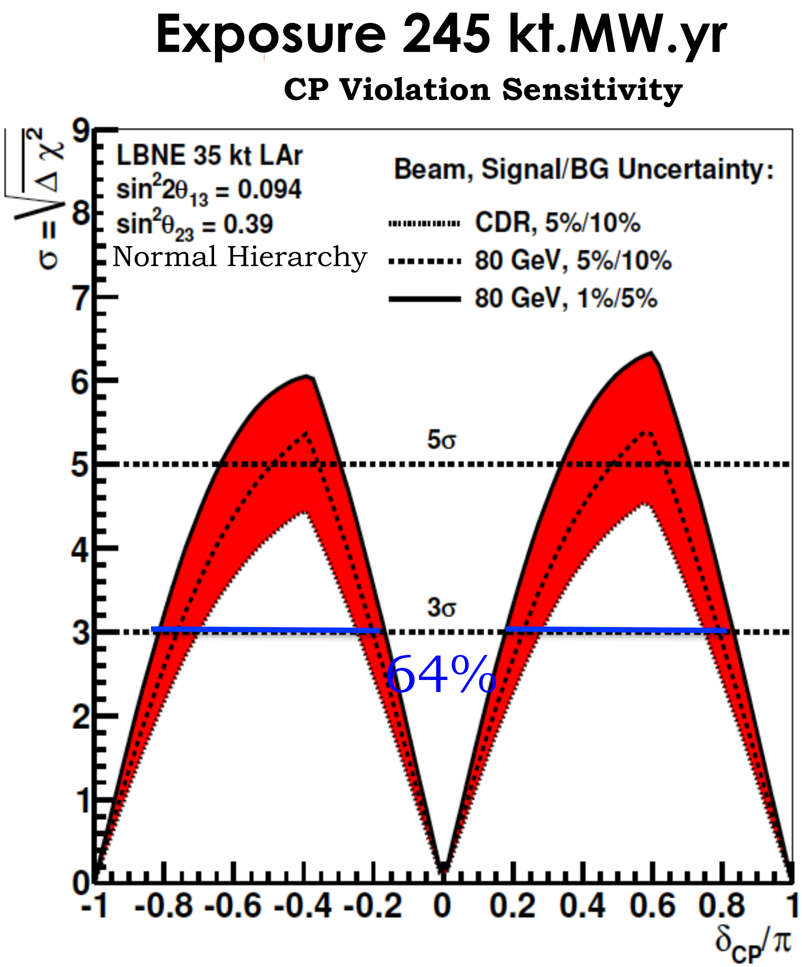
Sensitivity to MH

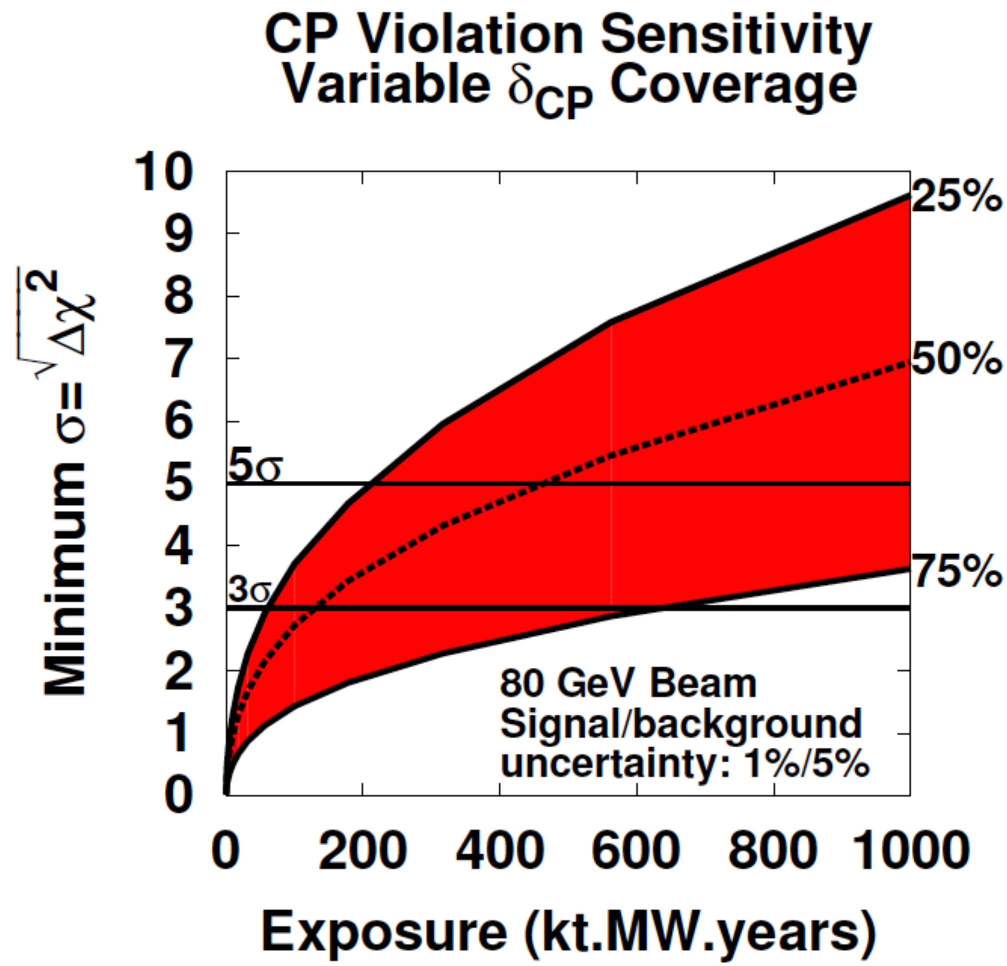
Exposure 245 kt.MW.yr
(700 kW x (5ν+5ν) yr
or 1.2 MW x (3ν+3ν) yr





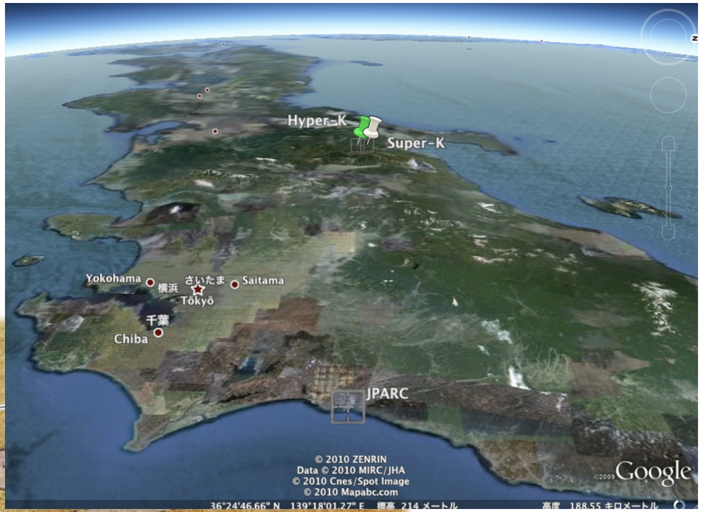
Sensitivity to CPV

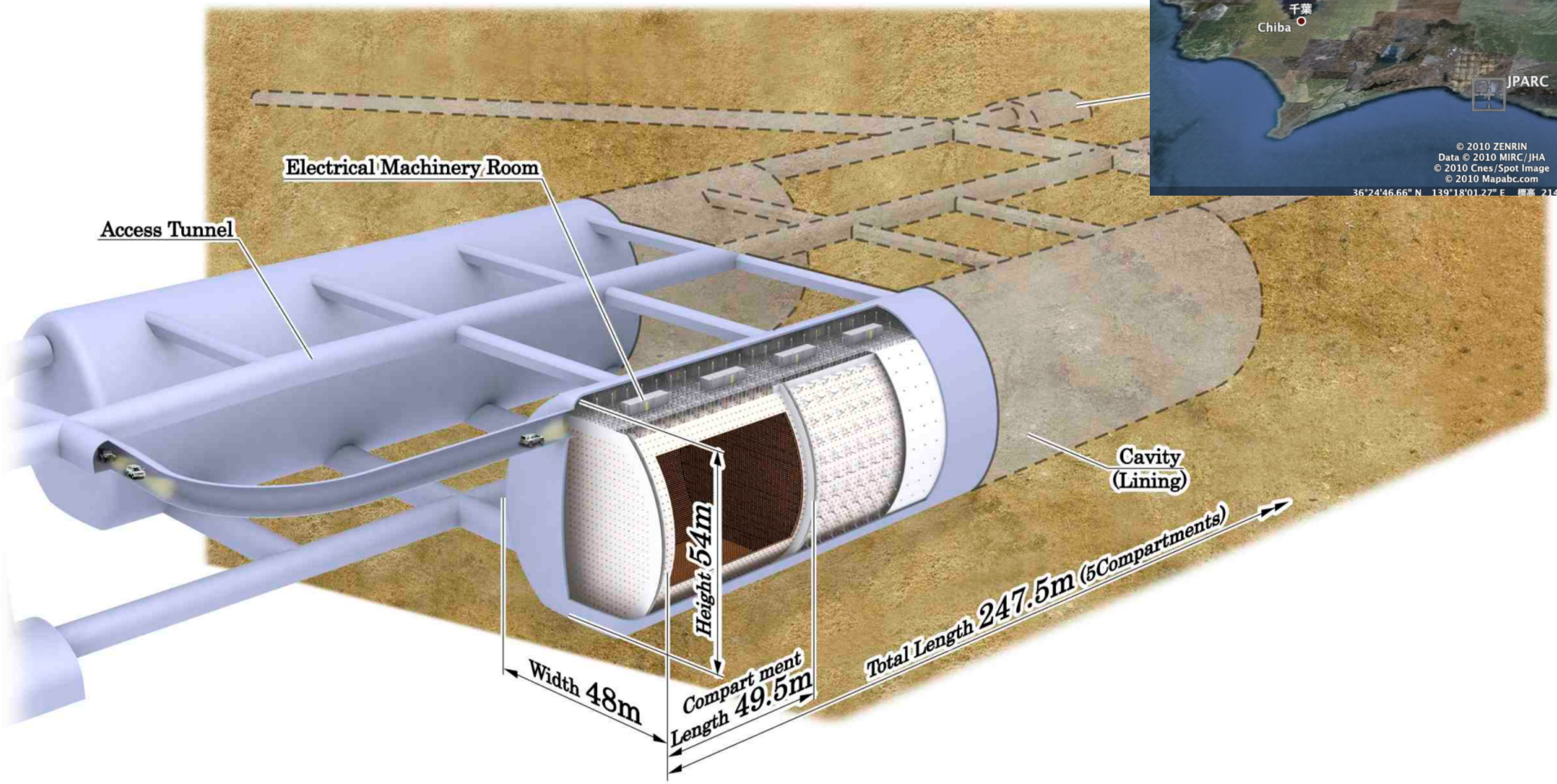




HyperK

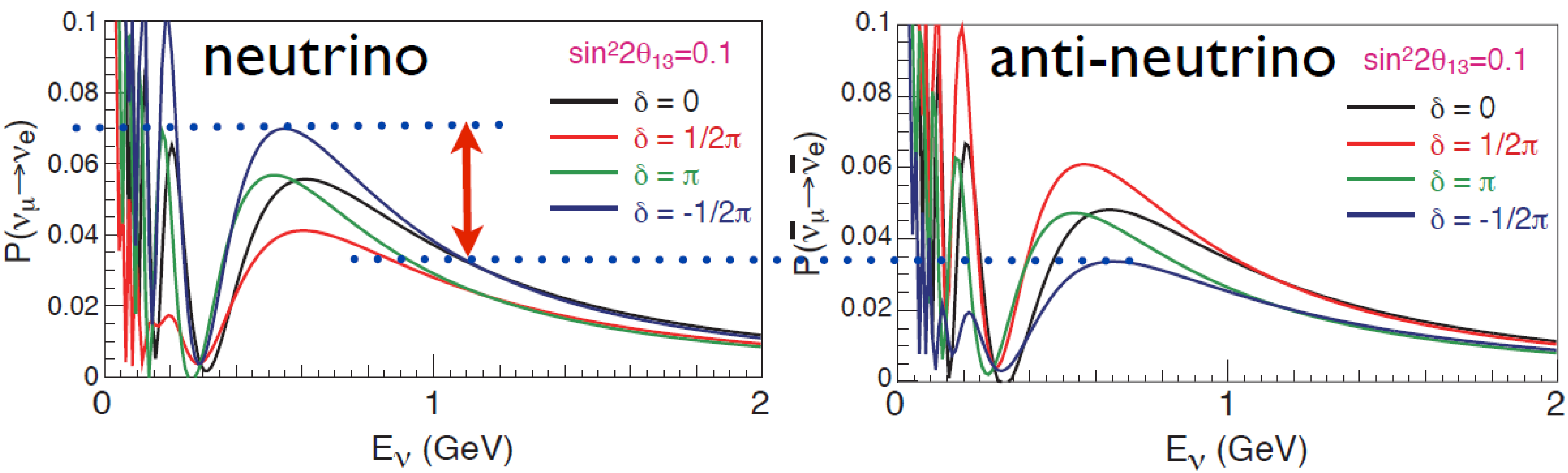
- J-PARC Neutrino beam (T2K)
- Improve SK technology
- 1 Mt water-Cherenkov detector





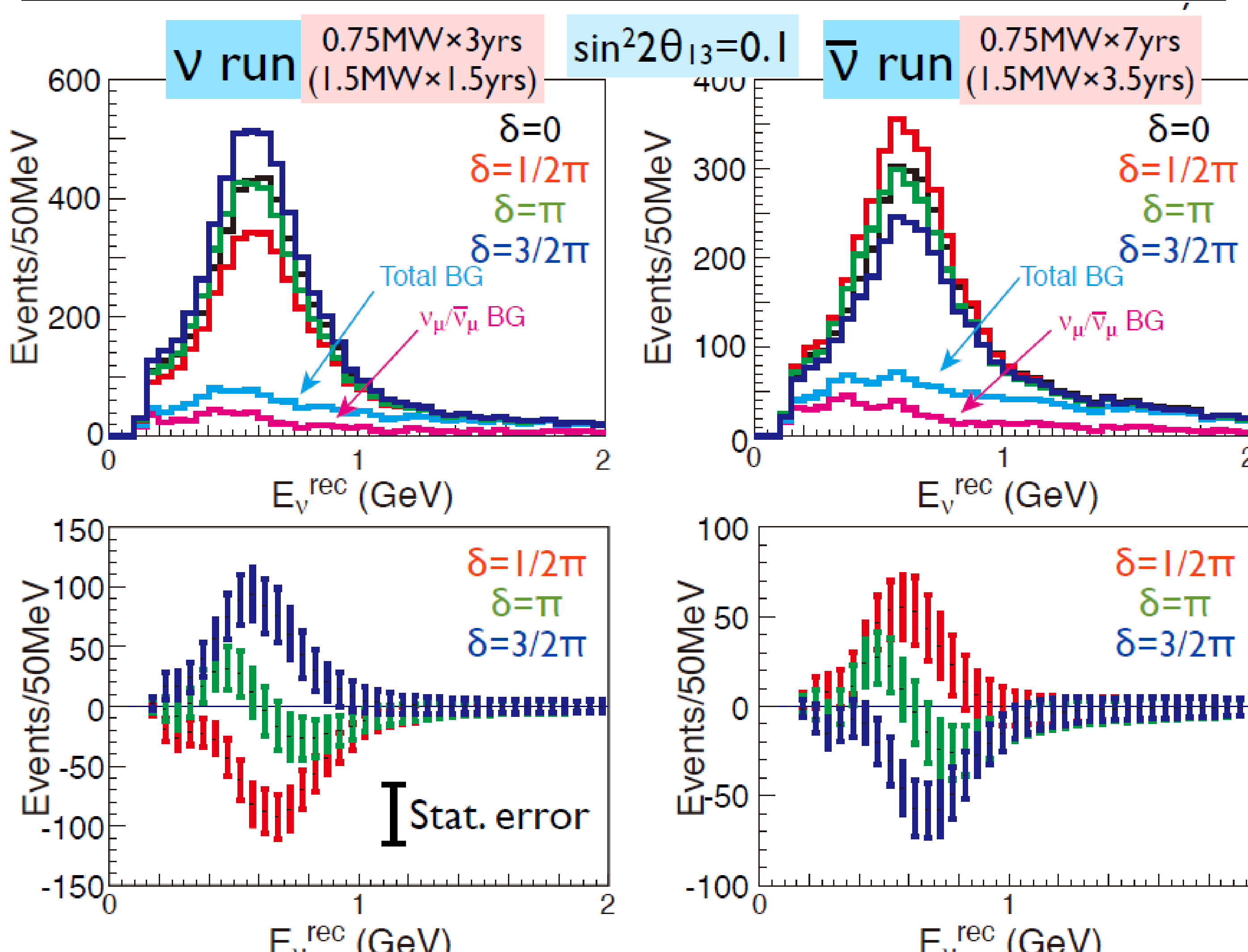
Oscillation Probability

- For HyperKamiokande
  - Large differences between neutrinos and anti-neutrinos
  - Mostly depending on CP-phase



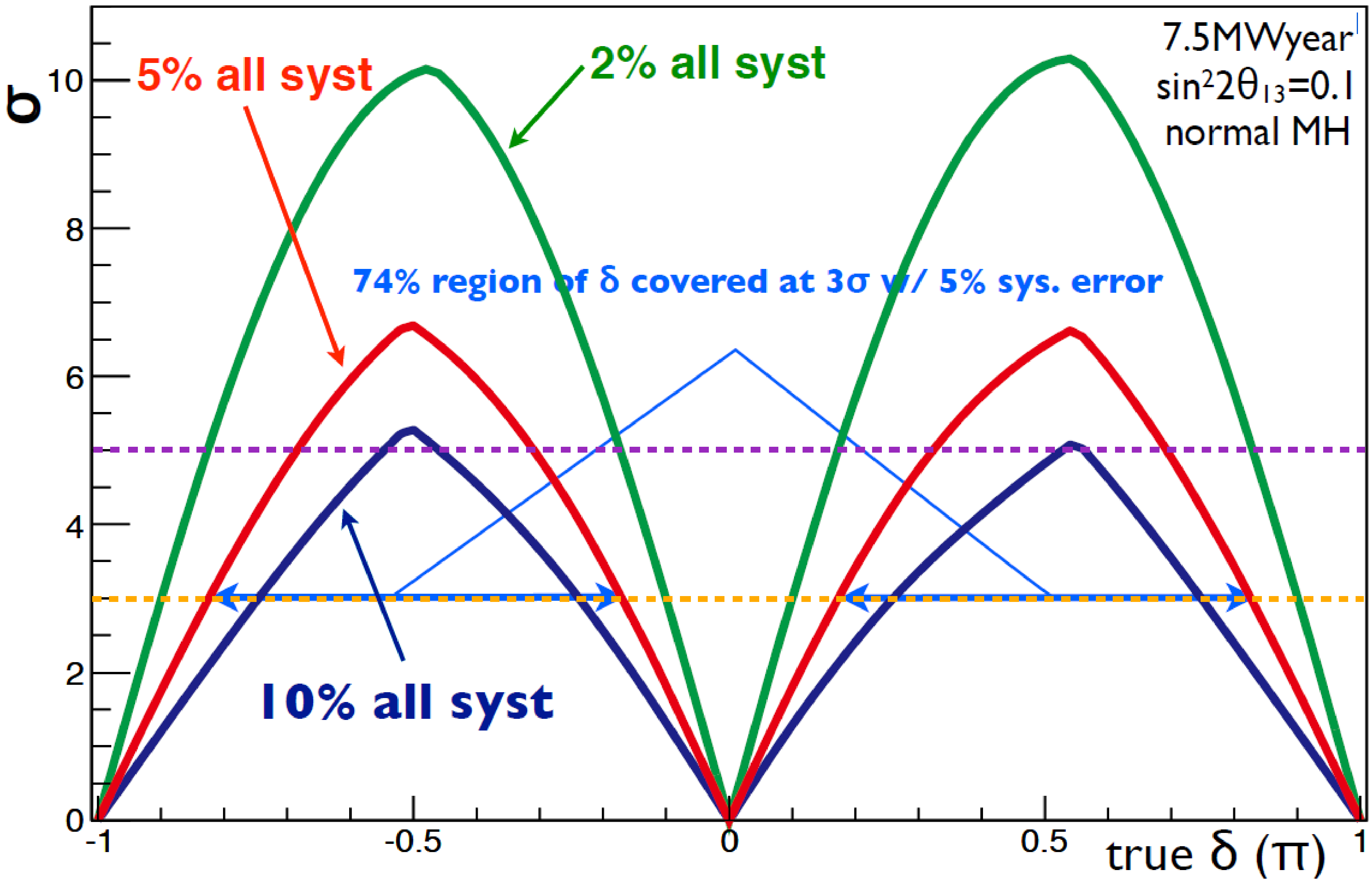
  - Little Matter effects
    - Short distance & low neutrino energy

Effect of δ



Number + shape: sensitive to all values of δ

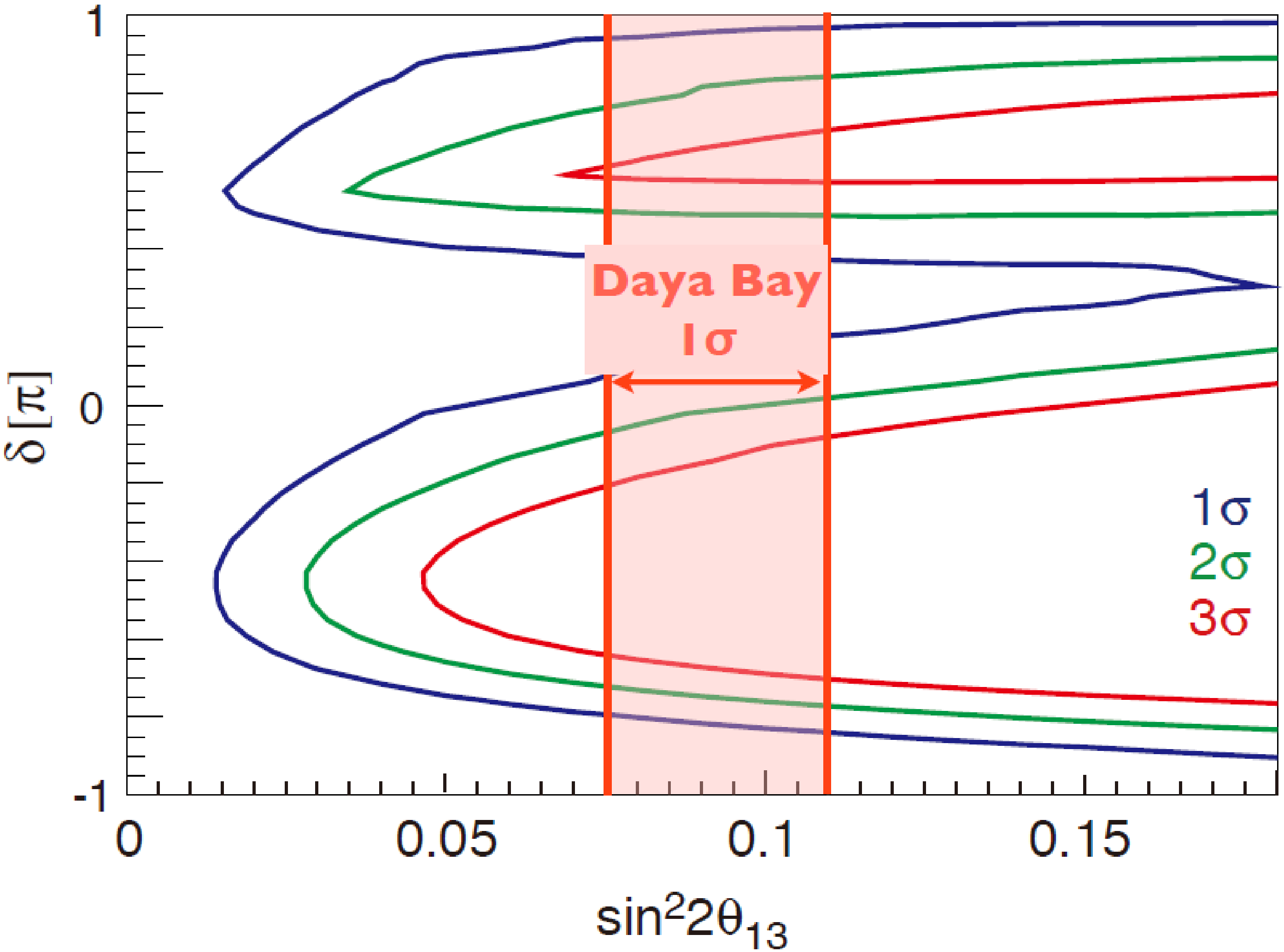
CPV Discovery Potential



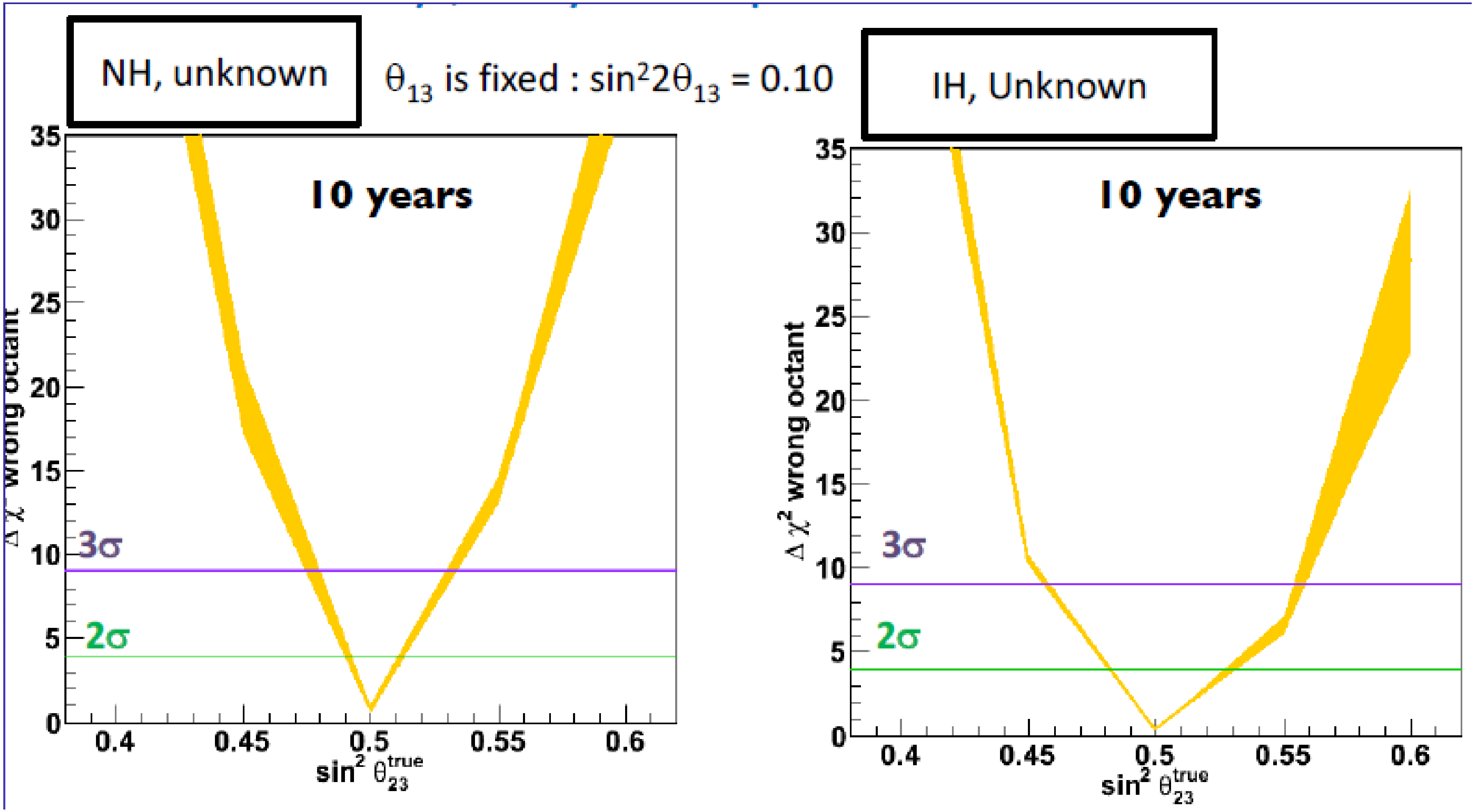
Mass Hierarchy

0.75MW× 10yrs

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



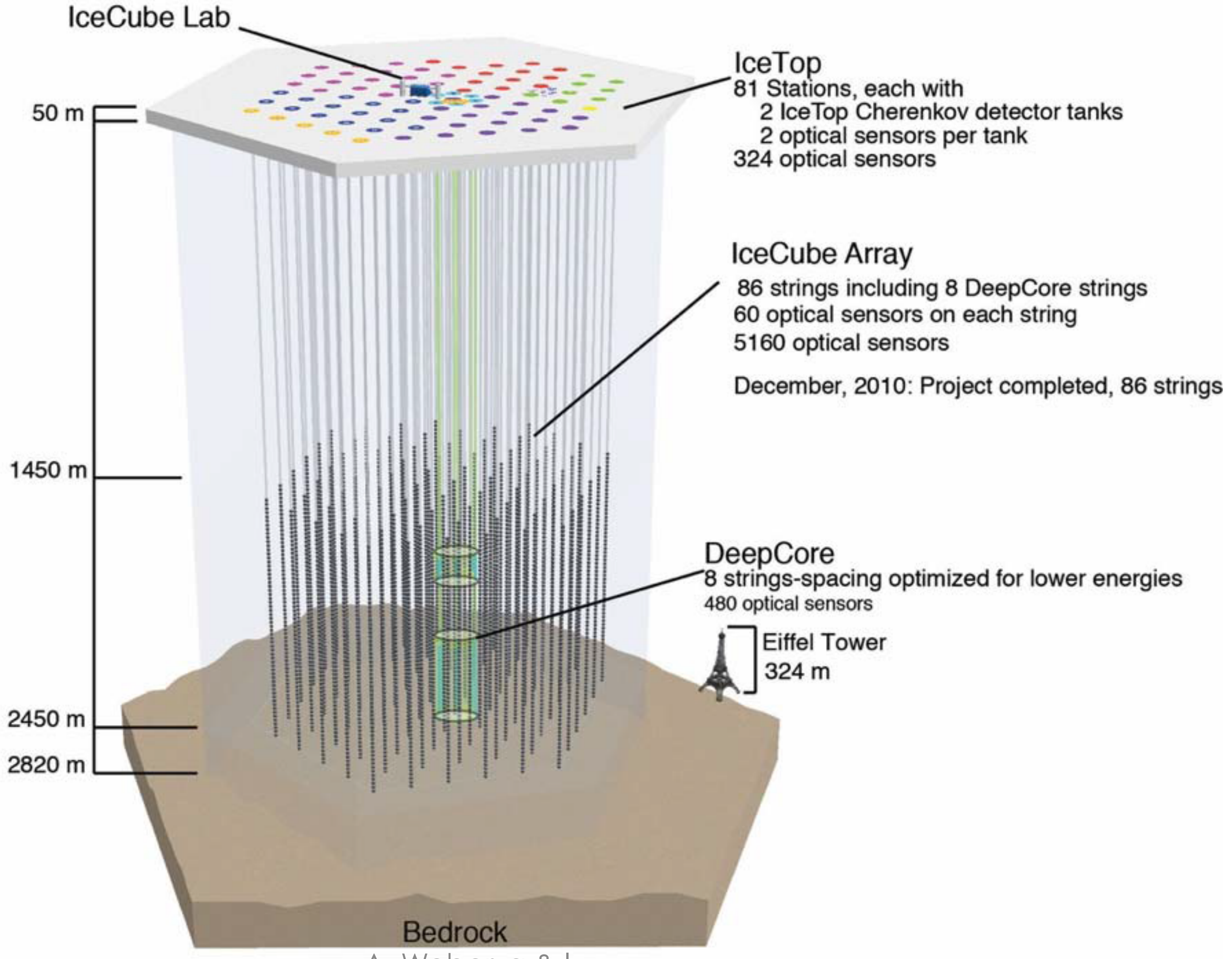
Octant



NH, unknown
θ13 is fixed : sin²2θ13 = 0.10
IH, Unknown
10 years
10 years
3σ
2σ
3σ
2σ
Δ χ² wrong octant
Δ χ² wrong octant
sin² θ23 true
sin² θ23 true
35
30
25
20
15
10
5
0
0.4
0.45
0.5
0.55
0.6

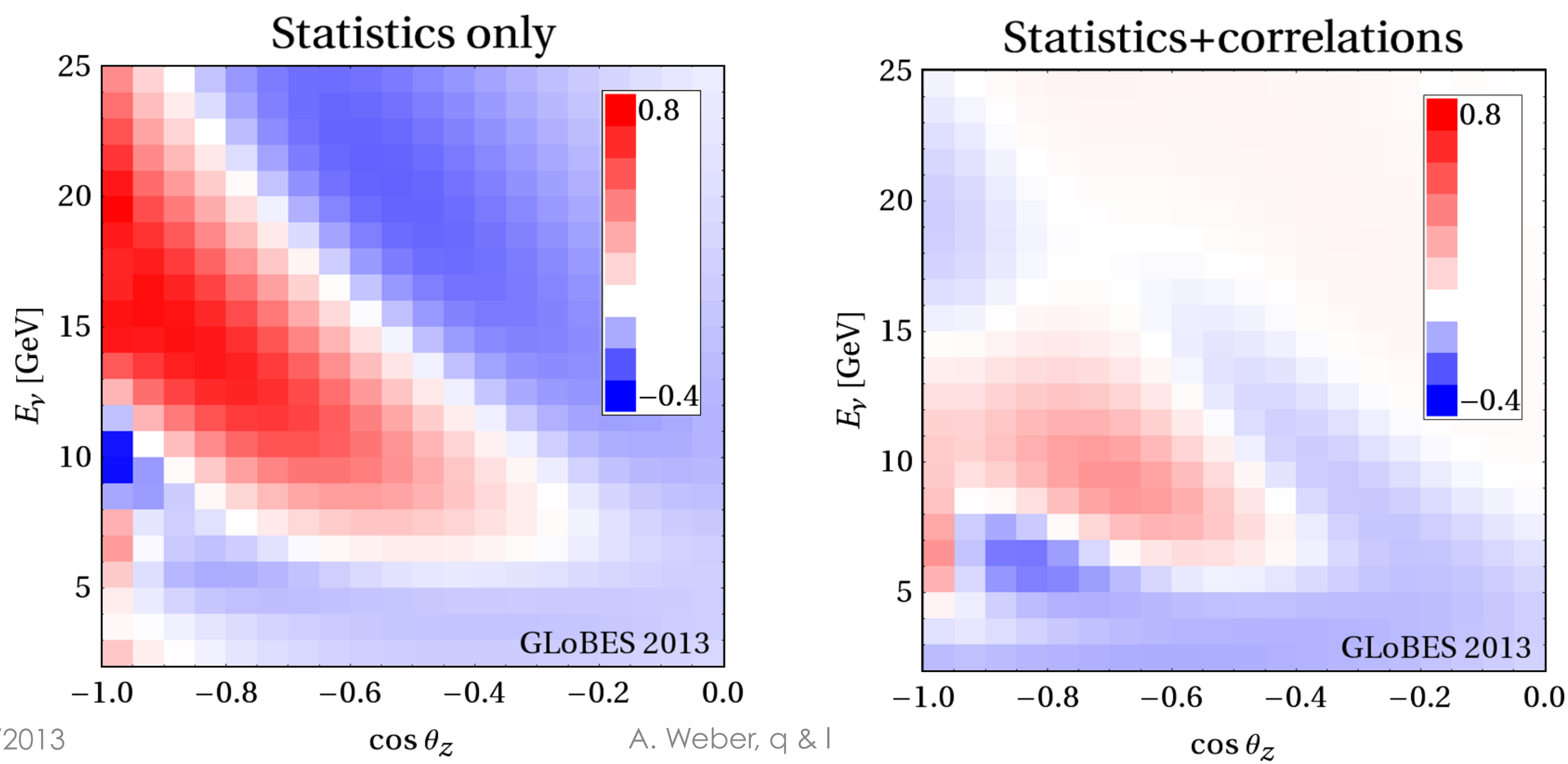
PINGU


PINGU


IceCube Lab
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock

The Signature

- Atmospheric Neutrinos oscillate
  - Mass ES are not weak interaction ES
  - What is the mass hierarchy?



Summarium

- Hunt for the MH and CPV is on
- Several contestants
  - Reactors
  - Atmospheric neutrinos
  - Intense beams
- Next generation of experiments
  - Complementary
  - Constrain standard oscillation picture
  - Determine unknown parameters
  - Precision experiments
- Large effort in theory and experiments is needed
  - Systematics can become the limit

… and more

SoLi∂

RESEARCH REACTOR

- **SCK•CEN BR2 Mol, Belgium**
- **45-80 MW, 4-5 cycles (20-25 days) per year**
- **Small effective core ~ 50cm diameter**

DETECTOR

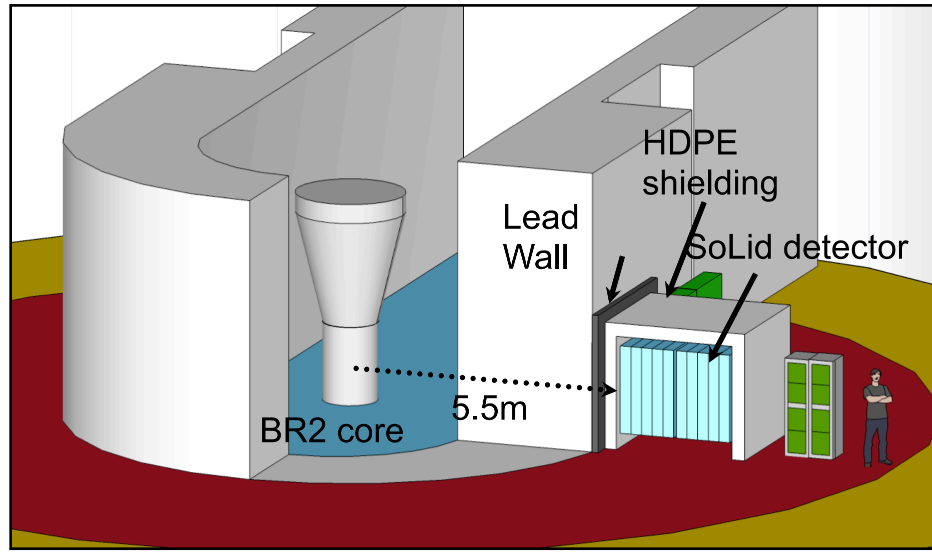
- **2.88t fiducial volume**
- **Novel type of composite solid scintillator detector (PVT + 6LiF:ZnS)**
- **2x 20 planes 1.2m x 1.2m x 1m with 576 5cm x 5cm x 5cm cubes**
- **read out by WLS fibres and Geiger-mode APDs (MPPC), 1920 channels total**
- **65MS/S dead timeless electronics**

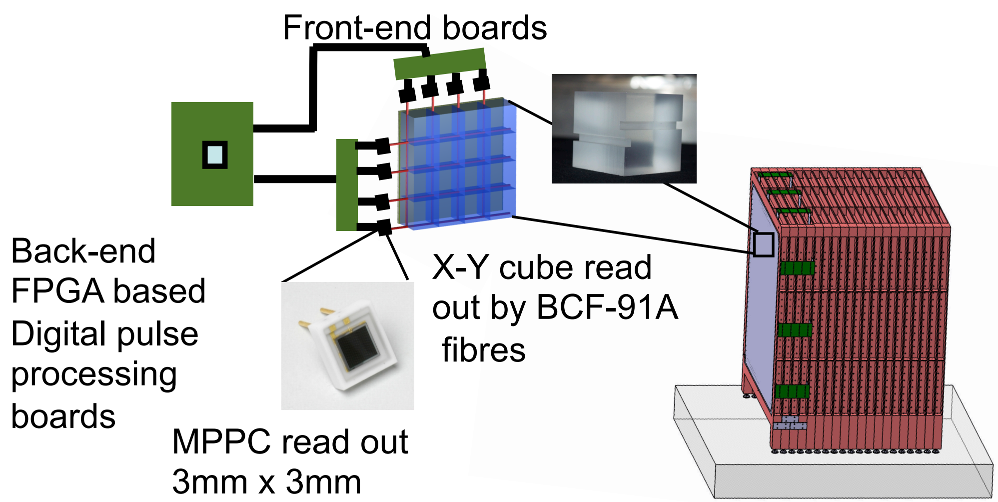
REACTOR-DETECTOR

- **Minimal distance @ 5.5m**
- **~1200 events/day reconstructed**

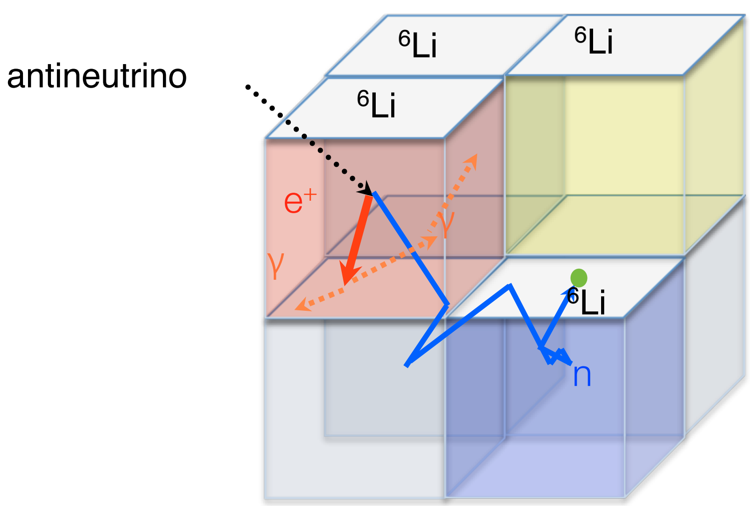
BACKGROUND

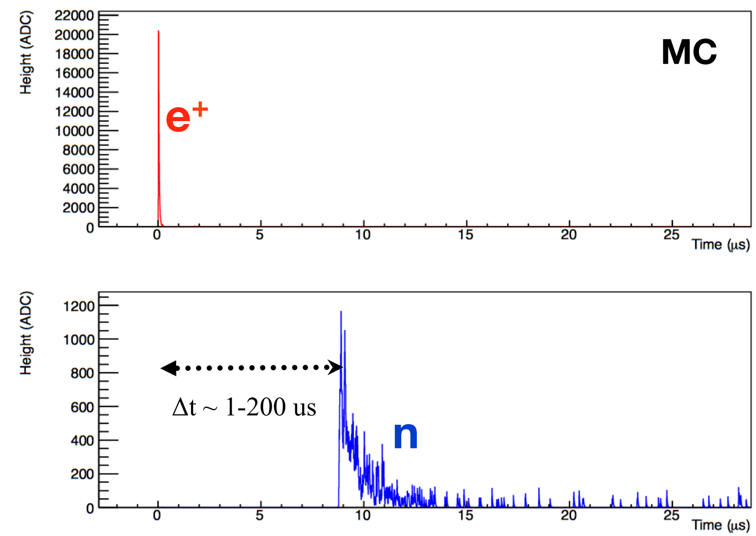
- **High signal to background ratio : S/B ~ 6**
- **Soft Gamma-rays (< 3 MeV)**
- **No reactor neutrons**
- **Overburden ~10 m.w.e**





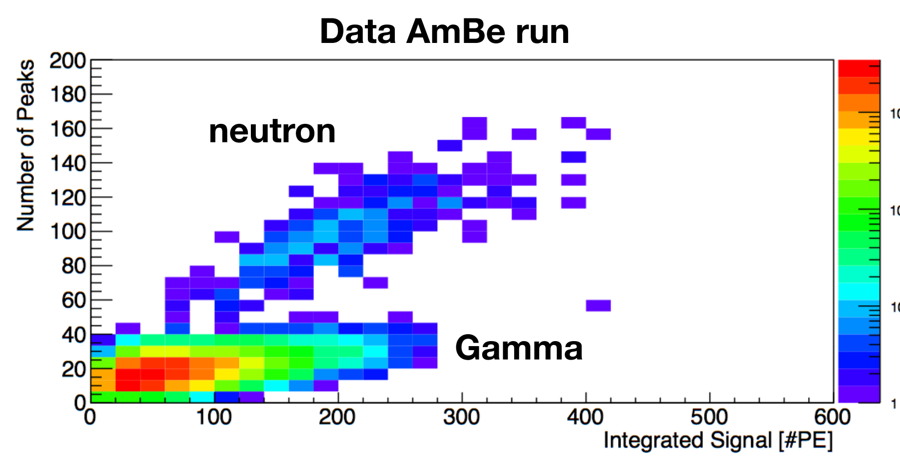
Anti-Neutrino Detection



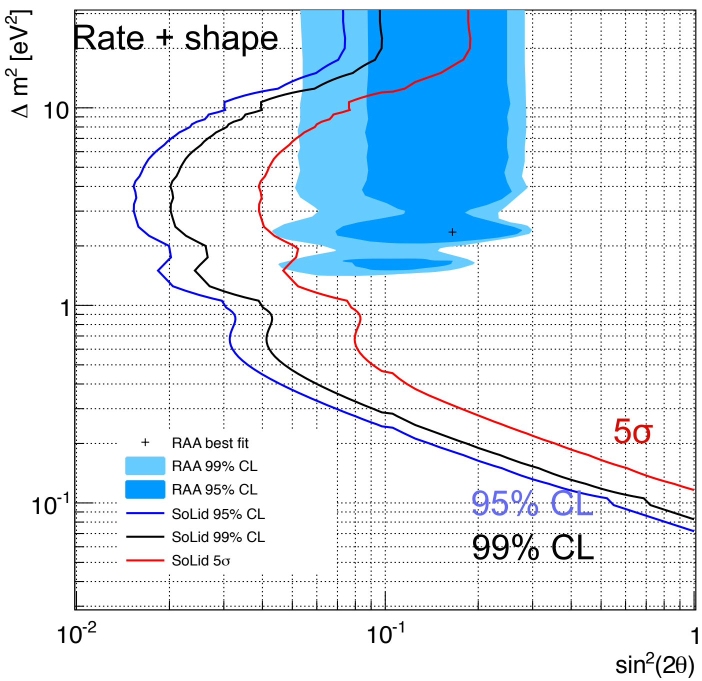


$${}^{6}_{3}\mathrm{Li} + \mathrm{n} \rightarrow {}^{2}_{4}\,\mathrm{He}\ (2.05\ \mathrm{MeV}) + {}^{1}_{3}\,\mathrm{T}\ (2.75\ \mathrm{MeV})$$

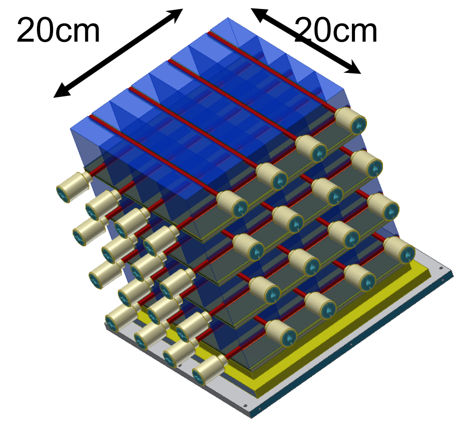
- Different response for neutron in ^{6}LiF:ZnS and other particles
  - High neutron-gamma rejection factor
- 3D reconstruction close to interaction point : topological information of IBD
- High light yield and good energy resolution
  - dE/E ~ 17% at 1 MeV
- Vertex resolution < 5 cm
- High background rejection capability using hit multiplicity and flexible fiducial cuts

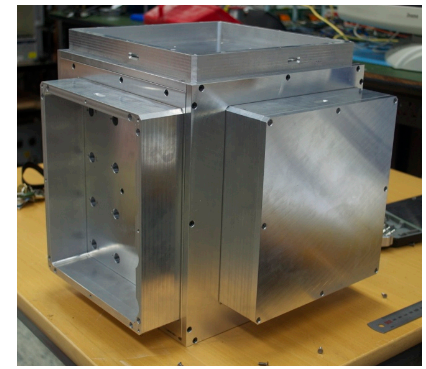


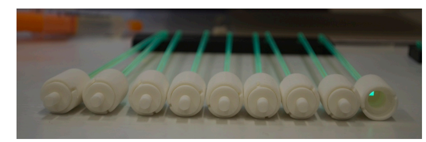
Sensitivity & Status



8kg Fiducial mass







- Average distance at 6.8m with 2.88t fiducial mass
- 300 days (~ two years running)
- 45% IBD efficiency
- L binning of 20 cm
- Systematics : normalisation 4.1%, total ~5%
- Physics run scheduled for start of 2016

- Development of small prototype
- under commissioning at Oxford
- Deployment at BR2 for August 2013 reactor cycle (~25-30 days)
  - study of background conditions
  - antineutrinos measurement trial at 5m from reactor core
    - expect 6 evts/day, S:B ~ 1:5