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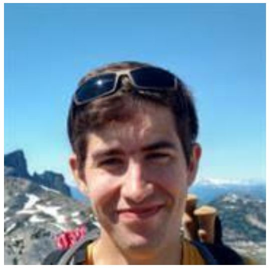
Monday 16th September

NuFACT 2024:
Working Group 1 Introduction



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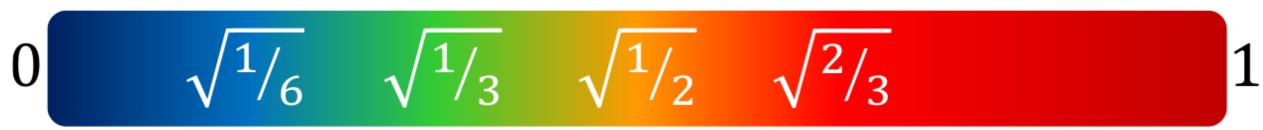
Neutrino oscillations

- Mixing of flavour and mass eigenstates

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

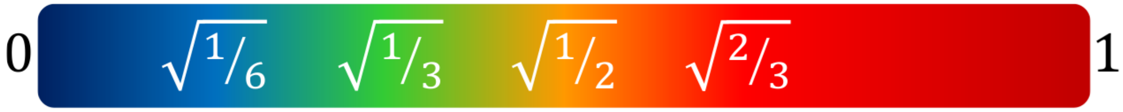
- Oscillation probability is function of neutrino energy, E, and propagation distance L

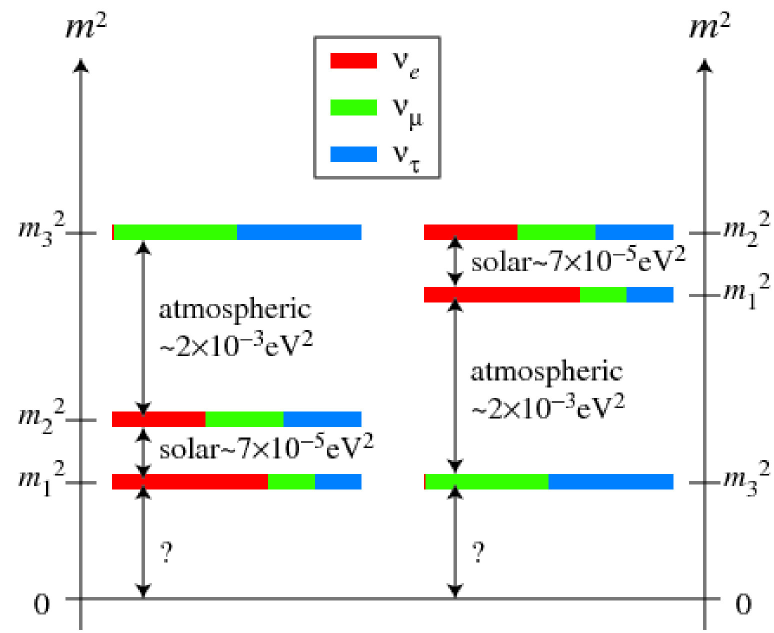


$$P_{\alpha\to\beta} = \left|\sum_i U^*_{\alpha i}\, U_{\beta i}\, e^{-im_i^2 L/2E}\right|^2$$

Neutrino oscillation details

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





What do we know ?

(F. Capozzi et al., Phys. Rev. D 104, 8, 083031)

- $\sin^2\theta_{23} = 0.455 \pm 0.018$
- $\sin^2\theta_{13} = 0.0223 \pm 0.0007$
- $\sin^2\theta_{12} = 0.303 \pm 0.13$
- $|\Delta m^2_{32}| = (2.45 \pm 0.03) \times 10^{-3}$ eV^2
- $\Delta m^2_{21} = (7.36 \pm 0.16) \times 10^{-5}$ eV^2

What don't we know?

- Do neutrinos violate CP?
- Is $m_3 > m_2$? (Mass Ordering)
- Is $\theta_{23} > 45^o$? (Octant)
- What is the value of m_1?
- Are neutrinos Majorana particles?
- New physics?

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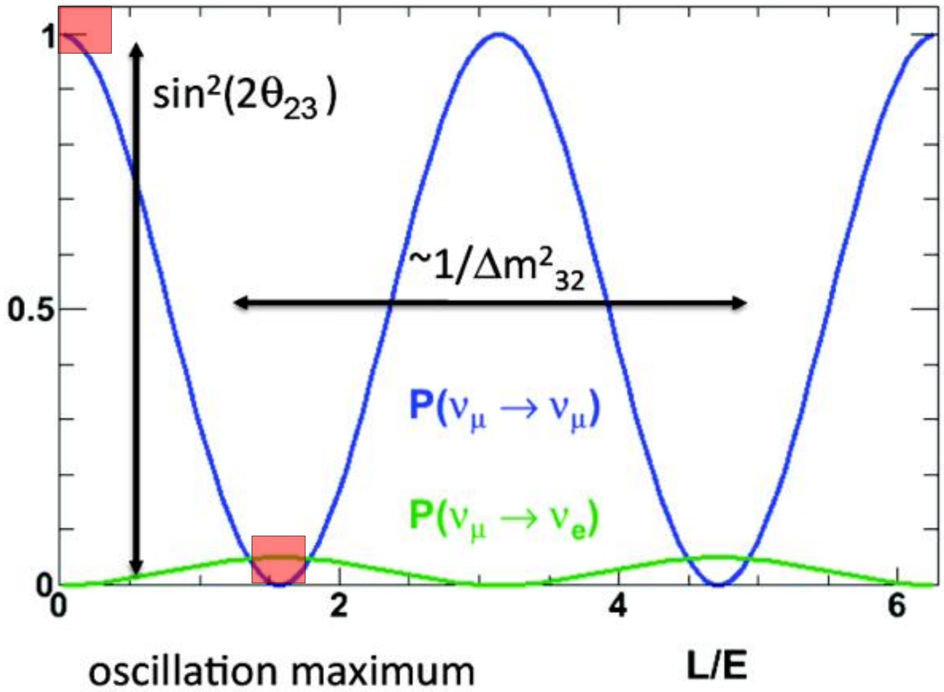
Long-baseline neutrino experiments

- Leading order oscillation probabilities for ν_μ survival and ν_e appearance

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



- Build two detectors
- One close to neutrino source
- Other at maximal oscillation

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Sensitivity to unknown oscillation parameters

$$P(\nu_\mu \to \nu_e) = 4c_{13}^{\ 2} s_{13}^{\ 2} s_{23}^{\ 2} \sin^2 \Delta_{31}$$ θ_{13}

$$+8c_{13}^{\ 2} s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$ CPC

$$-8c_{13}^{\ 2} c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$ CPV

$$+4s_{12}^{\ 2} c_{13}^{\ 2} (c_{12}^{\ 2} c_{23}^{\ 2} + s_{12}^{\ 2} s_{23}^{\ 2} s_{13}^{\ 2} - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta) \sin^2 \Delta_{21}$$ Solar

replace δ by –δ for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

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Sensitivity to unknown oscillation parameters

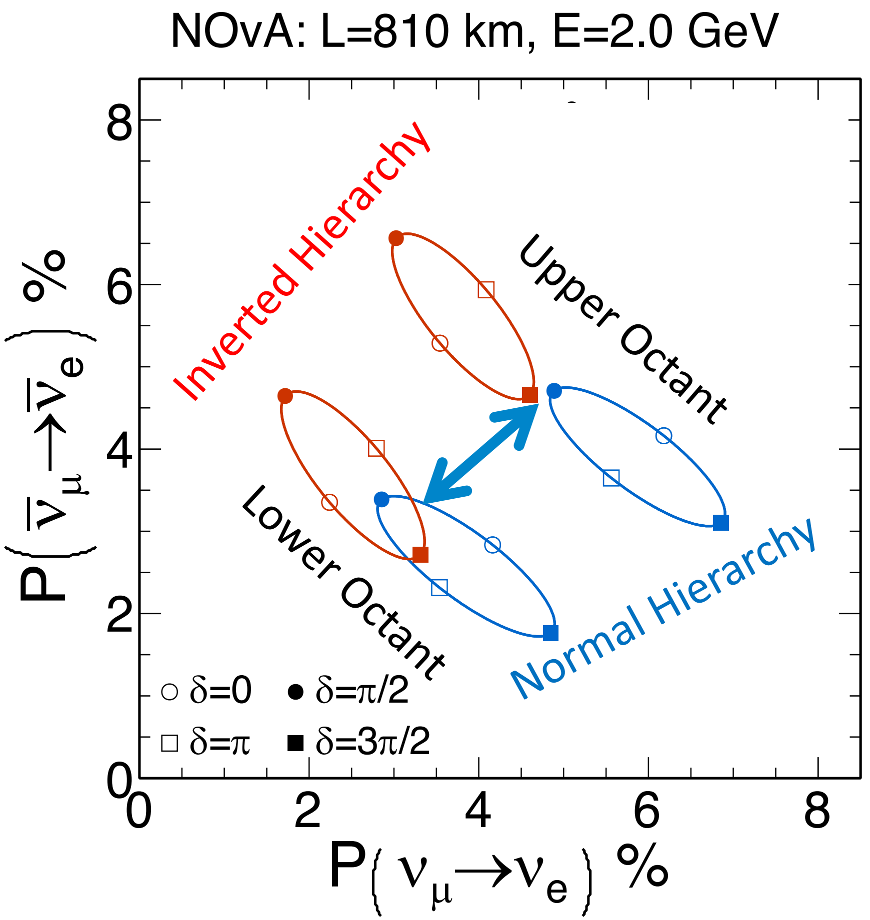

Image by A. Himmel / NOvA

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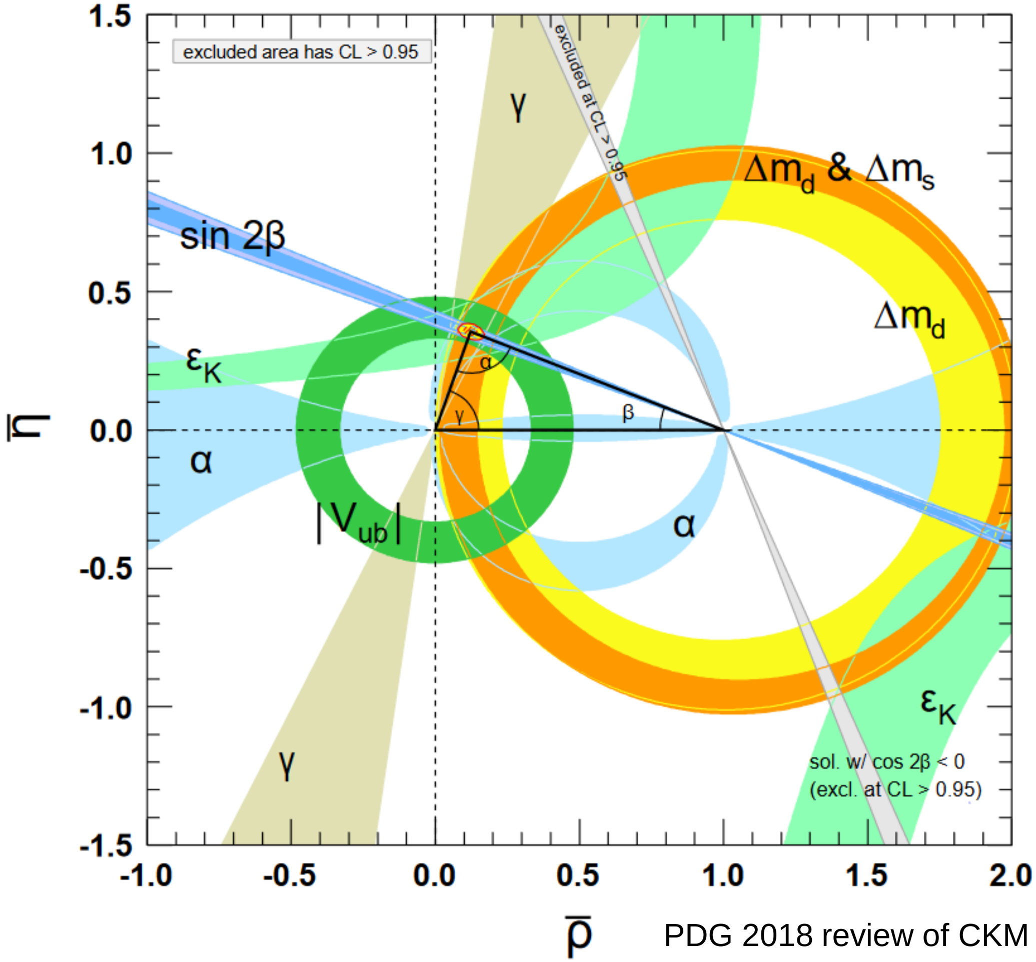
Beyond parameter measurement - unitarity

- Non-unitarity not seen in quarks (yet)
- Would indicate new physics
  - Generic search
- Requires **over-constraint** of PMNS parameters



PDG 2018 review of CKM matrix

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Unitarity measurements in PMNS

- Many contributions
  - Daya Bay
  - JUNO
  - SNO
  - Hyper-K / DUNE
  - DUNE / Hyper-K / IceCube

Experiment	Measured quantity with unitarity
Reactor SBL ($\overline{\nu}_e \to \overline{\nu}_e$)	$4\|U_{e3}\|^2 \left(1 - \|U_{e3}\|^2\right) = \sin^2 2\theta_{13}$
Reactor LBL ($\overline{\nu}_e \to \overline{\nu}_e$)	$4\|U_{e1}\|^2 \|U_{e2}\|^2 = \sin^2 2\theta_{12} \cos^4 \theta_{13}$
SNO (ϕ_{CC}/ϕ_{NC} Ratio)	$\|U_{e2}\|^2 = \cos^2 \theta_{13} \sin^2 \theta_{12}$
SK/T2K/MINOS ($\nu_\mu \to \nu_\mu$)	$4\|U_{\mu 3}\|^2 \left(1 - \|U_{\mu 3}\|^2\right) = 4 \cos^2 \theta_{13} \sin^2 \theta_{23} \left(1 - \cos^2 \theta_{13} \sin^2 \theta_{23}\right)$
T2K/MINOS ($\nu_\mu \to \nu_e$)	$4\|U_{e3}\|^2 \|U_{\mu 3}\|^2 = \sin^2 2\theta_{13} \sin^2 \theta_{23}$
SK/OPERA ($\nu_\mu \to \nu_\tau$)	$4\|U_{\mu 3}\|^2 \|U_{\tau 3}\|^2 = \sin^2 2\theta_{23} \cos^4 \theta_{13}$

S. Parke, M. Ross-Lonergan, Phys. Rev. D 93, 113009 (2016)

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Recent multi-experiment analyses

- T2K + NOvA
  - Similar neutrino source and event samples, but very different detectors and analysis methods
- T2K + SK
  - Identical detector but using different neutrino source and event samples, and different analysis methods
- Difficult, but essential to extract maximum information from current and future experiments
  - Focus of satellite workshop yesterday

Many experiments to enjoy

HYPER K

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

ICECUBE

SUPER K

NOvA

Daya Bay θ13

JUNO

T2K

SNO

KamLAND
Kamioka Liquid scintillator Anti-Neutrino Detector

NuFACT Open Questions

- WG1 conveners have selected four questions to consider during the conference
  - Probably we cannot answer them directly but I hope we can determine how to answer them in the future

1. **What are the needs for hadron production measurements for the future experiments?**
2. **What are the current and future systematic limitations on oscillation measurements and what can we do to address them?**
3. **How can we best combine experimental data to achieve the most accurate results?**
4. **What are the next steps for a unitarity test?**

WG1 Parallel Sessions

- Six parallel sessions over the week with talks broadly grouped together

- Monday – Current generation experiment results
- Tuesday 1 – Next generation experiment sensitivities
- Tuesday 2 – Near detectors in oscillation analyses
- Thursday 1 – WG1 x WG3: Neutrino flux for oscillations
- Thursday 2 – WG1 x WG5: BSM physics in neutrino oscillations
- Friday – New ideas

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Summary

- We have 6 WG1 parallel sessions at NuFACT 2024
  - Talks cover current and future oscillation experiments, including accelerator, atmospheric and reactor neutrinos
  - Joint sessions with WG3 and WG5
  - Poster session this evening

- Wide variety of topics presented by experts
  - Roughly 5 presentations per session to provide significant time for questions and discussions

- Lets have an interesting, fruitful and enjoyable week!