Neutrino properties: Mass hierarchy and CP-violation

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Outline

1. Neutrino properties
2. Mass hierarchy
3. CP-violation
4. Summary

with emphasis on astrophysical/astroparticle methods

Brief summary of what we know

Next big in neutrino physics?

Ultimate goal; connected to mass hierarchy determination
Neutrino properties
All well established/confirmed results fit well a framework with

- three neutrinos
- interactions described by the standard model
- with masses and mixing

It is widely believed that peculiar properties

Smallness of masses

Zero conserved charges

Large mixing

Which admits unique

Majorana nature
Lepton Mixing

Mixing parameters
\[ \tan^2 \theta_{12} = \frac{|U_{e2}|^2}{|U_{e1}|^2} \]
\[ \sin^2 \theta_{13} = \frac{|U_{e3}|^2}{\sin^2 \theta_{13}} \]
\[ \tan^2 \theta_{23} = \frac{|U_{\mu3}|^2}{|U_{\tau3}|^2} \]

Mixing matrix:
\[ \nu_f = U_{PMNS} \nu_{mass} \]

Standard parametrization
\[ U_{PMNS} = U_{23} I_{\delta} U_{13} I_{-\delta} U_{12} \]
\[ I_{\delta} = \text{diag}(1, 1, e^{i \delta}) \]

Normal mass hierarchy
\[ \Delta m^2_{ij} = m^2_i - m^2_j \]
\[ \Delta m^2_{32} = 2.5 \times 10^{-3} \text{ eV}^2 \]
\[ \Delta m^2_{21} = 7.5 \times 10^{-5} \text{ eV}^2 \]
Neutrino mass ordering

Normal mass hierarchy

- $\sum m > m_h$
- $|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$

Inverted mass hierarchy

- $\sum m > 2 m_h$
- $|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$

Fixed by solar neutrinos

Mass splittings

$|\Delta m^2_{ij}| \leftrightarrow D_{ij} = 4|U_{ei}|^2|U_{ej}|^2$

Oscillation depth
TBM Mixing pattern

P. F. Harrison, D. H. Perkins, W. G. Scott
L. Wolfenstein

\[ U_{tbm} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix} \]

\[ U_{tbm} = U_{23}(\pi/4) \ U_{12} \]

\[ \sin^2 \theta_{12} = 1/3 \]

Accidental, numerology, useful for bookkeeping

Accidental symmetry (still useful)

Not accidental

Lowest order approximation which corresponds to weakly broken (flavor) symmetry of the Lagrangian

with some other physics and structures associated

There is no relation of mixing with masses (mass ratios)

Parameters look like C-G coefficients
Can be resonantly enhanced in matter
2-3 mixing:
asymmetric for NO and IO
\( \sin^2 \theta_{23} = 0.45 \) (NO), = 0.58 (IO)

Small preference IO and 2\(^{nd}\) quadrant
atmospheric $\nu_\mu$ disappearance,
3 years of data

IceCube Collaboration
(M.G. Aartsen et al.).

$\Delta m_{32}^2 = (2.72 \pm 0.19/\mp 0.20) \times 10^{-3} \text{ eV}^2$

$\sin^2 \theta_{23} = 0.53 \pm 0.09/\mp 0.12$ (NO)

compatible and comparable in precision with accelerator experiments
Neutrino mass scale

Oscillations:

The heaviest neutrino

\[ m_h \gtrsim \sqrt{\Delta m_{31}^2} > 0.045 \text{ eV} \]

\[ \frac{m_2}{m_3} \gtrsim \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}} = 0.18 \]

the weakest mass hierarchy, related to large mixing

Cosmology:

\[ \Sigma m < 0.136 \text{ eV (95 \% CL)} \]

E. Di Valentino, et al
1507.08665 [astro-ph.CO]

\[ \Sigma m < (0.3 - 0.4) \text{ eV (95 \% CL)} \]

conservative

Planck 2015 + BAO + HST

Oscillations, & cosmology

\[ m_h \sim (0.045 - 0.10) \text{ eV} \]
Scales of new physics

High scale seesaw
Quark- lepton symmetry /analogy

GUT - Planck mass

28 orders of magnitude

Low scale seesaw, radiative mechanisms, RPV, high dimensional operators

Electroweak - LHC

Scale of neutrino masses themselves
Relation to dark energy, MAVAN?

Neutrino mass itself is the fundamental scale of new physics

Spurious scale?

\[
\frac{V_{EW}^2}{m_e}
\]
Complicated constructions, especially if quarks are included

Mixing

from symmetry to anarchy and randomness

Not much to add
- String landscape
- Multiverse?
PMNS & CKM

\[ U_{PMNS} = U_{CKM} + U_X \]

where \( U_{CKM} \sim V_{CKM} \)

has similar hierarchical structure determined by powers of \( \lambda = \sin \theta_C \)

From the Dirac matrices of charged leptons and neutrinos

Prediction for the 1-3 mixing

\[ \sin^2 \theta_{13} = \sin^2 \theta_{23} \sin^2 \theta_C (1 + O(\lambda^2)) \]

\[ \sin^2 \theta_{13} \sim \frac{1}{2} \sin^2 \theta_C \]

Quark mixing

C. Giunti, M. Tanimoto
H. Minakata, A Y S Z - Z. Xing
J Harada
S Antusch, S. F. King
Y Farzan, A Y S
M Picariello, ...

my prejudice

\[ U_X \] has some special form determined by symmetry related to mechanism that explains smallness of neutrino mass

\[ U_X \sim U_{23}(\pi/4) U_{12} \]

in a good agreement with measurements
What does this mean?

Quarks and leptons know about each other, Q L unification, GUT or/and Common flavor symmetries

Some additional physics is involved in the lepton sector which explains smallness of neutrino mass and difference of the quark and lepton mixing patterns

Two types of new physics

CKM

Neutrino new physics

Indicates SO(10): no CKM mixing in the first approximation

if not accidental
Challenges and Anomalies

Determination of unknowns within 3nu paradigm

- Mass hierarchy/ordering
- Absolute values of masses, type of spectrum
- CP-violation phase(s)
- Nature of neutrino mass: (Majorana-Dirac, hard - soft (effective))

Checks of Anomalies and their explanations

- Deficit of signal
- Excess of signal
- High sensitivity to steriles

- 1 eV sterile neutrino: not a small perturbation of the 3ν picture
- Absence of spectral upturn, large DN asymmetry

- Reactor, Gallium source
- LSND, MiniBooNE
- IceCube

Solar neutrino anomaly?
steriles? NSI?
Mass hierarchy
Mass hierarchy

Further advance important by itself
Step to discover CP

Phenomenology

Supernova neutrinos
Atmospheric neutrinos
bb0n decay
LBL
Solar neutrinos
Cosmology

Theoretical implications
Theoretical implications

Similar to quark spectrum

\[ \frac{m_2}{m_3} \sim \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}} = 0.18 \]

the weakest hierarchy

\[ \theta \sim \sqrt{\frac{m_2}{m_3}} \]

Normal vs. special

\[ \frac{\Delta m}{m} \sim \frac{\Delta m_{21}^2}{2 \Delta m_{32}^2} = 1.6 \times 10^{-2} \]

but 1-2 mixing strongly deviates from maximal

Pseudo-Dirac + 1 Majorana

Flavor symmetries

Broken $L_e - L_\mu - L_\tau$ symmetry

See-saw

Quark-lepton symmetry

Unification
Race for mass hierarchy

- Matter effect on 1-3 mixing
  - Oscillations, conversion

- Precise measurements of $\Delta m^2$ at reactors
  - JUNO, RENO-50

- Supernova neutrinos

- LBL experiments

- Atmospheric neutrinos

- PINGU
- ORCA
- INO

- Earth matter effects, energy spectra

- Cosmology
  - $\Sigma m$

- Double beta decay
\[ m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\phi} \]

Constraints from cosmological surveys and from oscillations. The 1\(\sigma\) region for the IH case is not present at this confidence level. The grey band is the 95\% C.L. excluded region coming from Cosmology.
Density increase $\rightarrow$ Normal mass hierarchy, neutrinos

$\nu_{1m}$

$\nu_{2m}$

$\nu_{3m}$
Flavor in matter

Density increase $\rightarrow$ Inverted mass hierarchy, neutrinos

$\nu_{2m}$

$\nu_{1m}$

$\nu_{3m}$

1-2 resonance

$\nu_e$ $\nu_\mu$ $\nu_\tau$
All these effects depend on the type of mass hierarchy. 

With known 1-3 mixing, all MSW transitions are adiabatic.
Hierachy affects

Strong suppression of the $\nu_e$ peak $\rightarrow$ NH

$\nu_e \rightarrow \nu_3$

Permutation of the electron and non-electron neutrino spectra

Time rise of the anti-$\nu_e$ burst initial phase: fast $\rightarrow$ IH

P. Serpico et al

Earth matter effects

Neutrino collective effects

Different for IH and NH cases; spectral splits at high energies $\rightarrow$ IH

G. Fuller, et al
R. Tomas et al

G. Fuller, et al
B. Dasgupta et al

Shock wave effect

in neutrino channels $\rightarrow$ NH
in antineutrino $\rightarrow$ IH

A. Dighe, A. S. C. Lunardini

in the antineutrino channel only $\rightarrow$ NH
in the neutrino channel only $\rightarrow$ IH

If the earth matter effect is observed for antineutrinos NH is established!
Earth matter effect and hierarchy

Normal hierarchy

Inverted hierarchy

Level crossings

No Earth matter effect provided that initial fluxes of $\nu_\mu'$ and $\nu_\tau'$ are identical.

Collective effects and shock waves may change this.

Adiabatic evolution
Atmospheric neutrinos

Oscillations in the Earth

\[ \nu_e \rightarrow \nu_\mu, \nu_\tau \]

Resonance enhancement of oscillations

\[ \Theta = 33^\circ \]

Parametric enhancement of oscillations

core-crossing trajectory

\[ \Theta_\nu \text{-zenith angle} \]
**Probabilities**

neutrinos

\[ P(\nu_x \rightarrow \nu_y) \]

\[ \cos \theta_z = -1.0 \]

\[ \cos \theta_z = -0.8 \]

\[ \cos \theta_z = -0.6 \]

\[ \cos \theta_z = -0.4 \]

E \[ \text{[GeV]} \]

antineutrinos

\[ P(\bar{\nu}_x \rightarrow \bar{\nu}_y) \]

\[ \cos \theta_z = -1.0 \]

\[ \cos \theta_z = -0.8 \]

\[ \cos \theta_z = -0.6 \]

\[ \cos \theta_z = -0.4 \]

E \[ \text{[GeV]} \]


NH - solid
IH - dashed
\( x = \mu \) - blue
\( x = e \) - red
Method

Measurement of $E - \theta$ distributions of different type of events. Compare events for the normal and inverted orderings

"tracks"

\[ \nu_\mu + N \rightarrow \mu + h \]
\[ \nu_\tau + N \rightarrow \tau + h \]
\[ \rightarrow \mu + \nu + \nu \]

Measurements

\[ E_\mu, \theta_\mu, E_h \]
\[ E_\nu = E_\mu + E_h \]
\[ E_h, E_\mu, \theta_\mu \rightarrow \theta_\nu \]

"cascades"

\[ \nu_e + N \rightarrow e + h \]
\[ \nu_\alpha + N \rightarrow \nu_\alpha + h \]
\[ \nu_\tau + N \rightarrow \tau + h \]
\[ \rightarrow h + \nu \]
\[ \rightarrow e + \nu + \nu \]

Measurements

\[ E_\nu, \theta_\nu \]

inelasticity

reconstruction
Track events

\[ \sim 10^5 \text{ events/year} \]

``Distinguishability``

Estimator of sensitivity

\[ S - \text{ asymmetry} \]

\[ |S| - \text{ significance} \]
Cascade events

``Distinguishability``

Statistical significance
Smeared distributions

Over energy and angle resolution functions

PINGU

tracks
cascades
distinguishability

PRELIMINARY

$\frac{N_{NH} - N_{NH}}{\sqrt{N_{NH}}}$

Ken Clark
Precision IceCube
Next Generation
Upgrade

K. Clark

40 strings
96 DOM's per string
K. Clark

Mass hierarchy

Parameters of the 2-3 sector

Deviation from maximal:
symmetry or no symmetry, Quadrant
Sensitivity to MH depends on
Oscillation Research with Cosmics in the Abyss

115 lines, 20m spaced,
18 DOMs/line, 6m spaced.
Instrumented volume ~3.8 Mt,
2070 OM

- 31 3” PMTs
- Digital photon counting
- Directional information
- Wide angle view

Poster: Ronald Bruijn
Dependence of sensitivity on time for fixed $\theta_{23}$ values and $\delta_{CP}$ fixed to zero

- Track vs shower event classification
- Full MC detector response matrices including misidentified and NC events
- Atmospheric muon contamination
- Neutral current event contamination
- Various Systematic uncertainties

Poster: Martijn Jongen
Dependence of sensitivity on $\theta_{23}$. Higher for NH than IH.

Second octant easier than first octant.

When fixing $\delta_{CP}$ to zero sensitivity increases by $\sim 0.5\sigma$. 
The 50 kt magnetized iron calorimeter (ICAL) detector at the India-based Neutrino Observatory (INO)

- Energy and direction of the muons;
- Energy of multi-GeV hadrons;
- Charge of muon

The energy and zenith angle dependence of the atmospheric neutrinos in the multi-GeV range.
The impact of systematic uncertainties on mass hierarchy sensitivity. The red (green) lines - without (with) systematic uncertainties. Long-dashed lines are for fixed values of parameters (1-3 mixing, 2-3 mixing, mass splitting), solid - marginalized.
CP-violation
Measuring CP-phase
Global fit
T2K + NOvA + reactors ~ 50 kw upgrade at 2-3σ
J-PARC+ SK

Dedicated experiments
J-PARC+ HK
DUNE LBNF
ESS

Europeanspalation source Lund

~ 5 - 7σ

result in 2030 - 2035

~ 2 bln US$

Long term and expensive commitment

Alternative?

All possible alternatives must be explored and scenarios of developments in the next 20 years should be considered
Megaton-scale Ice Cherenkov Array

**Ice Cube Deep Core**

- **PINGU**: Mass hierarchy
- **ORCA**: Mass hierarchy
- **Super-PINGU-ORCA**: 3 times denser array than PINGU
- **MICA**: Few Mtons in sub-GeV range

**Energy Ranges**
- 100 GeV
- 10 - 15 GeV
- 3 GeV
- 0.5 - 1 GeV
- 0.01 GeV

*S. Razzaque, A.Y.S. 1406.1407 hep-ph*
Large (10%) effect at $E \sim (0.5 - 1.5) \text{ GeV}$

The key: with change of the phase systematic shift of curves, the same for all zenith angles in mantle

Averaging over fast oscillations and integration over zenith angle does not wash out CP phase effect

### Probabilities

$\nu_e \rightarrow \nu_\mu$

**Parametric effects**

- 1-2 resonance
- 1-3 resonance

**NH**

S. Rassou, A.Y.S.
arXiv: 1406.1407 hep-ph
$\nu_\mu \rightarrow \nu_\mu$

- No phase shift
- Effect is opposite to $\nu_e \rightarrow \nu_\mu$
  with change of $\delta$
- Flavor suppression of effects for $\nu_\mu$ events
- Flavor identification is crucial
**Quick estimator (metric) of discovery potential**

For each energy-zenith angle bin $ij$ relative CP-difference

$$S_{ij} = \frac{N_{ij}^\delta - N_{ij}^\delta = 0}{\sqrt{N_{ij}^\delta = 0}}$$

If is true value $\Rightarrow N_{ij}^\delta$ corresponds to "true" value of events
$\Rightarrow N_{ij}^\delta = 0$ "measured" number of events

$|S_{ij}|$ - distinguishability of different values of CP-phase

**Total distinguishability**

$$S^{tot} = \left[ \sum_{ij} S_{ij}^2 \right]^{1/2}$$
For different values of CP phase

νμ - CC events (track + cascade)

S-distributions for different values of δ

Super PINGU 1 year

After smearing over neutrino energy and direction

S distributions

Neutrino images of the Earth

\( \nu_e \)-CC events (cascades)

S-distributions for different values of \( \delta \)

Super PINGU
1 year

After smearing over neutrino energy and direction

S. Razzague, A.Y.S.
arXiv: 1406.1407 v2
hep-ph

Can we measure this?
Effect of correlated systematic errors

Flavor misidentification can further reduce distinguishability by factor 1.5 - 2

Still $S_\sigma \sim 3-4$ for $\delta = \pi$ after 4 years of exposure
Enormous progress all mixing angles and mass splittings in $3\nu$ framework are measured.

Still physics behind neutrino mass and mixing is not yet identified.

Few challenges imply existence of new neutrino states-sterile neutrinos.

Measurements of missing parameters of the $3\nu$ paradigm - mass hierarchy, - CP phase, as well as - searches physics beyond $3\nu$ paradigm may lead to breakthrough in the field.

Identification of the neutrino mass ordering - next big in neutrino physics.

Large atmospheric neutrino detectors with low (few GeV) energy threshold PINGU, ORCA may be first in this race.

Measurements of the Dirac CP-phase ultimate in oscillation neutrino experiments.

A possibility to use further upgrade of PINGU, ORCA detectors to measure the CP phase should be explored.
Race for mass hierarchy:
PINGU, ORCA
JUNO, RENO 50
T2K, NOvA
Supernova neutrino bursts
Cosmology

2022 - 2026?
Tomorrow? But require better understanding collective effects

Fast developments of techniques of detection of low energy (atmospheric) neutrinos in multi Megaton detectors

Can address crucial issues in particle, neutrino physics:
- establishing neutrino mass ordering
- determination of the CP-phase
- searches for sterile neutrinos, and tests of existing hints
- searches for non-standard neutrino interactions, etc.

This may lead to major developments in the field
Backup slides
Daya Bay Collaboration (An, F.P. et al.)
arXiv:1505.03456 [hep-ex]
Global fit results

Normal ordering

- Posterior
- Profile $\mathcal{L}$

J. Bergstrom, et al, 1507.0436 [hep-ph]

NuFIT 2.0 (2015)
Global fit results

Inverted ordering

Posterior

Profile $\mathcal{L}$

Bayes

$\chi^2$
The neutrino oscillation probability at baselines of 295 (left), 810 (middle), and 7500 km (right) as a function of the neutrino energy. The red (blue) band corresponds to the normal (inverted) mass hierarchy and the band width is obtained by varying the value of delta. The probabilities for antineutrinos look similar with the hierarchies interchanged. Note the different scales of the axes.

Singlet of SM symmetry group $SU(3) \times SU(2) \times U(1)$

Non-local interactions which violate fundamental symmetries eg CPT

$F$ is composite fermionic operator

Singlet of symmetry group of hidden sector

Non-local interactions which violate fundamental symmetries eg CPT
H-asymmetry and significance

Quick estimator (metric) of discovery potential

For each \(ij\)-bin
Hierarchy asymmetry
H-asymmetry

\[
S_{ij} = \frac{[N_{ij}^{IH} - N_{ij}^{NH}]}{\sqrt{N_{ij}^{NH}}}
\]

If \(NH\) is true hierarchy → \(N_{ij}^{NH}\) "experimental" number of events
→ \(N_{ij}^{IH}\) "fit" number of events

\(|S_{ij}|\) statistical significance of establishing true hierarchy

Uncorrelated systematic error

\(N_{ij}^{NH} \rightarrow \sigma_{ij}^2 = N_{ij}^{NH} + (f \cdot N_{ij}^{NH})^2\)

Total distinguishability

\[S^{tot} = [\sum_{ij} S_{ij}^2]^{1/2}\]
Marginalized over 2-3 mixing

\[ \Delta m^2_{32} > 0 \]

\[ \Delta m^2_{32} < 0 \]

\[ \sin^2 2\theta_{13} \]

\[ \delta_{CP} \]

\[ 6 \times 10^{20} \rightarrow 7.8 \times 10^{21} \] by 2018

i.e. 13 times higher statistics

sensitivity to the phase \( \delta_{CP} \) at 90% C.L.
or better over

\(-115^\circ < \delta_{CP} < -60^\circ \) for NH

\(+50^\circ < \delta_{CP} < +130^\circ \) for IH.

if \( \theta_{23} = 45^\circ \)

\[ T2K \text{ Collaboration (K. Abe, et al.)}. \]

\[ \text{arXiv:1409.7469 [hep-ex]} \]

\[ \text{NOvA} \]

further substantial improvements

Distinguishing \(- \pi/2\) from 0 at > 3\( \sigma \) level?
\[ \sin^2 \theta_{32, \text{fit}} = 0.50 \]
\[ \sin^2 \theta_{32, \text{true}} = 0.42 \]
Mass ordering with reactors

Normal hierarchy

\[ \omega_{ij} = \frac{\Delta m_{ij}^2}{2E} \]

Oscillation frequency

Oscillation depth:

\[ D_{31} = 4|U_{e1}|^2|U_{e3}|^2 \]

\[ D_{32} \approx 2D_{31} \]

\[ \omega_{31} > \omega_{32} \]

Fourier analysis

Higher frequency - larger depth

Inverted hierarchy

\[ \omega_{31} < \omega_{32} \]

\[ \omega_{32} \]

\[ D_{32} = 4|U_{e2}|^2|U_{e3}|^2 \]

Higher frequency - smaller depth

S. Petcov
M. Piai
Jiangmen Underground Neutrino Observatory

\[ d = 700 \text{ m}, \ L = 53 \text{ km}, \ P = 36 \text{ GW} \]

20 kt LAB scintillator

\[ n + p \rightarrow d + \gamma \]

Key requirement:
energy resolution 3% at 1 MeV

Operation in 2020
\((3 - 4)\sigma\) in 6 years
Leptons versus quarks

**Leptons**

\[ \nu_f = U_{\text{PMNS}} \nu_{\text{mass}} \]

**Quarks**

\[ U_d = V_{\text{CKM}} U \]

\( U = (u, c, t) \)

combination of down-quarks produced with a given up quark
Determined with matter effects on the solar neutrinos

suppression at high energies is smaller than at low energies

\[ P_{ee} = \begin{cases} |U_{e2}|^2 \sim \sin^2 \theta_{12} \sim 0.3 & \text{for NH} \\ |U_{e1}|^2 \sim \cos^2 \theta_{12} \sim 0.7 & \text{for IH} \end{cases} \]

The problem is to determine the 1-3 or 2-3 ordering

Solar neutrinos are not sensitive to 1-3 ordering due to very small matter effect on 1-3 mixing:

\[ \sin \theta_{13}^m = \sin \theta_{13} \left(1 +/- \frac{2EV \cos 2\theta_{13}}{\Delta m_{31}^2}\right) \]

NH / IH few 10^{-2}
**Suppression of effects**

- **Integration**
  - Averaging and smoothing effects
  - Reconstruction of neutrino energy and direction

- **Detection**
  - Identification of flavor

- **Original fluxes**
  - \( \nu_e \) and \( \nu_\mu \)

- **Different flavors**: \( \nu_e \) and \( \nu_\mu \)

- **Screening factors**: 
  - \( 1 - r s_{23}^2 \)

- **Reduces CP-asymmetry**: 
  - \( 1 - \kappa_e \)
  - \( 1 - \kappa_\mu \)
The hierarchy sensitivity of ICAL with input normal hierarchy including correlated hadron energy information, with $|\Delta m^2_{\text{eff}}|$, $\sin^2 \theta_{23}$ and $\sin^2 2\theta_{13}$ marginalised over their $3\sigma$ ranges. Improvement with the inclusion of hadron energy is significant. $\chi^2_{\text{ICAL-MH}}$ as a function of the exposure assuming NH (left panel) and IH (right panel) as true hierarchy.
Cascade events $e^+ + \text{nutau}$

$S. \text{Razzque and A.Y.S.,}$
Oscillation probabilities

\[
P(\nu_\mu \rightarrow \nu_\mu) \\
P(\nu_\mu \rightarrow \nu_\nu)
\]

- NH, $\delta_{CP} = 0$
- IH, $\delta_{CP} = 0$
- NH, $\delta_{CP} = \pi/2$
- IH, $\delta_{CP} = \pi/2$

\[
\begin{align*}
\sin^2 2\theta_{23} &= 1.0 \\
\sin^2 2\theta_{13} &= 0.1 \\
\Delta m_{32}^2 &= 2.4 \times 10^{-3} \text{ eV}^2
\end{align*}
\]

$E$ (GeV)
FNAL - Ash River
L = 810 km, 14 kton
off axis 3.3°
E = 1 - 3 GeV

$\nu_\mu - \nu_e$ oscillations in matter
T2K Collaboration (K. Abe et al.).

Phys. Rev. D91 (2015) 7, 072010
Contribution of different sets of experimental results to the determination of the mass ordering, the octant of $\theta_{23}$ and of the CP violating phase.

Genesis of determination

**Solar Reactors**
**MINOS dis**

Atm nu contribution: excess of sub GeV nue events
L = 1300km, LAr TPC 35 kt
Mass hierarchies

at $m_Z$

up quarks | down quarks | charged leptons | neutrinos

$10^{-1}$ | $10^{-2}$ | $10^{-3}$ | $10^{-4}$ | $10^{-5}$

$m_{2}/m_{3} \geq \sqrt{\Delta m_{21}^2 / \Delta m_{32}^2}$

$\sim 0.18$

Neutrinos have the weakest mass hierarchy (if any) among fermions

Related to large lepton mixing?

$m_u m_t = m_c^2$

$\sin \theta_C \sim \sqrt{m_d/m_s}$

Gatto-Sartori-Tonin relation
Sensitivity to MH

KM3NeT/ORCA sensitivity (PRELIMINARY Feb 2015)

Median significance $\sigma$

Years of ORCA proposed detector operation
(115 strings, 18 DOMs/string)
Dirac CP-phase in the standard parametrization of the PMNS matrix

\[ \nu_f = U_{PMNS} \nu_{mass} \]

\[ U_{PMNS} = U_{23} I_\delta U_{13} I_{-\delta} U_{12} \]

\[ I_\delta = \text{diag} (1, 1, e^{i\delta}) \]

\[ \nu \rightarrow \nu^c \quad \nu^c = i \gamma_0 \gamma_2 \nu^+ \]

**CP-transformations:**

**Under CP-transformations:**

Matter potential

\[ U_{PMNS} \rightarrow U_{PMNS}^* \quad \delta \rightarrow -\delta \]

\[ V \rightarrow -V \]

usual medium is C-asymmetric which leads to CP asymmetry of interactions

Degeneracy of effects:

Matter can imitate CP-violation
Global Fit
Muon- and electron-channels contribute to net hierarchy asymmetry. Electron channel more robust against detector resolution effects:

- Muon channel (~10 M.yr) Perfect detector
- Electron channel (~10 M.yr) Perfect detector

$E, \theta$ smearing (kinematics + detector resolution)
Sensitivity

K. Clark

PRELIMINARY
Deviation from maximal symmetry or no symmetry

Quadrant

Sensitivity to MH depends on

\[
\sin^2 \theta_{32, \text{fit}} = 0.50
\]

\[
\sin^2 \theta_{32, \text{true}} = 0.42
\]
Muon- and electron-channels contribute to net hierarchy asymmetry. Electron channel more robust against detector resolution effects:
Symmetries of Hidden sector