DUNE: Status and Prospects

The 14th International Workshop on Tau Lepton Physics

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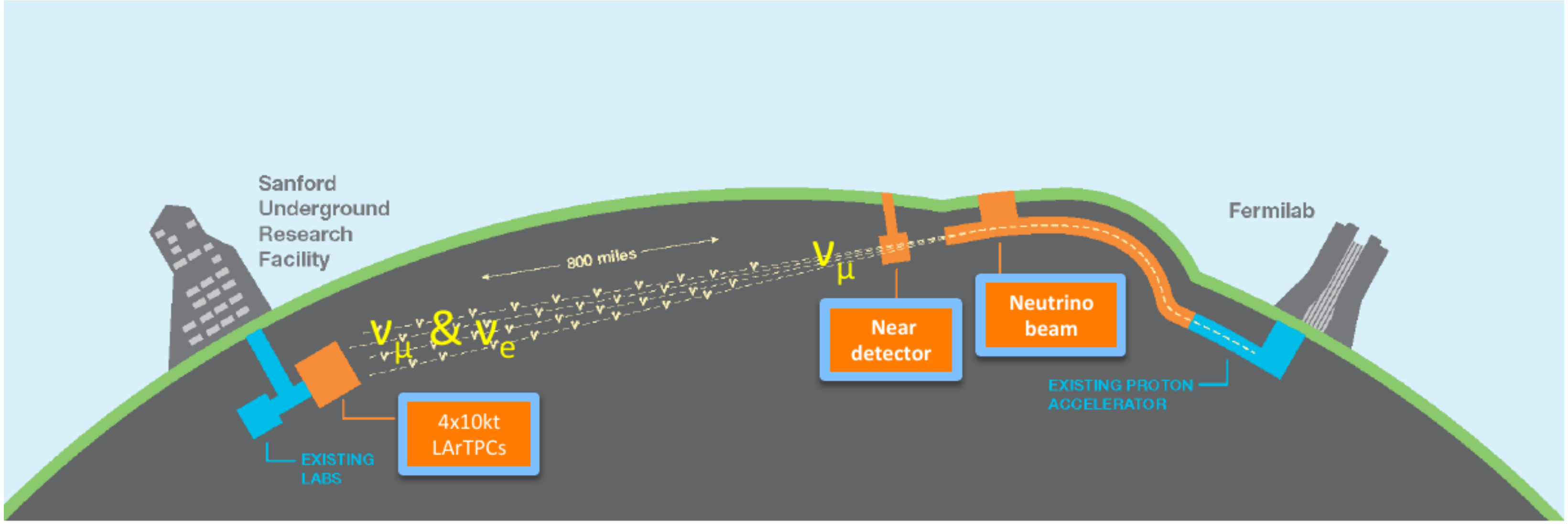
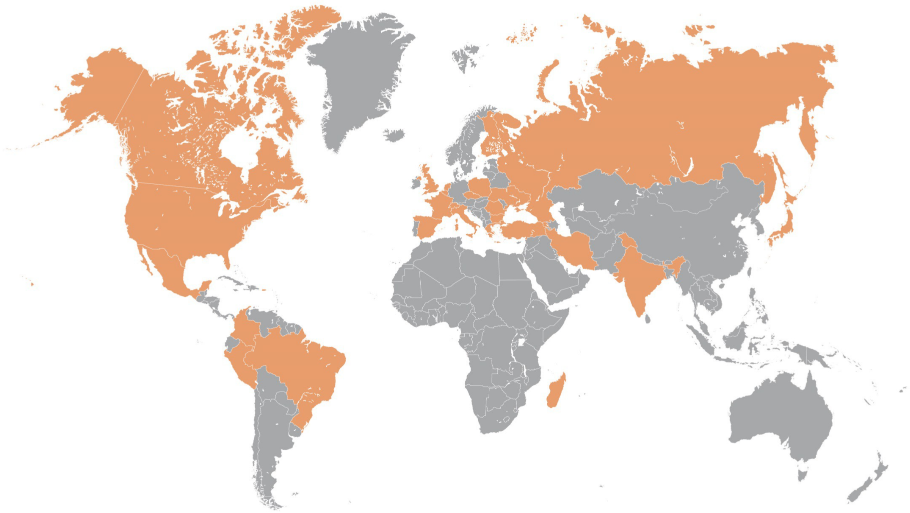
(Representing the DUNE collaboration)

DUNE

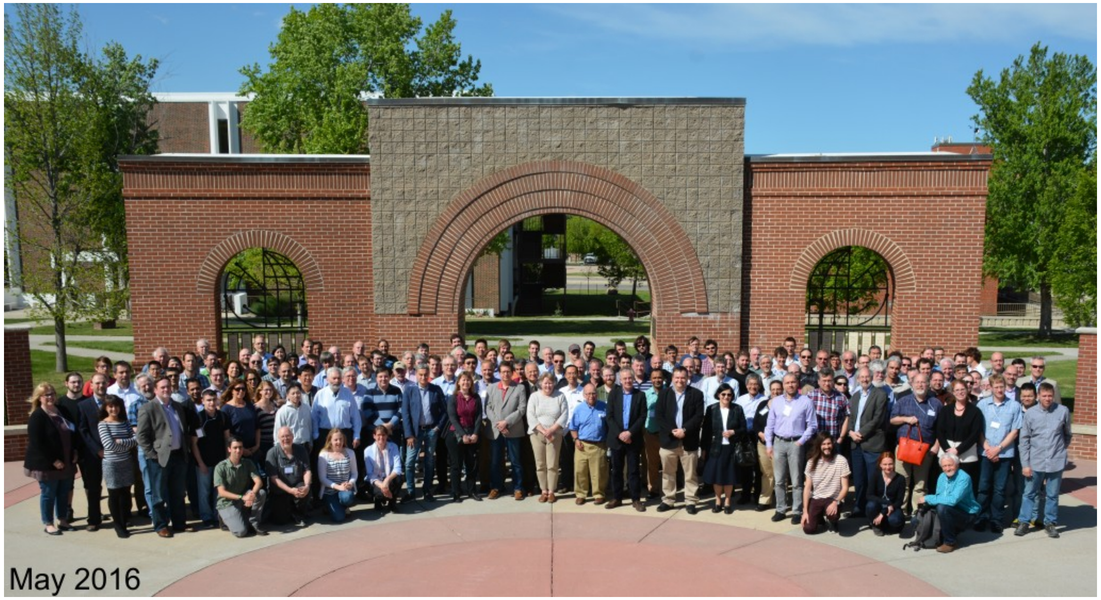
- Features of DUNE:
  - 1300 km baseline: "LBL"
  - Large (40 kt) LArTPC far detector and near detector
  - Far detector 1.5 km underground
  - Wide-band, on-axis beam
- Primary physics goals:
  - ν oscillations ($\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance)
    - MH, δ_{CP} , θ_{23} , θ_{13}
  - Nucleon decay
  - Supernova burst neutrinos



The Collaboration

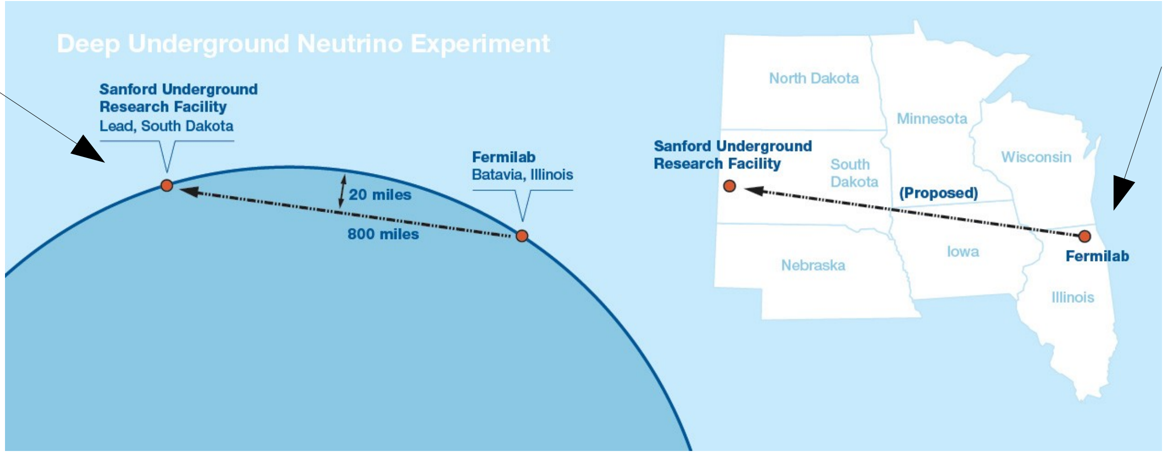


890 collaborators from 154 Institutions in 28 nations



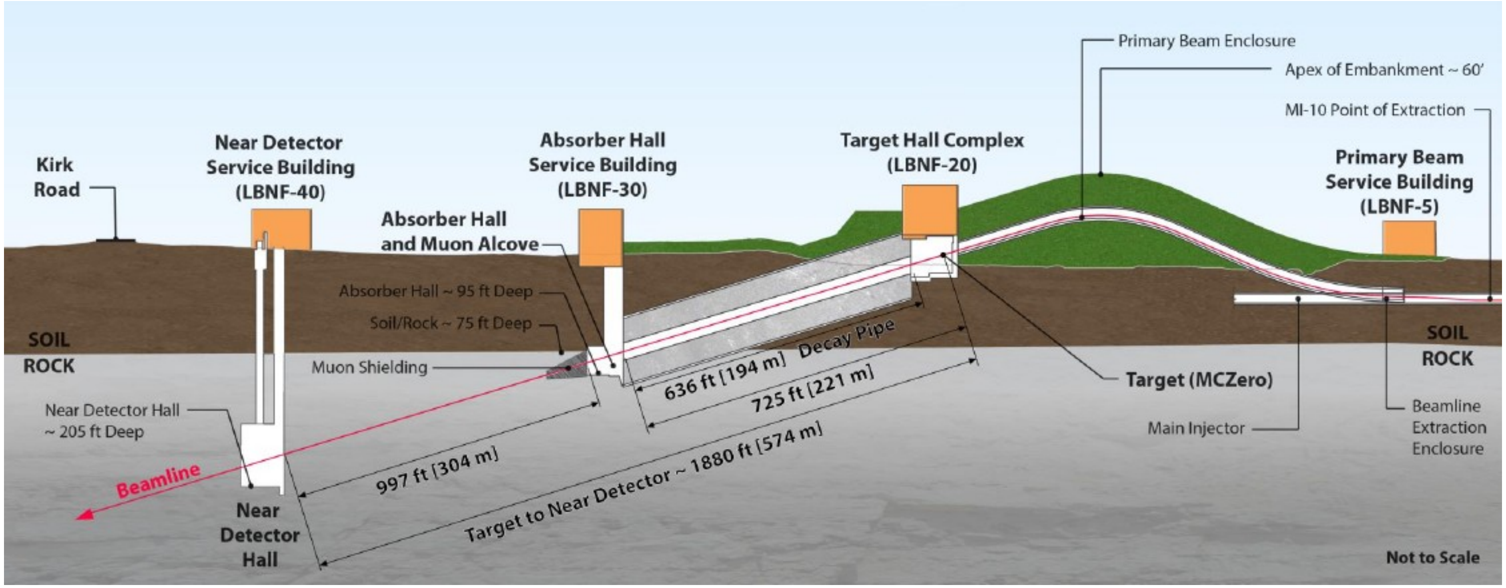
LBNF/DUNE

- LBNF (Long Baseline Neutrino Facility): DOE/Fermilab hosted project with international participation
  - LBNF houses, and delivers beam (i.e.beam-line) to detectors built by the DUNE collaboration



LBNF Beamline

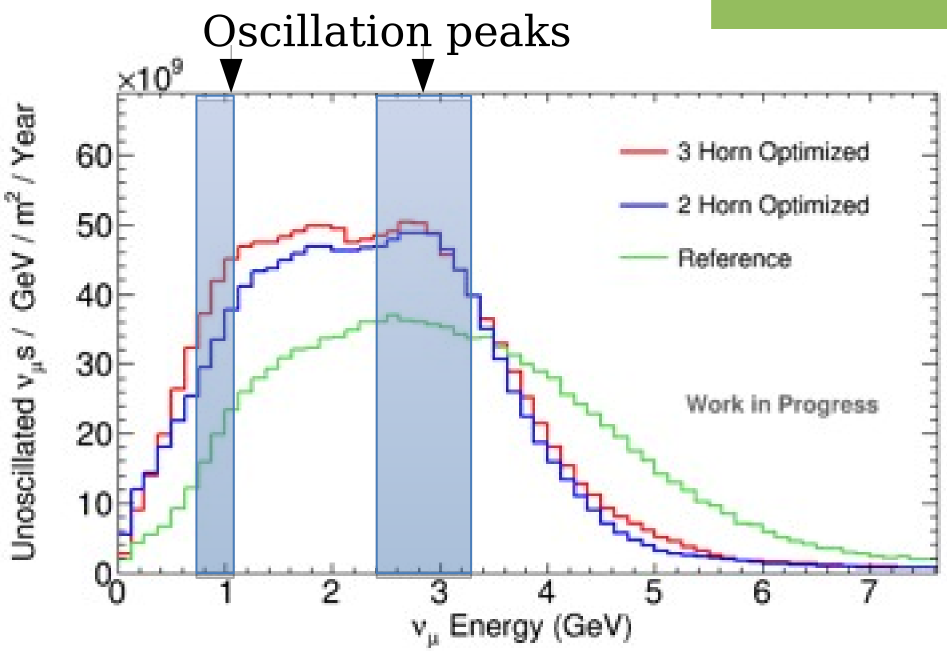
- **Conventional horn-focused Beam-Line:**
  - -60-120 GeV protons from Fermilab Main Injector
  - - 101 mrad beam pitch required to reach S. Dakota
  - -~200-m Decay pipe
  - -Near Detector Hall at edge of Fermilab site
  - -Critical contributions from international partners (UK, CERN)



LBNF Beam-line Characteristics

- DUNE CDR “Reference”(in green)
- Later adopted optimization procedure developed by LBNO
  - This led to DUNE CDR “optimized” configuration (in blue)
  - Further horn optimizations (in red)

→ Will use the optimized beam

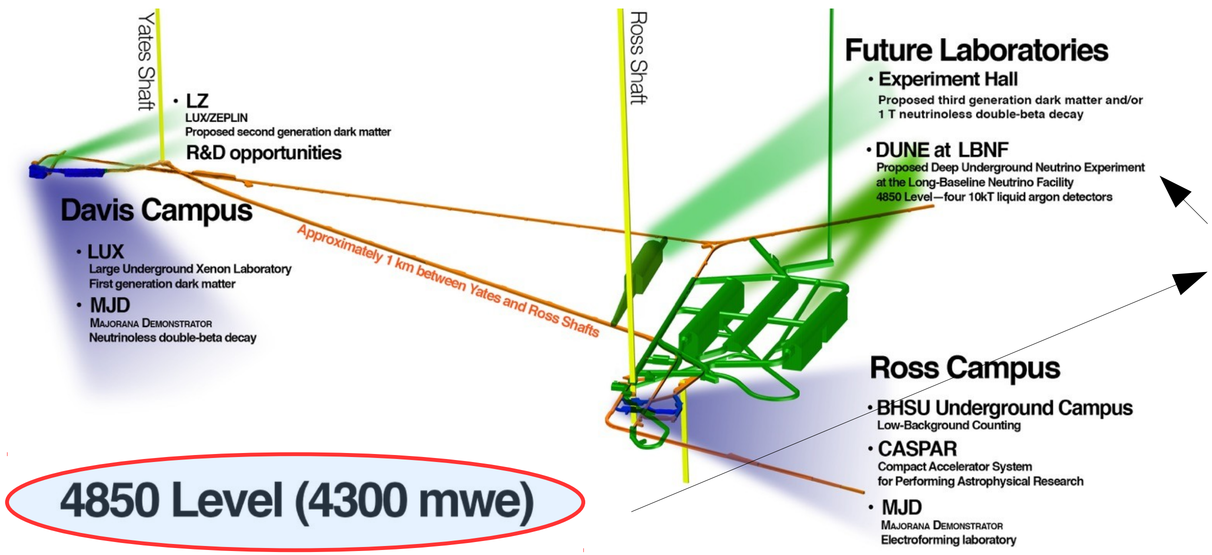


Parameter	CDR Reference Design	Optimized Design
Proton Beam Energy	80 GeV	80 GeV
Proton Beam Power	1.07 MW	1.07 MW
Target	Graphite	Graphite
Horn Current	230 kA	297 kA
Horn Design	NuMI-style	Genetic Optimization
Decay Pipe Length	204 m	241 m
Decay Pipe Diameter	4 m	4 m

LBNF: SURF

Sanford Underground Research Facility(SURF), Lead, S. Dakota

- The Homestake Gold Mine (present SURF location) was home to the famous DAVIS experiment
- **LBNF scope:** 4 detector chambers, utility cavern, connecting drifts
- **Extensive preparatory work** for LBNF/DUNE already done
- Begin excavation & surface building construction in 2017

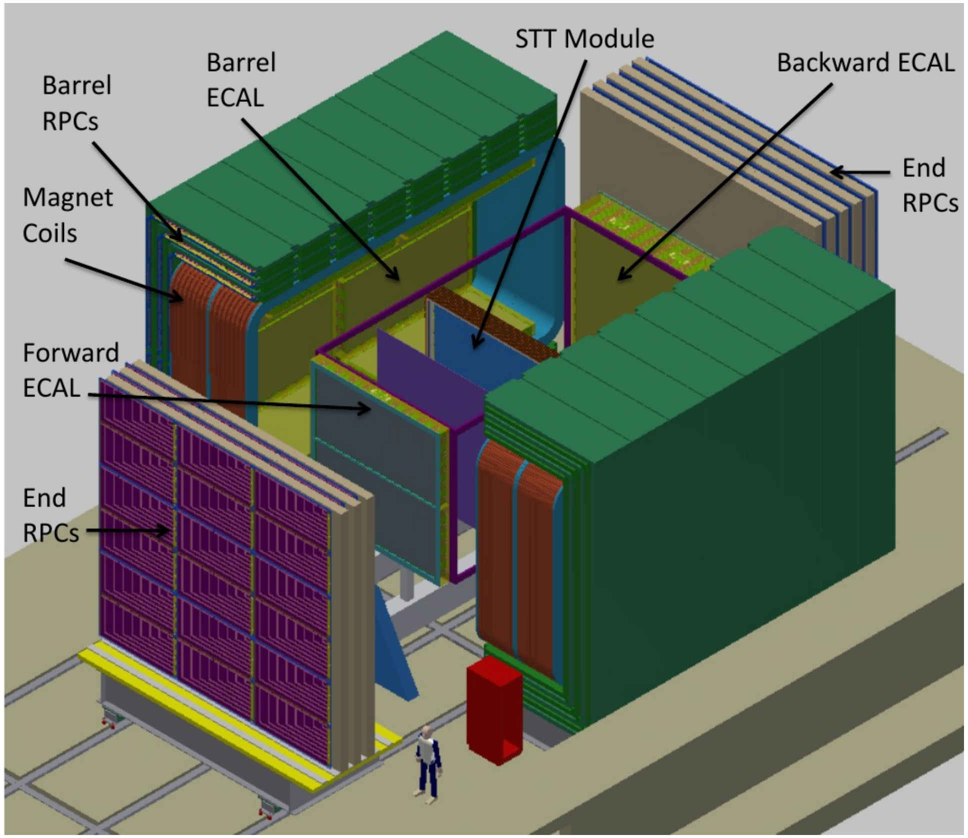


Far Detector Location

DUNE: Near Detector(s)

- Design inspired by the NOMAD detector:
  - Magnetized straw-tube based tracking system
  - Pb-scintillator sampling calorimetry
  - RPC-based muon tracker
  - Multiple Targets (incl. Argon)
- Additional NDs being investigated
  - High-pressure Ar Gas TPC
  - LArTPC, a la ArgonCube

Fine-Grained Tracker:



→ Primary purpose is to support the DUNE oscillation physics program but the LBNF beam-line provides a great opportunity to study ν interactions with large statistics and high resolution

DUNE: Far Detector Technology: LArTPC

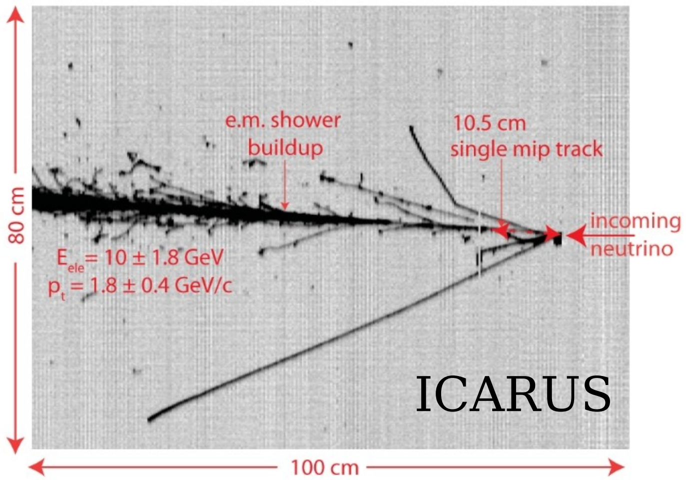
- The far detector will be located deep underground (@4850 feet (1480 meters)) with a fiducial mass of 40 kt
  - Study long-baseline oscillations with a 1300 km base-line
  - Includes an astroparticle physics program and nucleon decay searches.

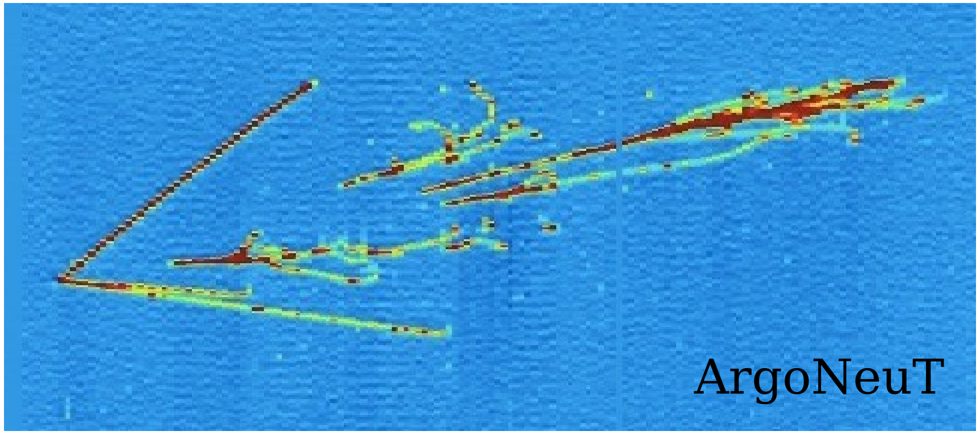
- The far detector will consist of four similar modules (~10kt each): Liquid Argon Time-Projection Chamber (LarTPC)

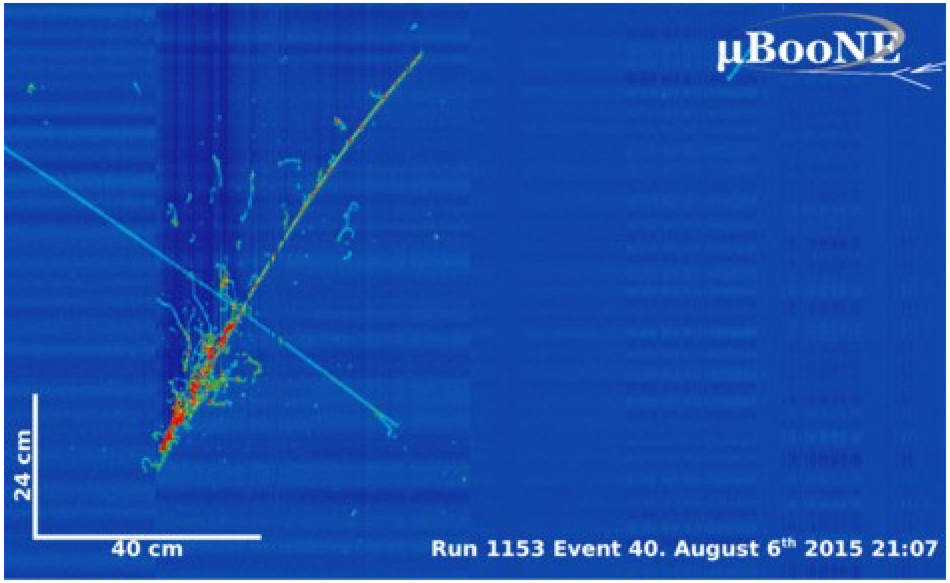
- A LArTPC provides excellent tracking and calorimetry performance.
  - Ideal for massive neutrino detectors requiring:
    - High signal efficiency and background discrimination,
    - Able to identify and precisely measure neutrino events over a wide range of energies
    - Excellent reconstruction capabilities of the kinematic quantities with high resolution.
  - The full imaging of events → study neutrino interactions and other rare processes with unprecedented resolution.

- However a LarTPC this large has never been built before (> x10 ICARUS) and therefore a substantial RD program is required…

LArTPC Imagery



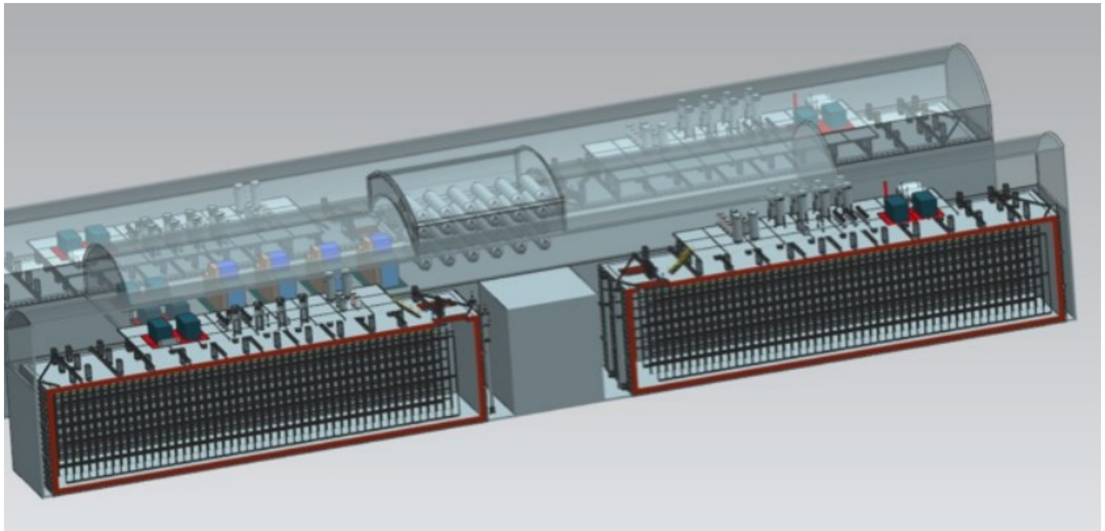




DUNE: Far Detector

Two Designs being considered: Single-Phase LArTPC

- Based on LBNE modular drift cell design:
  - Readout anode composed of wire planes embedded in the LAr volume
  - Suspended Anode (APA) / Cathode (CPA) plane assemblies – 3.6 m spacing
    - APA's w/ "wrapped" induction wire planes
  - Scintillation detection based on light guides embedded in APA's, SiPM read out

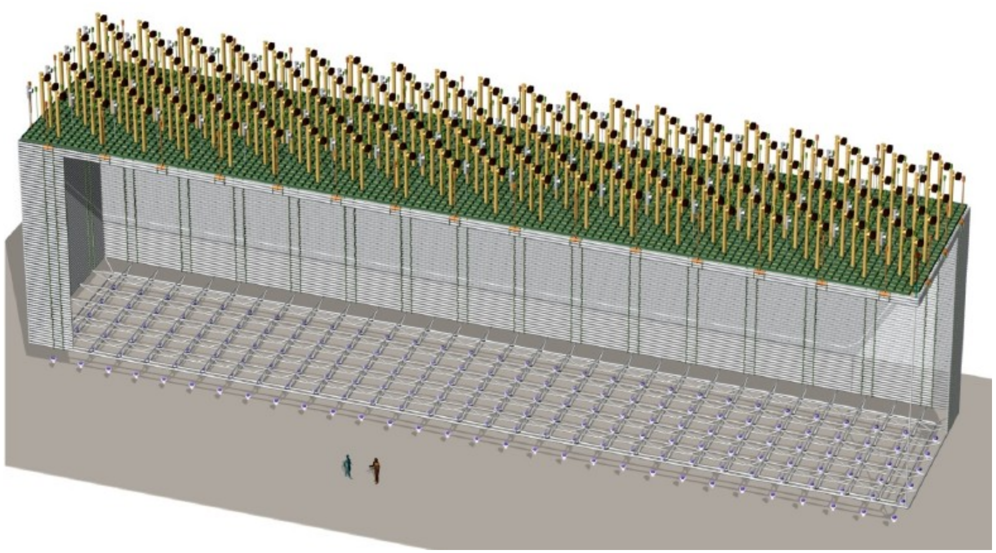


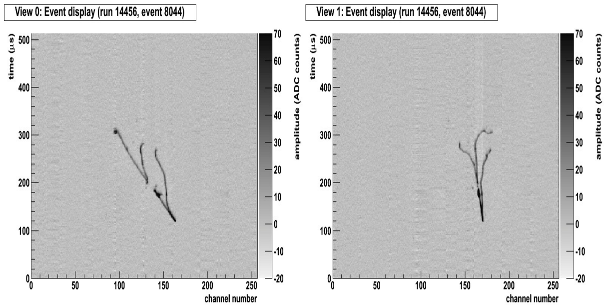
Active volume is 12 m high, 14.5 m wide and 58 m long

DUNE: Far Detector

Two Designs being considered: Dual-Phase LArTPC

- LBNO Design - Single TPC volume with Amplification in gas phase above liquid surface:
  - Allows for a finer readout pitch (3 mm), a lower detection-energy threshold
  - 12m max drift (vertical), LEM (Large Electron Multiplier) read-out
  - Features excellent S/N: ~100/1
  - Scintillation via PMT's below cathode



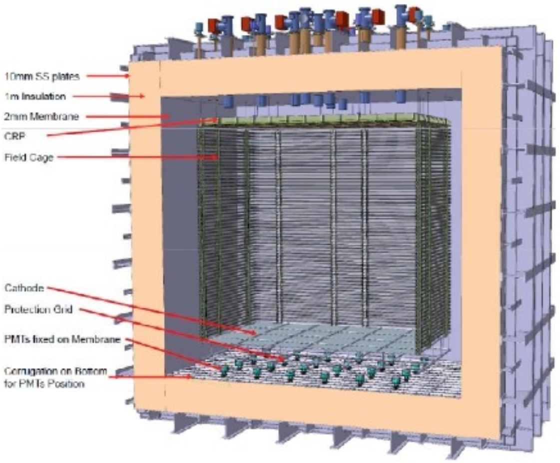


DUNE: Prototypes

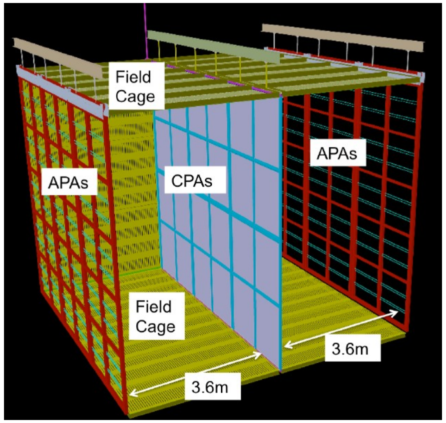
Two ProtoDUNE Detectors (SP & DP) operational at CERN in 2018

Provides key risk mitigation opportunity for Far Detector modules

Dual-Phase 6x6x6 m³ →



Single-Phase TPC prototype Consisting of 4 full size APA's Plus CPA's: 2 x 3.6 m² drift regions →



DUNE: R&D Path to Full Scale

- The DUNE 10-kt LArTPC Modules represent O(50x) increase in size compared to largest LArTPC modules built to date (ICARUS), 100x scale-up w.r.t. MicroBooNE

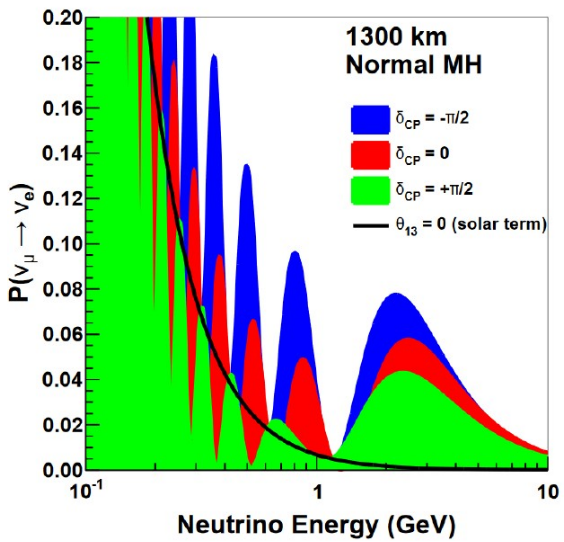
  - Learning how to built, maintain and operation the large-scale prototypes are important ingredients of the DUNE program
    - Understand production as well as operational issues
    - Provides training and opportunities for Test Beam data analyses (ProtoDUNE Science Program)
  - R&D Schedule
    - 35-ton single-phase TPC test at FNAL (completed)
    - 3x1x1 m^3 dual-phase TPC at CERN (WA105/NP02), operating Fall 2016
    - Associated dual & single phase ProtoDUNE's @ CERN (NP02,04), 2018
  - **Should consider these major experiments in their own right…**

DUNE: Physics Program

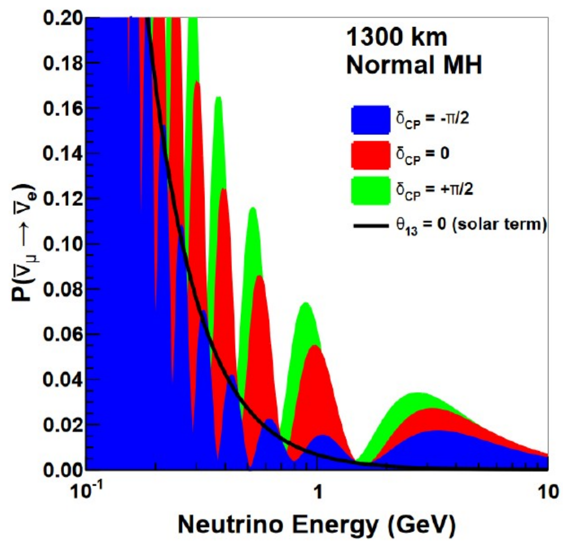
$$P(\nu_\mu \rightarrow \nu_e) \approx \boxed{\sin^2\Theta_{23}\,\sin^2 2\Theta_{13}} \frac{\sin^2(\Delta_{31} - \boxed{aL})}{(\Delta_{31} - \boxed{aL})^2}\Delta_{31}^2$$
$$+ \boxed{\sin 2\Theta_{23}\,\sin 2\Theta_{13}} \sin 2\Theta_{12} \frac{\sin(\Delta_{31} - \boxed{aL})}{(\Delta_{31} - \boxed{aL})}\Delta_{13} \frac{\sin(\boxed{aL})}{(\boxed{aL})}\Delta_{21}\cos(\Delta_{31} + \boxed{\delta_{CP}})$$
$$+ \boxed{\cos^2\Theta_{23}} \sin^2 2\Theta_{12} \frac{\sin^2(\boxed{aL})}{(\boxed{aL})^2}\Delta_{21}^2$$

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

Neutrinos



Antineutrinos



- $\sin^2(2\theta_{13})$ determines size of event sample
- δ_{CP} affects amplitude of oscillations
- Mass differences affects frequency of oscillations
- MH effects both amplitude and frequency

→ Studying oscillations in a wide band beam helps to sort out the complicated process: Allowing the simultaneous measurement of mass hierarchy, CP-violating phase, and neutrino mixing angles

DUNE: Physics Program

Sample sizes: (MH, θ_{23}, θ_{13}, δ) extracted from combined analysis of 4 samples:

(40kt•1.1 MW•3.5 yrs)

Anti-ν mode / 150 kt-MW-yr	νe appearance	νμ disappearance
Signal events (NH / IH)	**168 (438)**	**2639**
Wrong-sign signal (NH /IH)	47 (28)	1525
Beam νe background	105	–
NC background	9	41
Other background	13	18
ν mode / 150 kt-MW-yr	**νe appearance**	**νμ disappearance**
Signal events (NH / IH)	**945 (521)**	**7929**
Wrong-sign signal (NH /IH)	13 (26)	511
Beam νe background	204	–
NC background	17	76
Other background	22	29

DUNE Physics: Oscillations

Energy spectra for selected ν_e & ν_μ samples: CDR ref & opt beams

Top Plots

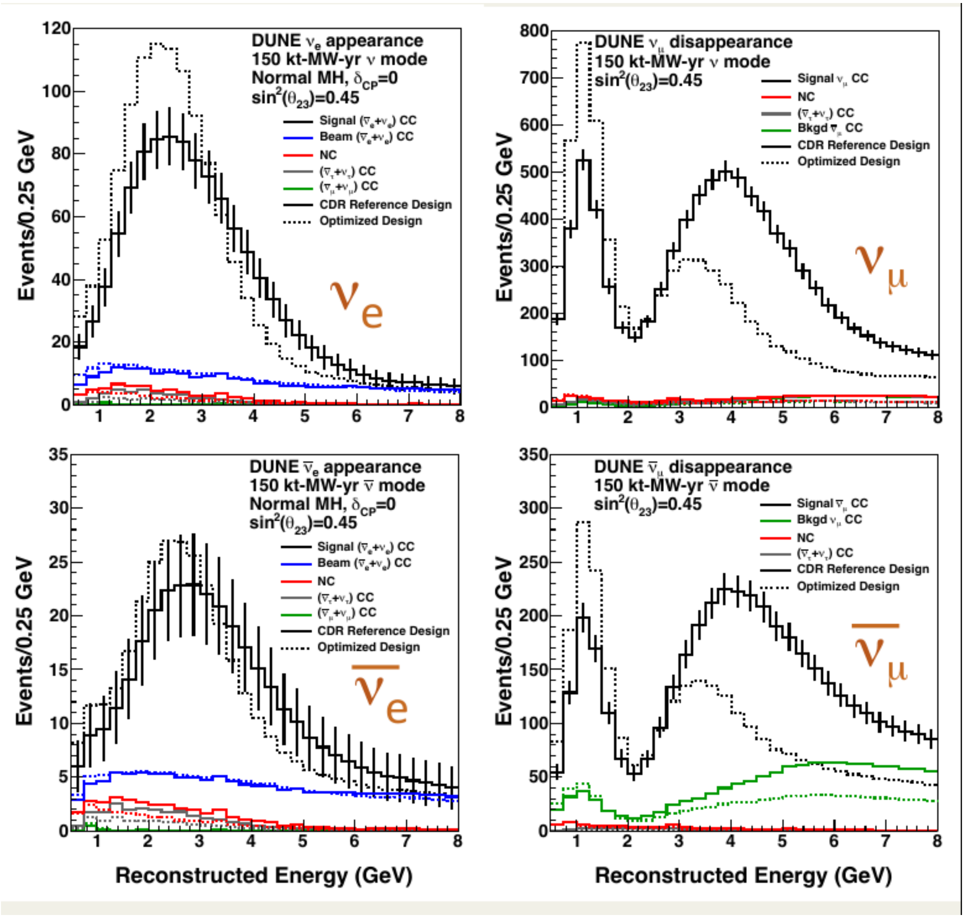
Neutrino-beam running
(150 kt-MW-yr)

Bottom:

Anti-neutrino beam mode
(150 kt-MW-yr)

Beam:

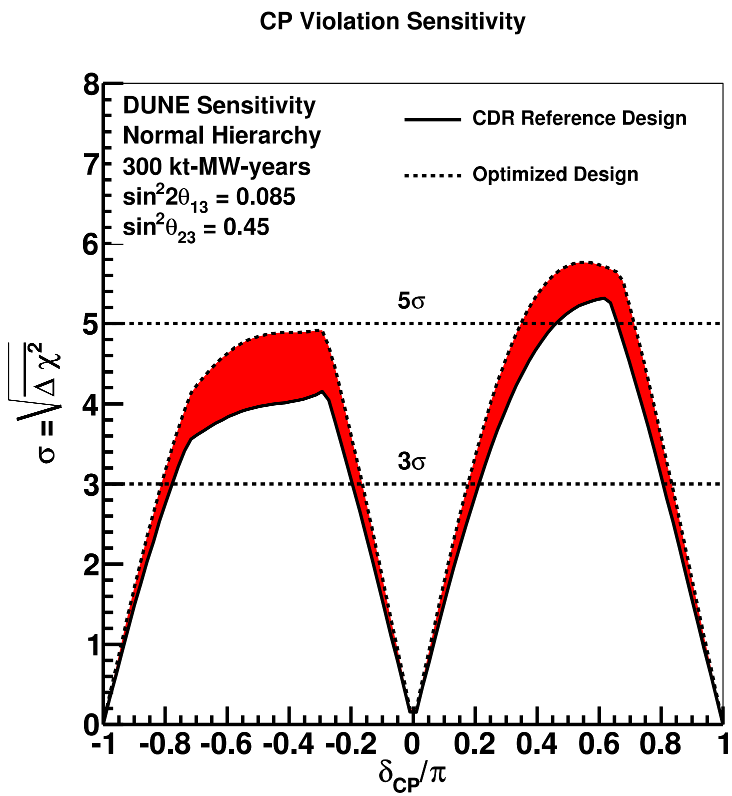
Solid = CDR reference
Dashed = CDR optimized
(Presently the optimized beam should be considered the default beam configuration)

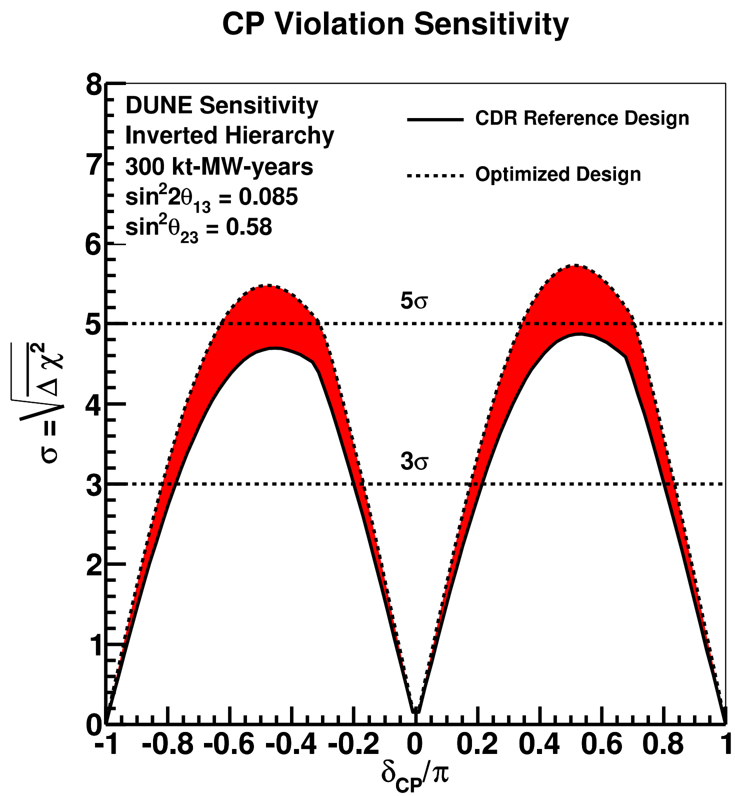


DUNE Physics:
CP Violation Sensitivity

Sensitivity to CP Violation, after 300 kt-MW-yrs (3.5+3.5 yrs x 40kt @ 1.07 MW)

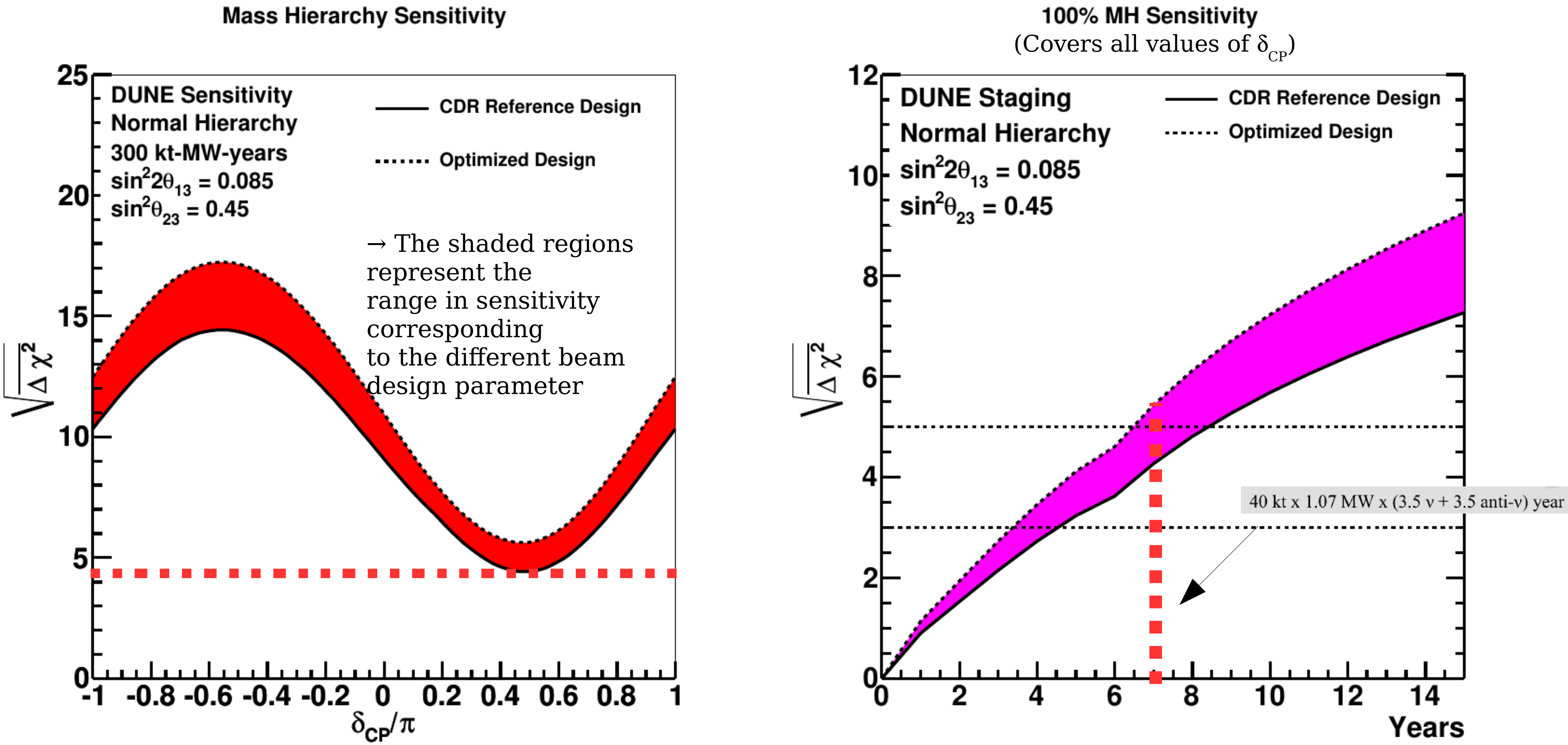
(Bands represent range of beam configurations)





DUNE Physics: MH Sensitivity

→ Discrimination (between NH and IH) parameter as a function of the unkown δ_{CP} for an exposure of 300 kt·MW·year (40 kt·1.07 MW·7 years).

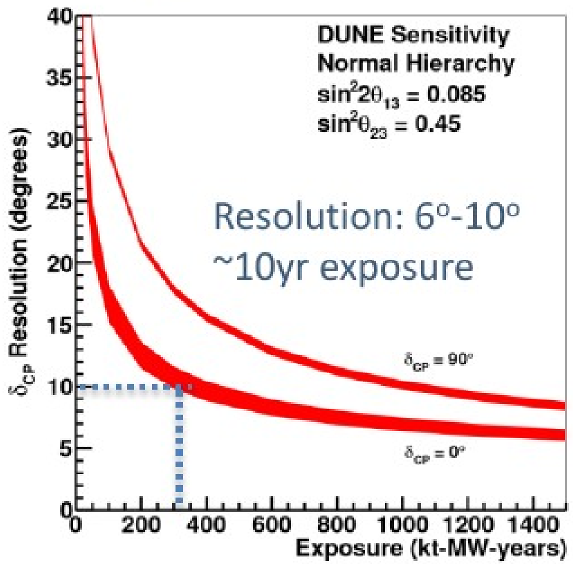


→ The minimum significance (the lowest point on the curve on the left) where the mass hierarchy can be determined any value of δ_{CP} as a function of years of running

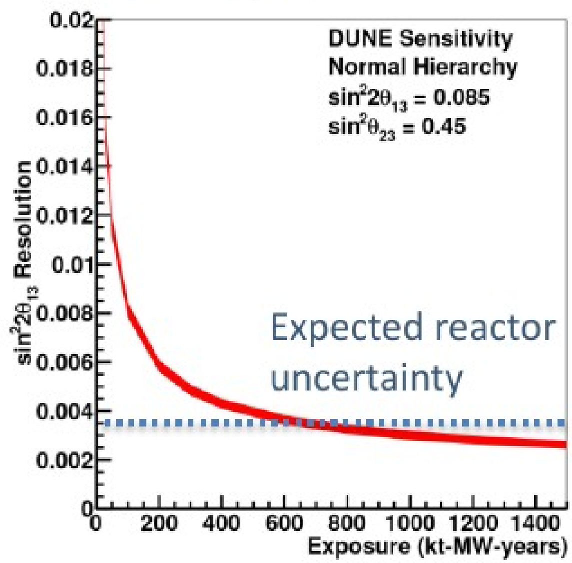
DUNE Physics

Precision Measurement Oscillation Parameters

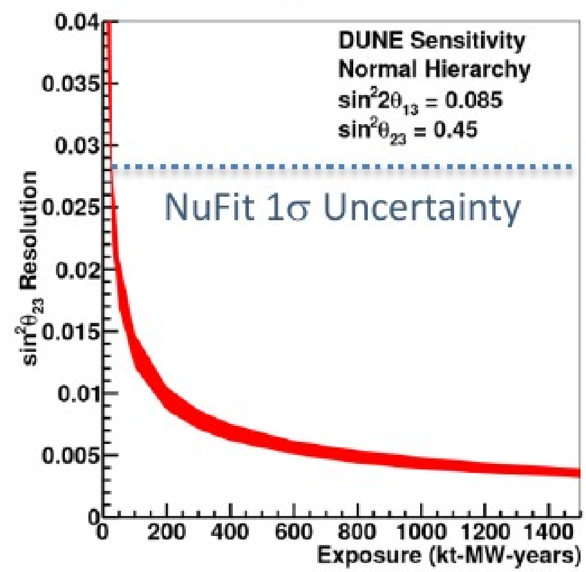
δ_{CP} resolution



$\sin^2\Theta_{13}$ resolution



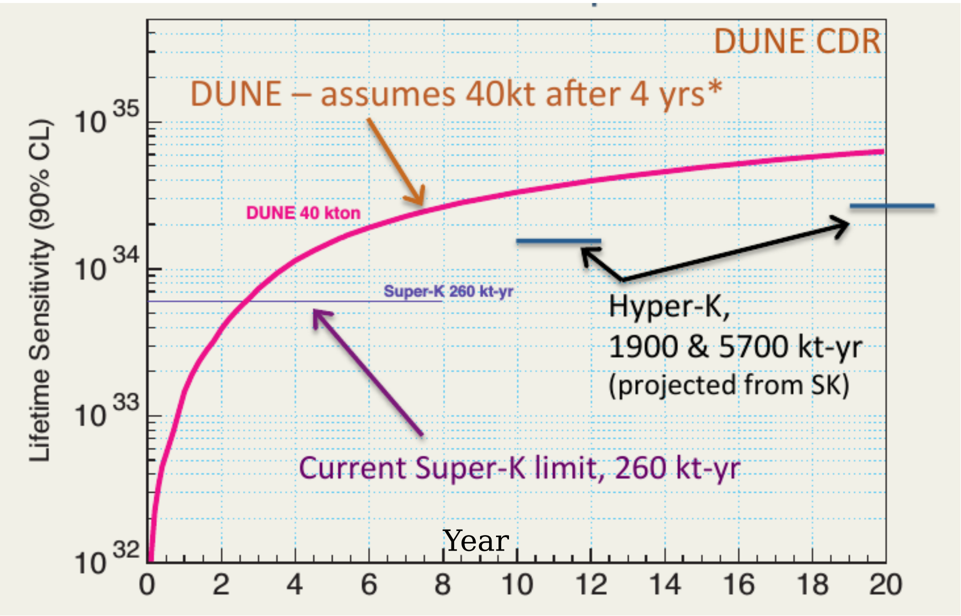
$\sin^2\Theta_{23}$ resolution

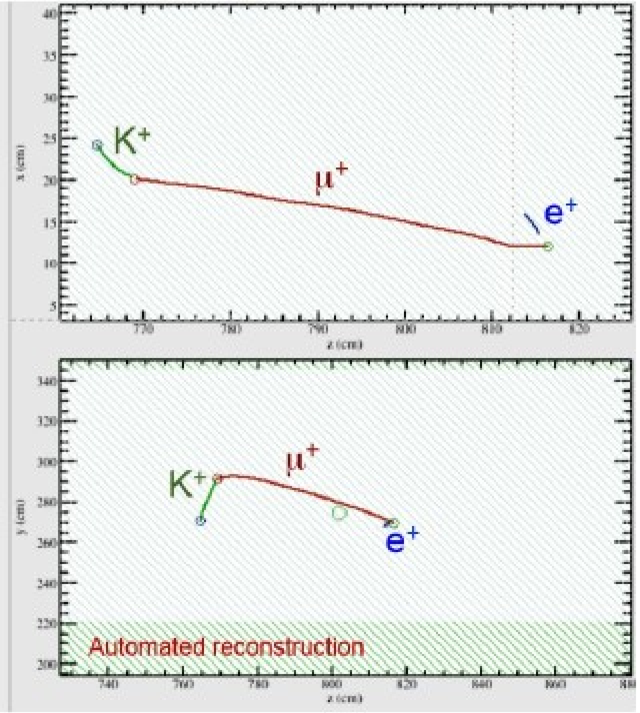


Exposure as a function of time in kt•MW•years.

DUNE Physics: Nucleon Decay

- Using the imaging and dE/dx, calorimetric capabilities of LArTPC: Enables sensitive, **background-free** searches
- Many modes accessible: SUSY-favored channel p → $K^+ \nu$



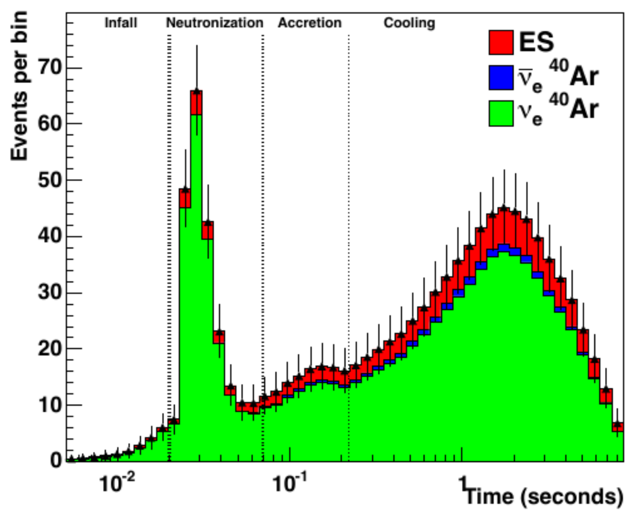


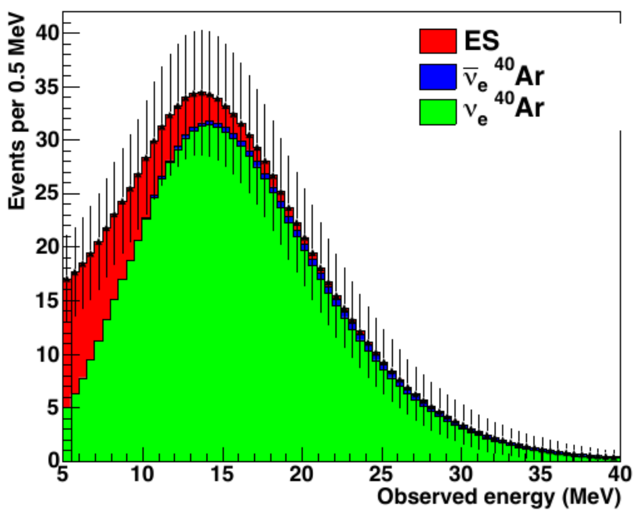
Simulated p → $K^+ \nu$ decay

DUNE Physics: Supernova ν Bursts

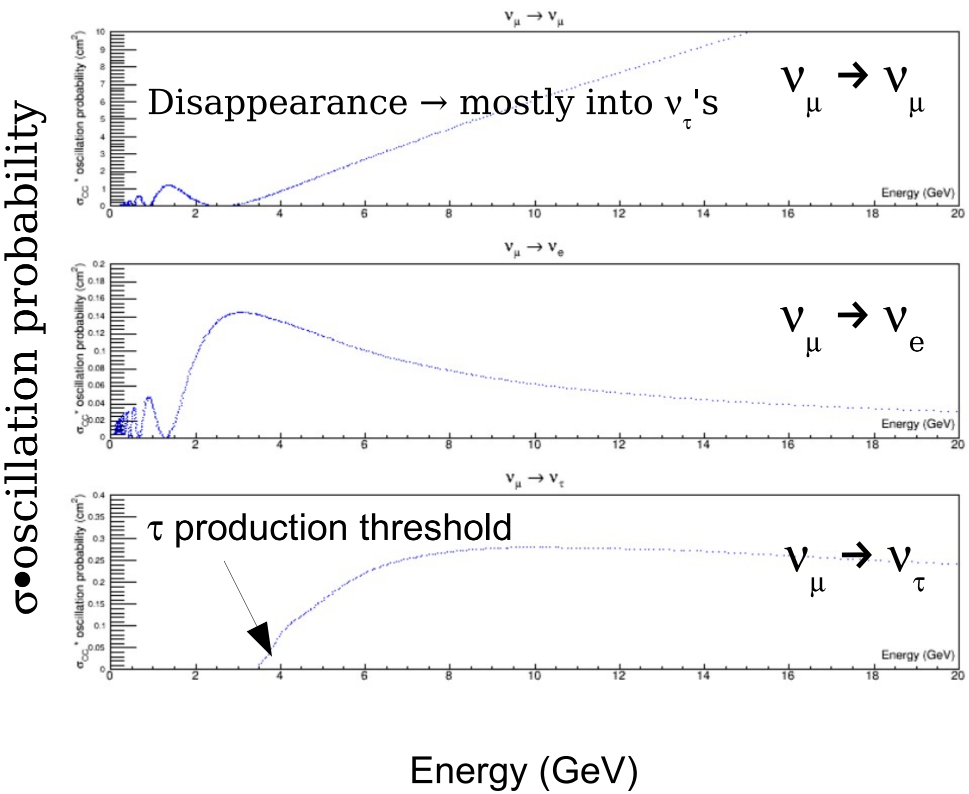
- Few thousand events expected from galactic SNB
- In LAr, dominant process is: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$
  - In contrast, anti-ν_e's dominate in water/organic scintillator-based detectors
  - LAr uniquely sensitivity to neutronization process at ~30 ms
- Elastic scattering events potentially give directionality
- Note distinct features in time (left plot) and energy (right plot) spectra

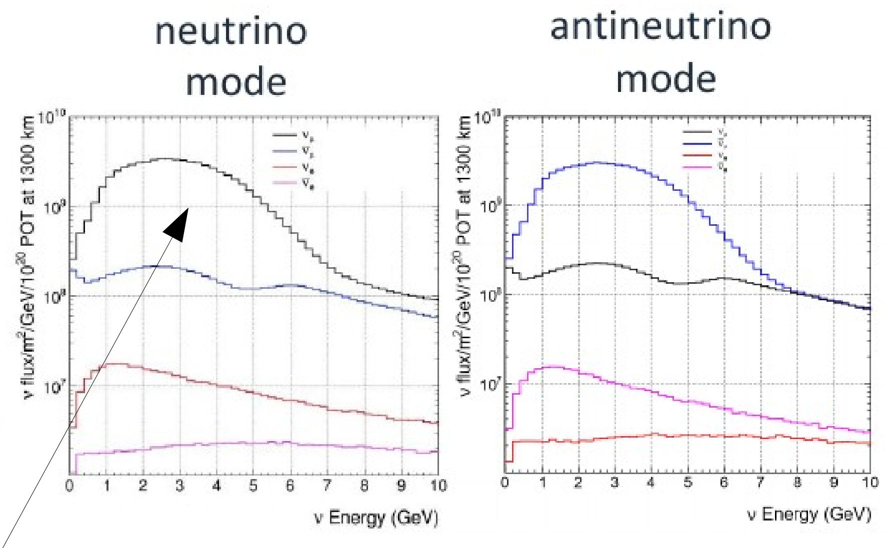
DUNE CDR





DUNE: Tau Neutrinos





Significant flux above 4 GeV

Could expect several hundred tau neutrino CC interactions/year/40kt
Note this is not observed CC ν_τ! - detection efficiencies being presently studied.

DUNE Timeline

2017	Cavern excavation
2018	ProtoDUNEs (SP & DP) operational at CERN
2020	Cryostat Construction
2022	Far detector installation (1st module)
2023	Far detector installation (2st module)
2024	**20 kt operational and first data taking**
2026	**First beam operations at 1.2 MW**

Start non-oscillation physics (2022–2023)

Summary

- LBNF/DUNE will be a world-leading facility for study of neutrino and astroparticle physics. Will address fundamental physics questions:
  - Neutrino Oscillations
  - Nucleon decay
  - Supernova burst neutrinos

- Long-baseline neutrino oscillation measurements in a broad band beam will allow simultaneous measurement of mass hierarchy, CP-violating phase, and neutrino mixing angles:
  - Allowing for detailed study of the neutrino mixing paradigm

- On path to understanding how to build a 40 kt of liquid argon detector and a 1.2 MW neutrino beam:
  - Construction phase starting → excavation of far site to start next year
  - LArTPC prototypes will be operational soon

- DUNE physics program will produce exciting results over its 20+ years of expected operation:
  - This program will be an international effort.

Backup Slides