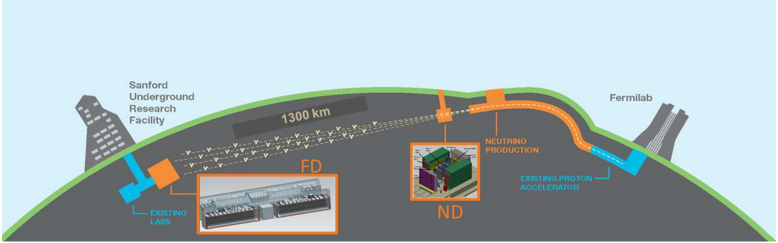
Neutrino Oscillations with DUNE/LBNF

TAUP 2015, 7-11 September 2015 Torino, Italy

Mary Bishai
Brookhaven National Laboratory



Outline

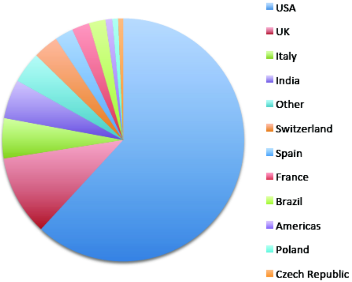
The Deep Underground Neutrino Experiment (DUNE) - A History

- **2008: The US Particle Physics Project Prioritization Panel (P5) recommended** *a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector at the proposed DUSEL laboratory and a high-intensity neutrino source at Fermilab* $\Rightarrow$ **The Long Baseline Neutrino Experiment (LBNE) project in the U.S.**
- **2008 - 2014: LAGUNA/LAGUNA-LBNO - Design of a pan-European infrastructure for Large Apparatus for Grand Unification, Neutrino Astrophysics, and Long Baseline Neutrino Oscillations.**
- **2013: European Strategy Report calls for CERN to support the European community in contributing to long baseline experiments outside Europe.**
- **2014: P5 issued the following recommendations:** *The U.S. will host a world-leading neutrino program ...... its long-term focus is a reformulated venture referred here as the Long Baseline Neutrino Facility (LBNF).*

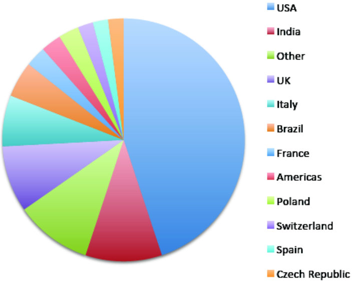
LBNE+LBNO+Others → **LBNF/DUNE**

The DUNE Scientific Collaboration

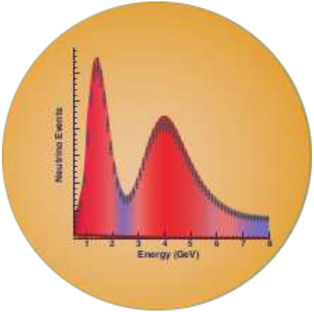
776 Collaborators



144 Institutes

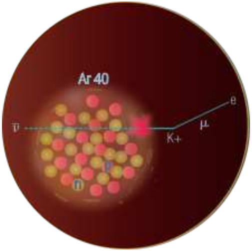


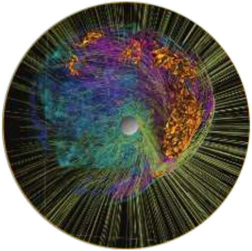
Scientific Objectives of DUNE



1. **precision measurements of the parameters that govern $\nu_\mu \to \nu_e$ oscillations; this includes precision measurement of the third mixing angle θ_{13}, measurement of the charge-parity (CP) violating phase δ_{CP}, and determination of the neutrino mass ordering (the sign of $\Delta m^2_{31} = m^2_3 - m^2_1$), the so-called mass hierarchy**
2. **precision measurements of the mixing angle θ_{23}, including the determination of the octant in which this angle lies, and the value of the mass difference, —Δm^2_{32}—, in $\nu_\mu \to \nu_{e,\mu}$ oscillations**

Scientific Objectives of DUNE



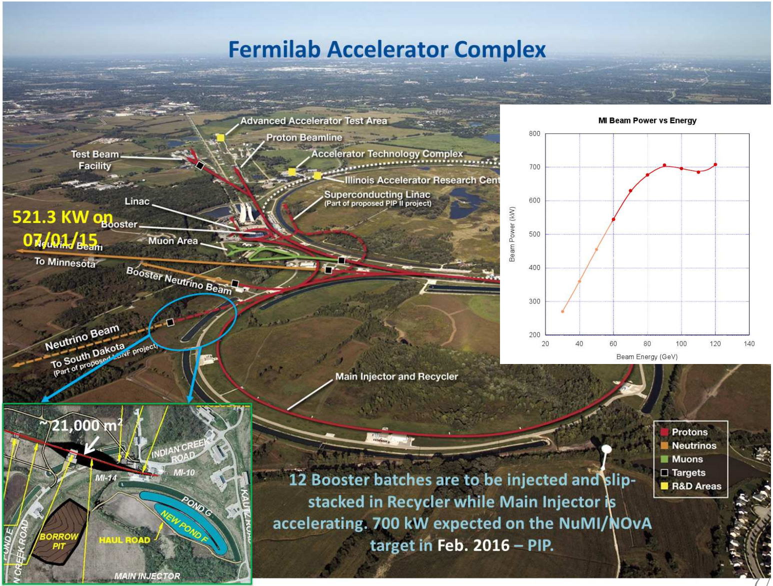


3. **search for proton decay, yielding significant improvement in the current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g., $p \to K^+\overline{\nu}$**

4. **detection and measurement of the neutrino flux from a core-collapse supernova within our galaxy, should one occur during the lifetime of DUNE**

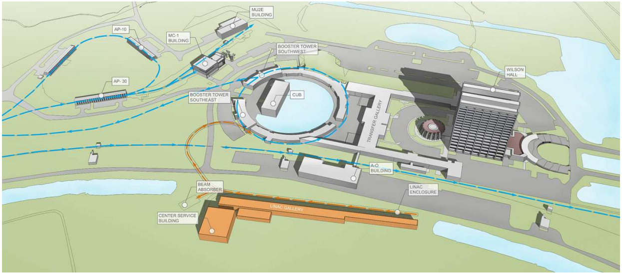
See talk by Vitaly Kudryavtsev on Wednesday.

The Fermilab Accelerator Complex



Proton Improvement Plan (PIP)-II

Planned upgrades to the Fermilab complex to increase proton intensity:



PIP-II replaces upstream portion of linac feeding into 8 GeV Booster:
1.03 MW at 60 GeV
1.07 MW at 80 GeV
1.20 MW at 120 GeV

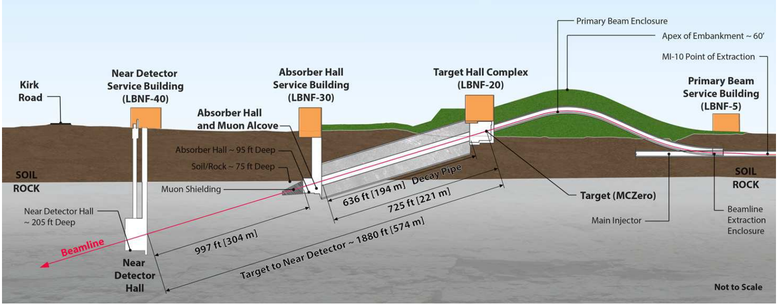
Ready by 2025

Further upgrades (PIP-III) would replace booster with Rapid Cycling Synchrotron (RCS) or SC Linac. Currently in R&D stage.

$\geq$ 2.0 MW at 60 GeV
$\geq$ 2.3 MW at 120 GeV

The LBNF Beamline

Novel concept beam-on-a-hill reduces cost.



Primary proton beamline: extracts 60-120 GeV designed for 1.2MW upgradable to 2.3MW

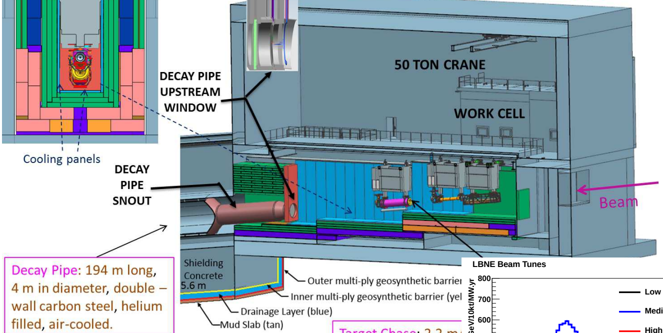
Targetry/focusing: uses NuMI horn design now being upgraded to operate at 230 kA, updated NuMI graphite target design partially inserted into first horn. New Be target design under consideration

Decay pipe: 4m in diameter, ~200m in length, Helium filled. 5.5m thick shielding using geo-membrane..

The LBNF Beamline

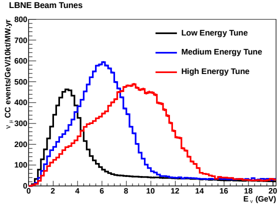
Advanced conceptual design with upgraded tunable NuMI focusing:

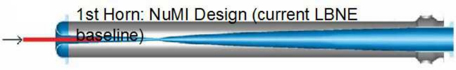
~ 40% of beam power in target chase
~ 30% of beam power in decay pipe



Decay Pipe: 194 m long, 4 m in diameter, double – wall carbon steel, helium filled, air-cooled.

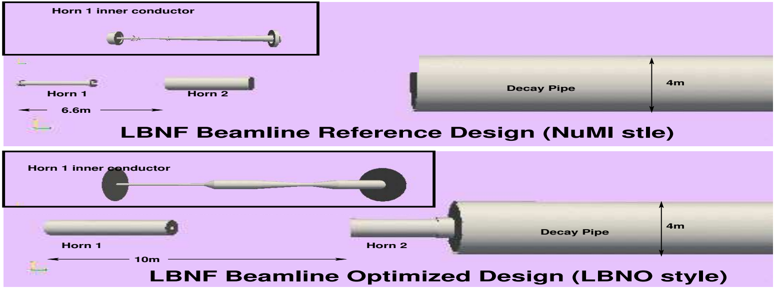
Target Chase: 2.2 m/ air-filled and air & w

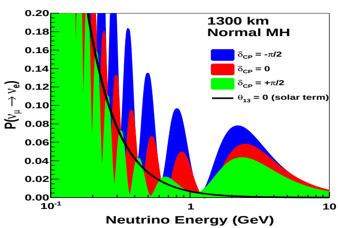


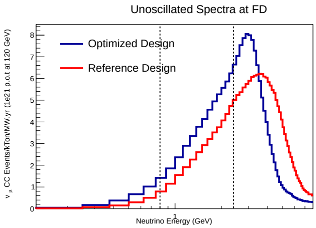


The LBNF Beamline

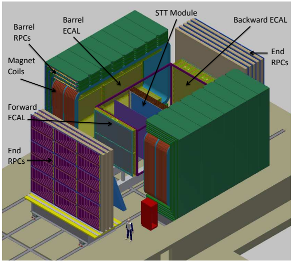
Optimized focusing design obtained from genetic algorithim:







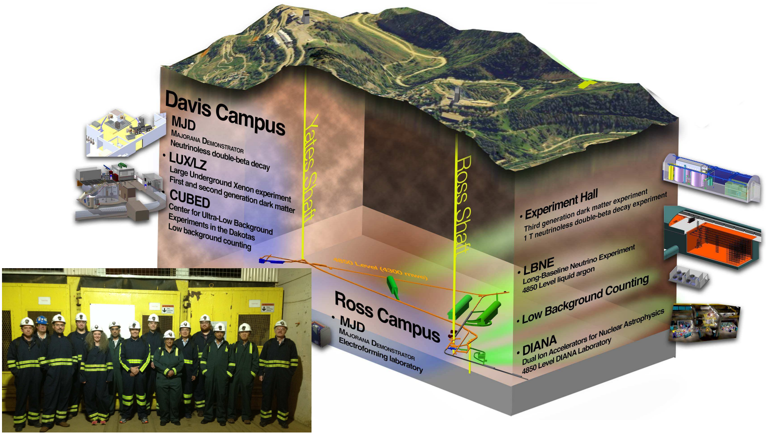
Reference design is a Fine Grained Tracker. Alternative/additional designs under consideration.



Performance Metric	Value
Vertex resolution	0.1 mm
Angular resolution	2 mrad
E_e resolution	5%
E_μ resolution	5%
$\nu_\mu/\overline{\nu}_\mu$ ID	Yes
$\nu_e/\overline{\nu}_e$ ID	Yes
NCπ^0/CCe rejection	0.1%
NCγ/CCe rejection	0.2%
NCμ/CCe rejection	0.01%

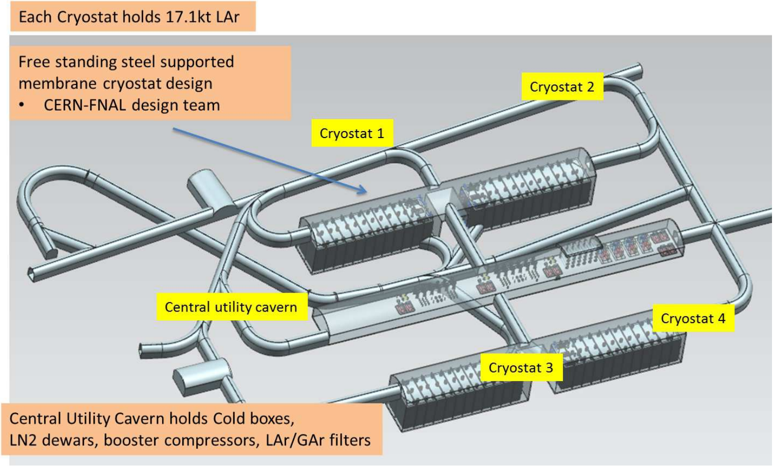
Parameter	Value
STT detector volume	$3 \times 3 \times 7.04$ m^3
STT detector mass	8 tons
Number of straws in STT	123,904
Inner magnetic volume	$4.5 \times 4.5 \times 8.0$ m^3
Targets	1.27-cm thick argon ($\sim$ 50 kg), water and others
Transition radiation radiators	2.5 cm thick
ECAL X_0	10 barrel, 10 backward, 18 forward
Number of scintillator bars in ECAL	32,320
Dipole magnet	2.4-MW power; 60-cm steel thickness
Magnetic field and uniformity	0.4 T; < 2% variation over inner volume
MuID configuration	32 RPC planes interspersed between 20-cm thick layers of steel

The Sanford Underground Research Facility



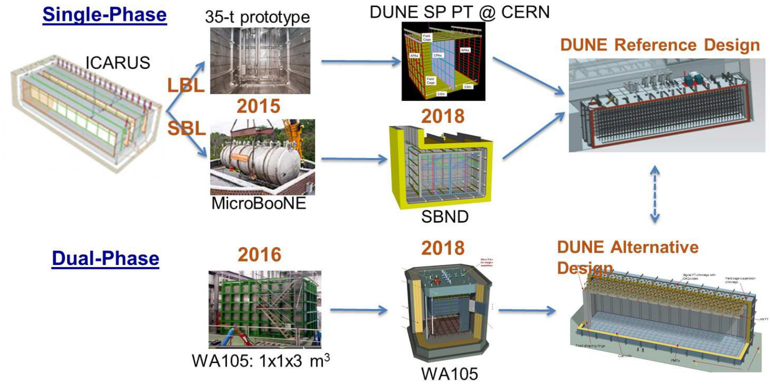
Experimental facility operated by the state of South Dakota. LUX (dark matter) and Majorana ($0\nu-2\beta$) demonstrator operational expts at 4850-ft level. Chosen as site of G2 dark matter experiment

DUNE 40-kton Far Detector Underground Layout



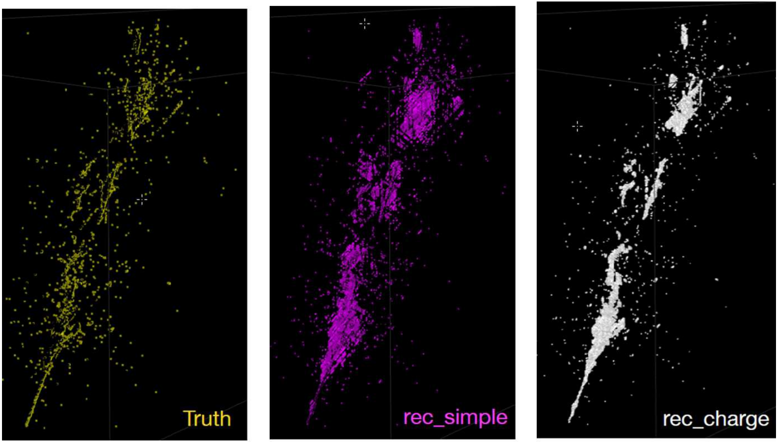
Approval of far site excavation (CD3a): December, 2015. Excavation starts in 2017.

DUNE FD Development



The first 10 kton LArTPC DUNE FD module will be single-phase. Construction commences in 2019.

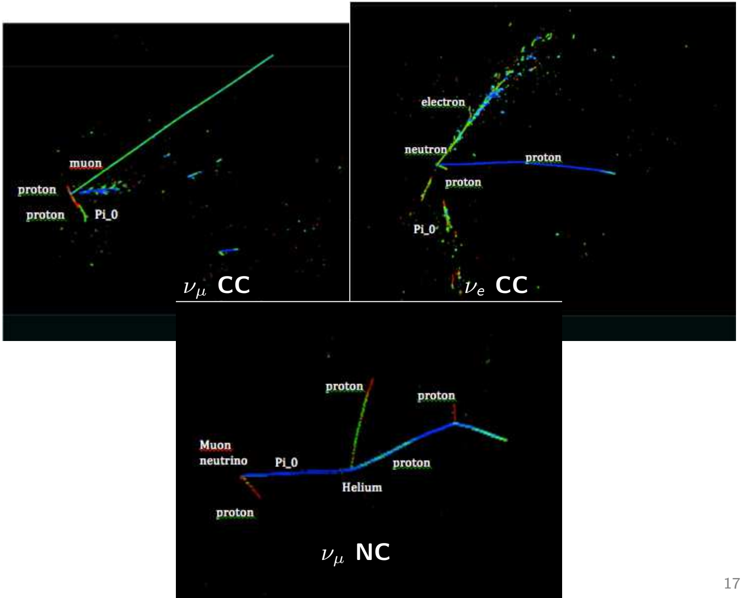
Simulation/Reconstruction in a Single Phase LArTPC (`http://www.phy.bnl.gov/wire-cell`)



Use only geometry information

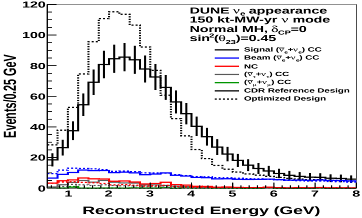
Use geometry and charge information

Simulation/Reconstruction in a Single Phase LArTPC (http://www.phy.bnl.gov/wire-cell)

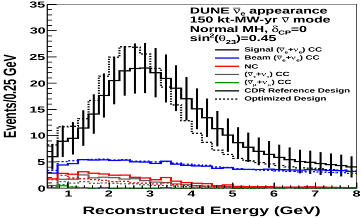


Oscillation signals

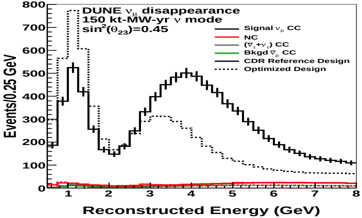
Exposure: 150 kT.MW.yr (equal $\nu/\bar{\nu}$) 1MW.yr $= 1 \times 10^{21}$ p.o.t at 120 GeV. ($\sin^2 2\theta_{13} = 0.085,\ \sin^2\theta_{23} = 0.45,\ \delta m^2_{31} = 2.46 \times 10^{-3}$ eV^2)



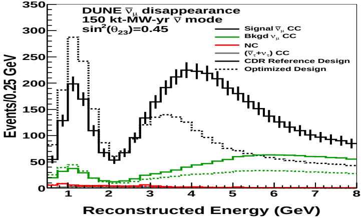
861 (945) ν_e, 13 (10) $\bar{\nu}_e$, 226 (243) bkg ref(opt)



167 (168) $\bar{\nu}_e$, 61(47) ν_e, 126 (127) Bkg ref(opt)



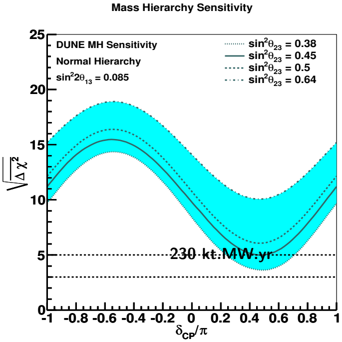
10842 (7929) ν_μ, 948 (511) $\bar{\nu}_\mu$, 151 (105) bkg

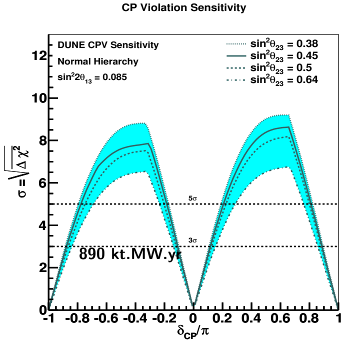


3754 (2639) $\bar{\nu}_\mu$, 2598 (1424) ν_μ, 89 (59) bkg

Simultaneous fit to all four samples to determine osc. params

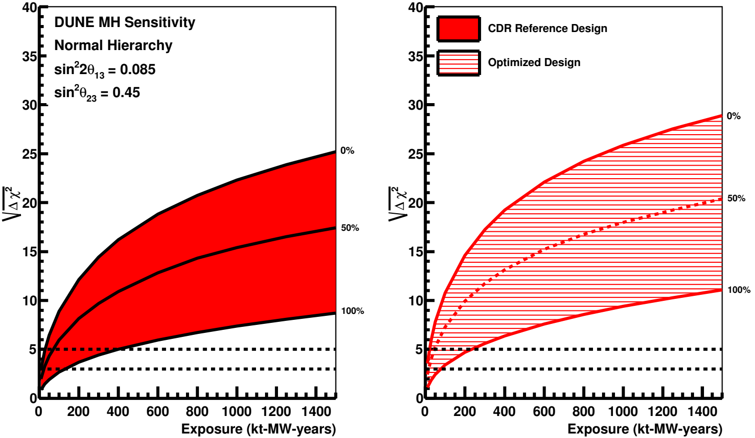
MH and CPV Sensitivities



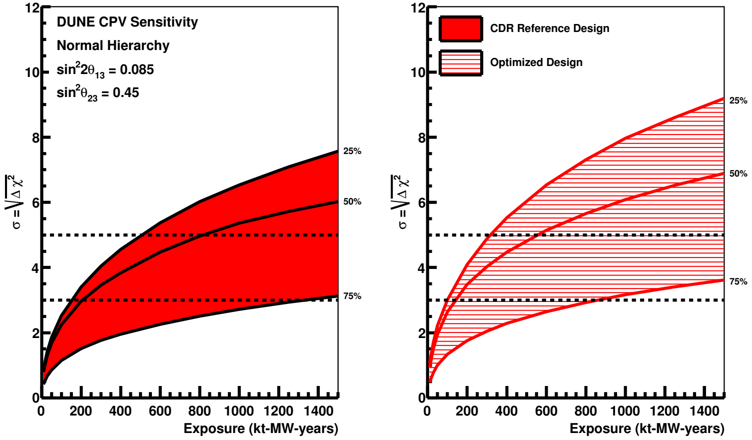


- **The CPV sensitivity is $\geq 3, 5\sigma$ for 75%,50% of $\delta_{\rm CP}$ with 1320,810 (850,550) kt.MW.yr for reference (optimized) beam designs.**
- **With 400 (230) kt.MW.yr, at the *worst sensitivity point* the MH $|\Delta\chi^2|$ value obtained in a typical data set will exceed 25, allowing DUNE on its own to rule out the incorrect mass ordering at a confidence level above $1 - 3.7 \times 10^{-6}$.**

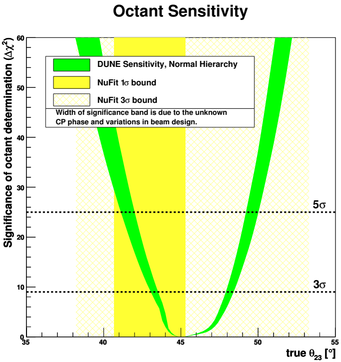
DUNE Physics Performance vs Exposure

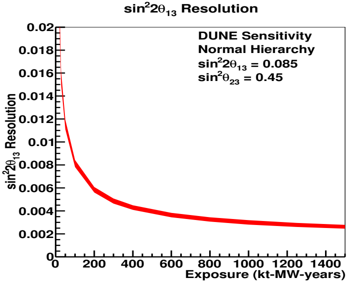


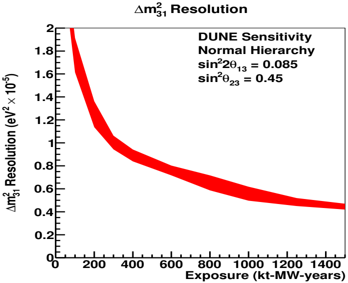
DUNE Physics Performance vs Exposure



Octant and Precision Measurements







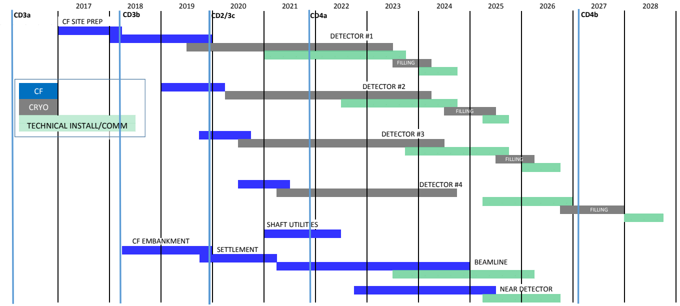
DUNE Physics Milestones

Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{\rm CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\rm CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{\rm CP} = 0$)	450	290
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	525	320
CPV at 5σ 50% of $\delta_{\rm CP}$	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of $\delta_{\rm CP}$	1320	850

DUNE Status Summary

The international physics communities in the US/Europe/Asia have recognized neutrino oscillation experiments as a top priority.

- **The DUNE concept has developed over a decade, with extensive studies of site, technology, physics capabilities.**
- **A large, diverse international collaboration has developed and is continuing to expand.**
- **Designs are being developed** *incorporating ideas of all partners.*



THANK YOU