# Longbase Neutrino Experiments

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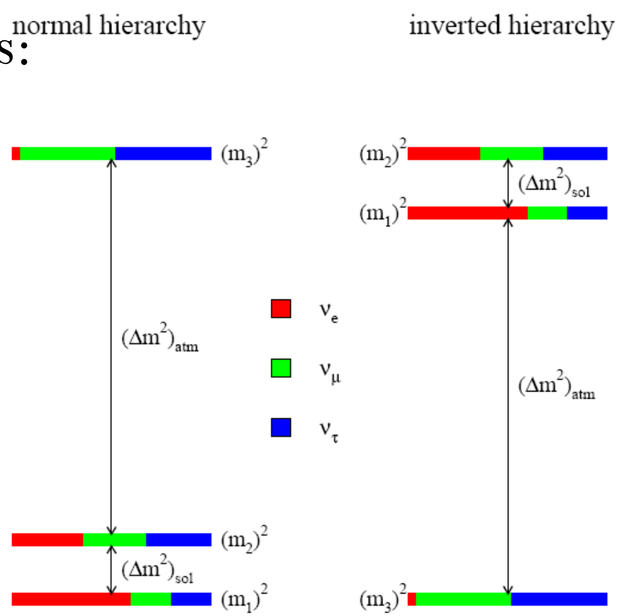
# Neutrino mixing

- Neutrino mixing is characterised by the PMNS matrix.

$$\mathbf{U}_{PMNS} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \boxed{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}$$

- Fundamental parameters of nature just like CKM
- Open questions for long baseline experiments:
  - Mass Hierarchy.
    - Either/or question.
    - Appears through matter effect.
  - CP Violating Phase $\delta$
  - Mixing Angles $\theta_{13}$, $\theta_{23}$ .
    - Octant of $\theta_{23}$
    - Is $\theta_{23}$ maximal?



# Oscillations and measurement

- Different oscillation channels are sensitive to different combinations of mixing parameters
  - In general we want to measure $P_{osc}(E_\nu)$

- Short Baseline Reactors: $p \sim \sin^2 2\theta_{13}$ , $\Delta m^2_{13}$
  - Directly measure $\theta_{13}$.
  - Solar term at longer baselines.

- Long Baseline: $p \sim \sin^2\theta_{23}\sin^2 2\theta_{13}$ , $\Delta m^2_{13}$
  - Combination of mixing angles
  - Octant important.
- Corrections
  - Matter Term $\rightarrow$ sign of $\Delta m^2_{13}$ , mass hierarchy.
  - CP Terms $\rightarrow$ CP Even and CP odd terms $\rightarrow$ CPV
  - Solar Term.

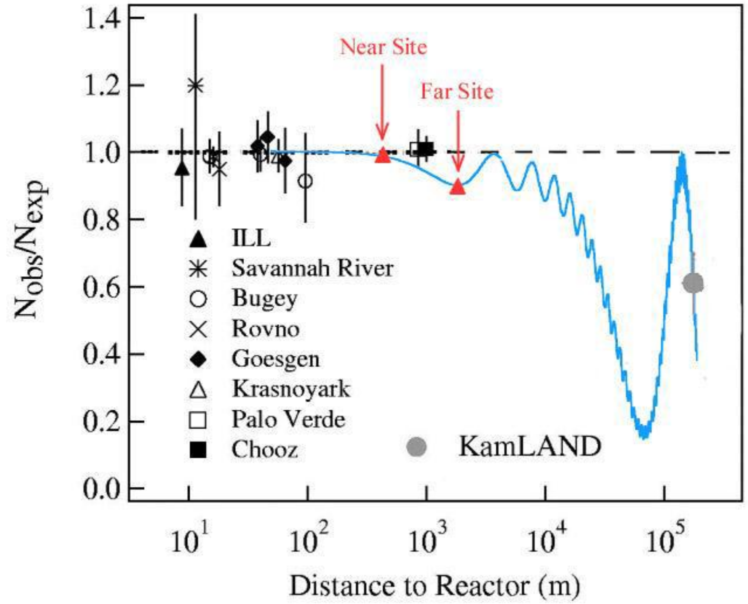
# Current Status

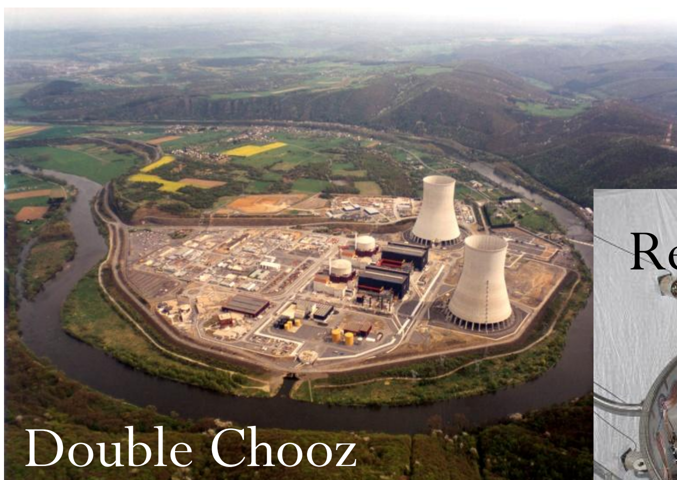
- Current programs first aim : $\theta_{13}$
  - Gatekeeper to CP Violation and Mass Hierarchy
  - Knowledge of $\theta_{13}$ required to plan next stages of neutrino program.
  - Discovery of non-zero $\theta_{13}$ key development of the last 12 months.

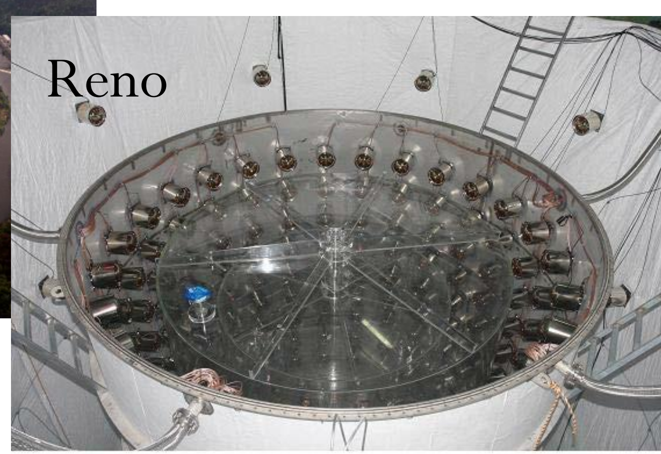
- Also aim to
  - Reduce uncertainties on other oscillation parameters
  - Start to test the 3 neutrino oscillation model

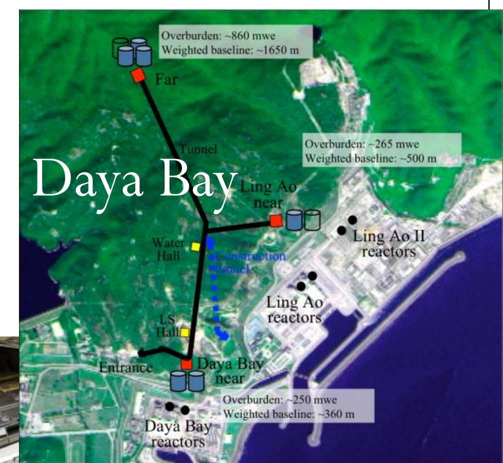
# Reactor Experiments

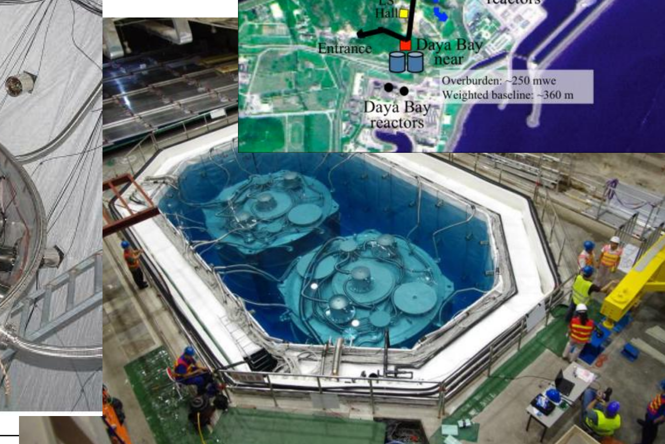
- Search for $\theta_{13}$ short baseline, disappearance mode.
  - $p(\bar{\nu}_e \rightarrow \bar{\nu}_e)$
- Clean measurement of $\theta_{13}$, independent of other mixing parameters
  - Does require $\Delta m^2$ from long baseline experiments.



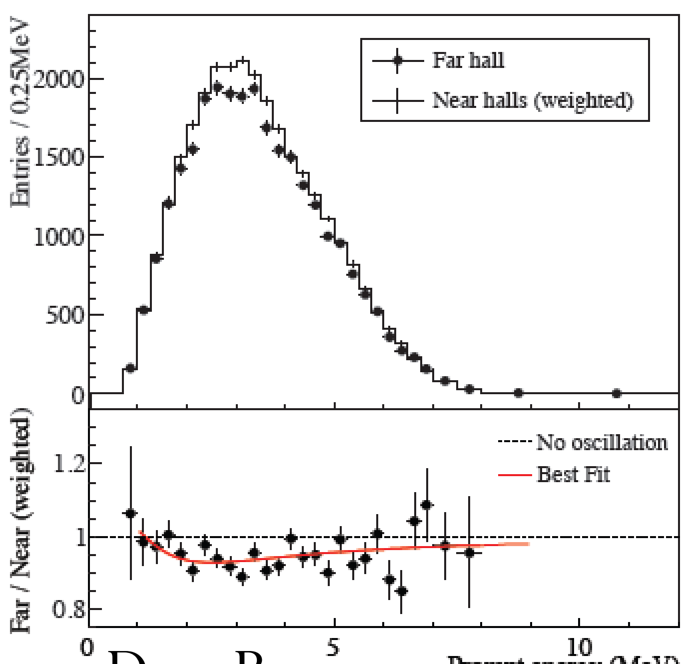



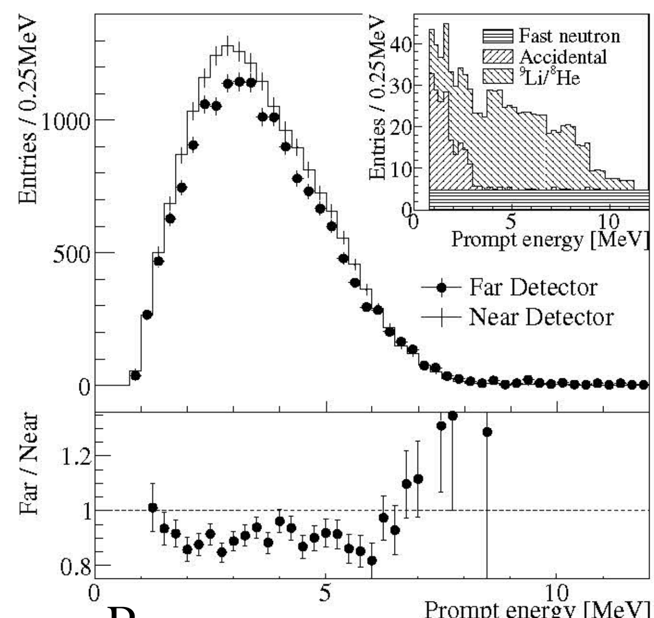



# Results from Reactors

- Measurement of non-zero $\theta_{13}$ at $> 5\sigma$ .
  - Daya Bay : $\mathrm{Sin}^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})\ 5.2\sigma$
  - Reno : $\mathrm{Sin}^2 2\theta_{13} = 0.113 \pm 0.013(\mathrm{stat}) \pm 0.019(\mathrm{syst})\ 4.9\sigma$

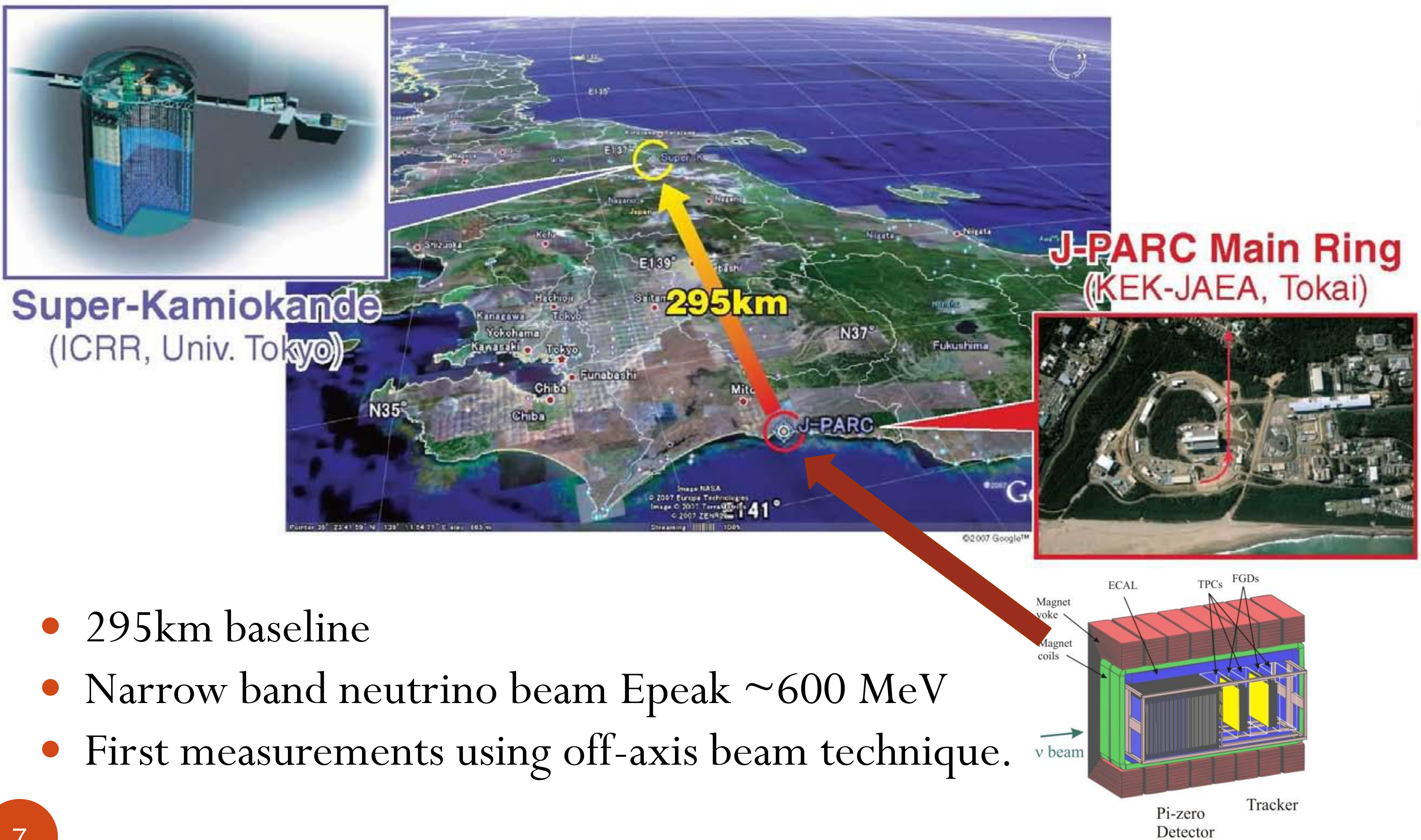



Daya Bay



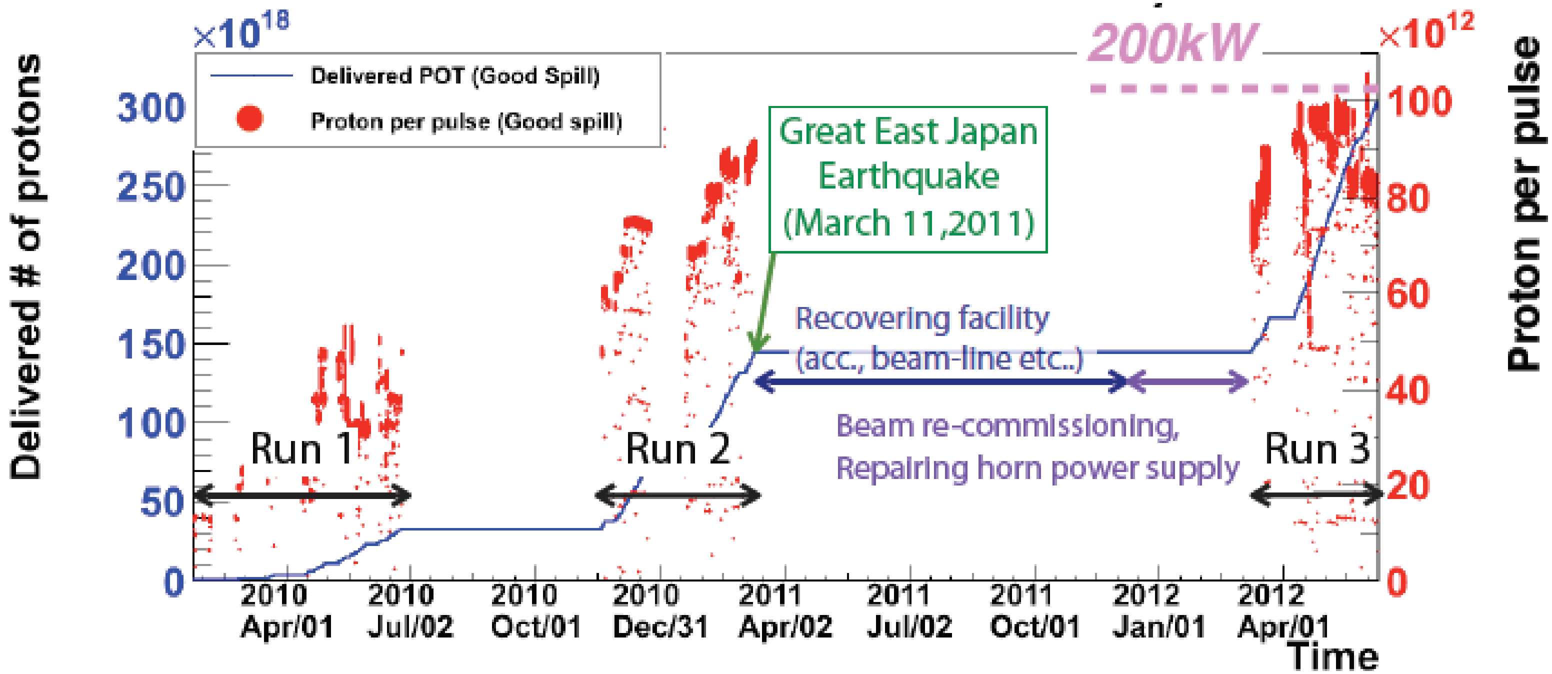

Reno

# T2K Experiment




- 295km baseline
- Narrow band neutrino beam Epeak ~600 MeV
- First measurements using off-axis beam technique.

# T2K Data




Run1 + 2 (2010-2011)
$1.43 \times 10^{20}$ p.o.t.

* ND280 Run1+2 data is used for oscillation analysis

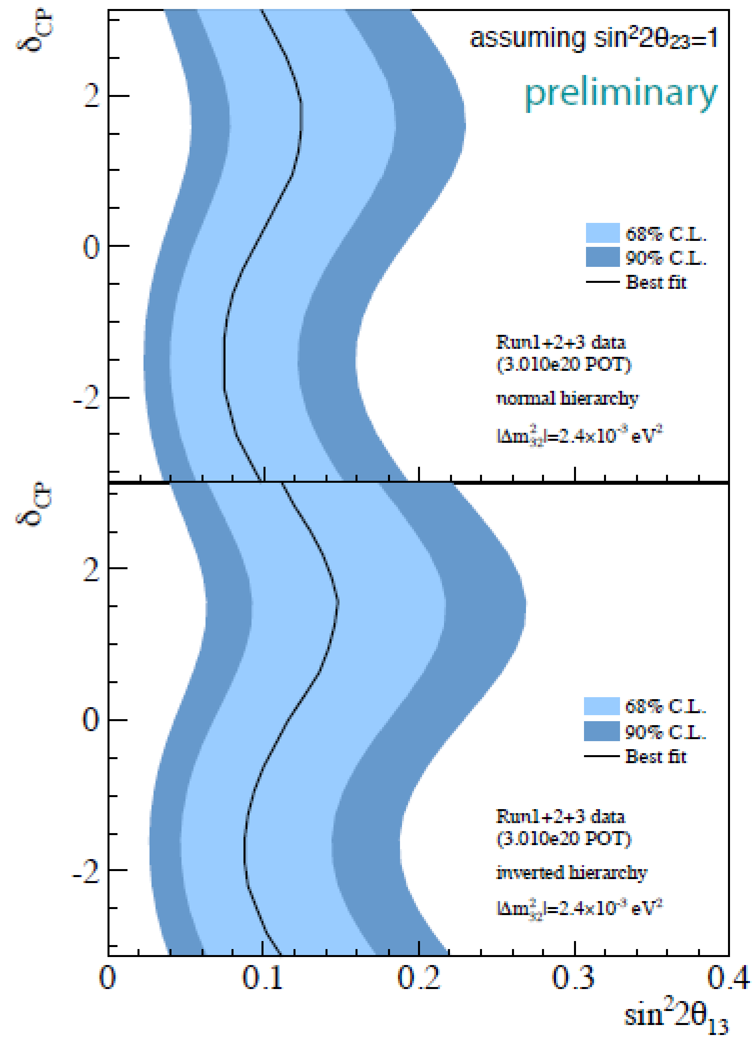
Run3 (2012) : $1.58 \times 10^{20}$ p.o.t

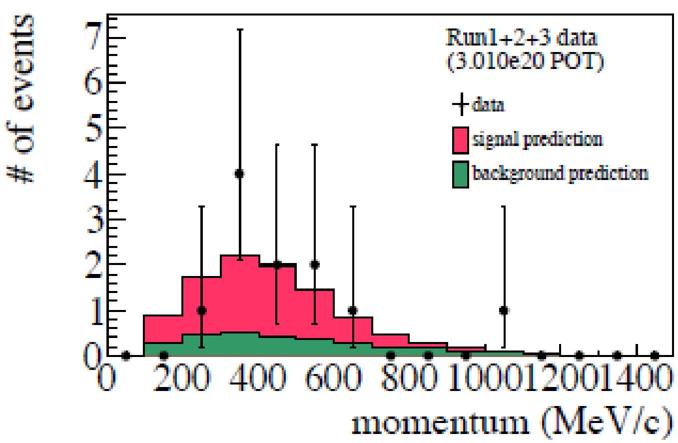
* including $0.21 \times 10^{20}$ p.o.t. with 200kA horn operation (13% flux reduction at peak) (250kA horn current for nominal operation)
* ND280 Run3 data is checked and consistent with Run1+2

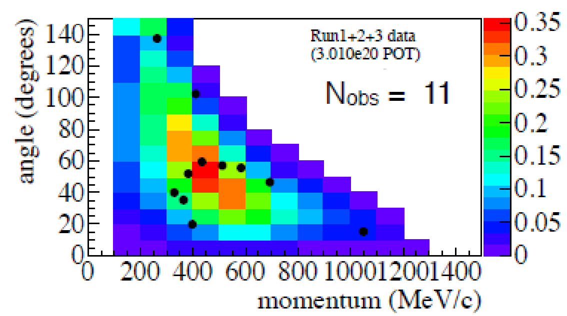
- T2K now running again and fully operational following the March 2011 earthquake.

# Detection of $\nu_\mu \rightarrow \nu_e$

- 11 events observed, 2.94 background expected
- Detection of $\theta_{13}$ at 3.2 $\sigma$.
- $\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$
  - Normal Hierarchy, $\delta$=0
- Fit uses data from near detector and NA61 to constrain neutrino flux and interactions at SK
  - Crucial part of the experimental program.

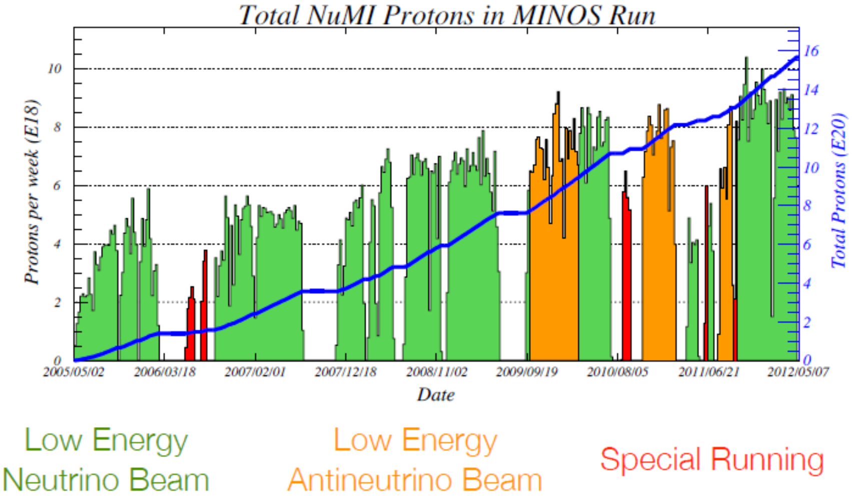


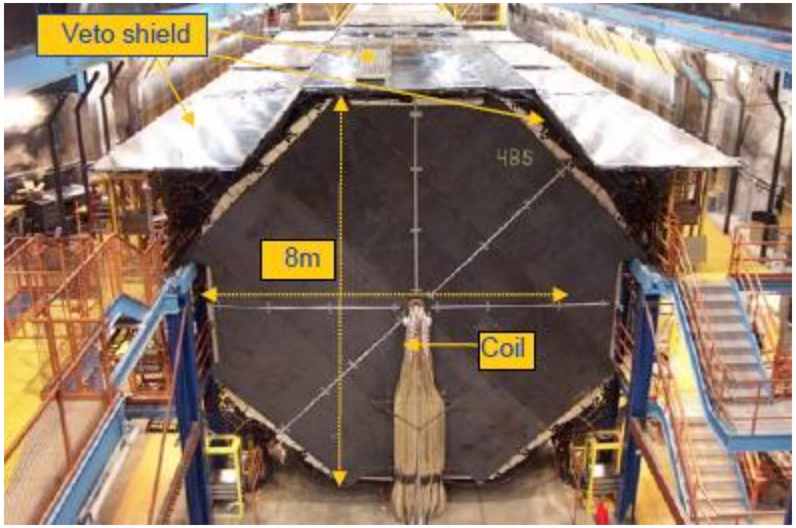



# Minos

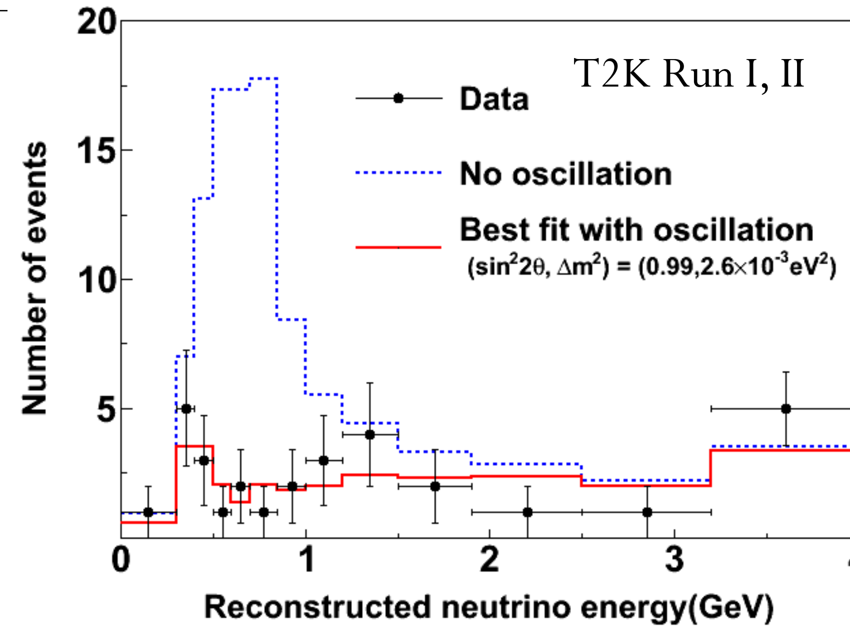
- 735 km baseline
- Uses NUMI beam in low energy configuration
  - Full dataset now collected.
- 5.4 kton magnetised iron calorimeter
  - 980 ton near detector

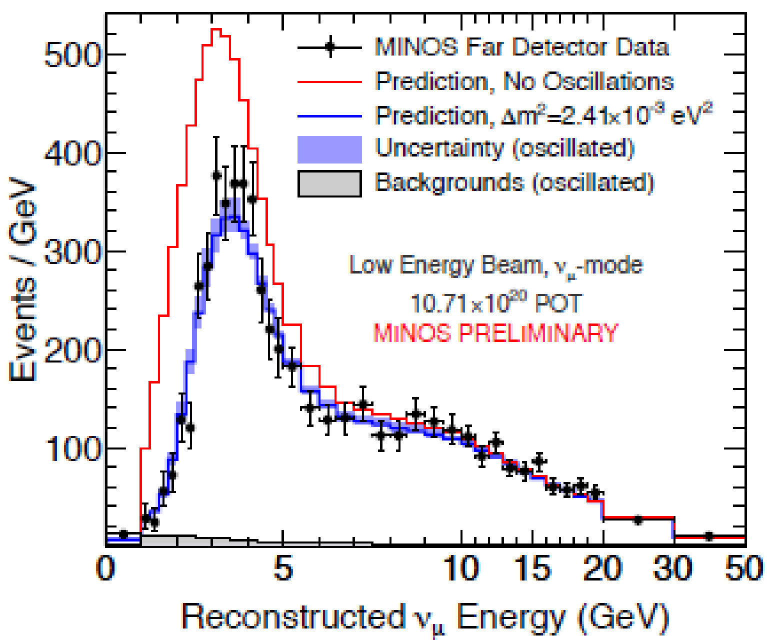



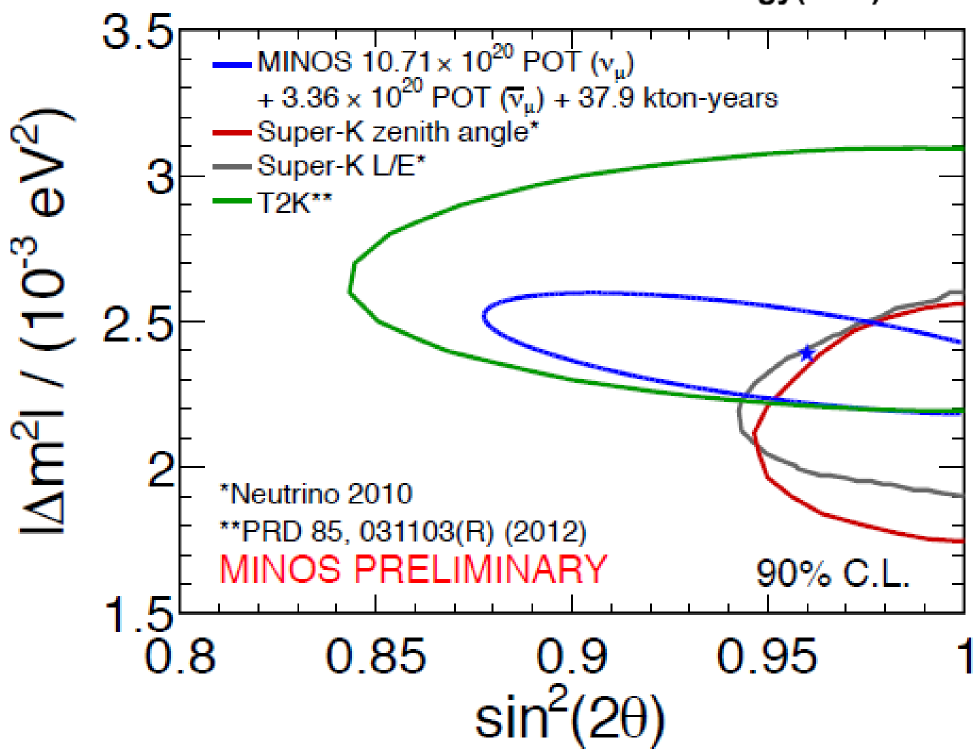



# Measurements of $\theta_{23}$

- Atmospheric neutrino results still very competitive.
- Crucial to improve measurement of $\theta_{23}$ as it appears with $\theta_{13}$ in long baseline probabilities.



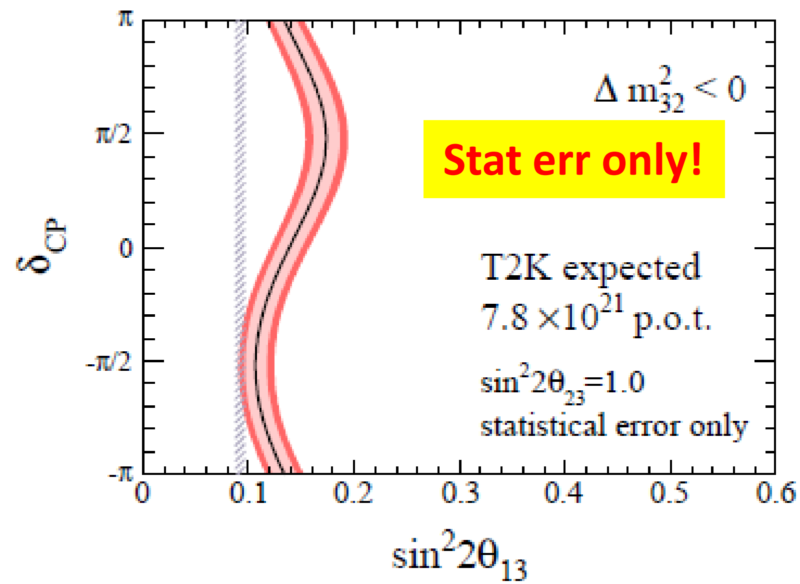



# Long baseline experiments to ~2020

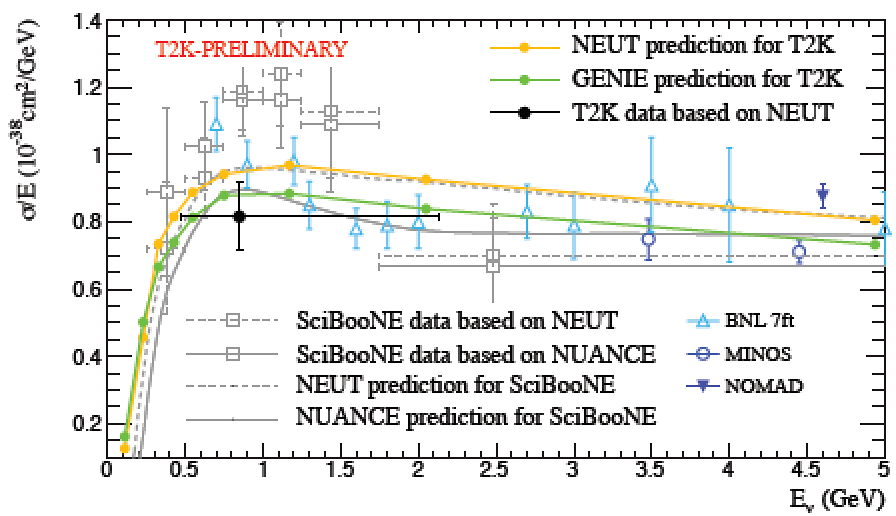
- For the next decade the neutrino community will be working to fully exploit existing neutrino beamlines:
  - JPARC-SK
  - NUMI
  - CNGS
- Improved measurements of $\theta_{13}$, $\theta_{23}$ and $\Delta m^2$.
  - Requires reduction in systematics with better cross section measurements.
- Potential sensitivity to CP violation in some scenarios.

# T2K Programme

- Plan to continue increasing beam power over the next 10 years.
  - Aim for 750kW by 2018
    - 400 MeV Linac upgrade in 2013 long shutdown.
  - Final target dataset 750kWx5x$10^7$s.
    - Current data ~ 5% of this.
- Significant reduction in error bars for $\theta_{13}$, $\theta_{23}$ and $\Delta m^2_{23}$
- Program of cross section measurements with near detector.

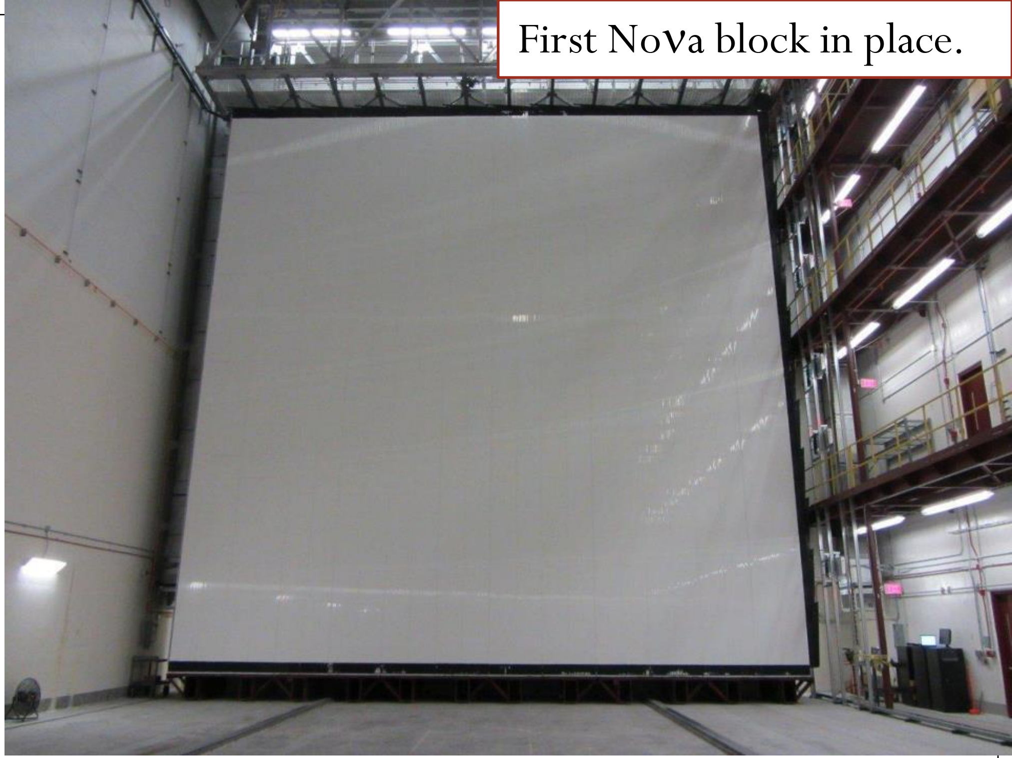


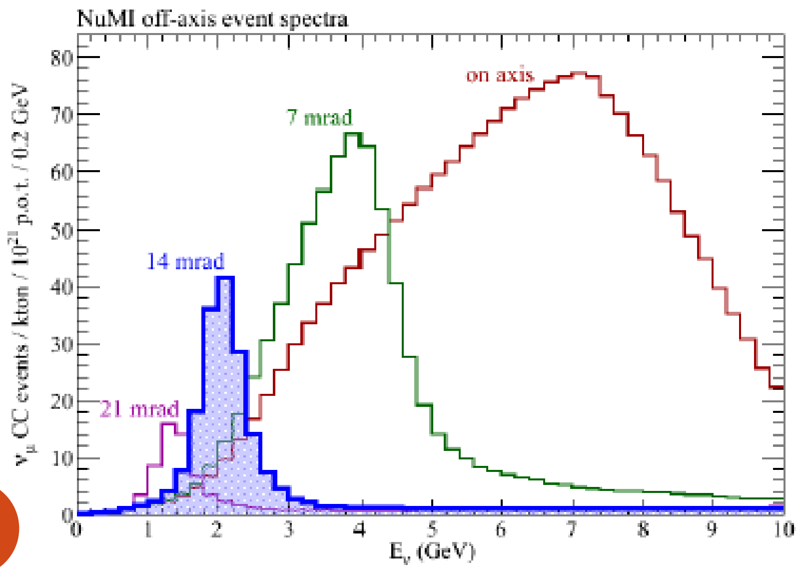

| Expected beam power | May 2012 | 2014 | 2018 |
|---|---|---|---|
| | 190kW | 300kW | 750kW |



# NOνA

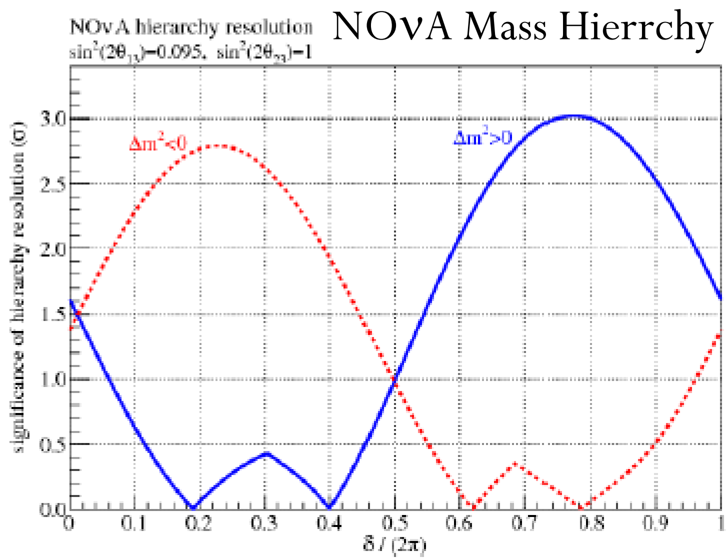
- Continued exploitation of the NUMI beamline.
- 14 kt totally active scintillatior detector.
  - On surface.
  - Ash River Mn
- Baseline 810km
  - 14mrad off axis
- Beam power 350 kW → ~700kW

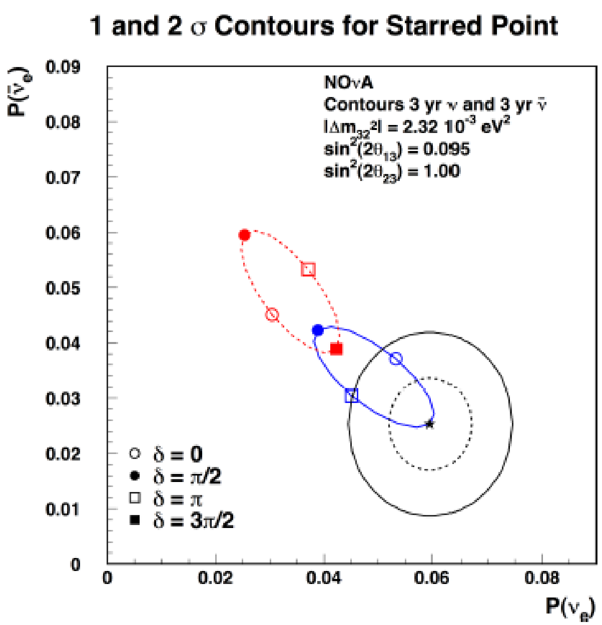


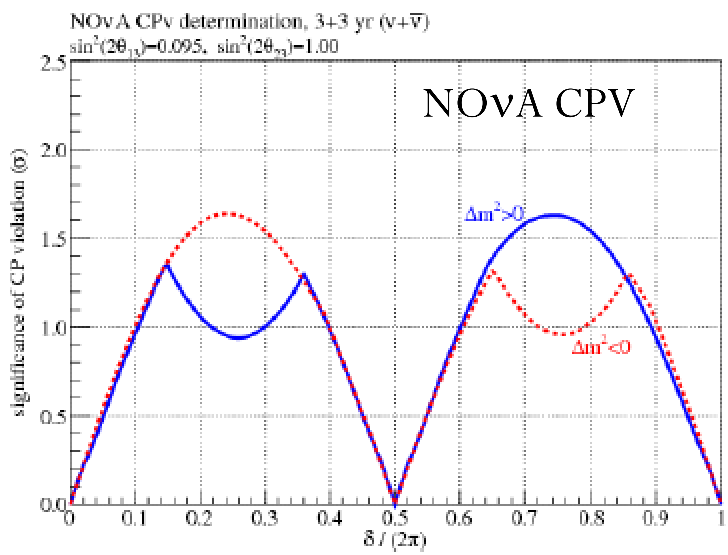




# NOνA physics reach

- Assume 3 yr ν/ 3 yr antiν.
- Potential for 5σ νe appearance in first year
- Investigate mass hierarchy, CPV and $\theta_{23}$ including octant in course of run.

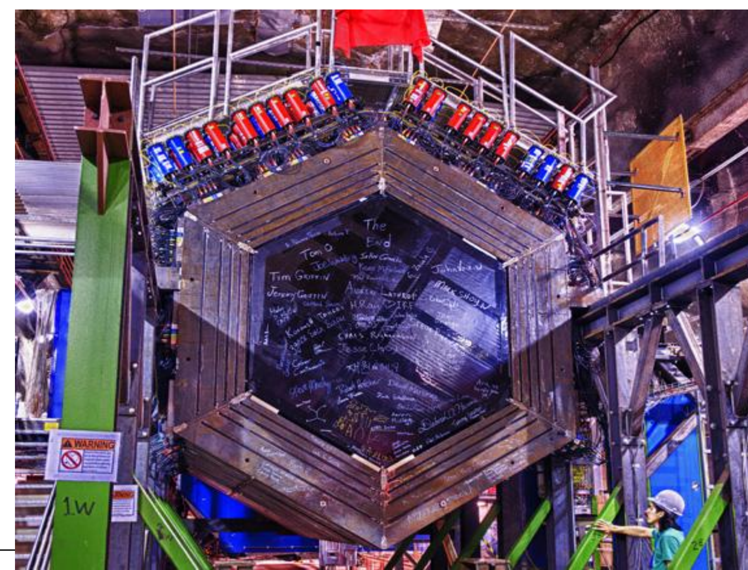


# Other experiments in the NUMI beamline

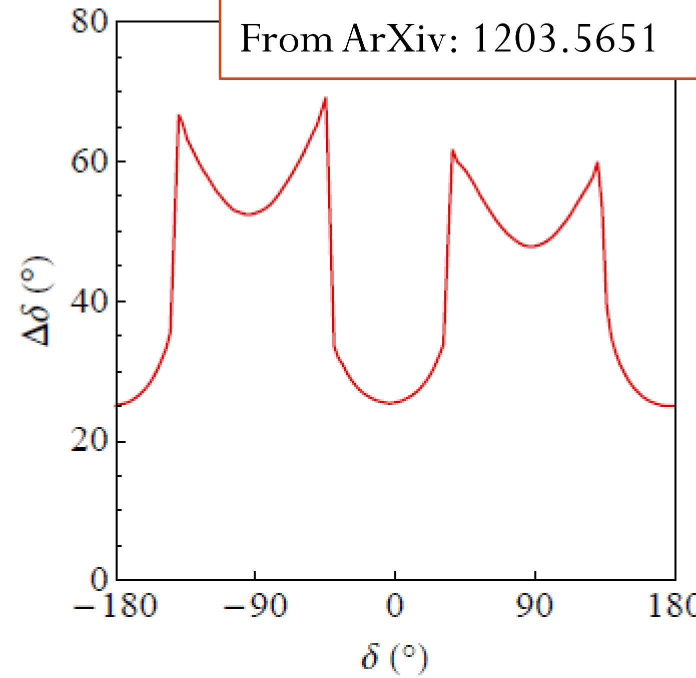
- MINOS+
  - Continued exploitation of MINOS detector
  - Sterile Neutrino Tests via Unitarity.
    - Disappearance at higher energy.
- MINERvA
  - Neutrino Cross Section Measurements
  - Started Operation in 2010
- Other options have been discussed
  - Glade
  - Water Cherenkov in Lake Superior.



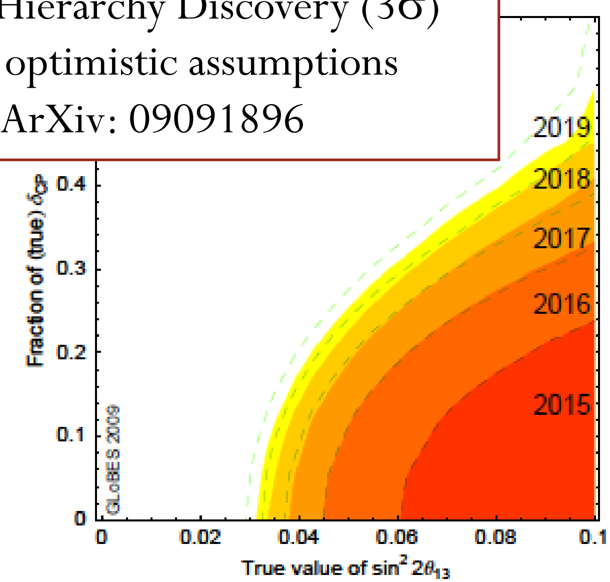
# Combining Results

- In many ways T2K and NO$\nu$A complement each other.
  - Different matter effects
  - Can help resolve ambiguities in the parameters and improve sensitivity to mass hierarchy and CPV.
  - Reactor experiments also contribute.
- Health warning:
  - Global fits be necessity assume the 3 neutrino mixing model.

Potential error on $\delta$
From ArXiv: 1203.5651




Mass Hierarchy Discovery ($3\sigma$)
Some optimistic assumptions
From ArXiv: 09091896



# Future long baseline experiments

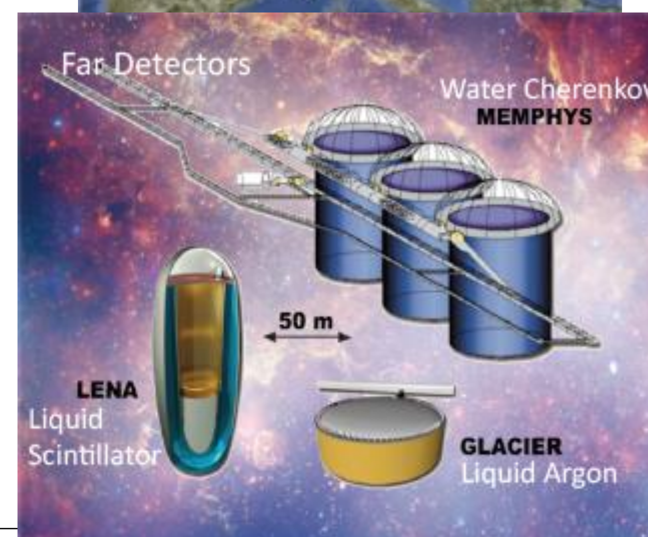
- The recent discovery of $\theta_{13}$ has crystallised the effort in the planning of the next generation of experiments.

- The following proposals are the culmination for a decade of work exploring new ideas and technologies.

- Next Generation experiments to:
  - Determine mass hierarchy, aim for $5\sigma$ precision.
  - Maximise sensitivity to CP violation.
  - Test the standard picture of 3 generation mixing.
  - Aim for a complementary broad physics program with astrophysical neutrino and proton decay measurements.

# The European Option: LAGUNA-LBNO

- European design study to investigate future long baseline experiments and large underground facilities.
- LAGUNA 2008-2011
  - Detailed investigation and engineering of 7 sites across Europe
  - Detector technologies and capabilities.
  - > 1000 pages of documentation produced.
- LAGUNA-LBNO 2011 -
  - Continued investigation and planning of 3 sites for long baseline neutrino experiments.
  - Pyhäsalmi Glacier, LENA
  - Frejus : Mephys
  - Further exploitation of CNGS.

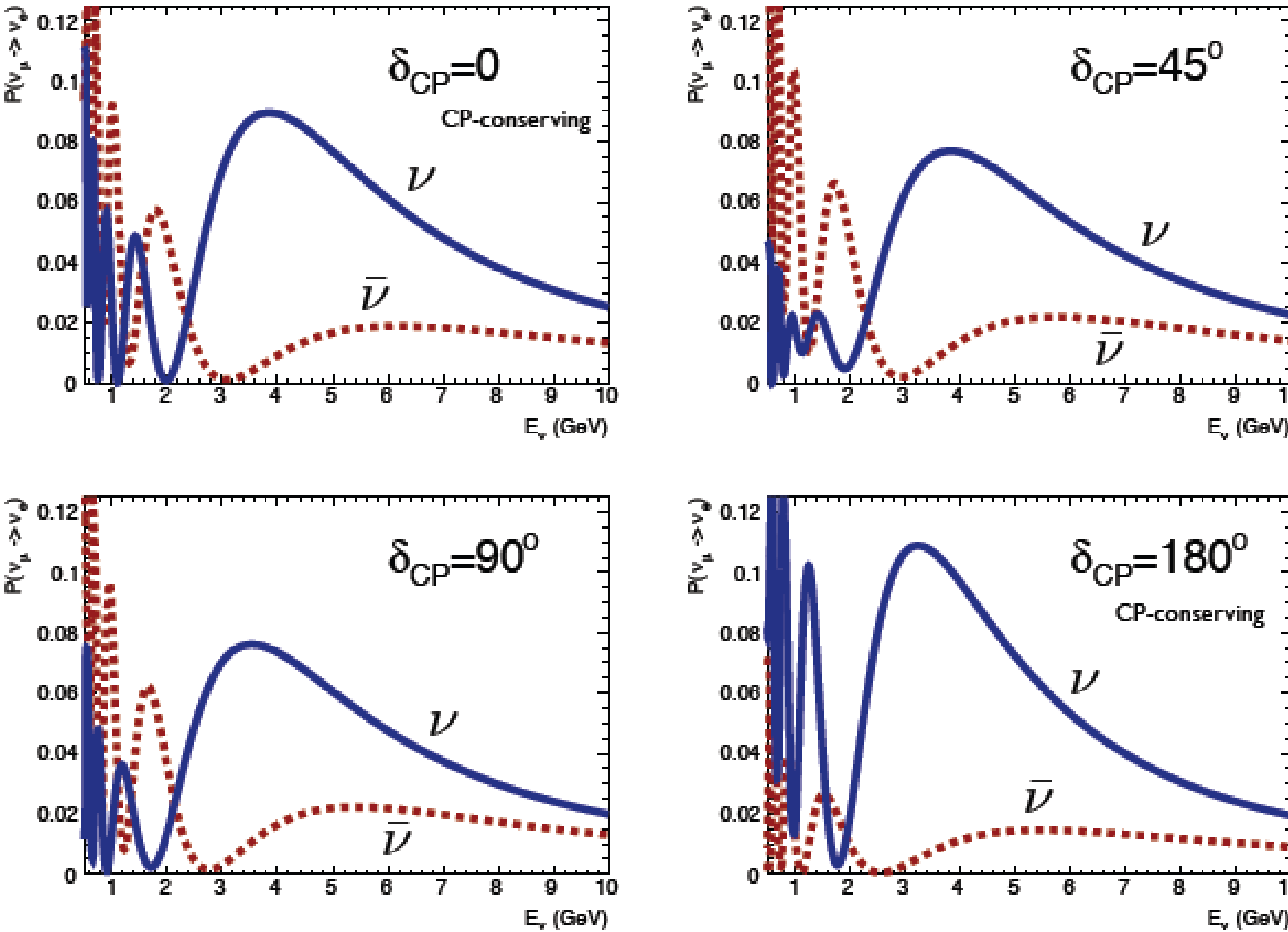



# CERN-Pyhäsalmi

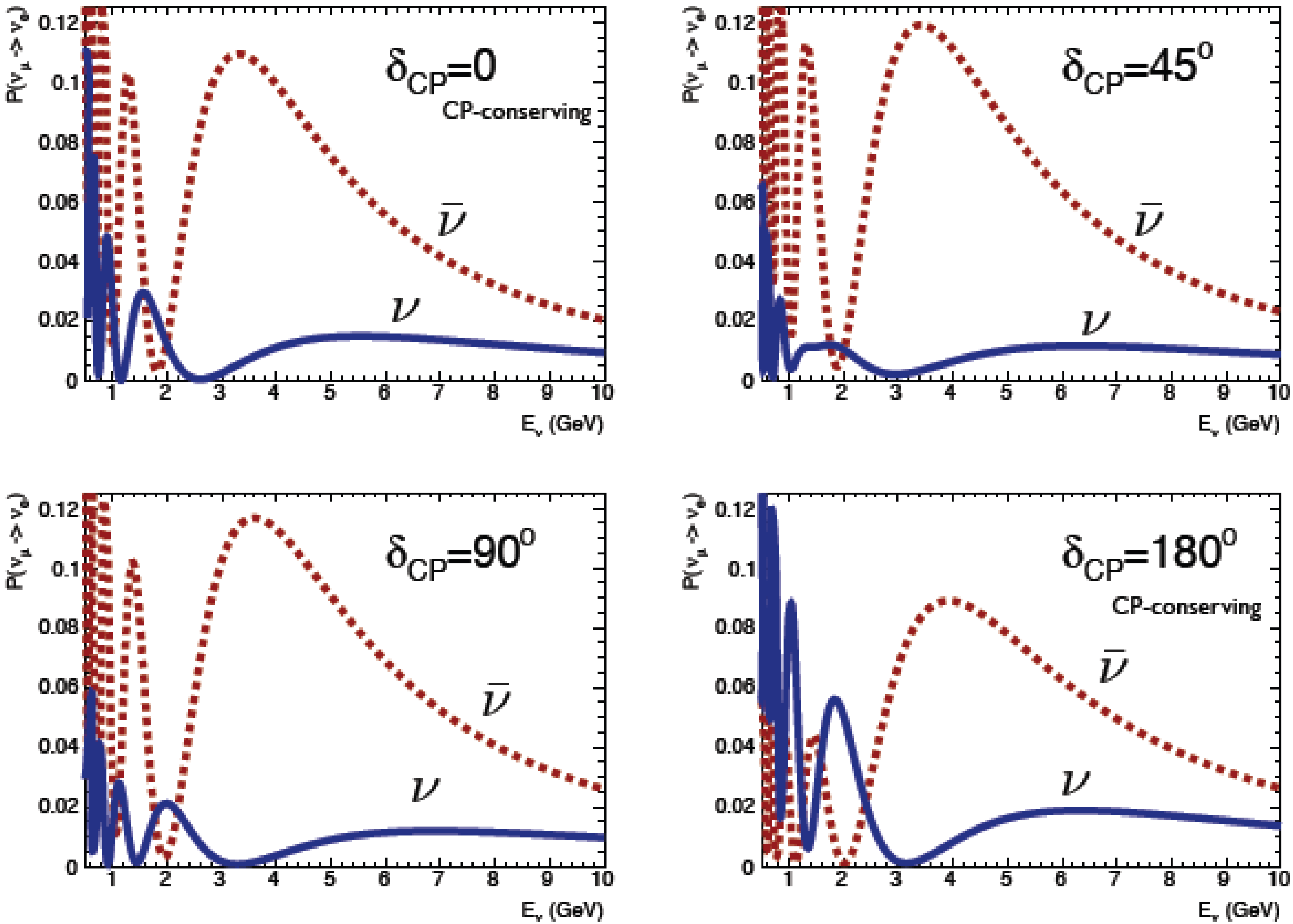
- Neutrino beam from SPS
  - 500kW
- Far site to host
  - 20kT double phase liquid argon TPC Glacier
  - 50kT magnetised iron calorimeter MIND.
- Resolve first and second oscillation maxima
  - Increases CP sensitivity
  - Test of oscillations
- Large distance
  - Spectacular matter effect!


2100 km from RAL, 1500 km from DESY, and 1160 km from Protvino.

# Signals at Pyhäsalmi : Normal Hierarchy



# Signals at Pyhäsalmi : Inverted Hierarchy

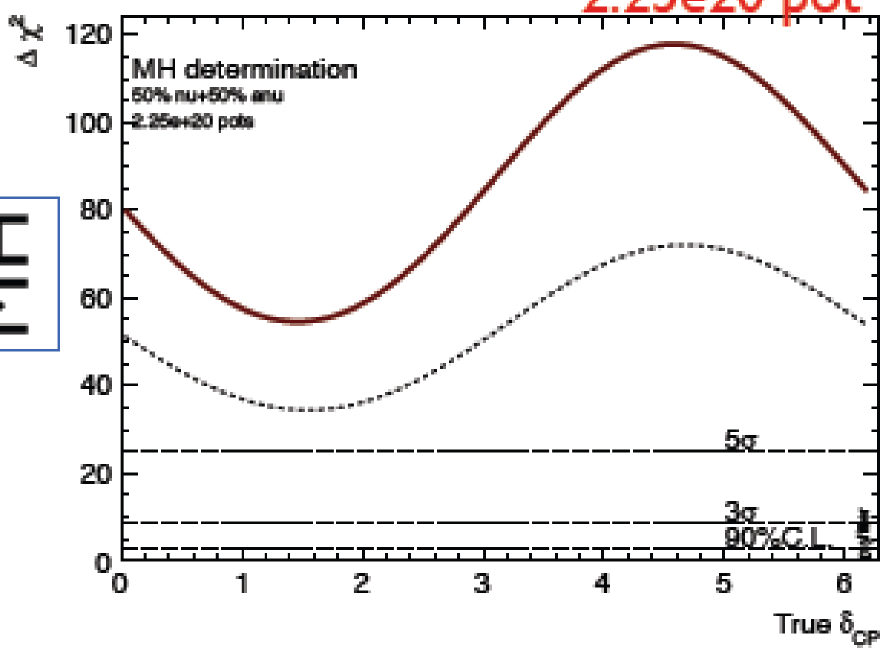


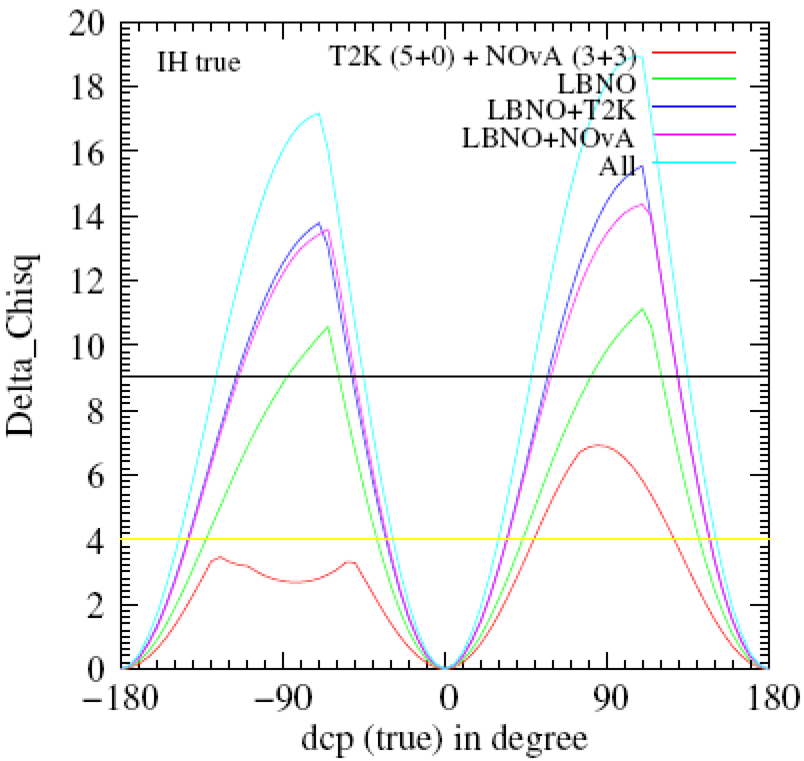
# Physics reach of CERN- Pyhäsalmi

- After 10 years:
  - Full coverage of matter effect at 5σ.
  - 71% (44%) coverage of CPV at 90% (3σ).

MH

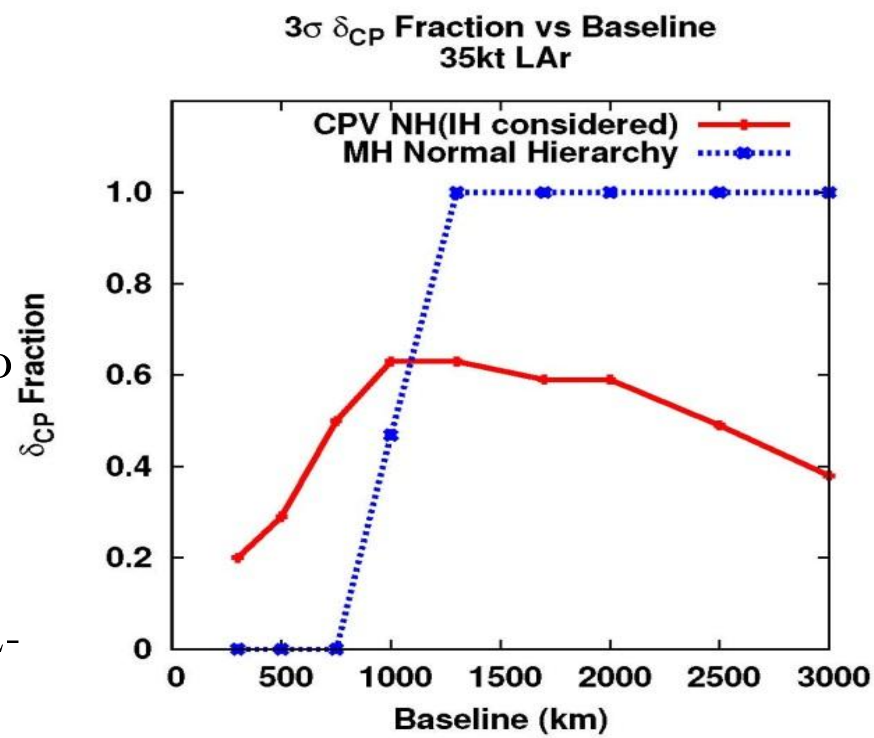
2.25e20 pot



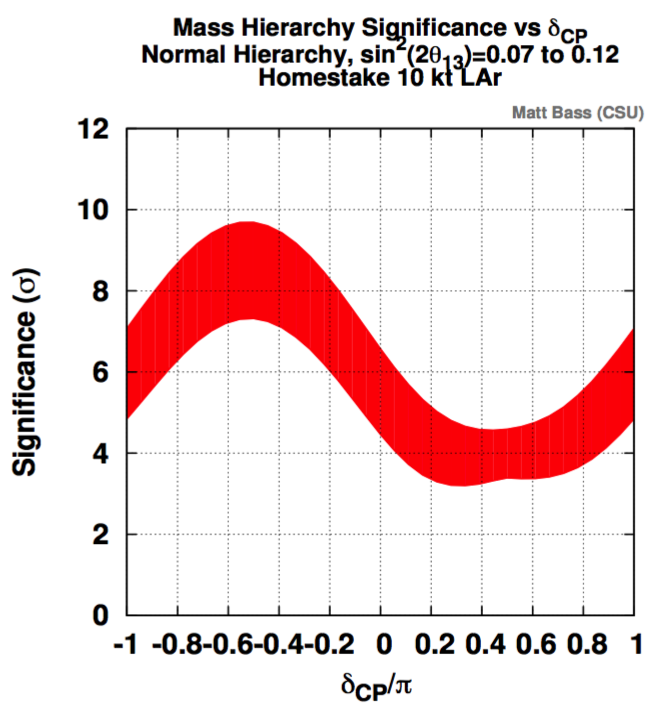
# US Program : LBNE

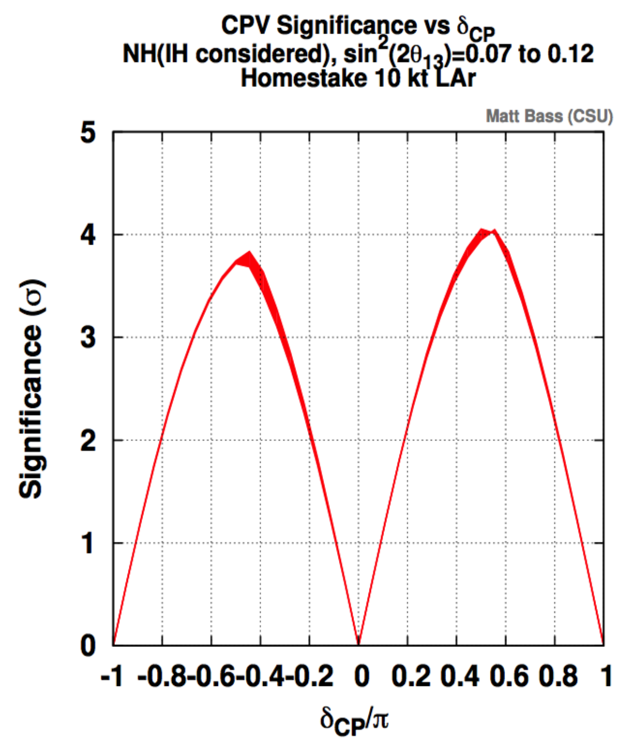
- Neutrino Beam from Fermilab to homestake
  - Baseline of 1300 km
  - Good sensitivity to matter effect and CP.
- Recently underwent reconfiguration to meet US budgetary constraints.
  - Requirements for a staged approach
- Phase 1
  - Construct upgradeable beamline FNAL-Homestake 700 kW.
  - 10 kt surface single phase LAr TPC.
  - No near detector.
- Aim for CD1 by years end.



# Physics Reach of LBNE phase 1

- Can determine mass hierarchy at 3σ .
- Some coverage of CP violation.
- Precision measurement of other oscillation parameters.

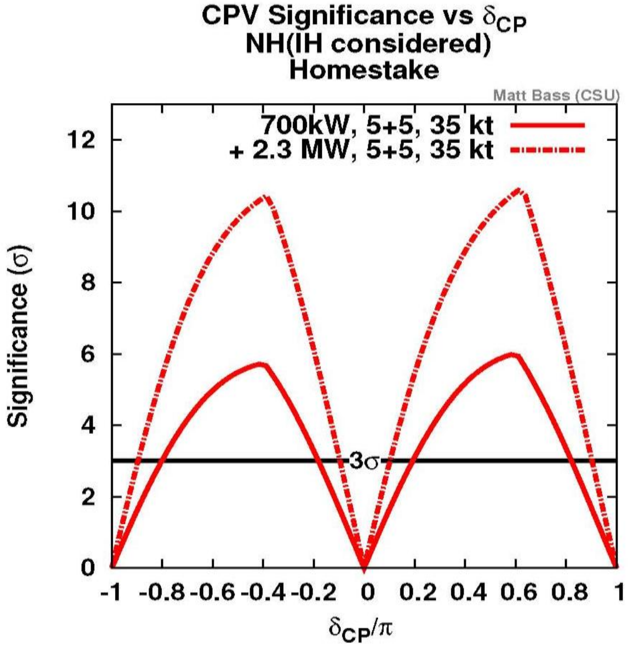


# Upgrades to LBNE

- Scope for future development
  - Far Detector underground : 35kt LAr
  - Intensity : Project X
  - Improved systematics : Near Detector(s)

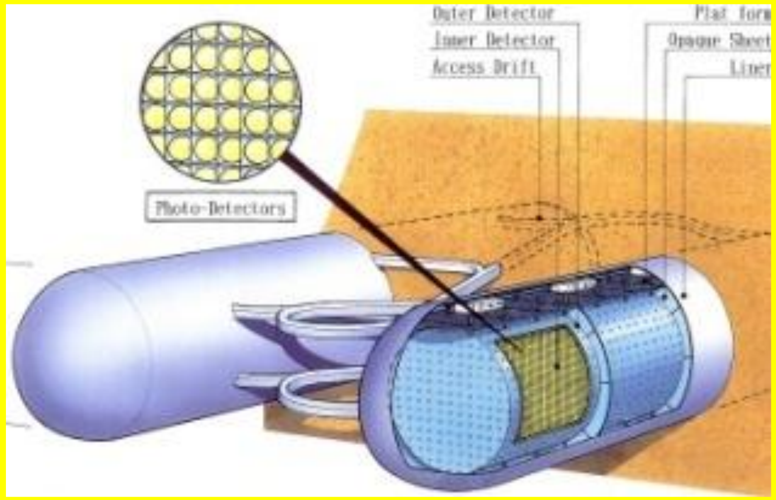
- There is also scope for foreign investment in phase 1.
  - 15% additional cost - far detector underground.
  - 15% additional cost - add near detector.
  - Open to contributions to any aspect of the project.

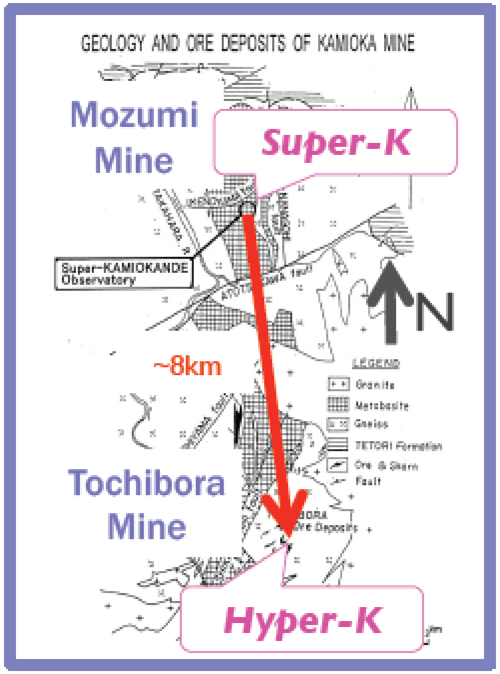



Final LBNE Configuration.
60% CP violation coverage at $3\sigma$.

# Japanese options

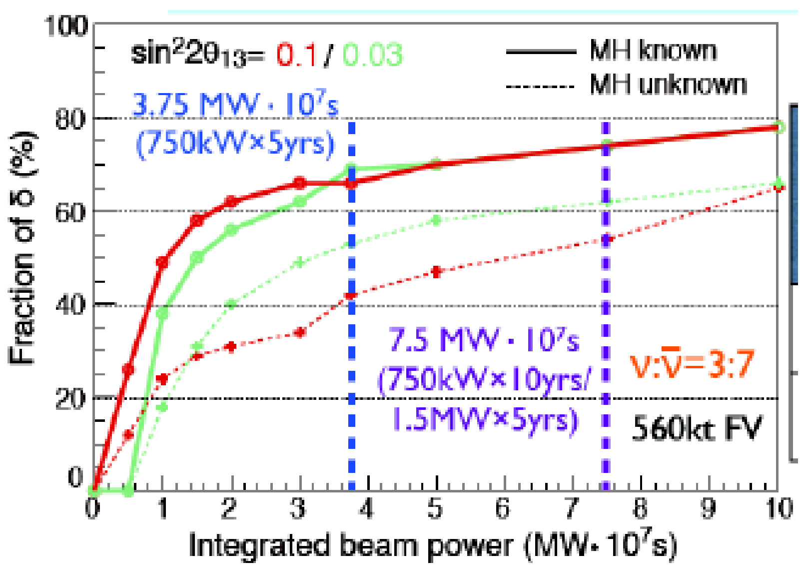
- Exploit the current JPARC neutrino beam.
  - Expect 750kW by ~2020.
- Hyper-Kamiokande
  - 0.56 Mton fiducial water Cherenkov
    - ~20 x SK
  - 2 caverns
  - 99000 PMTs
    - 20% coverage
  - Aim for construction in 2018
- Alternative
  - Okinoshima
  - L=658km OA=0.78deg
  - LAr far detector

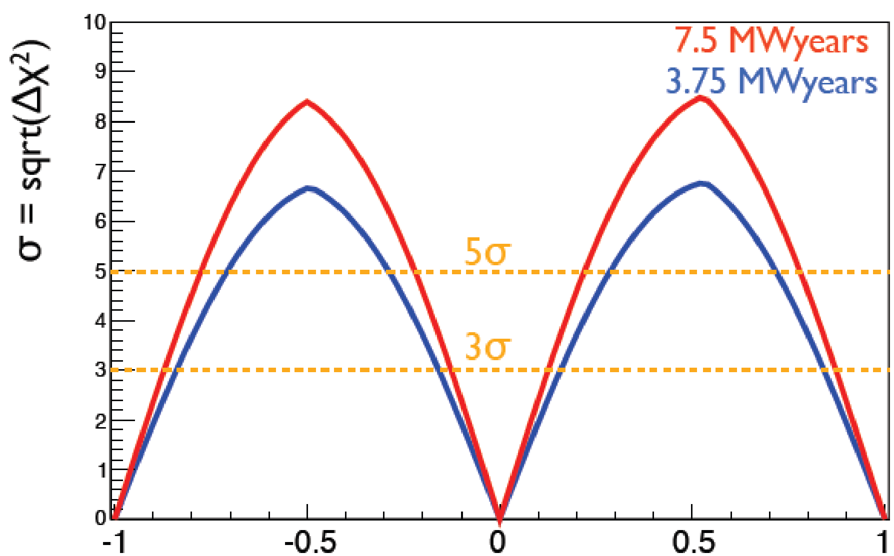


# Hyper Kamiokande Sensitivity

- Assume 3 year neutrino / 7 years anti neutrino.
  - 5% systematics
- Good sensitivity to CP
  - 77% (55%) coverage at 3 (5) sigma.
  - Aim to access to Mass Hierarchy though joint analysis with atmospheric neutrinos and other experiments.
- Rich physics program of proton decay, extraterrestrial and atmospheric neutrinos.



# Comments on the long baseline program

- The discovery of large $\theta_{13}$ has condensed the options for the next generation of long baseline experiments.
- $5\sigma$ measurement of the mass hierarchy and significant regions of the CP violating phase are possible.
- Mixing measurements should be made at high precision to test the 3 neutrino mixing paradigm.
- Experiments and facilities should be designed for further extension to future experiments, should the data guide us in that direction.
- Experiments to measure neutrino cross sections and hadron production will also be required and will play a key role in these measurements.

# Conclusions

- Discovery of $\theta_{13}$ signposts the next steps for long baseline neutrino experiments.
- There is an experimental program that will take us to ~2020
- To allow for clear and unambiguous discoveries we need to next generation experiments
  - Need to push forward with these steps.