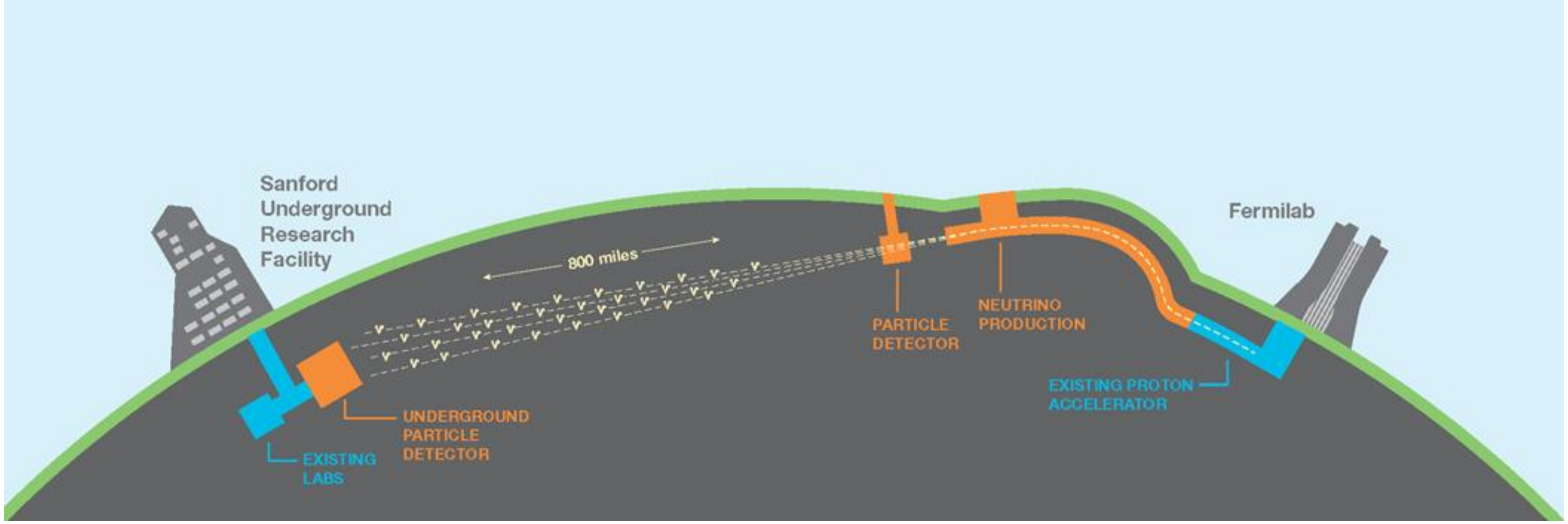
The Status of DUNE



EDSU2022

8 November 2022

Albert De Roeck, CERN

For the DUNE Collaboration

Neutrinos: What we do & do not know

- Neutral leptons with 3 active flavors
- Tiny small masses
  - Existing limits on sum of neutrino masses are order few hundred meV/c^2
- Flavor eigenstates (ν_e,ν_μ,ν_τ) ≠ mass eigenstates (ν_1,ν_2,ν_3)
  - Mixing described by PMNS matrix
  - All mixing angles and mass splittings have been measured
- Neutrinos detected via their interaction products
  - Neutrino interaction cross sections are small, $\mathcal{O}(10^{-38}$ cm^2/nucleon) at 1 GeV
- May be Majorana or Dirac

- Other kind of "Sterile" neutrinos?
- Direct measurement limits currently $\leq$ 1 eV/c^2
- *More precise measurements of mixing angles needed

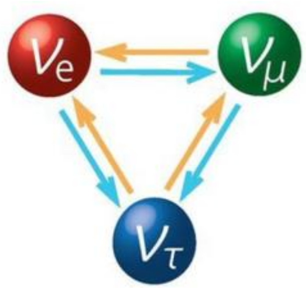
- *CP violation in PMNS?
- *Unitarity?

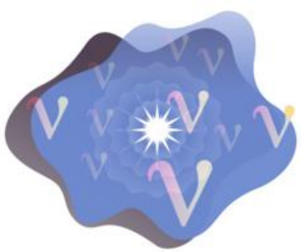
**Very large detectors are needed*

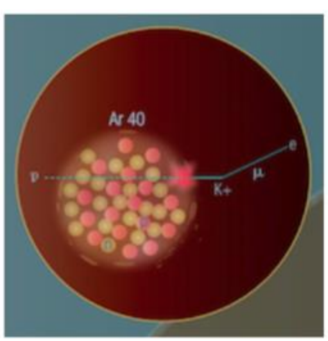
- Neutrino-nucleus interaction model has large uncertainties

- Majorana phases?

DUNE: The Main Physics Program







- Precision Neutrino Measurements: Neutrino Oscillations
  - Search for leptonic CP violation
  - Determine neutrino mass ordering
  - Precision PMNS measurements. Test 3-flavour paradigm
- Supernova Physics
  - Observation of time and flavour profile provides insight into collapse and evolution of supernova
- Baryon number violation (BSM physics)
  - LAr TPC technology well-suited to certain proton decay channels (*e.g.*, p→K+ν)
  - Δ(B-L) ≠ 0 channels accessible (*e.g.*, n→n)
- Other opportunities
  - Atmospheric and solar neutrino physics
  - Searches for dark matter, axions, HNLs etc in Near Detector Additional neutrinos?
  - Neutrino physics with the Near Detector.

DUNE – a global collaboration

Status October 2020:

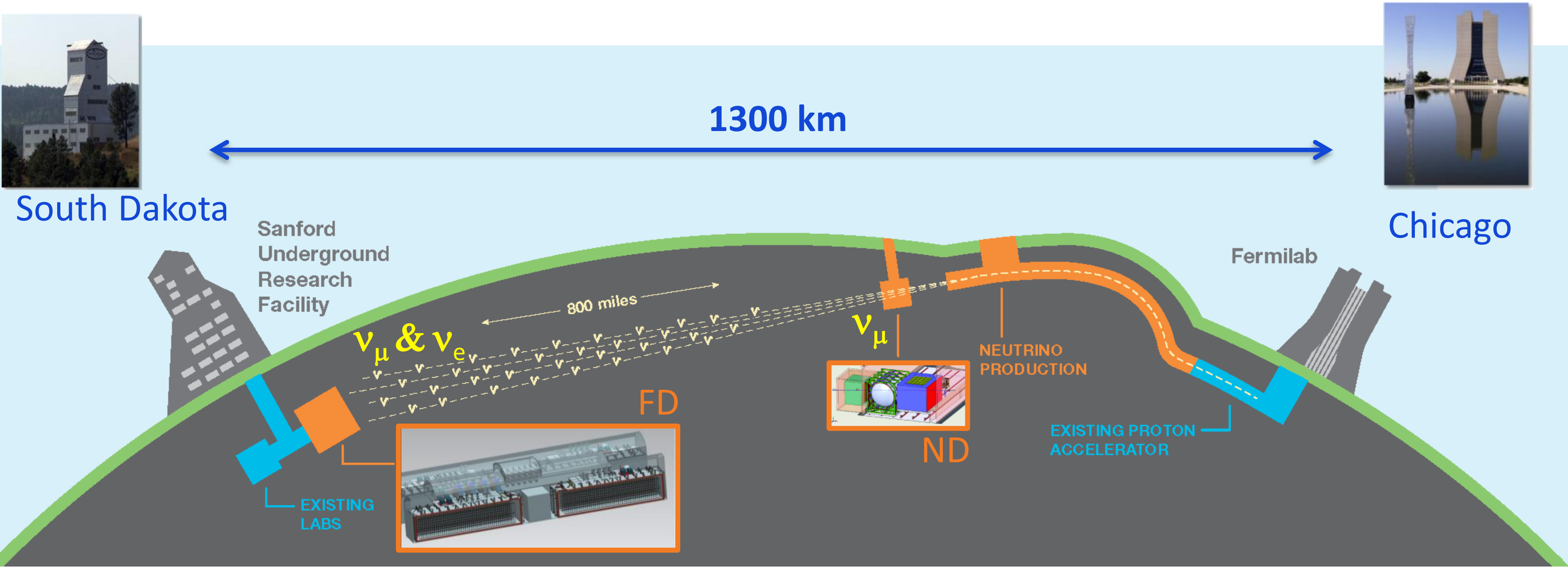
- 1400+ people
- 200+ Institutes
- 31 countries

Still more groups joining

Collaboration meeting at CERN end of January 2020 350 participants

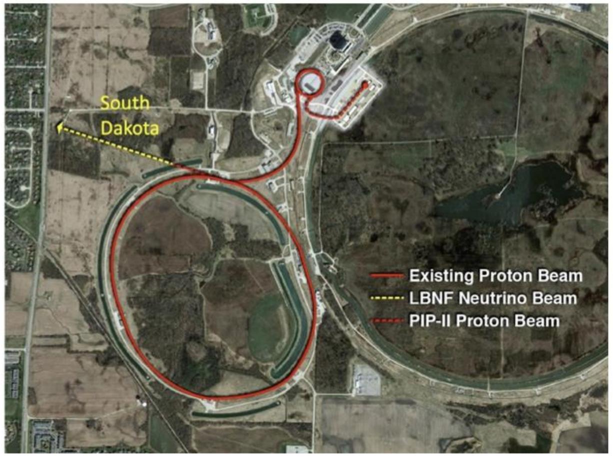
General Setup

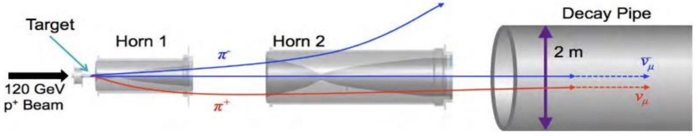
- LBNF/DUNE will consist of
  - An intense 1.2 MW upgradeable 60-120 GeV ν-beam fired from FNAL
  - A massive 70 kt (40kt fiducial) deep underground LAr Far Detector (FD) in South Dakota and a large Near Detector (ND) complex with multiple detectors at Fermilab



LBNF wide-band beam

At FNAL, Fermi NAtional Lab



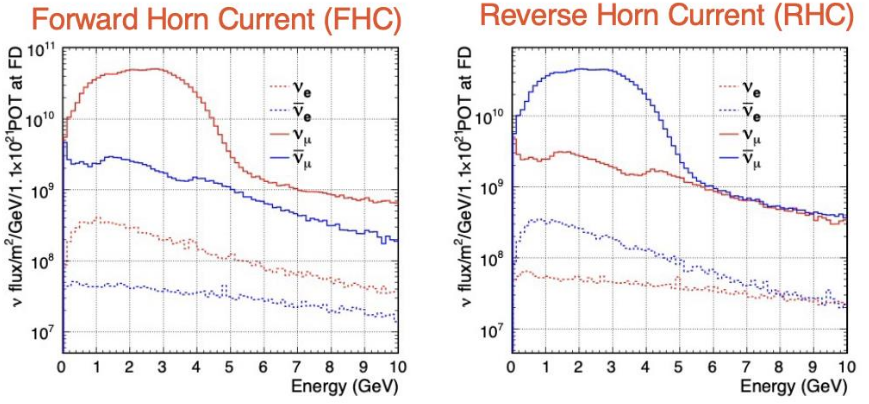


Horn-focused neutrino beam line optimized for CP violation sensitivity using genetic algorithm

1.2MW @ 100% efficiency=2x10^{21} pot/year
The 3-year ramp-up is equivalent to
one year of operation at 1.2MW from Day 1

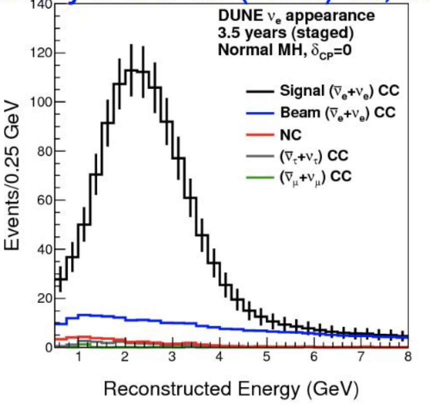
The LBNF neutrino beam will provide neutrinos and antineutrinos with energies from 0 to 8 GeV

Neutrino Flux at SURF, 1300 km away



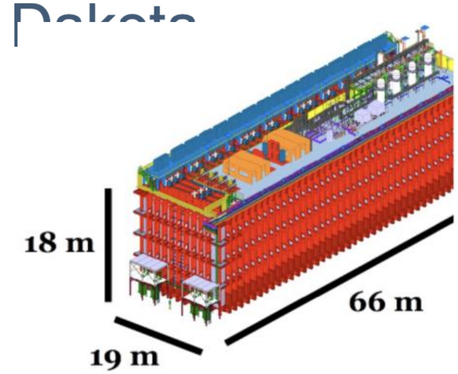
[Eur. Phys. J. C 80 (2020) 10, 978]

(DUNE CDR)

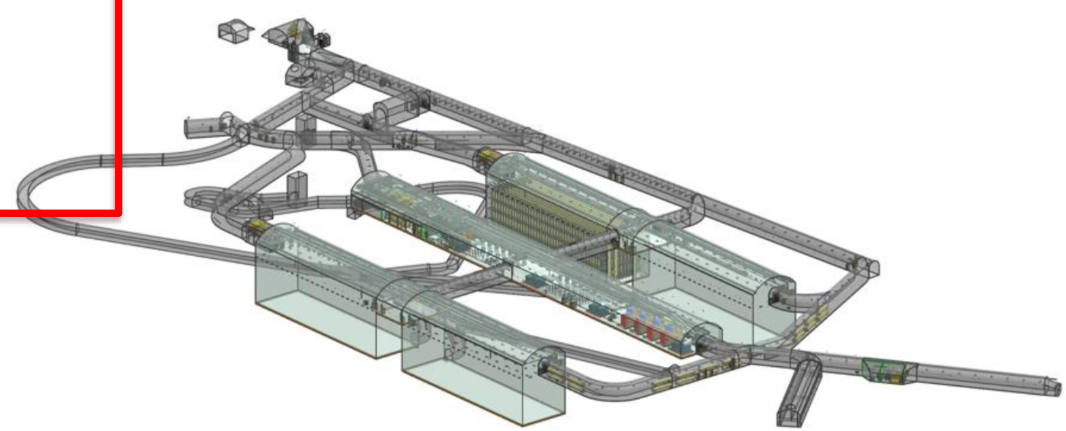


Far Detector

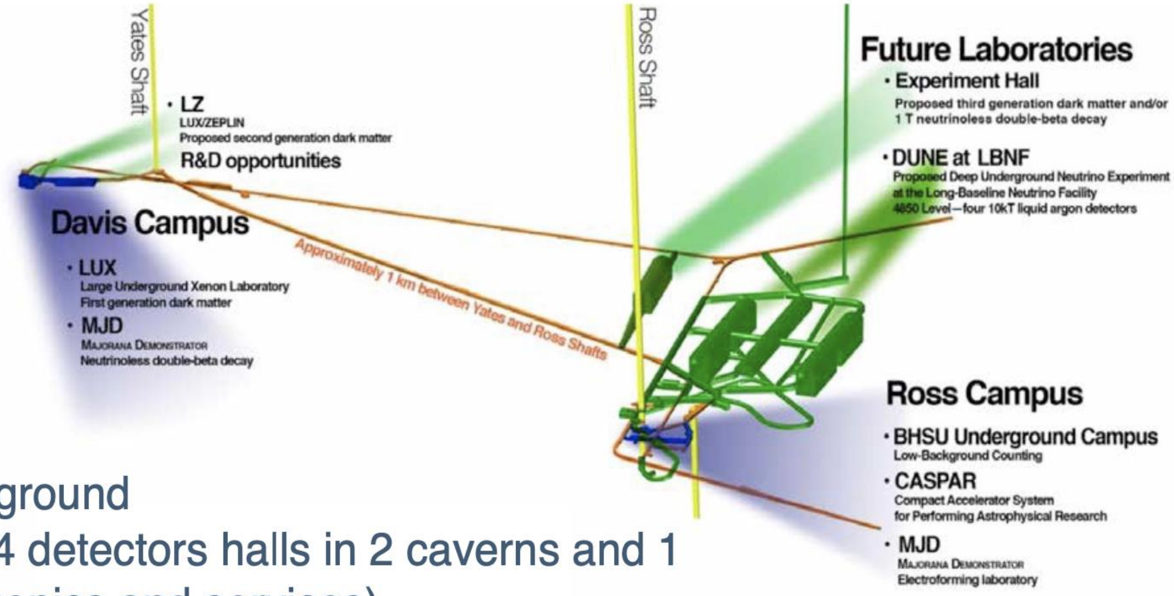
- Located at Sanford Underground Research Facility (SURF)
  1 mile underground at Homestake mine in South Dakota
  - SURF already hosts particle-physics experiments
  - Excavation for DUNE has started



- 4 modules with 70 kt of liquid Ar total
  - Each module contains 17 kt of argon, 18x19x66 m^3 volume
  - 1 Horizontal Drift (HD) Module
  - 1 Vertical Drift (VD) Module
  - 2 Modules of Opportunity

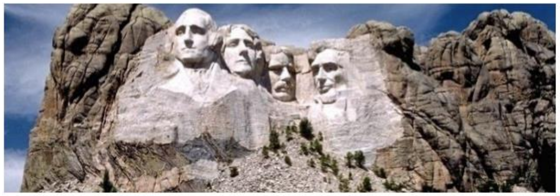


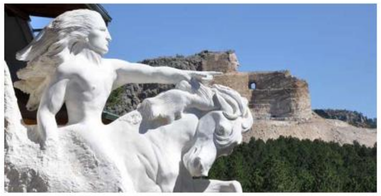
SURF



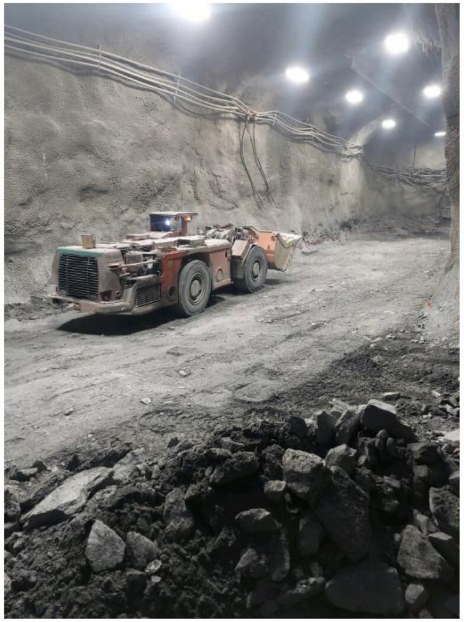
- Deepest laboratory in the US: 1.5 km underground
- Three main caverns: 4 detectors halls in 2 caverns and 1 support cavern (cryogenics and services)
- Excavation is ongoing *(875,000 tons of rock to be excavated)*
- FD first module installation second half of 2020's

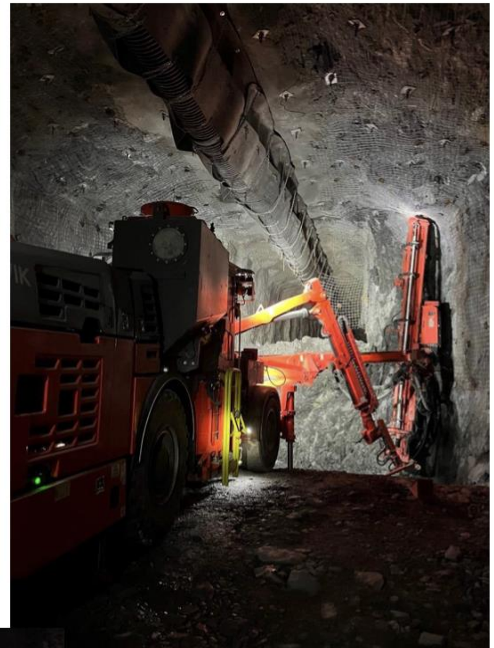
Previously known as Homestake (gold) Mine close to Lead,
in the Black Hills (South Dakota),
50 miles from Mount Rushmore and Crazy Horse statues

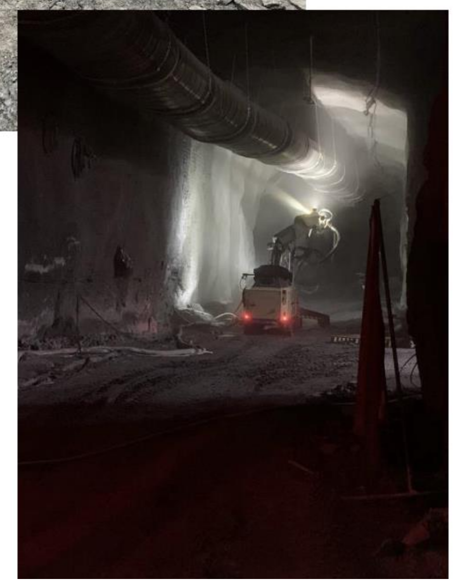




Excavation at SURF is ongoing



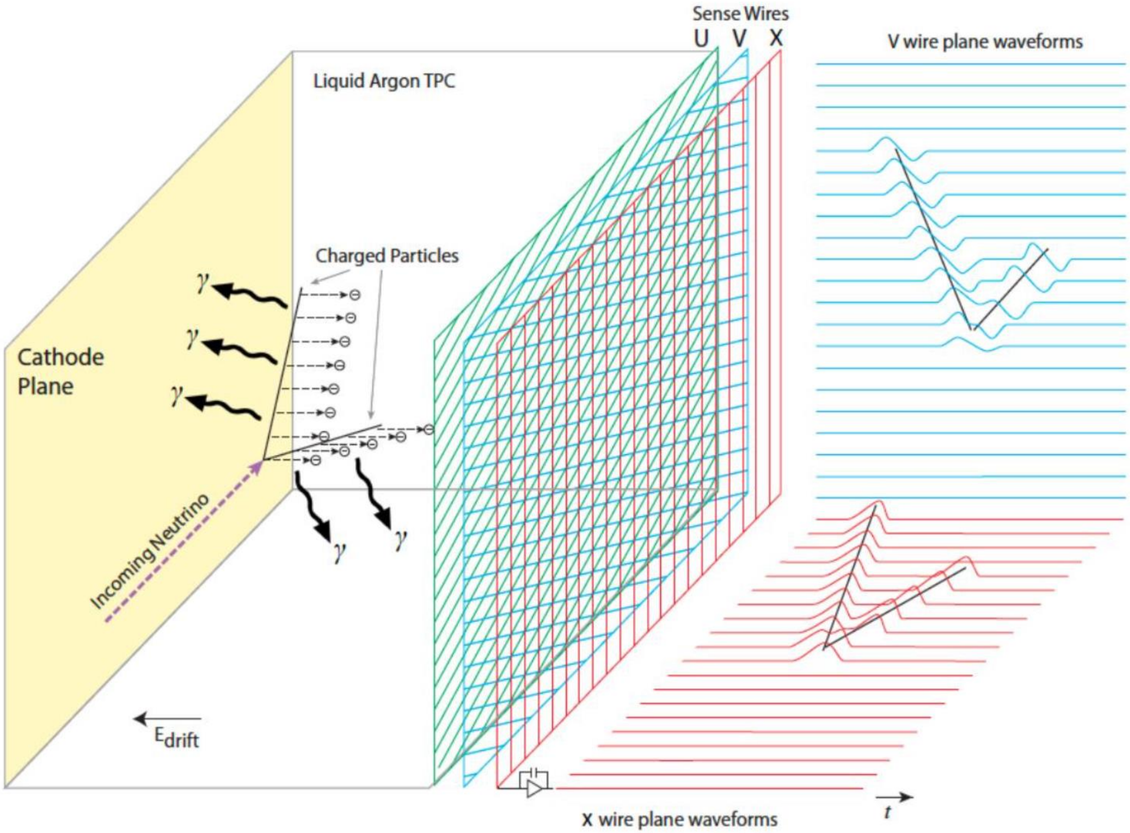




- Excavation advancing on schedule & budget
  -More than 27% complete by total rock volume
- Expect the construction of the caverns to be complete in 2024
  -Far Detector installation to follow-up.

Particle Detection

DUNE uses Liquid-Argon Time-Projection Chamber (LArTPC) as detector technology

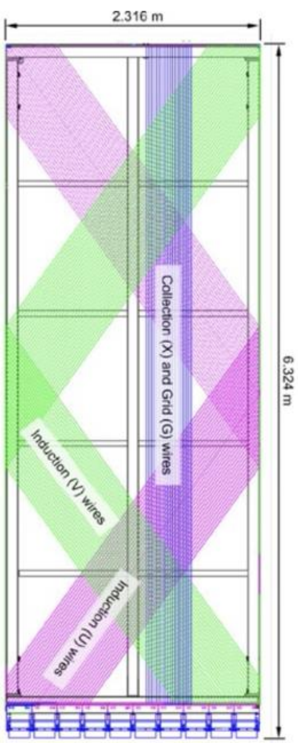


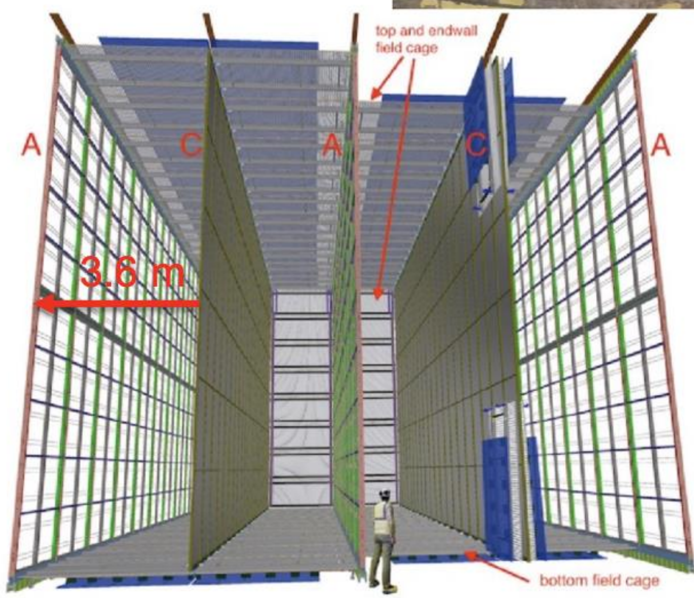
- Neutrinos interact in argon, produce charged particles
- Argon scintillates, light is quickly detected by photon detectors
- Charged particles ionize argon, electrons slowly drift to anode
- Anode is instrumented (readout wires)
  - Combining with light, reconstruct 3D events

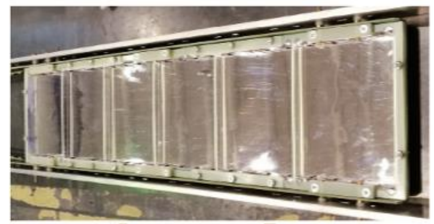
LArTPC Readout Technologies

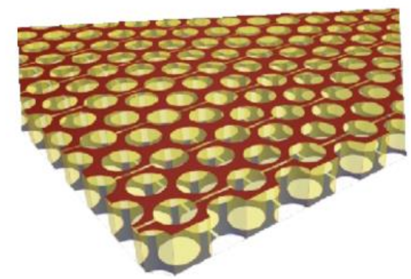
- **Module #1**
  - -3.6 m **horizontal drift**
  - -vertical anode wire planes
  - -vertical resistive cathode
  - -photon detectors

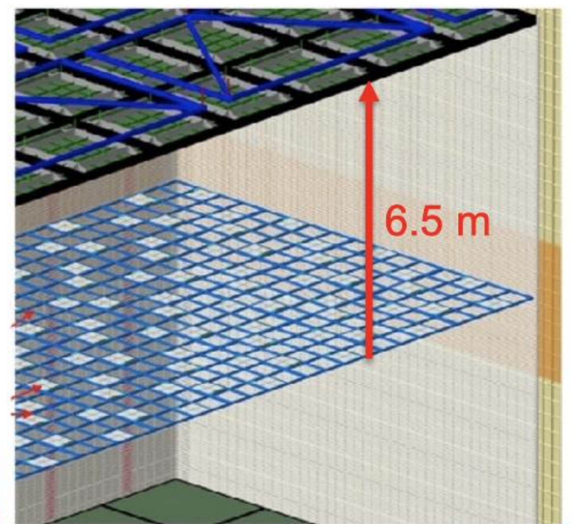
- **Module #2**
  - -6.5 m **vertical drift**
  - -horizontal PCB anode readout (CRP)
  - -horizontal grid cathode
  - -photon detectors





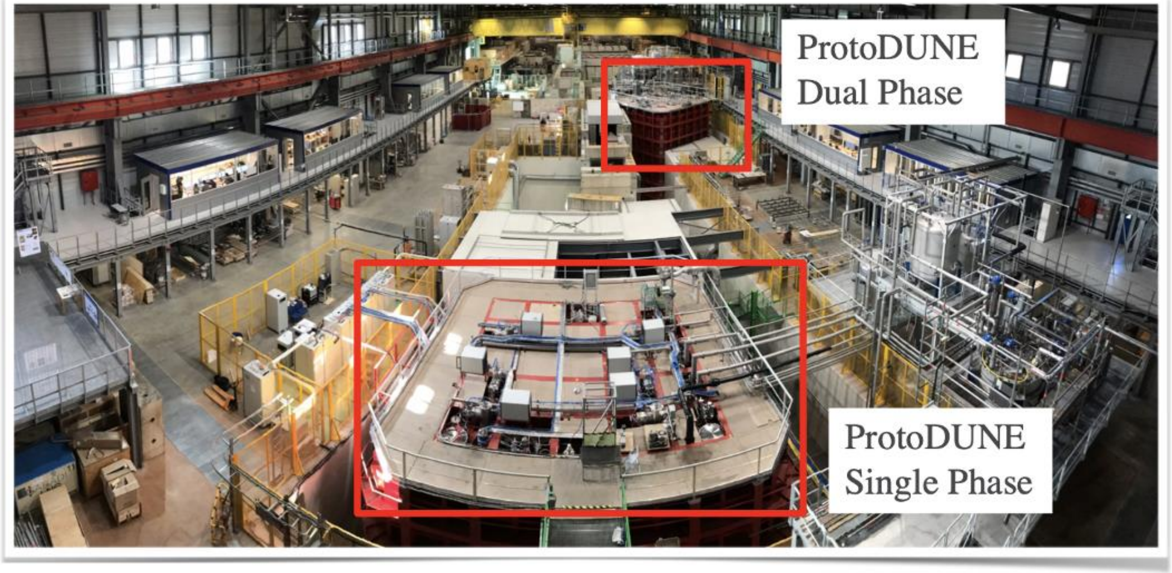






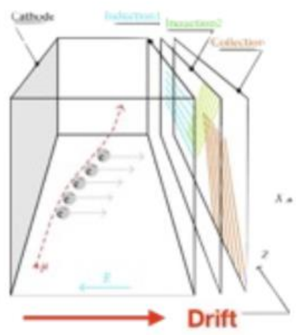
DUNE Far Detector Prototyping

- ProtoDUNEs at CERN Neutrino Platform

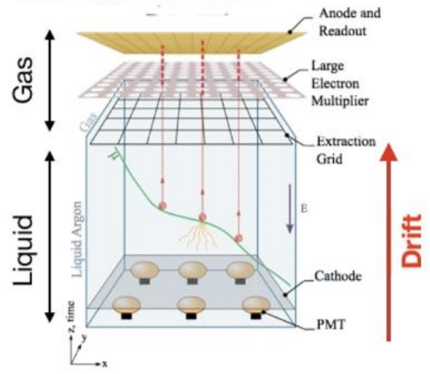


- **Two ~0.8 kt prototypes 6x6x7 m**
  -FD Design validation with full scale detector components.
- **Single-phase (HD) 2018-20**
  -Charged particle beam + cosmic rays
  -Event reconstruction, full analysis chain
  -Neutron calibration, Xe doping, HV tests
  -Phase-II starting 2022.
- **Dual-phase 2019-20**
  -Develop CRP technology, verify HV
  -Evolved into SP-Vertical Drift.

Single phase TPC



Dual phase TPC

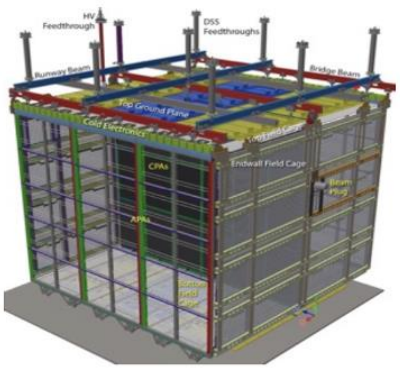


Now single phase with Vertical drift

ProtoDUNEs Current and next Phases

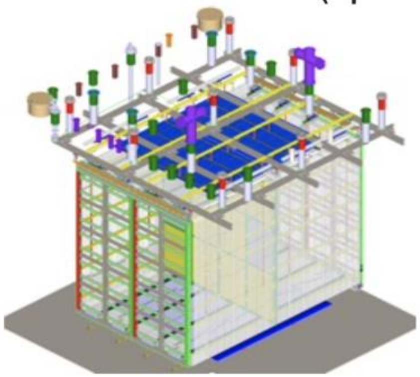
- ProtoDUNEs first phase highly successful: next phase is test of actual FD hardware.

ProtoDUNE-SP (operated 2018-20)



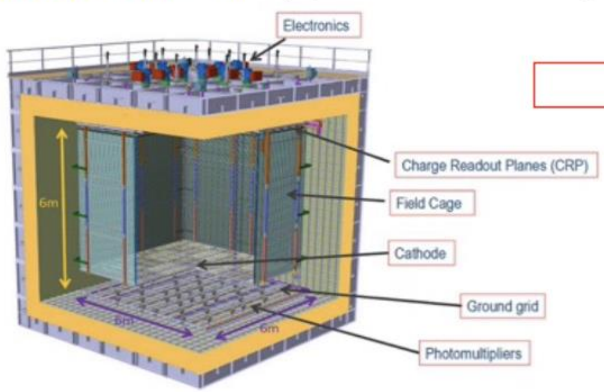
Performance paper: JINST 15 (2020) P12004
Detector paper: JINST 17 (2022) P01005

ProtoDUNE-HD (operate early 2023)



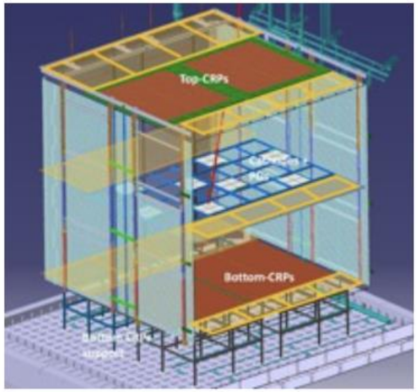
- Detector hardware near completion: Next step LAr fill In early 2023

ProtoDUNE-DP (operated 2019-20)



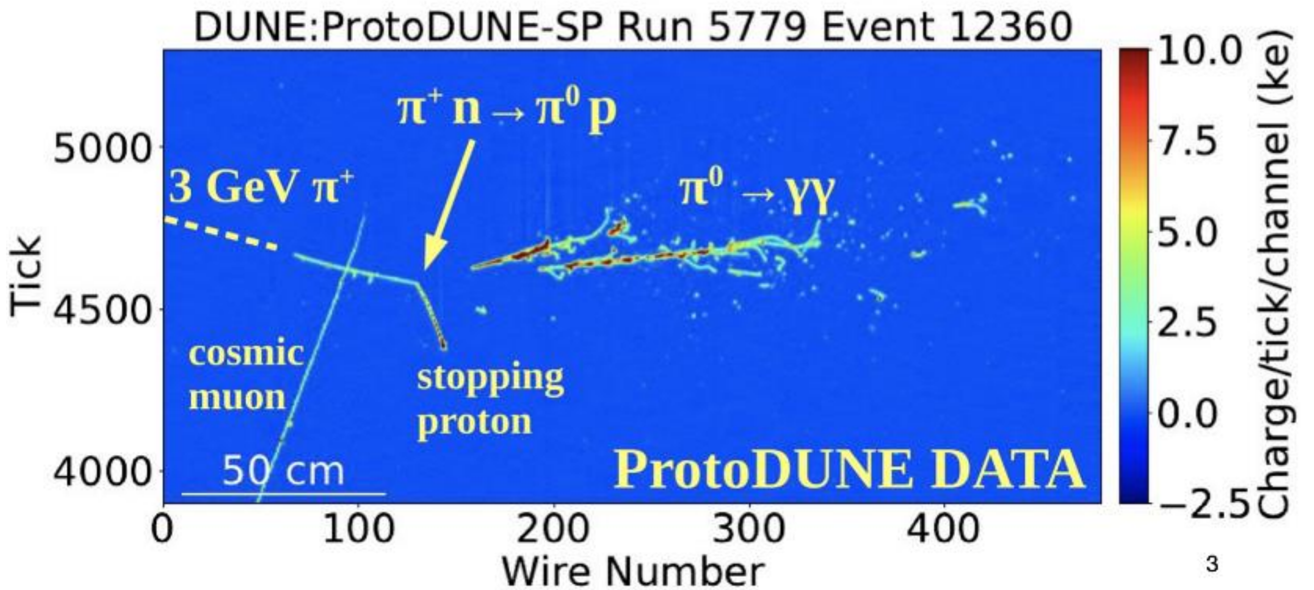
Photon-detector paper: Eur. Phys. J. C 82 (2022) 7, 618

ProtoDUNE-VD (operate late 2023)

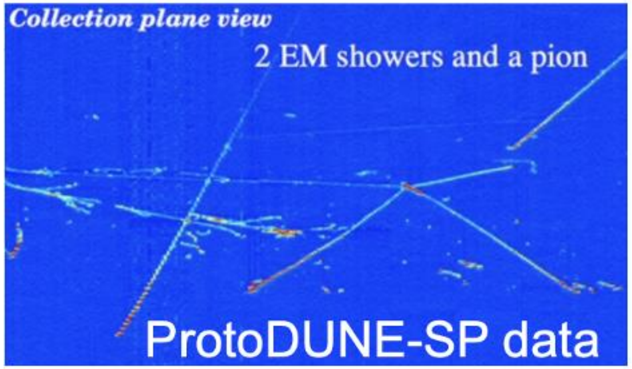


4% of the full size if the Far Detectors

LArTPC Events



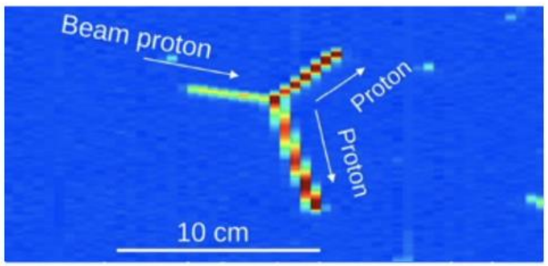
- DUNE will be excellent at imaging neutrino interactions
  - Both at high energy (~GeV) and low energy (~ 10 MeV)
- LArTPC technology: full tracking and calorimetry

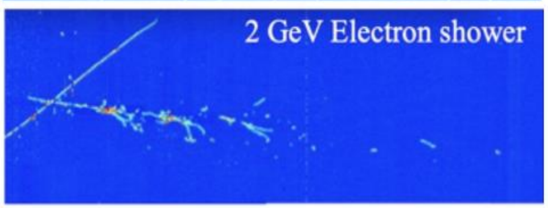


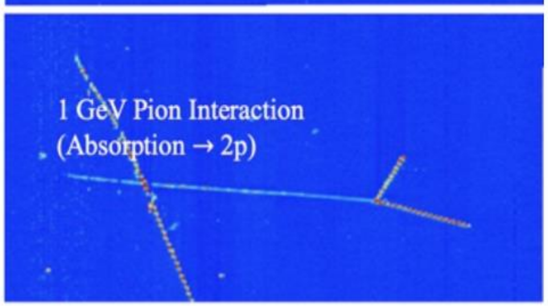
ProtoDUNE Results

➢ Hadron–Ar Cross Sections

- Measuring interaction cross sections helps reduce systematic uncertainties across DUNE's physics program.

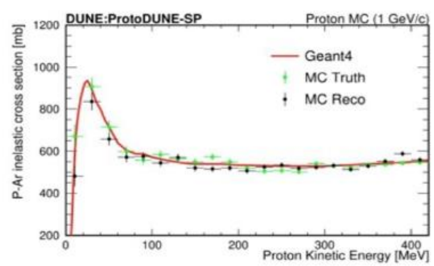


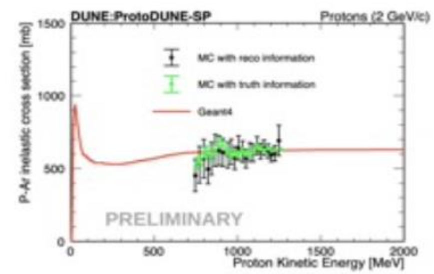




Proton Cross Section

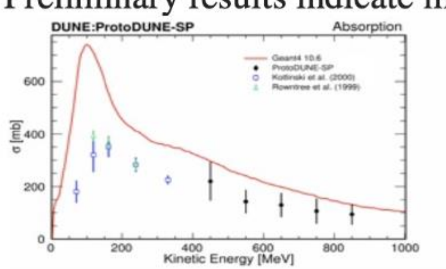
- Current analyses focusing on MC performance with 1 & 2 GeV/c central beam momentum runs.

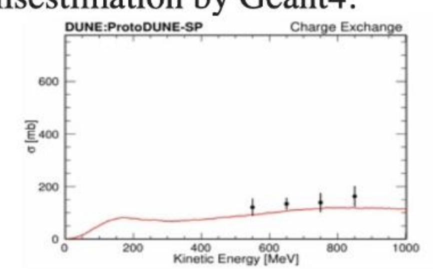




π^+-Ar Cross Sections

- Measure exclusive interactions with 1 GeV/c pion beam
  - -Absorption: $\pi^+ + Ar \rightarrow X +$ nucleons
  - -Charge Exchange: $\pi^+ + Ar \rightarrow X +$ nucleons $+\pi^0$
  - -Other: remaining inelastic interactions.
- Preliminary results indicate misestimation by Geant4.



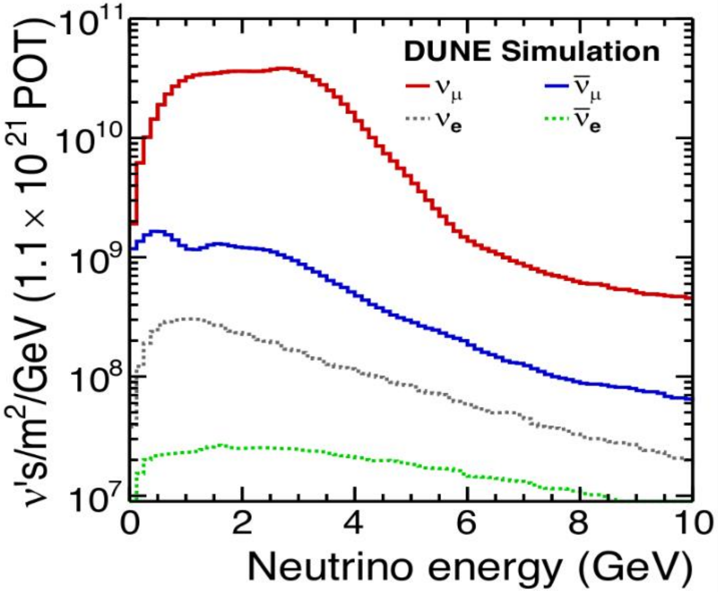


-> Improve the simulation!

12

LBNF neutrino beam

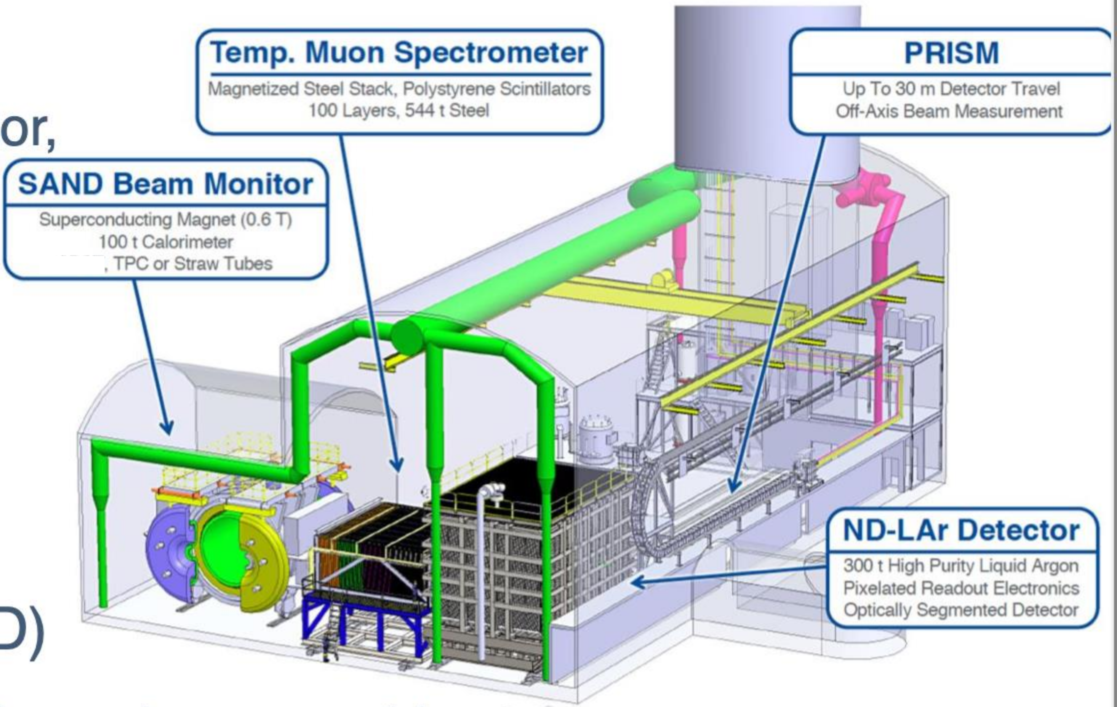
- Long Baseline Neutrino Facility (LBNF) Neutrino Beam will be generated at Fermilab, 1,300 km from Far Detector
- Proton-Improvement Plan II (PIP-II)
- 1.2 MW beam, upgradeable to 2.4 MW
- Wide energy spectrum



Final Design beamline and ND complex completed
NSCF will start reconstruction upon available funding

Near Detector complex

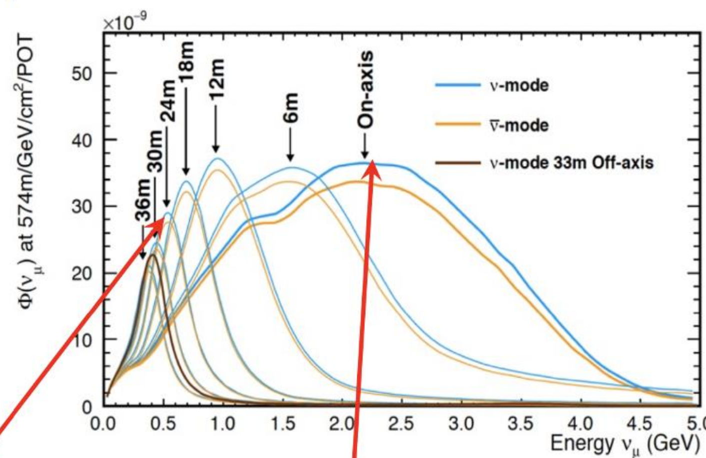
- Near Detector will be constructed to reduce systematics for primary goals of DUNE
  - Can be used for Beyond Standard Model searches
- ND-LAr
  - Same target as far detector, better segmentation
- Temp. Muon Spectrometer (TMS)
  - Upgradeable to ND-GAr
- System for on-Axis Neutrino Detection (SAND)

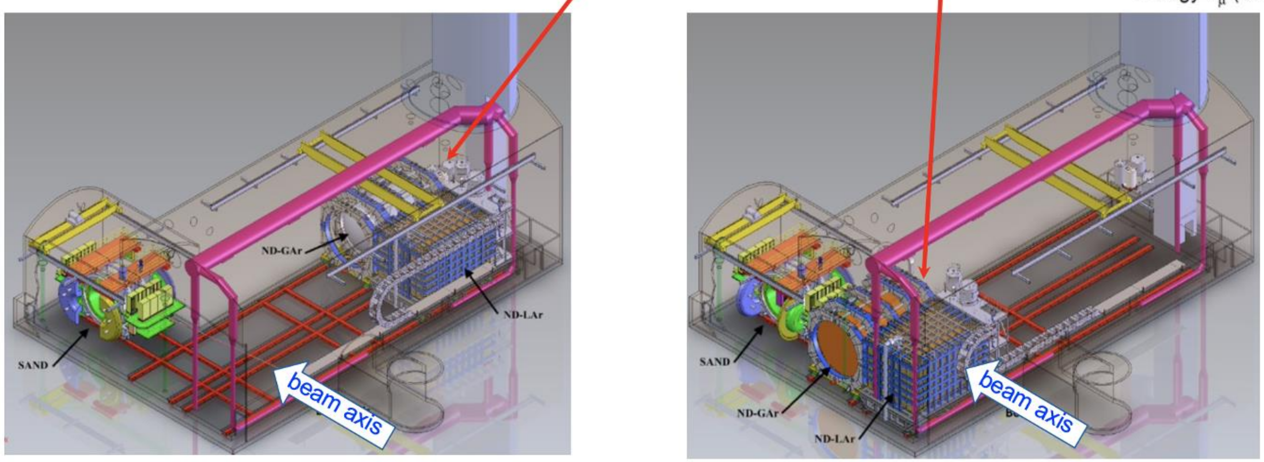


- PRISM: ND-LAr and TMS can be moved by 30 m

DUNE Prism Concept

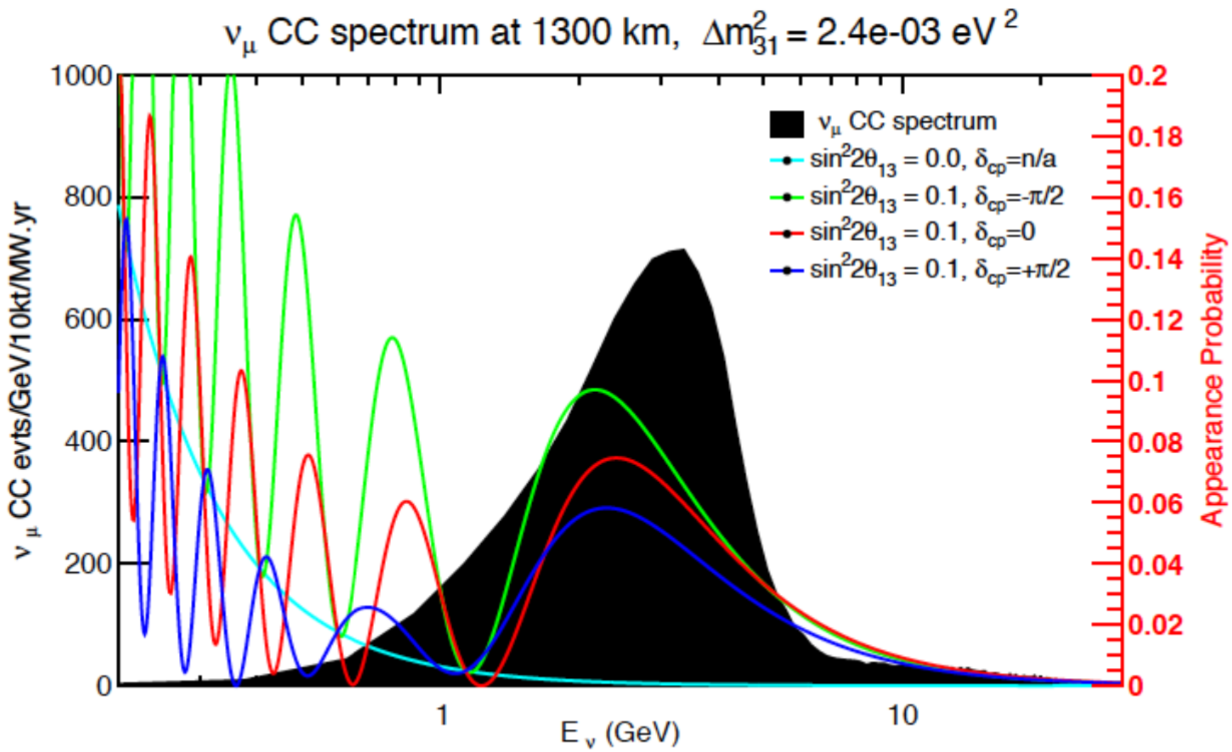
- Precision process independent spectrum measurement
- Moving ND detectors by 30m results in different measured energy spectra
- Linear combinations of these spectra can better reproduce oscillated FD spectrum which will reduce the uncertainties





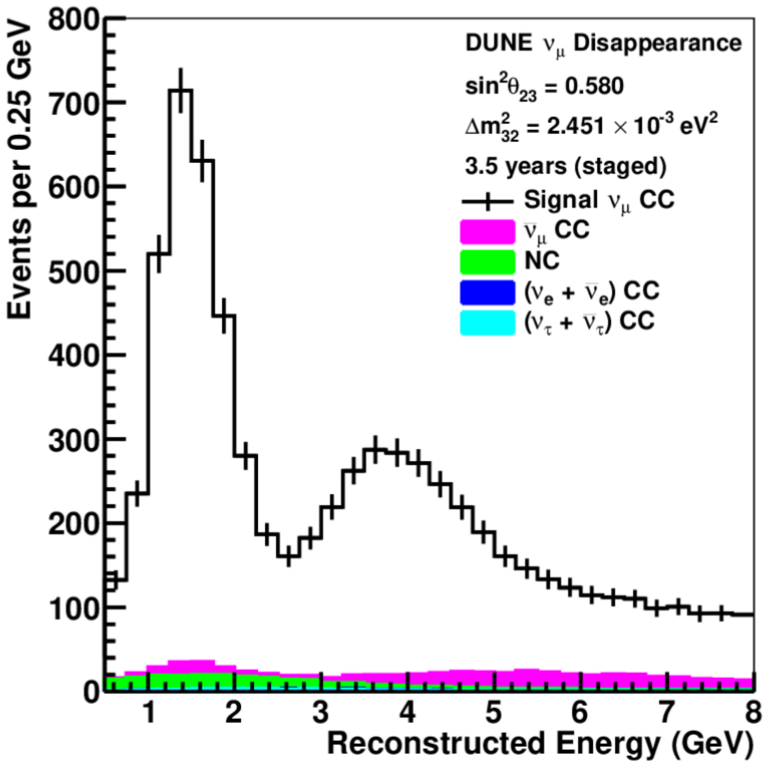
Neutrino oscillations at DUNE

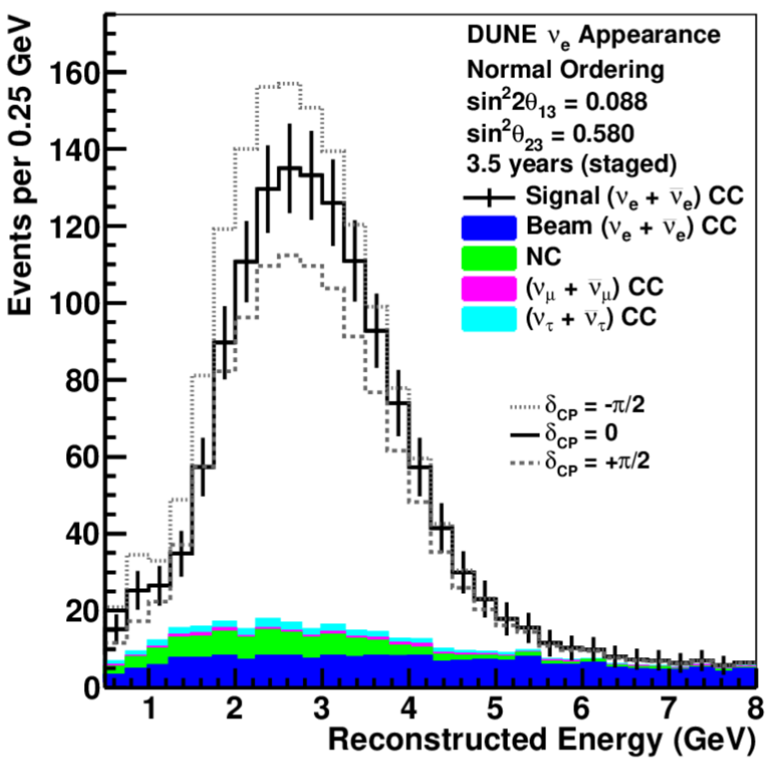
- DUNE is optimized to search for CP violation
- δ^{CP}, mass ordering, and other oscillation parameters affect measured energy spectrum
- Wide-band beam covers 1st and 2nd oscillation maxima



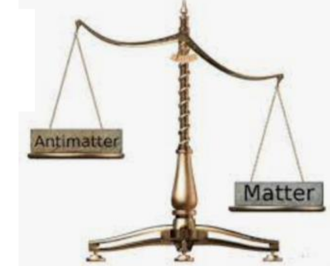
Energy distributions

- Looking for ν_μ disappearance and ν_e appearance as function of energy

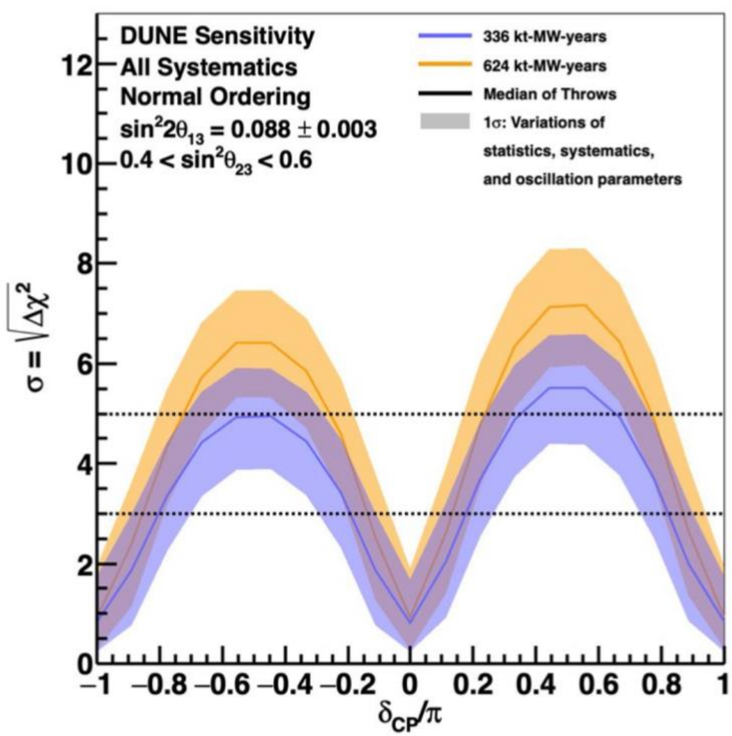


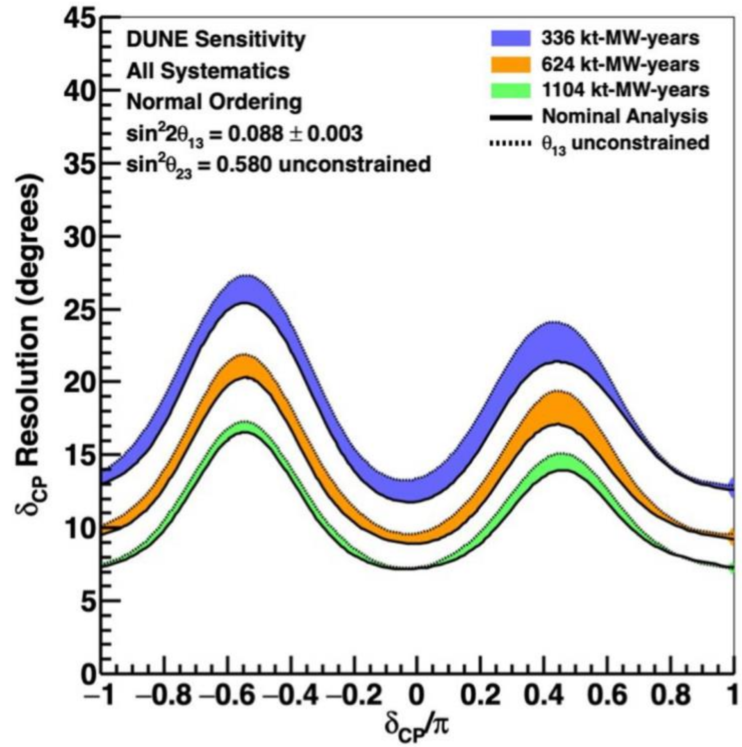


CP-violation sensitivity



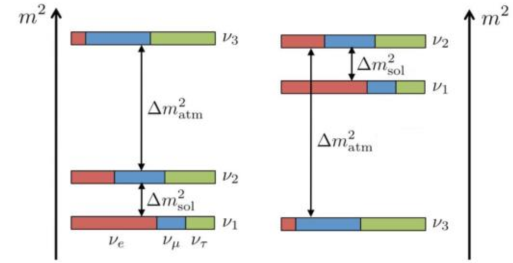
- DUNE can measure δ_{CP} over wide range of parameter values



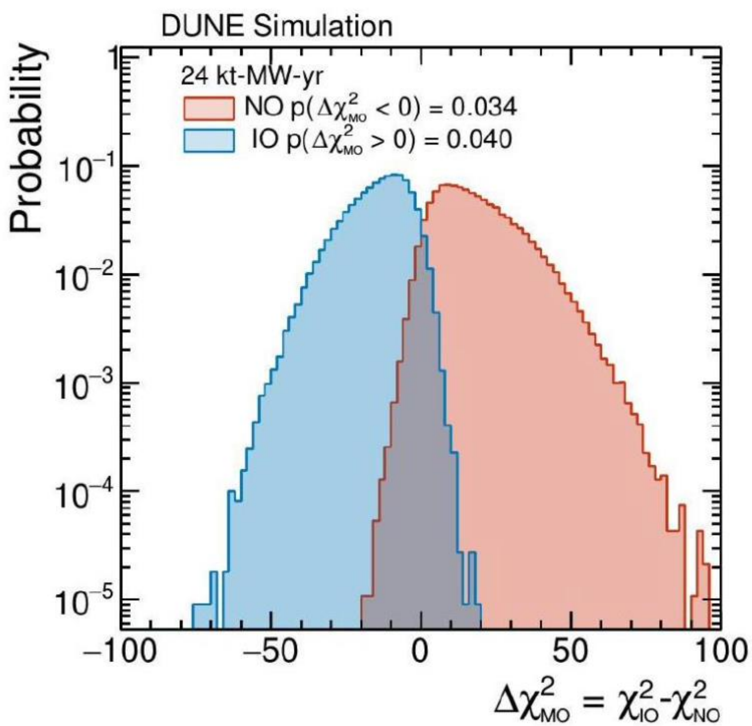


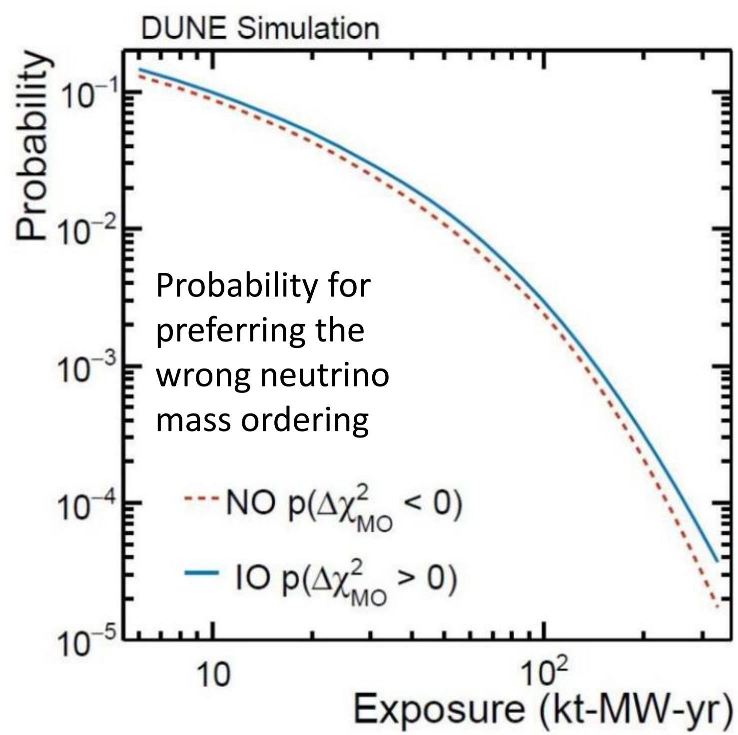
arXiv:2006.16043

Mass-ordering sensitivity



- After 1.2-MW beam is running, DUNE will need only 1-2 years of running to definitively measure mass ordering

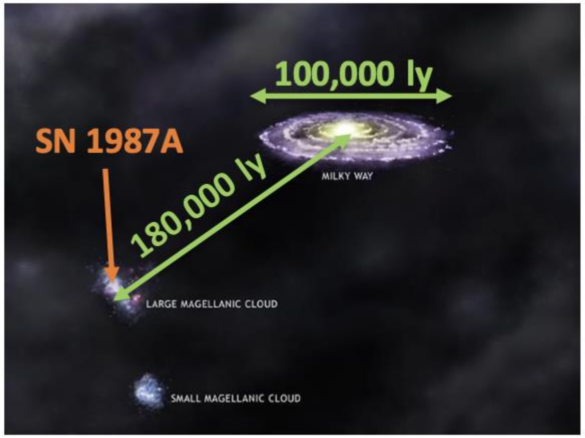




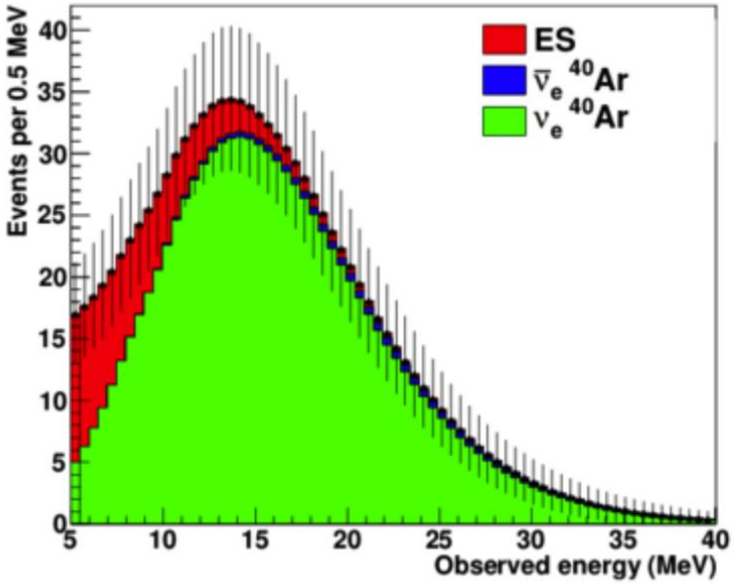
arXiv:2109.01301

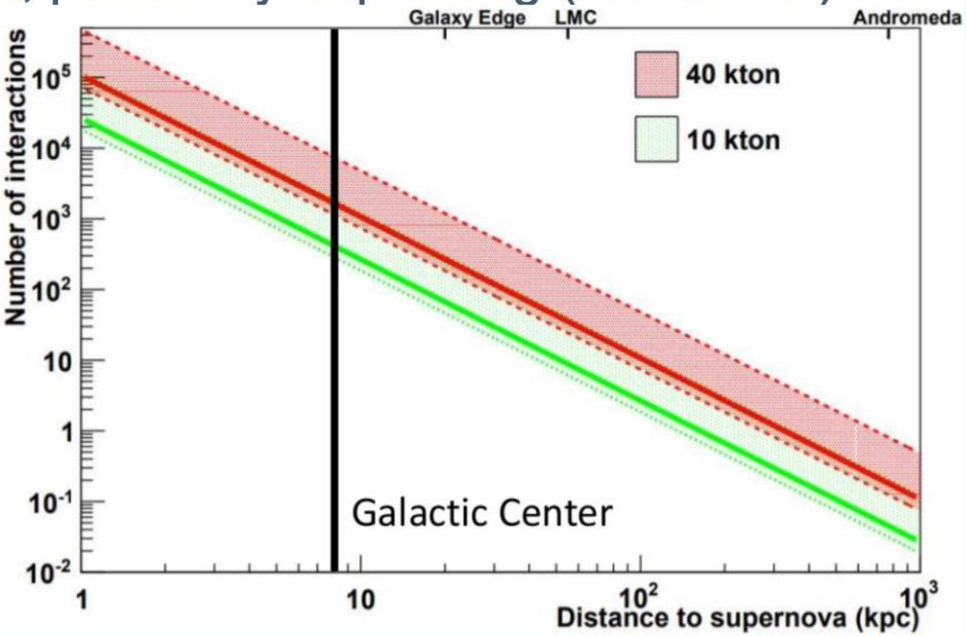
Probability < 0.01 to prefer the wrong neutrino mass ordering after 66 kt-MW-yr

Supernova neutrinos



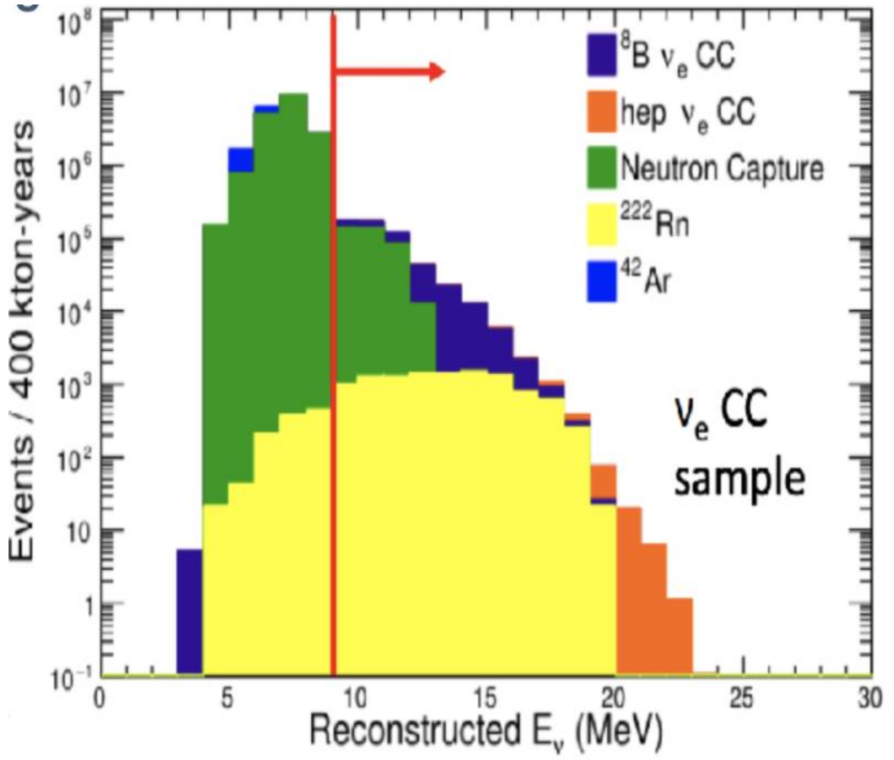
- Expect to detect 1,000s of neutrinos from supernova close to Milky Way center
  - On order of 1 event from Andromeda
  - The $\boldsymbol{\nu}_e$ flavor dominates. Detectable in DUNE via $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$
  - Great information for SN models, possibility of pointing (res. of ~5°)





Solar Neutrinos in DUNE

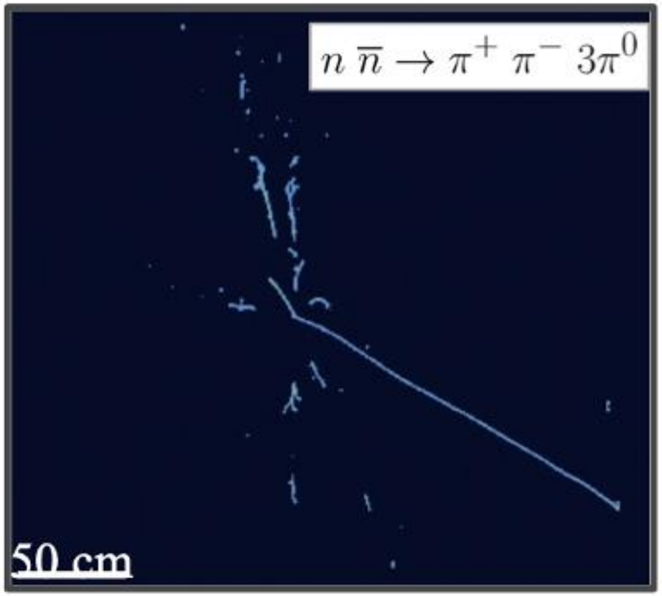
- DUNE will record an enormous amount of solar neutrinos → several events/day/kt.
- Backgrounds are very important. Neutron capture dominates (9 MeV analysis threshold).
- Discovery potential for hep neutrinos in DUNE!
- Precision of neutrino mixing and fluxes.
- DUNE has favorable sensitivity for measuring Δm^2_{21}.
- **On-going full DUNE study.**



Baryon Number Violation

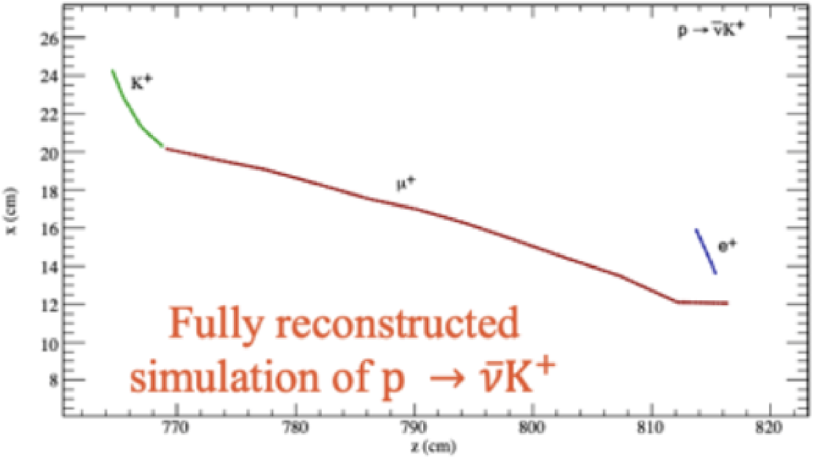
- Neutron anti-neutron oscillations and proton decay with 400kt-yr of data taking

FD: $n - \bar{n}$ oscillation



Free-neutron-equivalent sensitivity:
$\tau_{\text{free,osc}} > 5.5 \times 10^8$ s (90% C.L.)

FD: Proton Decays

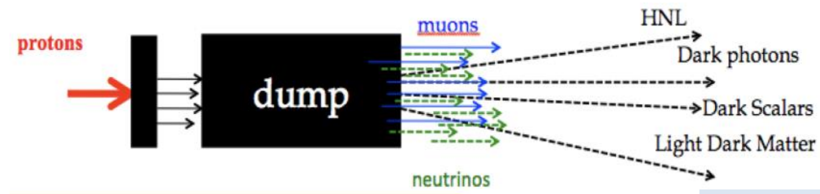


0.5 bkg events for 400 kt-yr, 30% signal efficiency
Sensitivity (no signal): $\tau/B >$ 1.3×10^{34} yr (90% C.L.)

1

Searches for BSM Physics

- High intensity proton beam on target/dump can be a source for low mass BSM particle production
- ND detectors at ~500m can detect BSM particle scattering or decays.
- Examples are: light dark matter, dark scalars, dark photons, axions, heavy neutral leptons (HNLs).
- Example shown here for HNLs

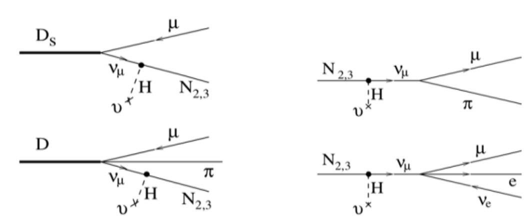


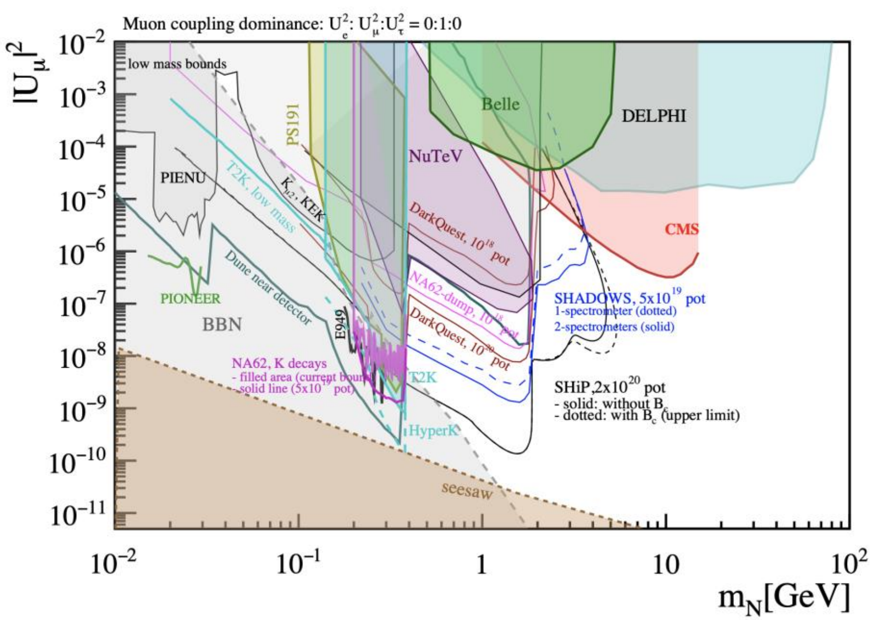
Example processes

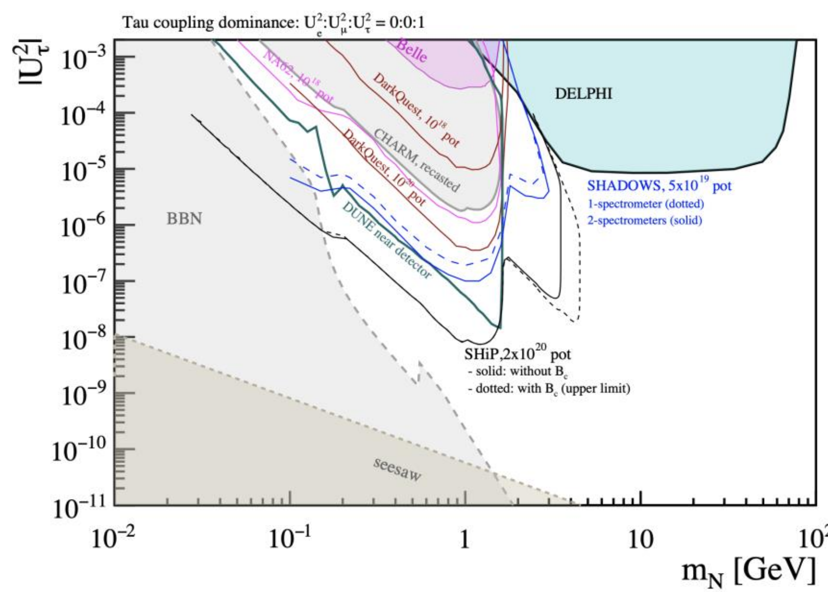
Production

Decay

--> Near Detecter





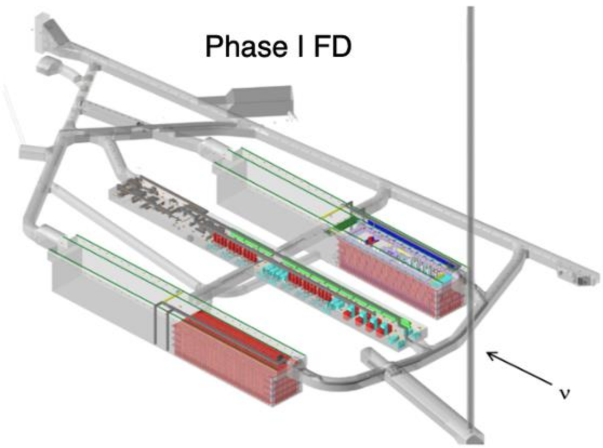


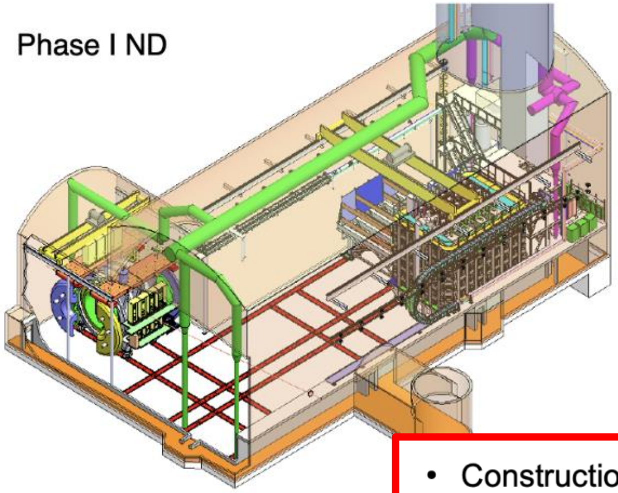
arXiv:2203.08039

DUNE Plans and Installation

- Phased construction plan to provide continuous progress toward physics goals beginning this decade

Phase I	Phase II Upgrades
•Ramp to 1.2 MW beam intensity •Two 17kt (10kt fid.) LAr TPC FD modules. One HD, one VD. •Near detector: ND-LAr + TMS (steel/scint. range stack) + SAND	•Proton beam upgraded to 2.4 MW •Four 17 kton LAr TPC FD modules •TMS upgraded to ND-Gar to provide enhanced ND interaction physics capabilities.

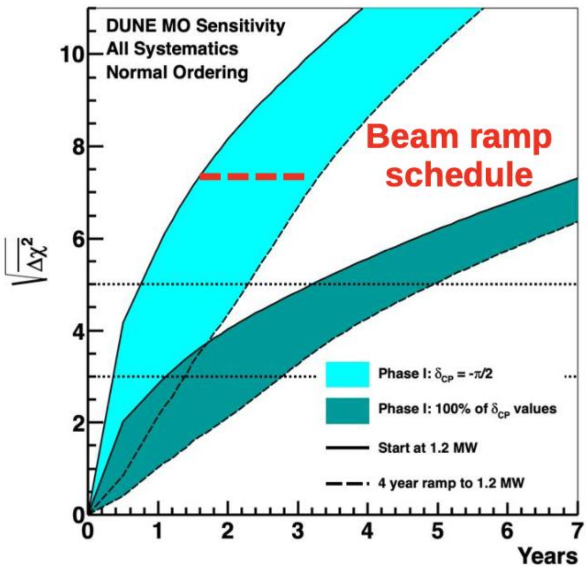


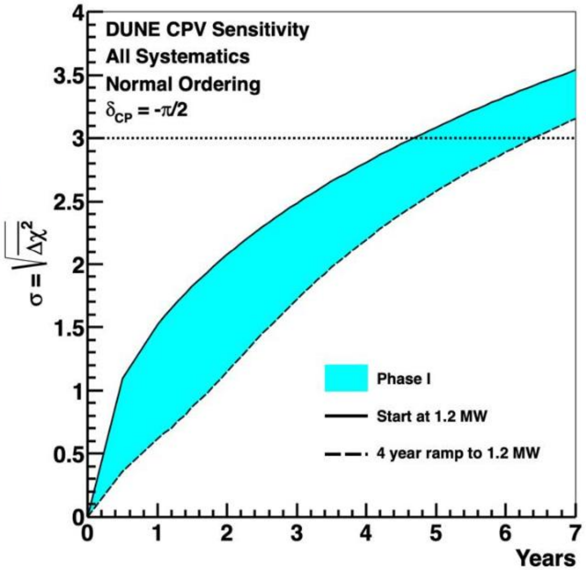


- Construction schedule funding limited:
  - FD late 2020s
  - Beam and ND by 2031

DUNE Sensitivity vs Staging

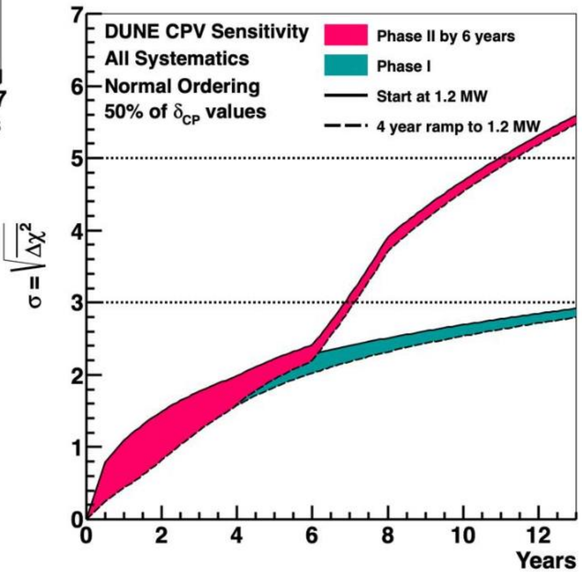
arXiv:2203.06100





Phase I:

- ✔ Unambiguous MO
- ✔ 3σ CPV at maximal δ_{CP}



Phase II:

- ✔ 5σ CPV for 50% of δ_{CP}
- ✔ Precision δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}

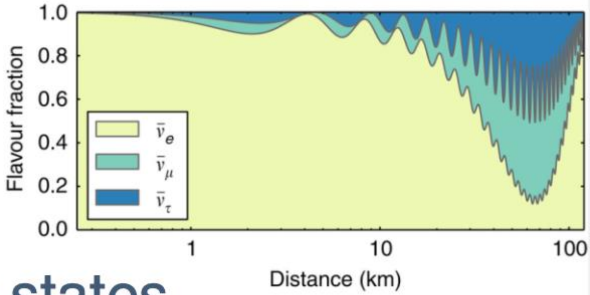
Requires 2.4 MW, 4 x FD modules + full ND

Summary

- The Deep Underground Neutrino Experiment (DUNE) is a next-generation long-baseline neutrino oscillation experiment, consisting of
  - High power, broadband neutrino beam
  - High capable near detector located on site at Fermilab
  - Massive liquid argon TPCs far detector located 1300 km at SURF underground facility
- The primary physics goals of the experiment are
  - Precise measurements of all parameters governing long-baseline neutrino oscillation parameters in a single experiment
  - Sensitivity to observe supernova, solar and atmospheric neutrinos, and access to BSM searches
- Milestones ProtoDUNEs successfully operated at CERN. Far side civil construction to be completed in 2024 with far detector installation next.
- Near site and beamline are fully designed. DUNE construction is phased to provide progress towards physics goals beginning end of this decade

Backup

Neutrino oscillations



- Neutrino mass states are different from flavor states
  - As neutrinos propagate, they change flavor
- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix converts between flavor and mass states

PDG 2022

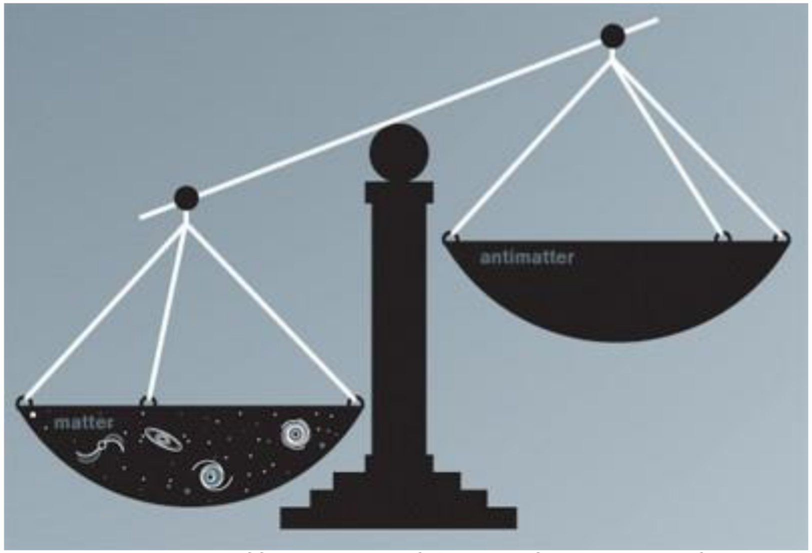
$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\rm CP}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,c_{23} \end{pmatrix} \qquad \begin{array}{l} c_{ij} \equiv \cos\theta_{ij} \\ s_{ij} \equiv \sin\theta_{ij} \end{array}$$

- Probability to observe neutrino of certain flavor also depends on differences between neutrino masses, $\Delta \mathrm{m}^2_{ij}$
- Neutrino oscillation parameters
  - Mixing angles θ_{ij}, mass differences $\Delta \mathrm{m}^2_{ij}$, CP-violation phase δ_{CP}
  - All but δ_{CP} have been measured

https://www.researchgate.net/figure/Illustration-of-neutrino-oscillations-The-expected-flavour-composition-of-the-reactor_fig4_273157809

CP violation

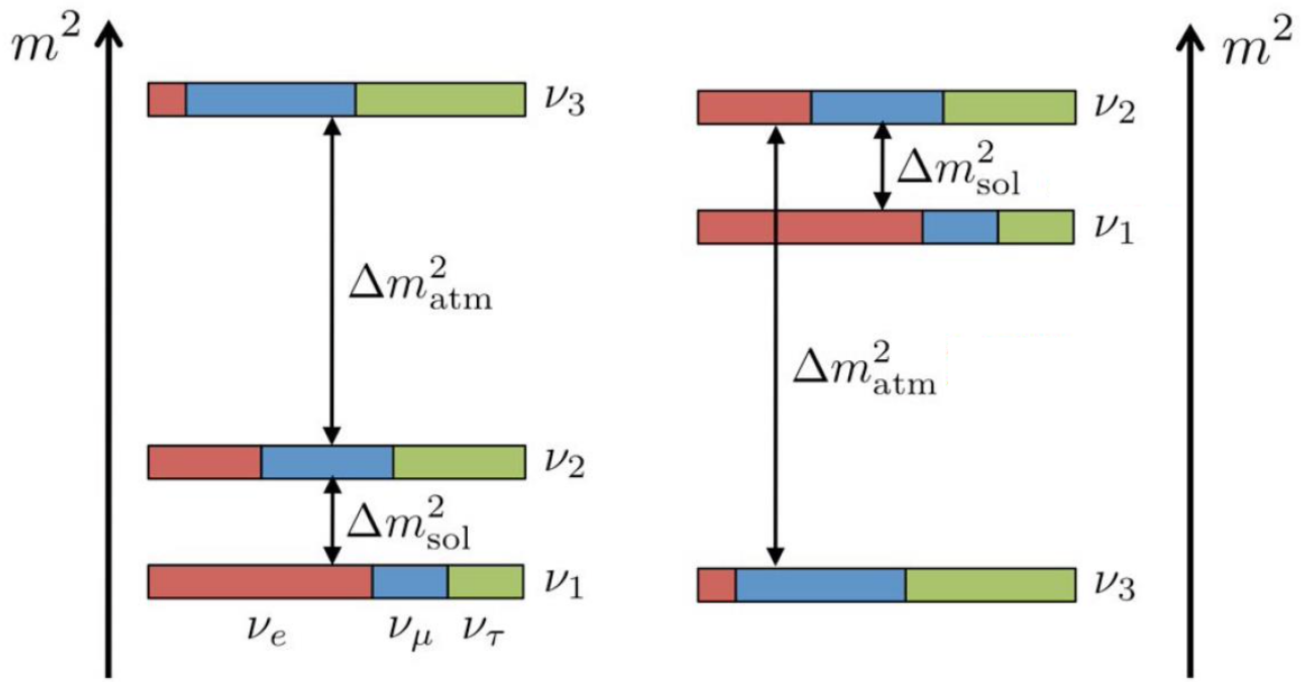
- One of major questions in physics
  - Why is our Universe mostly matter? Where is antimatter?
- Possible answer is CP violation
  - Observed CP violation in strong sector is too small to explain this
  - CP violation in lepton sector may be solution
    - Measuring δ_{CP} will help



https://essnusb.eu/glossary/cp-violation/

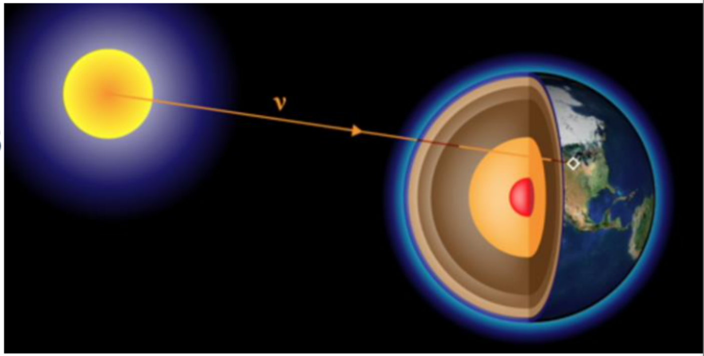
Neutrino mass ordering

- Measured absolute values of differences between mass states
- Two states have similar mass, one is different
- Is it 2 light states+1 heavy state or 2 heavy states+1 light state?



Astrophysical neutrinos

- Neutrinos can be used to study astronomical objects
  - Neutrinos barely interact → carry direct information from inside
    - Other particles scatter, charged particles bend in EM fields
- Sun – solar neutrinos
  - Thoroughly measured, still some questions
- Earth – geoneutrinos
  - Measured



- Supernovae – supernova neutrinos, relic supernova neutrinos
  - Measured only SN 1987A, will help understand supernova
- Outside Milky Way – extragalactic neutrinos
  - Measured, looking for sources

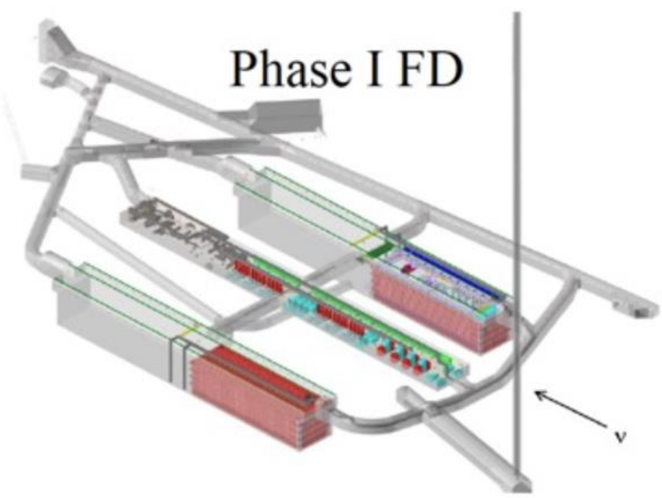
https://nus2surf.dunescience.org/wp-content/uploads/2017/09/solar-neutrinos-ara.png

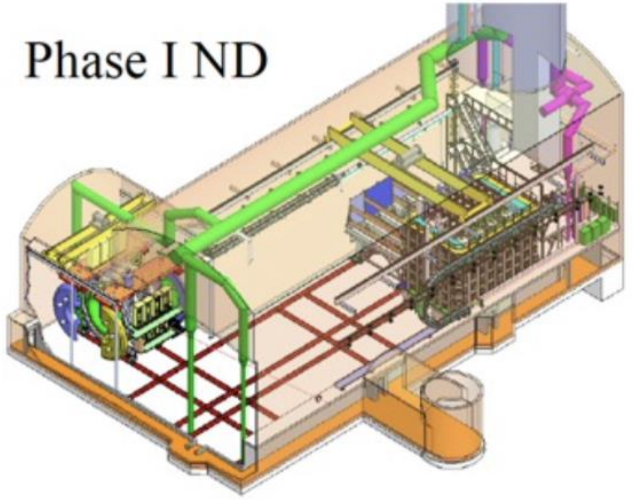
DUNE Plans and Installation

- DUNE construction is phased to provide continuous progress toward physics goals beginning this decade.

Snowmass Neutrino Frontier: "DUNE Physics Summary", arXiv:2203.06100

Parameter	Phase I	Phase II	Impact
FD mass	20 kt fiducial	40 kt fiducial	FD statistics
Beam power	up to 1.2 MW	2.4 MW	FD statistics
ND config	ND-LAr,TMS, SAND	ND-LAr, ND-GAr, SAND	Syst. constraints





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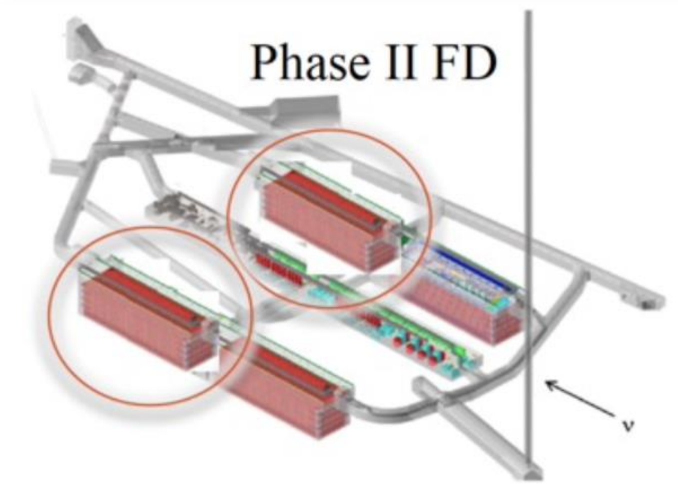
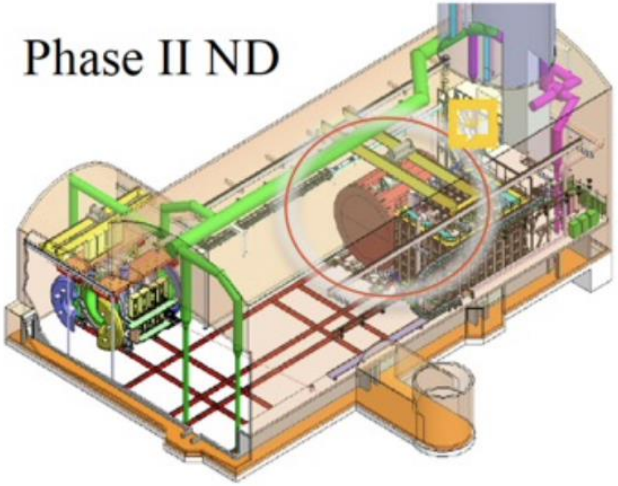
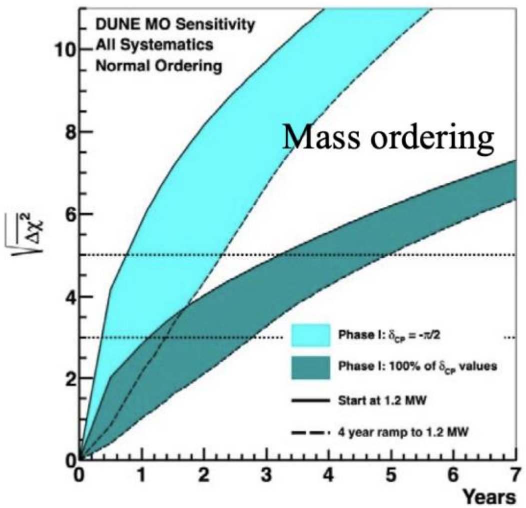
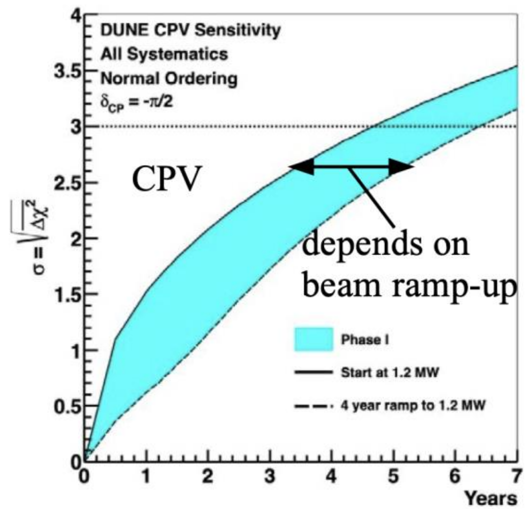
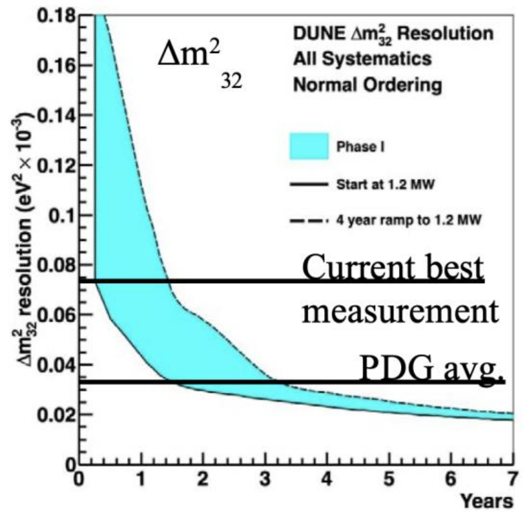




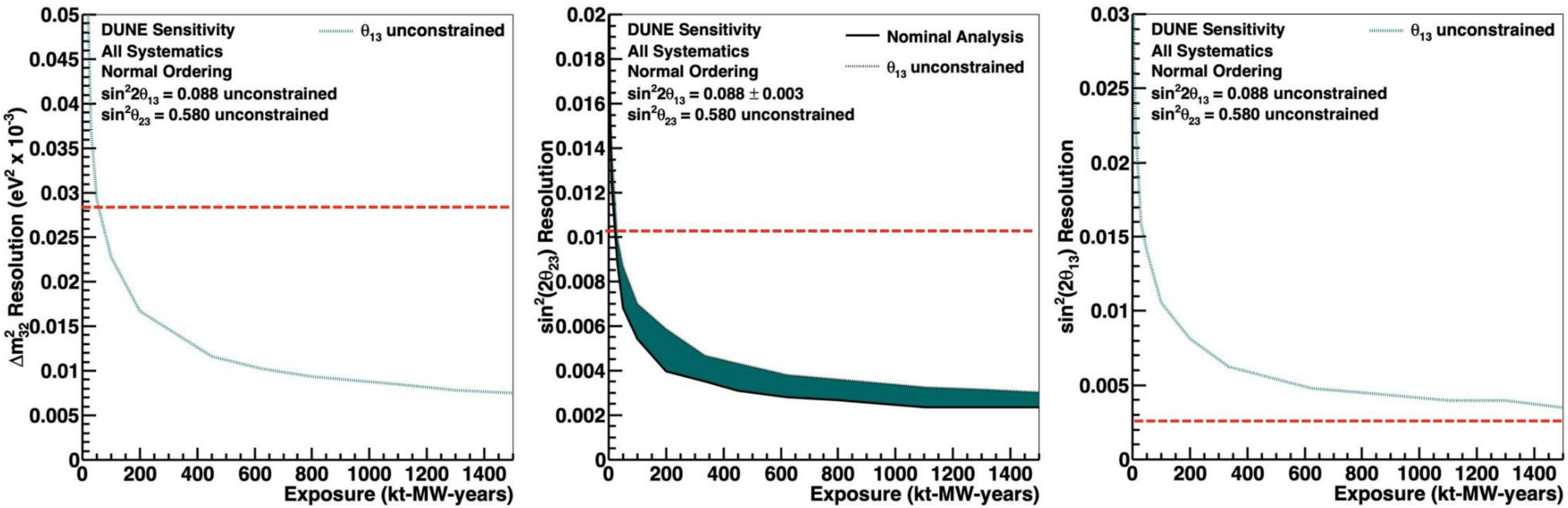
DUNE Phase 1


DUNE MO Sensitivity
All Systematics
Normal Ordering
Mass ordering
$\sqrt{\Delta\chi^2}$
Phase I: $\delta_{CP} = -\pi/2$
Phase I: 100% of δ_{CP} values
Start at 1.2 MW
4 year ramp to 1.2 MW
Years


DUNE CPV Sensitivity
All Systematics
Normal Ordering
$\delta_{CP} = -\pi/2$
CPV
depends on
beam ramp-up
$\sigma = \sqrt{\Delta\chi^2}$
Phase I
Start at 1.2 MW
4 year ramp to 1.2 MW
Years


Δm^2_{32}
DUNE Δm^2_{32} Resolution
All Systematics
Normal Ordering
Phase I
Start at 1.2 MW
4 year ramp to 1.2 MW
Current best
measurement
PDG avg.
Δm^2_{32} resolution ($eV^2 \times 10^{-3}$)
Years

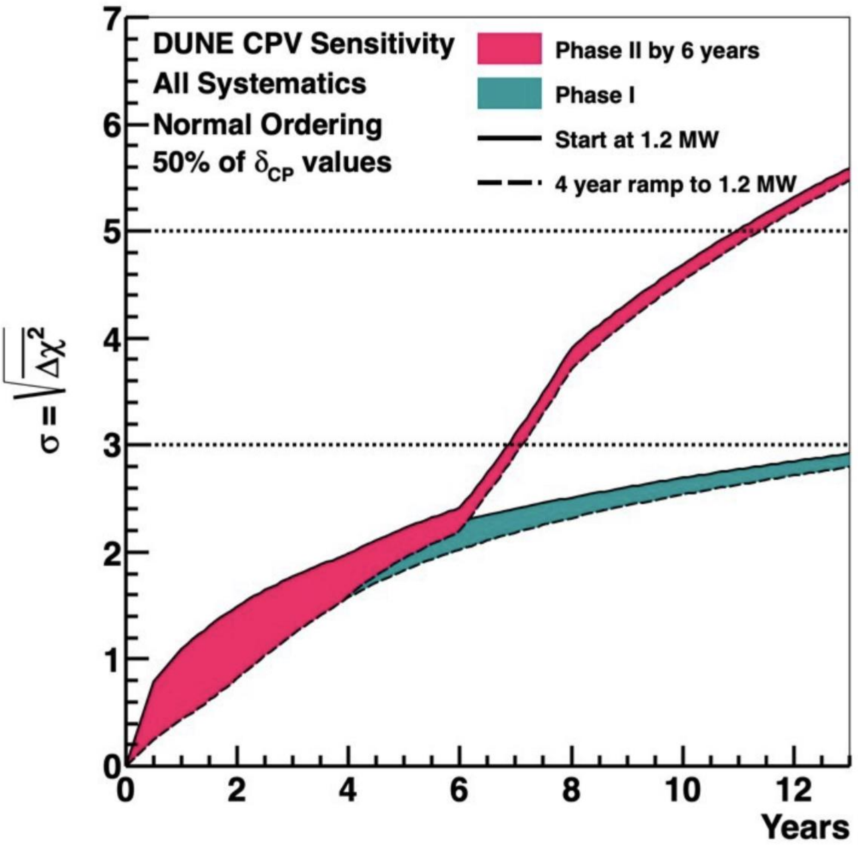
DUNE precision measurements



EPJC 80 (2020) 978

- Expected DUNE resolution vs exposure and **current global fit** (NuFit 5.0: JHEP 09 (2020) 178)
- Ultimate sensitivity approaches reactor θ_{13}
- Constrain δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13} and MO with a single experiment

DUNE Phase II Physics



- DUNE needs full Phase II (FD3&4, 2,4MW, MCND) scope to achieve precision physics goals defined in P5 report.
- CPV sensitivity for 50%of δCP values shown
  - Precision measurements are similarly affected
- Timescale for precision physics is driven by achieving full scope on aggressive timescale, early ramp-up is not as relevant
- Many BSM searches at the Near Detector will benefit from the beam upgrade:
  - Neutrino tridents, Milicharged particles, Heavy neutral leptons, Light dark matter, Anomalous ν_τ appearance etc.