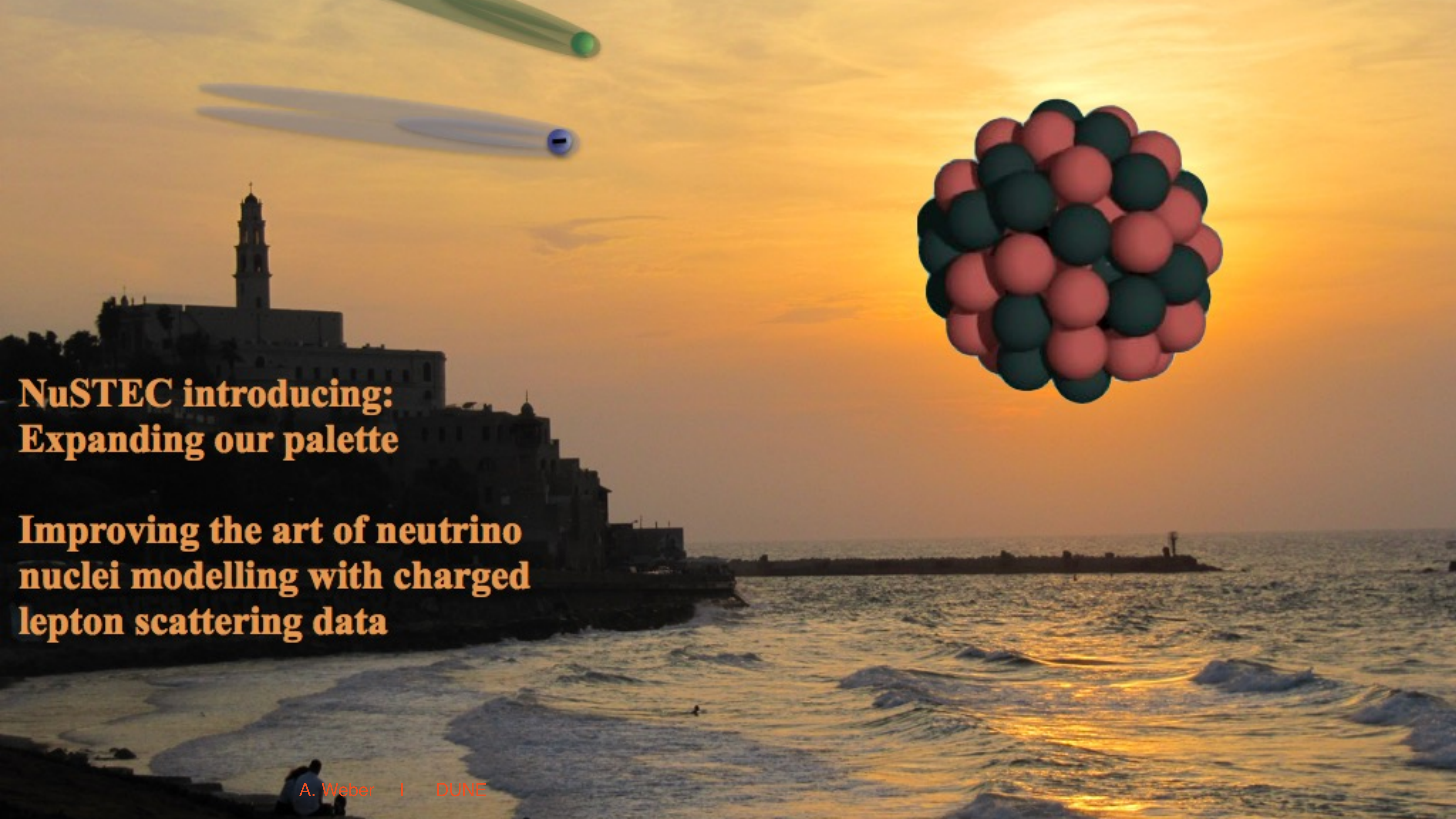


NuSTEC introducing: Expanding our palette

Improving the art of neutrino nuclei modelling with charged lepton scattering data

Implications & Motivation for DUNE

Alfons Weber

for the DUNE Collaboration

NuSTEC Workshop on Electron Scattering

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

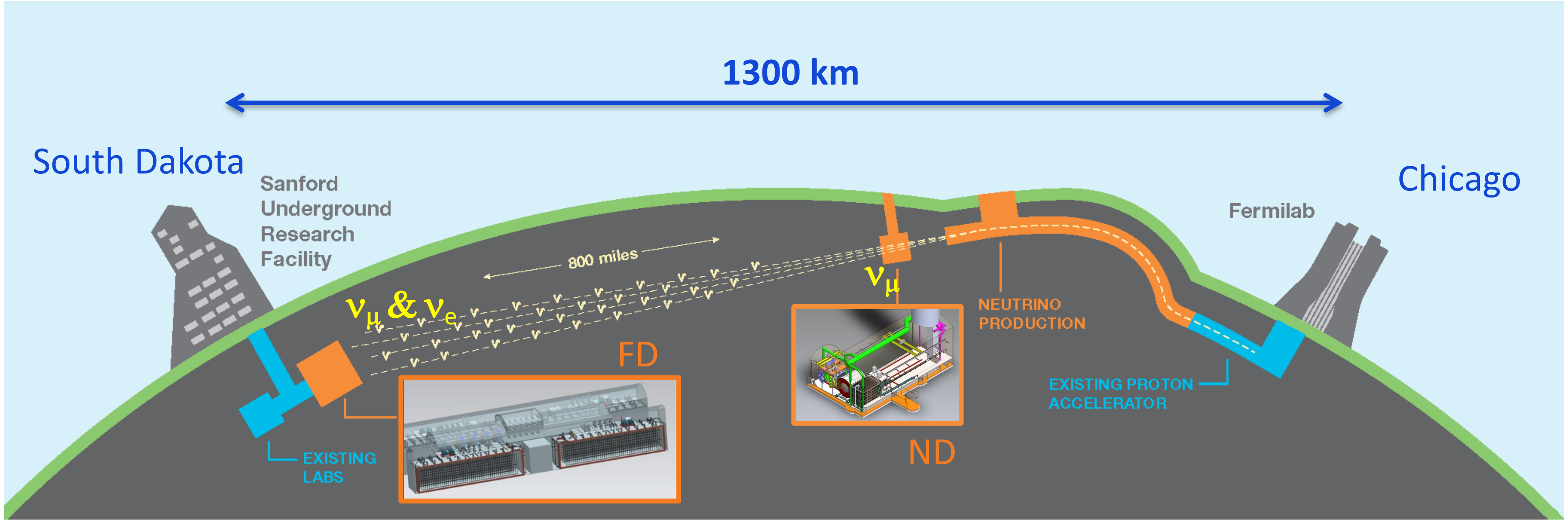
JG|U

Fermilab

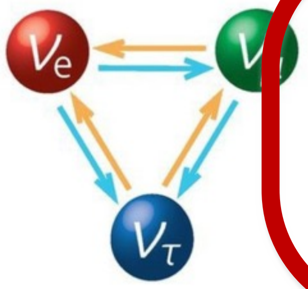
DUNE

DUNE General Setup

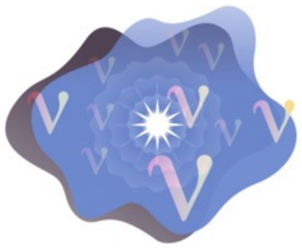
- LBNF/DUNE will consist of
  - An intense ν-beam fired from Fermilab 1.2 MW upgradeable to 2.4 MW
  - Highly capable near detector complex
  - A >20 kt fiducial mass LAr TPC far detector underground at SURF
  - A cavern for a full 40 kt detector system



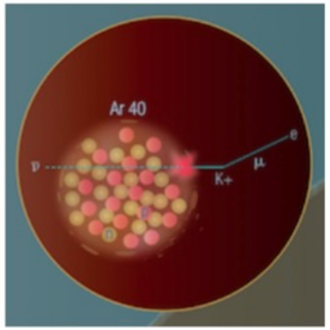
DUNE Physics Program



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



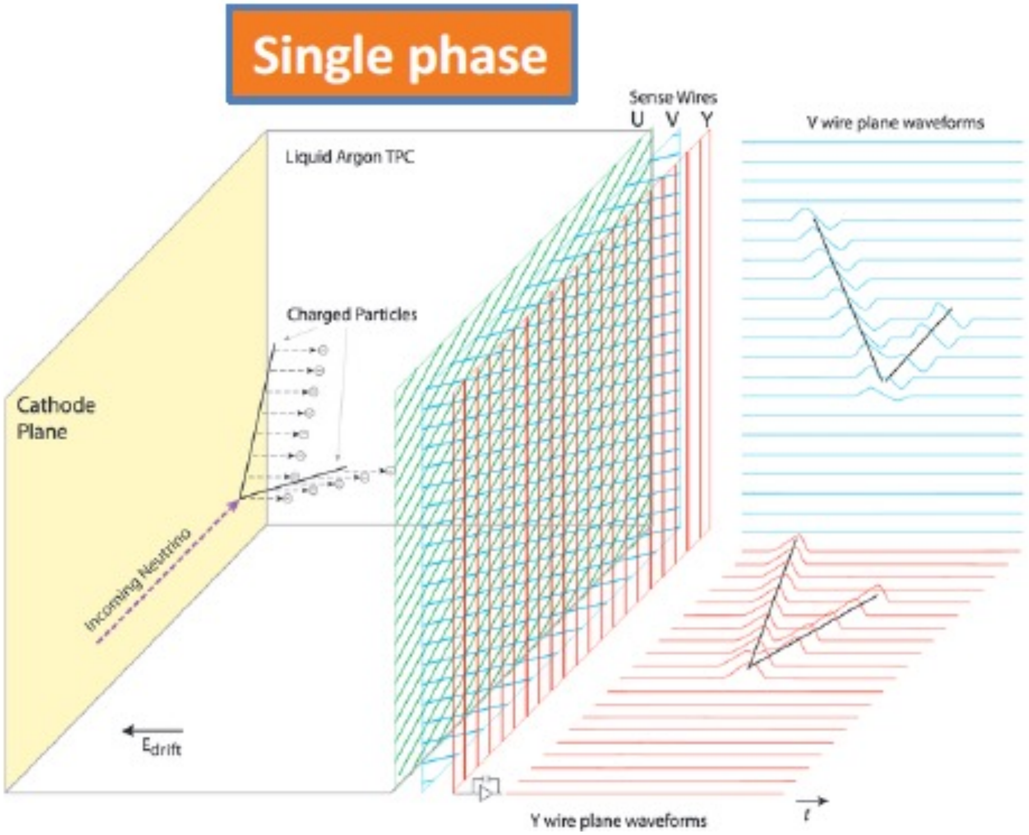
- Supernova Physics
  - Observation of time and flavour profile provides insight into collapse and evolution of supernova
  - Unique sensitivity to electron neutrinos

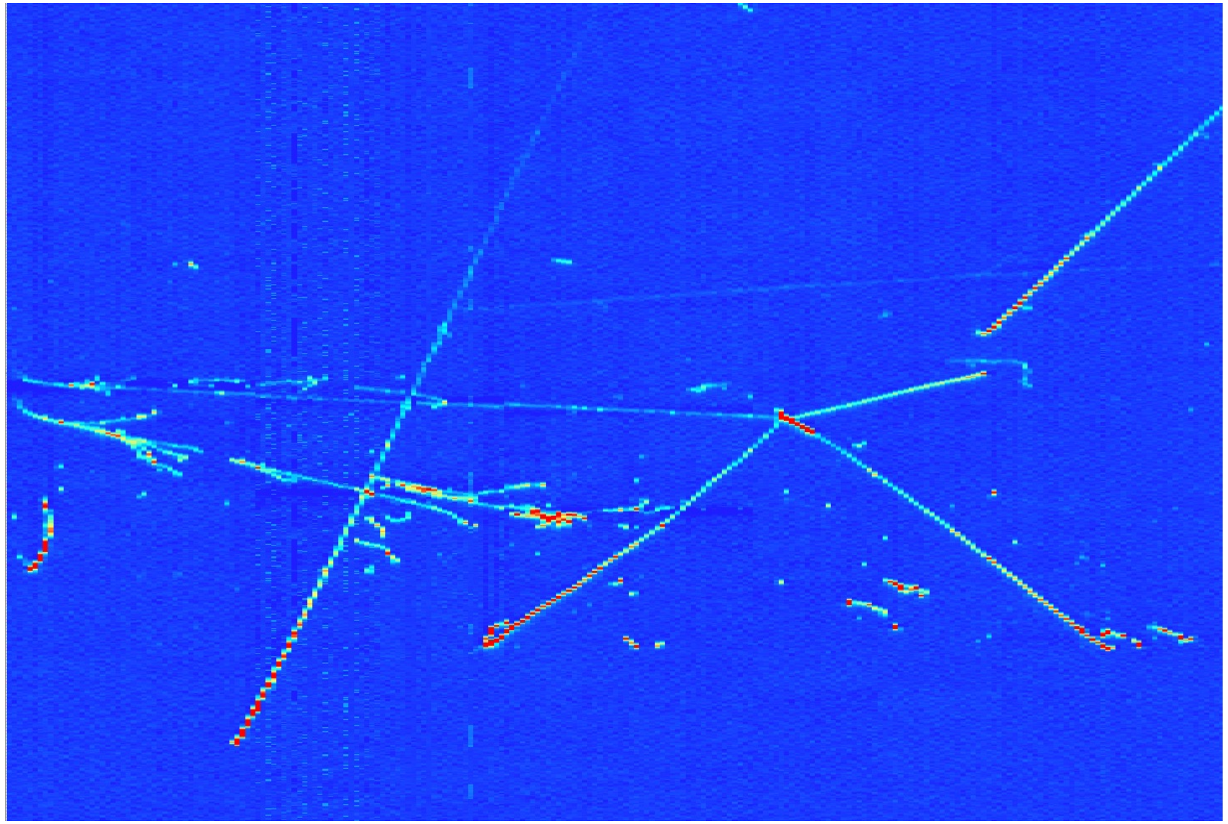


- Baryon number violation
  - Predicted by many BSM theories
  - LAr TPC technology well-suited to certain proton decay channels (*e.g.*, $p \rightarrow K + \nu$)
  - $\Delta(B-L) \neq 0$ channels accessible (*e.g.*, $n \rightarrow \bar{n}$)

Far Detector (LArTPC)

$$E_{\nu}^{rec} = E_{l}^{rec} + T_{p}^{rec} + T_{\pi^{+}}^{rec} + E_{\pi^{0}}^{rec} + T_{other}^{rec}$$



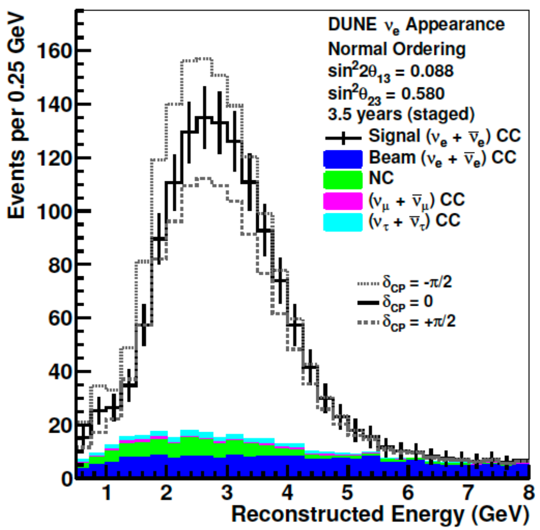


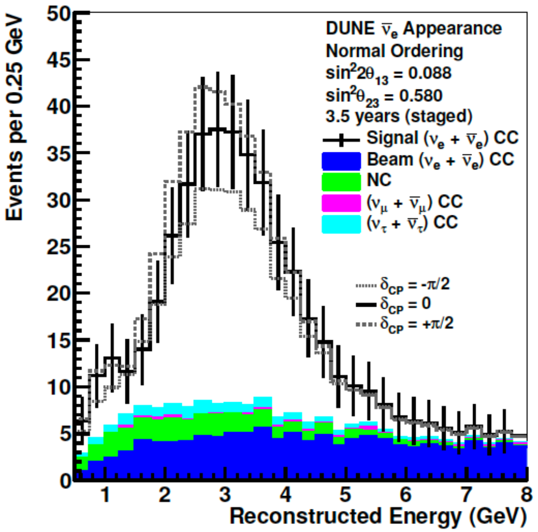
Measurement Strategy

neutrinos

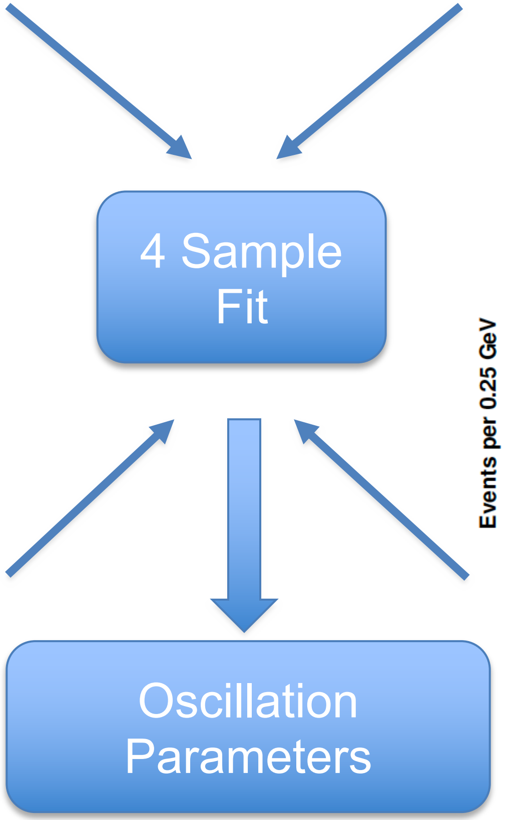
anti-neutrinos

electron

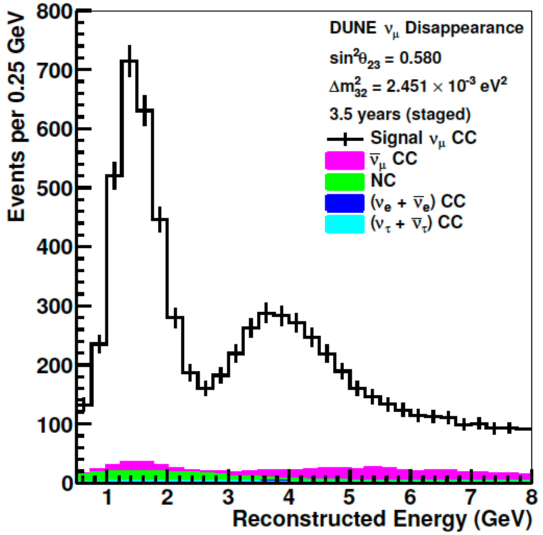


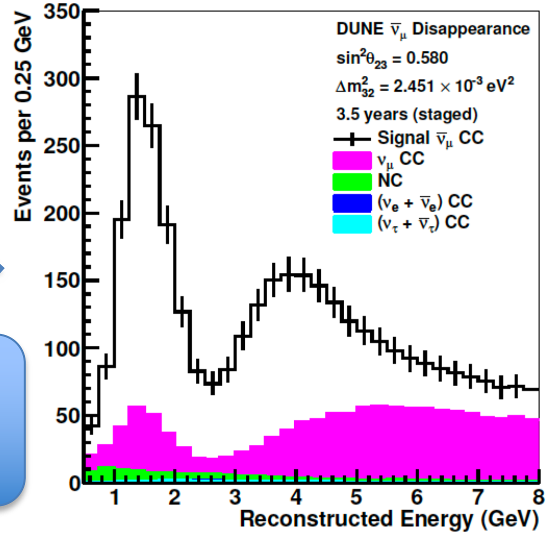


$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right)$$
$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta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



muon





See
DUNE Physics TDR
arXiv:2002.03005

Measuring Oscillations

- Oscillation probabilities

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

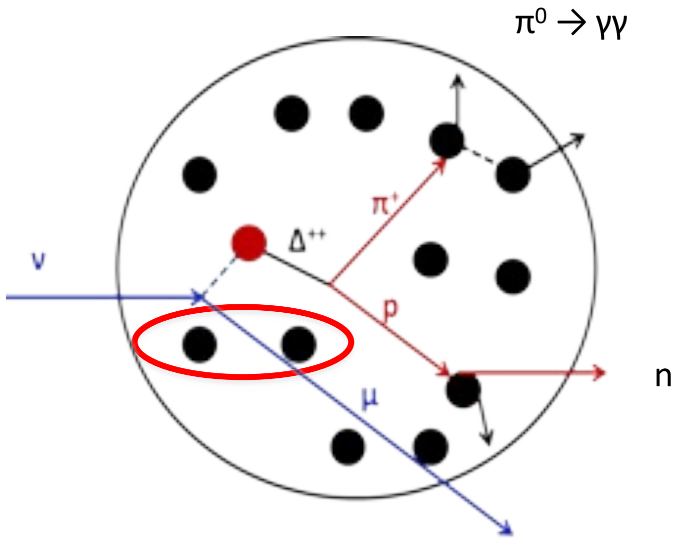
Well known (1-2%)

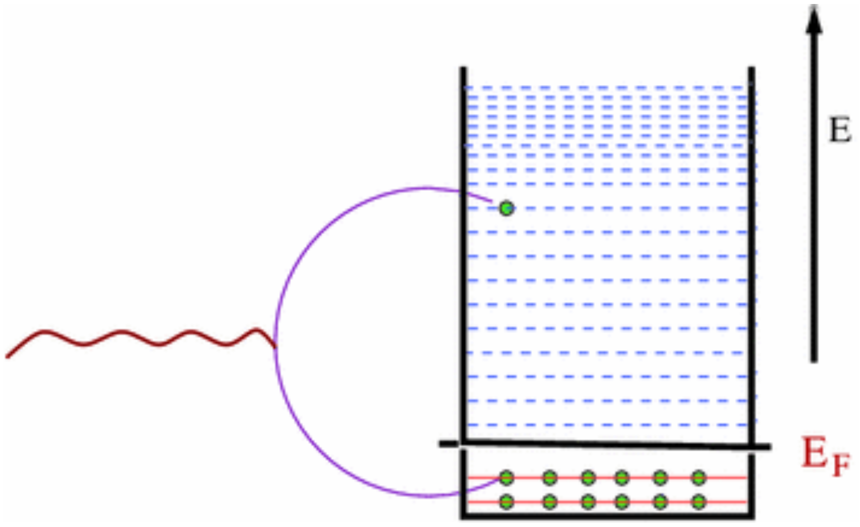
But in Reality

$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * T_{\nu_e}^{far}(E_\nu, E_{rec})\ dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * T_{\nu_\mu}^{near}(E_\nu, E_{rec})\ dE_\nu}$$

- No cancellations
  - Unless you unfold
- Need to understand especially
  - Detector effects in near and far detector
  - Relation of visible to neutrino energy
  - Cross section ratios
  - Near to far flux extrapolation
- Flux normalisation cancels
  - Shape is more important

Neutrino Interactions





- Tricky Problem
  - How to relate neutrino to measured energy?
  - Neutrino energy unknown
  - Nuclear recoil not measurable
  - Nucleus will absorb some energy

- In a Near Detector measure 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 $T_{\nu_x}^{near}(E_\nu, E_{rec})$

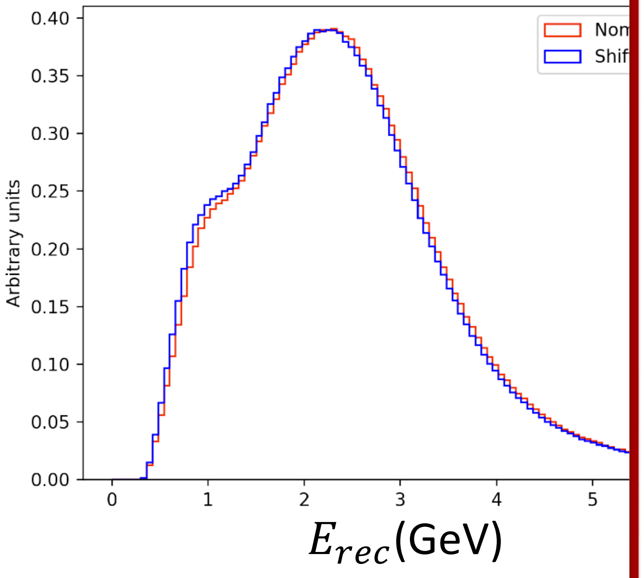
  Depends on

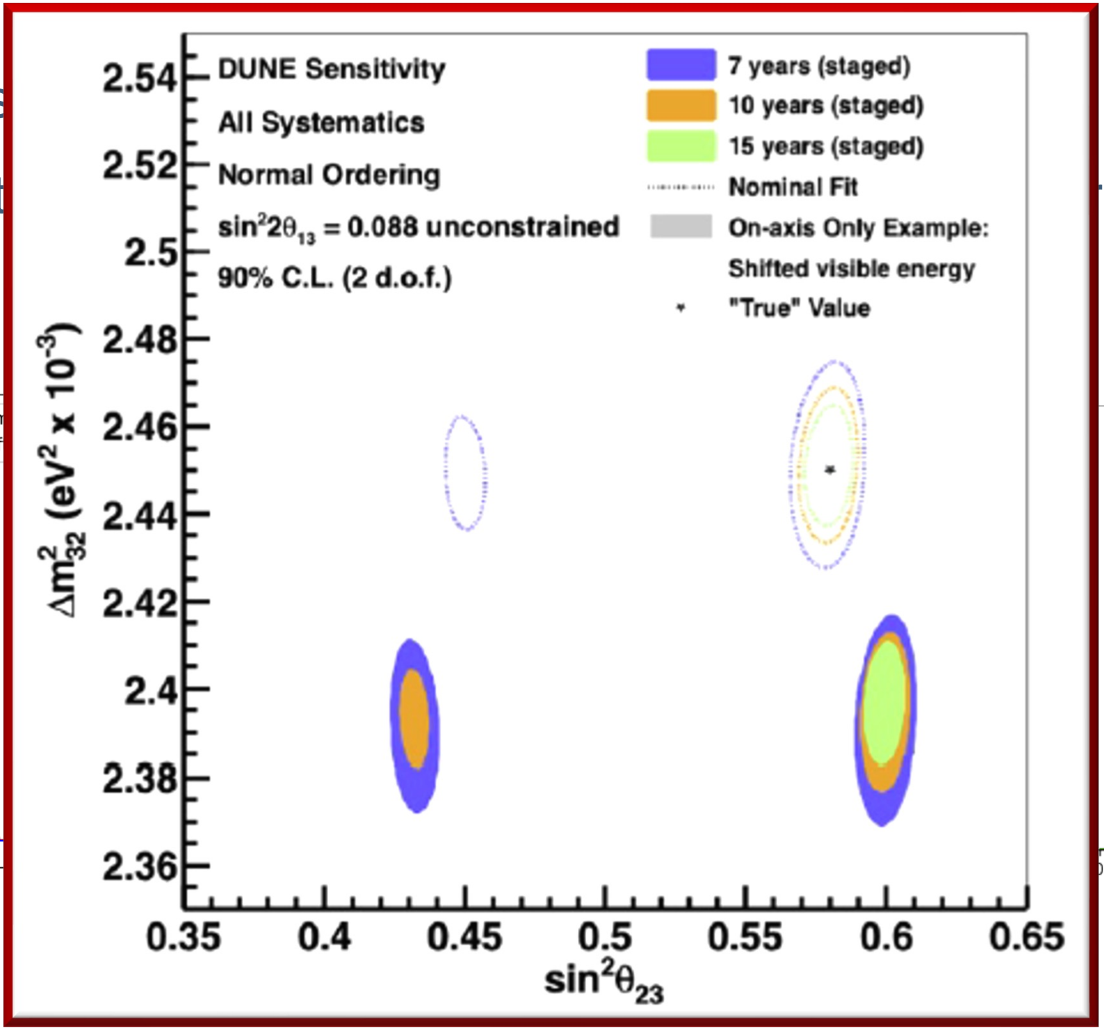
  - Detector effects
  - differential cross sections

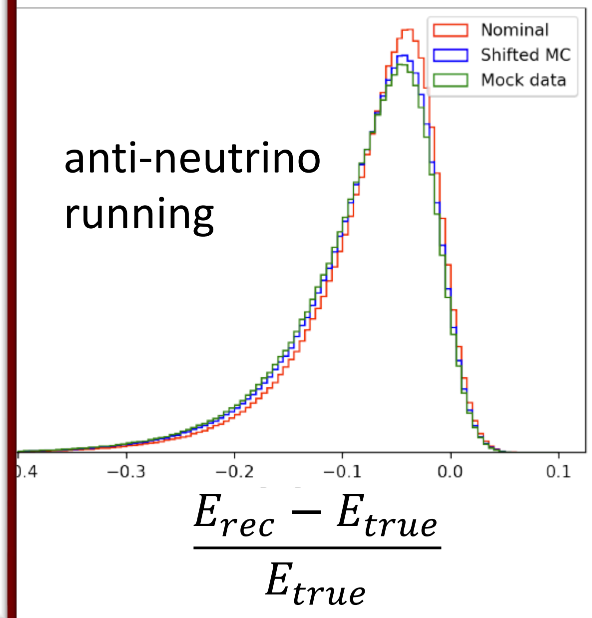
What Can Go Wrong?

DUNE ND CDR
arXiv:2103.13910

- Case Study
  - Proton has on 20% les
  - Fix this comparing Dat … ameters in generator







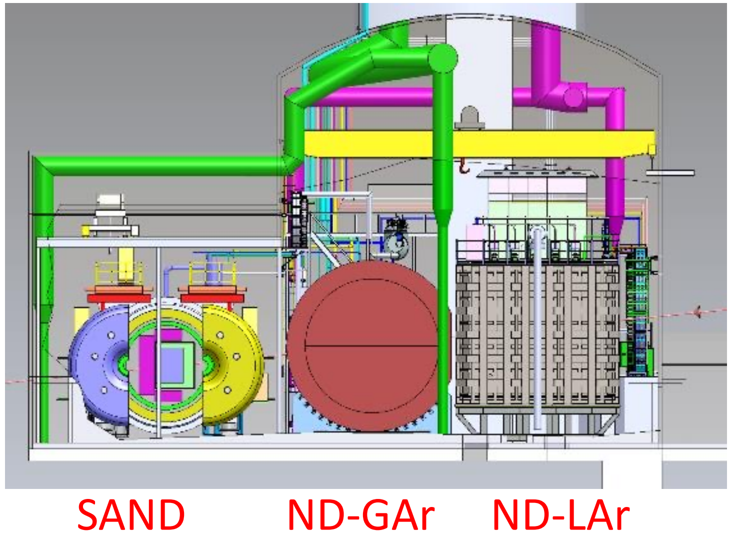
Overarching ND Requirements

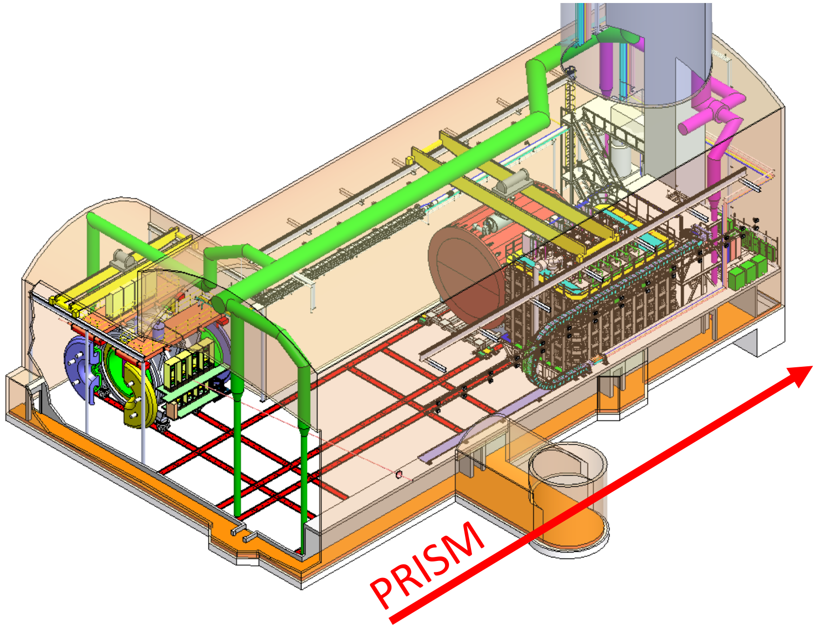
O0: Predict the neutrino spectrum at the FD: The Near Detector (ND) must measure neutrino events as a function of flavor and neutrino energy. This allows for neutrino cross-section measurements to be made and constrains the beam model and the extrapolation of neutrino energy event spectra from the ND to the FD.

O0.1	**Measure interactions on argon**	Measure neutrino interactions on argon, determine the neutrino flavor, and measure the full kinematic range of the interactions that will be seen at the FD.
O0.2	**Measure the neutrino energy**	Reconstruct the neutrino energy in CC events and control for any biases in energy scale or resolution.
O0.3	**Constrain the xsec model**	Measure neutrino cross-sections in order to constrain the cross section model used in the oscillation analysis.
O0.4	**Measure neutrino flux**	Measure neutrino fluxes as a function of flavor and neutrino energy.
O0.5	**Obtain data with different neutrino fluxes**	Measure neutrino interactions in different beam fluxes in order to disentangle flux and cross sections and verify the beam model. **(PRISM)**
O0.6	**Monitor the neutrino beam**	Monitor the neutrino beam energy spectrum with sufficient statistics to be sensitive to intentional or accidental changes in the beam on short timescales.

The Near Detector Complex

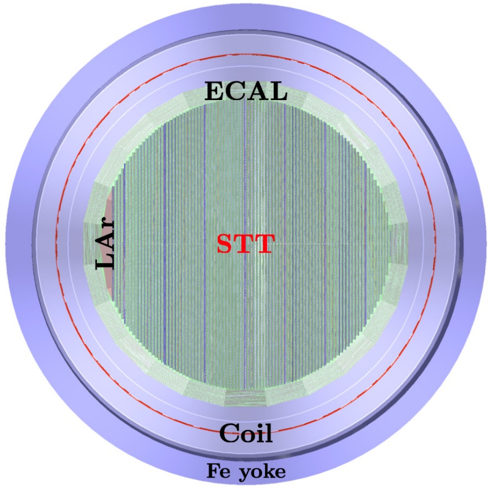
- Four main components
  - **S**ystem for on-**A**xis **N**eutrino **D**etection (**SAND**)
  - Liquid argon detector (**ND-LAr**)
  - Downstream tracker with gaseous argon target (**ND-GAr**)
  - ND-LAr and ND-GAr systems can move off-axis (**PRISM** concept)
- High statistics constrains
  - Cross section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

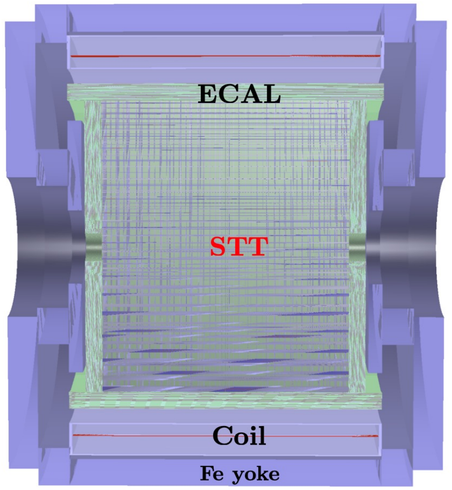


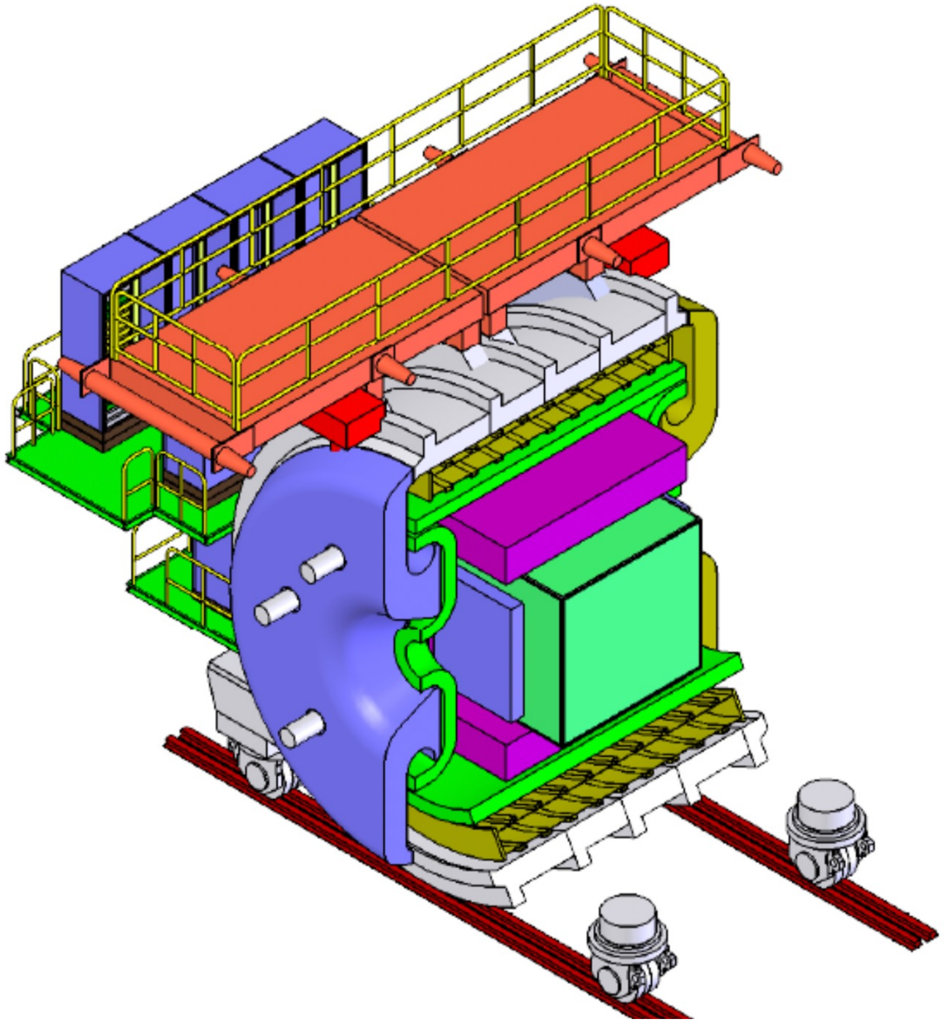


SAND

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

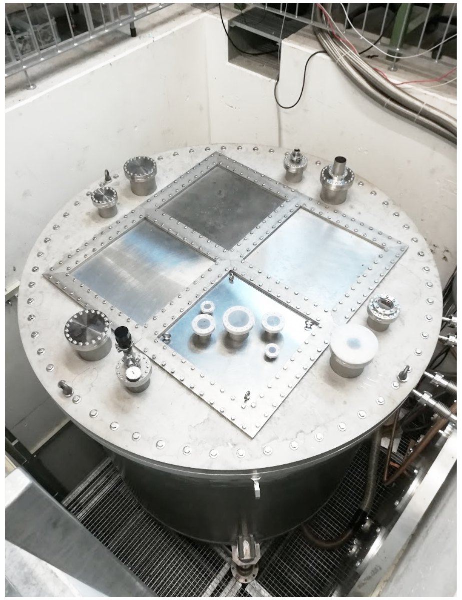


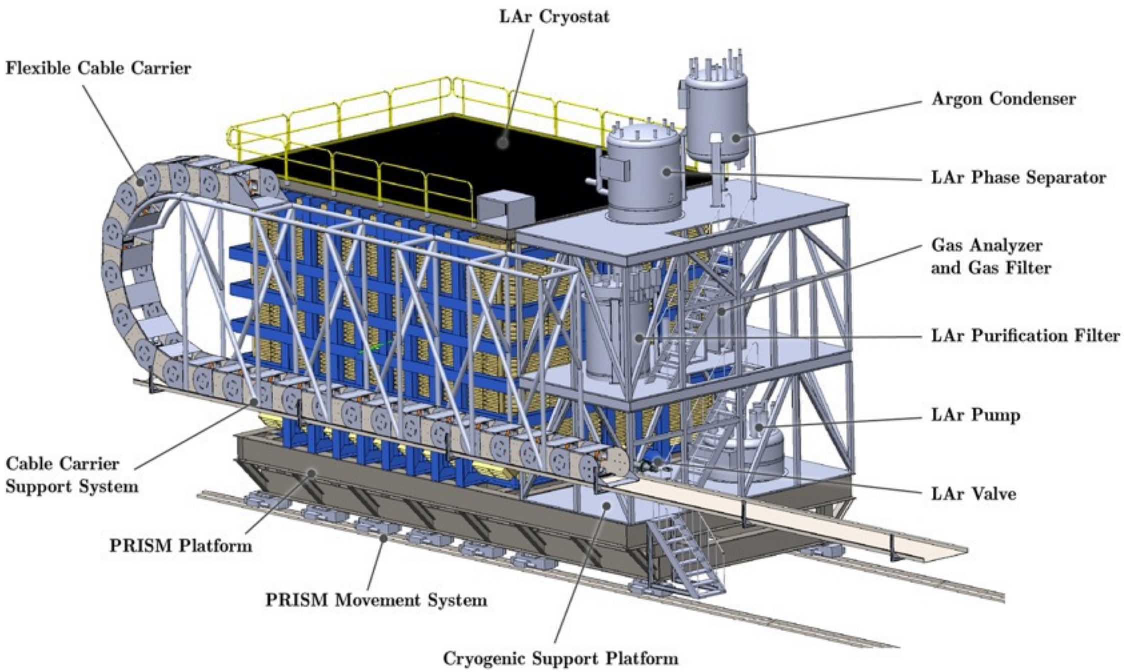


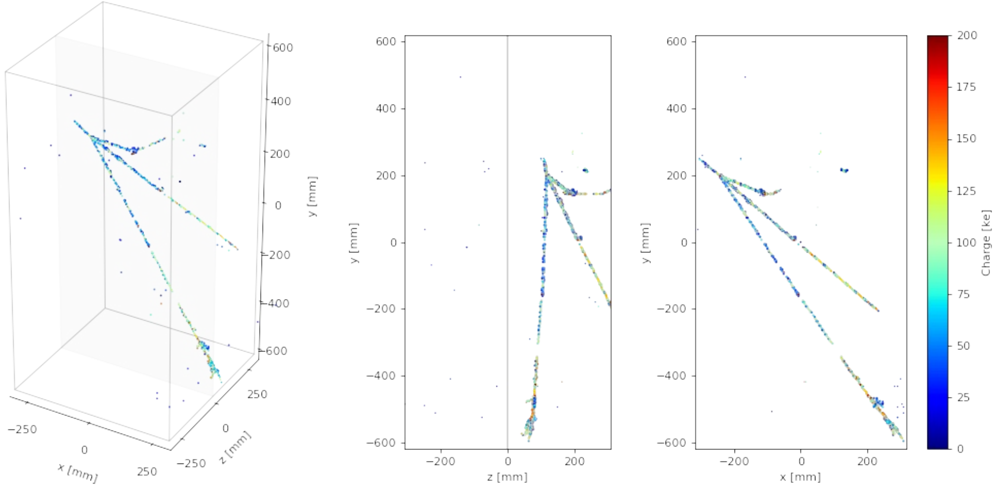


ND-LAr: Liquid Argon TPC

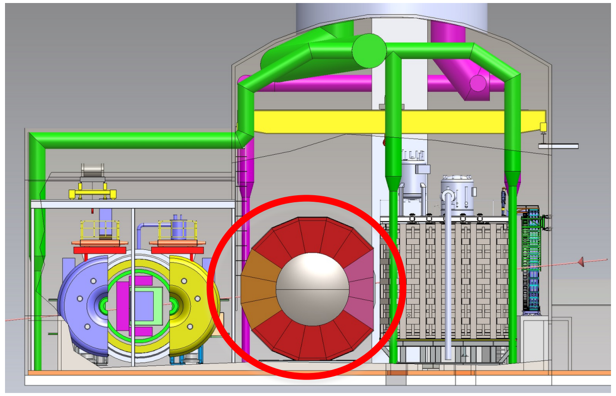
- LAr TPC
  - Study detector effects
  - Similar to far detector technology
- High event rate
  - Need compartmentalisation
  - Pixelized readout

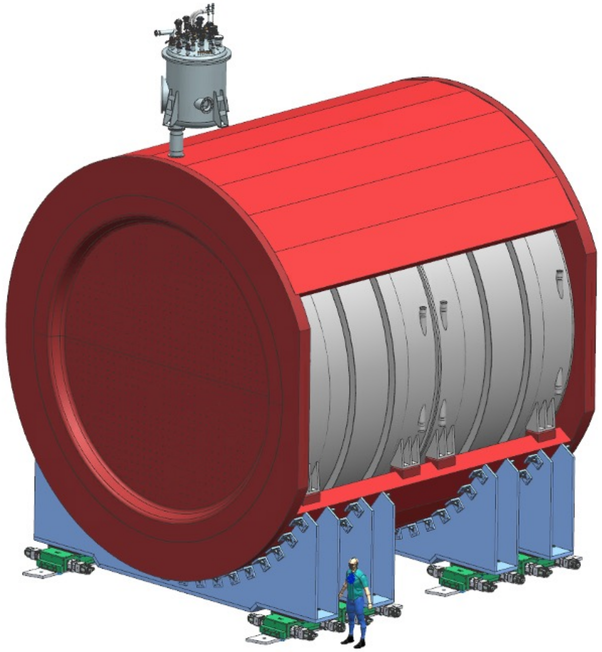




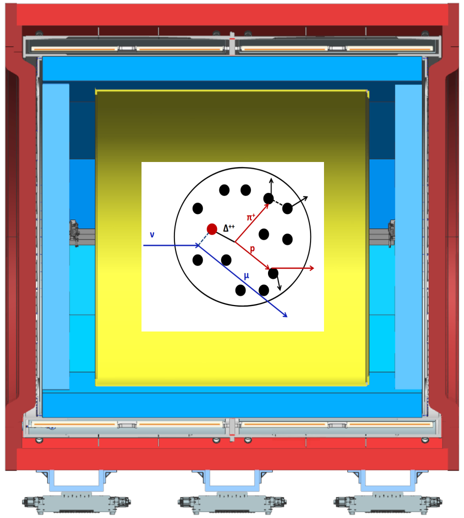


ND-GAr: Gaseous Argon TPC



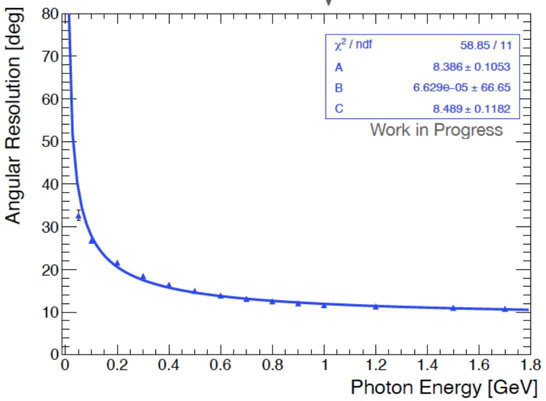


- Main detector components
  - High pressure (10 bar) gas TPC
  - ECAL **&** SC magnet
- Interactions on Ar gas
  - Low tracking threshold
  - Can detect neutrons
- Study nuclear effects

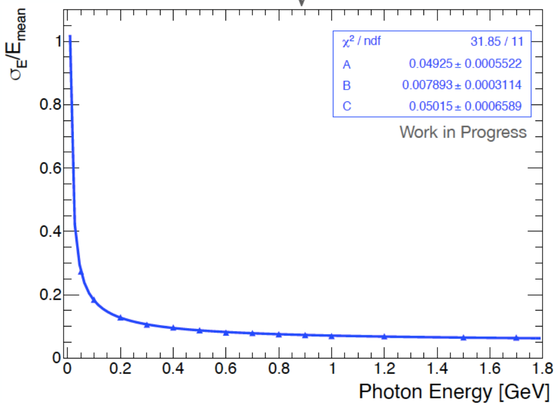


ECAL Performance

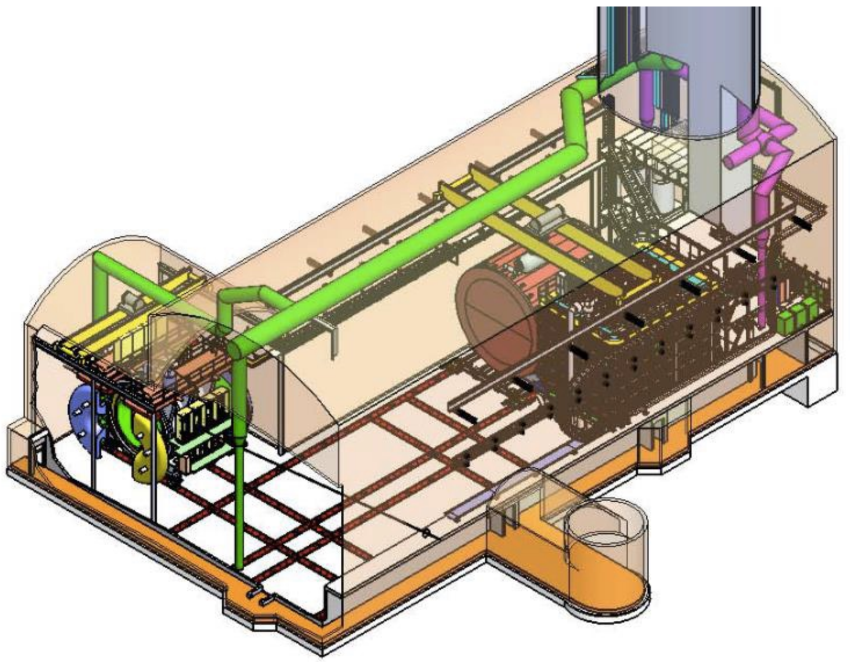
$$AngularResolution = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

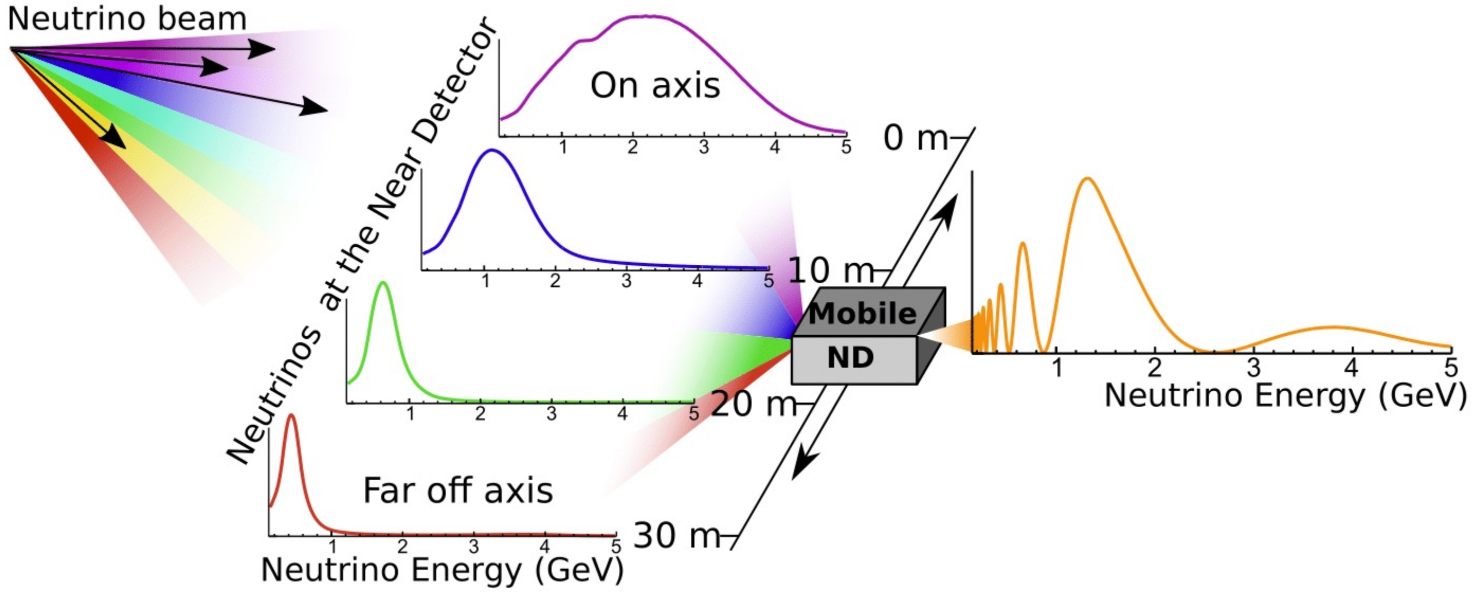


$$\frac{\sigma_E}{E_{mean}} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$



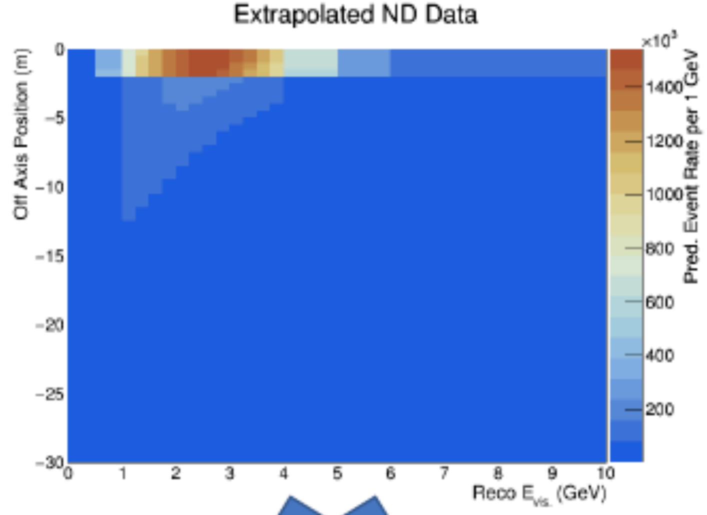
PRISM Concept

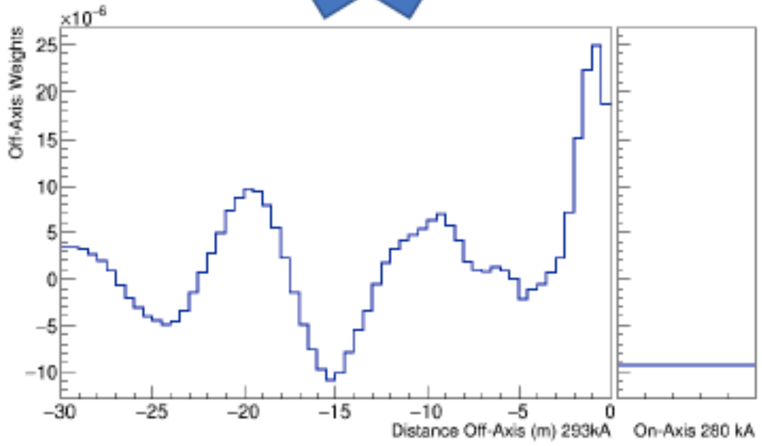


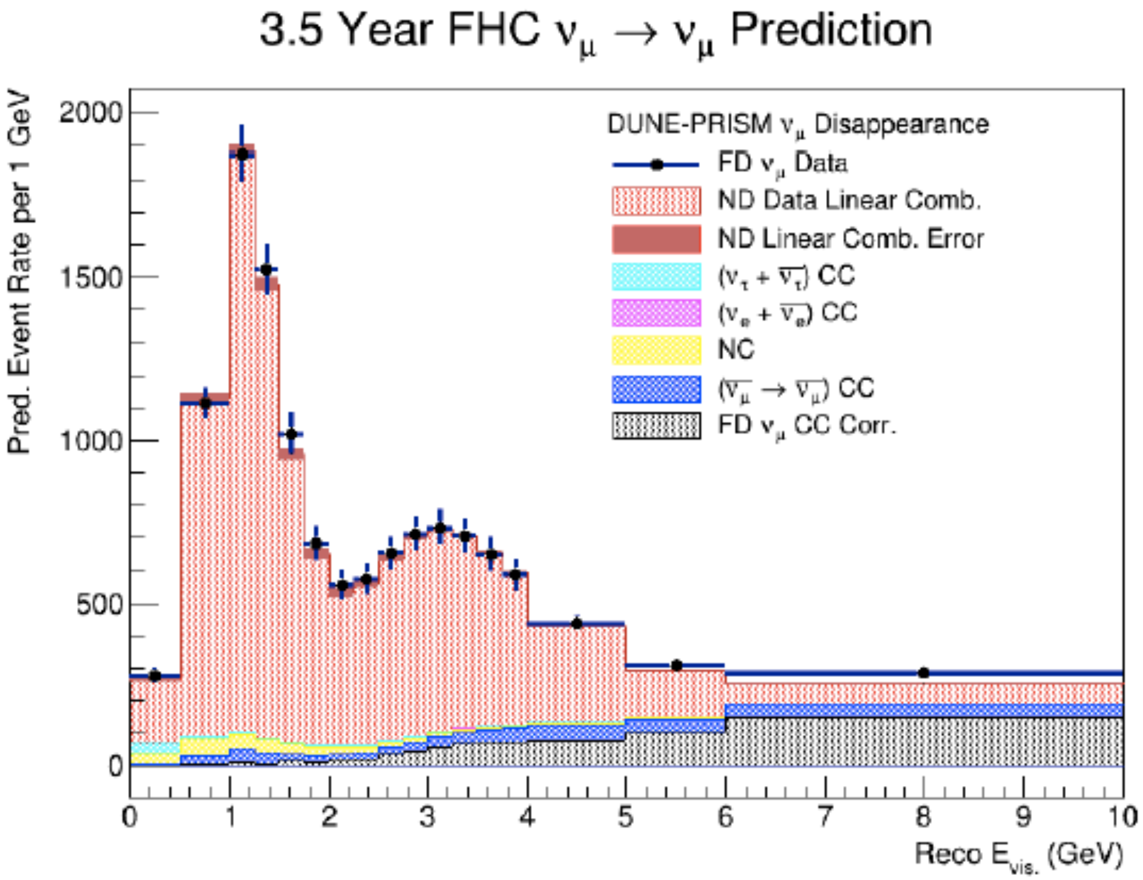


- Neutrino spectrum changes when going off-axis
- Can measure event rates with different fluxes
- Direct linear combination of date at different positions to construct FD oscillated spectrum
- Need to understand detector differences and flux only

PRISM Analysis



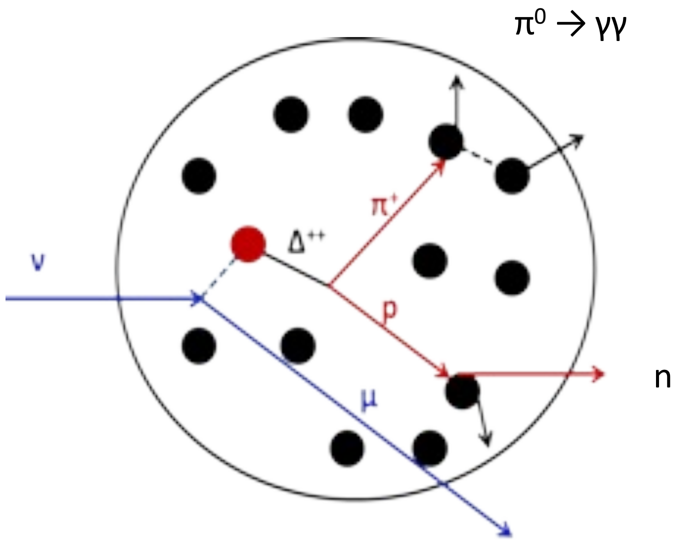




$$\frac{dN_\nu^{det}}{dE_{rec}} = \int \phi_\nu^{det}(E_\nu) * \sigma_\nu^{target}(E_\nu) * D_{\nu_\mu}^{det}(E_\nu, E_{rec}) \, dE_\nu$$

Where are we?

- DUNE needs to make FD prediction, which have a 1-2% accuracy
  - ➢ Event rate and energy scales
- We don’t really understand neutrino interactions
- Need to understand
  - ➢ Cross sections
  - ➢ Nuclear effects (FSI, IS)
  - ➢ All the particles emerging from the nucleus (full differential exclusive cross sections)
- Near Detector Design
  - ➢ Constrain uncertainties
  - ➢ Become independent from uncertainties



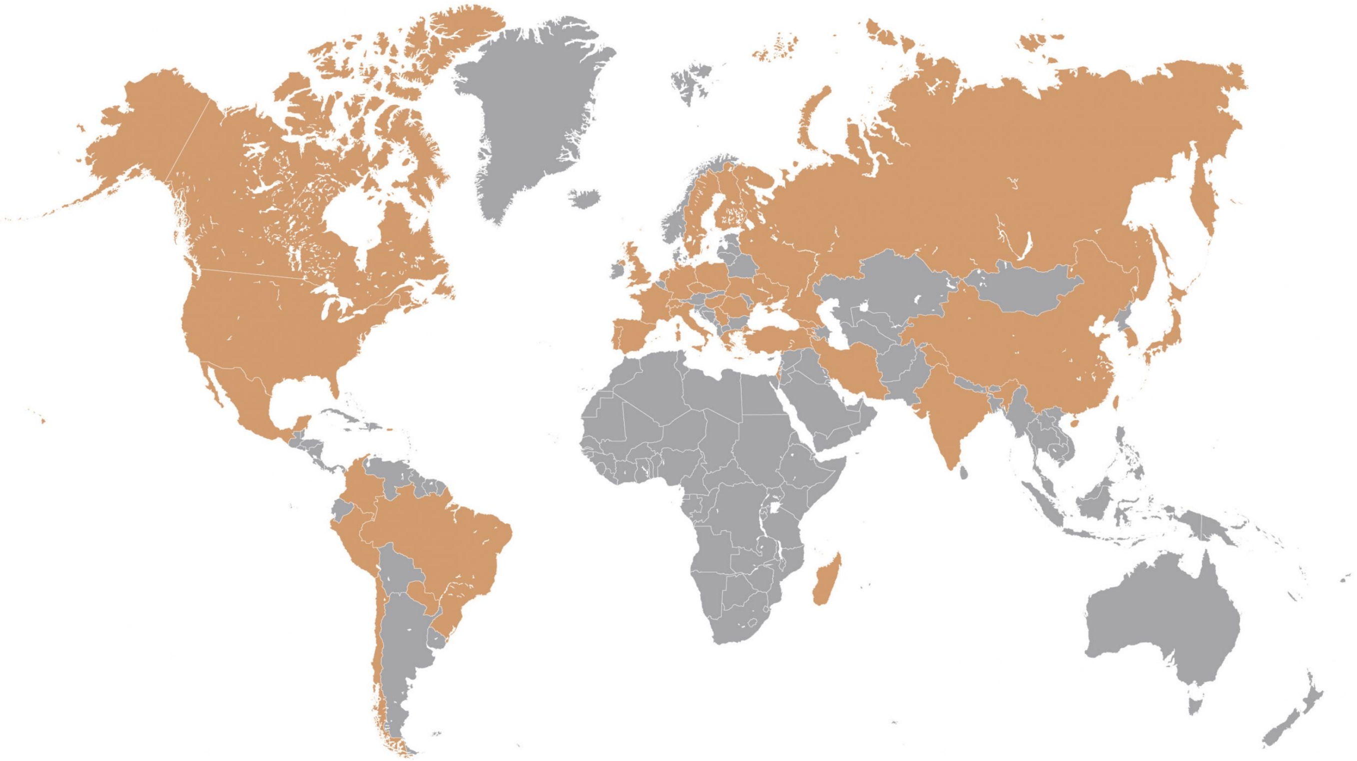
Summary and Conclusion

- DUNE is an neutrino facility with an exciting physics program
- We have designed a capable Near Detector complex to constrain uncertainties
  - ND-Lar
    Liquid Argon TPC similar to FD
  - ND-Gar
    Gaseous Argon Target with low tracking threshold & neutron sensitivity
  - PRISM Concept
    Measure at different off-axis angles/fluxes
  - SAND
    Measure flux and beam stability
- Will need to reach 1-2% systematic uncertainties
  - But this cannot be done without understanding the cross section

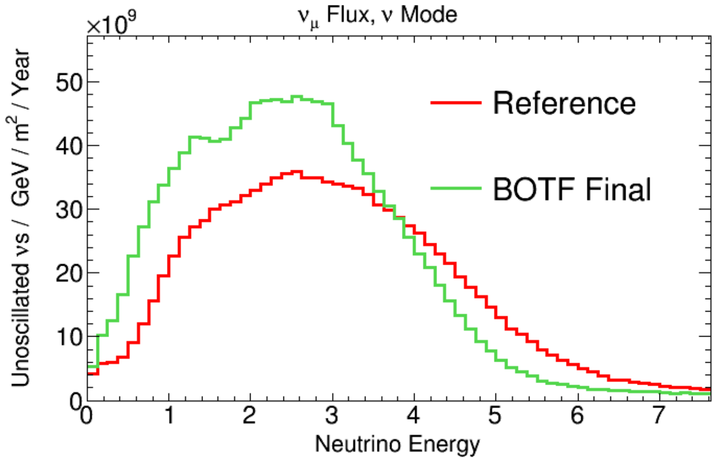
Backup

The DUNE Collaboration

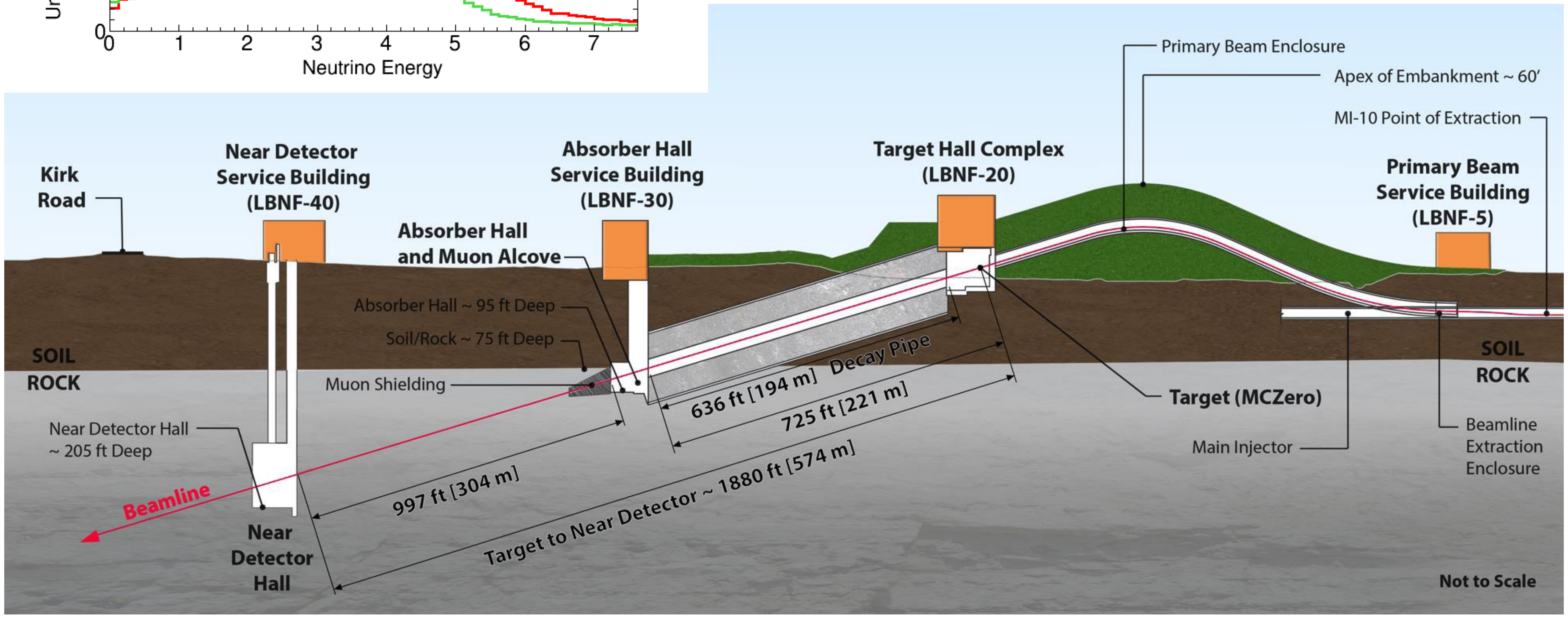
- International Collaboration
  - 1350 members
  - 200+ Institutions
  - 34 countries & CERN



Beam

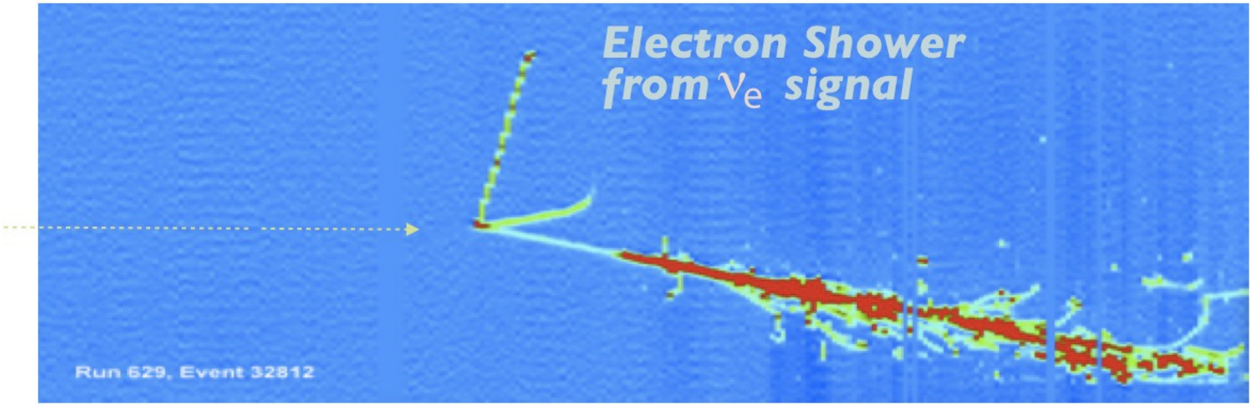


- Proton beam energy 60-120 GeV
- Power 1.2 MW ➔ 2.4 MW
- Neutrinos and anti-neutrinos

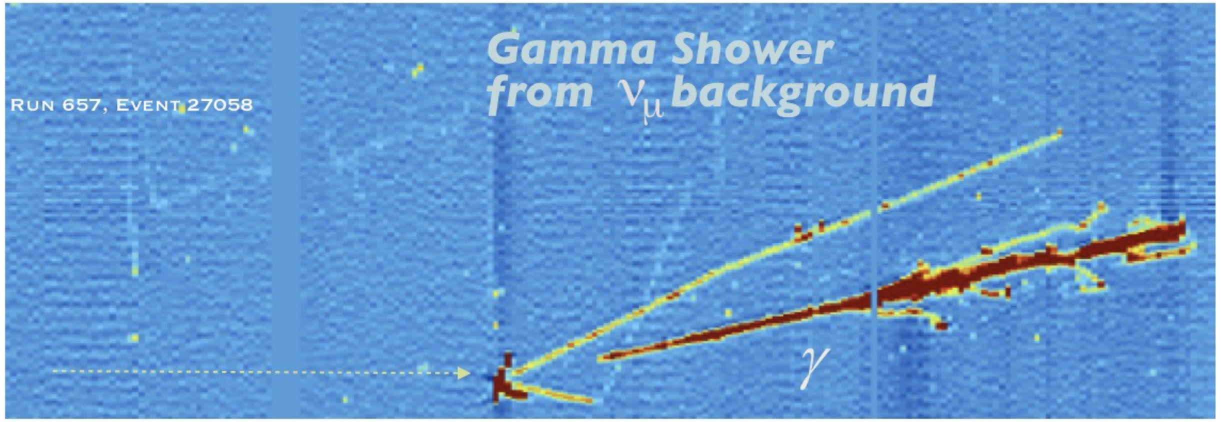


Event identification

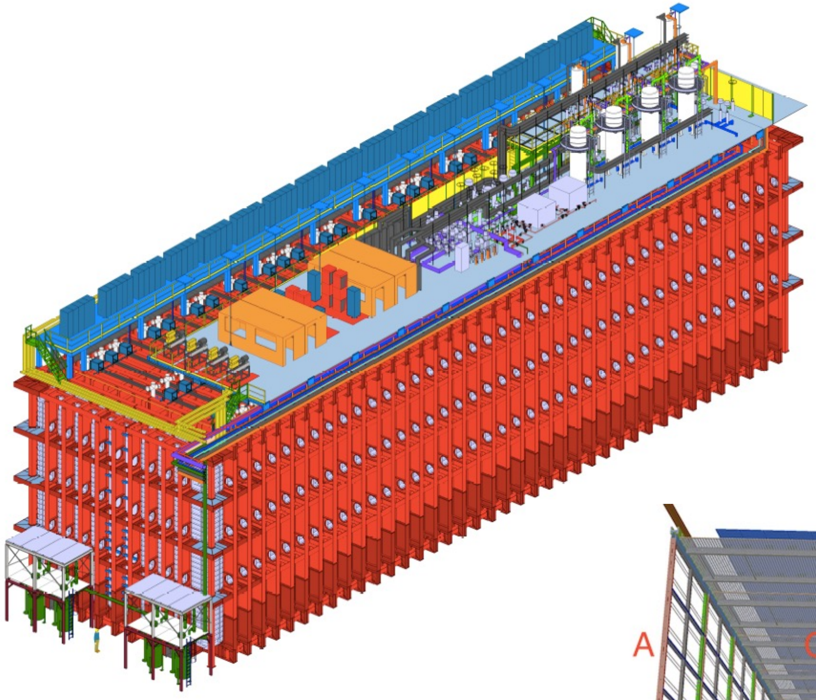
ν_e

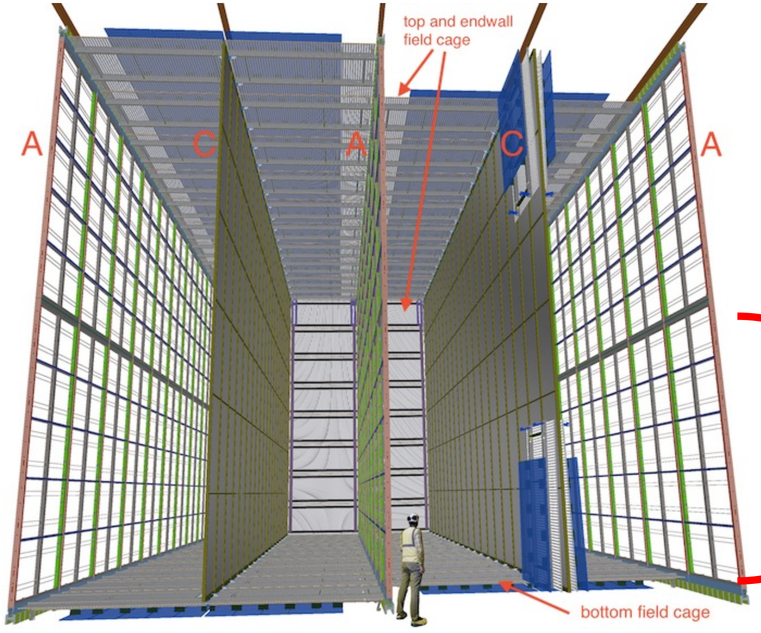


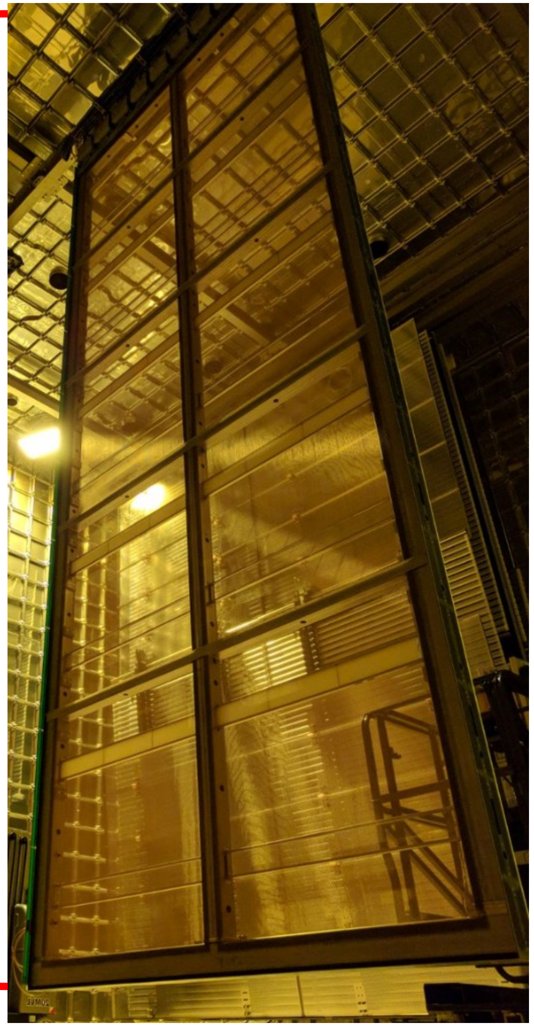
ν_μ



DUNE Far Detector (II)

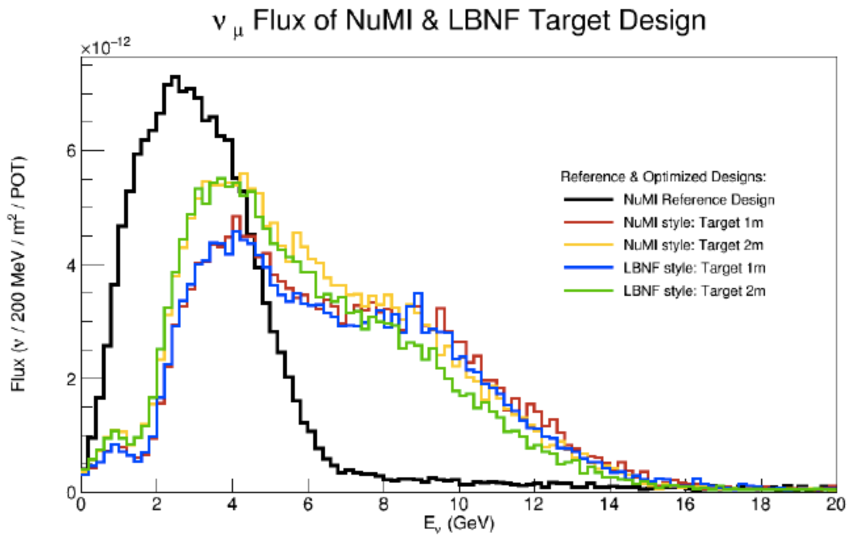


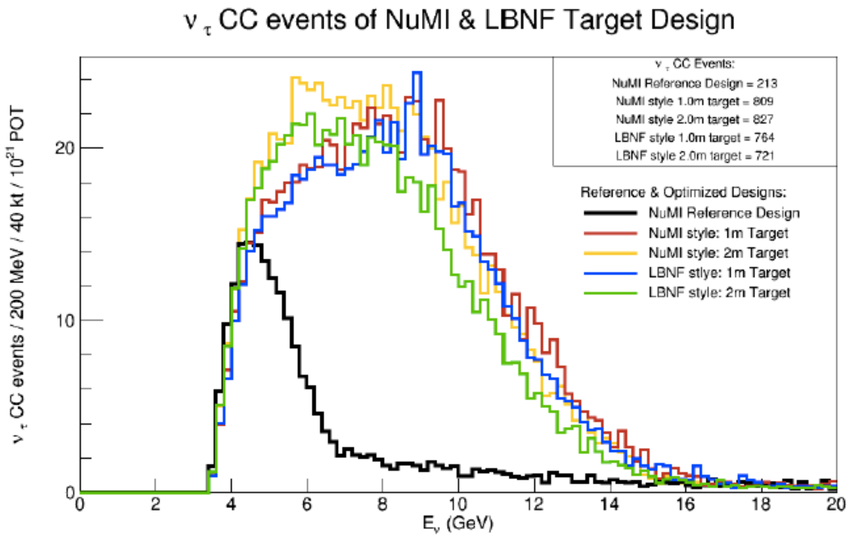




High Energy Tune

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

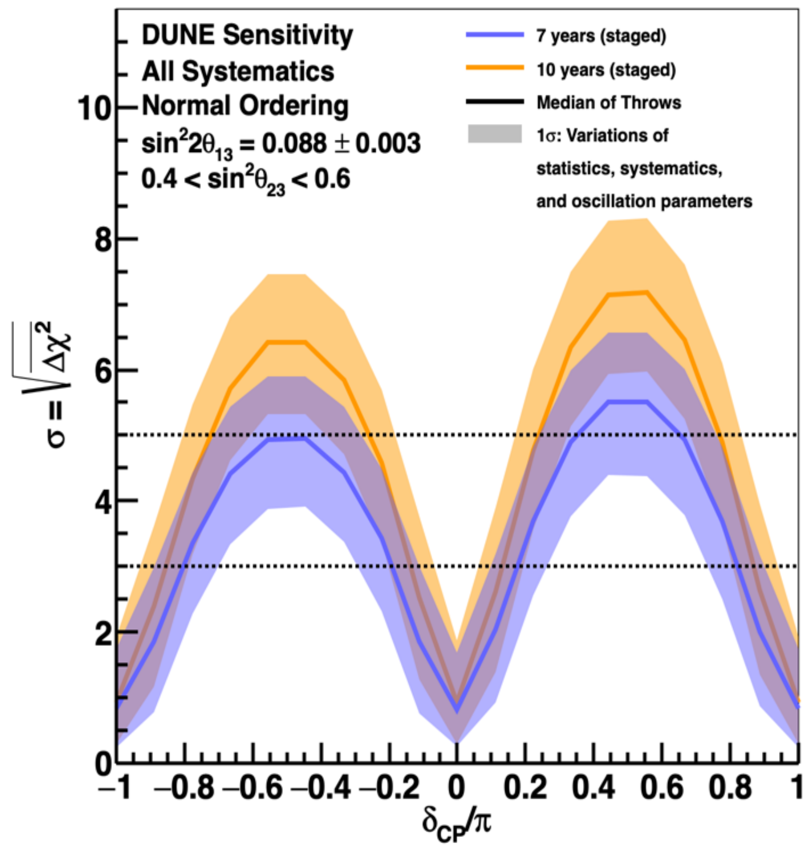




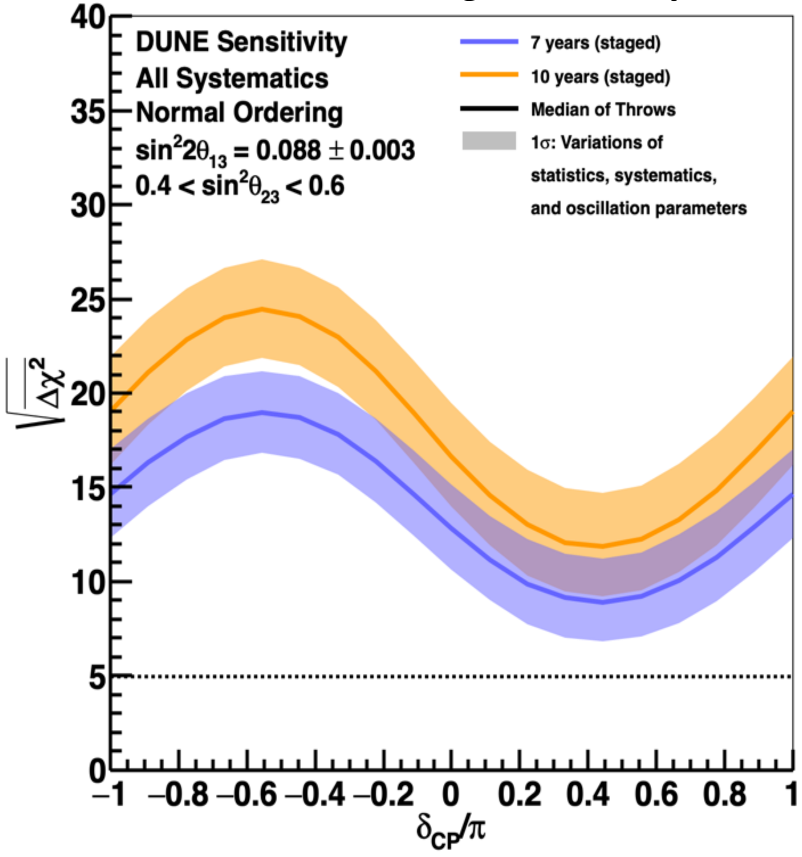
- Physics
  - Tau appearance
  - NSI

DUNE Sensitivity

*CP*v sensitivity



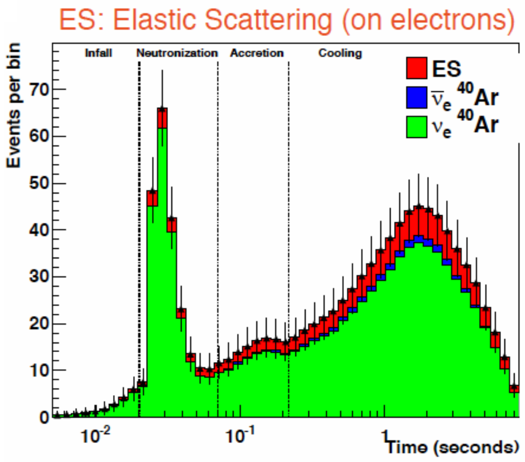
Mass ordering sensitivity



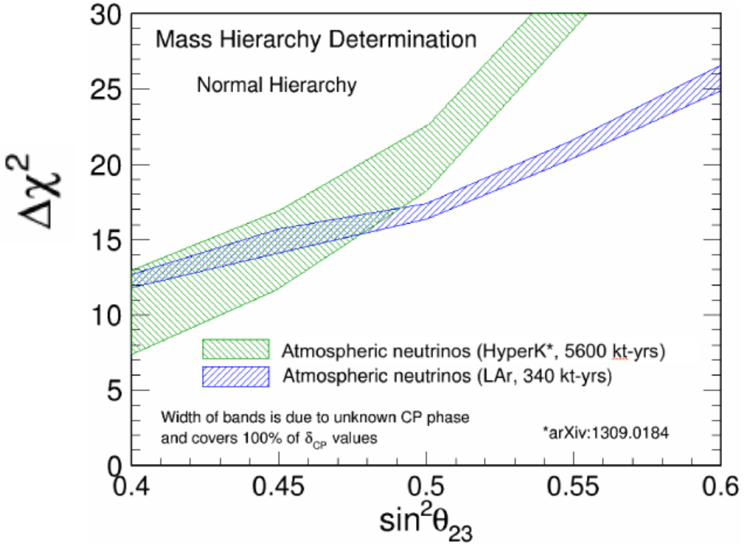
Move quickly to potential ***CP* violation discovery**
Rapid, definitive **mass ordering determination** (>5σ)

Other Physics

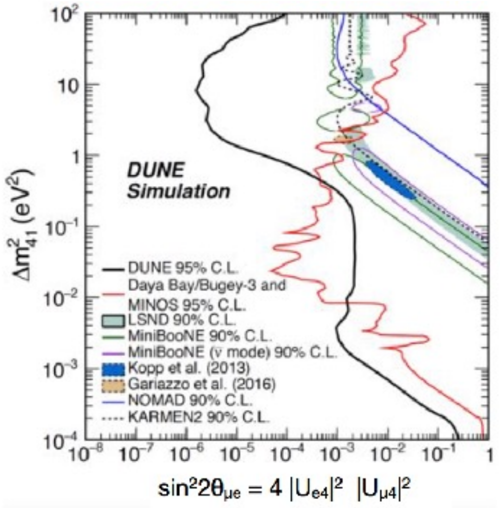
supernova



atmospherics



atmospherics



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