Latest Results from Neutrino Oscillation Experiments

Anselmo Cervera Villanueva
IFIC (UV-CSIC)
Valencia

On behalf of the T2K Collaboration
Neutrino sources

Atmosphere

Sun

Supernovae

Reactors

Accelerators
Neutrino sources

Atmosphere

Sun

Supernovae

Reactors

Accelerators

SK neutrino picture
Flavour mixing

\[ \nu_\alpha L = \sum_{k=1}^{n} U_{\alpha k} \nu_k L \]

\( m_1 \)
\( m_2 \)
\( m_3 \)

(arbitrary sizes)

weak eigenstates

(\( \nu_e \), \( \nu_\mu \), \( \nu_\tau \))
Flavour mixing

\[ \nu_\alpha L = \sum_{k=1}^{n} U_{\alpha k} \nu_k L \]

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

\( c_{ij} = \cos \theta_{ij} \quad s_{ij} = \sin \theta_{ij} \)

PMNS mixing matrix

Pontecorvo–Maki–Nakagawa–Sakata

\[ \nu_e \quad \nu_\mu \quad \nu_\tau \]

weak eigenstates

\[ m_1 \quad m_2 \quad m_3 \]

mass eigenstates

Dirac

Anselmo Cervera Villanueva, IFIC (UV-CSIC)—Valencia

SUSY 20016, MELBOURNE
Flavour mixing

\[ \nu_\alpha L = \sum_{k=1}^{n} U_{\alpha k} \nu_k L \]

\( m_1 \), \( m_2 \), \( m_3 \)

mass
eigenstates

\( \theta_{13} \), \( \delta_{\text{CP}} \)

PMNS mixing matrix

Pontecorvo–Maki–Nakagawa–Sakata

\[ U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{23} & s_{23} & 0 \\ 0 & -s_{23} & c_{23} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} & 0 \\ 0 & 1 & 0 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} & 0 \\ 0 & -s_{12} & c_{12} & 0 \end{pmatrix} \begin{pmatrix} c_{21} & s_{13} & 0 & 0 \\ -s_{21} & -s_{13} e^{i\delta} & 0 & 0 \\ c_{12} & c_{13} & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \]

\( c_{ij} = \cos \theta_{ij} \)
\( s_{ij} = \sin \theta_{ij} \)

weak
eigenstates

Dirac

Anselmo Cervera Villanueva, IFIC (UV-CSIC)—Valencia
Flavour mixing

\[ \nu_\alpha L = \sum_{k=1}^{n} U_{\alpha k} \nu_k L \]

\( \theta_{23} \), \( \theta_{13}, \delta_{\text{CP}} \), \( \theta_{12} \)

PMNS mixing matrix

U =
\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{21} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[ c_{ij} = \cos \theta_{ij} \]
\[ s_{ij} = \sin \theta_{ij} \]

Dirac
Flavour mixing

\[ \nu_\alpha L = \sum_{k=1}^{n} U_{\alpha k} \nu_k L \]

**Weak eigenstates**

- \( \nu_e \)
- \( \nu_\mu \)
- \( \nu_\tau \)

**PMNS mixing matrix**

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{21} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
e^{i\alpha_1} & 0 & 0 \\
0 & e^{i\alpha_2} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

**Connection between solar and atmospheric**

**Solar sector**

**Atmospheric sector**

**Dirac**

**Majorana**

- \( \Delta m^2_{12} \)
- \( \Delta m^2_{23} \)
- \( \Delta m^2_{ij} = m^2_i - m^2_j \)
Neutrino oscillations

Requirements: Massive neutrinos & different masses

\[ P_{\nu_\mu \nu} \sim \sin^2 2\theta \cdot \sin^2 \left( \frac{\Delta m^2 \cdot L}{4E_{\nu}} \right) \]

2-family approx. for illustration purposes

\[ \Delta m^2 \]

\[ \sin^2 2\theta \]

\[ L/E \text{ (km/GeV)} \]

Source \rightarrow \nu_\mu \rightarrow \nu_\mu \rightarrow \nu_\tau \rightarrow \nu_e \rightarrow \text{detector}
Neutrino oscillations

Requirements: Massive neutrinos & different masses

weak Hamiltonian

\[ E_\nu \]

source \( \nu_\mu \)

\[ \nu_\mu \]

free Hamiltonian

(mass eigenstates)

\[ P_{\nu_\mu, \nu_\tau} \sim \sin^2 2\theta \cdot \sin^2 \left( \frac{\Delta m^2 \cdot L}{4E_\nu} \right) \]

2-family approx. for illustration purposes

weak Hamiltonian

\[ \nu_\mu \]

\[ \nu_\tau \]

\[ \nu_e \]

detector

\[ \Delta m^2 \]

\[ \sin^2 2\theta \]

\[ L/E \text{ (km/GeV)} \]
Neutrino oscillations

Requirements: Massive neutrinos & different masses

weak Hamiltonian

free Hamiltonian (mass eigenstates)

weak Hamiltonian

\[ P_{\nu_{\mu}\nu} \sim \sin^2 2\theta \cdot \sin^2 \left( \frac{\Delta m^2 \cdot L}{4E_{\nu}} \right) \]

2-family approx. for illustration purposes

\[ \nu, \nu_{\tau}, \nu_e \]

\[ \Delta m^2 \]

\[ \sin^2 2\theta \]

\[ L \]

\[ E_{\nu} \]

source

\[ \nu_{\mu} \]
Neutrino oscillations

Requirements: Massive neutrinos & different masses

Weak Hamiltonian

Free Hamiltonian (mass eigenstates)

$$P_{\nu_{\mu}\nu} \sim \sin^2 2\theta \cdot \sin^2 \left(\frac{\Delta m^2 L}{4E}\right)$$

2-family approx. for illustration purposes

Weak Hamiltonian

Requirements:

- Massive neutrinos & different masses

2-family approx. for illustration purposes

normal hierarchy (NH)

inverted hierarchy (IH)

$$\Delta m^2_{23}$$

$$\Delta m^2_{12}$$

$$\sin^2 2\theta$$

$$\Delta m^2$$

$$L/E$$ (km/GeV)
A bit of recent history

1998: Super-Kamiokande discovered neutrino oscillations ($\nu_\mu \rightarrow \nu_x$)

1999: K2K (Japan) is the first Long-Baseline (LBL) $\nu$-osc experiment

2001: SNO discovered the solar transition ($\nu_e \rightarrow \nu_x$)

2002: Kamland (Japan) reactor experiment confirms solar transition ($\bar{\nu}_e \rightarrow \bar{\nu}_x$)

2002: Nobel Prize for Koshiba and Davis

2011: T2K (Japan, LBL) has 2.5$\sigma$ indication of $\nu_\mu \rightarrow \nu_e$ (and $\theta_{13} \neq 0$)

2012: Daya-Bay (China) reactor experiment measured $\theta_{13} \neq 0$ ($\approx 8.4^\circ$)

2013: T2K discovers (> 7$\sigma$) the $\nu_\mu \rightarrow \nu_e$ transition

2014: NOvA (US) LBL experiment began data-taking

2015: OPERA (Italy, LBL) discovers $\nu_\mu \rightarrow \nu_\tau$ oscillation

2015: US and EU LBL programs collapse into DUNE

2015: Nobel Prize for Kajita and McDonald
A bit of recent history

1998: Chooz (France) puts a limit on $\theta_{13} (<12^\circ)$
1998: Super-Kamiokande discovered neutrino oscillations ($\nu_\mu \rightarrow \nu_x$)
1999: K2K (Japan) is the first Long-Baseline (LBL) $\nu$-osc experiment
2001: SNO discovered the solar transition ($\nu_e \rightarrow \nu_x$)
2002: K2K (Japan) is the first Long-Baseline (LBL) $\nu$-osc experiment
2002: Nobel Prize for Koshiba and Davis
2011: T2K (Japan, LBL) has 2.5$\sigma$ indication of $\nu_\mu \rightarrow \nu_e$ (and $\theta_{13} \neq 0$)
2012: Daya-Bay (China) reactor experiment measured $\theta_{13} \neq 0$ (~8.4$^\circ$)
2013: T2K discovers (> 7$\sigma$) the $\nu_\mu \rightarrow \nu_e$ transition
2014: NOvA (US) LBL experiment began data-taking
2015: OPERA (Italy, LBL) discovers $\nu_\mu \rightarrow \nu_\tau$ oscillation
2015: US and EU LBL programs collapse into DUNE
2015: Nobel Prize for Kajita and McDonald
### Experimental strategies

<table>
<thead>
<tr>
<th>$\theta_{23}\sim42^\circ$ (8.4%), octant ?</th>
<th>$\theta_{13}\sim8.9^\circ$ (2%), $\delta_{CP}$ ?</th>
<th>$\theta_{12}\sim34^\circ$ (4.5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\begin{pmatrix} 1 &amp; 0 &amp; 0 \ 0 &amp; c_{23} &amp; s_{23} \ 0 &amp; -s_{23} &amp; c_{23} \end{pmatrix}$</td>
<td>$\begin{pmatrix} c_{13} &amp; 0 &amp; s_{13}e^{-i\delta} \ 0 &amp; 1 &amp; 0 \ -s_{13}e^{i\delta} &amp; 0 &amp; c_{13} \end{pmatrix}$</td>
<td>$\begin{pmatrix} c_{21} &amp; s_{12} &amp; 0 \ -s_{12} &amp; c_{12} &amp; 0 \ 0 &amp; 0 &amp; 1 \end{pmatrix}$</td>
</tr>
</tbody>
</table>

- $\Delta m_{12}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$ (3.4%)
- $|\Delta m_{23}^2| \sim 2.4 \times 10^{-3} \text{ eV}^2$ (2.4%)
- $\text{sign}(\Delta m_{23}^2)$ unknown

Anselmo Cervera Villanueva, IFIC (UV-CSIC)—Valencia

SUSY 20016, MELBOURNE
Experimental strategies

\[\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \quad \begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix} \quad \begin{pmatrix}
c_{21} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}\]

\[\Delta m_{12}^2 \sim 7.5 \times 10^{-5}\text{ eV}^2 \quad (3.4\%)\]

\[|\Delta m_{23}^2| \sim 2.4 \times 10^{-3}\text{ eV}^2 \quad (2.4\%)
\]

\[\text{sign}(\Delta m_{23}^2)\text{ unknown}\]
**Experimental strategies**

$\theta_{23} \sim 42^\circ$ (8.4%), octant?

$\theta_{13} \sim 8.9^\circ$ (2%), $\delta_{CP}$?

$\theta_{12} \sim 34^\circ$ (4.5%)

$\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}$

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

$\begin{pmatrix}
c_{21} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}$

- Independent $\theta_{13}$ measurement at reactor experiments

$\Delta m_{12}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$ (3.4%)

$|\Delta m_{23}^2| \sim 2.4 \times 10^{-3} \text{ eV}^2$ (2.4%)

$\text{sign}(\Delta m_{23}^2)$ unknown

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 (\Delta m_{ee}^2 \frac{L}{4E}) - \cos^2 \theta_{13} \sin^2 2\theta_{12} \sin^2 (\Delta m_{21}^2 \frac{L}{4E}) \]

\[ \sin^2 (\Delta m_{ee}^2 \frac{L}{4E}) = \cos^2 \theta_{12} \sin^2 (\Delta m_{e1}^2 \frac{L}{4E}) + \sin^2 \theta_{12} \sin^2 (\Delta m_{e2}^2 \frac{L}{4E}) \]

- short baseline
- long baseline

\[ |\Delta m_{ee}^2| \]

Baseline [km]

1st gen: Chooz: $\sin^2 2\theta_{13} < 0.2$

2nd gen: Double Chooz

RENO

Daya Bay

KamLAND
Experimental strategies

\[ \theta_{23} \sim 42^\circ \ (8.4\%), \ \text{octant ?} \quad \theta_{13} \sim 8.9^\circ \ (2\%), \ \delta_{\text{CP}} \ ? \quad \theta_{12} \sim 34^\circ \ (4.5\%) \]

- Independent \( \theta_{13} \) measurement at reactor experiments

\[ P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{13} \sin^2 (\Delta m^2_{ee} L/4E) - \cos^2 \theta_{13} \sin^2 2\theta_{12} \sin^2 (\Delta m^2_{21} L/4E) \]

- \( \theta_{13}-\delta_{\text{CP}} \) measurement at LBL experiments: \( \nu_e \) appearance

\[ P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \sin 2\theta_{12} \sin \theta_{13} \sin 2\theta_{23} \times \frac{\sin^2(1-x)\Delta}{(1-x)^2} \times \cos \Delta \frac{\sin[x\Delta]}{x} \]

\[ \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{1}{30} \quad \Delta = \frac{\Delta m^2_{31} L}{4E} \quad x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}} \]

M. Freund, Phys.Rev. D64 (2001) 053003

- \( \sin^2 2\theta_{13} \) dependence of leading term
- \( \theta_{23} \) dependence of leading term: “octant” dependence (\( \theta_{23} = \pi/4 \) or \( \pi/2 \)?)
- CP odd phase \( \delta \): asymmetry of probabilities \( P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e) \) if \( \sin \delta \neq 0 \)
- Matter effect through \( x \): \( \nu_e (\bar{\nu}_e) \) enhanced in normal (inverted) hierarchy

Anselmo Cervera Villanueva, IFIC (UV-CSIC)—Valencia
Daya Bay reactor experiment

- $\bar{\nu}_e$ detection by Inverse Beta Decay (search for $\bar{\nu}_e$ disappearance)
- High statistics with 6 powerful reactors: 4th largest in the world
- Small reactor flux uncertainty by relative measurement: 2 near sites, 1 far site
- Small detector uncertainty with multiple identical detectors
Latest results

Anselmo Cervera Villanueva, IFIC (UV-CSIC)—Valencia

See talk by B. ROSKOVEC, at 14:00 in flavour physics WG

1230 days data

Best (by far) measurement of $\theta_{13}$

$$\sin^2 2\theta_{13} = [8.41 \pm 0.33] \times 10^{-2}$$

Significant precision on $\Delta m^2_{23}$

$$|\Delta m^2_{ee}| = [2.50 \pm 0.08] \times 10^{-3} \text{eV}^2$$

$$\Delta m^2_{32} (\text{NH}) = [2.45 \pm 0.08] \times 10^{-3} \text{eV}^2$$

4% 3.3%
Other reactor experiments

• **Double-Chooz (France):** first results including near detector data
  - Lots of improvements in calibration and systematics but not new results since Moriond’16

• **RENO (Korea):**  
  - Phys. Rev. Lett. 116, 211801 (May 2016)
The T2K experiment

- **T2K** (Japan) was the first **off-axis** neutrino oscillation experiment, started taking data early 2010 and in 2011 published the first indication of **electron neutrino appearance** (and non-zero $\theta_{13}$), which was later discovered (> 5σ) in 2013.

- Taking data in anti-neutrino mode since 2014

- Next goals:
  - Discover $\bar{\nu}_e$ appearance
  - Search for strong indication of CP violation
T2K detectors

Super-Kamiokande
Mt. Ikenoyama 1,360m
Mt. Noguchi-Goro Dake 2,924m

Neutrino Beam
295km

J-PARC
Near Detector

T2K detectors

Anselmo Cervera Villanueva, IFIC (UV-CSIC) — Valencia

SUSY 20016, MELBOURNE
T2K detectors

Super-Kamiokande

Mt. Noguchi-Goro Dake 2,924m

Mt. Ikenoyama 1,360m

Near Detector

295km

Neutrino Beam

J-PARC

T2K detectors

Detector hall

Access tunnel

Control room

Inner Detector

Outer Detector

Photo multipliers

μ SK MC

e/γ
T2K detectors

Super-Kamiokande

Mt. Noguchi-Goro Dake
2,924m

Mt. Ikenoyama
1,360m

Neutrino Beam
295km

J-PARC

Near Detector

T2K detectors

μ
SK MC

e/γ

SA1 Magnet Yoke

Solenoid Coil

UA1 Magnet Yoke

TPCs

P0D

P0D ECAL

Barrel ECAL

Downstream ECAL

Access tunnel

Detector hall

Control room

Inner Detector

Outer Detector

Photo multipliers

4m

39m
Off-axis concept

30 GeV protons  3 magnetic horns  Decay volume  Beam dump

\[ p \xrightarrow{\pi, k} \mu, e, \nu_\mu, \nu_e \xrightarrow{\text{hadron production}} \xrightarrow{\text{focussing}} \xrightarrow{\text{decay}} \text{Absorption of } \nu_\mu, \nu_e \]
Off-axis concept

30 GeV protons  3 magnetic horns  Decoy volume  Beam dump

\[ \pi \rightarrow \mu \rightarrow e \]

\[ \nu_\mu \rightarrow \nu_\mu \quad \text{>99\%} \]

\[ \nu_e \rightarrow \nu_e \quad \text{<1\%} \]

hadron production  focussing  decay  Absorption of \( \mu \)'s y e's

2.50
Off-axis concept

30 GeV protons 3 magnetic horns Decay volume Beam dump

\[ \pi^+ \rightarrow \mu^+ \rightarrow e^- \]

\[ \nu_\mu > 99\% \quad \nu_e < 1\% \]

hadron production focussing decay Absorption of \( \mu \)'s \( \nu_e \)'s

**tuned narrow band beam**

\[ \sin^2 2\theta_{23} = 1.0 \quad \Delta m_{32}^2 = 2.4 \times 10^{-3} \text{eV}^2 \]

Anselmo Cervera Villanueva, IFIC (UV-CSIC)—Valencia

SUSY 20016, MELBOURNE
Off-axis concept

30 GeV protons  3 magnetic horns  Decay volume  Beam dump

p  k  k

hadron production  focussing  decay  Absorption of μ's and e's

Tuned narrow band beam

\sin^22\theta_{23} = 1.0  \quad \Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2

ν_\mu > 99%  ν_e < 1%

2.5^0

Lower ν_e contamination (<1 %)

Neutrino beam
Data taking summary

- Started data taking with anti-neutrinos in 2014
- Continuous rise in power from ~225 kW (2014) to 420 kW (2016)

![Graph showing accumulated POT and beam power over time]

27 May 2016
POT total: $1.510 \times 10^{21}$

$\nu$-mode POT: $7.57 \times 10^{20}$ (50.14%) → 6.9x10$_{20}$ analysed
$\bar{\nu}$-mode POT: $7.53 \times 10^{20}$ (49.86%)

POT = Protons on Target

Anselmo Cervera Villanueva, IFIC (UV-CSIC) — Valencia
4 neutrino samples

\( \bar{\nu}_\mu \) disappearance  \( \nu_e \) appearance

\( \nu_\mu \) disappearance  \( \bar{\nu}_e \) appearance

\( \nu_\mu \) appearance  \( \bar{\nu}_e \) disappearance

\( \nu_e \) appearance  \( \bar{\nu}_\mu \) disappearance

**E\(_{\text{rec}}\) distribution assuming 2-body quasi-elastic kinematics**

**Table:**

<table>
<thead>
<tr>
<th>sample</th>
<th>obs.</th>
<th>Exp. not osc.</th>
<th>( \delta_{CP} )</th>
<th>( \delta_{CP} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_\mu )</td>
<td>125</td>
<td>489.9</td>
<td>127.2</td>
<td>127.5</td>
</tr>
<tr>
<td>( \nu_e )</td>
<td>32</td>
<td>5.8</td>
<td>22.7</td>
<td>26.9</td>
</tr>
<tr>
<td>( \bar{\nu}_\mu )</td>
<td>66</td>
<td>184.8</td>
<td>64.1</td>
<td>64.2</td>
</tr>
<tr>
<td>( \bar{\nu}_e )</td>
<td>4</td>
<td>2.3</td>
<td>6.9</td>
<td>6.0</td>
</tr>
</tbody>
</table>

**next goal:** probe (5\( \sigma \)) of \( \bar{\nu}_e \) appearance
Antineutrino analysis

- This is the 2015 analysis. Results to be updated at ICHEP
- Best results for $\bar{\nu}_\mu$ disappearance with one year of data
- Allow test of CPT symmetry. For the moment consistent with neutrino results

[Graph from Phys. Rev. Lett. 116, 181801 (2016)]
First fully joint analysis

- First fully joint analysis across all modes of oscillation

\[ \nu_\mu \rightarrow \nu_e \quad \nu_\mu \rightarrow \nu_\mu \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \]

T2K has the most precise measurement of $\theta_{23}$
Hints of CP violation

- no CP-violation ($\delta_{CP}=0$) excluded at 90% CL. Best fit $\delta_{CP} \sim -\pi/2$
- Almost a 2\(\sigma\) effect
The NOvA experiment

- NOvA, in the US, started data taking in 2014
- A similar concept to T2K but different detector type (scintillator), and much **longer baseline** (810 km): it has **better sensitivity to mass hierarchy** (the sign of $\Delta m^2_{23}$)
Latest results

~20% of planned exposure (6.05x10^{20} POT)

**ν_μ disappearance**
- 78 events observed in FD
  - 473±30 with No Oscillation
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic

**ν_e appearance**
- Observe 33 events in FD
  - background 8.2±0.8

>8σ signal
Hints of non maximal mixing

- Maximal mixing ($\theta_{23} = 45^\circ$) excluded at 2.5$\sigma$

$$\sin^2 \theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

- Weakly prefer normal mass hierarchy and $\delta_{CP} \sim 3\pi/2 (-\pi/2)$
- $\delta_{CP} \sim \pi/2$ excluded at 3$\sigma$ for IH
Summary of current results
Summary of current results

$\theta_{23}$-$\Delta m^2_{23}$

- compatible for all experiments also between $\nu$ & $\bar{\nu}$ (no CPT)
- Maximal mixing ($\theta_{23}=45^\circ$) excluded at $2.5\sigma$ by NOvA
Summary of current results

\( \theta_{23} - \Delta m^2_{23} \)

- compatible for all experiments also between \( \nu \) & \( \bar{\nu} \) (no CPT)
- Maximal mixing (\( \theta_{23}=45^\circ \)) excluded at 2.5\( \sigma \) by NOvA

\( \theta_{13} - \delta_{CP} \)

- small preference for \( \delta_{CP} \approx -\pi/2 \) and normal mass hierarchy (\( \Delta m^2_{23}>0 \)) from T2K and NOvA
- \( \theta_{13} \), dominated by Daya Bay, also compatible
What’s next?

• The combination of all current experiments will probably result in a measurement of the mass hierarchy and an indication of non-zero $\delta_{\text{CP}}$ (2-3 sigma)

• A new generation is needed to measure CP: larger or more precise detectors, more powerful beams
T2K phase II

- Proposed to cover the gap between T2K/NOvA and the next generation of experiments: HK/DUNE (from 2020 to 2026)
- Same far detector (SK) + beam upgrade: collect $20 \times 10^{21}$ p.o.t.
- New improved near detector complex and reduced systematics
- Could achieve $>3\sigma$ sensitivity on CP violation
Hyper-Kamiokande (HK)

- 560 kiloton (fiducial) water-Cherenkov detector with high intensity beam from J-PARC
- Multipurpose machine with all of the physics topics of Super-K and T2K, plus a few more

Physics in 2026

http://www.hyper-k.org/en/
Deep Underground Neutrino Experiment

- High Intensity Wide Band beam from Fermilab to SURF (Homestake mine)
- 40 kton: 4 Liquid Argon TPC detectors of 10 ktons each
  - Lower mass compensated by much larger efficiency
- Oscillation physics in 2026
Outlook

- **Neutrino oscillations** have been a very vibrant field for the last two decades, crucial for the understanding of neutrino properties, as mixing angles and mass-square splittings, which were measured with **precisions better than 4%, except** $\theta_{23}$ (~8%)

- Three unknowns remain: $\delta_{CP}$, $\text{sign}(\Delta m^2_{23})$ and $\theta_{23}$ octant

- With hints on these three unknowns, the current generation of experiments, **T2K, NOvA, Daya Bay**, etc, should be able to achieve $3\sigma$ sensitivity on $\delta_{CP}$ and $\text{sign}(\Delta m^2_{23})$, even more in **T2K-II**

- A new generation of experiments as **DUNE** and **HK** will cover a larger phase space of $\delta_{CP}$ with sensitivities **beyond 5\sigma**

- Is that the full story? What about sterile neutrinos? Let’s be opened to surprises …