Oscillation physics at DUNE Long Baseline

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on behalf of the DUNE Collaboration

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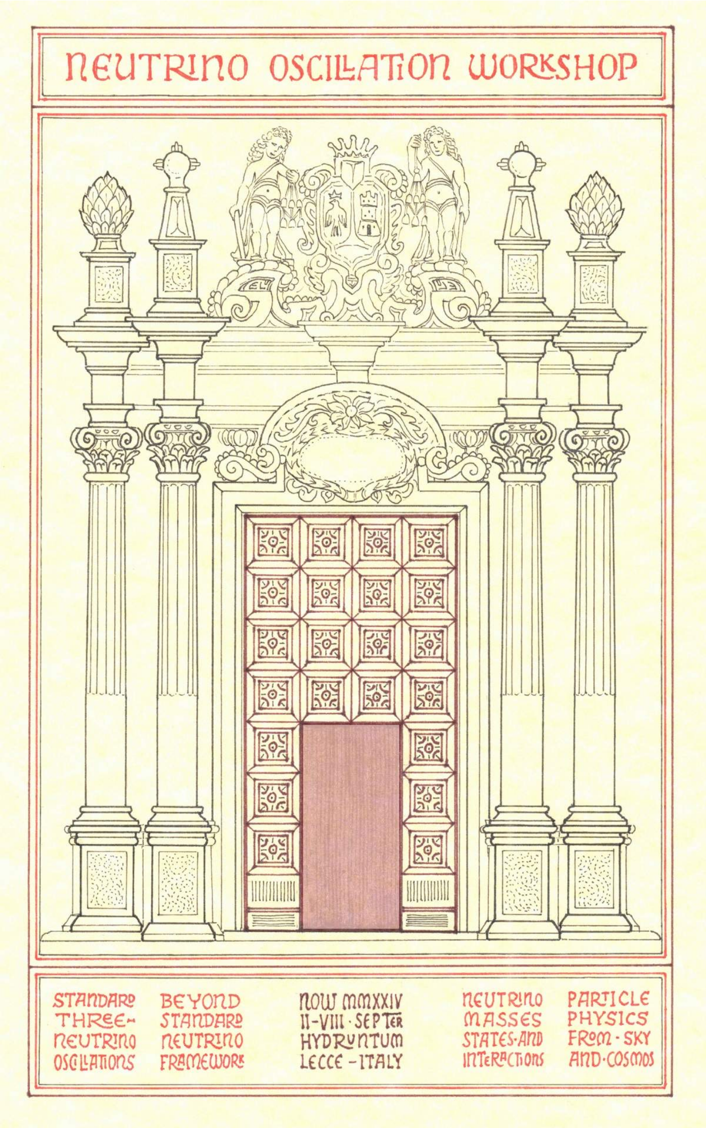


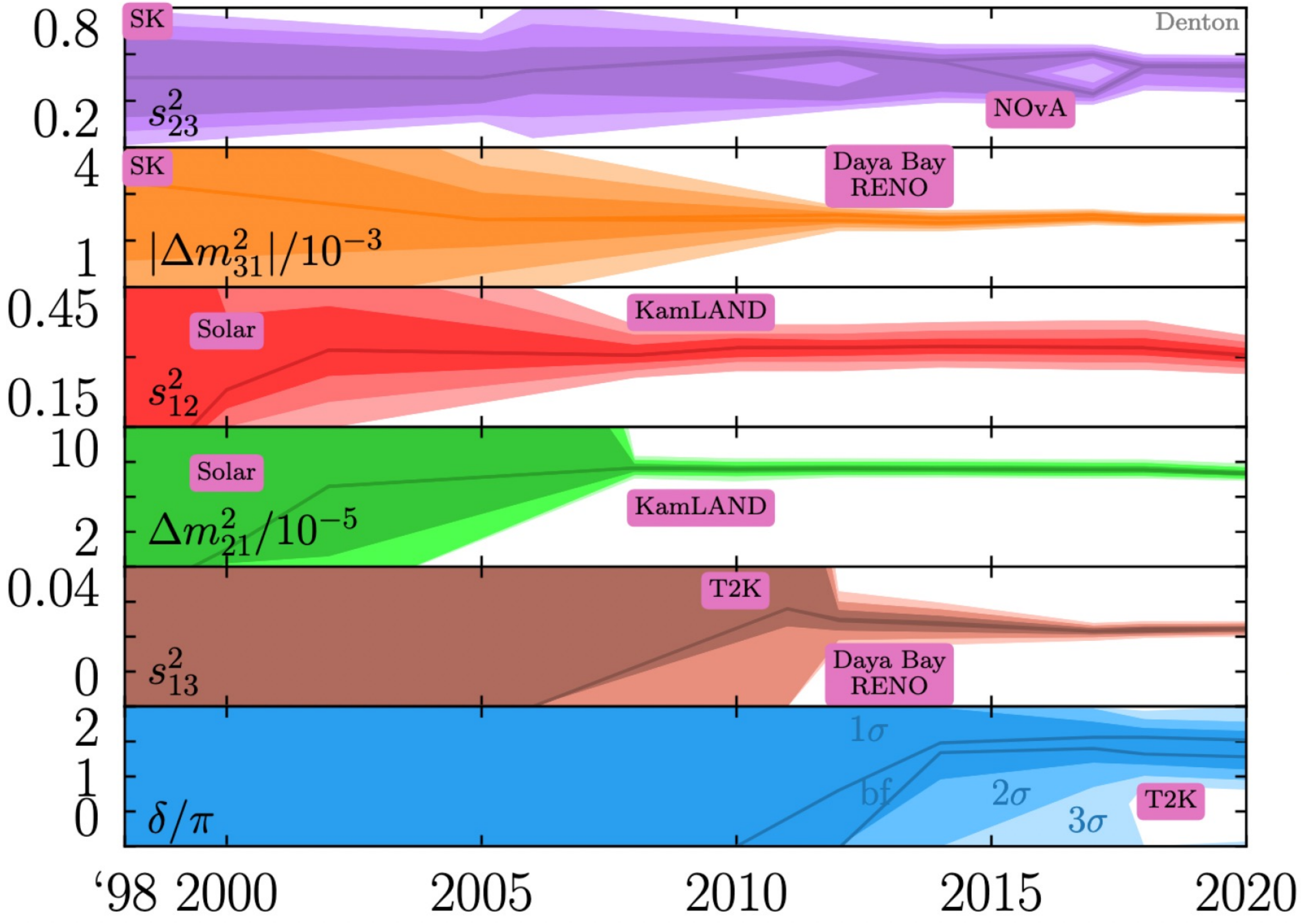
Long-baseline Neutrino Oscillation: what we know

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- The 3 know flavor states ν_e, ν_μ, ν_τ are linear combination of 3 mass eigenstates ν_1, ν_2, ν_3 through the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) unitary matrix U_{PMNS}
- Previous oscillation experiments determined the two mass-squared differences and the three mixing angles

Atmospheric/LBL	Reactor/LBL	Reactor/Solar
$\theta_{23} \sim 45^o$	$\theta_{13} \sim 8.5^o$	$\theta_{12} \sim 33^o$
$\Delta m^2_{32} \sim \pm 2.5 \times 10^{-3} eV^2$	$\delta_{CP}???$	$\Delta m^2_{12} \sim 7.5 \times 10^{-5} eV^2$

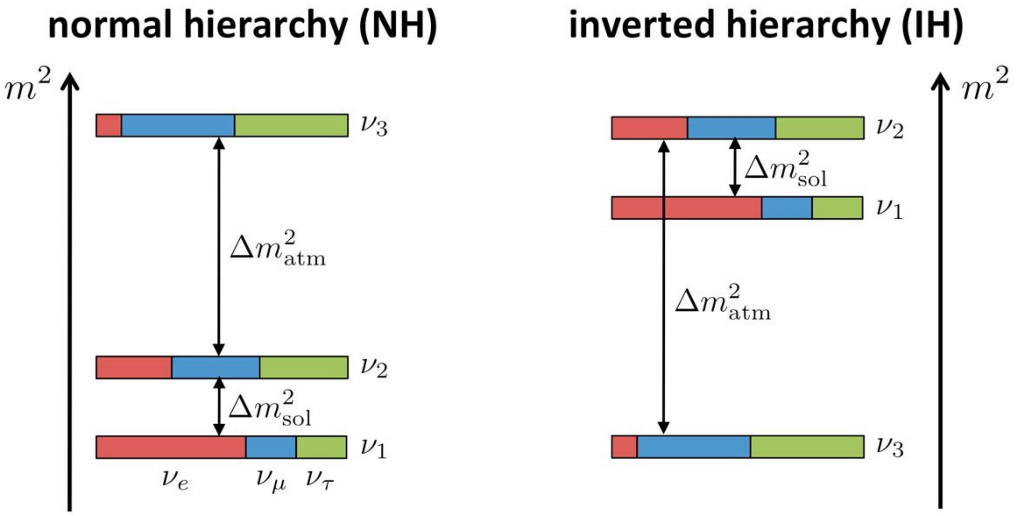
The era of precision for neutrino physics



Remarkable progresses in last 20 years in determining neutrino properties

Long-baseline Neutrino Oscillation: what is still missing?

- **Goal for next generation experiments:**
- Measure CP and determine if δ_{CP} is violated
- Determine the neutrino mass ordering (sign of $\Delta m^2{}_{31}$)
- Determine the octant of θ_{23}
- **Understand if our three-flavor picture of the oscillation is complete**
- Finally we also don't know the absolute neutrino mass or if neutrino is its own anti-particle (not accessible with osc. exp.)



Neutrino Oscillation in the 3-flavor model

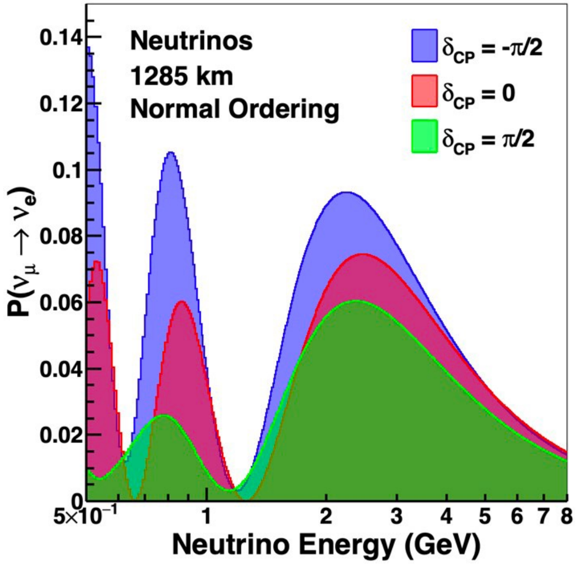
$$P_{\nu_\mu\to\nu_e,(\bar{\nu}_\mu\to\bar{\nu}_e)} \approx 4\,\sin^2\theta_{13}\,\sin^2\theta_{23}\frac{\sin^2\Delta}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\,\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2} + 8\,\alpha\,J_{\mathrm{CP}}^{\max}\cos(\Delta\pm\delta_{\mathrm{CP}})\frac{\sin\Delta A}{A}\,\frac{\sin\Delta(1-A)}{1-A}$$

$$J_{\mathrm{CP}}^{\max} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}$$

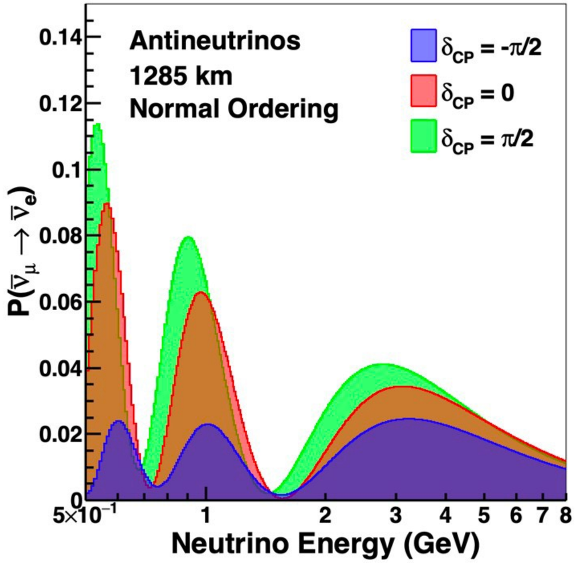
$$\Delta \equiv \frac{\Delta m^2_{31}L}{4E_\nu} \qquad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}} \qquad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \qquad V_C = \sqrt{2}G_F n_e\,.$$

for $\bar{\nu}$
- «minus» sign
- V→ -V

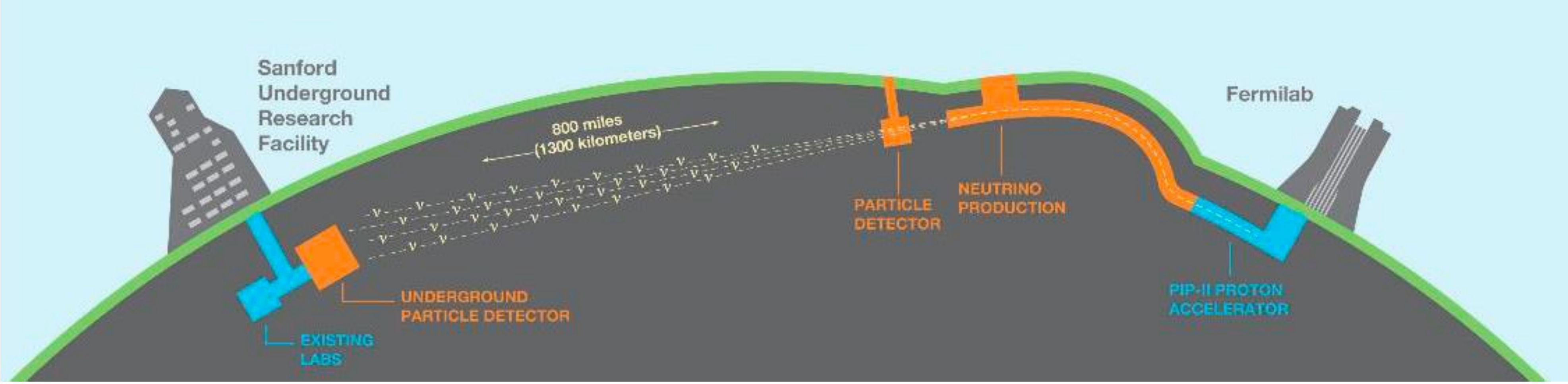
α, Δ , A are sensitive to the sign of Δm^2_{31}



- Measure neutrino and antineutrino oscillation as a function of L/E
- **Very long baseline** → large matter effect
- CPV and mass ordering are totally non-degenerate
- **Broadband neutrino energy** → high statistics over full oscillation period. Spectral information resolves degeneracies between θ_{23}, θ_{13} and δ_{CP}

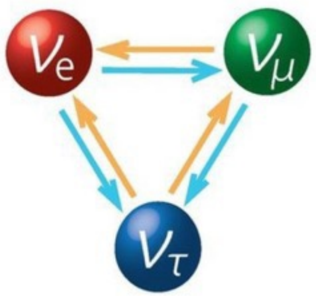


The Deep Underground Neutrino Experiment (DUNE)

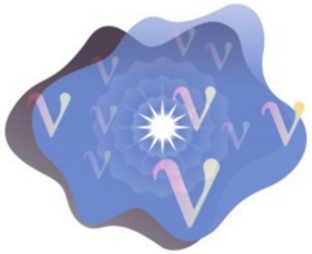


- The **most powerful neutrino beam in the world** (1.2MW upgradable to 2.4 MW) will be sent from **Fermilab** (Chicago) to **SURF** (South Dakota) along 1300 km distance to be detected by four liquid argon **far detector** modules (70 kton LAr) at 1.5 km deep underground and a **near detector** complex at 560 m from the neutrino source
  - **wide-band neutrino energy spectrum** enables detailed fitting of the oscillation parameters
  - **Long-baseline** allows to unambiguous measurement of the neutrino mass ordering
  - **LAr TPC technology** allows for precise reconstruction of the neutrino interactions
  - The **Near Detector complex** allows for a careful control of systematics
  - The **underground location** of the Far Detector modules enables a wide astroparticle measurement program

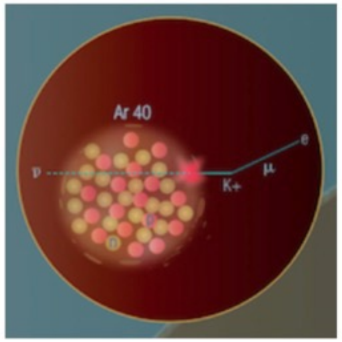
DUNE: a broader physics program



- **Long-baseline wide-band neutrino beam**
  - Measurement of CP violation phase and determination of neutrino mass ordering in a single experiment with spectral information
- **Underground location (1600 m) →Access to astrophysical neutrinos**
  - Supernova neutrino burst detection → sensitive to ν_e component
  - Atmospheric neutrino → capability of ν_τ identification
  - Solar neutrinos → potential detection of hep flux

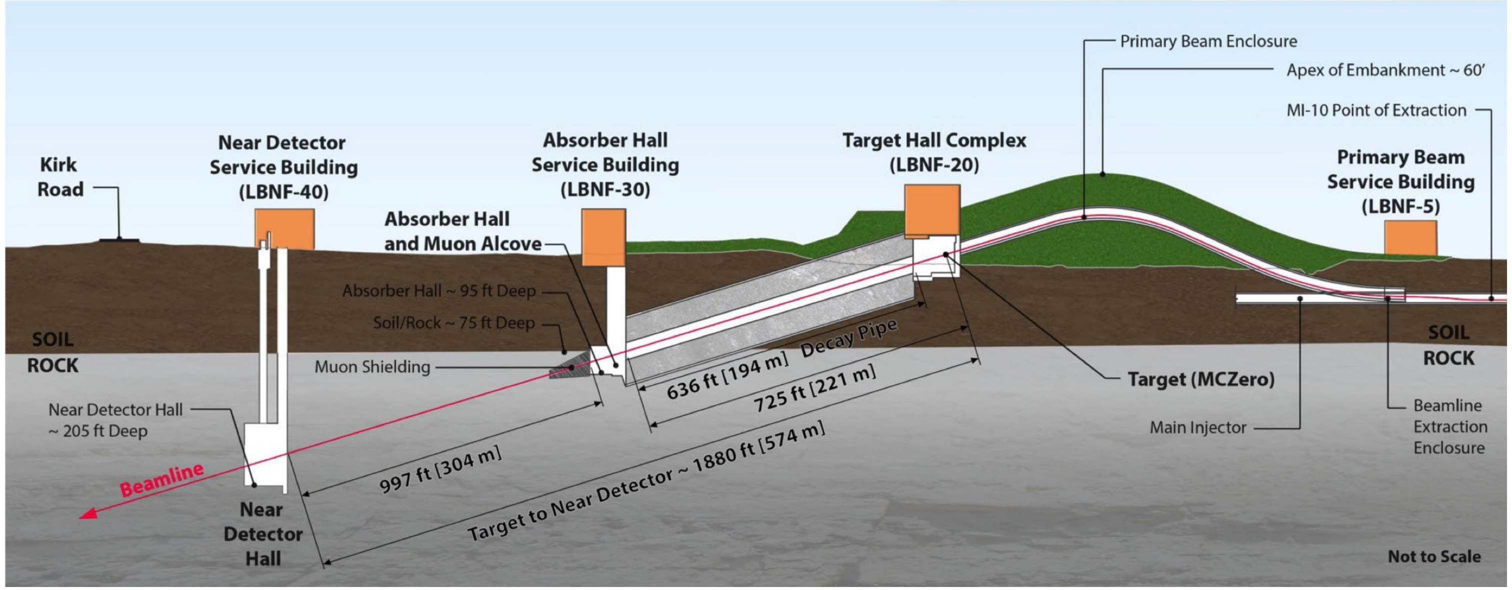


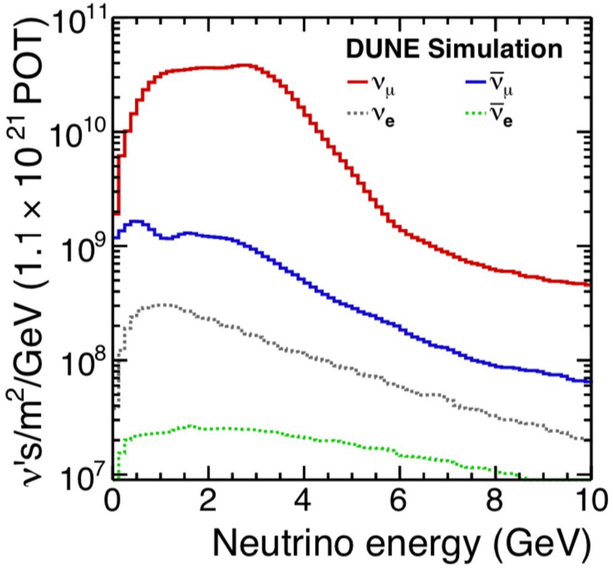
- **Massive detector with excellent tracking and calorimetric information**
  - Search for nucleon decay like the baryon number violating channel $p \to \nu\, k^+$



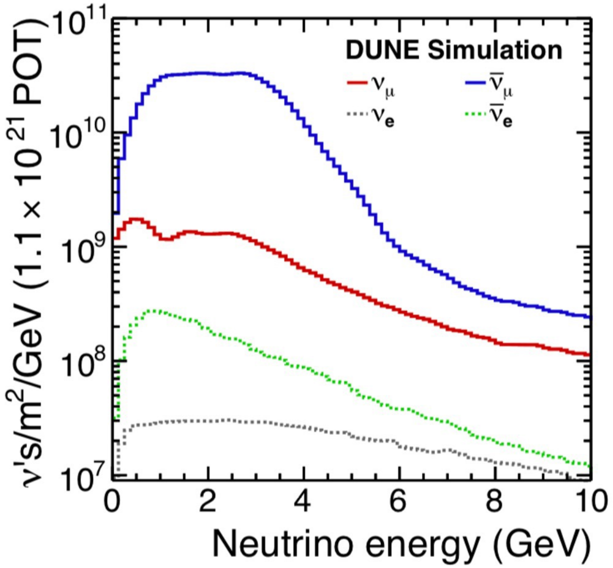
- **Intense beam and capable Near Detector Complex**
  - Precise neutrino physics
  - BSM search

The Long Baseline Neutrino Facility





FHC (ν-mode)

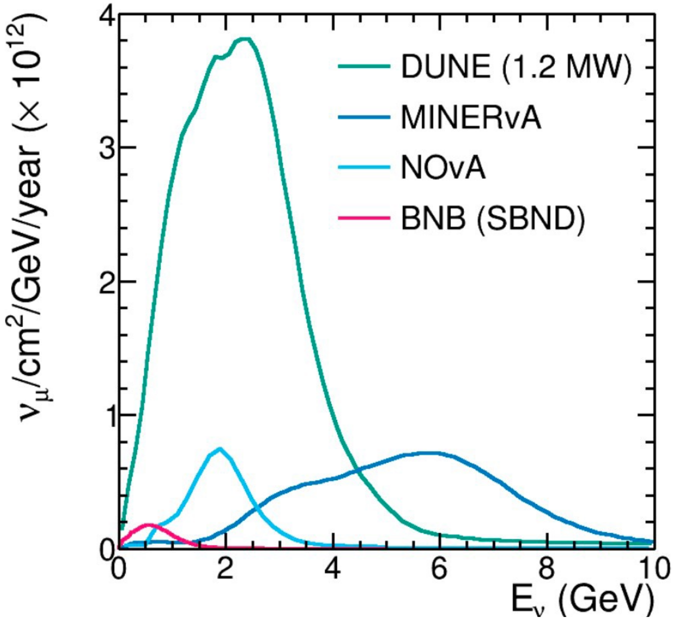


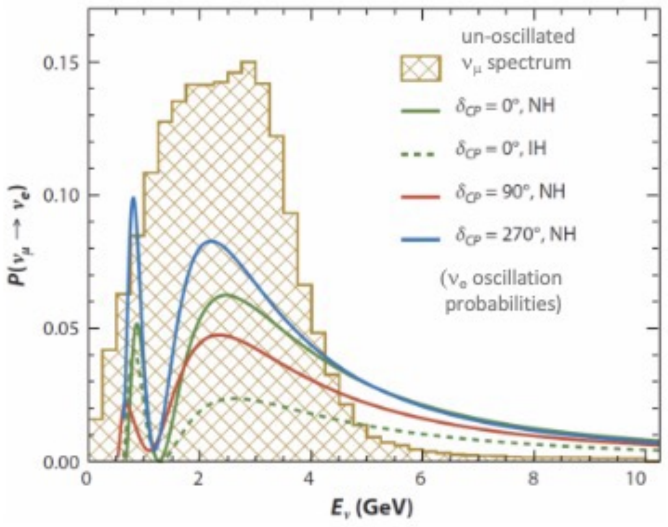
RHC ($\bar{\nu}$-mode)

- High intensity primary proton beam (60-120 GeV) on a graphite target (1.1 – 1.9)x10^{21} pot/yr
- Neutrino beamline at a slope of 5.8°
- Expected neutrino fluxes :
- Forward Horn Current (FHC) neutrino-enhanced
- Reverse Horn Current (RHC) antineutrino-enhanced,
- Wide band beam

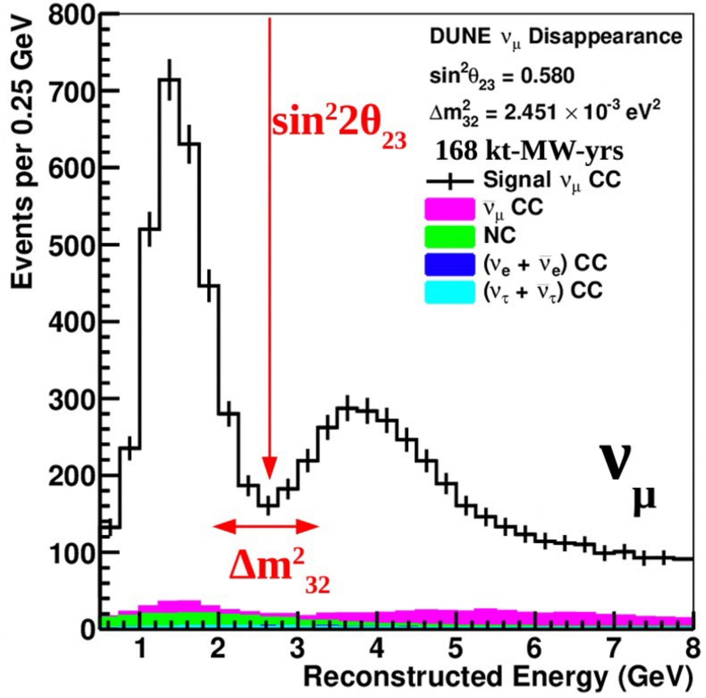
The Long Baseline Neutrino Facility

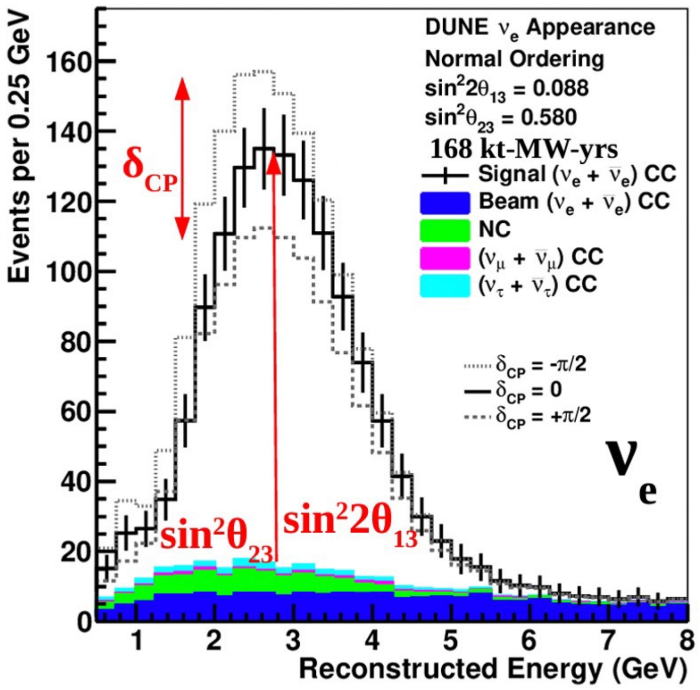
- DUNE neutrino beam is far higher intensity than present-day experiments
- Very high flux covering the full neutrino oscillation curve between the oscillation minimum (1.27 GeV) and the oscillation maximum (2.54 GeV) with coverage of second maximum (0.8 GeV)
- Recent development: Beam upgrade (ACE-MIRT) could increase beam intensity > 2MW by decreasing the time between spills from 1.2 s to 0.6 s, can be achieved before DUNE operations begin.
- More neutrino sooner





A lot of neutrinos

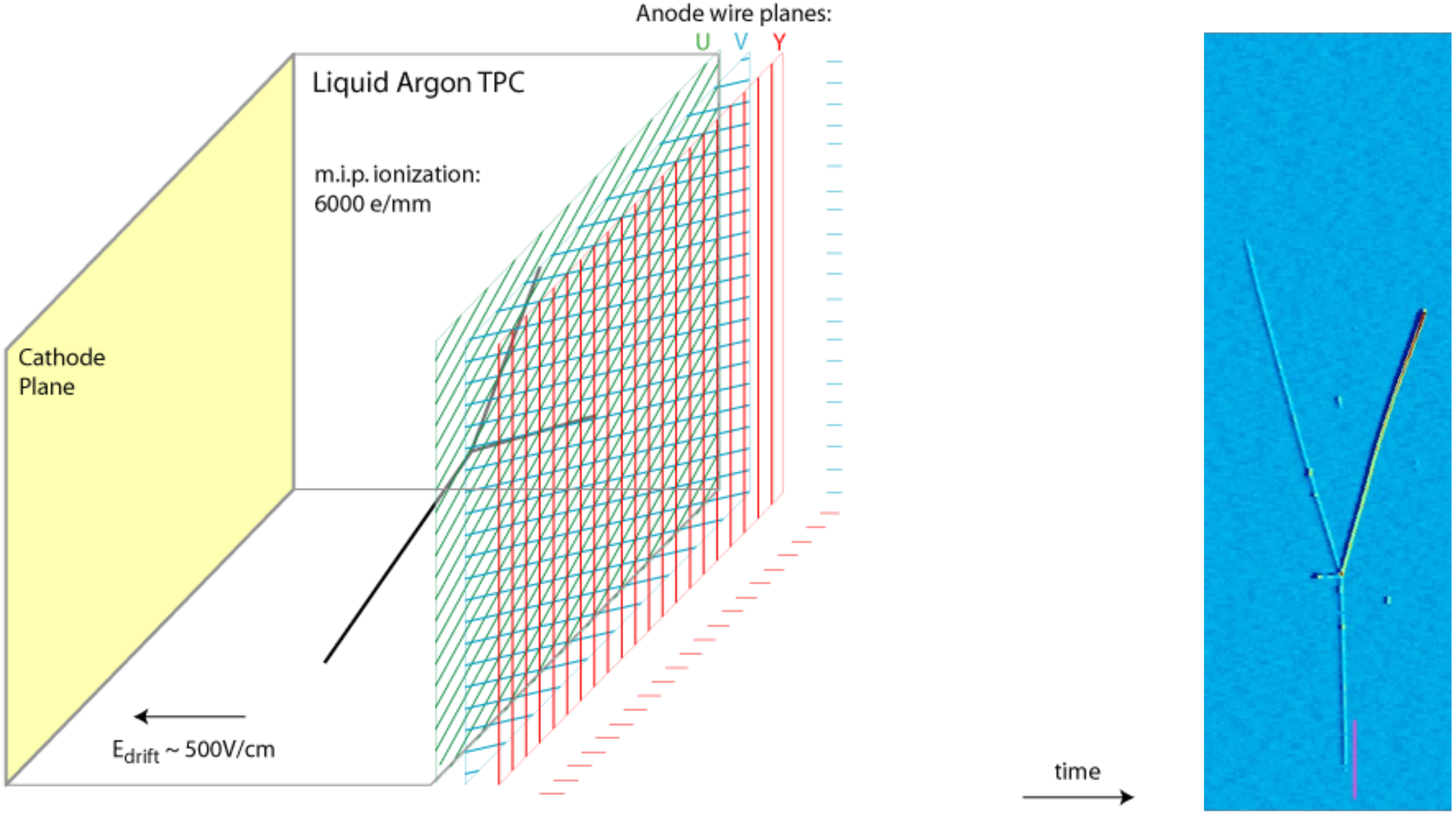




- **ν_μ disappearence: $|\Delta m^2{}_{32}|, \theta_{23}$**
- **ν_e appearance:** octant of θ_{23} , δ_{CP} , mass ordering
- In the first year DUNE will collect 150 oscillated $\boldsymbol{\nu_e}$ events (assuming a beam rump up to 1.2MW, 2FD, Normal Order and δ_{CP} =0)

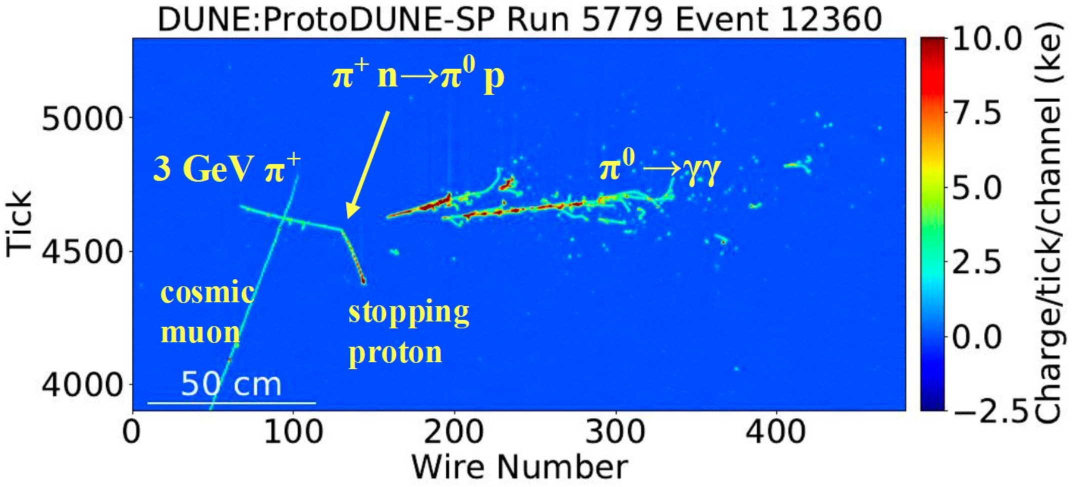
LAr TPC: working principle

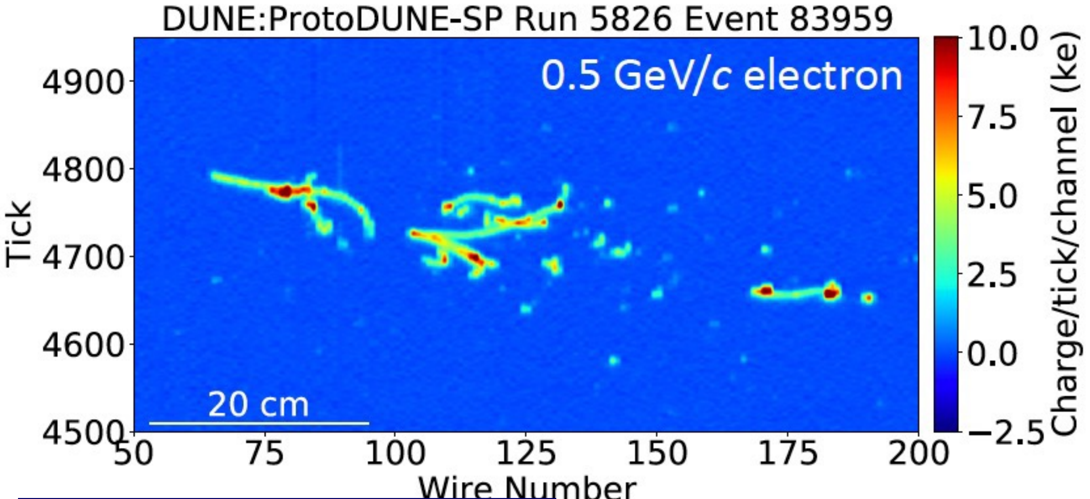
- Detection principle first conceived by C. Rubbia (1977)
- Charged particle from neutrino interaction in LAr produces free **ionization electrons** and **scintillation light** (128 nm)
- Light is quickly detected by photon detection system
- Electrons slowly drift to anode instrumented with readout wires/strip
- Each wire/strip plane provide a 2D (s, t) view of the ionization event. Multiple 2D views results in a 3D image of the event



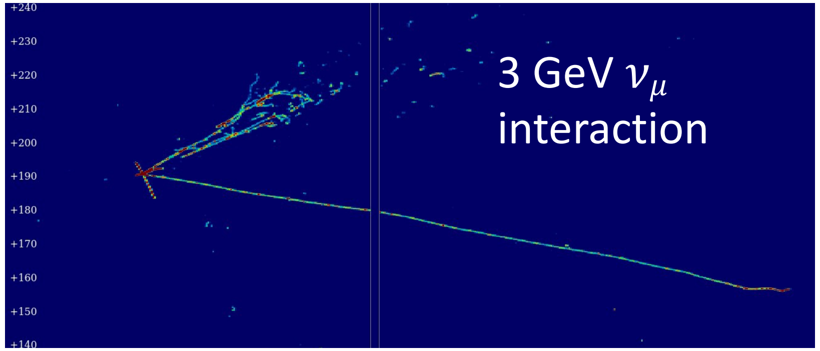
LAr TPC: particle imaging at kTon scale, flavor identification & energy reconstruction

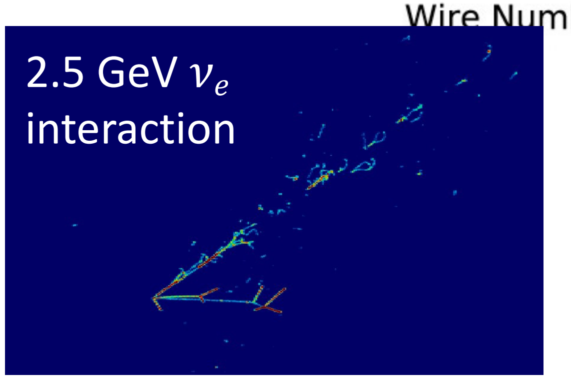
ProtoDUNE data





Simulated neutrino events



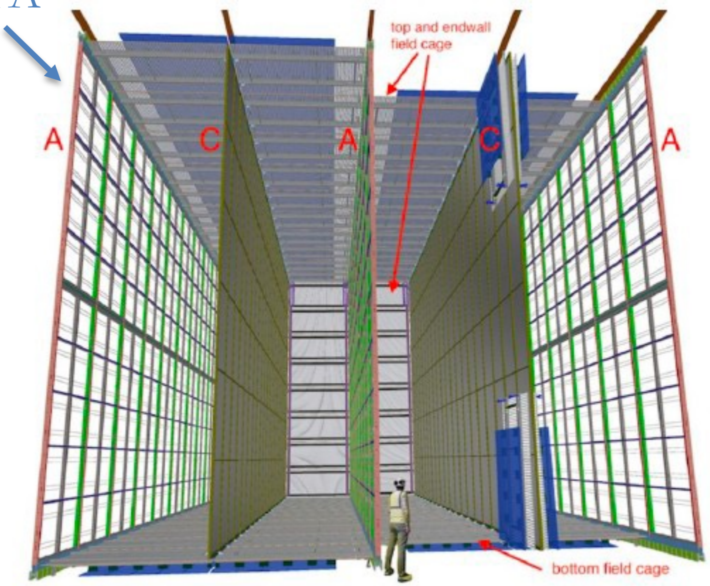


- Good capability of pion reconstruction (in final state for 60% of DUNE interactions)
- Excellent electron/muon separation

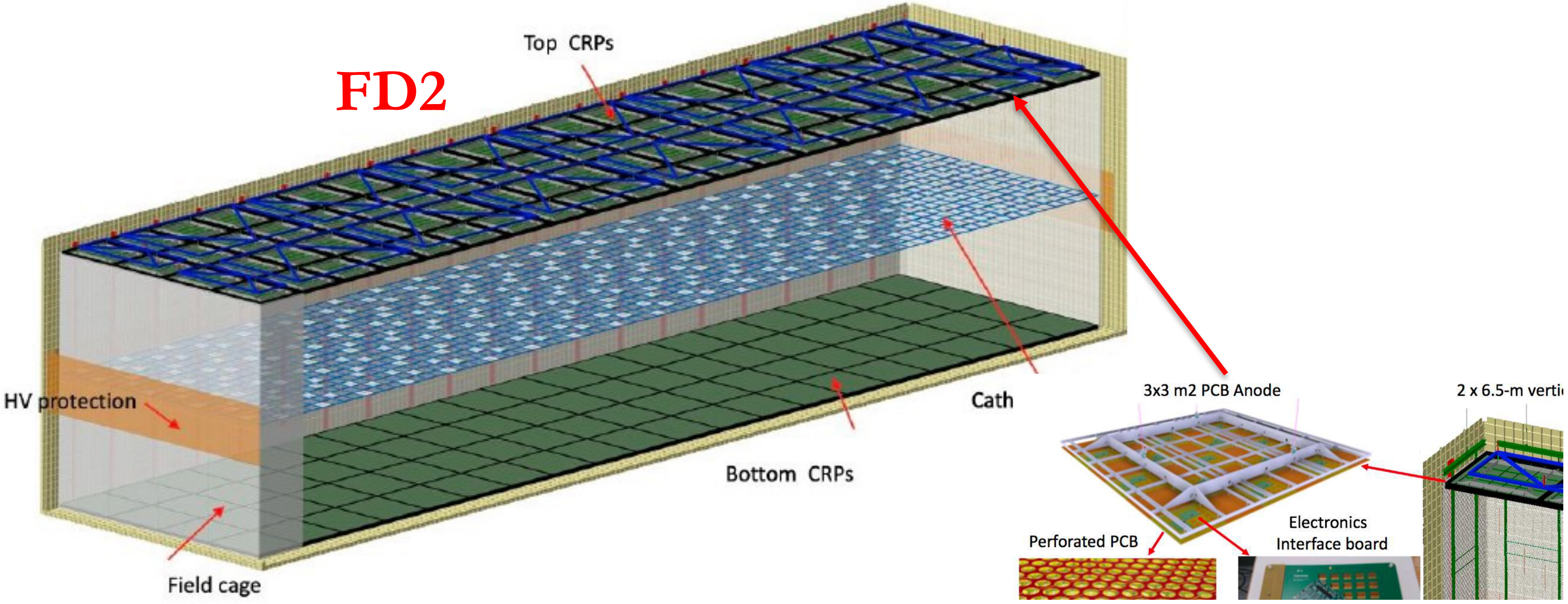
Far detector: two different readout technologies

FD1

APA



FD2

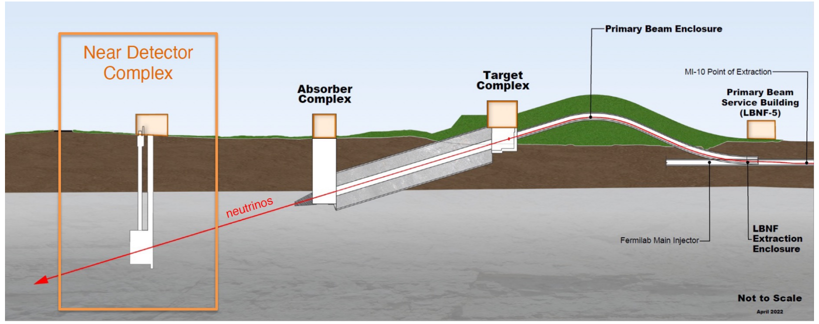


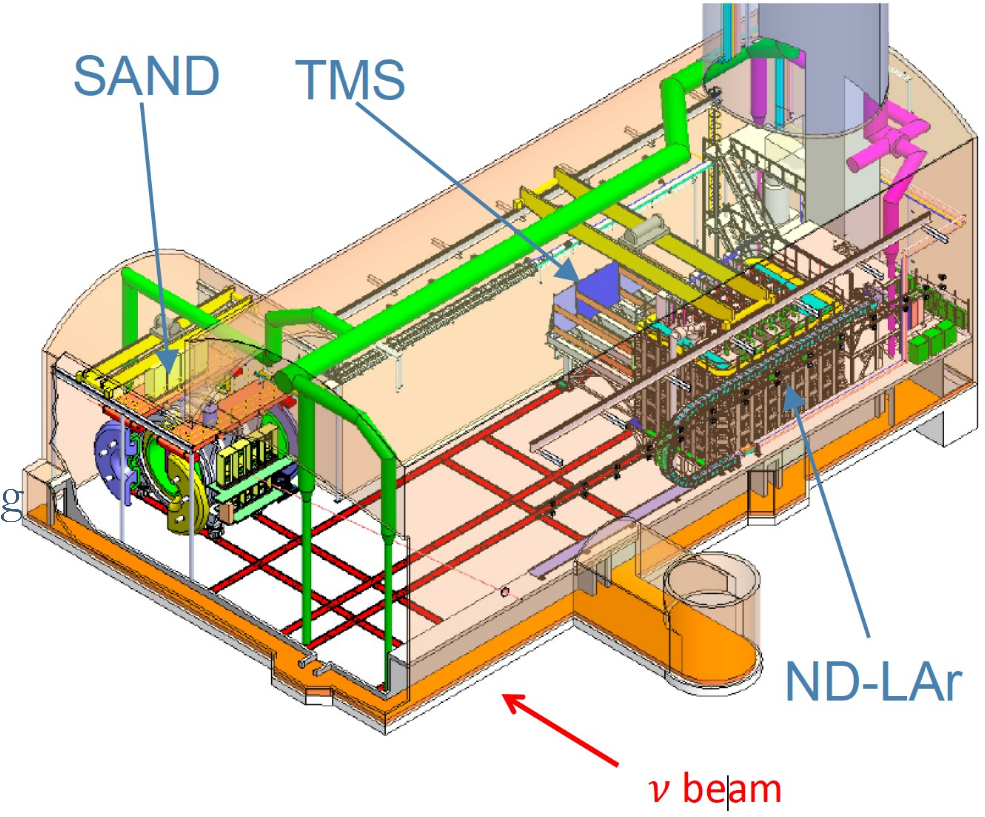
Charge Readout Planes (CRP)

- **FD1 module** will use Horizontal Drift technology: four **3.5 m drift** regions (3.5 m x 12 m x 58 m), charge readout with **348,000** wires in **150** Anode Planes Assembly (APA). Similar to ICARUS, MicrobooNE, SBND. Photon detection: X-Arapuca module (SiPM based light trap), about 300,000 SiPM
- **FD2 module** will use Vertical Drift technology (two volumes 13.5 m x **6.5 m drift** x 60 m), charge readout with strips (**perforated PCB**). Photon detection on the field cage walls and on the cathode@300 kV; decoupling from HV achieved with optical fibers for power and signal transmission. Larger active volume, cheaper than FD1 and similar performances

Near Detector Complex

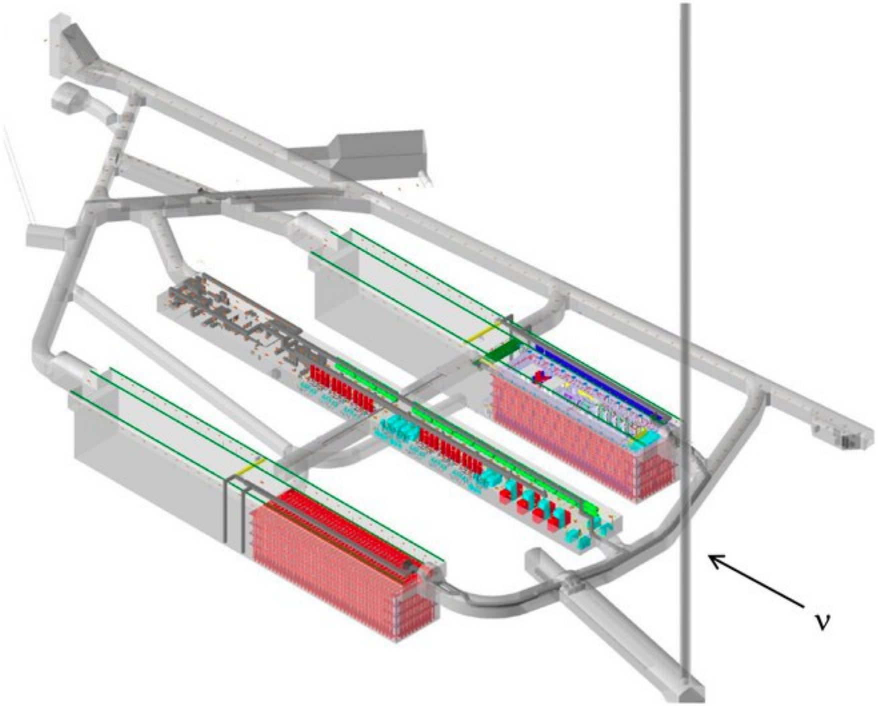
- Main purpose is
  - **to measure the rate and spectrum of ν's before oscillations**
  - **Constraint systematic uncertainties (flux, cross-sections, detector response) for oscillation measurement**
- ND is a (movable) LArTPC (ND-LAr) + muon spectrometer (TMS) and a fixed magnetized tracker+calorimeter (SAND)
- Off-axis data constrains energy dependence of neutrino cross sections
- Same target and same technology to predict reconstructed Eν in Far Detector
- On-axis magnetized detector (SAND) for beam monitoring and neutrino energy measurement: repurposes solenoid magnet and ECAL from KLOE,
- SAND allows fine-grained, particle-by-particle reconstruction with very low rescattering, excellent for highly exclusive neutrino-nucleus measurements





DUNE Construction: Phase I

- 2026 start detector installation
- Full near + far site facility and infrastructure
- Two 17 kt LArTPC modules
- 1.2 MW upgradeable neutrino beamline
- Movable LArTPC ND+muon spectrometer, SAND
- On-axis near detector



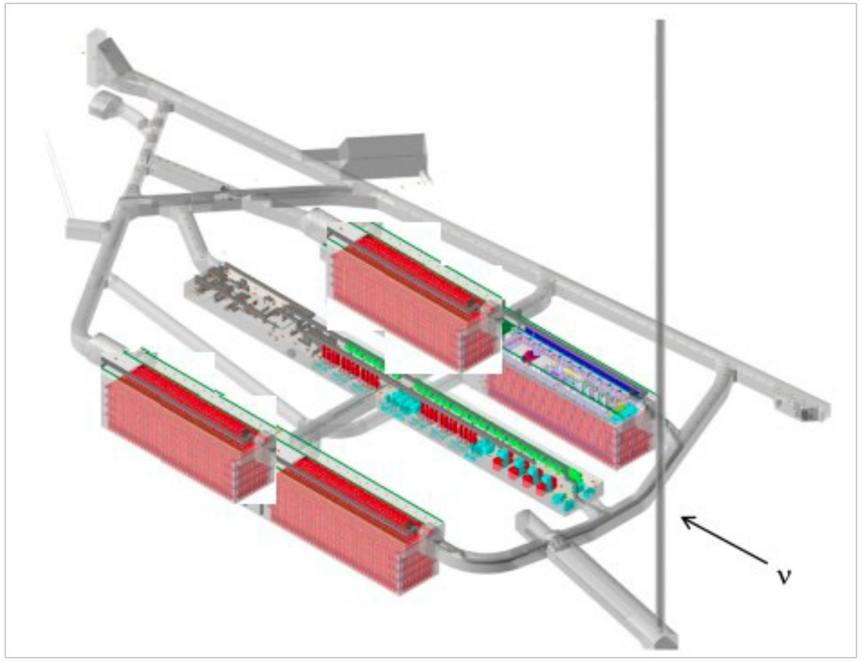
Building DUNE: construction schedule

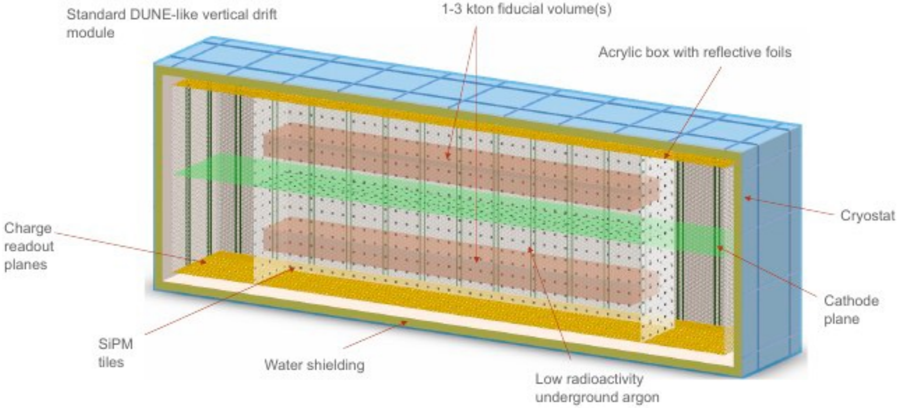
- **Far site excavation is complete**
- Next: Building and Site infrastructure work until mid-2025
- Cryostat warm structure has been shipped from CERN to US, to be installed in 2025-26
- **Detector installation in 2026-27**
- Purge and fill with liquid argon in 2028
- **Physics in early 2029**
- **Beam physics with Near Detector 2031**

Transport to A Coruña harbour: April

DUNE Construction: Phase II

- Two additional Far Detector modules (on overall fiducial ≥40 kt)
- Beamline upgrade to > 2 MW (ACE-MIRT)
- More capable Near Detector (ND-GAr)
- Vertical Drift module is the baseline design for Phase II FD modules
- Several proposal to improve light collection (FD3): Aluminum Profiles with Embedded S-Arapuca (APEX) and PoWER (POlymer Wavelenght shifter ed Enhanched Reflection)
- The phased construction program allows the development of the technology to expand the DUNE physics scope ($0\nu\beta\beta$), dark matter…)
- FD4 is the «Module of Opportunity», more ambitious design are being considered, including pixel readout, integrated charge-light readout, low-background modules and non-LAr technologies





ProtoDUNEs at CERN

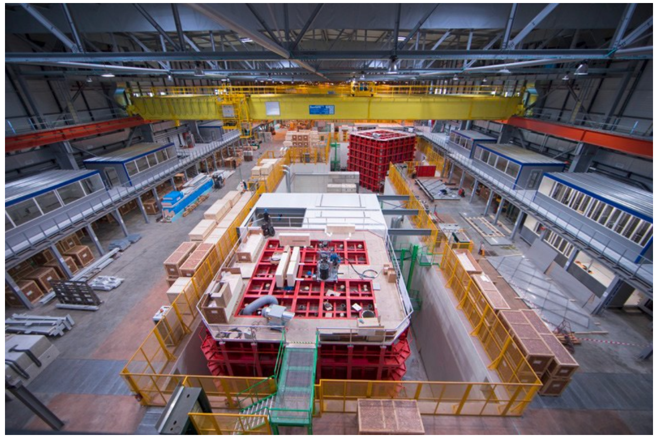
- **First Phase of ProtoDUNEs**
  - Construction and operation of ProtoDUNEs at CERN (2018-2020)
  - Succesfull demonstration of the DUNE LArTPC
  - Several ongoing analysis (hadron-Ar cross section)
- **Second Phase of ProtoDUNEs (2020-2023 construction + operations 2024-2025)**

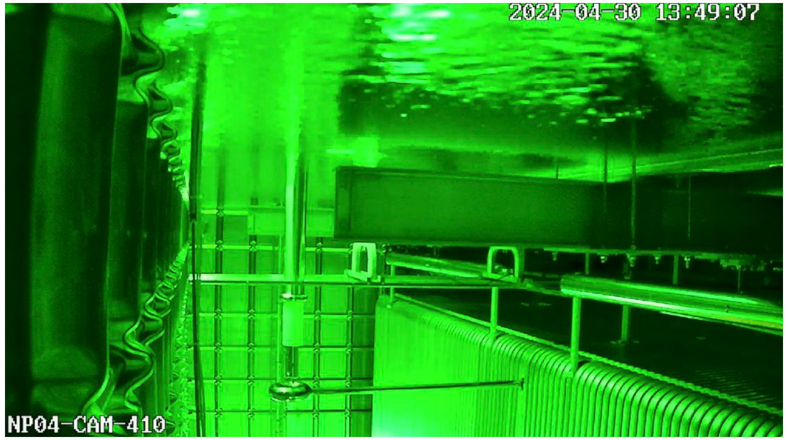
ProtoDUNE Horizontal Drift

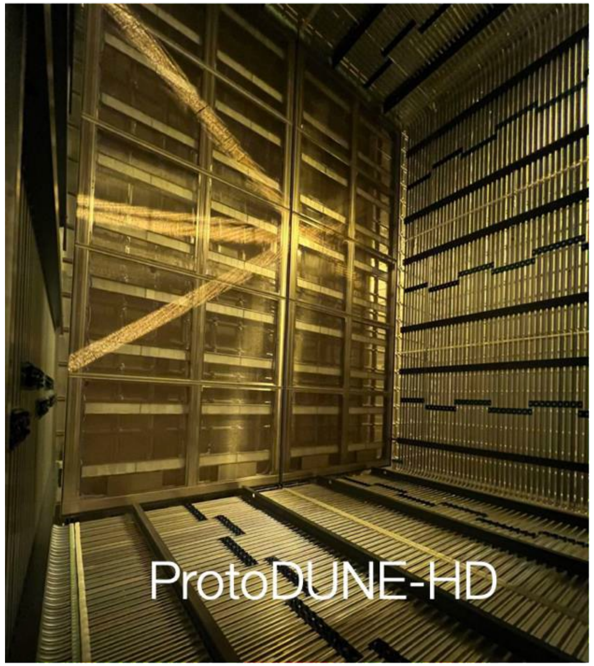
- Final technical solution for all FD-HD subdetectors
- Detector filled and currently taking data with charged-particle beams and cosmic muons

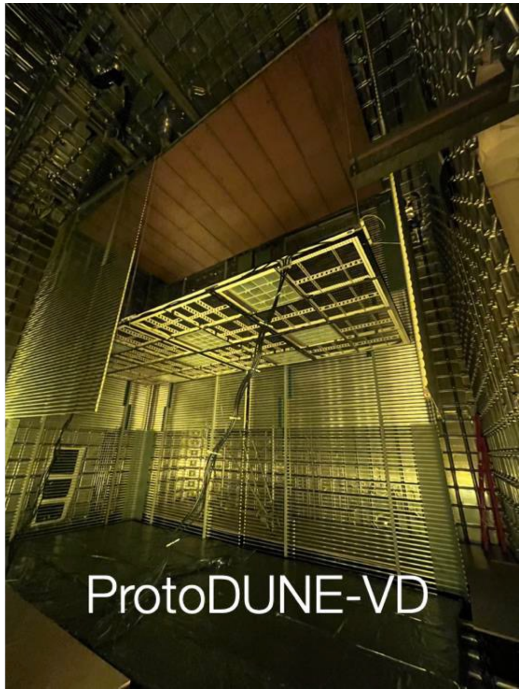
ProtoDUNE-Vertical Drift

- Realization of a Module-0 detector in 2022-2023
- LAr will be transferred to ProtoDUNE-VD in October with operations starting in early 2025



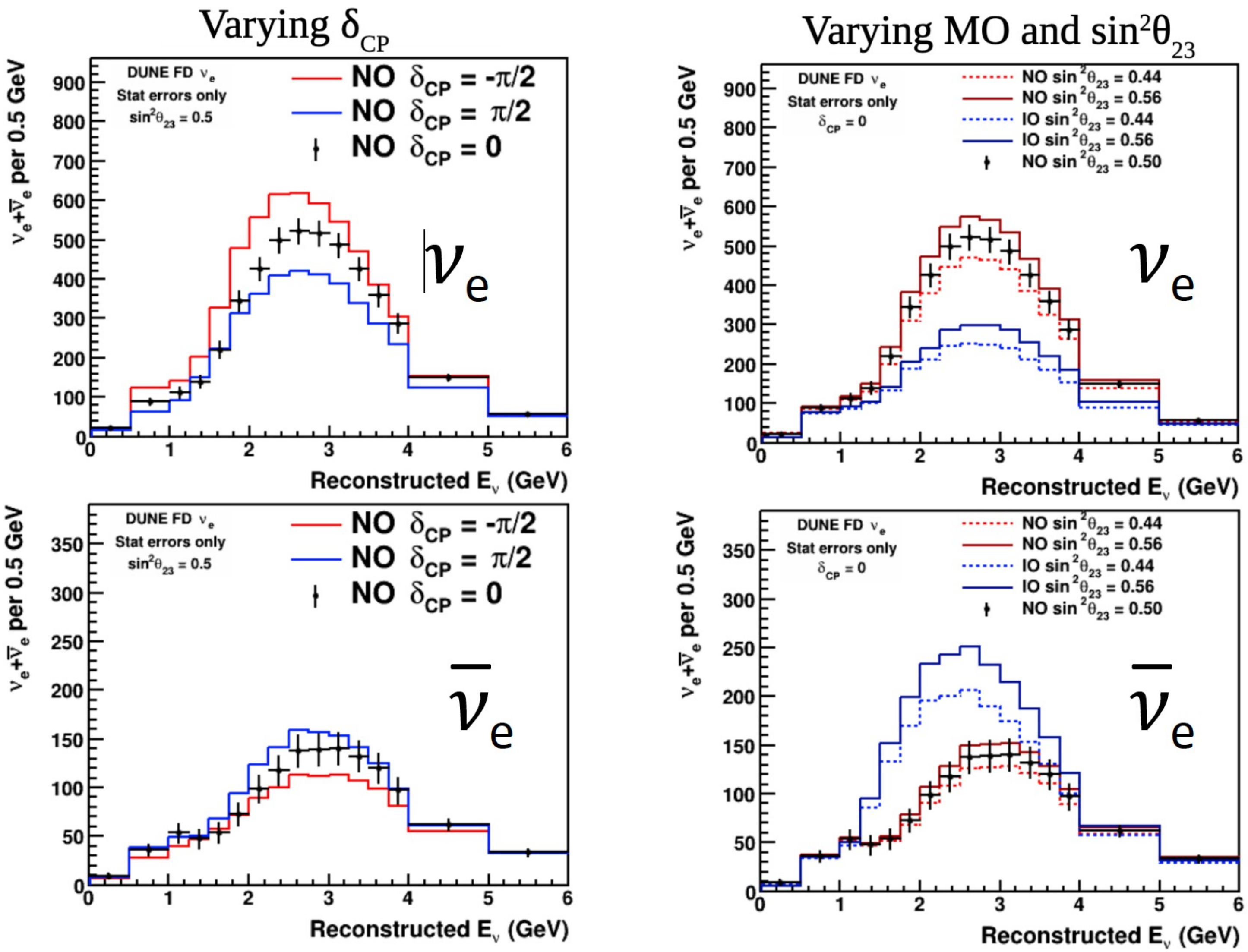






Neutrino energy spectra at Far Detector

- **Sensitivity to δ_{CP}**
  - If $\delta_{CP} \sim -\pi/2$ is DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- **Sensitivity to mass ordering (MO)**
  - If MO is normal, DUNE will measure a **much larger** enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance, with respect to inverted order
- **MO, δ_{CP} and θ_{23}** all affect spectra with different shape, additional handle on resolving degeneracies

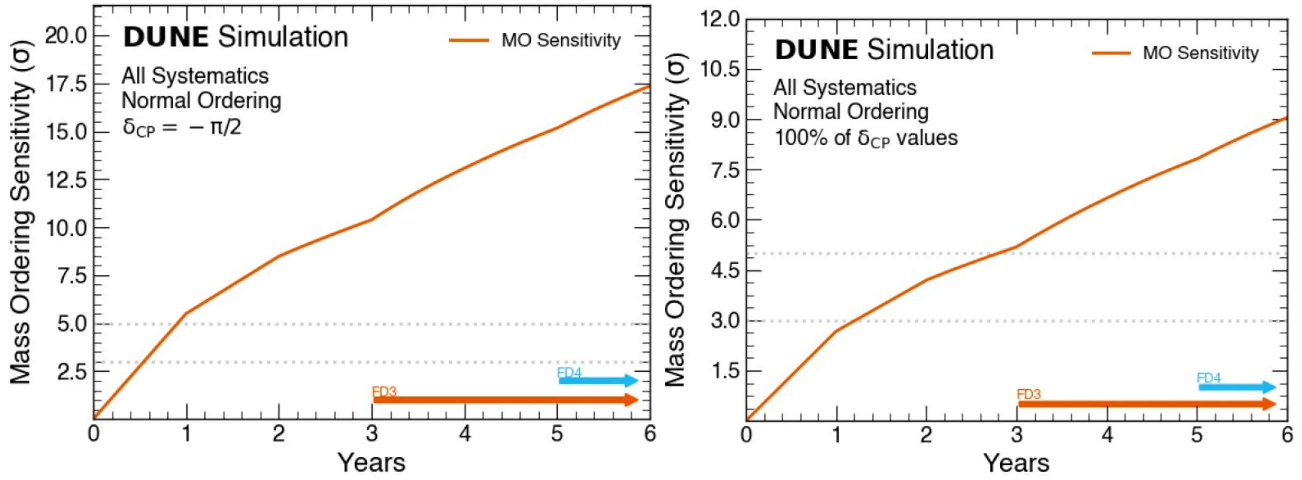


Mass order and CPV DUNE Sensitivity

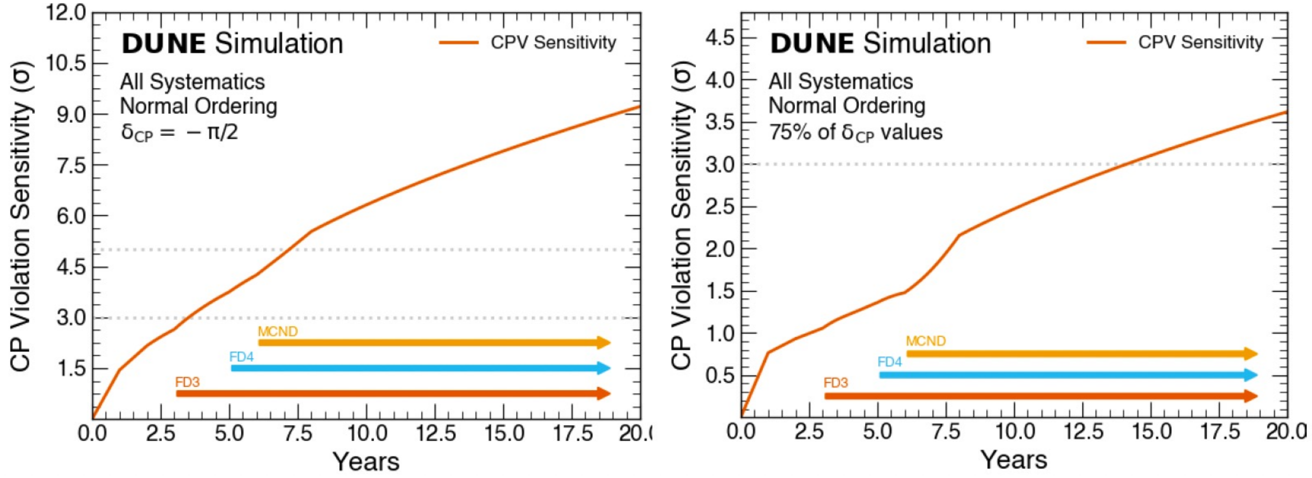
- **For best-case oscillation scenario DUNE will reach**
  - $>5\sigma$ Mass Ordering sensitivity in 1 year
  - $>3\sigma$ CPV sensitivity in 3.5 years
- **For worst-case oscillation scenario**
  - $>5\sigma$ Mass Ordering sensitivity in 3 year (no matter the value of δ_{CP} or any other parameter)
- **In long term** DUNE can establish CP violation at $> 3\sigma$ for 75% possible values of δ_{CP}

Neutrino mass ordering

Eur. Phys. J. C 80, 978 (2020)

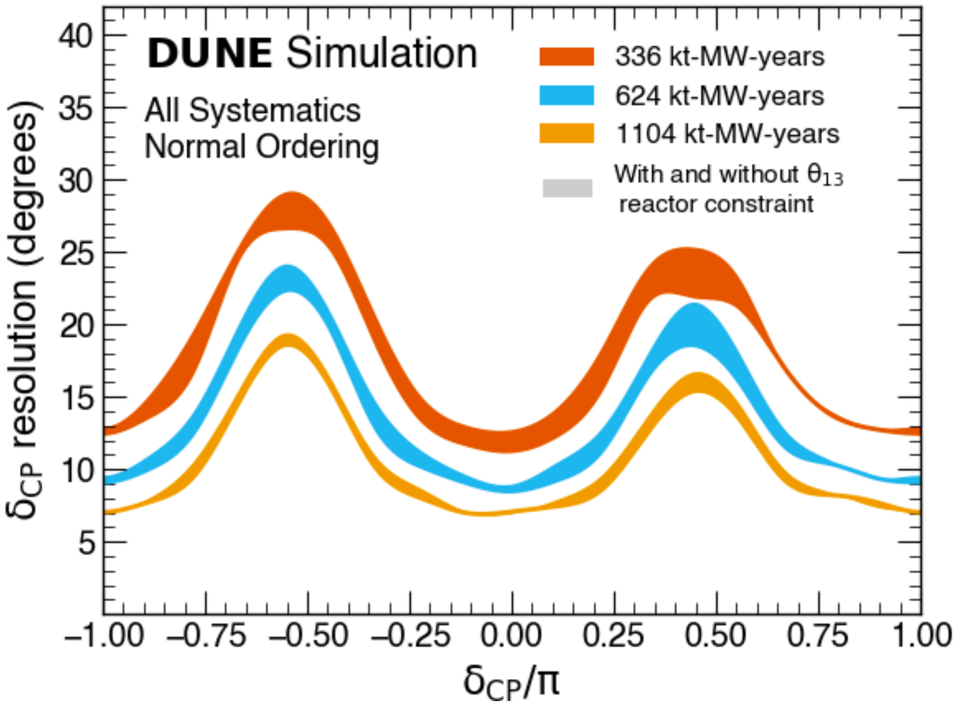


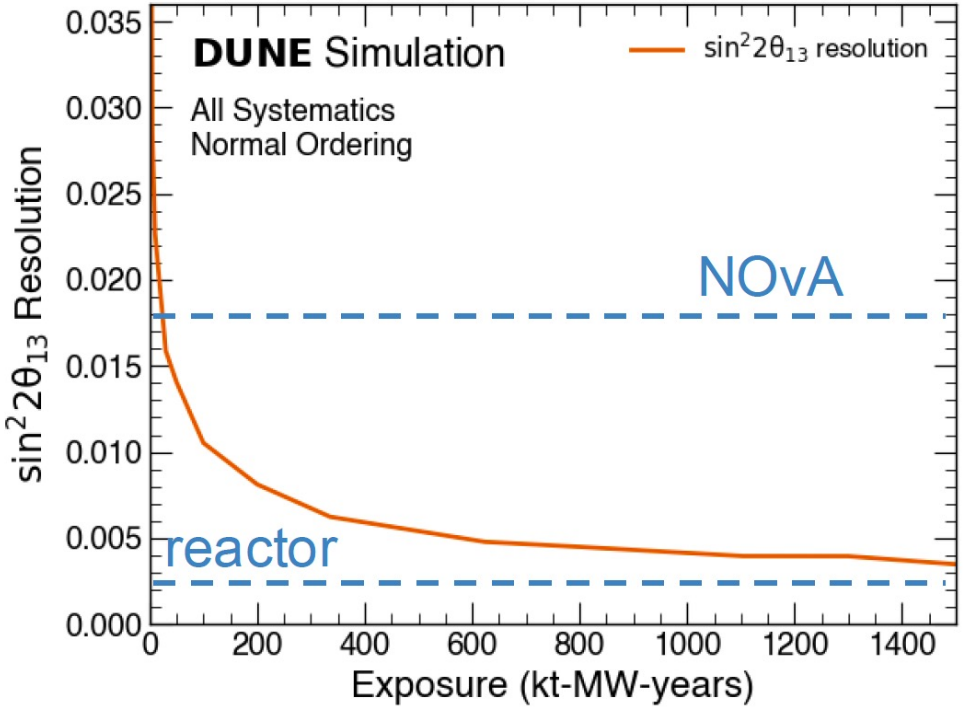
CP violation sensitivity



DUNE precision measurements

- Ultimate precision 6°-16° in δ_{CP}
- World-leading precision (for long baseline experiments) in θ_{13}





Astrophysical neutrinos in DUNE

- **Neutrinos from atmospheric, solar and core collapse supernovae**
  - Argon target gives unique sensitivity to MeV-scale electron neutrinos
    - **Charged Current (CC) interaction on Ar**

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^* \; (E_\nu > 1.5 \text{ MeV})$$

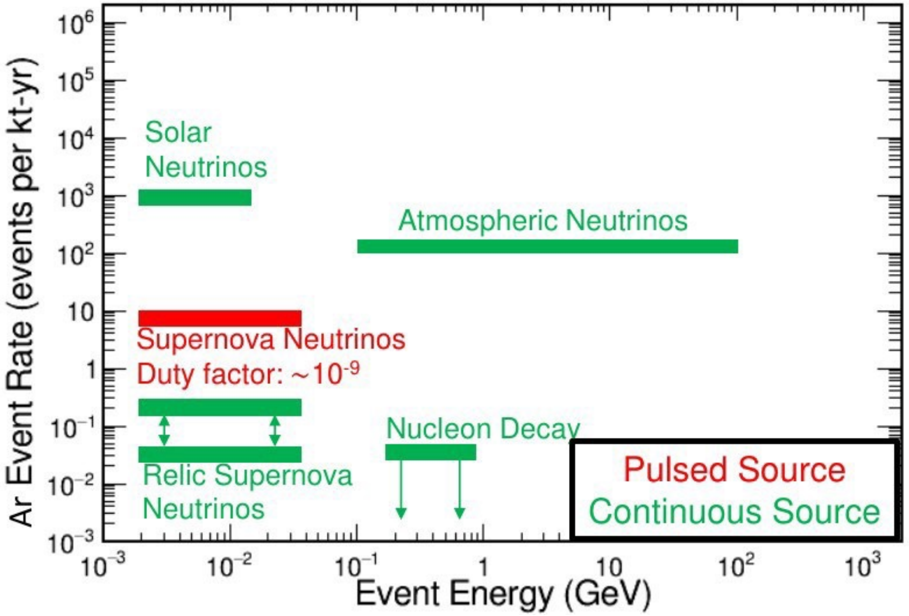
$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^* \; (E_\nu > 7.5 \text{ MeV})$$

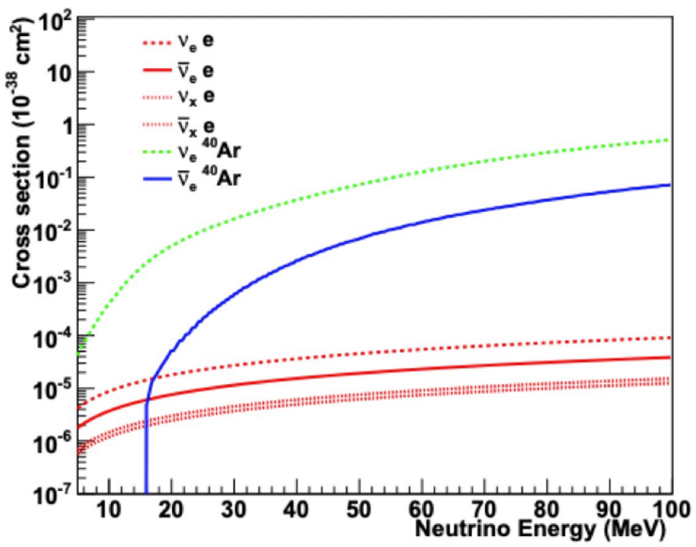
    - **ES on electrons**

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(pointing)}$$

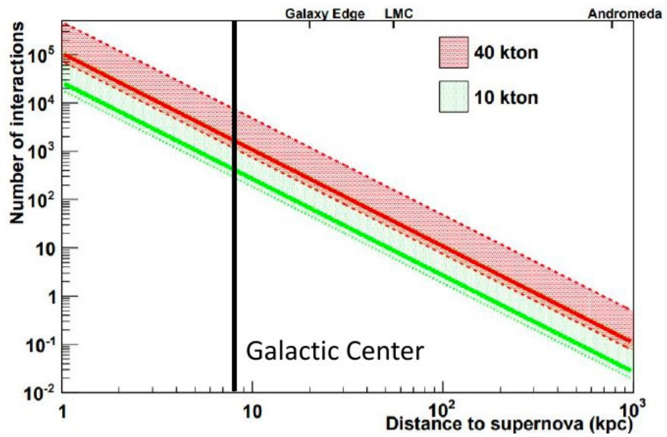
    - **Neutral Current (NC) interaction on Ar**

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

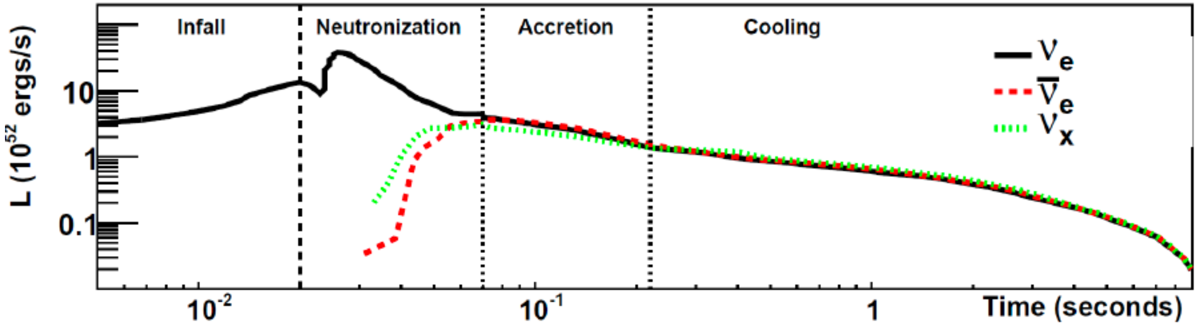


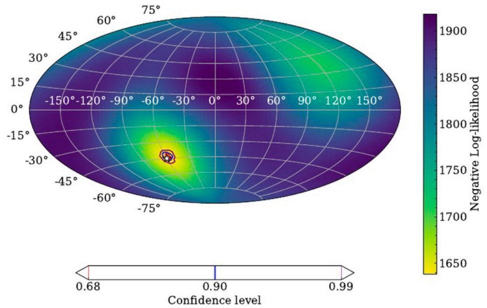


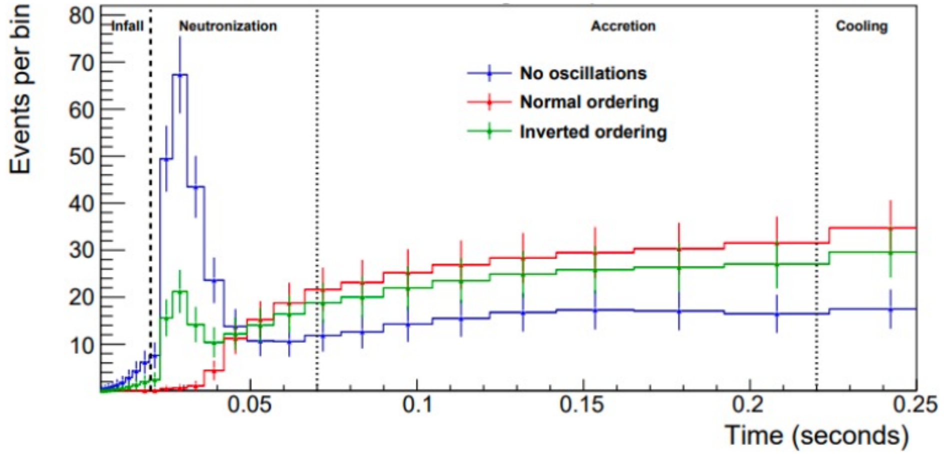
Supernova burst neutrinos



- **DUNE will observe thousand of neutrino interactions from a galactic supernova burst**
- **Time and energy spectra are sensitive to core collapse mechanism and stellar evolution**
  - Neutronization through electron capture (depending from oscillation and MO)
  - Matter falling into core during accretion
  - Emission cools as neutrinos diffuse
- **Pointing capabilities: ES channel, about 5° resolution**



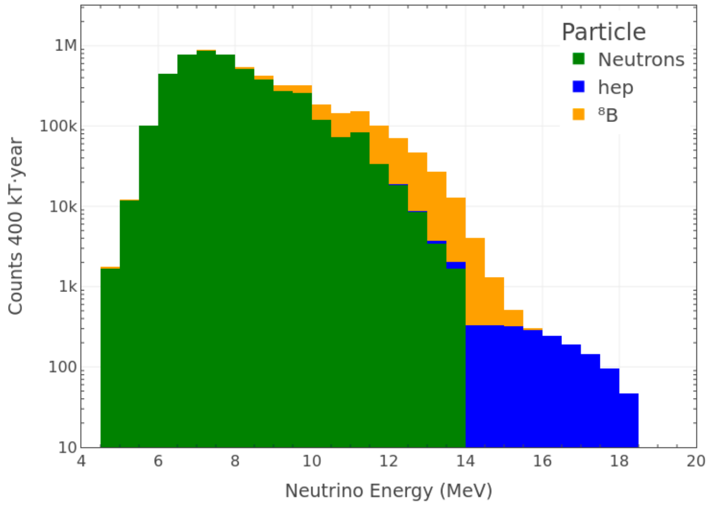


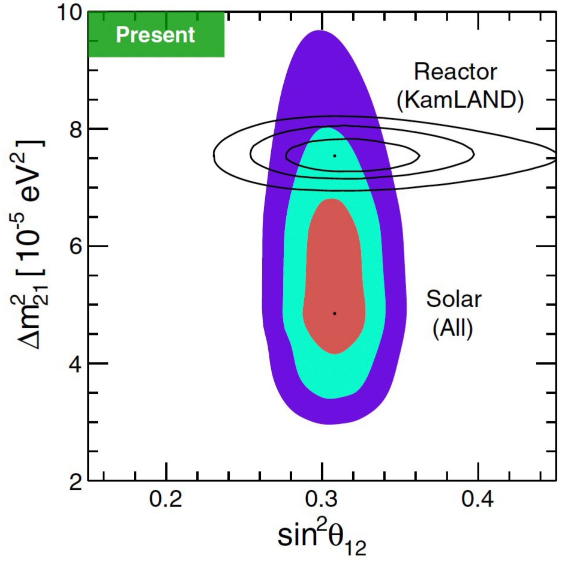


DUNE sensitivity to solar neutrinos

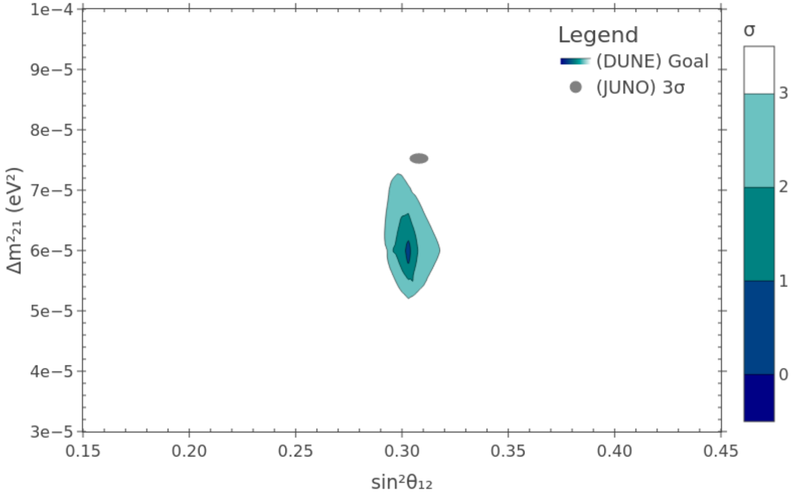
- Neutrinos from the Sun
  - DUNE has excellent sensitivity to **^{8}B solar neutrinos** above ~10 MeV, and discovery sensitivity to the **hep solar flux**
  - DUNE can improve upon existing solar oscillation measurement via **day-night asimmetry** induced by matter effect (bottom plot shows hypothetical DUNE result at old best fit point)

Reco solar ν_e spectrum in DUNE



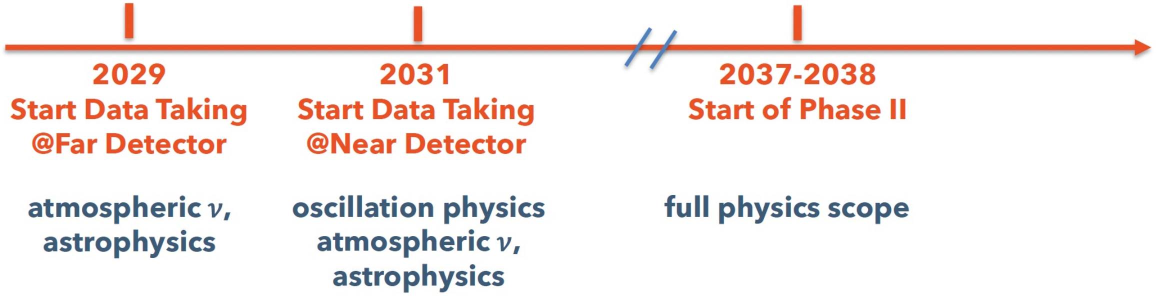


DUNE goal contours for solar best-fit



Summary

- **DUNE is a next generation long-baseline oscillation experiments and astrophysics neutrino observatory**
- Very reach program in the next decade (20 years Lifetime)
  - Neutrino and anti-neutrino Oscillations with CPV investigation
  - Studies of MeV-scale neutrinos
  - BSM searches
- **LNBF and DUNE making rapid progress on facility construction, with excavation complete and components under construction**
- **DUNE science begins in this decade**



2029
Start Data Taking
@Far Detector

atmospheric ν,
astrophysics

2031
Start Data Taking
@Near Detector

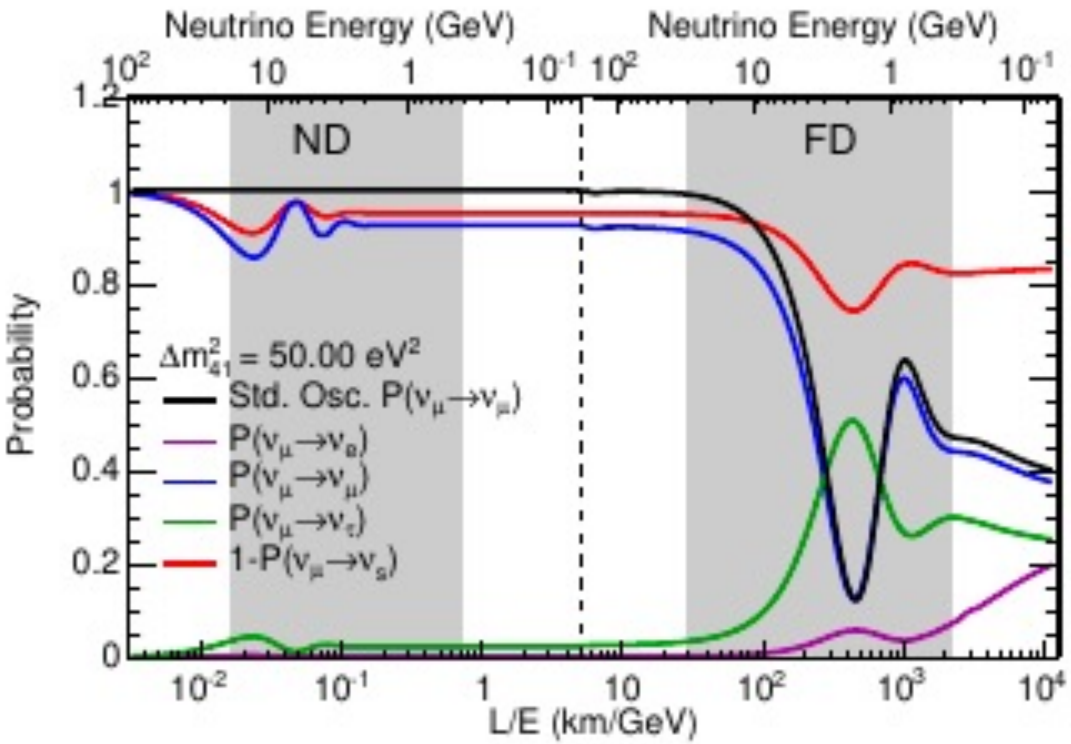
oscillation physics
atmospheric ν,
astrophysics

2037-2038
Start of Phase II

full physics scope

Backup Slides

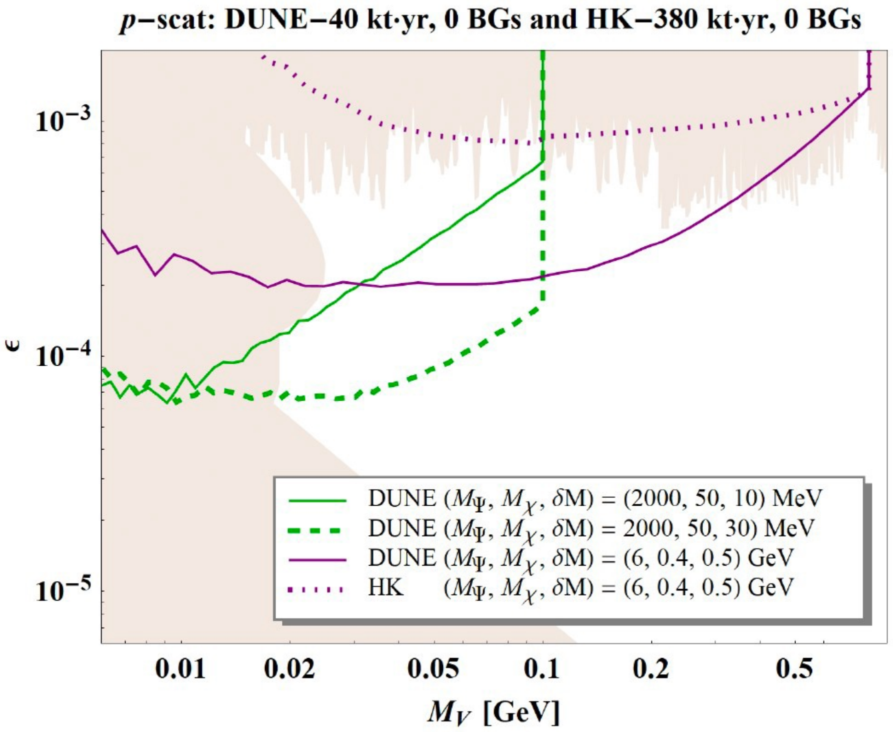
Beyond three-flavor ν Oscillation



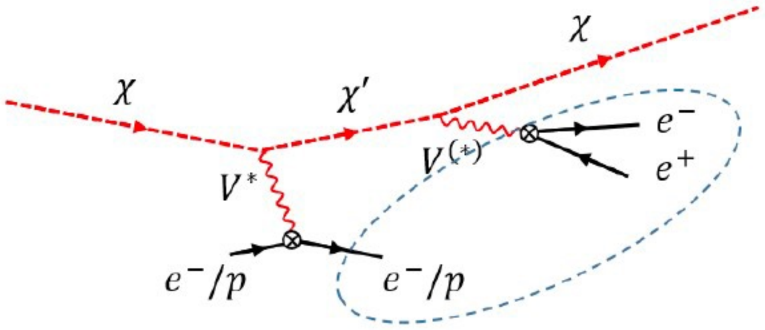
Active-sterile mixing would distort standard oscillation probabilities

- DUNE will be sensitive to this effect through both the Near and Far detectors
- Wide-band LBNF beam enables probes over large regions of parameter space
- Plot shows distortion of standard oscillation probabilities for L/E or ν energies at ND and FD

BSM searches with the Far detector



- DUNE due to large mass and long exposure time is sensitive to rare processes (proton decay, n-nbar oscillation) and new physics of cosmogenic origin
- Boosted Dark Matter produce low energy soft e/p and spatially proximate e+e- pair



See talk from Nikolina Ilic
DUNE sensitivity to BSM searches