BERKELEY LAB

Neutrinos

Kevin Wood

Lawrence Berkeley National Laboratory

June 23, 2022

Outline

I. About me and my academic journey

II. Elementary particle physics and neutrinos

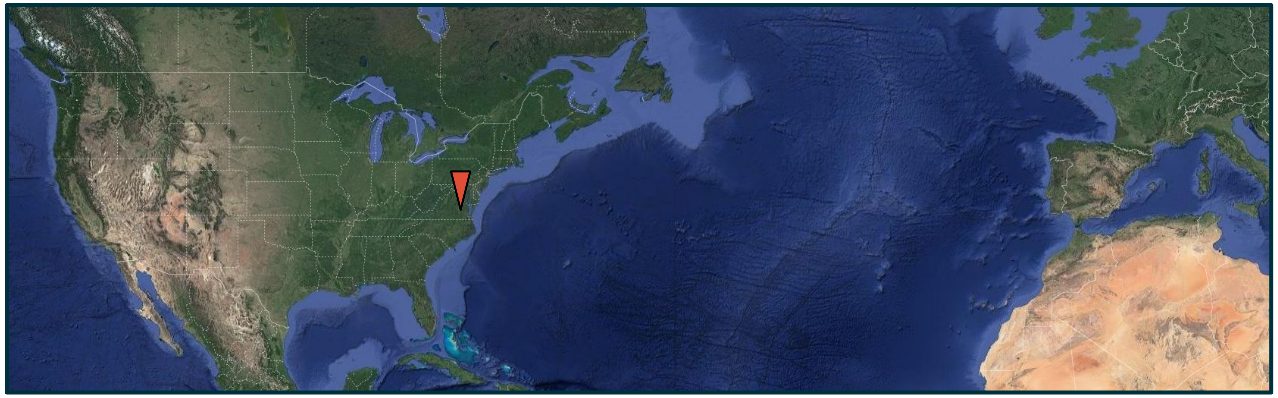
III. Measuring neutrino oscillations
(with accelerator-based long-baseline experiments)

Part I

Career Path

- Grew up in the West End of Richmond, Virginia
  - Godwin High School
- Interested in math and science (almost as much as sports)
- End of senior year, my physics teacher spoke about modern physics
  - state of the art technology being developed
  - to answer *deep* and interesting questions

2010

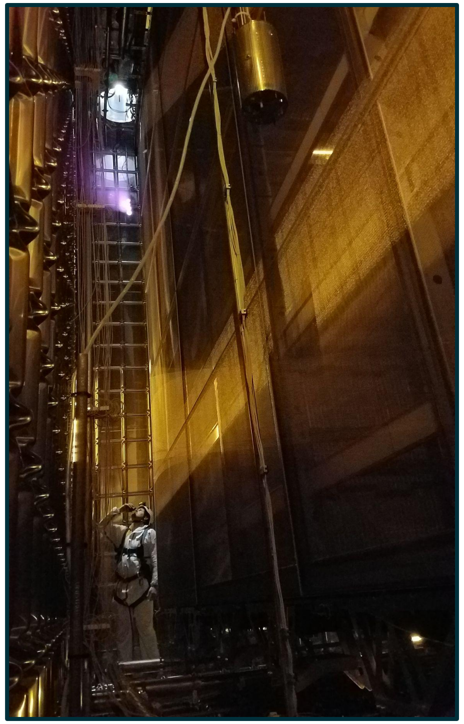


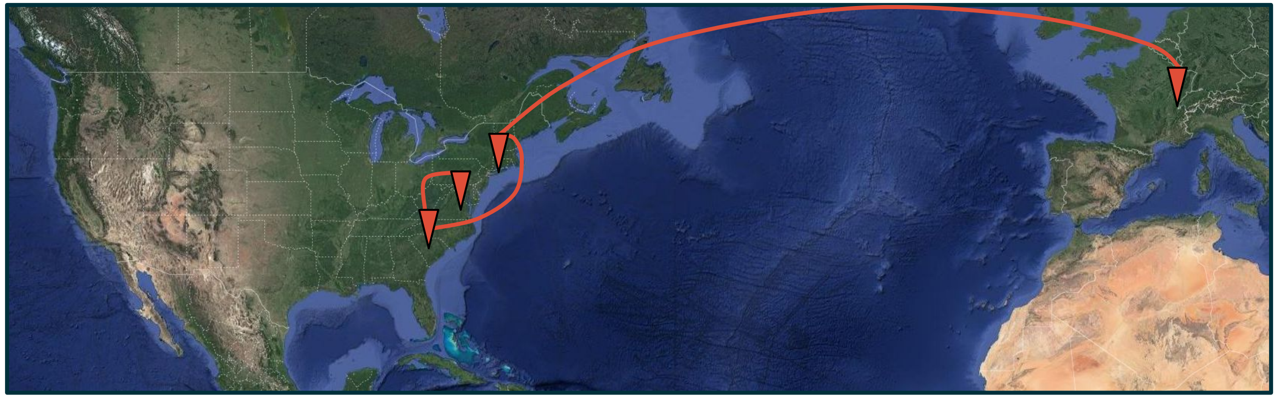
MILLS E. GODWIN HIGH SCHOOL | UofSC South Carolina | Stony Brook University | BERKELEY LAB Bringing Science Solutions to the World

- Did my undergraduate studies at the University of South Carolina
  - The real USC?...
- Majored in physics and math
- Got involved with undergraduate research early on
  - Research project in a different field of physics each summer
    - Nuclear (Jefferson Lab)
    - Condensed matter
    - Particle physics (Fermilab) (pic.)

2014

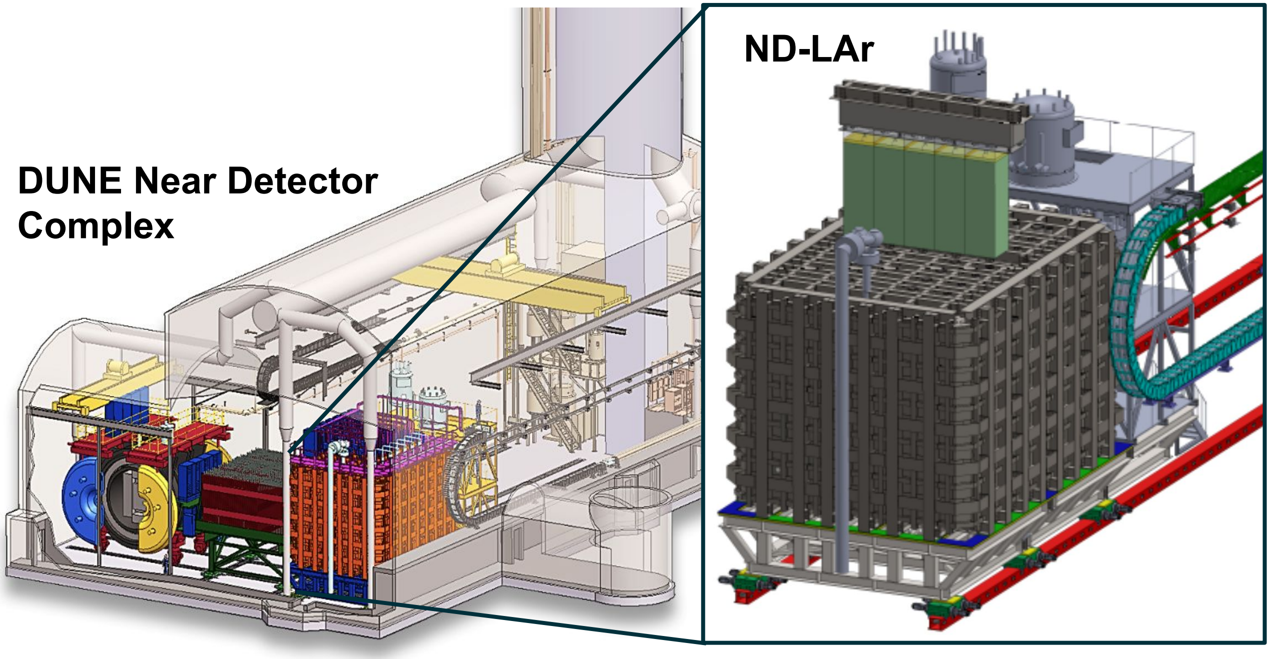
- Graduate school at Stony Brook University
  - Long Island, NY
- ~2 years of course work
- ~2 years building and operating a particle detector at CERN (pics.)
  - France/Switzerland
  - “ProtoDUNE-SP” detector
- ~2 years analyzing data from the T2K experiment
  - long-baseline neutrino oscillation
  - Japan

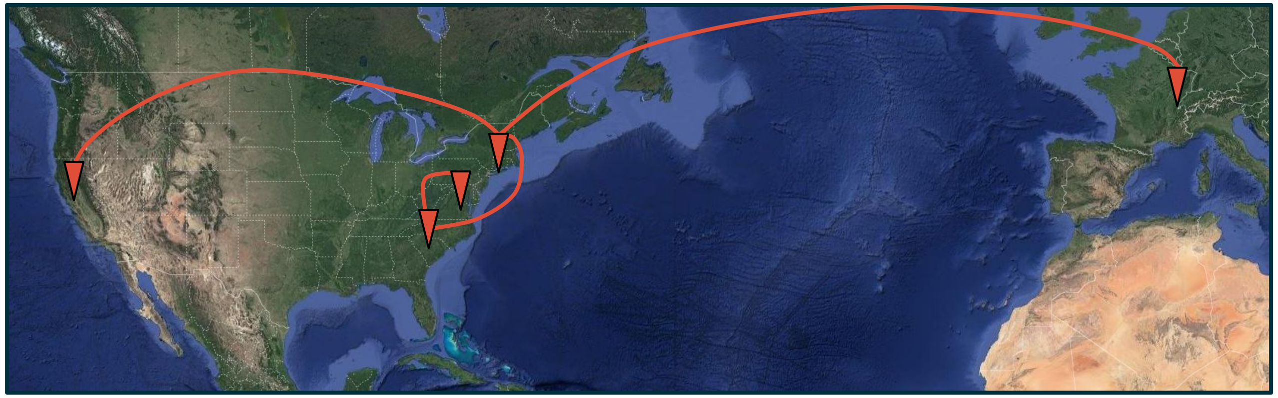




MILLS E. GODWIN HIGH SCHOOL | UofSC South Carolina | Stony Brook University | BERKELEY LAB Bringing Science Solutions to the World

- Postdoc research fellow at LBNL for ~1 year now
  - Chamberlain Fellow
- Just moved to CA a few months ago
- DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT
  - Next generation long-baseline neutrino oscillation experiment
- + working on a joint analysis between two current generation experiments taking data currently
  - T2K + NOvA



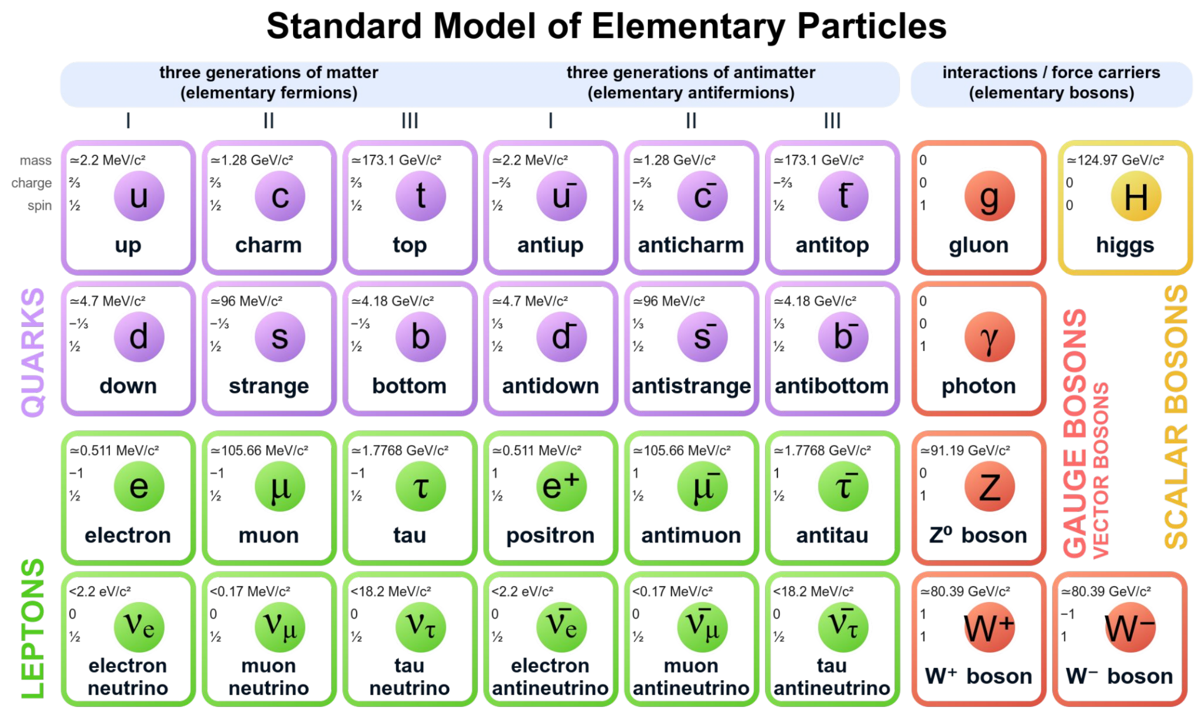


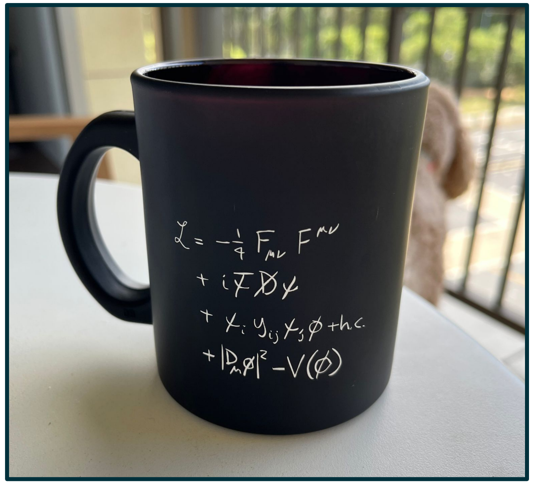
Part II

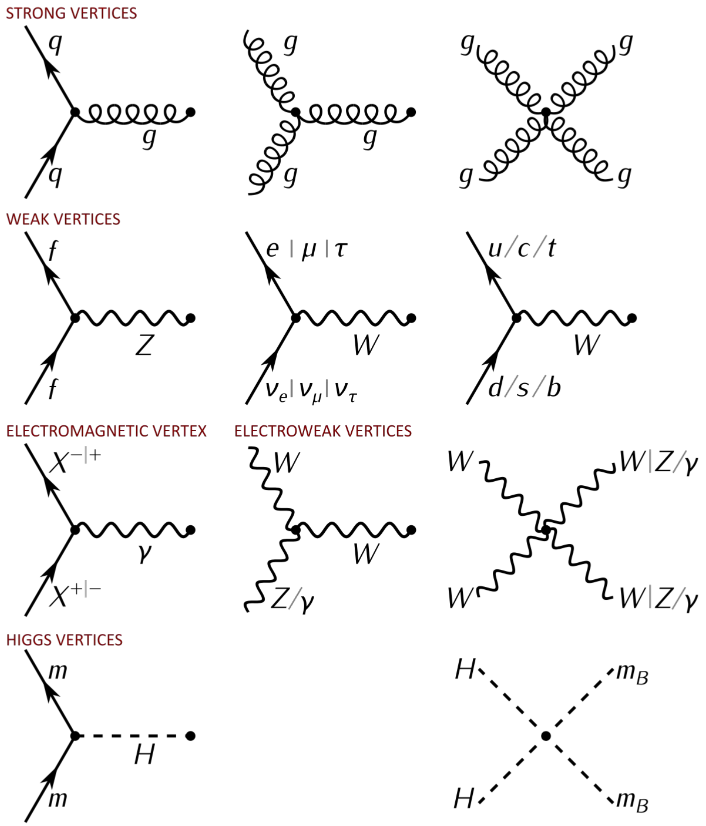
Elementary particle physics and neutrinos

The Standard Model of Particle Physics

- 3 ingredients: matter content, forces, rules (mathematical description)
- ***Quantum*** Field Theory (QFT) is the mathematical framework, ***symmetry*** is the guiding theoretical principle, ***observation*** grounds it in reality







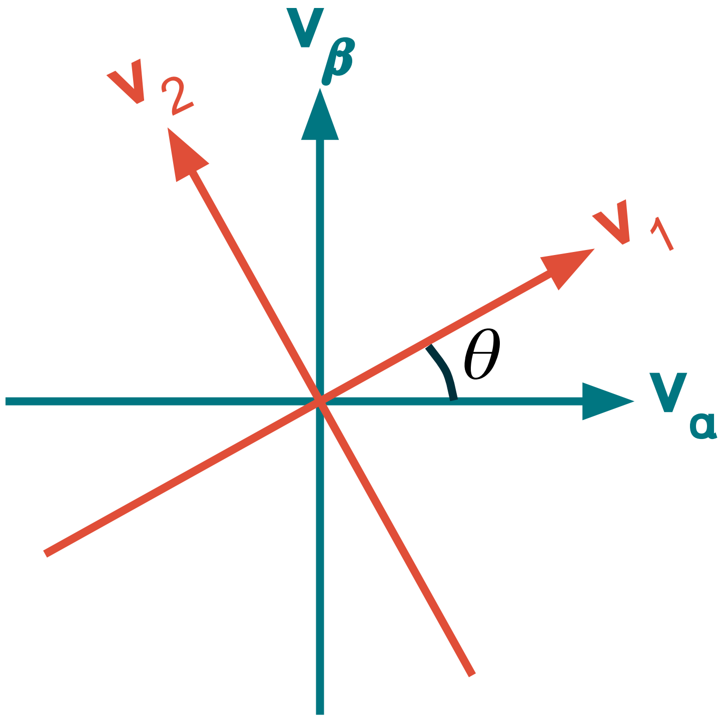
Neutrinos

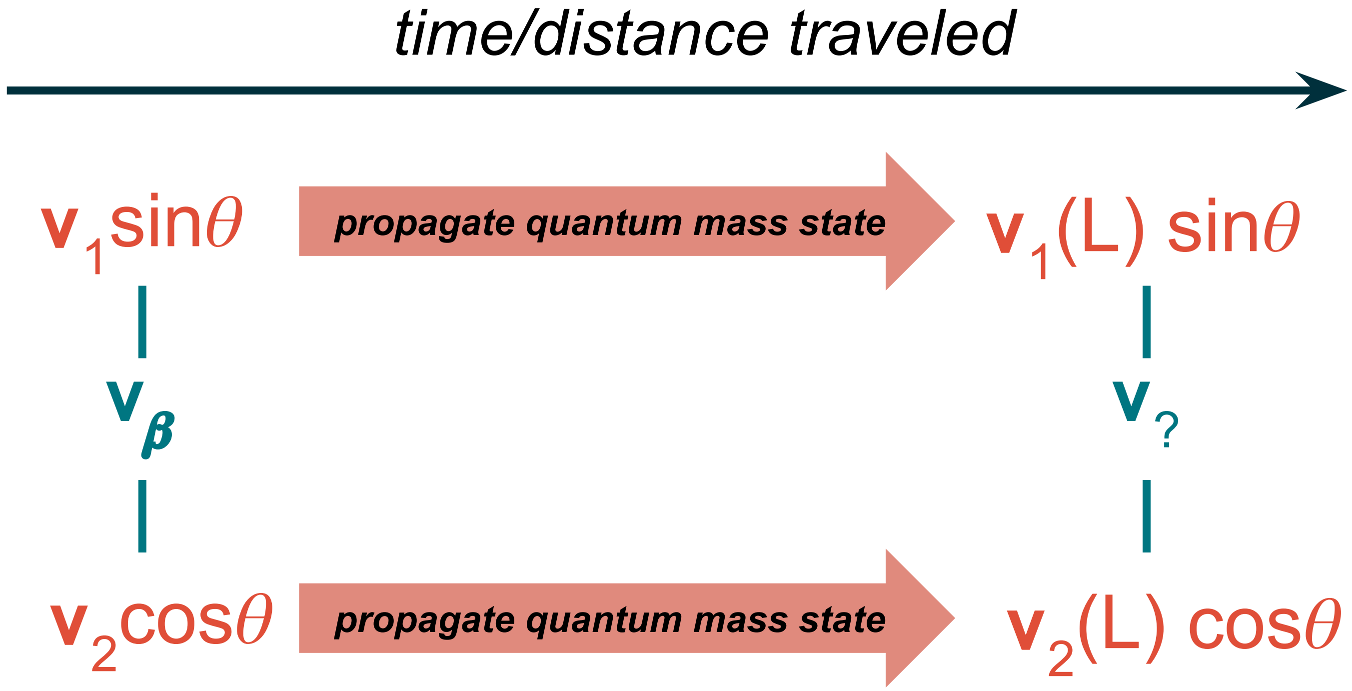
- “little neutral ones”
- Fundamental particles of the Standard Model
- 3 interaction states or *flavors*
- One set of matter states, one set of antimatter states

- Most abundant (Standard Model) matter particle in the universe!
- Much less massive than all of the other matter particles (fermions)
- Only feels the weak force
  - Not the electromagnetic nor strong forces

Neutrino Oscillations

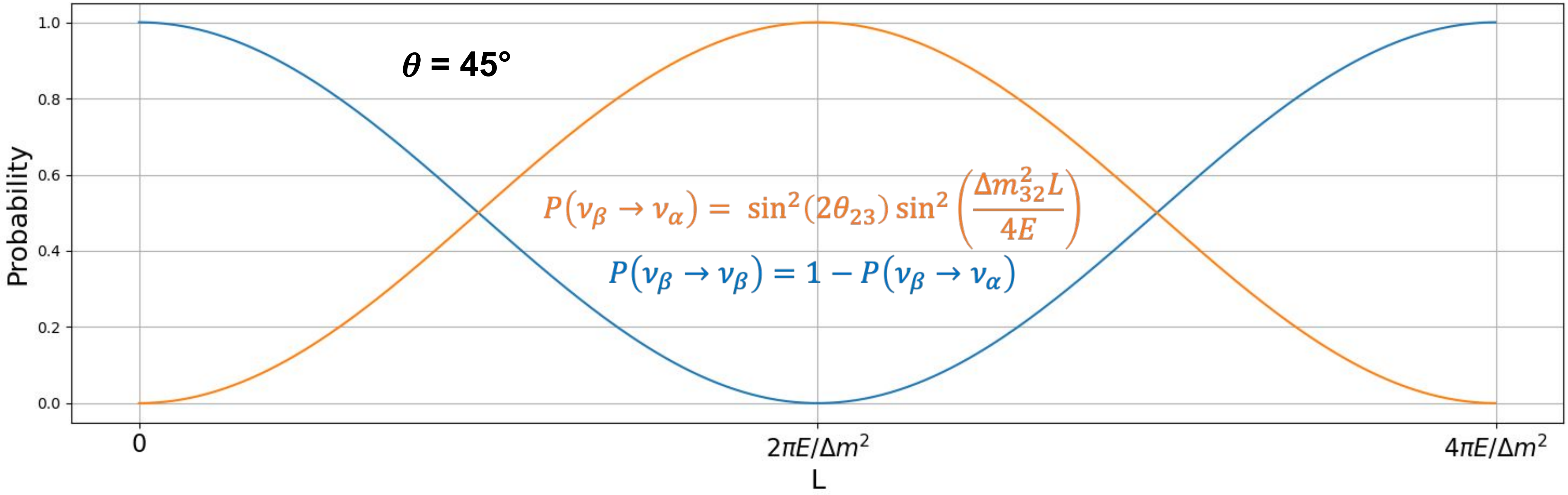
- A *quantum* effect that is observable over very large distances
- Neutrinos are produced and detected in interaction states, but these aren't necessarily the same ("mass") states that govern their evolution





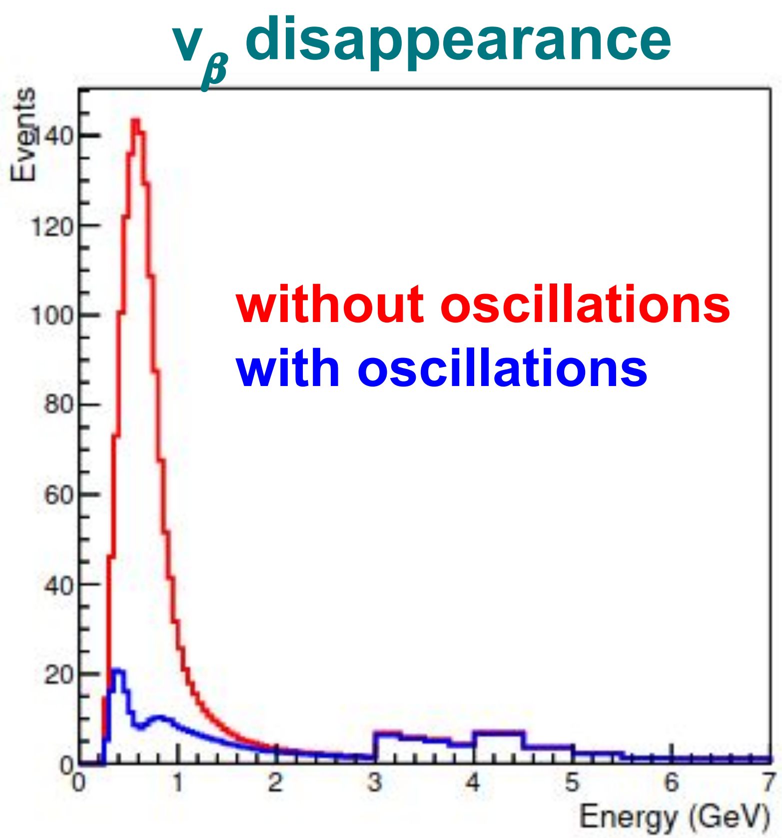
Neutrino Oscillations

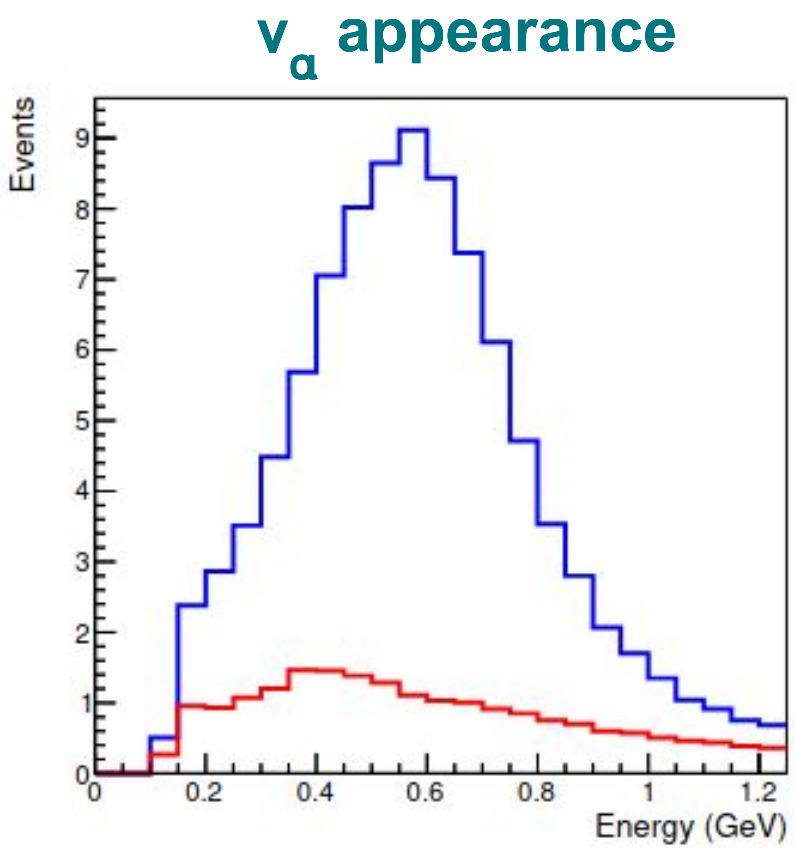
- A quantum effect observable over very large distances
- Neutrinos are produced and detected in interaction states, but these aren't necessarily the same ("mass") states that govern their evolution



Neutrino Oscillations

- A quantum effect observable over very large distances
- Neutrinos are produced and detected in interaction states, but these aren't necessarily the same ("mass") states that govern their evolution



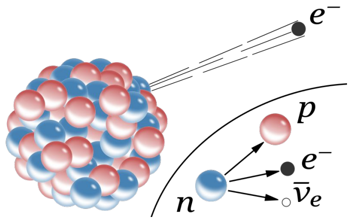


Part III

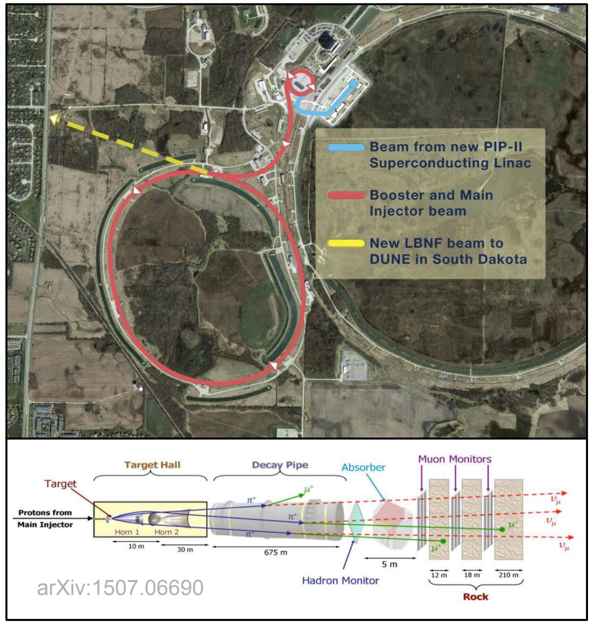
Measuring neutrino oscillations

Neutrino Sources

- Need weak* processes to create neutrinos *(as in the nuclear force)
- Bananas are neutrino sources… but not great ones for experiments.
  - Through beta decay

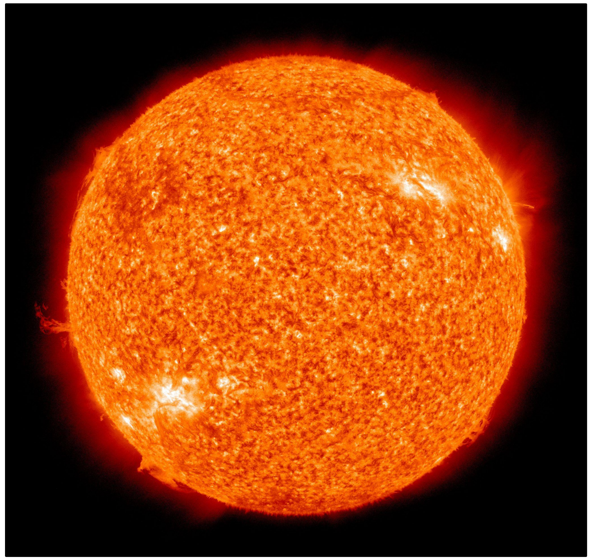


accelerator-based

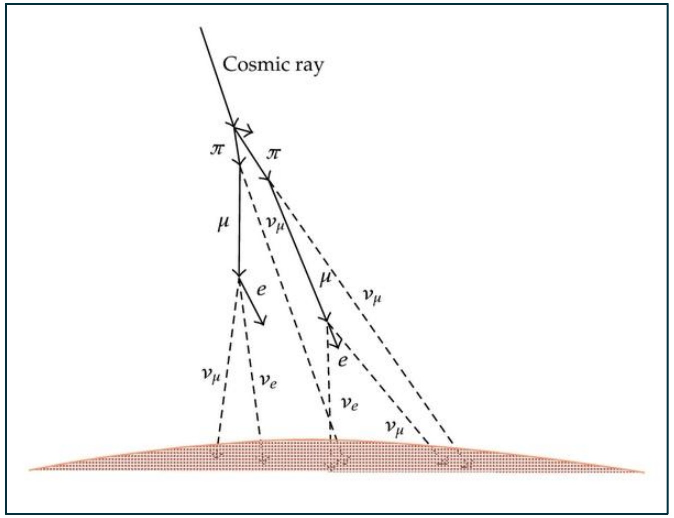


nuclear reactors

solar

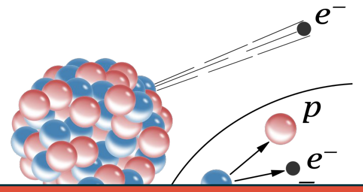


atmospheric



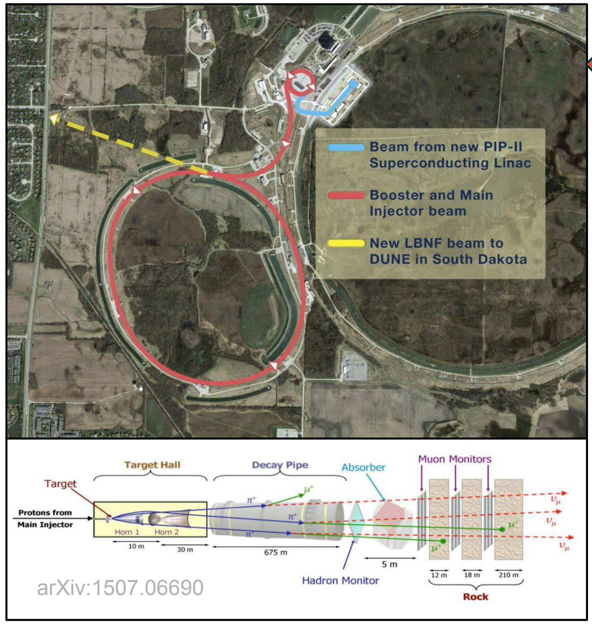
Neutrino Sources

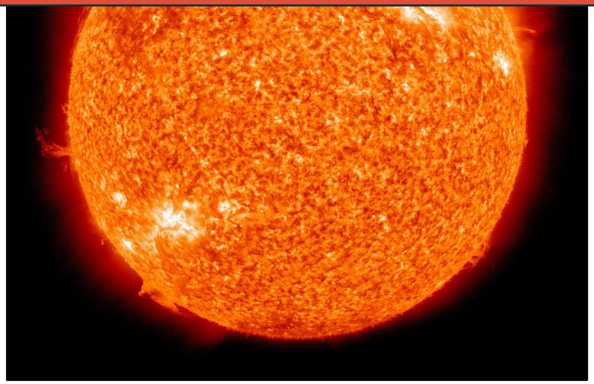
- Need weak* processes to create neutrinos *(as in the nuclear force)
- Bananas are neutrino sources… but not great ones for experiments.
  - Through beta decay

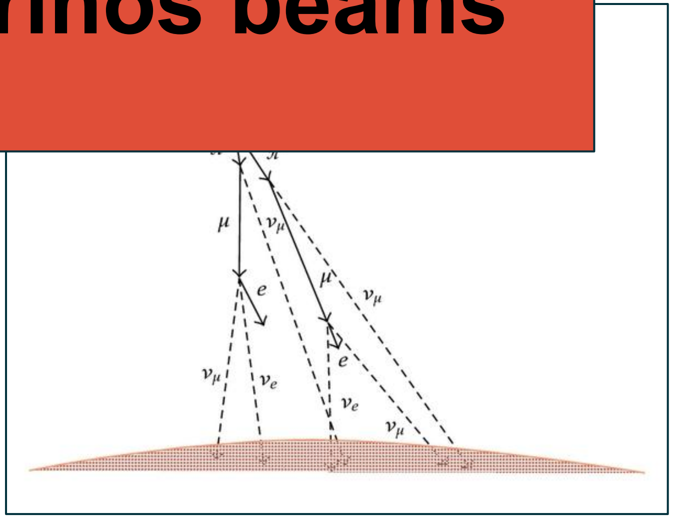


more on accelerator neutrinos beams

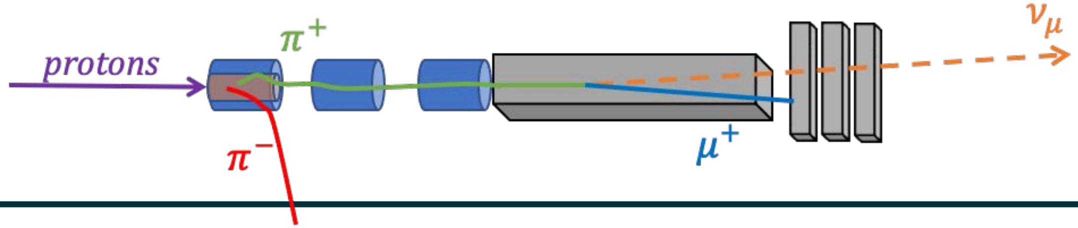
accelerator-based



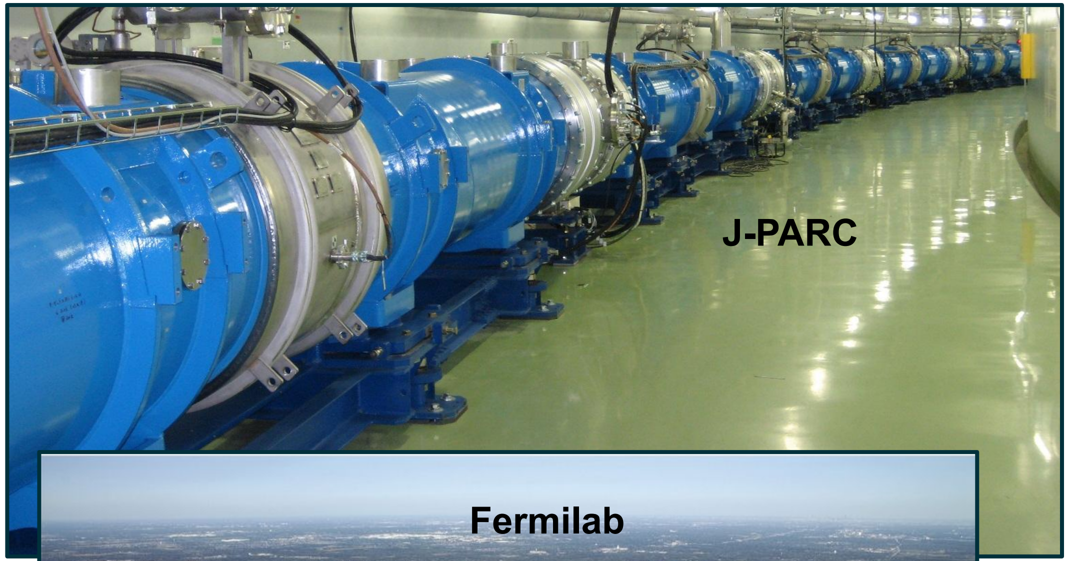


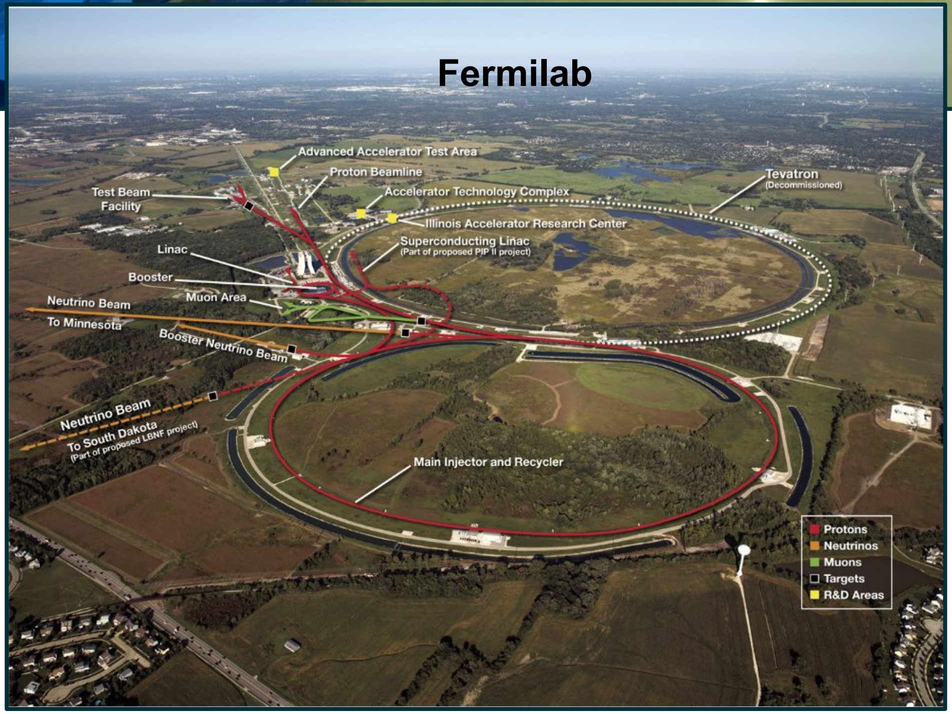


Accelerator Neutrinos

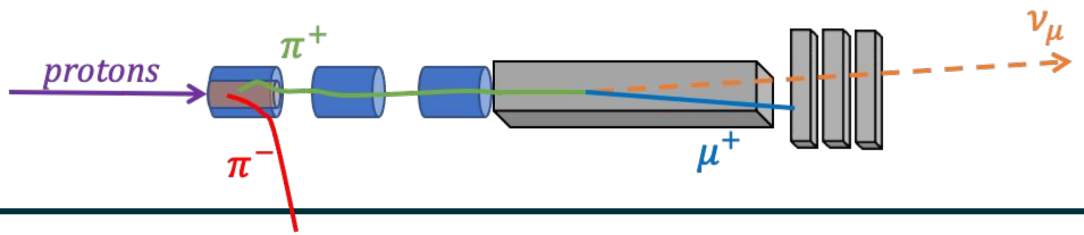


1) Accelerate protons up to energies of 10-100 GeV (>99.99% speed of light)
2) Collide those protons onto a stationary target, producing a spray of massive particles (predominantly pions)
3) Focus charged pions with magnetics before they decay in flight into lighter particles, including neutrinos
4) Non-neutrino content eventually gets absorbed, and a beam of neutrinos remains

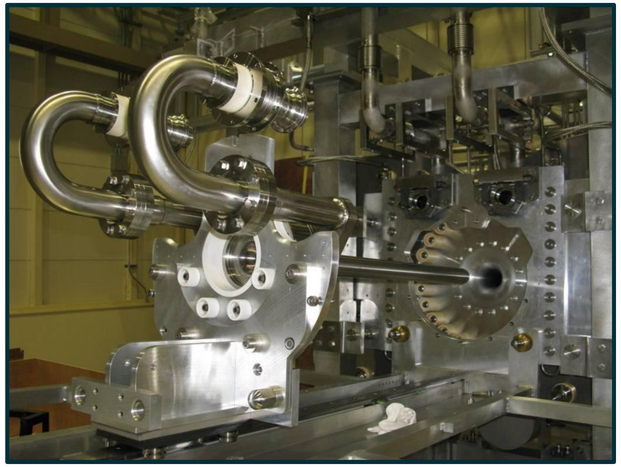


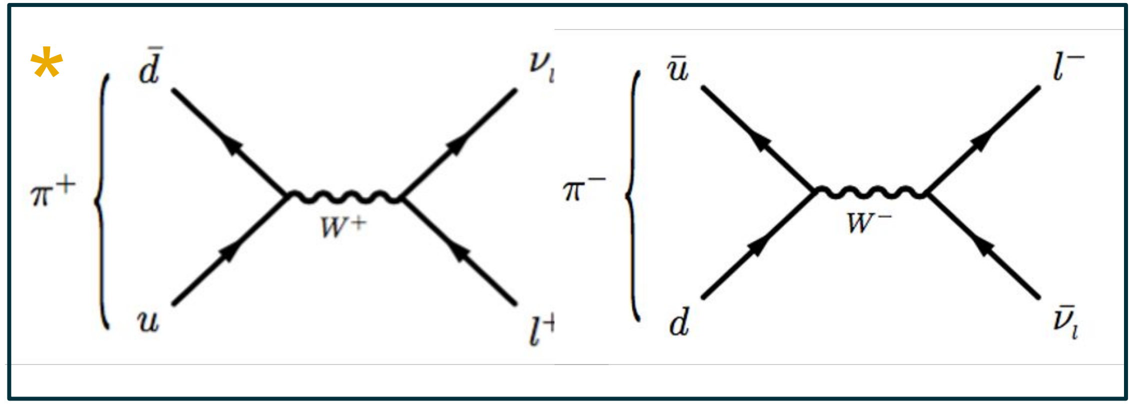


Accelerator Neutrinos

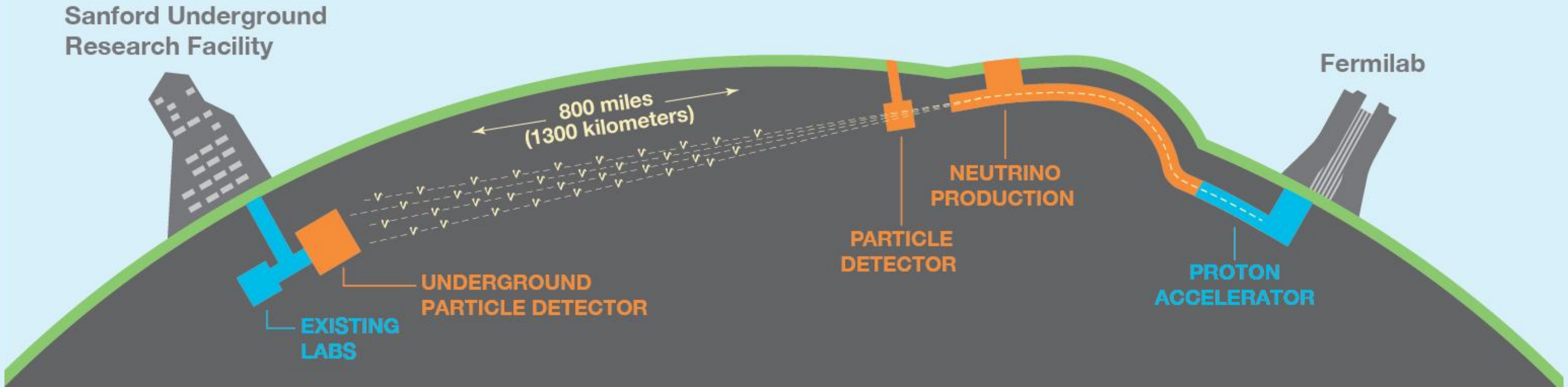


1) Accelerate protons up to energies of 10-100 GeV (>99.99% speed of light)
2) Collide those protons onto a stationary target, producing a spray of massive particles (predominantly pions)
3) Magnetics focus and sign select* pions before they decay in flight into lighter particles, including neutrinos
4) Non-neutrino content eventually gets absorbed, and a beam of neutrinos remains

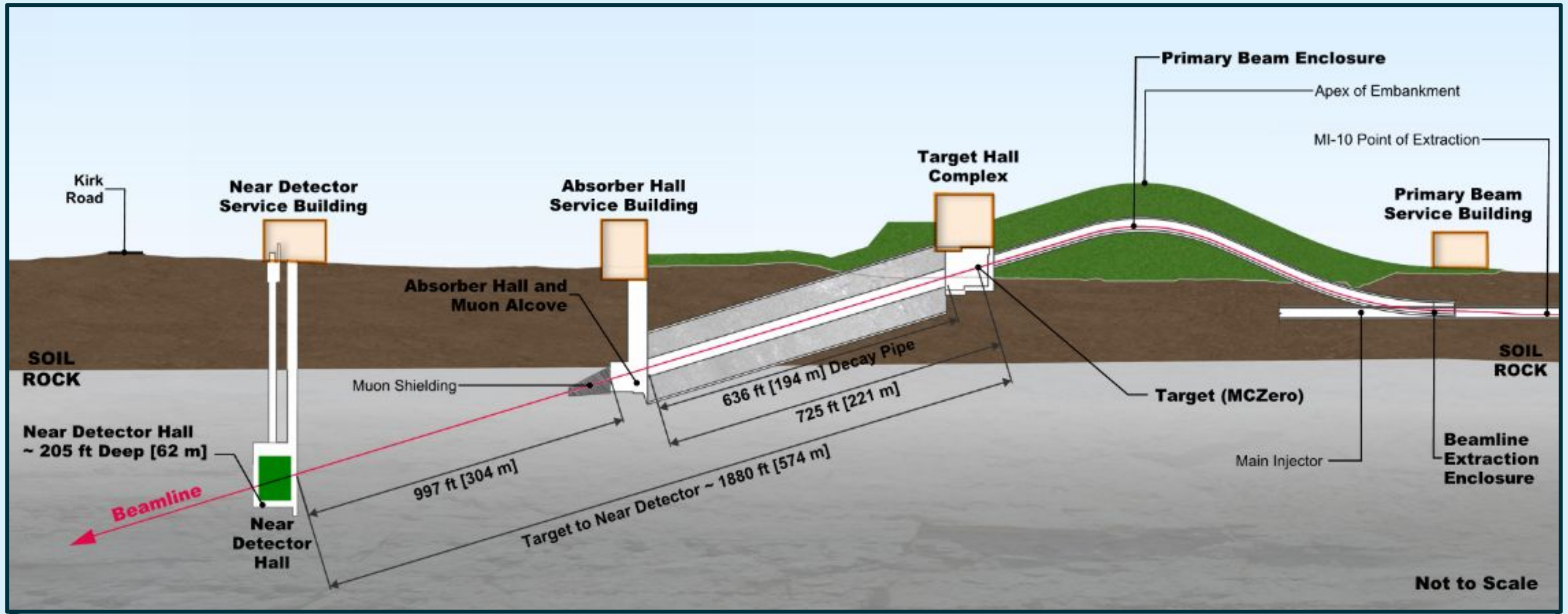


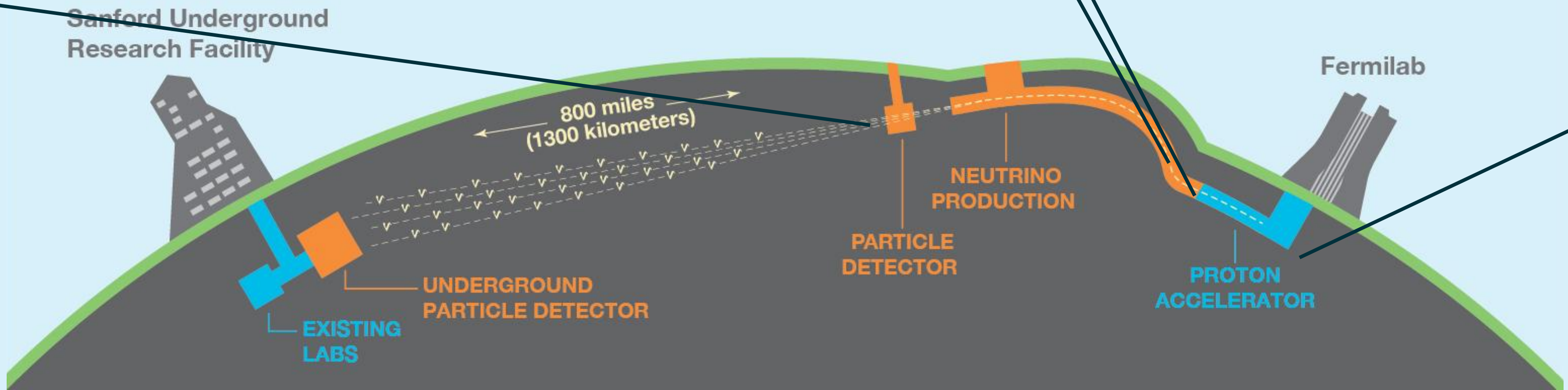


Neutrino Oscillations with DUNE

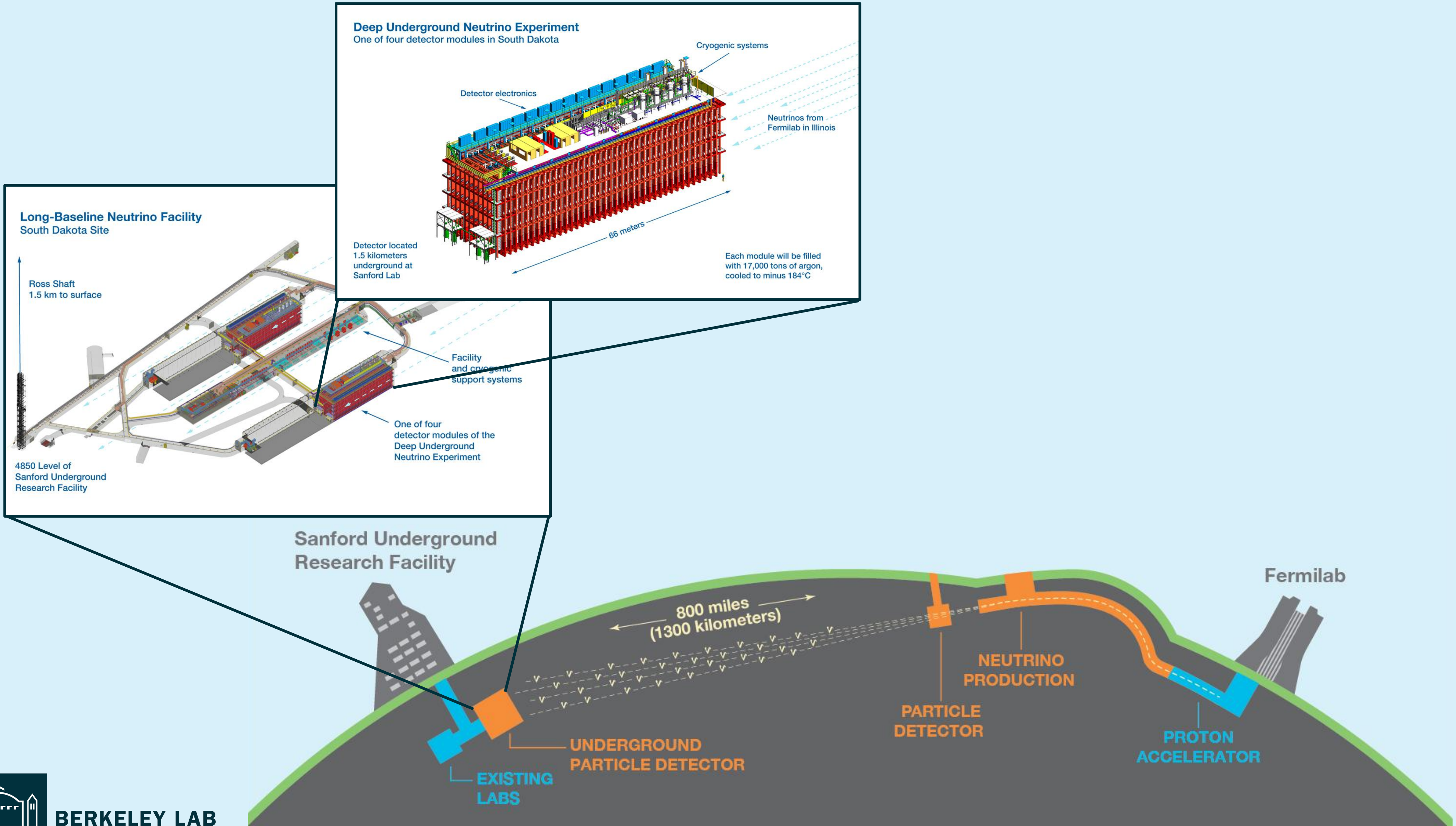


Neutrino Oscillations with DUNE

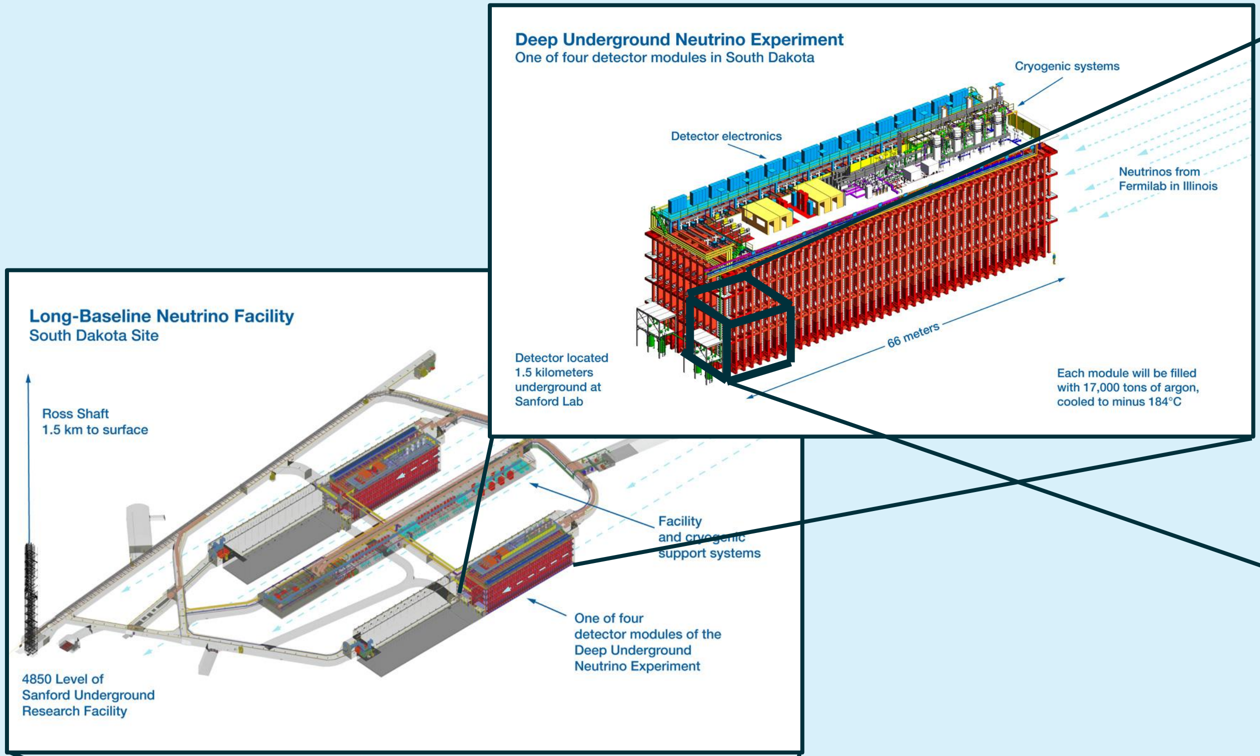


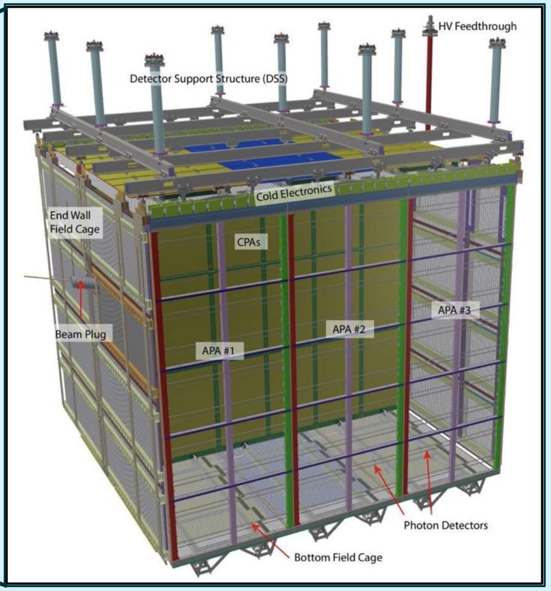


Neutrino Oscillations with DUNE

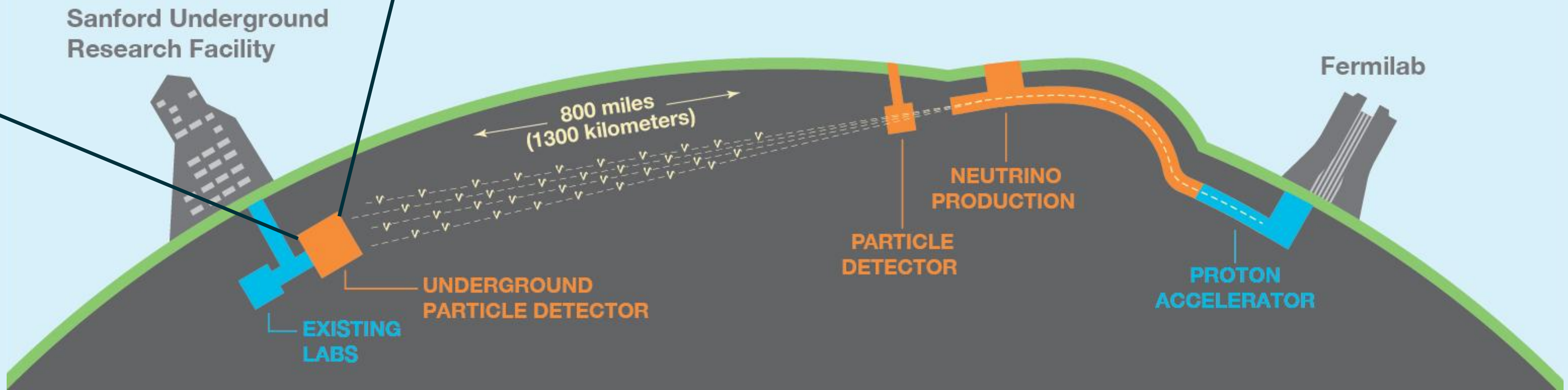


Neutrino Oscillations with DUNE



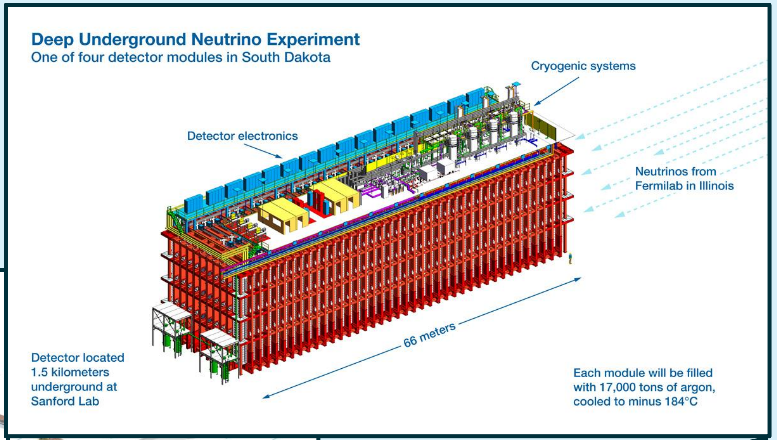


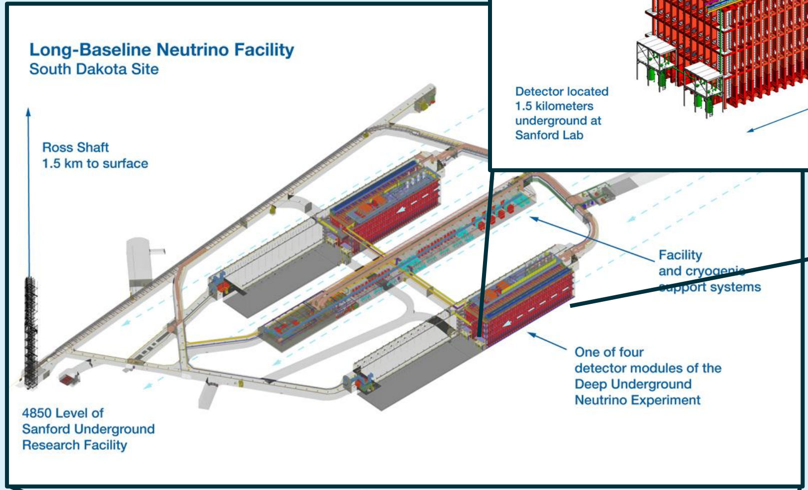
ProtoDUNE-SP

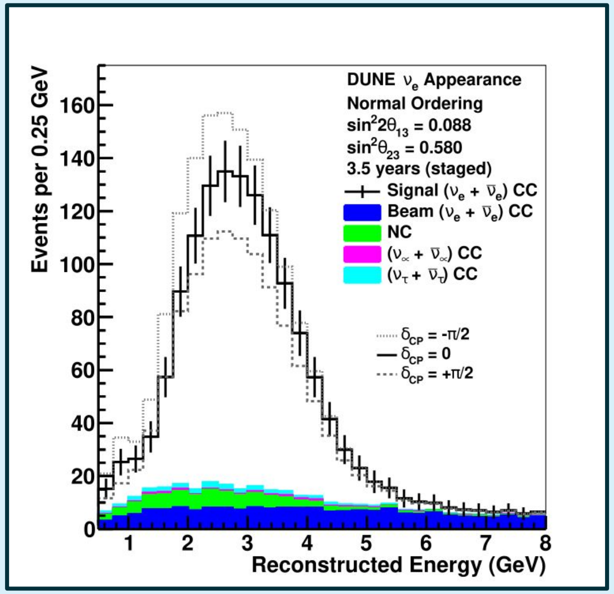


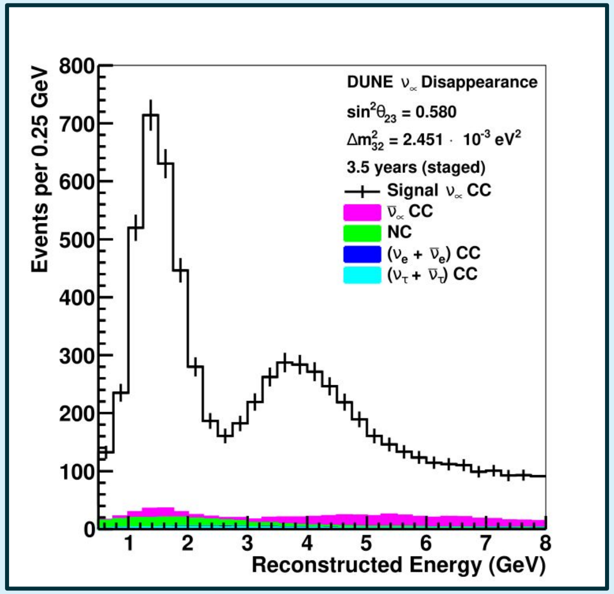
Neutrino Oscillations with DUNE

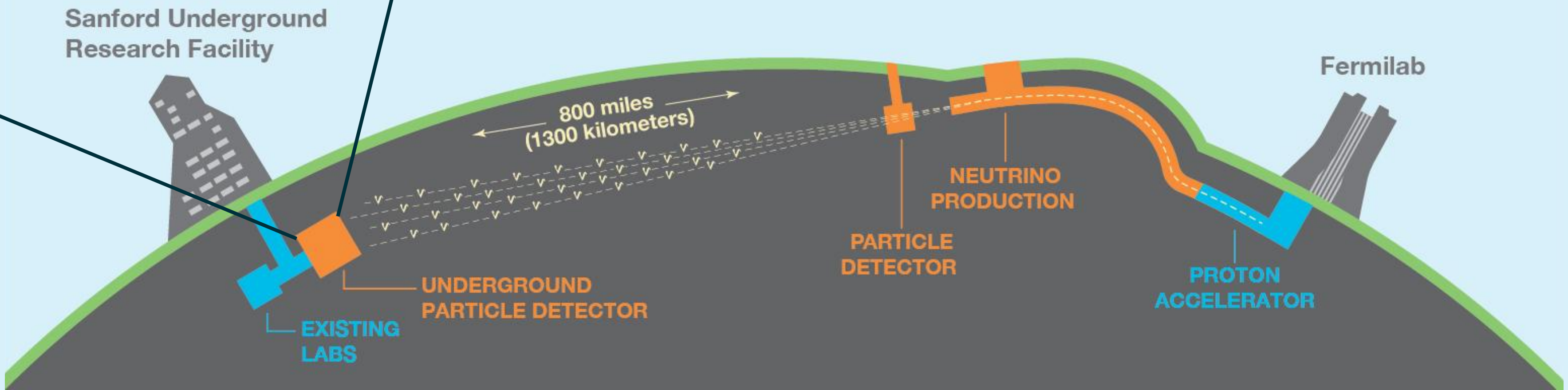
DEEP UNDERGROUND NEUTRINO EXPERIMENT



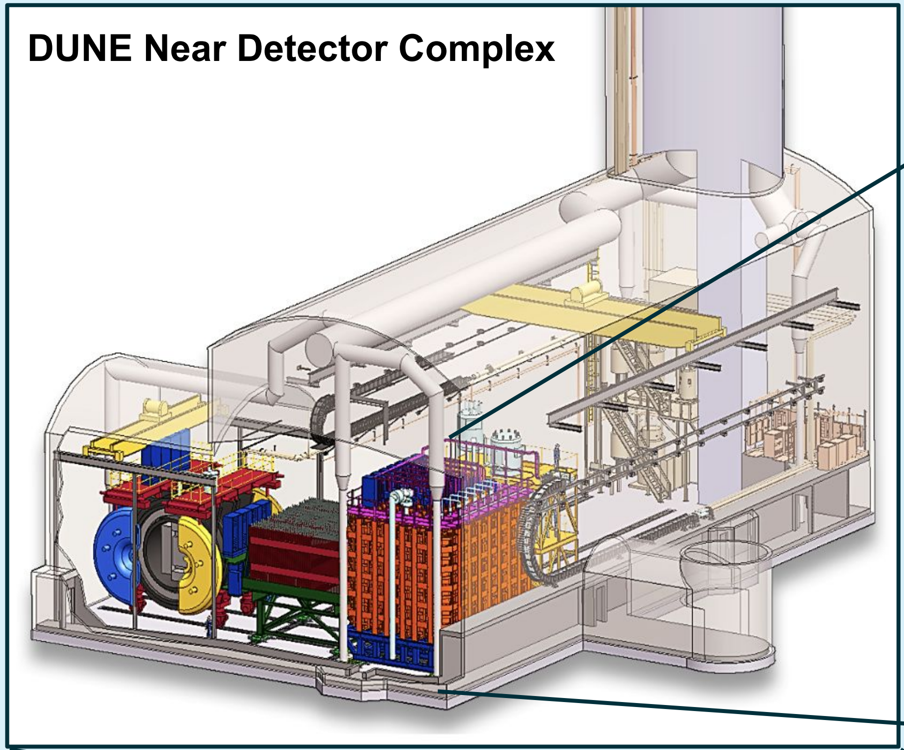


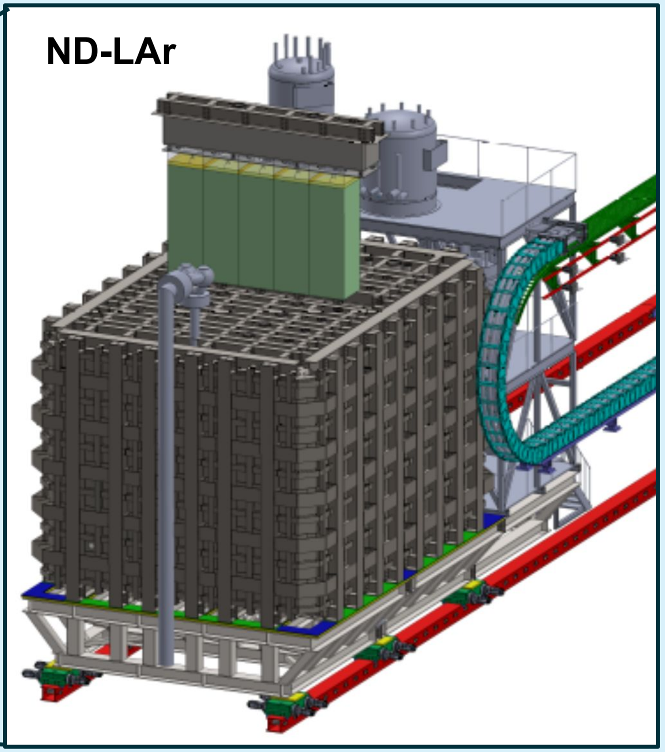


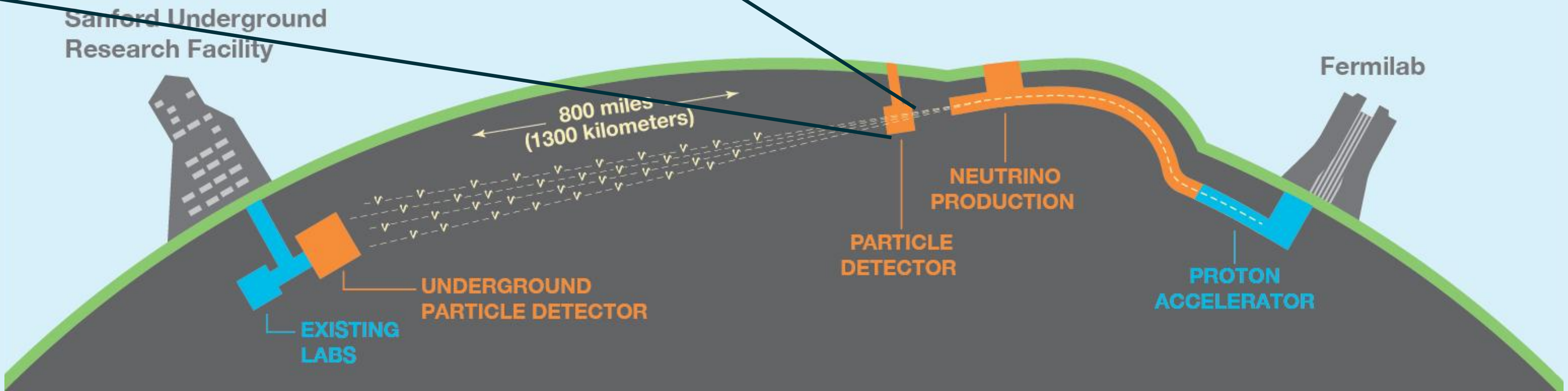




Neutrino Oscillations with DUNE







BERKELEY LAB

Concluding Remarks

- Science is interesting!
- Develop sophisticated technologies to address fundamental questions
- The types of experiments I described today will investigate whether neutrinos and antineutrinos oscillate differently
  - Remember the importance of symmetries!
  - There are hints, and if confirmed it would provide support for a theoretical mechanism that can explain an outstanding question: *Why does anything exist?*

Thanks!

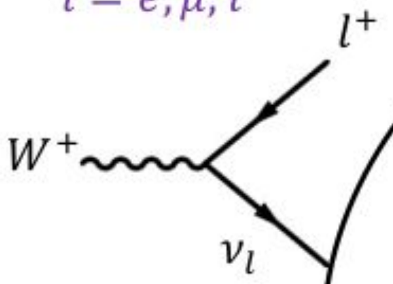
Backups

Neutrino Oscillations

produced in flavor eigenstates | *propagate in mass eigenstates* | *observed in flavor eigenstates*

flavor states

$l = e, \mu, \tau$



mass states

$i = 1, 2, 3$

$$|\alpha(0)\rangle = |\nu_l\rangle = \sum_i c_i |\nu_i\rangle$$

$$|\alpha(x)\rangle = \sum_i c_i |\nu_i\rangle e^{-ip_i \cdot x}$$

$$\Longrightarrow |\langle \nu_{l'} | \alpha(x) \rangle|^2 \neq \delta_{ll'}$$

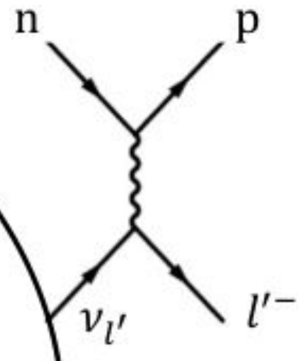
$s_{ij} \equiv \sin\theta_{ij}$

$c_{ij} \equiv \cos\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Majorana phases (no effect on oscillations)

U_{PMNS}



What do we (not) know?

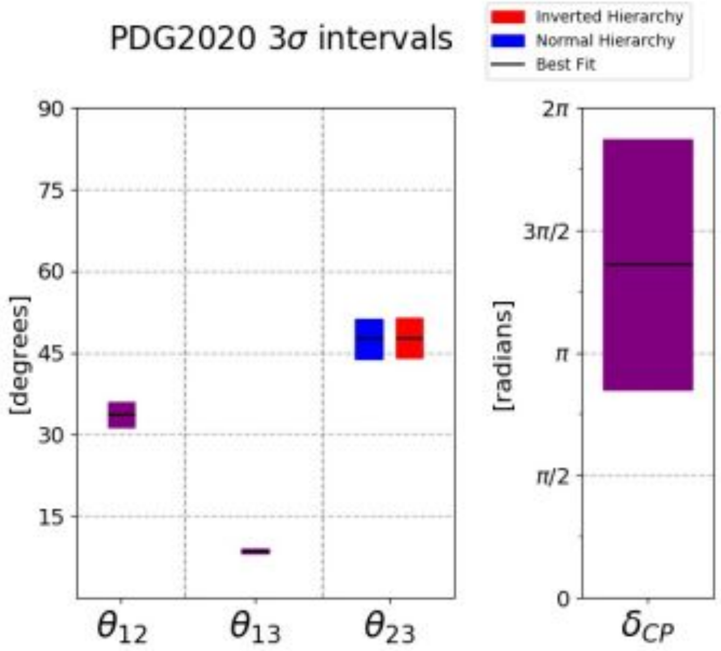
$$P_{osc}(\theta_{ij}, \Delta m^2_{ij}, \delta_{CP}, L/E)$$

mixing angles (3)

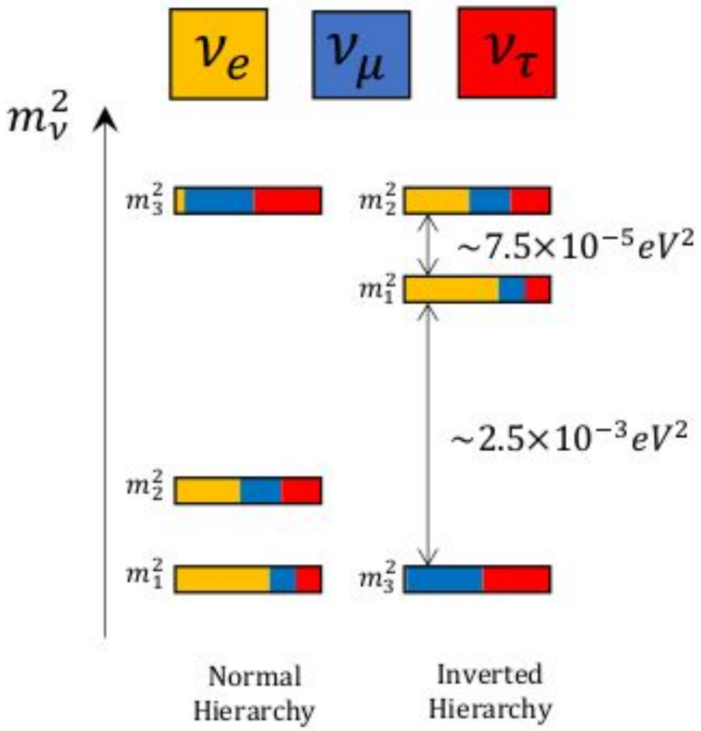
CP-violating phase

mass squared splittings (2)

Baseline (distance traveled by ν), Energy of neutrino



Δm^2's measured at few-% level



Neutrinos oscillate!

Octant of θ_{23}?

CP Violated?

Mass hierarchy?

Mass nature/origins

Oscillation Probabilities

3 Flavor Case

$a[\mathrm{eV}^2/c^4] = 7.56 \times 10^{-5} \rho[\mathrm{g/cm}^3] E_\nu [GeV]$

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

[For antineutrino oscillation probabilities: $\delta \to -\delta, a \to -a$]

$$P(\nu_\mu \to \nu_e) = 4c^2_{13}s^2_{13}s^2_{23}\sin^2\phi_{31}\left(1 + \frac{2a}{\Delta m^2_{31}}(1-2s^2_{13})\right)$$

$$+ 8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\phi_{23}\sin\phi_{31}\sin\phi_{21}$$

subleading, CP-odd

$$- 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\phi_{32}\sin\phi_{31}\sin\phi_{21}$$

$$+ 4s^2_{12}c^2_{12}(c^2_{12}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\phi_{21}$$

$$- 8c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})\frac{aL}{4E_\nu}\cos\phi_{32}\sin\phi_{31}$$

$$P(\nu_\mu \to \nu_\mu) = 1 - 4(s^2_{12}c^2_{23} + s^2_{13}s^2_{23}c^2_{12} + 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)s^2_{23}c^2_{13}\sin^2\phi_{31}$$

$$- 4(c^2_{12}c^2_{23} + s^2_{13}s^2_{23}s^2_{12} - 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)s^2_{23}c^2_{13}\sin^2\phi_{32}$$

$$- 4(s^2_{12}c^2_{23} + s^2_{13}s^2_{23}c^2_{12} + 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta)$$

$$\times (c^2_{12}c^2_{23} + s^2_{13}s^2_{23}s^2_{12} - 2s_{12}s_{13}s_{23}c_{12}c_{23}cos\delta)\sin^2\phi_{21}$$