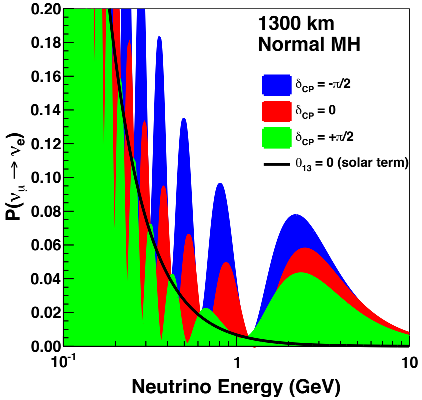
Status of the Deep Underground Neutrino Experiment - DUNE

Thomas Patzak, on behalf of the DUNE Collaboration

http://www.dunescience.org/

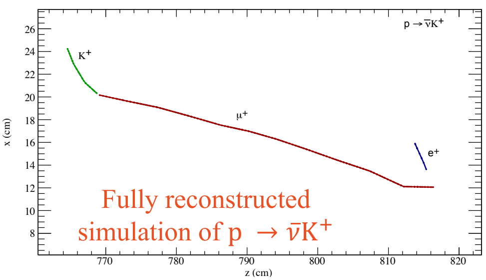
Why ?

Scientific Goals of the DUNE Experiment: 1



Neutrino Oscillations

- Discover CP (5 σ) violation in the neutrino sector
- Measure δ_{CP} with 7 – 14 % resolution
- 5 σ determination of the neutrino mass ordering
- Precision measurement of the PMNS matrix
- Testing the 3 ν paradigm -> Unitarity test



Proton Decay

- GUTs predict decay probability and modes
- DUNE FD deep underground and huge volume
- Very good PID and tracking capabilities

Supernova Neutrinos

- DUNE FD deep underground and huge volume
- Neutrinos from galactic core collapse
- Unique signature to supernova ν_e's

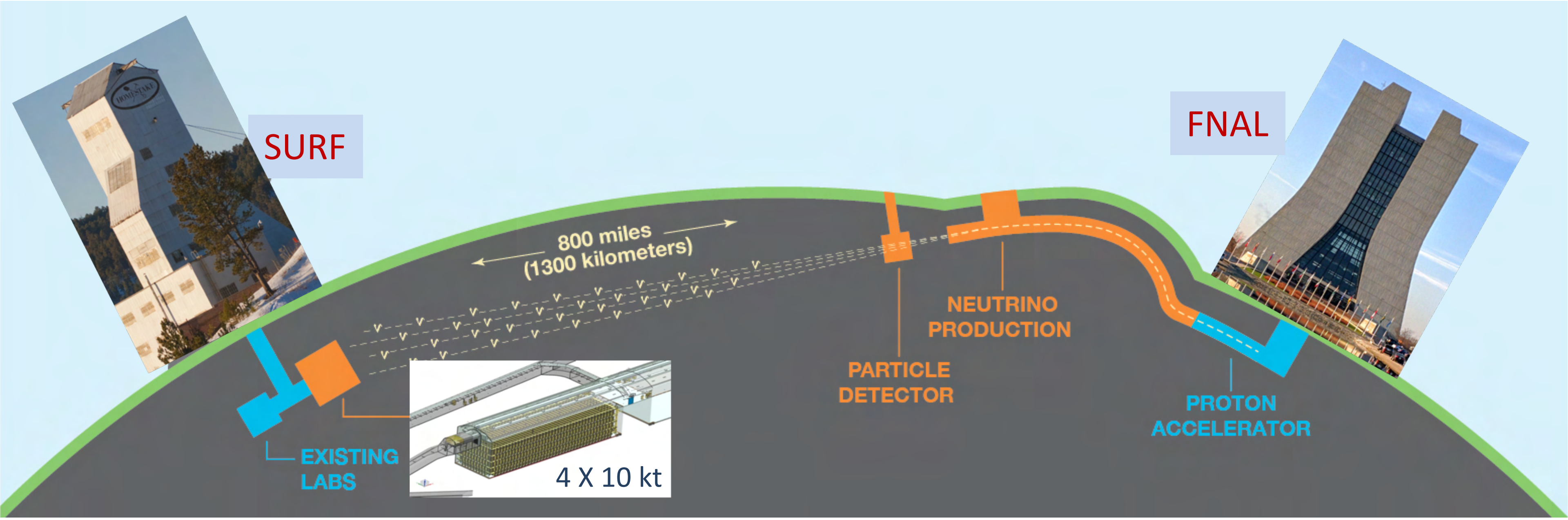
Scientific Goals of the DUNE Experiment: 2

- ν_τ appearance
- Sterile neutrinos
- Search for Non Standard Interactions (NSI)
- Physics with atmospheric neutrinos: e.g. oscillations, mass hierarchy, BSM
- Searches for n – nbar oscillations
- Study of neutrino interactions in the near detector
- Searches for dark matter signatures

- Measurement of solar neutrino if threshold permits
- Potentially first observation of diffuse supernova neutrinos
- Detection of High Energy Neutrinos from astrophysical sources

How ?

The Deep Underground Neutrino Experiment - DUNE



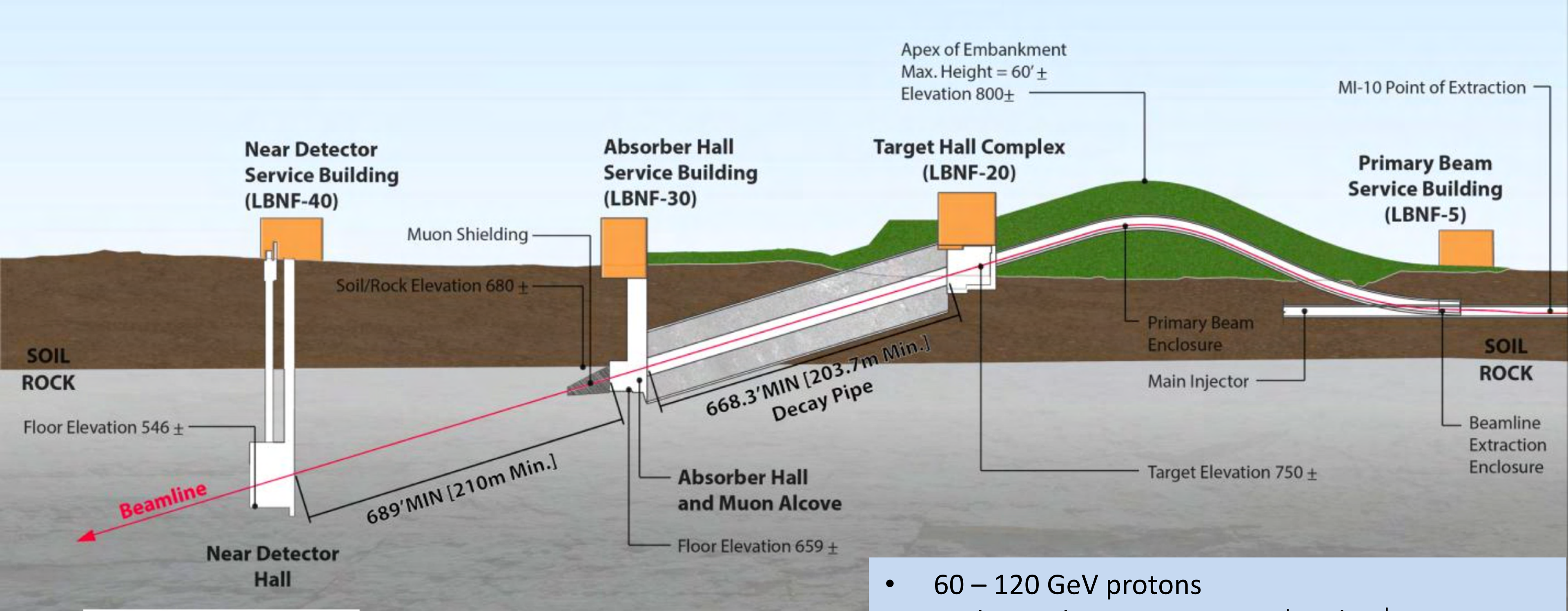
- A high-intensity wide-band neutrino beam originating at FNAL:
  - 1.2 MW from 60 – 120 GeV proton beam upgradable to 2.4 MW.
- Fine-grained near detector complex to measure the neutrino flux:
  - enabling unprecedented studies of neutrino interactions.
- A ~ 4 x 10 kt fiducial mass liquid argon far detector:
  - located at 1300 km from Fermilab at SURF's 4850 ft / 1.5 km level (4300 m.w.e.)

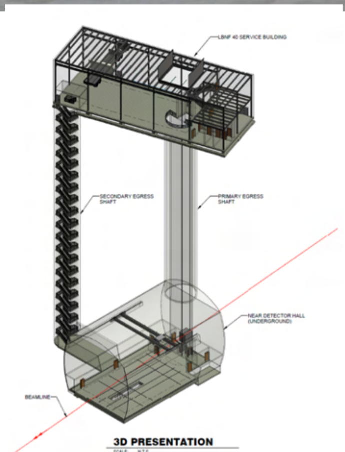
DUNE Collaboration in May 2018

1100 Collaborators from 175 Institutions in 31 Nations

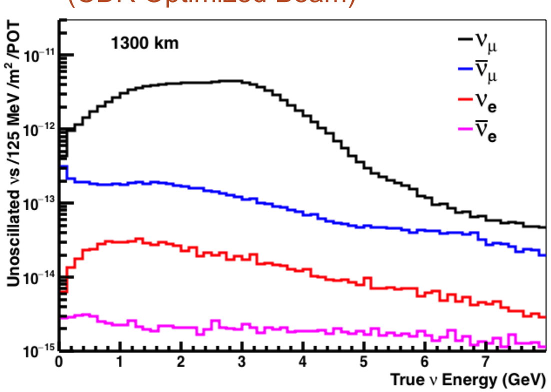
Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Spain, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Romania, Russia, South Korea, Sweden, Switzerland, Turkey, UK, Ukraine, USA

Long Baseline Neutrino Facility - LBNF



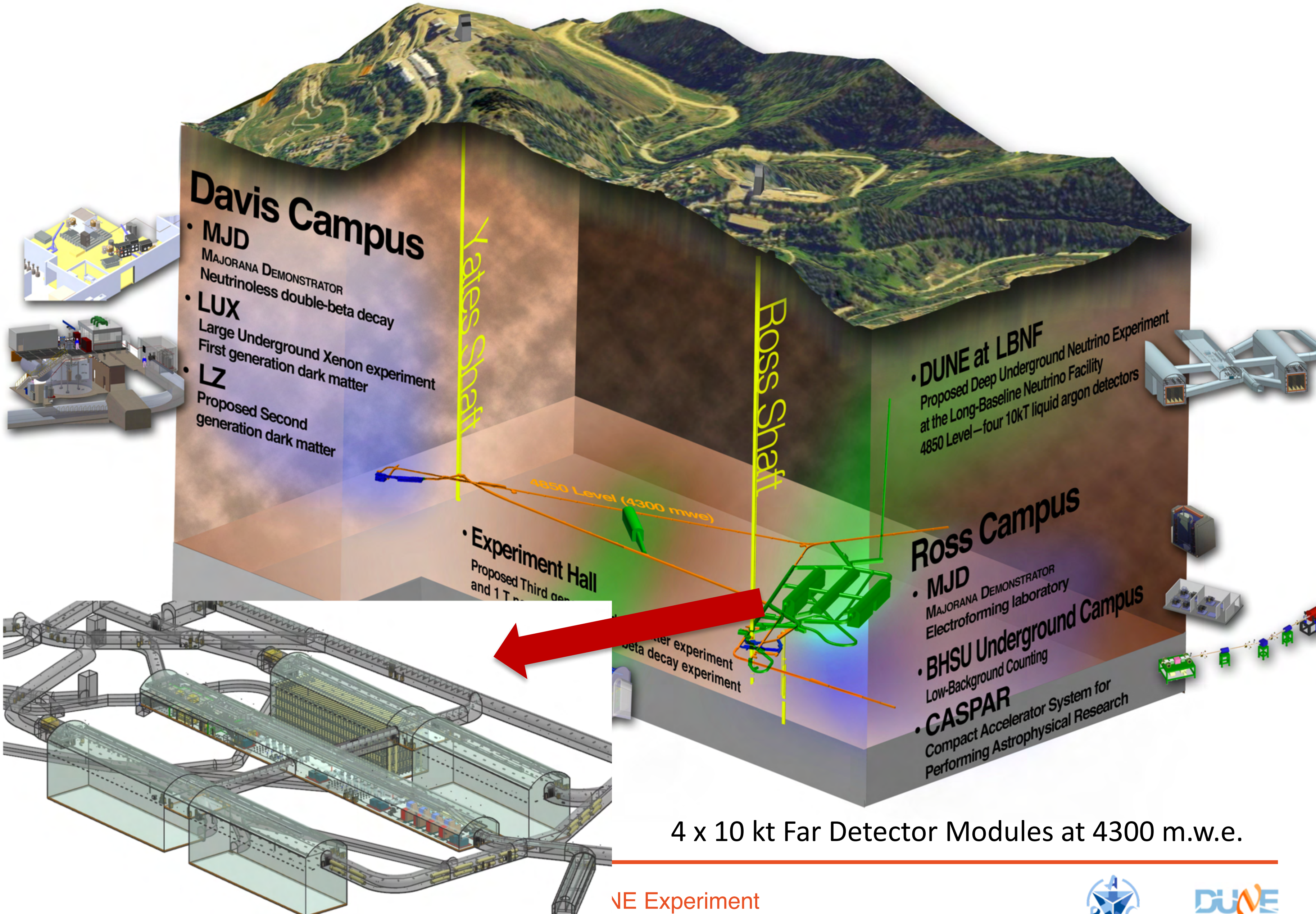


Neutrino Flux at 1300 km
(CDR Optimized Beam)



- 60 – 120 GeV protons
- Wide Band Beam = covers 1st and 2nd max.
- Neutrino and Anti-neutrino running
- Initially 1.2 MW with 80 GeV protons
- Upgrade to 2.4 MW in ≈ 2033
- DUNE ND design concept is an integrated system composed of multiple detectors:
  - Highly segmented LArTPC
  - Magnetized multi-purpose tracker
  - Electromagnetic calorimeter
  - Muon chambers

Sandford Underground Research Facility - SURF

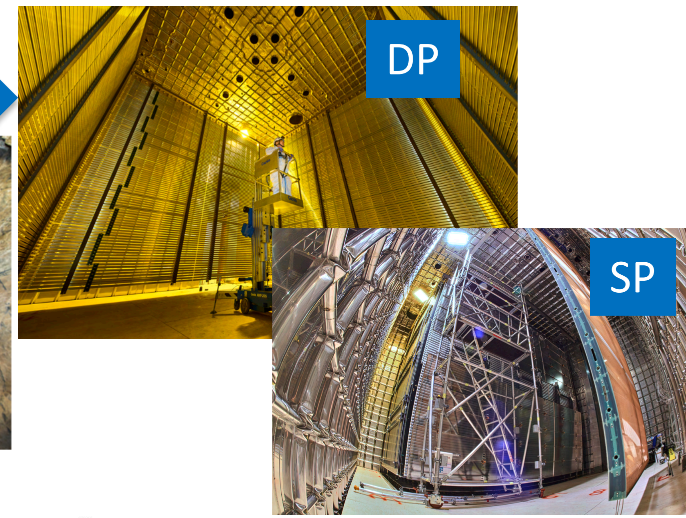


4 x 10 kt Far Detector Modules at 4300 m.w.e.

Time Line of the Experiment

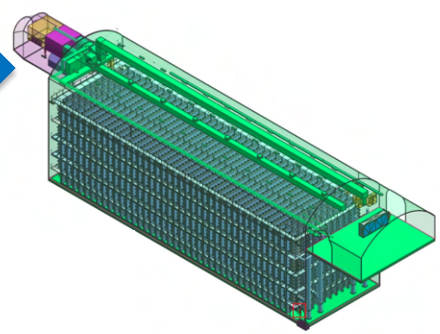
2017 Groundbreaking at – 1500 m

2018 Start operation of ProtoDUNE SP/DP @ CERN

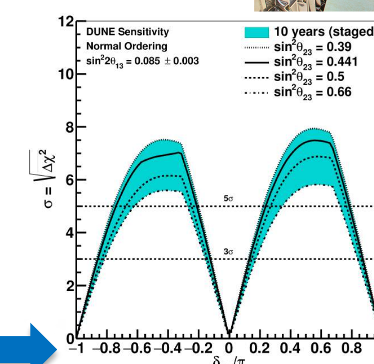


2019 Main Cavern Excavation

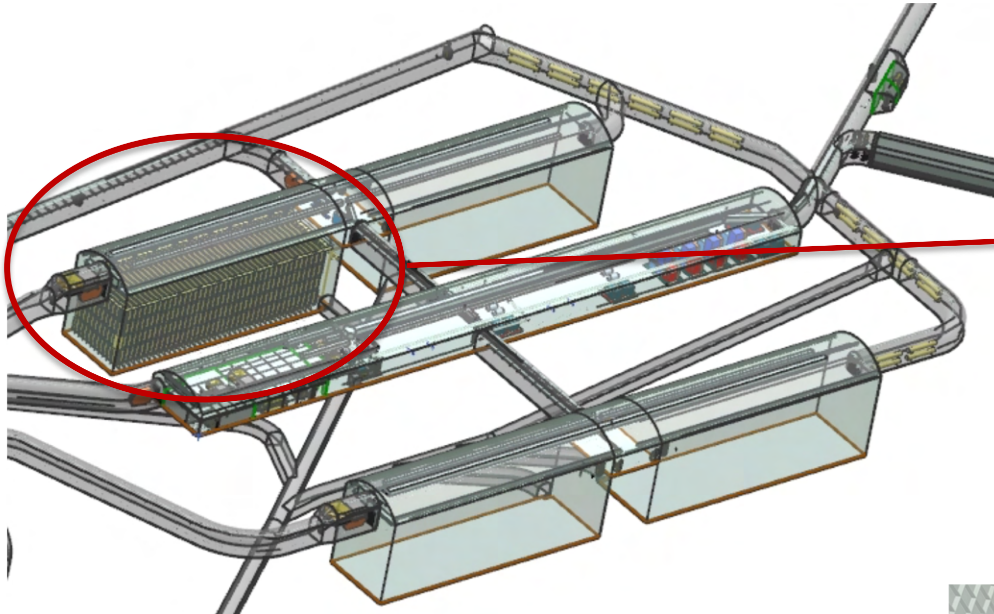
2022 Start FD Construction

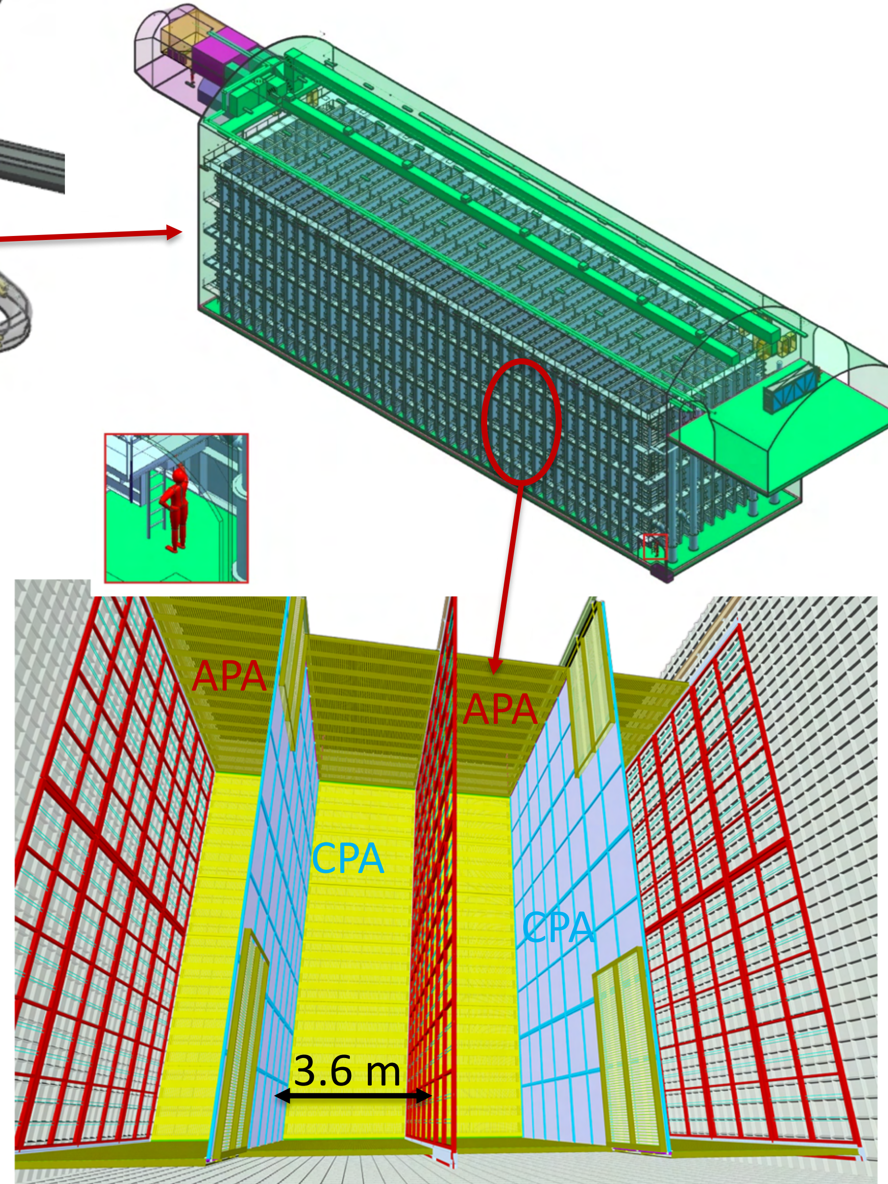


2026 Beam with 2 x 20 kt detector



DUNE Neutrino Detectors: Single Phase LAr TPC





- Anode wires immersed in LAr
- Anode and Cathode Plane Assemblies (APA, CPA) suspended from ceiling
- Drift distance: 3.6 m, wire pitch: 5 mm
- 2 Induction wires +-37.7° and 1collection wire, wrapped around APA
- 384,000 readout wires, 150 APA's
- 12 m high, 15.5 m wide, 58 m long
- Photon detectors: light guides+SiPMs, embedded in APAs

DUNE Neutrino Detectors: Dual Phase LAr TPC

Dual phase: 10 kt module

80 3x3 m^2 "CRPs"
(Charge Readout Planes)

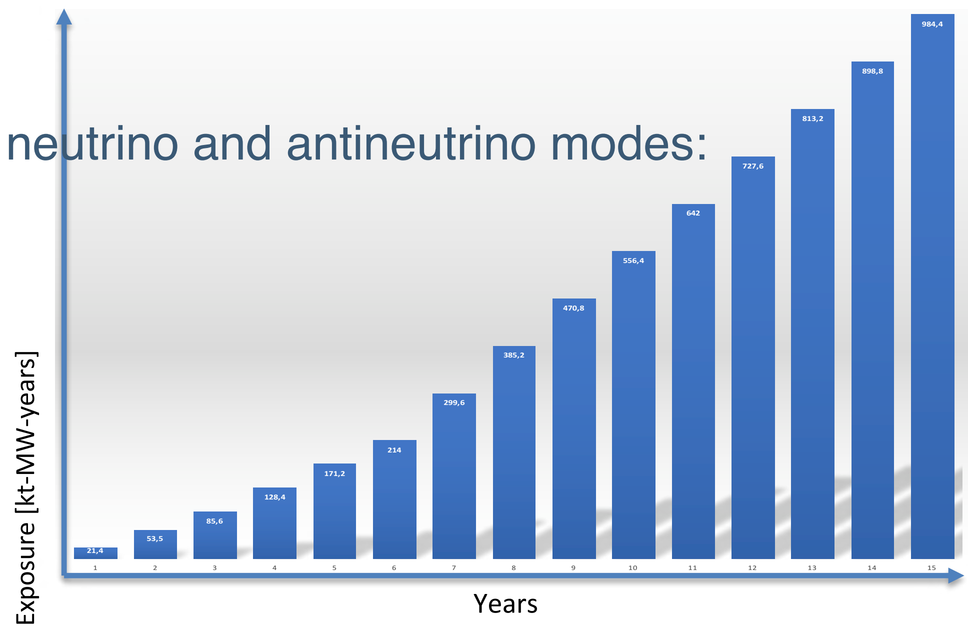
- Electrons extracted from LAr to gaseous volume
- Signal amplified by Large Electron Multiplier (LEM) in gas phase
- Charge collected and recorded on 2-D segmented anode, 3 mm pitch, 153,600 channels
- Drift distance: 12 m (vertical)
- Better Signal/Noise
- Photon detectors: PMT below cathode

DUNE Neutrino Detectors

- Four identical detector modules of 17 kt total argon or 10 kt fiducial volume each
- TDR for both detector technologies is due in April 2019
- 2021: Start installation of the 1st FD module, based on Single Phase technology
- 2023: Start installation of the 2nd FD module, based on Dual Phase technology
- Final choice on the technology is pending on the success of the ProtoDUNEs and finances
- 2024: Start commissioning and data taking with cosmics
- 2026: Start with 1.2 MW beam

Staging scenario with equal running in neutrino and antineutrino modes:

- **Year1**(2026): 20-kt FD,1.2 MW beam
- **Year2**(2027): 30-kt FD
- **Year4**(2029): 40-kt FD
- **Year7**(2032): 2.4 MW beam

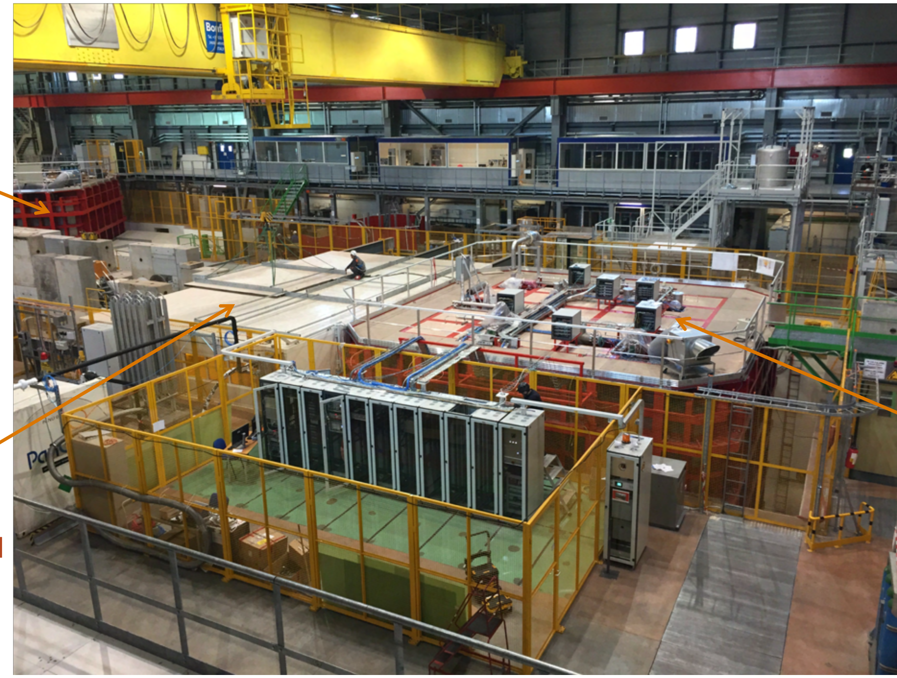


Single & Dual Phase Prototypes at CERN

Motivations:

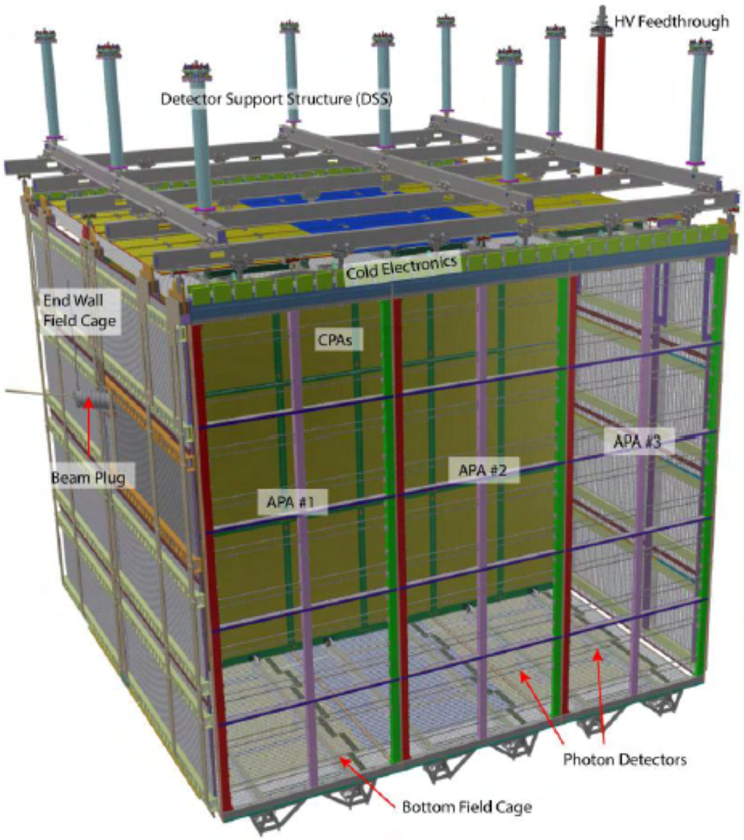
Last Prototype to evaluate all engineering aspects
- Underground construction
- Detector design
- Cryogenics system
- VHV system

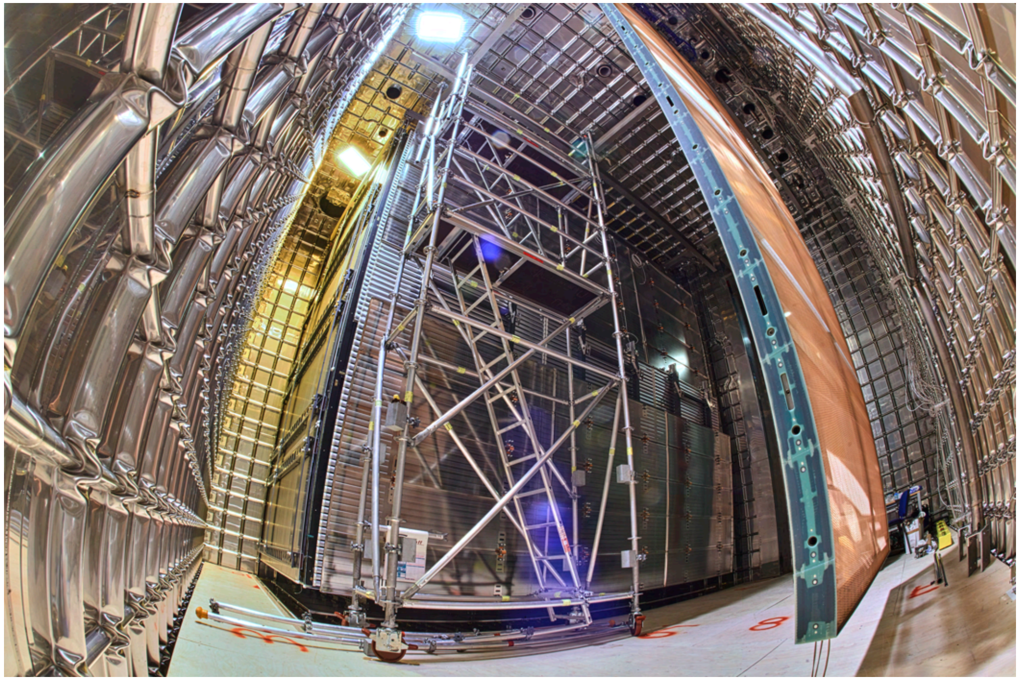
Perform Physics measurements:
- Charged Particle Beams (e, $K^{+/-}$, $\pi^{+/-}$, p, $\mu^{+/-}$)
- Validate simulations for particle ID, energy reconstruction, tracking
- E / γ separation
- π^+ / π^- response
- π^0 production
- EM and Had. Shower reconstruction
- dE/dx measurements
- Validate reconstruction algorithms



Neutrino Platform (EHN1 @ CERN)

Single Phase Prototype

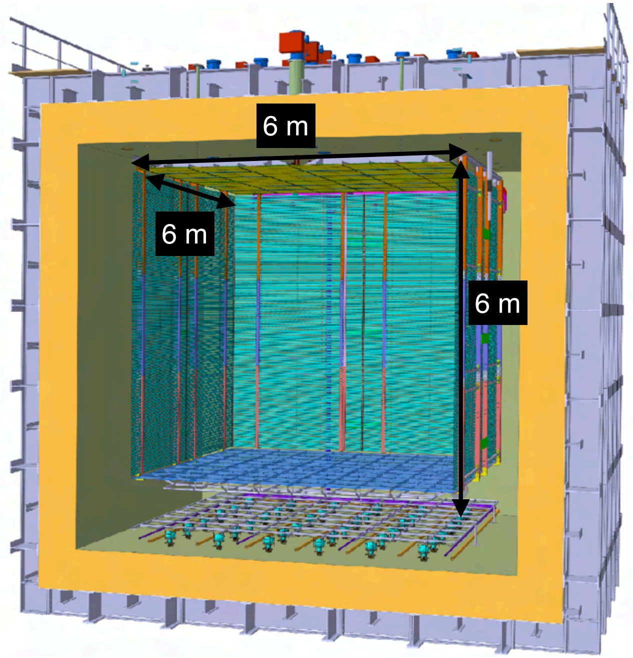




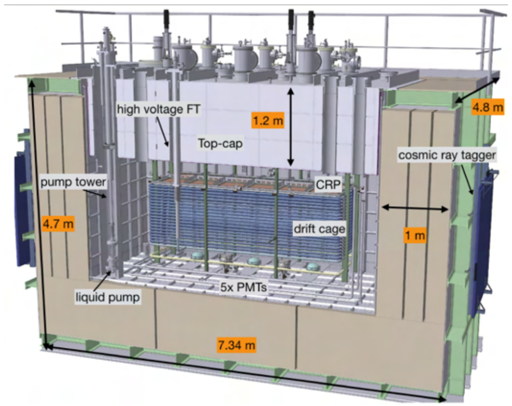
6 x 6 x 6 m^3 active volume (≈ 300 t LAr)

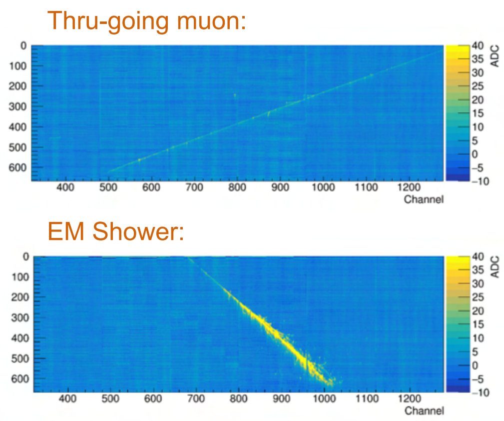
- May 2018: Single Phase installation completed
- July 2018: Cooldown Single Phase
- August November 2018: Beam

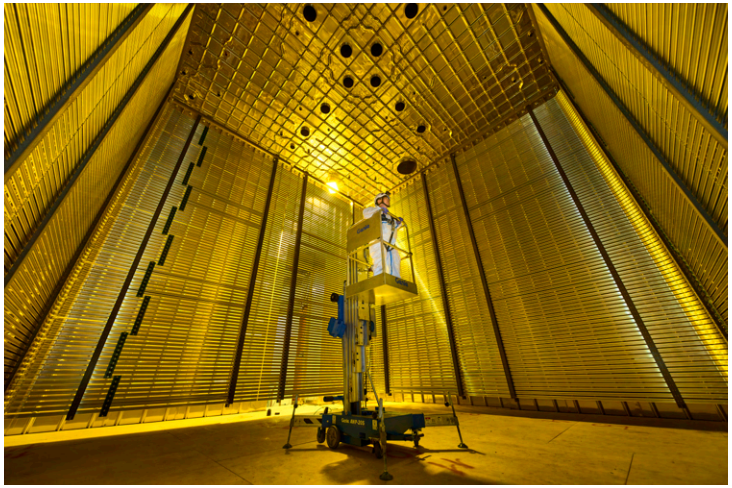
Dual Phase Prototype



6 x 6 x 6 m^3 active volume (≈ 300 t LAr)







3 x 1 x 1 m^3 Prototype

- Successfully running June – November 2017
- Cold but accessible electronics successfully tested
- Valuable lessons learnt for future detectors:
  - Quality control
  - Engineering
  - Cryogenics
  - VHV
  - Legal issues for cryostat and procurement

Fall 2018: Dual Phase installation to be completed

Just posted the paper Tuesday:

http://arxiv.org/abs/1806.03317

Some examples of physics measurements

Results and figures from:

- DUNE Conceptual Design Report (CDR) arXiv:1512.06148
- GLoBES configurations arXiv:1606.09550

Neutrino Oscillations with DUNE

ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$-\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta m^2_{31} L}{4E} \qquad A = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

- DUNE measures ν_e appearance probability and ν_μ disappearance probability with ν_u and anti-ν_u beam.
- ν_e appearance: mass hierarchy, δ_{CP} and octant of θ_{23}
- ν_μ disappearance: high precision $|\Delta m_{32}|$ and $\sin^2 2\theta_{23}$, constrain octant

Neutrino Oscillation Measurement Strategy

ν_e / $\bar{\nu}_e$ appearance:

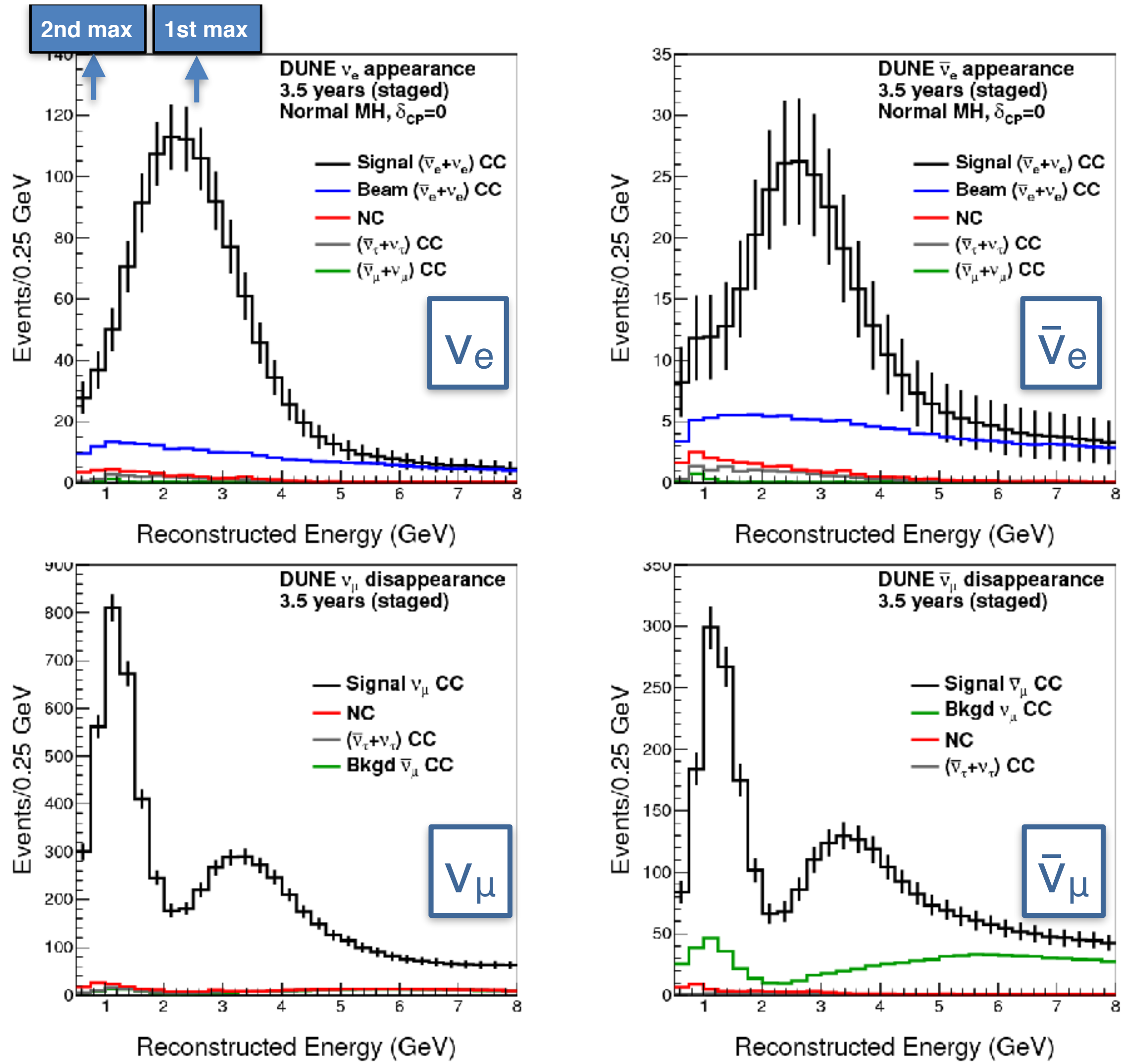
Fit to four samples

↓

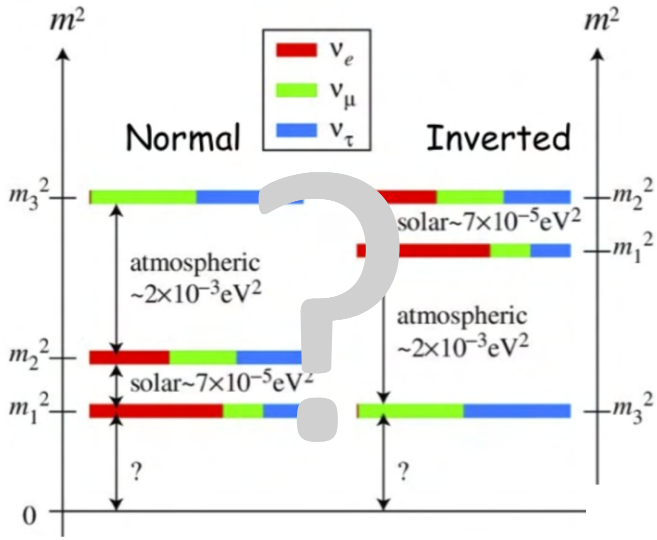
oscillation parameters

ν_μ / $\bar{\nu}_\mu$ disappearance:

Details about oscillation sensitivity calculations in arXiv:1606.09550



Sensitivity to Neutrino Mass Hierarchy



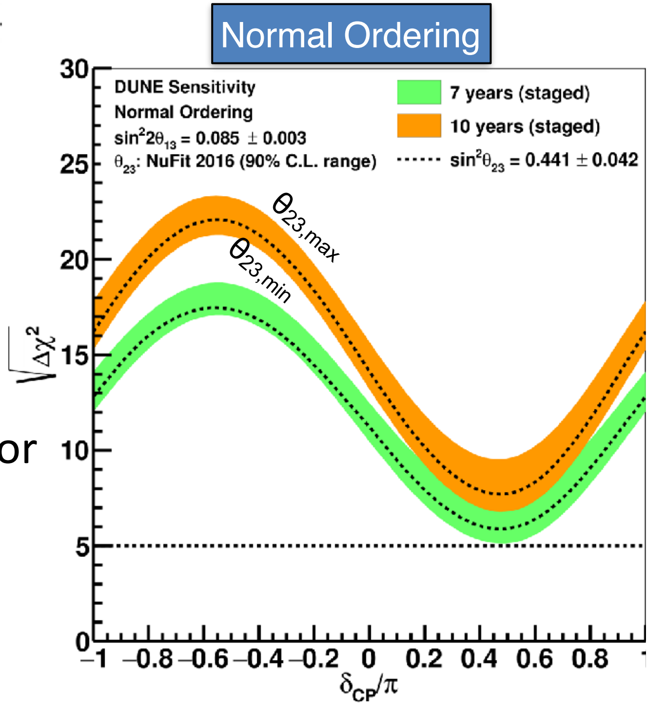
- 5σ sensitivity for any δ_{CP}

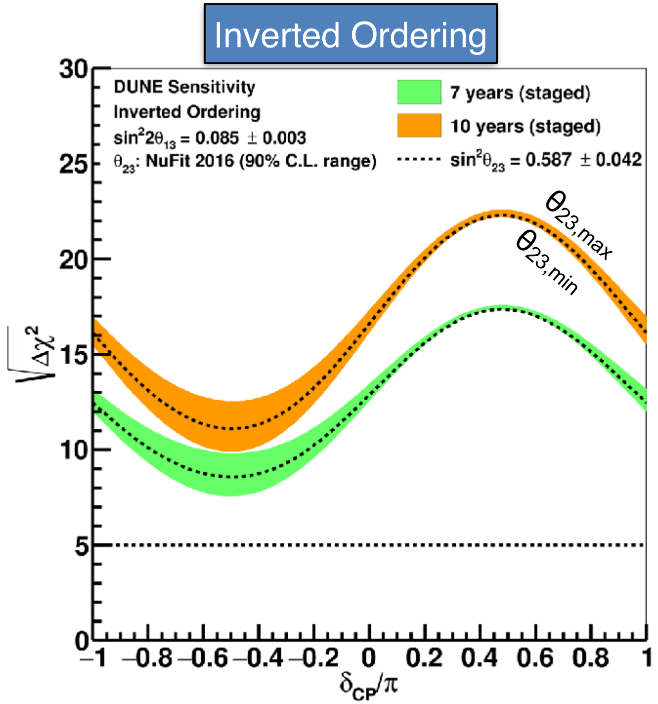
Matter effects modify the oscillation probability:

$$P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23}\sin^2 2\theta_{13}^m \sin^2\frac{\Delta_{13}^m L}{2}$$

The probability is enhanced for

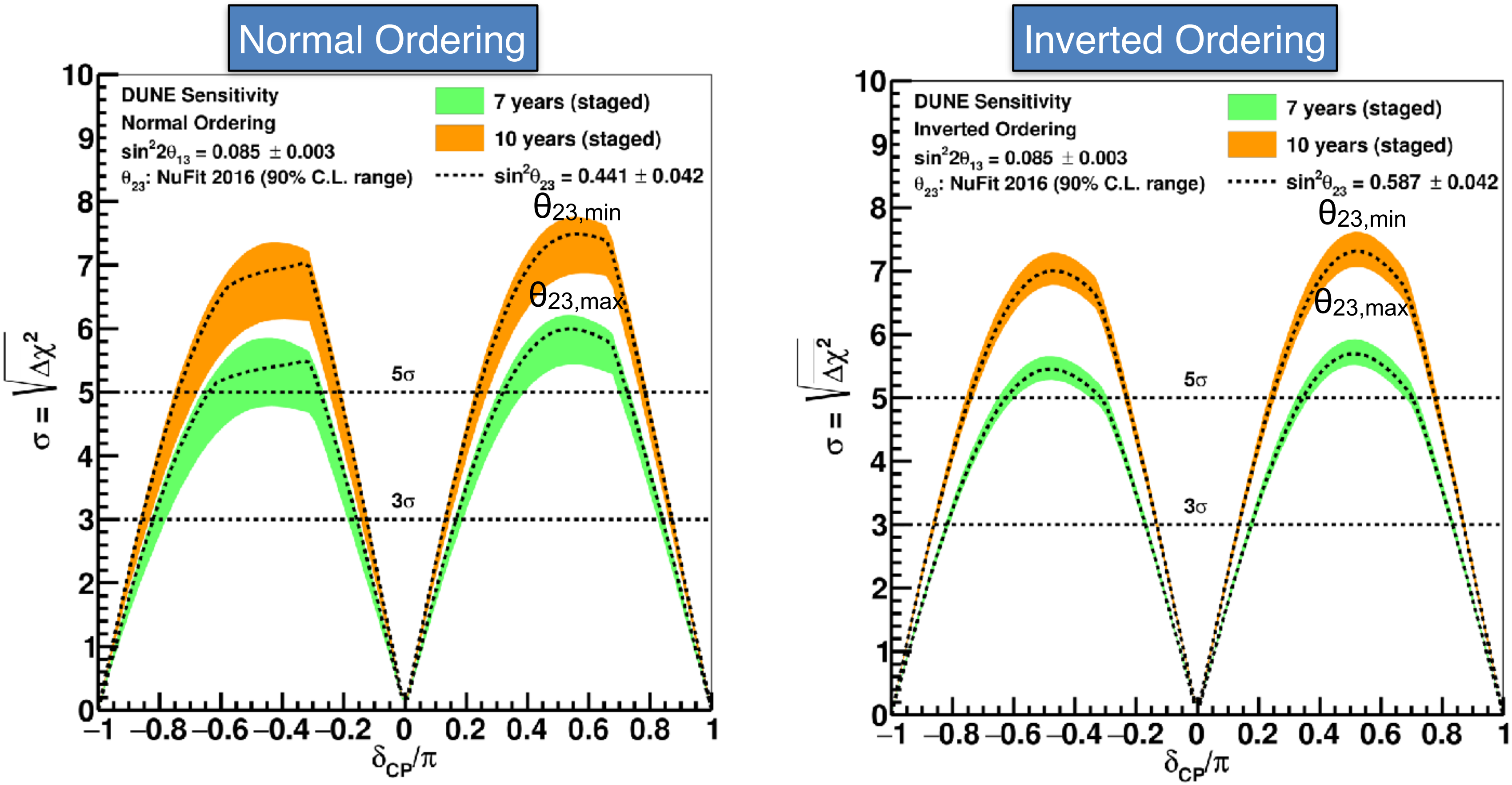
- neutrinos if $\Delta m^2 > 0$
- antineutrinos if $\Delta m^2 < 0$





Sensitivity to leptonic CP violation

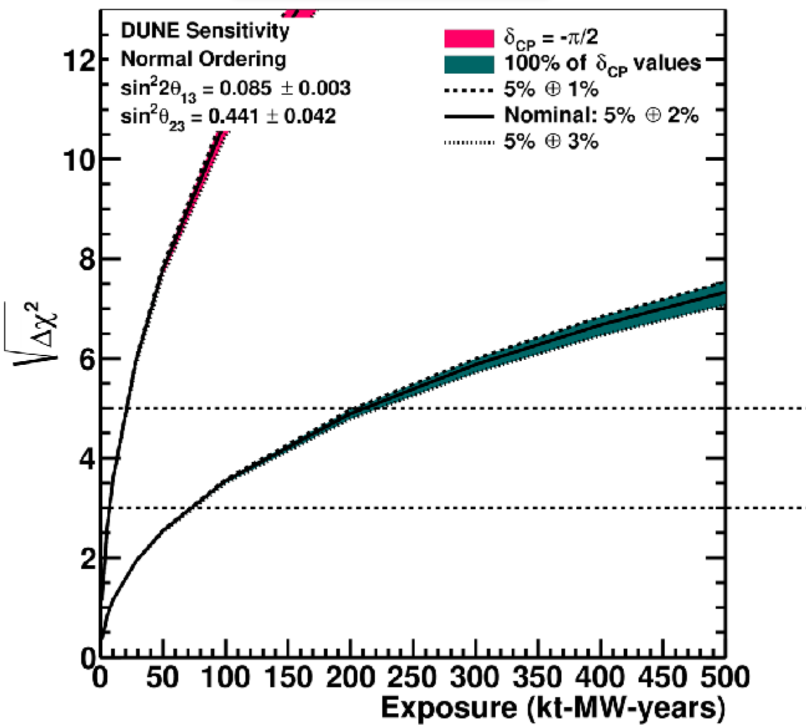
- 5σ sensitivity after 300 kt·MW·yr exposure (7 yr)



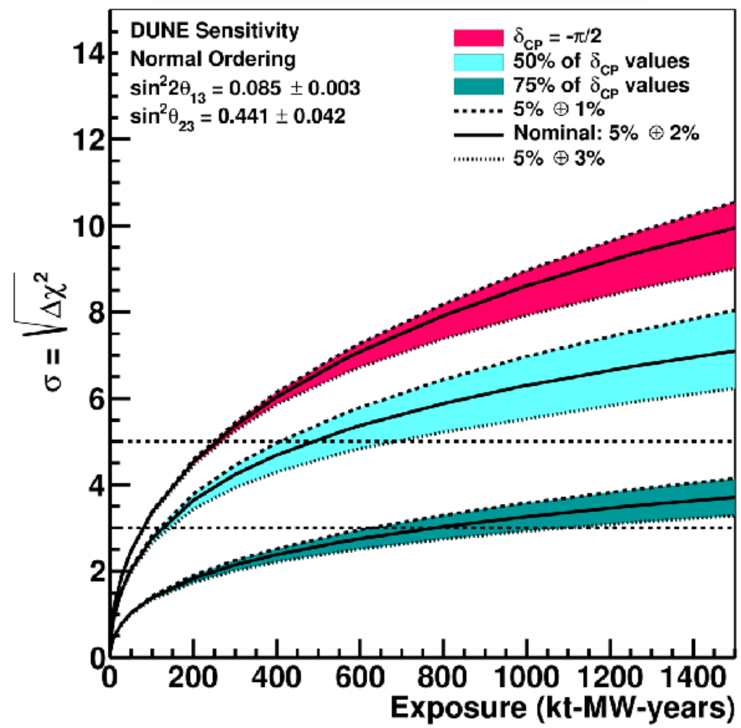
Effect of systematic uncertainties

- Width of sensitivity bands: 1-3% ν_e signal normalisation uncertainty
- Small impact on MH. For CP, important to keep uncertainty at ≲2%

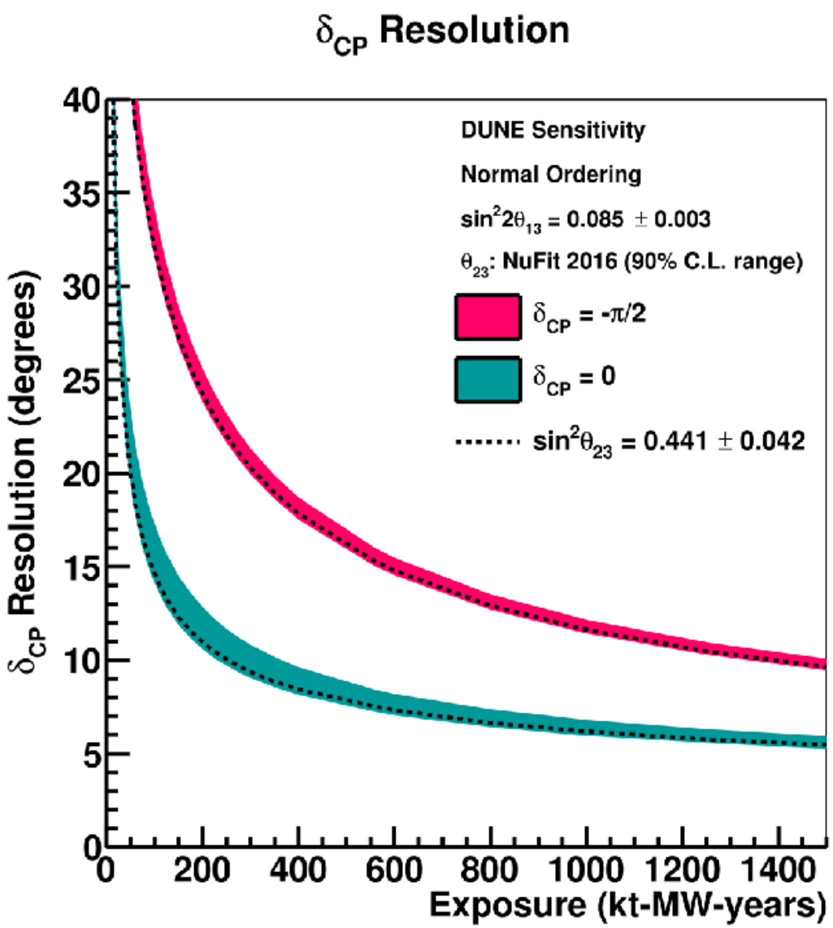
MH Sensitiivity

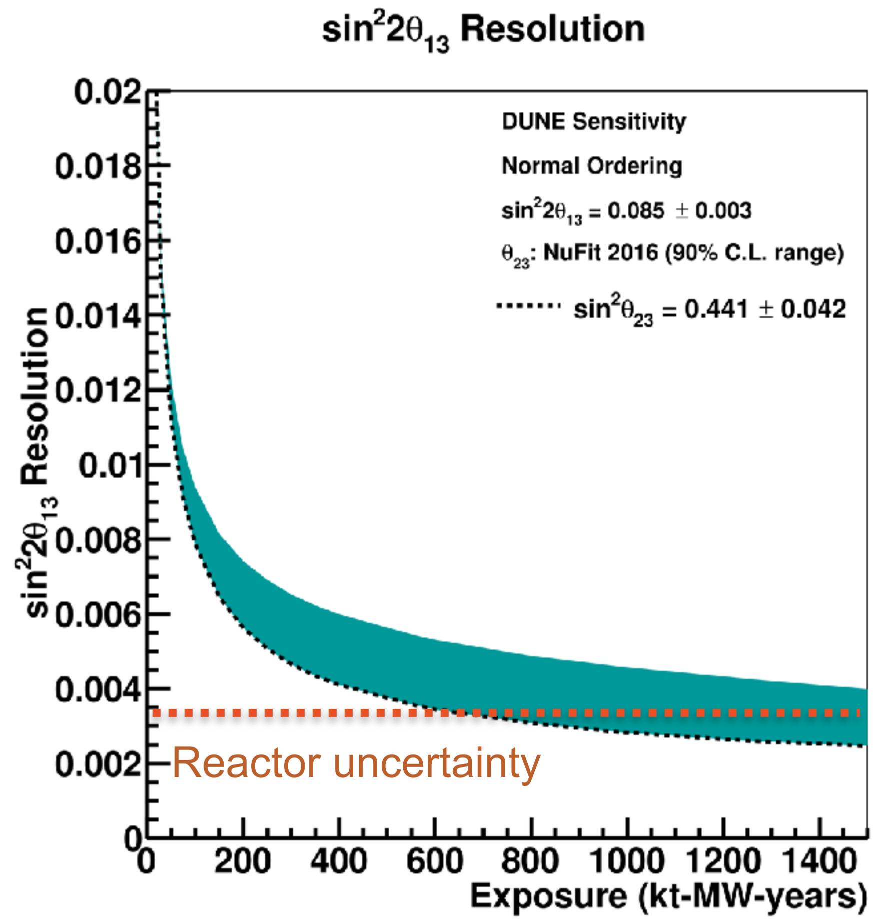


CP Violation Sensitiivity

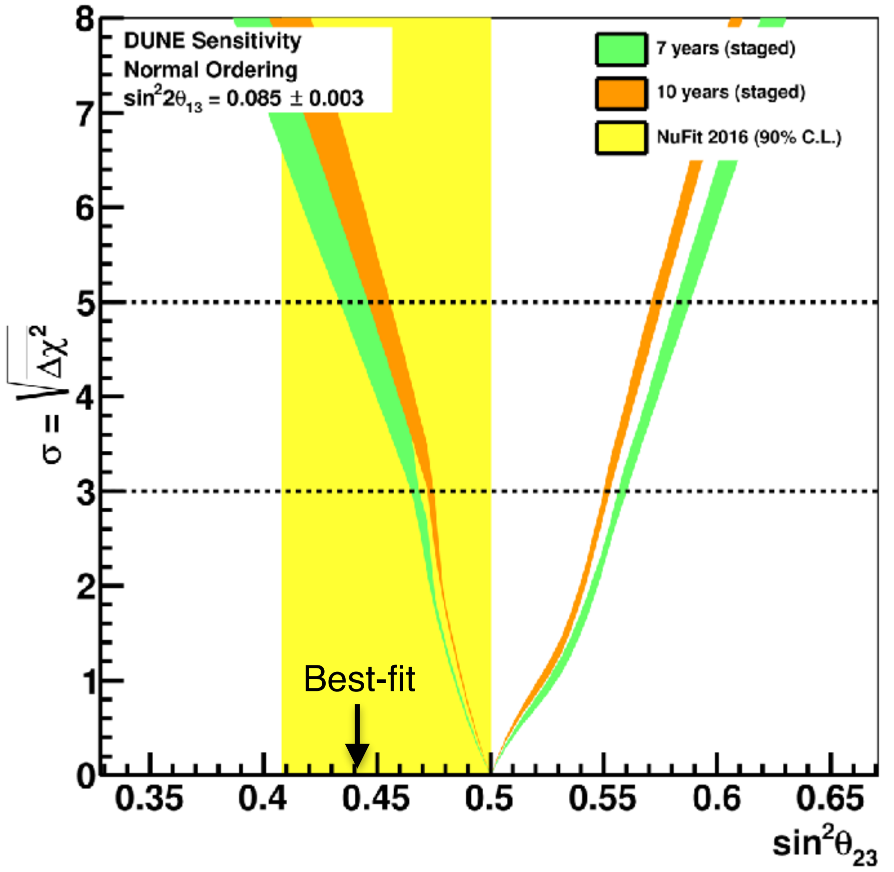


DUNE Resolution for δ_{CP} and $\sin^2 2\theta_{13}$



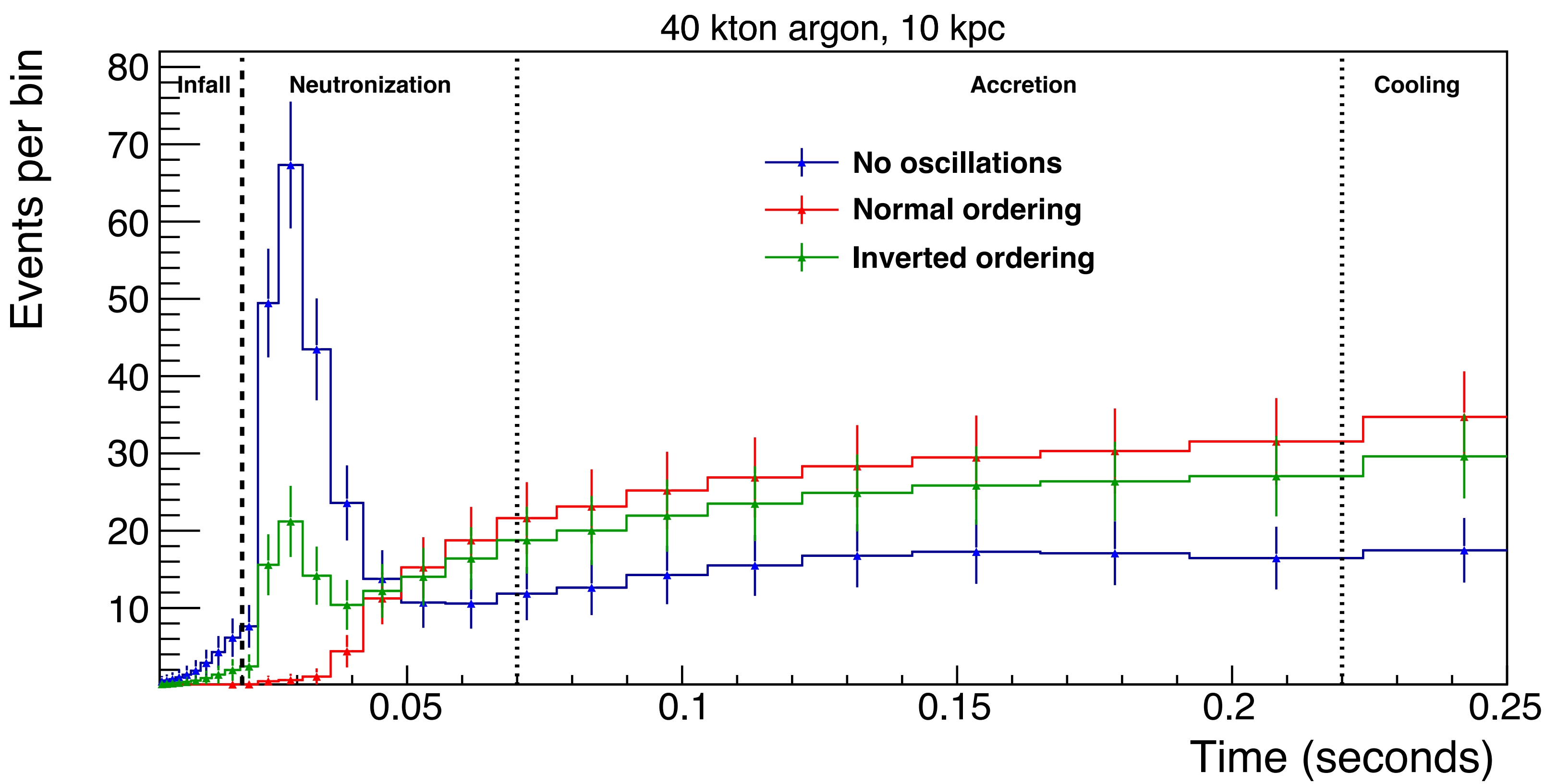


Sensitivity to θ_{23} octant



Supernova Neutrino Bursts

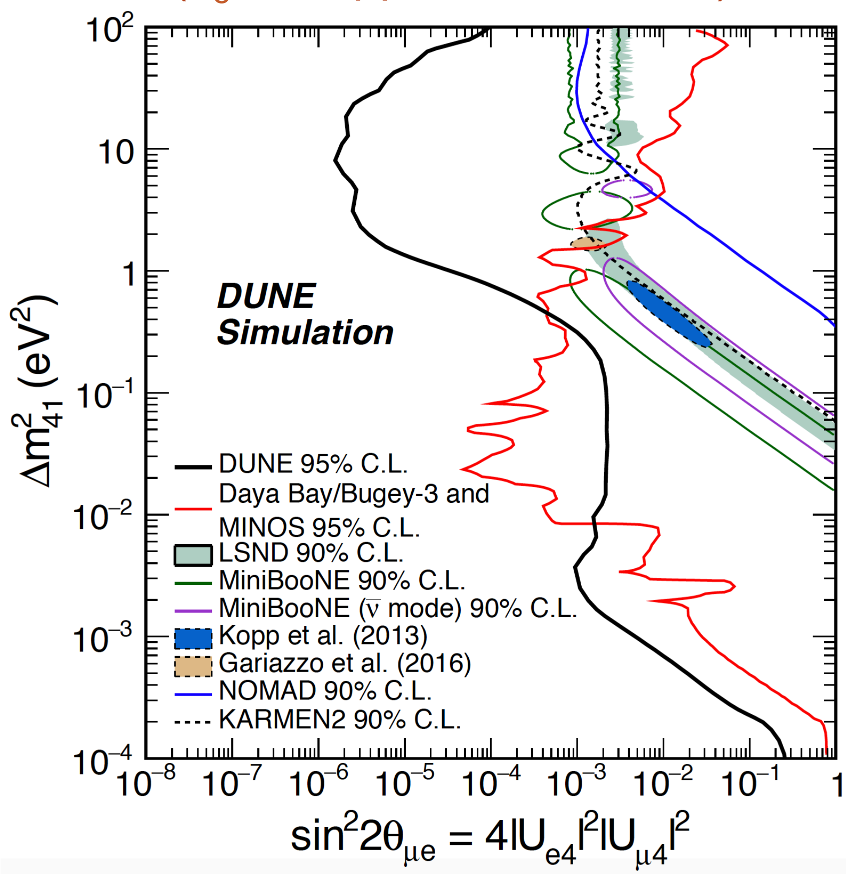
- Vast information from flavor-energy-time profile of events
- Unique sensitivity to ν_e's:
  - Elastic scattering: $\nu_x + e^- \to \nu_x + e^-$ ($x = e, \mu, \tau$)
  - Absorption: $\nu_e + {}^{40}Ar \to e^- + {}^{40}K^*$, $\overline{\nu}_e + {}^{40}Ar \to e^+ + {}^{40}Cl^*$



Searches for Physics Beyond Standard Model (BSM) with DUNE

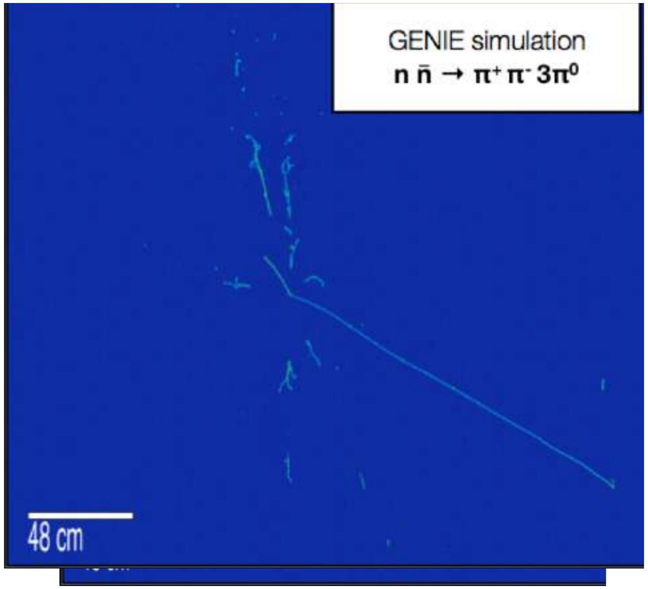
- DUNE sensitive to many BSM particles and processes
  - Light dark matter
  - Boosted dark matter
  - Sterile neutrinos
  - Non-standard interactions, non-unitary mixing, CPT violation
  - Neutrino trident searches
  - Large extra dimensions
  - Neutrinos from dark matter annihilation in sun

Sterile Neutrino Sensitivity
(ν_e CC appearance at ND)



Credit: A. Sousa: "Searching for Beyond the Standard Model Physics with the DUNE Experiment", presented in the Neutrino 2018 conference.

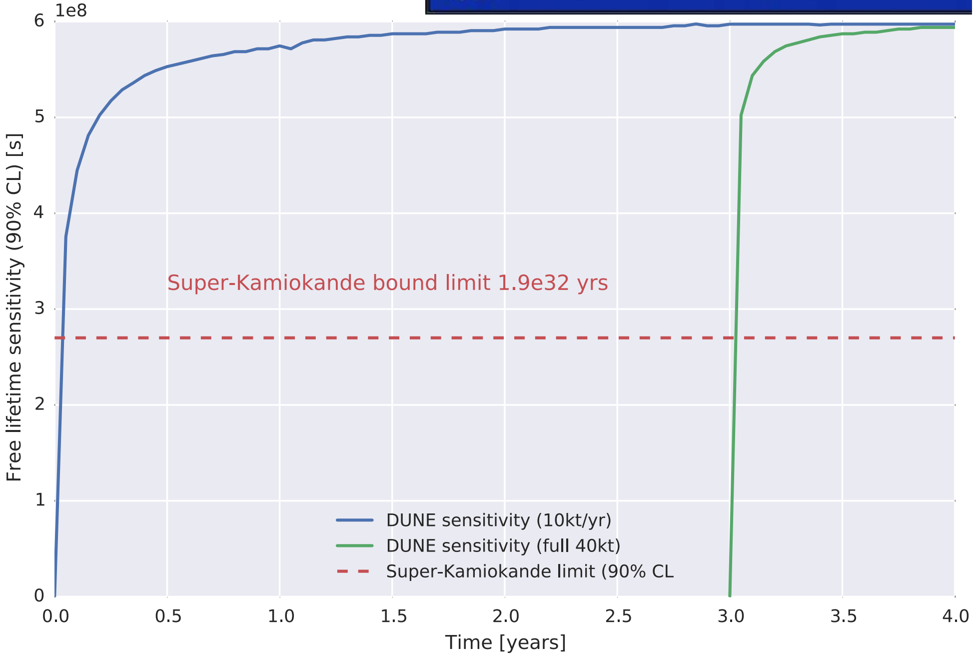
n – nbar Oscillations



- BSM process that violates baryon number

- 'Star'event topology consists of charged and neutral pions

- Convolutional Neural networks being investigated to identify $n - n$bar oscillation over dominant atmospheric ν background



Credit: Joshua Barrow, "Neutron-Antineutron Transformation at the Deep Underground Neutrino Experiment", presented at the International Workshop on Particle Physics at Neutron Sources 2018, Institut Laue-Langevin, Grenoble, France, May 25th, 2018

Interesting points for this workshop from the ND Physics:

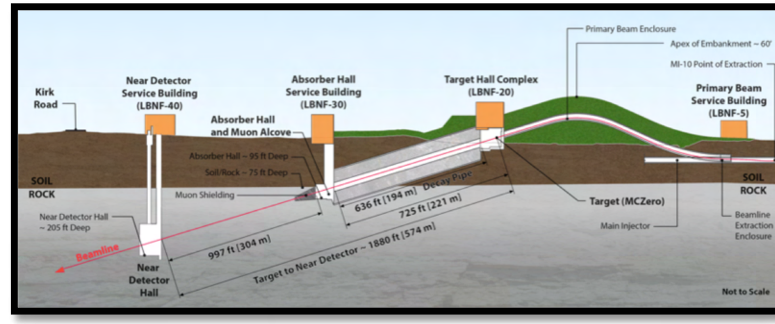
- The near detector plays a crucial role to minimize the uncertainties for oscillation physics
- Precision measurements of structure functions and differential cross sections directly affect the oscillation measurements by providing accurate simulations of neutrino interactions.

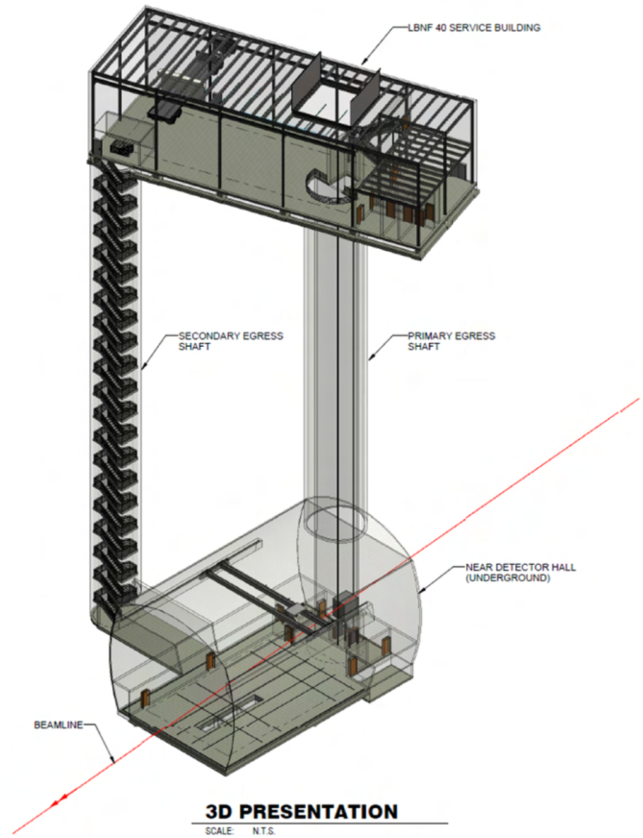
- Neutrino and Anti-neutrino – Nucleon interactions allow:

  1. Measurement of form factors and structure functions
  2. QCD analysis, tests of perturbative QCD and quantitating the non-perturbative QCD effects
  3. d/u Parton distribution functions at large x, which is the limiting error in the ν_τ -CC measurements/searches at the far detector
  4. Sum rules and the strong coupling constant
  5. Quark-hadron duality

DUNE Near Detector

- Primary purpose is to **constrain systematic uncertainty** for long-baseline oscillation analysis
  - Constrain flux, cross-section, and detector uncertainties
- DUNE ND design concept near final
  - Active ND Design Group
  - ND Conceptual Design Report (CDR) planned for 2019
- DUNE ND design concept is an integrated system composed of multiple detectors:
  - Highly segmented LArTPC
  - Magnetized multi-purpose tracker
  - Electromagnetic calorimeter
  - Muon chambers
- Conceptual design will preserve option to move ND for off-axis measurements

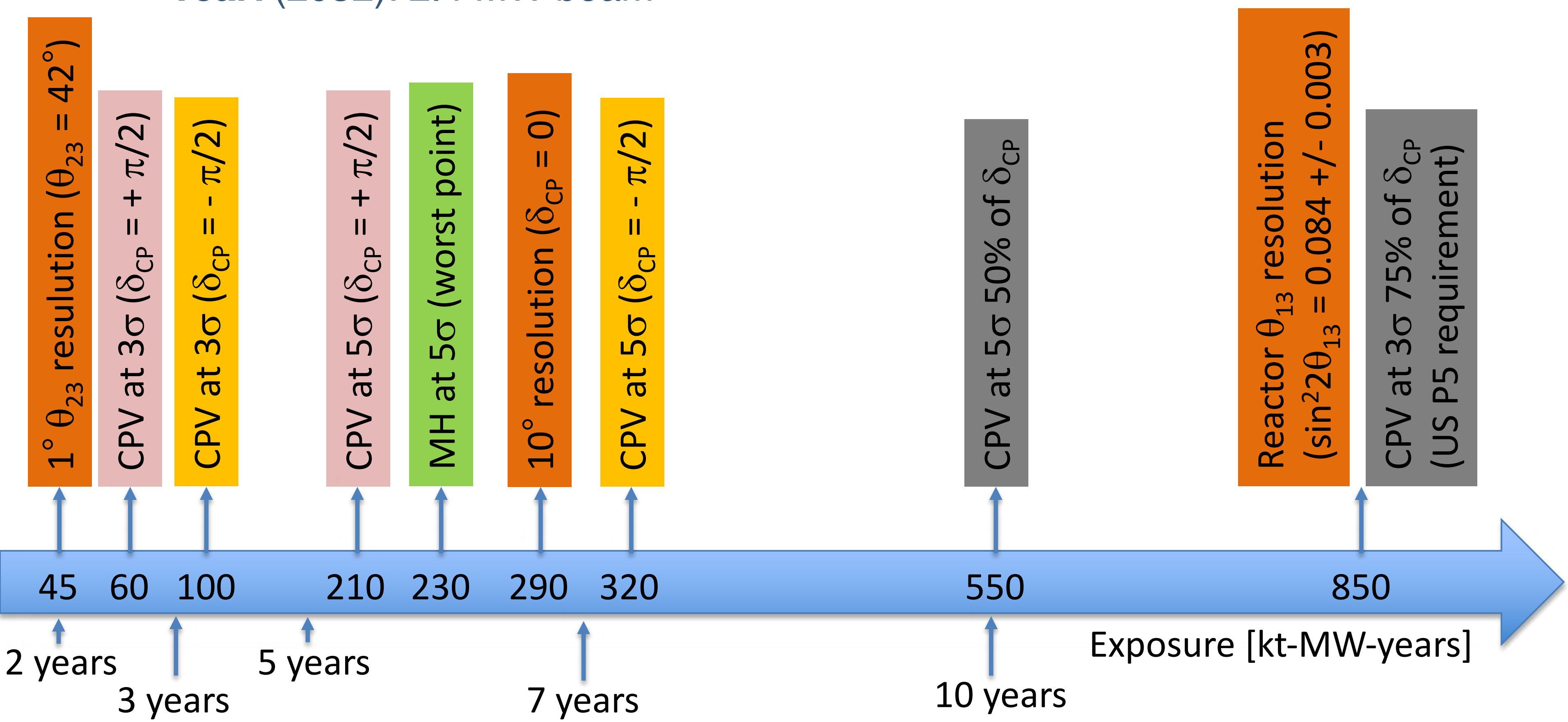




Physics milestones vs Exposure kt-MW-years

Staging scenario with equal running in neutrino and antineutrino modes:

- **Year1**(2026): 20-kt FD,1.2 MW beam
- **Year2**(2027): 30-kt FD
- **Year4**(2029): 40-kt FD
- **Year7**(2032): 2.4 MW beam



Conclusions - 1

- DUNE at LBNF is a next-generation experiment for neutrino, nucleon decay and astroparticle physics
- Gathers world wide community: > 1000 physicists
- Aims to be the "definitive" experiment based on conventional neutrino beams and the next mega-science project after the LHC
- Unique Experiment: Spectral measurement, sensitive to ν_e AND ν_τ appearance, unitarity check
- LBNF/DUNE groundbreaking at SURF in July 2017!
- Physics data-taking starts in 2024, beam from FNAL available in 2026

Conclusions - 2

- Very rich science program:
  - Precision measurement of and unitarity check of the neutrino mixing matrix
  - Discovery (5σ) of the neutrino mass ordering
  - Potential discovery (5σ) of CP violation in the neutrino sector
  - Potential discovery of nucleon decay
  - Detection and spectral / timing measurement of SN burst neutrinos
  - Potential detection of DSN neutrinos
  - Physics with atmospheric neutrinos
  - Search for NSI
  - Neutrino physics with the near detector
  - Dark Matter searches

Thank you for your attention!

Extra slides

DUNE CDR Systematics

- Sensitivities in DUNE CDR are based on GLoBES calculations in which the effect of systematic uncertainty is approximated using signal and background normalization uncertainties.

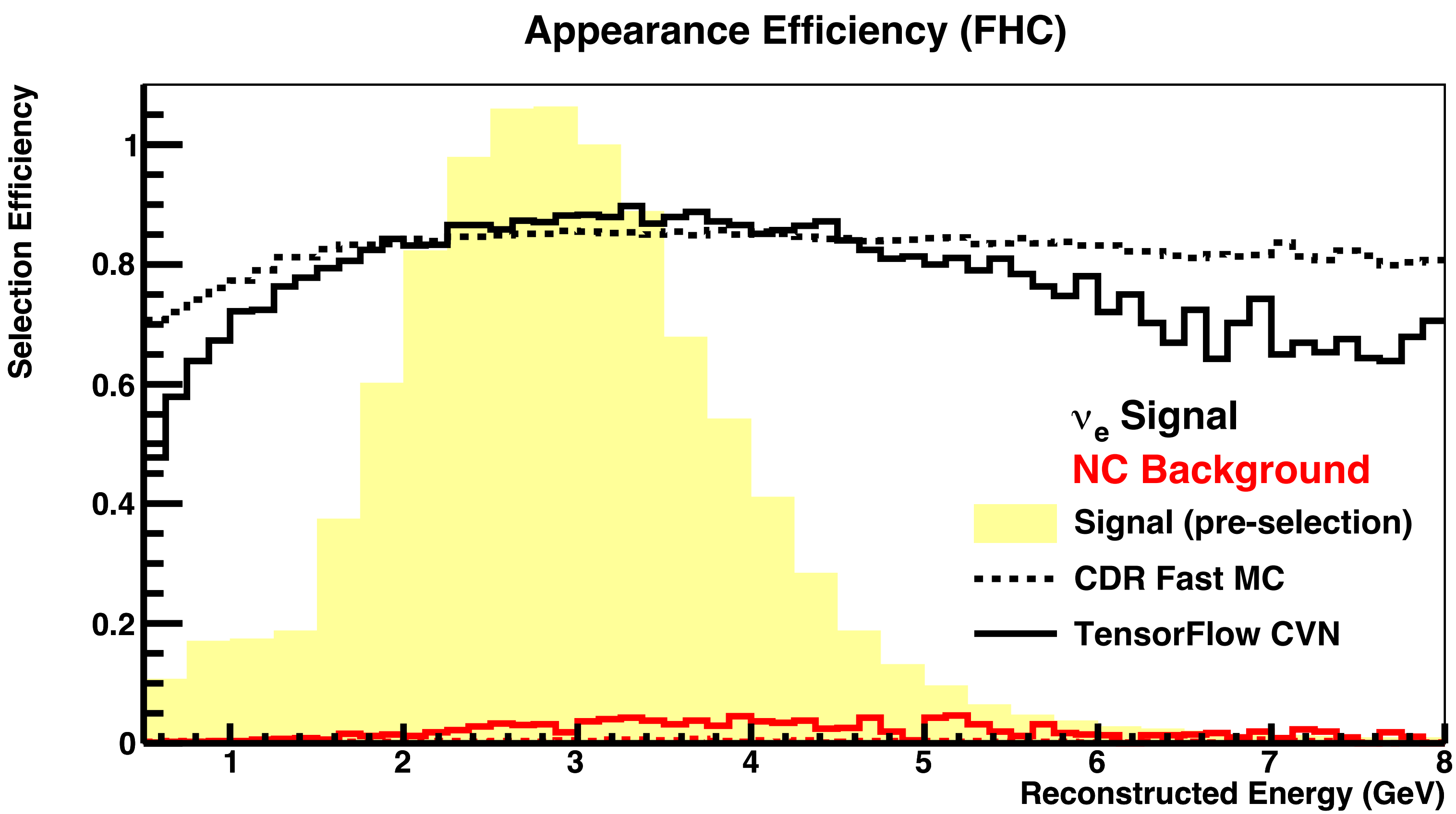
  Spectral uncertainty not included in this treatment.

- Signal normalization uncertainties are treated as *uncorrelated* among the modes (ν_e, ν_e, ν_μ, ν_μ) and represent the residual uncertainty expected after constraints from the near detector and the four-sample fit are applied.
  - $\nu_\mu = \nu_\mu = 5\%$ → Flux uncertainty after ND constraint
  - $\nu_e = \nu_e = 2\%$ → Residual uncertainty after ν_μ and ν/ν constraint
- Oscillation parameter central values and uncertainties are taken from NuFit 2016 (arXiv:1611.01514). Parameters are allowed to vary constrained by 1/6 of the $\pm 3\sigma$ range in the global fit.

Monte Carlo Analysis (New!)

- GEANT4 beam simulation of updated beam design
- Full LArSoft Monte Carlo simulation
  - Shared framework among many LArTPC experiments
  - GENIE event generator
  - GEANT4 particle propagation
  - Detector readout simulation including realistic waveforms and white noise
- Automated signal processing and hit finding
- Automated energy reconstruction
  - Muon momentum from range (contained) or multiple Coulomb scattering (exiting)
  - Electron and hadron energy from calorimetry
- Event selection using convolutional visual network (CVN)
- Oscillation analysis using CAFAna fitting framework
  - Shared framework with NOvA
- CDR-style systematics analysis (update coming in 2019)
- Results shown here are for single phase; dual phase analysis in progress

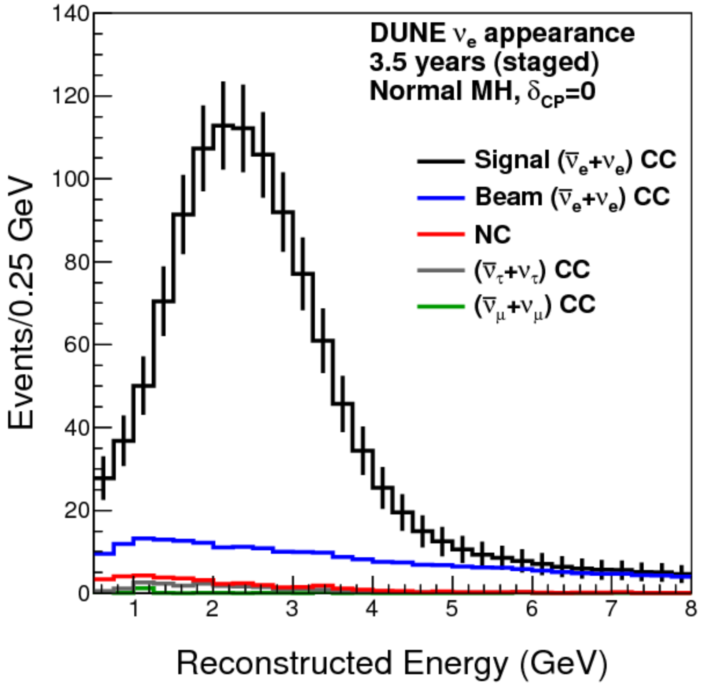
Selection Efficiency



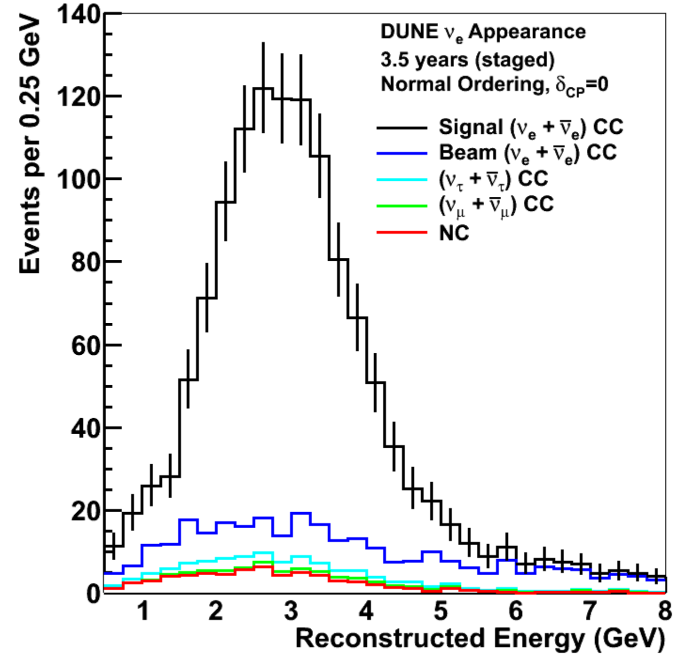
CVN ν_e event selection efficiency similar to that from CDR Fast MC

Monte Carlo Analysis Results

CDR



New!



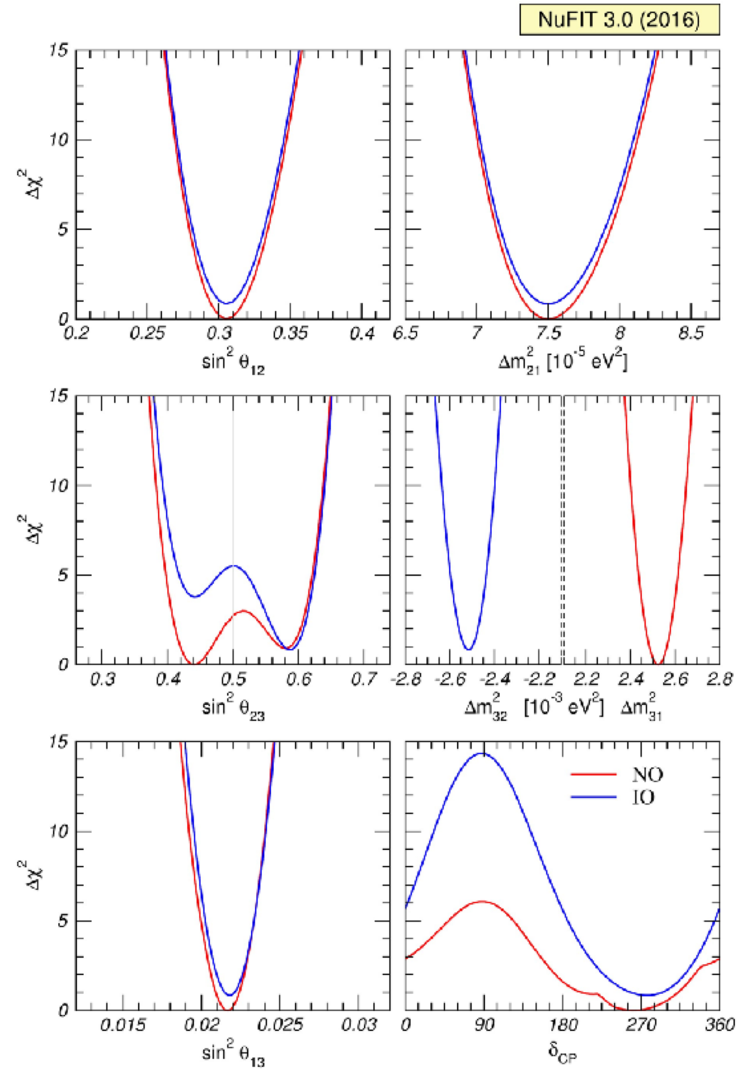
Sensitivity from MC-based analysis with automated reconstruction and event selection exceeds CDR sensitivity!

Full update of sensitivity plots with detailed systematics planned for TDR in 2019

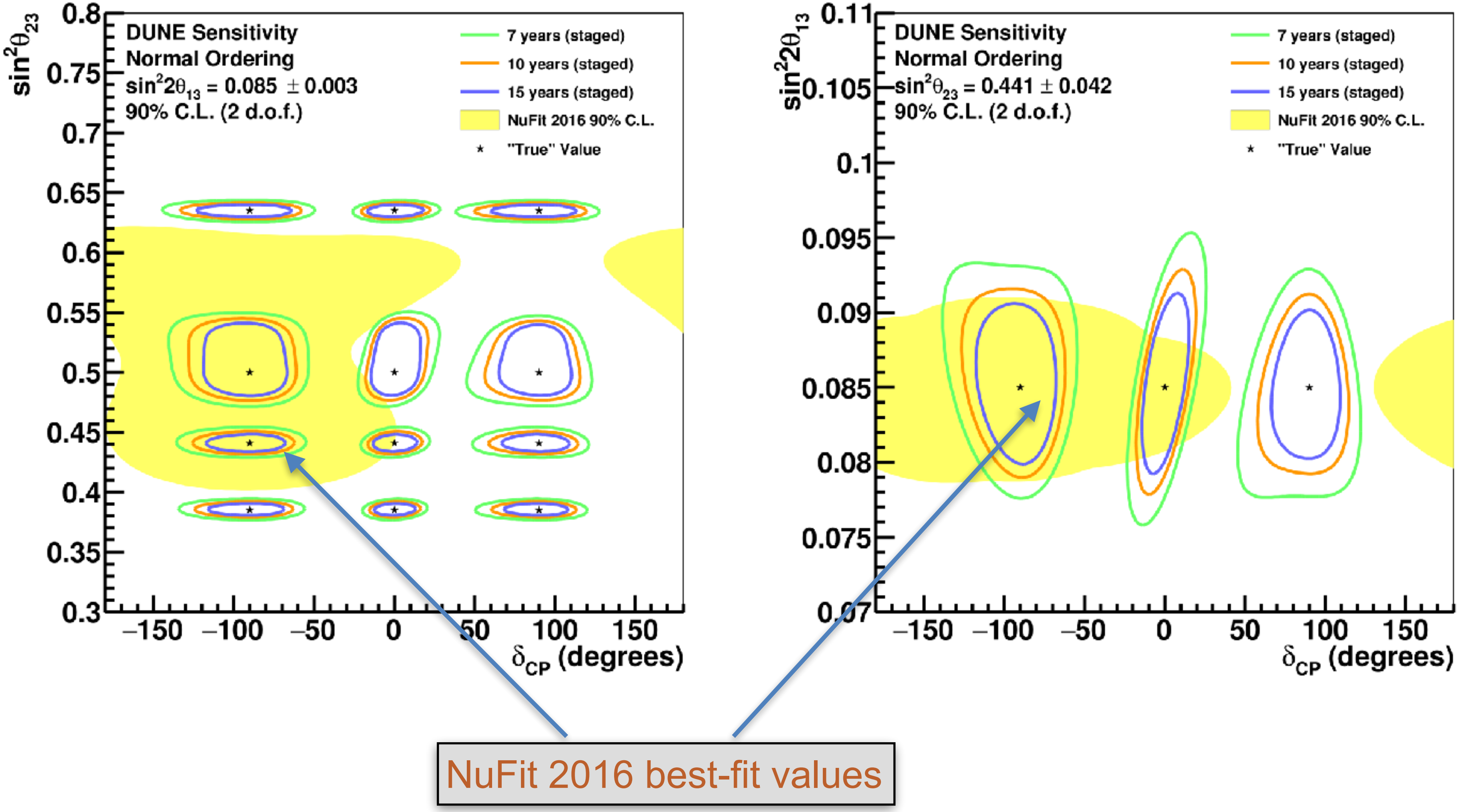
Oscillation sensitivity assumptions

- Oscillation priors from NuFit2016
- GLoBES-based fit to FD samples with parametrised FD response and ND constraints

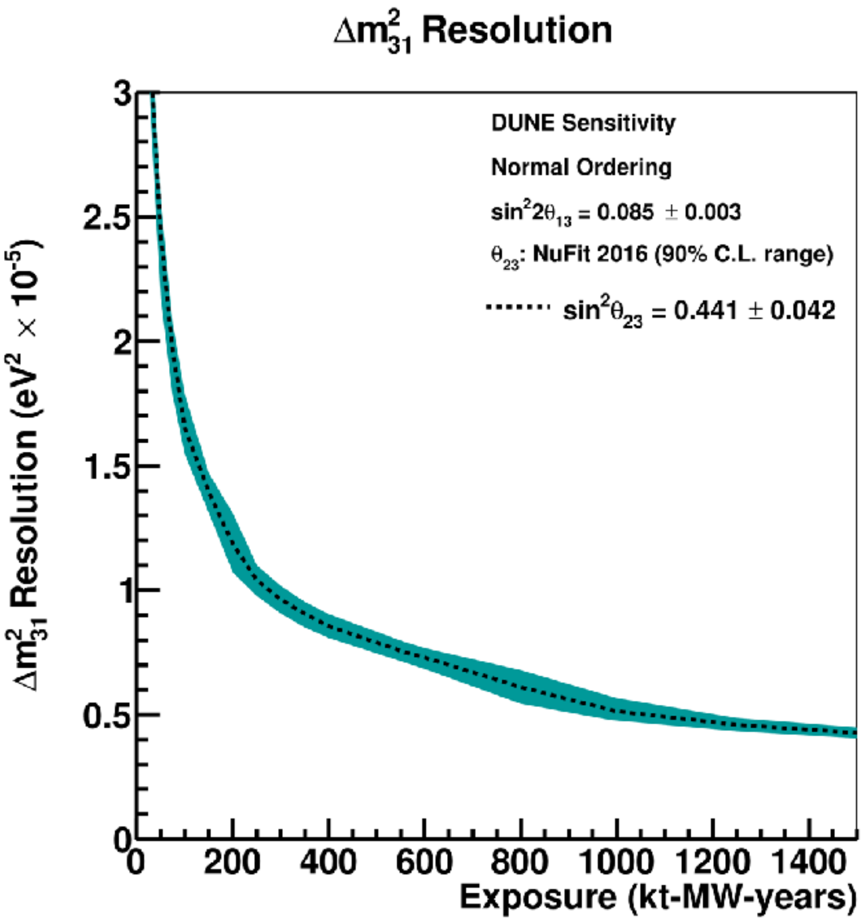
arXiv:1606.09550

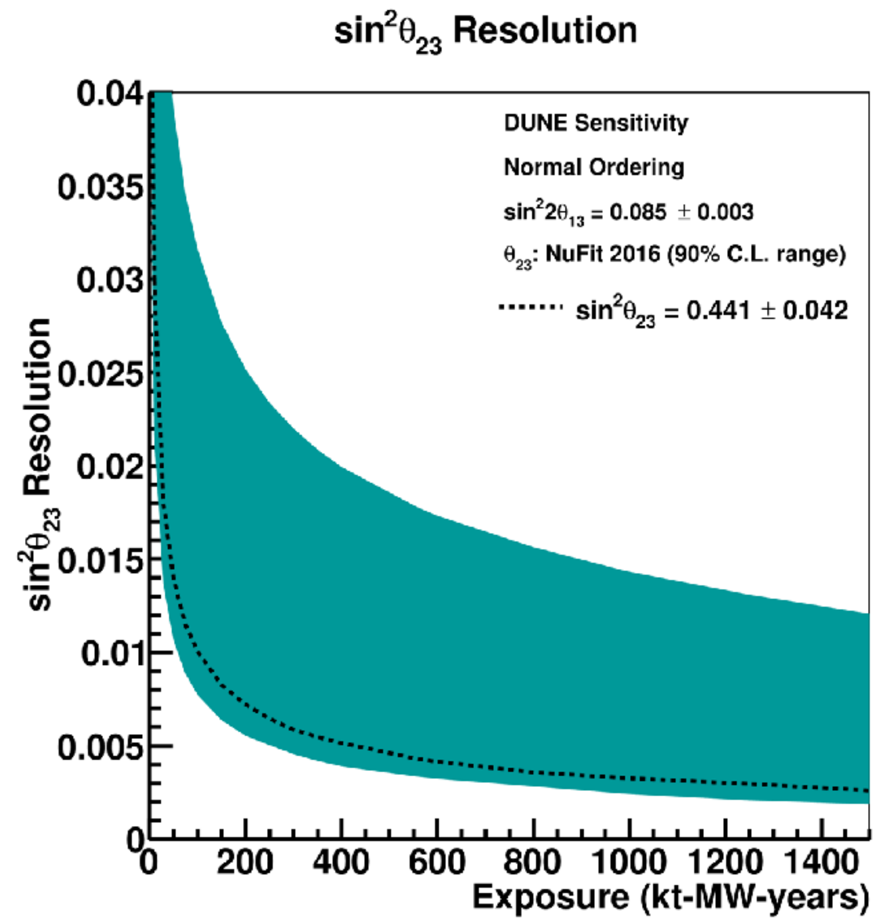


Two-dimensional allowed regions



Uncertainties on oscillation parameters

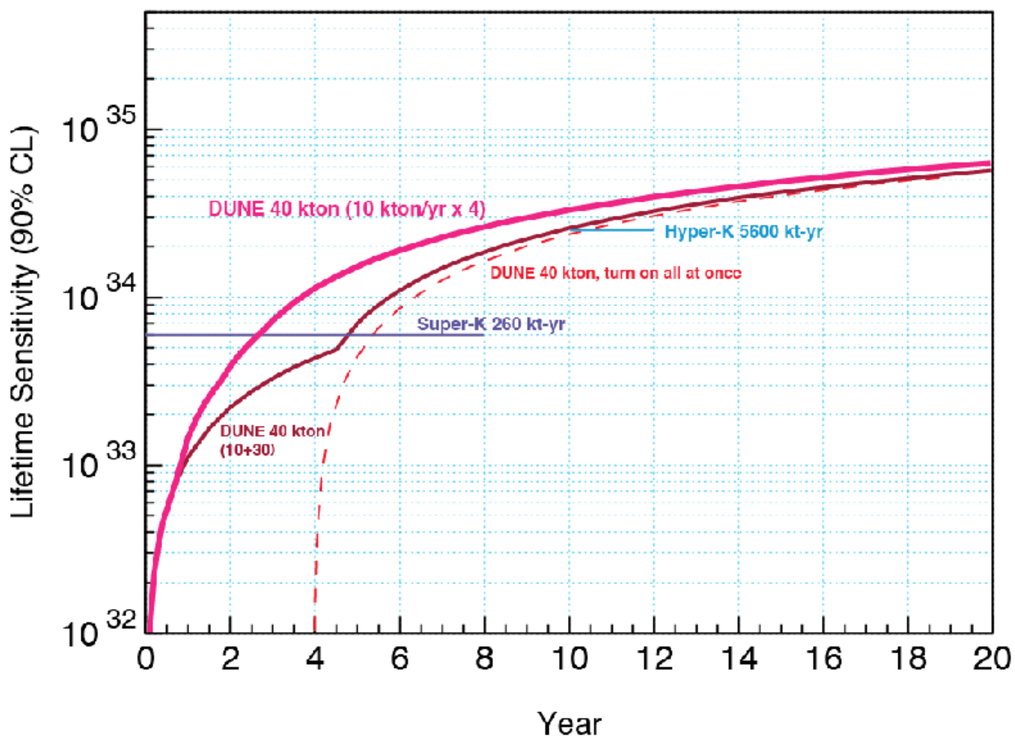




- **Current**: $\delta(\Delta m^2_{31}) = 4\times10^{-5}$ eV^2, $\delta(\sin^2\theta_{23}) = 0.04$

Nucleon decay searches in DUNE

- DUNE's excellent particle identification and tracking capabilities → cast as wide a net as possible for nucleon decay searches
- Unique sensitivity to modes with kaons, e.g. $p \to \bar{\nu} K^+$



Nucleon decay

- Limits and sensitivities compared with ranges predicted by Grand Unified Theories, for benchmark decay modes: