Recent Progress in Neutrino Physics

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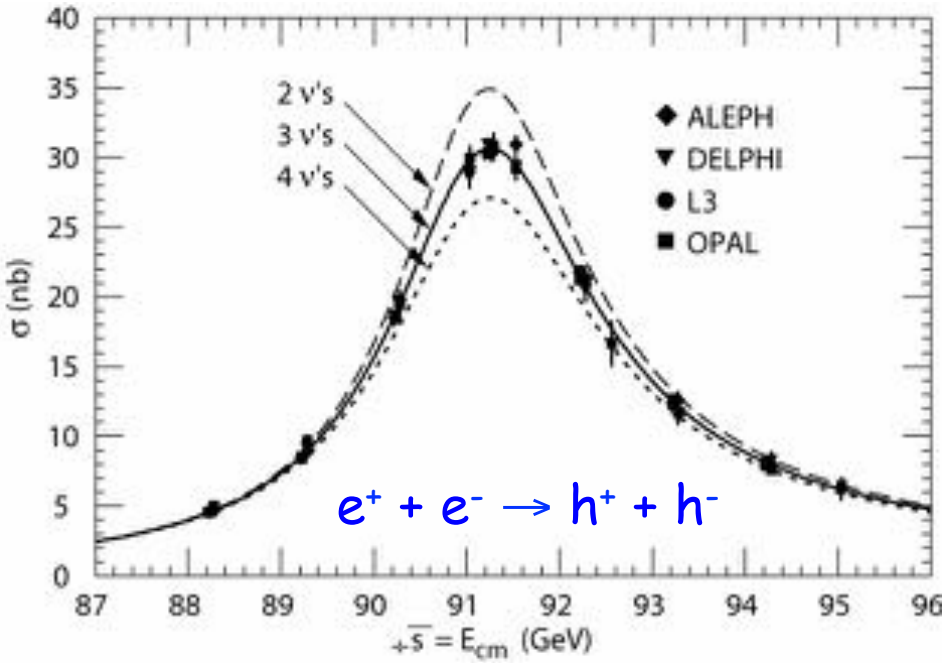
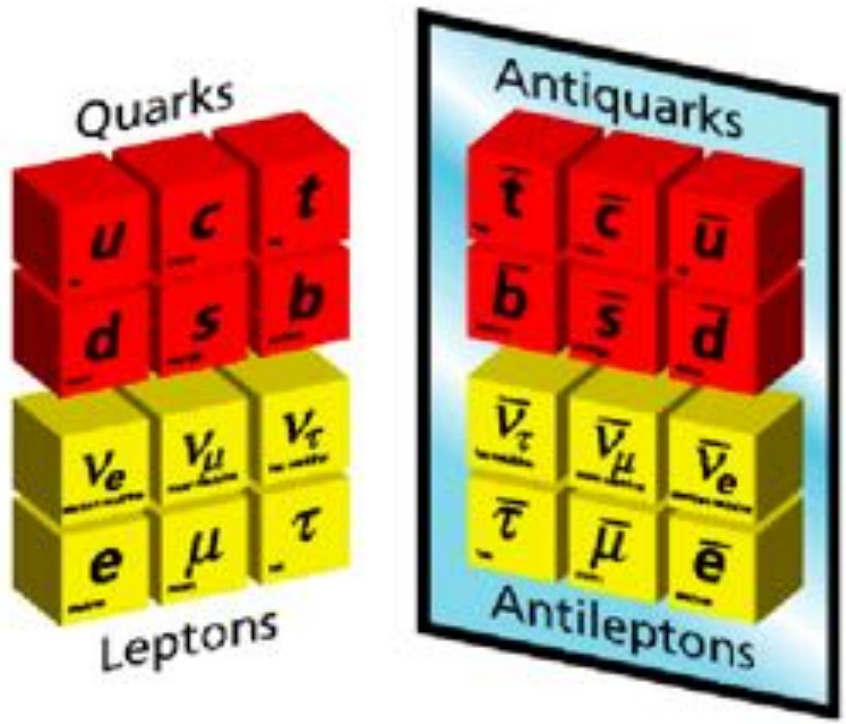
Jeju, Korea, 22 June 2016

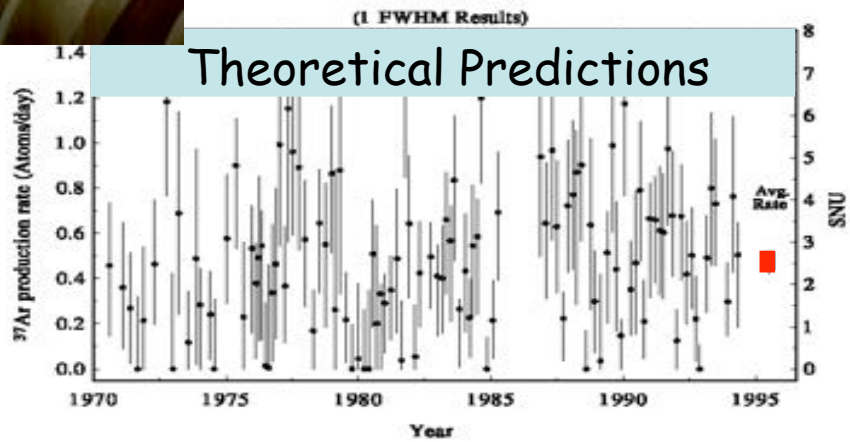
Standard Model Of Particle Physics





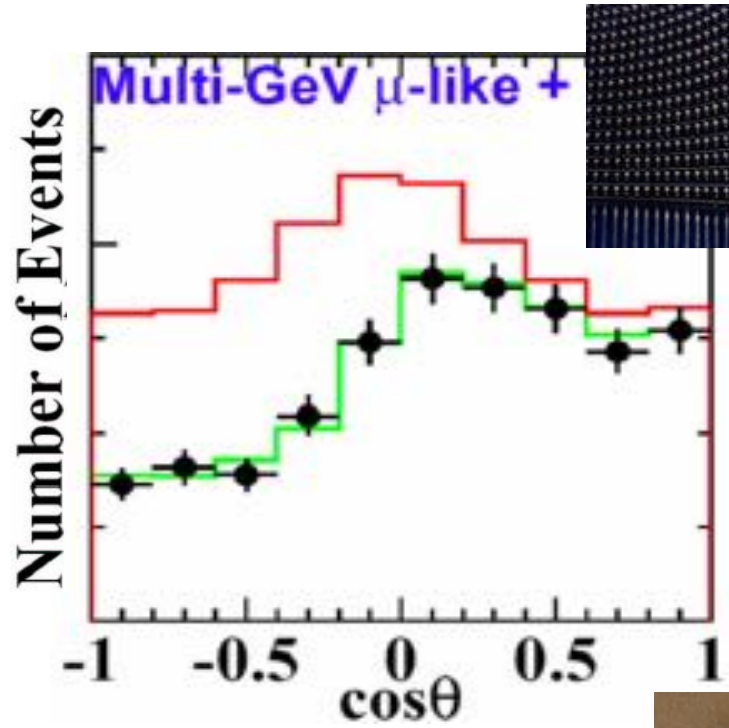
- Three types of massless neutrinos in the Standard Model of particle physics
- Neutrinos only participate in weak interactions.

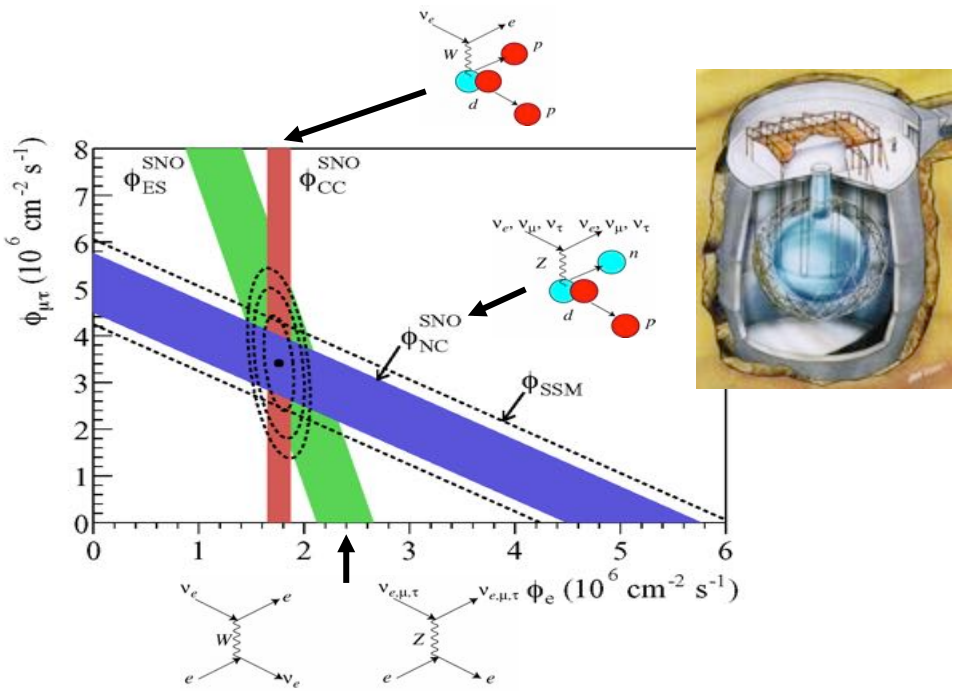
Discoveries of Neutrino Oscillation

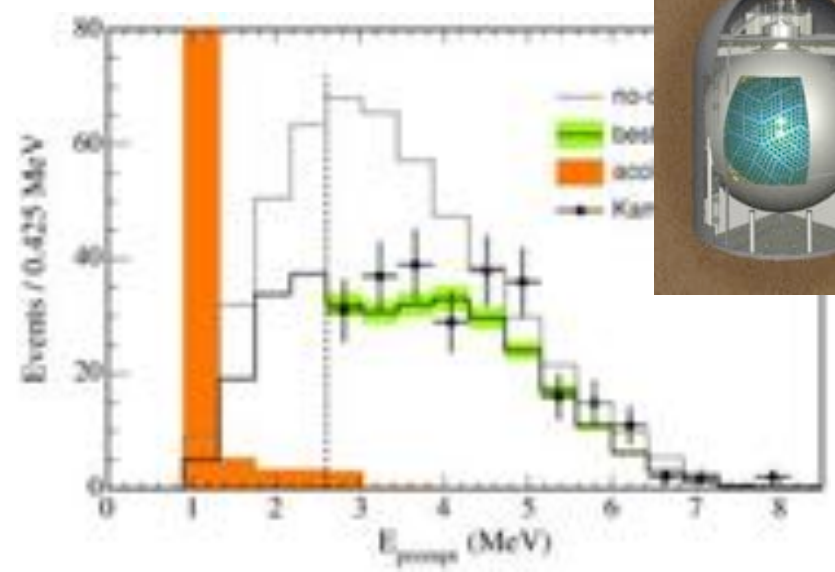


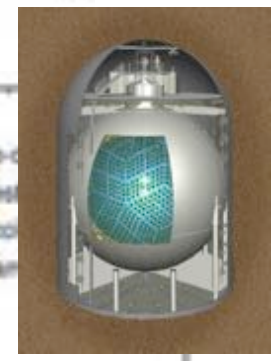
Theoretical Predictions

1 SNU = 10^{-36} interaction/atom/s









Neutrino Mixing

Weak eigenstates ≠ mass eigenstates

Neutrinos have mass → Physics beyond SM ?

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix

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

Weak eigenstates

ν_e ν_μ ν_τ

Described by

θ_{12} θ_{23} θ_{13}

δ

Mass eigenstates

m_1 m_2 m_3

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

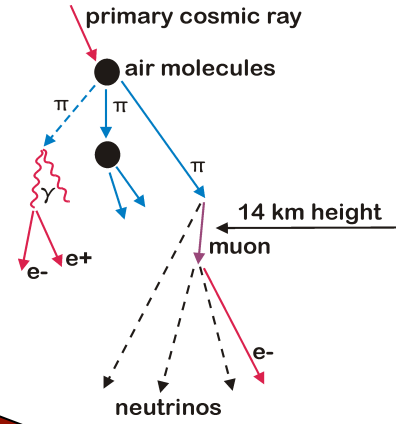
Normal Hierarchy: $\Delta m_{32}^2 > 0$

Inverted Hierarchy: $\Delta m_{32}^2 < 0$

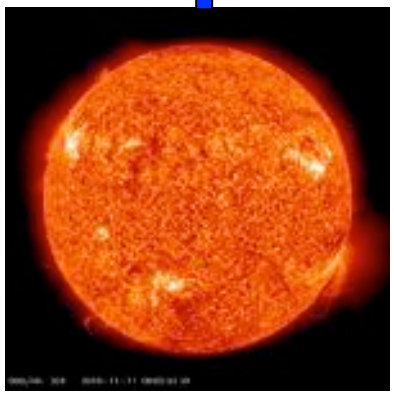
Mixing Angles & CP Phase

accelerator ν

atmospheric ν



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



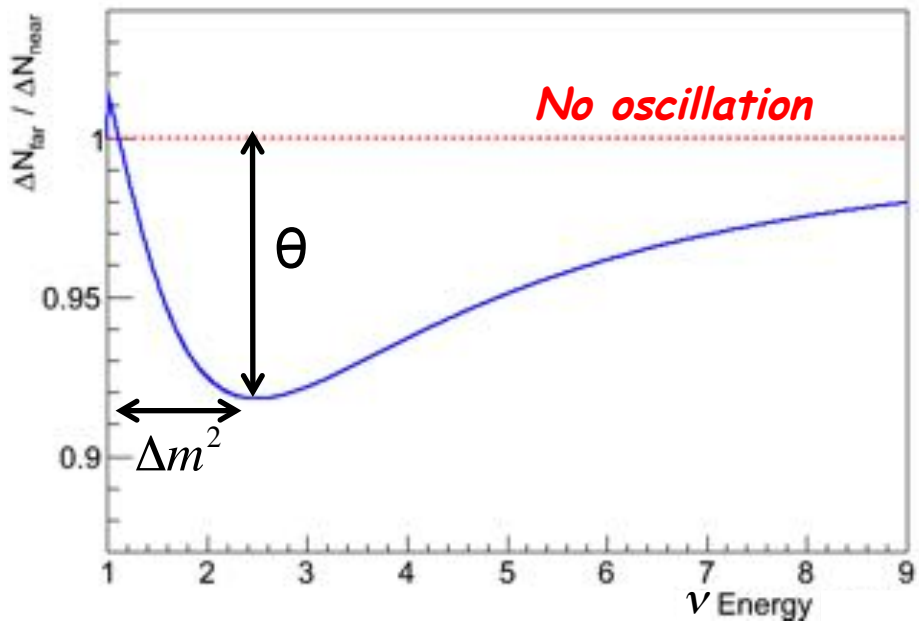
solar ν

reactor $\bar{\nu}$

Neutrino-oscillation Experiments

- Disappearance measurements:

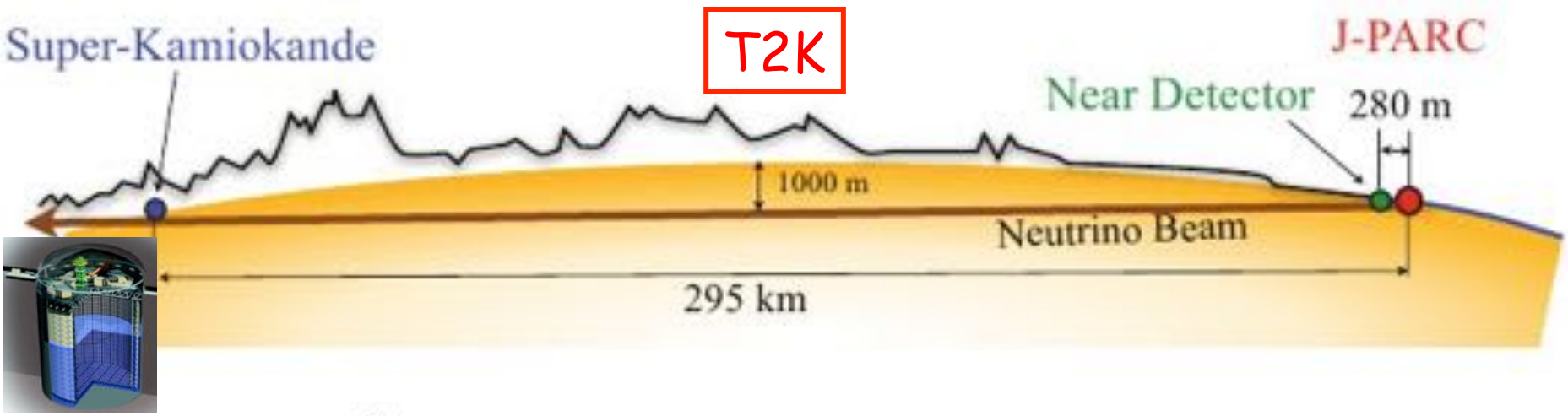
$$P(\nu_\alpha \to \nu_\alpha) \sim 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

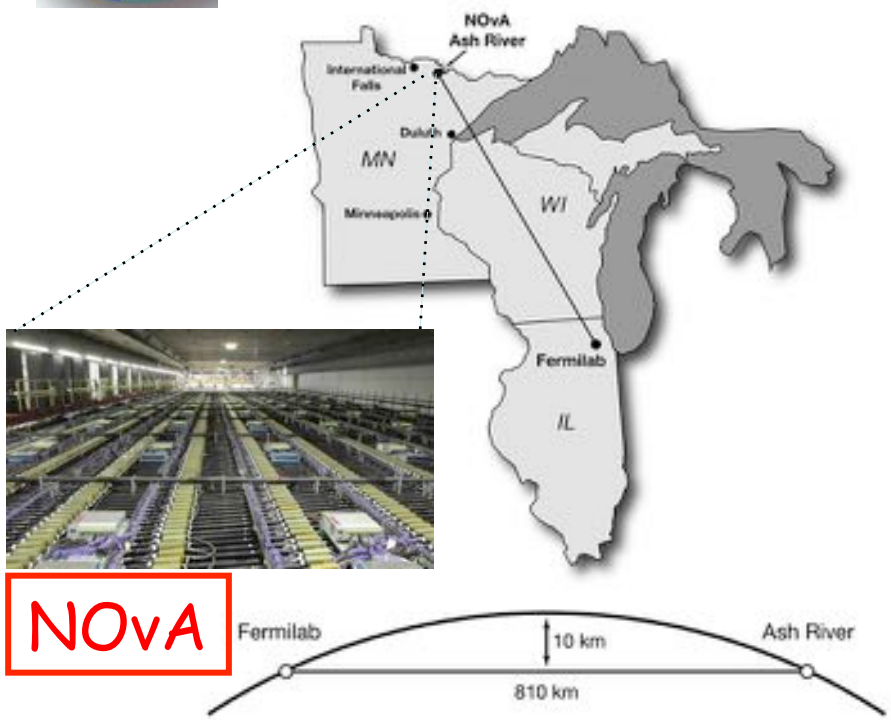


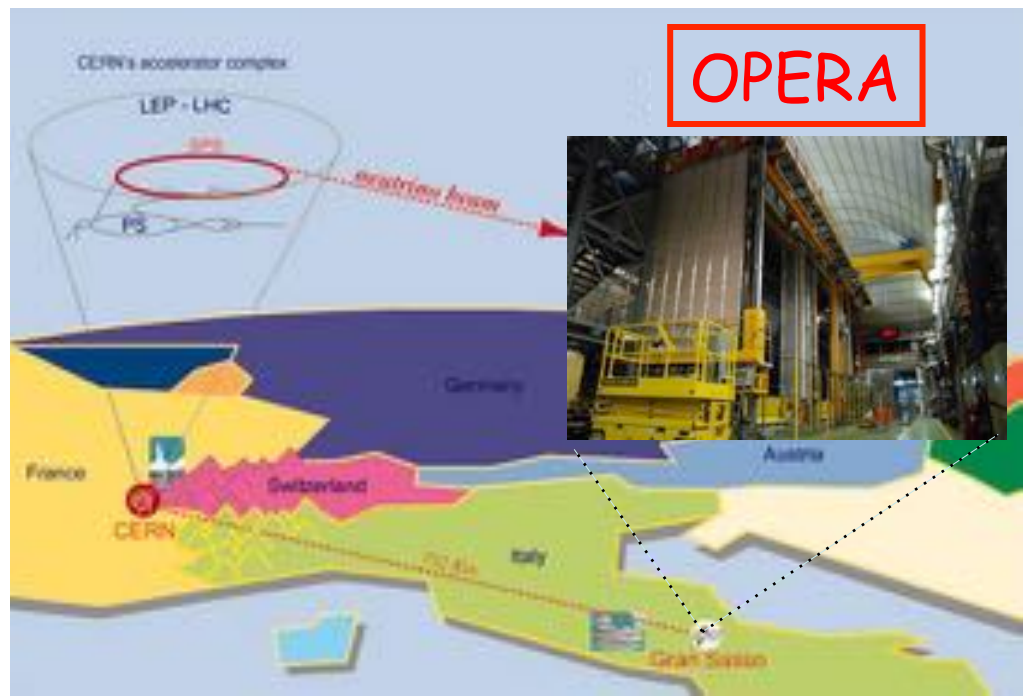
- Appearance measurements:

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

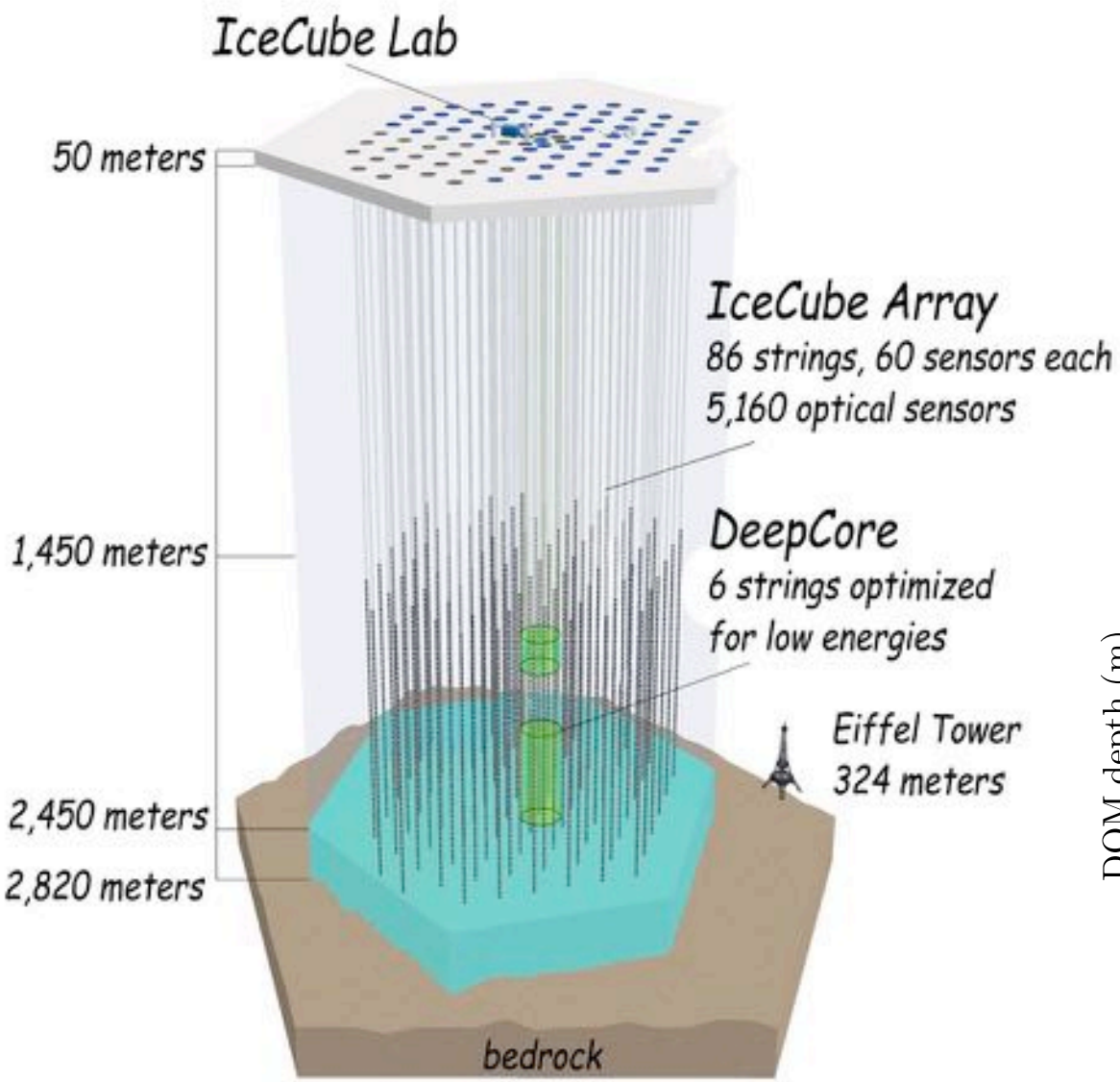
Accelerator-based Experiments

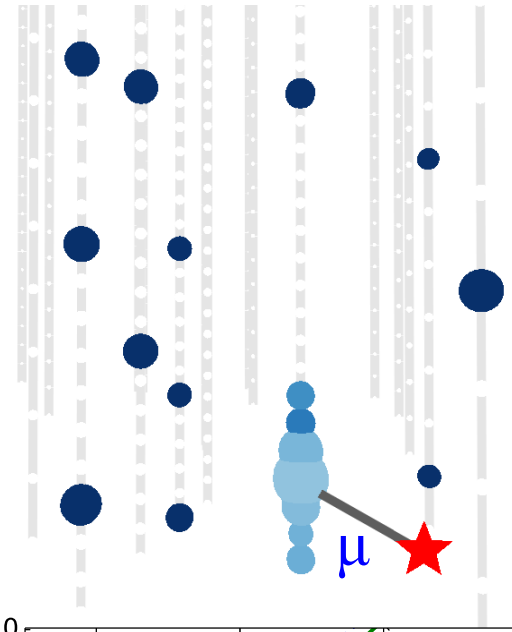


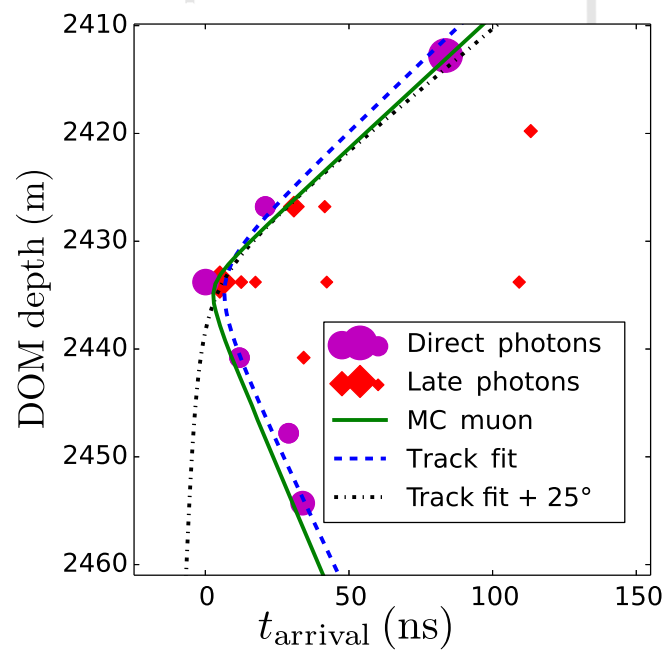




Atmospheric ν_μ Experiment

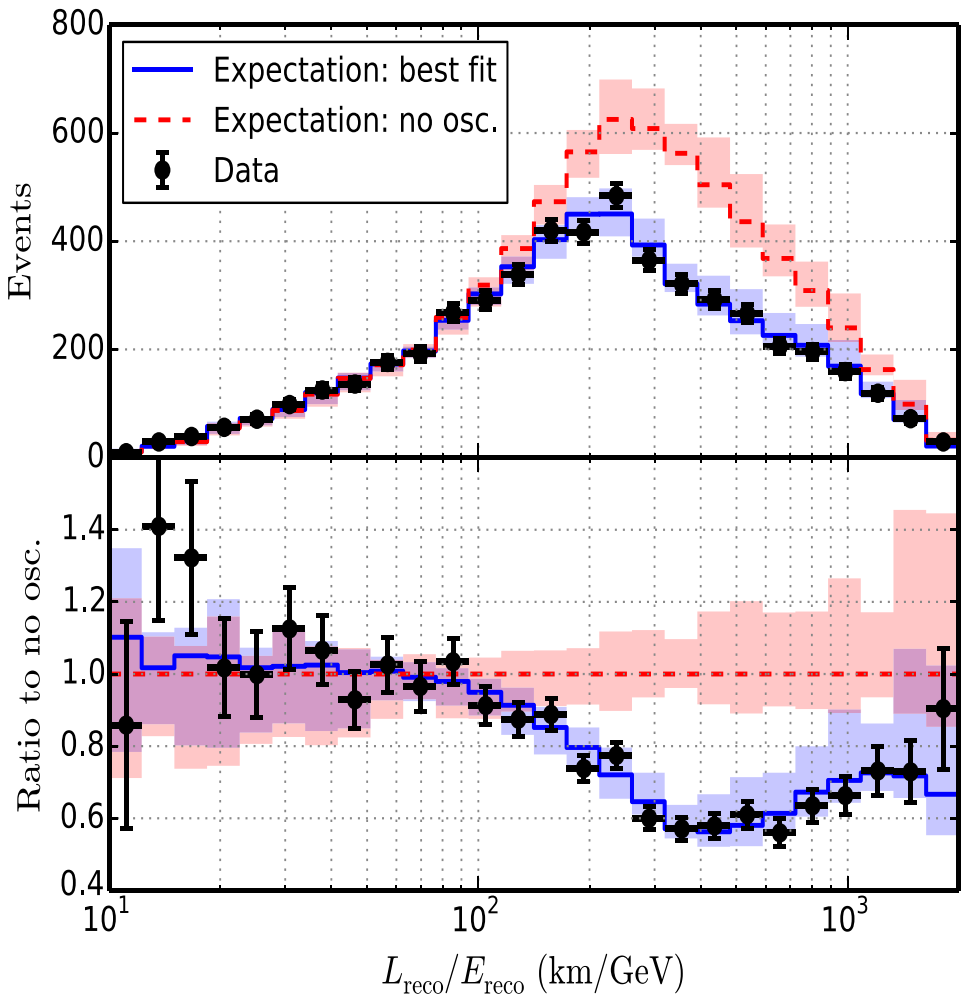




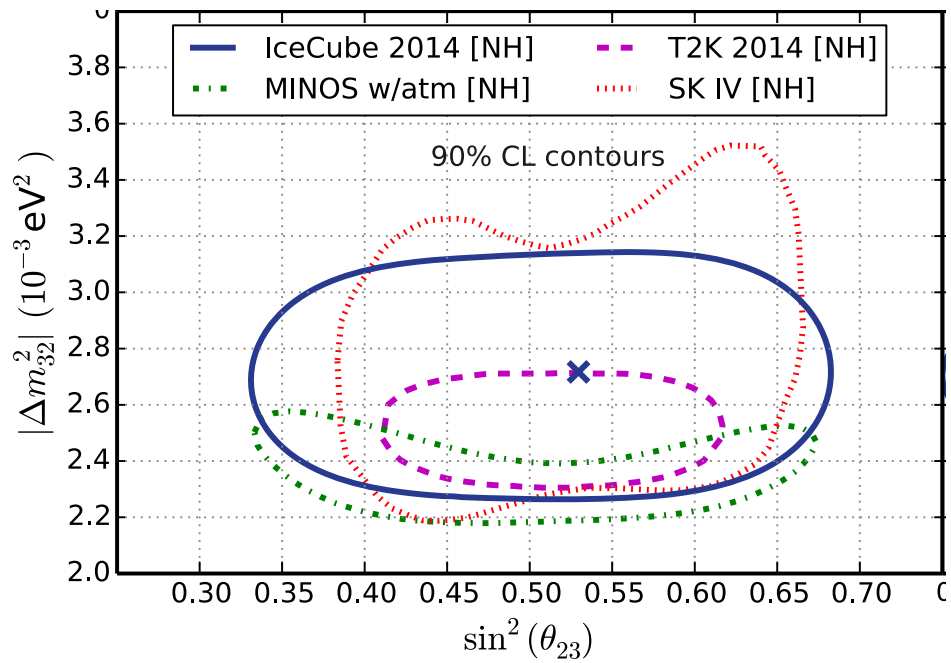


Disappearance of Atmospheric ν_μ

IceCube-DeepCore: 3 years of data



PRD 91, 072004 (2015)



Best-fit values:

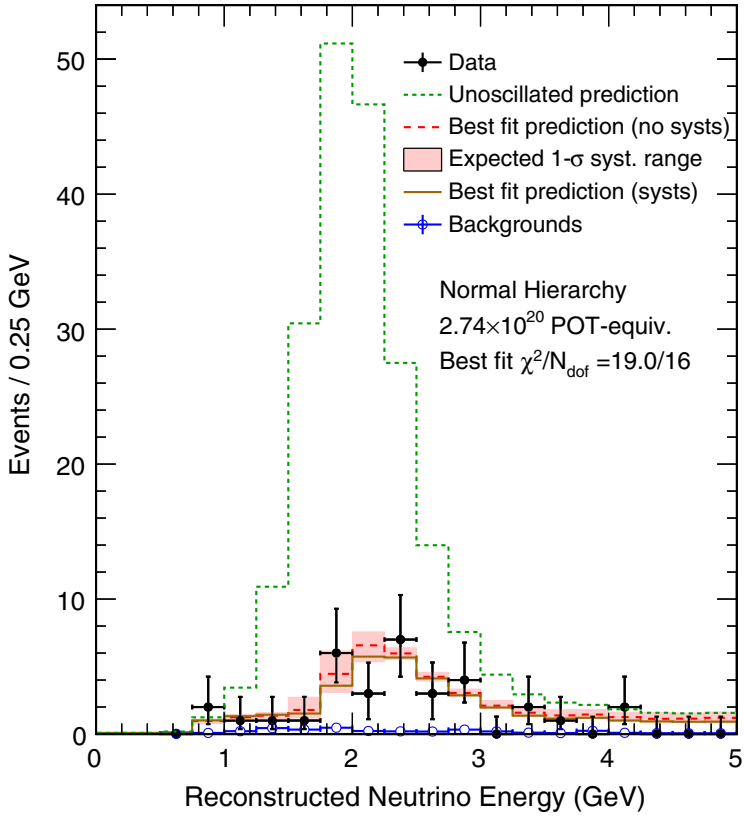
$\sin^2\theta_{23} = 0.53^{+0.09}_{-0.12}$

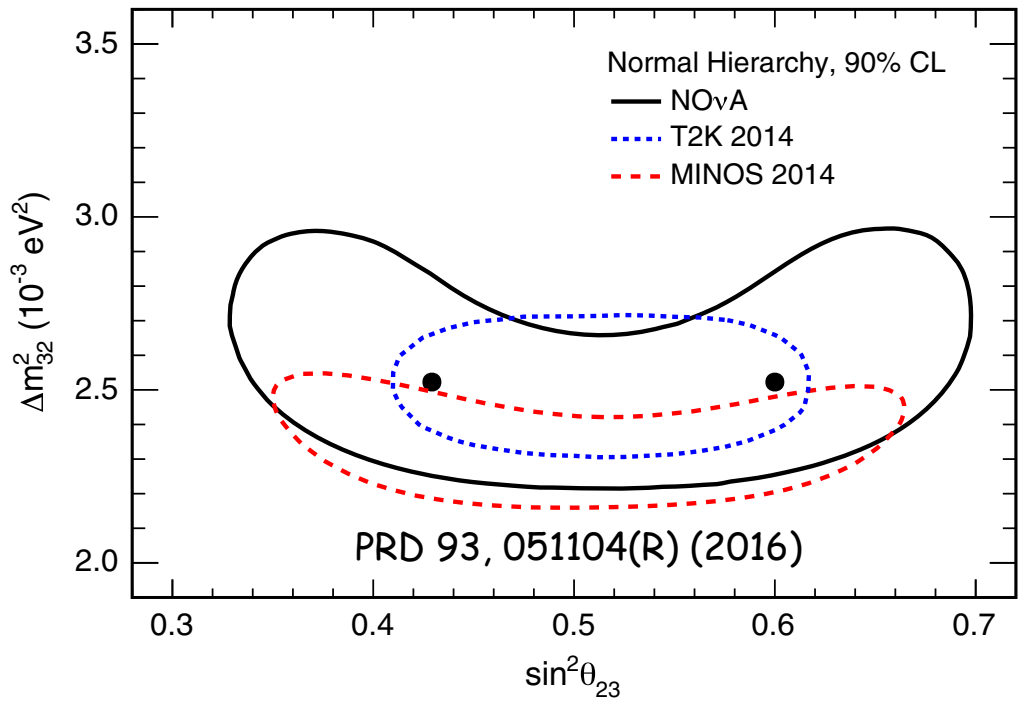
$\Delta m^2_{32} = (2.72^{+0.19}_{-0.20}) \times 10^{-3}$ eV^2

Disappearance of ν_μ

Based on 7.6% of planned exposure:

Obtained 33 events but expected 211.8±12.5 if no oscillation



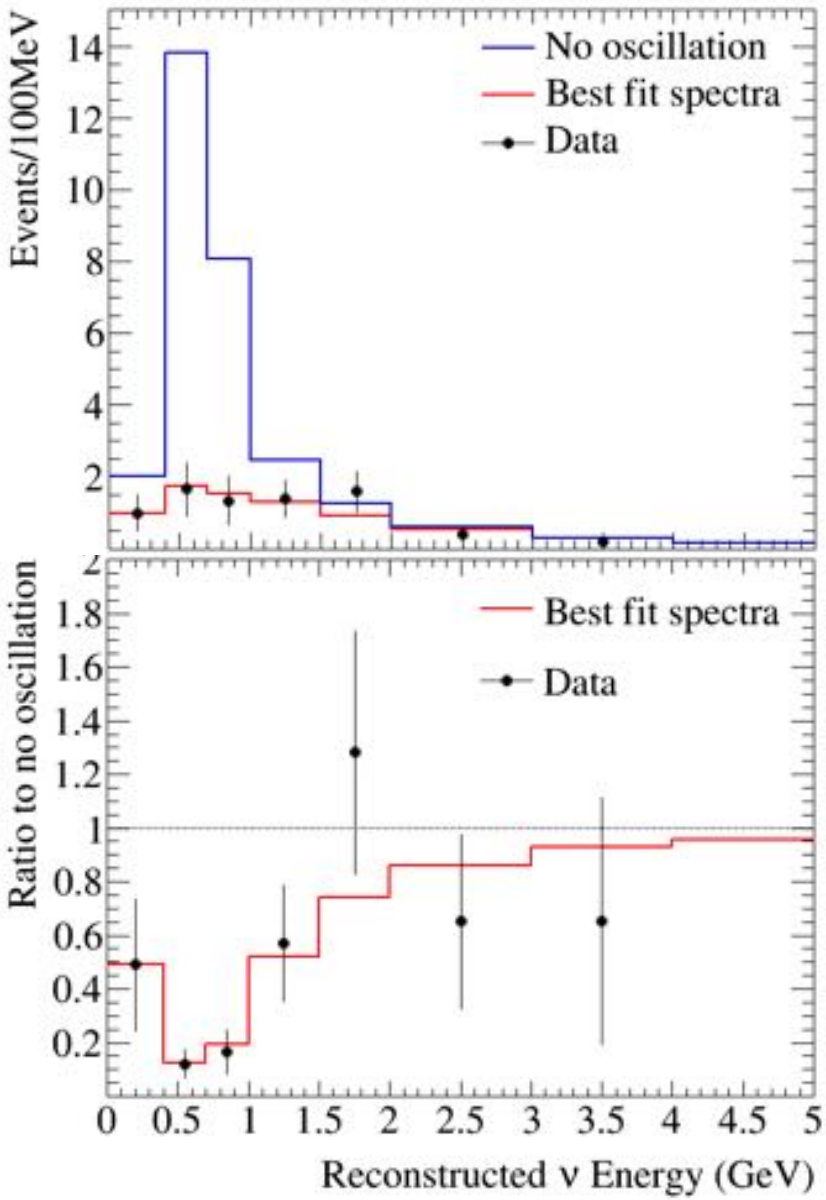


Best-fit values of θ_{23} and Δm^2_{32}:

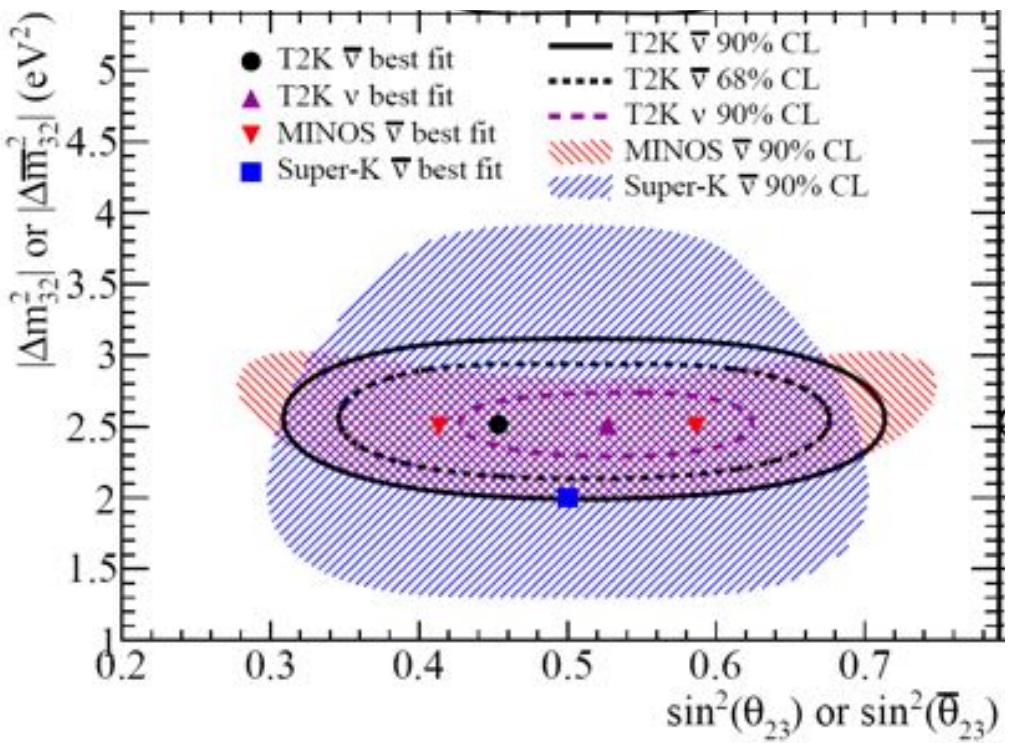
	$\sin^2\theta_{23}$	Δm^2_{32} (x 10^{-3} eV^2)
Normal Hierarchy	0.43 or 0.60	$2.52^{+0.20}_{-0.18}$
Inverted Hierarchy	0.44 or 0.59	-2.56 ± 0.19

Disappearance of Accelerator $\bar{\nu}_\mu$

Nielsen (T2K), 14 March 2016



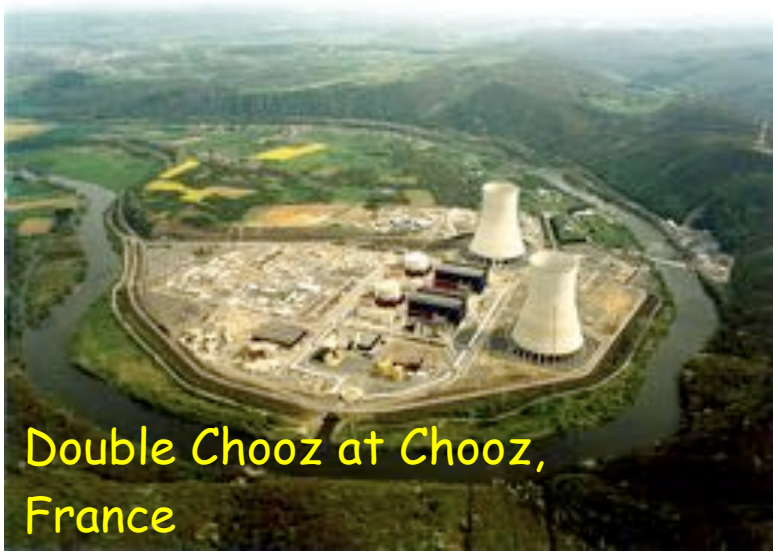
- 4 x 10^{20} protons on target
- Found 34 $\bar{\nu}_\mu$ candidates



$$\sin^2\bar{\theta}_{23} = 0.45^{+0.19}_{-0.07}$$

$$|\Delta\bar{m}^2_{32}| = 2.51^{+0.29}_{-0.26} \times 10^{-3}\ \mathrm{eV}^2$$

Reactor-based Experiments



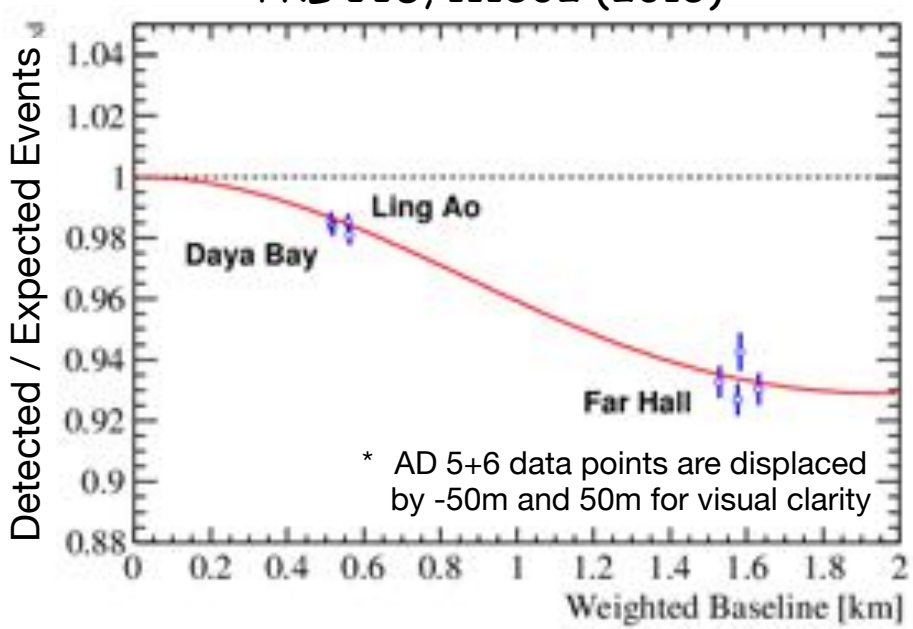
Experiment	Reactor Power (GW_{th})	Flux-weighted Baseline (m) Near/Far	Target mass (t) Near/Far	Overburden (mwe) Near/Far
Daya Bay	17.4	(470,576)/1650	(40,40)/80	(250,265)/860
Double Chooz	8.5	400/1050	8.3/8.3	120/300
RENO	16.5	409/1444	16.5/16.5	120/450

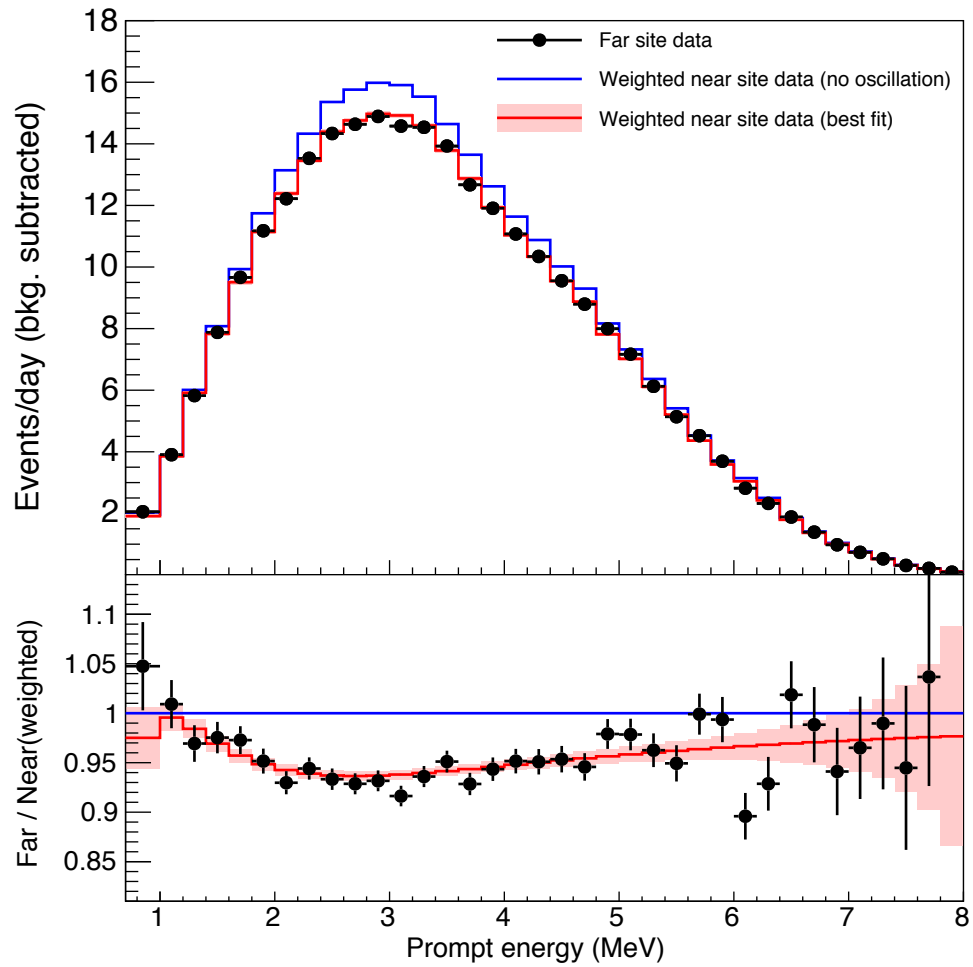
Rate+Spectral Analysis (2015)

Collected >10^6 $\bar{\nu}_e$ reactions using n-Gd capture with 6 & 8 ADs

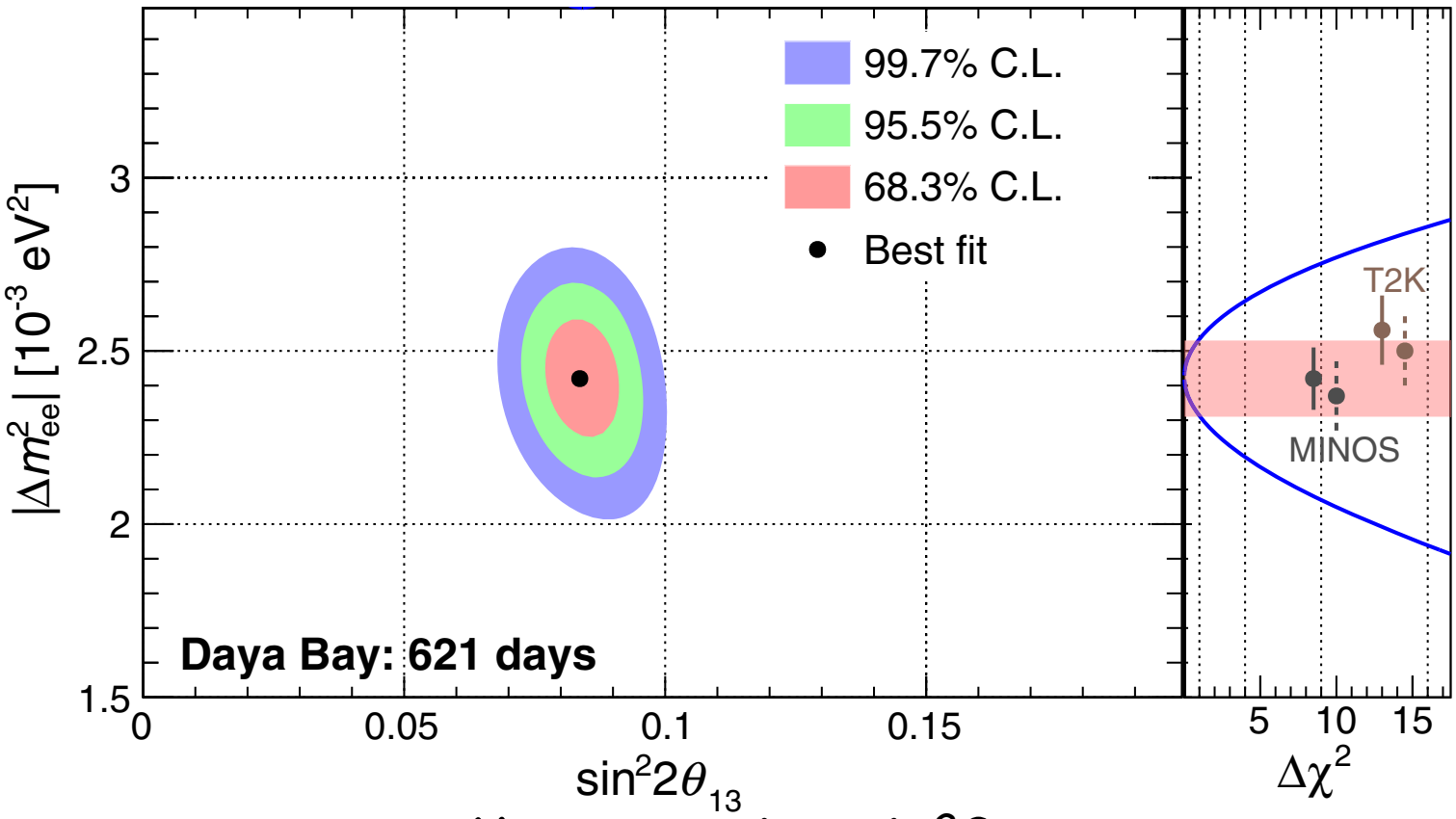
- Over 150,000 IBD events at the far hall

PRL **115**, 111802 (2015)





Latest Results on $\sin^2 2\theta_{13}$ and Δm^2_{ee}



Support 3-flavour paradigm

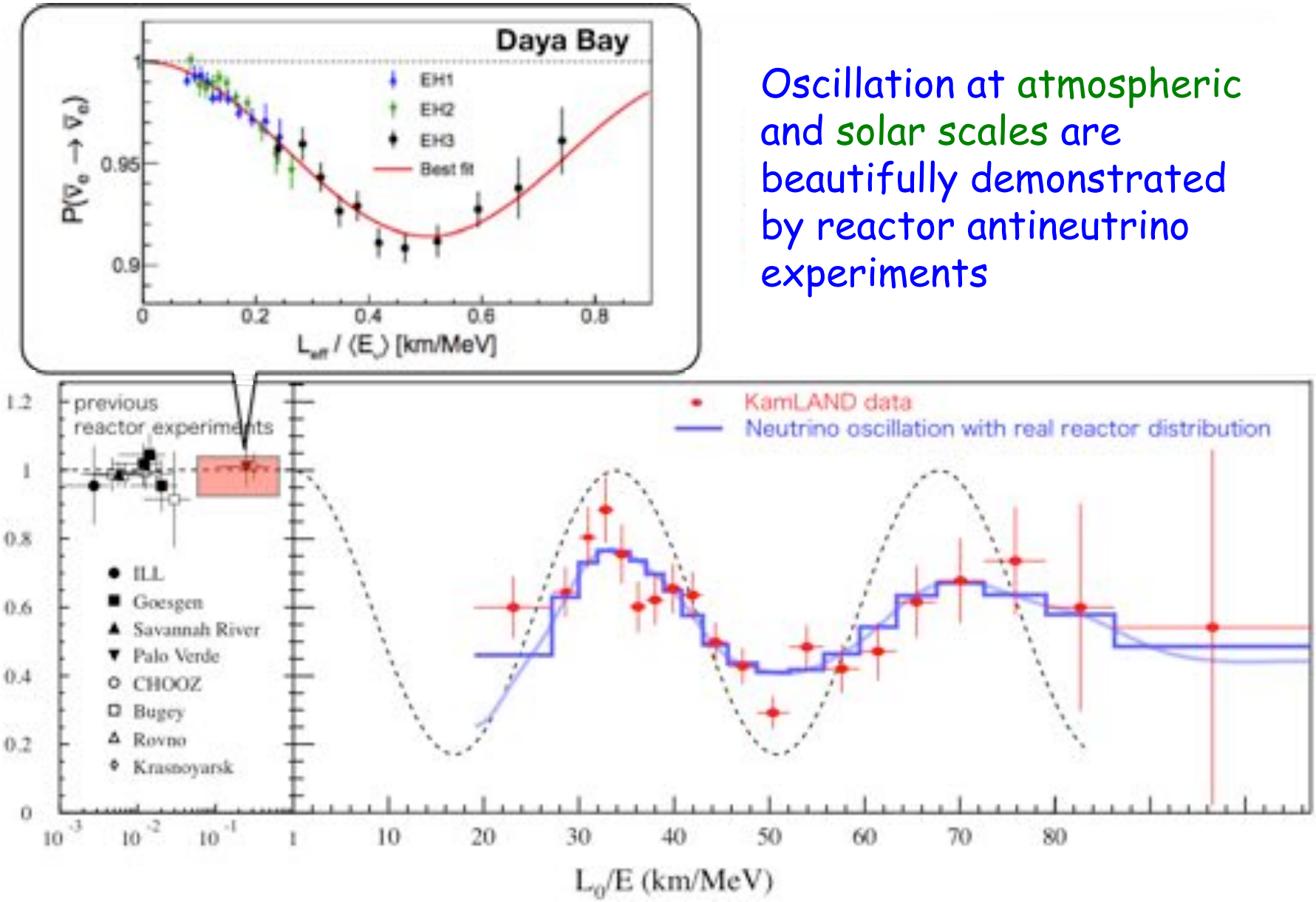
- Most precise $\sin^2 2\theta_{13}$:

  $\sin^2 2\theta_{13} = 0.084 \pm 0.005$

- Most precise $|\Delta m^2_{ee}|$:

  $|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}$ eV^2

Unambiguous Oscillation Pattern

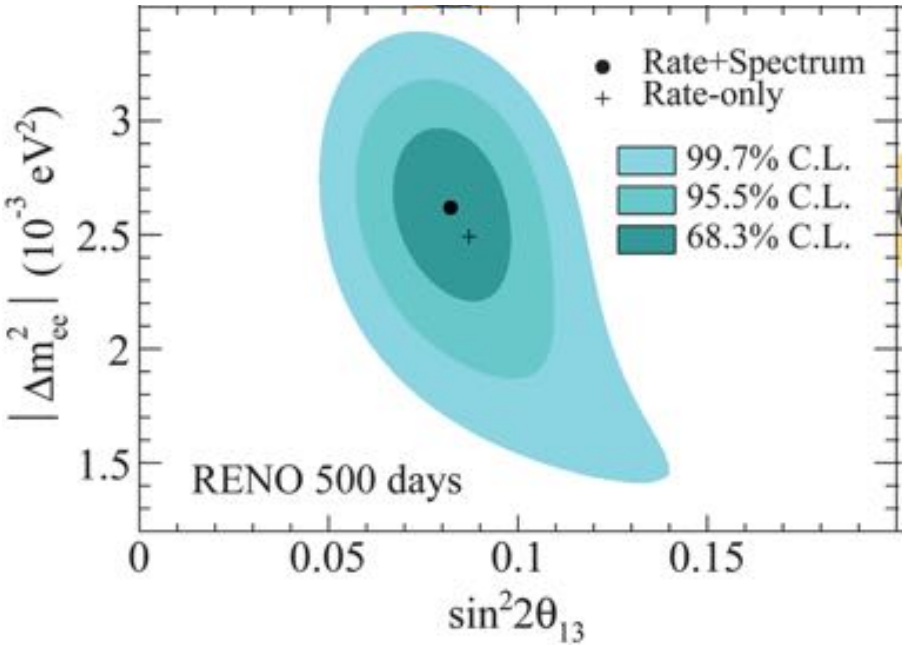


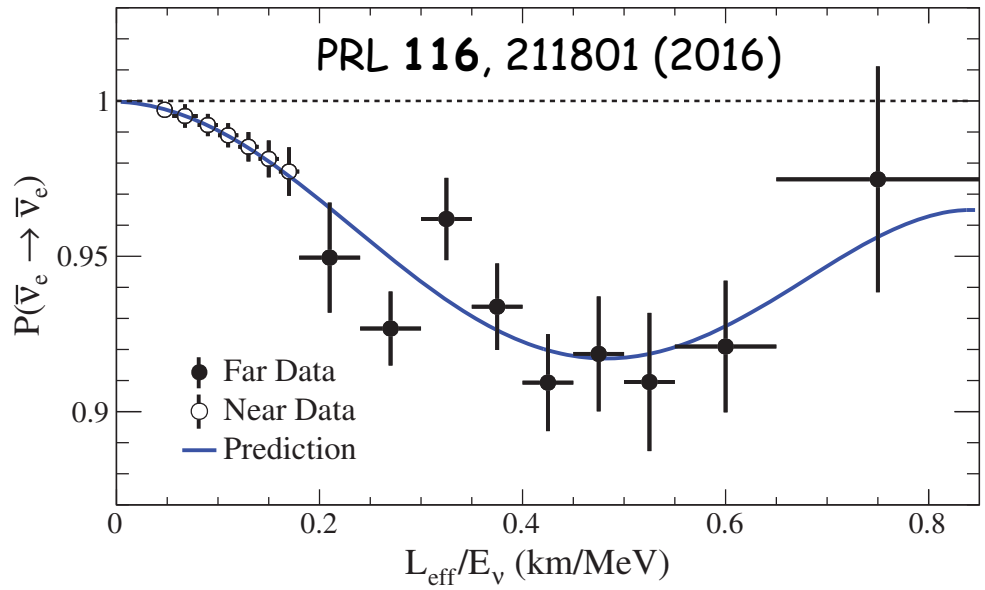
Oscillation at atmospheric and solar scales are beautifully demonstrated by reactor antineutrino experiments

Latest n-Gd Results on Oscillation

Based on 500 days of events with n-Gd capture

- 291k events (3% bkgd) in near site & ~32k (5% bkgd) in the far hall



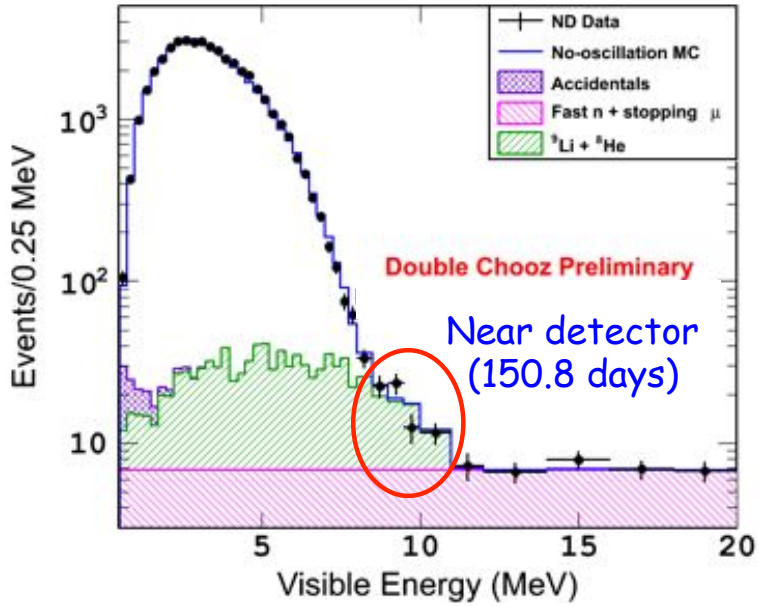


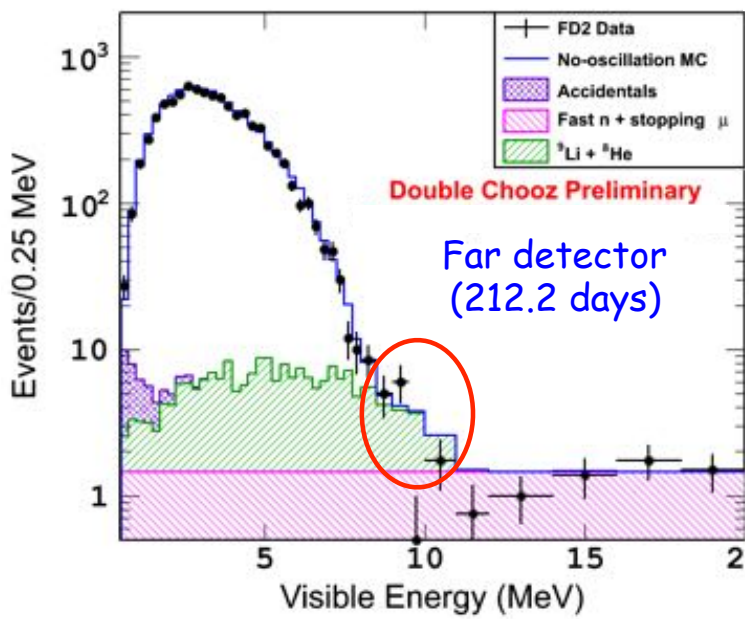
$$\sin^2 2\theta_{13} = 0.082 \pm 0.009\,(\text{stat}) \pm 0.006\,(\text{syst})$$

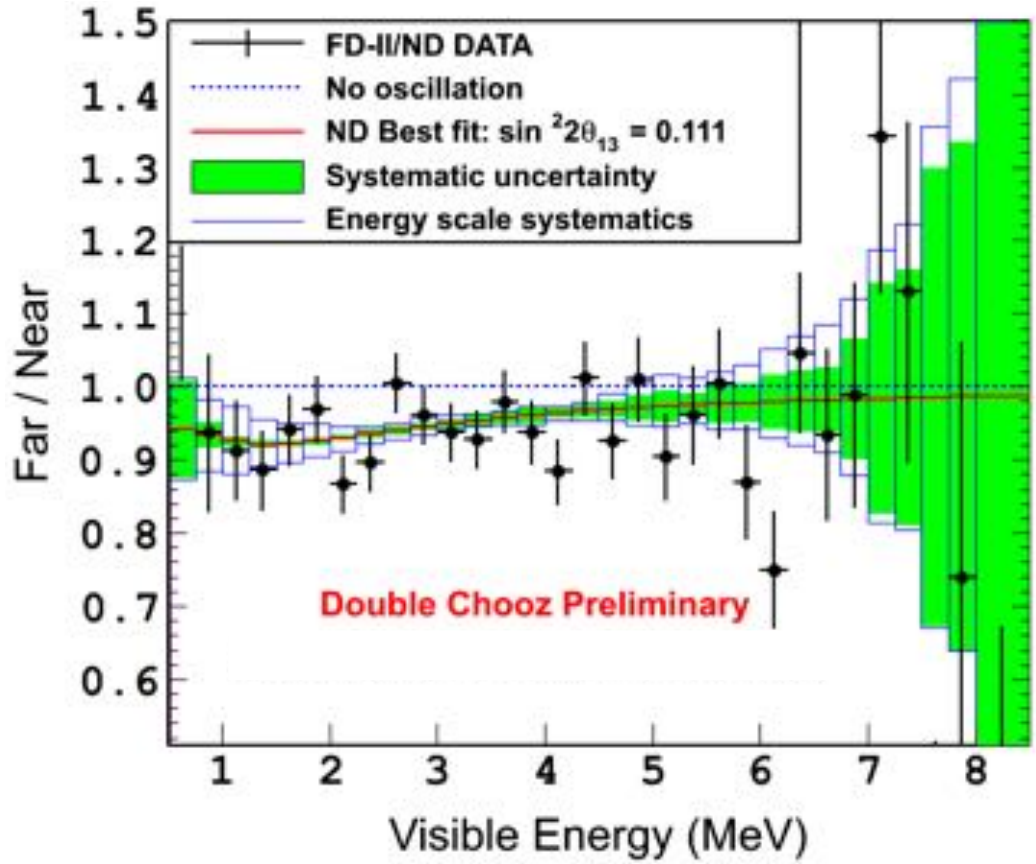
$$|\Delta m^2_{ee}| = [2.62^{+0.21}_{-0.23}\,(\text{stat})^{+0.12}_{-0.13}\,(\text{syst})] \times 10^{-3}\ \text{eV}^2$$

First Result Using Near-Far Detectors

Cabrera: FNAL seminar, 15 Mar 2016



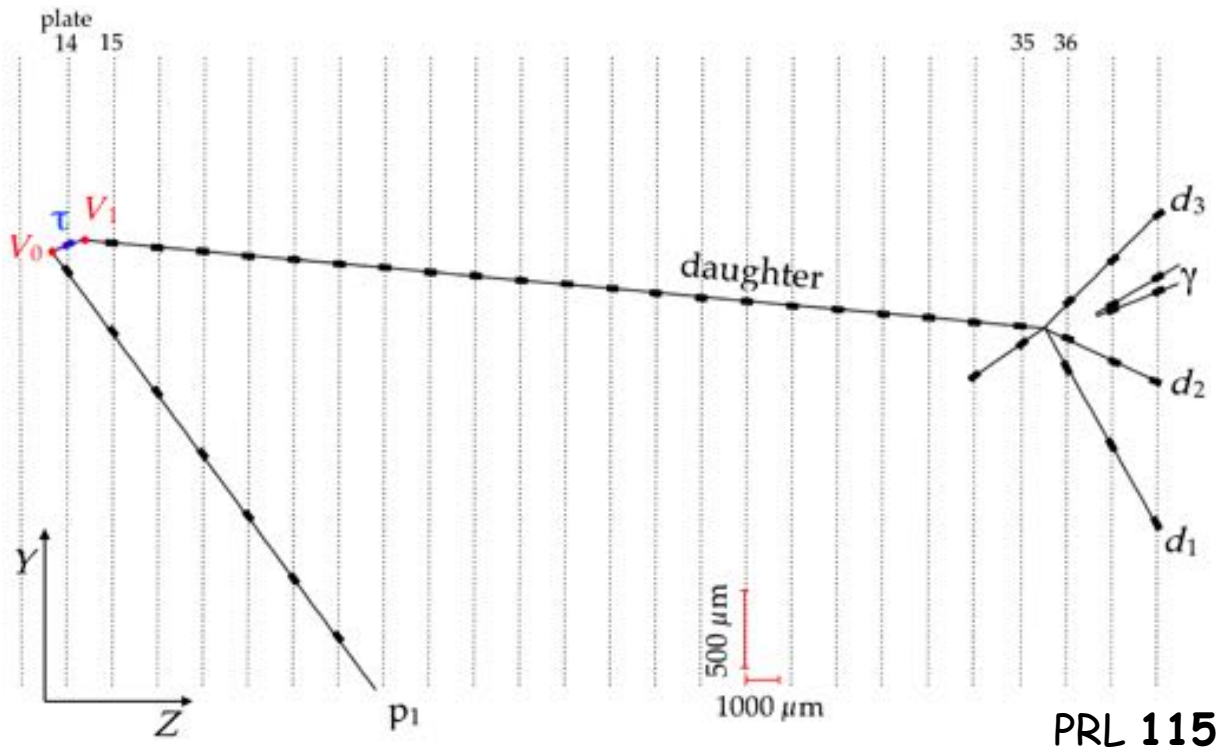




DC $\sin^2 2\theta_{13} = 0.111 \pm 0.018$

c.f.: DyB $\sin^2 2\theta_{13} = 0.084 \pm 0.005$

OPERA: Evidence of $\nu_\mu \rightarrow \nu_\tau$

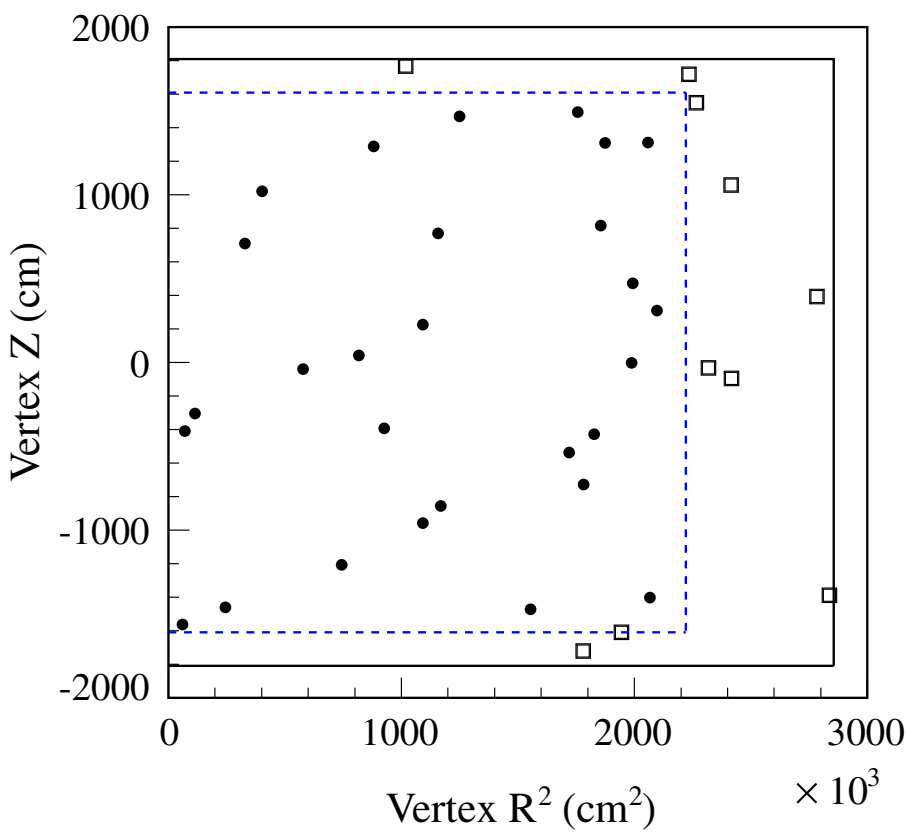


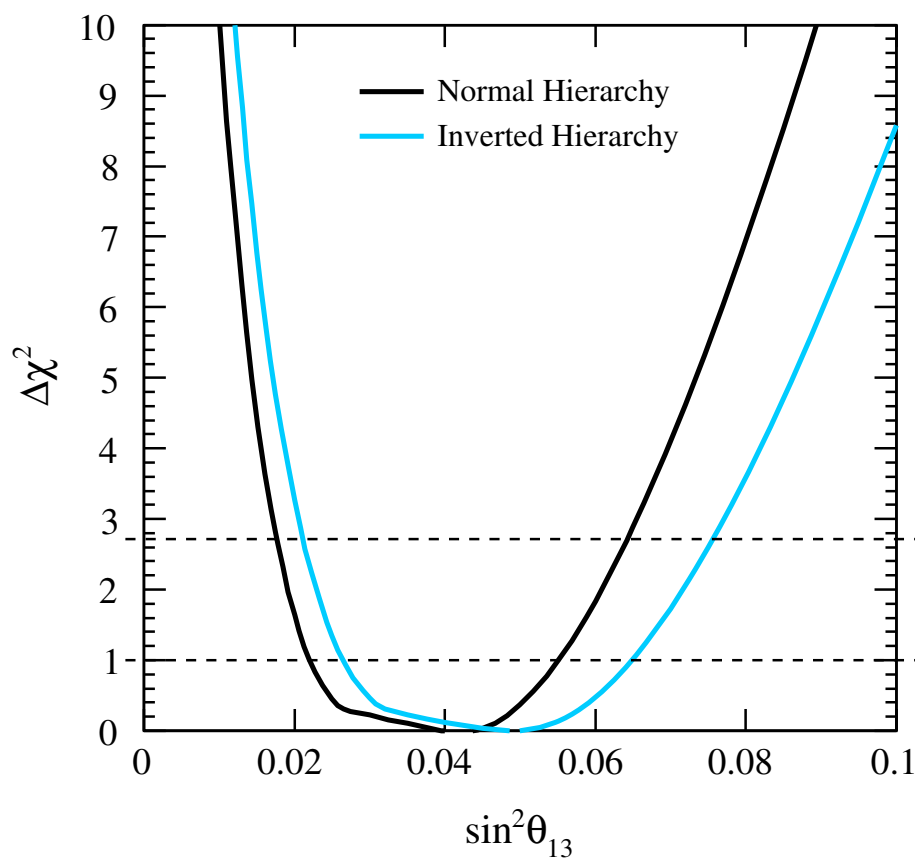
PRL **115**, 121802 (2015)

Mode	Background	Expect	Detected
$\tau \rightarrow 1h$	0.04±0.01	0.52±0.10	3
$\tau \rightarrow 3h$	0.17±0.03	0.73±0.14	1
$\tau \rightarrow \mu$	0.004±0.001	0.61±0.12	1
$\tau \rightarrow e$	0.03±0.01	0.78±0.16	0
Total	0.25±0.05	2.64±0.53	5

Evidence of $\nu_\mu \rightarrow \nu_e$

- Observed 28 ν_e events
  - expected ~5 if $\theta_{13} = 0$
  - unambiguous observation of ν_e appearance (>7 s.d.)

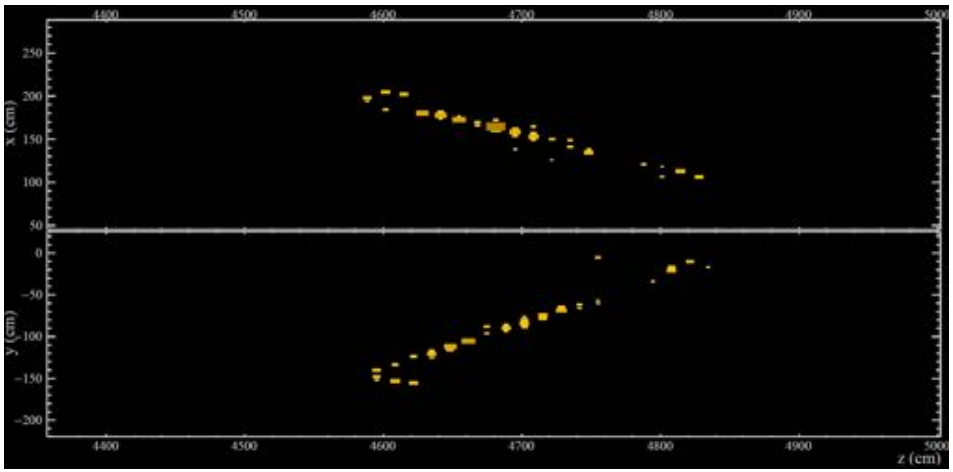


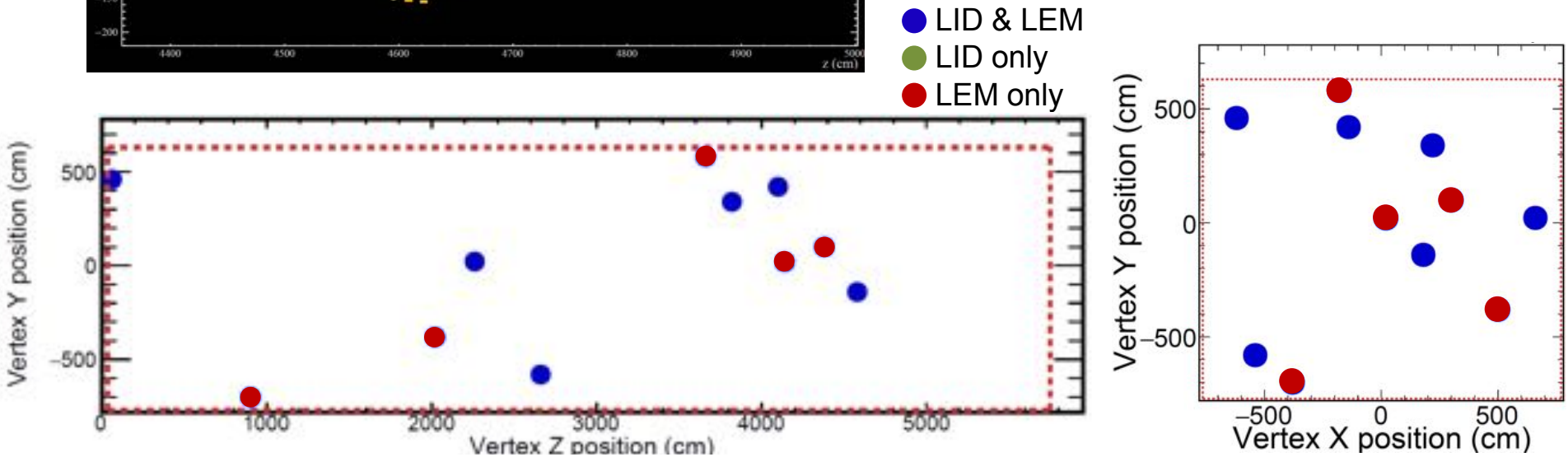


PRD **91**, 072010 (2015)

Further Evidence of $\nu_\mu \rightarrow \nu_e$

1. LID (Likelihood Identification based on dE/dx) yielded 6 events.
2. LEM (Library Event Matching) found 11 events

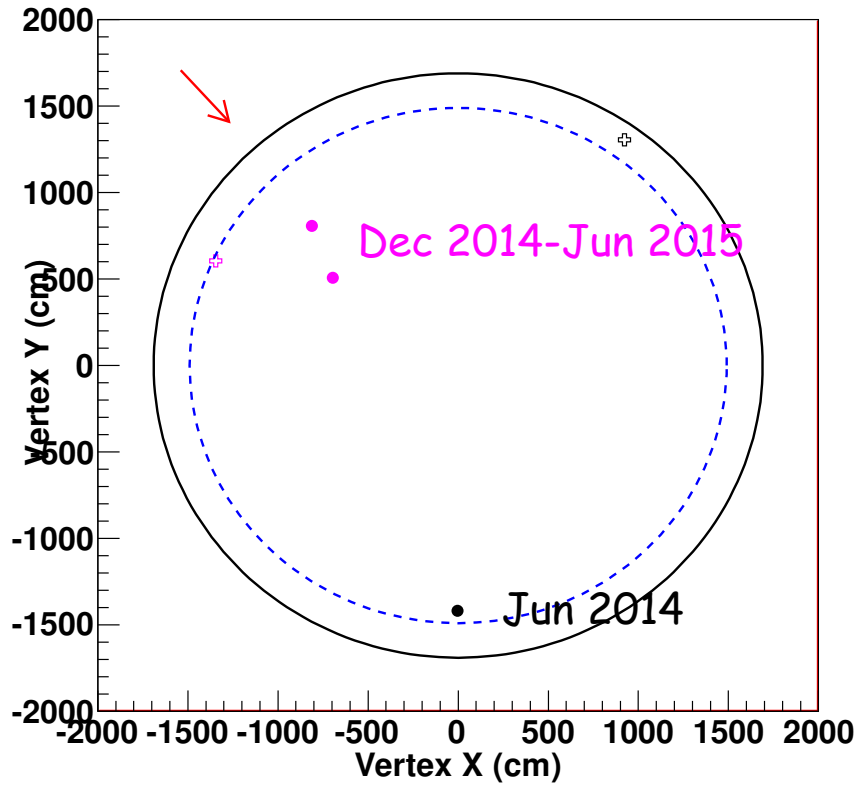




Evidence of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

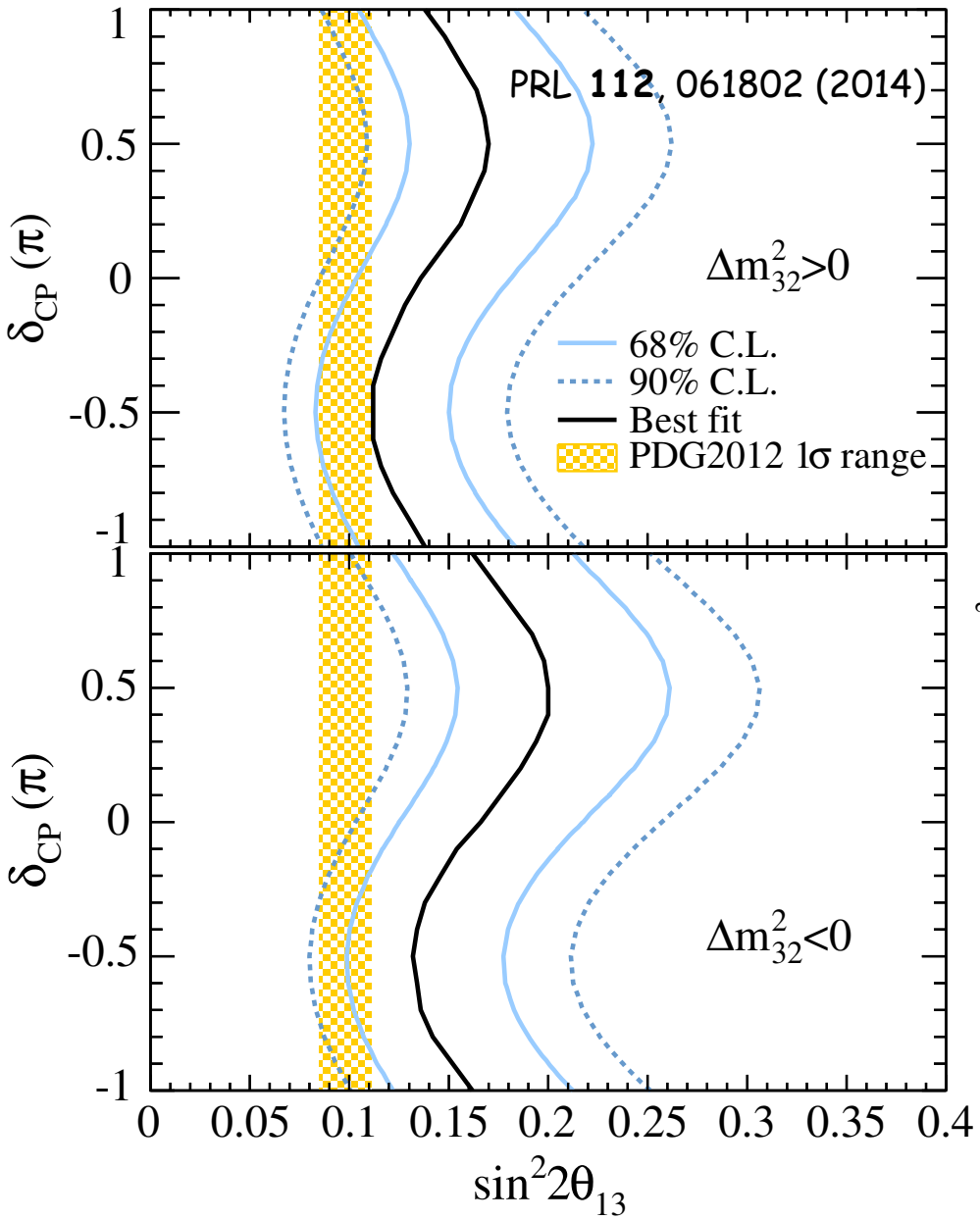
- Observed 3 $\bar{\nu}_e$ events
  - expected ~4, including ~1 background event
  - limited by statistics

anti-ν_e candidates



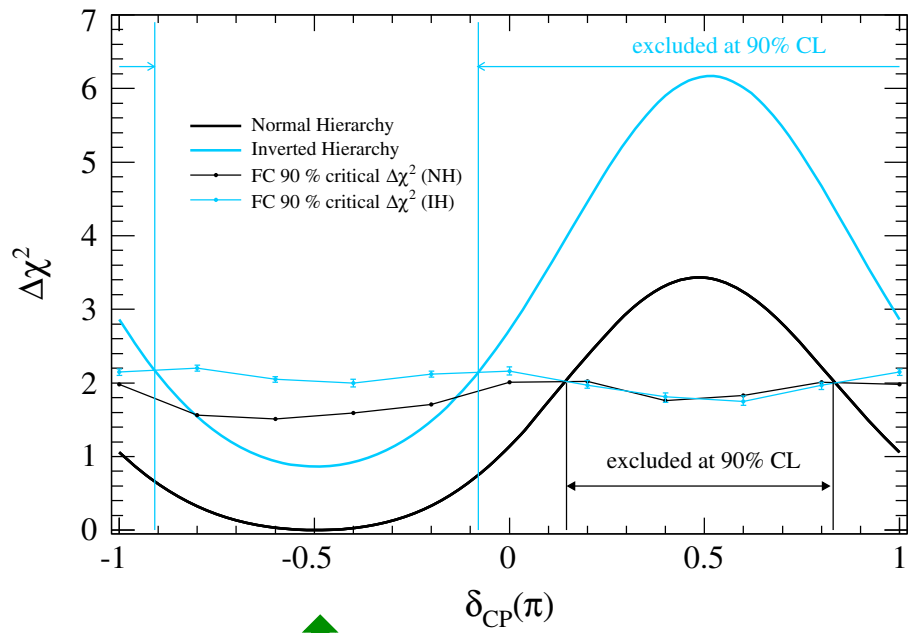
- Expect to obtain x10 more events

Extracting δ



- Used $\sin^2 2\theta_{13} = 0.095 \pm 0.010$ (PDG 2013) to constrain δ_{CP} :

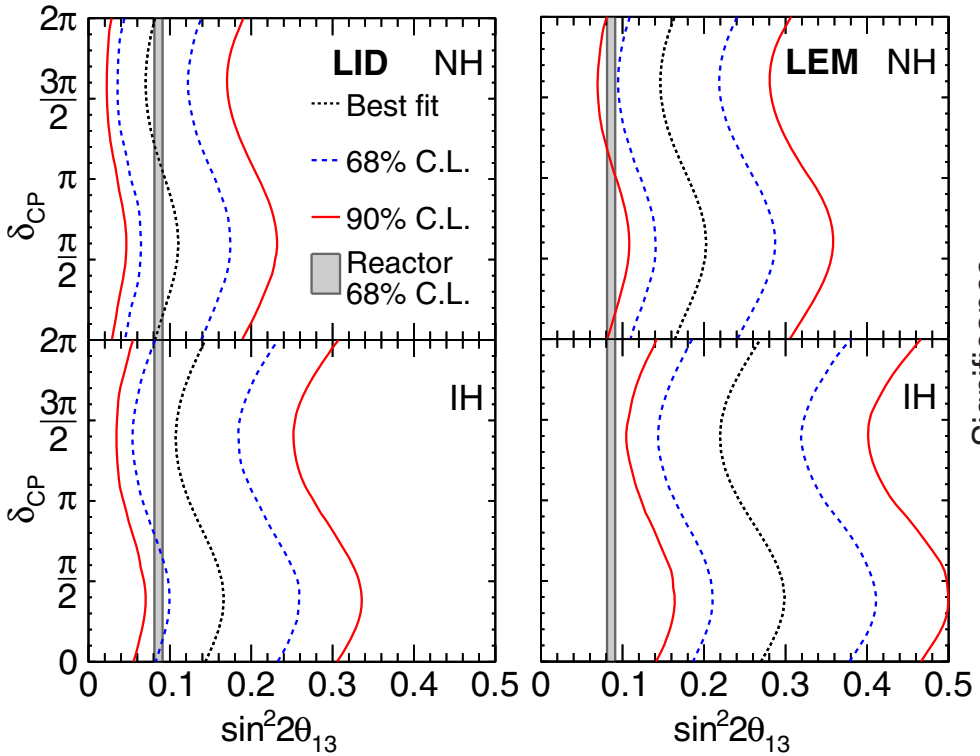
PRD 91, 072010 (2015)

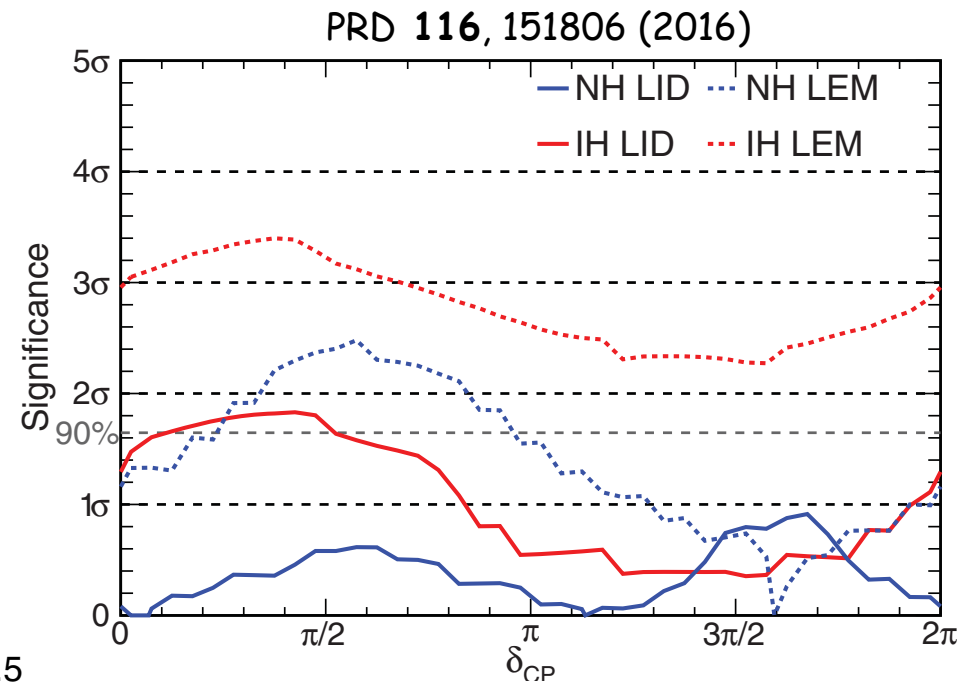


preferred

Another Attempt on δ

- Inputs: $\sin^2 2\theta_{13} = 0.086 \pm 0.005$ and $\sin^2\theta_{23} = 0.5$





- Both LID and LEM samples prefer:
  - Normal hierarchy
  - δ near 3π/2
- Consistent with T2K's results

Mixing Parameters in 2014-2015

- $\sin^2 2\theta_{12} = 0.846 \pm 0.021$ (solar, reactor and accelerator)
- $\sin^2 2\theta_{13} = 0.093 \pm 0.008$
  - $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ (Daya Bay 2015)
  - Is θ_{13} obtained with accelerators really larger than the one determined with reactors?
- $\sin^2 2\theta_{23} > 0.92$ at 90% C.L., or $\theta_{23} = 45 \pm 7.1$
  - Is $\theta_{23} > 45$ or $\theta_{23} < 45$?
- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
- $|\Delta m^2_{32}| = (2.44 \pm 0.06) \times 10^{-3}$ eV^2
  - Hints suggested normal mass hierarchy
- δ could be about $3\pi/2$ or -1.5

Tackling Mass Hierarchy With Reactor $\bar{\nu}_e$

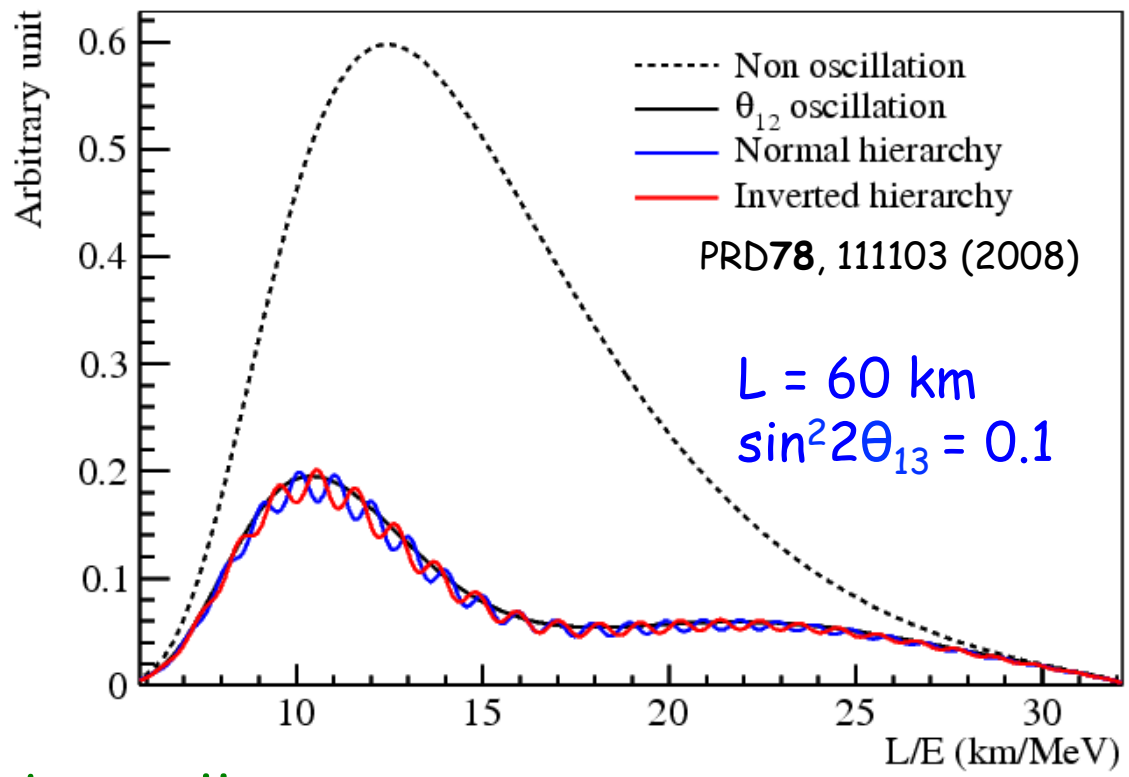
- Survival probability of $\bar{\nu}_e$ is given by:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

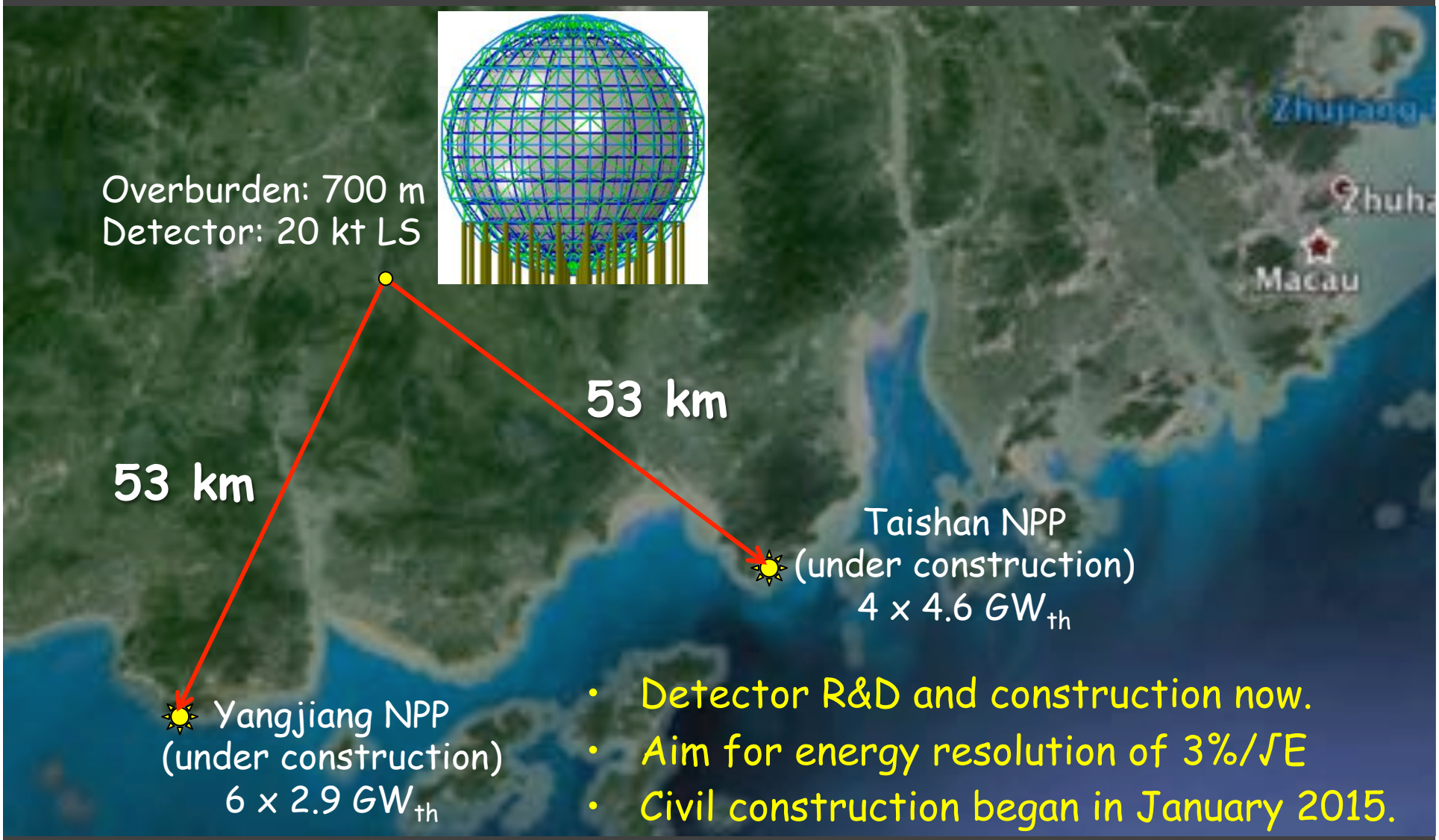
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \qquad P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

- Large θ_{13} enables determination of mass hierarchy with reactors

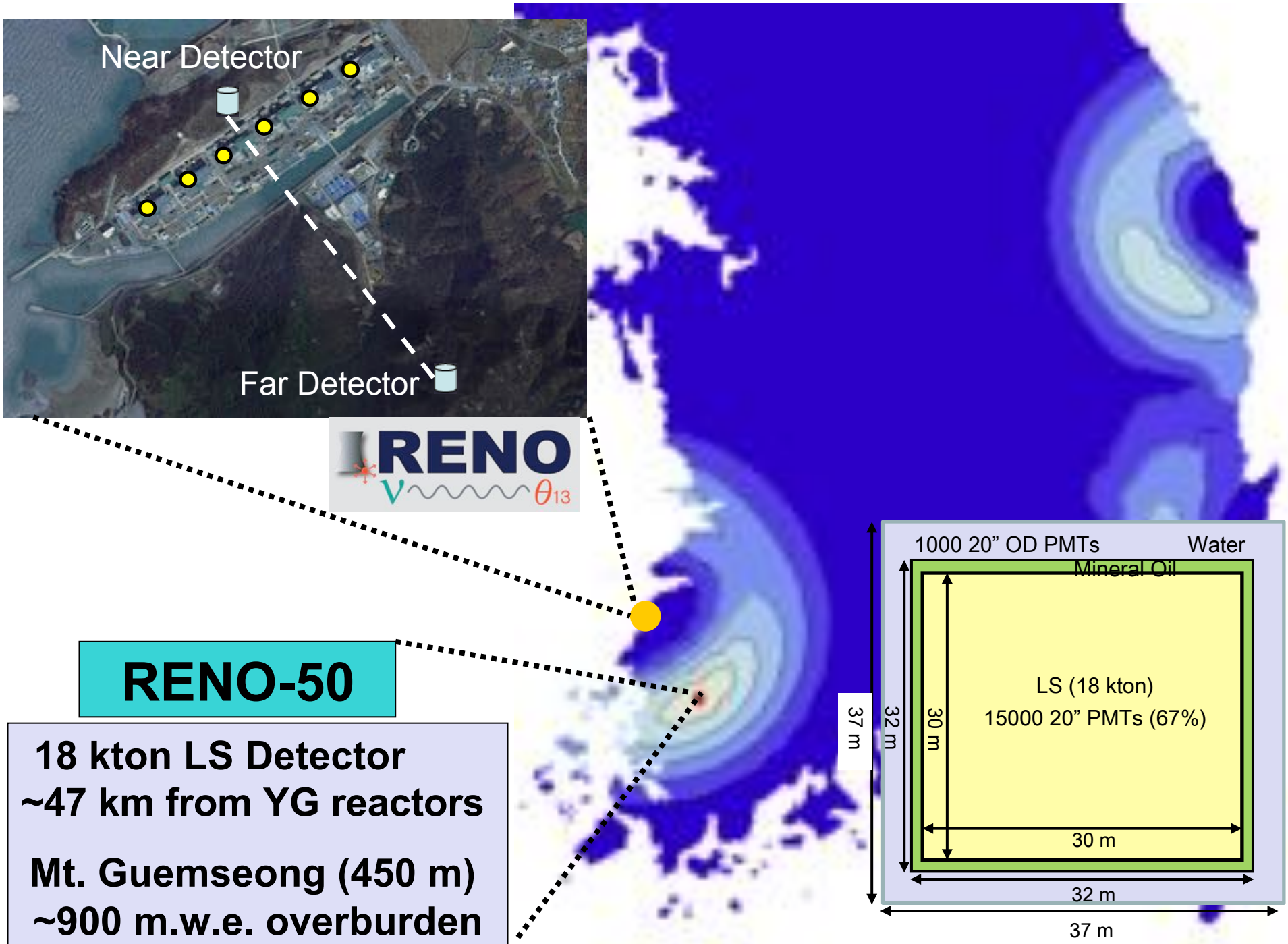


- Need high statistics and excellent energy measurement.

JUNO in China



- Detector R&D and construction now.
- Aim for energy resolution of $3\%/\sqrt{E}$
- Civil construction began in January 2015.
- Begin data taking in 2020.



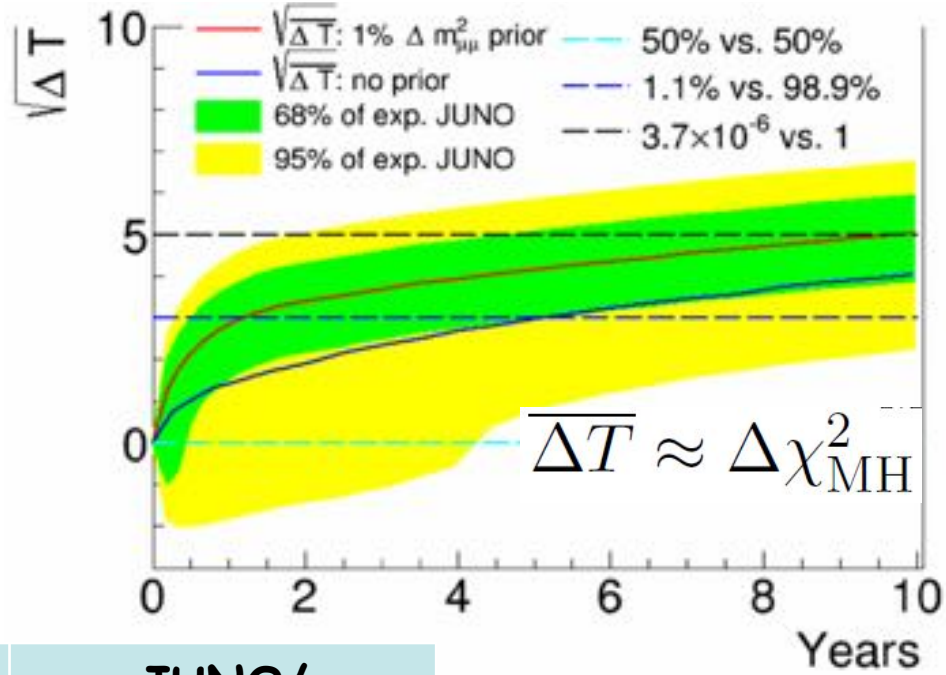
RENO-50

18 kton LS Detector
~47 km from YG reactors

Mt. Guemseong (450 m)
~900 m.w.e. overburden

Scientific Potential of JUNO/RENO-50

- Resolve the mass hierarchy
  - ~4 standard-deviation discrimination in 6 years

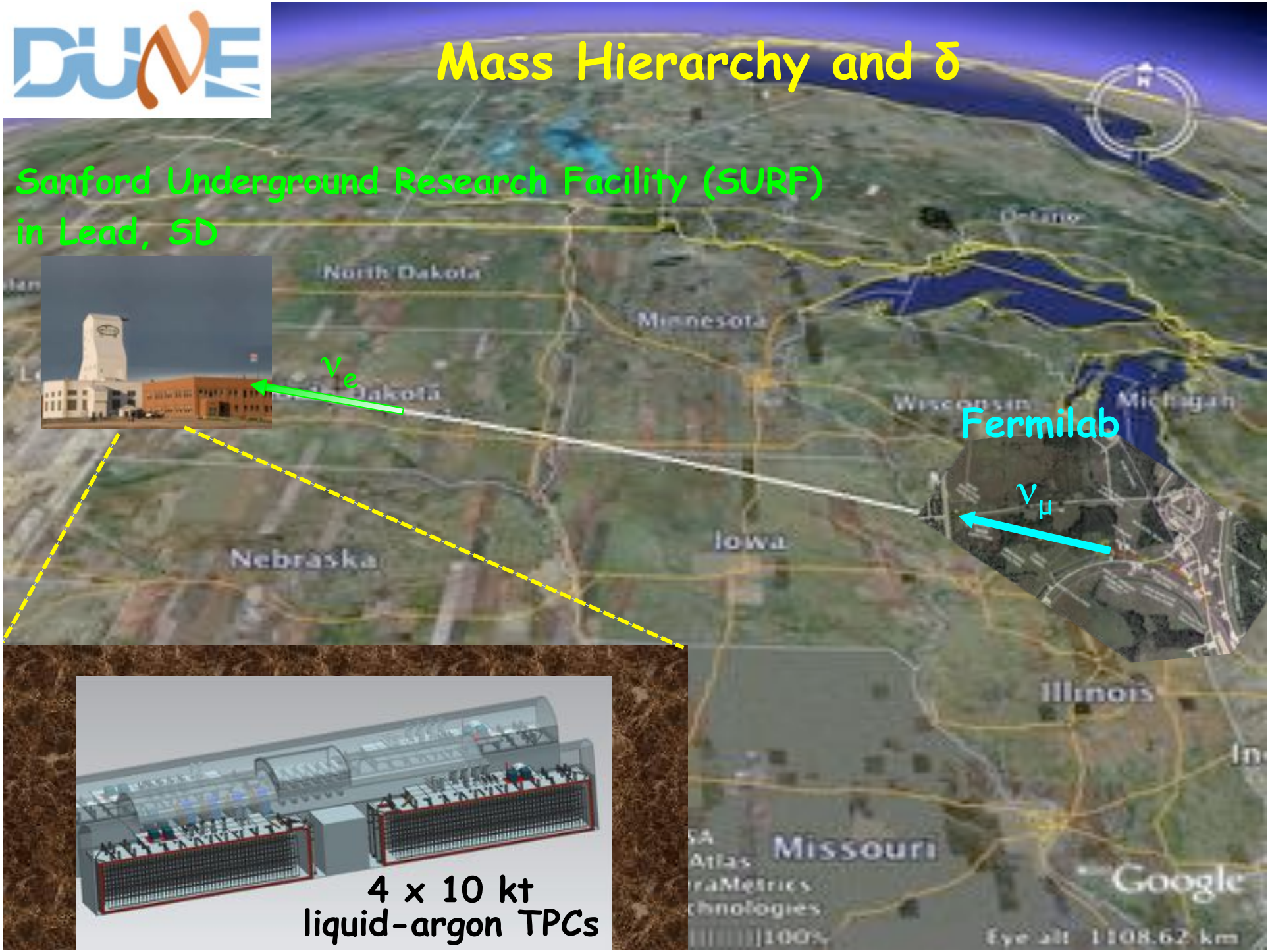


- Precision determination of neutrino-mixing parameters

	Current fractional precision	JUNO/ RENO-50
$\sin^2 2\theta_{12}$	3%	0.7%
Δm^2_{21}	3%	0.6%
Δm^2_{31}	2.5%	0.6%

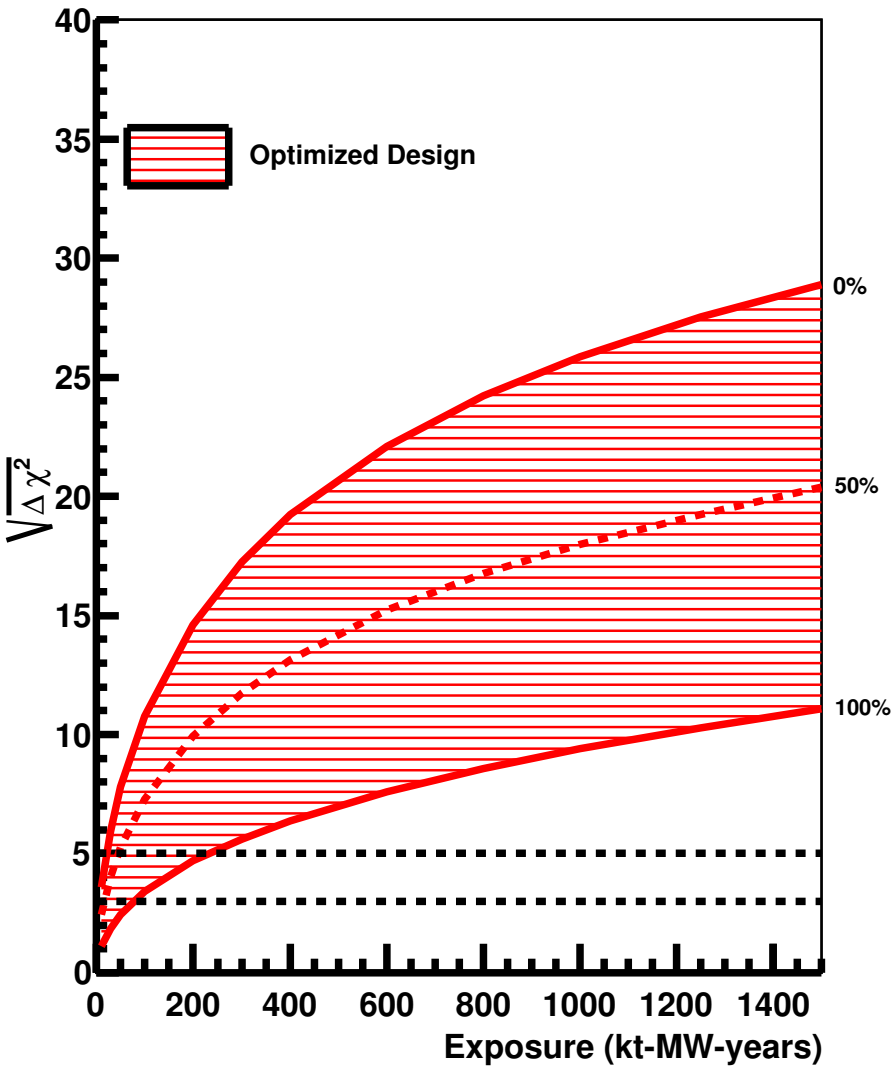
- Search for supernova neutrinos
  - ~5000 events for supernovae occur at 8 kpc
- Study geo-neutrinos

Mass Hierarchy and δ

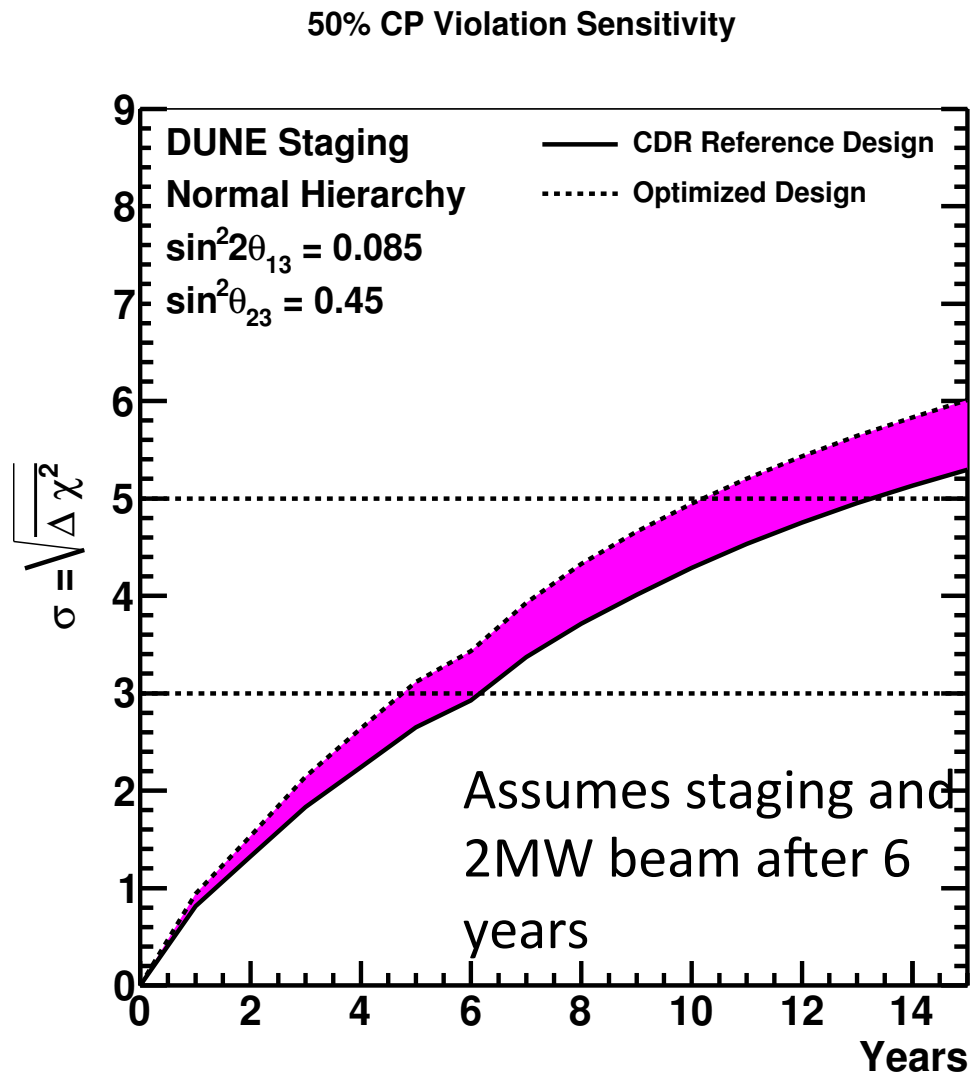


Physics Potential of DUNE

- Definitive determination of mass hierarchy:



- CP violation:

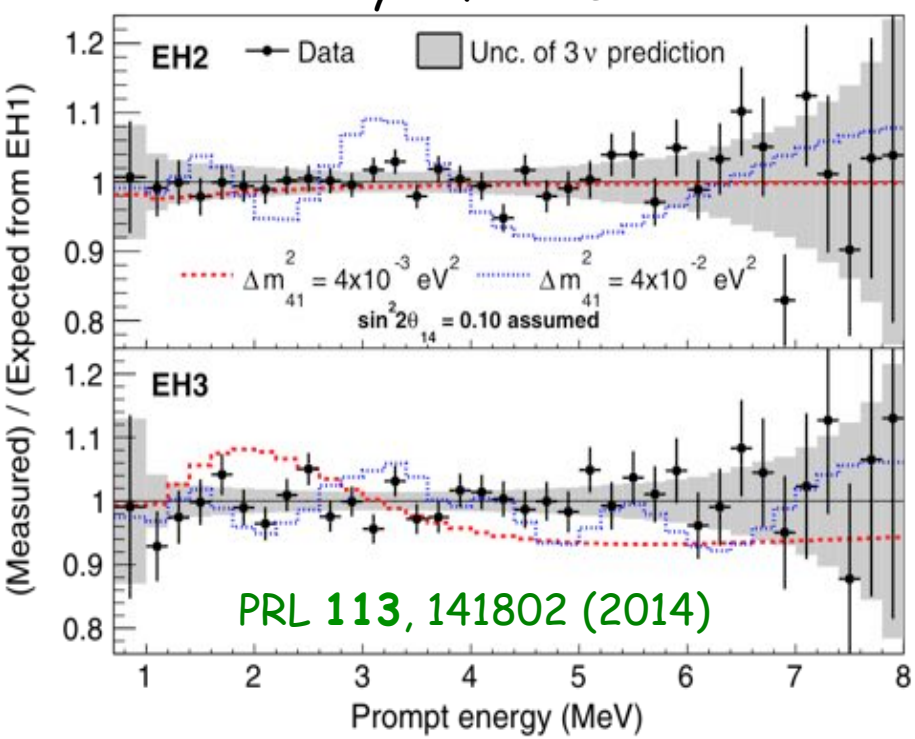


Search For Light Sterile Neutrino

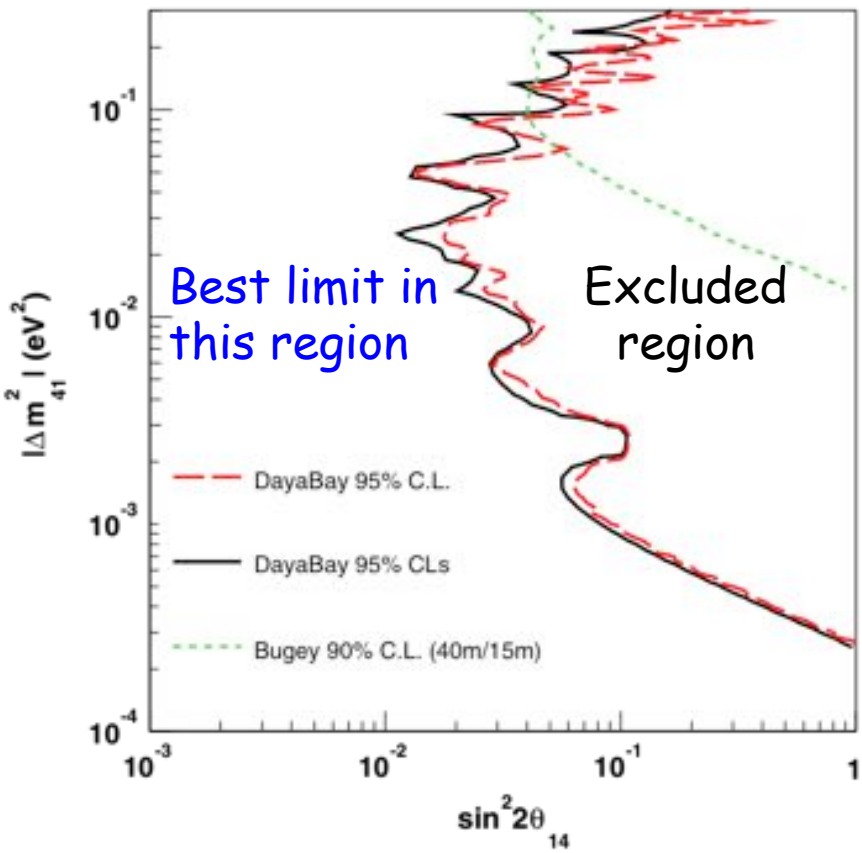
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{14} \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) - \cos^4\theta_{14} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right)$$

- Multiple baselines and detectors
  - cover a broad mass range to search for sterile neutrino
  - relative measurement of energy spectra reduces systematic errors

217 days of 6-AD data



PRL **113**, 141802 (2014)



Summary

- Discoveries of neutrino oscillation point to new physics beyond the Standard Model
- With accelerator ν_μ beams, we have seen clear evidence of ν_μ disappearance and appearance of $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$
- Tremendous progress has been made in measuring the mixing parameters in the last few years:
  - Precision of mixing angle ($\sin^2 2\theta$): ~5% or better
  - Precision of Δm^2: < 5%
- The prospect for further improvement in determining these fundamental parameters is bright
- No compelling evidence of sterile neutrinos is found yet