Neutrino Oscillation Physics with LBNF & DUNE

Jennet Dickinson

290e Seminar

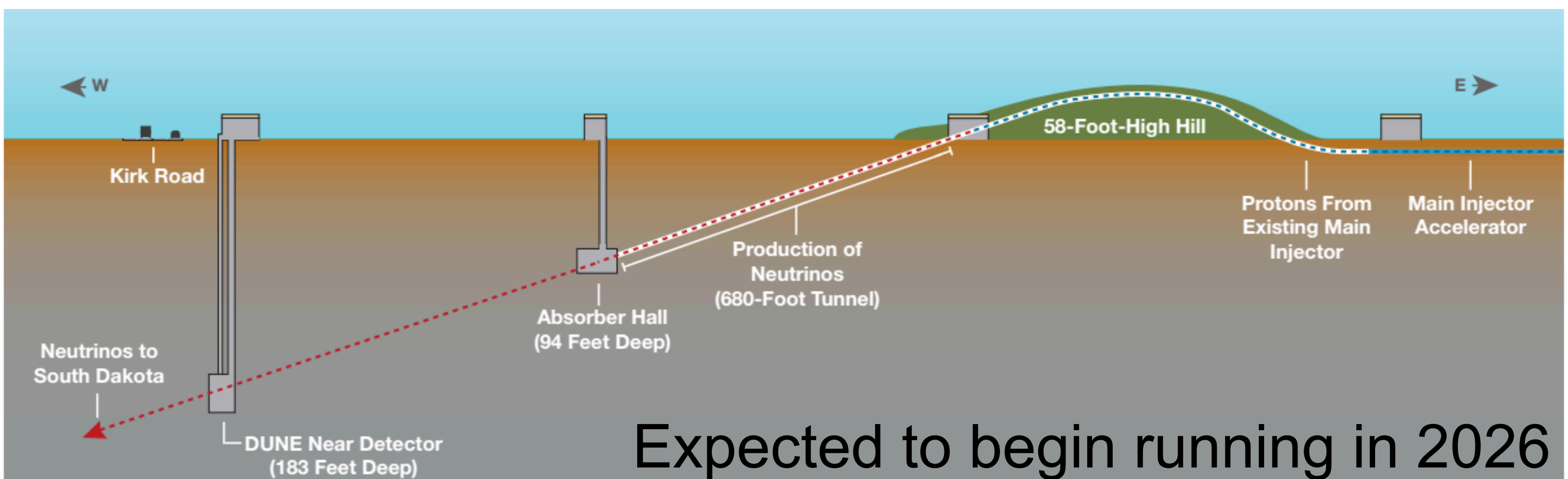
September 28, 2016

Outline

- LBNF and the DUNE detectors
- Why matter effects matter
- Measuring the mass hierarchy and δ_{CP}
  - What we can gain from long baselines

LBNF: Long Baseline Neutrino Facility

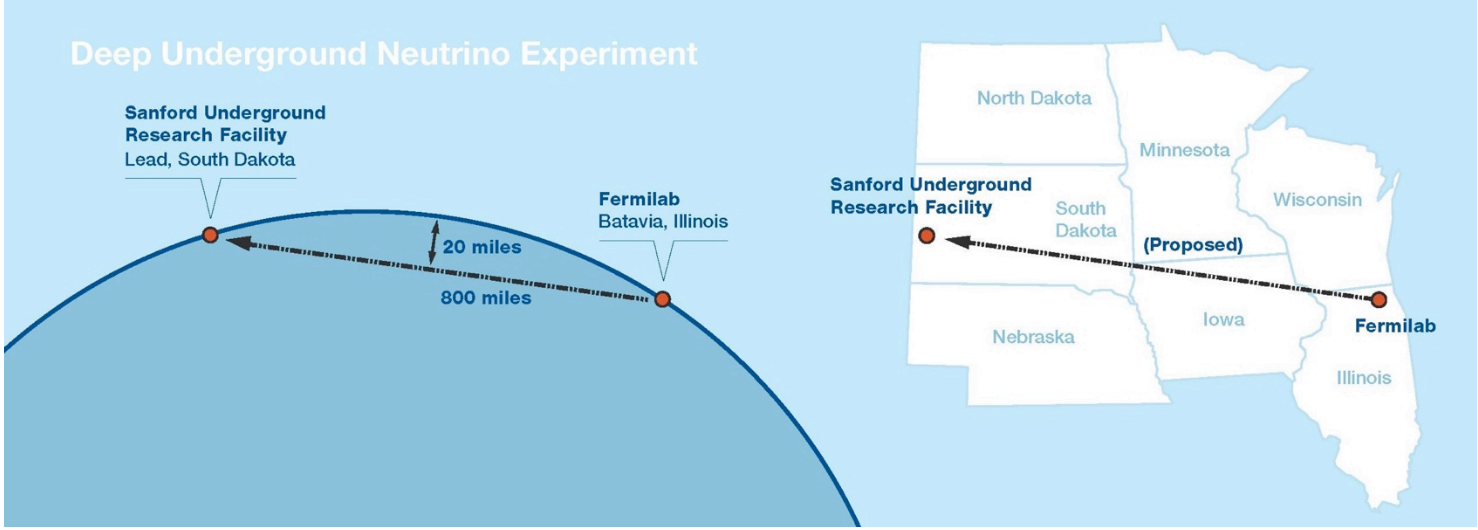
- A high intensity neutrino beam directed from Fermilab to SURF in Lead, SD
- The beam design will be very similar to Fermilab's NuMI beam



Expected to begin running in 2026

DUNE: Deep Underground Neutrino Experiment

- DUNE will measure the oscillation of muon neutrinos into electron neutrinos by looking at charged current ν_e events
  - Includes a near detector at Fermilab, and a far detector at SURF

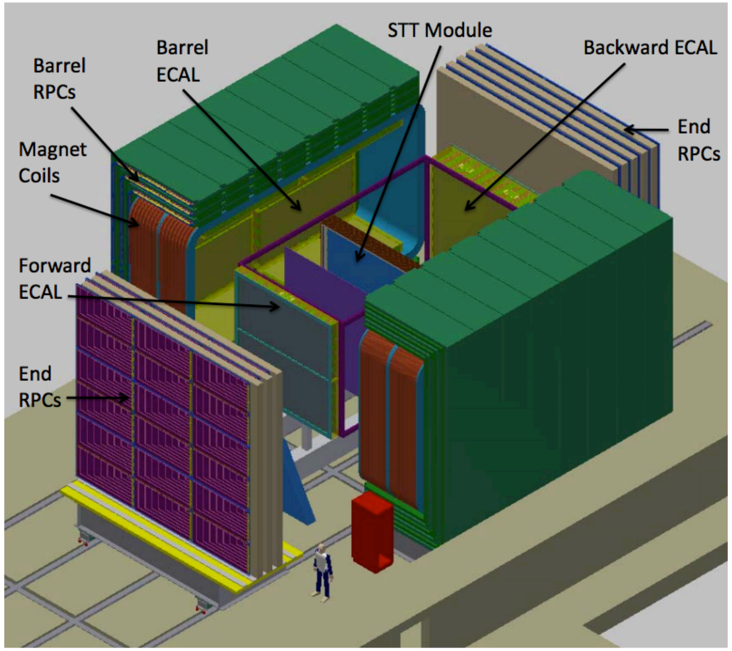


DUNE: The near detector

- The near detector will help reduce systematic uncertainty by:
  1. Understanding the beam composition
     - How much ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$ do we see before oscillations?
     - What is the energy spectrum?
  2. Making precise measurements of neutrino interaction cross sections

DUNE: The near detector

- The near detector: a fine-grained tracker
  - Straw tube tracking detector
  - Electromagnetic calorimeter
  - Dipole magnet, to distinguish ν, $\bar{\nu}$ CC events
  - Muon identifiers

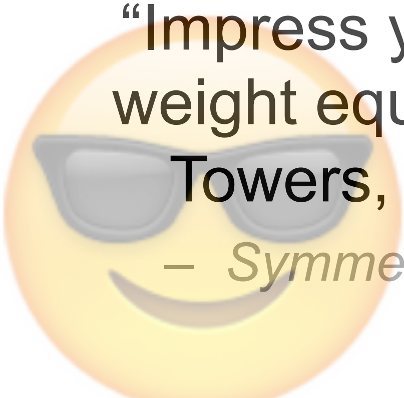


DUNE: The far detector

- The far detector will be composed of four Liquid Argon TPCs, with a total fiducial volume of 40 kt
  - Good for tracking and calorimetry
  - Effective particle ID allows for good separation between electron and muon neutrino CC events
- Will be located at SURF, in a mine 4850 ft underground in Lead, SD
  - A new cavern is being excavated here

DUNE: The far detector

- The far detector will be composed of four Liquid Argon TPCs, with a total fiducial volume of 40 kt
  - Good for tracking and calorimetry
  - Effective particle ID allows for good separation between electron and muon neutrino CC events

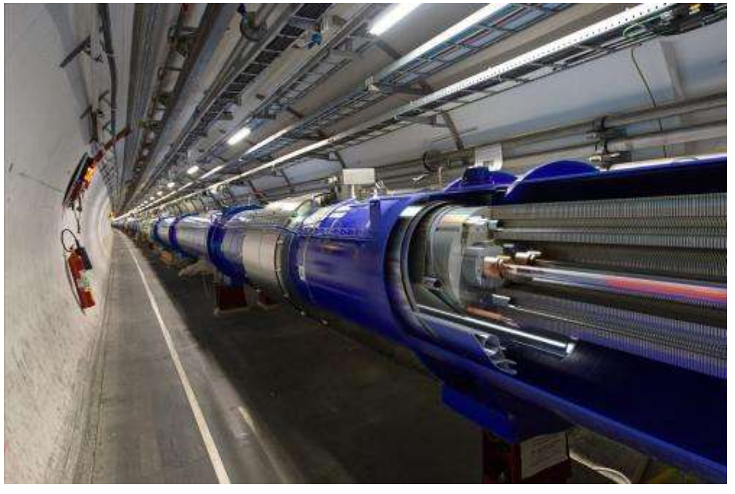


"Impress your friends by saying that crews will move the weight equivalent of 2.2 Empire State Buildings, 80 Eiffel Towers, 4700 blue whales or 18 billion(ish) Twinkies"

– *Symmetry Magazine*, "Five Fascinating facts about DUNE"

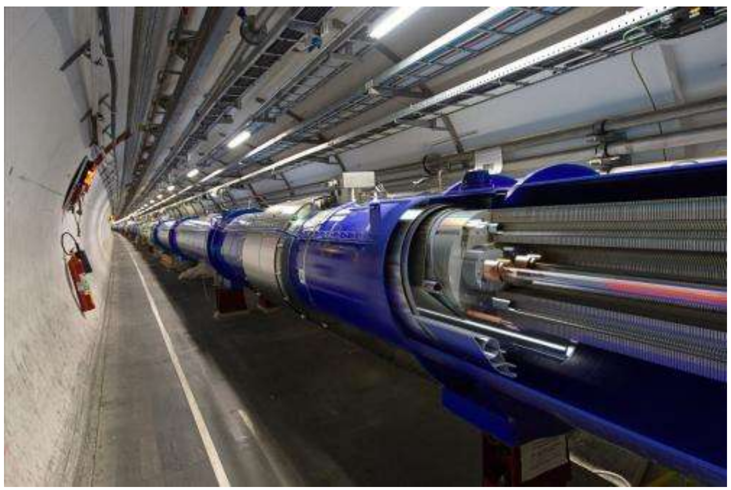
Shooting ν from FNAL to SURF

- The neutrinos will travel 1300km! That would be a long beam-pipe...



Shooting ν from FNAL to SURF

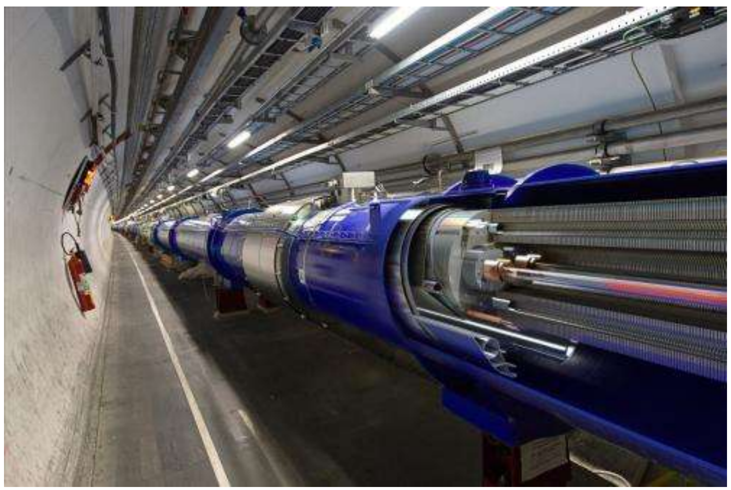
- The neutrinos will travel 1300km! That would be a long beam-pipe...



- We don’t need one! Can’t the neutrino beam go straight through the earth?

Shooting ν from FNAL to SURF

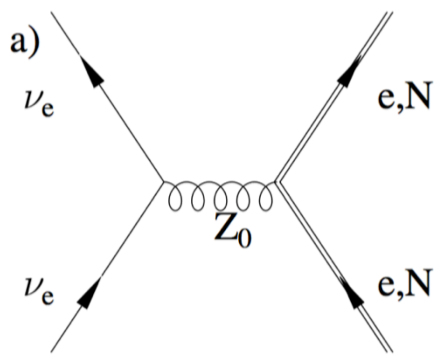
- The neutrinos will travel 1300km! That would be a long beam-pipe...



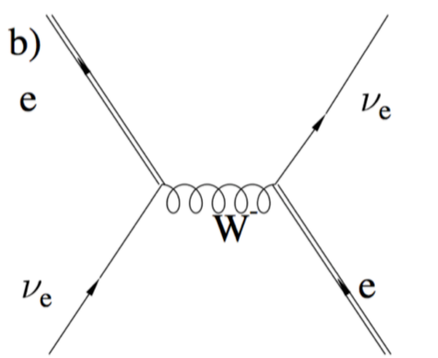
- We don't need one! Can't the neutrino beam go straight through the earth?

- Yes, but we can't ignore the fact that the earth is there…

Matter effects



- Neutral current scattering
  - Independent of neutrino flavor
  - Does not change oscillations



- Charged current scattering
  - There are electrons in matter, but not μ^- or τ^- (or e^+ / μ^+ / τ^+)
  - Will affect oscillation probability and ν-$\bar{\nu}$ asymmetry

Matter effects: simple example

- Take the Schrodinger equation for 2ν oscillations, written in mass state basis:

$$i\frac{d}{dt}\begin{bmatrix}a_1\\a_2\end{bmatrix} = \frac{1}{4p}\begin{bmatrix}-\Delta m_{21}^2 & 0\\0 & \Delta m_{21}^2\end{bmatrix}\begin{bmatrix}a_1\\a_2\end{bmatrix}$$

Matter effects: simple example

- Take the Schrodinger equation for 2ν oscillations, written in mass state basis:

$$i\frac{d}{dt}\begin{bmatrix}a_1\\a_2\end{bmatrix} = \frac{1}{4p}\begin{bmatrix}-\Delta m_{21}^2 & 0\\0 & \Delta m_{21}^2\end{bmatrix}\begin{bmatrix}a_1\\a_2\end{bmatrix}$$

- Using the mixing matrix U, we can re-write this in flavor state basis

$$i\frac{d}{dt}\begin{bmatrix}a_e\\a_\mu\end{bmatrix} = \frac{1}{4p}\begin{bmatrix}-\Delta m_{21}^2\cos 2\theta_{12} & \Delta m_{21}^2\sin 2\theta_{12}\\\Delta m_{21}^2\sin 2\theta_{12} & \Delta m_{21}^2\cos 2\theta_{12}\end{bmatrix}\begin{bmatrix}a_e\\a_\mu\end{bmatrix}$$

Matter effects: simple example

- Only ν_e experience matter effects, so only the ee component of our Hamiltonian changes:

$$i\frac{d}{dt}\begin{bmatrix} a_e \\ a_\mu \end{bmatrix} =$$

$$\frac{1}{4E}\begin{bmatrix} -\Delta m_{21}^2 \cos 2\theta_{12} + 4E\sqrt{2}G_F \rho_e(x) & \Delta m_{21}^2 \sin 2\theta_{12} \\ \Delta m_{21}^2 \sin 2\theta_{12} & \Delta m_{21}^2 \cos 2\theta_{12} \end{bmatrix} \begin{bmatrix} a_e \\ a_\mu \end{bmatrix}$$

- The new term depends on neutrino energy, G_F, and the electron density along the neutrino path

Oscillation probability in matter

- Now we have a lot more work to do to get the oscillation probabilities in matter…

Oscillation probability in matter

- Now we have a lot more work to do to get the oscillation probabilities in matter…
- Luckily someone else already did that

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

With $a = G_F N_e/\sqrt{2}$ and $\Delta_{ij} = \Delta m_{ij}^2 L/4E$

Oscillation probability in matter

- Now we have a lot more work to do to get the oscillation probabilities in matter…
- Luckily someone else already did that

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

With $a = G_F N_e/\sqrt{2}$ and $\Delta_{ij} = \Delta m_{ij}^2 L/4E$

- Including these matter effects may seem like a pain, but they will end up helping us!

Oscillation probability in matter

- For anti-neutrino oscillation probability, take

$$a \to -a, \quad \delta_{CP} \to -\delta_{CP}$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq \quad & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\ & +\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) \\ & +\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2 \end{aligned}$$

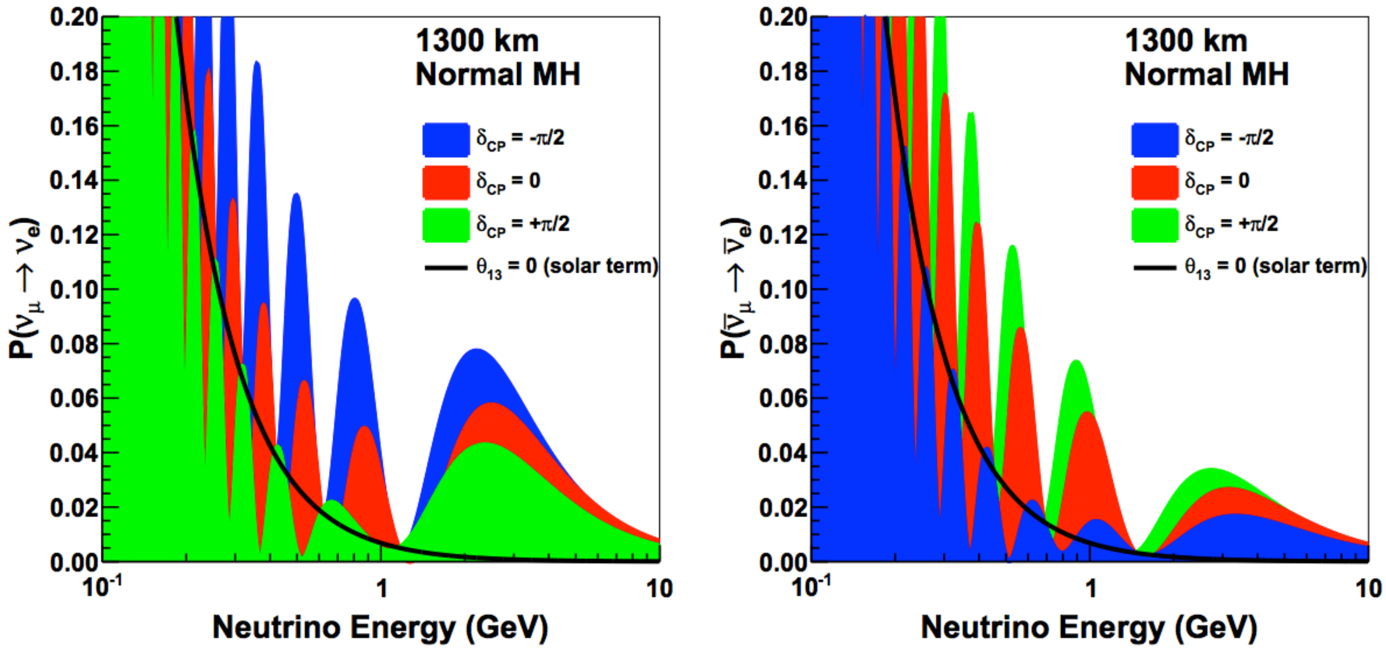
With $a = G_F N_e/\sqrt{2}$ and $\Delta_{ij} = \Delta m_{ij}^2 L/4E$

- Even if $\delta_{CP} = 0$, we still get ν-$\bar{\nu}$ asymmetry from matter effects

Oscillation probability in matter

- For anti-neutrino oscillation probability, take

$$a \to -a, \quad \delta_{CP} \to -\delta_{CP}$$



Neutrinos **Antineutrinos**

Measuring CP violation

- CP violation in the neutrino sector has many implications for particle physics and cosmology
- What do we know about δ_{CP} right now?
  - Current constraint from the PDG:

$$|J_{CP}| = \frac{1}{8}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\sin\delta \leq 0.045$$

- How can DUNE do better?

Measuring CP violation

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

- This asymmetry is what we look at to measure CP violation
  - Get contributions from nonzero δ_{CP} and from matter effects
  - Can we tell the difference between the two?

Measuring CP violation

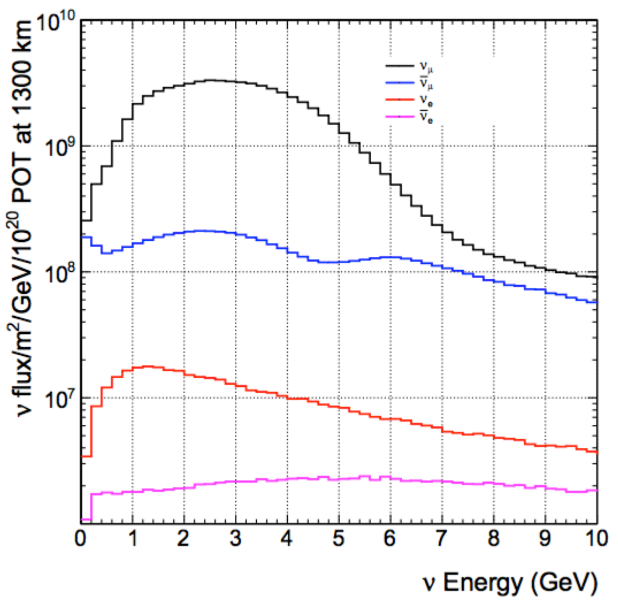
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

- This asymmetry is what we look at to measure CP violation
  - Get contributions from nonzero δ_{CP} and from matter effects
  - Can we tell the difference between the two?

YES, if our experiment has a long baseline

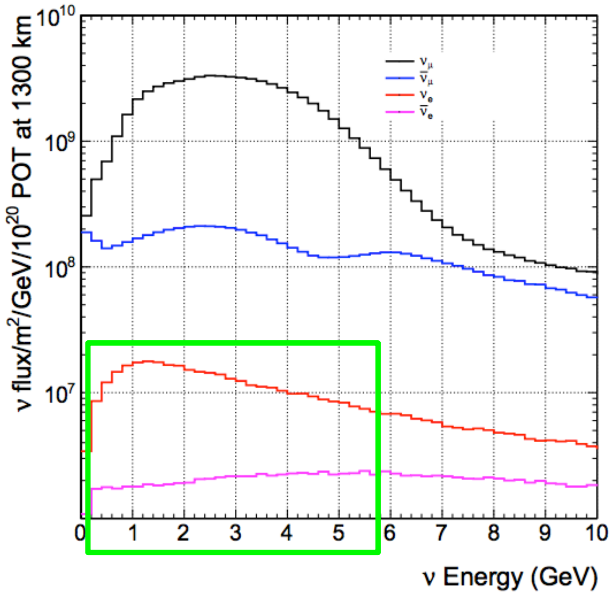
Why does baseline matter?

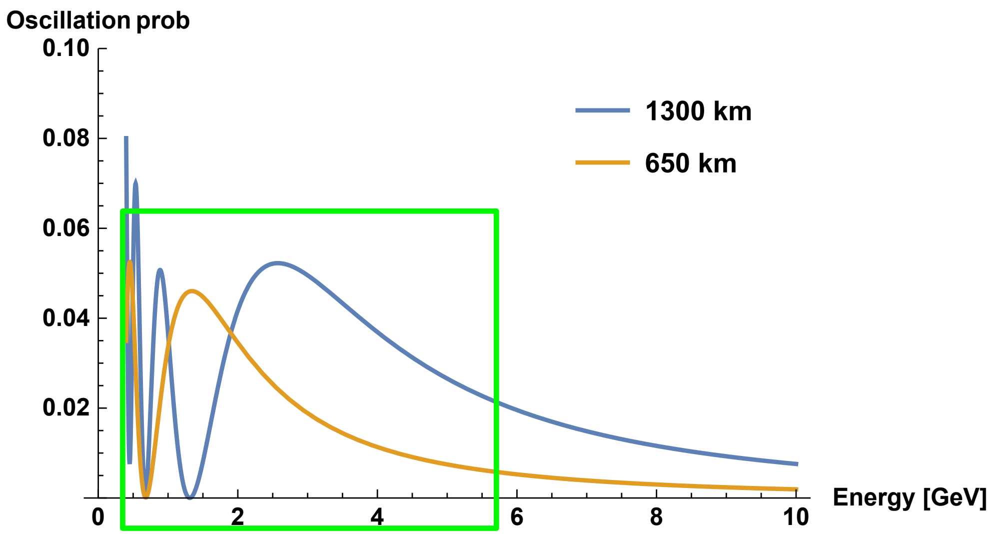
- Flux delivered by LBNF at the far detector (ν mode)



Why does baseline matter?

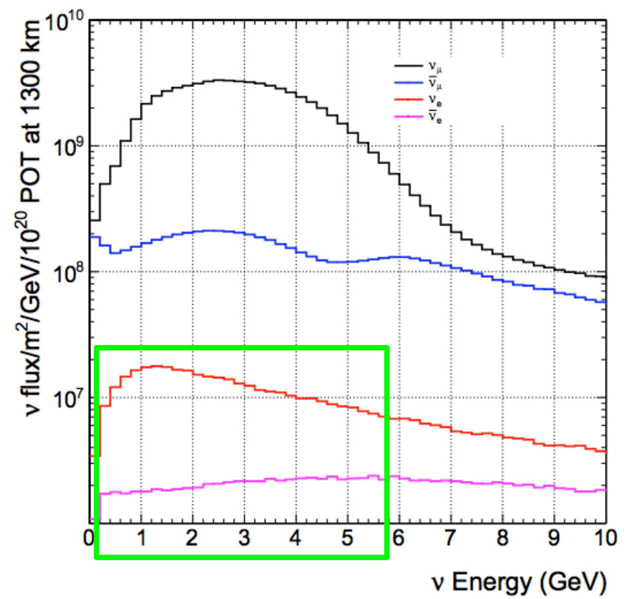
- Flux delivered by LBNF at the far detector (ν mode)
- The two highest energy peaks in the oscillation probability are accessible

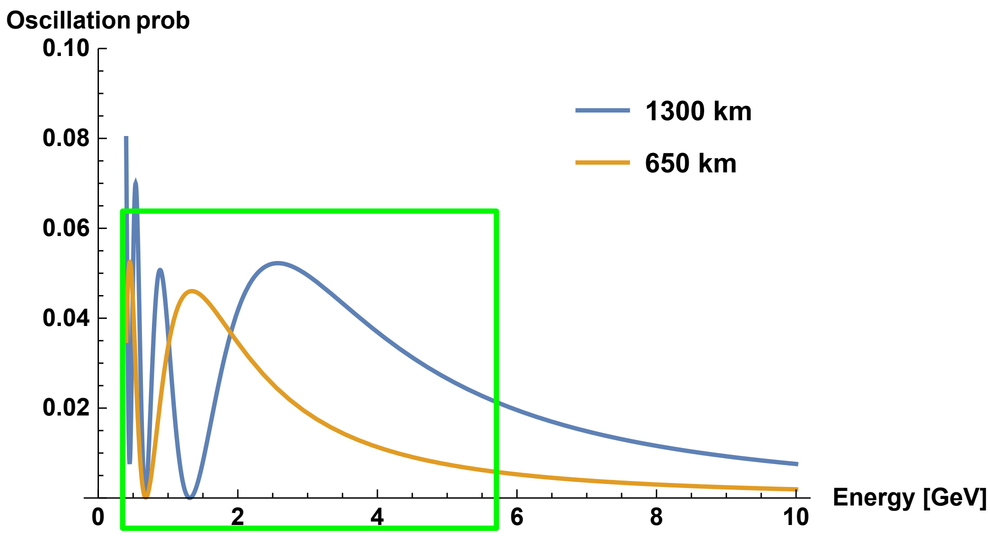




Why does baseline matter?

- Flux delivered by LBNF at the far detector (ν mode)
- The two highest energy peaks in the oscillation probability are accessible

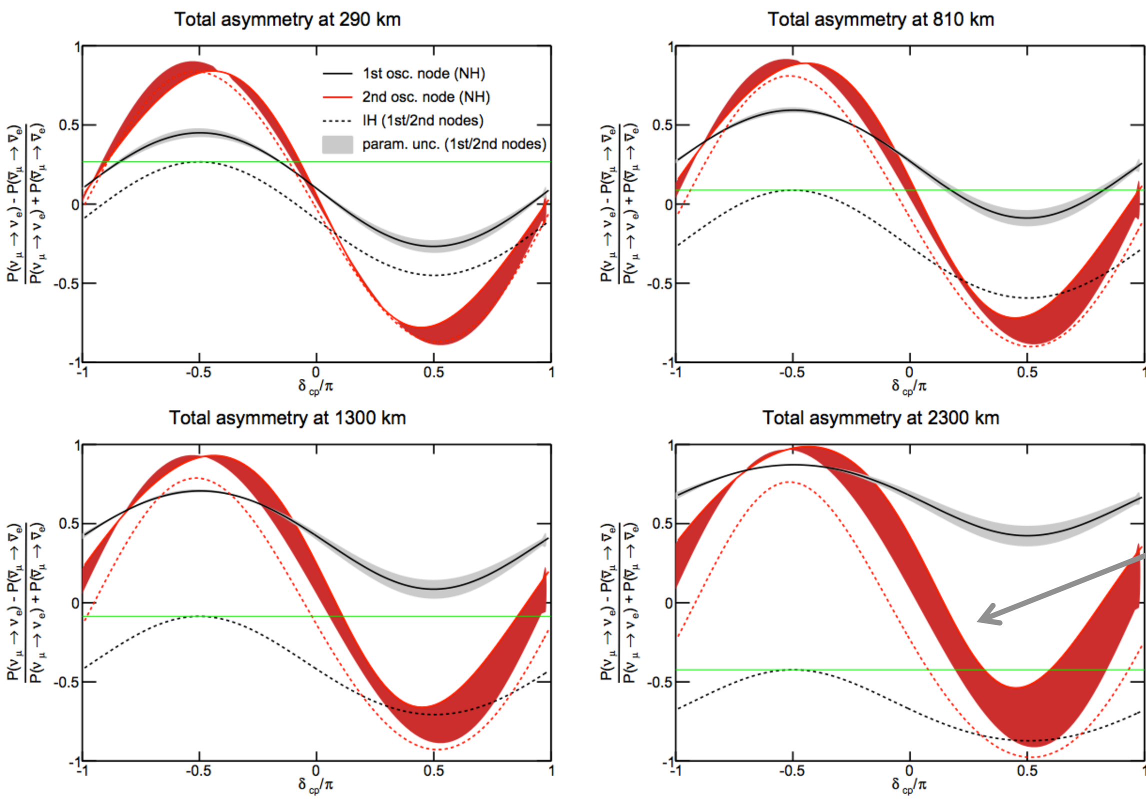




- Both peaks are pushed to lower energy when we cut the baseline in half

Does the second peak help us?

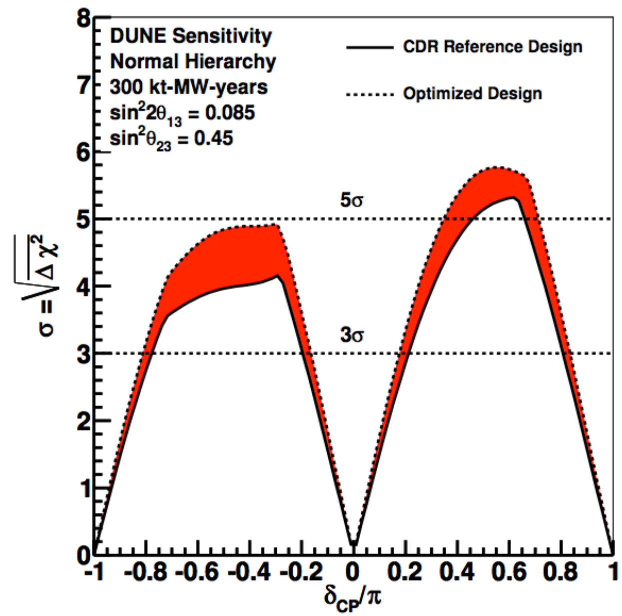
- A_{CP} at the second oscillation peak (red) is much more sensitive to δ_{CP}!



Even more so for longer baselines!

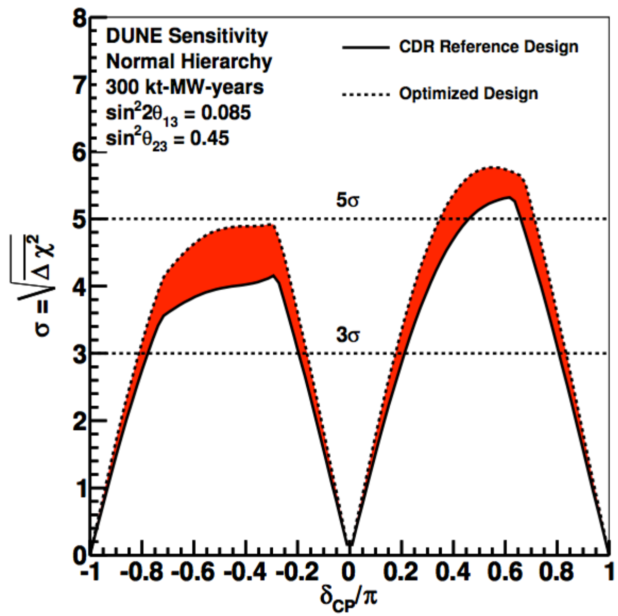
Projected sensitivity to δ_{CP}

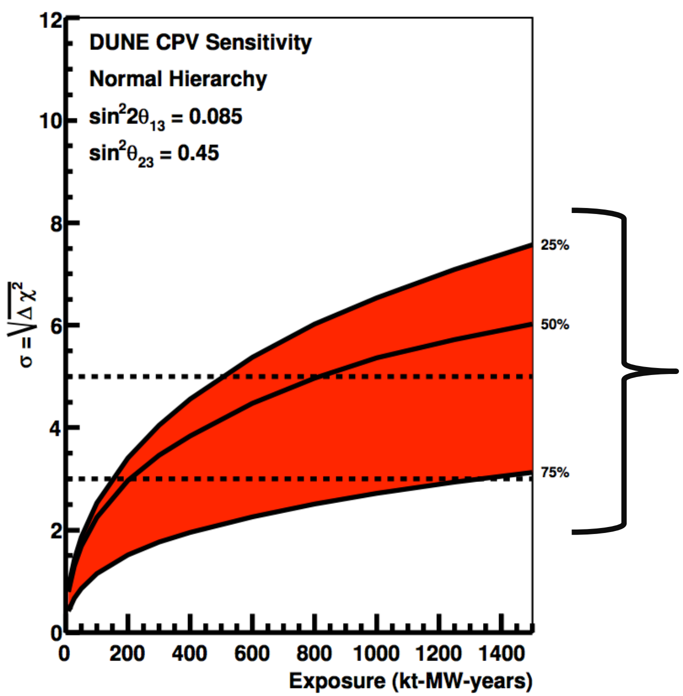
- For normal mass hierarchy, corresponding to 7 years running (3.5 ν, 3.5 $\bar{\nu}$ mode)



Projected sensitivity to δ_{CP}

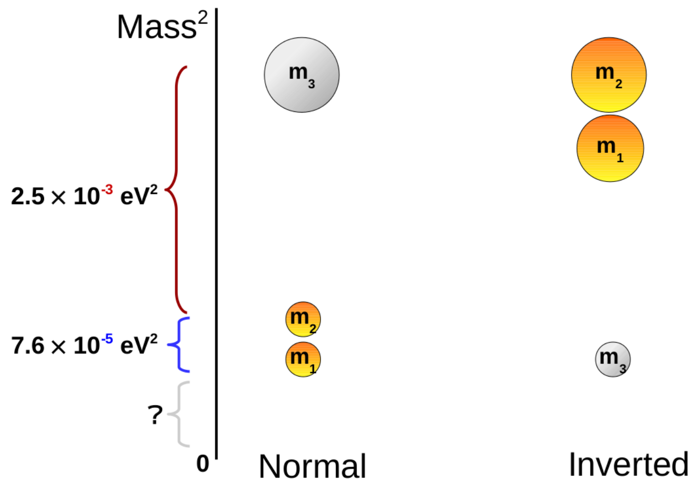
- For normal mass hierarchy, corresponding to 7 years running (3.5 ν, 3.5 $\bar{\nu}$ mode)





Percentage of δ_{CP} values DUNE is sensitive to at a given level of significance

Determining the mass hierarchy



- Available data doesn't allow us to determine the sign of Δm^2_{31}
  - Is m_3 the lightest or the heaviest neutrino?
- How is DUNE sensitive to this?

Determining the mass hierarchy

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

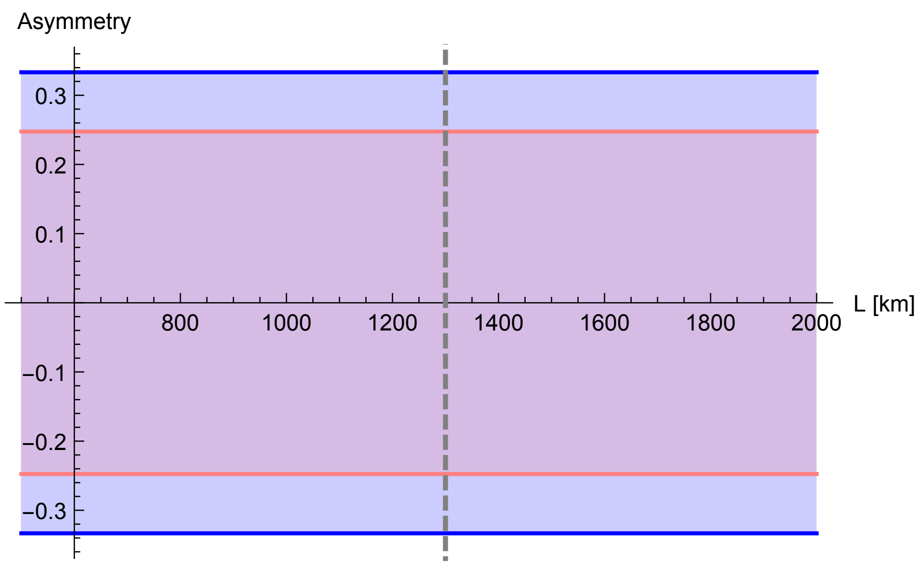
- When you include matter effects, this depends on the sign of Δm^2_{31}

$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq \quad & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\ & + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) \\ & + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2 \end{aligned}$$

With $a = G_F N_e/\sqrt{2}$ and $\Delta_{ij} = \Delta m^2_{ij} L/4E$

Determining the mass hierarchy

- This is where the matter effects will really help us out!
  - A_{CP} at the first peak calculated from ***vacuum*** oscillation probabilities, vs. baseline:



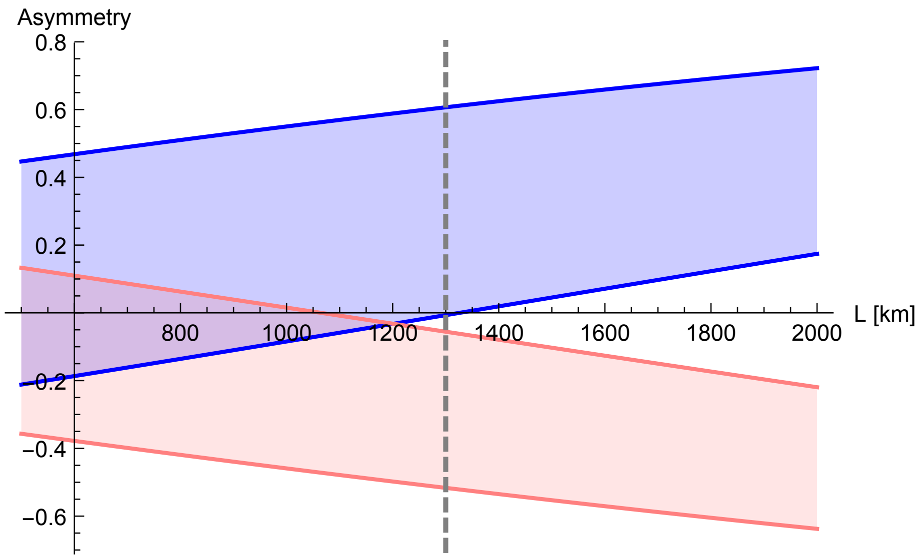
DUNE far detector

Blue: normal hierarchy, full range of δ_{CP} values

Pink: inverted hierarchy, full range of δ_{CP} values

Determining the mass hierarchy

- This is where the matter effects will really help us out!
  - A_{CP} at the first peak calculated ***including matter effects***, vs. baseline:



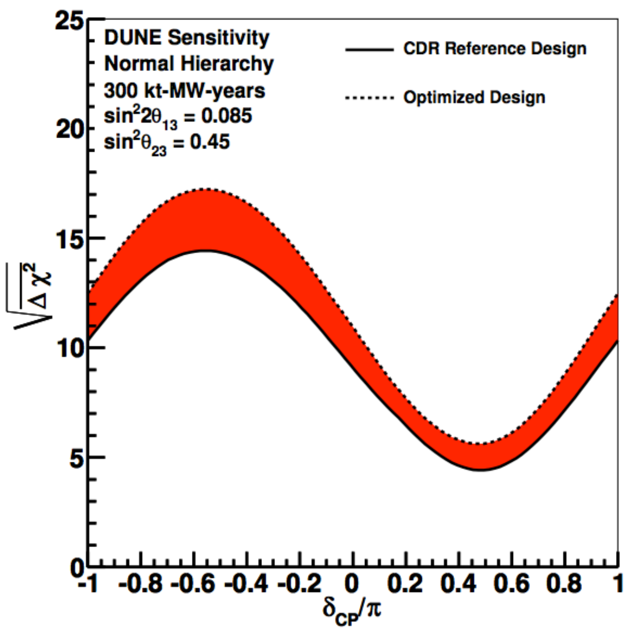
DUNE far detector

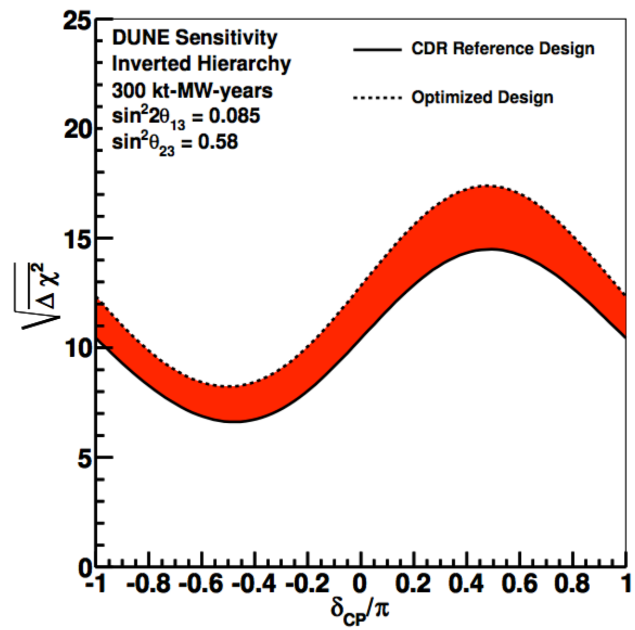
Blue: normal hierarchy, full range of δ_{CP} values

Pink: inverted hierarchy, full range of δ_{CP} values

Projected sensitivity to MH

- After 7 years running, DUNE will be able to determine the mass hierarchy at ≥5σ significance for all values of δ_{CP}





Summary

- DUNE and LBNF comprise a long baseline, high intensity neutrino program, expected to come online in 2026
- After 7 years running DUNE will
  - Be sensitive to more than 50% of possible values of δ_{CP} at $\geq 3\sigma$ level
  - Take advantage of matter effects and determine the neutrino mass hierarchy at $\geq 5\sigma$

Main sources

- DUNE CDR: https://web.fnal.gov/project/LBNF/ReviewsAndAssessments/LBNF_DUNE%20DOE%20CD-1%20Refresh%20Review/SitePages/Conceptual%20Design%20Report.aspx
- https://arxiv.org/pdf/0710.0554v2.pdf
- http://arxiv.org/pdf/1311.0212.pdf
- LBNE Science Program: https://web.fnal.gov/project/lbnearchive/LBNE%20at%20Work/LBNE%20Science%20Program/SitePages/Home.aspx
- PDG neutrino mixing: http://pdg.lbl.gov/2012/reviews/rpp2012-rev-neutrino-mixing.pdf