DUNE Oscillation Physics

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for the DUNE Collaboration

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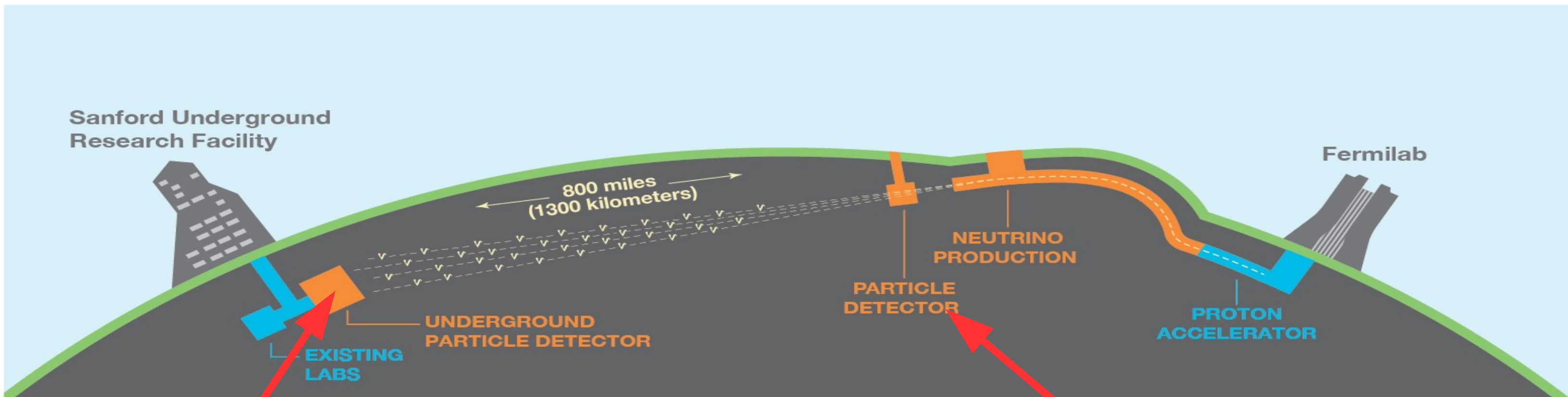
DUNE

Deep Underground Neutrino Experiment

A next generation experiment for **neutrino science, nucleon decay,** and **supernova physics**



Far detector at Sanford Underground Research Facility (SURF)

Neutrino beam and near detector at Fermilab

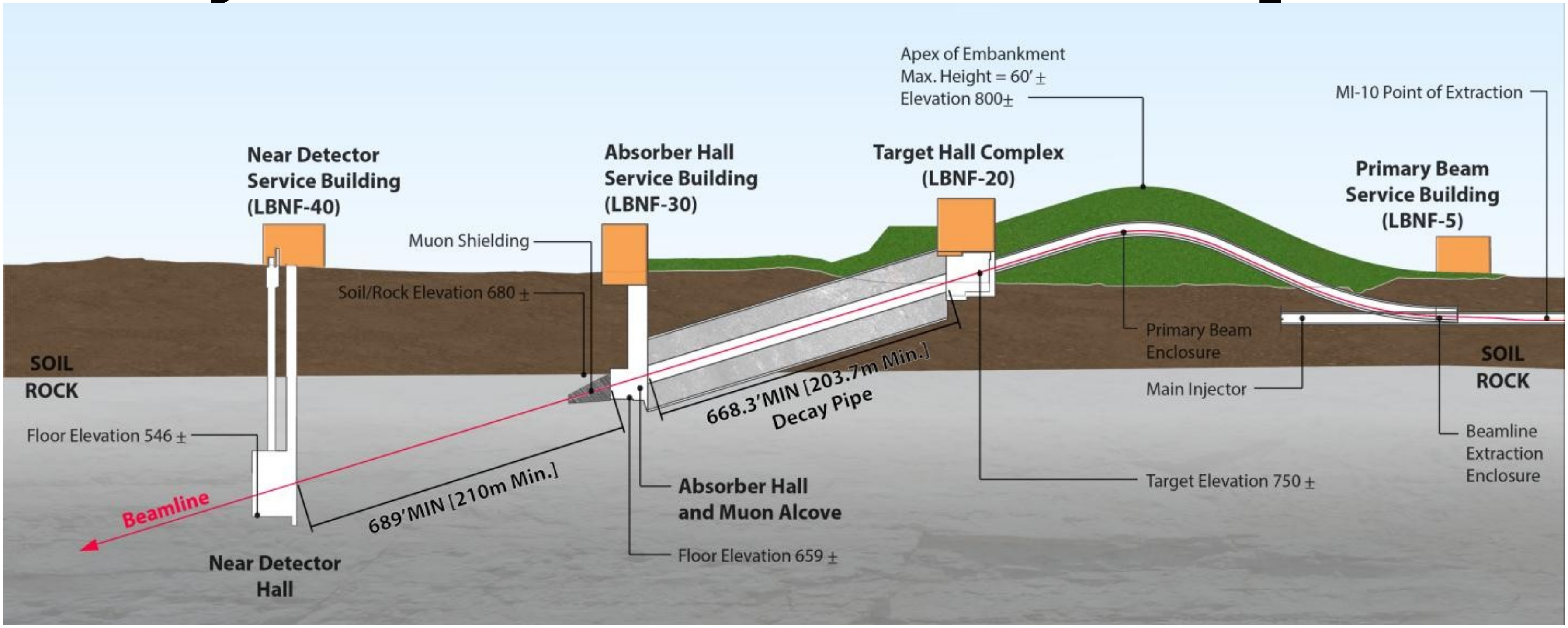
Primary Physics goals

- ν oscillation physics
    - Precise measurements of the oscillation parameters θ_{23}, θ_{13}, Δm^2_{31}
    - Neutrino mass hierarchy
    - Octant of θ_{23}
    - CP Violation and measurement of δ_{cp}

- Nucleon decay
- Supernova neutrinos
- Physics beyond the standard model

DUNE Neutrino Beam

Long Baseline Neutrino Facility(LBNF)

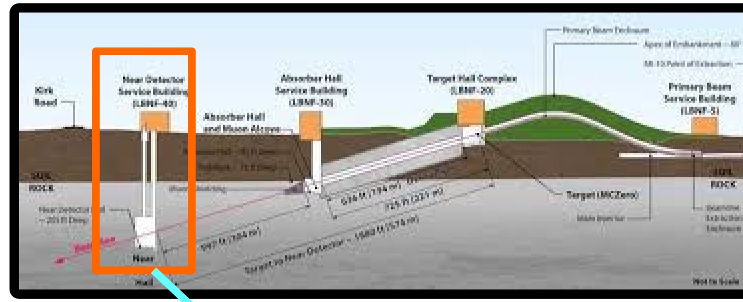


* Most intense neutrino beam : “LBNF”
* 60-120 GeV protons from Fermilab Main Injector
* Horn-focused beam line similar to NuMI beam line
* Initial power: 1.2 MW; plan(2032) to upgrade to 2.4 MW

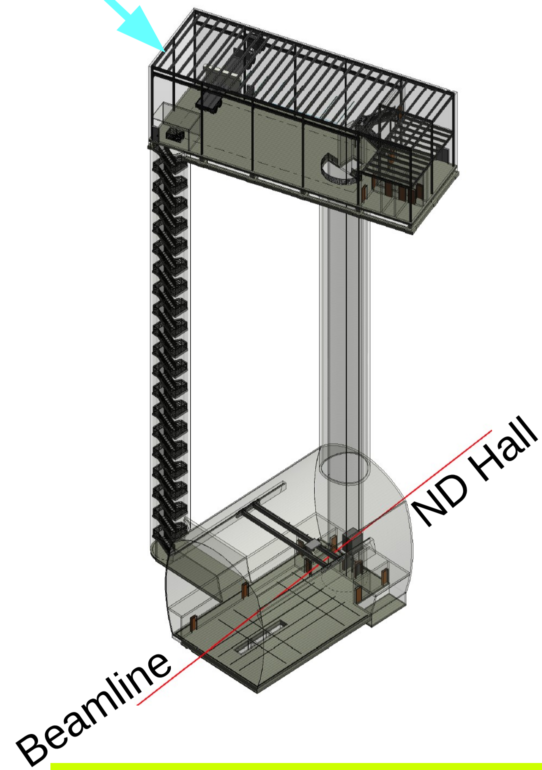
Detail talk by Mary Bishai

DUNE Near Detector (ND)

- Primary Purpose: constrain systematic uncertainty for long baseline oscillation analysis



- High precision cross-section and short baseline measurements

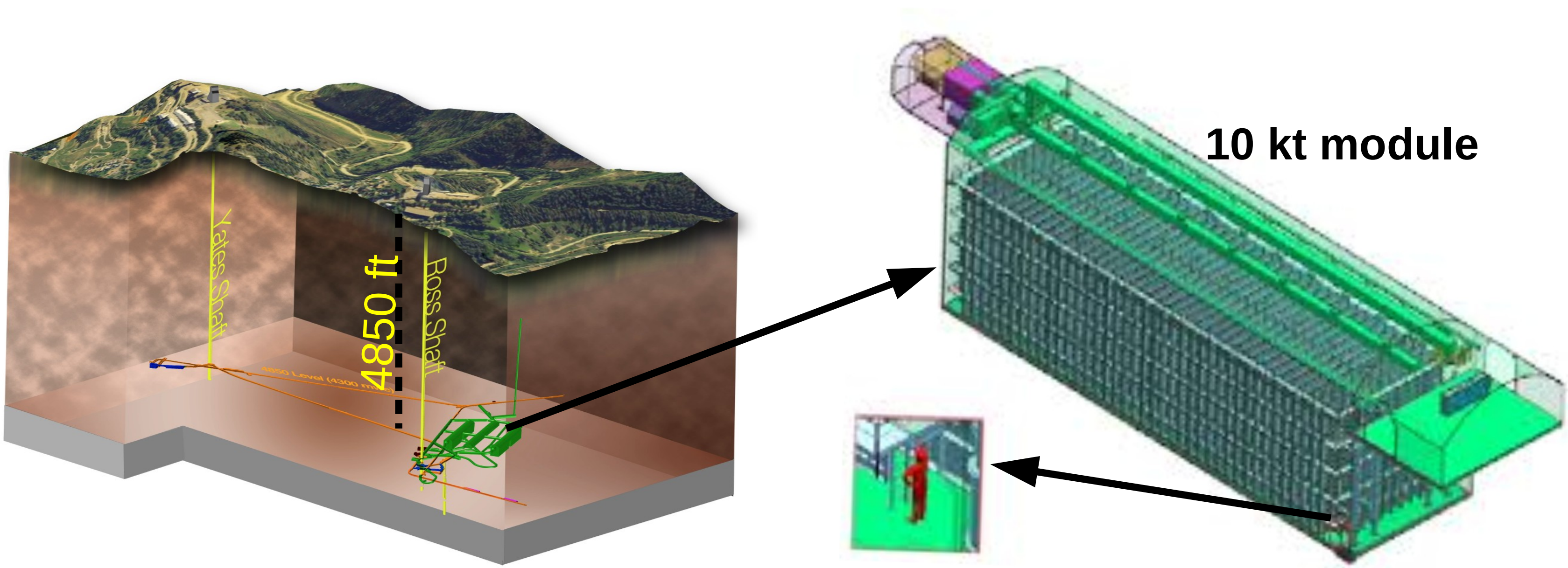


- DUNE ND design concept near final
- DUNE ND design concept is an integrated system composed of multiple detectors:
  * Highly segmented LArTPC
  * Straw tube tracker
  * Electromagnetic calorimeter
  * Muon chambers

Detail talk by Albert De Roeck

DUNE Far Detector(FD)

- Two FD designs of Liquid Argon Time Projection Chamber (LArTPC) are considered: single phase (only LAr) and dual phase (LAr + GAr)
- Four 10-kt (fiducial) modules, totally 40-kt (fiducial)LAr at 4850ft level



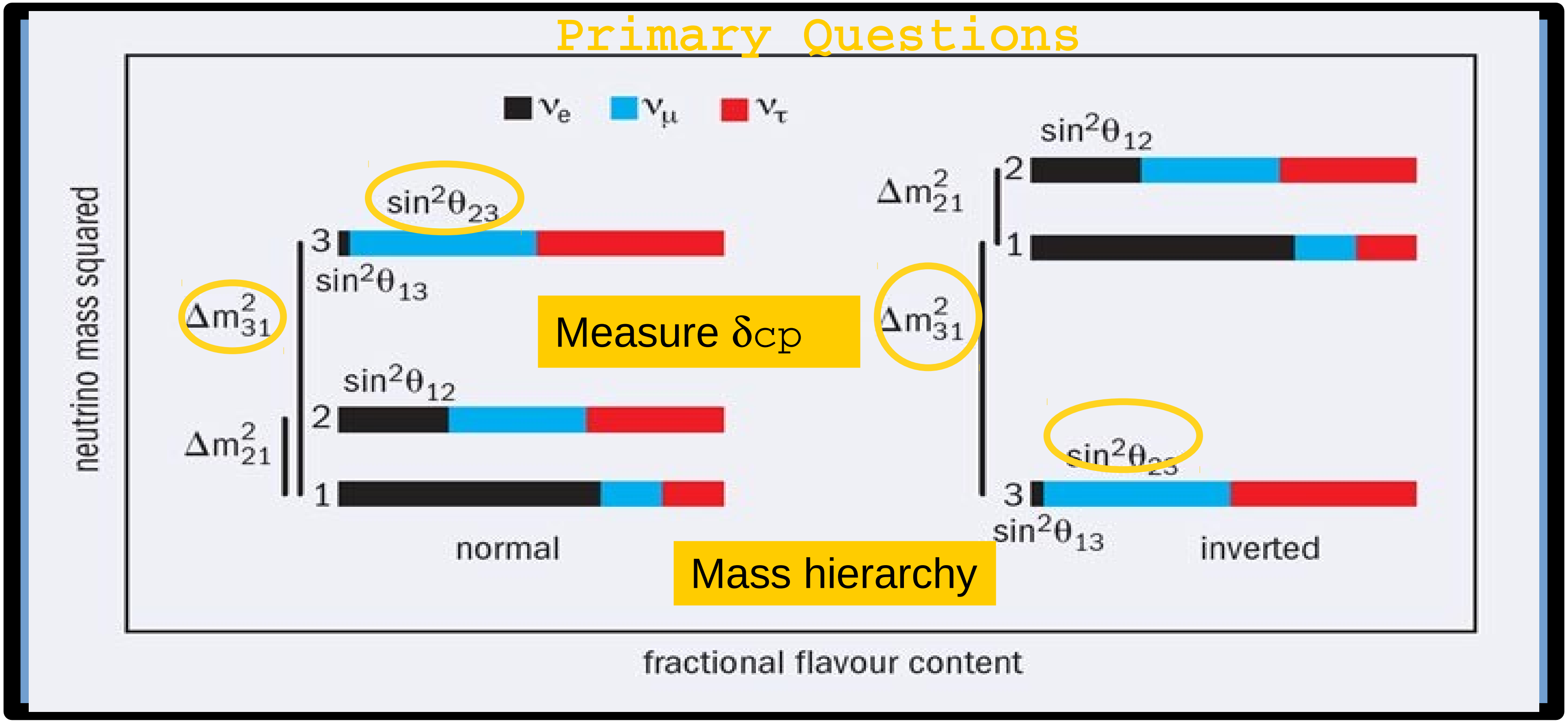
At SURF

DUNE Timeline

- 2018 : protoDUNEs at CERN
- 2019 : Technical Design Report
- 2019 : Far Site Primary Excavation Begins
- 2022 : First Module Installation Begins
- 2024 : Physics data Begins
- 2026 : Neutrino Beam Available(1.2MW)

* DUNE Far Detector Interim Design Reports are available (on arXiv:1807.10334, 1807.10327,1807.10340)

Neutrino Oscillations



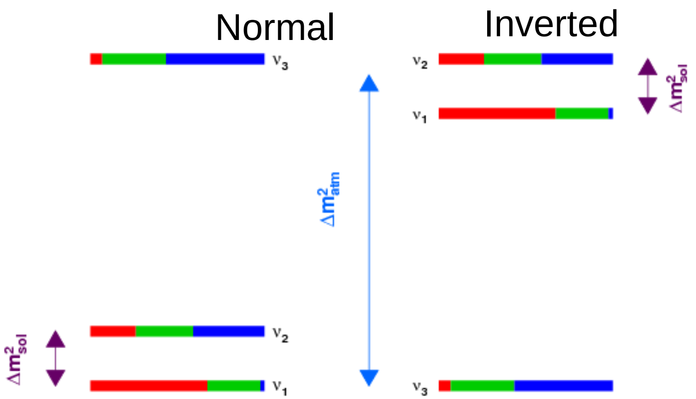
Neutrino mixing matrix :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$|U_{e3}| \neq 0$
(recent discovery)

Neutrino oscillations : Primary questions

ν mass hierarchy:



- Are the states ν_1 & ν_2 heavier or lighter than ν_3 ?

CP Violation:

- $\delta_{CP} \neq (0,\pi)$?, Neutrino and anti-neutrino asymmetry

Octant of θ_{23} :

- $\sin^2\theta_{23} \neq 0.5$? Non maximal mixing? If so, which way?

Precision oscillation measurements

$\nu_\mu \rightarrow \nu_e$ Appearance

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

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

$$a = G_F N_e/\sqrt{2}$$

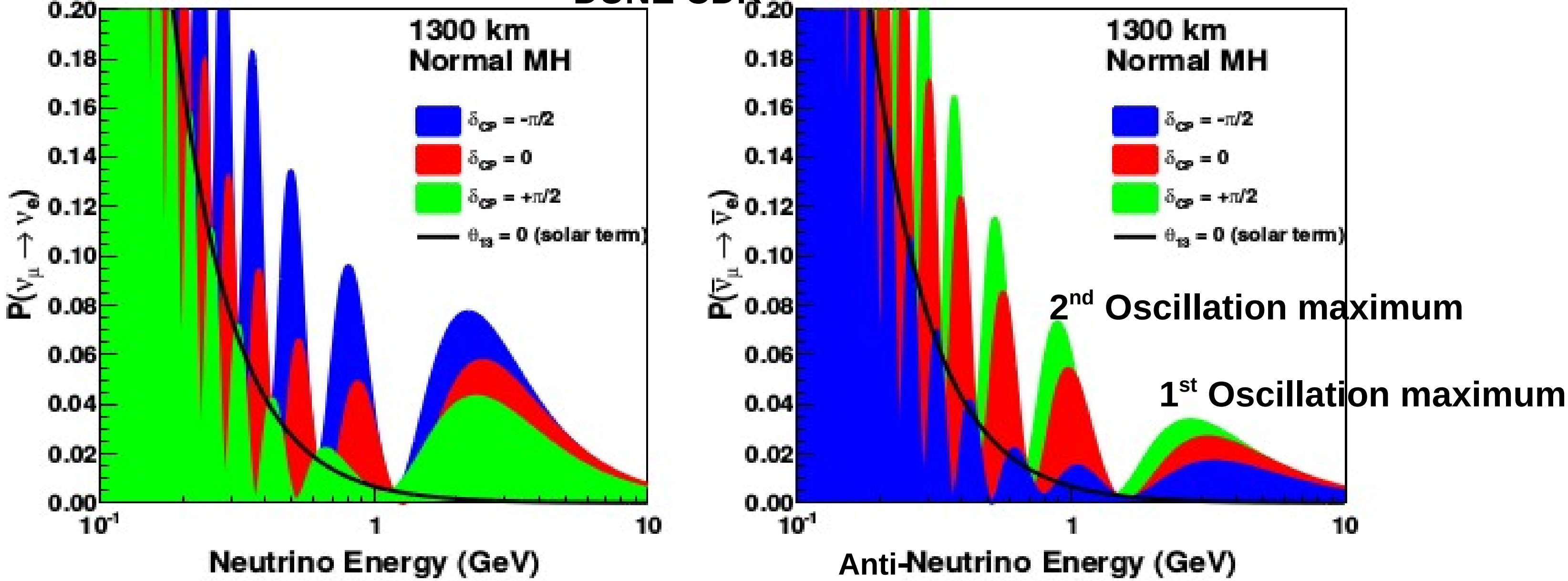
- ν_e appearance probability depends on : θ_{23}, θ_{13}, δ_{cp}, matter effect
- Large value of $\sin^2 2\theta_{13}$ provides significant ν_e events
- Large matter effect help for the determination of hierarchy
- θ_{23} octant measurement from ν_μ disappearance channel

Oscillations at DUNE

Neutrino

Anti-Neutrino

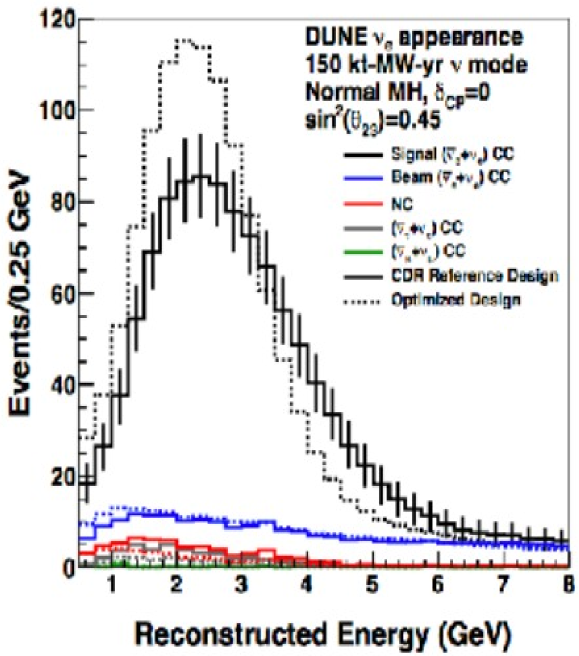
DUNE CDR



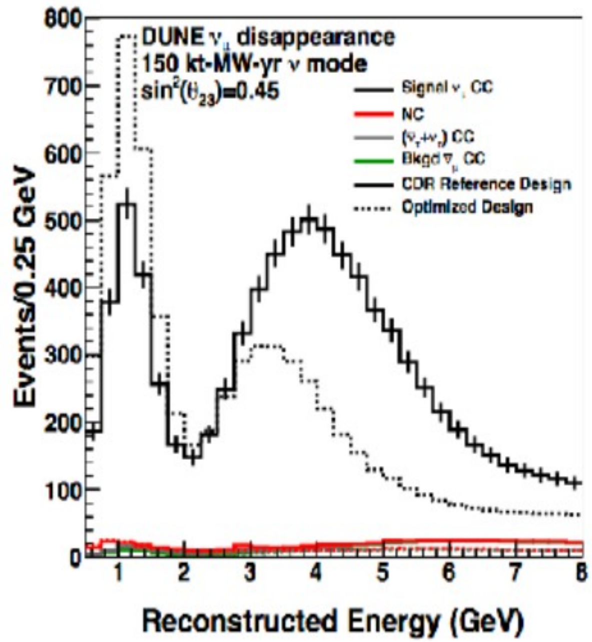
- δ_{cp} affects both the amplitude and the frequency of oscillation
- Measure ν_e appearance with ν_μ beam to determine δ_{cp}, MH
- Measure ν_μ dis-appearance with ν_μ beam to determine octant, MH
- Wide band beam covers 1st and 2nd oscillation maxima

Appearance and disappearance spectra

ν_e appearance



ν_μ dis-appearance



- Reconstructed spectra based on GEANT4 beam simulation, GENIE event generator, and Fast MC
- Simultaneous fit to four spectra to extract oscillation parameters
- Systematics applied using normalization uncertainties
- GLoBES configurations arXiv:1606.09550

Staging

- 2026:20kt far detector with 1.2MW beam
- 2027: 30kt far detector
- 2029: 40kt far detector
- 2032 : Upgrade to 2.4MW beam

Systematic Uncertainties

- The effect of systematic uncertainty is approximated using signal and background normalization uncertainties

- Signal normalization uncertainty is 5±2% in both neutrino and anti-neutrino modes.

  → ν_μ & $\bar{\nu}_\mu = 5\%$ (constraints from the near detector)

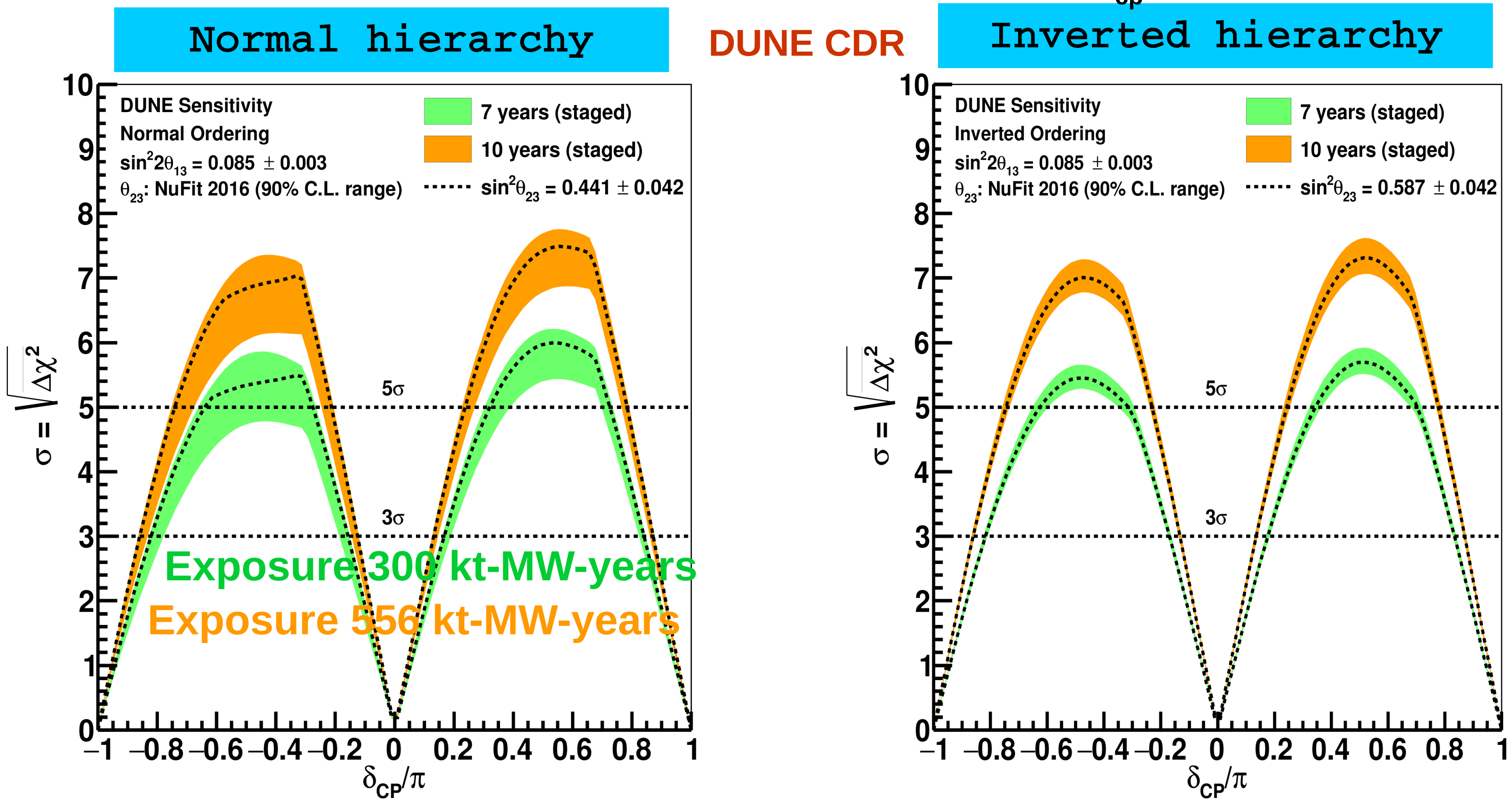
  → ν_e & $\bar{\nu}_e = 2\%$ (constraints from the near detector and fit)

- 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.

CP violation sensitivity

Significance with which CP violation ($\delta_{cp} = 0, \pi$) can be determined as a function of true value of δ_{cp}



Width of band corresponds to 90% C.L. variations in value of θ_{23} based on NuFit 2016 fit values

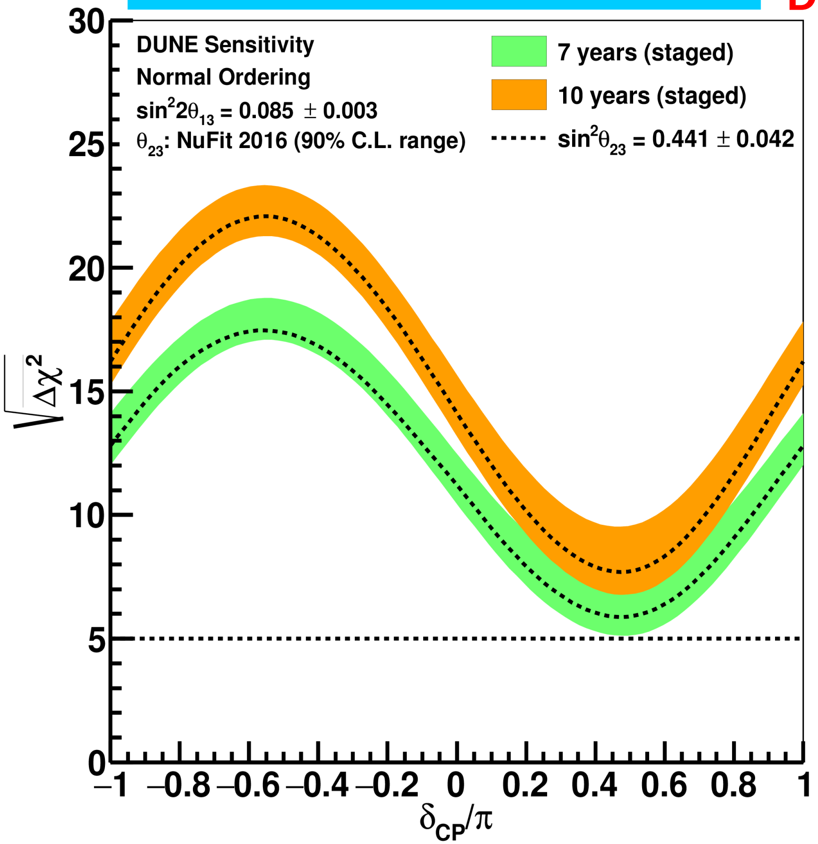
Mass hierarchy sensitivity

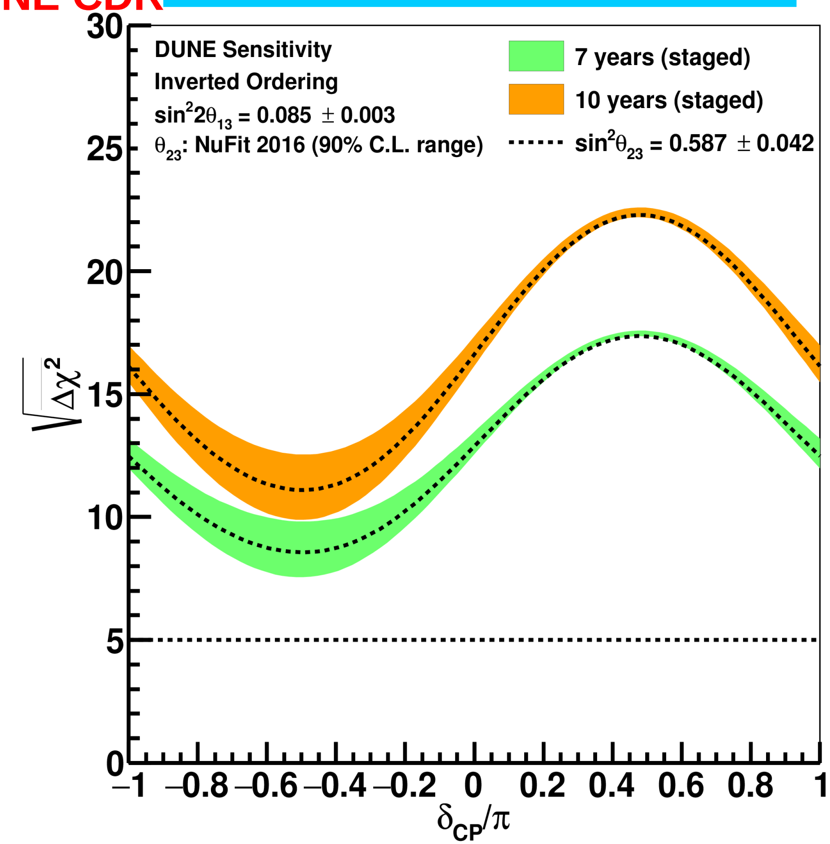
Sensitivity to determination of mass hierarchy as a function of true value of δ_{cp}

Normal hierarchy

DUNE CDR

Inverted hierarchy





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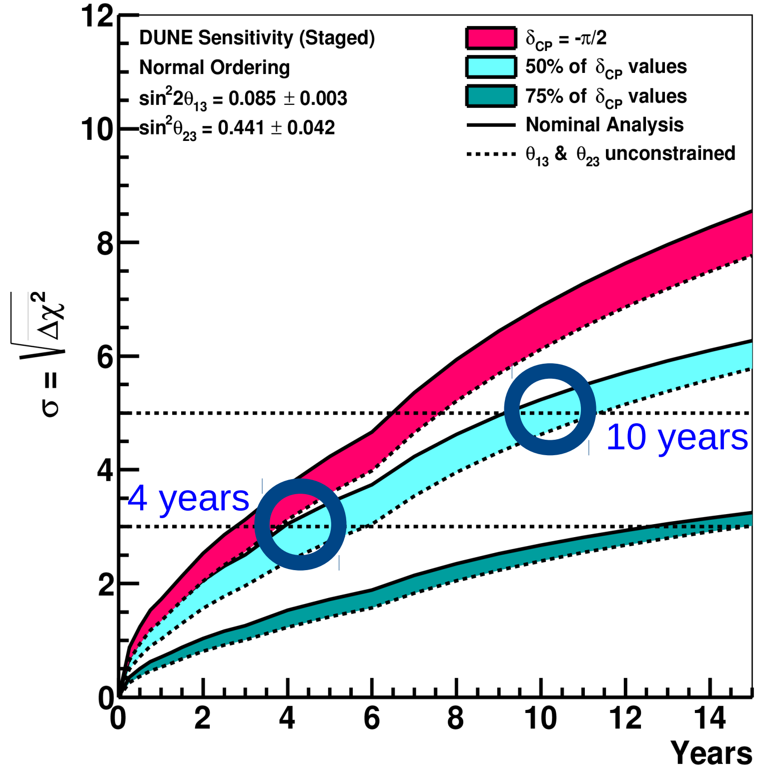
Sensitivity vs.time

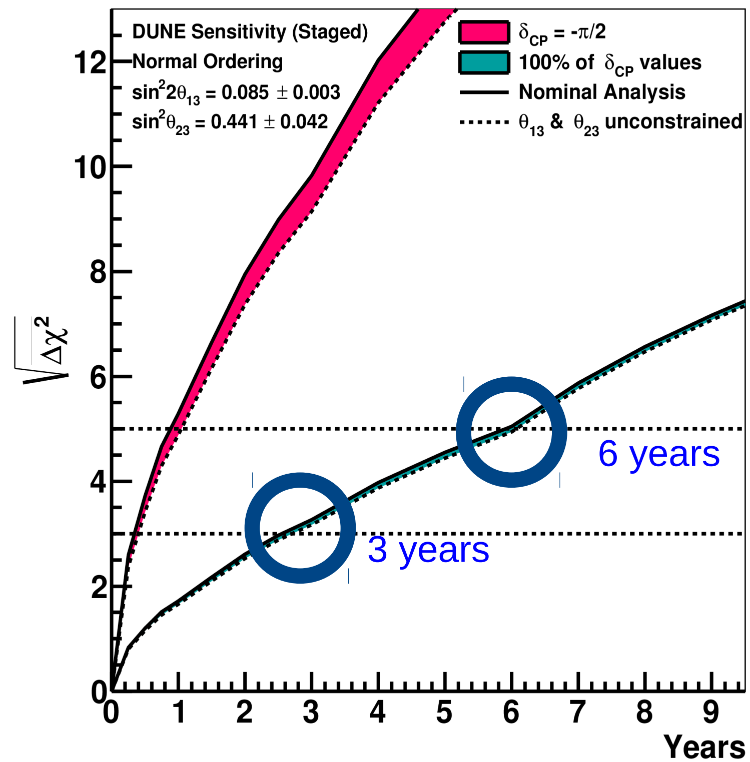
Significant milestones within few years of beam run

DUNE CDR

CP violation sensitivity



Mass hierarchy sensitivity

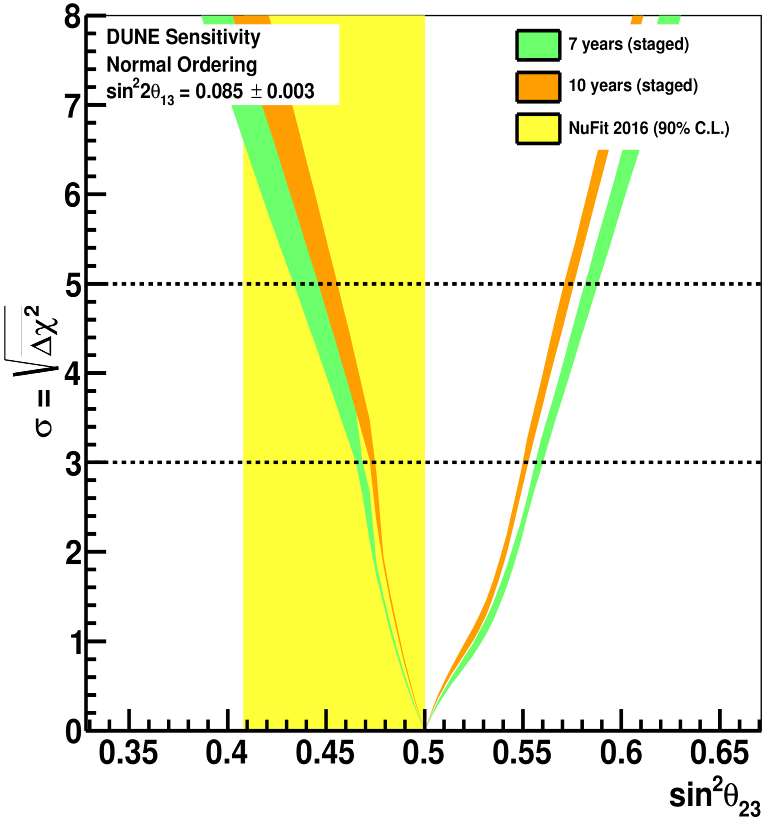


Width of band corresponds to 90% C.L. variations in value of θ_{23} based on NuFit 2016 fit values

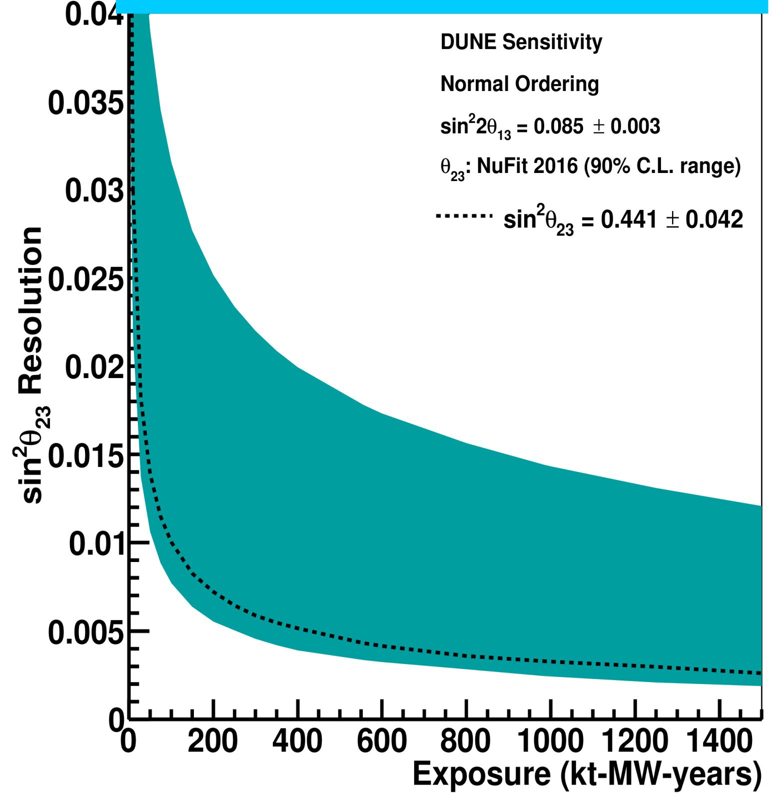
Sensitivity to θ_{23} Octant and θ_{23} resolution

- **DUNE CDR**

Octant sensitivity



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



Yellow shaded band represents 90% C.L. allowed region for value of $\sin^2\theta_{23}$ from NuFit 2016

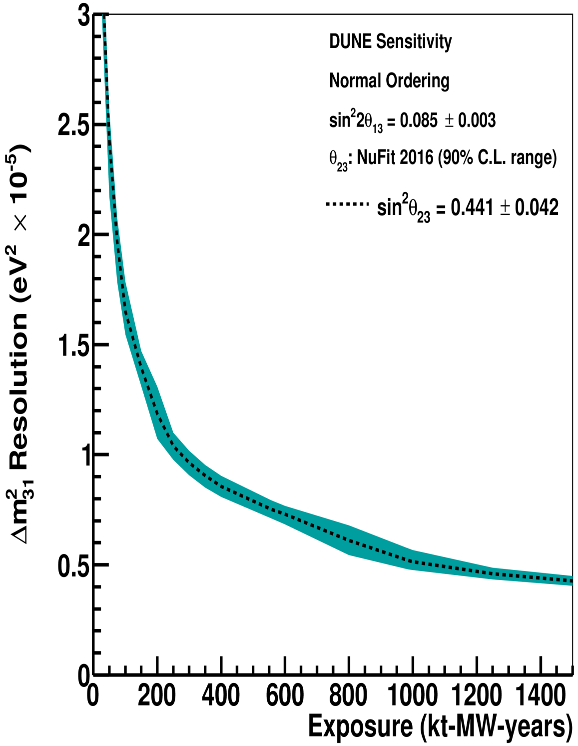
Resolution worsens with increasing θ_{23} .

Oscillation parameter resolution

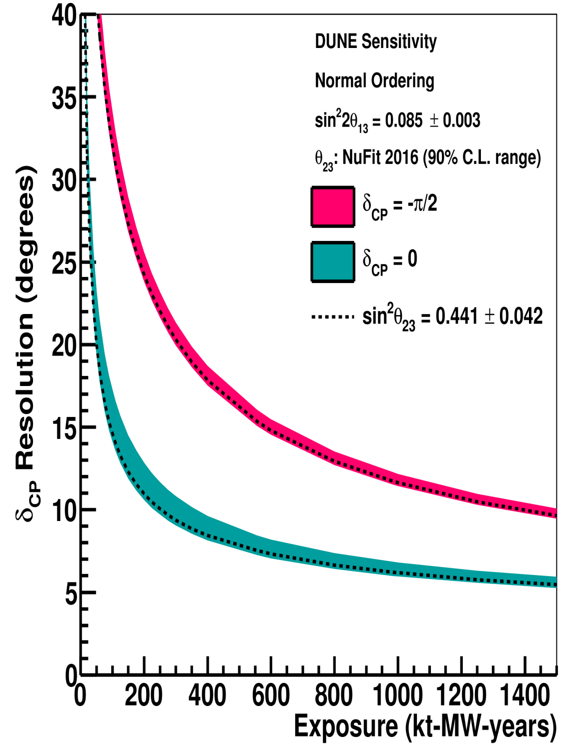
Normal hierarchy :

DUNE CDR

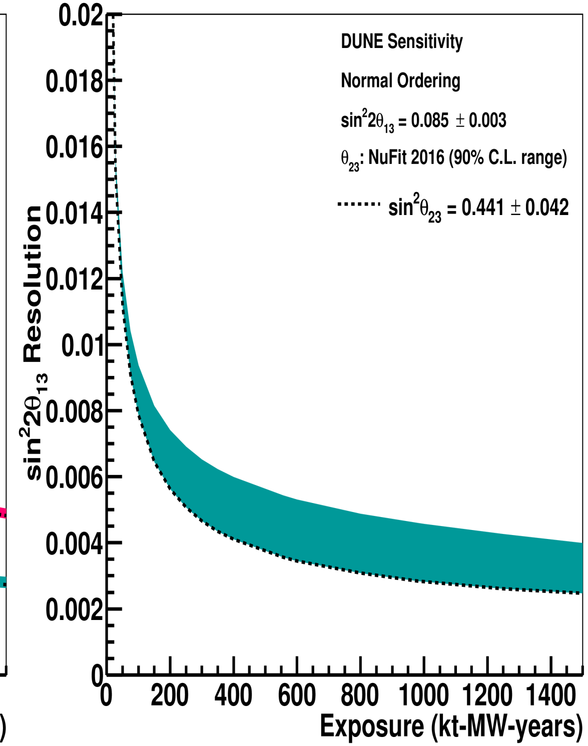
Δm^2_{31} resolution



δ_{cp} resolution



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



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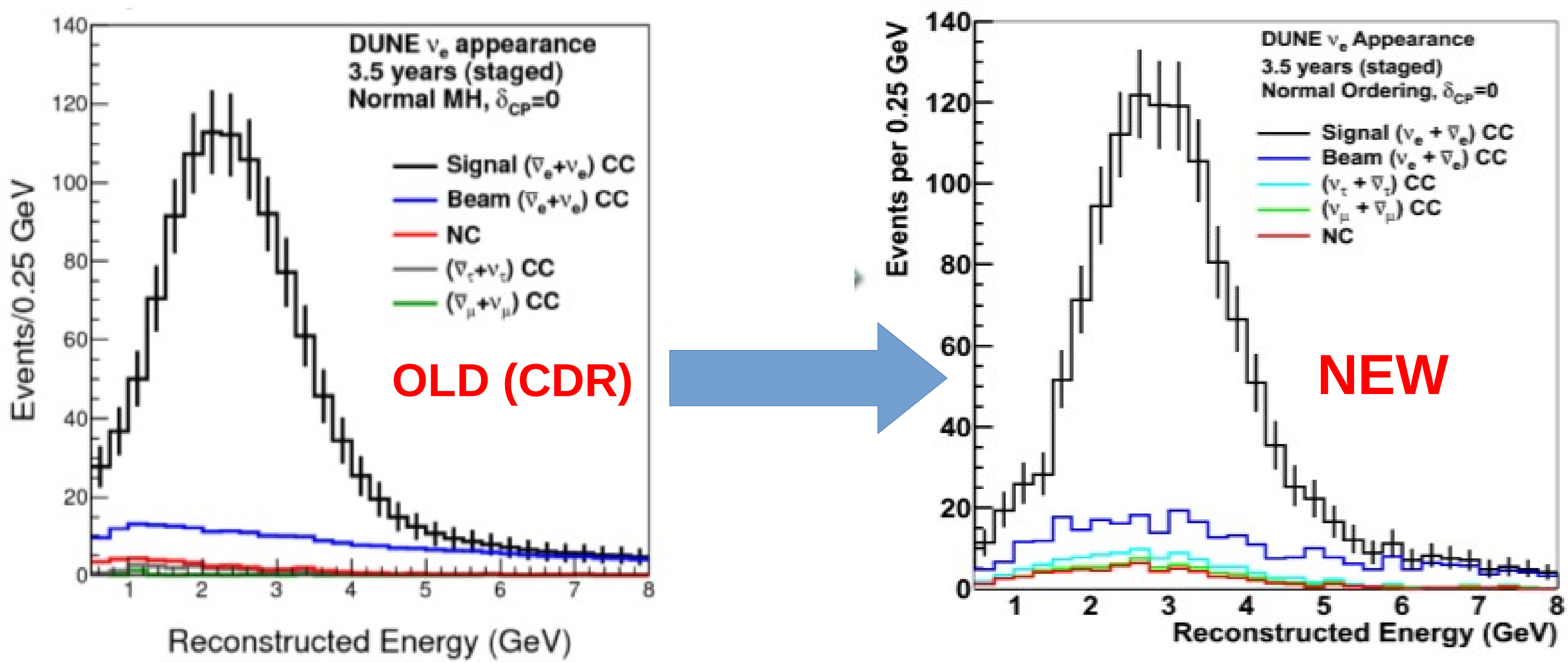
Physics milestone

DUNE IDR arxiv:1807.10334

Physics milestone	Exposure (kt · MW · year)	Exposure (years)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	29	1
CPV at 3σ ($\delta_{CP} = -\pi/2$)	77	3
MH at 5σ (worst point)	209	6
10° δ_{CP} resolution ($\delta_{CP} = 0$)	252	6.5
CPV at 5σ ($\delta_{CP} = -\pi/2$)	253	6.5
CPV at 5σ 50% of δ_{CP}	483	9
CPV at 3σ 75% of δ_{CP}	775	12.5
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	857	13.5

Monte-Carlo Studies(New!)

- GEANT4 beam simulation of updated beam design
- Full LArSoft Monte Carlo simulation
- Automated energy reconstruction
- Event selection using convolutional visual network (CVN)
- CDR-style systematics analysis



- Sensitivity from MC-based analysis with automated reconstruction and event selection exceeds CDR sensitivity!
- Full update planned for TDR 2019!

Summary

- The DUNE experiment with the world's most intense neutrino beam, a deep underground site, and massive LAr detectors, will be enable to address the most fundamental questions in particle physics
- **DUNE has a broad physics program**
  - DUNE will determine Mass hierarchy and can measure CP violation with 5σ
  - Precision oscillation parameter measurements
  - Search for Nucleon Decay and Supernova Burst ν
  - And a rich BSM physics program both inside and outside the neutrino sector
- Far site construction and prototypes are underway this year

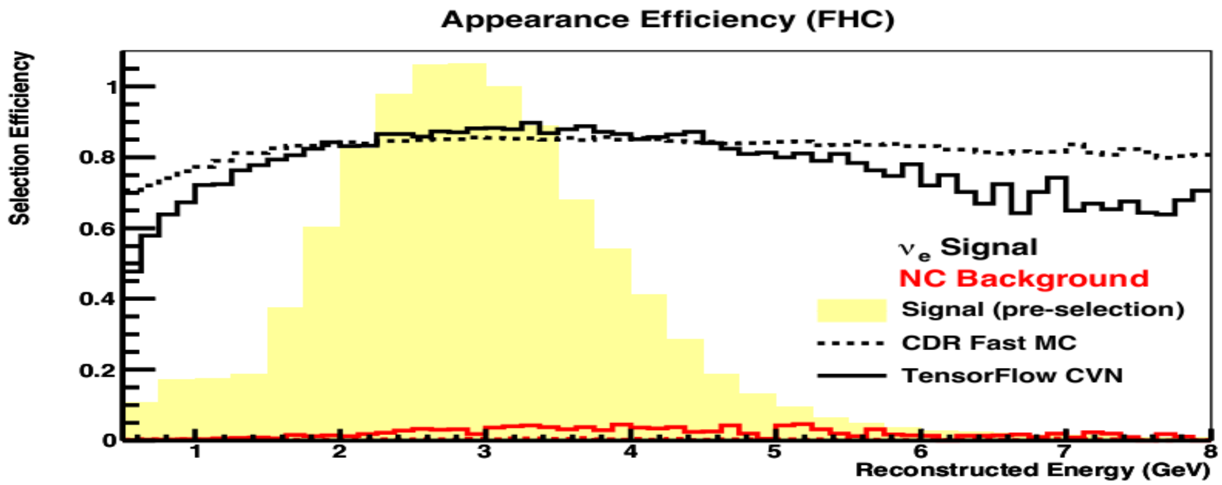
Thank You

EXTRAS

CVN Event selection

- ResNet architecture implemented in TensorFlow
- DUNE MC images classified into categories

  ν_e CC, ν_μ CC, ν_τ CC, NC
- Event selection performed by applying cuts on ν_e CC-like and ν_μ CC-like CVN classifiers
- Selection efficiency :



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