Chasing Neutrinos (from 1989 to today)

Symposium in Honor of PBM
August 24 to 26, 2016

Peter Paul, Stony Brook

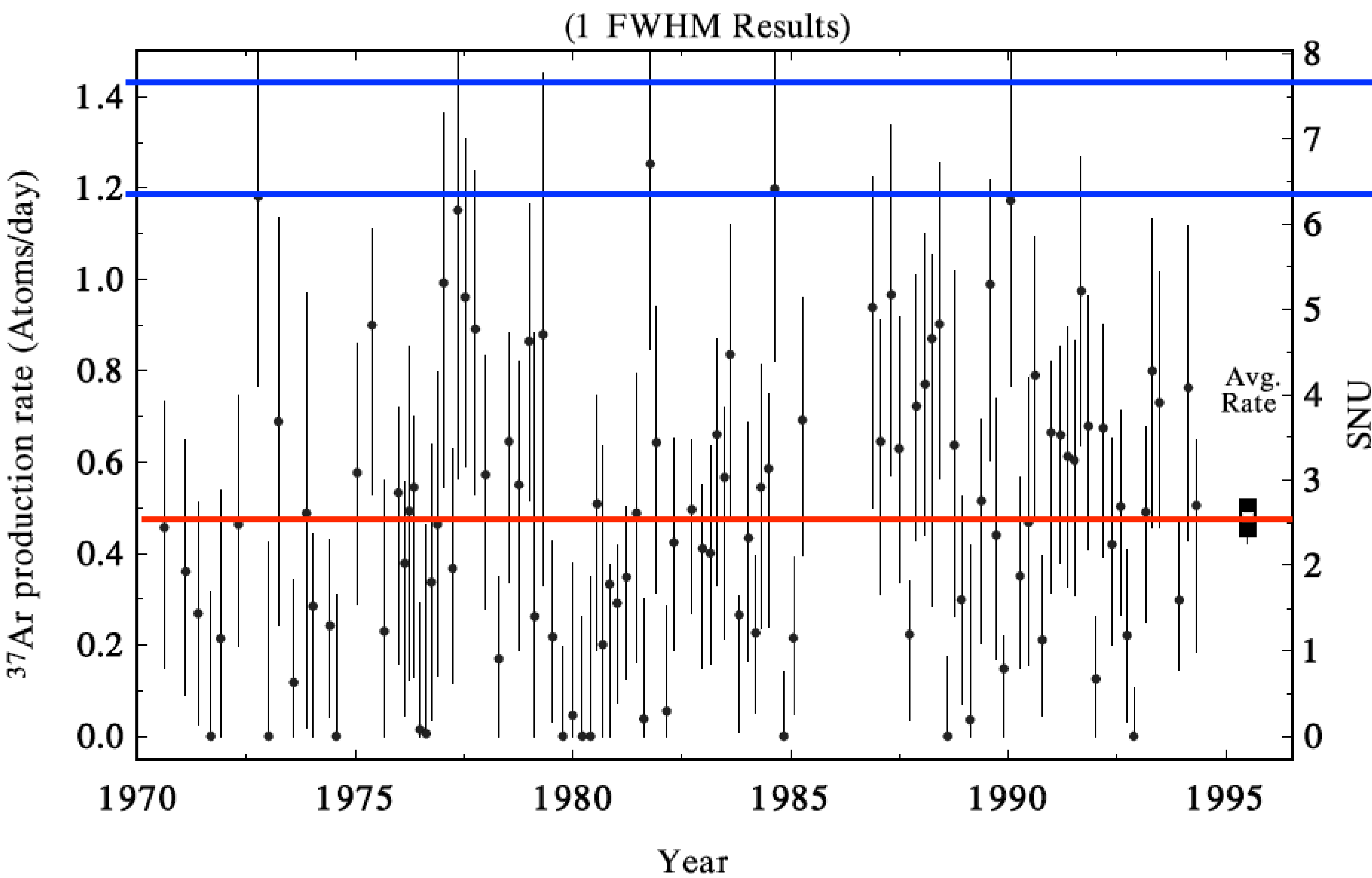
Quarks have mass, little mixing between them

In 1980s neutrinos assumed massless, no mixing, Today Neutrinos have mass and large mixing. Why the difference?

Stony Brook and BNL were/are heavily involved in both sectors.

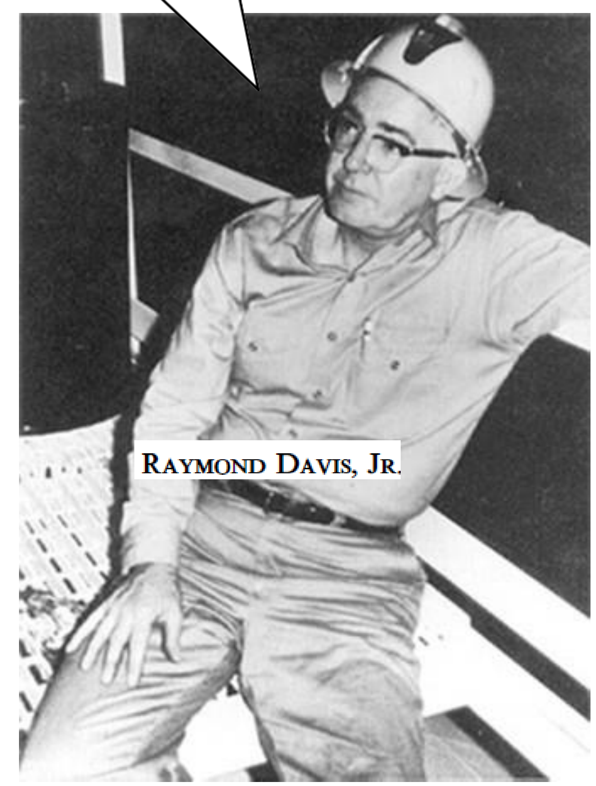
- PBM's major work in the quark sector.
- He was also part of seminal development in neutrino sector

It started with the missing Solar Neutrinos



Expected
rate of $!_e$
from the sun

Some of the ν_e
from the sun
are missing.



The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

Recommendations on Three Large Detector Proposals

Nuclear Science Advisory Committee

June 1, 1989

C. The SNO Proposal: This proposal represents an exceptional opportunity to create and work at a unique world class facility. It has a very high potential for fundamental discoveries in solar physics and in the properties of neutrinos. The use of 1 kT of $D_2 0$ for the detection of neutrinos is a unique chance to measure not only the flux but also the spectrum of solar neutrinos in real time , as well as the total flux of all neutrino flavors and their mixing. The facility will be an excellent detector for neutrinos from supernovas.

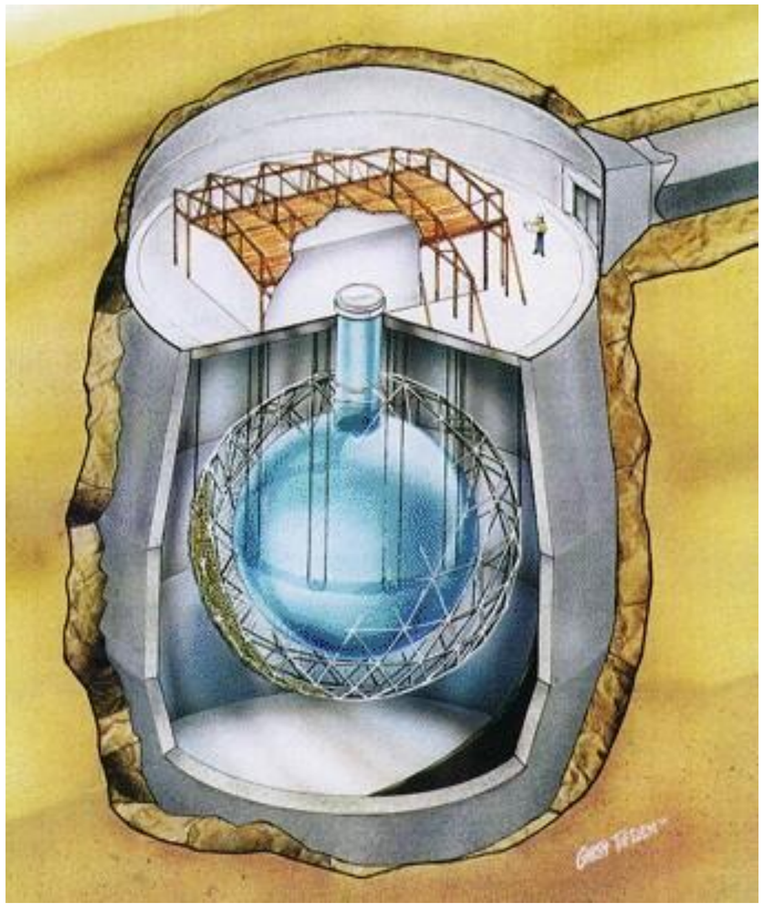
NSAC enthusiastically recommends that the US participation in the project be funded immediately.

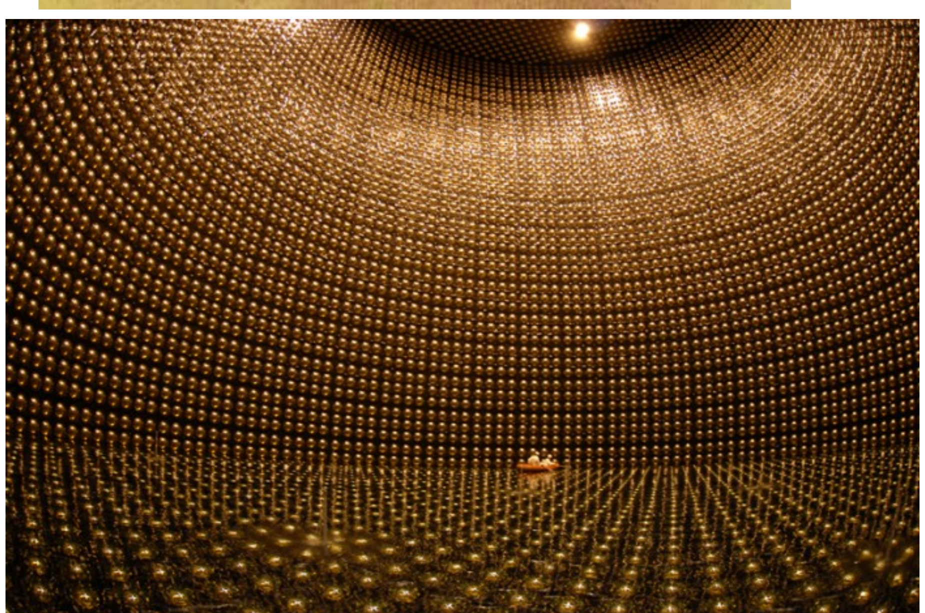
PBM was member of NSAC at that time.
This decision gave international credence to SNO

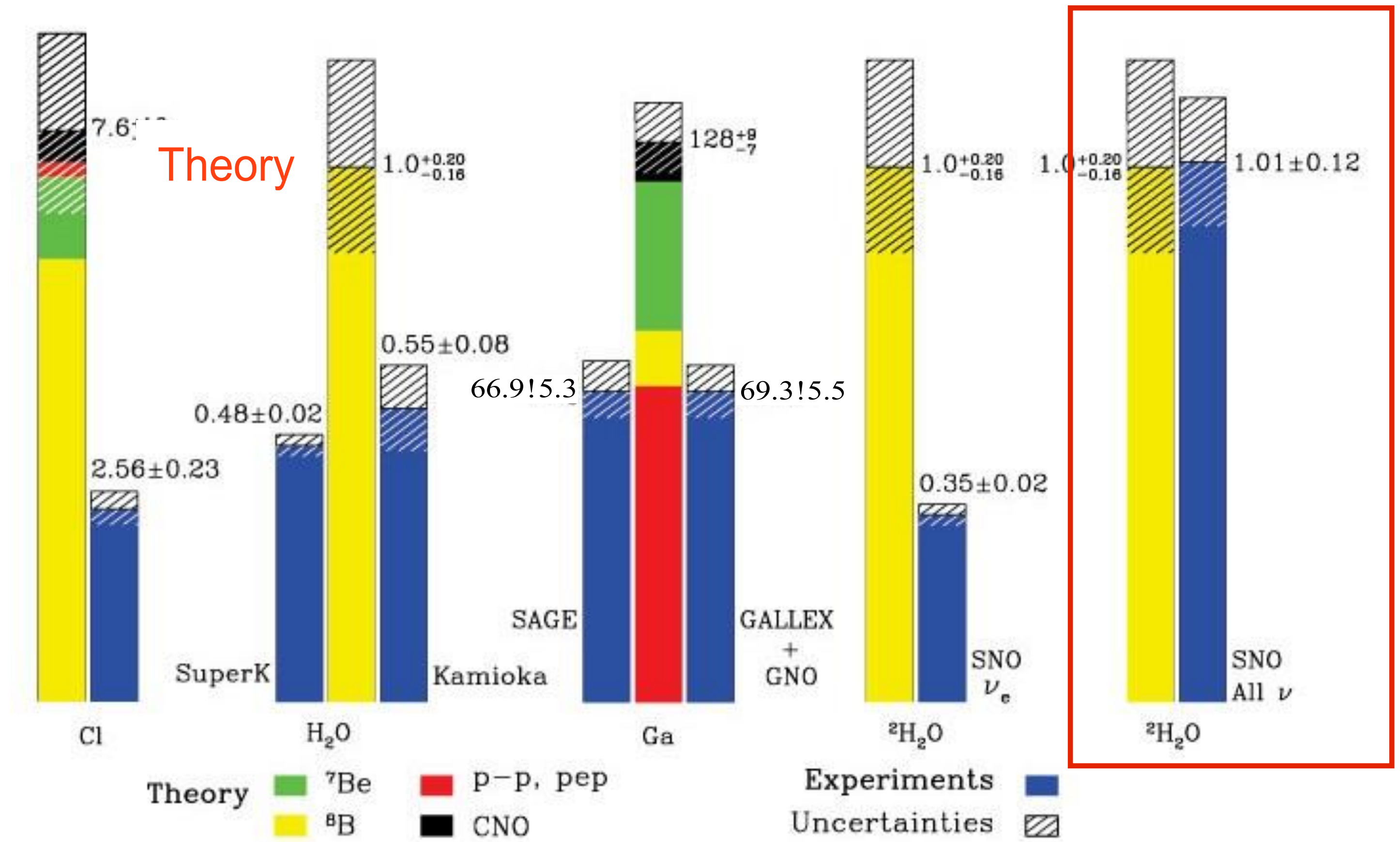
The SNO detector filled with heavy water was sensitive to all neutrino flavors

Observed Neutrino Oscillation gave mass to neutrinos

SNO and Super-K gave the answer







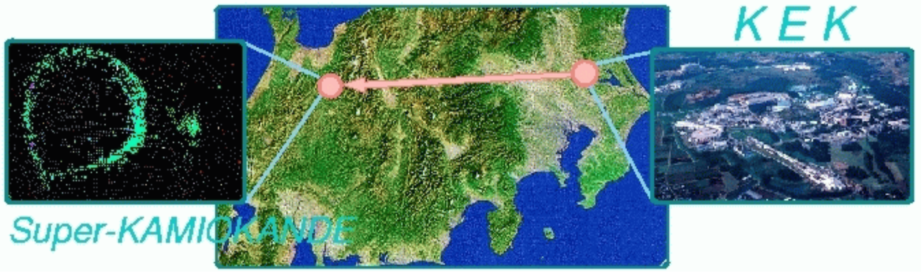
νe missing

But $\nu e + \nu\mu + \nu\tau$ agree

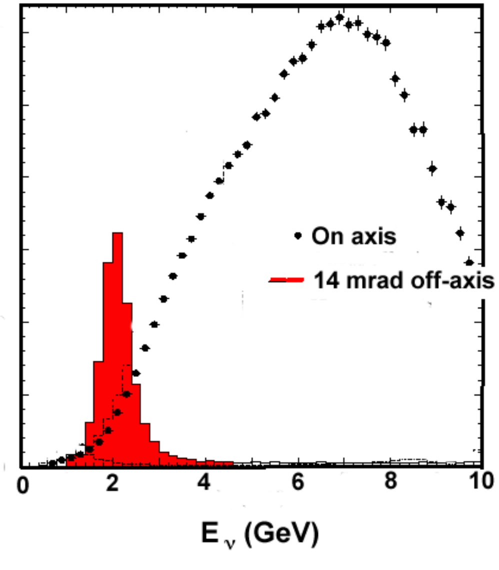
The 2015 Nobel Prize in Physics was given to Art McDonald and Takaaki Kajita for demonstrating neutrino oscillations with neutrinos from the sun and the atmosphere.

Neutrino Oscillations with Accelerator Generated ν_μ Beams ca. 2002

The K2K Experiment



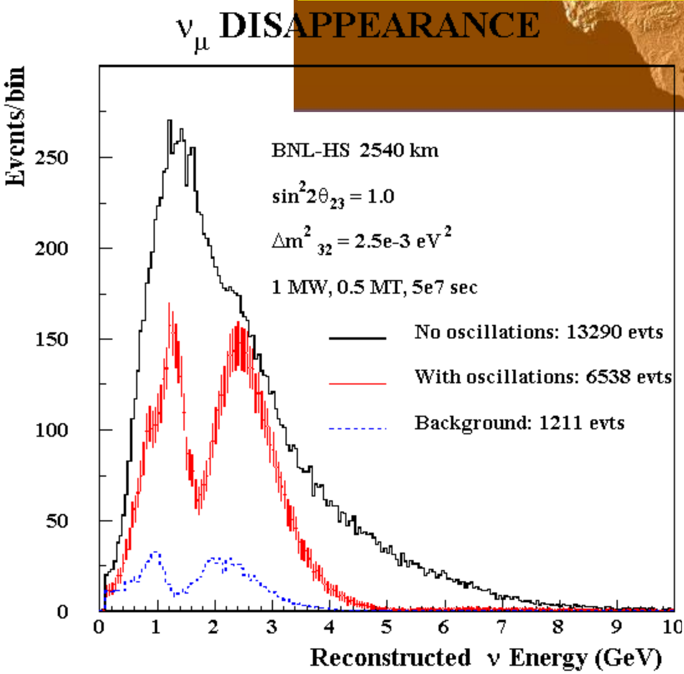
From KEK to Super-K detector



OFF axis beam provides narrow neutrino energy

The BNL experiment

From AGS to Home Stake Mine

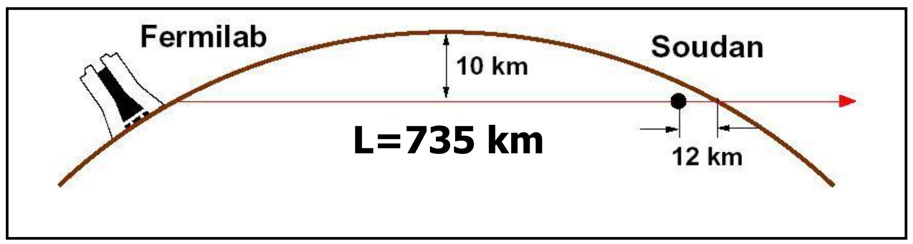


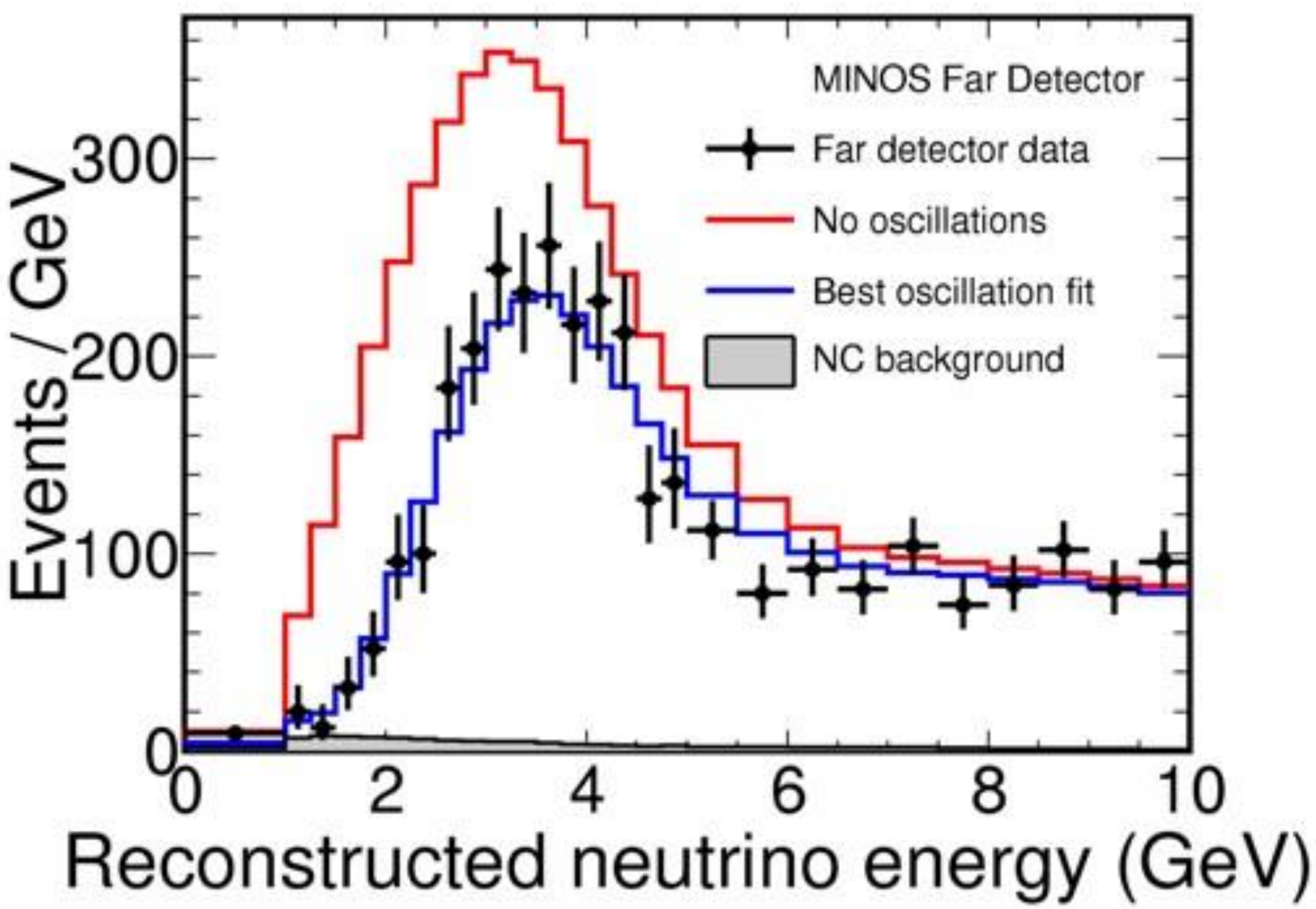
Wide energy neutrino beam shows several oscillation maxima

MINOS at Fermilab and K2K in Japan show muon neutrino disappearance

MINOS

BNL: Milind Diwan's group





The paradigm: 3-ν mixing

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

With $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$:

Atmospheric ν_μ | Reactor $\overline{\nu}_e$, Accelerator ν_μ | Solar ν_e | Majorana CP phases

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\theta_{23} \approx \theta_{atm} \approx 45°;\ \theta_{12} \approx \theta_{sol} \approx 34°;\ \theta_{13} \leq 10°$$

Delta is a CP violating phase, which is the most important goal of the experiments. Other experiments will determine if neutrinos are Majorana particles and alpha is needed.

Accelerator $\nu_\mu \rightarrow \nu_e$ appearance

unknowns

$$P[\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e] \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31}$$
$$+ \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}$$
$$\sin\Delta_{31} \sin\Delta_{21} \cos(\Delta_{32} \pm \delta)$$
$$+ \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 \Delta_{21}$$

ν

$\bar{\nu}$

(solar)

Experiment measures the difference of squared masses; thus the mass hierarchy is ambiguous

$$(\Delta_{ij} \equiv 1.27 \Delta m_{ij}^2 (eV^2) L(km) / E(GeV))$$

Sensitivity to mass hierarchy via “matter effects”:

Passage through matter:

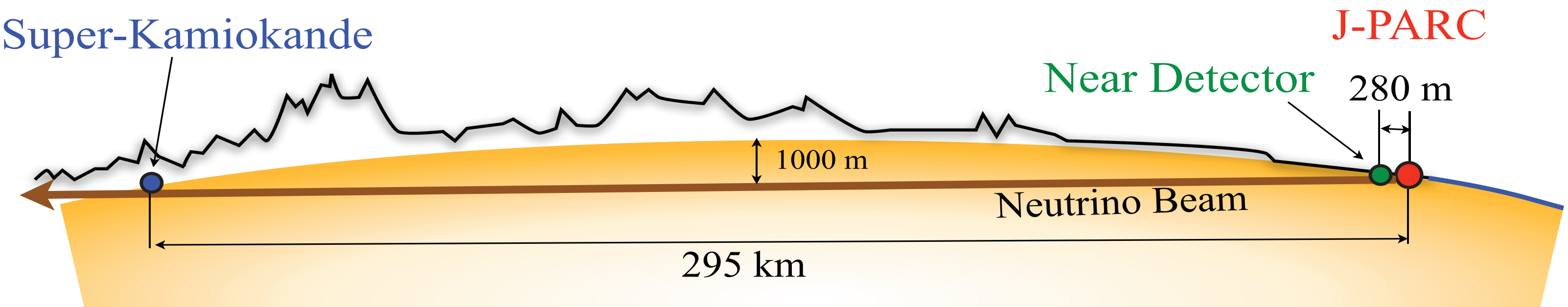
Normal: increases $\nu_\mu \rightarrow \nu_e$, decreases $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Inverted: decreases $\nu_\mu \rightarrow \nu_e$, increases $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Note: $\sin 2\theta_{13}$ a factor in all the physics we are after!

The T2K (Tokai to Kamioka) Experiment

(http://t2k-experiment.org/)



"The T2K Experiment", K. Abe, et al., Nucl. Instr. and Meth. A **659**, 106 (2011)

How can we measure the CP violating phase delta

In general,

$$P_{\alpha\to\beta}=\delta_{\alpha\beta}-4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

For three generation, ν_e appearance (accelerator experiments)

$$P(\nu_\mu\to\nu_e)=\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}+\text{subleading terms}$$

Sensitivity to θ_{23} octant

Full appearance probability includes term that goes as sin(δ):

CPV term $\propto \pm\sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta$

Sensitivity to CPV-δ

Sign flip for neutrino vs. antineutrino

Need non-zero value for all three mixing angles including θ_{13}

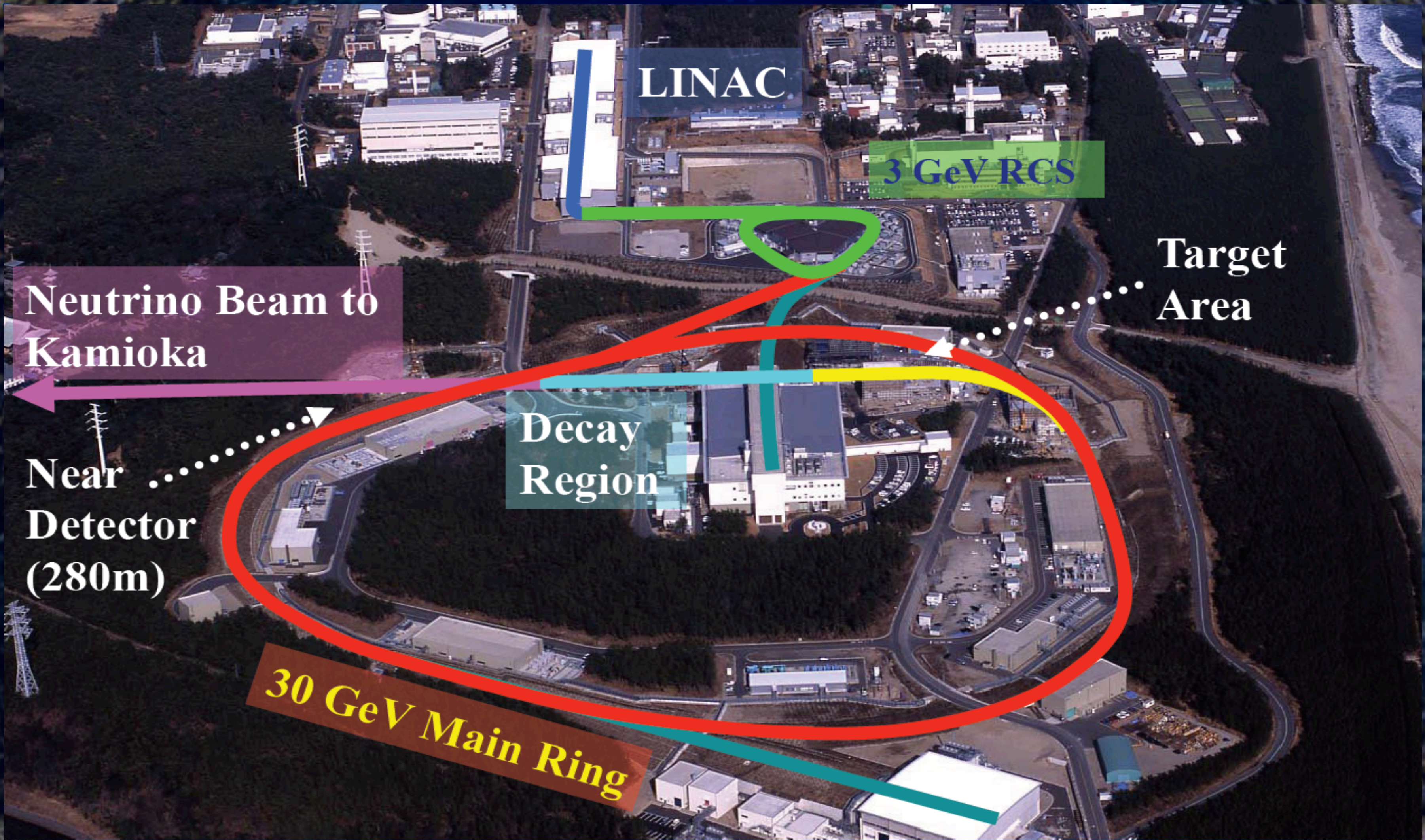
Complementary

For anti-ν_e disappearance (reactor experiments)

$$P(\bar{\nu}_e\to\bar{\nu}_e)=1-4C^2_{13}S^2_{13}\cdot\left(C^2_{12}\sin^2\Delta_{13}+S^2_{12}\sin^2\Delta_{23}\right)+4S^2_{12}C^2_{12}C^4_{13}\sin^2\Delta_{12}$$

No CPV-δ dependence, Pure θ_{13} measurement

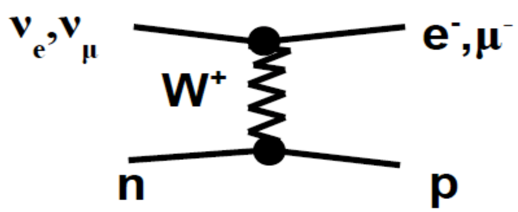
J-PARC Accelerator Complex and Neutrino Beamline



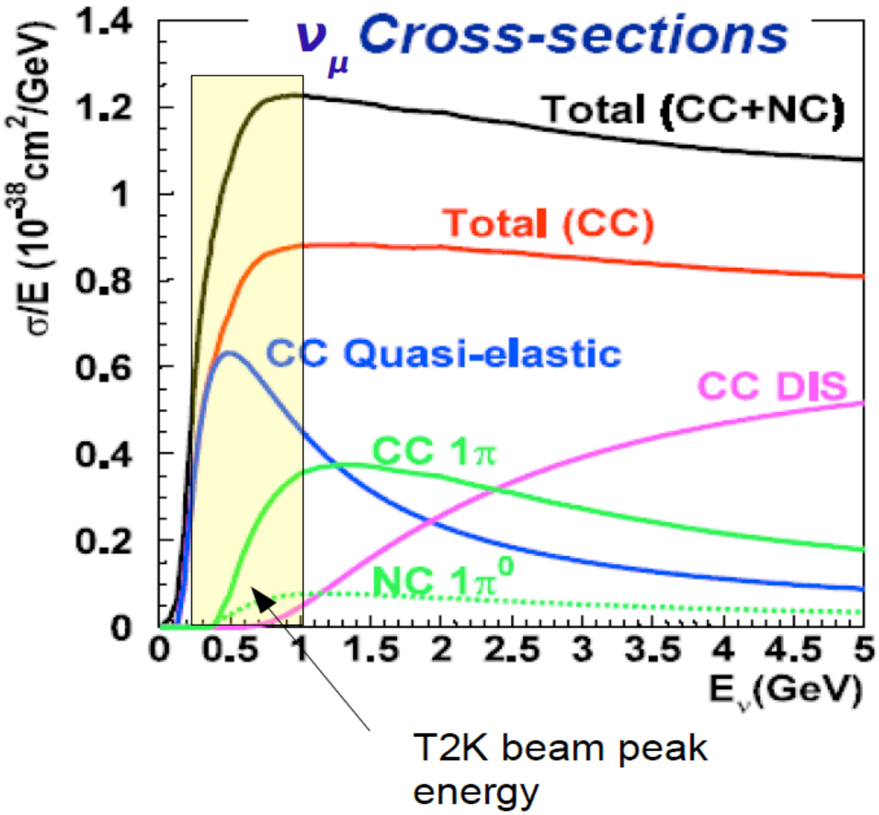
Neutrino Interactions at the T2K Energy Range

In region of interest for T2K:

Large contribution from charge current quasi-elastic (CCQE)

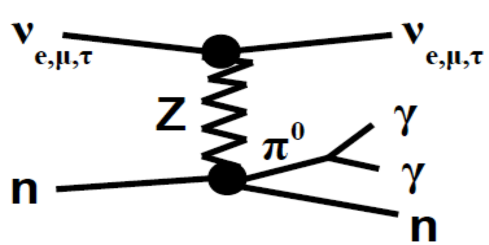


T2K signal at SK



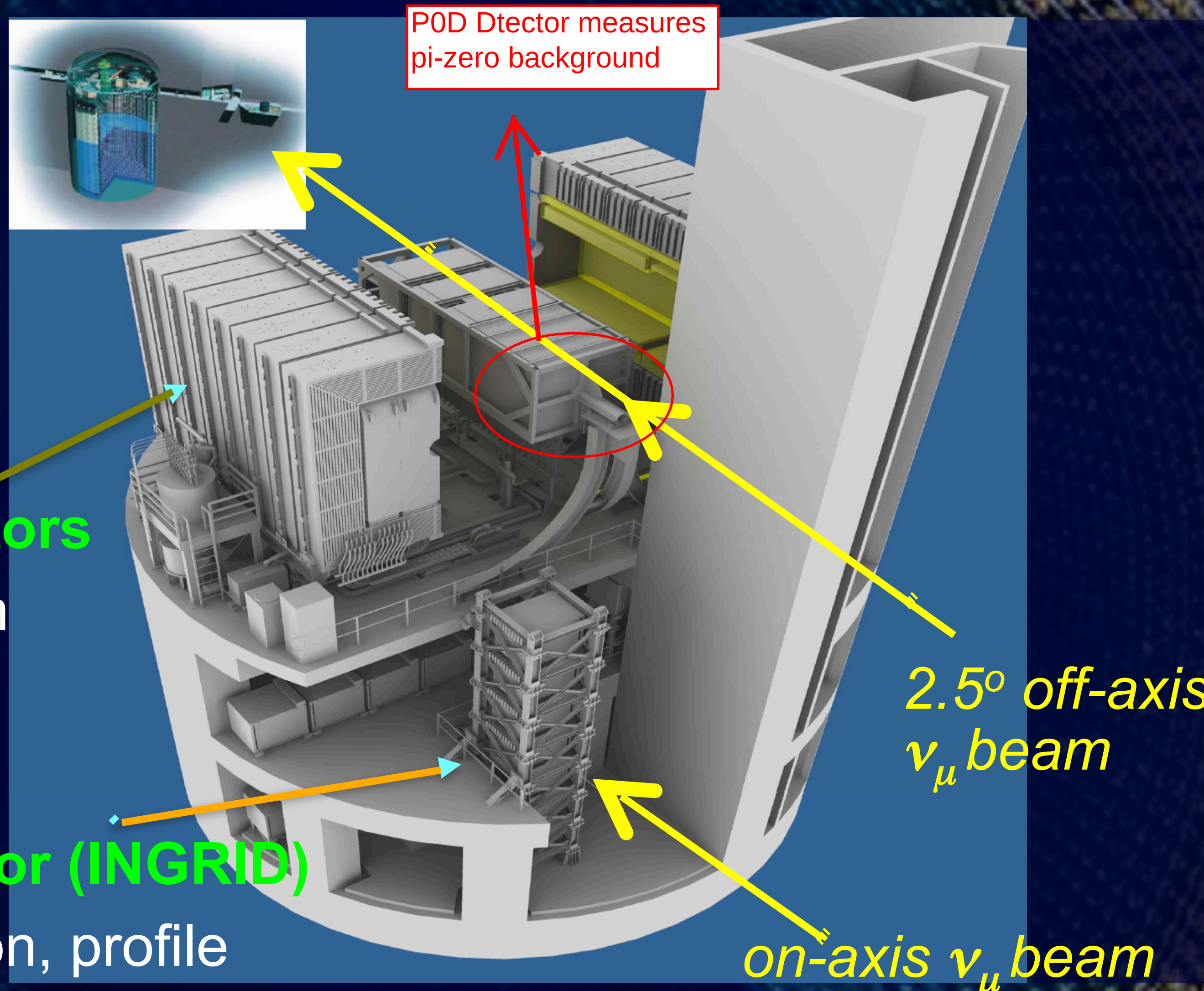
Significant CCπ component with additional pion in final state

NCπ^0 is significant background mode:



Photons from π^0 can fake an electron

T2K Near Detector Complex



Off-Axis Detectors

- ν flux/spectrum
- cross-sections

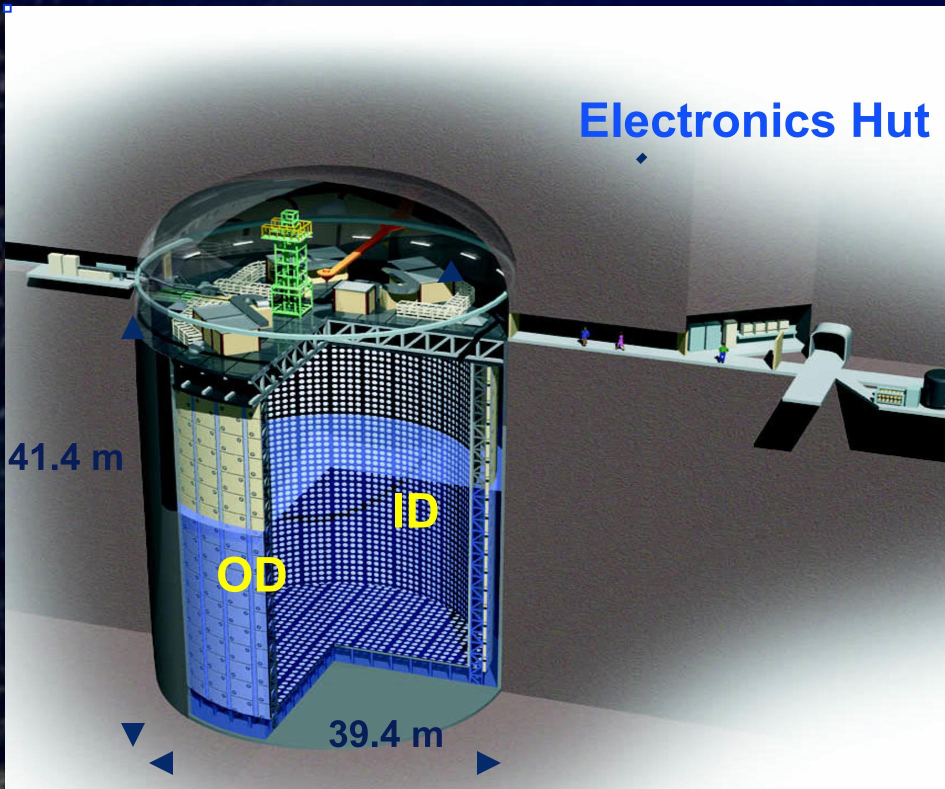
On-Axis Detector (INGRID)

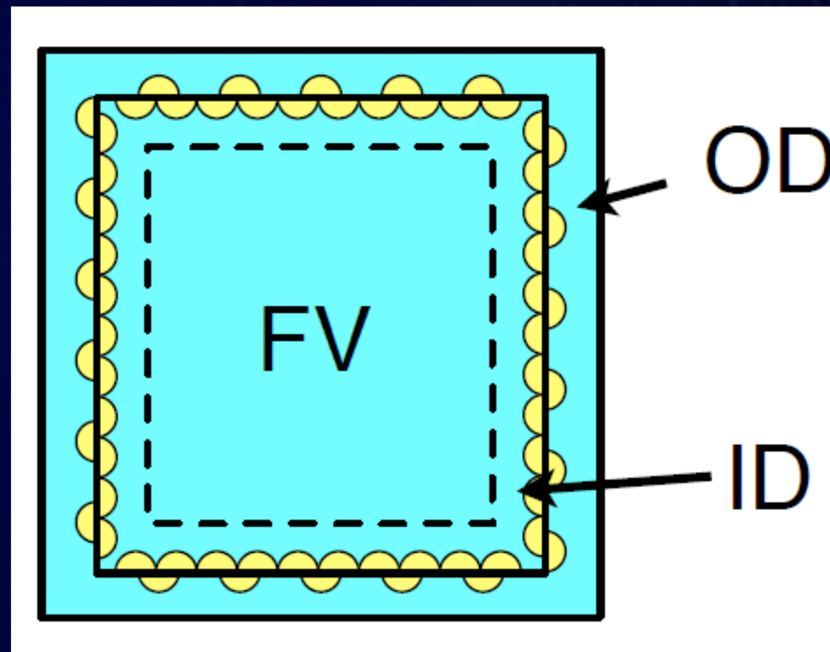
- ν beam direction, profile

The Far Detector: Super-Kamiokande

50 kton Water Cherenkov Detector

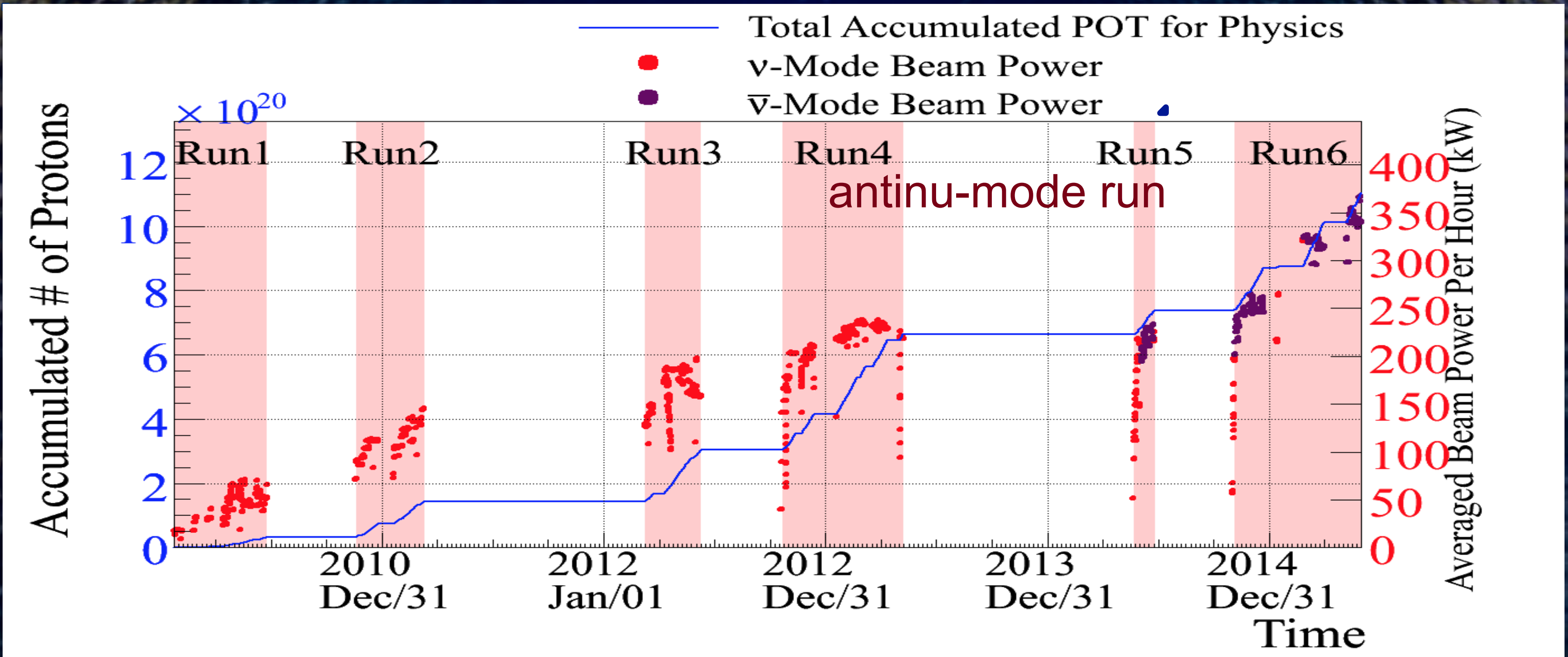
- Inner Detector (ID) w/ 11,000 20" PMTs
- Outer Detector (OD) w/ 1,840 8" PMTs
- 40% Photocathode coverage





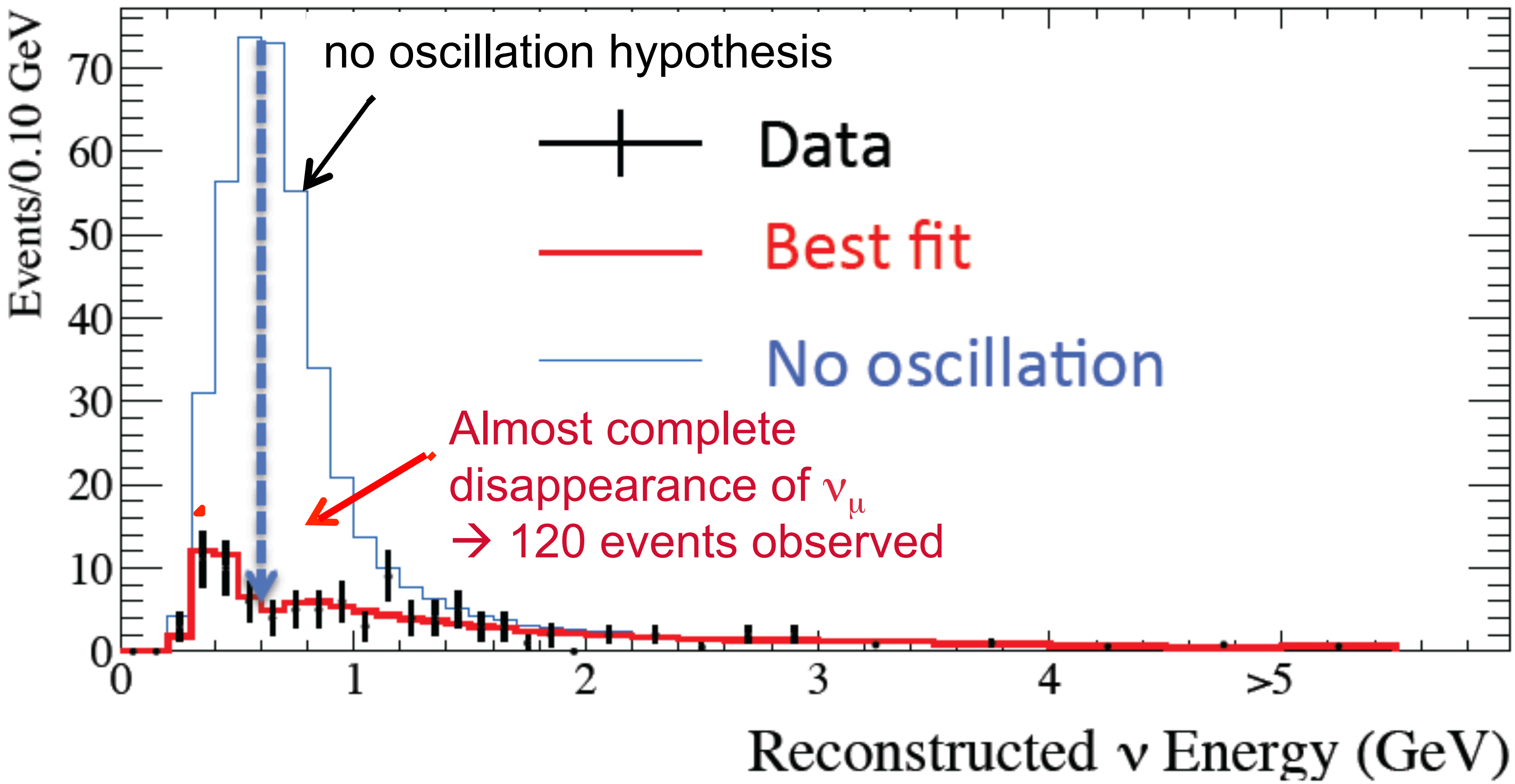
Fully Contained (FC) events
FCFV events for analysis

T2K Accumulated # Protons on Target (POT), and J-PARC Main Ring Beam Power

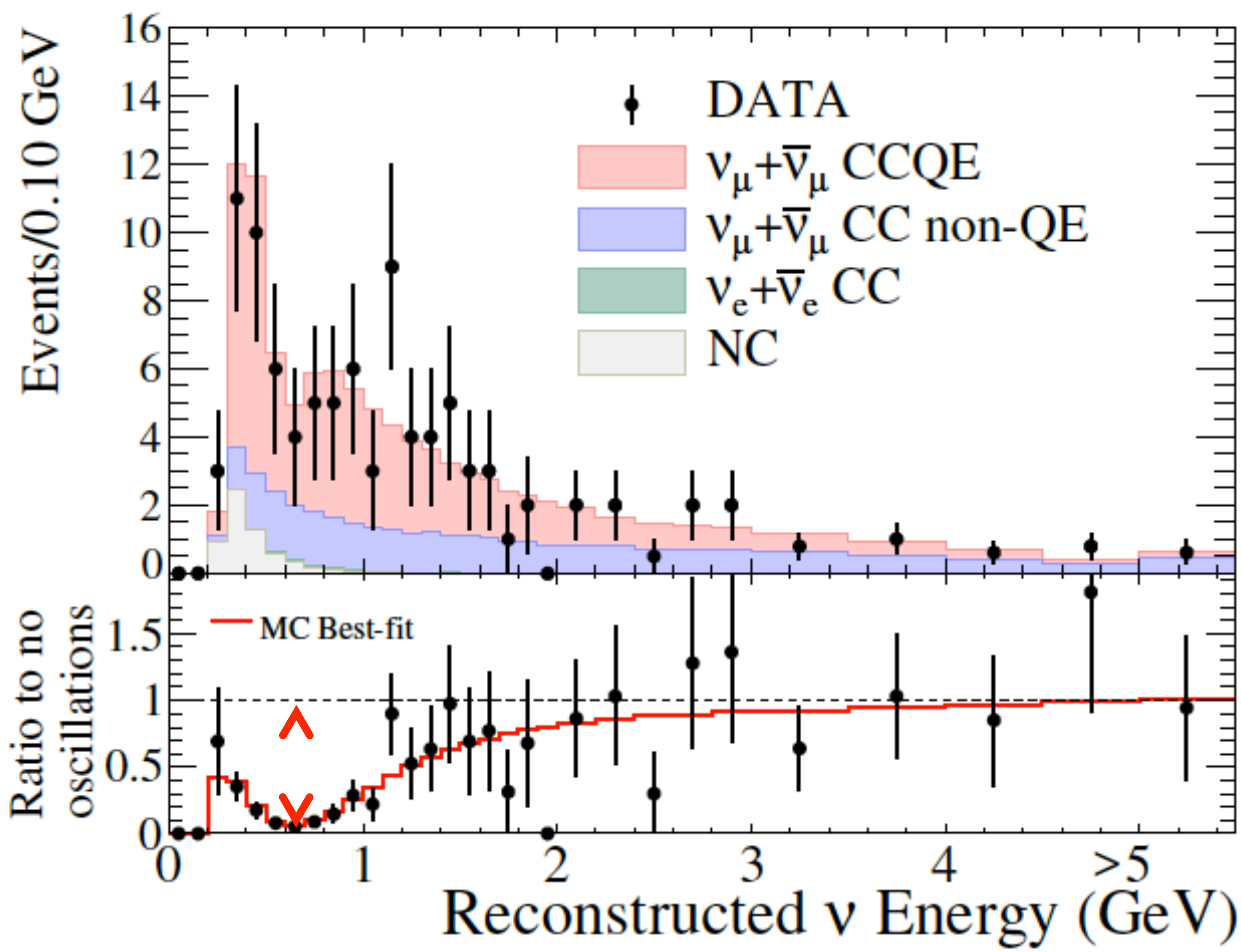


- Stable operation at ~450 kW achieved (design power: 750 kW)
- Antineutrino-mode run since June 2014
- Total POT for physics (as of June 2015): 7.04×10^{20} (nu-mode), 4.00×10^{20} (antinu-mode) → ~ 14% of the total approved POT (7.8×10^{21})

T2K New Results on ν_μ Disappearance



T2K New Results on ν_μ Disappearance

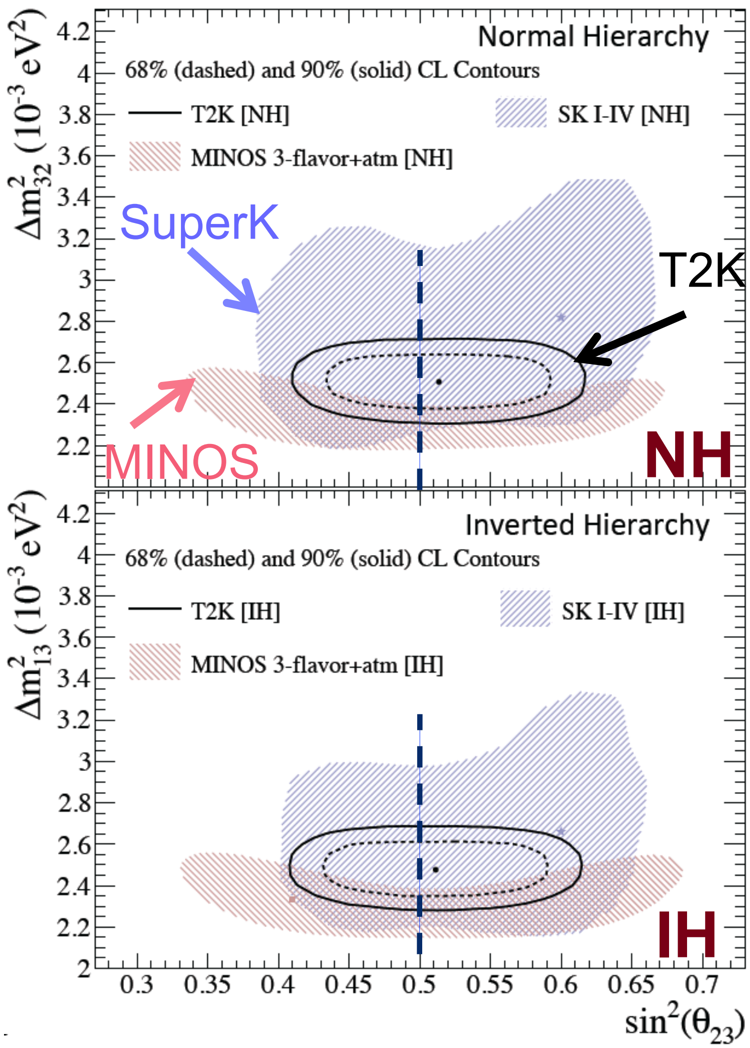


Maximum dip:

location → Δm^2_{32}

size → $\sin^2 2\theta_{23}$

ν_μ Disappearance Confidence Regions



T2K and SuperK: Separate C.L. for NH & IH
MINOS: C.L. from the global minimum

T2K Run 1-4 Best Fit Point (NH):

$\Delta m^2_{32} = 2.51 \pm 0.1 \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$

- The best fit is consistent with the maximal mixing but not exactly at the maximal mixing
- T2K now has the smallest error on θ_{23}, (~3°)

Note: osc. Max for $\sin^2 2\theta_{13} = 0.098$:

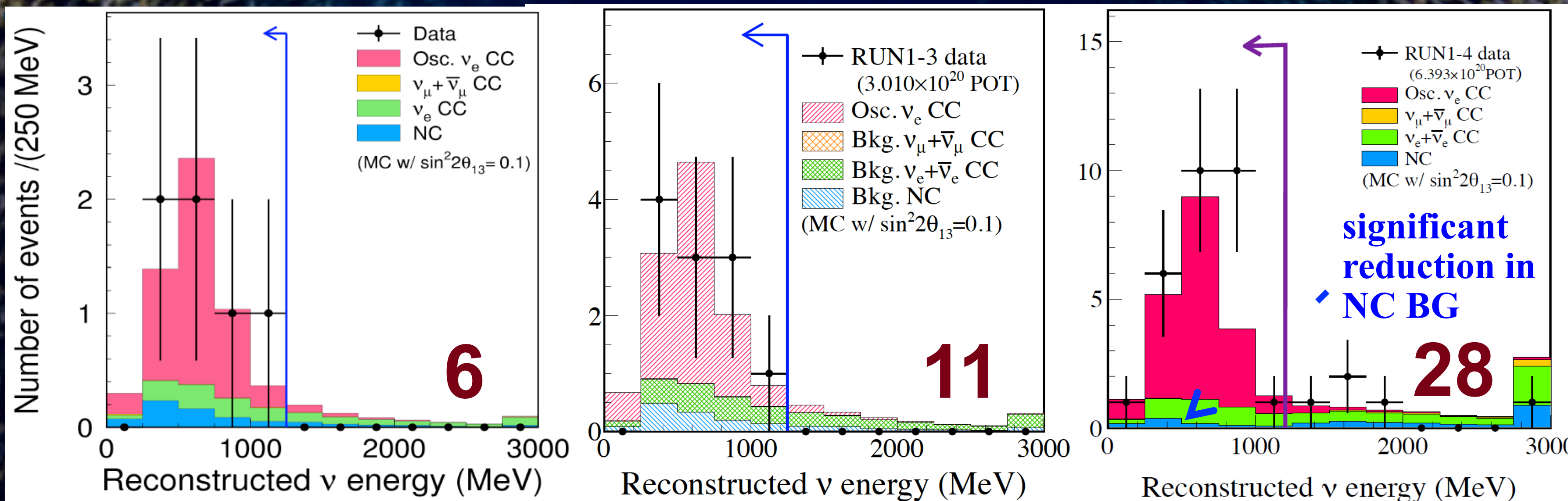
$\sin^2\theta_{23} = 0.513$ (or $\theta_{23} = 45.74°$)

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(c^4_{13}\ \sin^2 2\theta_{23} + s^2_{23}\ \sin^2 2\theta_{13}\right) \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

Leading

Next-to-leading is different between 1st/2nd octants

T2K Reconstructed E_ν Spectrum of the Final Selected Events



Year	2011	2012	2013
POT (10^{20})	1.43	3.01	6.57
$N^{obs.}_{\nu_e}$	6	11	28
N^{exp}_{BG}	1.5 ± 0.3	3.3 ± 0.4	4.92 ± 0.55
$\sin^2 2\theta_{13}$(T2K)	0.11	$0.088^{+0.049}_{-0.033}$	$0.140^{+0.038}_{-0.032}$
Significance	2.5σ	3.1σ	7.3σ
Systematic Error (%) on N^{exp}_{tot}	17.5	9.9	8.8

- θ_{13}= 0 is excluded at 7.3σ level of significance

→ Observation of ν_e appearance from a ν_μ beam!

Reactor $\overline{\nu}_e$ disappearance

Reactor experiment determines theta-13 unambiguously independent from CPV

$$P[\overline{\nu_e} \rightarrow \text{Not}\,\overline{\nu_e}] \cong \sin^2 2\theta_{13} \sin^2 \Delta_{31} + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

small at max of first term

Accelerator-based oscillation experiments

- θ_{13}>0
- mass *ordering* if θ_{13} large enough
- CP violation if θ_{13} large enough
- parameter extraction limited by degeneracies

combine energies or reactor

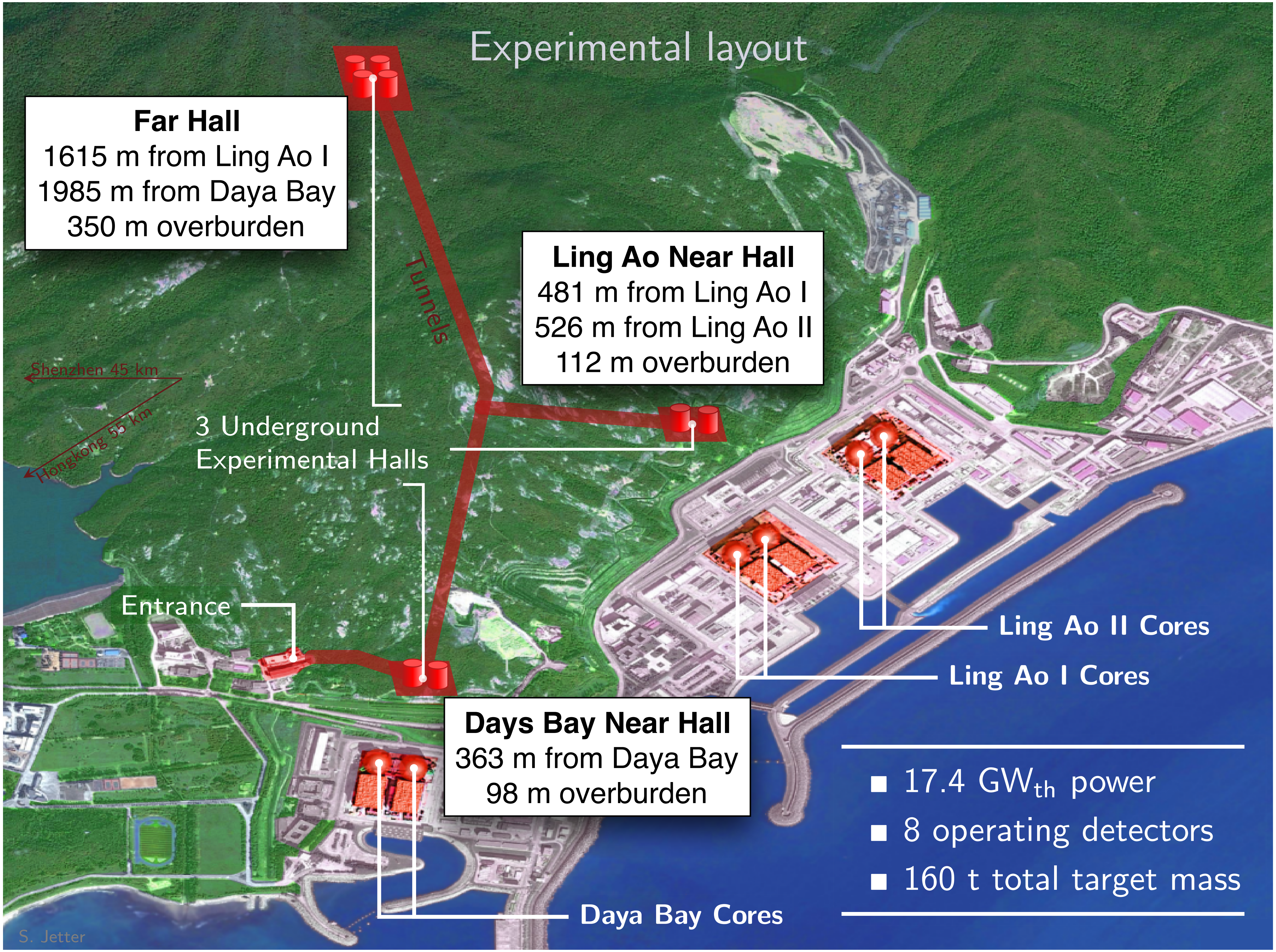
Reactor-based oscillation experiments

- measure only θ_{13} but without ambiguity
- combine with accelerator to break degeneracies

in some regions, if sufficient precision

Eight Detectors in Three Halls

Daya Bay Experiment



- 17.4 GW_{th} power
- 8 operating detectors
- 160 t total target mass

Combined nGd and nH Results

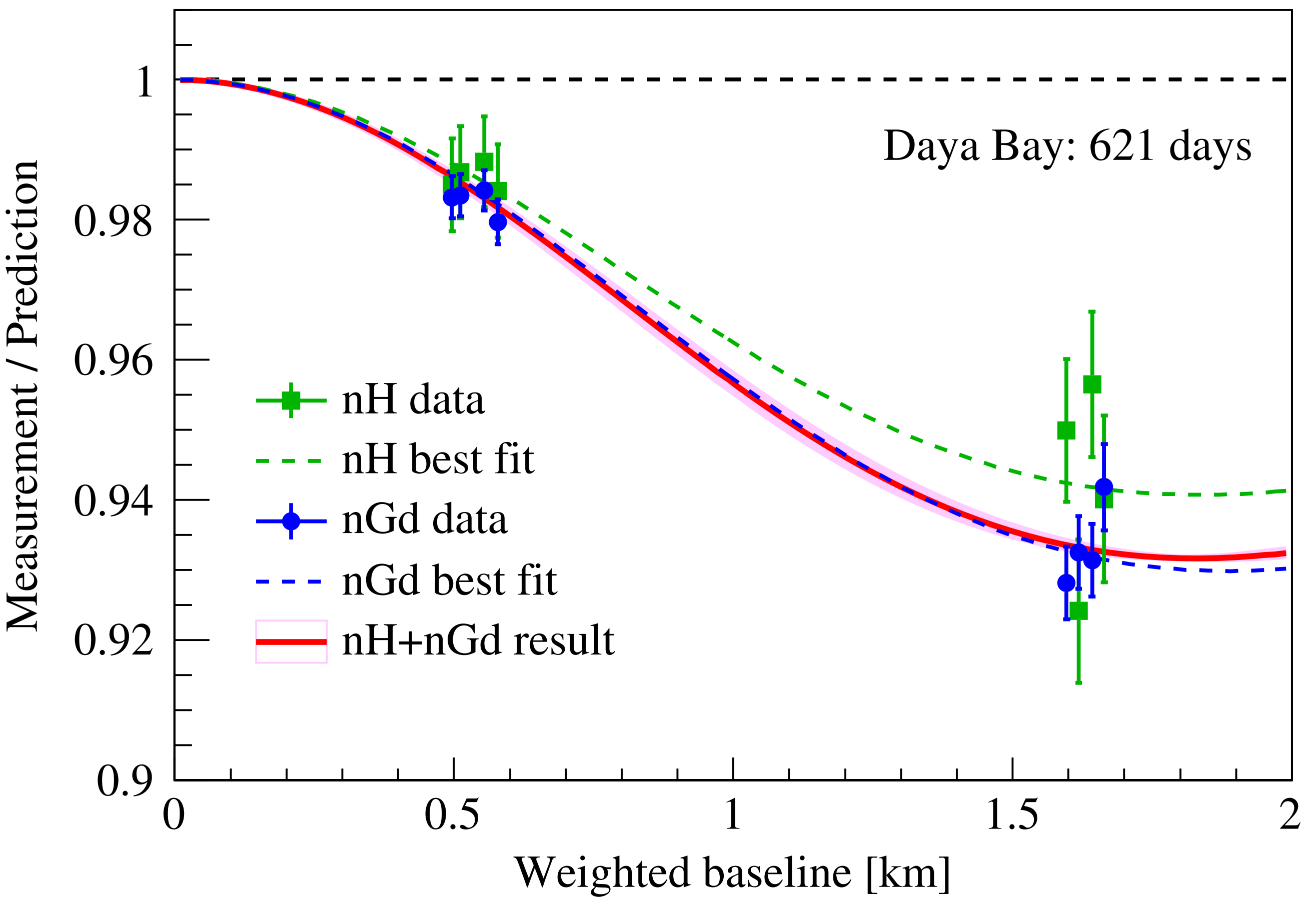
Correlation between datasets estimated for efficiencies, backgrounds and reactor-related uncertainties

Combine the nGd result with nH

$$\sin^2 2\theta_{13} = 0.071 \pm 0.011 \quad \text{(nH)}$$

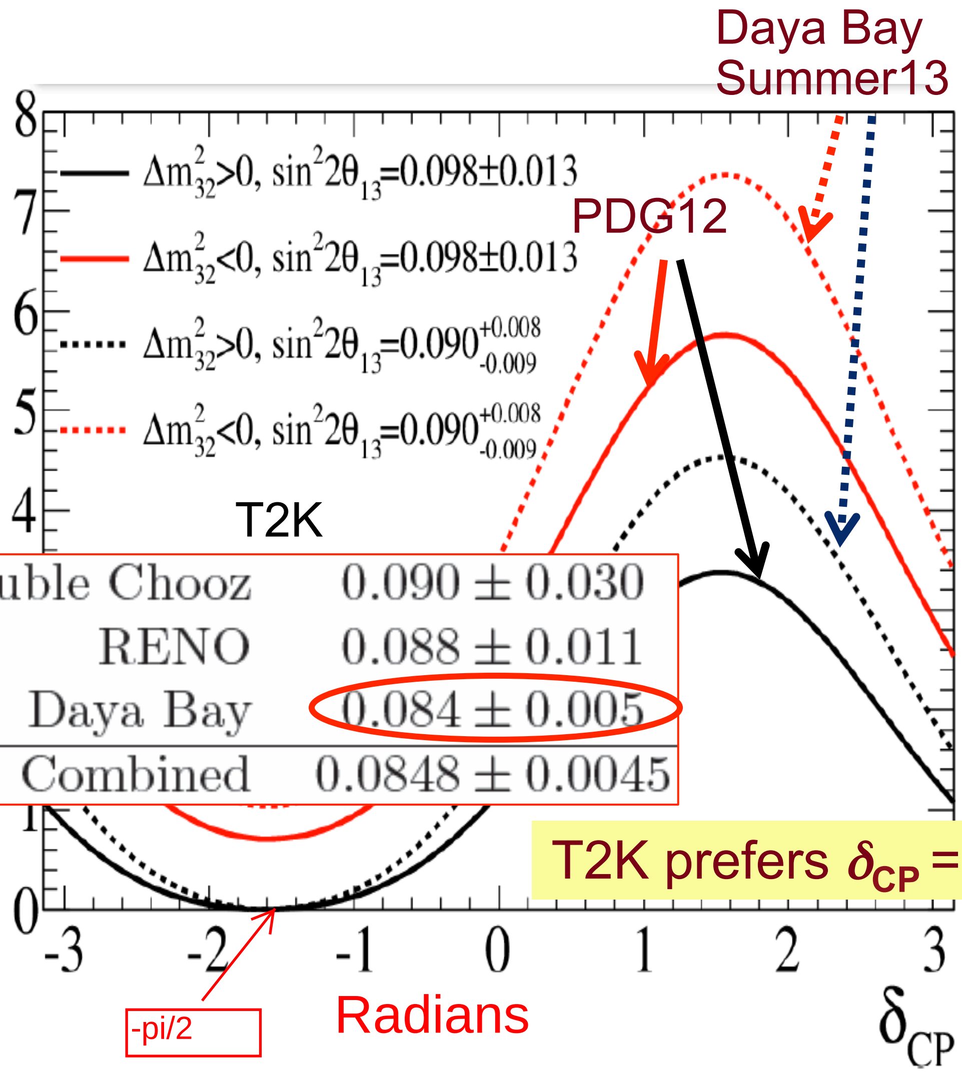
$$\sin^2 2\theta_{13} = 0.084 \pm 0.005 \quad \text{(nGd)}$$

$$\sin^2 2\theta_{13} = 0.082 \pm 0.004 \quad \text{(Combined)}$$



Overall correlation coefficient of 0.02 indicates independence of the analyses

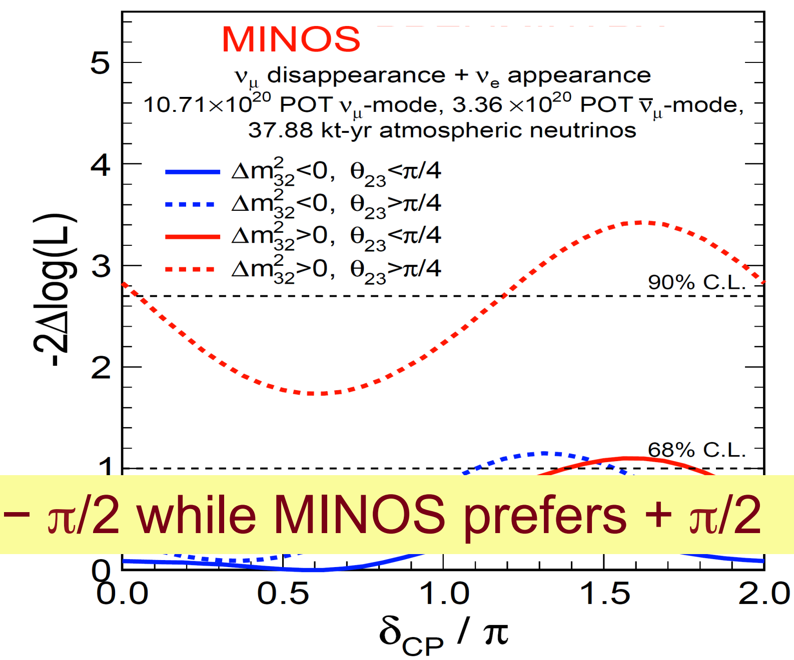
Impact of Reactor Measurement of θ_{13} on δ_{CP} and Comparison with MINOS



Double Chooz	0.090 ± 0.030
RENO	0.088 ± 0.011
Daya Bay	0.084 ± 0.005
Combined	0.0848 ± 0.0045

T2K: Marginalized over Δm^2_{32}, $\sin^2 2\theta_{23}$ and $\sin^2 2\theta_{13}$

Note the x-axis scales are different and the y-axis scales are adjusted to be same

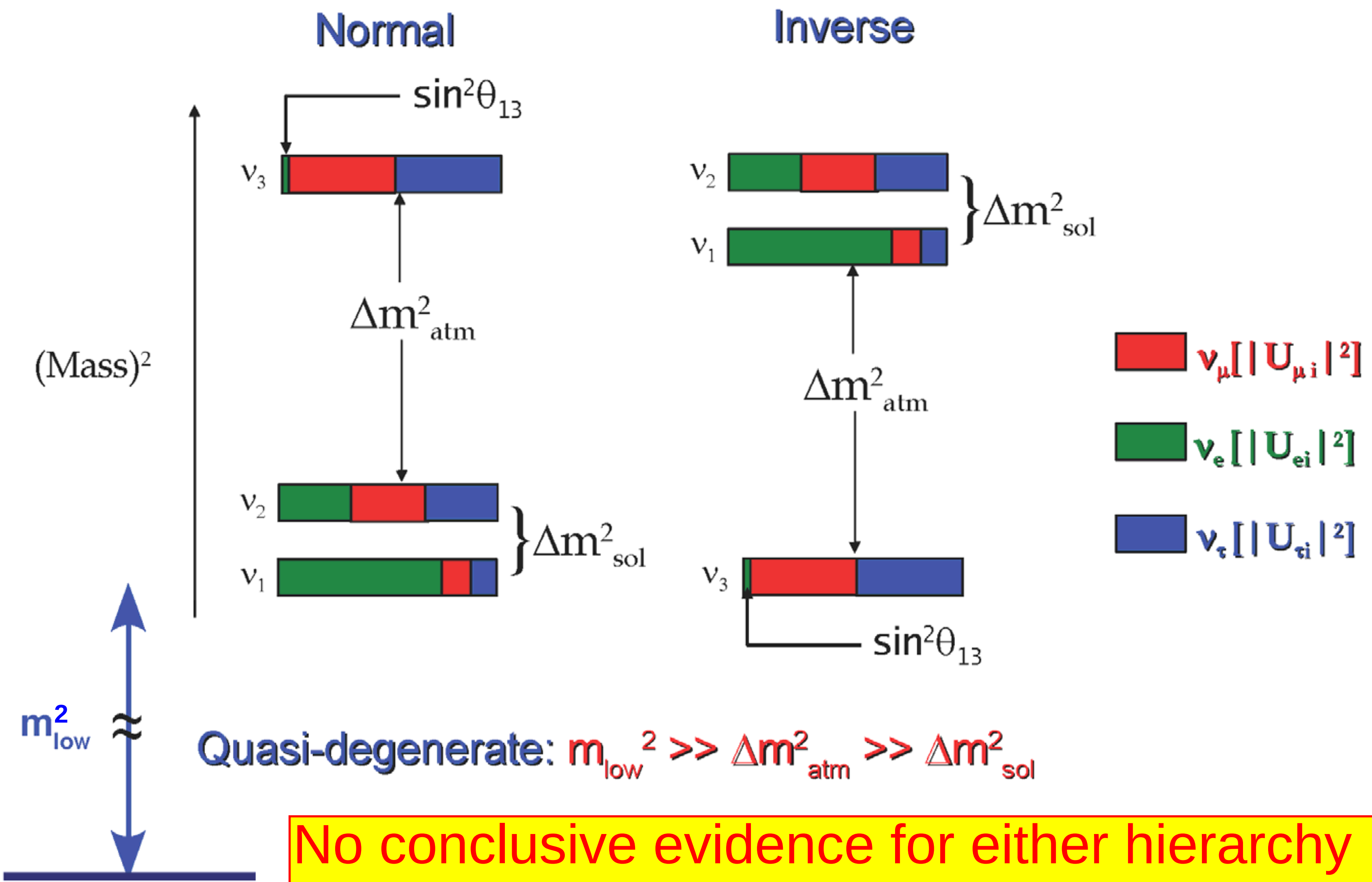


T2K prefers $\delta_{CP} = -\pi/2$ while MINOS prefers $+\pi/2$

Remaining Unknown Neutrino Properties

- θ_{23}> 45°, = 45° (maximal) or < 45°
  → maximal mixing may indicate a profound hidden symmetry
- δ_{CP} (≠ 0, i.e. CPV?)
- Mass ordering (NH or IH?)
- Is PMNS matrix correct description of the lepton sector?
- Any sterile ν
- Absolute m_ν
- Dirac/Majorana

The mass hierarchies



Quasi-degenerate: $m_{low}^2 >> \Delta m^2_{atm} >> \Delta m^2_{sol}$

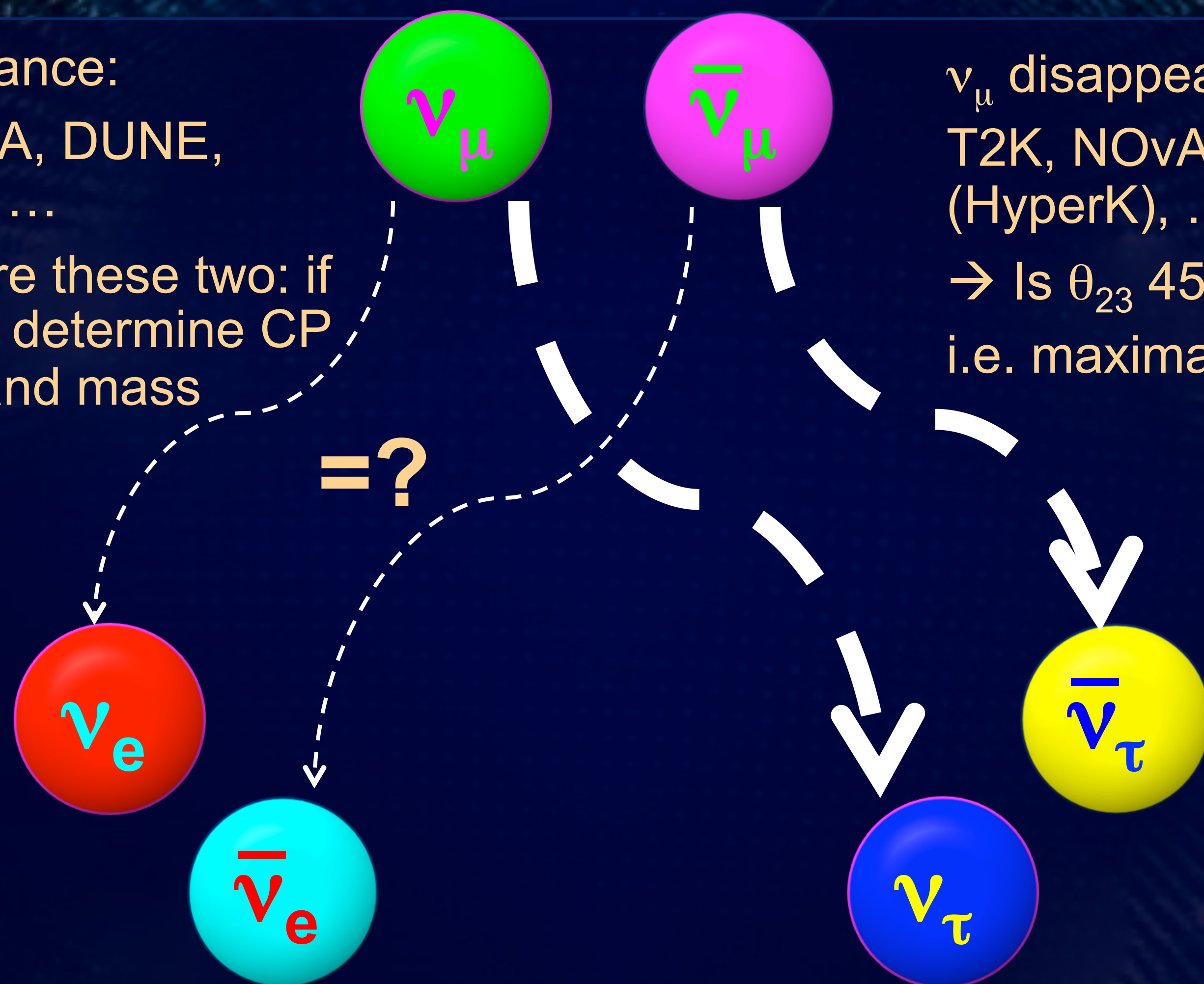
No conclusive evidence for either hierarchy

Physics Goals of Future Long Baseline Accelerator Based Neutrino Oscillation Experiments

ν_e appearance:

T2K, NOvA, DUNE, (HyperK), …

→ compare these two: if not equal, determine CP violation and mass ordering



ν_μ disappearance:

T2K, NOvA, DUNE, (HyperK), …

→ Is θ_{23} 45^o ?

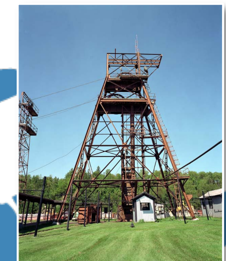
i.e. maximal mixing?

The Breakthrough Prize in Fundamental Physics 2016

- Seven Representatives and Five Groups of Collaborations
  - ¬Super-Kamiokande, K2K/T2K, SNO, KamLAND, Daya Bay
    - SBU NN group is in Super-Kamaiokande, K2K and T2K
- Citation

  “For the fundamental discovery and exploration of neutrino oscillations, revealing a new frontier beyond, and possibly far beyond, the standard model of particle physics”

NOvA



- Long-baseline, off-axis neutrino oscillation experiment
- Study neutrinos from NuMI beam at Fermilab
- At 14 mrad off-axis, energy peaked at 2 GeV
- Functionally identical detectors
  - ND on site at Fermilab
  - FD 810 km away in Ash River, MN
  - Measurement at ND is directly used to predict FD

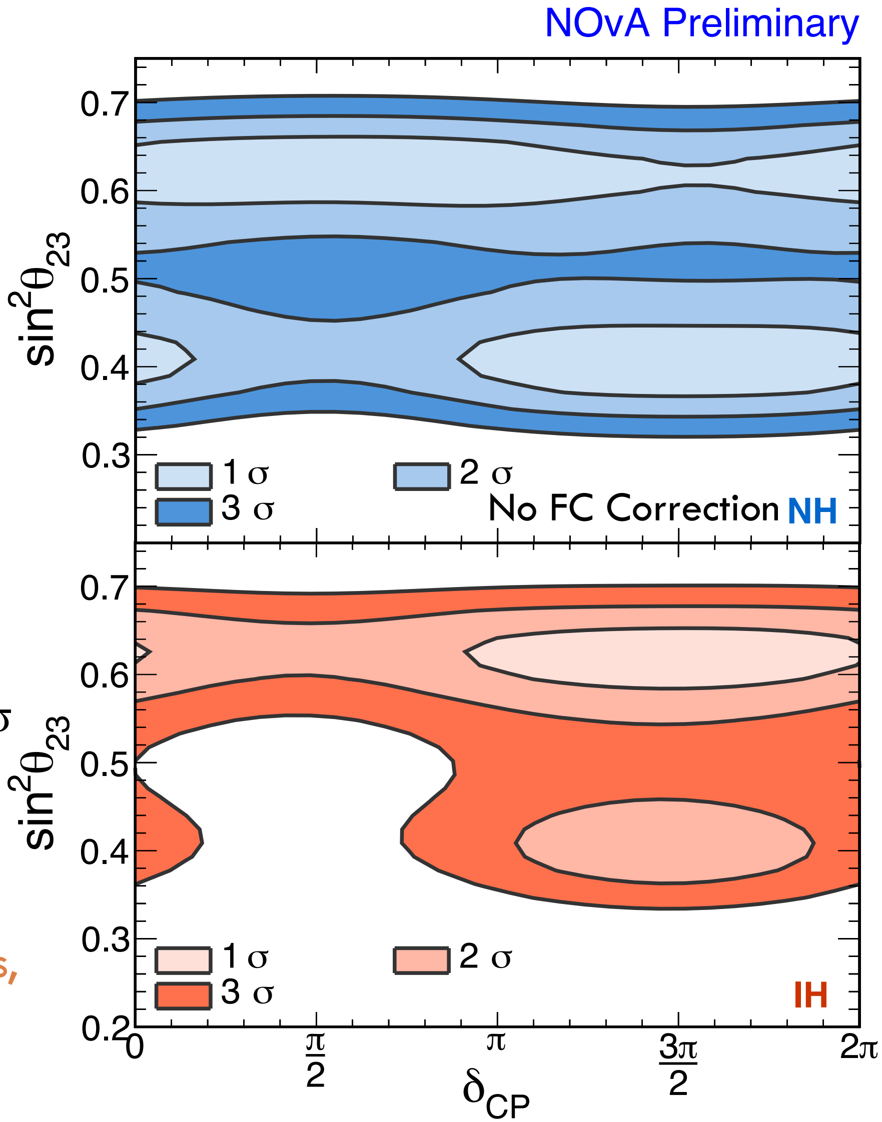
Contours

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated
- Global best fit Normal Hierarchy

$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants and hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around $\delta_{CP}=\pi/2$

Antineutrino data will help resolve degeneracies, particularly for non-maximal mixing
Planned for Spring 2017



The End

Detecting Reactor Neutrinos

Inverse Beta Decay

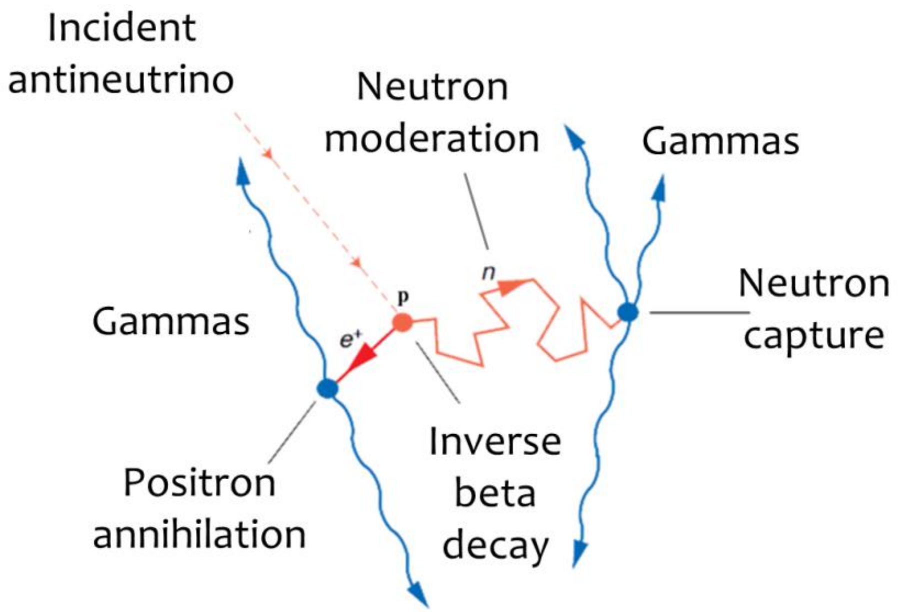
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Prompt signal $e^+ + e^- \rightarrow \gamma s$

Delayed signal

$n + p \rightarrow D + \gamma$ 2.2 MeV 200 μs

$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma s$ 8/8.5 MeV 30 μs

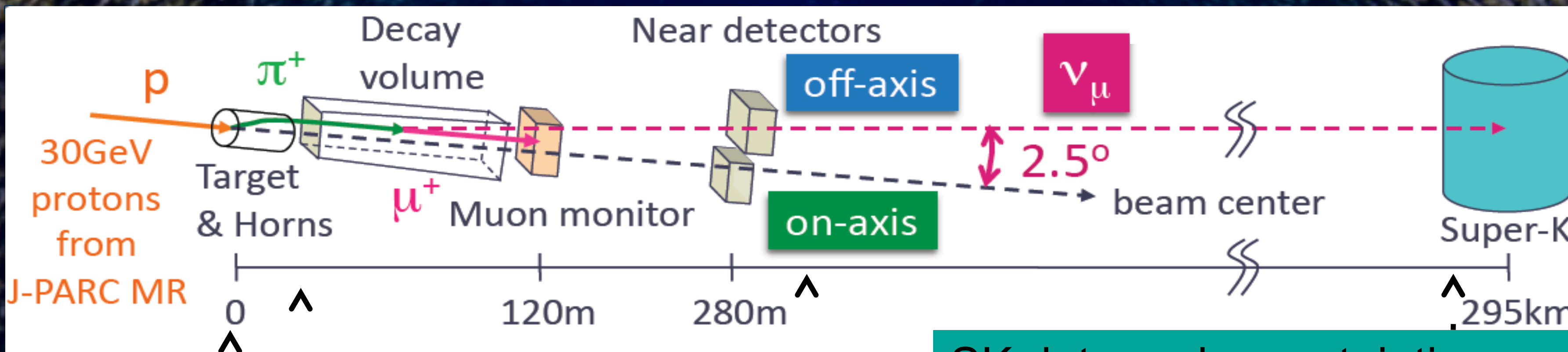


Extract θ_{13} from $\overline{\nu_e}$ deficit

$$\frac{N_{\text{Far}}}{N_{\text{Near}}} = \left(\frac{N_{\text{target,Far}}}{N_{\text{target,Near}}}\right)\left(\frac{L_{\text{Near}}}{L_{\text{Far}}}\right)^2\left(\frac{\varepsilon_{\text{Far}}}{\varepsilon_{\text{Near}}}\right)\left[\frac{P_{\text{survival}}(E, L_{\text{Far}})}{P_{\text{survival}}(E, L_{\text{Near}})}\right]$$

Study Far/Near event ratio and spectral distortion

T2K Experimental Setup and Oscillation Analysis Strategy



SK data and uncertainties (detector and uncorrelated σ)

Fit

Measured oscillation parameters

Near detector data

Fit

Tracking inside horns and He vessel

GEANT3+GCALOR

Φ

Constrained Φ σ

Proton beam interaction in the target

→Hadron production

FLUKA, NA61, etc.

σ

Neutrino-nucleus interactions (NEUT)

MiniBooNE, MINERvA

Predicted Φ and correlated σ at SK

$$\Phi^{SK} \cdot P_{osc} \cdot \sigma^{H2O}_{reaction} \cdot \varepsilon_{SK} dE_\nu$$

Neutrino Oscillations

flavor states — *mass states*

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

production — *propagate*

Parameters: one CP phase, two mass splittings, and three mixing angles

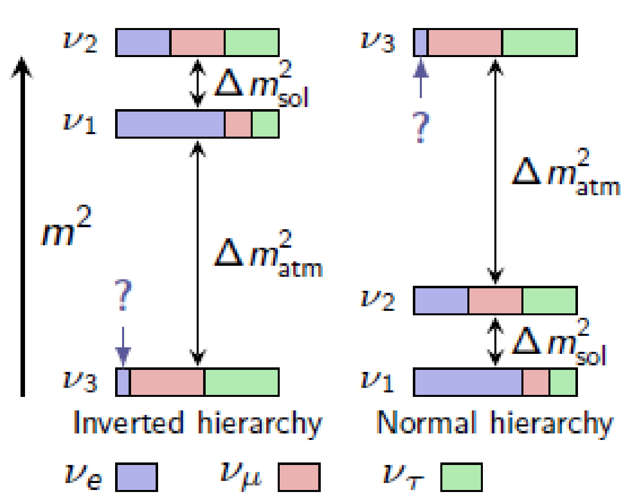
$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

short baseline — **long baseline**

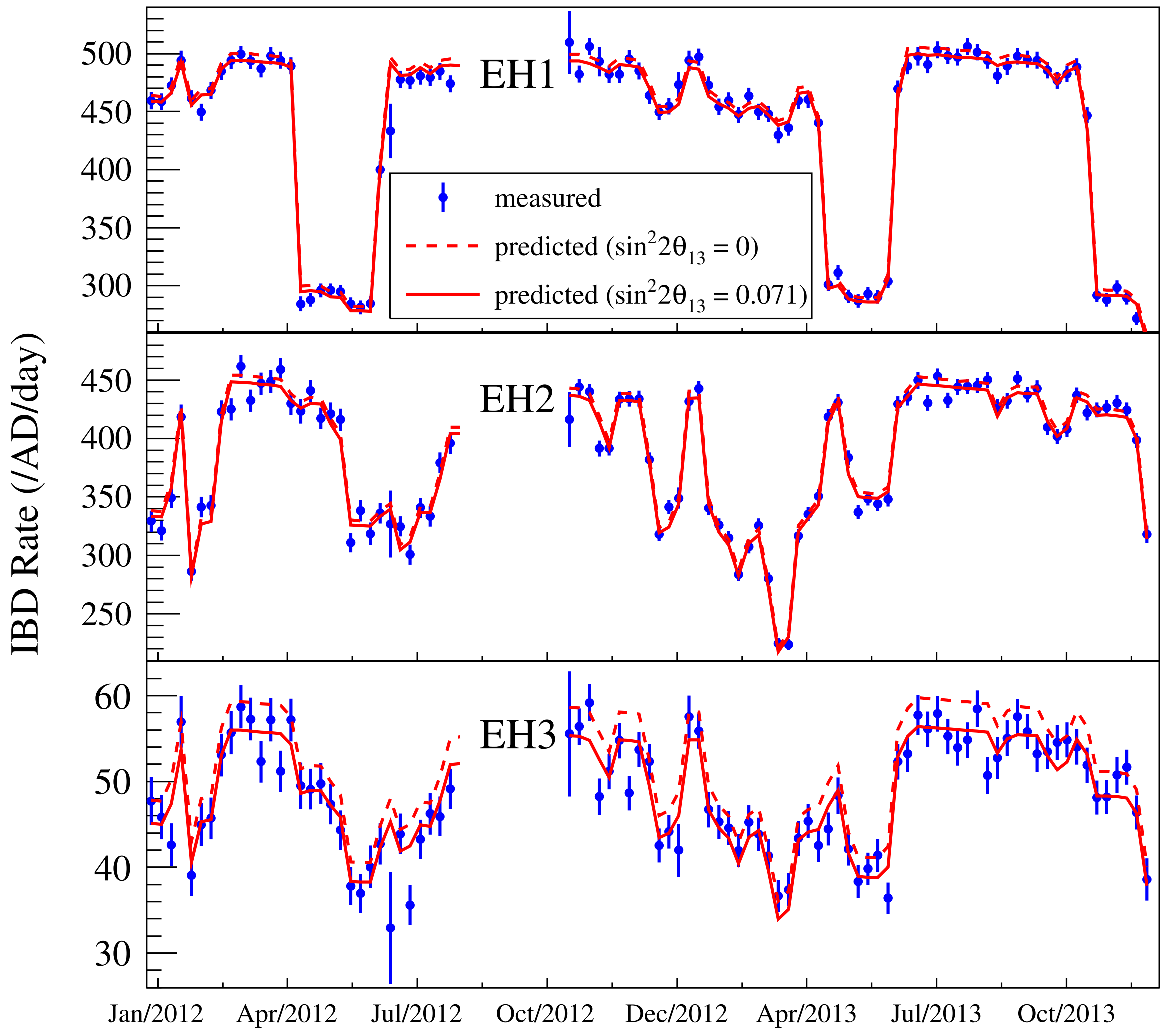
$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\theta_{13}\sin^2(\Delta m^2_{ee}\frac{L}{4E}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta m^2_{21}\frac{L}{4E})$$

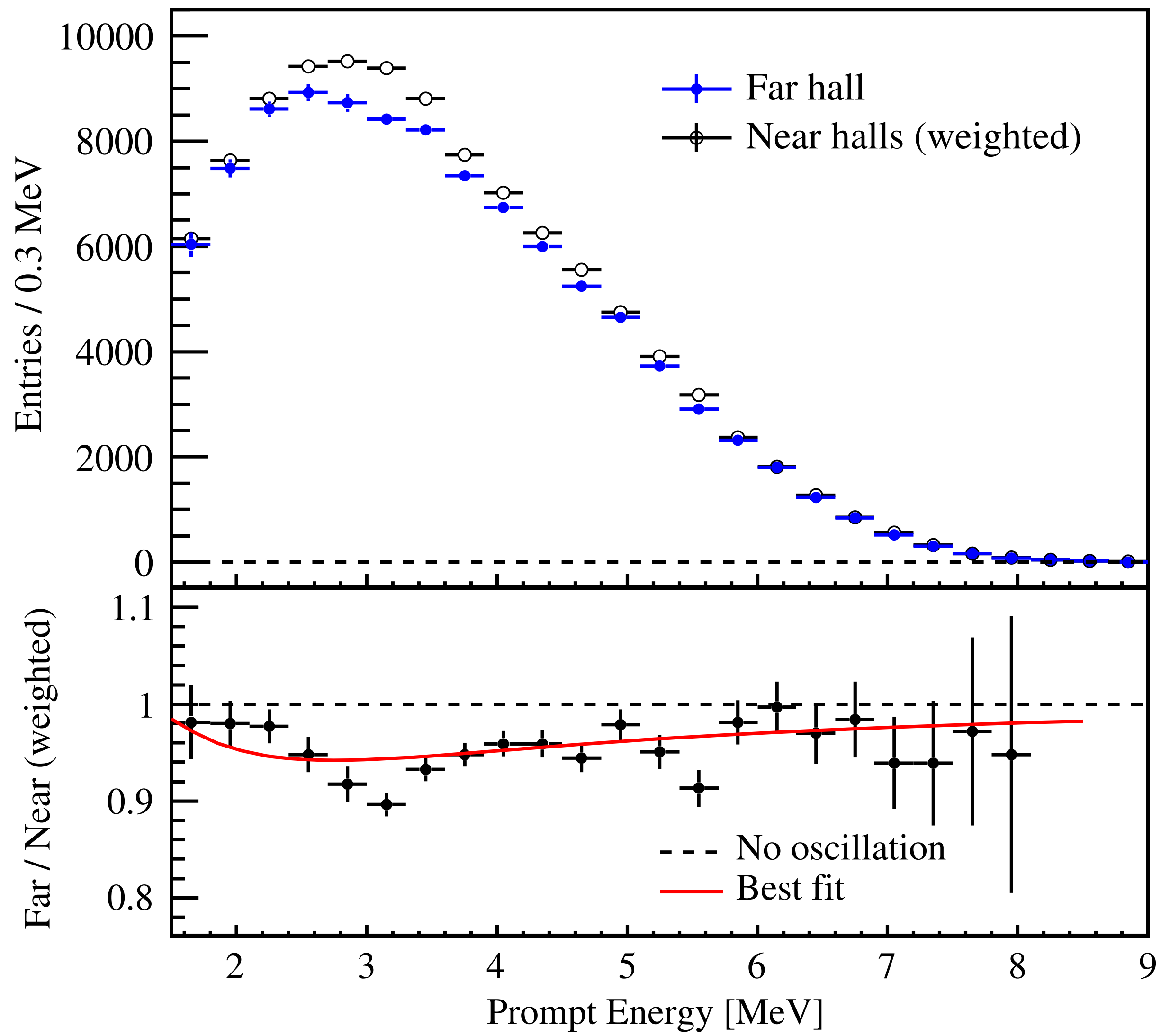
$$\sin^2(\Delta m^2_{ee}\frac{L}{4E}) \equiv \cos^2\theta_{12}\sin^2(\Delta m^2_{31}\frac{L}{4E}) + \sin^2\theta_{12}\sin^2(\Delta m^2_{32}\frac{L}{4E})$$

Remaining unknowns: mass hierarchy and CP Phase



New nH Oscillation Results





- Statistical uncertainty reduced by 49% vs 6AD nH result
- Systematics reduced by 26%
  - *Improved study of cosmogenic backgrounds and neutron capture efficiency*

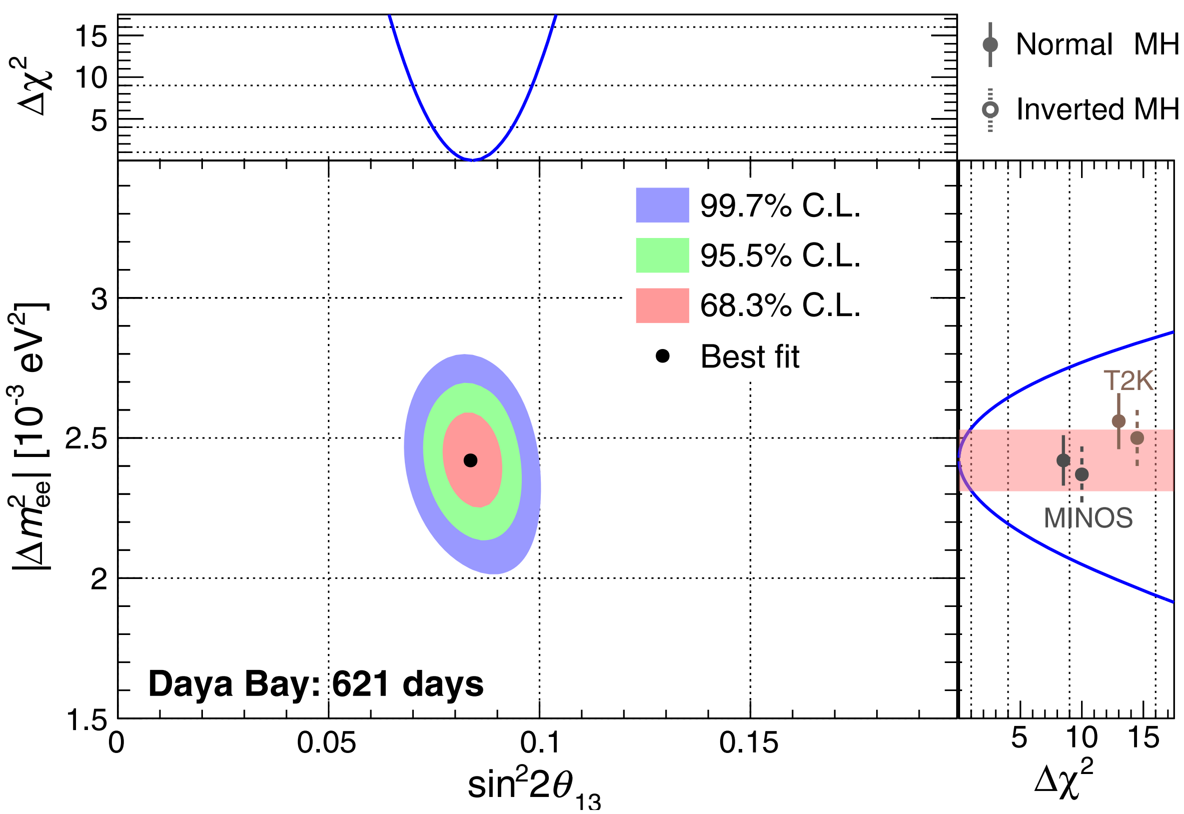
Oscillation analysis based on rate information

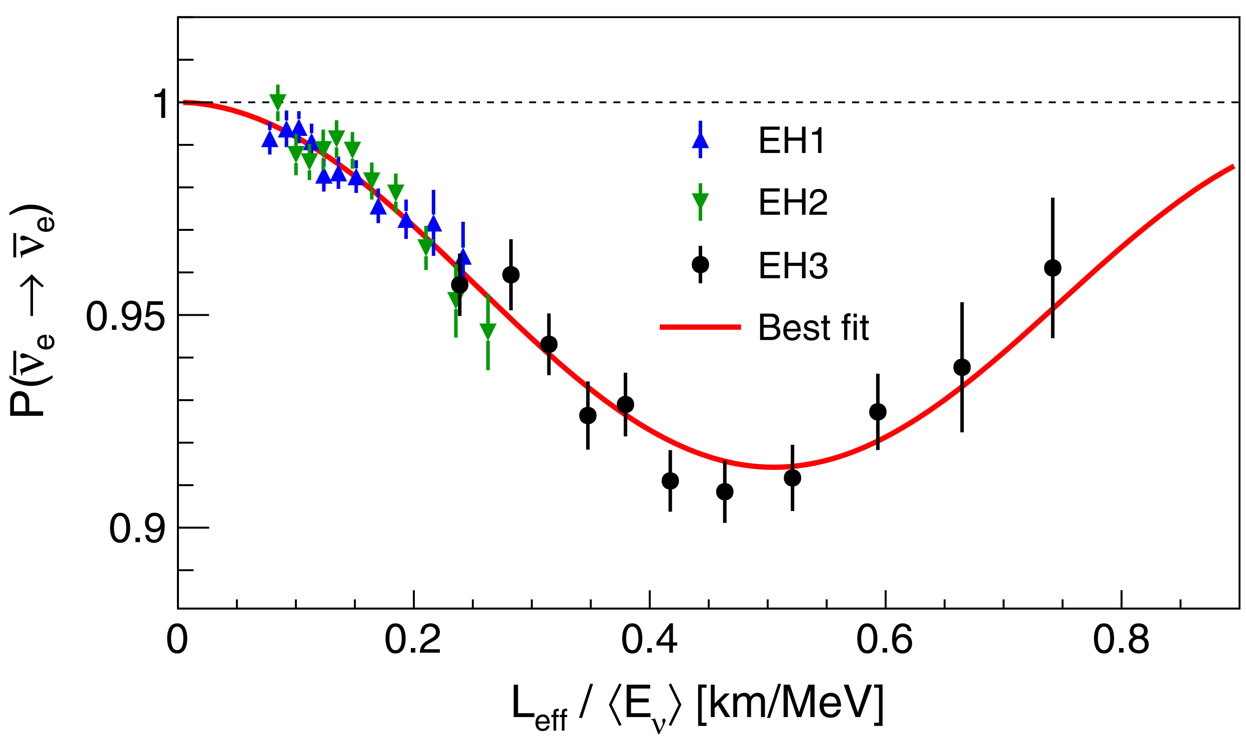
$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

Updated nGd Oscillation

PRL 115, 111802 (2015) PHYSICAL REVIEW LETTERS week ending 11 SEPTEMBER 2015

New Measurement of Antineutrino Oscillation with the Full Detector Configuration at Daya Bay





- Mass splitting consistent with n_mu measurements from Minos and T2K
- Map out full L/E curve using energy information from each experimental hall
  - L_{eff} takes into account multiple detectors and multiple reactor cores
  - E_ν has detector response removed from prompt energy

New nH Oscillation Results

Data Sample:

- Same exposure as recent nGd results

Key Features:

- Independent sample of IBD events
- Different systematics

Challenges:

- Higher accidental backgrounds
- More energy leakage at detector edge

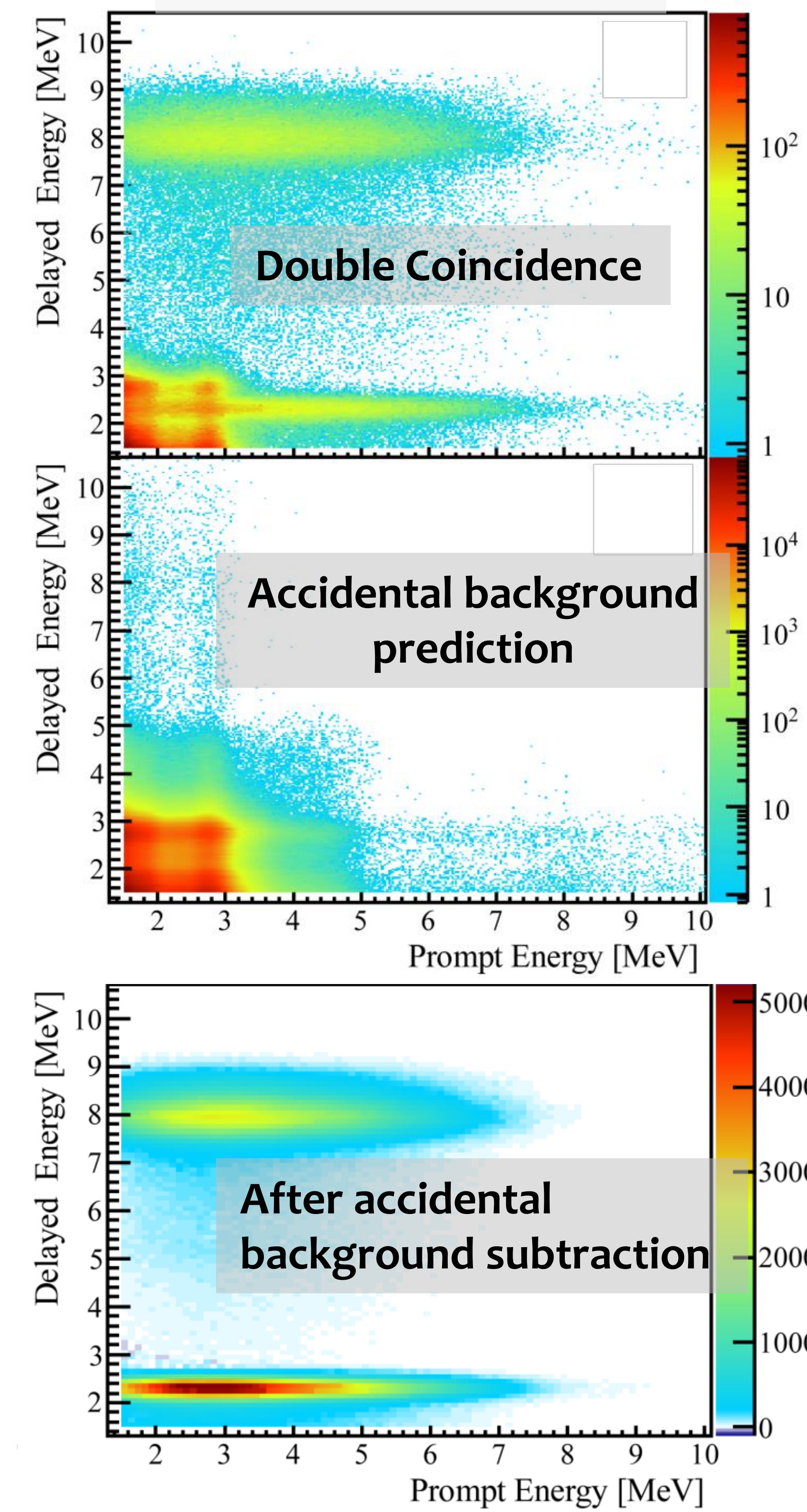
Strategy:

- Prompt Energy Cut: 1.5MeV
- Delay Energy: Peak ±3σ (1.9-2.7MeV)
- Distance between prompt and delay: 0.5m
- Statistical accidental subtraction (from data)

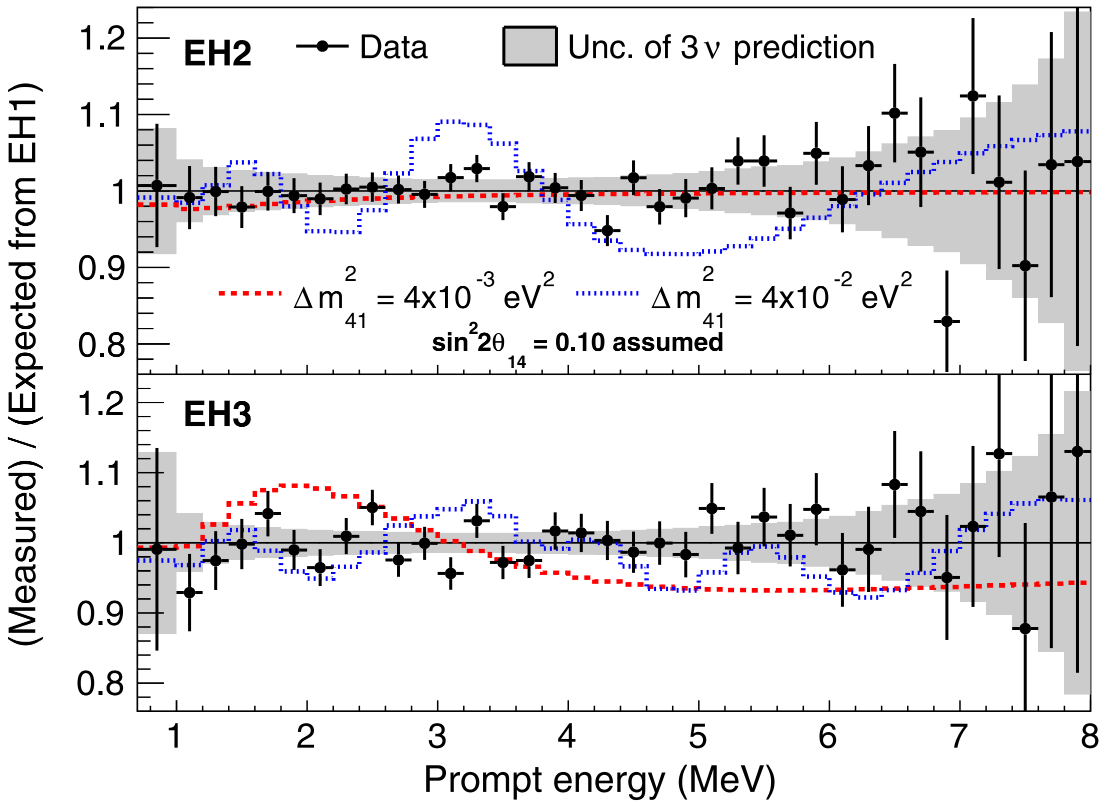
PHYSICAL REVIEW D **93,** 072011 (2016)

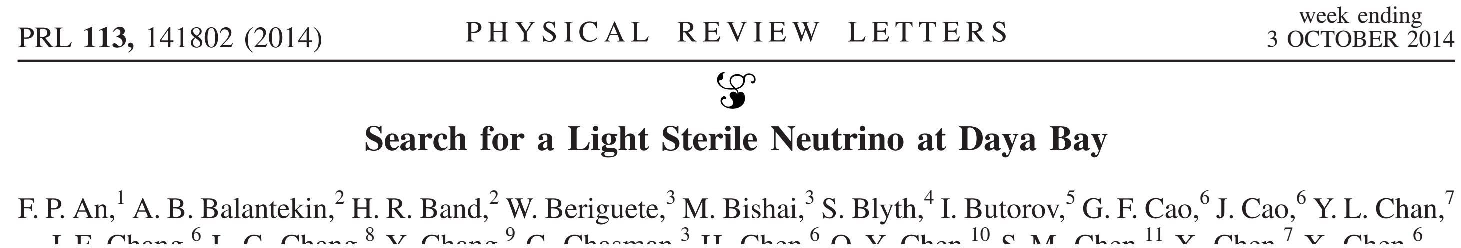
New measurement of θ_{13} via neutron capture on hydrogen at Daya Bay

F. P. An,[1] A. B. Balantekin,[2] H. R. Band,[3] M. Bishai,[4] S. Blyth,[5,6] D. Cao,[7] G. F. Cao,[8] J. Cao,[8] W. R. Cen,[8] Y. L. Chan,[9] J. F. Chang,[8] L. C. Chang,[10] Y. Chang,[6] H. S. Chen,[8] Q. Y. Chen,[11] S. M. Chen,[12] Y. X. Chen,[13] Y. Chen,[14] J. H. Cheng,[10]



Sterile Neutrino Search



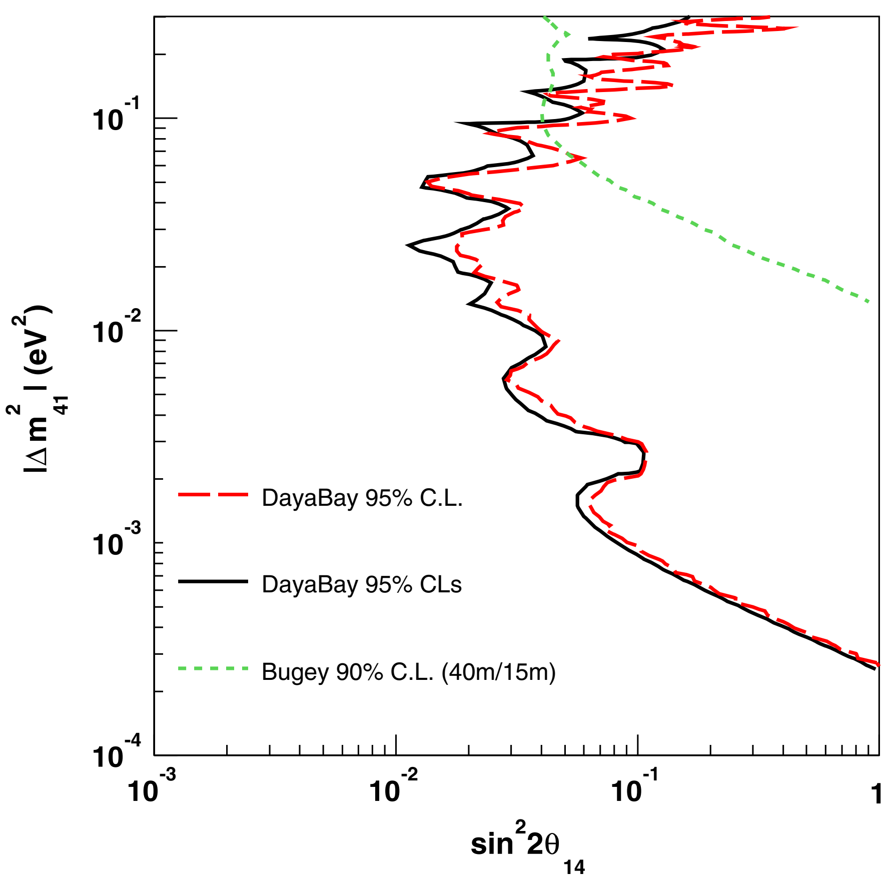


PRL 113, 141802 (2014) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2014

Search for a Light Sterile Neutrino at Daya Bay

F. P. An,[1] A. B. Balantekin,[2] H. R. Band,[2] W. Beriguete,[3] M. Bishai,[3] S. Blyth,[4] I. Butorov,[5] G. F. Cao,[6] J. Cao,[6] Y. L. Chan,[7]

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{14} \sin^2(\Delta m^2_{41} \frac{L}{4E}) - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2(\Delta m^2_{ee} \frac{L}{4E})$$

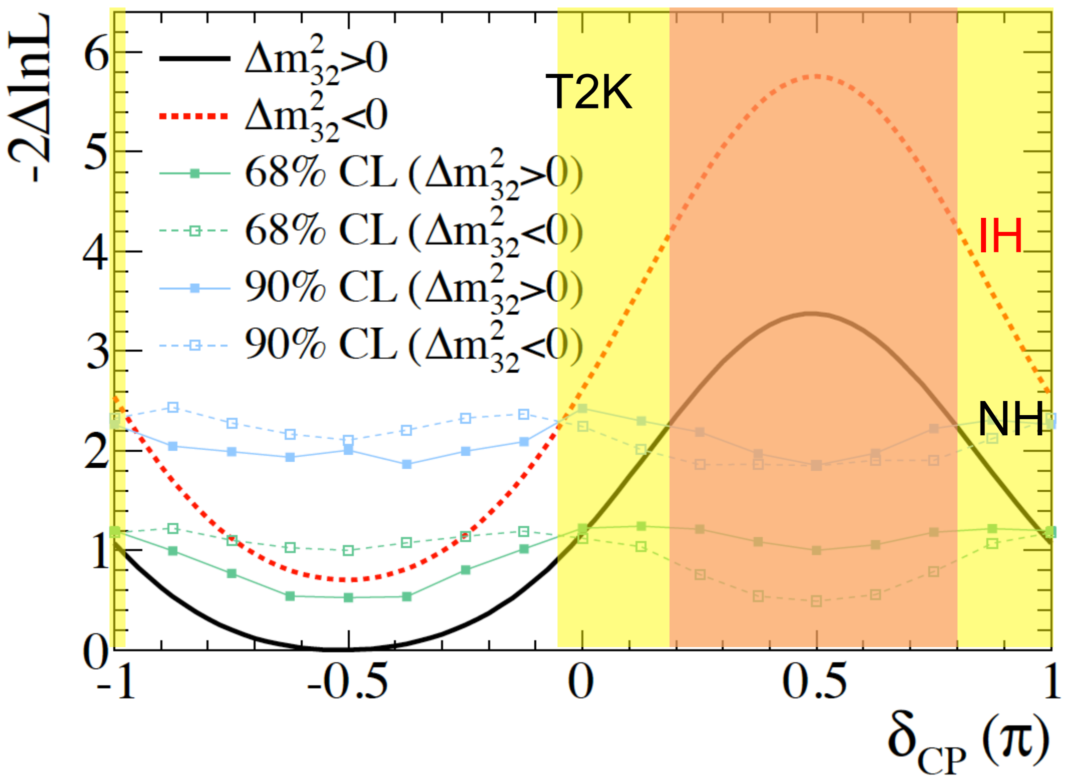


- Multiple detectors at different baselines provide unique probe for sterile neutrinos
- Relative measurement at different baselines
- No significant oscillation observed, consistent with 3-flavor neutrino oscillation
- Most stringent limit in the mass splitting range: $10^{-3}\text{eV}^2 < |\Delta m^2_{14}| < 10^{-1}\text{eV}^2$

First step to measure δ_{CP}
T2K ν_e Appearance Analysis

T2K: Marginalized over Δm^2_{32}, $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$

Best fit values of δ_{CP}: −1.65 (NH), −1.57 (IH)
(Note the physical boundaries at $\pm\pi/2$)



90% C.L. excluded regions using Feldman-Cousins method:

$$\Delta\chi^2 = \chi^2_{true} - \chi^2_{min}$$

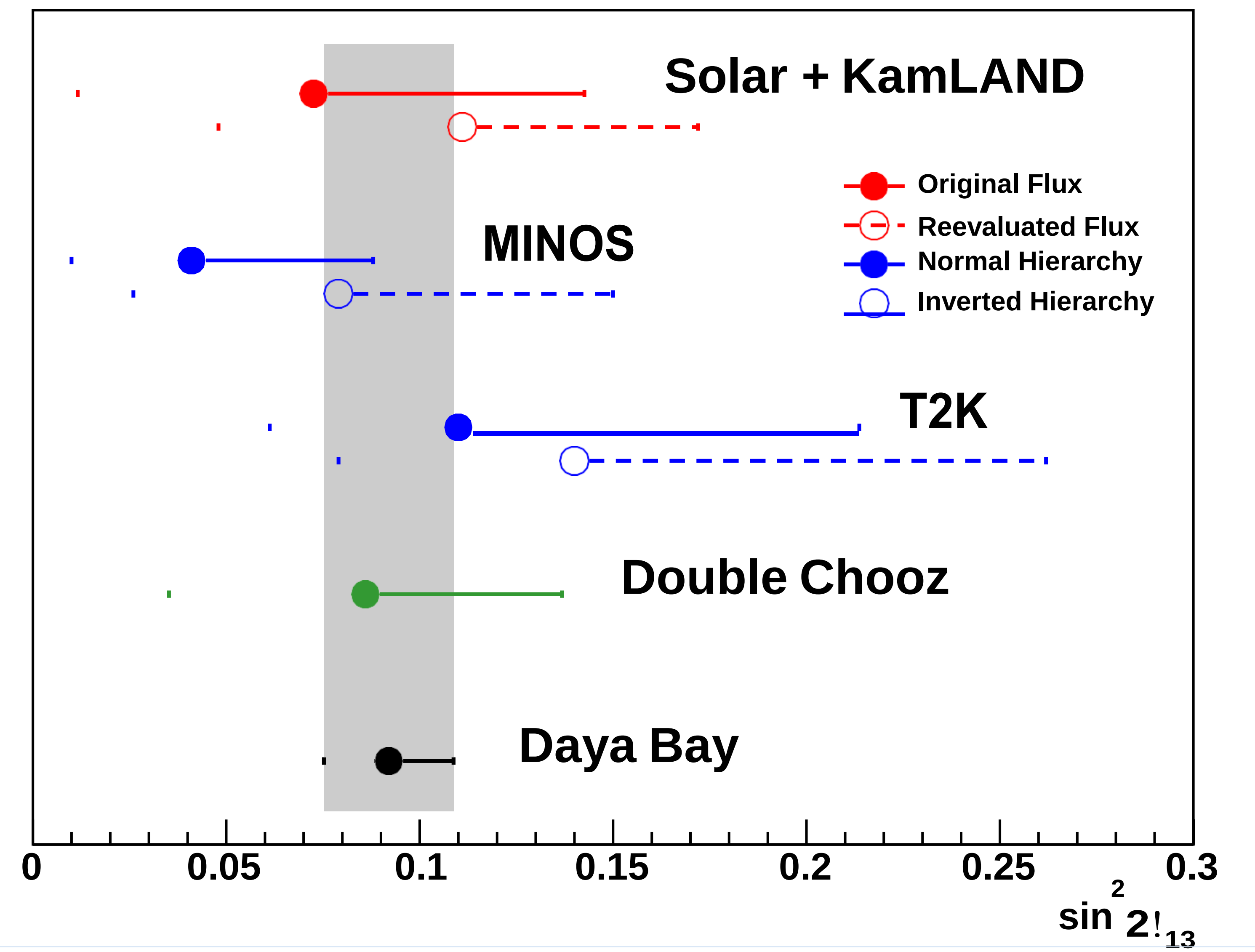
(global minimum)

$$\Delta\chi^2 < \Delta\chi^2_{crit}$$

NH: $0.19\pi < \delta_{CP} < 0.80\pi$,
IH: $-\pi < \delta_{CP} < -0.97\pi$
and $-0.04\pi < \delta_{CP} < \pi$

Theta13 Global

Daya Bay surpasses all existing estimates



Expect more statistics and improvements in analysis

Expected and Observed # of Electron Antineutrino Events at Super-Kamiokande

Normal Hierarchy with actual POT (0.4x10²¹)

Expected events at SK (NH)	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	1.961	2.636	3.288
Background $\nu_\mu \rightarrow \nu_e$	0.592	0.505	0.389
Background NC	0.349	0.349	0.349
Background other	0.826	0.826	0.826
Total	3.73	4.32	4.85

Expectation based on the T2K nu-mode best fit oscillation parameters

Inverted Hierarchy with actual POT (0.4x10²¹)

Expected events at SK (IH)	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.481	3.254	3.939
Background $\nu_\mu \rightarrow \nu_e$	0.531	0.423	0.341
Background NC	0.349	0.349	0.349
Background other	0.821	0.821	0.821
Total	4.18	4.32	4.85

Total number of events at SK so far: 3 !

Landscape of the Current Experimental Data on MH and δ_{CP}

- Emerging Consistent Landscape
  - Normal Mass Hierarchy and δ_{CP} ~ $-\pi/2$ is favored
    - T2K ν_e appearance (neutrino-mode) data
    - T2K antineutrino-mode data
    - Super-Kamiokande atmospheric neutrino data
    - NOvA neutrino-mode data
    - Except MINOS (accelerator + atmospheric neutrino) combined data set
- However, significance of the results is statistically limited

➔ Need next generation experiments for discoveries of ~5 σ level of significance

Conclusions

- 2015 has been a great year for neutrinos w/ Nobel Prize and Breakthrough Prize
  - Reflection of the exciting and remarkable progresses made in the last two decades
- Physics goals for the post non-zero θ_{13} /ν_e appearance era are now clearly defined for the world neutrino oscillation community
  - Determination of δ_{CP}, mass hierarchy and θ_{23} (=0, <45, >45?)
    - We may have an initial hint that $\delta_{CP} = -\pi/2$
  - T2K along with NOvA will lead the world in determining these parameters at least for the next decade
  - Next generation experiments such as DUNE@LBNF should follow in order to ensure the discoveries
- Neutrino oscillation (i.e. the existence of massive neutrino states) is the only phenomena beyond the Standard Model observed in laboratory venue today
- Measurement of CPV in the lepton sector will provide critical experimental input to our understanding of the matter–antimatter asymmetry in the universe
- Nature kindly gave us the non-zero neutrino mixing angles and **ν_e appearance** in order for us to be able to probe CP violation

Summary

- Updated reactor oscillation analyses with enlarged datasets for both nGd and nH selections
- Combined analysis with 621 days of data: $\sin^2 2\theta_{13} = 0.082 \pm 0.004$
- Precision measurements of antineutrino flux and energy spectra performed with 217 days of data:
  - Flux consistent with previous short baseline experiments, Measured/Predicted = 0.946
  - Spectral measurement disagrees with Huber model at 4σ between 4-6MeV
- **Data collection will continue through 2017, precision will continue to improve for all measurements**

4 GOALS OF NEUTRINO OSCILLATION PHYSICS

- Precise determination of Δm^2_{32} and $\sin^2 2\theta_{23}$and definitive observation of oscillatory behavior.
- Detection of $\nu_\mu \to \nu_e$ in the appearance mode. If $\Delta m^2_{\nu_\mu \to \nu_e} = \Delta m^2_{32}$ then $|U_{e3}|^2\,(= \sin^2\theta_{13})$ is non-zero.
- Detection of the matter enhancement effect in $\nu_\mu \to \nu_e$. Sign of Δm^2_{32}; i.e. which neutrino is heavier.
- Detection of CP violation in neutrino physics. Phase of $|U_{e3}|$ is CP violating and causes asymmetry in the rates $\nu_\mu \to \nu_e$ versus $\bar{\nu}_\mu \to \bar{\nu}_e$.

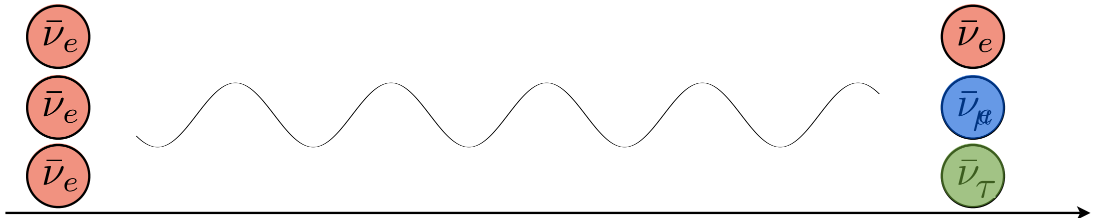
  It will be good to do it all in same experiment with only neutrino beam (no antineutrino).

The Hunt For θ_{13}

neutrino weak eigenstate ≠ mass eigenstate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Oscillation



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

$\theta_{12} \sim 35^\circ$
Solar ν
Long-Baseline Reactor ν

$\theta_{13} < 10^\circ$
Short-Baseline Reactor ν
Accelerator ν

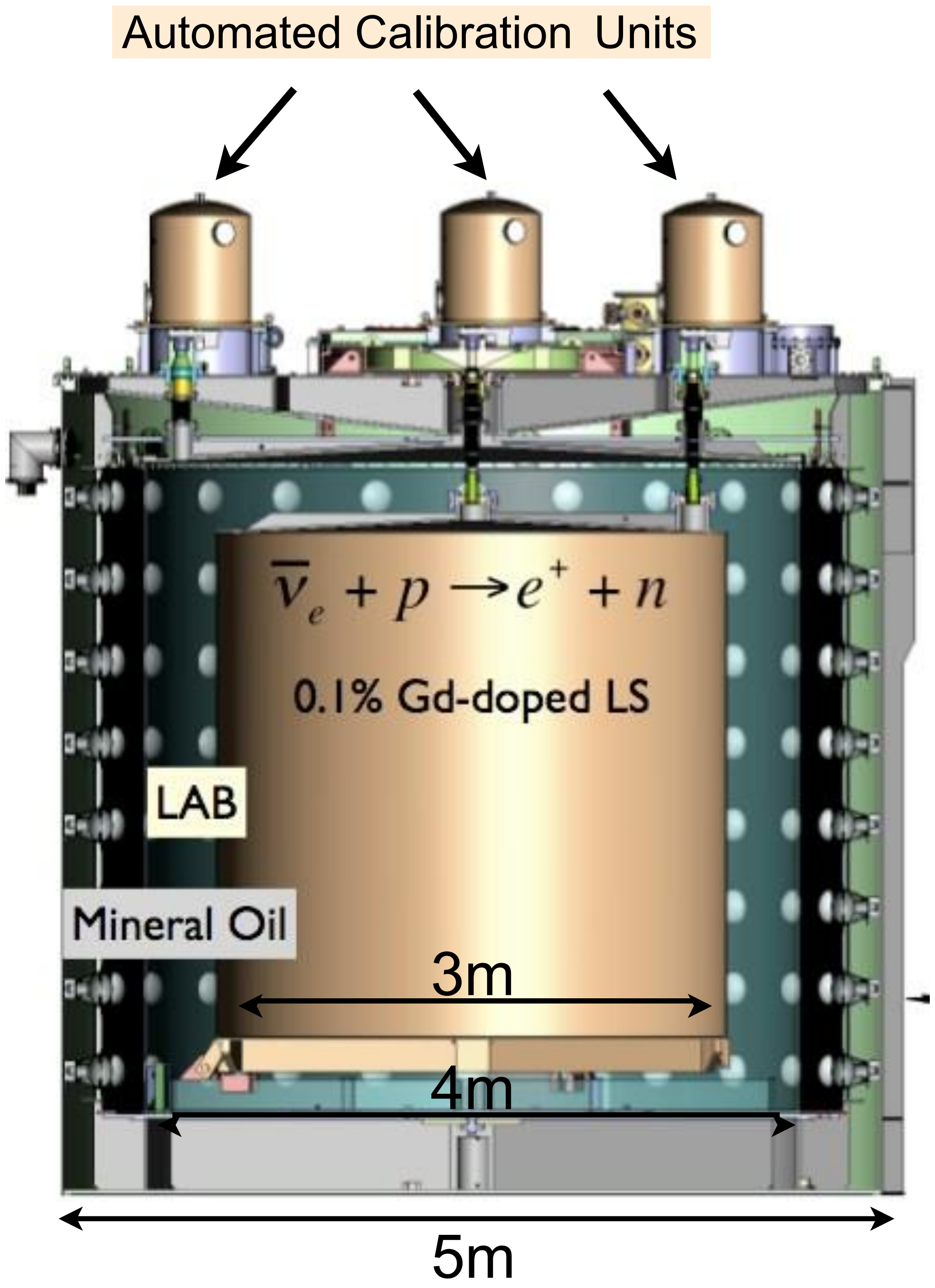
$\theta_{23} \sim 45^\circ$
Atmospheric ν
Accelerator ν

Or big?

θ_{13} is the least known mixing angle

Is it tiny?

Anti-neutrino Detector



6 'functionally identical' detectors

$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

Each detector has 3 nested zones separated by Acrylic Vessels:

- Inner: 20 tons Gd-doped LS (target volume)
- Mid: 20 tons LS (gamma catcher)
- Outer: 40 tons mineral oil (buffer)

Each detector has:

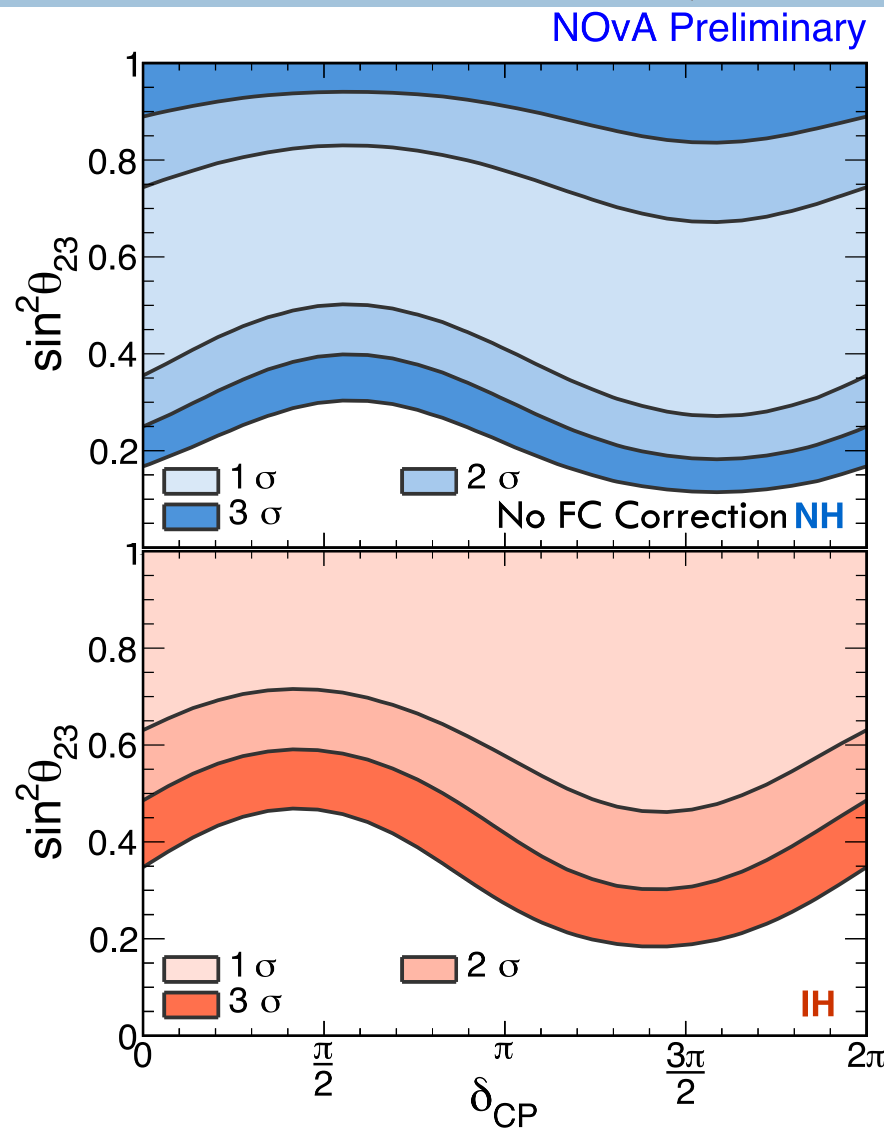
- 192 8-inch Photomultipliers (PMTs)
- Optical reflectors at top/bottom of cylinder
- (7.5/√E[MeV] + 0.9)% energy resolution

Summary of Achievements by the Breakthrough Prize winning Experiments other than SK & SNO

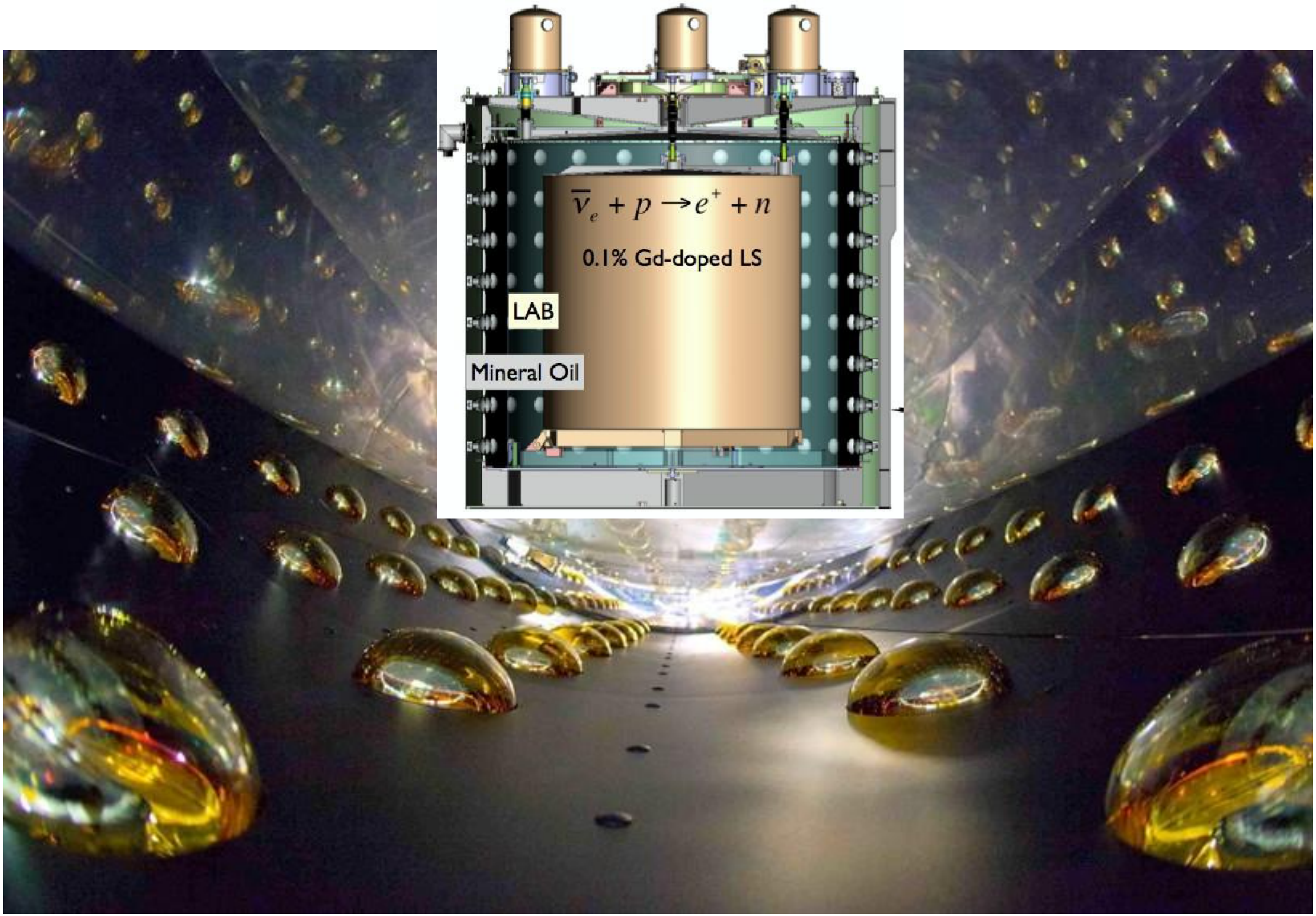
- K2K
  - ¬Confirmation of the SuperK atmospheric neutrino oscillation results w/ accelerator produced neutrino beam
- T2K
  - ¬Discovery of electron neutrino appearance from a muon neutrino beam
- KamLAND
  - ¬Precision measurement of solar neutrino oscillation parameters using reactor neutrinos
- Daya Bay
  - ¬Measurement of non-zero θ_{13} using reactor neutrinos

Contours

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain $\sin^2(2\theta_{13})=0.085\pm0.05$
  - Constrain $\Delta m^2=2.44\pm0.06\times10^{-3}\ eV^2$ $(-2.49\pm0.06\times10^{-3}\ eV^2, IH)$
  - Systematic effects included as nuisance parameters (normalization, flux, calibration, cross section, and detector response effects)



Interior of Antineutrino Detector



Current Status of Neutrino Oscillation Parameter Measurements

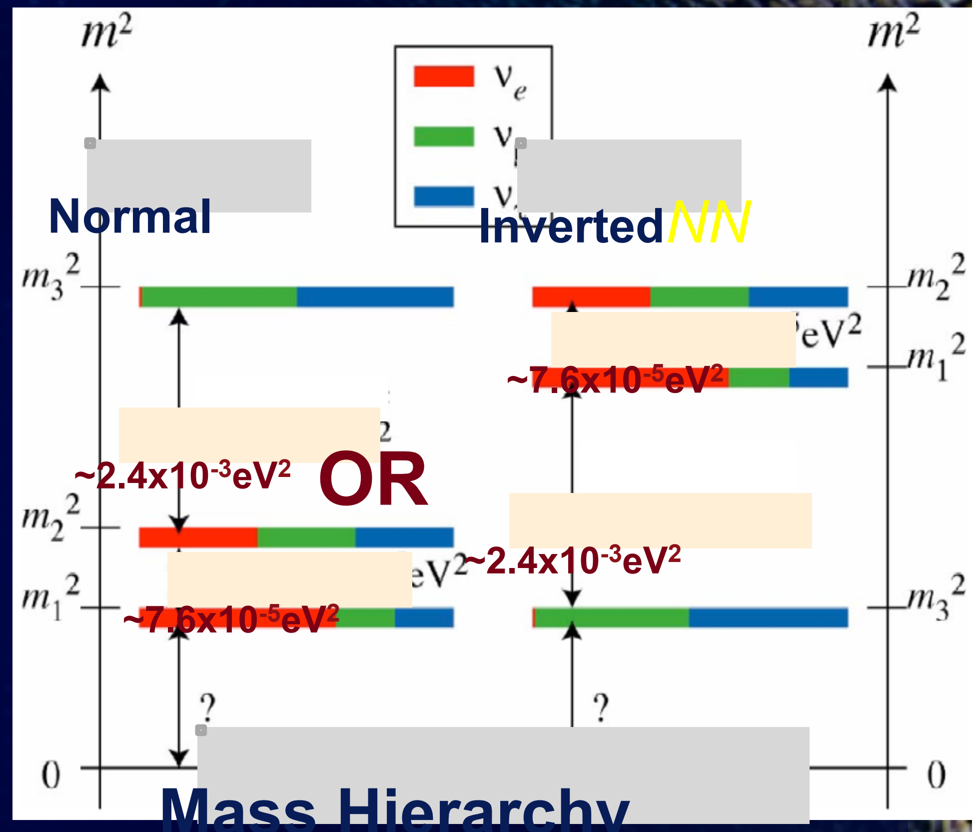
- Remarkable progress!
- All mixing angles are now known
  - θ_{12} = 33.9° ± 1.0°
  - θ_{13} = 8.4° ± 0.4°
  - θ_{23} = 45° ± 6° (90% C.L.)
    → largest uncertainty

All three angles are non-zero and relatively large

→ allows exploration of CPV in the lepton sector

$P(\nu_\mu \rightarrow \nu_e)$

$\propto$ leading term + …
+ term($\sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\sin\delta_{CP}$)



Critical for the ν-less double-β decay searches that would determine the Majorana-nature of ν