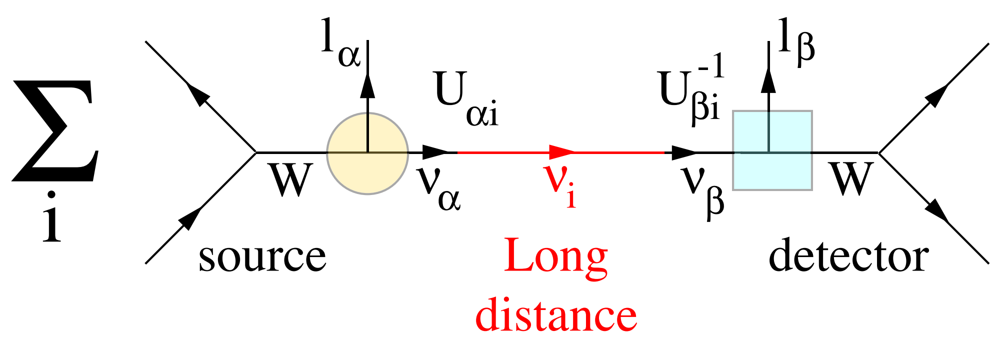
Neutrino oscillations

Neutrino mass and flavour eigenstates

- At production and detection, neutrinos are associated with a charged lepton ⇒ well defined flavour ν_α $(\alpha = e, \mu, \tau)$

- Propagation occurs in a mass eigenstate ν_i $(i = 1, 2, 3)$ which can be different from the flavour eigenstates ν_α.
  - ν_i and ν_α are related via a **unitary** matrix U $(U^\dagger U = 1)$



⇒ if ν_α is produced, it may be detected as ν_β $(\beta \neq \alpha)$

Neutrino propagation state

- A neutrino flavour state $|\nu_\alpha\rangle$ is a superposition of mass eigenstates $|\nu_i\rangle$

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

  - flavour-α fraction of $|\nu_i\rangle$: $|\langle\nu_\alpha|\nu_i\rangle|^2 = |U_{\alpha i}|^2$

- Consider the two-flavour oscillations (ν_e, ν_μ), for which U is a 2×2 rotation matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- A neutrino produced as ν_e at $t = 0$ will evolve to a superposition of a ν_e and ν_μ at time t (and a phase difference will develop due to the mass difference)

$$|\nu(t)\rangle = \cos\theta e^{-iE_1 t}|\nu_1\rangle + \sin\theta e^{-iE_2 t}|\nu_2\rangle$$

Neutrino oscillation probability

- To evaluate the probability of oscillation $\nu_e \rightarrow \nu_\mu$, project the state $|\nu(t)\rangle$ onto $|\nu_\mu\rangle$

$$|\langle\nu_\mu|\nu(t)\rangle|^2 = 4\sin^2\theta\cos^2\theta\sin^2\frac{(E_1 - E_2)t}{2} = \sin^2 2\theta\sin^2\frac{\Delta m^2}{4E}t$$

- The probability for oscillation from ν_e to ν_μ is therefore

$$P_{\rm osc} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

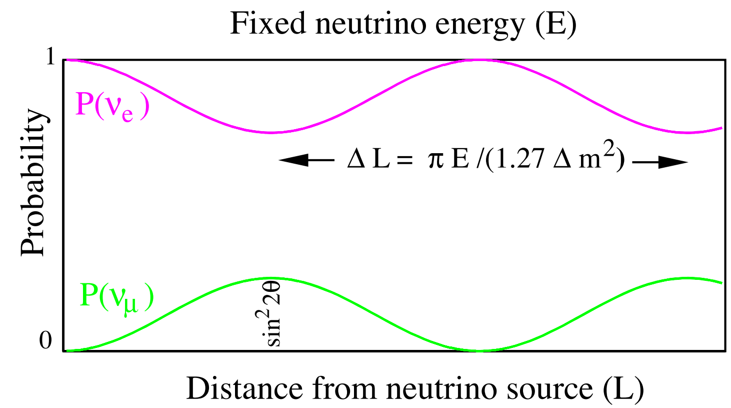
$(\hbar = c = 1)$

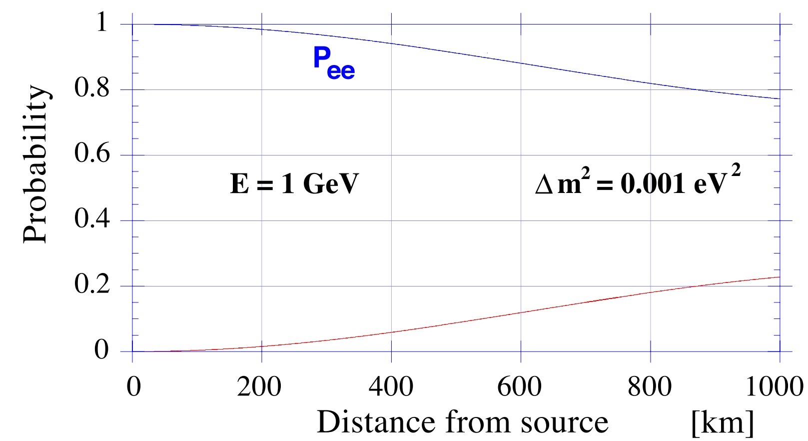
- $E/(1.27\Delta m^2)$ is the characteristic oscillation length

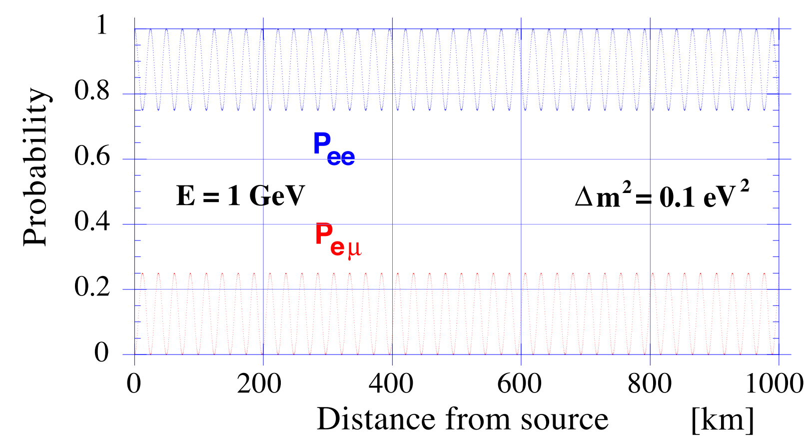
$$P_{\mathrm{osc}} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

- Two fundamental properties
  - $\sin^2 2\theta$: magnitude of the oscillation
  - $\Delta m^2 = m_1^2 - m_2^2$: the difference between the squares of the neutrino masses
- Sensitivity depends on
  - L : distance from source to detector
  - E : neutrino energy
- Small Δm^2 : neutrinos need time to develop the slow oscillation
- Large Δm^2 : rapid oscillations average out

$\Rightarrow$ choose L/E to select sensitivity to Δm^2







$$P_{\text{osc}} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

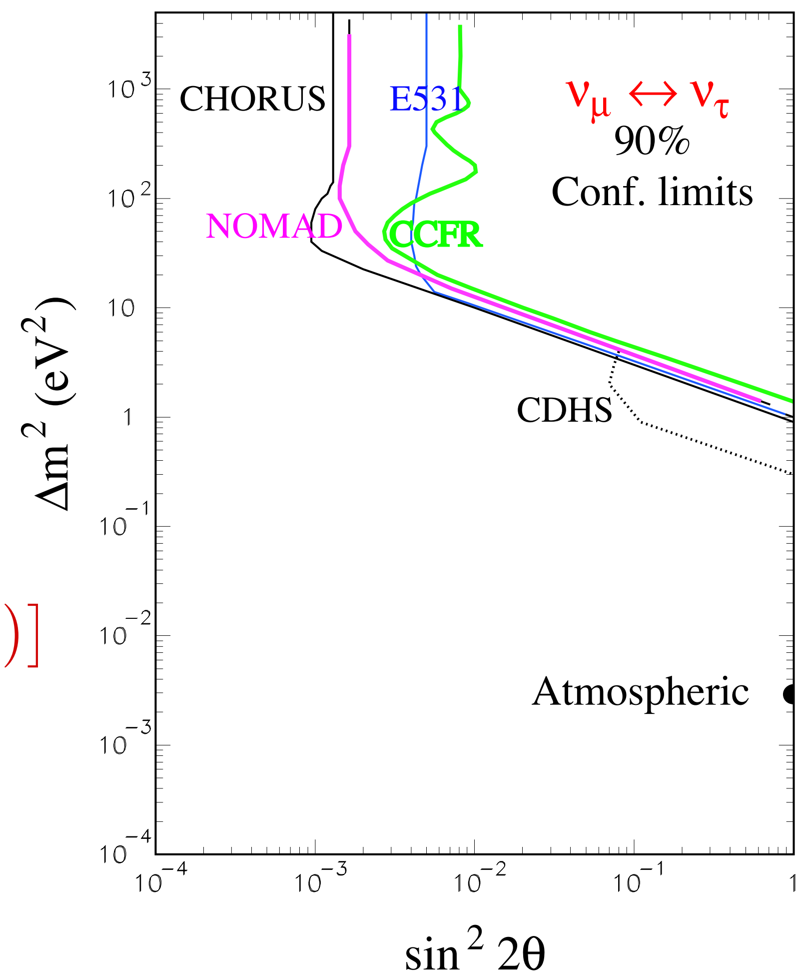
- Display the experimental results in the $(\sin^2 2\theta\,, \Delta m^2)$ plane
- If no oscillation is observed, determine the limits according to the experimental sensitivity
  - take into account the fact that in a real experiment, E and L have some spread $\Rightarrow$ convolution of P_{osc} with a gaussian function of mean $b_0 = 1.27\,L/E$ and width σ_b

$$\langle P_{\text{osc}}\rangle = \frac{1}{2}\sin^2 2\theta\left[1 - \cos(2b_0\Delta m^2)\exp\left(-2\sigma_b^2(\Delta m^2)^2\right)\right]$$

- Large Δm^2 $\quad\rightarrow sin^2 2\theta = 2\left\langle P_{\text{osc}}\right\rangle$
- Small Δm^2 $\quad\rightarrow \Delta m^2 = \frac{1}{\sigma_b}\left(\left\langle P_{\text{osc}}\right\rangle/\sin^2 2\theta\right)^{1/2}$

Hints and excluded regions

$\nu_\mu \rightarrow \nu_\tau$



Oscillations in vacuum

- Consider only two flavours ν_e and ν_μ (can be generalised to 3 flavours)
- In vacuum, the propagation eigenstates are the mass eigenstates

$$H\left|\nu_1\right\rangle = E_1\left|\nu_1\right\rangle$$
$$H\left|\nu_2\right\rangle = E_2\left|\nu_2\right\rangle$$

- In (ν_e, ν_μ) basis, H is not diagonal : $H_\nu = \begin{pmatrix} H_{ee} & H_{\mu e} \\ H_{e\mu} & H_{\mu\mu} \end{pmatrix}$

where
$$H_{ee} = E_1 \cos^2\theta + E_2 \sin^2\theta \simeq \frac{1}{2}\left(2E + \frac{\mu^2}{2E} + \frac{\Delta m^2}{2E}\cos 2\theta\right)$$
$$H_{\mu\mu} = E_1 \sin^2\theta + E_2 \cos^2\theta \simeq \frac{1}{2}\left(2E + \frac{\mu^2}{2E} - \frac{\Delta m^2}{2E}\cos 2\theta\right)$$
$$H_{\mu e} = H_{e\mu} = -(E_2 - E_1)\sin\theta\cos\theta \simeq -\frac{1}{2}\frac{\Delta m^2}{2E}\sin 2\theta$$
with $\mu^2 = m_1^2 + m_2^2$ and $\Delta m^2 = m_1^2 - m_2^2$

- Diagonalise H_ν to determine the propagation (=mass) eigenstates
  - one can subtract E from diagonal without modifying the eigenstates $\rightarrow H_\nu'$

- Look for the eigenstates of

$$H'_\nu = \frac{1}{2E}\begin{pmatrix} M^2_{ee} & M^2_{\mu e} \\ M^2_{e\mu} & M^2_{\mu\mu} \end{pmatrix}$$

$$M^2_{ee} = \frac{1}{2}(\mu^2 + \Delta m^2 \cos 2\theta)$$
$$M^2_{e\mu} = -\frac{1}{2}\Delta m^2 \sin 2\theta$$
$$M^2_{\mu\mu} = \frac{1}{2}(\mu^2 - \Delta m^2 \cos 2\theta)$$

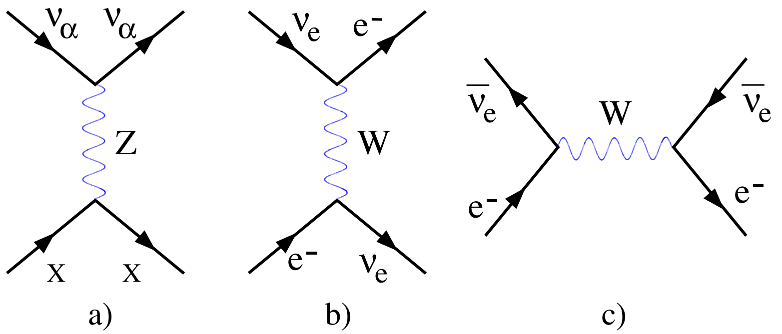
- In matter, must add coherent ν scattering, characterised by an additional potential diagonal in (ν_e, ν_μ) basis
  - all neutrinos have Z^0 exchange

    $\rightarrow V_Z \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ same for both flavours
    $\Rightarrow$ can be ignored (diagonal)

  - only ν_e have $W^\pm$ exchange

    $\rightarrow V_W \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$ only for ν_e

    $$V_W = \sqrt{2} G_F N_e = 7.63 \times 10^{-14} \frac{Z}{A} \rho [\mathrm{eV}]$$



a) : neutral current of ν_α , $\alpha = e, \mu, \tau$
X = p, n, Nucleus, e^-
b) : charged current of ν_e
c) : charged current of $\overline{\nu}_e$.

  - the matrix becomes:

$$\begin{pmatrix} M^2_{ee} + 2EV_W & M^2_{\mu e} \\ M^2_{e\mu} & M^2_{\mu\mu} \end{pmatrix}$$

Neutrino states in matter

- Consider a constant density medium
- Diagonalise the mass matrix and set $B = 2EV_W$

  - two mass eigenvalues

$$m^2 = \frac{1}{2}(\mu^2 + B) \pm \frac{1}{2}\sqrt{(\Delta m^2 \cos 2\theta - B)^2 + (\Delta m^2)^2 \sin^2 2\theta}$$

  - mixing angle in matter

$$\tan 2\theta_m = \frac{\sin 2\theta}{\cos 2\theta - \frac{B}{\Delta m^2}}$$

- Maximal mixing (i.e. resonance) occurs when

$$B = 2EV_W = 2E \times 7.63 \times 10^{-14}\frac{Z}{A}\rho = \Delta m^2 \cos 2\theta$$

$$\Rightarrow \rho_{\text{res}} = \frac{\Delta m^2 \cos 2\theta}{1.526 \times 10^{-13}\frac{Z}{A}E}$$

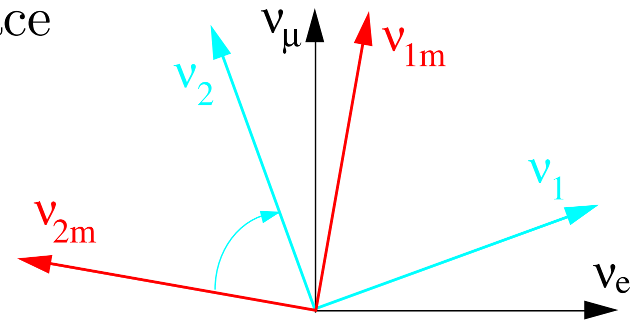
- Then:

$$\nu_e = \cos\theta_m \nu_1 + \sin\theta_m \nu_2$$

$$\nu_\mu = -\sin\theta_m \nu_1 + \cos\theta_m \nu_2$$

MSW effect in the Sun

- The Sun density varies from $150\,\mathrm{g/cm^3}$ ($\approx 6\times 10^{25}\, e^-/\mathrm{cm}^3$) in the center to ≈ 0 at the surface



- Consider adiabatic transition where the density varies little over an oscillation length
  $\Rightarrow$ density is approximately constant

  - ν_e produced in the center: $\rho \gg \rho_{\mathrm{res}} \Rightarrow B$ is large $\Rightarrow \tan 2\theta \to 0$
    $\Rightarrow \theta_{\mathrm{m}} \to \pi/2$ (large angle solution) $\Rightarrow \nu_e$ is in a pure ν_2 state

  - ν_2 travels outwards through the resonance region
    $\Rightarrow$ the neutrino remains in the same ν_2 state

  - the neutrino emerges as ν_2 in vacuum where $\theta_{\mathrm{m}} = \theta$

  - ν_2 is now a mixture of ν_e and ν_μ

- This is the Mikheyev-Smirnov-Wolfenstein (MSW) effect

$$P_{ee} = |\langle \nu_e | \nu_2 \rangle|^2 = \sin^2\theta$$

$$P_{e\mu} = |\langle \nu_\mu | \nu_2 \rangle|^2 = \cos^2\theta$$

Three-family mixing

- Write flavour mixing matrix for three neutrino families

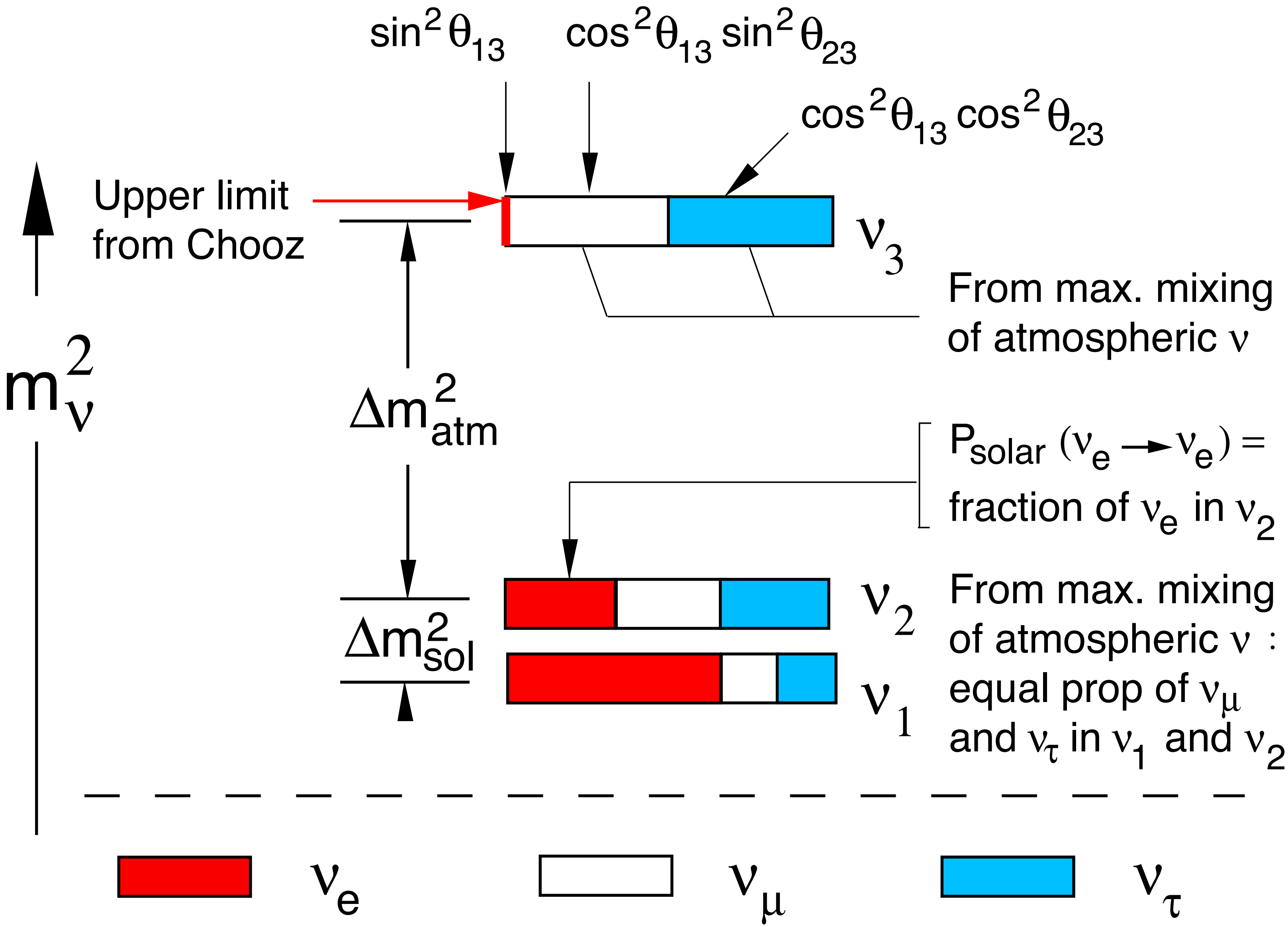
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Express the unitary matrix U as product of 3 rotations

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

atmospheric neutrinos **cross-mixing** **solar neutrinos**

- $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$
- θ_{12} characteristic of solar oscillations
- θ_{23} characteristic of atmospheric neutrinos
- δ is the CP phase; no CP violation if $\theta_{13} = 0$



$\sin^2\theta_{13}$
$\cos^2\theta_{13}\,\sin^2\theta_{23}$
$\cos^2\theta_{13}\,\cos^2\theta_{23}$
Upper limit from Chooz
ν_3
From max. mixing of atmospheric ν
m_ν^2
Δm^2_{atm}
$P_{solar}(\nu_e \to \nu_e) =$ fraction of ν_e in ν_2
ν_2
ν_1
Δm^2_{sol}
From max. mixing of atmospheric ν : equal prop of ν_μ and ν_τ in ν_1 and ν_2
ν_e
ν_μ
ν_τ

Experimental results on neutrino oscillations

Measurements of neutrino oscillations

- Solar neutrinos $\rightarrow \theta_{12}$
- Atmospheric neutrinos
- Reactor experiments
- Accelerator experiments

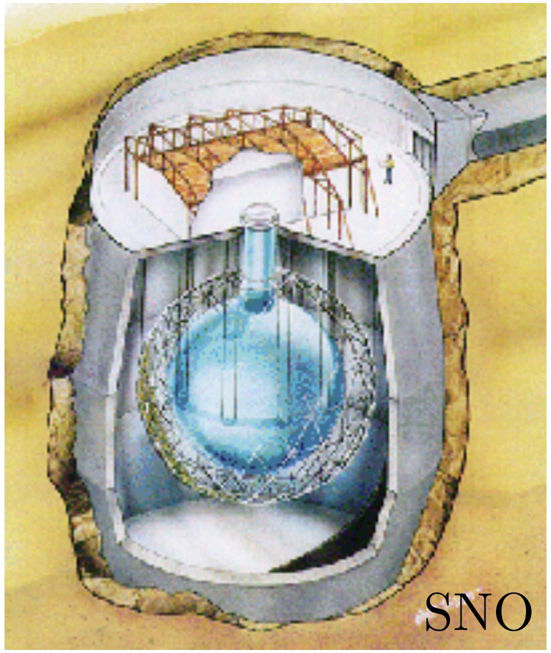
$$P_{\text{osc}} = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

- Sensitivity of possible oscillation experiments:

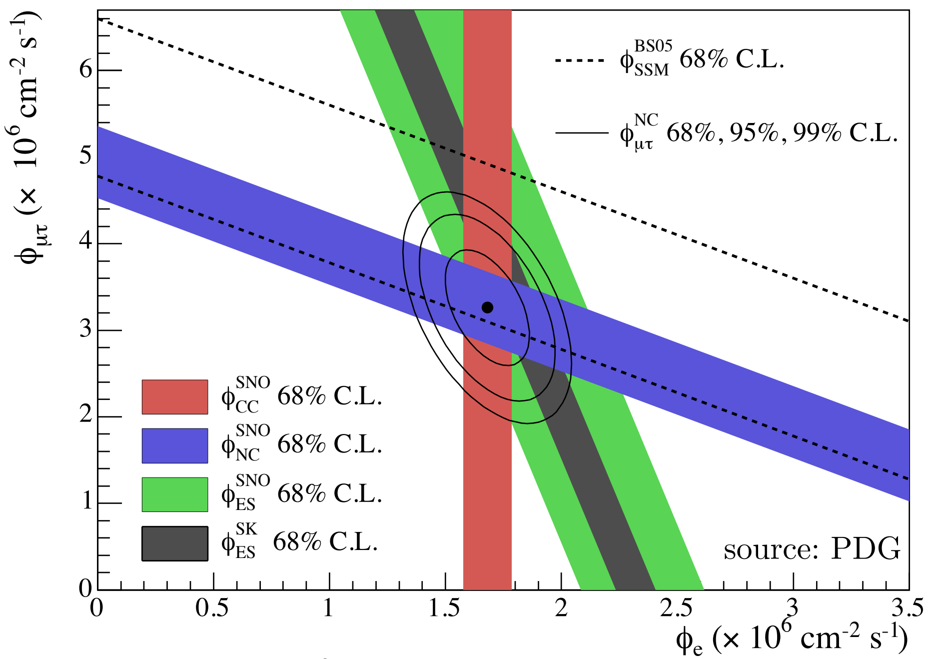
Source	Type of ν	$\overline{E}$[MeV]	L[km]	min(Δm^2)[eV^2]
Reactor	$\overline{\nu}_e$	~ 1	1	$\sim 10^{-3}$
Reactor	$\overline{\nu}_e$	~ 1	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1	~ 1
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric ν's	$\nu_{\mu,e}, \overline{\nu}_{\mu,e}$	$\sim 10^3$	10^4	$\sim 10^{-4}$
Sun	ν_e	~ 1	1.5×10^8	$\sim 10^{-11}$

Solar neutrino mixing parameters

- We have already discussed the ν_e deficit in Chlorine, Gallium, and water Cherenkov experiments
- The SNO experiment showed that the deficit was only seen in charged current processes, but not in neutral current processes
  ⇒ consistent with $\nu_e \rightarrow \nu_\mu, \nu_\tau$ oscillations



- Flux of $\nu_\mu + \nu_\tau$ as function of flux of ν_e for neutrinos above 5 MeV (^{8}B)



Global fit for solar mixing parameters:

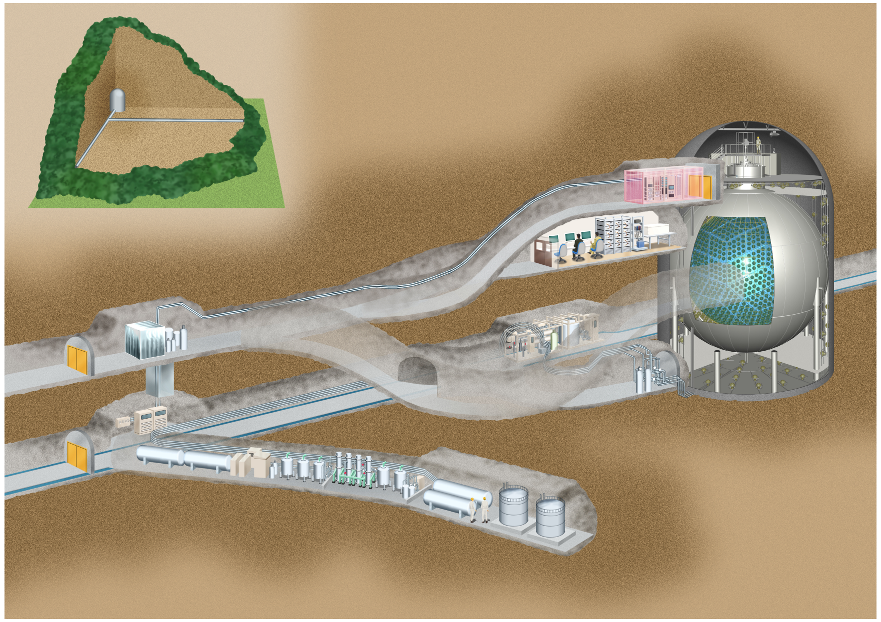
$$\Delta m^2_\odot = (7.6 \pm 0.2) \times 10^{-5} \mathrm{eV}^2$$

$$\tan^2\theta_\odot = 0.47^{+0.05}_{-0.04}$$

KamLAND ($\bar{\nu}_e$ disappearance)

- Goal: search for $\bar{\nu}_e$ disappearance from reactors at ≈180km
- anti-neutrinos emitted with energy <8MeV
- 1-kton ultra-pure liquid scintillator, at Kamiokande (Japan)

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

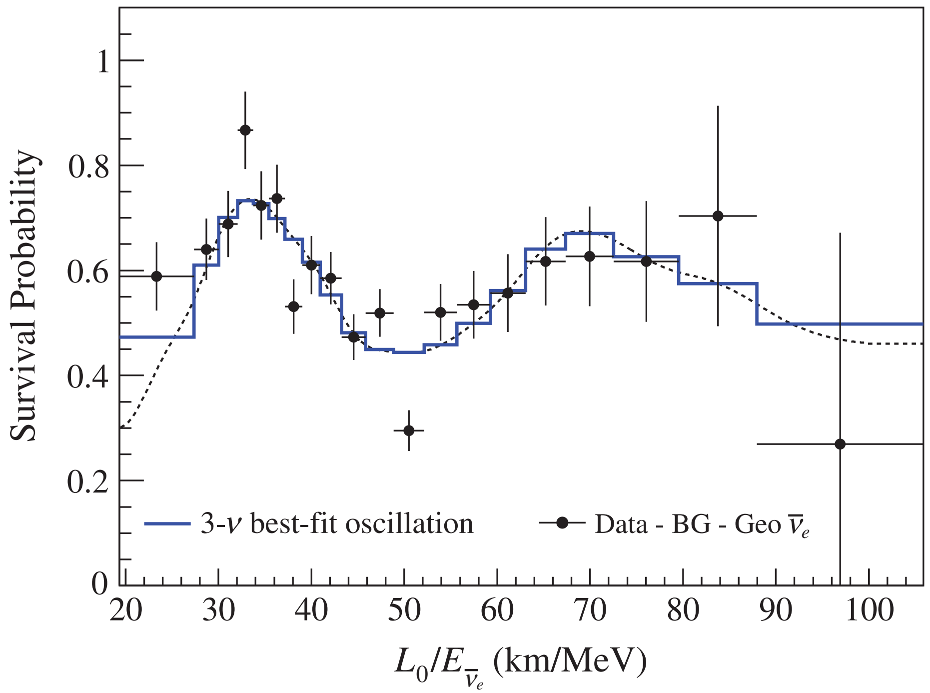


- Detection threshold: 2.6MeV
- Detect delayed coincidence of positron and 2.2MeV γ from neutron capture
- Observes clear evidence for ν_e disappearance (assuming CPT)

$$\frac{N_{\rm obs} - N_{\rm BG}}{N_{\rm NoOsc}} = 0.611 \pm 0.085 \pm 0.041$$

⇒ confirmation of solar neutrino oscillations ($\nu_e \rightarrow \nu_{(\mu\,\text{or}\,\tau)}$)

Mixing parameters from KamLAND

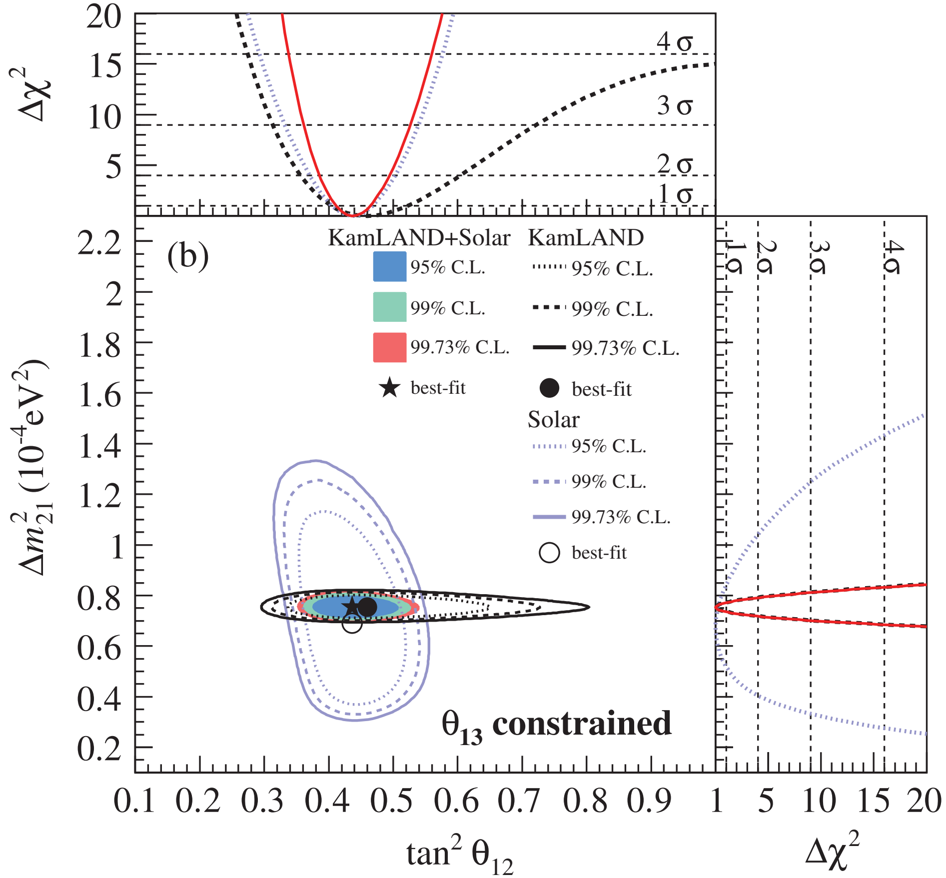


Ratio of the background-subtracted electron anti-neutrino spectrum to the expectation for no-oscillation as a function of L_0/E. L_0 is the effective baseline taken as a flux-weighted average ($L_0 = 180\,\text{km}$)

Global fit

$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$$
$$\Delta m^2_{12} = (7.53 \pm 0.18) \times 10^{-5}\ \text{eV}^2$$
$$\sin^2\theta_{13} = 0.023 \pm 0.002$$

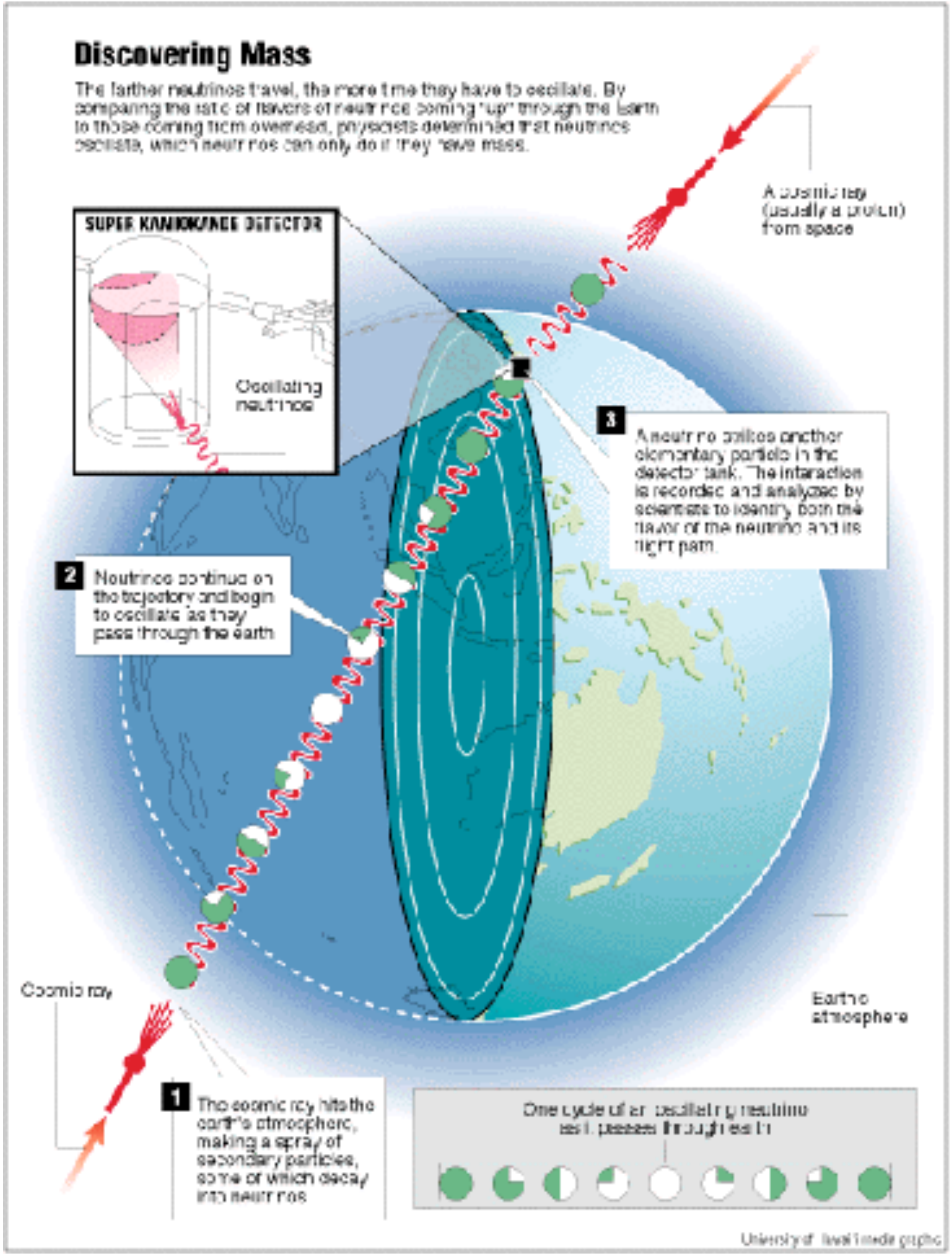
Allowed region for oscillation parameters. Data from KamLAND and solar experiments



Phys. Rev. D88 (2013) 033001

Atmospheric neutrinos

- Isotropy of $\geq 2\,\text{GeV}$ cosmic rays and assuming no ν_μ absorption $\Rightarrow$ expect equal upward and downward fluxes
  - downward ν : $L \simeq 15\,\text{km}$
  - upward ν : $L \simeq 12'500\,\text{km}$
- Observe $\sim 1/2$ upward flux relative to downward

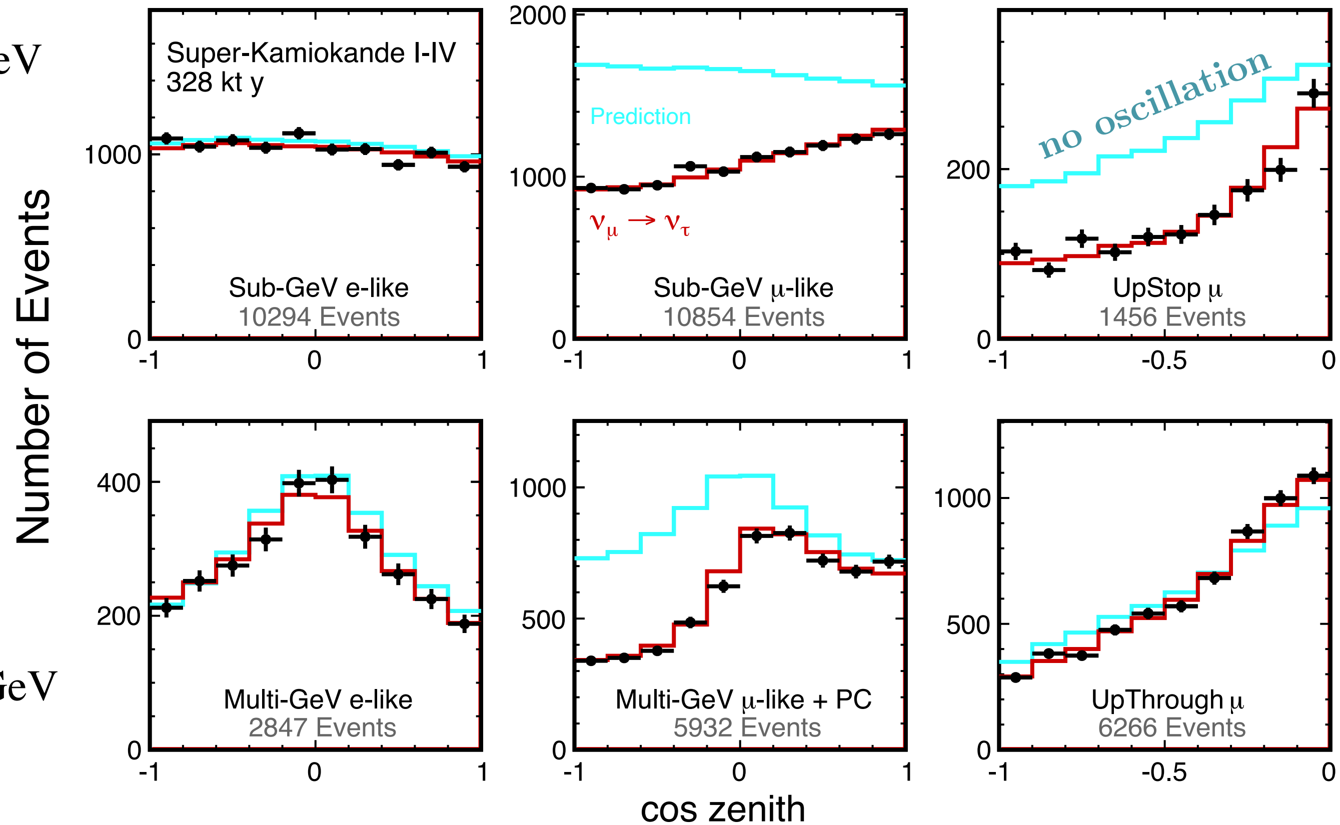


Evidence for atmospheric ν oscillations

- Super Kamiokande

Sub-GeV ⇔ $E_{vis} < 1.33\,\text{GeV}$

Multi-GeV ⇔ $E_{vis} > 1.33\,\text{GeV}$



PDG 2022

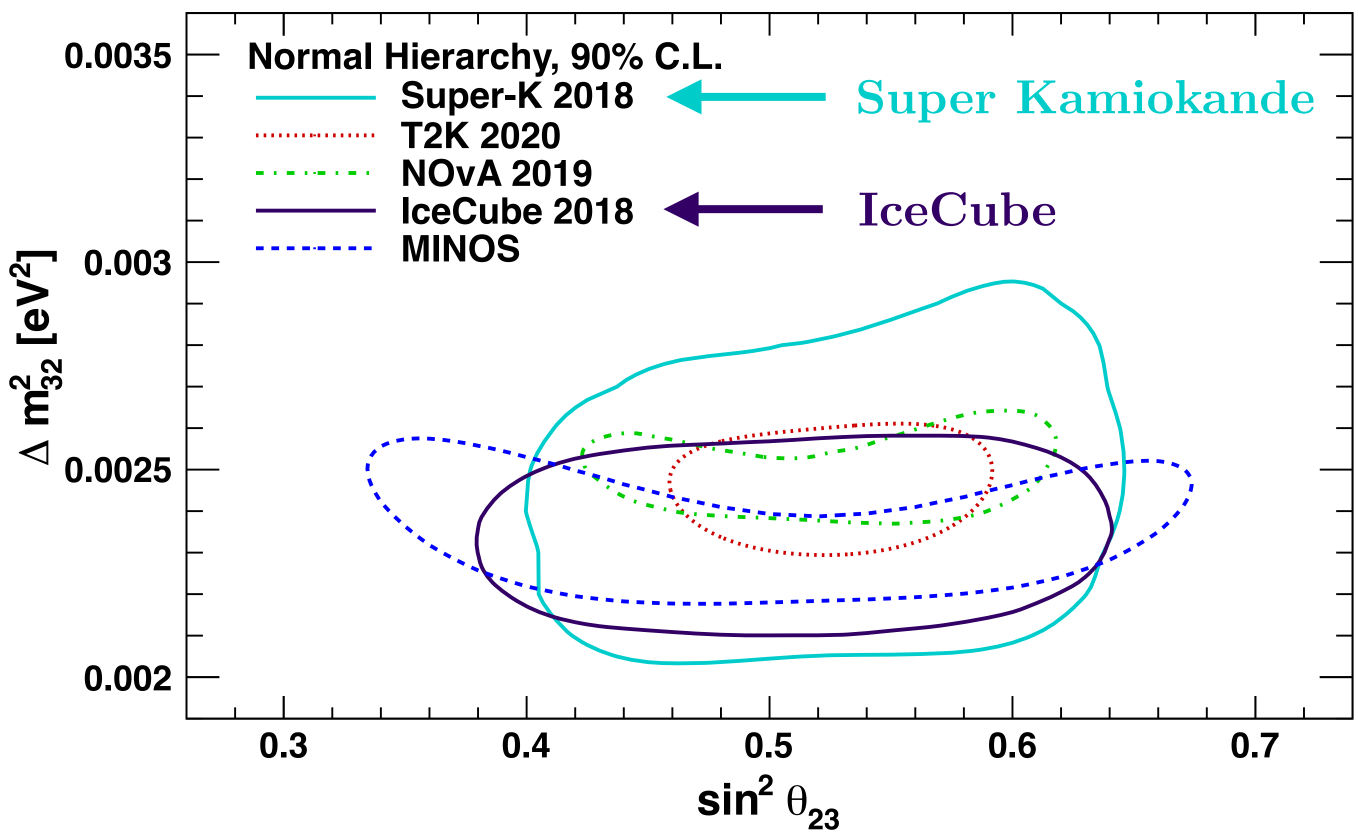
- Consistent with $\nu_\mu \to \nu_\tau$ oscillation

$$\Rightarrow \Delta m^2 = 2.2 \times 10^{-3}\,\text{eV}^2 \text{ and } \sin^2 2\theta = 1.0$$

- To be confirmed with accelerator-generated ν_μ (Opera, K2K)

Atmospheric ν oscillation results

Experiment	$\sin^2\theta_{23}$	$|\Delta m^2_{32}|$ $[10^{-3}\mathrm{eV}^2]$
Antares [244]	$0.50^{+0.2}_{-0.19}$	$2.0^{+0.4}_{-0.3}$
IceCube [245]	$0.51^{+0.07}_{-0.09}$	$2.31^{+0.11}_{-0.13}$
Super-Kamiokande (Super-K) [246]	$0.588^{+0.031}_{-0.064}$	$2.50^{+0.13}_{-0.20}$

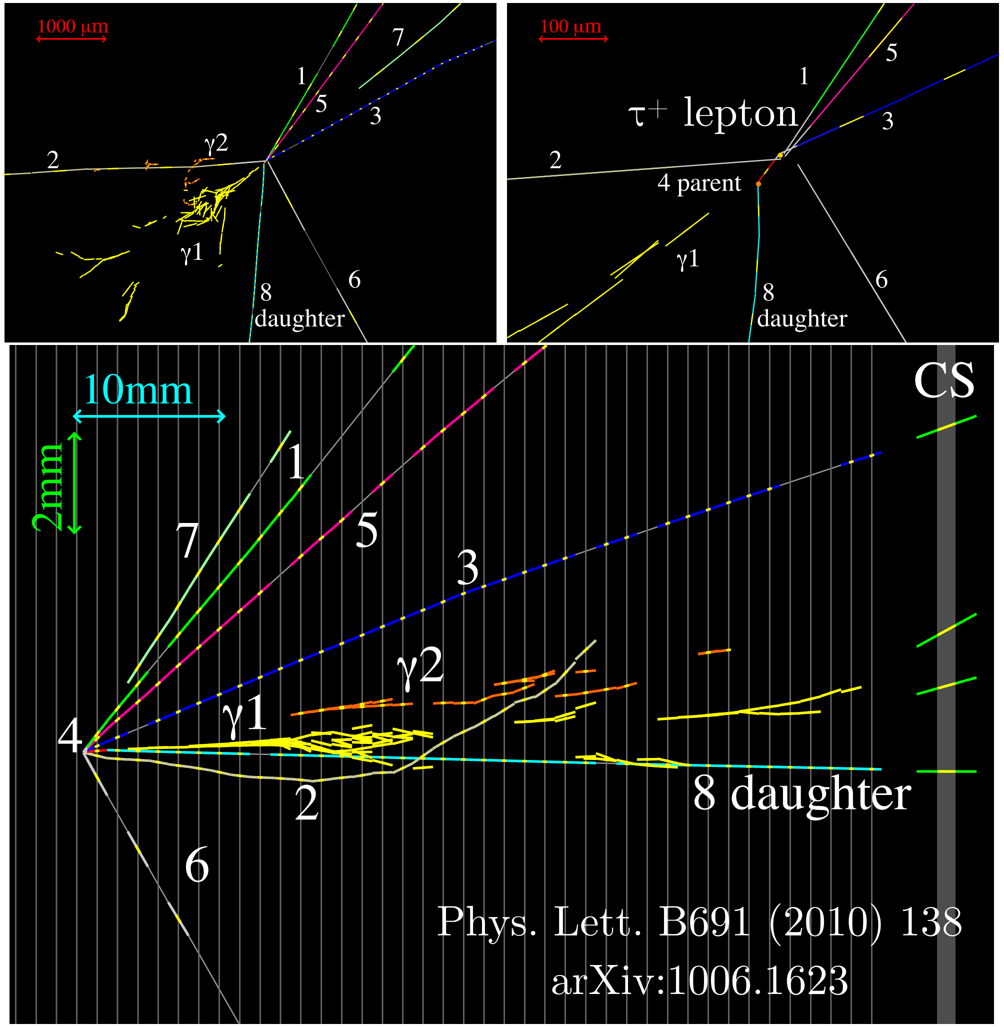


M. Sajjad Athar, et.al., "Status and perspectives of neutrino physics", arXiv:2111.07586

$\nu_\mu \rightarrow \nu_\tau$ at OPERA

- ~17GeV ν_μ beam from CERN SPS to Gran Sasso (Italy)
  - $L = 732\,\text{km}$
- With 18×10^{19} protons on target, OPERA observes ν_τ appearance
  - $\nu_\mu \rightarrow \nu_\tau$ during its flight from CERN
  - $\tau^\pm$ lepton created in charged current interaction
- Observe 10 ν_τ candidates, with 2.0 ± 0.4 expected background $\Rightarrow 6.1\sigma$ significance
- Compatible with $|\Delta m^2_{23}| = 2.5 \times 10^{-3}\,\text{eV}^2$ and full mixing ($\sin^2(2\theta_{23}) = 1$)

Phys. Rev. Lett. 129 (2018) 211801
arXiv:1804.04912



Phys. Lett. B691 (2010) 138
arXiv:1006.1623

Parametrisation of the mixing matrix

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

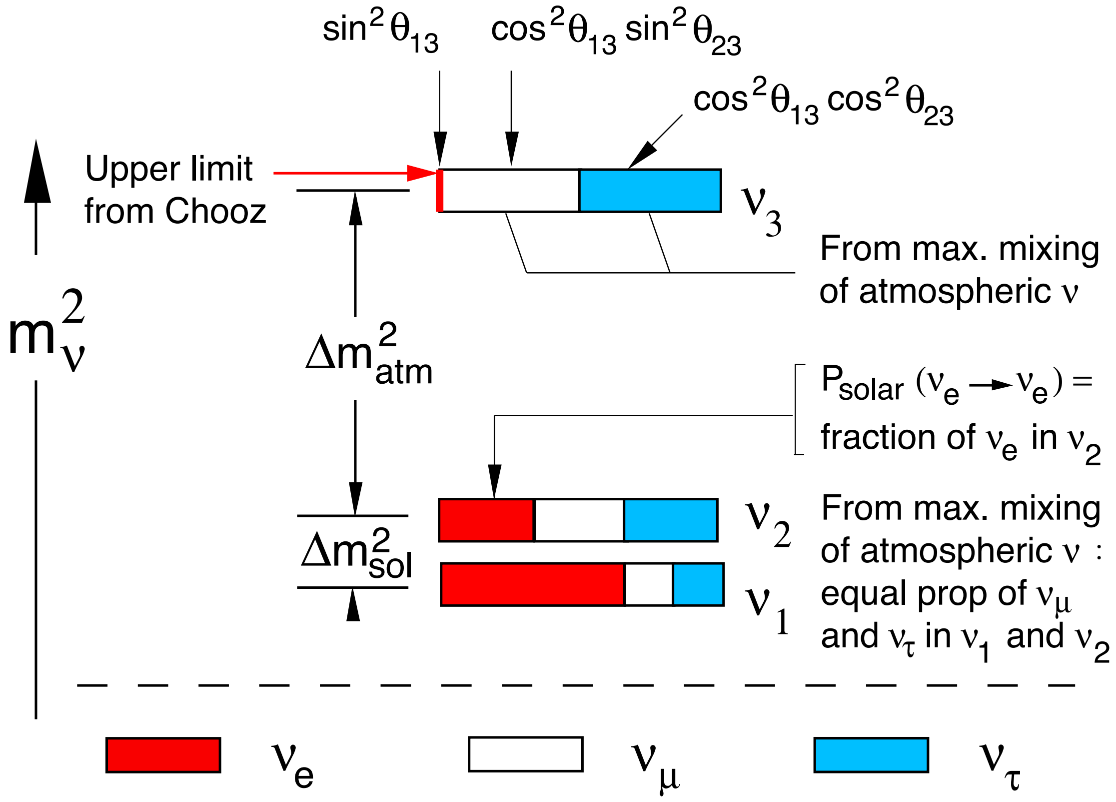
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric neutrinos **cross-mixing** **solar neutrinos**

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -c_{12}s_{13}s_{23} - s_{12}c_{23} & -s_{12}s_{13}s_{23} + c_{12}c_{23} & c_{13}s_{23} \\ -c_{12}s_{13}c_{23} + s_{12}s_{23} & -s_{12}s_{13}c_{23} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix}$$

The "preferred" solution (approximated)

- Fraction of ν_e in $\nu_3 = |U_{13}|^2 = \sin^2\theta_{13}$ is small $\Rightarrow$ neglect
- Fraction of ν_e in $\nu_2 = P_{\text{solar}}(\nu_e \rightarrow \nu_e) = \sin^2\theta_{12} = |\langle \nu_e | \nu_2 \rangle|^2 \simeq 1/3$
- Fraction of ν_e in $\nu_1 = 1 - 1/3$
- 50% ν_μ and 50% ν_τ in ν_3 $(0.5 = c_{23}^2 = s_{23}^2)$
- ν_μ and ν_τ in ν_1 and ν_2 in equal ratios



The "preferred" solution

- Based on solar and atmospheric neutrino oscillation results
- Global fit to solar and atmospheric data only
  $\Rightarrow$ determine mixing matrix parameters θ_{ij} and Δm^2_{ij}

Table 14.1: The best-fit values and 3σ allowed ranges of the 3-neutrino oscillation parameters, derived from a global fit of the current neutrino oscillation data (from [58]) . For the Dirac phase δ we give the best fit value and the 2σ allowed range. The values (values in brackets) correspond to $m_1 < m_2 < m_3$ ($m_3 < m_1 < m_2$). The definition of Δm^2, which is determined in the global analysis in [58] is: $\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$. Thus, $\Delta m^2 = \Delta m^2_{31} - \Delta m^2_{21}/2 > 0$, if $m_1 < m_2 < m_3$, and $\Delta m^2 = \Delta m^2_{32} + \Delta m^2_{21}/2 < 0$ for $m_3 < m_1 < m_2$. We give the values of $\Delta m^2_{31} > 0$ for $m_1 < m_2 < m_3$, and of Δm^2_{23} for $m_3 < m_1 < m_2$, obtained from those for Δm^2 quoted in [58].

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

source: PDG 2018

- Remarks:
  - mixing of atmospheric neutrinos is maximal
  - $\sin^2\theta_{13}$ small
    $\Rightarrow$ solar and atmospheric neutrinos almost decoupled

Oscillation parameters from all neutrino experiments (source: PDG)

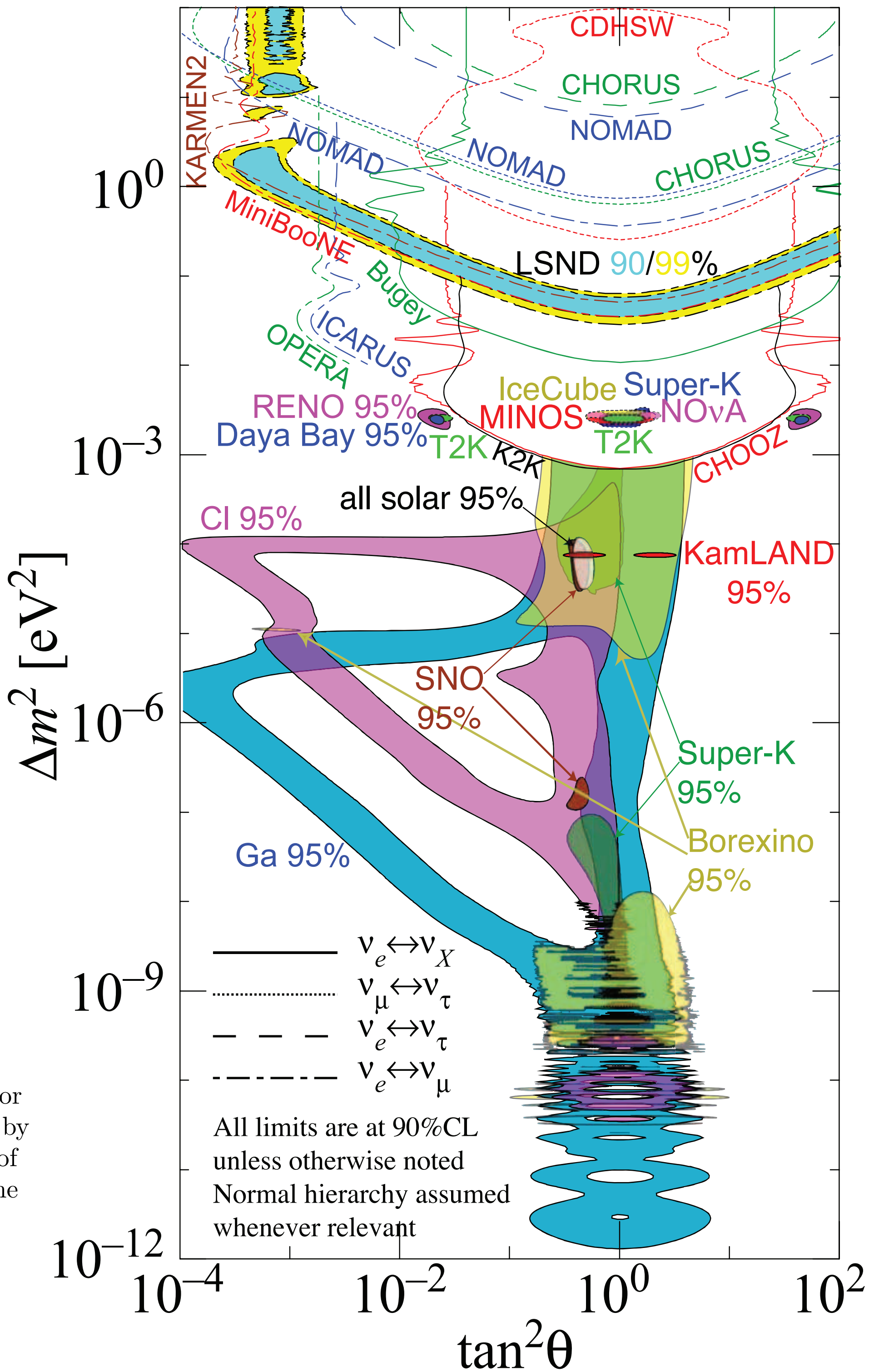


Figure 14.16: The regions of squared-mass splitting and mixing angle favored or excluded by various neutrino oscillation experiments. The figure was contributed by H. Murayama (University of California, Berkeley, and Kavli IPMU, University of Tokyo). References to the data used in the figure and the description of how the figure was obtained can be found at `http://hitoshi.berkeley.edu/neutrino`.

What needs to be measured next?

- The model describes well the solar and atmospheric neutrino data
- But cross-mixing parameters (θ_{13}) is not measured directly
- Need to determine:
  - θ_{13}
  - CP phase δ
  - mass ordering
  - absolute scale $\rightarrow$ absolute mass measurements (e.g. in β decay)

How to measure θ_{13}?

- CP violation and our ability to determine the sign of Δm^2 depends on $\sin\theta_{13}$ ⇒ high experimental priority!

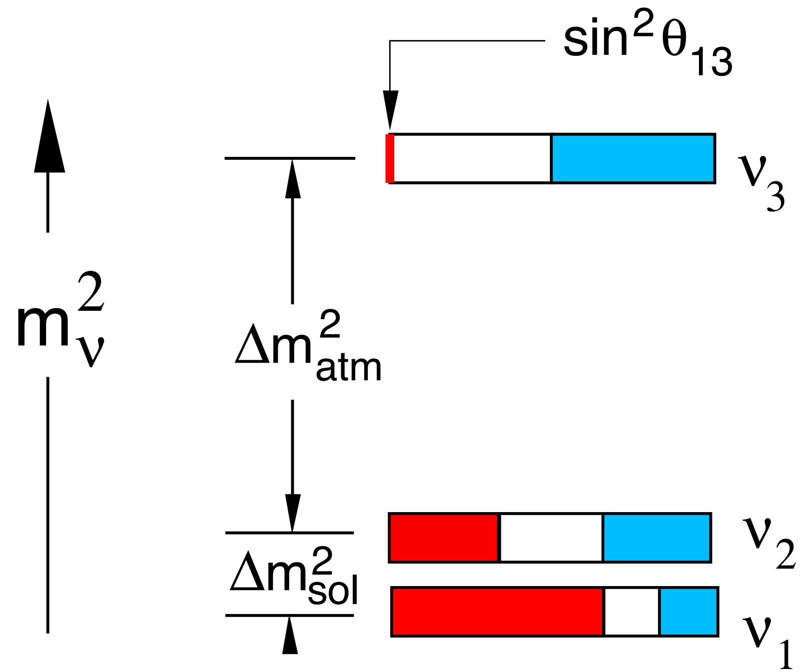
- How can we measure $\sin\theta_{13}$?

- Approximation: $\Delta m^2_{12} \approx 0$
  ⇒ $\Delta m^2_{13} = \Delta m^2_{23} \equiv \Delta m^2$

- Consequences:

  - $\nu_\mu \to \nu_\tau$:
    $$P_{\text{osc}} = 4(s_{23}c_{23}c^2_{13})^2 \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$
    ⇒ c_{13} is not sensitive to θ_{13}

  - $\nu_\mu \to \nu_e$:
    $$P_{\text{osc}} = 4(s_{23}c_{13}s_{13})^2 \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$
    ⇒ s_{13} is very sensitive to θ_{13}



⇒ Need an experiment with:
- L/E sensitive to Δm^2_{atm}
- involvement of ν_μ and ν_e

Determination of θ_{13}

- Select L/E to be at the maximum of $\sin^2\left(\frac{1.27\Delta m^2_{23}L}{E}\right)$
  $\Rightarrow L/E \approx 400 - 500\,\mathrm{km/GeV}$

- Two possibilities :

  A. Reactor experiments :

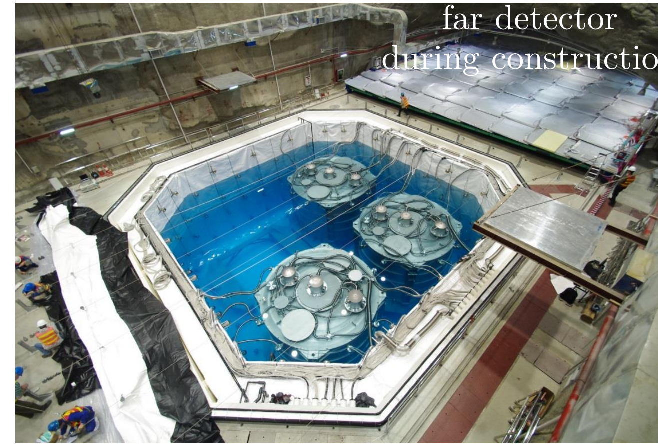
  - $\bar{\nu}_e$ **disappearance**; $L \simeq 1.5\,\mathrm{km}$; use far and near detectors to reduce systematics uncertainties to $<1\%$
  - Proposed experiments: Kashiwazaki (24.3 GW); Double-CHOOZ (8.5 GW); Daya Bay (6×2.9 GW)

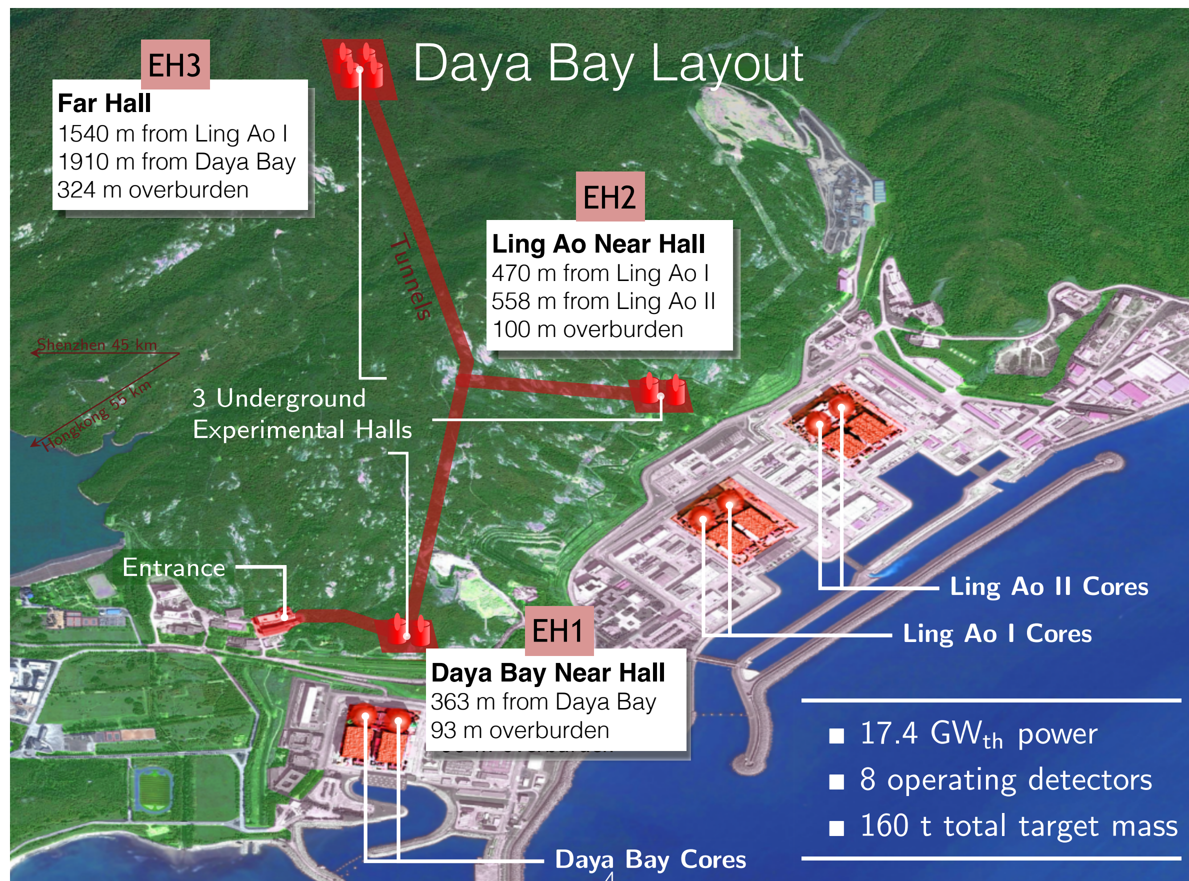
  B. Accelerator experiments :

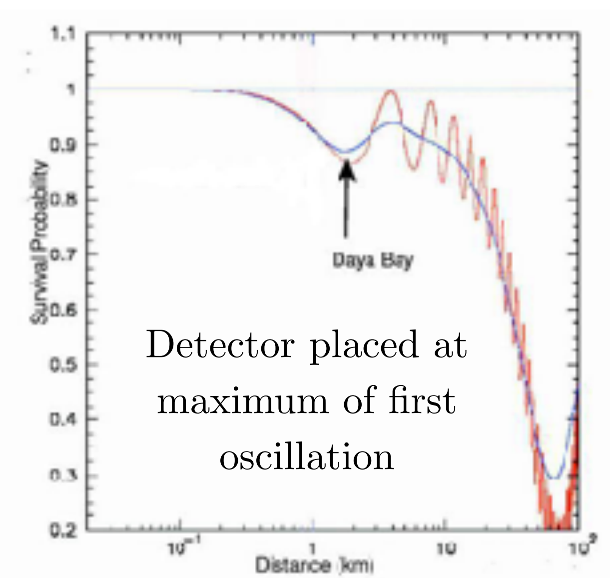
  - ν_e **appearance in a ν_μ beam**; $L >$ several $100\,\mathrm{km}$
  - use low energy "narrow band" beam
  - advantages: no charged current from ν_μ ; reduced neutral currents because running at low energy
  - detectors optimised for ν_e detection

Daya Bay experiment $[\theta_{13}]$

- 6 nuclear power plants of 2.9 GW in Guang Dong province, near Hong Kong
- 4 near detectors and 4 far detectors
  - grouped in 3 locations (2 near, 1 far)
- Far detector placed close to oscillation maximum
- Detection in Gd doped liquid scintillator

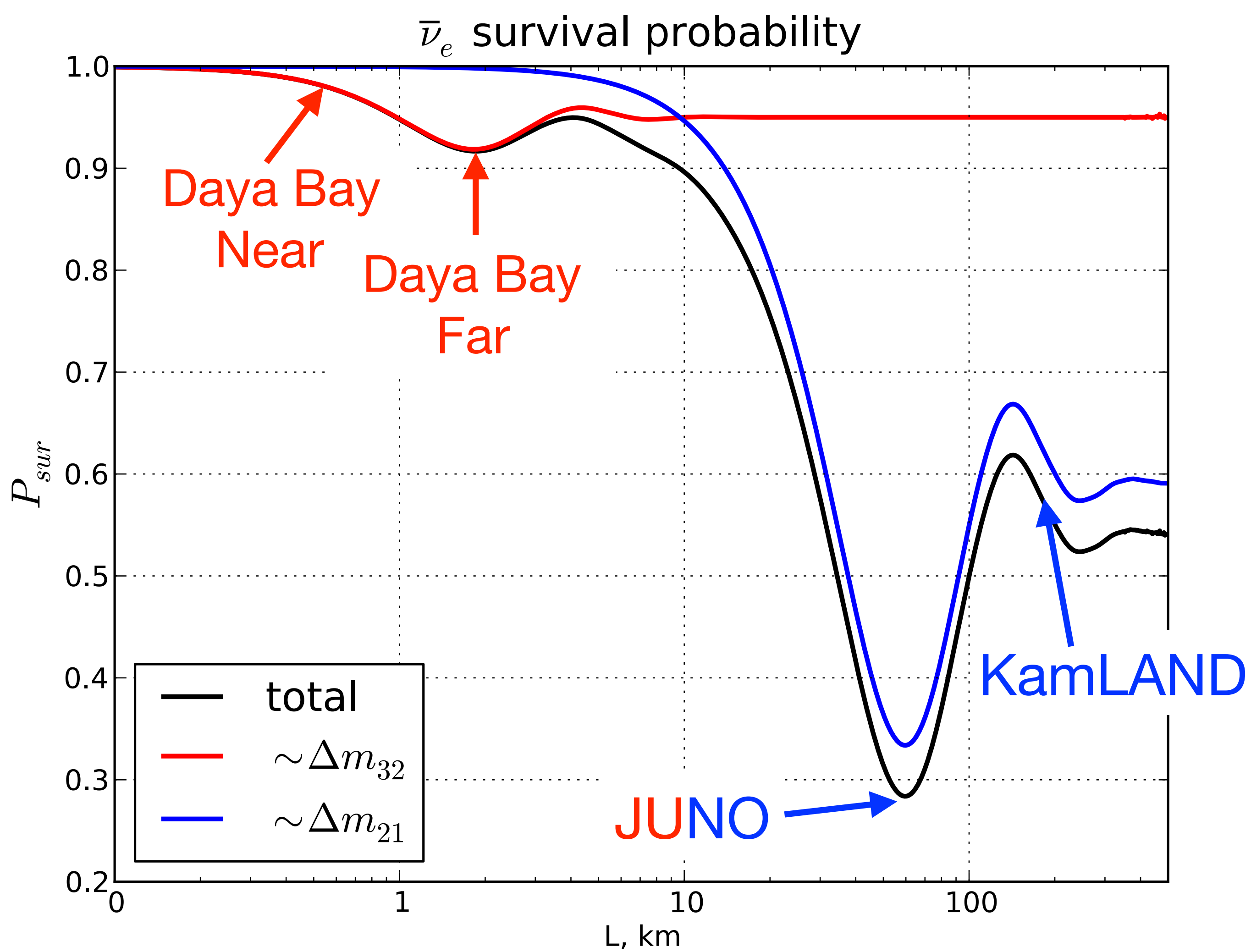






$\bar{\nu}_e$ disappearance

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{12} L}{4E}\right)$$



From J. Pedro Ochao Ricoux
CERN EP Seminar
20 February 2017

Daya Bay results on θ_{13}

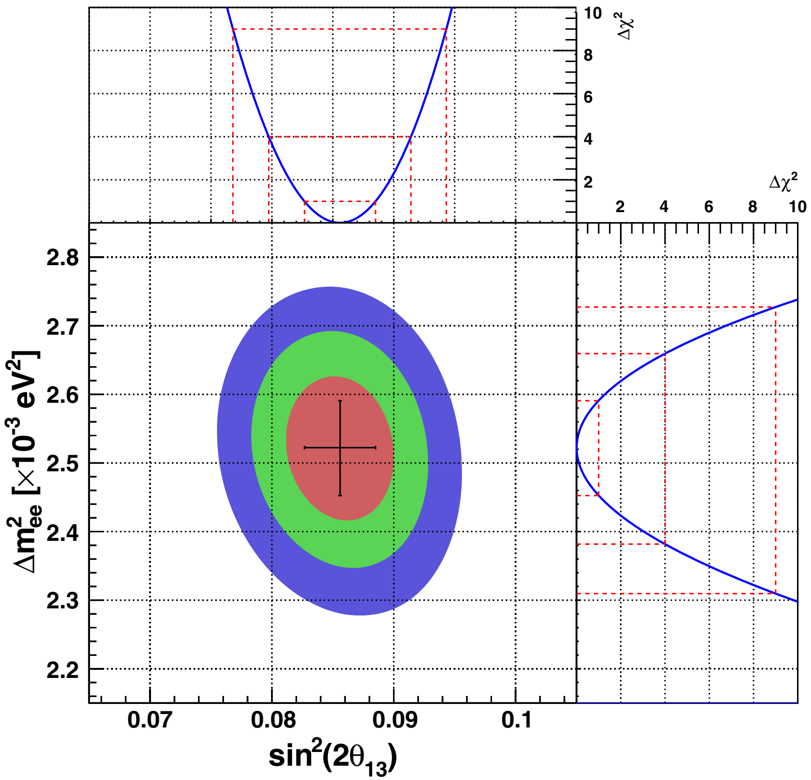


FIG. 4. The 68.3%, 95.5%, and 99.7% C.L. allowed regions in the Δm^2_{ee}-$\sin^2 2\theta_{13}$ plane. The one-dimensional $\Delta\chi^2$ for $\sin^2 2\theta_{13}$ and Δm^2_{ee} are shown in the top and right panels, respectively. The best-fit point and one-dimensional uncertainties are given by the black cross.

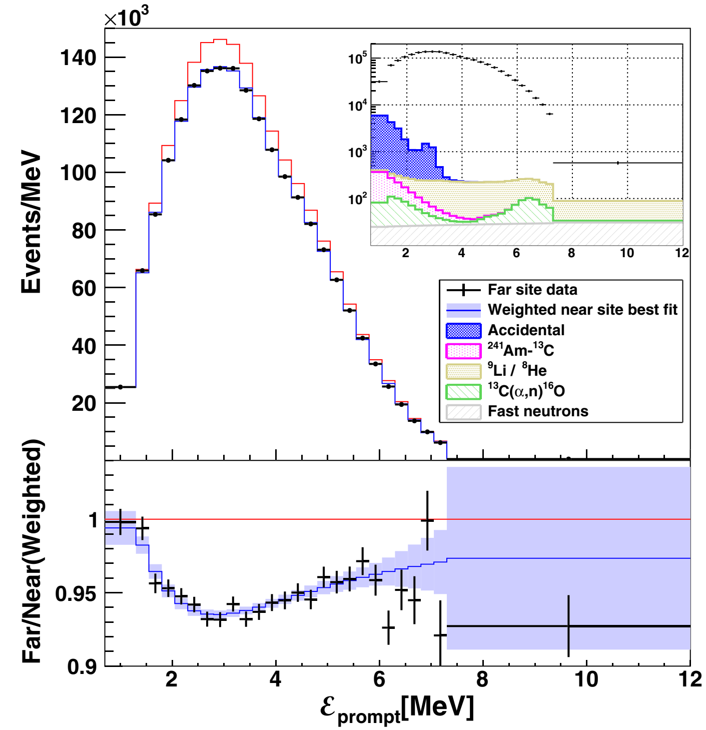


FIG. 3. The background-subtracted spectrum at the far site (black points) and the expectation derived from near-site measurements excluding (red line) or including (blue line) the best-fit oscillation. The bottom panel shows the ratios of data over predictions with no oscillation. The shaded area is the total uncertainty from near-site measurements and the extrapolation model. The error bars represent the statistical uncertainty of the far-site data. The inset shows the background components on a logarithmic scale. Detailed spectra data are provided as Supplemental Material [14].

$\Rightarrow \sin^2 2\theta_{13} = 0.0856 \pm 0.0029$

Phys. Rev. Lett. 121 (2018) 241805

arXiv:1809.02261

Accelerator experiments [θ_{13}]

- J-PARK to SuperKamiokande (T2K)
  - hadron facility at Tokai
  - 0.77MW source of 50GeV protons
  - ν_μ line to Kamioka (295km),
    with energy <1GeV (2.5° off axis)
  - low ν_e contamination (<0.5%)

	$\langle E_\nu \rangle$ [GeV]	L [km]	L/E [km/GeV]
T2K	0.7	295	421
NOνA	2.0	810	405

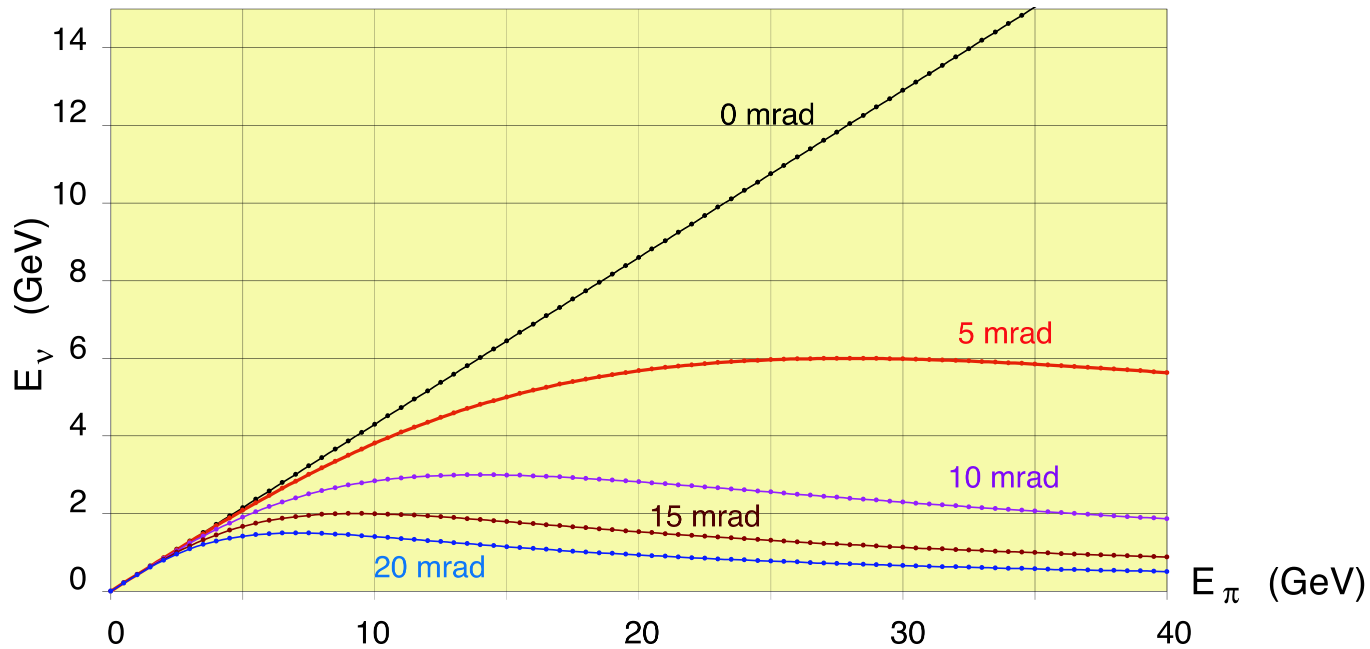
- NuMi Off axis (NOνA)
  - surface detector at Ash River (MN, USA)
  - off axis neutrinos from Fermilab (810km, 12km off axis)
  - narrow band ν_μ of a few GeV
  - low ν_e contamination (<0.5%)
  - pulsed beam ⇒ use timing to reject background

Why off-axis experiments?

- Neutrinos are produced in $\pi \to \mu\nu_\mu$ decays

$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma_\pi^2 \theta^2}$$

$1^\circ = 17.4\,\mathrm{mrad}$



- On-axis ν energy is proportional to the pion energy
- Off-axis ν energy is almost independent of E_π

  $\Rightarrow$ know at which energy to expect ν_e CC from oscillations

- Low ν_e contamination (<1%)

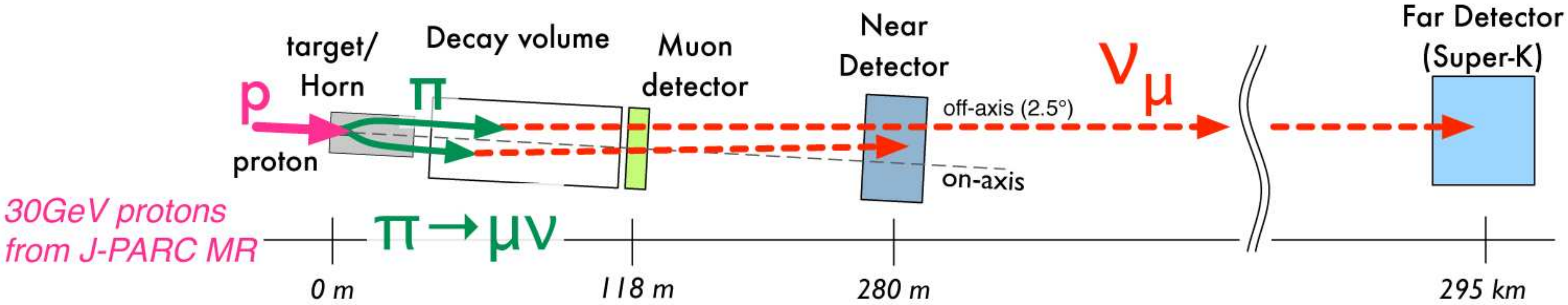
T2K experiment

- Goal: observe ν_e appearance in ν_μ beam, to measure θ_{13}
  - $\sin^2\theta_{13} < 0.15$ @90% CL (CHOOZ and MINOS)

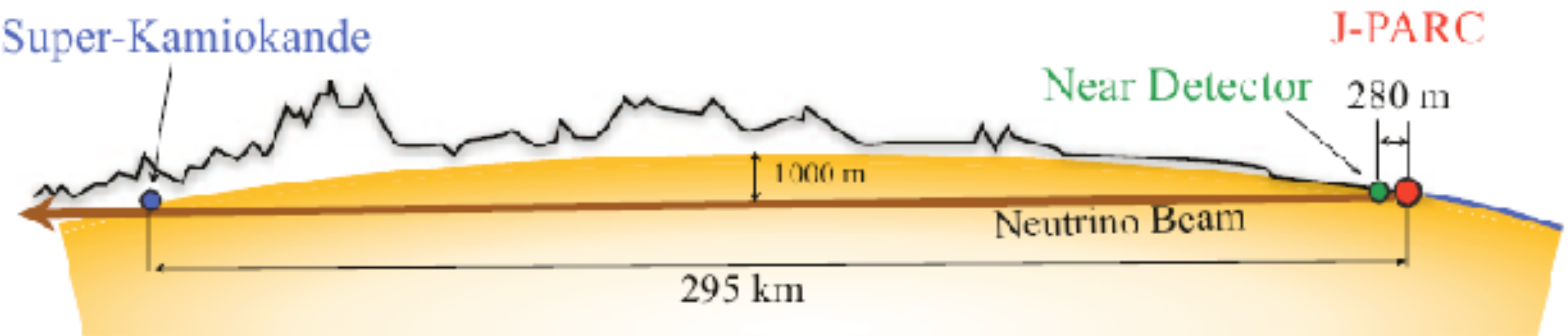
$$P_{\rm osc} = 4(s_{23}c_{13}s_{13})^2 \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

- Opens the possibility to measure CP violation in the lepton sector: $P_{\mu e} \propto s_{12}s_{13}\sin\delta$

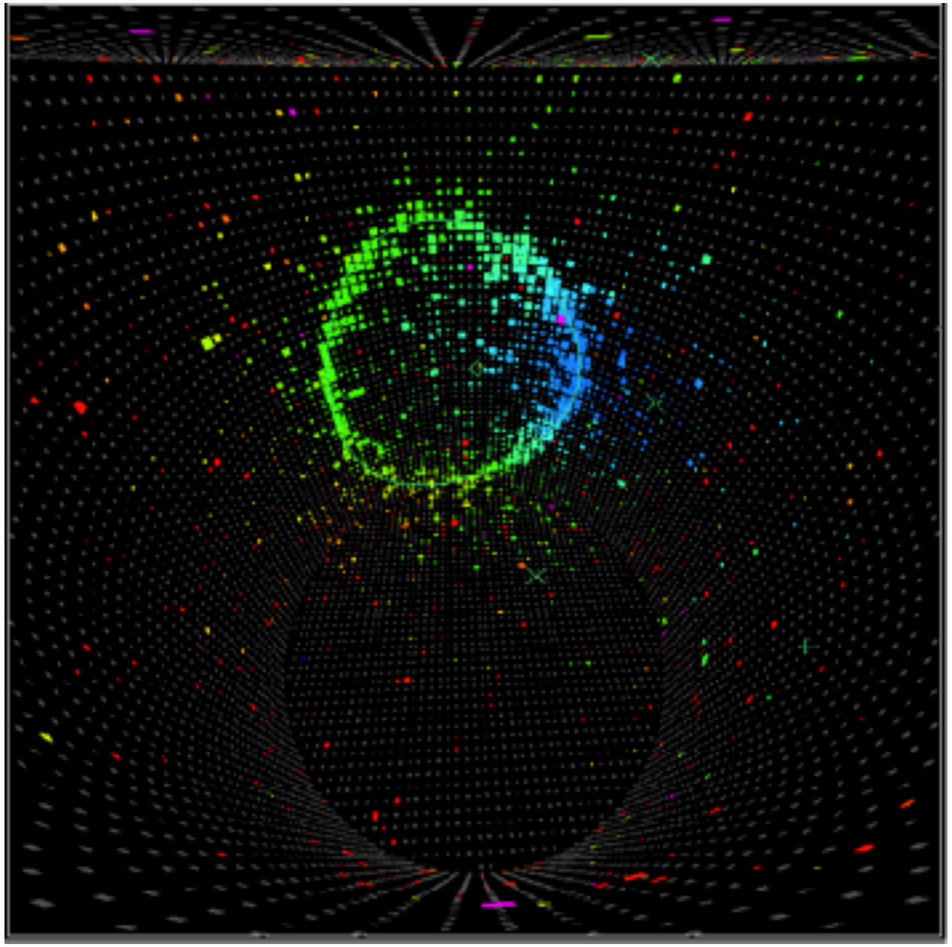
- T2K design principle :



T2K experiment



- Super-Kamiokande (SK) used as far detector
- Use off-axis ν beam to reduce high-energy tail
- Excellent performance for single-particle event
  - ν_e signal from $\nu_e + n \rightarrow e^- + p$
    (CCQE = charged current quasi-elastic)
  - this process dominates at sub-GeV energies

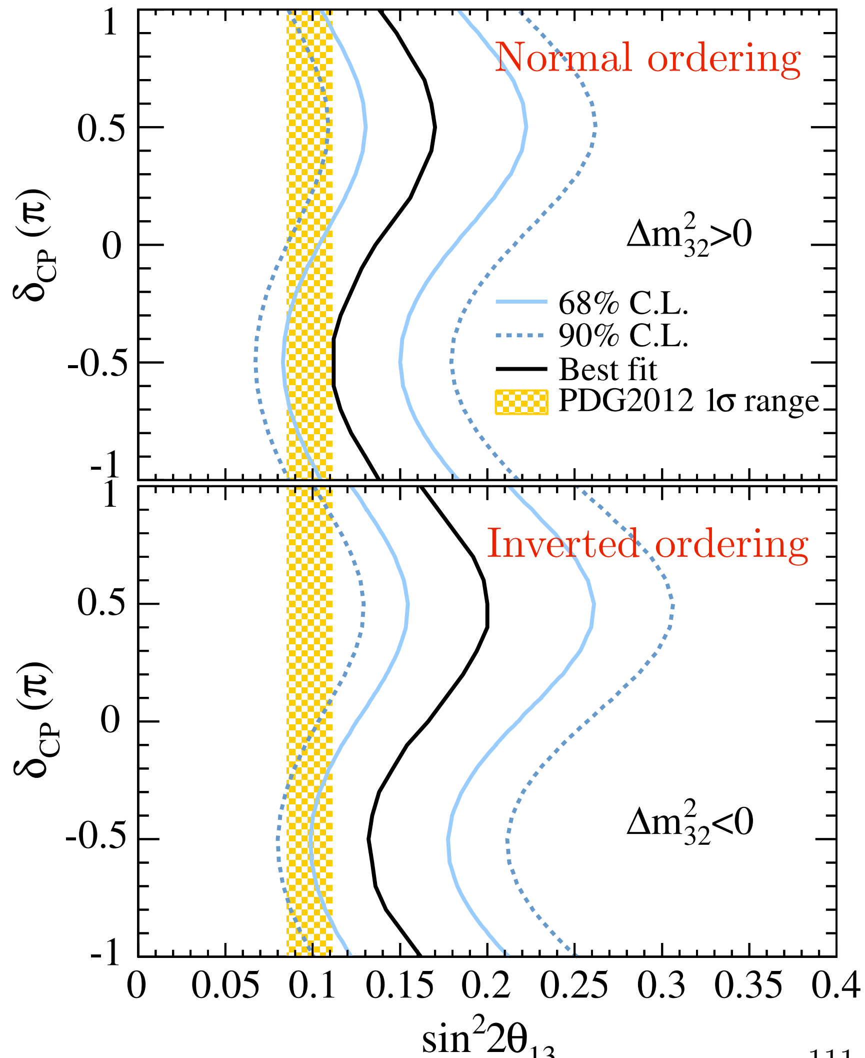


T2K results: ν_e appearance

- First observation of ν_e appearance [Phys. Rev. Lett. 112 (2014) 061802]
  - observe 28 single-ring electron-like events at SK
  - expect 4.92 ± 0.55 events if $\sin^2 2\theta_{13} = 0$
  - probability for background fluctuation corresponds to 7.3σ significance

$$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$$

$$\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037}$$



Some sensitivity to δ_{CP}!

T2K ν_e and anti-ν_e results

- T2K can run with μ^+ and μ^- beams $\Rightarrow$ combined analysis
  - sensitivity to δ_{CP} and mass ordering

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}$$
$$\overset{(+)}{-}\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E}$$
$$\times\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}\sin\delta_{CP}$$

Phys. Rev. D96 (2017) 092006

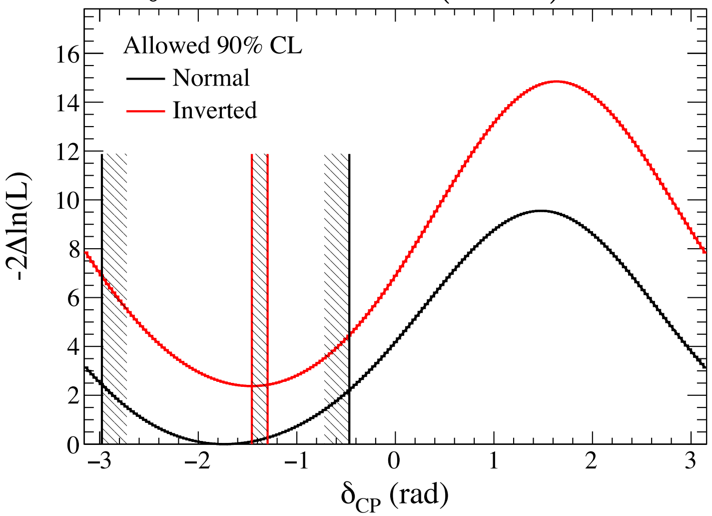


FIG. 43. One dimensional $\Delta\chi^2$ surfaces for oscillation parameter δ_{CP} using T2K data with the reactor constraint. The critical $\Delta\chi^2$ values obtained with the Feldman-Cousins method are used to evaluate the 90% confidence level with the proper coverage.

TABLE I. Number of ν_e and $\overline{\nu}_e$ events expected for various values of δ_{CP} and both mass orderings compared to the observed numbers.

Normal	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\overline{\nu}_e$	6.0	6.9	7.7	6.8	4

Inverted	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Observed
ν_e	25.4	21.3	17.1	21.3	32
$\overline{\nu}_e$	6.5	7.4	8.4	7.4	4

arXiv:1701.00432 (2017)

Combination of T2K and other experiments

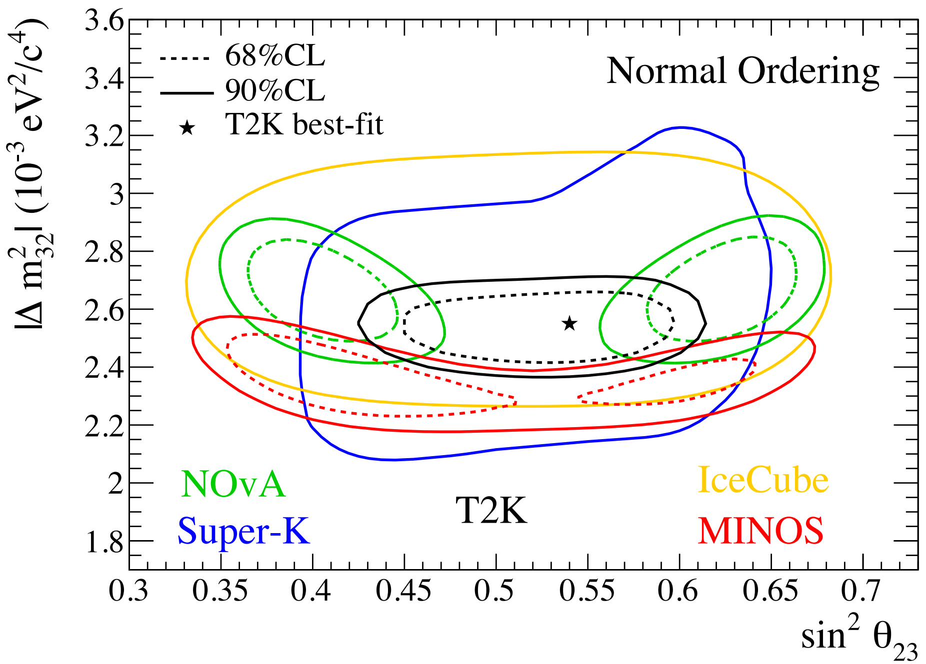


FIG. 40. Allowed region at 90% confidence level for oscillation parameters $\sin^2\theta_{23}$ and Δm^2_{32} using T2K data with the reactor constraint ($\sin^2(2\theta_{13}) = 0.085 \pm 0.005$). The normal mass ordering is assumed and the T2K results are compared with NOνA [86], MINOS [87], Super-K [88], and IceCube [89].

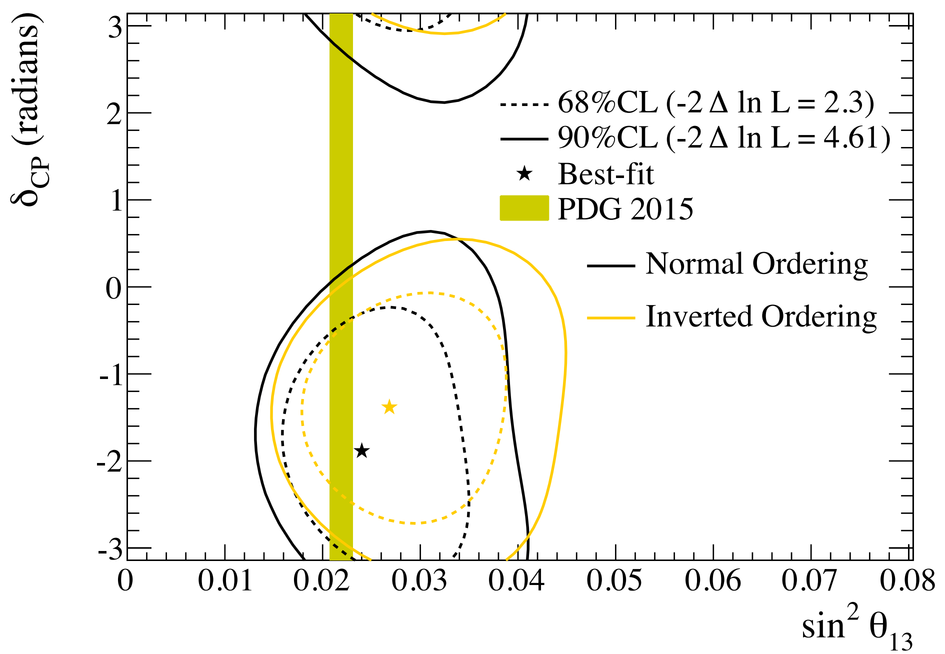


FIG. 5. The 68% (90%) constant $-2\Delta \ln L$ confidence regions in the $\delta_{CP} - \sin^2\theta_{13}$ plane are shown by the dashed (continuous) lines, computed independently for the normal (black) and inverted (red) mass ordering. The best-fit point is shown by a star for each mass ordering hypothesis. The 68% confidence region from reactor experiments on $\sin^2\theta_{13}$ is shown by the yellow vertical band.

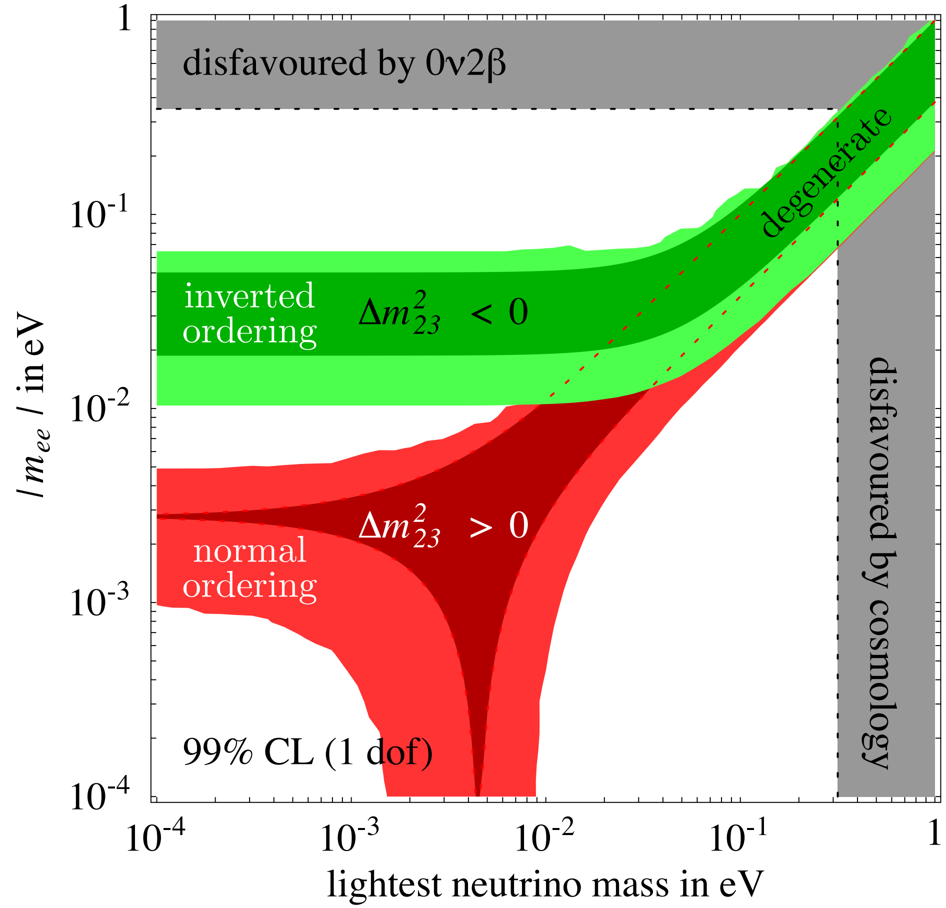
Phys. Rev. D96 (2017) 092006

Mass ordering

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

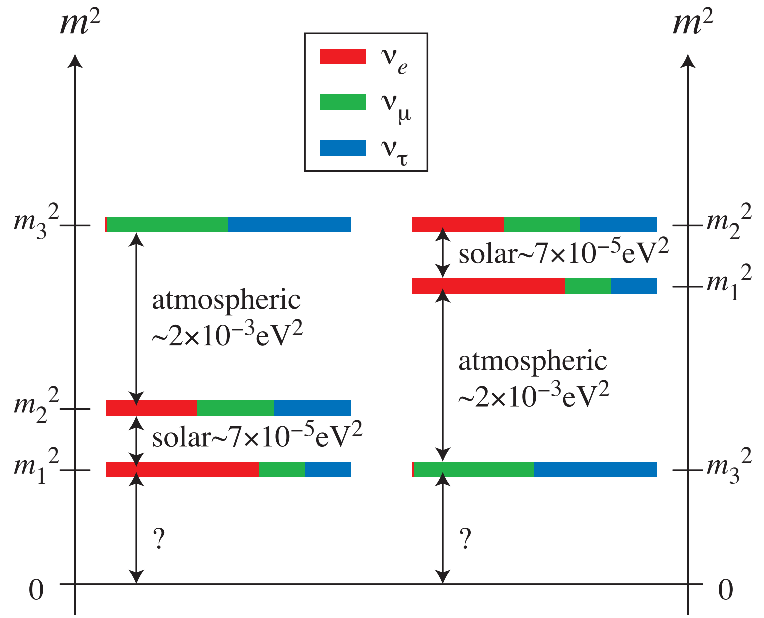
$$\langle m_{ee} \rangle = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 + |U_{e3}|^2 m_3$$

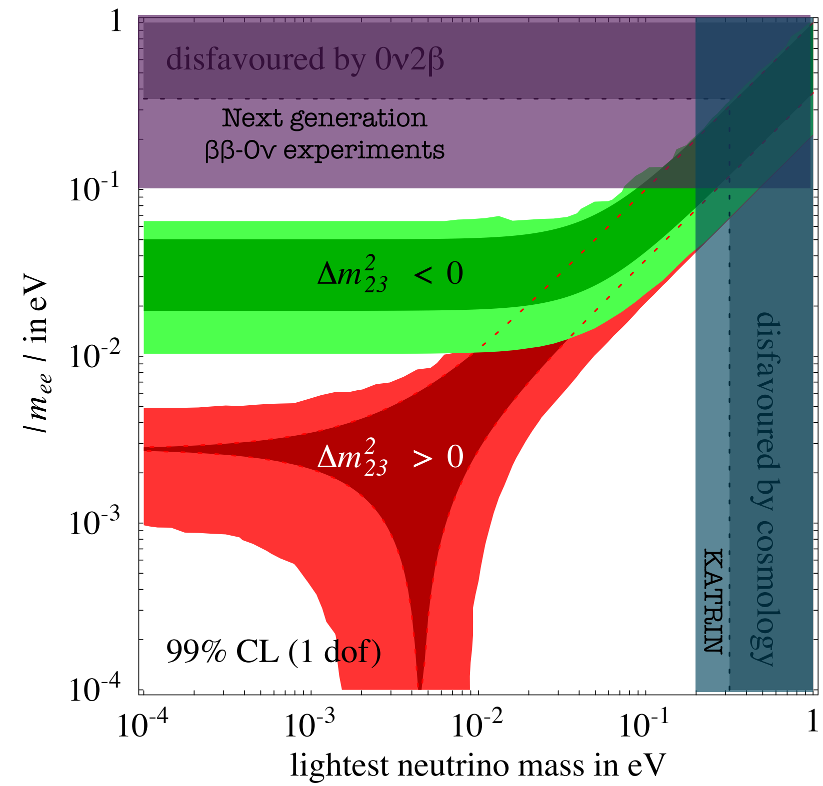
- Normal ordering:
  - $m_3 > m_{1,2}$ and U_{e3} small
    $\Rightarrow \langle m_{ee} \rangle$ small
- Inverted ordering:
  - $m_{1,2} > m_3$ and larger U_{e1} and U_{e2}
    $\Rightarrow \langle m_{ee} \rangle$ large
- Degenerate:
  - all masses approximately the same
    $\Rightarrow$ no difference between normal and inverted



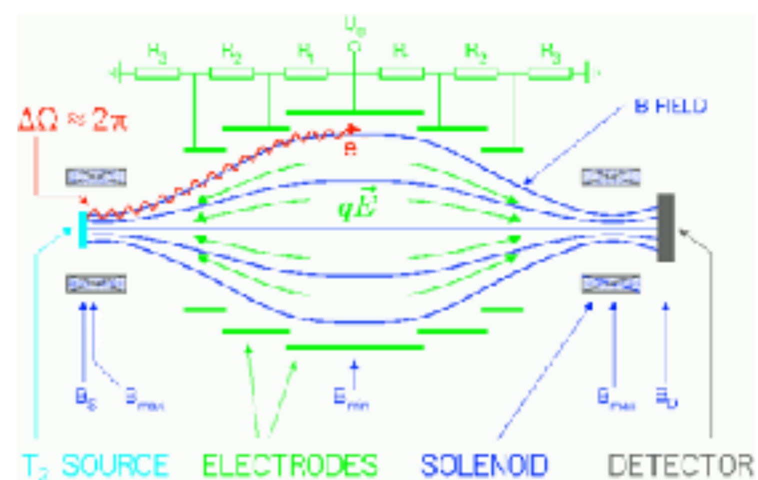
Δm² and absolute mass scale

- Oscillation measurements
  $\rightarrow \Delta m^2 \Rightarrow$ mass difference up to a sign
  $\rightarrow$ hierarchy known if sign of Δm^2_{13} is determined





- Absolute mass scale from direct mass measurements
  - end-point tritium β decay (KATRIN)
  - from SN-1987A



Summary on neutrino physics

- **3 types** of neutrinos (2.984 ± 0.008 from LEP data)
- Neutrinos oscillate $\Rightarrow$ they have a non-zero mass
  - mixing angles:
    - θ_{12} from solar and reactor (KamLAND) data
    - θ_{23} from atmospheric neutrinos
    - θ_{13} from reactor data (Daya Bay) and accelerator experiments (T2K)
  - direct mass measurements $\Rightarrow$ $m < 0.8\,\text{eV}/c^2$
- δ CP phase and mass ordering still to be determined
  - first sensitivity on δ_{CP} from the T2K experiment
- Other main questions about the nature of neutrinos:
  - are neutrino **Majorana or Dirac** particles? $\rightarrow$ $0\nu2\beta$ experiments
  - what is the **mass generation mechanism**? $\rightarrow$ seesaw?

Addendum on the velocity of neutrinos

Neutrino velocity measurements

- Fermilab (1979)
  - $E_\nu > 30\,\text{GeV}$ $\Rightarrow |v-c|/c < 4\times10^{-5}$
  - [Phys. Rev. Lett. 43 (1979) 1361]

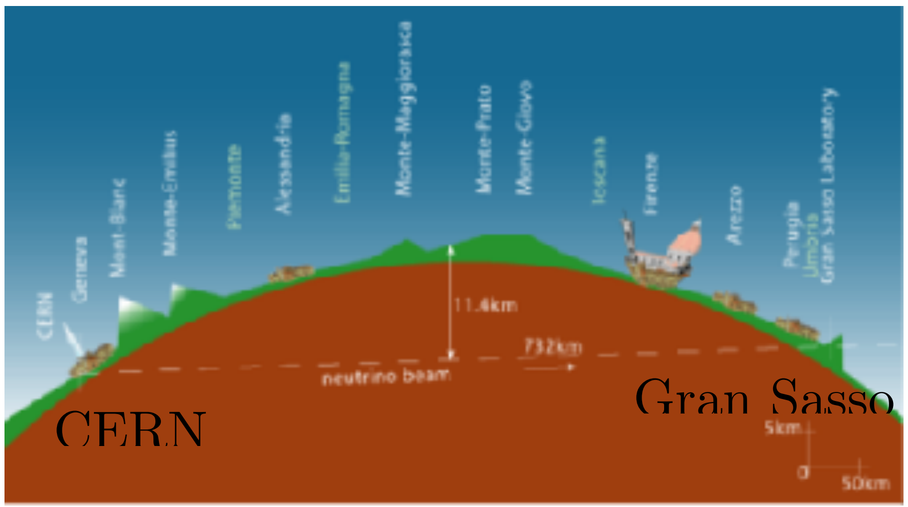
- Supernova SN1987A
  - $E_\nu \approx 10\,\text{MeV},\ D = 50\,\text{kpc}$ $\Rightarrow |v-c|/c < 2\times10^{-9}$
  - [Phys. Lett. B 201 (1988) 353]

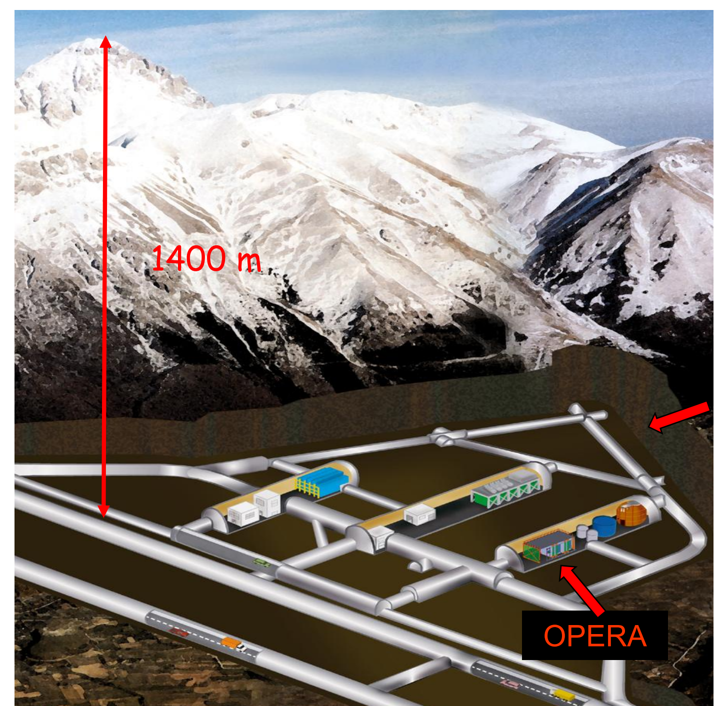
- Minos experiment (2007)
  - $E_\nu \approx 3\,\text{GeV},\ D = 730\,\text{km}$ $\Rightarrow |v-c|/c = (5.1\pm2.1)\times10^{-5}\,(1.8\sigma)$
  - [Phys. Rev. D 76 (2007) 072005]

- Opera (2011)
  - $E_\nu \approx 17\,\text{GeV},\ D = 730\,\text{km}$ $\Rightarrow |v-c|/c = (2.4\pm0.5)\times10^{-5}\,(6.2\sigma)$

Opera experiment

- neutrino beam from CERN SPS
  - $\approx 17\,\mathrm{GeV}$ neutrinos
  - $732\,\mathrm{km}$ baseline

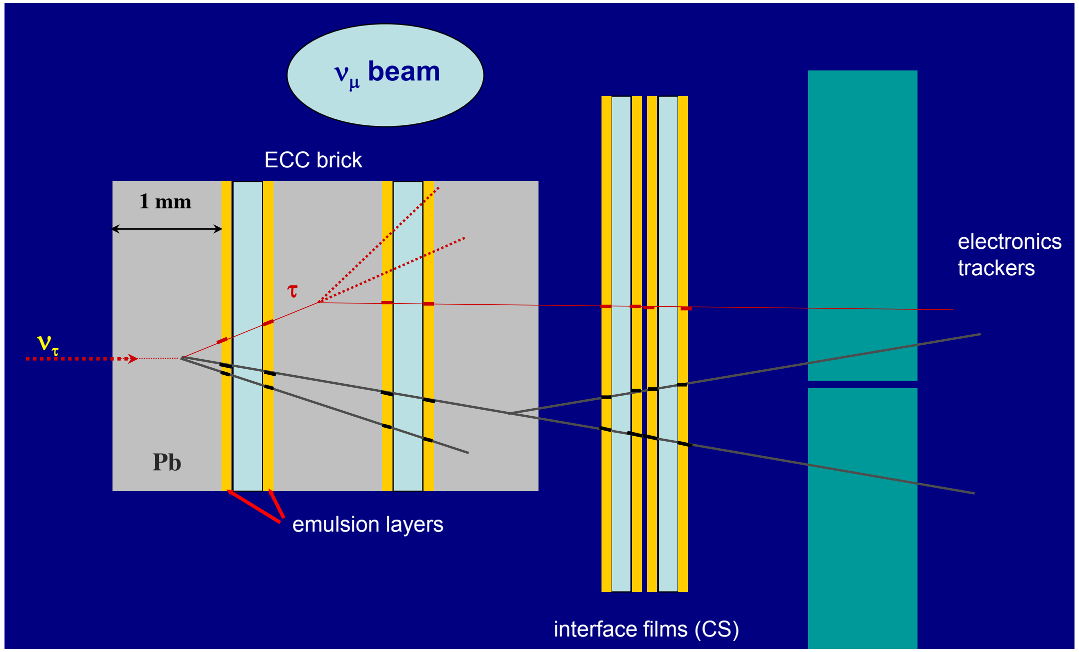


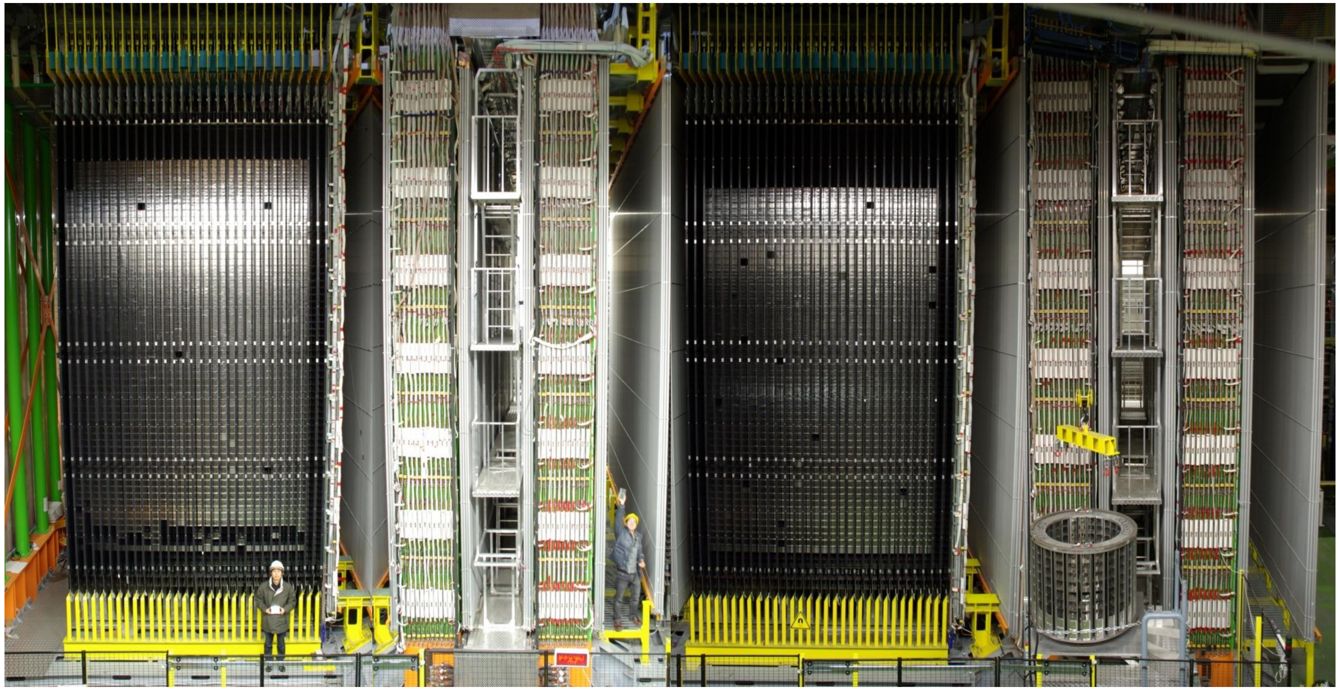


- Opera detector at Gran Sasso Lab
  - 150000 emulsion “bricks” ($\rightarrow \nu_\tau$)
  - Scintillator tracker ($\rightarrow$ timing)
  - Goal: measure $\nu_\mu \rightarrow \nu_\tau$ oscillations

Opera detector: principle

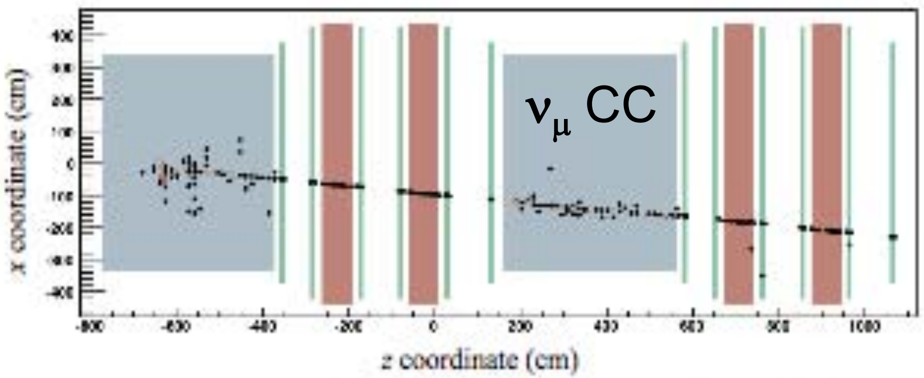
- record ν_τ interactions in emulsion layers
- record time of event with electronics tracker
- compute location of event, recover brick at location, and develop the emulsion

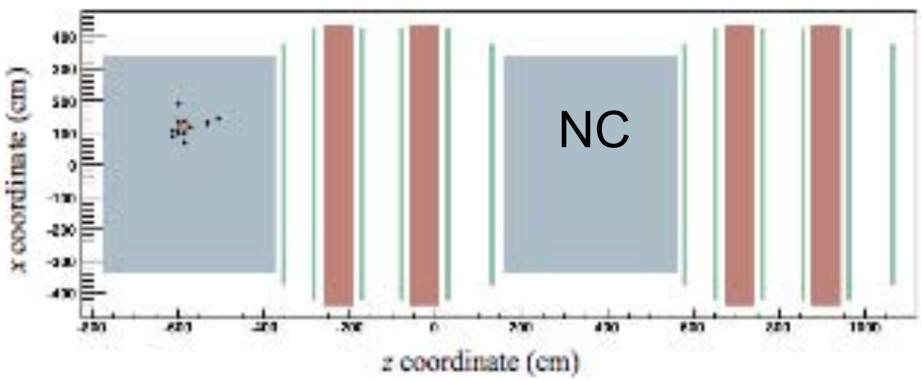




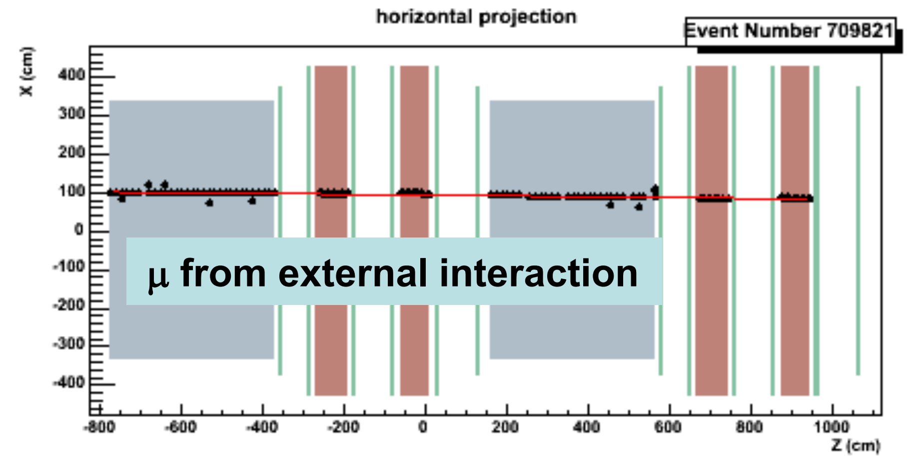
Opera events

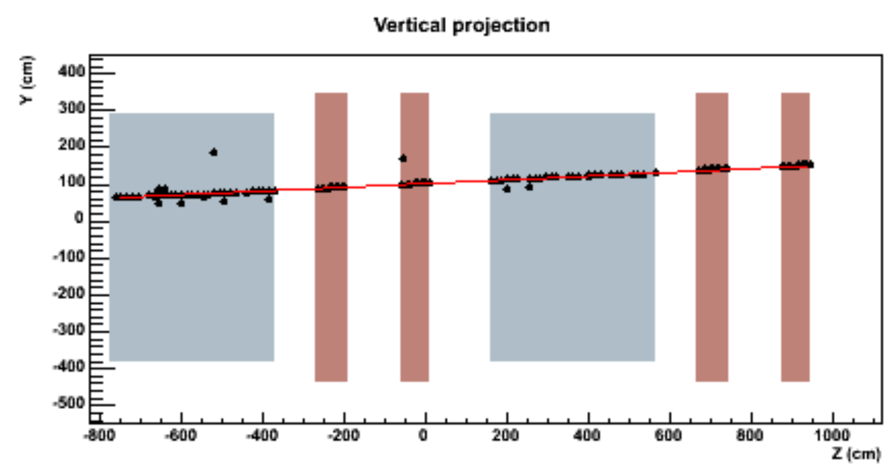
Charged current interaction





Neutral current interaction





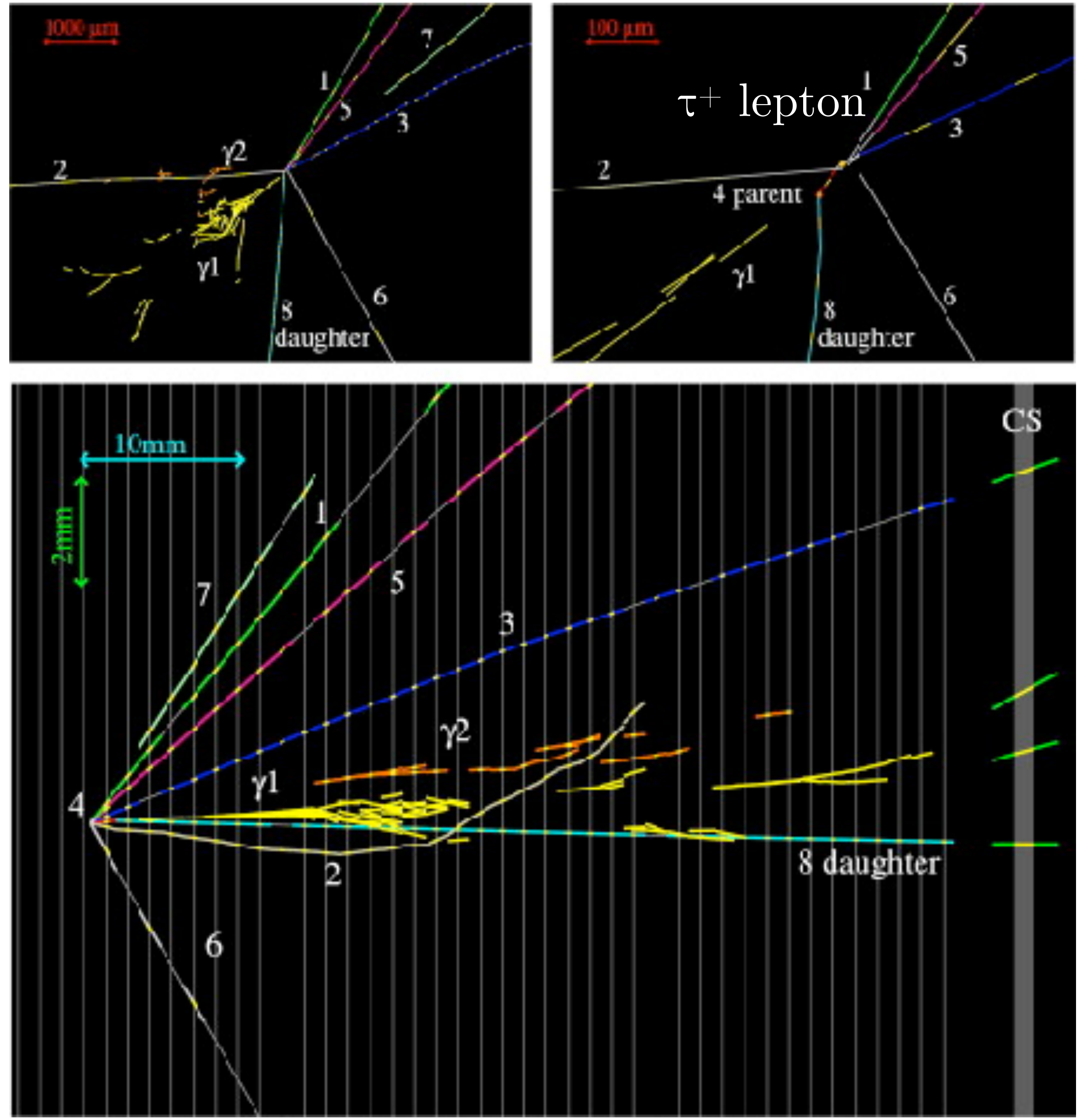
Opera ν_τ event

- ν_τ appearance event
- confirms expected $\nu_\mu \rightarrow \nu_\tau$ oscillations

- Main objective of the experiment...

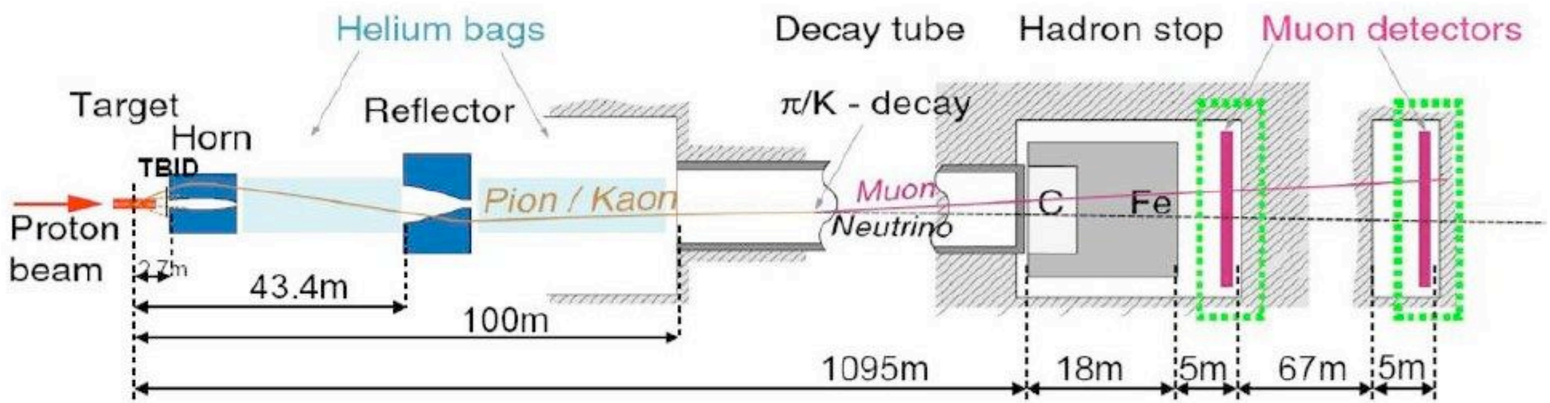
  ...but many more neutrino physics measurements can be done!

  $\rightarrow$ e.g. neutrino velocity

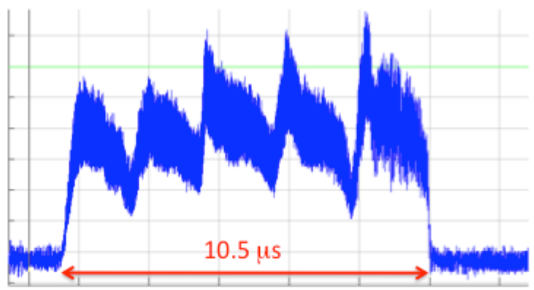


Neutrino velocity measurement: Δt

- ν_μ production at CERN SPS: proton (400GeV) $\rightarrow \pi/K \rightarrow \mu + \nu_\mu$

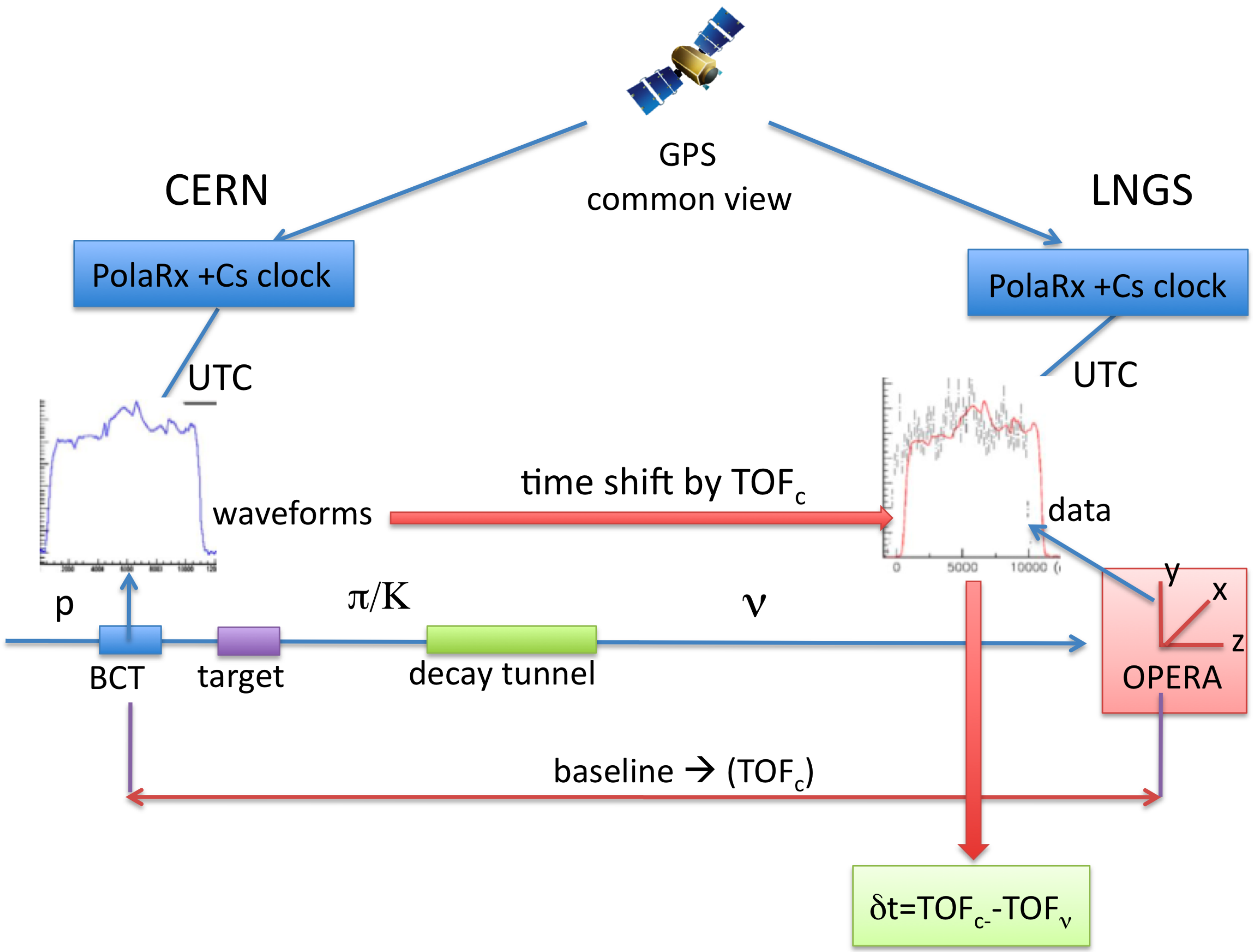


- $10.5\,\mu$s extractions $\Rightarrow$ proton which produced the measured neutrino is unknown! $\Rightarrow$ nature of the measurement is statistical $\Rightarrow$ precision much better than $10.5\,\mu$s !



- Propagation time calculated as $\Delta t = t_1 - t_0$
  - t_0 at the time SPS proton hits the target
  - t_1 at time the muon is detected in Opera detector
  - time synchronisation accuracy: $< 10\,$ns ($\Leftrightarrow$3m at speed of light)

Principle of the ν velocity measurement



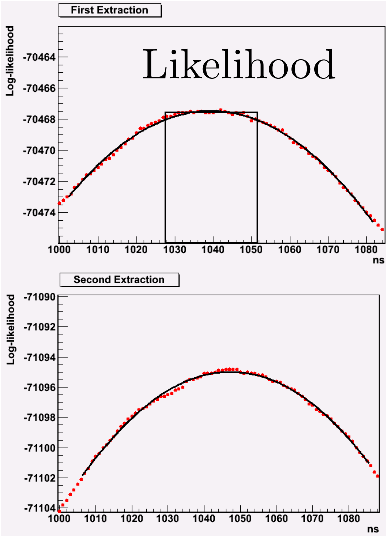
- Geodesic baseline measured with 20cm accuracy :

$$731278.0 \pm 0.2 \text{ m} \quad \Rightarrow 2.7\times10^{-7} \text{ relative precision}$$

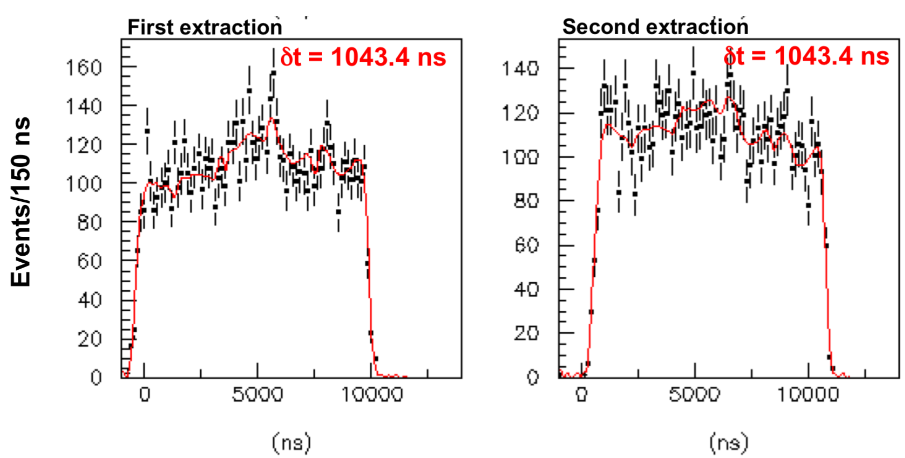
Data analysis

- 15233 selected events (7235 internal + 7988 external)
- Blind analysis ⇒ unkown (=secret) constant offset is applied to the result
- Fit the measured arrival time distribution to the measured proton extraction distributions ⇒ maximise the likelihood:

$$\mathcal{L} = \prod_{i}^{N} \mathcal{P}(t_j - \delta t)$$



[where $\mathscr{P}$ is the time PDF of proton extractions, t_j is the time of the measured neutrino in Opera, and δt is the parameter to measure]



- δt gives the deviation between the time of flight of a particle traveling at the speed of light and that of the neutrino

Results

- Unblinding ⇒ apply correction of –985.6ns
  - baseline effects (+Earth rotation effect: 2.2ns)
  - CERN SPS and Opera time delays
  - GPS synchronisation
- Results :

$$\delta t = TOF_c - TOF_\nu = (57.8 \pm 7.8\ (\text{stat.})\ ^{+8.3}_{-5.9}\ (\text{sys.}))\ \text{ns}.$$

$$(v-c)/c = \delta t / (TOF'_c - \delta t) = (2.37 \pm 0.32\ (\text{stat.})\ ^{+0.34}_{-0.24}\ (\text{sys.})) \times 10^{-5}.$$

  - significance of the result = 6.2σ

- First crosschecks could not invalidate this rather surprising result!

Announcements and solution

- September 2011
  - the result was presented to the community (and to the press)
- January-February 2012
  - identification of a faulty optical fibre connection between external GPS signal and the Opera master clock
  - this faulty connection induced an artificial delay of about 50ns...
    ⇒ after correction, the ν velocity is compatible with c
  - statement from Opera Collaboration on 28 February 2012

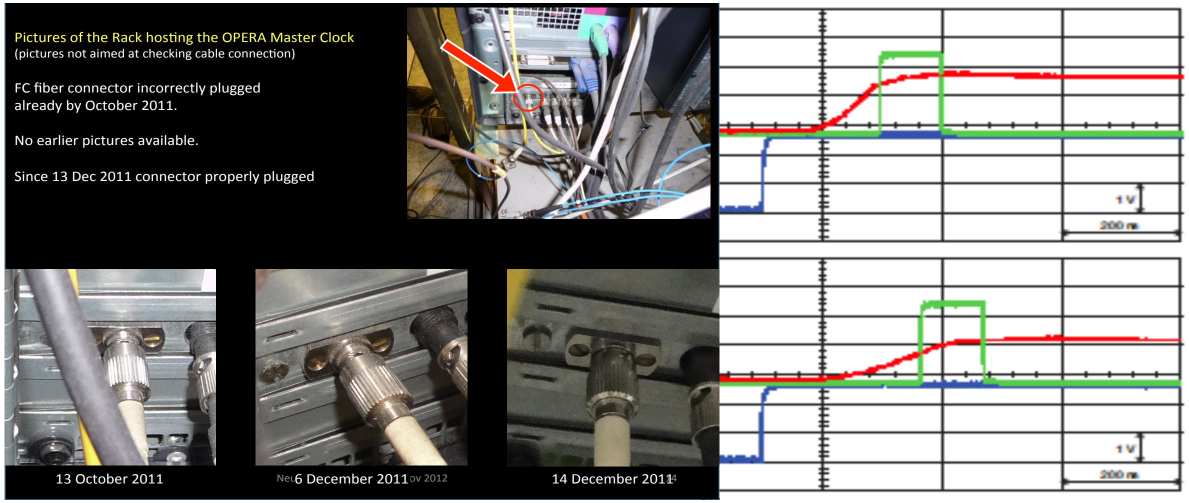


Fig. 12a). *The 8.3 km electro-optical cable arrives to OPERA from the External lab. b) Signals in OPERA: upper graph the cable is properly connected, lower graph the cable is not connected properly: the green signal is delayed by 73 ns.*

End of the story

- Reanalysis $\Rightarrow \delta t = (6.5 \pm 7.4(\text{stat})\,^{+8.3}_{-8.0}(\text{syst}))\,\text{ns}$

http://arxiv.org/abs/1109.4897

- Dedicated data taking run in 2012

$$\Rightarrow \delta t = (0.6 \pm 0.4(\text{stat}) \pm 3.0(\text{syst}))\,\text{ns}$$

http://arxiv.org/abs/1212.1276

All's well that ends well

- What can we learn from this story?
  a. high-precision measurements are difficult
  b. mistakes are common; some are more noticeable than others...
  c. constructive scientific communication depends on the scientist's honesty, and emotions must be kept aside