Neutrino Mixing and the Search for CP Violation

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HEP 2015

Developments in High Energy Physics and Cosmology

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UNIVERSITY OF LIVERPOOL

A century of elusive neutrinos

- 1930: proposed by Pauli
  - 1934: beta decay theory, including neutrino, by Fermi
- 1956: observation of the neutrino (Reines, Cowan)
- 1957: the neutrino is left-handed (Goldhaber)
- 1962: muon-neutrino discovery at the AGS (Brookhaven)
- 1963: neutrino mixing proposed by Pontecorvo, Nakagava (PMNS)
- 1968: solar neutrino problem in Davis experiment first results
- 1973: ν-e elastic scattering at CERN (discovery of neutral currents)
- 1999: Super-Kamiokande establishes atmospheric neutrino oscillations
- 2001: SNO establishes solar neutrino oscillations
- 2003-05: KAMLAND & K2K observe man-made neutrino oscillations
- 2012-13: T2K, Daya Bay, RENO establish large θ_{13}
- 2015-20: T2K, NoVA searching for MH, evidence of CPV
- 2025-35: DUNE, T2HK to discover CPV, measure "unitarity triangle"

Neutrinos: facts and open questions

- ✓ No neutrino mass term (mechanism) in Standard Model
- ✓ 3 mass eigenstates (ν_1, ν_2, ν_3) mixing into 3 WI eigenstates (ν_e, ν_μ, ν_τ)

- ? Unitarity of mixing matrix – extra states (steriles)
- ? Mass Hierarchy (MH)
- ? CP Violation
- ? θ_{23} exactly 45°; octant

- ➢ Baryon Asymmetry: Leptogenesis?
- ➢ Inflation and Unification (coincidences?):
  - ➢ Seesaw, heavy neutrinos ~10^{14}GeV
  - ➢ Inflation field ~10^{13}GeV
  - ➢ Interaction unification ~10^{16}GeV

3 neutrino mixing

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

flavour states — PMNS matrix — mass states

$$U_{PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{bmatrix} \begin{bmatrix} C_{13} & 0 & S_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -S_{13}e^{+i\delta_{CP}} & 0 & C_{13} \end{bmatrix} \begin{bmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric, ν_μ Long BL — ν_μ Long BL, reactor Short BL — Solar, reactor Long BL

C_{ij} (S_{ij}) represent $\cos\theta_{ij}$ ($\sin\theta_{ij}$), δ_{CP} the CP violating phase

Majorana phases ignored

Neutrino oscillation probability

- 2-neutrino mixing

In vacuum (no matter effect)

$$P(\nu_\alpha \rightarrow \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

Amplitude determined by mixing angle θ

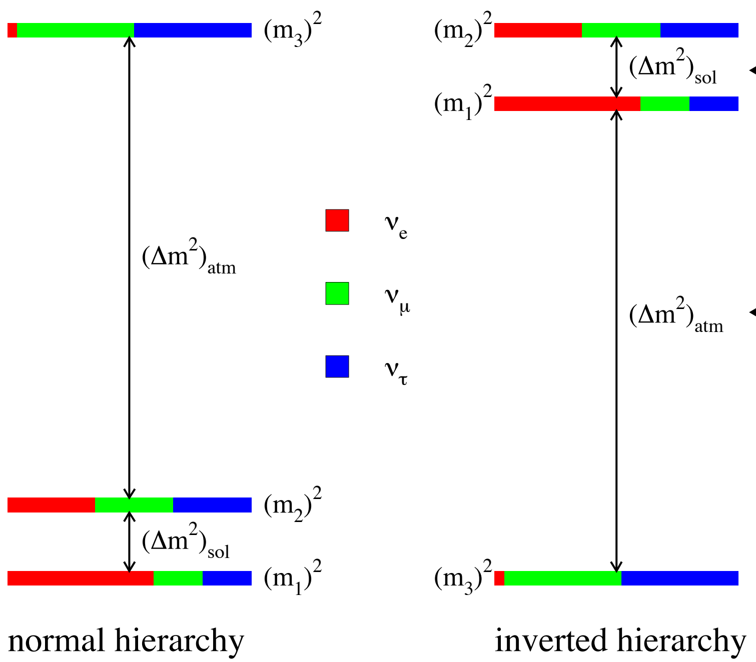
Frequency determined by mass splitting Δm and L/E

- 3-neutrino mixing including matter effect

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = \; & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \boxed{\cos \delta_{CP}} - S_{12} S_{13} S_{23}) \cos \Phi_{32} \sin \Phi_{31} \sin \Phi_{21} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \boxed{\sin \delta_{CP}} \sin \Phi_{32} \sin \Phi_{31} \sin \Phi_{21} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \boxed{\cos \delta_{CP}}) \sin^2 \Phi_{21} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E_\nu} \cos \Phi_{32} \sin \Phi_{31},
\end{aligned}
$$

$\Phi_{ji} = \Delta m_{ji}^2 L / 4E_\nu$ $\quad a \equiv 2\sqrt{2} G_F n_e E_\nu$

Mass hierarchy



We know:

$$m_1^2 < m_2^2$$

$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

Oscillations sensitive to $|\Delta m^2|$

Matter effect in the Sun determines sign of Δm_{12}^2

MH sensitivity of Long BL experiments improves with distance (DUNE > T2HK)

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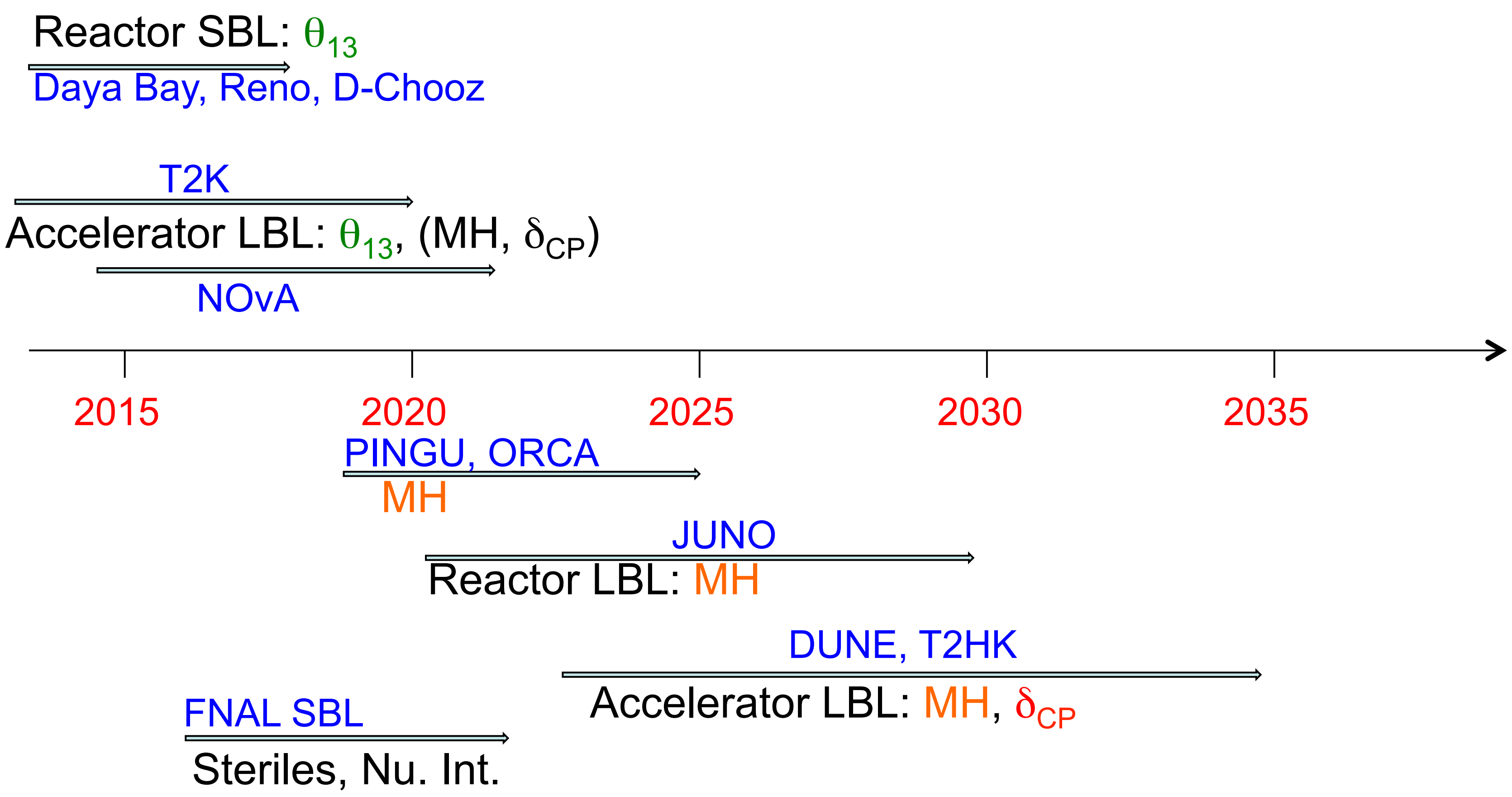
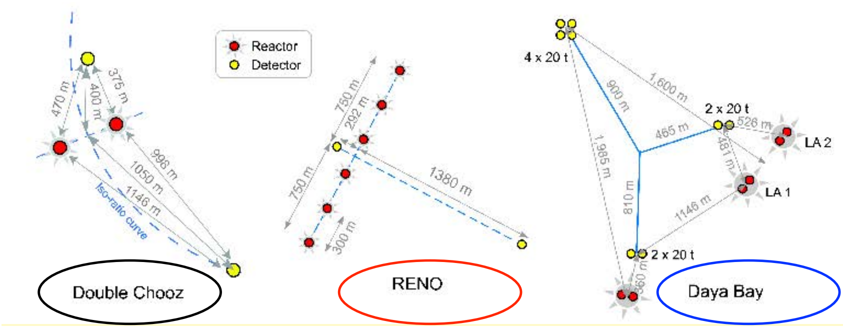
Neutrino oscillation experiments

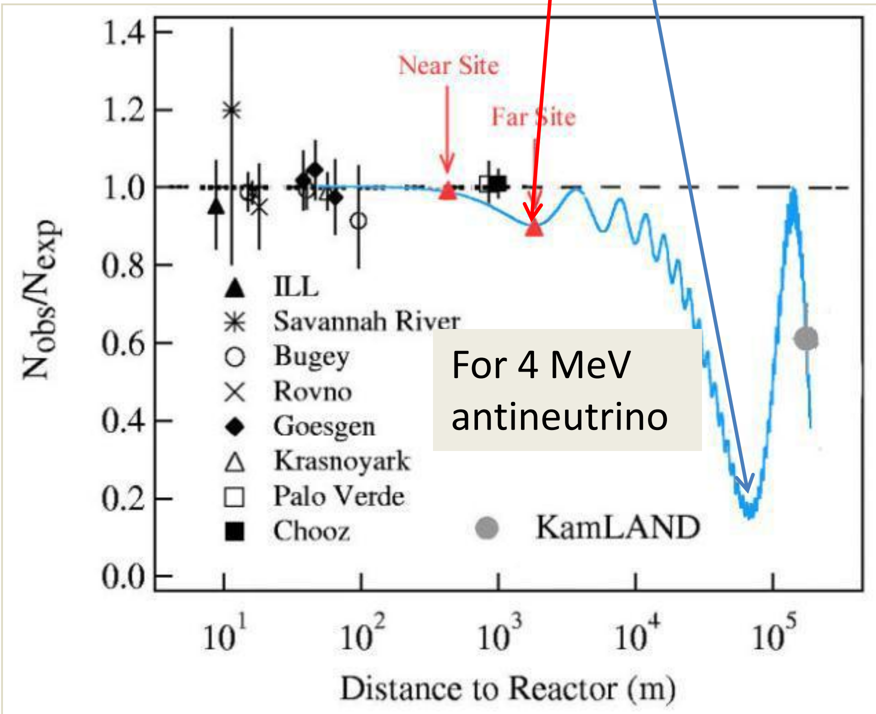


Reactor Short BaseLine experiments

- 2-neutrino mixing (ν_e disappearance)
- No parameter degeneracy
- Clean measurement of θ_{13}
- Liquid scintillator
  - Gd doping: increases neutron capture efficiency
- High statistics
- Near & Far detectors: control systematics

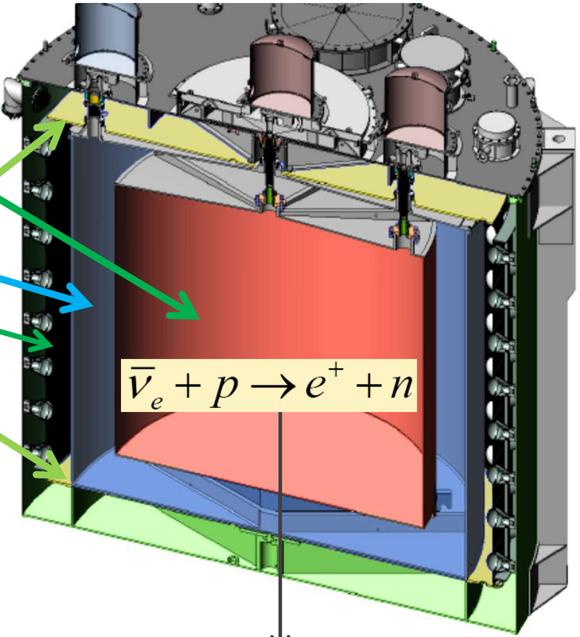
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(\frac{\Delta m^2_{ee} L}{4E_\nu}) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\frac{\Delta m^2_{21} L}{4E_\nu})$$



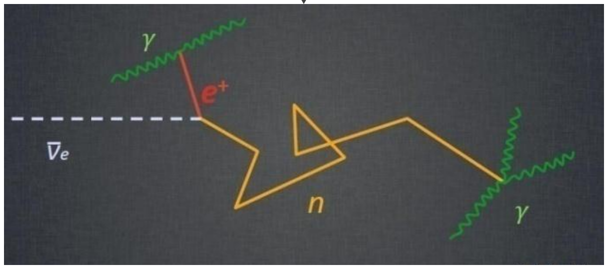


A Daya Bay detector

- Three zones structure:
  - Target: 20 t 0.1% Gd-loaded scintillator
  - γ-catcher: 20 t scintillator
  - Buffer shielding: mineral oil
- Top and bottom optical reflectors double the photon coverage.
- 192 8'' PMTs collect ~160 p.e./MeV

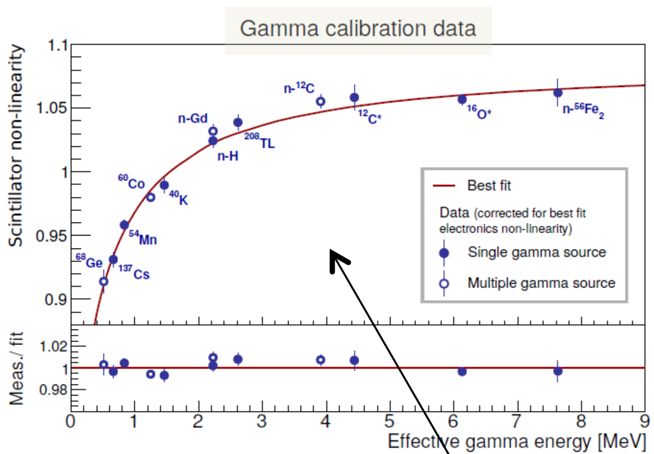


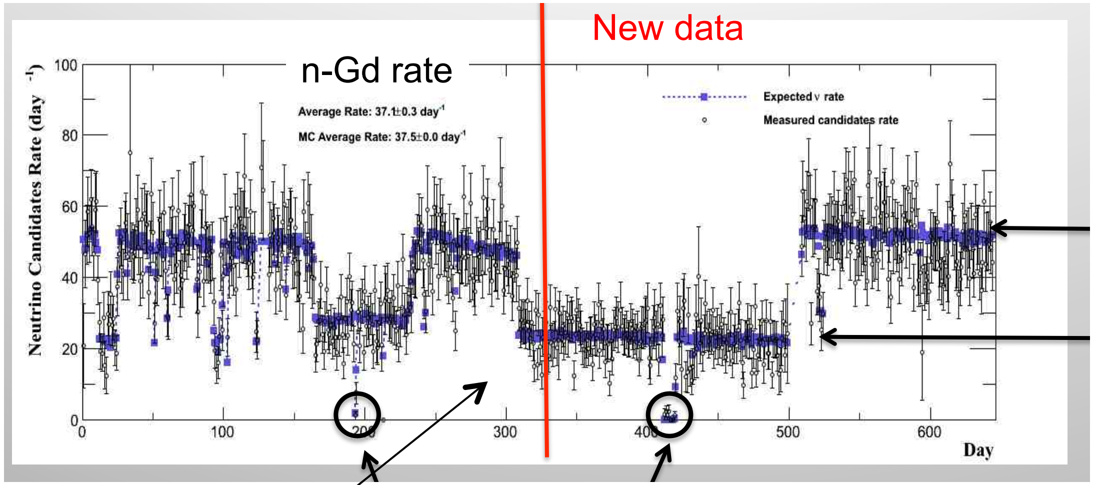
8 identically designed detectors to reduce systematic uncertainties



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

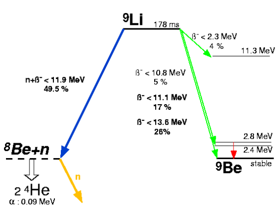
Reactor experiment systematics control

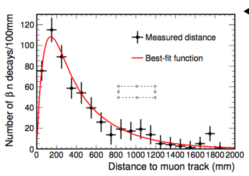




Energy non-linearity, Daya Bay

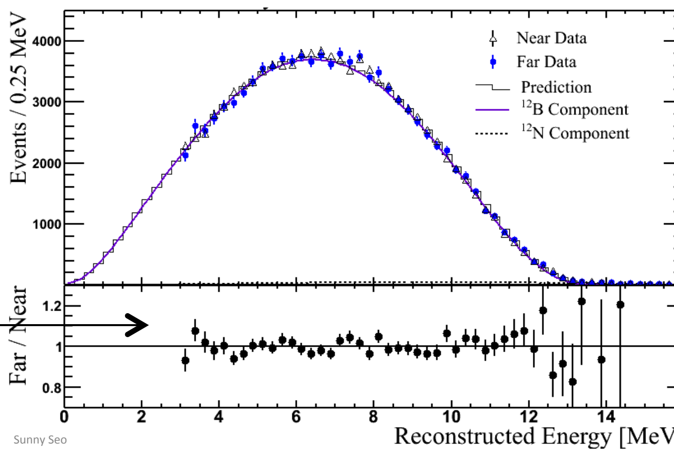
Rate vs reactor power, D-Chooz



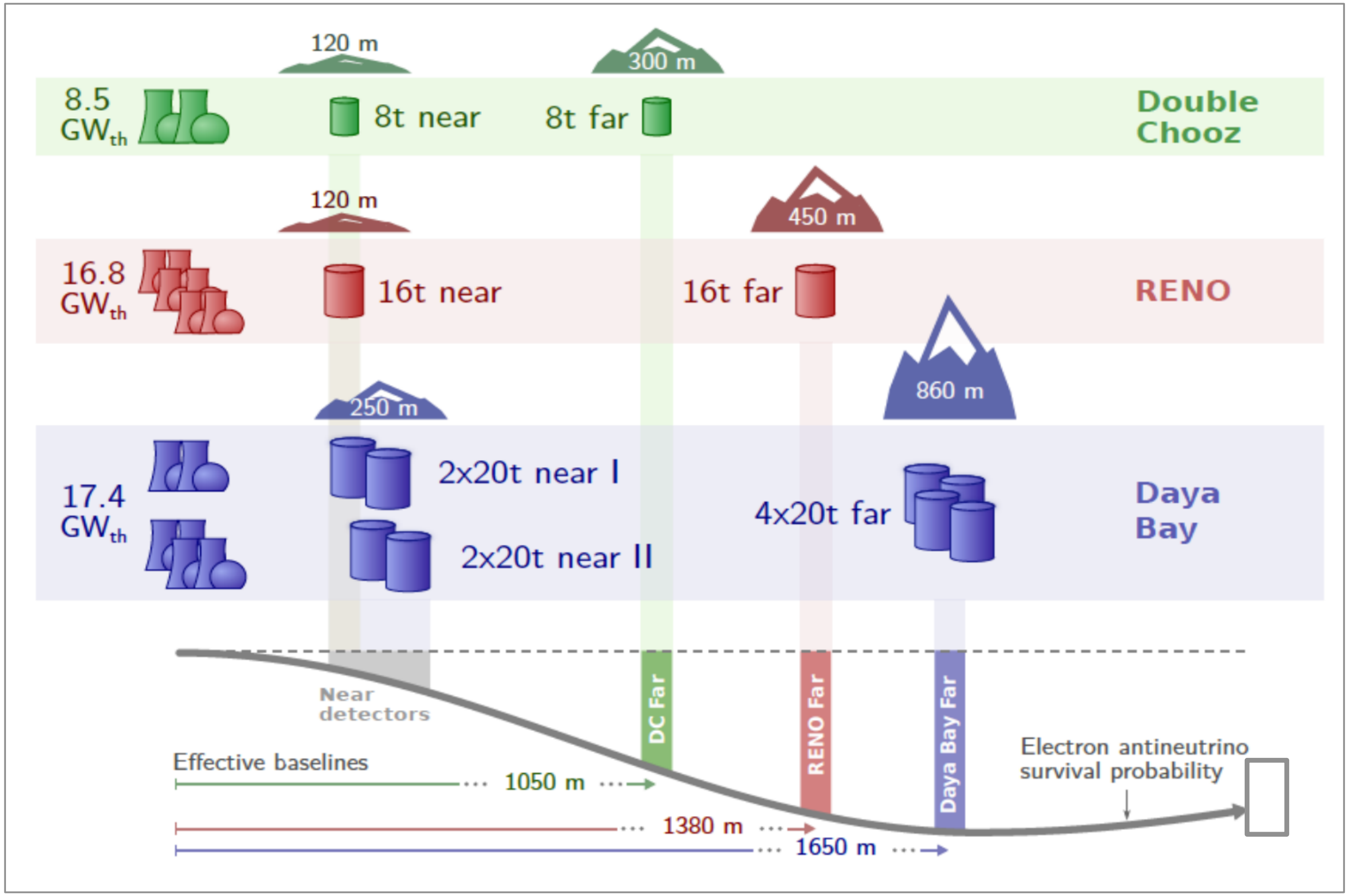


Cosmogenics: ^{9}Li, D-Chooz

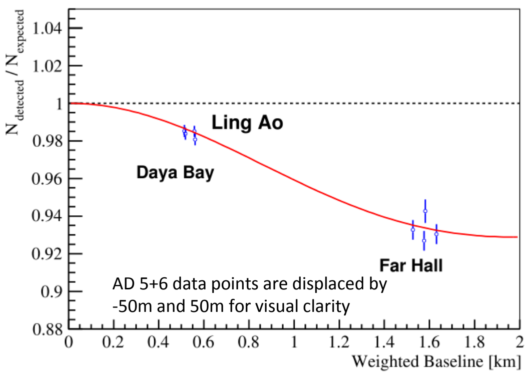
Far-Near efficiency, ^{12}B spectrum, RENO

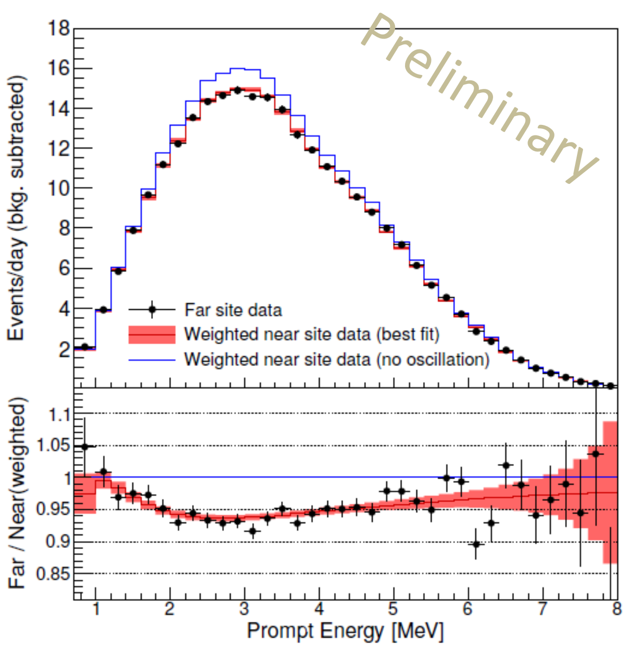


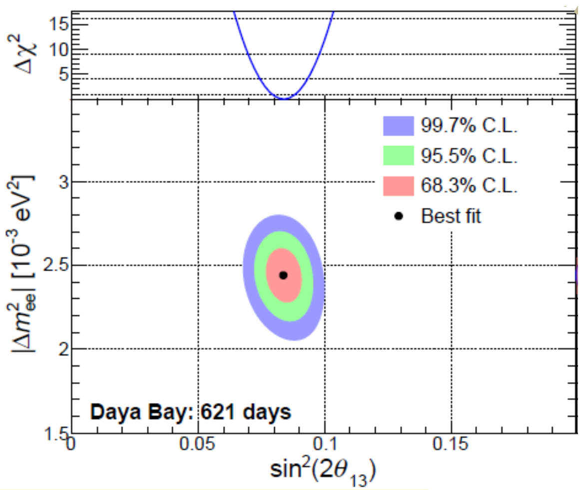
Reactor measurements of θ_{13}



Reactor results



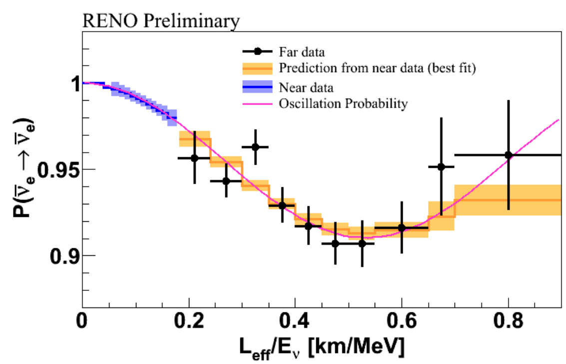




$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

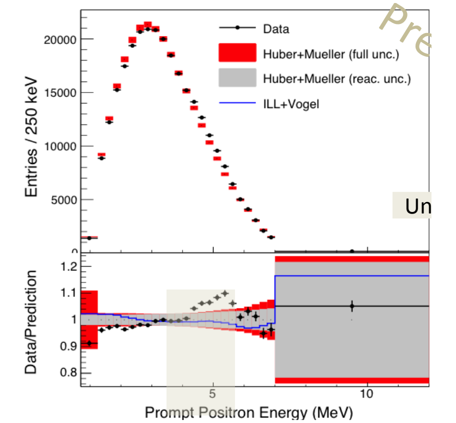
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3} (eV^2)$$

$$\chi^2 / NDF = 134.7/146$$

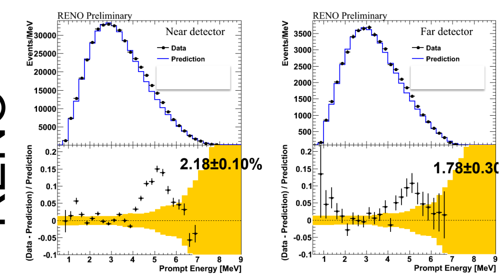


5MeV bump

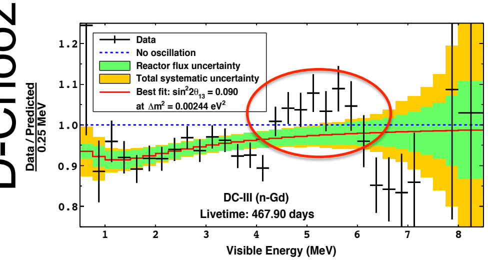
Daya Bay



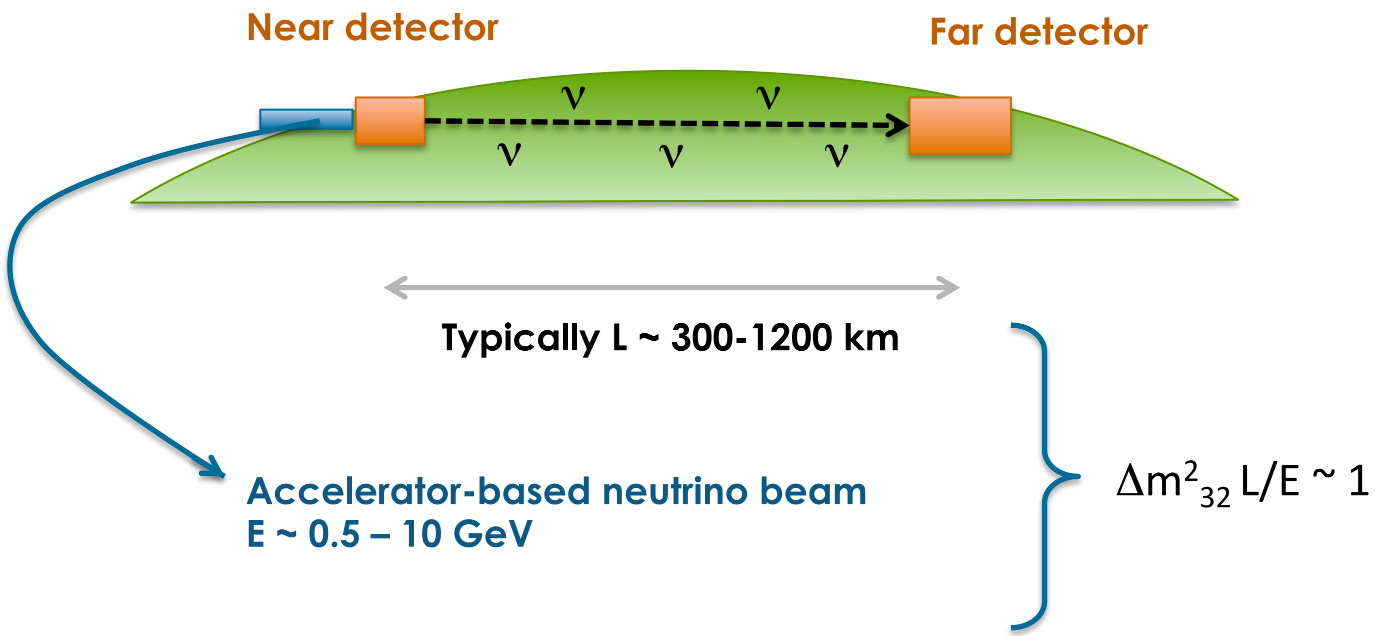
RENO



D-Chooz



Accelerator Long BaseLine experiments



Two types of oscillation searches:

ν_μ **($\rightarrow\nu_\tau$) disappearance**: θ_{23}

ν_e **appearance**: sensitivity to θ_{13} and δ_{CP}, mass hierarchy, through sub-leading terms in the appearance oscillation probability (α L/E) and matter effect (α L×E)

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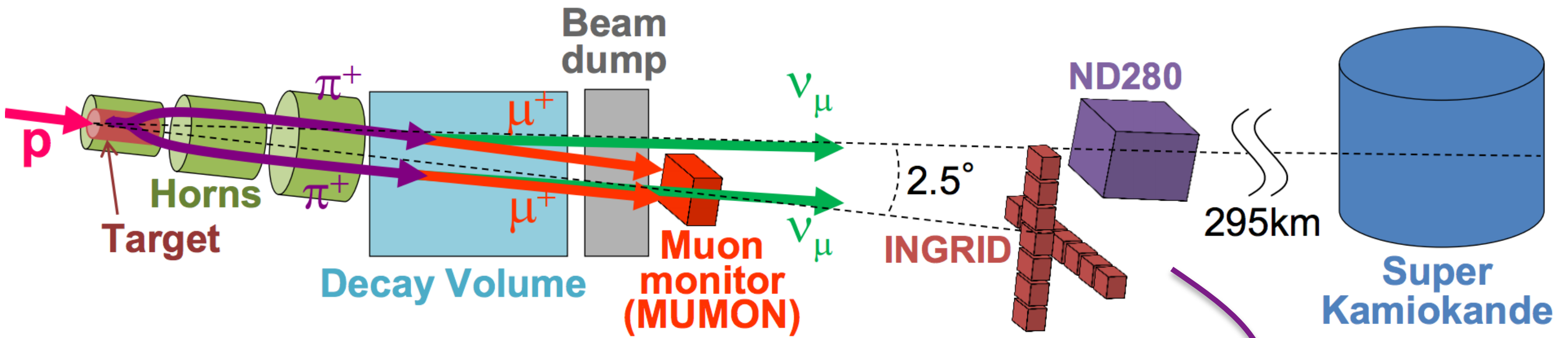
T2K



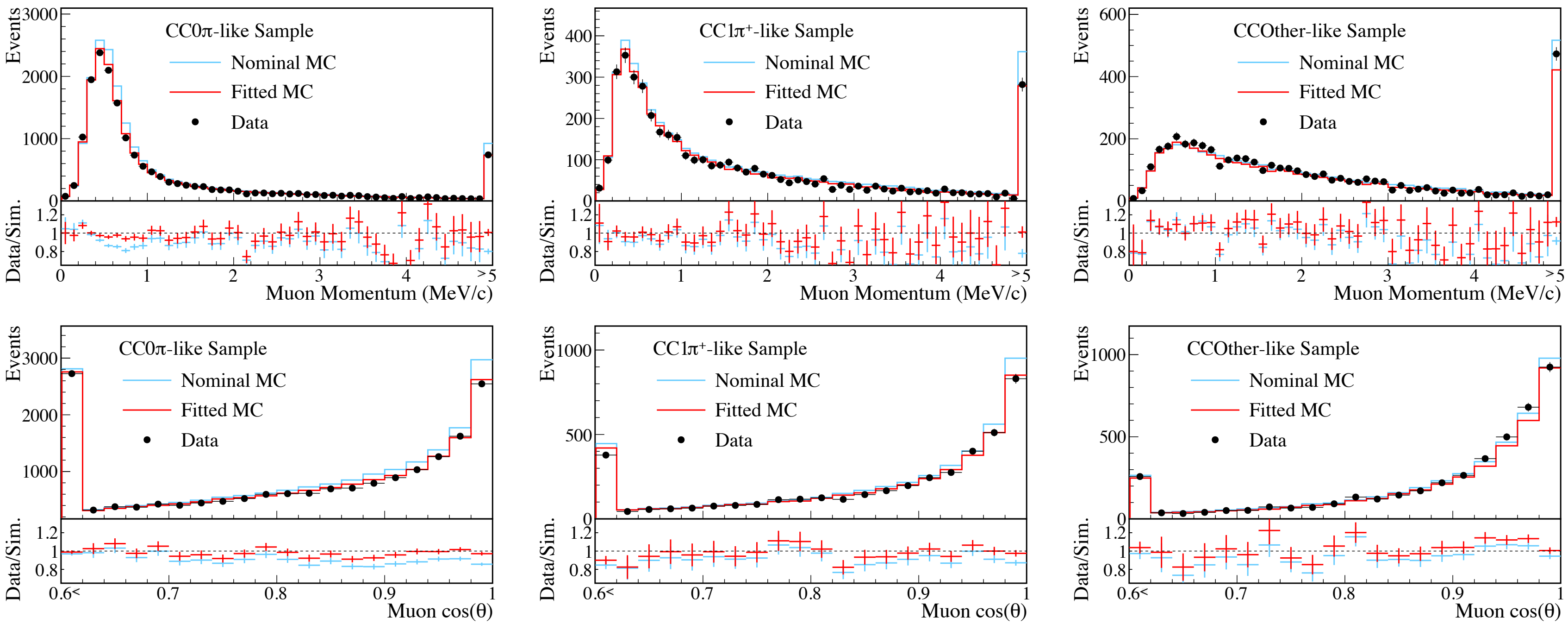
- The first off-axis long-baseline neutrino oscillation experiment
- Narrow band beam, peak E = 600 MeV, L = 295km (matter effect correction of order 5%)

Near detector complex: INGRID (on-axis) and ND280 (off-axis) constrain neutrino flux and cross-section.

Far detector: Super-K is a 50kton Water Cherenkov capable of efficient muon/electron discrimination.

Searches for ν_μ disappearance and ν_e appearance with sensitivity to θ_{13}, δ_{CP}.

T2K: the power of the Near Detector



Constrain rate (flux × cross section) and cross section parameters with ND data

Correlation between energy/samples taken into account

ν_e at SK can be constrained by ν_μ at ND(same parent particle)

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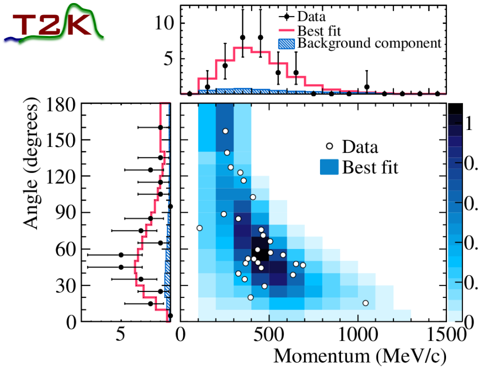
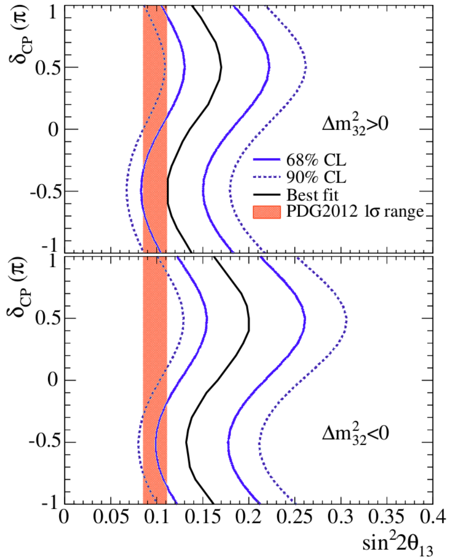
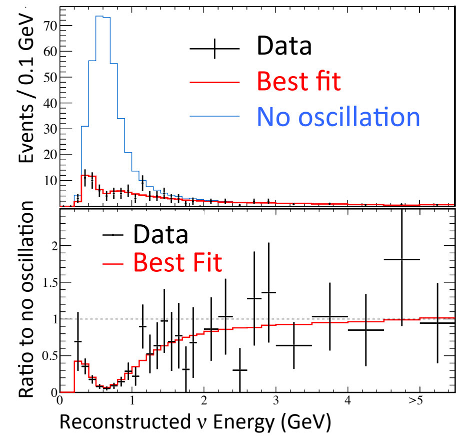
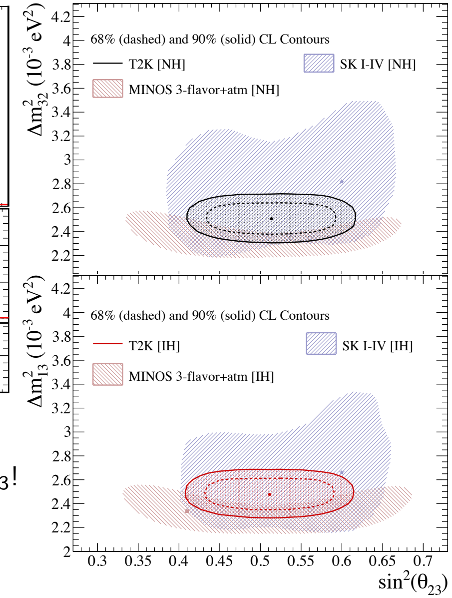




- Discovery of $\nu_\mu \to \nu_e$ at 7.3σ!
- Phys. Rev. Lett. **112**, 061802, February 2014





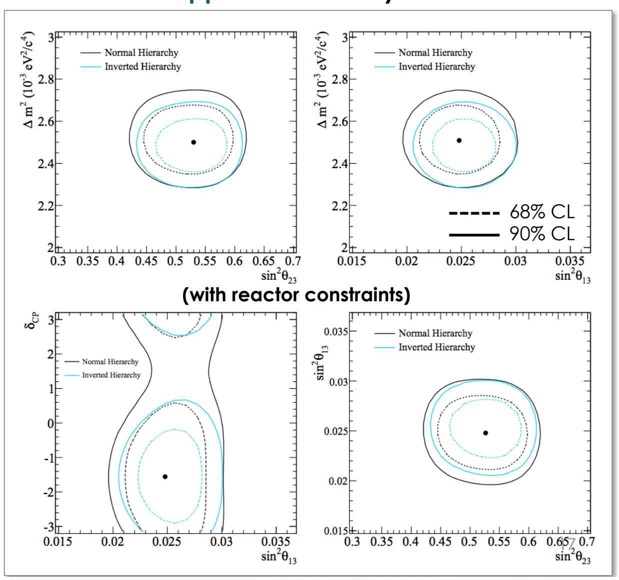
- World leading measurement of θ_{23}!
- Phys. Rev. Lett. **112**, 181801, May 2014

Combined appearance + disappearance analysis!

[arXiv:1502.01550]
2010-2013 data runs:
10% of total expected data

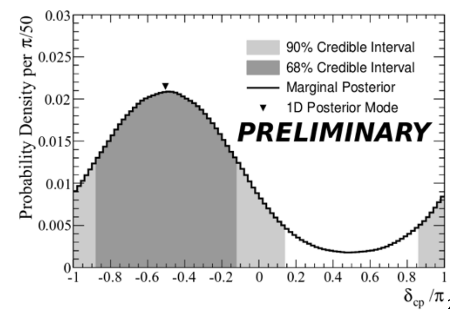
Simultaneous ν_μ and ν_e fit under a **three-flavor oscillation hypothesis**: **Vary δ_{CP}, Δm^2_{32}, θ_{13}, θ_{23}.** Frequentist approach.

Combined with reactor experiments: hints toward $\delta_{CP} = -\pi/2$



Bayesian probability

	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	0.179	0.078	0.257
$\sin^2\theta_{23} > 0.5$	0.505	0.238	0.743
Sum	0.684	0.316	1.0



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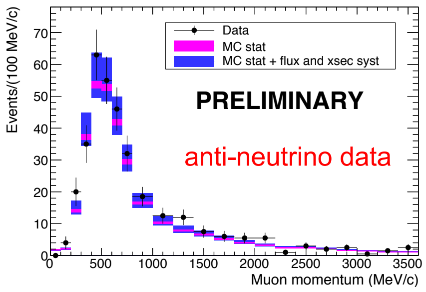
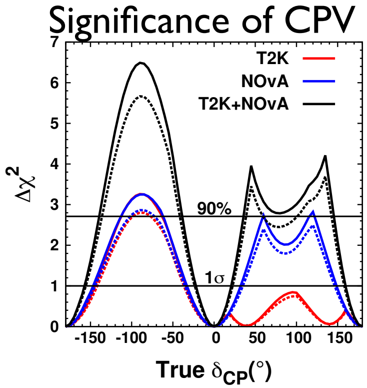
T2K status & outlook

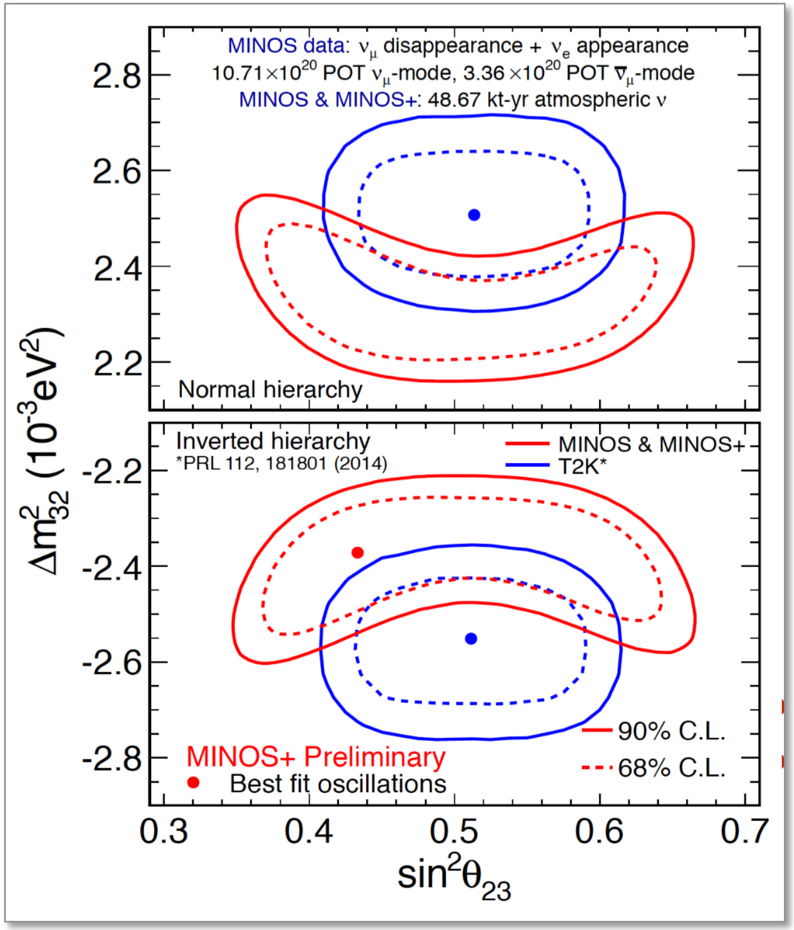
- Last run: stable beam at 320kW
- Plan for 2015: 350kW
- Recently exceeded integrated 10^{21} POT (approved for 8×10^{21})
- So far 70% neutrinos, 30% antineutrinos
- Aim for summer 2015: antineutrino oscillation with $\sim 5 \times 10^{20}$ POT

- Continue to 2021, search for CP Violation with up to 2.5σ sensitivity
- Combine with NOvA and SK to increase reach





MINOS/MINOS+ recent results



[arXiv:1502.07715]

New results from a three-flavor combined disappearance and appearance analysis

Beam and atmospheric neutrino data

Best fit (IH):
$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\,\mathrm{eV}^2$
$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

Most precise $|\Delta m^2_{32}|$ measurement!
Consistent with maximal mixing.
Marginal preference for inverted hierarchy, lower octant of θ_{23}.

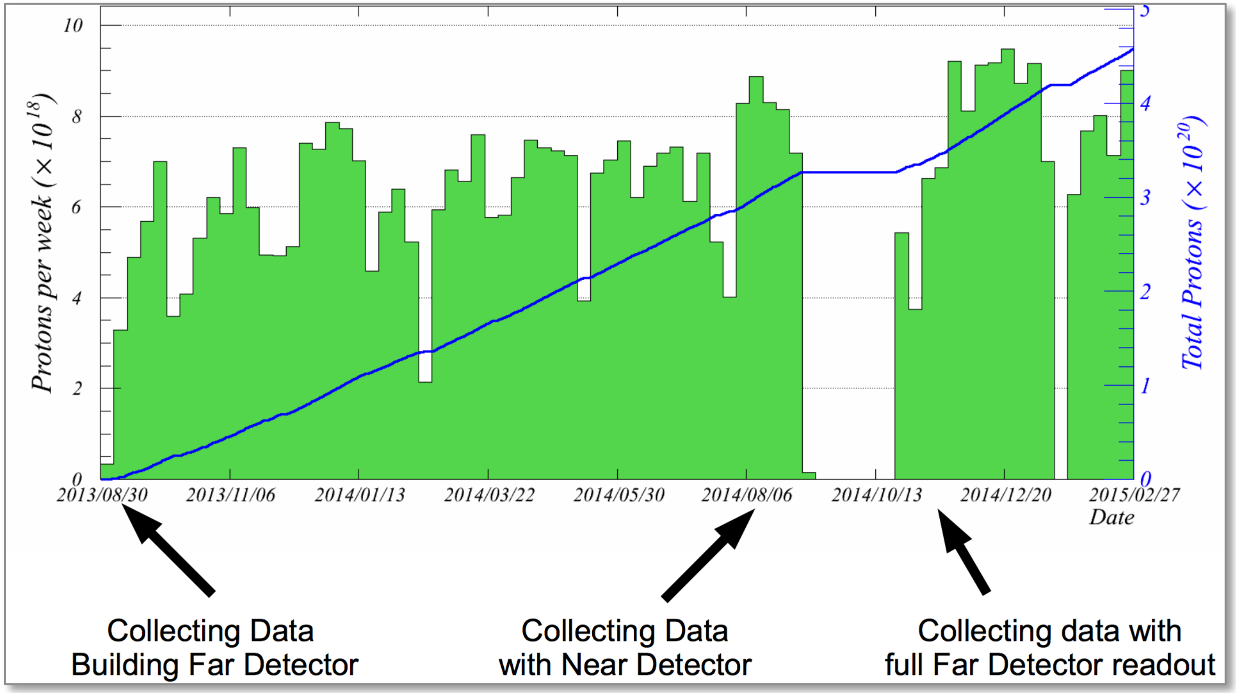
NOvA

$E \approx 2$ GeV, $L = 810$ km

[NuTel2015]

Physics goals:
ν_e appearance:
θ_{13}, δ_{CP}, mass hierarchy
ν_μ disappearance:
$\sin^2 2\theta_{23}$, $|\Delta m^2_{32}|$

Combined appearance and disappearance:
→ **octant of θ_{23}**

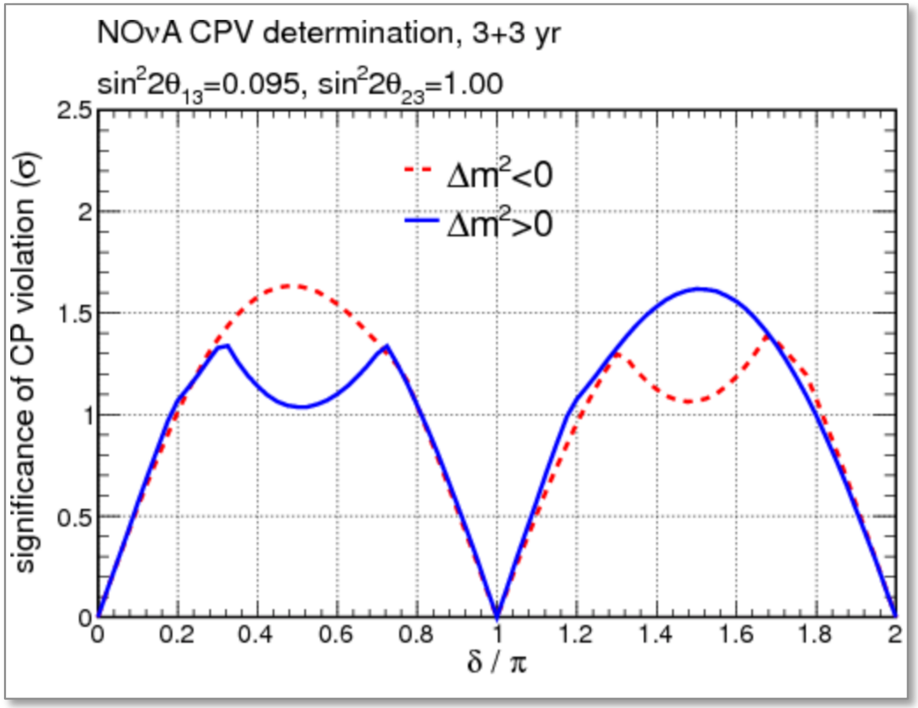


Construction complete and data taking with both detectors ongoing!
First oscillation results expected in the next few months!

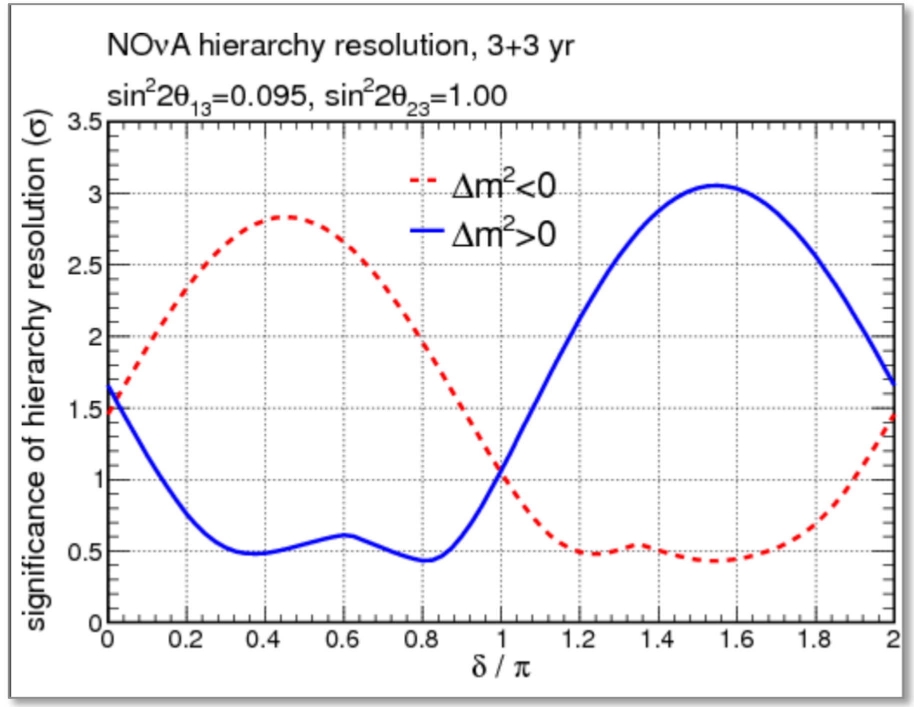
Sensitivity to ν_e appearance is about 3 sigma **with current data**.

NOvA expected sensitivity

[NuTel2015]



Ruling out no CP violation as function of true value of δ_{CP}



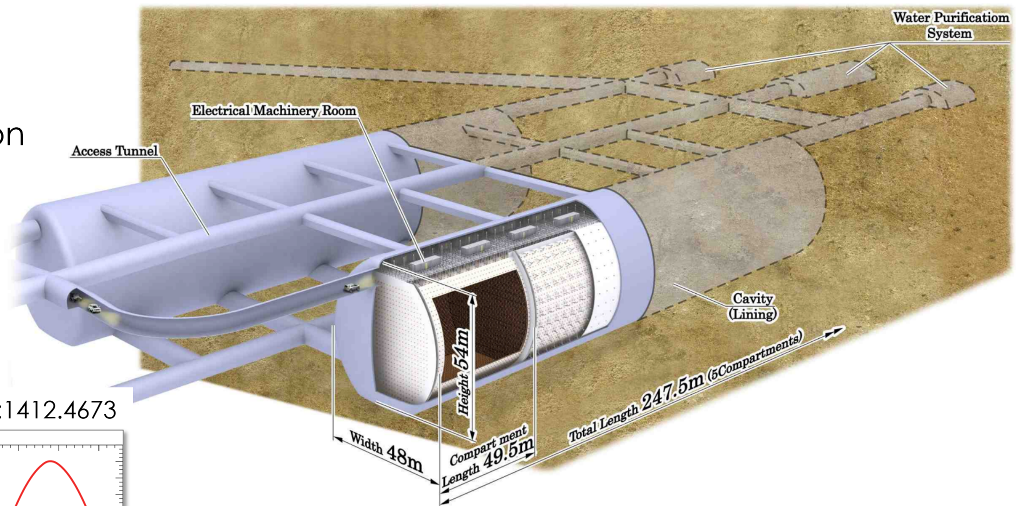
Hierarchy resolution as a function of true value of δ_{CP}

Future experiment: T2HK

Megaton-scale Water Cherenkov detector (20-25x larger than Super-K)

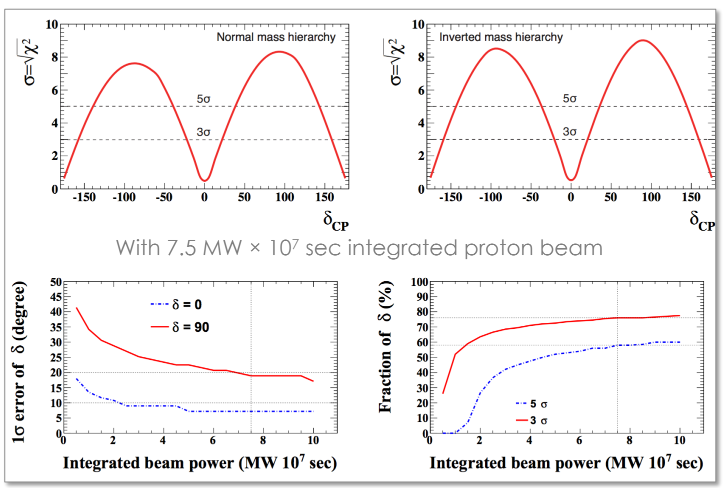
Goal: δ_{CP} determination

- Increased zenith angle resolution
- e/μ discrimination
- Low energy threshold
- Statistical separation of ν_e vs. $\overline{\nu}_e$
- Large statistics!



Hyper-K δ_{CP} reach:

arXiv:1412.4673



δ_{CP} error of <19 deg for all values

76% (68%) parameter space coverage at 3σ (5σ)

R&D funded in Japan and UK
Final funding decision by 2017

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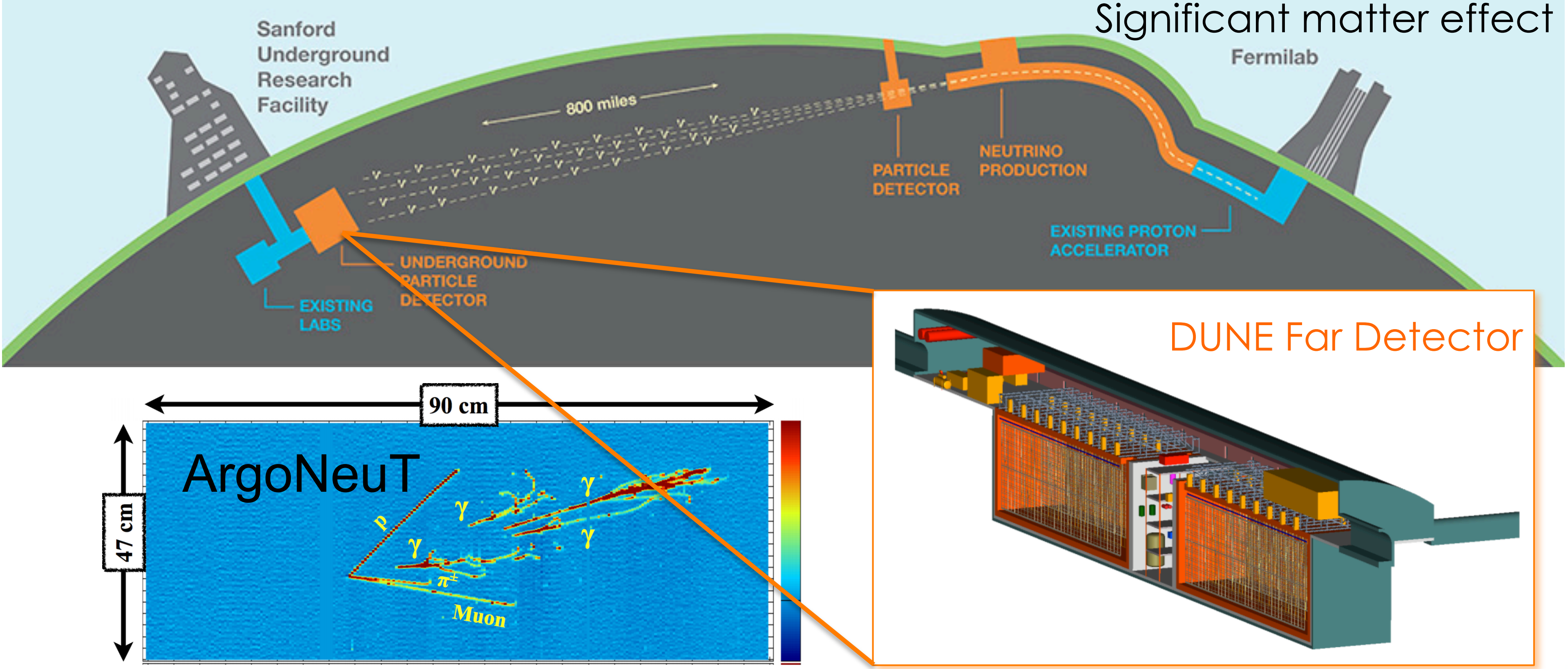
Future experiment: DUNE

Deep Underground Neutrino Experiment *(formerly LBNE/ELBNF/LBNF)*

Primary physics goal: δ_{CP} and neutrino mass hierarchy

34 kton Liquid Argon Time Projection Chamber (LArTPC), 1.5km underground
E = 0.5-5 GeV, L = 1200 km
Significant matter effect



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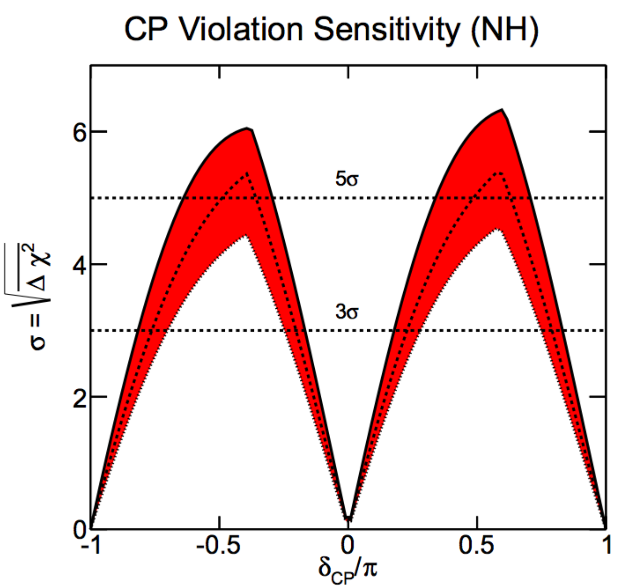
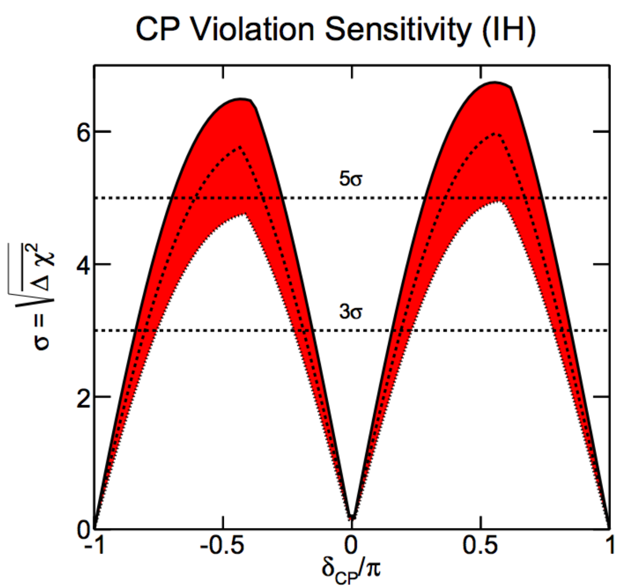
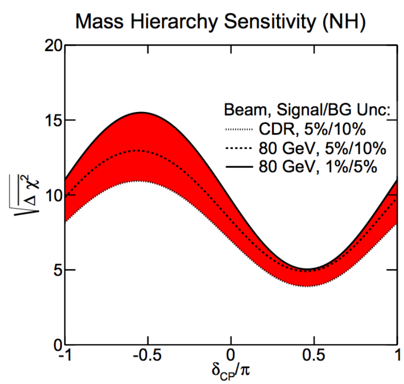
LBNF and DUNE

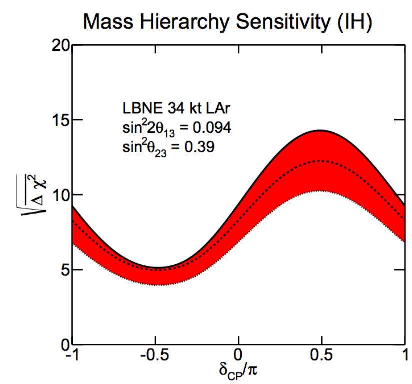
- Long Baseline Neutrino Facility at Fermilab and SURF (FNAL/DOE)
  - Proton complex, neutrino beam, ND and FD facilities
  - PIP-II upgrade to deliver 1.2MW, tunable, wide-band n beam by 2024
  - Further upgrades to 2.4MW by ~2030
- DUNE: 550 signatories, 147 institutions, 24 countries
  - To construct and operate a (staged) 40 kt LAr detector at SURF, 1300 km from Fermilab, underground at 4300 mwe
  - And a high-granularity, high-precision Near Detector
- To integrate 120 kt*MW*yr by ~2035
  - CP violation
  - Mass Hierarchy
  - Test the 3-neutrino paradigm (unitarity of PMNS)
  - Search for nucleon decay
  - Atmospheric and astrophysical neutrino measurements
- First collaboration meeting Jan 2015, second as we speak

DUNE expected sensitivity



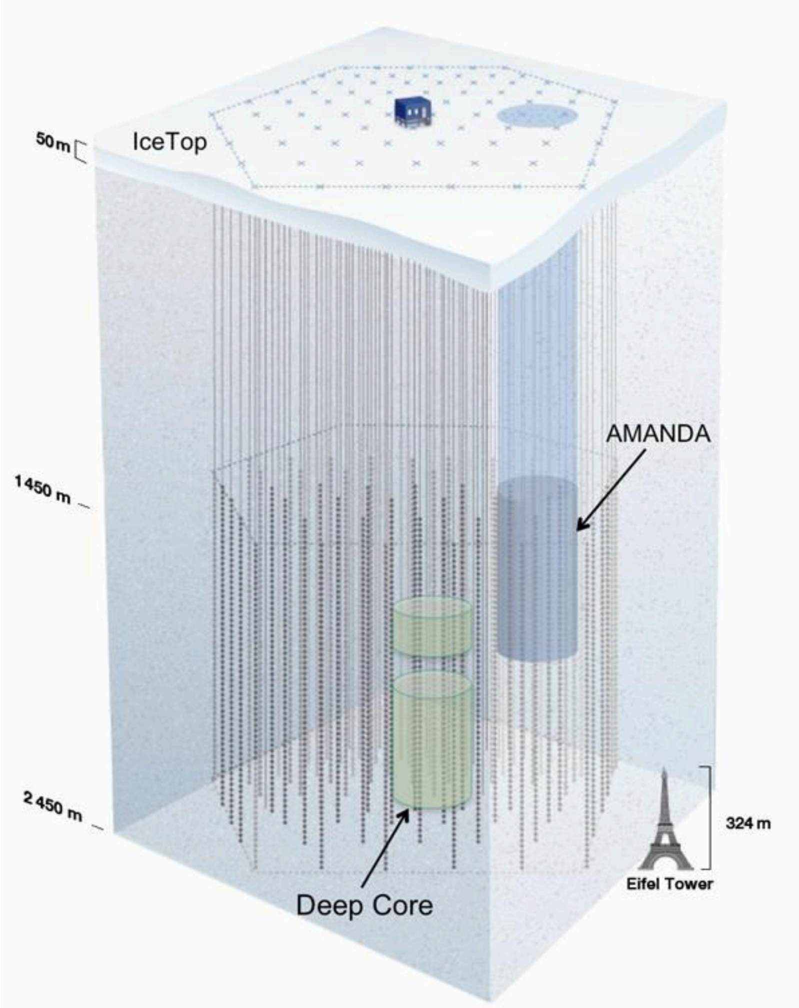


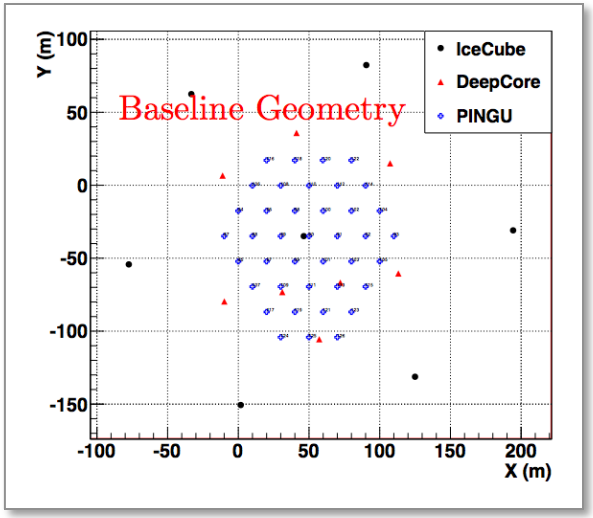




Future experiment: PINGU

Precision **I**ceCube **N**ext **G**eneration **U**pgrade





A new in-fill array for IceCube
PINGU LOI, arXiv:1401.2046

Primary goal: precision measurement of atmospheric oscillations with a focus on the **neutrino mass hierarchy determination**
(exploiting earth MSW effect)

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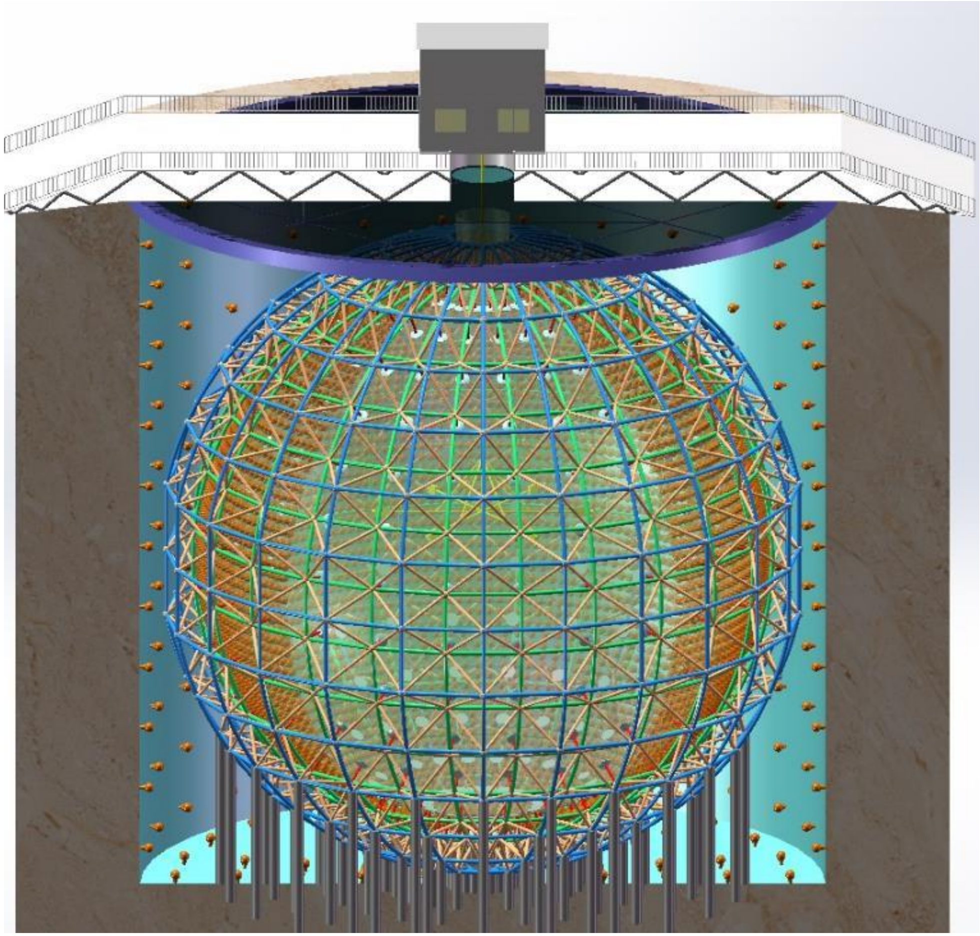
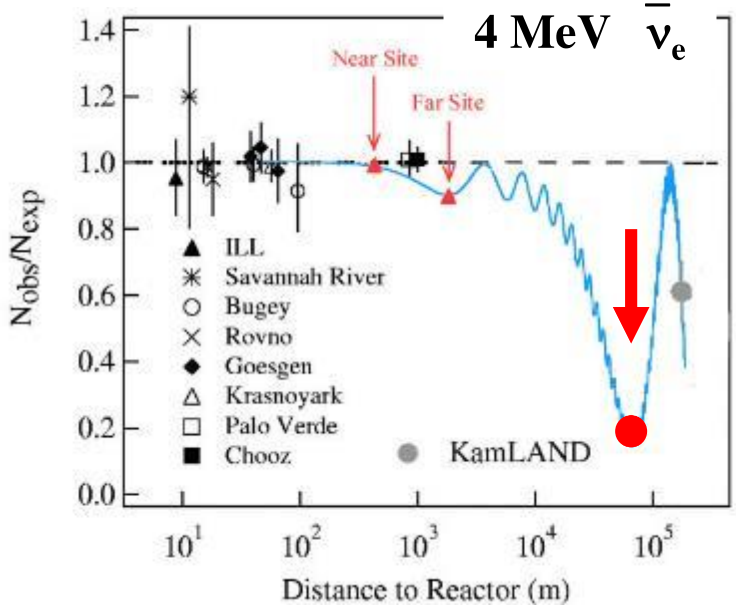
JUNO

- **Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013. ~ 300 M$.**

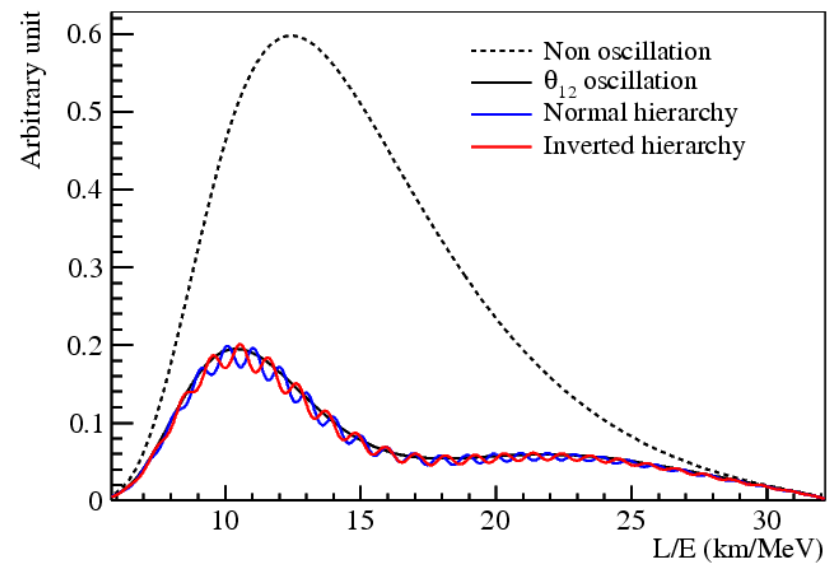


- **20 kton LS detector**
- **3% energy resolution**
- **700 m underground**
- **Rich physics possibilities**
  - ⇨ **Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters**
  - ⇨ **Supernovae neutrino**
  - ⇨ **Geoneutrino**
  - ⇨ **Solar neutrino**
  - ⇨ **Atmospheric neutrino**
  - ⇨ **Exotic searches**

JUNO oscillation measurements



Access to MH



Detector under 700m overburden
53 km from two new power station complexes
26.6 GW by 2020 start, increasing to 35 GW

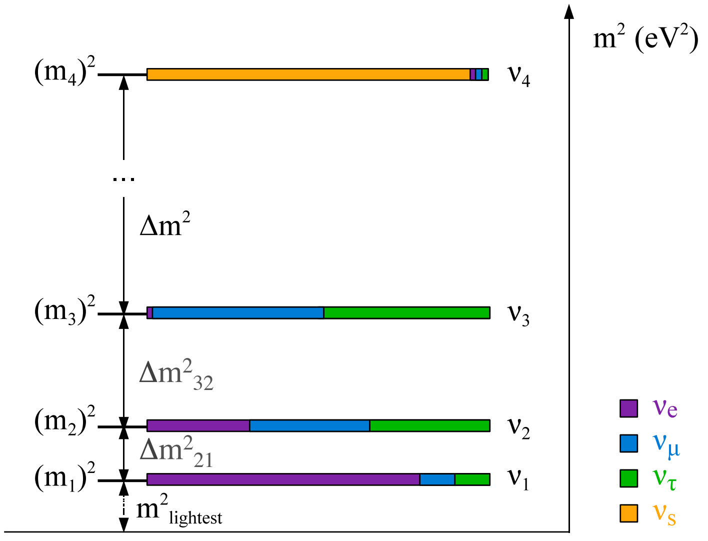
Other issues: sterile signs / anomalies

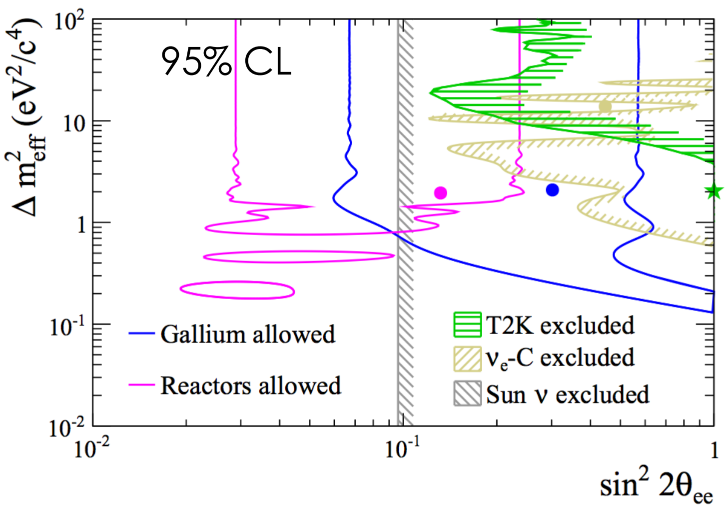
- LSND anti-ν_e appearance (3.8σ, 1995)
- MiniBooNE appearance, similar, 2012
- Reactor rate deficit, 2-3σ, compatible
  - Flux shape and integral?
- Gallium source deficit
- MINOS+ preliminary: stringent constraints
- T2K ND: central solutions exclusion

SBN programme at FNAL (LAr detectors)

- SBND
- MicroBooNE
- ICARUS

3 baselines in Booster beam for final resolution

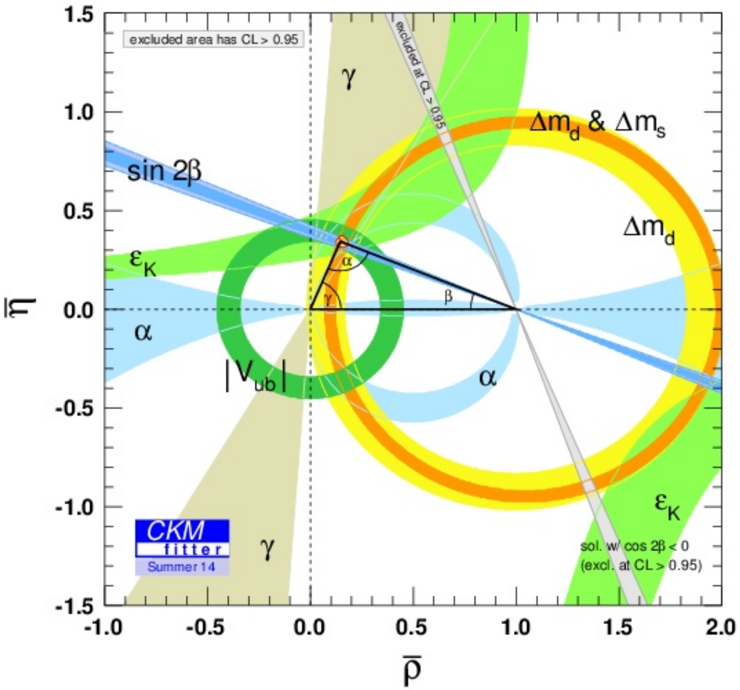




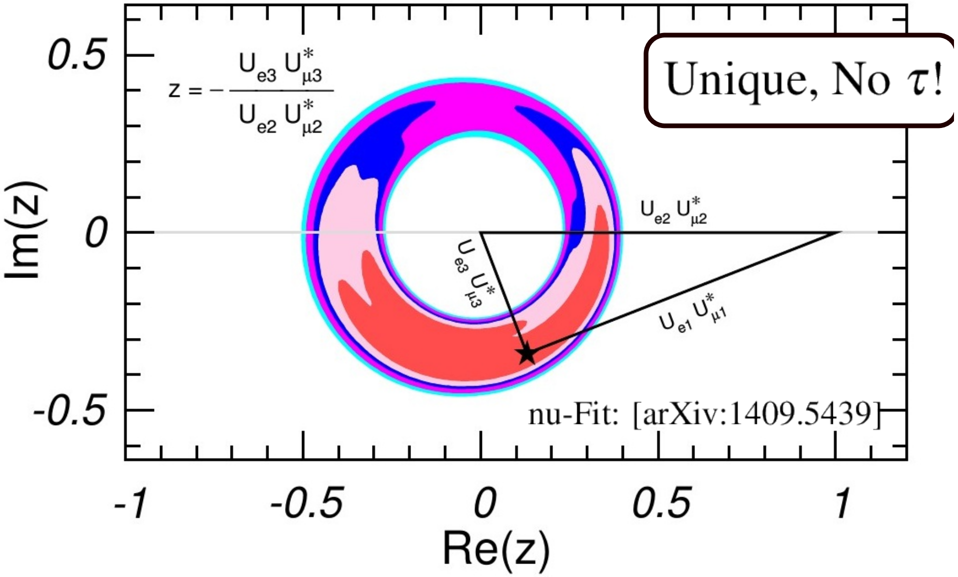
Outlook

- Exciting recent results
  - Accelerator and reactor experiments start to provide hints of δ_{CP} and MH
  - New results to come from T2K, NOvA, MINOS/MINOS+ in the next 5 years
- Next generation experiments (DUNE, Hyper-K, PINGU, JUNO) hold great promise for the next two decades
- A strong Short Baseline programme at FNAL will explore the sterile / anomalies landscape
- Most probably new questions will come up, a few discoveries, and hopefully some breakthrough to "the other side" of the "TeV scale" of the LHC

Quarks vs neutrinos



Unitarity *Not* assumed



Unitarity *Is* assumed.

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