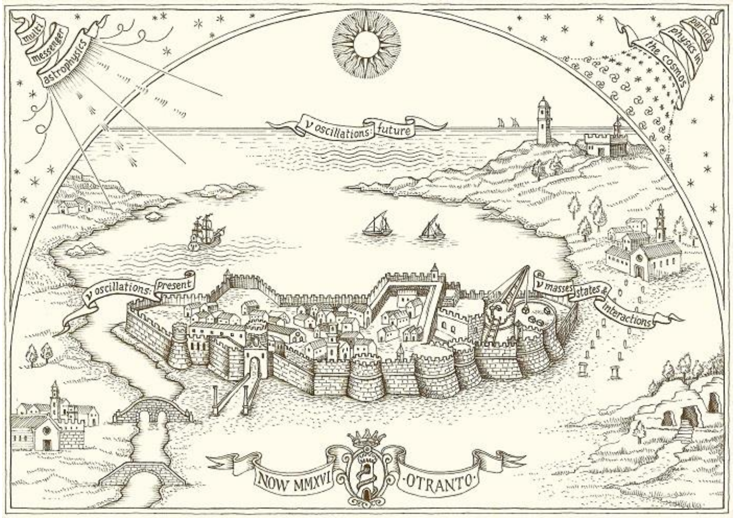
Neutrino Oscillations Physics at DUNE

Dorota Stefan for the DUNE Collaboration

Neutrino **O**scillation **W**orkshop

September 6, 2016



DUNE: Deep Underground Neutrino Experiment

dunescience.org

- DUNE has broad international support and is growing: ~70 new collaborators this calendar year.
- **894 Collaborators** from 154 Institutions in 28 countries in total.

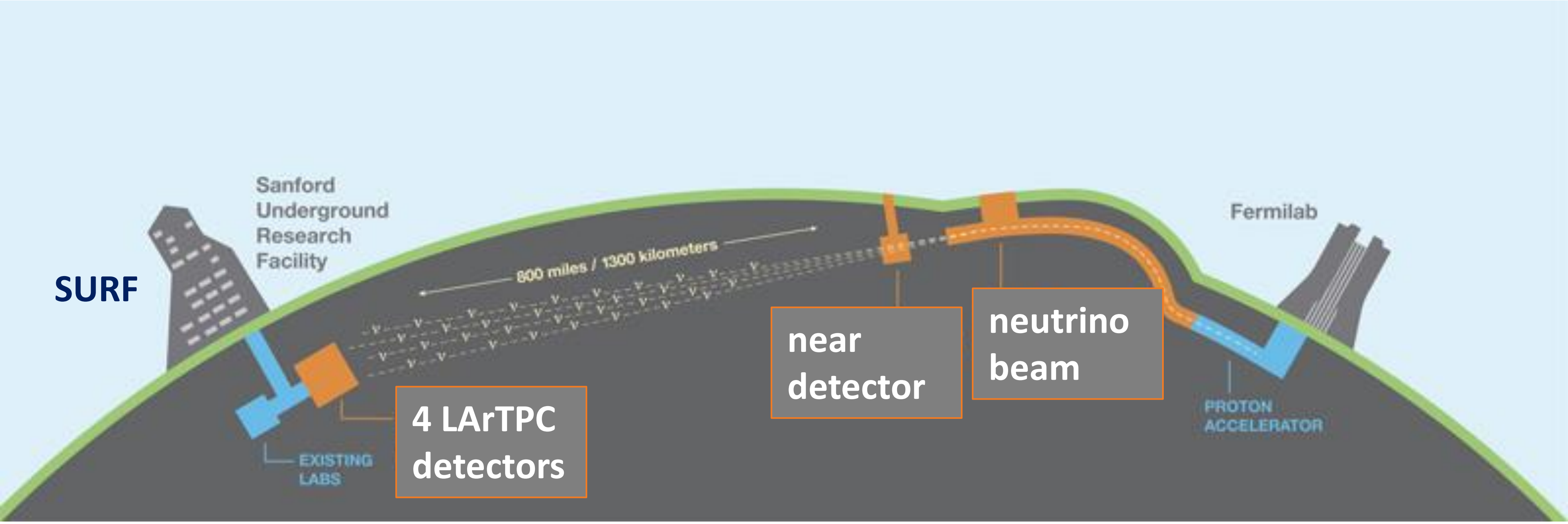
Deep Underground Neutrino Experiment
physics goals

- **Long Baseline Neutrino Oscillations**.
- Proton Decay.
- Neutrino Astrophysics, including supernovae neutrino bursts.
- **Atmospheric neutrinos**.
- Neutrino cross-sections.
- **Sterile neutrinos**.

Deep Undeground Neutrino Experiment

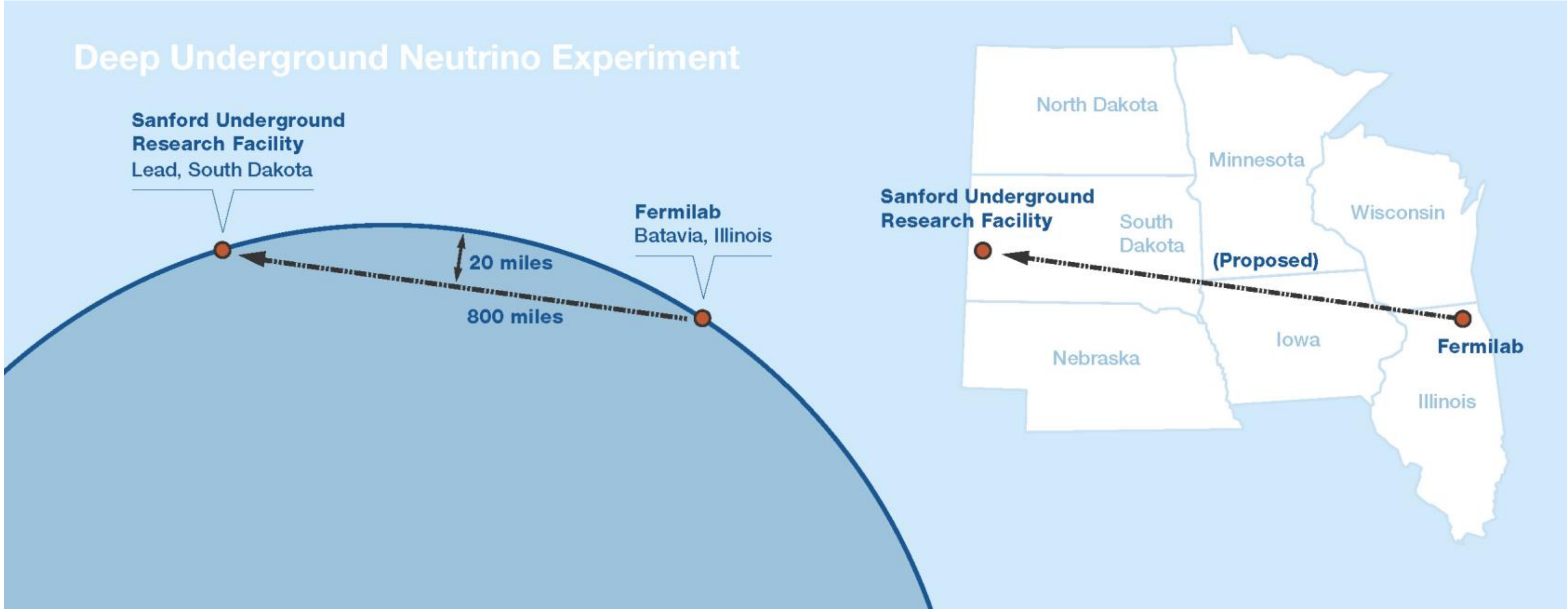
- DUNE will use the world's most intense neutrino beam.
- DUNE will use the world's largest LArTPC neutrino detector to study neutrinos.
- Ongoing extensive prototyping and testing program to ensure that all parts of the technology are thouroughly studied and tested.

DUNE and Long Baseline Neutrino Facility (LBNF)



- A high-intensity wide-band neutrino beam originating at FNAL:
  1.2 MW proton beam upgradable to 2.4 MW.
- Fine-grained near detector complex to measure the neutrino flux:
  enabling unprecedented studies of neutrino interactions.
- A ~40kt fiducial mass liquid argon far detector:
  - located 1300 km baseline at SURF's 4850 ft / 1.5km level (2300 mwe),
  - staged construction of four ~ 10 kt detector modules. First module to be installed starting in 2024.

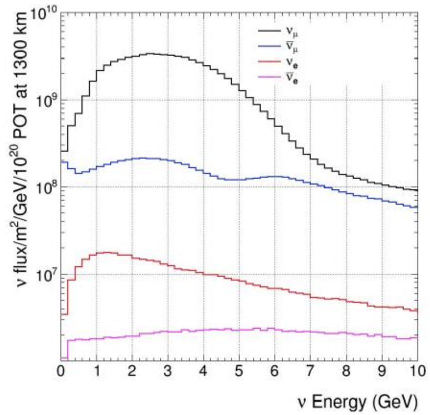
Long Baseline Neutrino Facility (LBNF) and DUNE



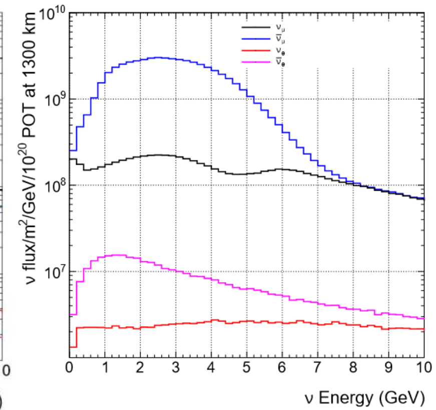
LBNF

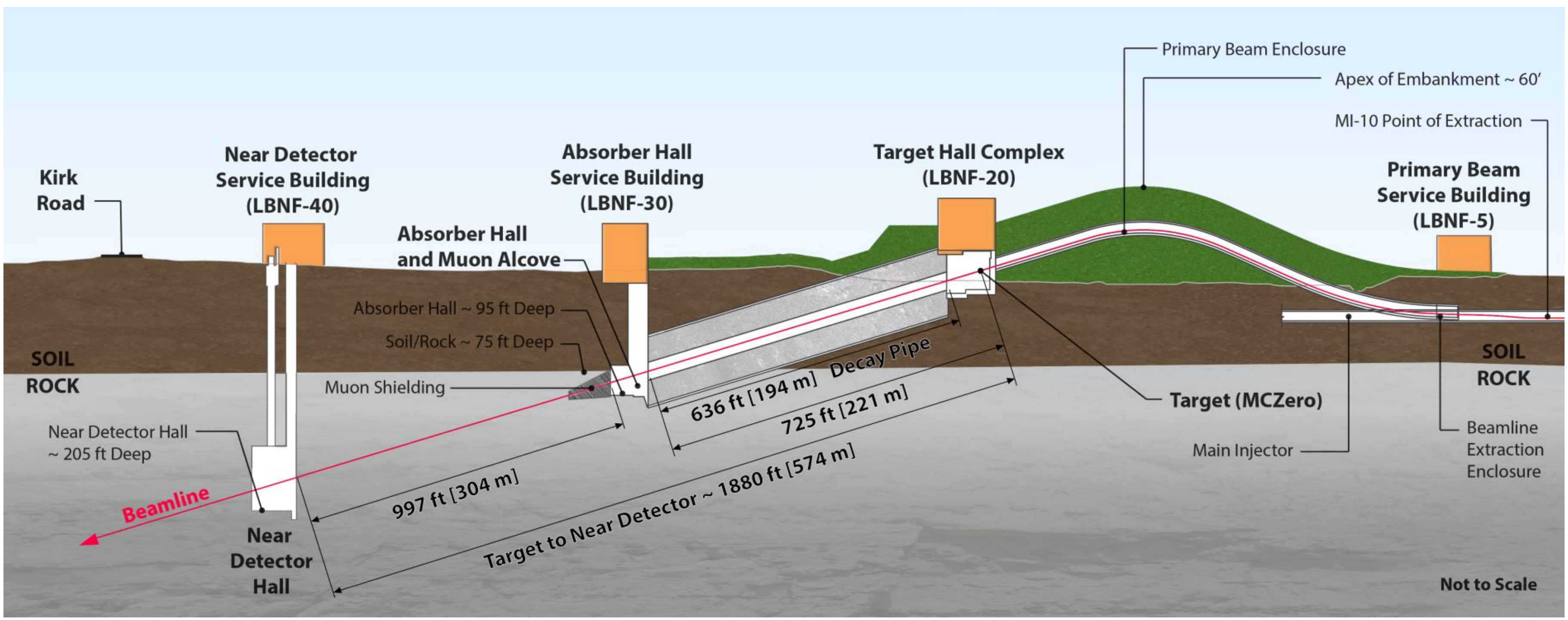
- **60 – 120 GeV proton beam energy**.
- **Initial power 1.2 MW upgradable to 2.4 MW**.
- 10^{21} protons on target per year.
- Beam optimization: inspired by LBNO approach, **genetic algorithm used to optimize horn design** => increases neutrino flux at lower energies for better physics sensitivity.

neutrino mode

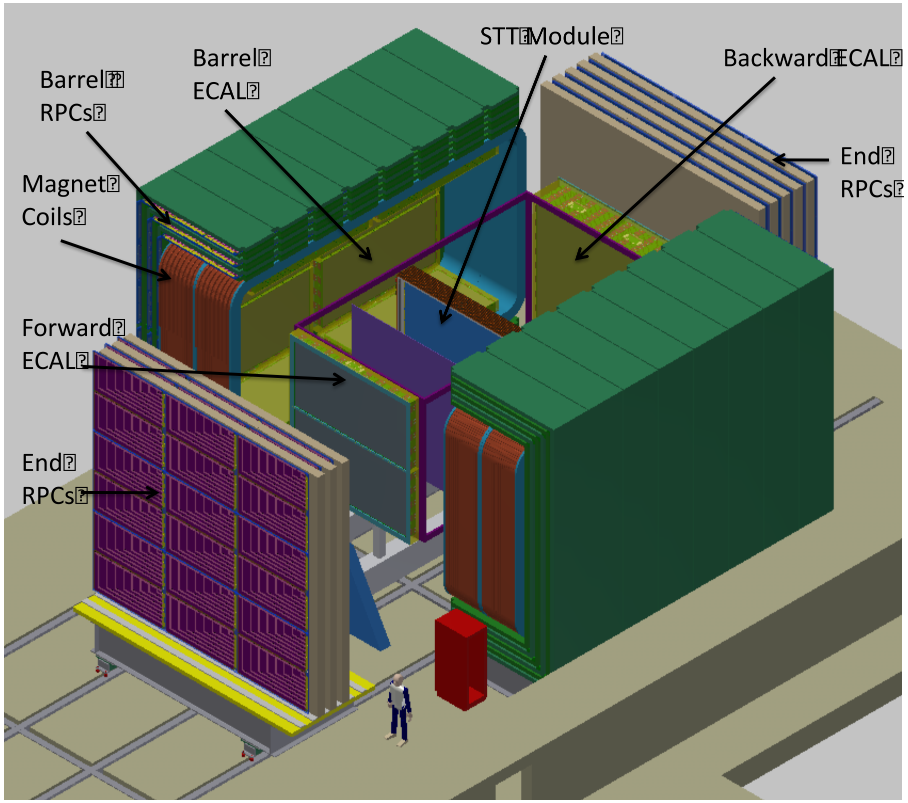


antineutrino mode





Near Detector



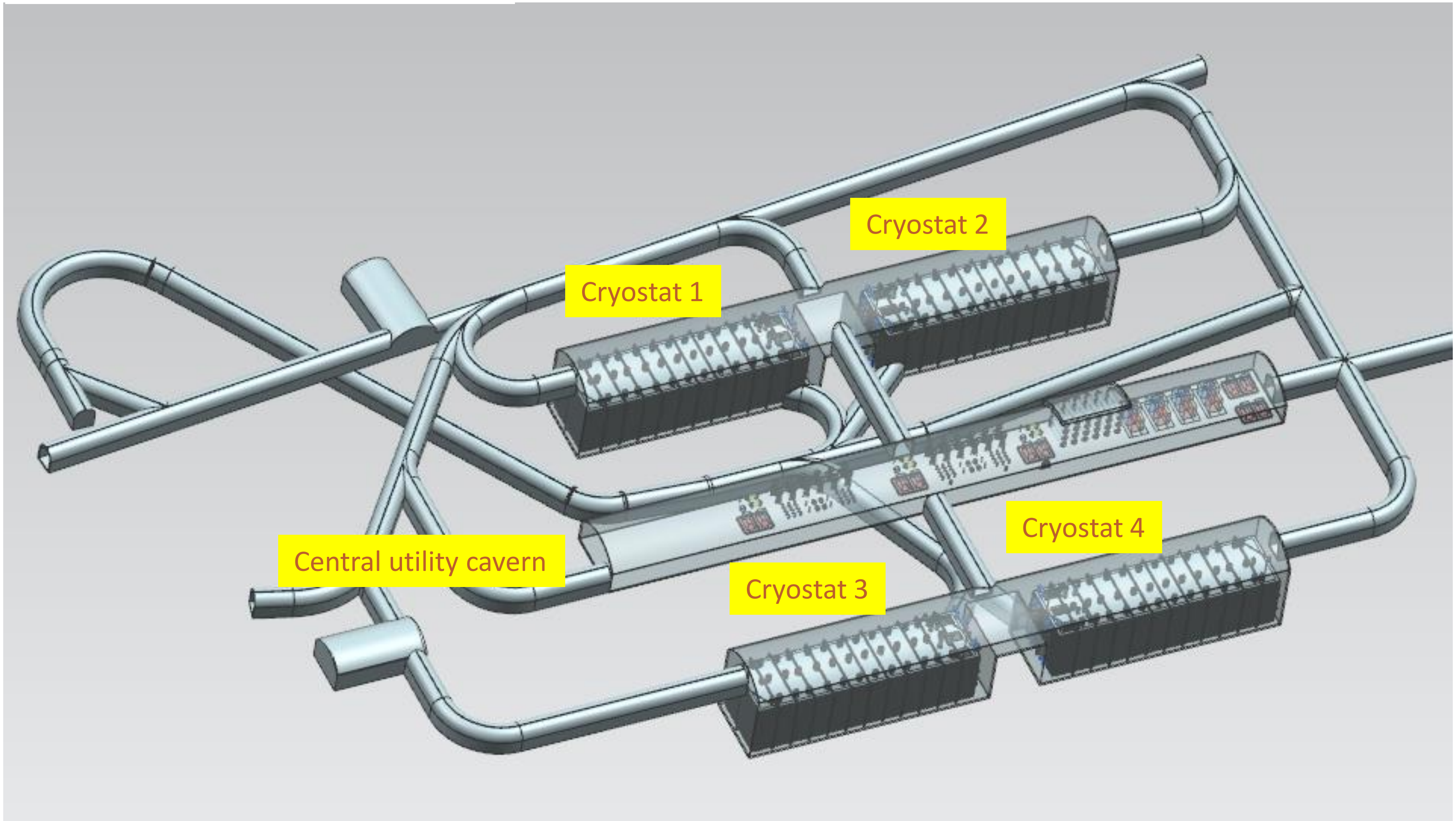
Goals of near detector:

- Constraining the systematic uncertainties in oscillation studies: precisely measure the neutrino fluxes: ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$.
- Precision measurements of neutrino interactions e.g. cross sections, exclusive processes, structure of nucleons and nuclei.
- Conducting searches for new physics e.g. sterile neutrinos.

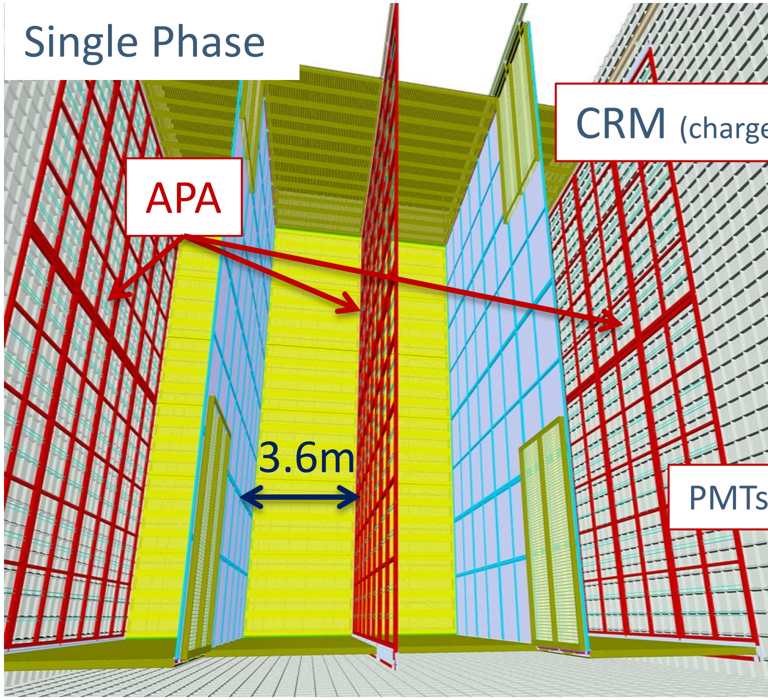
- **Fine grained tracker inspired by NOMAD**.
- Magnetized straw-tube based tracking system.
- Lead-scintilator ECAL.
- RPC muon tracker.
- Considered options: magnetized LArTPC, high pressure GArTPC.

Far Detector

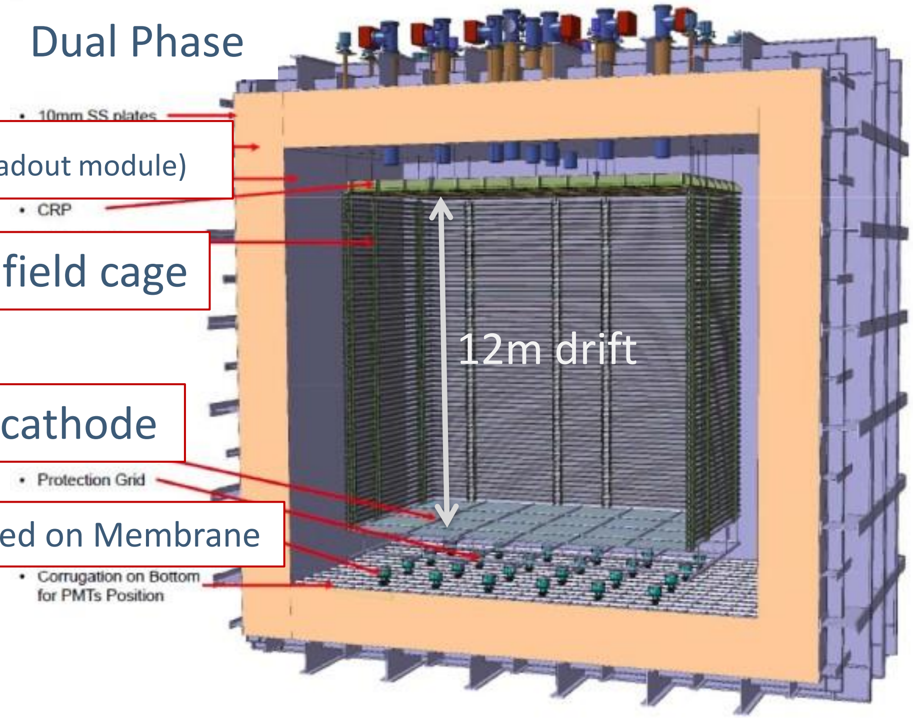
Each Cryostat holds 17.1kt LAr



Far Detector: Single Phase, Dual Phase



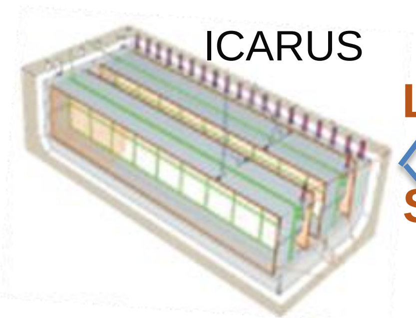
- Readout of ionization charge: **A**node **P**lane **A**ssemblies with three instrumented wire planes on each side (1 collection view + 2 induction views).
- Scintillation light collected by Silicon Photomultiplier (SiPM).
- Four horizontal drift regions 3.6 m each.



- Readout of ionization charge:
  - ionization electrons extracted into Ar gas phase
  - charge amplification via large electron multipliers (LEM)
  - CRM readout: 2 views in *collection* mode
- Single, 12m long vertical drift.
- Scintillation light collected by PMTs located below cathode.

LArTPC development path

Single-Phase

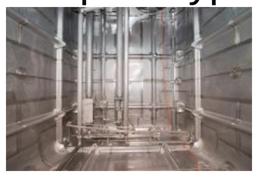


ICARUS

LBL

SBL

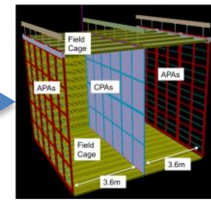
35-t prototype



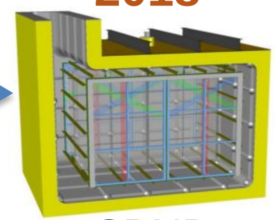
2015

MicroBooNE

DUNE SP PT @ CERN

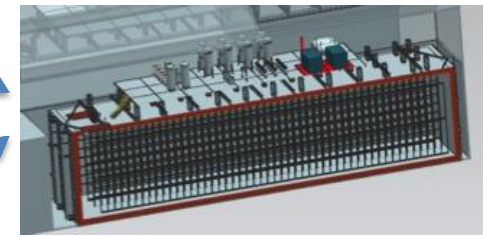


2018



SBND

DUNE Reference Design

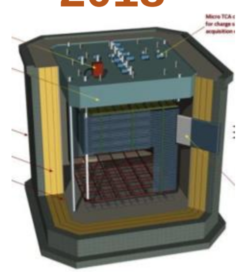


Dual-Phase

2016

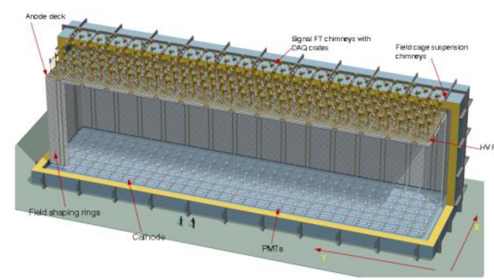
WA105: 1x1x3 m^3

2018



DUNE DP PT @ CERN

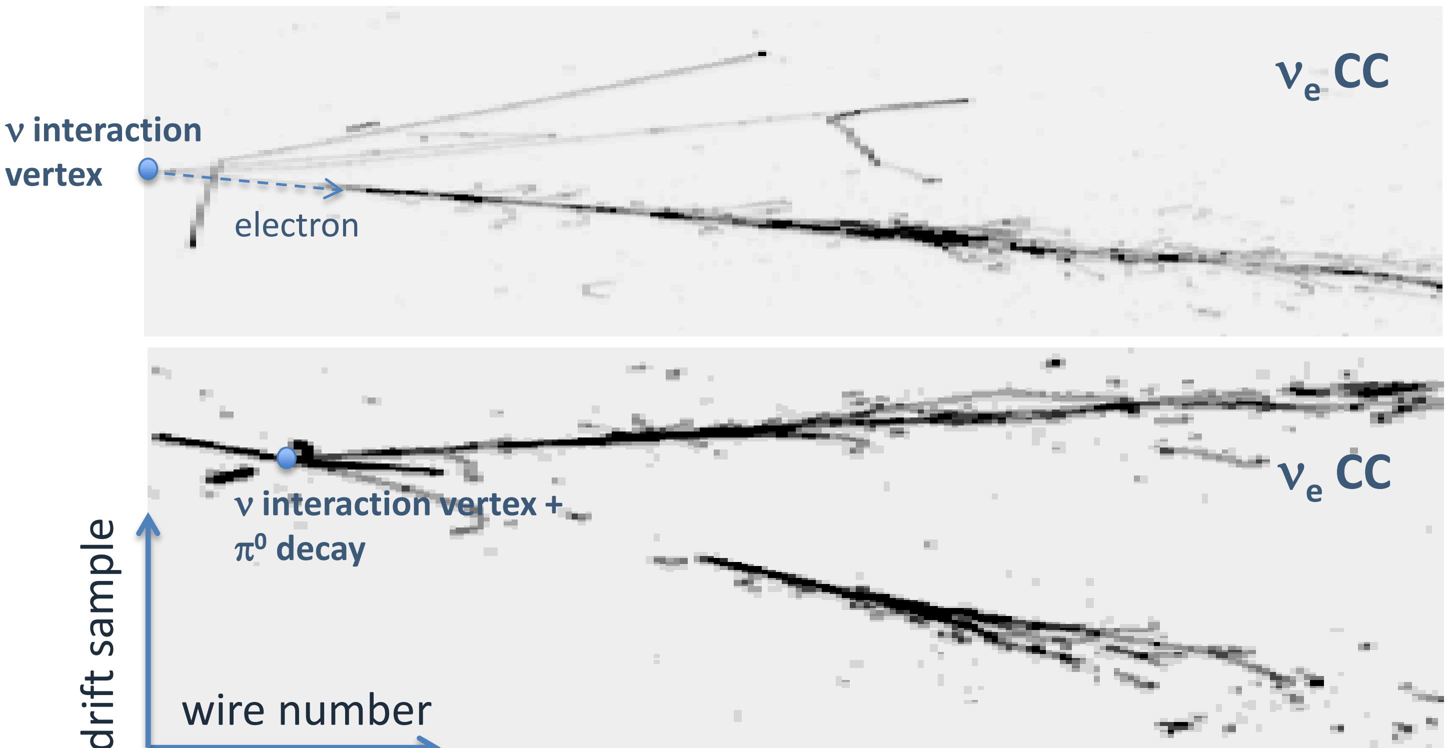
DUNE Alternative Design



Neutrino Platform @ CERN in Paola Sala's talk

Liquid Argon TPC

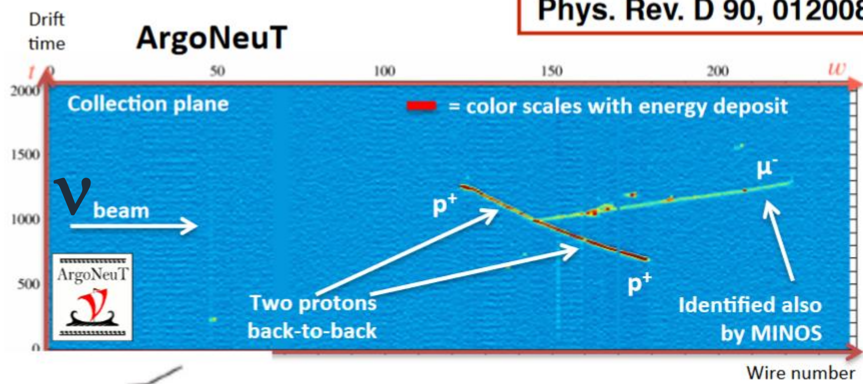
- Has both excellent spatial and calorimetric resolution: visibility of neutrino vertex region details makes this technology very competitive with respect to other solutions.
- Provides high quality tracking of charged particles tracks down to low momenta.

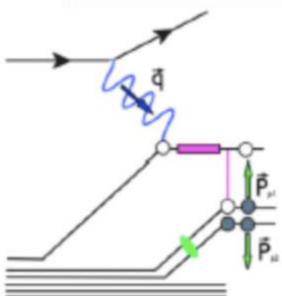


LArSoft, Genie, G4, simulated neutrino interaction in DUNE far detector

Similar topologies of events are expected in DUNE

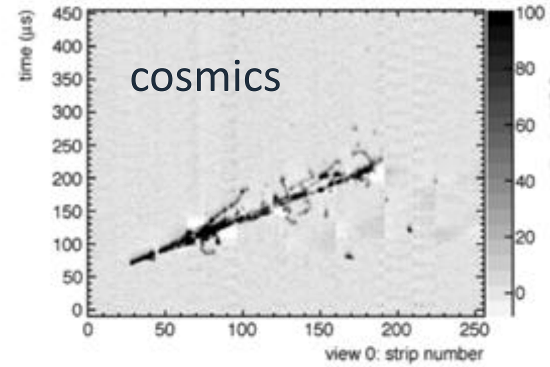
Phys. Rev. D 90, 012008 (2014)



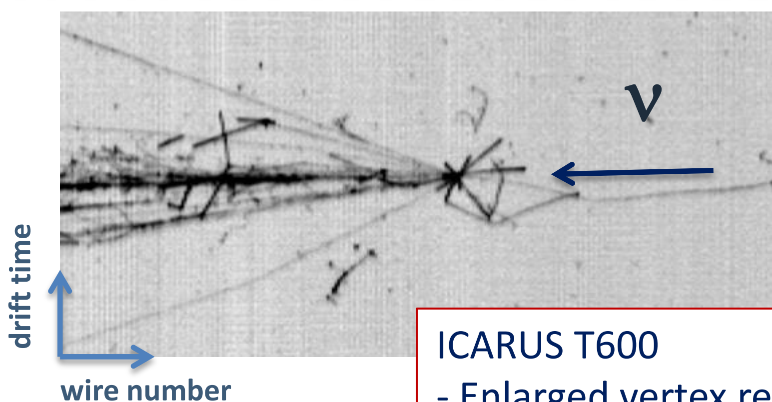


b-to-b proton events described by pion production and re-absorption model

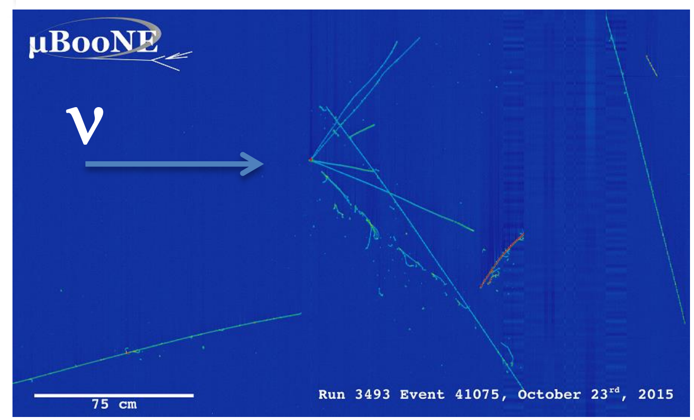
EM shower



Zurich 200 liter prototype
arXiv: 1301.4817



ICARUS T600
- Enlarged vertex region



Long baseline neutrino oscillations physics

Selected topics:

- CPV in the leptonic sector.
- Neutrino mass ordering.
- Precision Oscillation Physics and testing the 3-flavor paradigm.

$\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\Theta_{23} \sin^2 2\Theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$

$$+ \sin 2\Theta_{23} \sin 2\Theta_{13} \sin 2\Theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{13} \frac{\sin(aL)}{(aL)} \Delta_{21} \cos(\Delta_{31} + \delta_{CP})$$

$$+ \cos^2\Theta_{23} \sin^2 2\Theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2$$

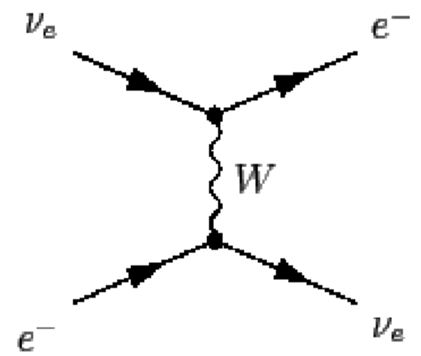
$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$
$a = G_F N_e / 2^{1/2}$

ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP} and matter effects – measurements of all four in a single experiment.

Matter Asymmetry

Electrons are present in matter while positrons and other leptons are not:

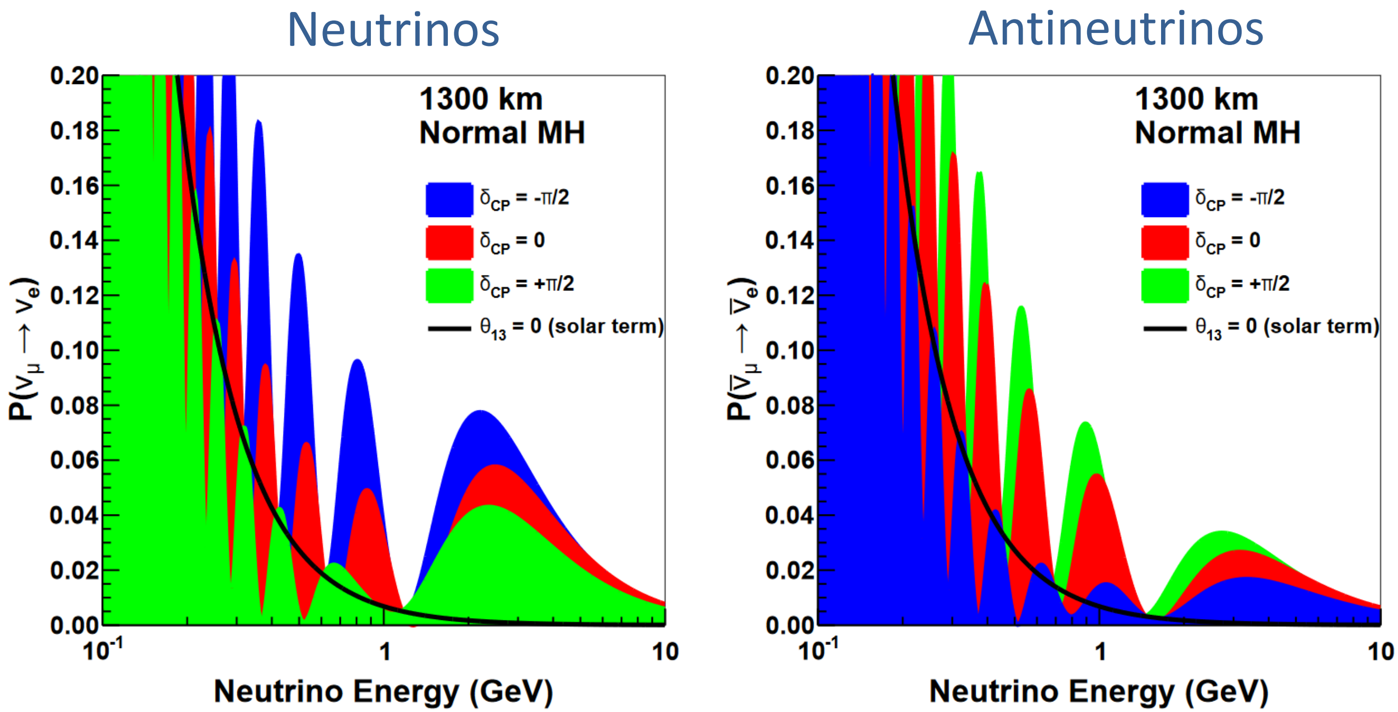
- CC matter effects occur for ν_e only, $\bar{\nu}_e$ (and ν_μ, ν_τ) have only NC matter effect interactions.
- **Normal hierarchy**: matter effect enhances ν_e appearance probability and suppresses $\bar{\nu}_e$ appearance probability (opposite for inverted hierarchy).



Charged-Current Coherent Forward Scattering on Electrons:

ν_e only

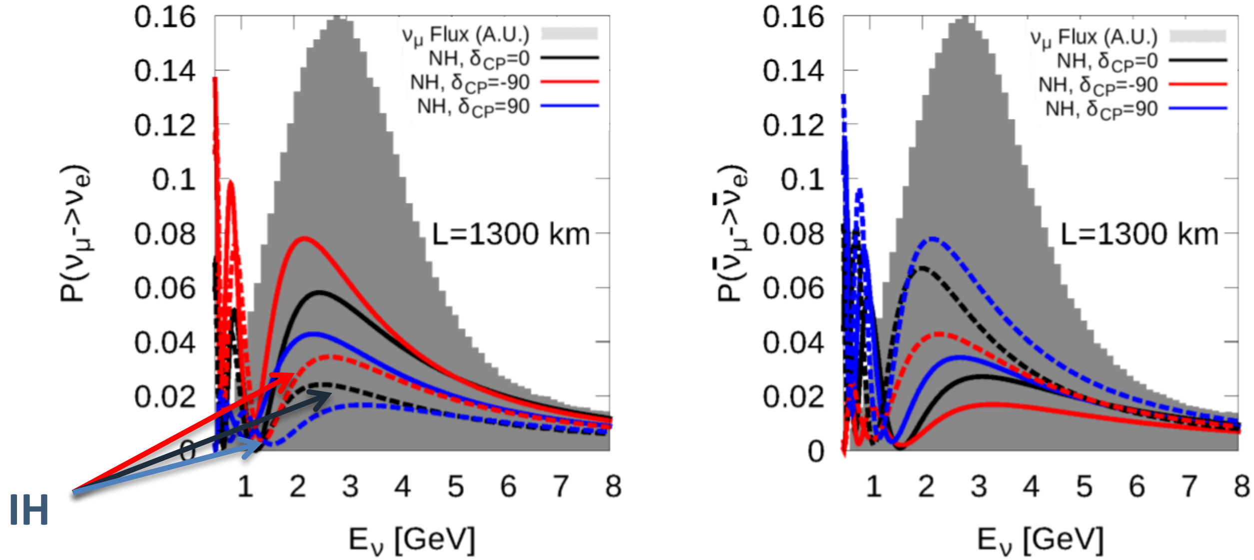
δ_{CP}



- δ_{CP} affects both the amplitude and frequency of oscillation.
- Measurements of rate of ν_e appearance and spectrum of oscillations down to at least 500 MeV.

CDR, arXiv: 1512.06148

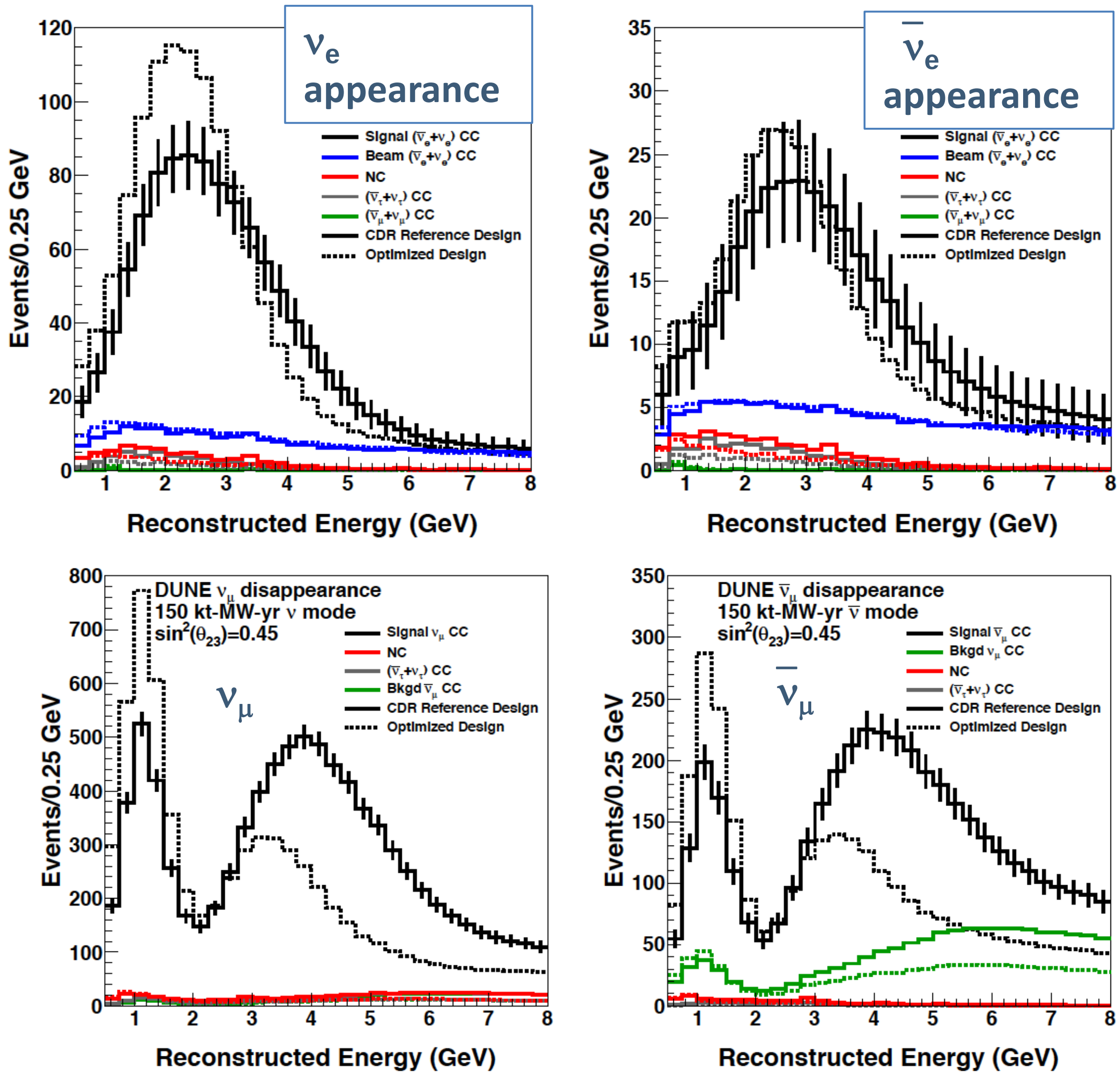
Appearance Probability vs MH/δ_{CP}



Neutrino Oscillation Parameter Sensitivity in Future Long Baseline Experiment, Matthew Bass, PhD Thesis

- Longer baseline enables the extraction of both MH and δ_{CP} even with the 1st oscillation maximum only (but 2^{nd} helps).
- ~ 1300 km the degeneracy between the asymmetries from matter and CP-violation effects can be resolved.

Neutrino appearance and disappearance spectra



- Sensitivities to the neutrino mass hierarchy and the degree of CP violation are obtained by simultaneously fitting:
  - ν_e / $\bar{\nu}_e$ appearance.
  - ν_μ/ $\bar{\nu}_\mu$ disappearance.
- The DUNE analysis will be a 3-flavor oscillation fit such that uncertainties correlated among the four samples will largely cancel.

CDR, arXiv: 1512.06148

Sources of systematic uncertainty

neutrino beam flux

cross sections

detector response parameterization

some **TPC reconstruction** is taken into account

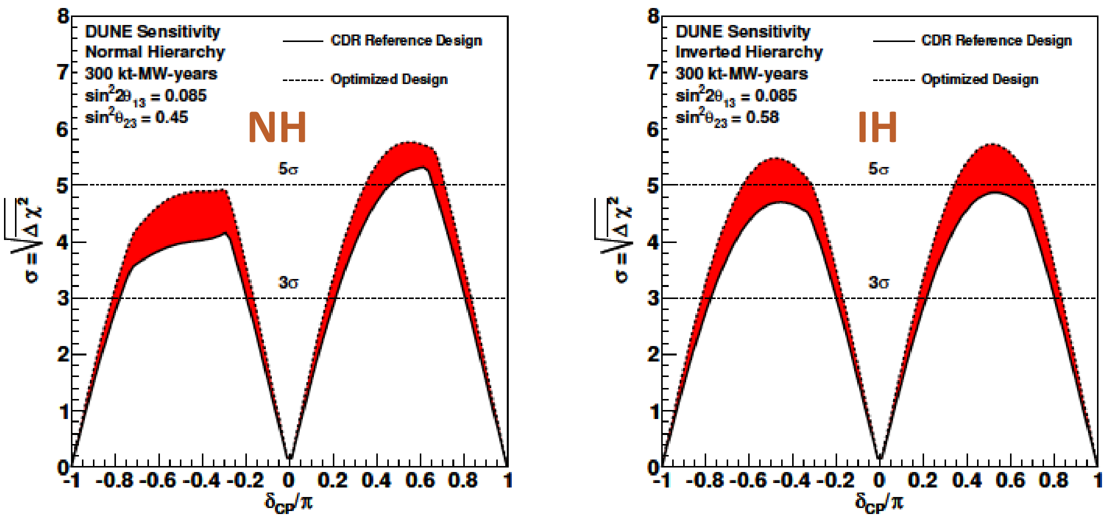
SENSITIVITIES

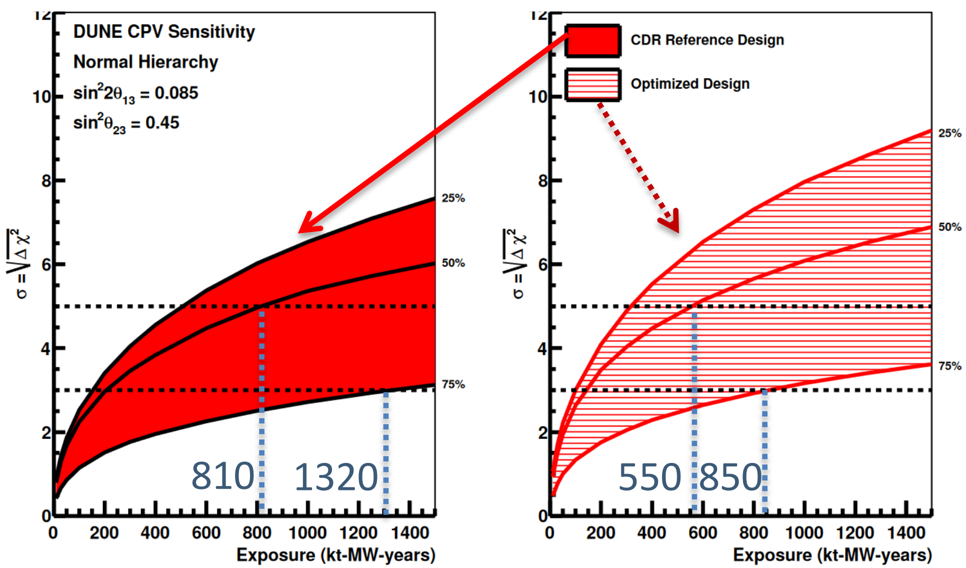
Sensitivities based on **GLoBES** calculations.

Goal for CPV discovery:
- 5% correlated uncertainty (shared between all samples).
- 2% uncorrelated uncertainty for ν_e / $\bar{\nu}_e$.

CDR, arXiv: 1512.06148

Sensitivities: CP-Symmetry Violation





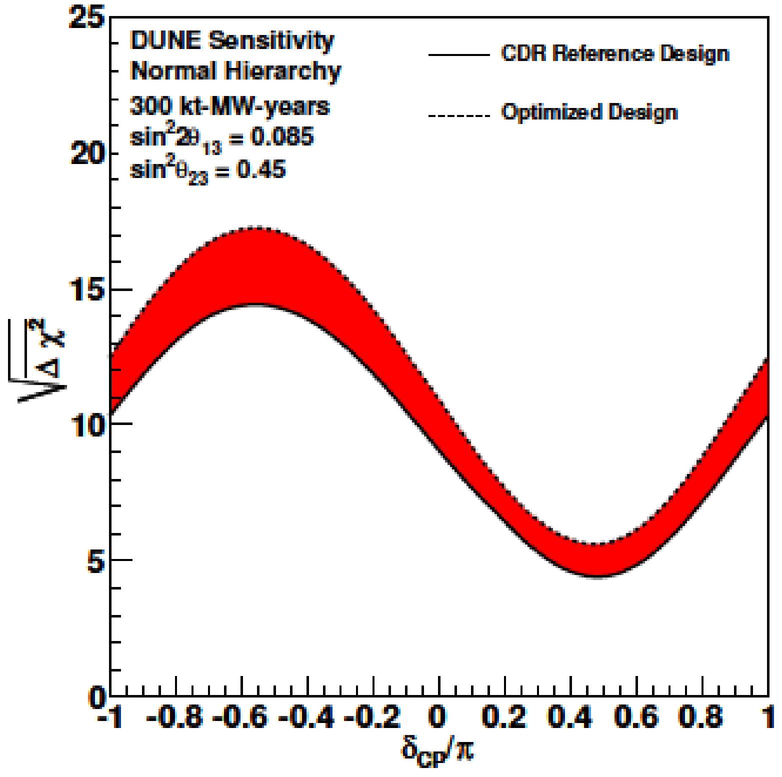
- Significance with which the CP violation can be determined as a function of the value of δ_{CP} with seven years of data taking.

- Significance with which the CP violation can be determined for **25%, 50%, 75% of δ_{CP}**

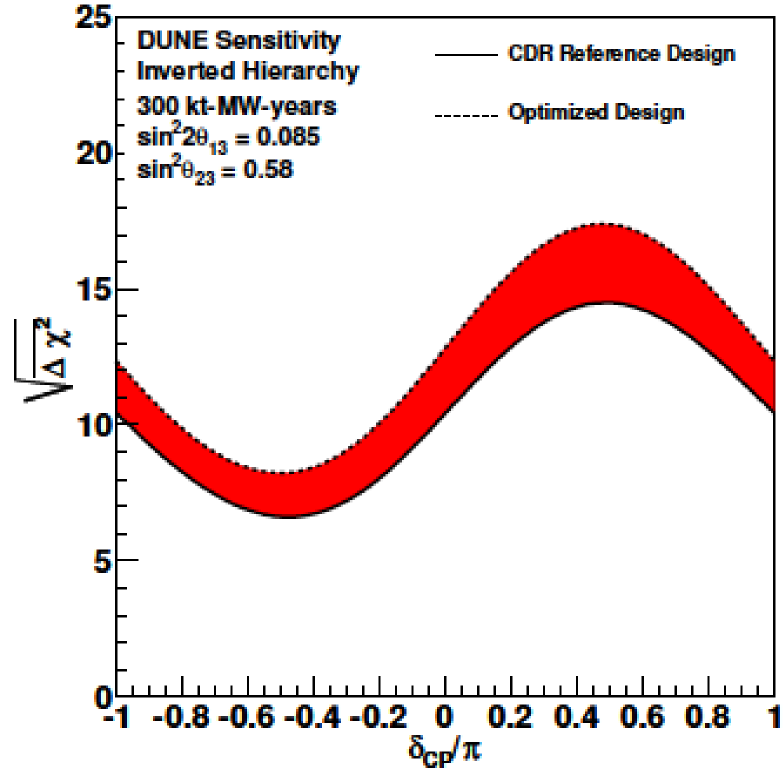
CDR, arXiv: 1512.06148

Sensitivities: mass hierarchy

Normal hierarchy



Inverted hierarchy

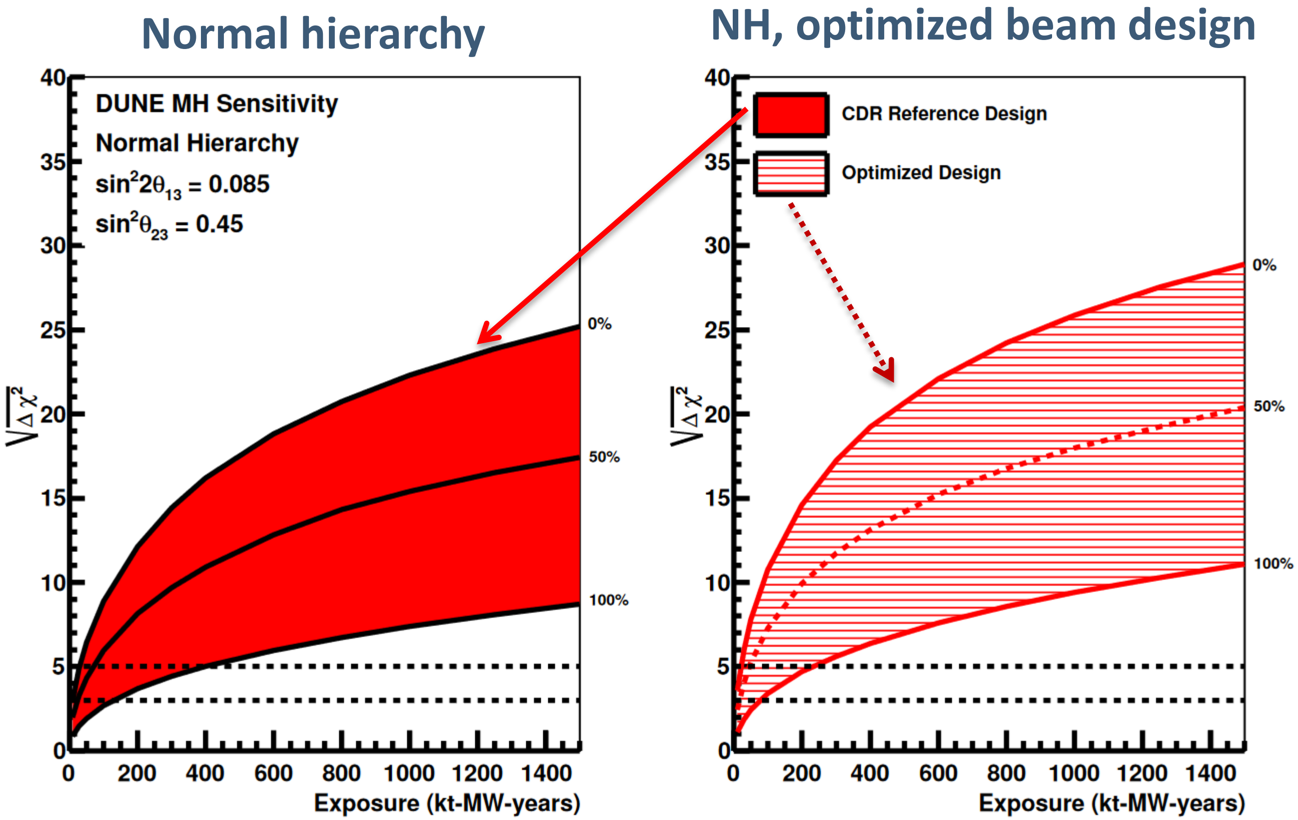


DUNE's goal is to determine the MH with a significance of at least $\sqrt{\chi^2} = 5$ for all δ_{CP} values.

Analysis of the corresponding atmospheric-neutrino samples will improve the precision with which the MH is resolved.

CDR, arXiv: 1512.06148

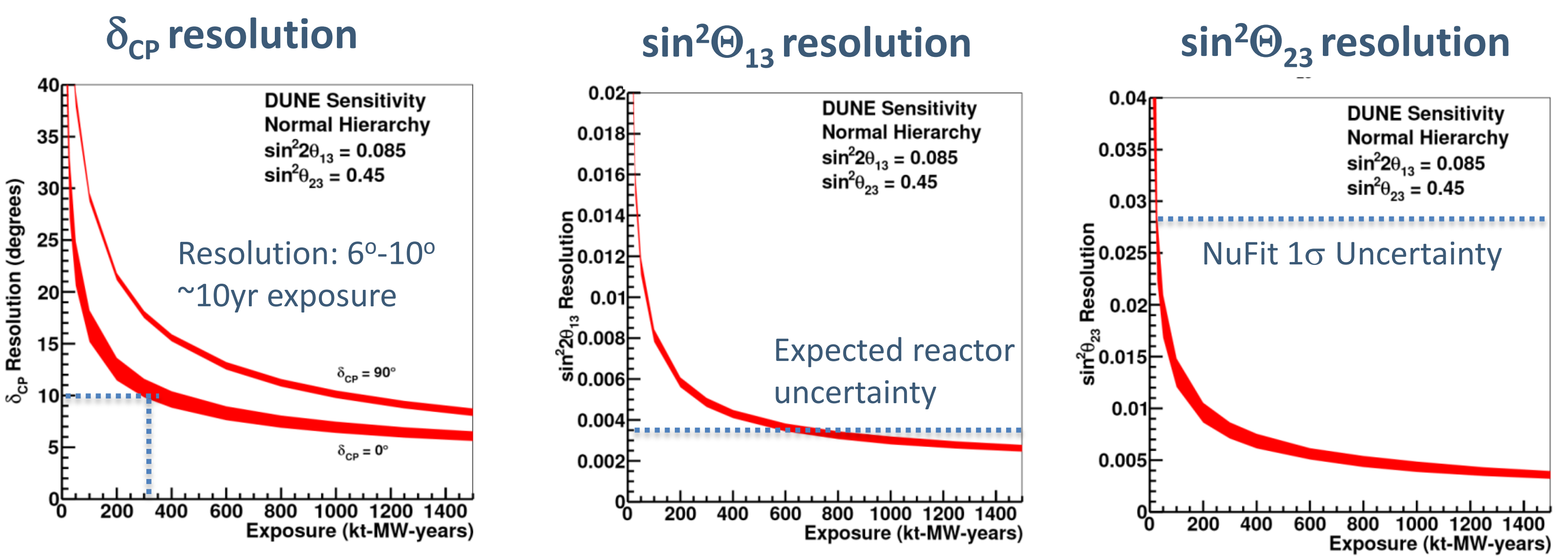
Mass hierarchy



DUNE can determine the neutrino mass hierarchy and it could be achieved in a few years of data taking.

CDR, arXiv: 1512.06148

Precision Oscillation Parameters



- Exposure as a function of time in kt MW years.
- Near the end of experiment run:
  - Below 10° in δ_{CP} resolution → important for constraing CPV models.
  - Test of unitarity with independent measurement of θ_{13} (using ν_e / $\bar{\nu}_e$ appearance vs. ν_e disappearance from reactor experiments).

CDR, arXiv: 1512.06148

Physics milestone

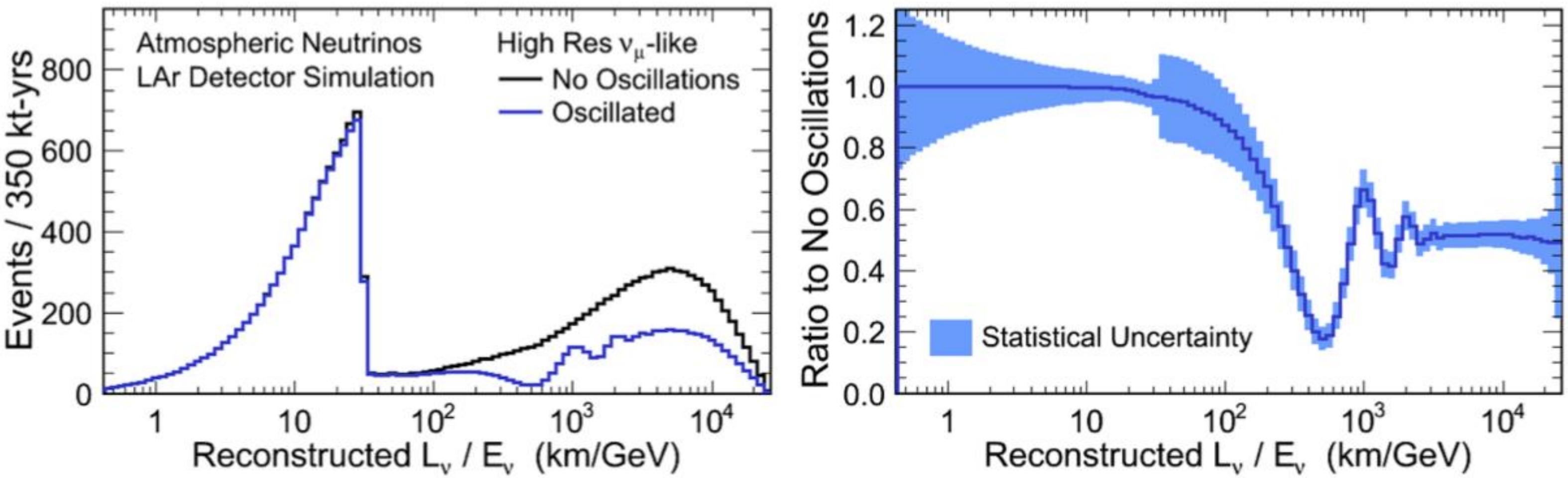
40 kt x 1.2 MW ~ 50kt MW

Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)	
1° θ_{23} resolution ($\theta_{23} = 42°$)	70	45	**1 year**
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70	60	
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160	100	**2 years**
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280	210	
MH at 5σ (worst point)	definite MH determination	230	**5 years**
10° resolution ($\delta_{CP} = 0$)	450	290	
CPV at 5σ ($\delta_{CP} = -\pi/2$)	525	320	**7 years**
CPV at 5σ 50% of δ_{CP}	810	550	
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	reactor θ_{13} resolution	850	
CPV at 3σ 75% of δ_{CP}	1320	850	

CDR, arXiv: 1512.06148

Atmospheric neutrinos

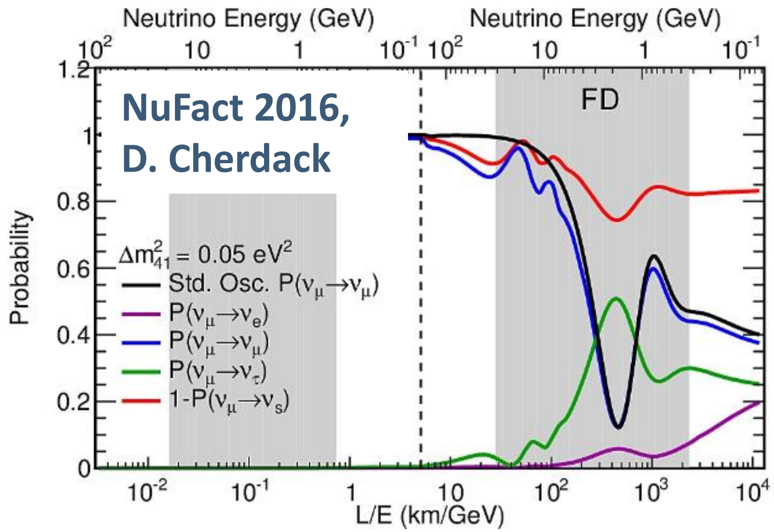
- Atmospheric neutrino flux is very sensitive to matter effects, to both Δm^2 values, and covers a wide range of L/E.
- MH with atmospheric neutrinos is nearly independent from the CP-violating phase.
- Event rate: 14k e-like, 20k μ-like fully contained for 350kt-yr exposure.

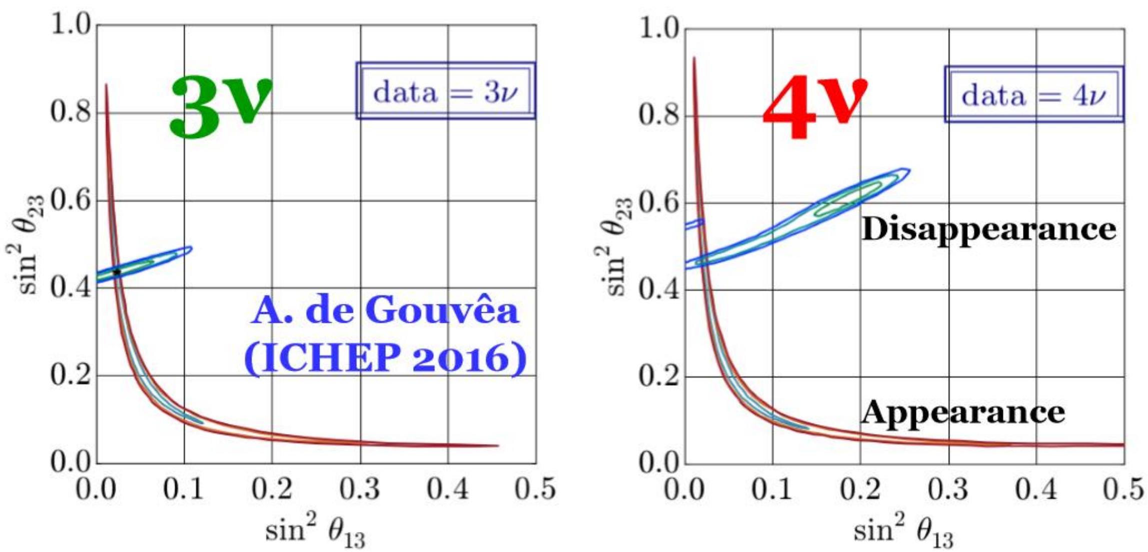


CDR, arXiv: 1512.06148

Sterile Neutrinos

- Searches for sterile neutrinos at DUNE can be done using both the ND and FD.
- One sign of failure of 3ν paradigm: different best-fit parameters for appearance, disappearance modes.





A Sterile Neutrino at DUNE, arXiv: 1507.03986

3ν to both dataset

Near future

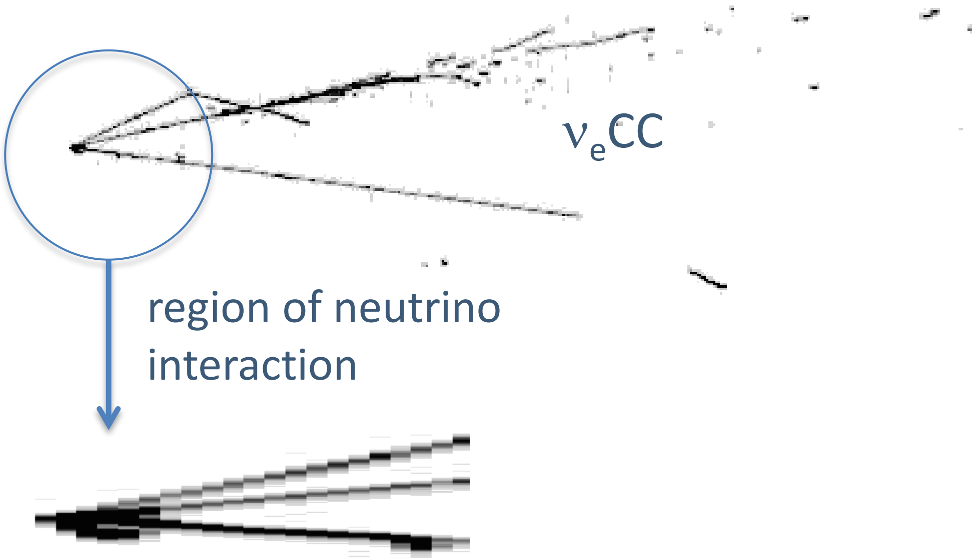
- 2017: start of excavation at the far site (SURF).
- 2018: ProtoDUNEs, Single Phase, Dual Phase at CERN.
- Detector components will be identical to what is currently foreseen for the first 10kt DUNE detector module and serve as an important engineering milestone.
- A charged particle beam with energies in the sub-GeV to few GeV energy range will be directed at protoDUNE.
- **Well characterized charged particle beam can provide critical calibration measurements as well as invaluable data sets needed to develop methods of reduction of systematic detector uncertainties for DUNE**.

DUNE event reconstruction

Reconstruction is a key element to explore neutrino physics with LArTPC. Reconstruction will contribute to systematics uncertainties in DUNE.

Aim of reconstruction:

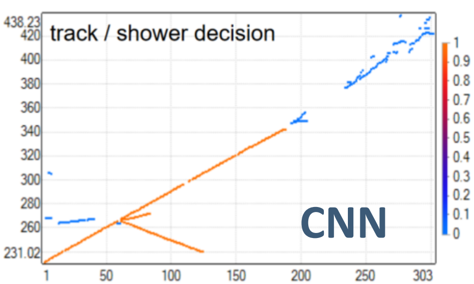
- Find primary vertex.
- Identify outgoing particles.
- Measure their momenta.



LArSoft, Genie, G4, simulated neutrino interaction in DUNE far detector

Event reconstruction in DUNE

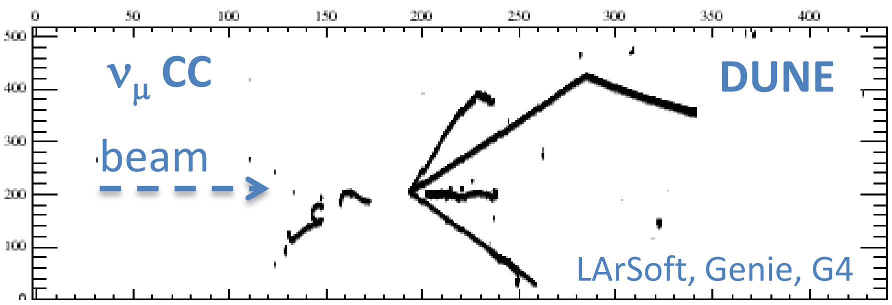
- ArgoNeuT, MicroBooNE, LArIAT use the same framework (LArSoft) and produced results with automated reconstruction… BUT
- We have still lots of challenges in order to meet the DUNE requirements and be able to perform physics.
- Huge progress, strong teams from international teams. Developed reconstruction is promptly validated on data.
- Effort is made to combine all strong features of different approaches to be able to perform highest quality physics.

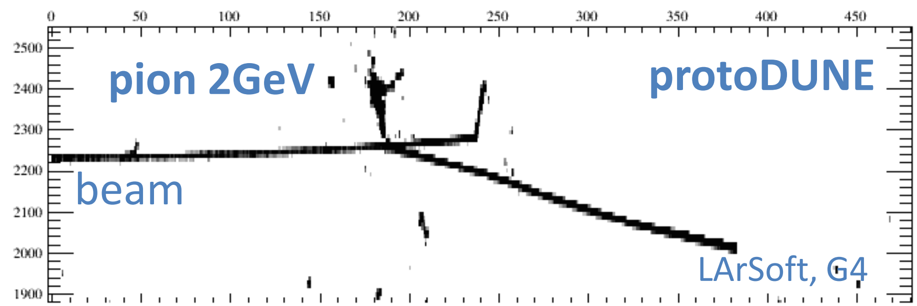


First stage of reconstruction is based on deep NN approach

Reconstruction in protoDUNE and ν physics in DUNE

- Reconstruction/analysis tools developed for protoDUNE will be used in DUNE physics.
- **Detector calibration**: particle identification, π^0 reconstruction, Michel electron energy reconstruction.
- **Background rejection**: separation of cosmic muons from beam events.
- **Physics**: cross sections measurements, multiplicity in hadronic interactions, hadron shower topology and shower development, studies of hadron interaction complexities and energy scale at different topologies.

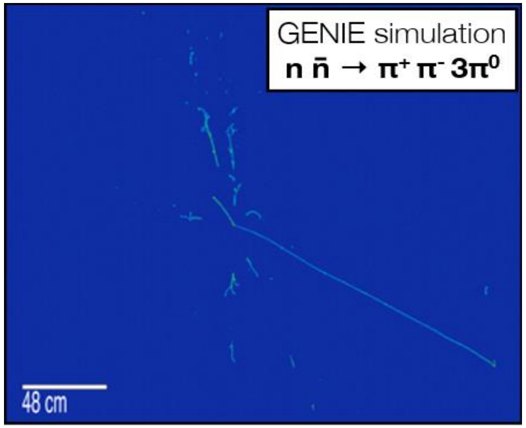




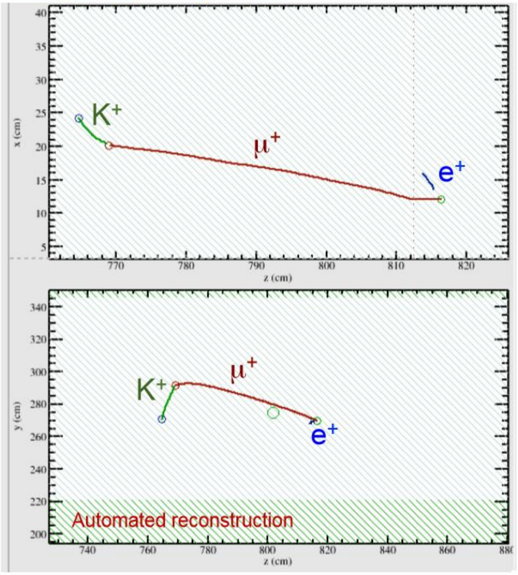
No beam physics in DUNE

DUNE will address fundamental physics questions:

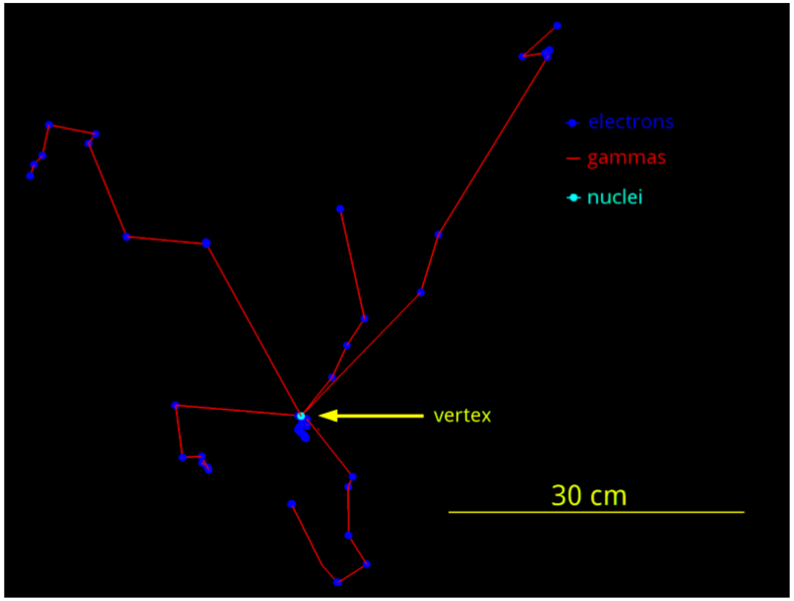
- Baryon asymmetry (CP violation + nucleon decay).
- Grand unified theories.
- Supernovae.



Simulated $p \rightarrow K^+ \nu$ event



Simulated charged-current supernova ν_e event



Summary

- DUNE physics program will produce results at each stage of 20+ year operation.
- DUNE will be able to unambiguously determine the neutrino mass hierarchy and measure the value δ_{CP}.
- LArTPC technology is of great interest due to its potential in investigation of neutrinos properties.
- Reconstruction is a key element to perform physics with LArTPC: experience from ICARUS, ArgoNeuT, MicroBooNE, LArIAT and contribution from several strong teams.
- Construction phase starting: beginning excavation of far site next year and in 2018 ProtoDUNEs will collect important data – stay tuned!

backup