Neutrino Physics: Experimental Status

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Outline of the talk

I. Neutrino oscillation parameters.
II. Review of experimental status.
III. Global fit of oscillation data.
IV. Summary.

I. Neutrino oscillation parameters and observables

Neutrino oscillations

Charged-current interaction:

$$\mathcal{L}_{\mathrm{CC,\,leptonic}} = -\frac{g}{\sqrt{2}} W^{-}_{\lambda} \begin{pmatrix} \bar{e}_L & \bar{\mu}_L & \bar{\tau}_L \end{pmatrix} \gamma^{\lambda} \underbrace{U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}_{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}} + \mathrm{H.c.}$$

⇒ **Neutrino flavour eigenstates produced in charged-current interaction $\neq$ mass eigenstates!**

Flavour transition probability → oscillations in L/E

$$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_{j=1}^{3} U_{\beta j} U^{*}_{\alpha j} e^{-i m_j^2 L/2E} \right|^2 .$$

Neutrino oscillations

Flavour transition probability → oscillations in L/E

$$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_{j=1}^{3} U_{\beta j} U^*_{\alpha j} e^{-i m_j^2 L/2E} \right|^2 .$$

Observables in oscillation experiments: $P_{\nu_\alpha \to \nu_\beta}$

→ Can infer information about

- Parameters of U:
  - three mixing angles θ_{12}, θ_{23}, θ_{13},
  - one phase δ,
- Two mass-squared differences:
  - $\Delta m^2_{21} = m^2_2 - m^2_1 > 0$,
  - $\Delta m^2_{31} = m^2_3 - m^2_1$.

The sign of Δm^2_{31} is unknown at the moment:

$m_3 > m_1$ (normal spectrum) or $m_3 < m_1$ (inverted spectrum).

Neutrino oscillations

In many cases:

Flavour transition probability =
transition probability for the 2-flavour case (2 parameters θ, Δm^2)

$$P_{\nu_\alpha \to \nu_\beta} = \frac{1}{2}\sin^2(2\theta) \times \left(1 - \cos\frac{\Delta m^2 L}{2E}\right)$$

+ small corrections from all other parameters.

In general: Effect of oscillations is large if oscillation phase is $\mathcal{O}(1)$, *i.e.*

$$\frac{\Delta m^2 L}{2E} \sim \mathcal{O}(1).$$

Δm^2 fixed by nature, E roughly fixed by neutrino source → Have to **choose appropriate baseline** L!

⇒ Short and long-baseline experiments.

In the following we will have a look on a **selection** of current oscillation experiments and their results.

II. Experimental status of neutrino physics

- Oscillation parameters,
- Reactor neutrino energy spectra,
- Astrophysical neutrino fluxes,
- Bounds on absolute neutrino masses,
- Search for light sterile neutrinos,
- Effective mass for neutrinoless double beta decay,
- . . .

Reactor mixing angle θ_{13}, Δm^2_{31}

(Ref.: https://commons.wikimedia.org/wiki/Nuclear_energy: Philippsburg2.jpg)

Daya Bay

Daya Bay is a short-baseline ($L \sim \mathrm{km}$) reactor ($E \sim \mathrm{MeV}$) neutrino experiment in southern China.

- Probing θ_{13} by measuring the $\overline{\nu_e} \to \overline{\nu_e}$ survival probability.
- 2 near detector sites (360-470 m from nearest reactor),
- 1 far detector site (1.52-1.93 km from all 6 reactors).

As for all current reactor experiments: **Use of near and far detectors eliminates uncertainties due to flux estimation.**

Current best-fit result:[1]

$$\begin{aligned} & \sin^2(2\theta_{13}) = 0.082 \pm 0.004, \quad [\sim 5\% \text{ error}], \\ \rightarrow \quad & \sin^2\theta_{13} = 0.021 \pm 0.001, \\ & |\Delta m^2_{31}| \approx |\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}\,\mathrm{eV}^2. \end{aligned}$$

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[1] arXiv: 1603.03549

Daya Bay

Additional results: Neutrino flux and neutrino energy spectrum:

$$\frac{\text{flux}}{\text{pred. Huber-Mueller}} = 0.946 \pm 0.022, \quad \frac{\text{flux}}{\text{pred. ILL-Vogel}} = 0.991 \pm 0.023.$$

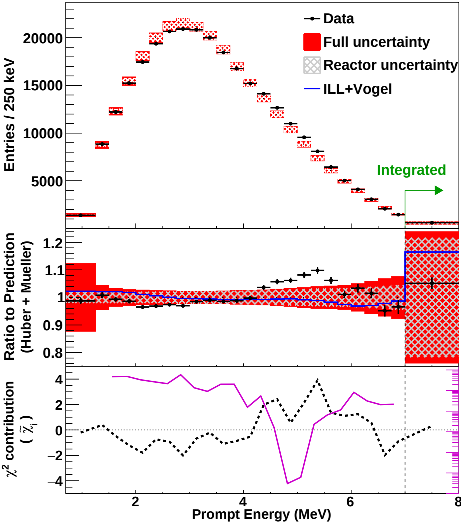
Small ($\sim 2\sigma$) deviation of measurement from Huber-Mueller prediction.
$\rightarrow$ oscillation into sterile neutrinos at very short baselines?

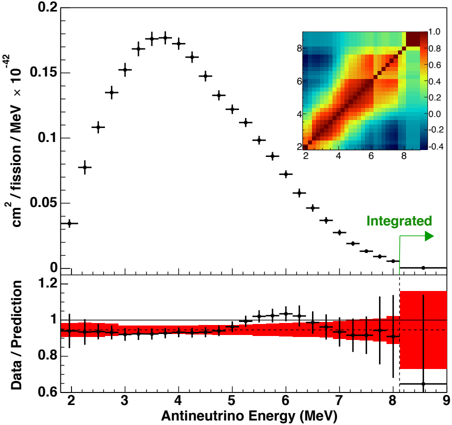
$\rightarrow$ Both theoretical predictions consistent with data at $< 3\sigma$, but:

Inverse beta decay ($\overline{\nu_e} + p \rightarrow n + e^+$) positron spectrum deviates from prediction by more than 2σ [local between $4 - 6\,\text{MeV}$ 4σ]. Effect also in (computed) antineutrino spectrum.

Distortion in spectrum ("bump") first observed by Double Chooz in 2014. Then confirmed by RENO and Daya Bay!

Daya Bay





(Plots taken from arXiv:1508.04233.)

Double Chooz

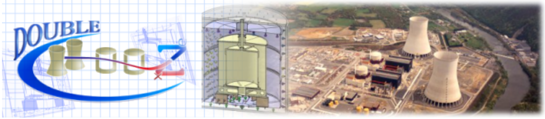
Short baseline reactor experiment in France with

- one near detector ($L = 400\,\mathrm{m}$)
- and one far detector ($L = 1050\,\mathrm{m}$).

Current best result [M. Ishitsuka, Moriond 2016]:

$$\begin{aligned} & \sin^2(2\theta_{13}) = 0.111 \pm 0.018, \\ \rightarrow\quad & \sin^2\theta_{13} = 0.029 \pm 0.005. \end{aligned}$$

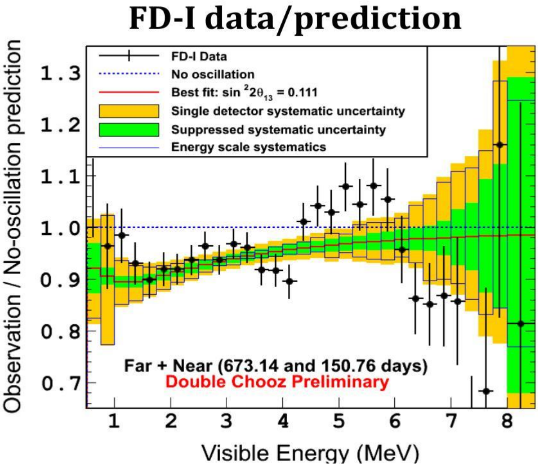
Mean value of $\sin^2(2\theta_{13})$ 35% larger than mean value of Daya Bay.
Statistical errors expected to decrease rapidly with further measurements.



(Picture taken from: http://doublechooz.in2p3.fr)

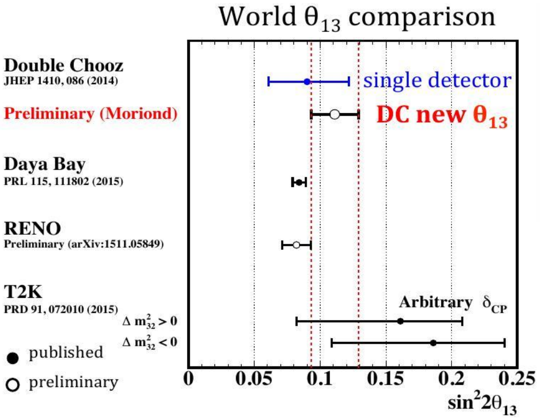
Double Chooz

“Bump” at 4 to 6 MeV:



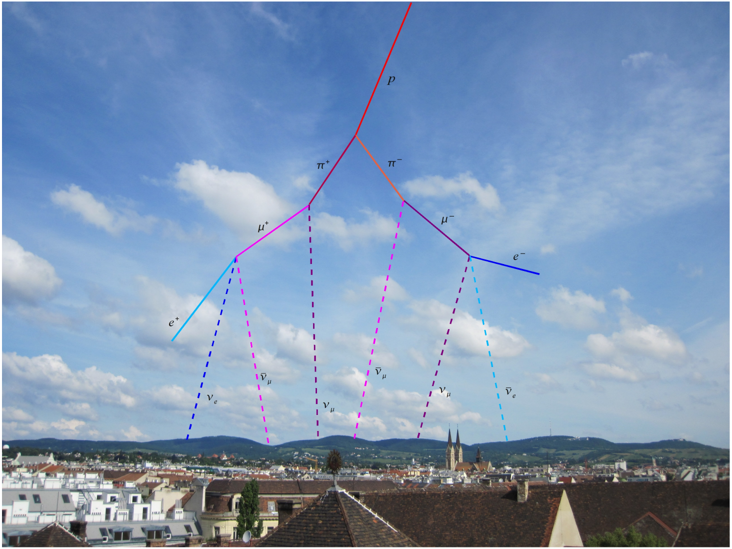
(Plot taken from the talk by M. Ishitsuka at Moriond 2016).

Reactor mixing angle measured by different experiments



(Plot taken from the talk by M. Ishitsuka at Moriond 2016).

Atmospheric mixing angle θ_{23}, Δm^2_{32}



NOνA

NuMI (Neutrinos at the Main Injector) **O**ff-Axis ν_e **A**ppearance.

- Accelerator experiment,
- Baseline 810 km (U.S.A.: Fermilab → Ash River Trail),
- Mean ν_μ energy $E \sim 2$ GeV (FWHM=1 GeV); Off-Axis beam (narrower energy distribution),
- $E = 2\,\text{GeV}$ at $L = 810\,\text{km}$ corresponds to the **first maximum** of ν_μ-disappearance probability.

First results: ν_μ-**disappearance**:[2]

$$\begin{aligned} \text{NO:} \quad & \Delta m^2_{32} = (2.52^{+0.20}_{-0.18}) \times 10^{-3}\,\text{eV}^2, \quad \sin^2\theta_{23} \in [0.38, 0.65]\ (68\%\ \text{CL}), \\ \text{IO:} \quad & \Delta m^2_{32} = (-2.56 \pm 0.19) \times 10^{-3}\,\text{eV}^2, \quad \sin^2\theta_{23} \in [0.37, 0.64]\ (68\%\ \text{CL}). \end{aligned}$$

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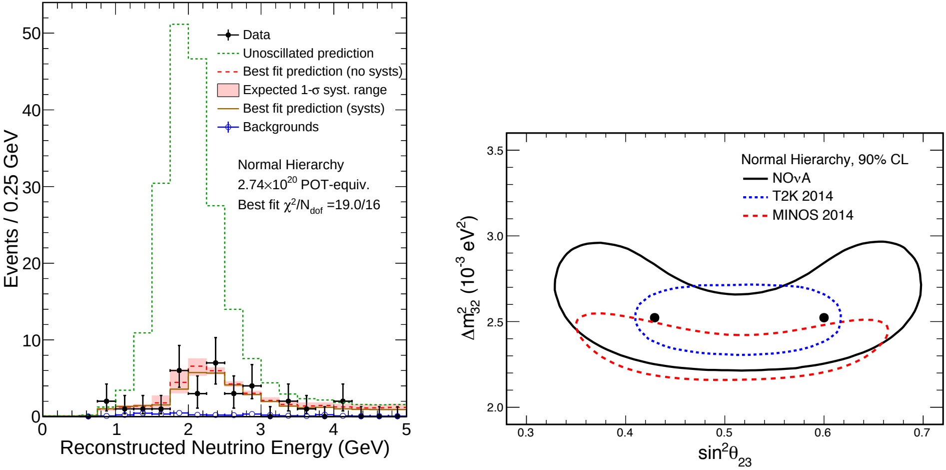
[2] Phys. Rev. D93 (2016) no. 5, 051104 [arXiv:1601.05037]

NOνA, T2K, MINOS



left: NOνA signal; right: comparison NOνA, T2K, MINOS.

(Plots taken from arXiv:1601.05037.)

IceCube DeepCore

IceCube is a km^3 detector in clear antarctic ice at the south pole.

Atmospheric neutrinos:

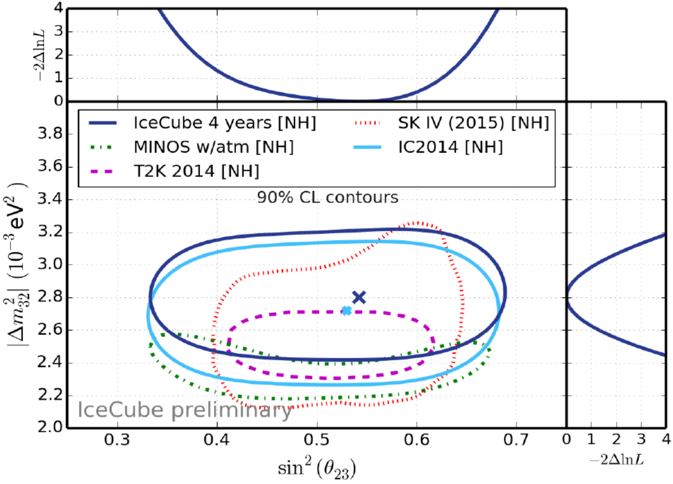
- Come from all over the atmosphere → baselines from $\mathcal{O}(10\,\mathrm{km})$ to $\mathcal{O}(10^4\,\mathrm{km})$,
- Mean ν_μ energy $E \sim 10 \text{ to } 100$ GeV.

4-year results for ν_μ-**disappearance** [Talk by J. Auffenberg at Moriond 2016]:

$$\sin^2\theta_{23} = 0.53^{+0.08}_{-0.13}, \quad \Delta m^2_{32} = 2.80^{+0.20}_{-0.16} \times 10^{-3}\,\mathrm{eV}^2.$$

(For normal neutrino mass spectrum)

Global results from atmospheric and long-baseline accelerator neutrino experiments



(Plot taken from the talk by J. Auffenberg at Moriond 2016).

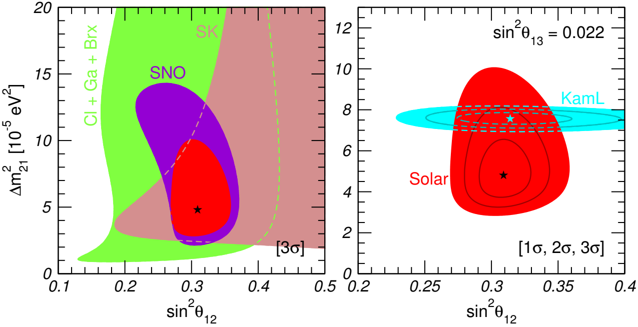
Solar mixing angle θ_{12}, Δm^2_{21}

(Ref.: https://en.wikipedia.org/wiki/Sun#/media/File:Sun_in_February.jpg)

Two ways to determine the solar mixing angle θ_{12}

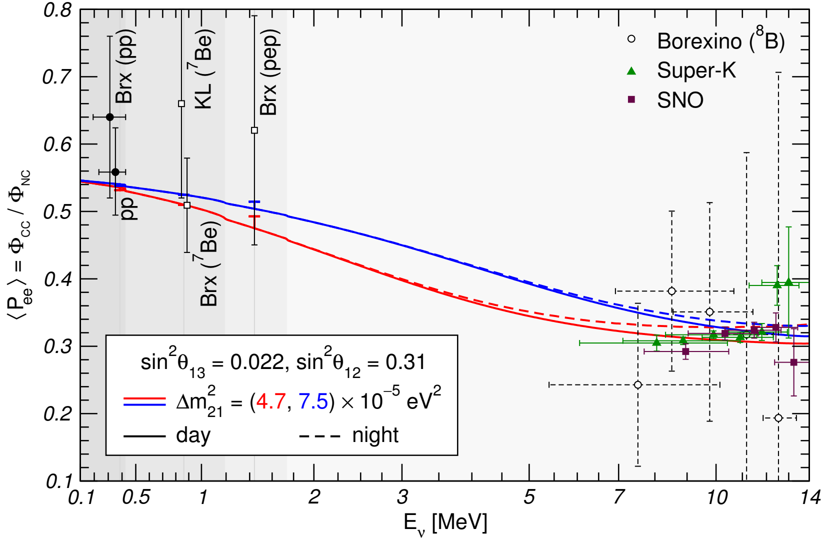
- From the solar neutrino flux (MSW effect in the Sun).
- With Earth-based oscillation experiments using reactor neutrinos: $\Delta m^2_{21}/E$ very small → Need long baseline $\sim \mathcal{O}(100\,\mathrm{km})$ → KamLAND experiment.

Two independent measurements: consistent but in slight tension.



left: solar only, right: solar (global) compared to KamLAND.
(Plot taken from Maltoni, Smirnov arXiv: 1507.05287)

Solar neutrinos and the MSW effect



(Plot taken from Maltoni, Smirnov arXiv: 1507.05287)

III. Global fit of oscillation data

Most recent global fit

F. Capozzi *et al.* arXiv: 1601.07777;

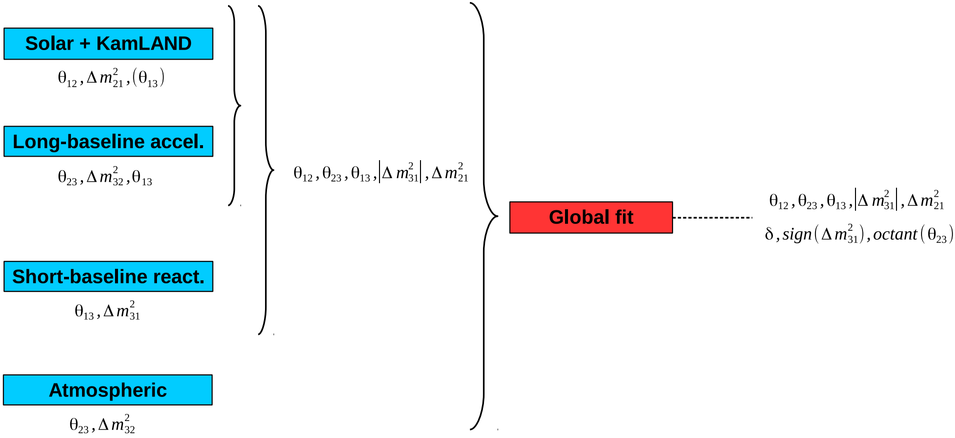
Included data:

- Solar and KamLAND data: Borexino, GALLEX-GNO, Homestake*, Kamiokande*, KamLAND, SAGE, Super-Kamiokande, SNO*.
- Long-baseline accelerator experiments: T2K, NOνA, MINOS.
- Short-baseline reactor experiments: Double Chooz, Daya Bay, RENO.
- Atmospheric neutrino data: Super-Kamiokande*, IceCube DeepCore.

Important: KamLAND requires reactor neutrino spectrum as input → re-analyzed in the light of the observed “bump” in the reactor neutrino energy spectrum.

* = Nobel prize in Physics.

Global fit strategy [arXiv: 1601.07777]



Solar + KamLAND

$\theta_{12}, \Delta m^2_{21}, (\theta_{13})$

Long-baseline accel.

$\theta_{23}, \Delta m^2_{32}, \theta_{13}$

$\theta_{12}, \theta_{23}, \theta_{13}, |\Delta m^2_{31}|, \Delta m^2_{21}$

Short-baseline react.

$\theta_{13}, \Delta m^2_{31}$

Atmospheric

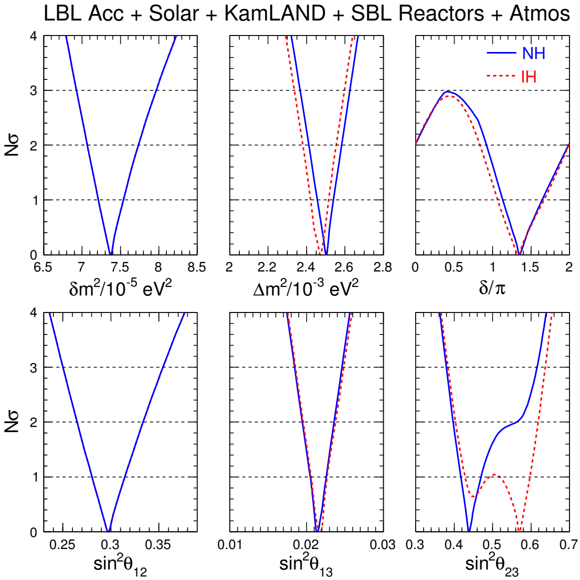
$\theta_{23}, \Delta m^2_{32}$

Global fit

$\theta_{12}, \theta_{23}, \theta_{13}, |\Delta m^2_{31}|, \Delta m^2_{21}$

$\delta, sign(\Delta m^2_{31}), octant(\theta_{23})$

Global fit results [arXiv: 1601.07777]



(Plot taken from arXiv:1601.07777.)

Remarks

- θ_{13} is the best determined mixing angle.
- θ_{23} has the largest error bars. Maximal 23-mixing valid at two sigma.
- Octant of θ_{23} (best-fit) flips when changing NO $\leftrightarrow$ IO. Why still octant ambiguity? Reason: Different experiments predict different octants!
- What about δ? **No single experiment gives strong hints on δ at the moment!** The preference for δ comes from global fits only! At three sigma δ is still undetermined!

  $\rightarrow$ Have to be patient and wait . . .

IV. Summary

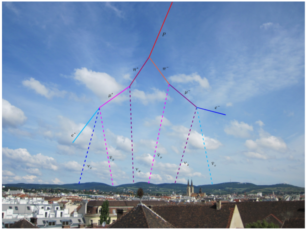
Summary

- Best-determined oscillation parameter is now θ_{13}. Reason: Concept of near/far detectors: Flux ambiguity no longer a problem.
- Measured reactor antineutrino flux / prediction < 1 in all experiments. → sterile neutrinos?
- Reactor neutrino energy spectrum shows a “bump” compared to the theoretical expectation. Origin unclear (new physics, nuclear physics?).
- New best-fit value for $\sin^2(2\theta_{13})$ from Double Chooz is 35% larger than best-fit value of Daya Bay.
- Atmospheric mixing angle now the least well determined one. New results from atmospheric neutrino experiments come from IceCube DeepCore. New results from long-baseline accelerator experiments from NOνA.
- Octant ambiguity for θ_{23} comes from different results from different experiments.

Summary

- Solar neutrinos: Two different methods to determine solar oscillation parameters: Solar neutrinos and Earth-based long-baseline reactor experiments (KamLAND). → Results are in 1σ tension.
- Most recent global fit by Capozzi *et al.*:
  - No strong indications for octant of θ_{23}. At $< 2\sigma$ maximal mixing allowed.
  - No indication for mass ordering.
  - Indication for $\delta \sim 3\pi/2$; at 3σ still completely undetermined.

Thank you for your attention!



Backup slides

The “bump” in the reactor neutrino energy spectrum

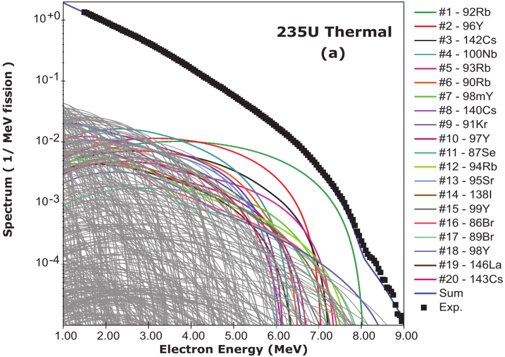
Double Chooz, Daya Bay and RENO all see the bump in the same place ($4-6$ MeV).

- Computation of energy spectrum to be expected is **highly nontrivial!**
- Computed spectrum quite sensitive to used data sets.
- Possible nuclear physics origins have been suggested, but none proven.

→ Still a lot of discussion going on!

Example: Electron energy spectrum for $^{235}\mathrm{U}$

About 10^4 β-decay branches contribute to the total spectrum!



(Plot taken from A. A. Sonzogni *et al.* Phys. Rev. C **91** (2015) no.1, 011301.)

Prospects for the mass ordering

In two flavour-regime $P_{\nu_\alpha \to \nu_\beta}$ depends only on $|\Delta m^2|$! $\Rightarrow$ In general the dependence of $P_{\nu_\alpha \to \nu_\beta}$ on $\mathrm{sign}(\Delta m^2_{31})$ is weak!

Conventional technique: Use matter effect (sensitive to $\mathrm{sign}(\Delta m^2_{31})$) at long baselines ($\sim 1000\,\mathrm{km}$).

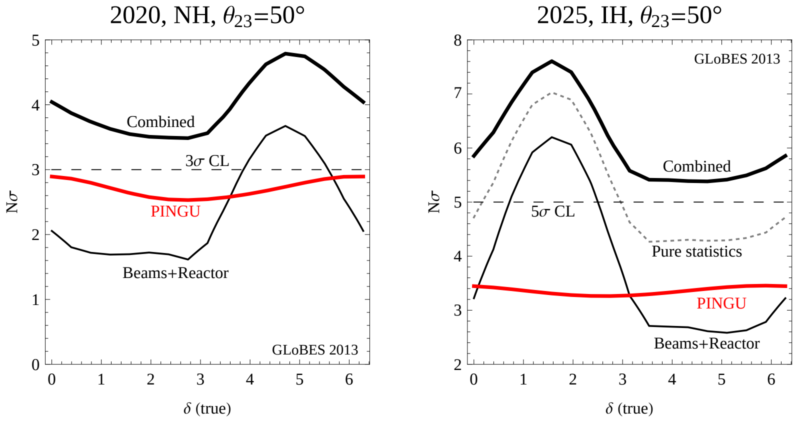
Existing beam experiments like T2K and NOνA will most likely not allow a high confidence level determination of the mass ordering, δ_{CP} and the octant of θ_{23}.

→ Example: High-energy resolution upgrade of IceCube DeepCore:

PINGU = Precision IceCube Next Generation Upgrade.

Prospects for the mass ordering

W. Winter [arXiv: 1305.5539]:



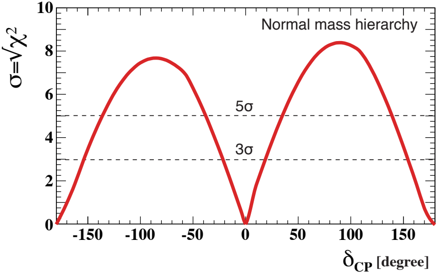
No single exp. can achieve 5σ discovery of mass ordering by 2025!

Neutrino beam to PINGU: 4σ to 6σ after 5 years of operation plausible.

Prospects for δ_{CP}

Example: Hyper-Kamiokande [arXiv: 1412.4673] (if approved, possibly starts data taking in 2025).

$\rightarrow \sim 10$ **years minimum till we would get first direct hints on** δ_{CP} **from Hyper-K.**

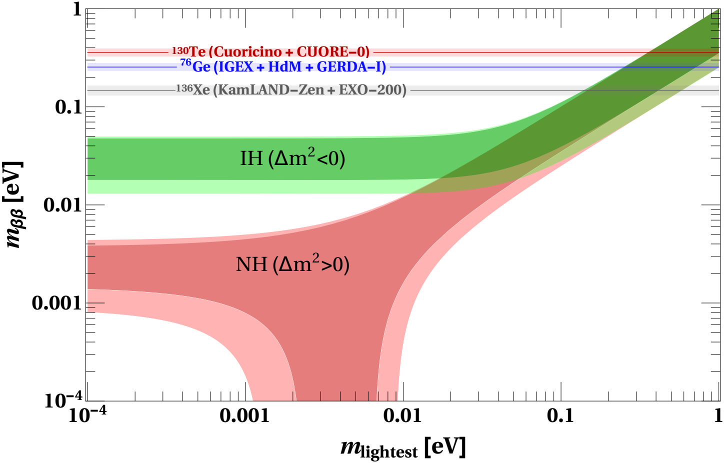


(Plot taken from arXiv: 1412.4673.)

T2K/NOνA: by 2020: $\delta_{\mathrm{CP}} \neq 0$ **at** 1.5 **to** 2.5σ**.**

$(\beta\beta)_{0\nu}$: Current upper bounds on $m_{\beta\beta}$

Dell'Oro *et al.* arXiv: 1601.07512



Why is determination of $\sin^2\theta_{23}$ so hard?

Reason:

$$\frac{d\sin^2\theta}{d\sin^2(2\theta)} = \frac{1}{4\cos^2(2\theta)}.$$

For close to maximal mixing we have $\sin^2(2\theta_{23}) \approx 1 \Rightarrow \cos^2(2\theta_{23}) \approx 0$.

$\Rightarrow$ Error on $\sin^2\theta$ strongly enhanced!