DUNE
The Next Generation Neutrino Experiment

Alfons Weber

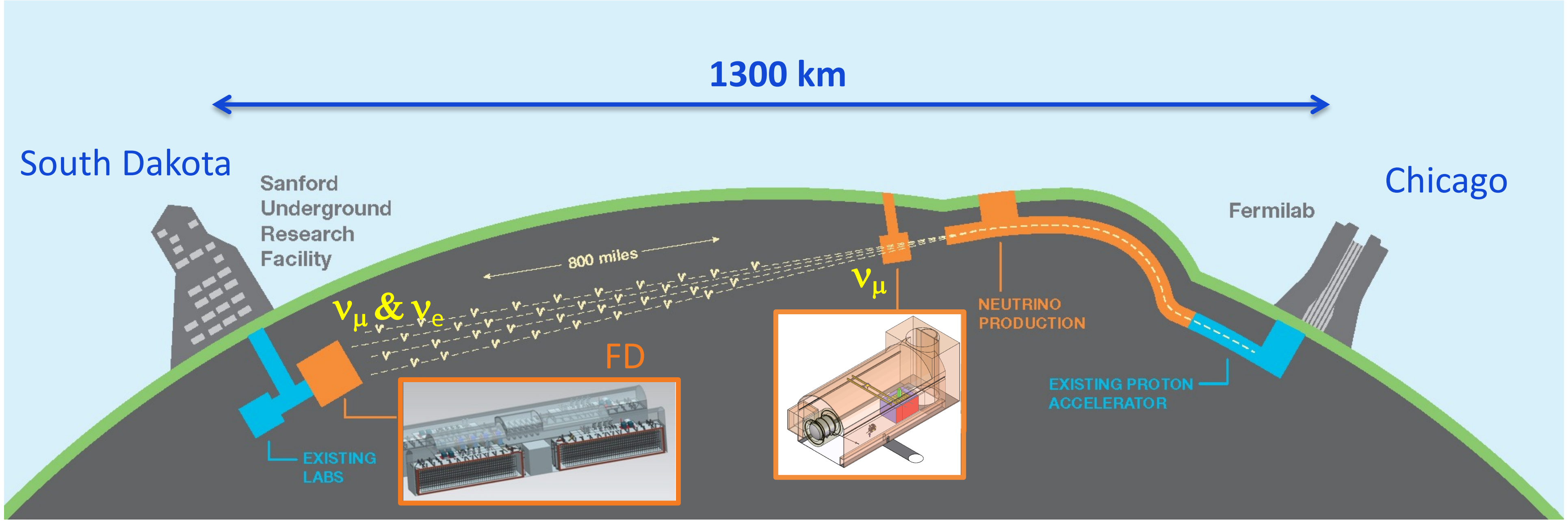
Physics at the Terascale

14th Annual Meeting of the Helmholtz Alliance
November 2021

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U
Fermilab

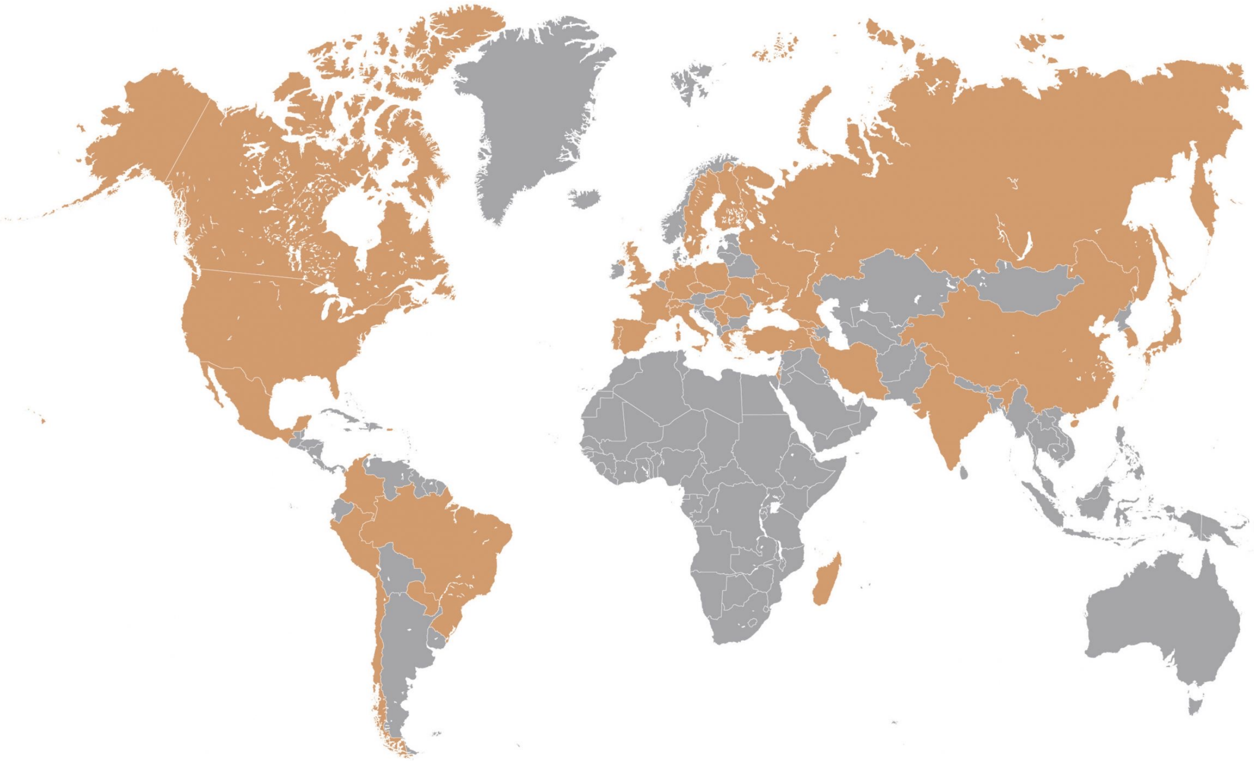
DUNE General Setup

- LBNF/DUNE will consist of
  - An intense ν-beam fired from Fermilab 1.2 MW upgradeable to 2.3 MW
  - Highly capable near detector complex
  - A >20 kt fiducial mass LAr TPC far detector underground at SURF
  - A cavern for a full 40 kt detector system

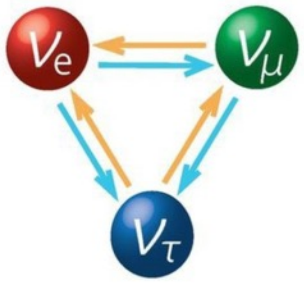


The DUNE Collaboration

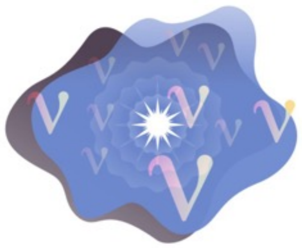
- International Collaboration
  - 1350 members
  - 200+ Institutions
  - 34 countries & CERN



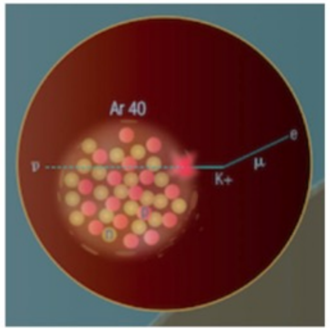
DUNE Physics Program



- Neutrino Oscillations
  - Search for leptonic CP violation
  - Determine neutrino mass ordering
  - Precision PMNS measurements

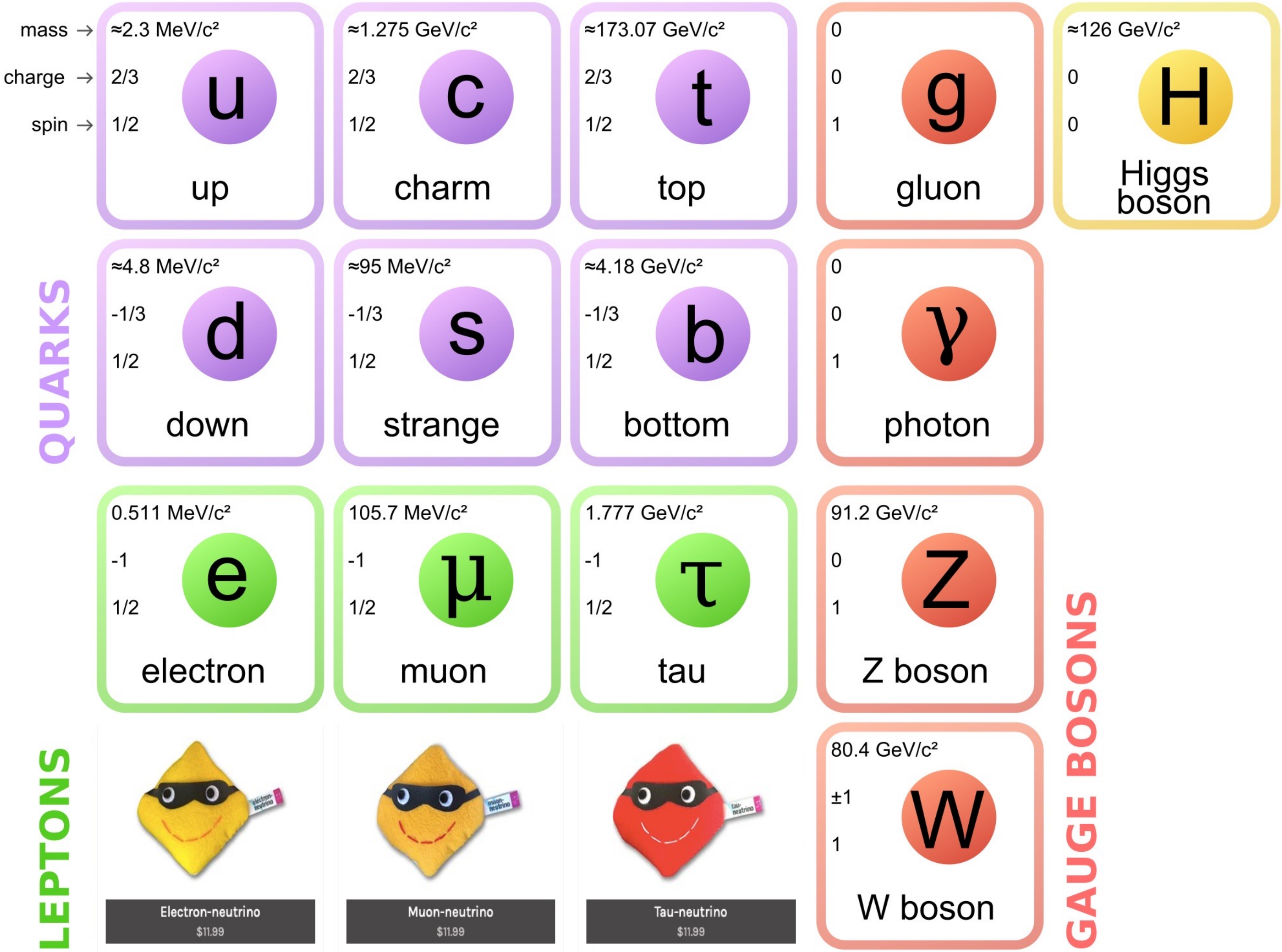


- Supernova Physics
  - Observation of time and flavour profile provides insight into collapse and evolution of supernova
  - Unique sensitivity to electron neutrinos



- Baryon number violation
  - Predicted by many BSM theories
  - LAr TPC technology well-suited to certain proton decay channels (*e.g.*, $p \rightarrow K+\nu$)
  - Δ(B-L) ≠ 0 channels accessible (*e.g.*, $n \rightarrow \bar{n}$)

Neutrinos



https://www.particlezoo.net/

Neutrino-Mixing: The PMNS Matrix

- Neutrinos have mass (BSM)
  - mass eigenstates ≠ weak interaction eigenstates
  - Analogue to CKM-Matrix in quark sector!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

weak
"flavour eigenstates"

Mass eigenstates
m_1, m_2, m_3

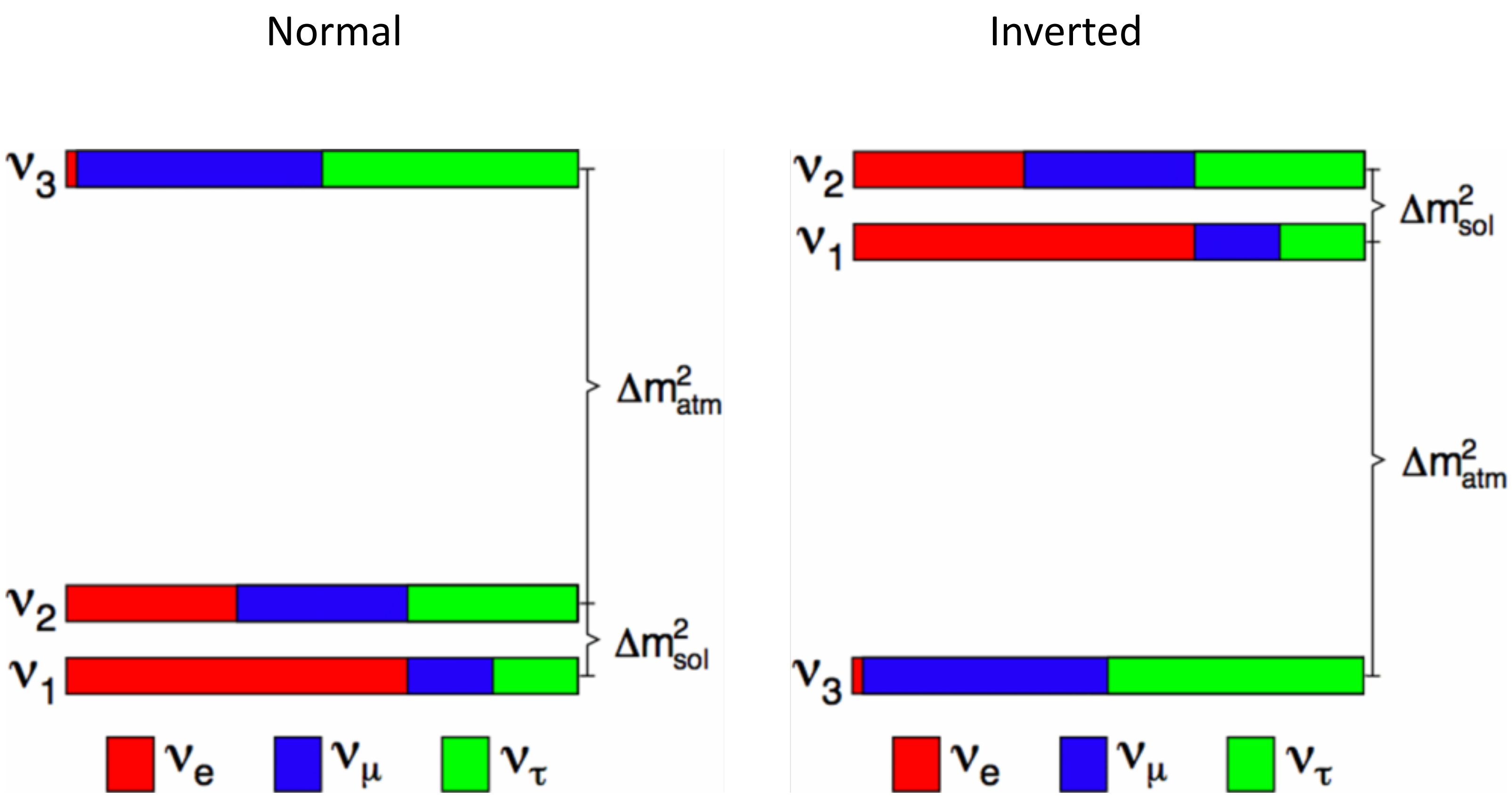
Unitary mixing matrix:
3 mixing angles
& complex phases

Pontecorvo-Maki-
Nakagawa-Sakata

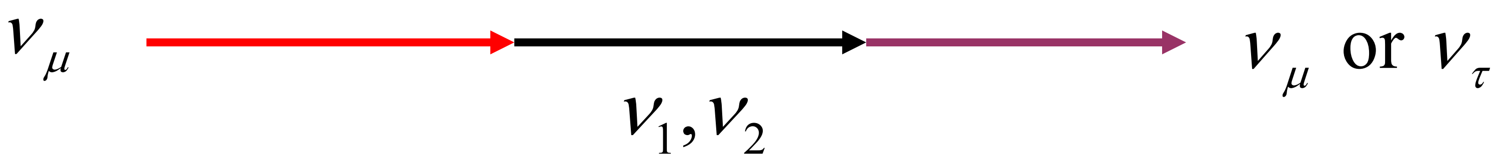
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle and Δm_{ij}^2 = mass^2 difference

Mass Ordering (~~Hierarchy~~)

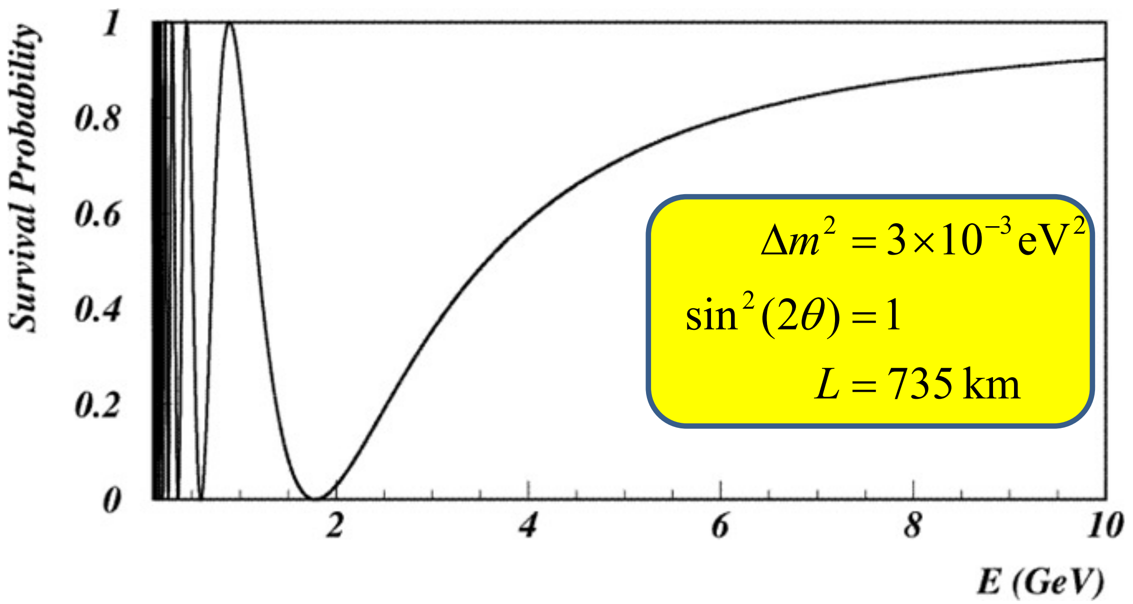


Neutrino Oscillations for Dummies



$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

- Measure prob.
  - Survival
  - Appearance
- Result
  - Mixing angle
  - Mass differences



Matter Effects

- Simplified treatment: two neutrinos only
- In vacuum

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

in matter

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_m)\sin^2\left(\frac{\Delta m_m^2 L}{4E}\right)$$

$$\text{with } \sin(2\theta_m) = \frac{\sin(2\theta)}{\sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}}$$

$$\Delta m_m^2 = \Delta m^2 \sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}$$

$$A = \pm \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

- Matter modifies oscillation probability
  - Sign of mass difference matters (opposite for anti-ν)
  - Larger effect at higher energies

The Fully Monty

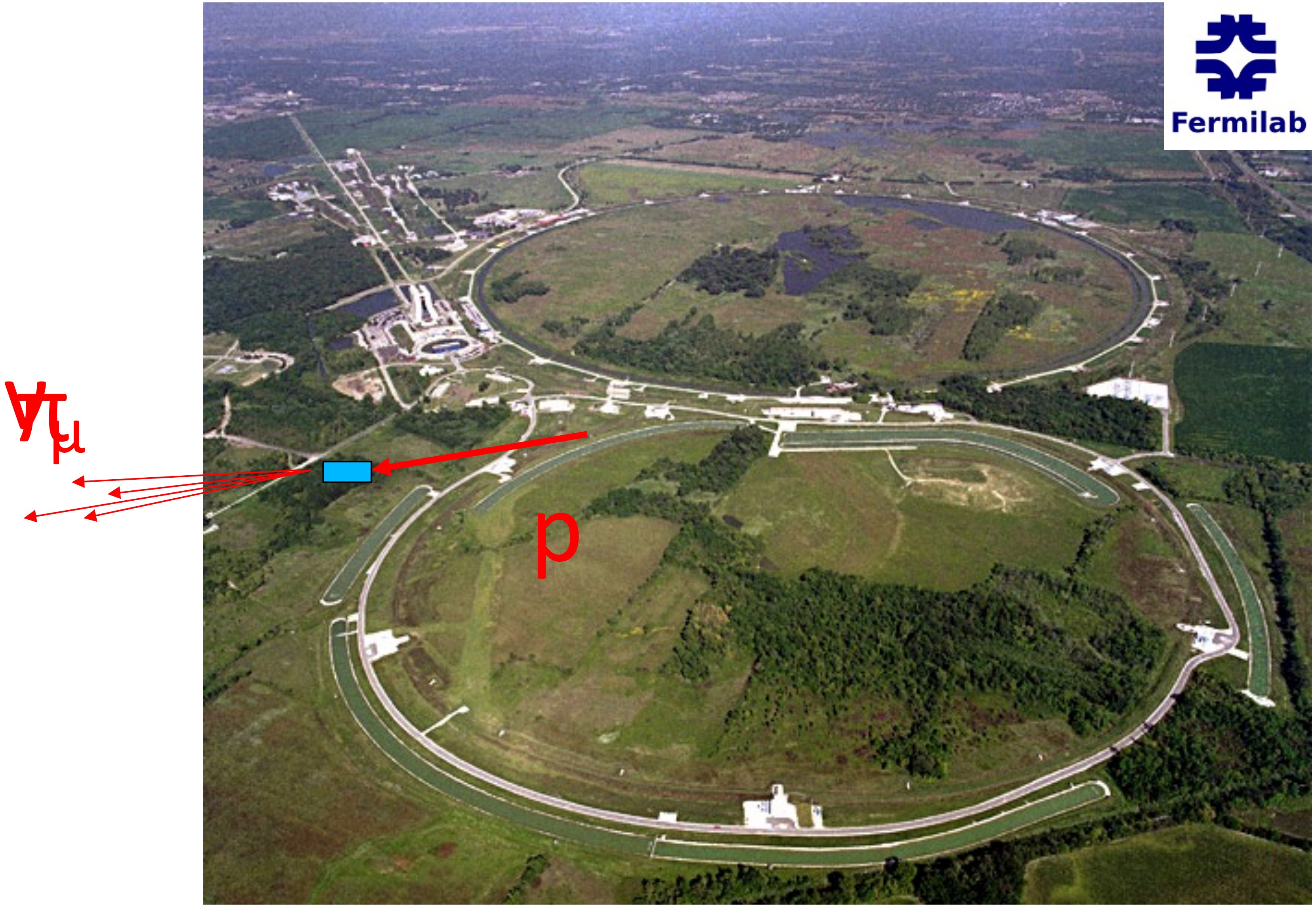
- Life isn't that easy
  - 3 Flavour oscillations & Matter effects

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- The full formula

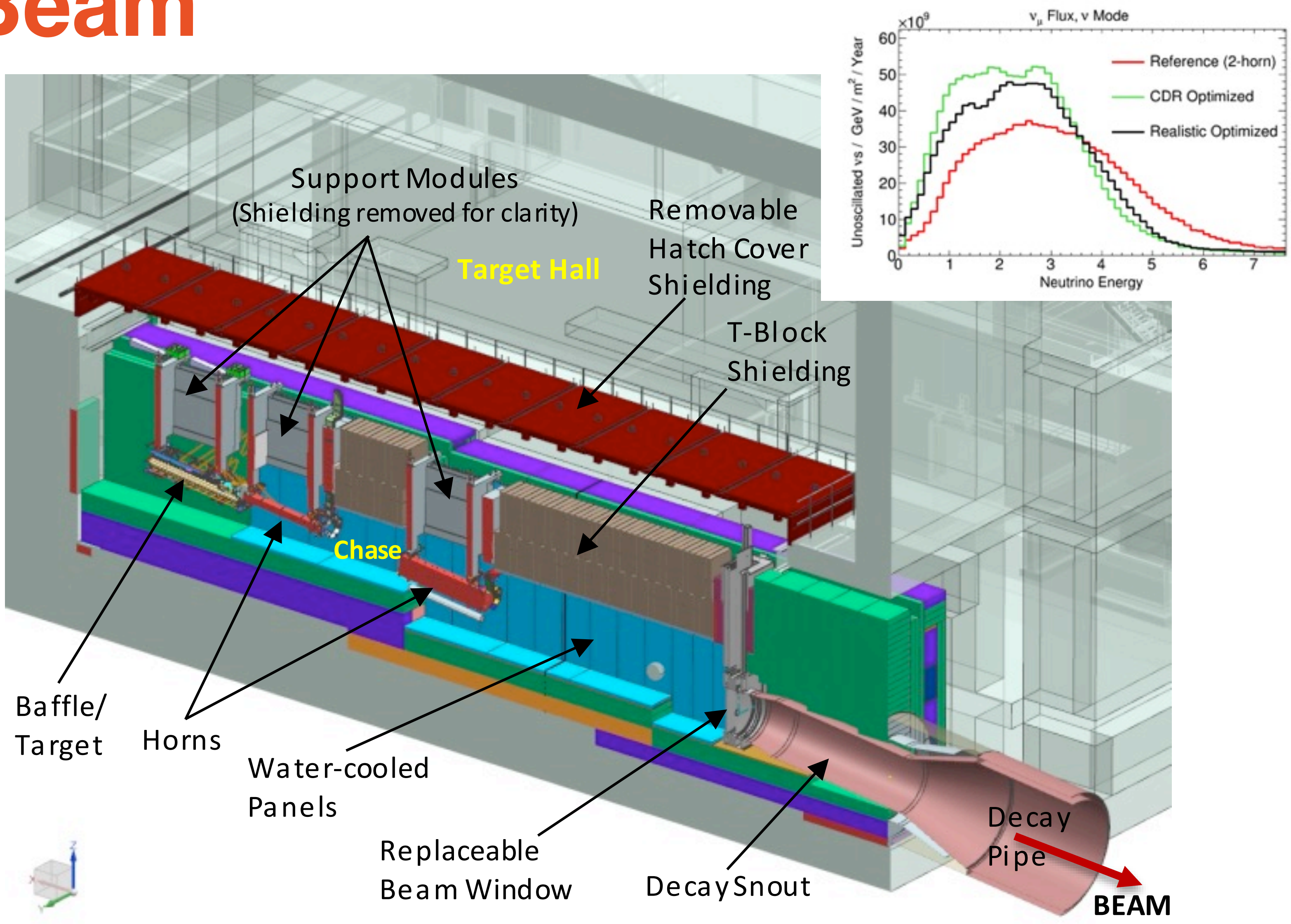
$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \quad (1 - 2S_{13}^2)\right)$$
$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$
$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{AL}{4E} (1 - 2S_{13}^2)$$

Making Accelerator Neutrinos

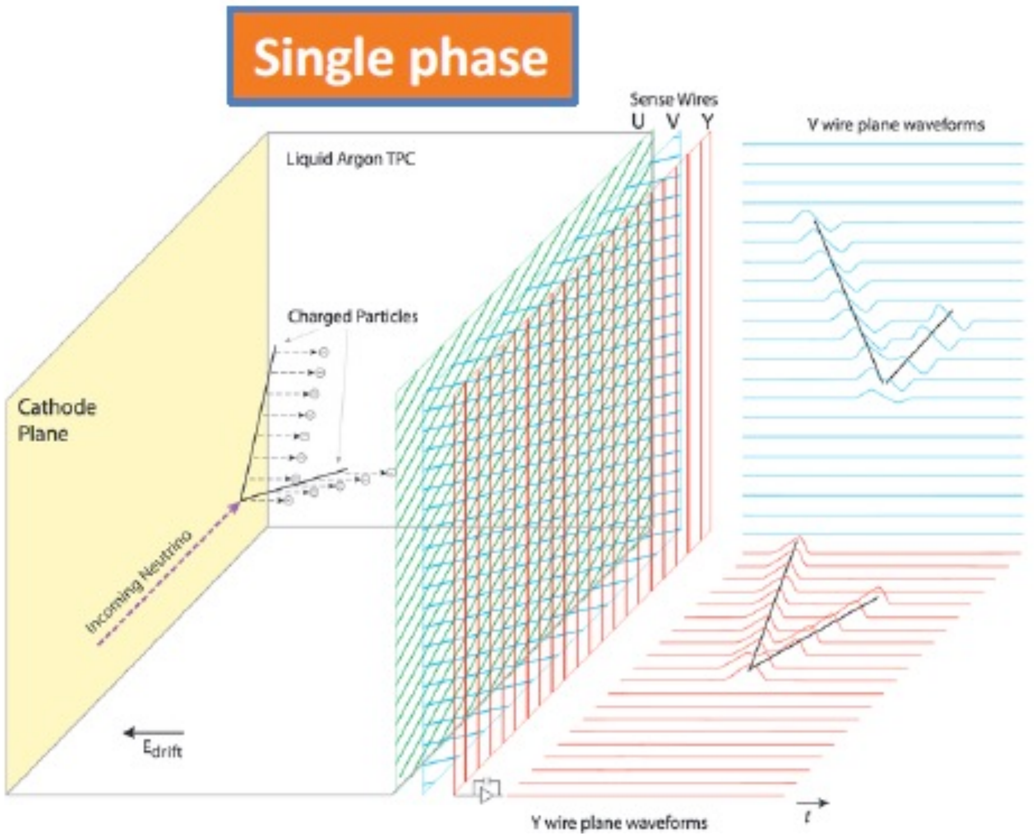


LBNF Neutrino Beam

- Design
  - optimised for CP sensitivity
  - Facility for 2.4 MW proton beam
- Carbon target
  - For Pion production
  - Can withstand 1.2 MW
- 3 Magnetic horns
  - Select pions of right polarity and energy
- Decay Pipe
  - 200 m
- Hadron Absorber



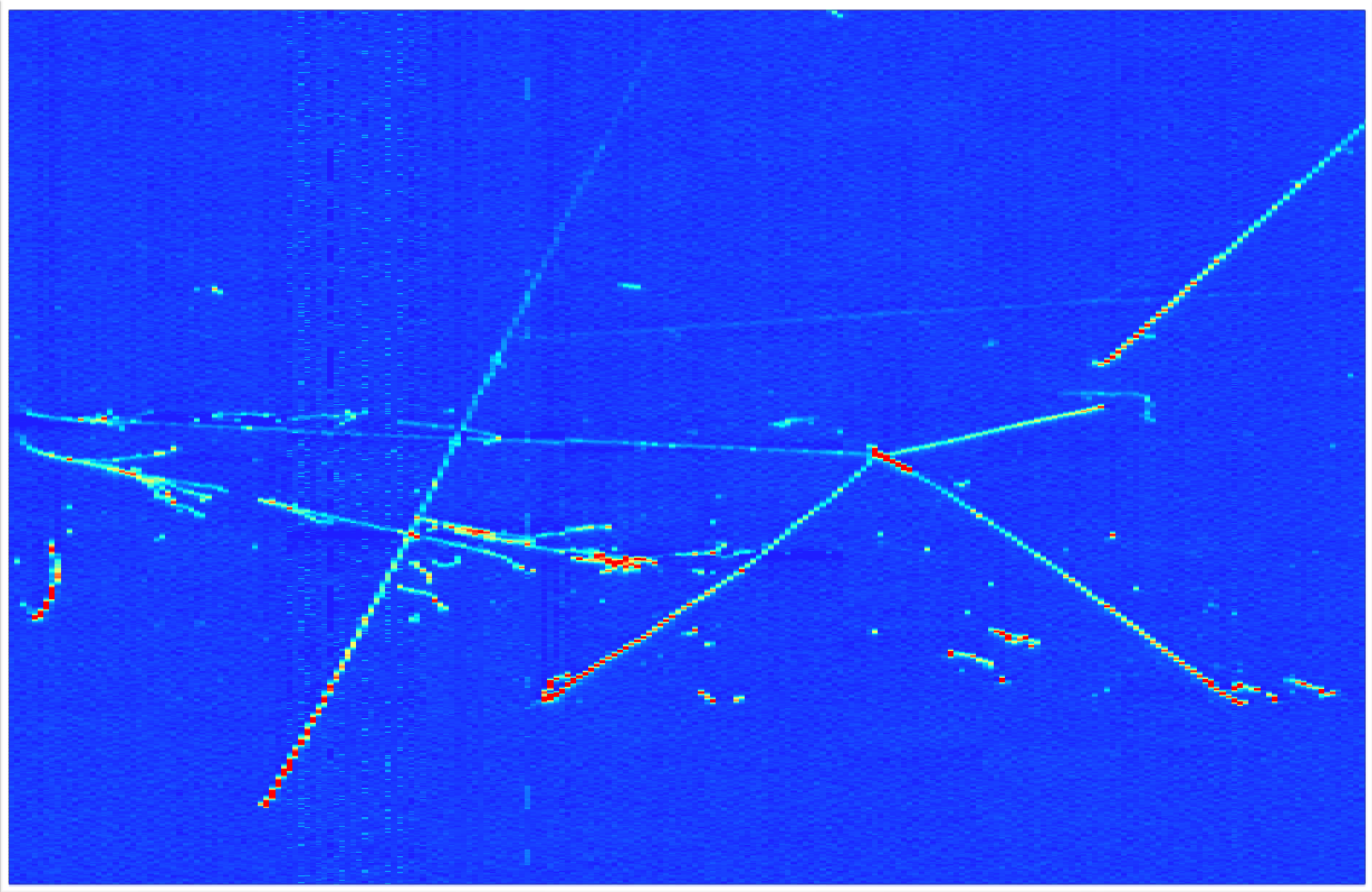
Far Detector (LArTPC)



Why Liquid Argon ?

- **Dense**:
  40% denser than water
- **Cheap**:
  abundant (1% of atmos.)
- **Ionizes easily**:
  55,000 electrons/cm
- **Excellent scintillation**:
  20,000 photons/MeV
  (@ 500 V/cm)

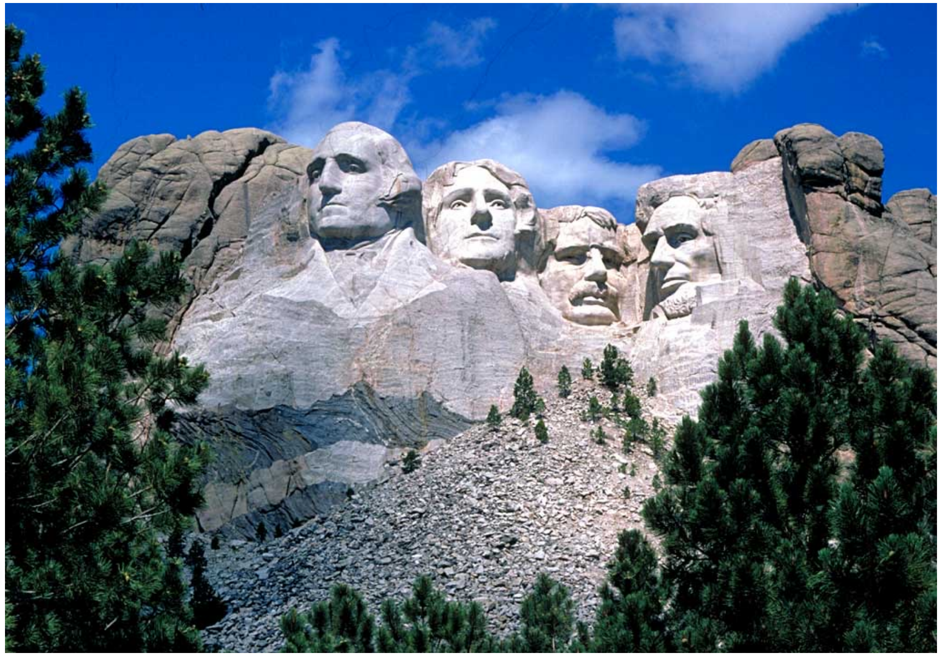
Unmatched Imaging Details

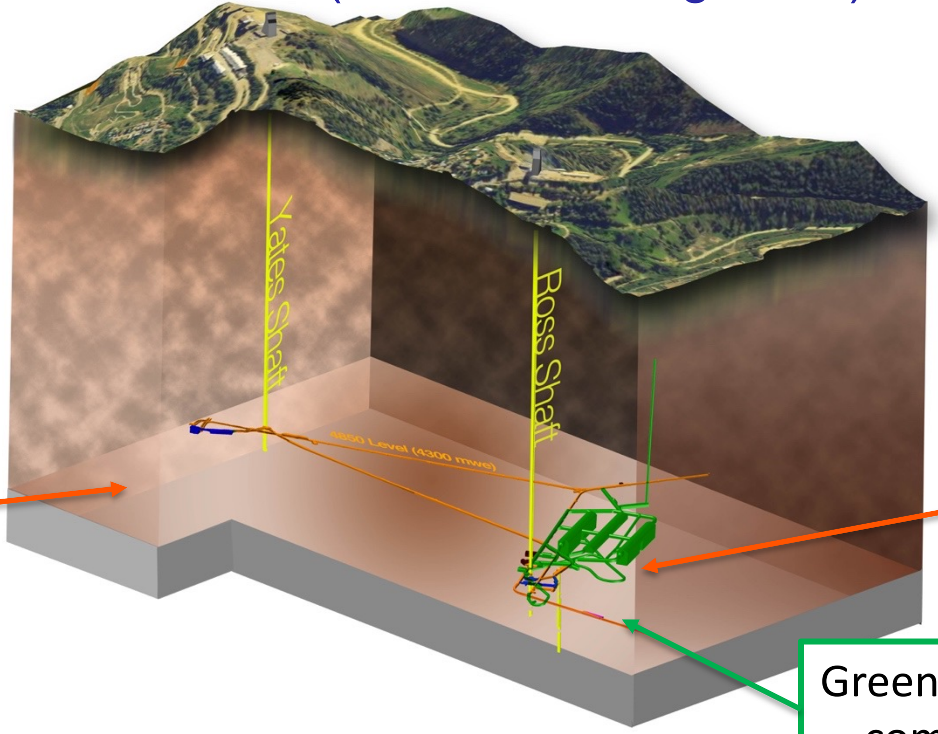


Underground Laboratory SURF

DUNE Far Detector site

- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~ 1 mile underground)





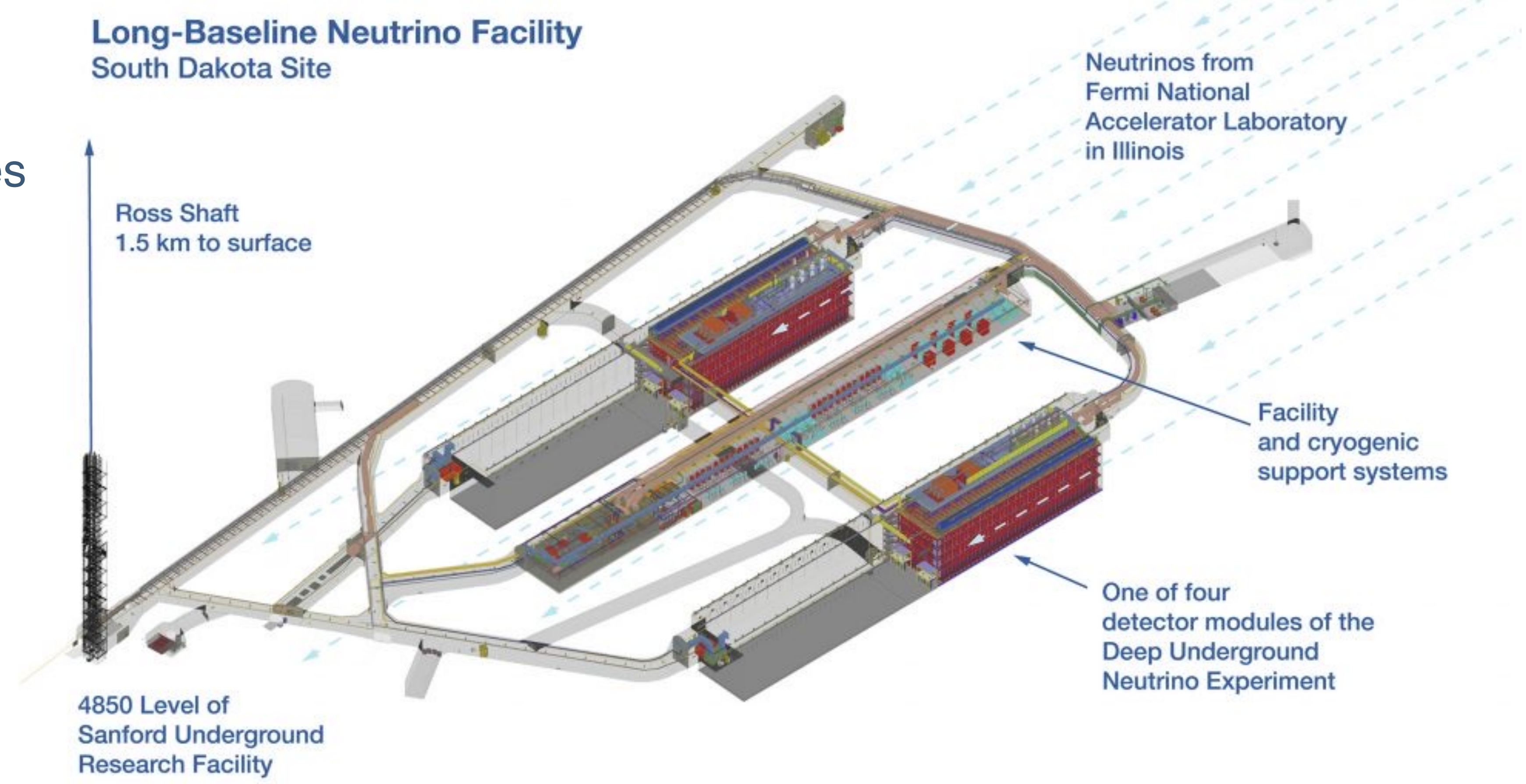
Davis Campus:
- LUX
- Majorana
- …
- **LZ**

Ross Campus:
- CASPAR
- …
- **DUNE**

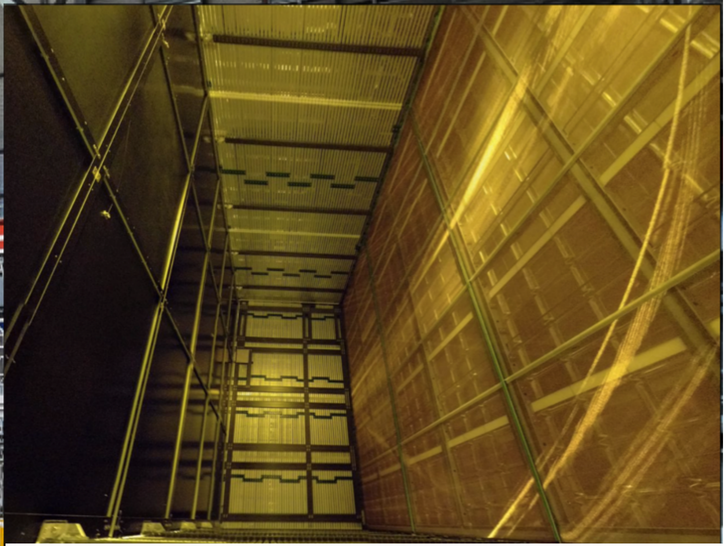
Green = new excavation commenced in 2017

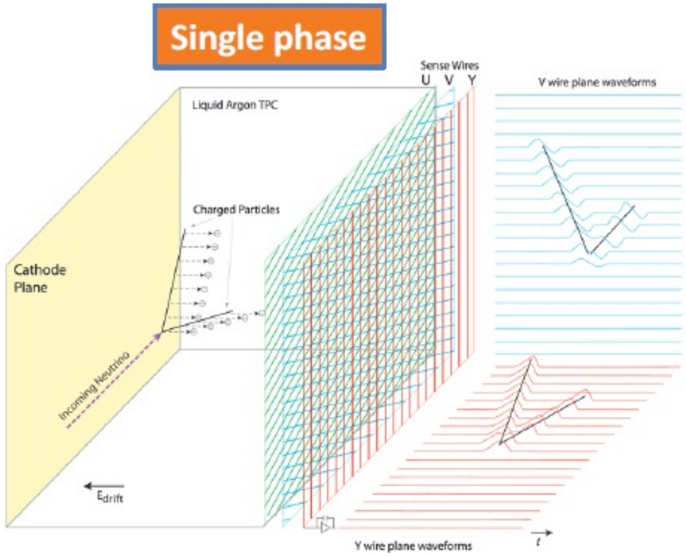
DUNE Far Detector

- 2x 17 kton LAr TPCs
  - Each 10 kton fiducial mass
- Space for up to 4 modules
- Excavation has started

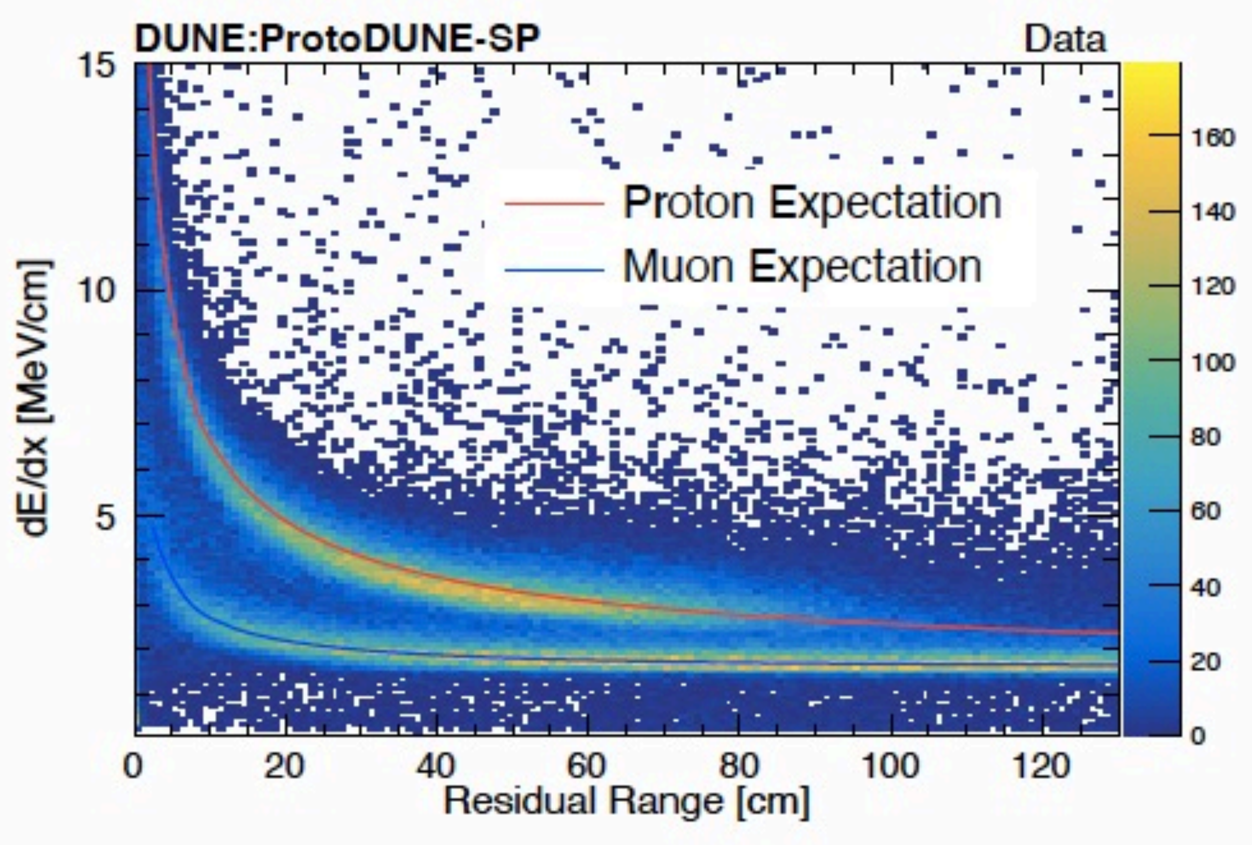


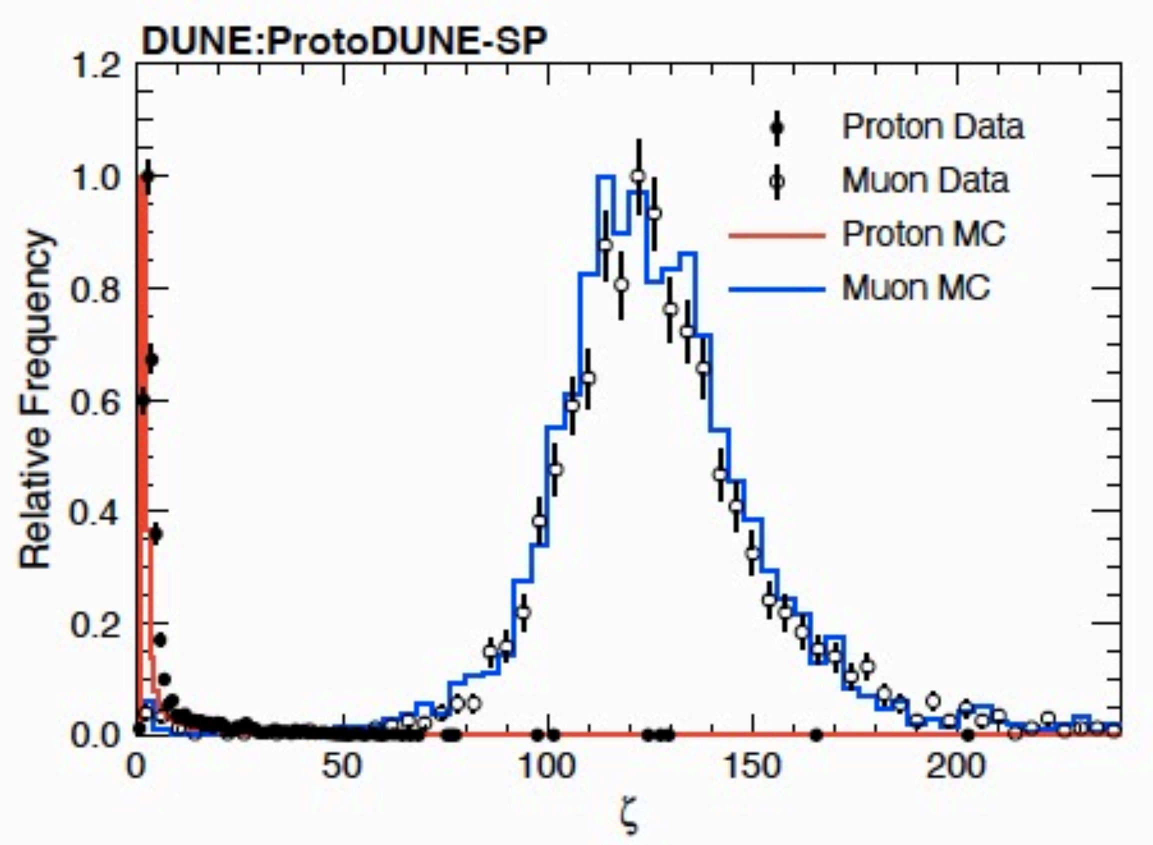
ProtoDUNE @ CERN





ProtoDUNE Performance





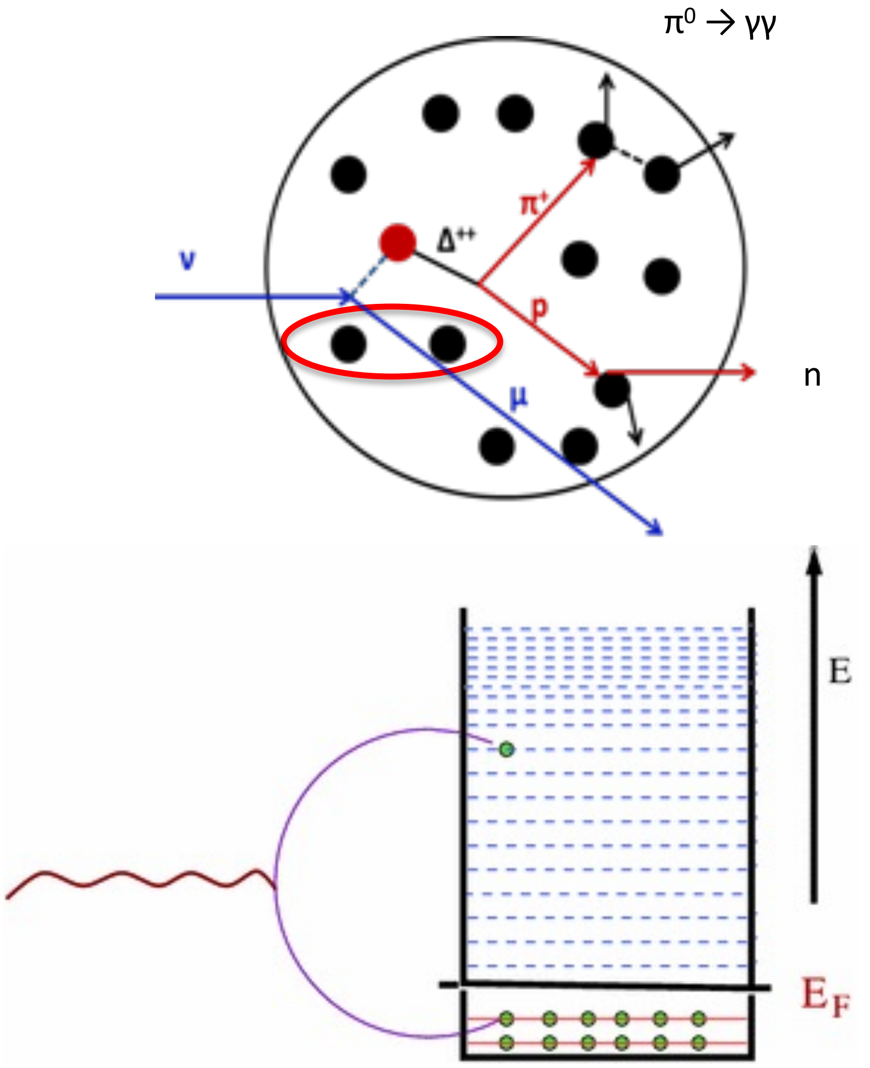
Measuring Oscillations

- Oscillation probabilities

$$P_{\nu_\mu \rightarrow \nu_e}(E_\nu) = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{far,no-osc}(E_\nu)} = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}\ (E_\nu)}$$

Well known (1-2%)

Neutrino Interactions



- Tricky Problem
  - How to relate neutrino to measured energy?
  - Neutrino energy unknown
  - Nuclear recoil not measurable
  - Nucleus will absorb some energy
- Charged and neutral particles
  - p from curvature in B-field
  - Calorimetric energy for γ
  - β from ToF of neutron (recoil)

What does the ND need to measure?

- ND Fluxes

  $$\phi_{\nu_x}^{near}(E_\nu)$$

  - Prior constrained 5-10%

- Total and differential cross sections on Argon

  $$\frac{d^n\sigma_{\nu_x}^{Ar}}{da\ db\ dc\ \ldots}(E_\nu)$$ (Largely unknown)

- True to reconstruction “matrix”

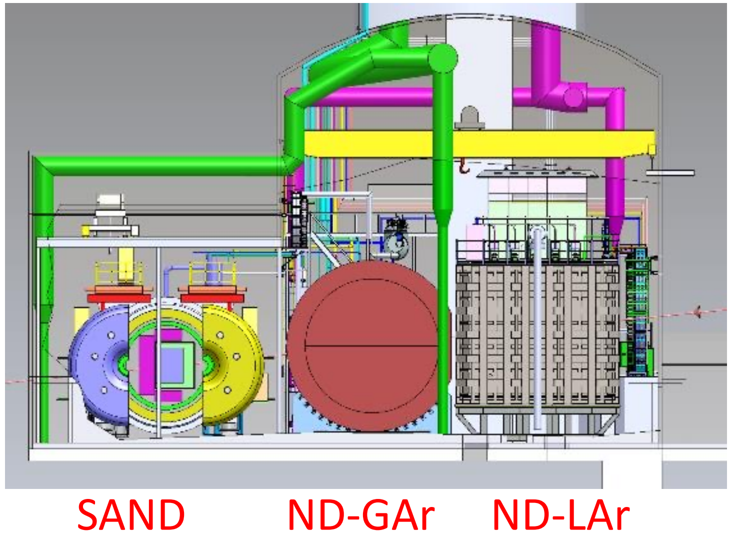
  $T_{\nu_x}^{far}(E_\nu, E_{rec})$ and $T_{\nu_x}^{near}(E_\nu, E_{rec})$

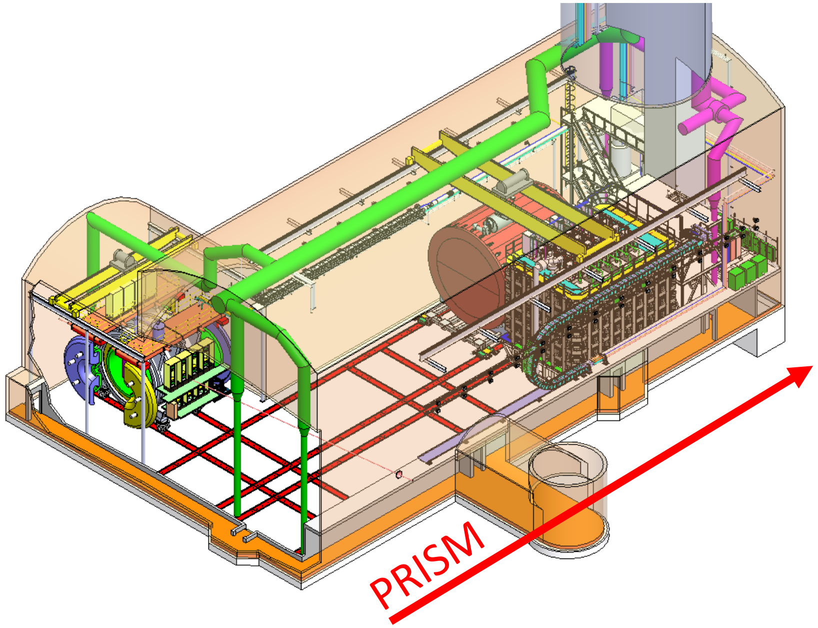
  Depends on

  - Detector effects
  - differential cross sections

The Near Detector Complex

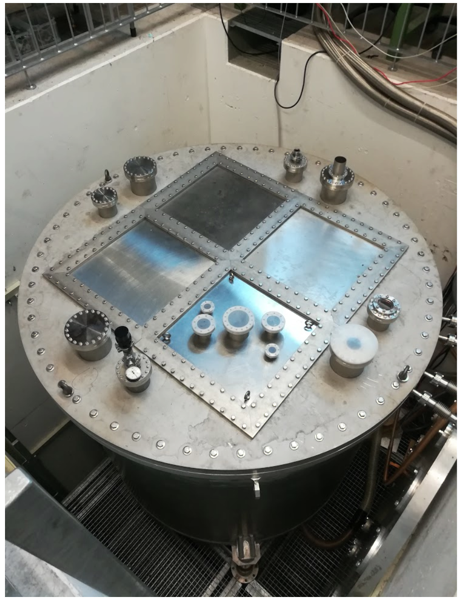
- Four main components
  1. Liquid argon detector (**ND-LAr**)
  2. Downstream tracker with gaseous Ar-target (**ND-GAr**)
  3. ND-LAr and ND-GAr systems can move off-axis (**PRISM** concept)
  4. **S**ystem for on-**A**xis **N**eutrino **D**etection (**SAND**)
- High statistics constrains
  - Cross section & neutrino flux

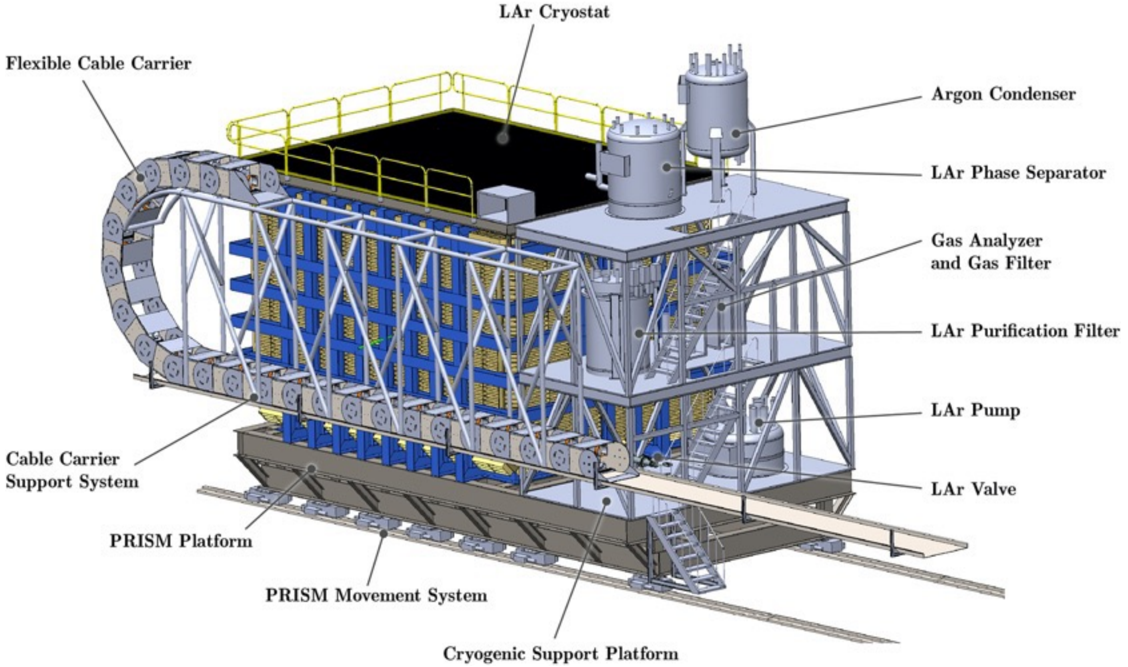


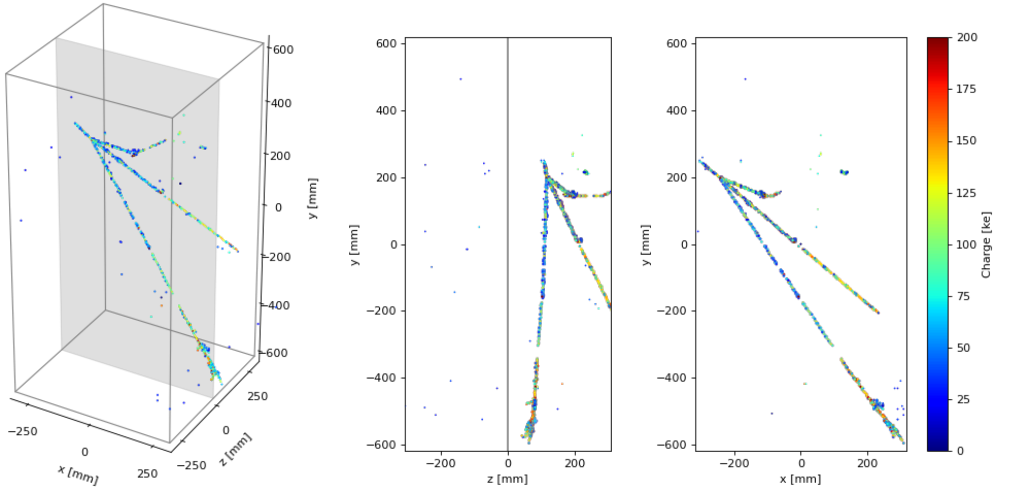


ND-LAr: Liquid Argon TPC

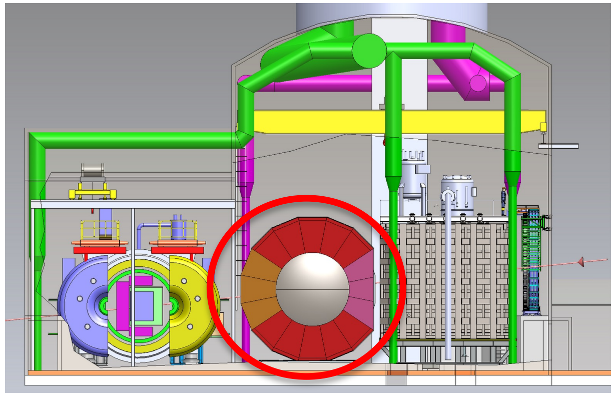
- LAr TPC
  - Study detector effects
  - Similar to far detector technology
- High event rate
  - Need compartmentalisation
  - Pixelized readout

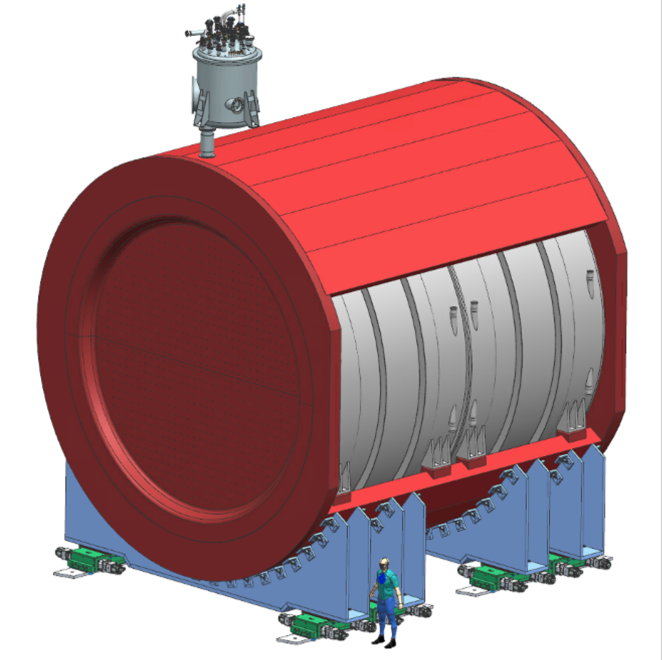




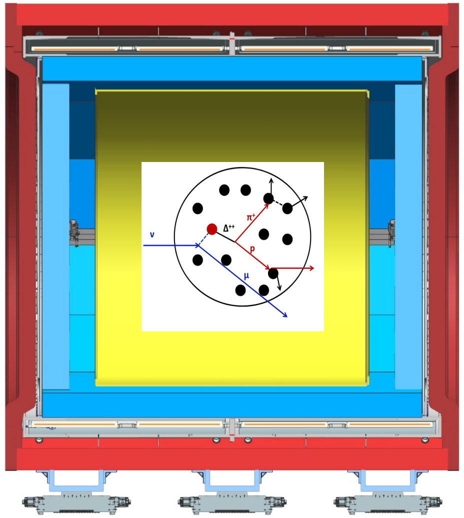


ND-GAr: Gaseous Argon TPC



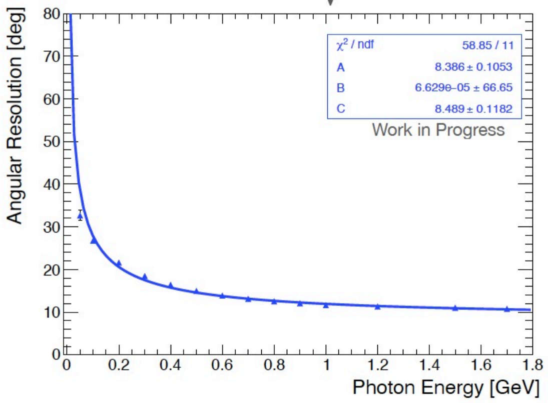


- Main detector components
  - High pressure (10 bar) gas TPC
  - ECAL
  - SC magnet
- Interactions on Ar gas
- Can move off-axis

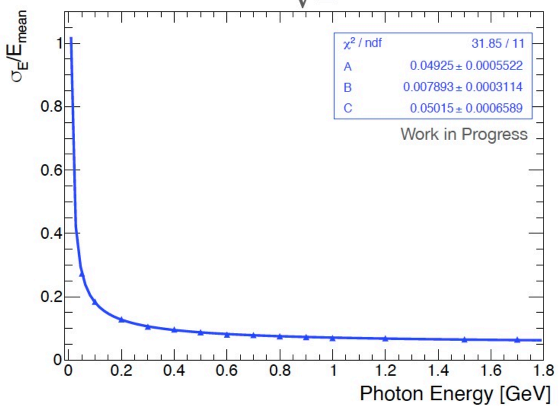


ECAL Performance

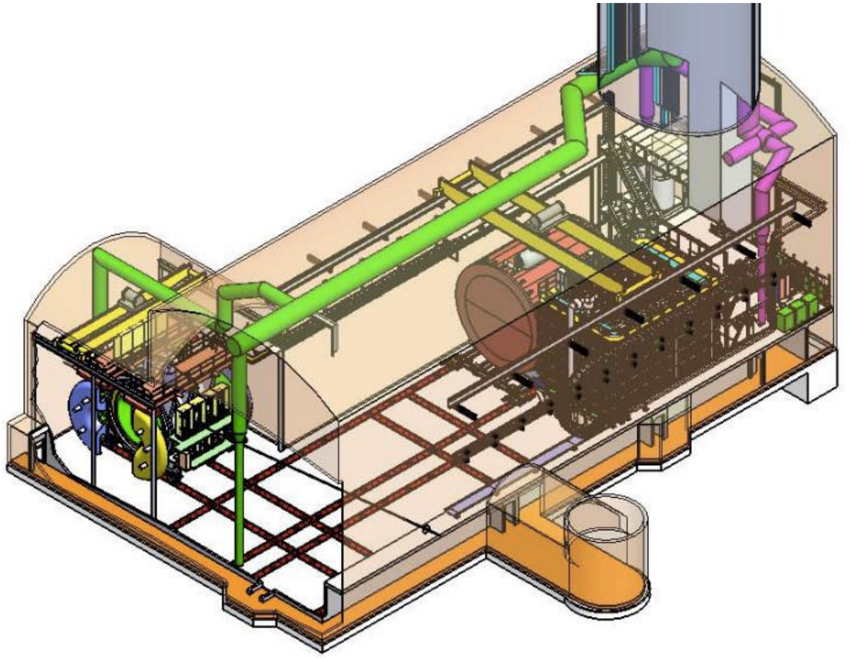
$$AngularResolution = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

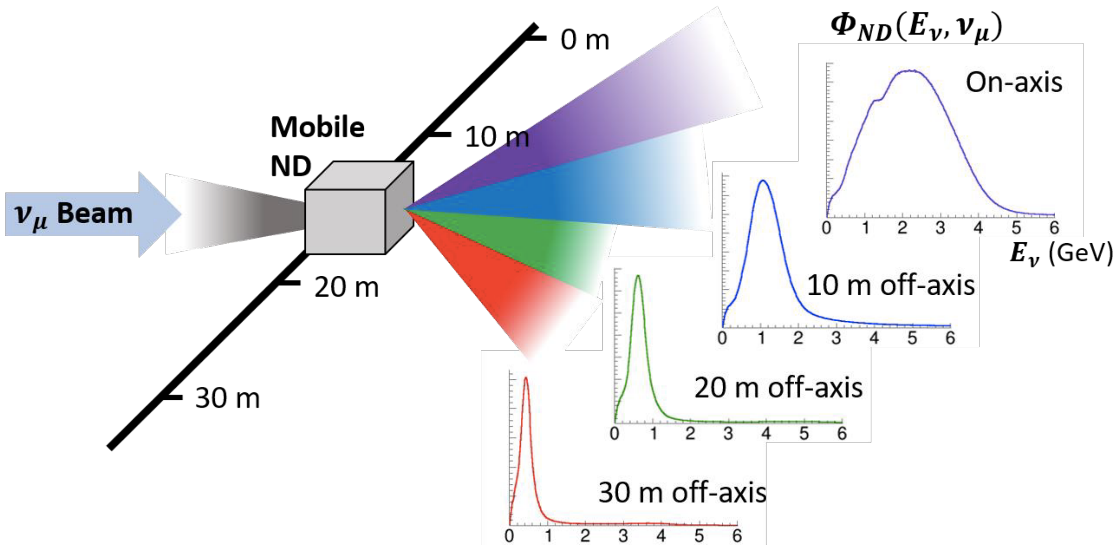


$$\frac{\sigma_E}{E_{mean}} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$



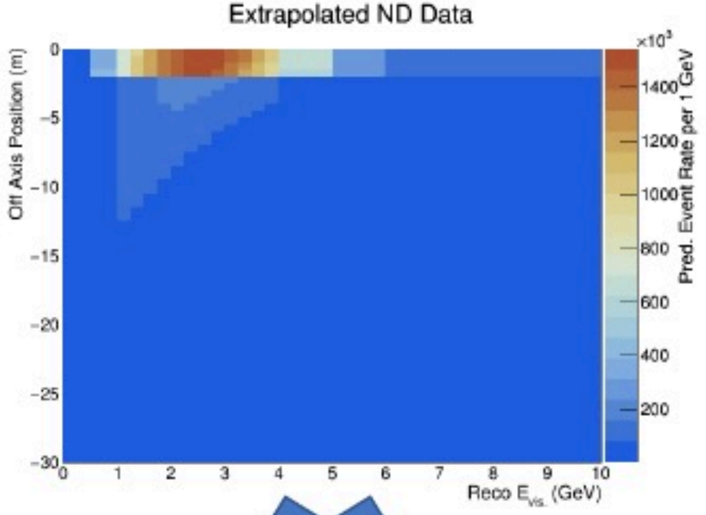
PRISM Concept

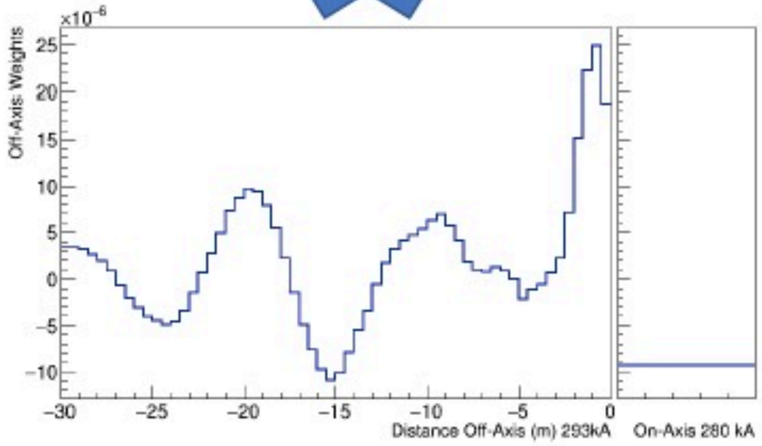


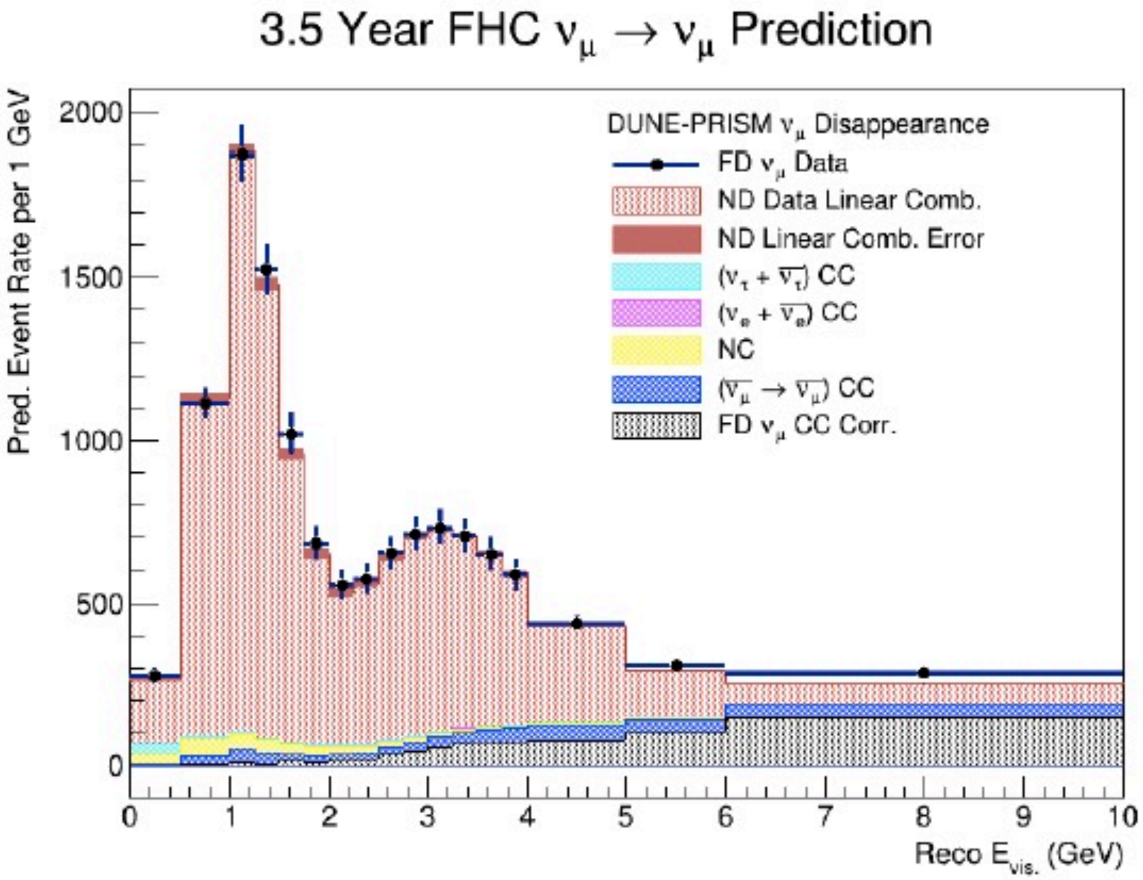


- Neutrino spectrum changes when going off-axis
- Direct linear combination of date at different positions to construct FD oscillated spectrum
- Need to understand detector differences and flux only

PRISM Analysis



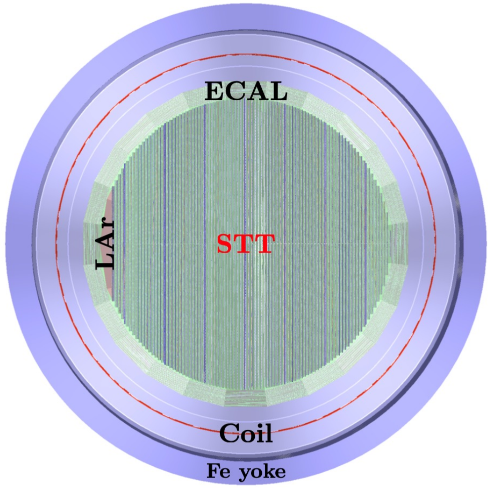


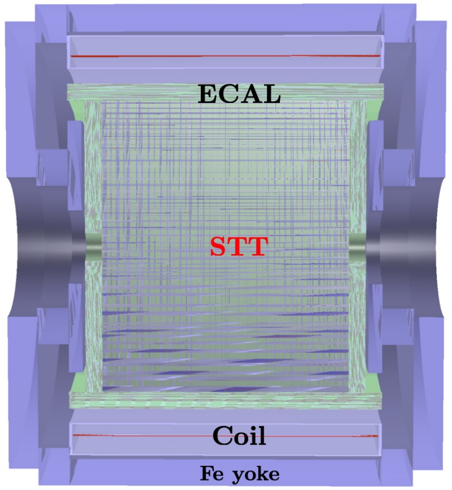


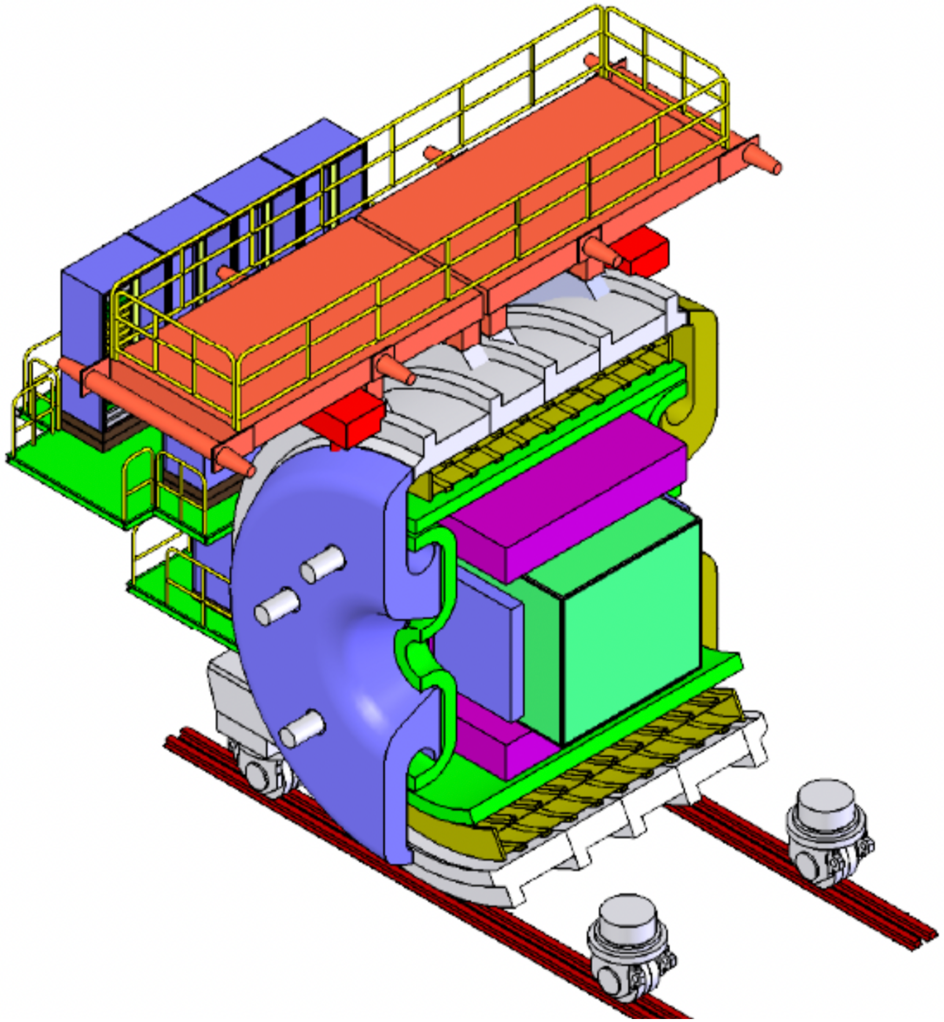
$$\frac{dN_\nu^{det}}{dE_{rec}} = \int \phi_\nu^{det}(E_\nu) * \sigma_\nu^{target}(E_\nu) * D_{\nu_\mu}^{det}(E_\nu, E_{rec})\ dE_\nu$$

SAND

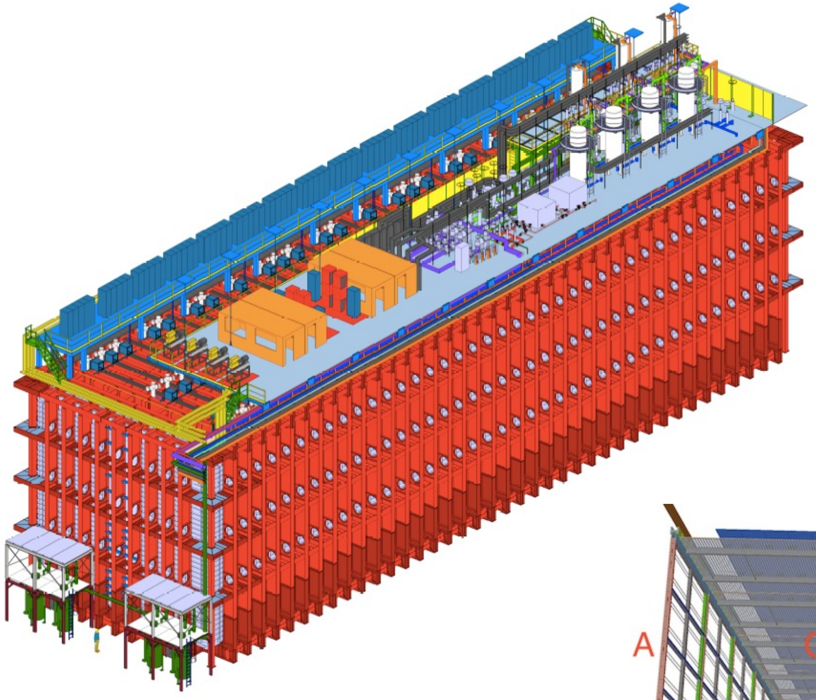
- On-Axis Beam monitor (formerly KLOE)
  - ECAL & magnet
  - Straw-Tube-Tracker (CH_2-Target)
  - Small LAr Target (GRAIN)
- Task
  - Measure neutrino flux
  - Monitor beam stability

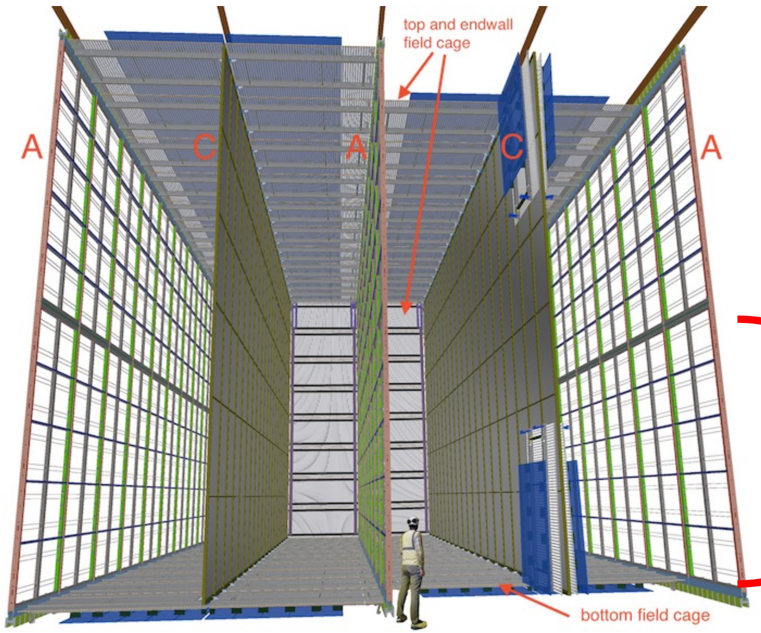


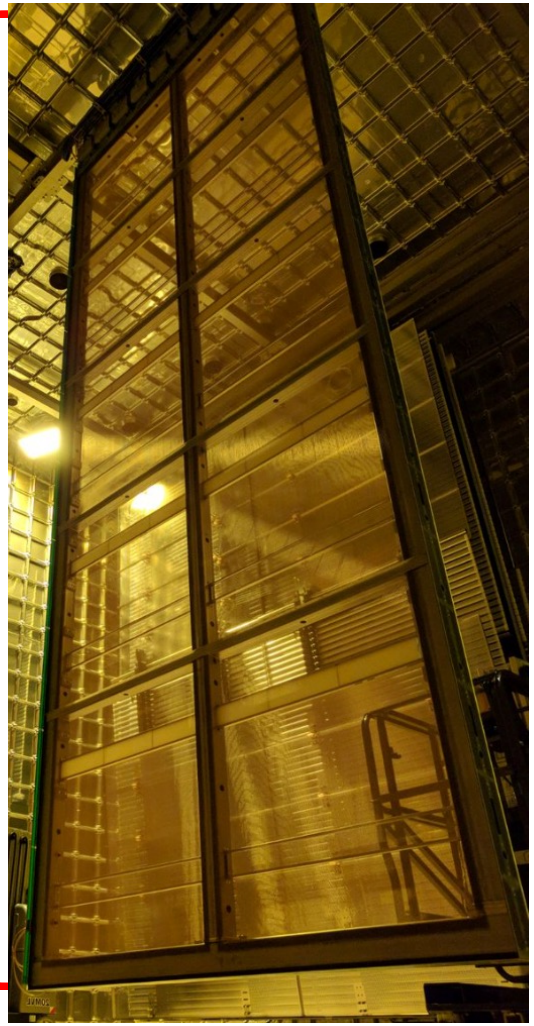




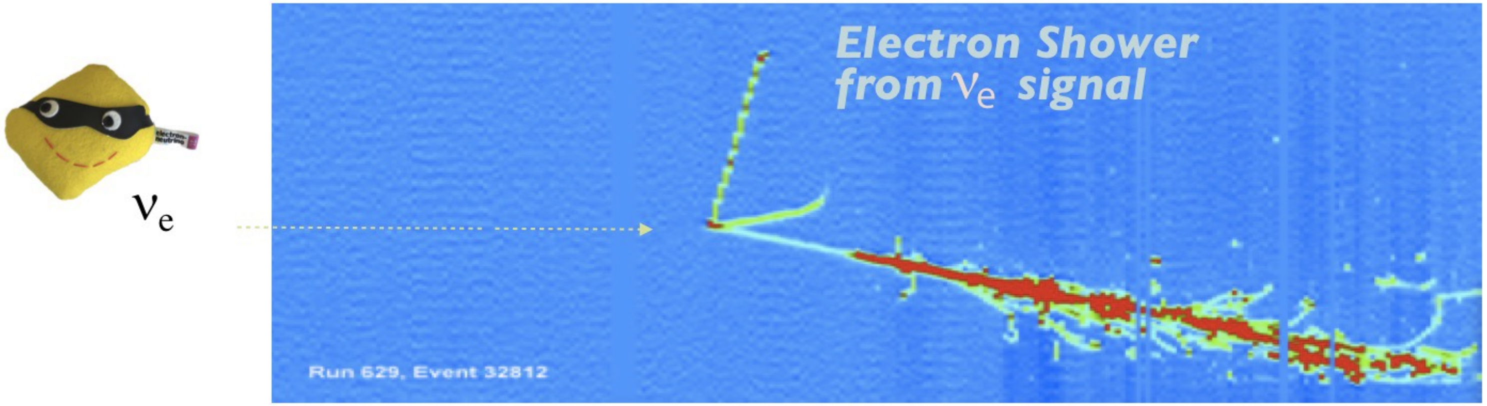
DUNE Far Detector (II)

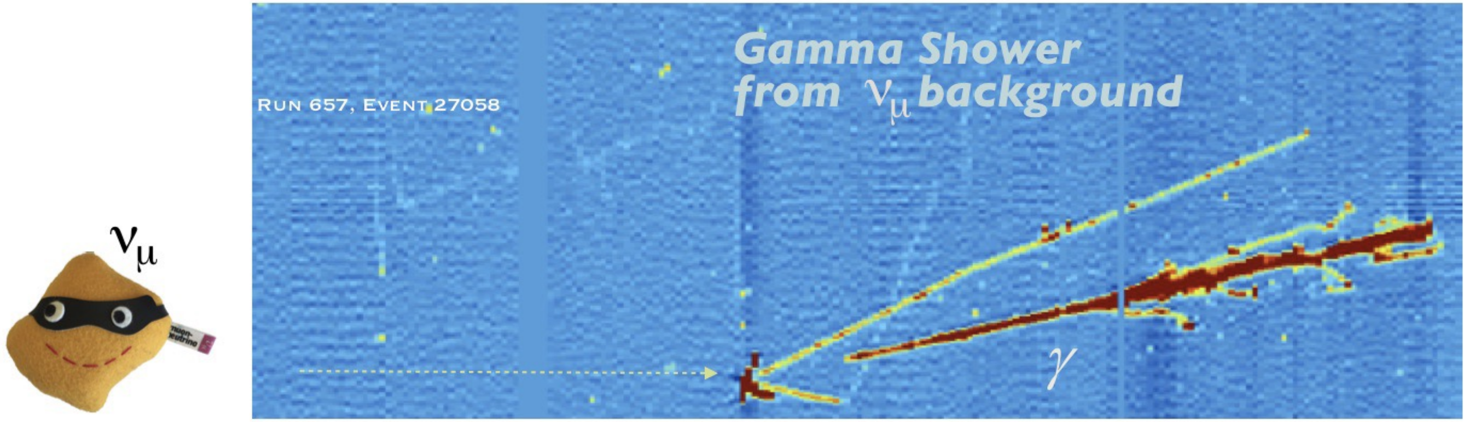




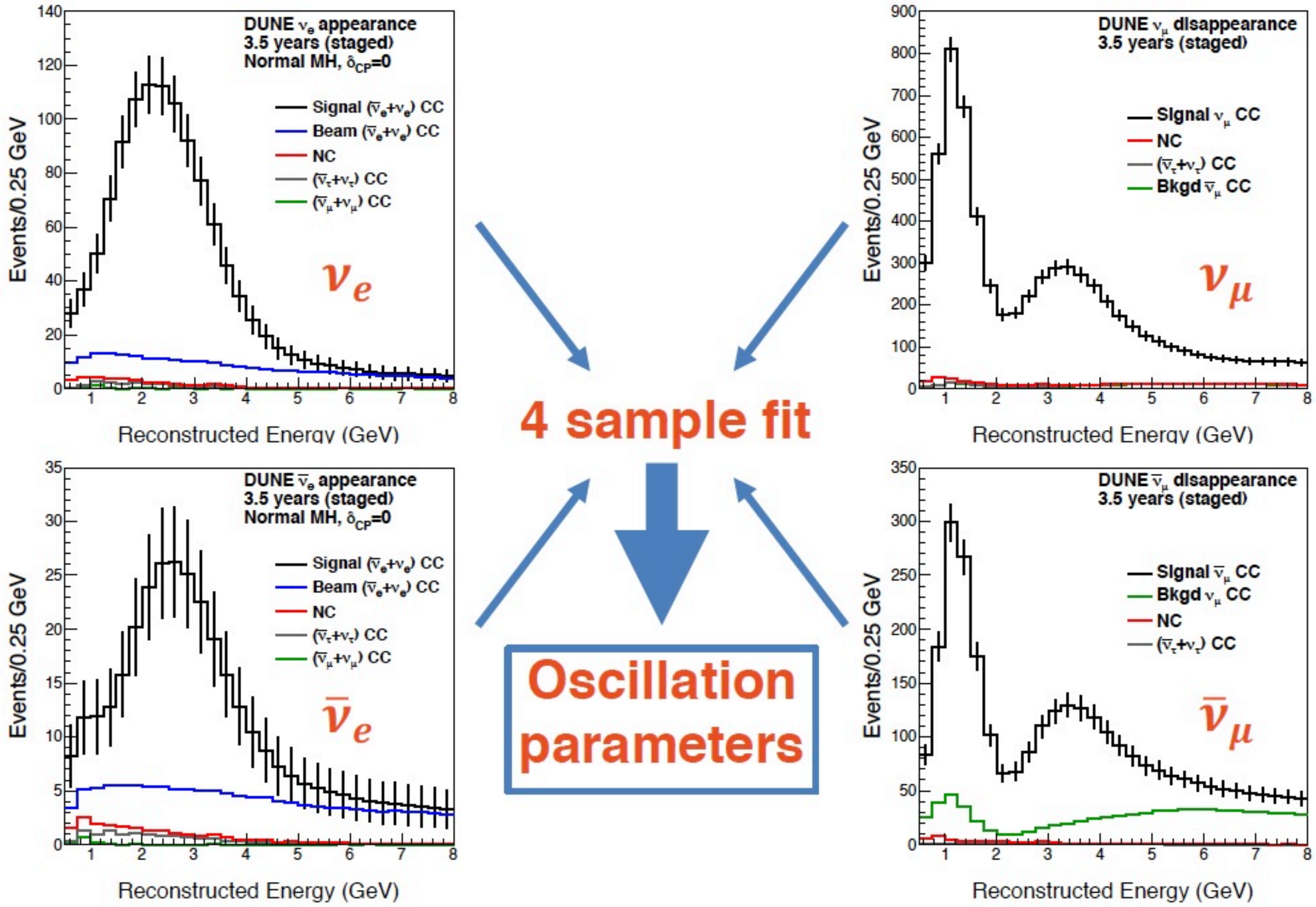


Event identification





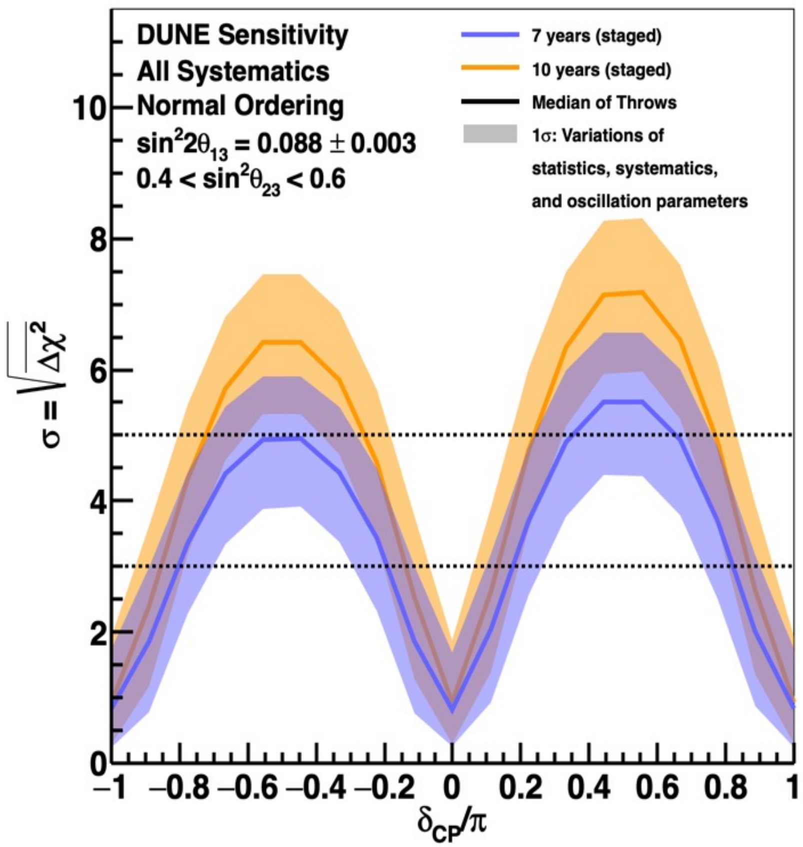
Measurement Strategy



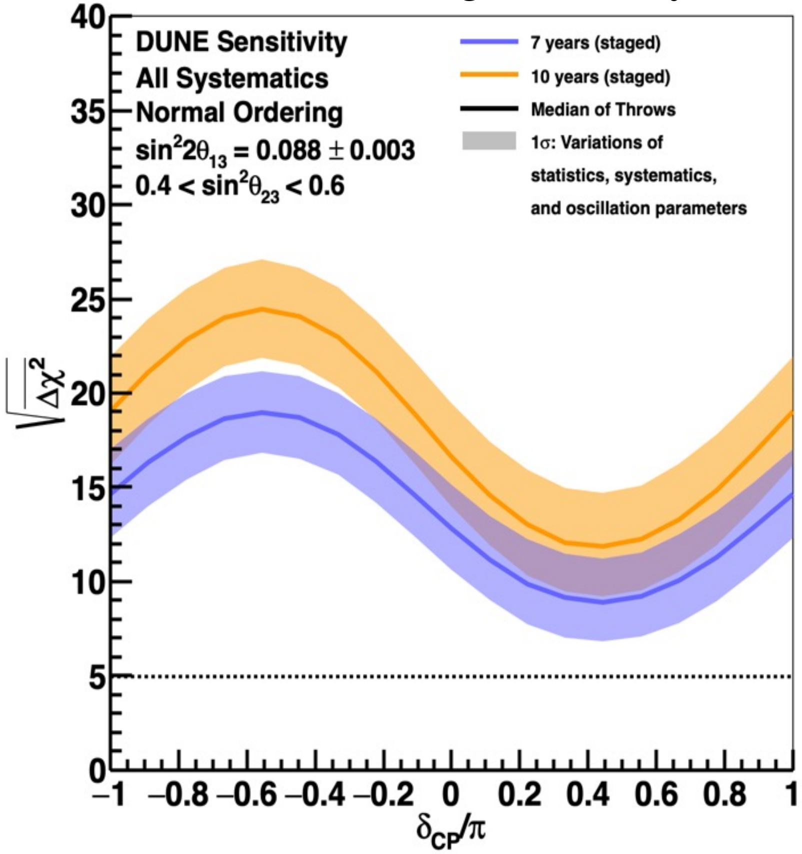
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\,(1-2S_{13}^2)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
&+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2\frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} (1-2S_{13}^2)
\end{aligned}
$$

DUNE Sensitivity

*CP*v sensitivity



Mass ordering sensitivity



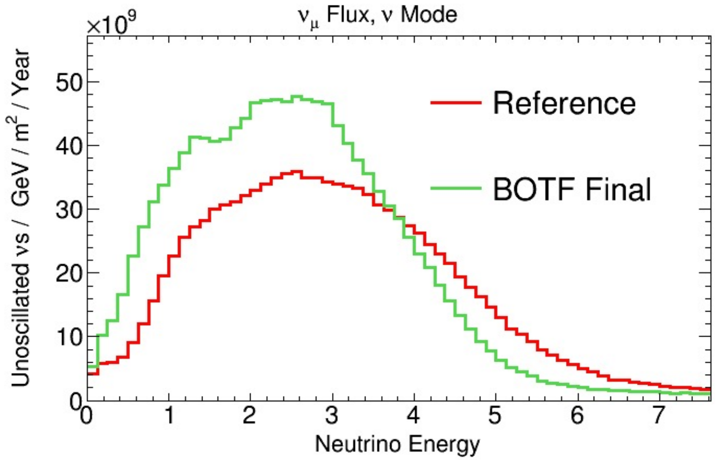
Move quickly to potential ***CP* violation discovery**
Rapid, definitive **mass ordering determination** (>5σ)

Summary and Conclusion

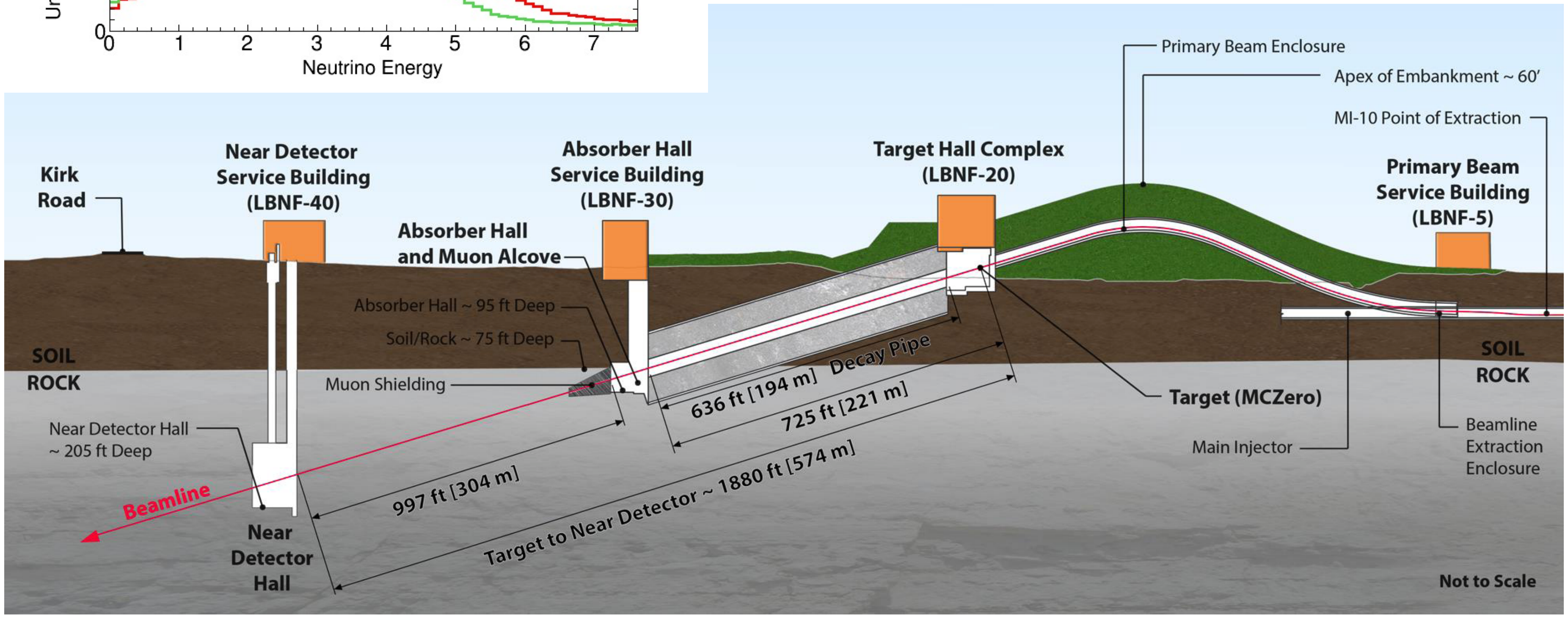
- DUNE is an neutrino facility with an exciting physics program
  - Optimised for neutrino oscillation measurements
    - Precision parameter measurements
    - CP violation
    - mass ordering
    - Is the three neutrino paradigm correct?
  - Wider physics program
    - Baryon number violation
    - Supernova (& solar) neutrinos
    - Non-Standard Interactions
    - dark sector searches with Near Detector, …
- International Collaboration with strong support by funding agencies

Backup

Beam

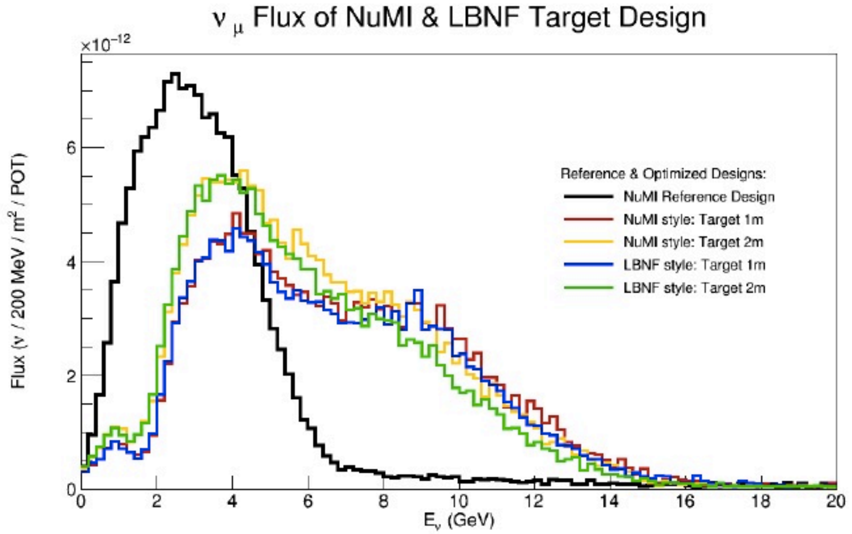


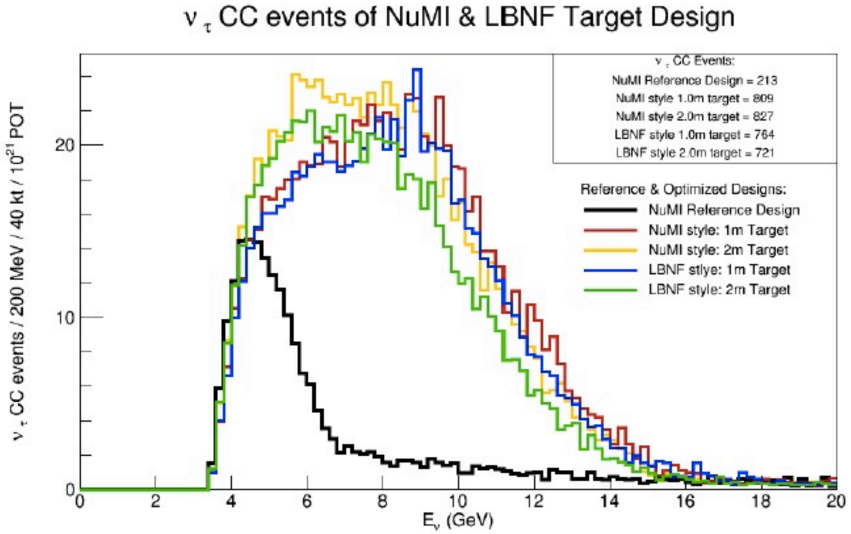
- Proton beam energy 60-120 GeV
- Power 1.2 MW → 2.4 MW
- Neutrinos and anti-neutrinos



High Energy Tune

- Can change the flux by changing
  - Target positions
  - Horns (shape, position, current)

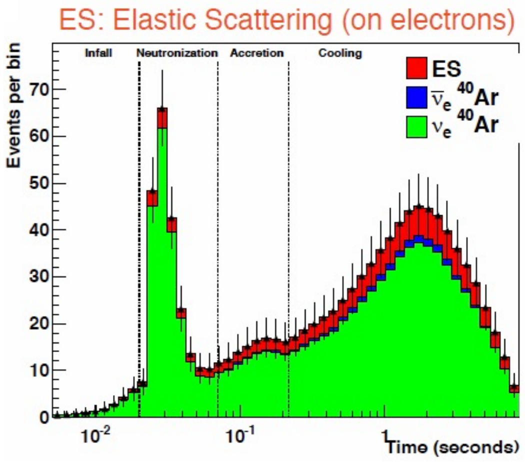




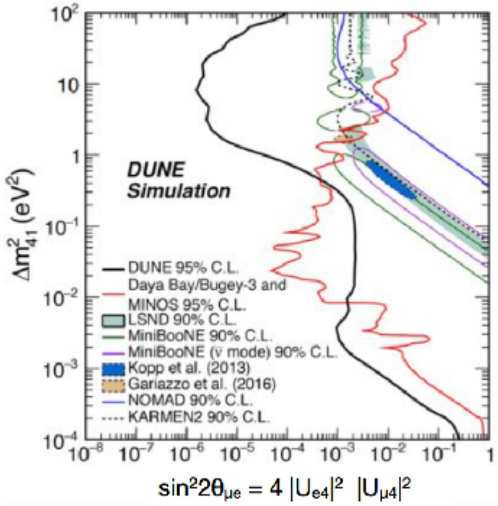
- Physics
  - Tau appearance
  - NSI

Other Physics

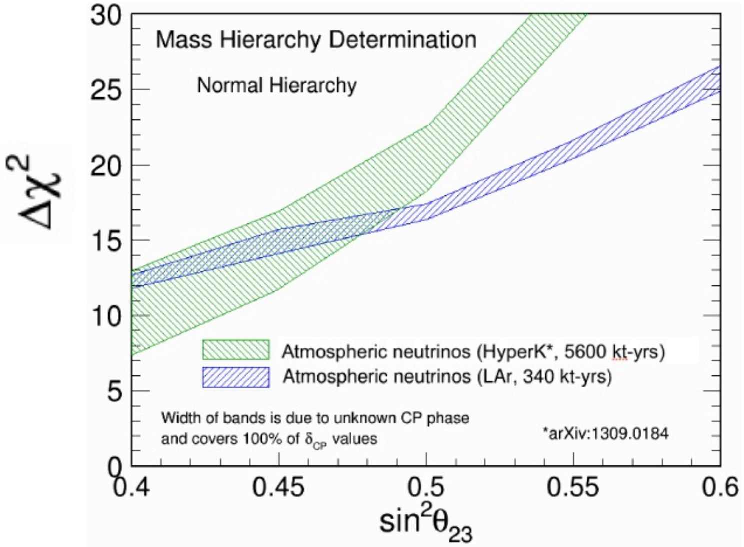
supernova



atmospherics



atmospherics



- Dark matter
- Large extra dimensions
- Dark photons
- NS interactions