The DUNE message to Snowmass

Chris Marshall, University of Rochester
for the DUNE international collaboration

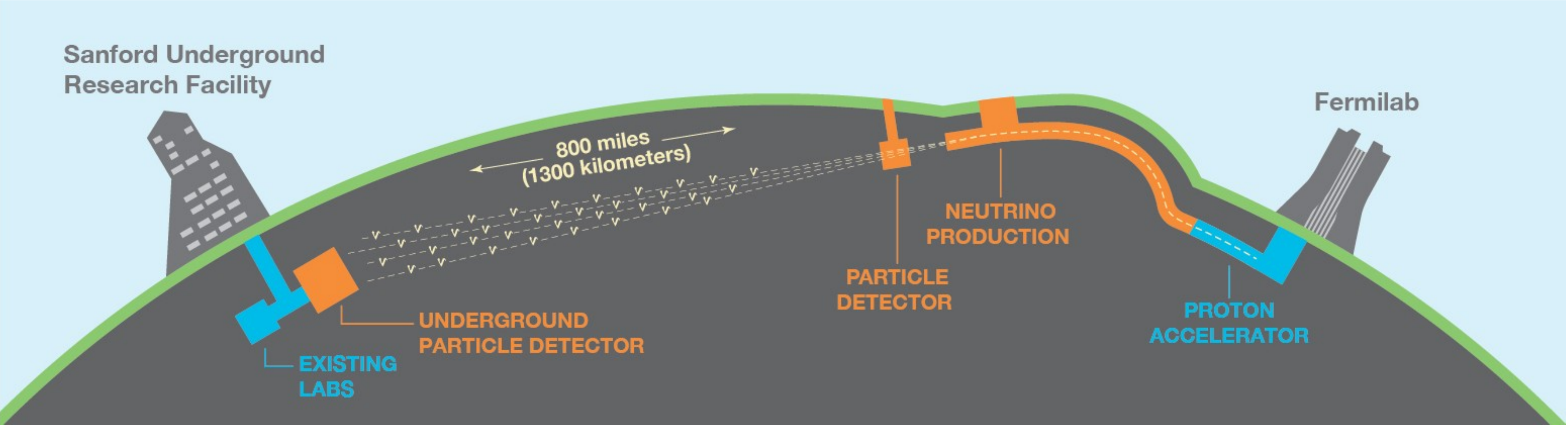
Snowmass Summer Study, Seattle
18 July, 2022

UNIVERSITY of ROCHESTER

Tomorrow: DUNE physics in detail

- Two sessions tomorrow morning are dedicated to the DUNE physics program
- 8am: Neutrino oscillation physics
  - Neutrino oscillations in DUNE (Callum Wilkinson)
  - Neutrino interactions uncertainties (Kevin McFarland)
  - The DUNE Near Detector (Dan Cherdack)
- 10am: Low-energy and BSM physics
  - MeV-scale neutrino physics in DUNE (Dan Pershey)
  - Beyond 3-flavor oscillations in DUNE (Alex Sousa)
  - Direct BSM searches (Jae Yu)

DEEP UNDERGROUND NEUTRINO EXPERIMENT



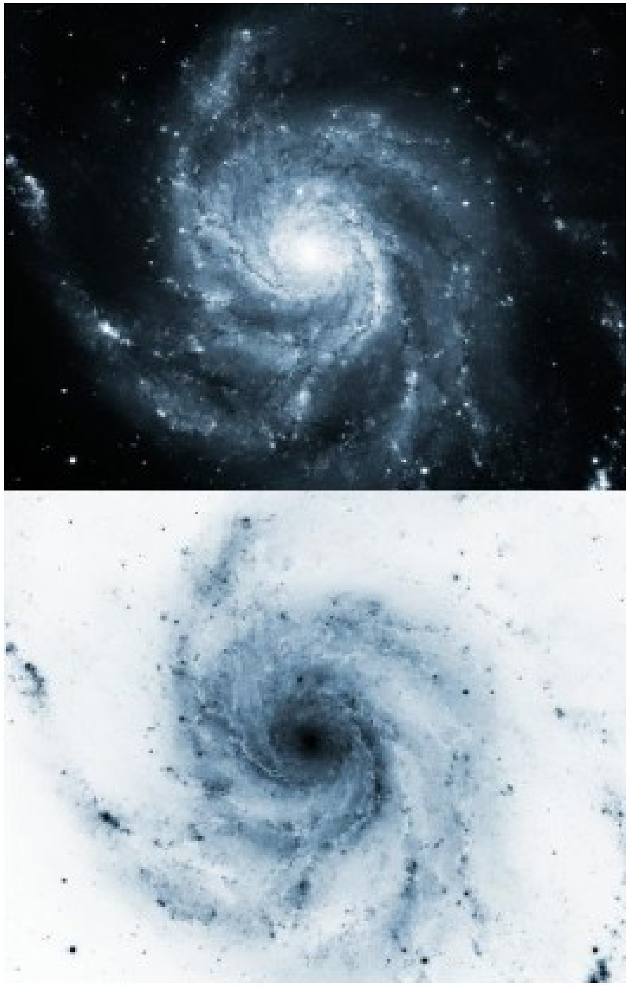
- High intensity neutrino beam, near detector complex at Fermilab
- Large, deep underground LArTPC far detectors at SURF
- Precision neutrino oscillation measurements, MeV-scale neutrino physics, broad program of physics searches beyond the Standard Model

This talk

- Motivation: neutrino oscillations as part of a broad physics program
- Designing DUNE: precision, robustness, and breadth
- DUNE physics potential
- Getting there: phased construction and opportunities for expanded scope
- The message for Snowmass

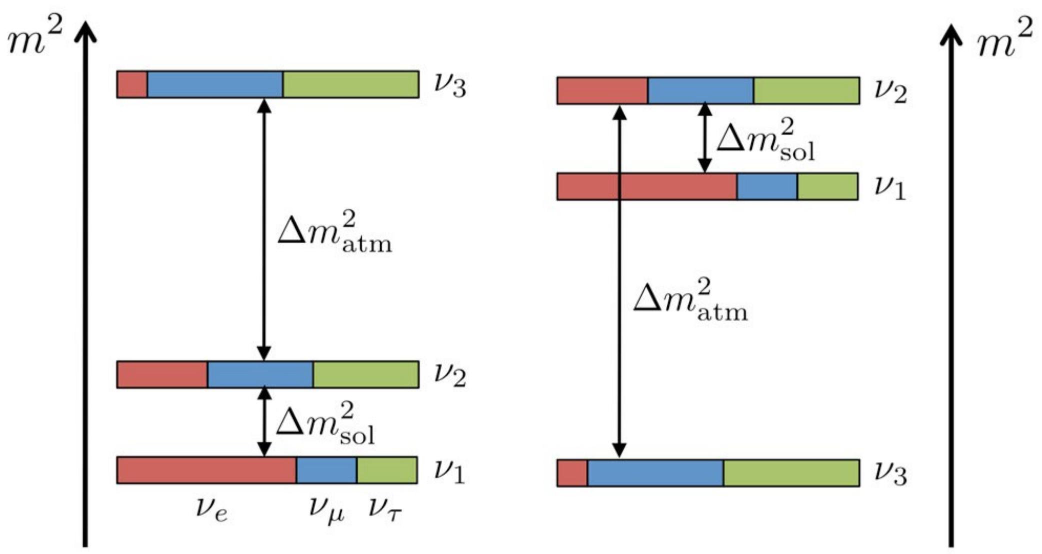
Neutrino oscillations: Big picture questions

- What is the origin of neutrino mixing? Is there an underlying flavor symmetry, and how is it broken?
- What is the origin of the neutrino masses? Why are the neutrinos so light?
- Is leptogenesis a viable explanation of the baryon asymmetry of the Universe?
- Is the νSM complete? Are there additional neutrinos?



Searching for answers: precision neutrino oscillation measurements

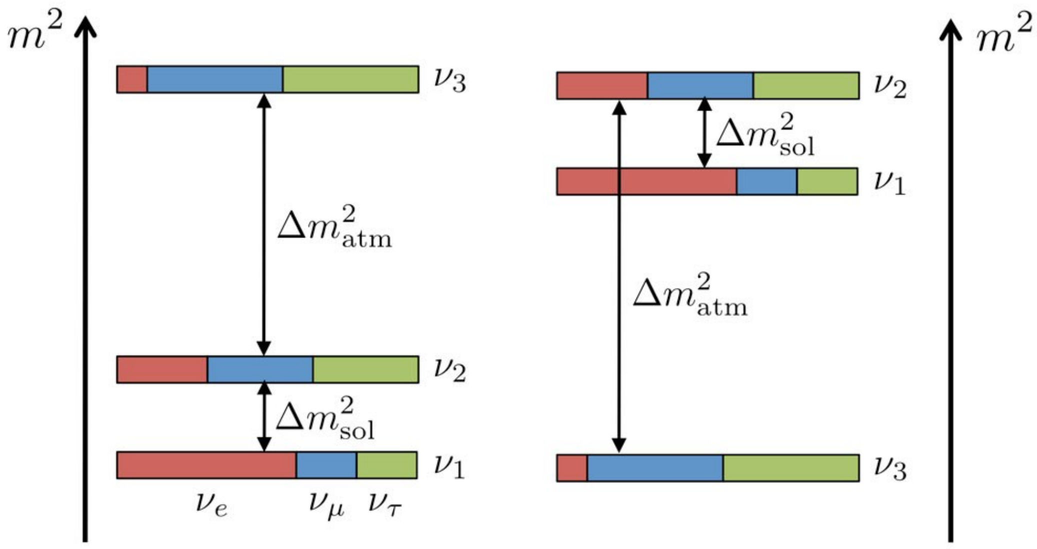
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- Measure neutrino oscillations precisely, including $\nu_\mu \rightarrow \nu_e$ that is sensitive to CP violation
- Test the three-flavor paradigm → overconstrain the system

Neutrino oscillations: current status

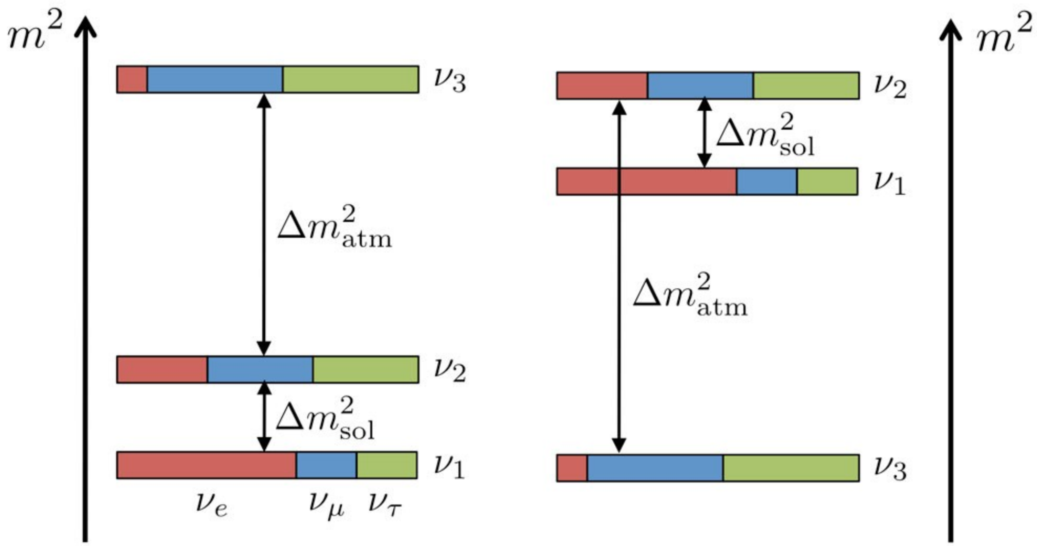
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- Current precision:
  - θ_{13} ~ 2.7% (reactor $\bar{\nu}_e$ disappearance)
  - $|\Delta m^2_{32}|$ ~ 3% (reactor $\bar{\nu}_e$ disappearance and accelerator ν_μ disappearance), mass ordering unknown
  - $\sin^2\theta_{23}$ ~ 0.5 ± 0.1 (atmospheric and accelerator ν_μ disappearance + ν_e appearance)
  - δ_{CP} unknown

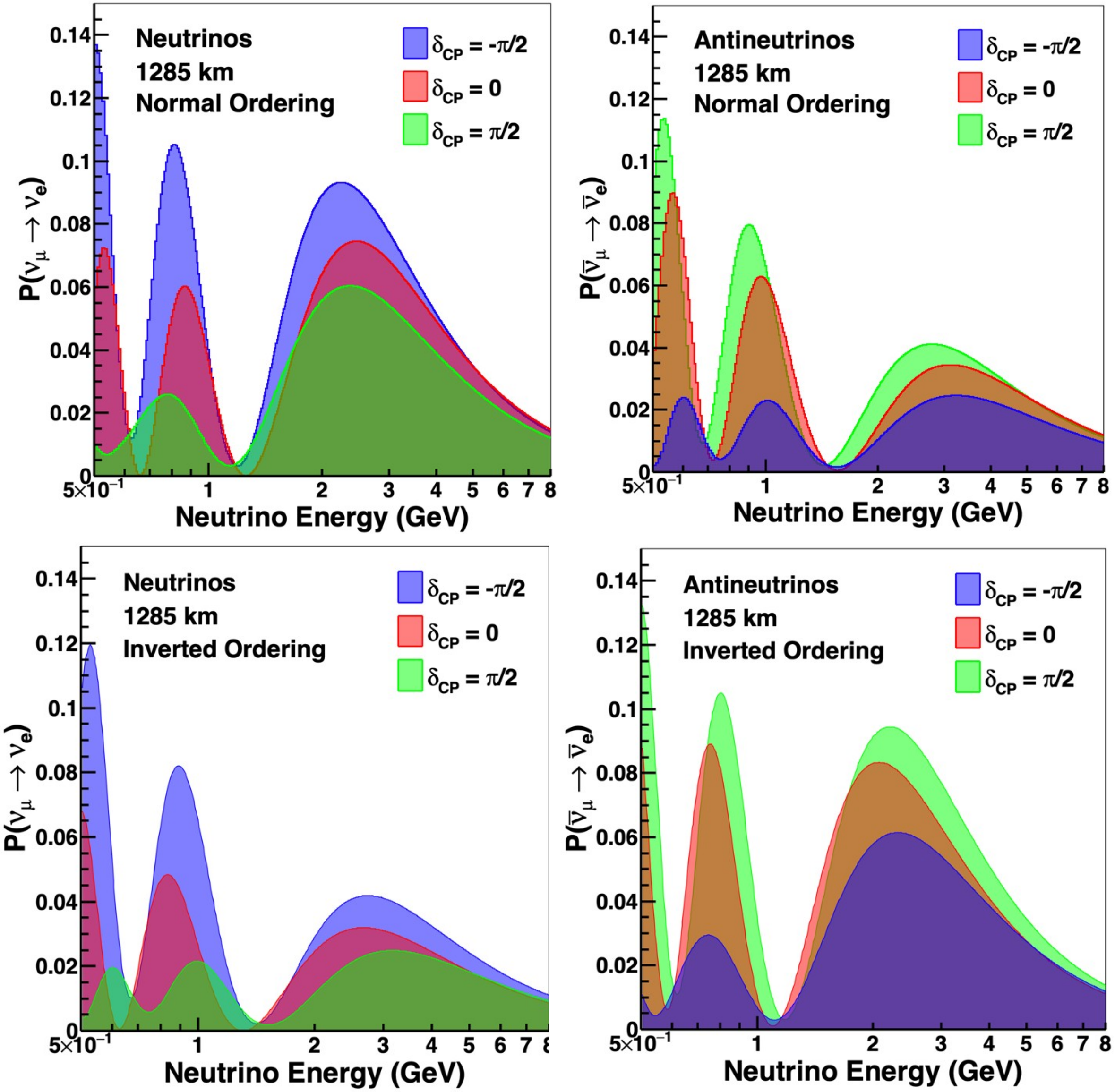
Neutrino oscillations: Next Generation goals with $\nu_\mu \rightarrow \nu_e$

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- Measure δ_{CP}
- Improve precision on $\sin^2\theta_{23}$
  - Is it maximal?
  - Resolve the octant
- Measure θ_{13} with ν_e appearance and similar precision to reactor → unitarity test
- Overconstrain the system → does the PMNS matrix hold up?

Resolve ambiguities by measuring $\nu_\mu \rightarrow \nu_e$ vs. L/E in wideband beam

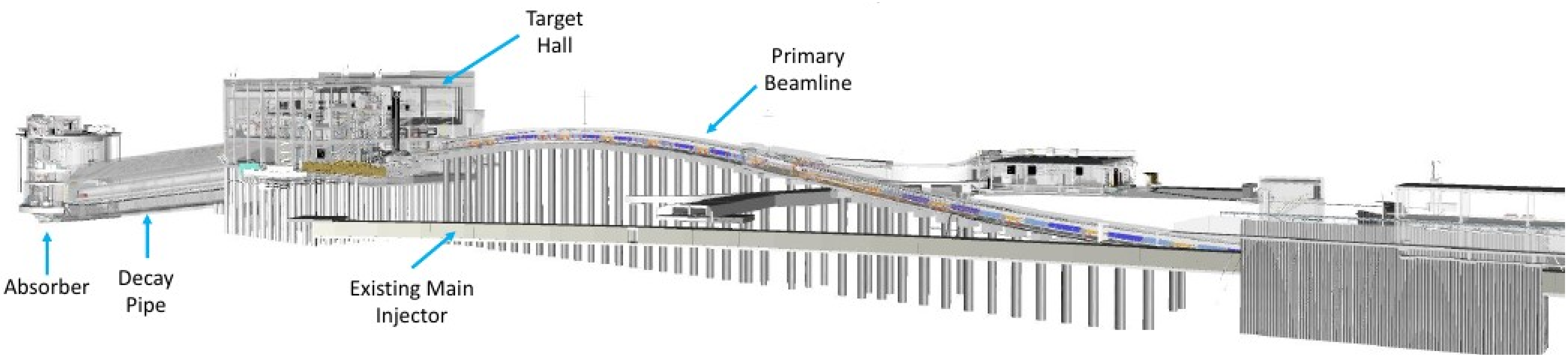


- DUNE is designed to resolve degeneracies by measuring flavor transitions as a function of energy over more than a full oscillation period
  - Determine MO and measure δ_{CP}, regardless of the true values
  - World-leading precision
- Test if three-flavor paradigm fits together, as a function of L/E, in one experiment
- Expect the unexpected: robust system for resolving deviations from νSM

UNIVERSITY of ROCHESTER

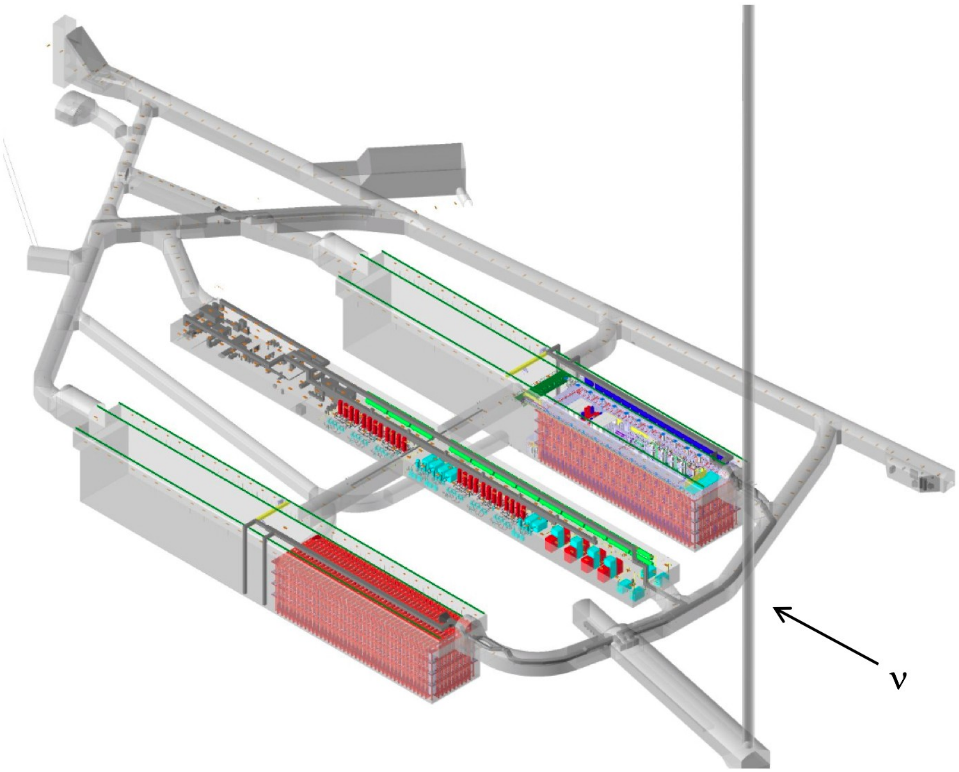
Neutrino oscillations as part of a broad physics program

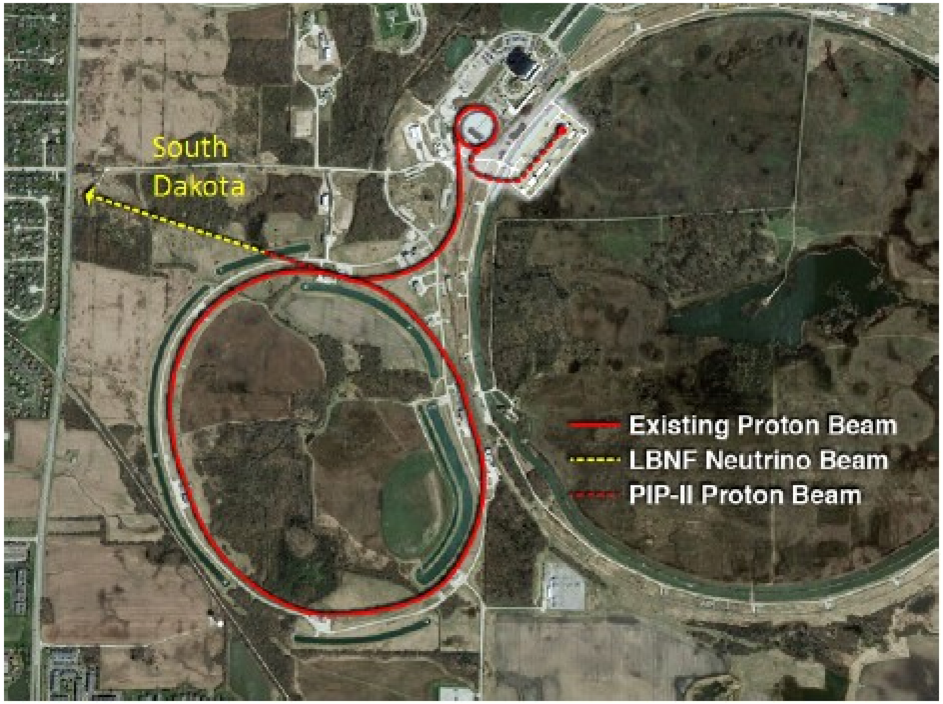
- DUNE FD has excellent low-energy neutrino and BSM sensitivity:
  - Large mass
  - Deep underground
  - High resolution
  - Low thresholds
- Boosted BSM searches → high intensity beam and capable ND



LBNF: World-leading neutrino beam intensity, underground facilities

- 1.2 MW neutrino beam, upgradeable to 2.4 MW
- Deep underground far site to accommodate four 17-kiloton detector modules





LBNF: World-leading neutrino beam intensity, underground facilities

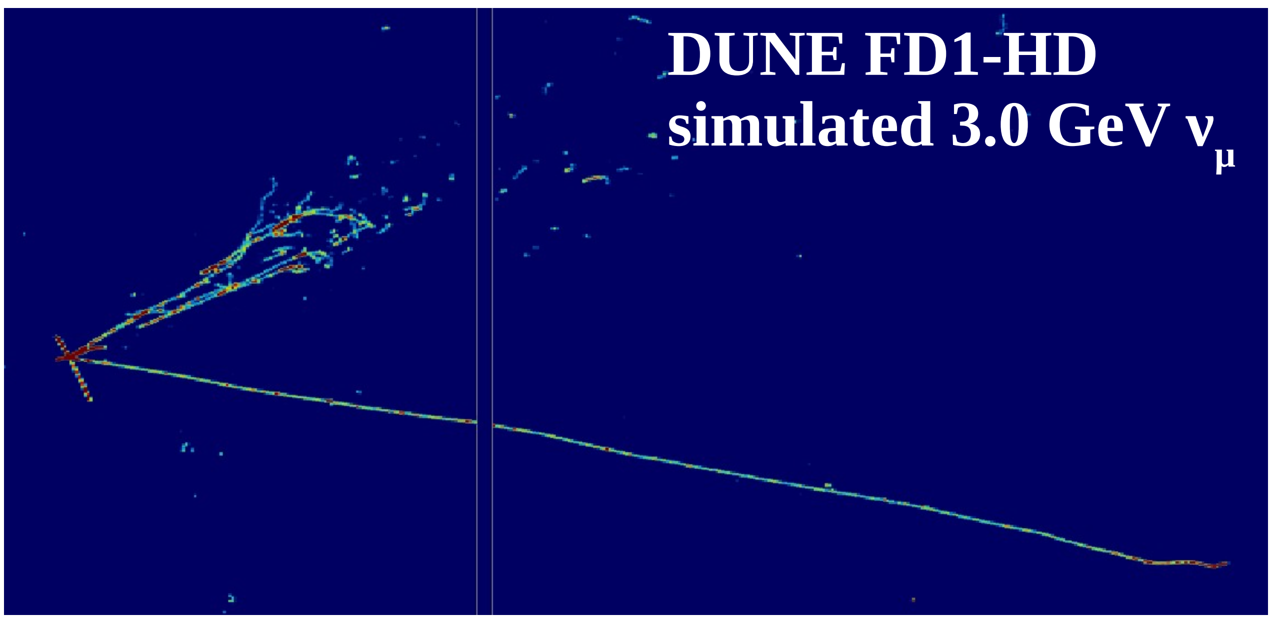
- Construction is underway at both SURF and Fermilab

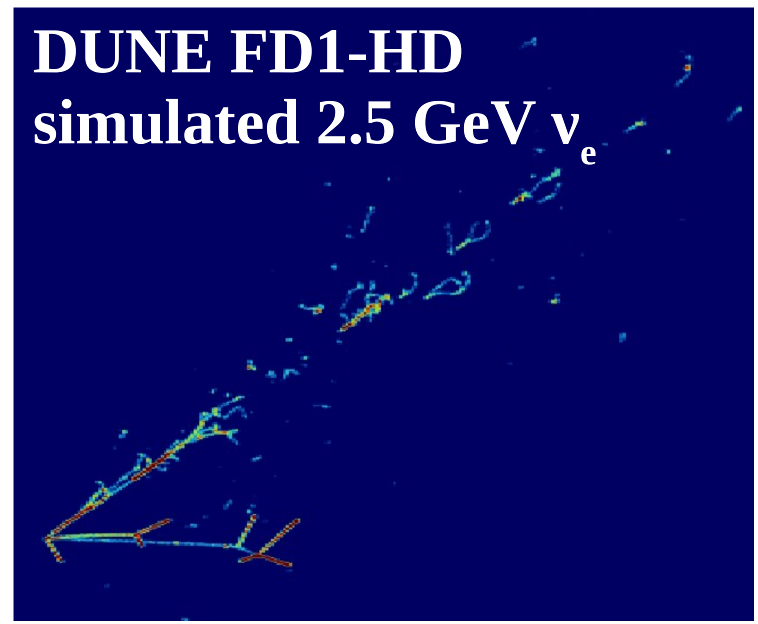
North cavern breakthrough January 2022

PIP-II construction May 2022

LArTPC technology provides exquisite resolution

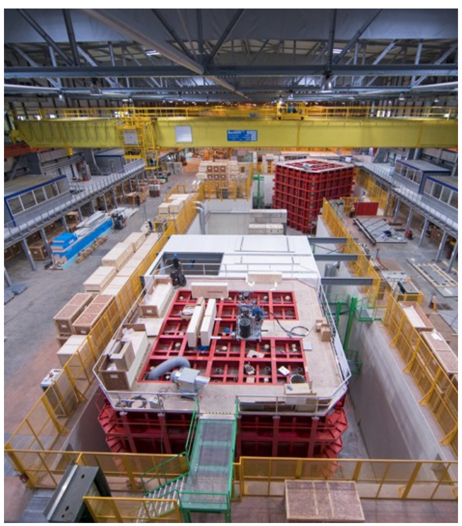
- Clean separation of ν_μ and ν_e charged currents
- Precise energy reconstruction over broad E_ν range
- Low thresholds: sensitivity to few-MeV neutrinos, hadrons

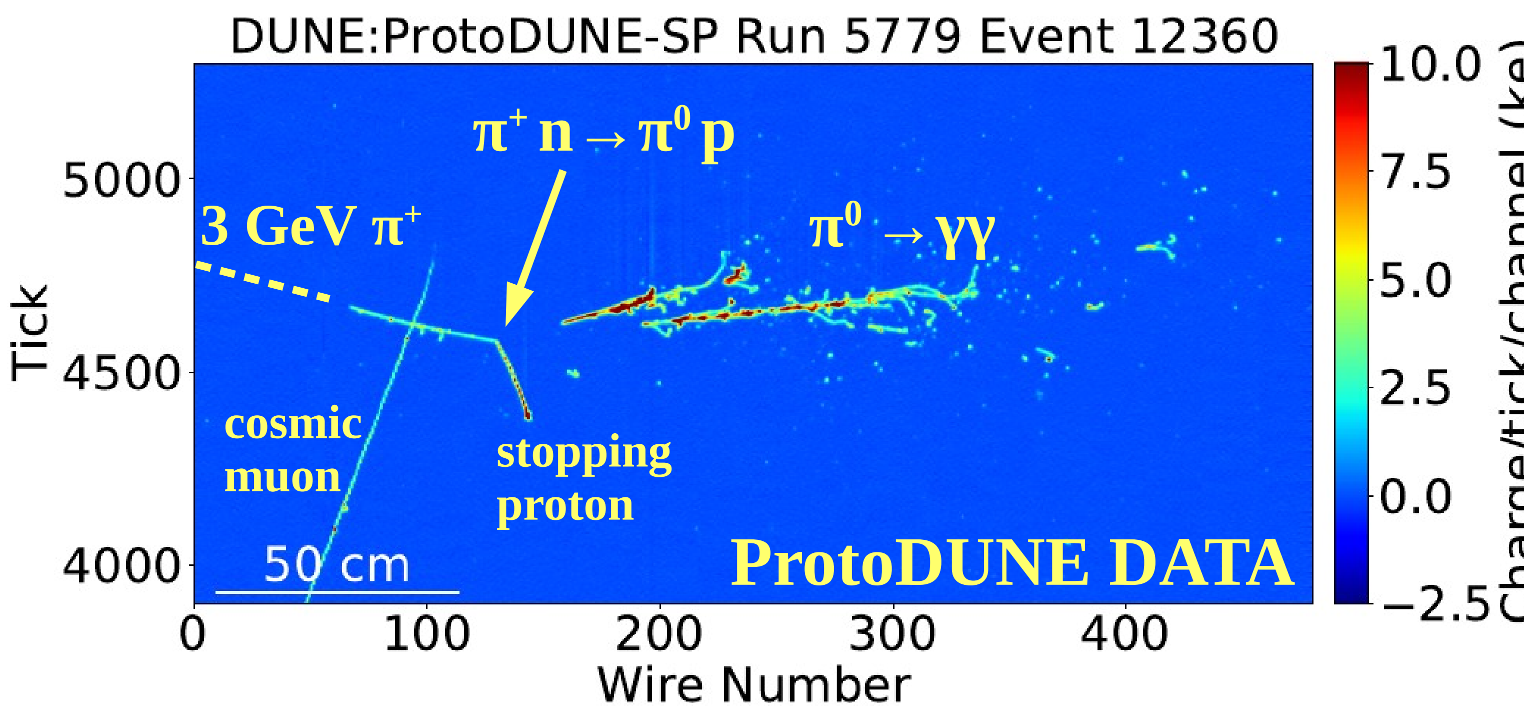




LArTPC technology provides exquisite resolution

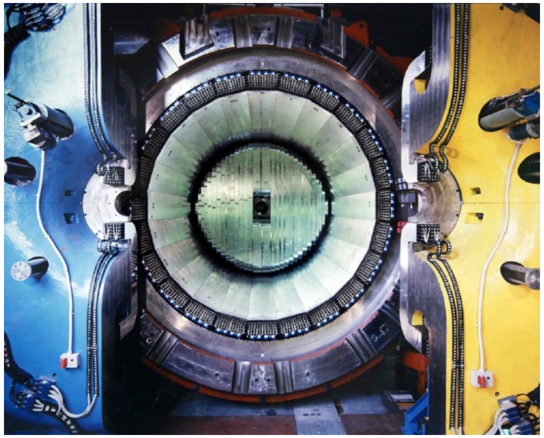
- ProtoDUNE is full scale in the drift direction
- Successful operation at CERN: low noise, stable HV, high purity → demonstrates LArTPC technology and DUNE design

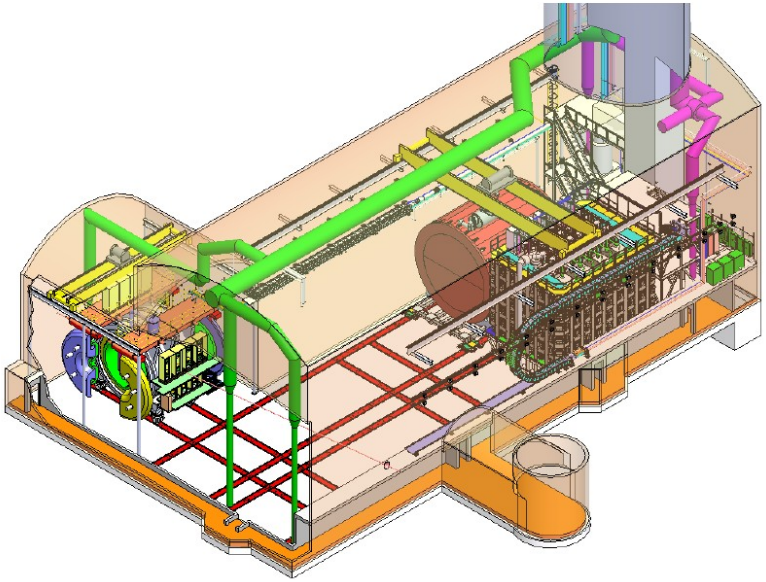


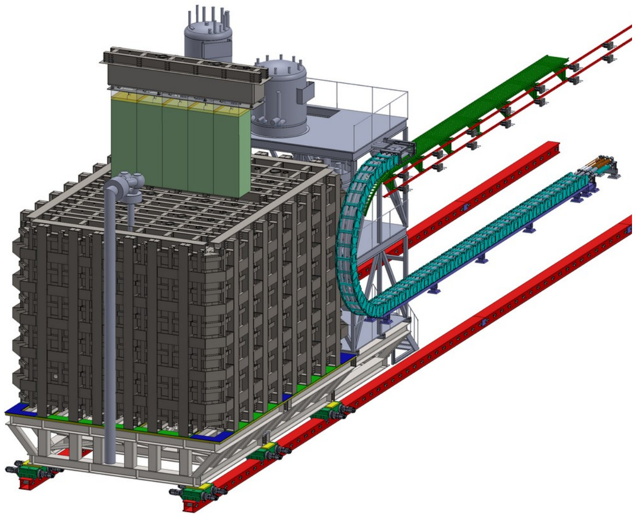


Near Detector: constraints to enable world-class measurements

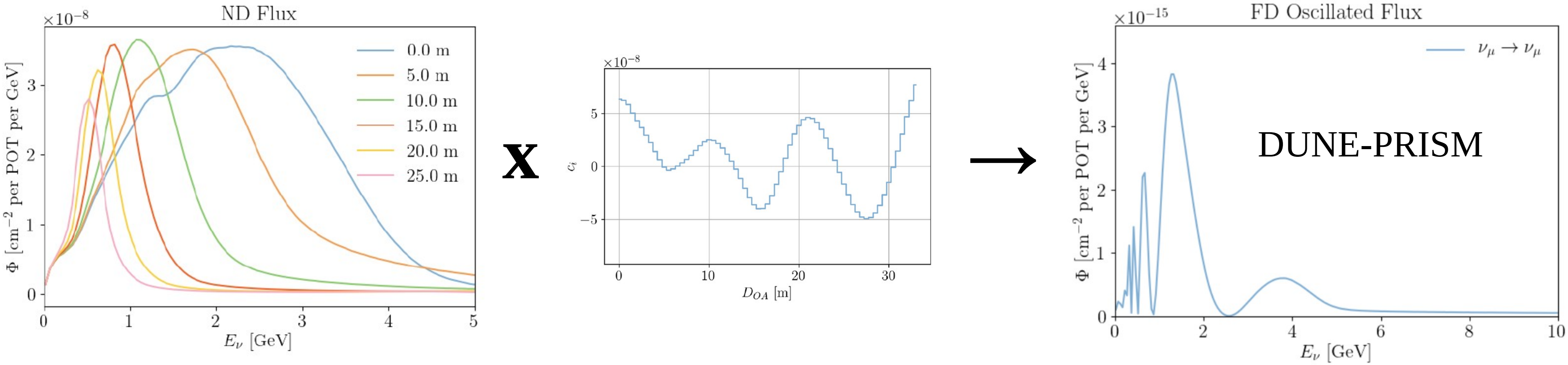
- LArTPC detector: same nuclear target and detector technology near & far
- Movement system to facilitate measurements in different neutrino fluxes
- On-axis magentized low-density tracker and spectrometer

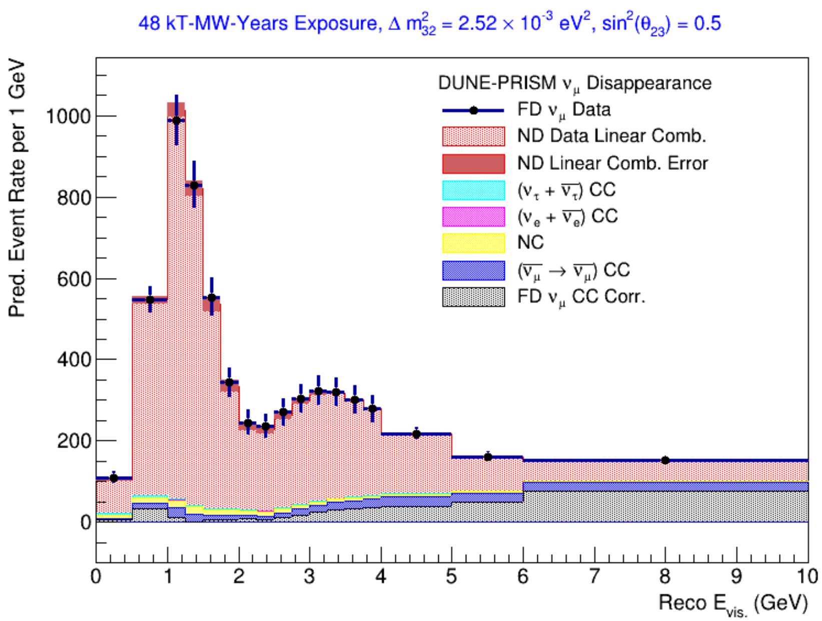






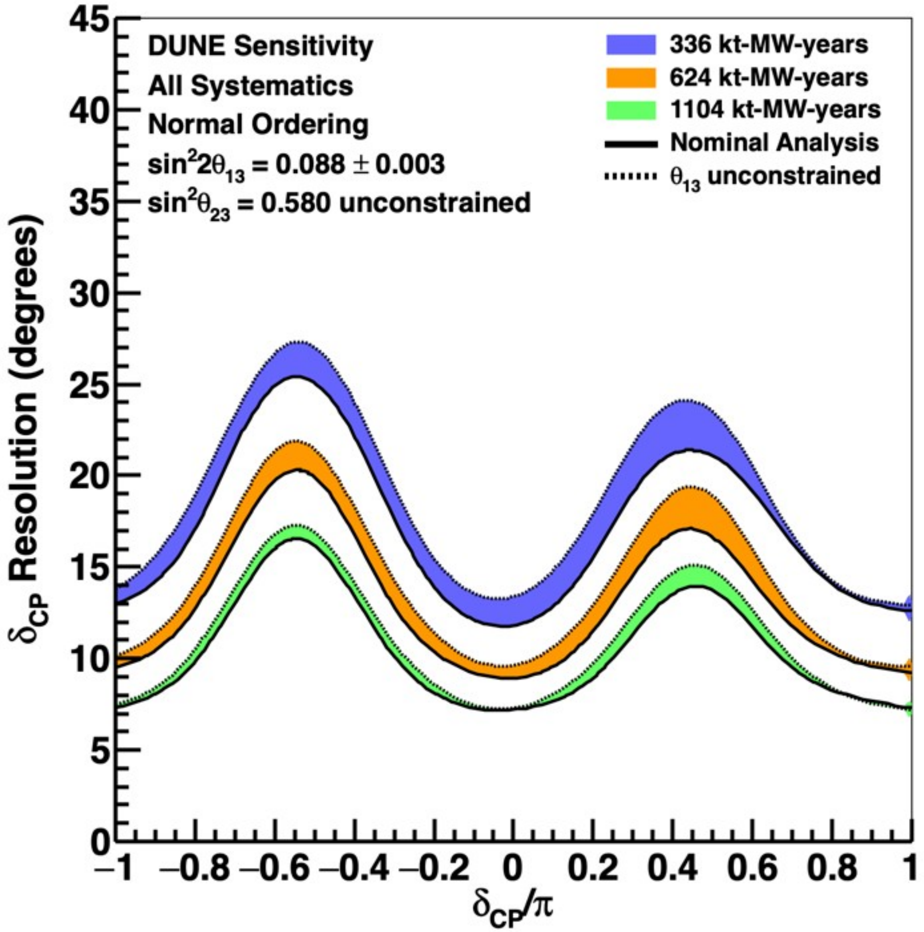
PRISM plays a critical role in enabling DUNE's precision

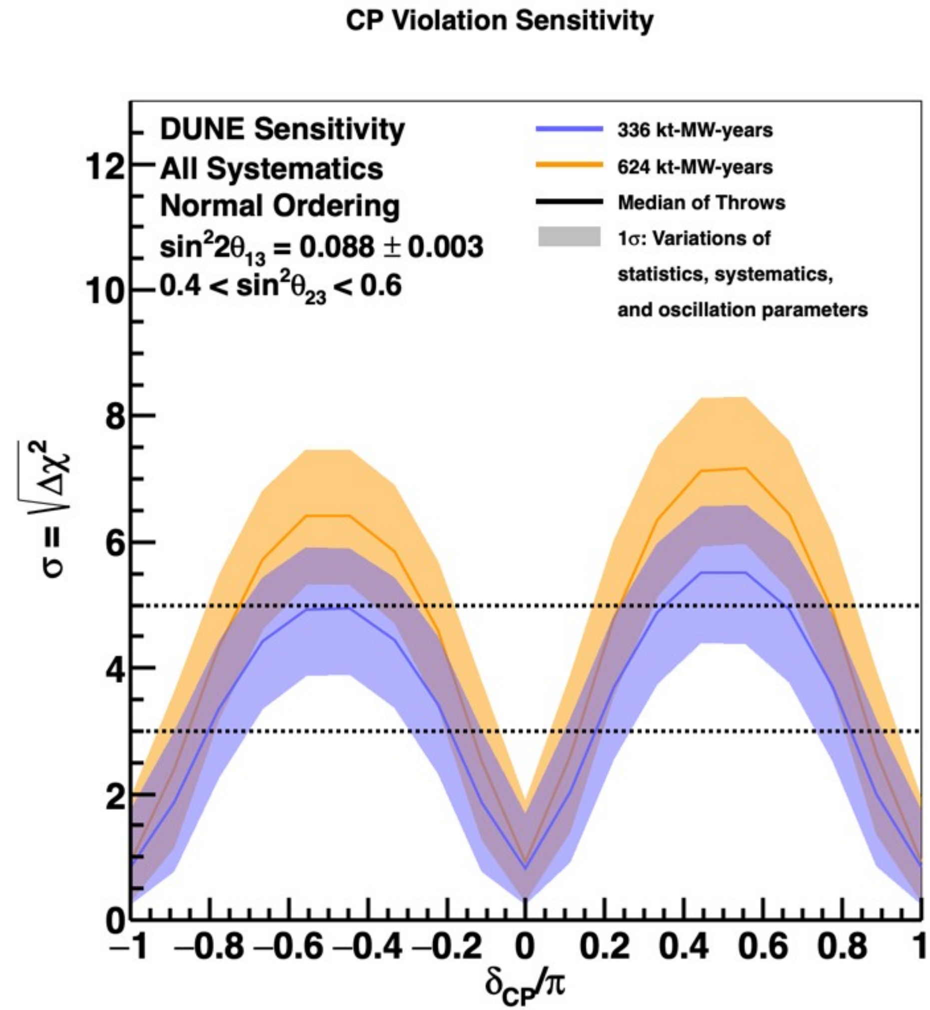




- FD flux ≠ ND flux → uncertainties in energy dependence of flux, cross sections
- ND flux changes with angle → take ND data in different fluxes → build linear combination to match FD *oscillated* spectra
- For LBL: robust analysis approach with very minimal dependence on interaction modeling
- Also extends dark matter sensitivity

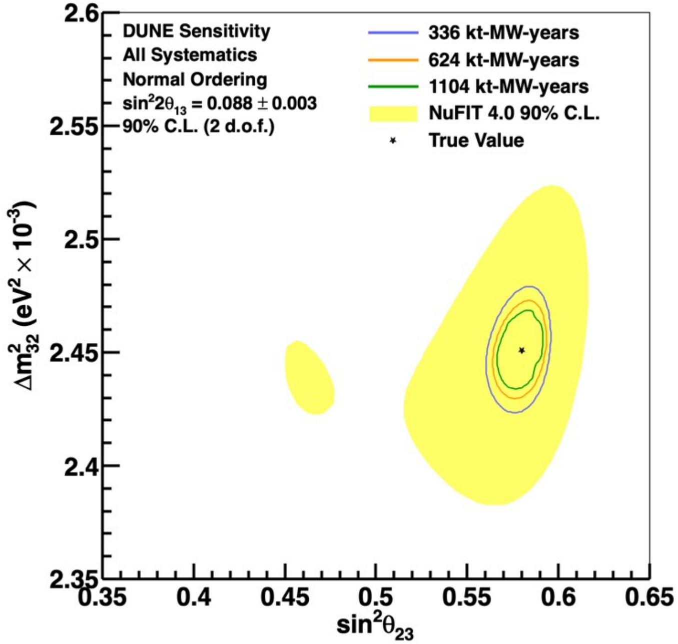
Physics potential: CP violation

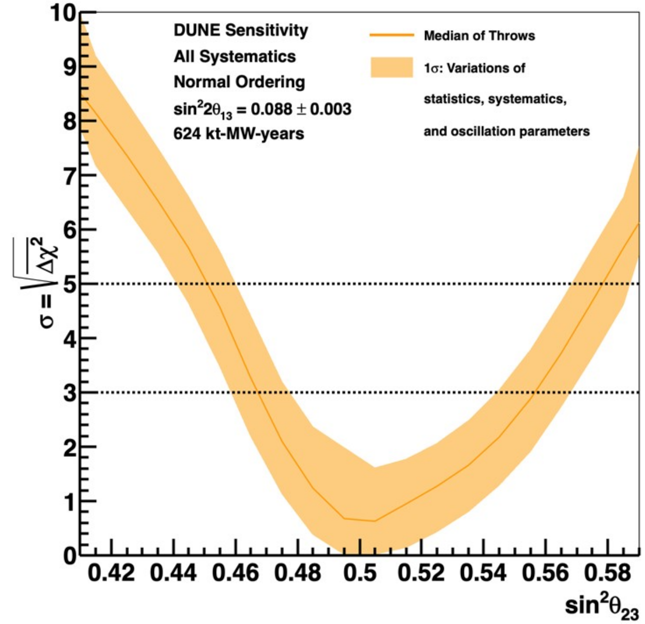


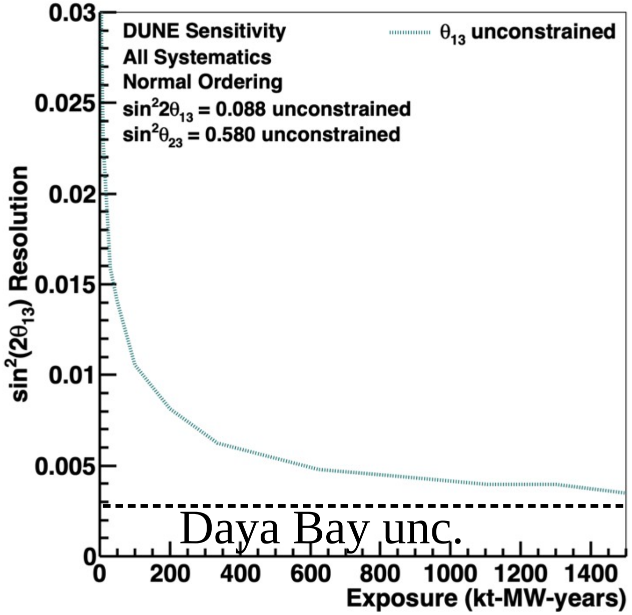


- 7° resolution to δ_{CP}, discovery sensitivity to CP violation over a broad range of possible values

Physics potential: precision measurements, non-unitarity tests

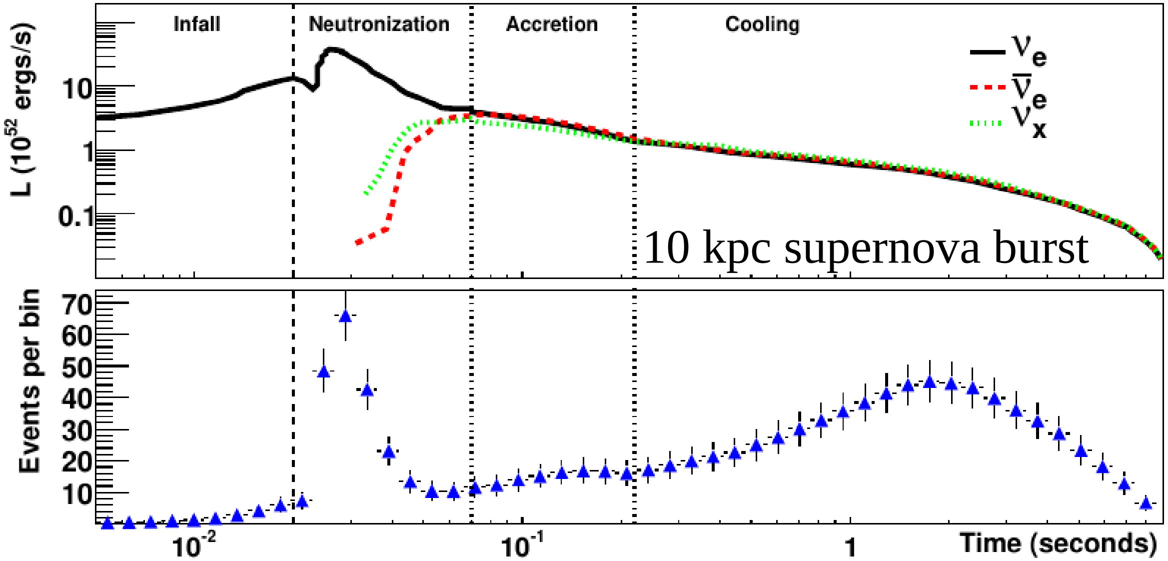


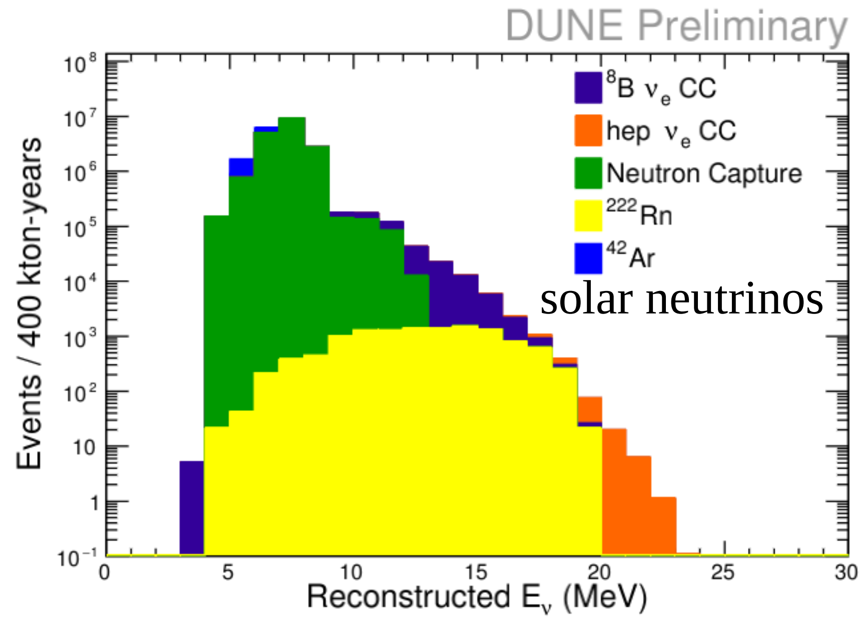




- Excellent on Δm^2_{32} and θ_{23}, including octant, and unique PRISM measurement technique that is less sensitive to systematic effects
- Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor data directly tests PMNS unitarity

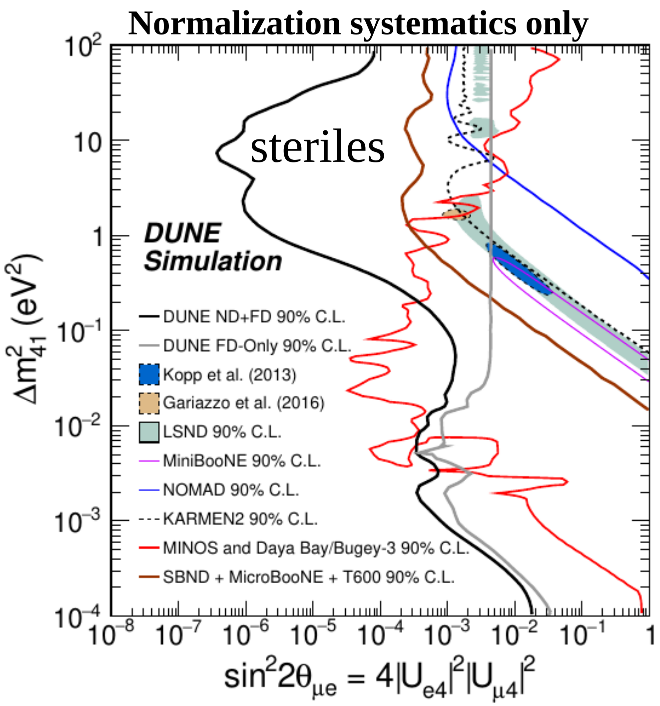
MeV-scale physics: unique opportunities with ν_es

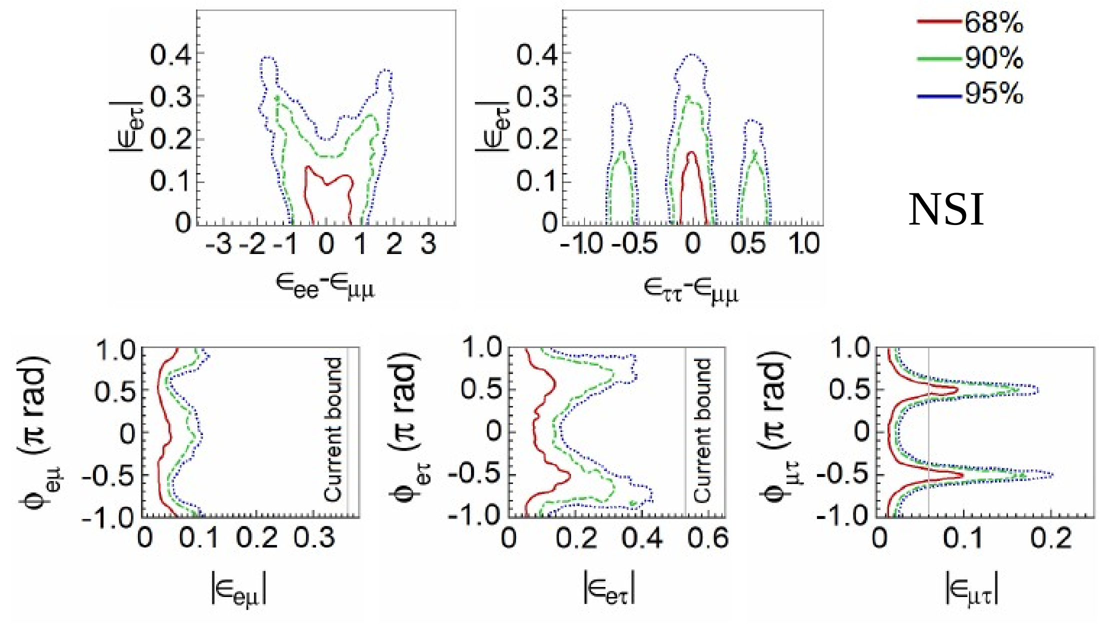




- Large detector + underground + low thresholds = sensitivity to supernova neutrinos
- Ar target makes DUNE uniquely sensitive to ν_e flux → measure neutronization burst, and highly complementary to other water/hydrocarbon detectors which measure predominantly $\bar{\nu}_e$
- Solar neutrino sensitivity to ^{8}B and hep fluxes, and capability to measure solar mixing parameters θ_{12} and Δm^2_{12}

Beyond the 3-flavor SM picture: non-standard oscillation effects



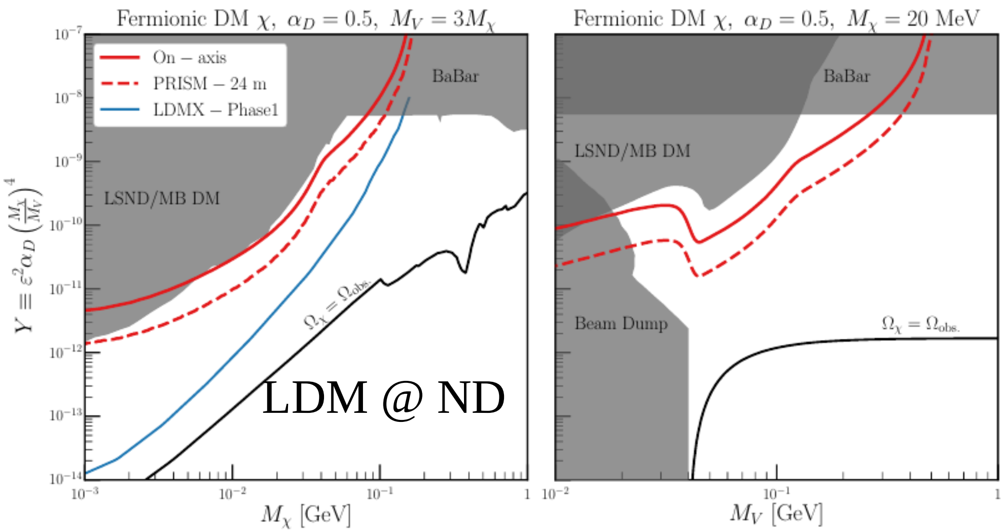


- Combination of ND + FD, and broad energy spectrum → broad Δm^2 coverage for sterile searches
- Both ND and FD have excellent μ/e resolution, and also ability to tag τ charged currents → complete 3-flavor test
- If inconsistency is observed, having multiple experiments at different baselines but the same L/E will be important for understanding the origin

DUNE is an excellent BSM physics experiment

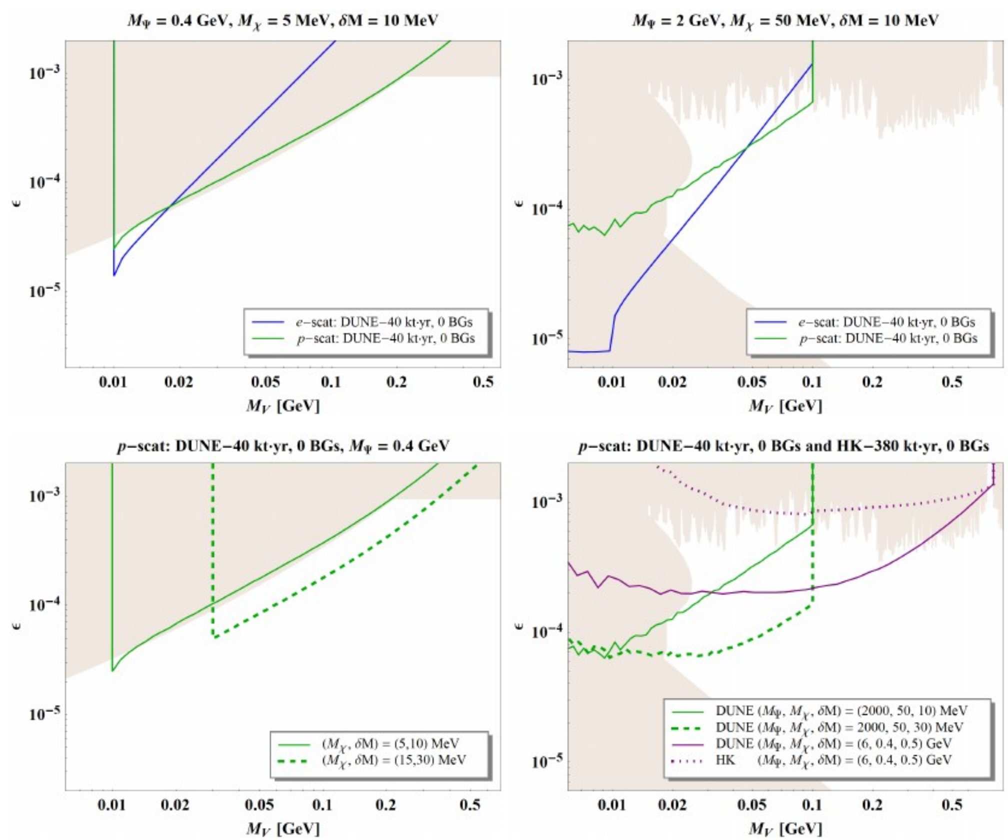
- For exotics of cosmic origin:
  - Large target mass
  - Deep underground → low background
  - Exquisite imaging, sensitivity to hadrons
- For exotics produced in hadron-nucleus collisions:
  - World-leading beam intensity
  - Excellent detectors at ~500m, including a 150-ton detector (scattering), and a large, low density detector (decays)

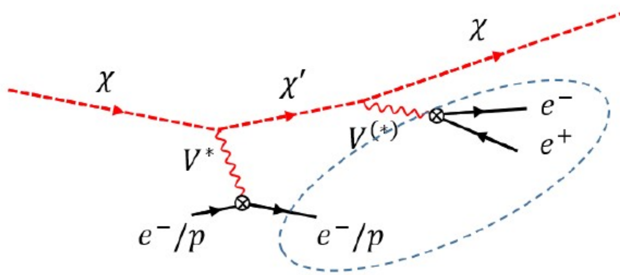
Not just Neutrino Frontier: Dark matter at DUNE ND & FD



- ND-LAr is sensitive to DM produced in beamline, off-axis data helps to control SM backgrounds

- FD is sensitive to inelastic dark matter of cosmic origin

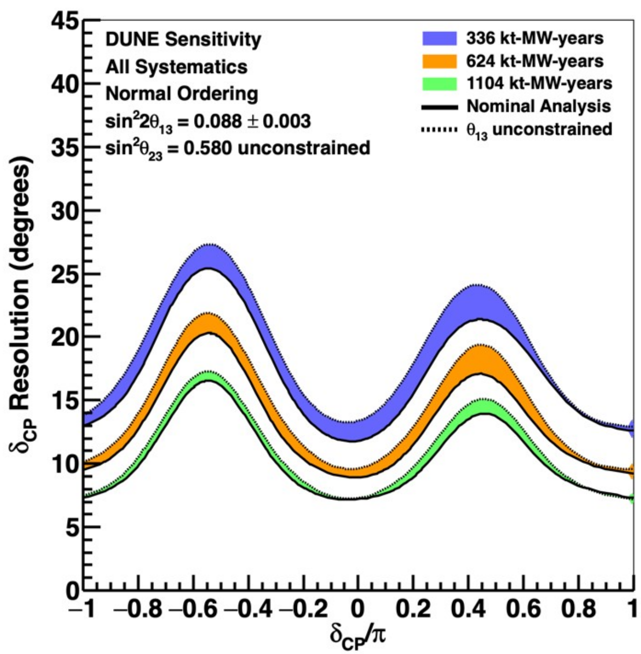


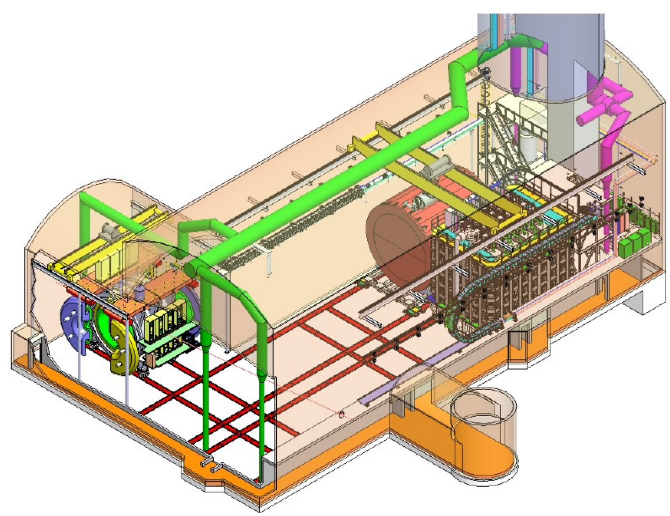


UNIVERSITY of ROCHESTER

Why DUNE?
Precision, robustness, breadth

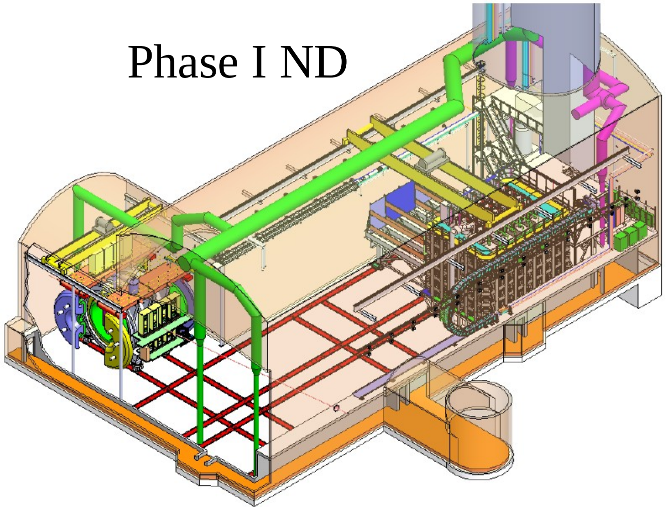
- DUNE may not make the first few-σ mass ordering determination, but DUNE will make the strongest, most robust measurement, >8σ regardless of δ_{CP}, θ_{23}
- DUNE may not make the first few-σ CPV observation if δ_{CP} is large, but DUNE will make the most precise measurement of δ_{CP}, no matter what it is

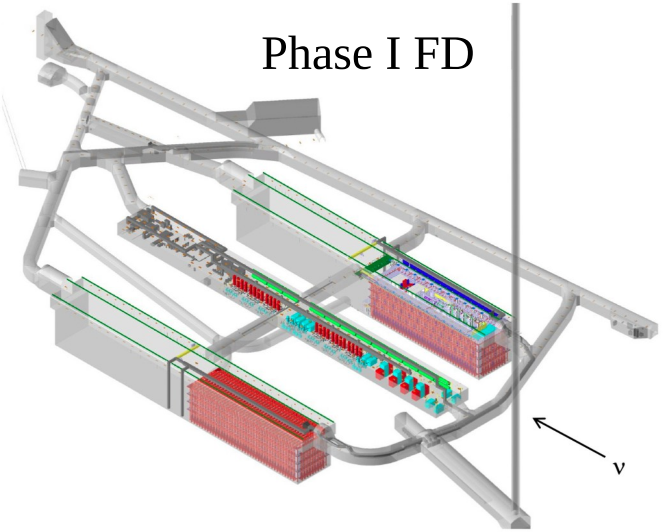




Getting there: phased construction

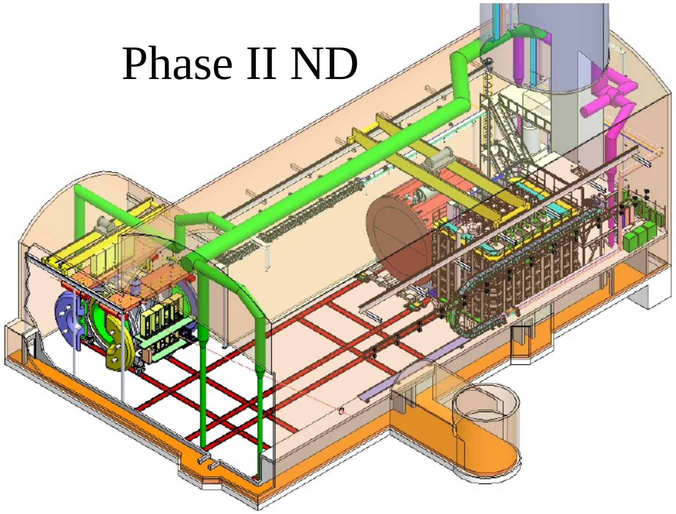
- DUNE Phase I:
  - Neutrino beam with 1.2 MW intensity
  - Two 17kt LAr TPC FD modules, but underground conventional facilities and infrastructure to support four modules
  - Near detector: ND-LAr + TMS (movable) + SAND
- Construction schedule is funding limited → changes to the funding profile have a significant impact on the schedule
- Current CD1-RR schedule has FD 1&2 taking physics data in 2029, beamline and ND by 2031
- The US DOE scope of Phase I was reviewed last week in CD1-RR

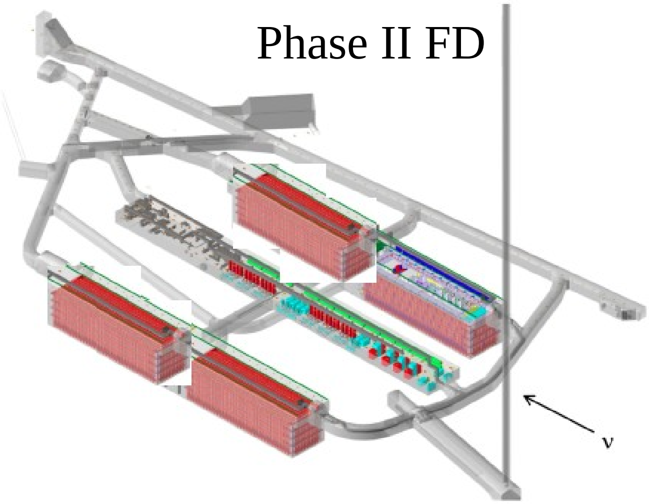




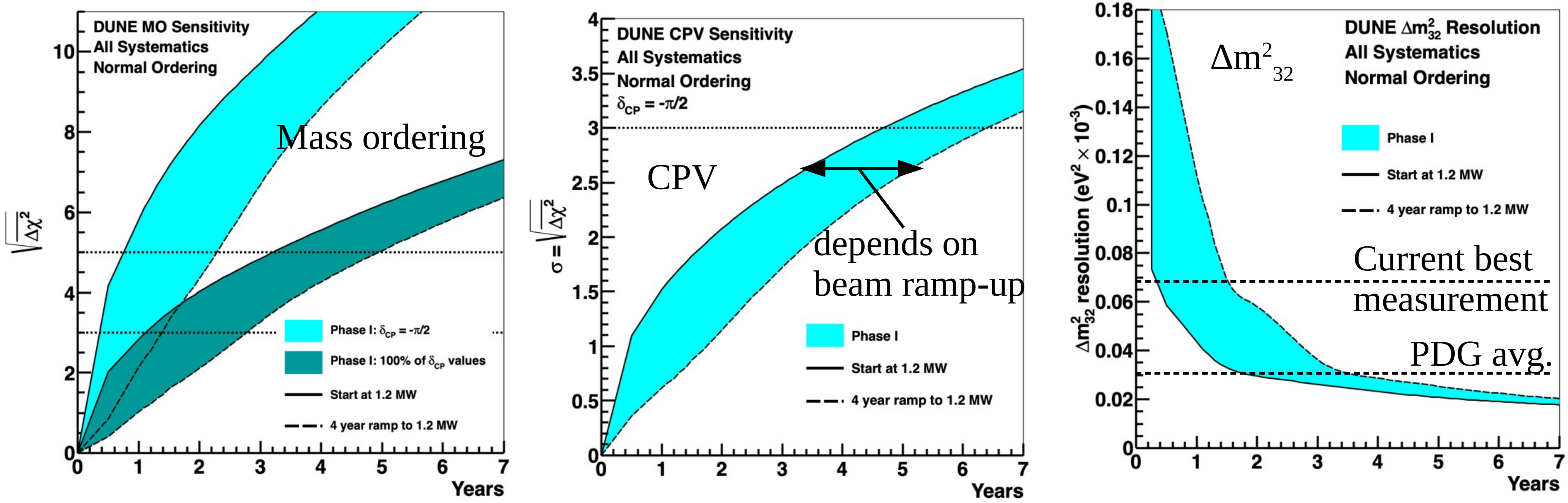
Getting there: Phase II upgrades

- DUNE Phase II:
  - Fermilab proton beam upgrade to 2.4 MW
  - Two additional 17kt FD modules
  - Near detector: ND-LAr + MCND (movable) + SAND
- Beam upgrade benefits all Fermilab experiments: dedicated session Wednesday on Booster replacement options (AF-NF AF2-AF5-NF)
- ND upgrade is driven by improved performance at reducing systematics
- Opportunities to expand physics scope with 3rd & 4th FD modules: dedicated session Wednesday (NF)





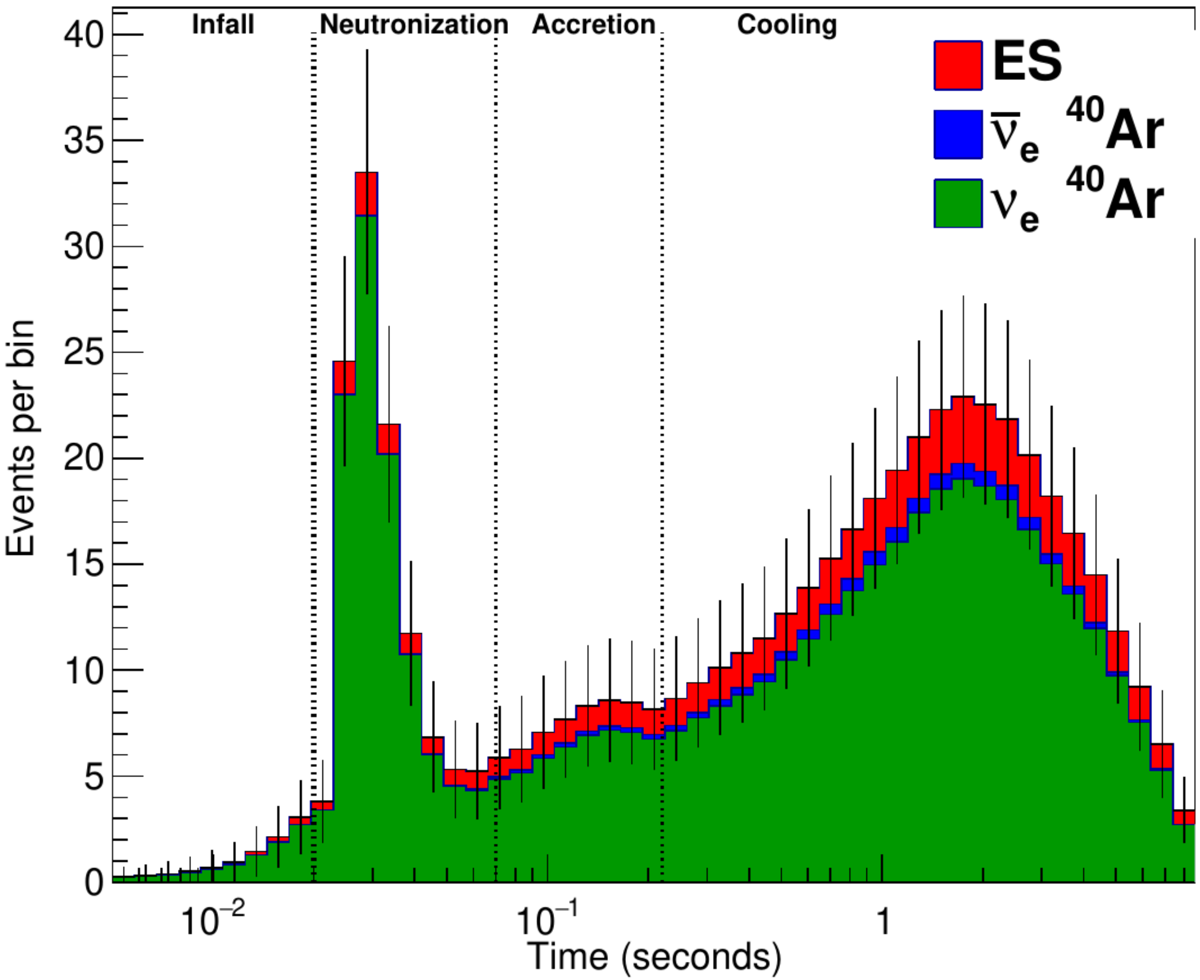
DUNE Phase I: world-leading MO, sensitivity to maximal CPV



- Phase I will do world-class long-baseline neutrino oscillation physics:
  - Only experiment with 5σ mass ordering capability regardless of true parameters
  - Discovery of CPV at 3σ if CP violation is large
  - World-leading precision on other parameters, (e.g. surpass current Δm^2_{32} error in ~2-3 years)

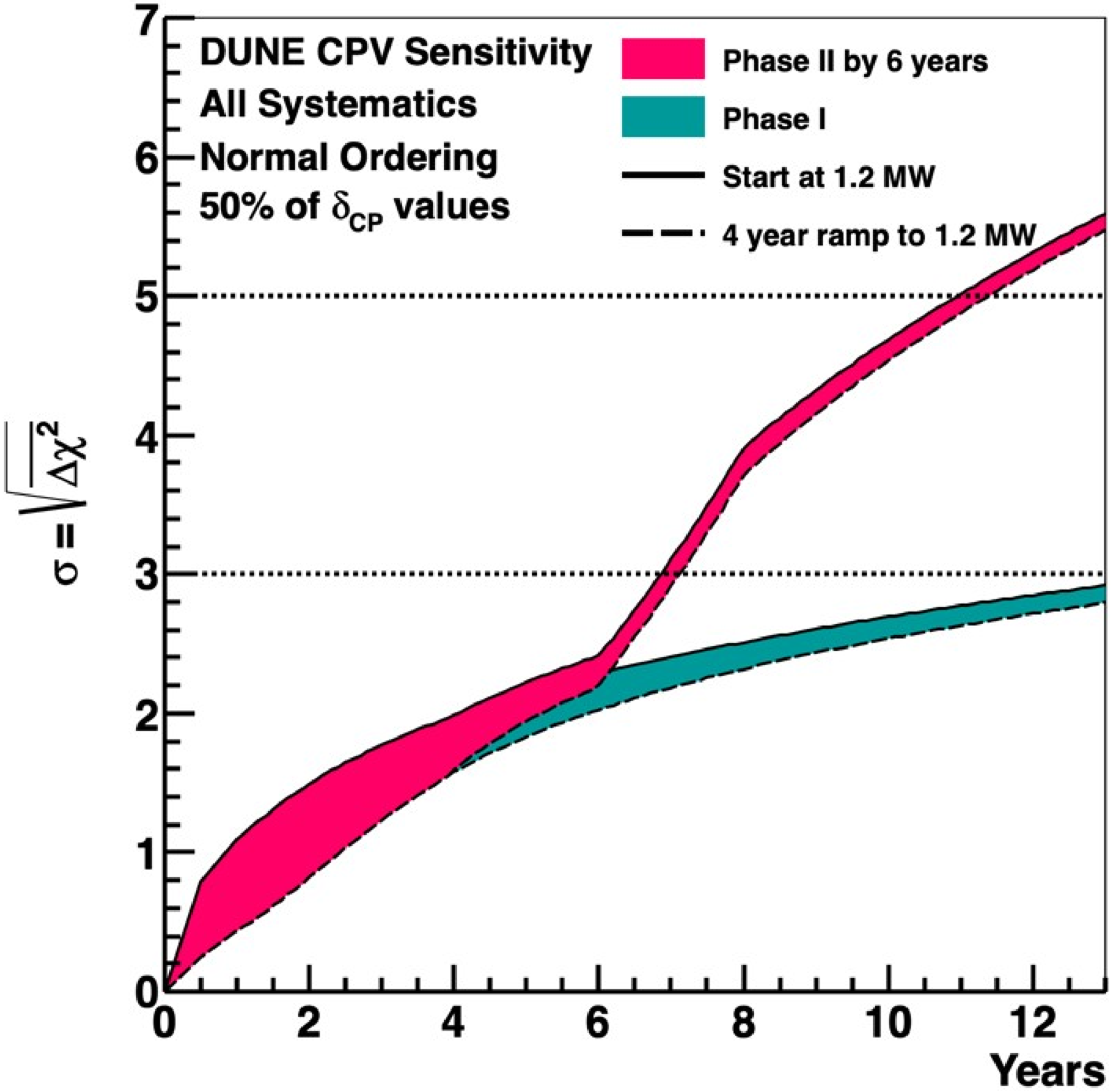
UNIVERSITY of ROCHESTER

Non-beam physics with Phase I



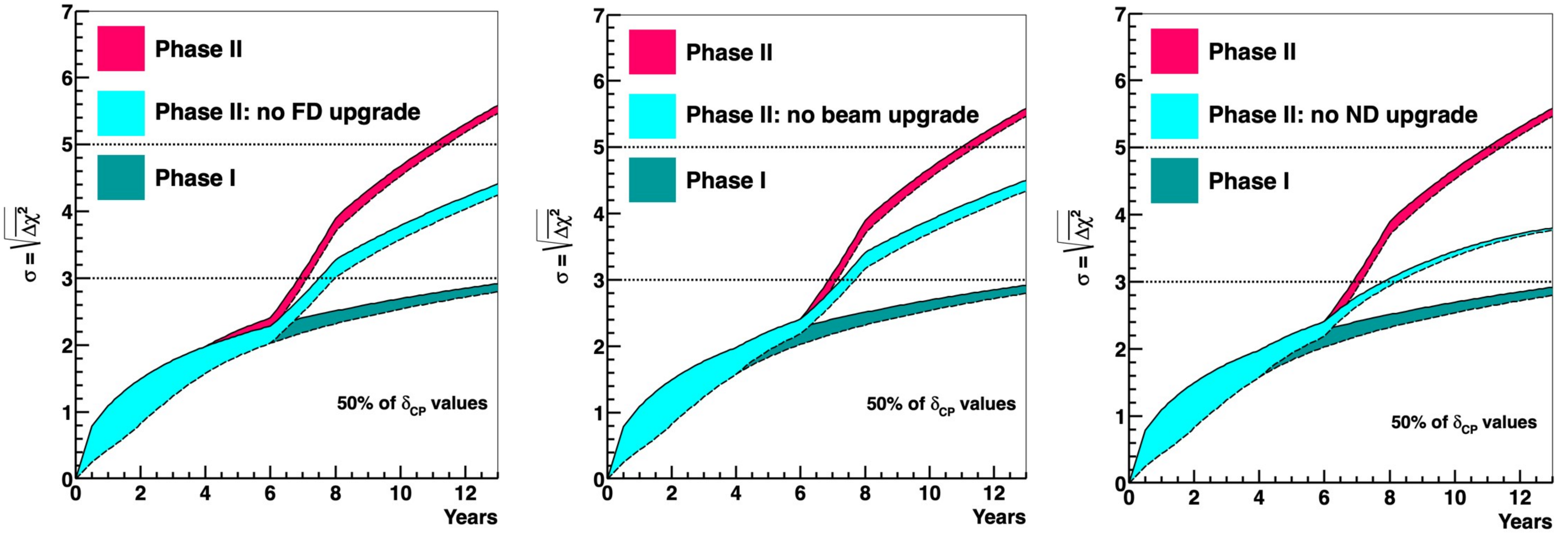
- DUNE is already very sensitive to a galactic supernova burst with Phase I
- Shown is the time distribution for a hypothetical 10 kpc SNB with 20 kton FD mass

DUNE's long-term goals require full scope (Phase II)



- DUNE needs full Phase II scope to achieve precision physics goals defined in P5 report
- CPV sensitivity for 50% of δ_{CP} 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

Phase II requires 40kt, 2.4MW, upgraded near detector



- To achieve the precision physics goals, including CPV sensitivity for a broad range of δ_{CP} values, all three upgrades are required
- Plots show the effect of removing one of them, resulting in a significant loss of sensitivity

Module(s) of opportunity

Workshop logo or something

- Technologies for FD-3 and FD-4 are not yet established → opportunities to expand the physics reach of DUNE
- Many exciting ideas from the community
- Dedicated MoO session on Tuesday morning
- MoO Workshop open to community: 2-4 November in Valencia, Spain

MoO: expanding scope while preserving core physics

Plots from MoO talks?

Plots from MoO talks?

- Additional 20 kton fiducial mass is critical for core oscillation physics, low energy and BSM goals of DUNE – it is part of Phase II
- It is a priority for DUNE that FD-3 and FD-4 meet the needs of the LBL program, including the systematic constraints of the Near Detector
- We welcome ideas for expanding the scope → the broader HEP community should decide which scope expansions to pursue

DUNE's message to Snowmass

Snowmass 2021

- DUNE Phase I should be realized in this decade
  - Every effort should be made to resolve funding profile issues that could delay first physics results into the 2030s
- Realization of the full DUNE Phase II should be the highest priority
  - Pursue upgrades aggressively such that the full DUNE scope is achieved in the 2030s
- R&D work to design detectors that broaden the physics scope while fulfilling the core goals of DUNE should be supported

The 2014 P5 report emphasized the importance of LBNF/DUNE

Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

For a long-baseline oscillation experiment, based on the science Drivers and what is practically achievable in a major step forward, we set as the goal a mean sensitivity to CP violation[2] of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}. By current estimates, this goal corresponds to an exposure of 600 kt*MW*yr assuming systematic uncertainties of 1% and 5% for the signal and background, respectively. With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this exposure implies a far detector with fiducal mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable near detector. **The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power. The experiment should have the demonstrated capability to search for supernova (SN) bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.**

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

The PIP-II project at Fermilab is a necessary investment in physics capability, enabling the world's most intense neutrino beam, providing the wideband capability for LBNF, as well as high proton intensities for other opportunities, and it is also an investment in national accelerator laboratory infrastructure. The project has already attracted interest from several potential international partners.

Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

DUNE is well on its way to achieving Phase I

- Assembled international collaboration of >1300 scientists and engineers from 37 countries + CERN (and counting)
- Built, operated, and analyzed ProtoDUNE large-scale prototype at CERN, demonstrating the detector design will work
- Produced detailed technical design report of the Far Detector SP module and physics program, and conceptual design report for Near Detector
- Far site excavation, preparation for beamline and near site conventional facilities underway
- **DUNE is well on its way to Phase I → let's finish what we started**

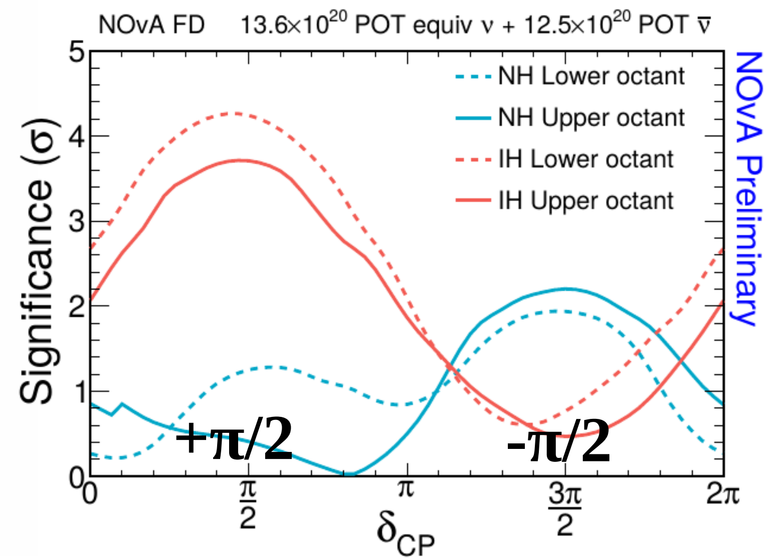
Thank You

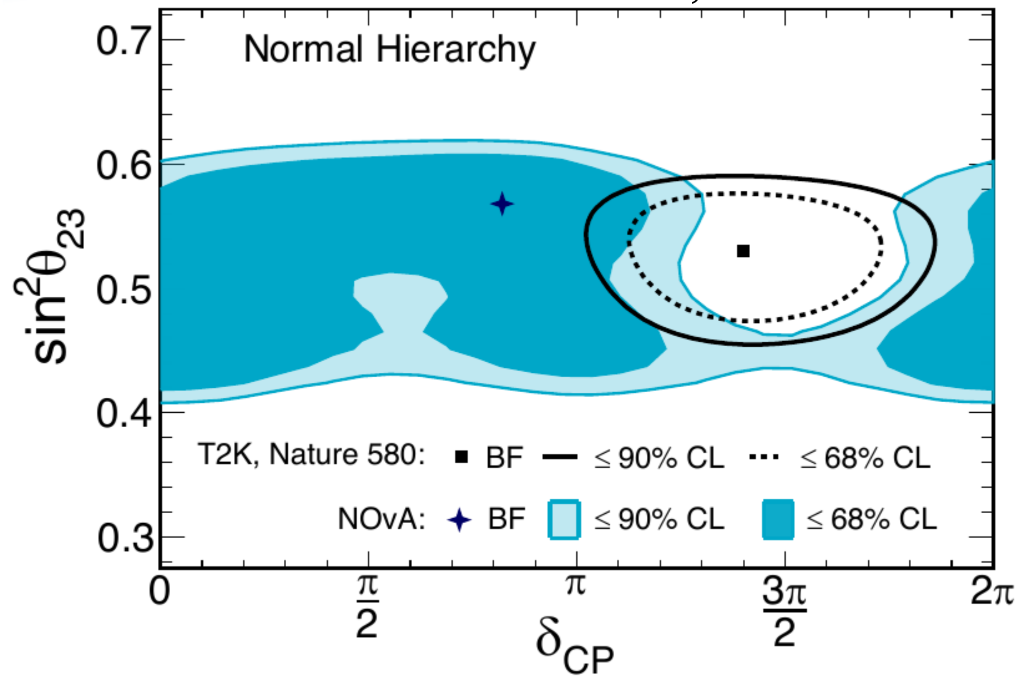
DUNE Collaboration, May 2022, Fermilab

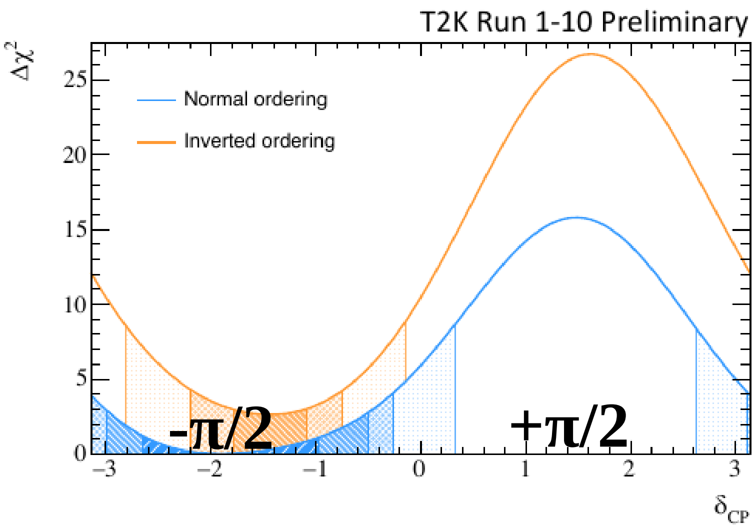
Backups

Mass ordering and CPV status: Some exclusions, little clarity

A. Himmel, Neutrino2020

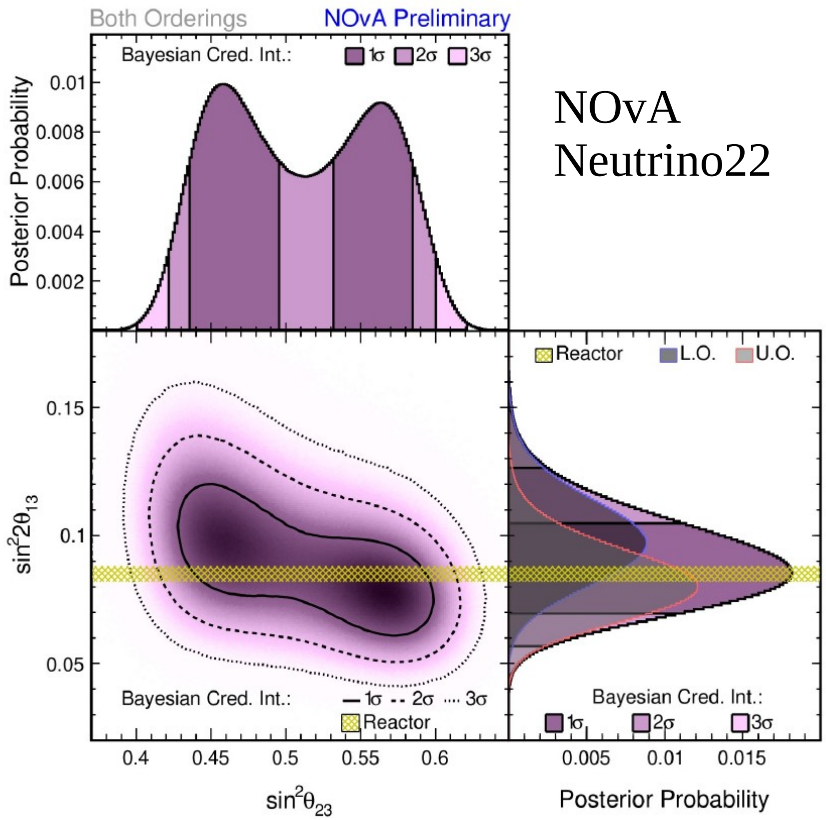






- Weak preferences for normal ordering
- CPV significance in T2K has decreased to <2σ with additional data, CP conserving values allowed by NOvA at <1σ
- Some regions of joint phase space are excluded at >3σ by T2K and NOvA, with mild tension at best-fit
- **We really do not know the mass ordering or δ_{CP}**

$\nu_\mu \rightarrow \nu_e$ depends on four parameters in a complicated way



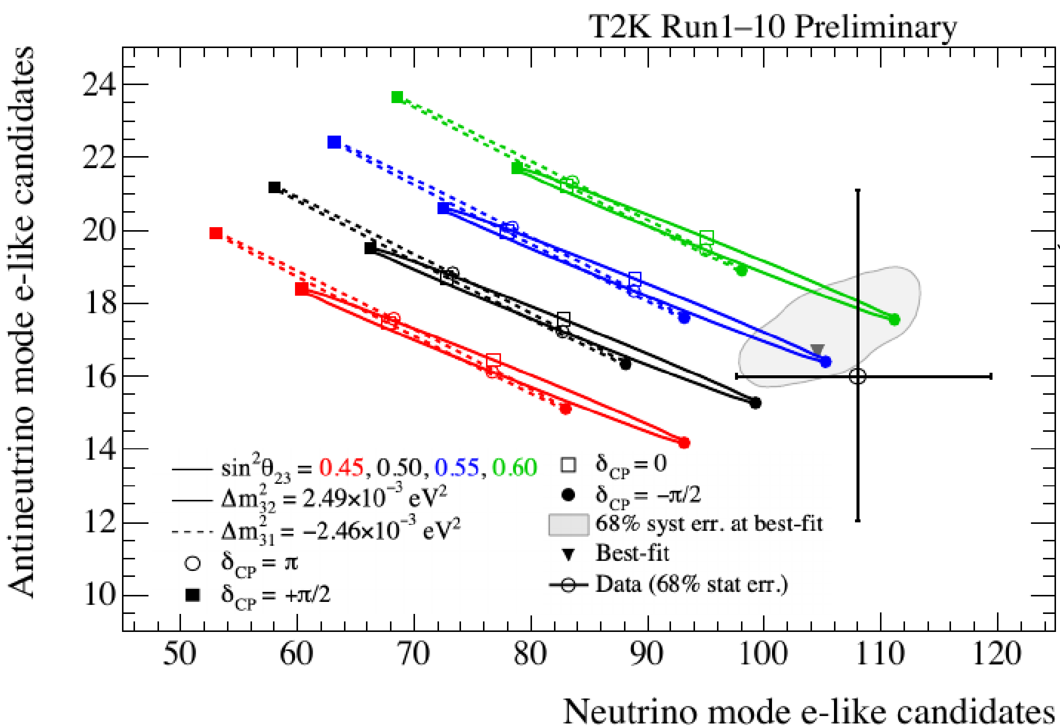
NOvA
Neutrino22

- Every measurement is actually a contour in a 4D space
- We are getting to the level of precision where correlations between parameters (including δ_{CP}) are really important
  - Energy dependence is a critical tool for resolving ambiguities between parameters
- Joint fits with multiple experiments become very difficult when systematics become important

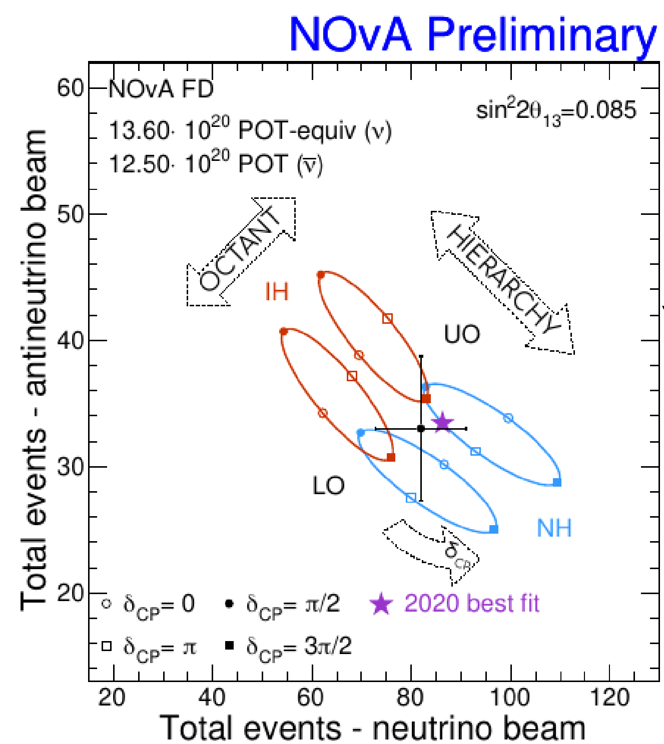
$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$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

What makes DUNE unique? Long baseline, wideband beam

- Narrow-band experiments (T2K, NOvA, T2HK) make oscillation measurements by essentially counting the number of ν_e and $\bar{\nu}_e$, and comparing it to the expectation for various different parameter combinations
- For shorter baselines, there is a degeneracy between the mass ordering, δ_{CP}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$

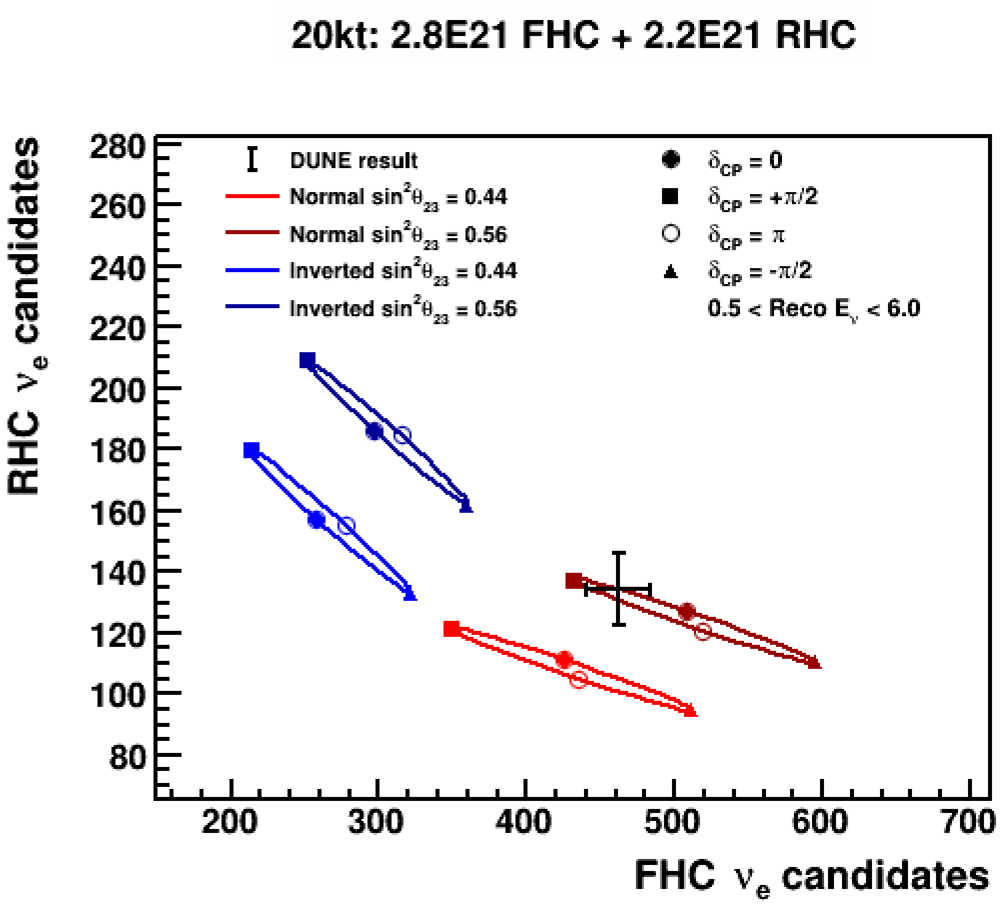


P. Dunne, Neutrino2020



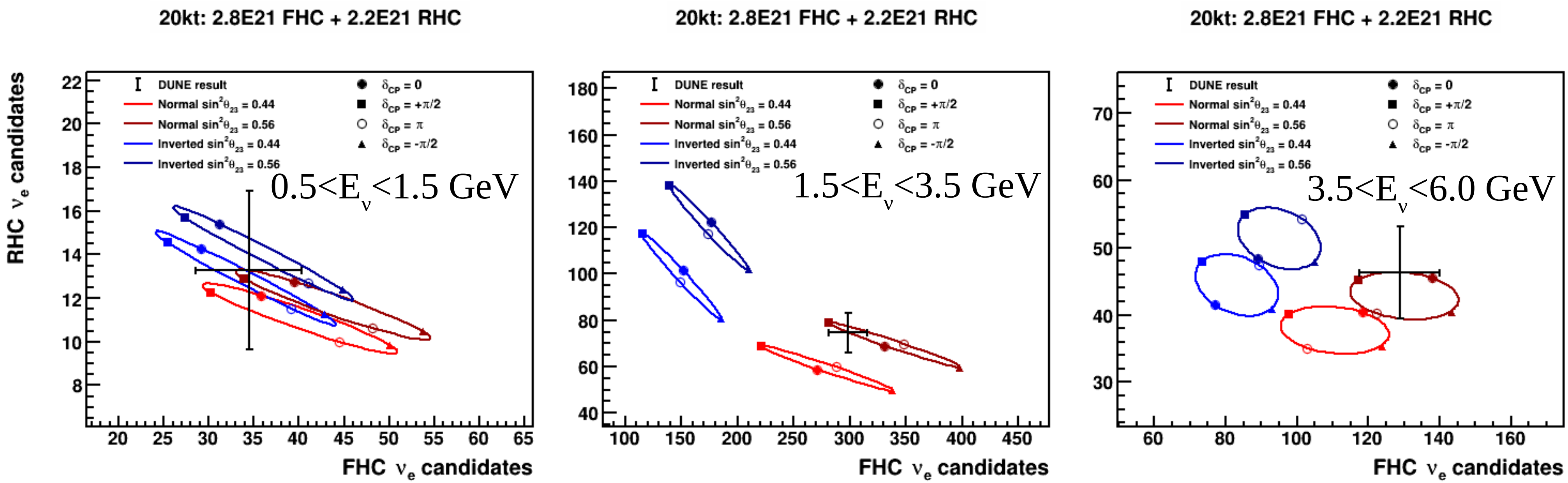
A. Himmel, Neutrino2020

DUNE's long baseline separates the ellipses → no degeneracy



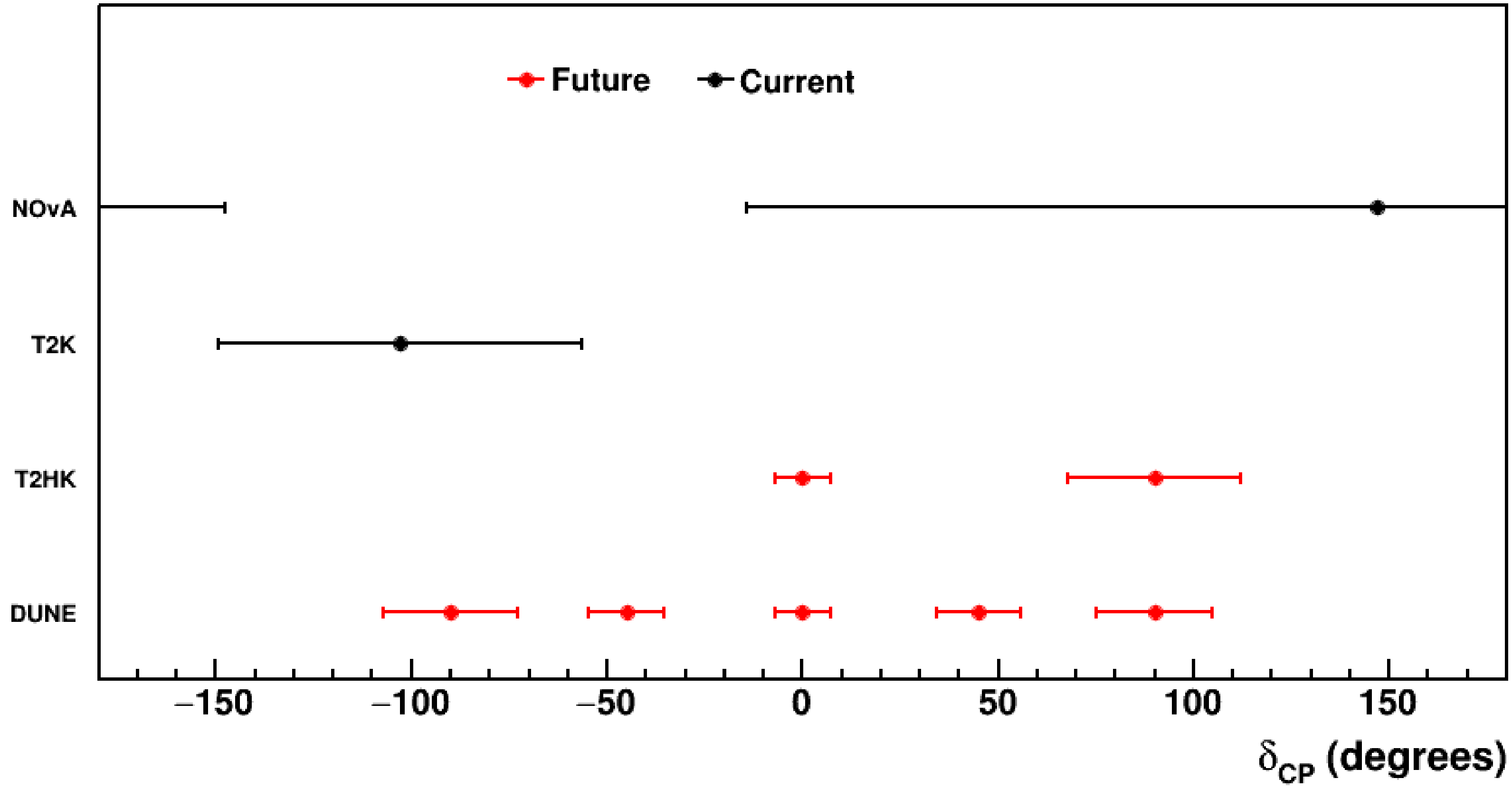
- Data point shows a hypothetical 6-year DUNE Phase I measurement, integrated over 0.5-6 GeV
- Mass ordering flips between blue and red → there is no degeneracy in DUNE due to the very long baseline

Spectral information from DUNE's wideband beam



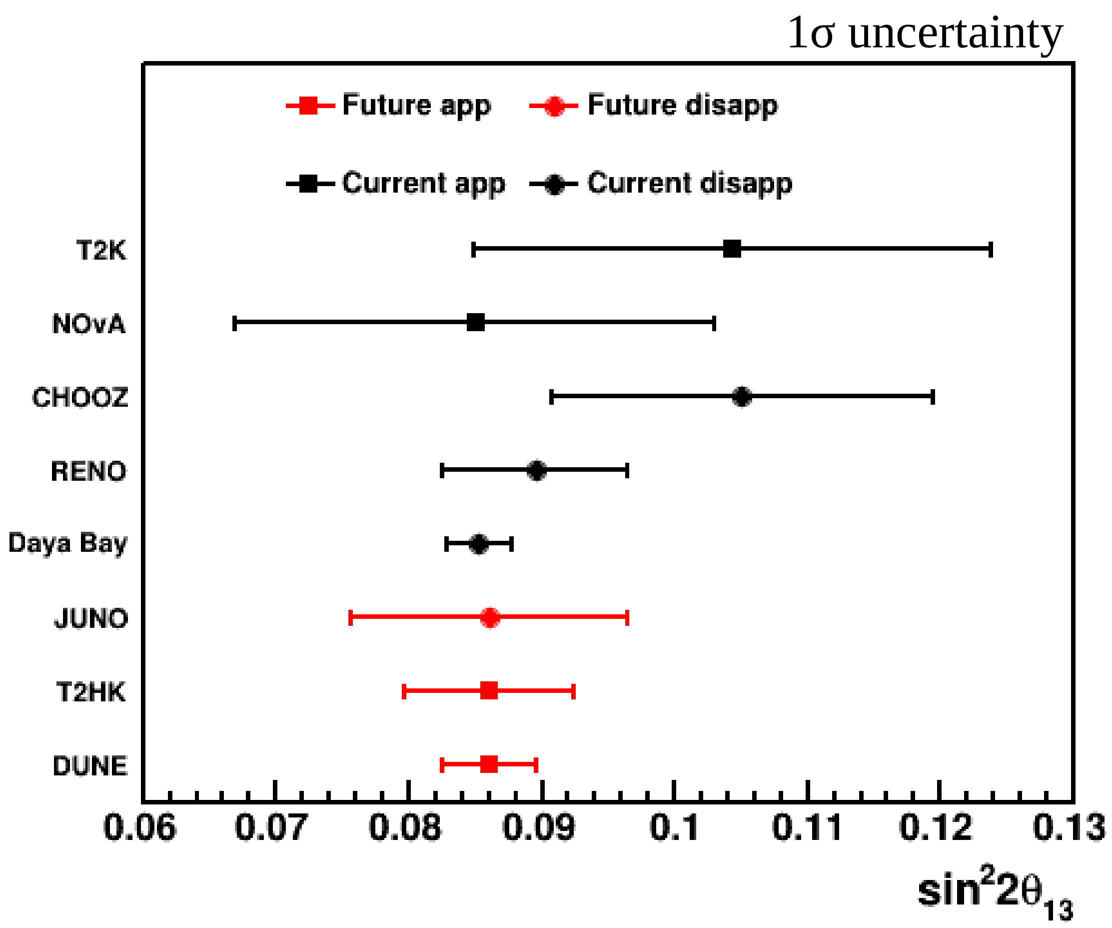
- But DUNE does not just count events, we measure energy → essentially DUNE can make this plot 20 times in different energy bins
- The shape of the ellipses is different at different L/E → further resolve degeneracy between parameters by incorporating spectral information
- LArTPC technology is motivated by the need to *measure* neutrino energy over a broad range

δ_{CP}



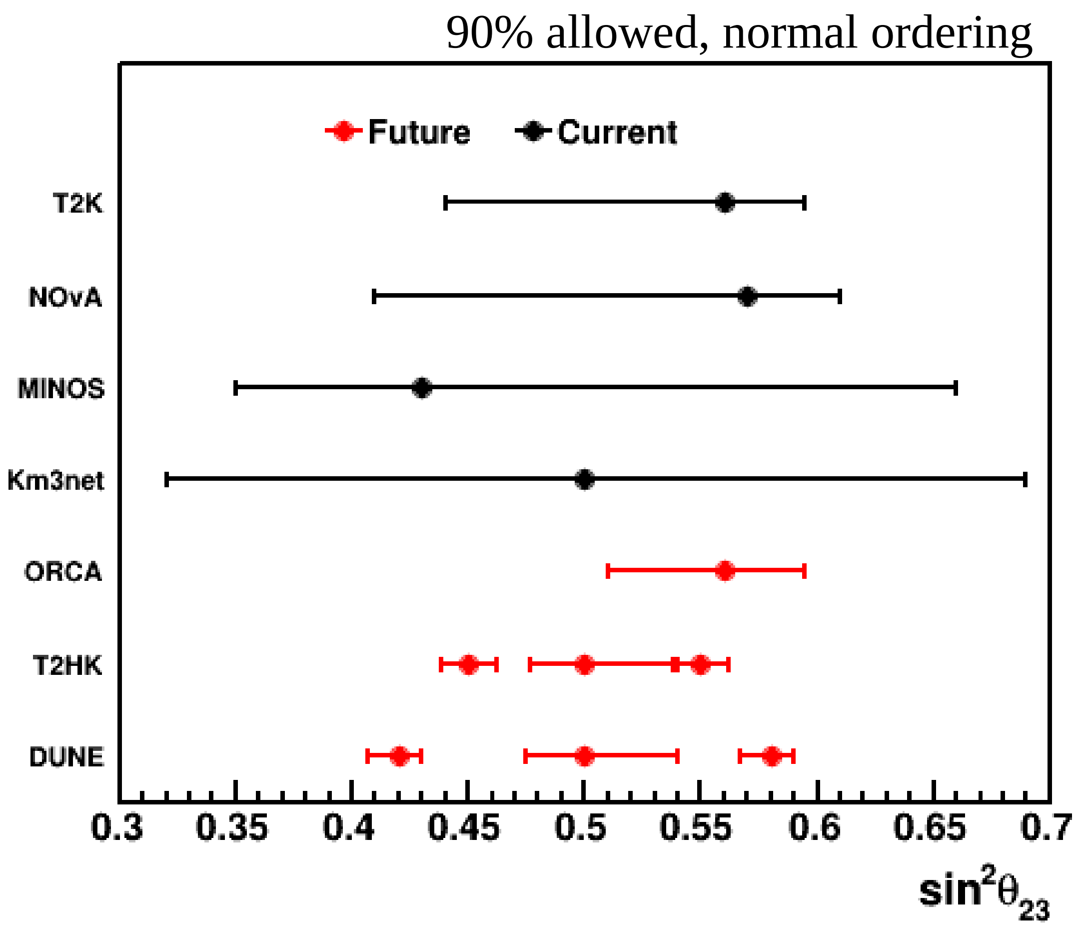
- T2HK and DUNE have comparable precision at δ=0, DUNE is slightly better at δ=π/2
- For values in between 0 and π/2, wideband beam is incredibly important for DUNE to measure δ, for narrow L/E one is only sensitive to sin(δ)

θ_{13}



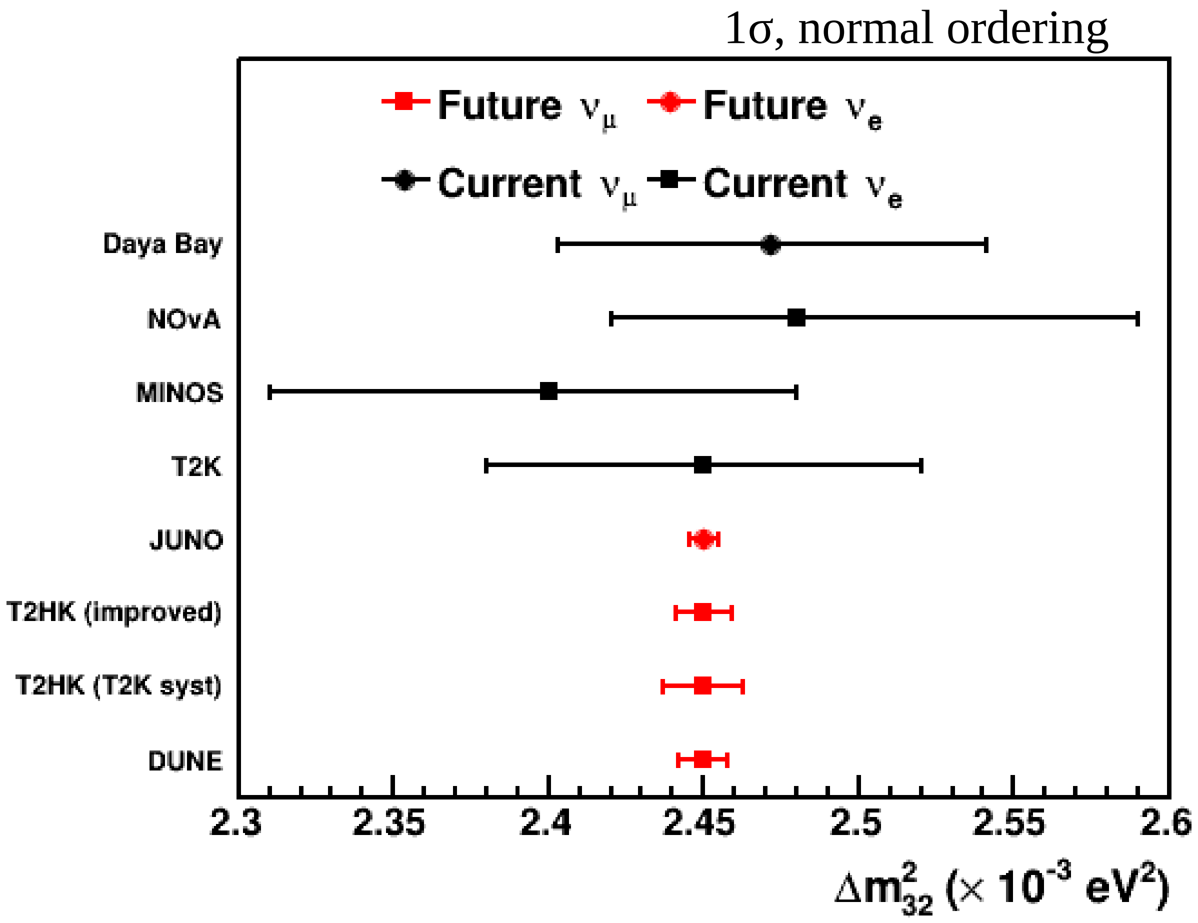
- Daya Bay has world-best 2.8% precision, which will not be surpassed
- Comparing measurements from appearance and disappearance is a non-unitarity test – DUNE has by far the best precision of any appearance experiment

θ_{23}



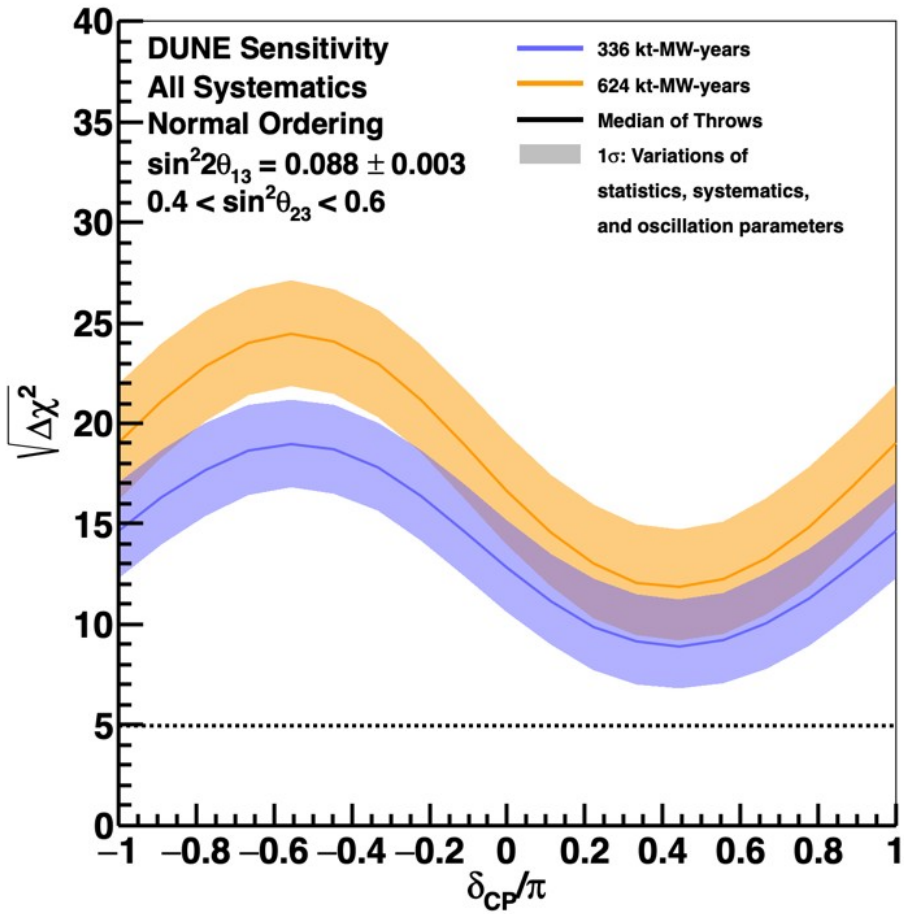
- Current experiments cannot distinguish octant at 90% level
- DUNE and T2HK have similar precision, and excellent ability to distinguish octant if it is non-maximal → test for flavor symmetry in neutrino mixing

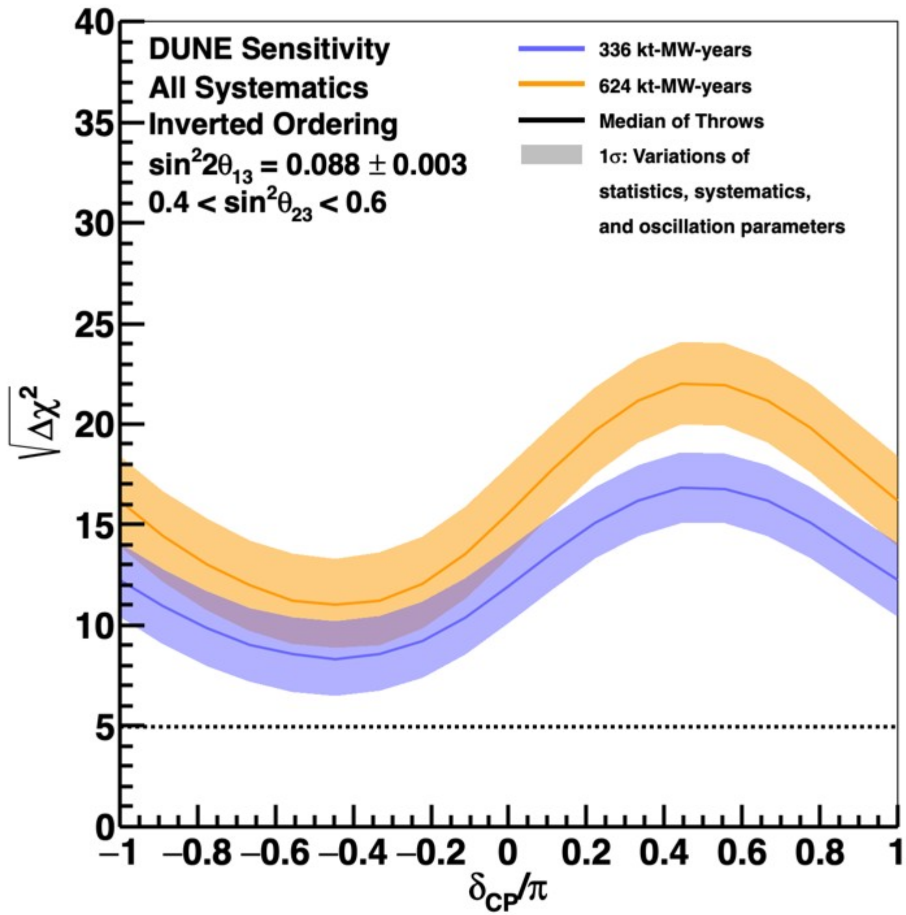
Δm^2_{32}



- Future experiments will greatly improve on current precision
- JUNO has best overall precision
- DUNE precision is ~6x better than any current experiment

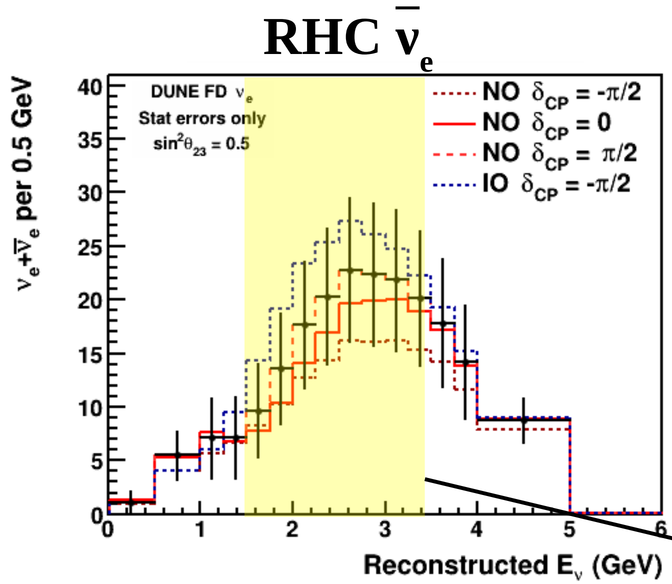
Physics potential: Mass ordering

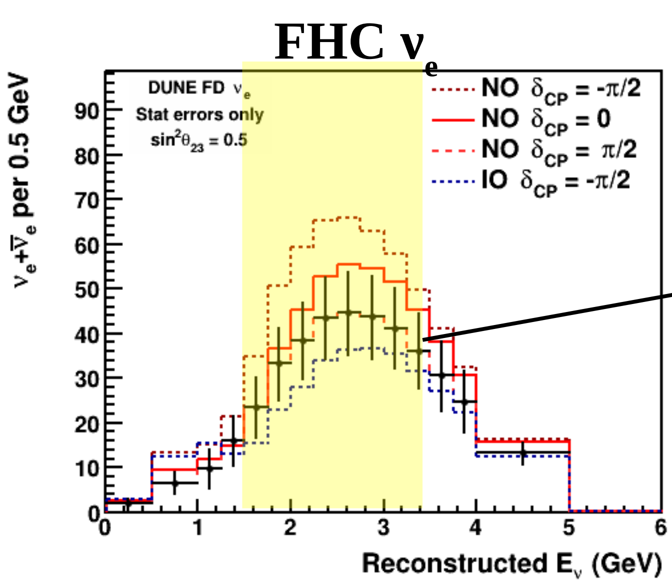


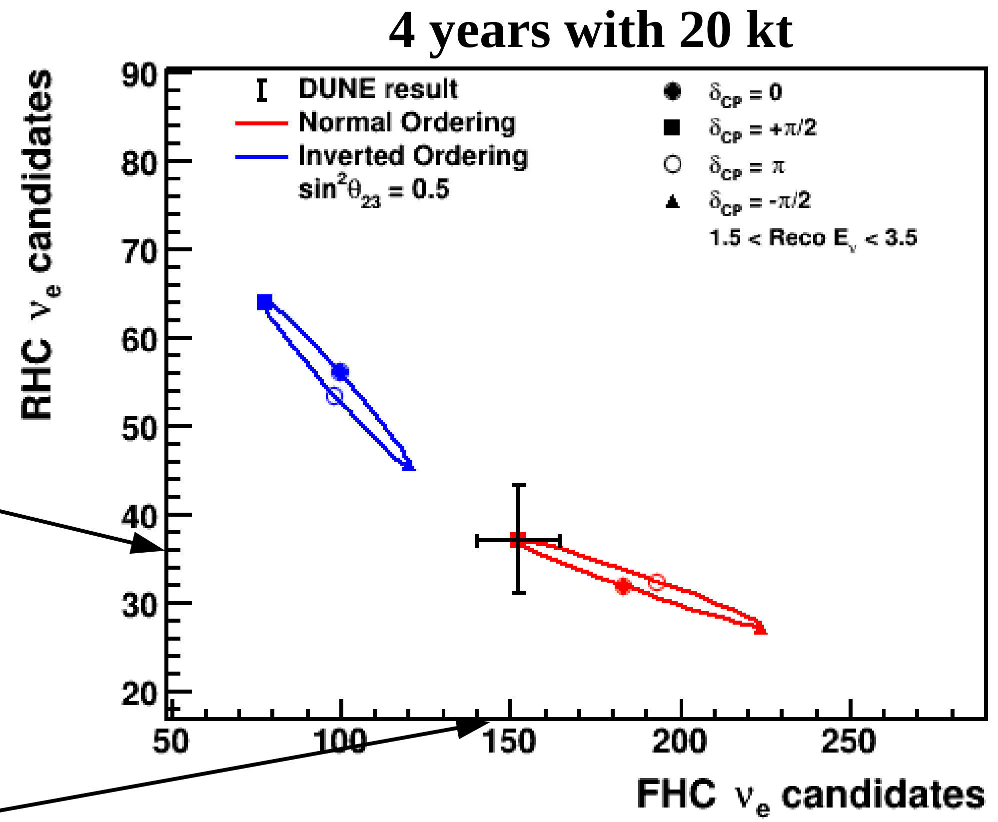


- Regardless of the values of other parameters, and without dependence on other experiments, DUNE has unprecedented and unrivaled ability to definitively resolve the mass ordering

Mass ordering in DUNE: 20 kt 4 yrs



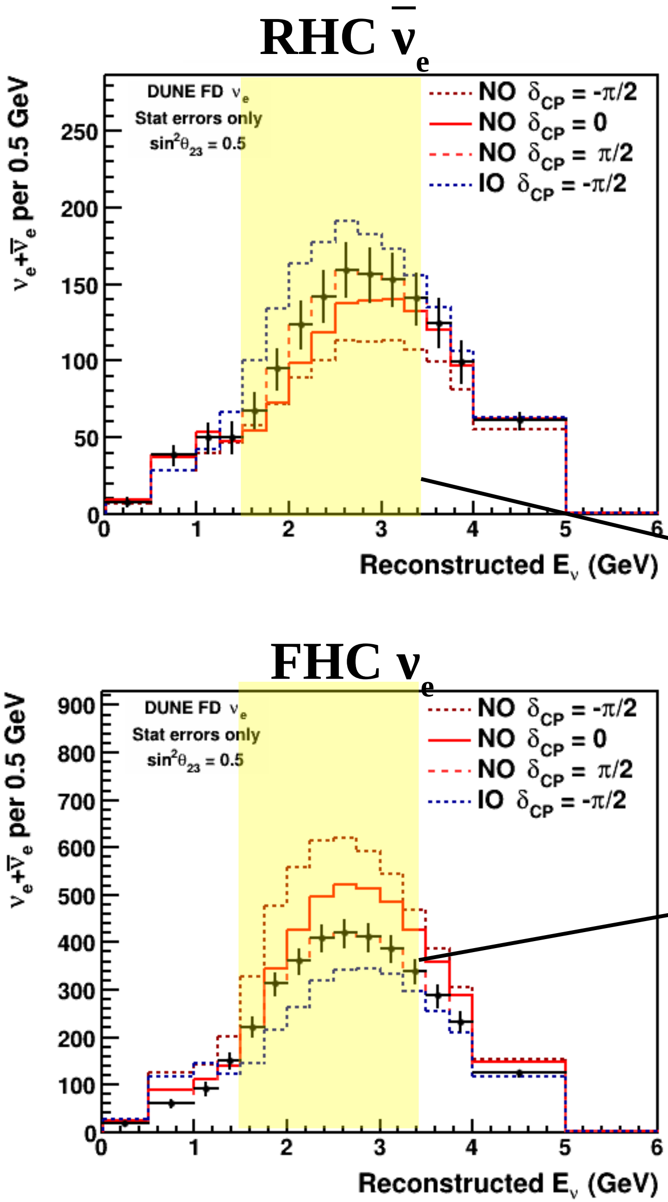


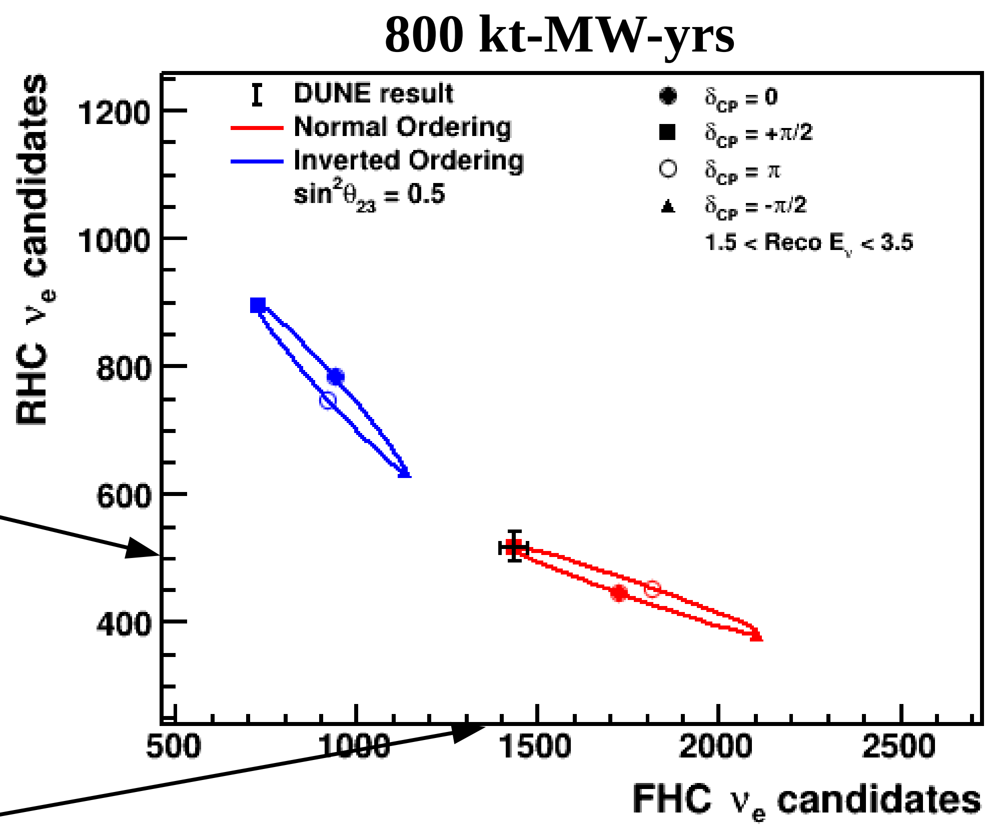


- First 4 years of running with 2 FD modules in most conservative beam ramp to 1.2 MW
- Large difference between NO & IO expectations are derived directly from ND → clear discovery

UNIVERSITY of ROCHESTER

Mass ordering in DUNE: long term

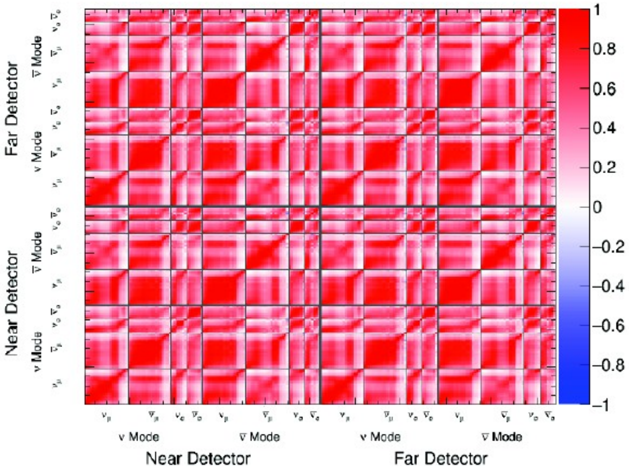




- After 6 years of full DUNE with 2.4 MW (800 kt-MW-yrs total exposure)
- Enormous difference between NO & IO expectations are derived directly from ND → clear discovery

Detailed treatment of systematics from flux, cross section, detector

Flux unc. correlation matrix



FD response parameterization

$$E'_{rec} = E_{rec} \times (p_0 + p_1\sqrt{E_{rec}} + \frac{p_2}{\sqrt{E_{rec}}})$$

Particle type	Allowed variation		
	p_0	p_1	p_2
all (except muons)	2%	1%	2%
μ (range)	2%	2%	2%
μ (curvature)	1%	1%	1%
p, $\pi^{\pm}$	5%	5%	5%
e, γ, π^0	2.5%	2.5%	2.5%
n	20%	30%	30%

GENIE reweight parameters

Description	1σ
Quasielastic	
Axial mass for CCQE	$^{+0.25}_{-0.15}$ GeV
CCQE vector form factors (BBBA05 ↔ Dipole)	N/A
Fermi surface momentum for Pauli blocking	±30%
Low W	
Axial mass for CC resonance	±0.05 GeV
Vector mass for CC resonance	±10%
Branching ratio for $\Delta \to \eta$ decay	±50%
Branching ratio for $\Delta \to \gamma$ decay	±50%
θ_π distribution in Δ rest frame (isotropic → RS)	N/A
High W	
$A_{\rm HT}$ higher-twist in BY model scaling variable ξ_w	±25%
$B_{\rm HT}$ higher-twist in BY model scaling variable ξ_w	±25%
$C_{\rm V1u}$ valence GRV98 PDF correction in BY model	±30%
$C_{\rm V2u}$ valence GRV98 PDF correction in BY model	±40%
Other neutral current	
Axial mass for NC elastic	±25%
Strange axial form factor η for NC elastic	±30%
Axial mass for NC resonance	±10%
Vector mass for NC resonance	±5%
Misc.	
Vary effective formation zone length	±50%

FSI parameters

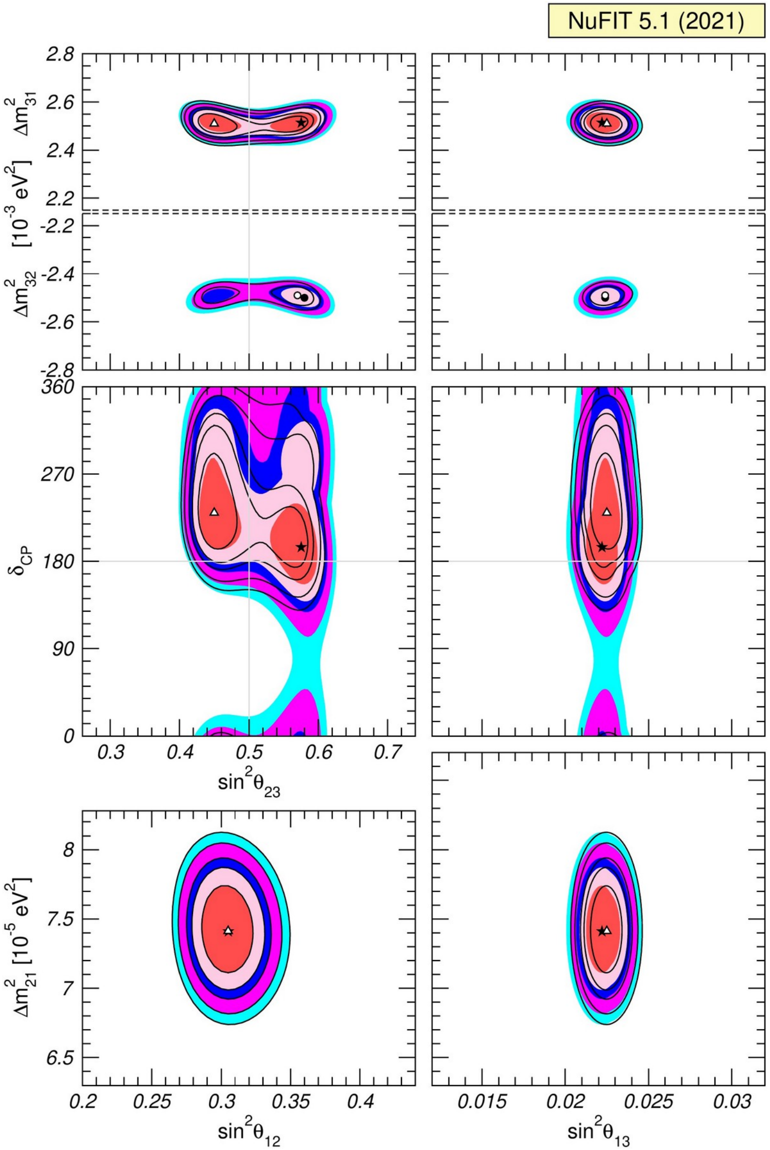
Description	1σ
Nucleon charge exchange probability	±50%
Nucleon elastic reaction probability	±30%
Nucleon inelastic reaction probability	±40%
Nucleon absorption probability	±20%
Nucleon π-production probability	±20%
π charge exchange probability	±50%
π elastic reaction probability	±10%
π inelastic reaction probability	±40%
π absorption probability	±20%
π π-production probability	±20%

Custom DUNE uncertainties

Uncertainty	Mode
BeRPA	$1p1h$/QE
MnvTune1	$2p2h$
MnvTuneCV	$2p2h$
MnvTune2	$1p1h$/QE
ArC2p2h	$2p2h$ Ar/C scaling
E_{2p2h}	$2p2h$
Low Q^2 1π	RES
MK model	ν_μ CC-RES
CC Non-resonant $\nu \to \ell + 1\pi$	ν DIS
Other Non-resonant π	$N\pi$ DIS
$\nu_\mu \to \nu_e$	$\nu_e/\overline{\nu}_e$
$\nu_e/\overline{\nu}_e$ norm	$\nu_e,\overline{\nu}_e$

UNIVERSITY of ROCHESTER

Neutrino oscillations: what we know in 2022

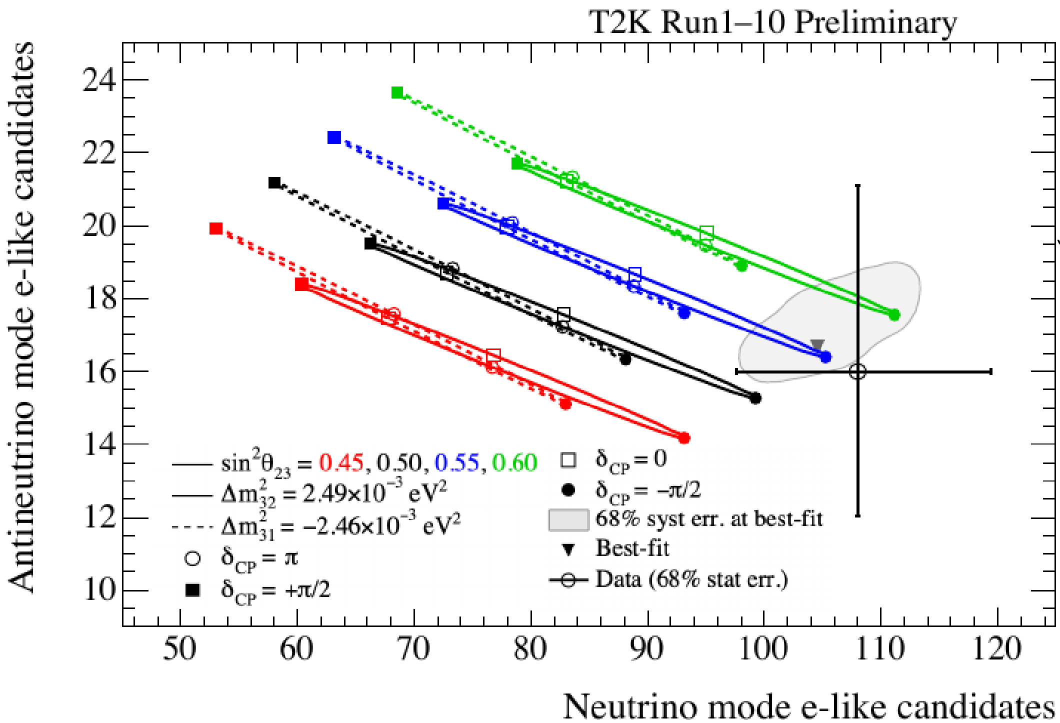


$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\rm CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\rm CP}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

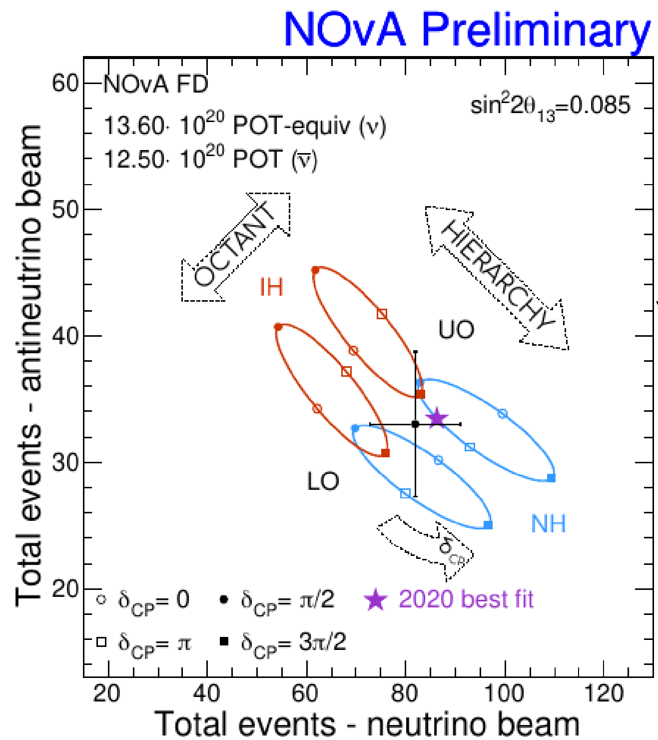
- In the νSM, the PMNS matrix is unitary and can be written in terms of three mixing angles and a CP-violating phase
- Over the past ~30 years, a worldwide program of solar, reactor, atmospheric, and accelerator neutrino experiments have measured all three mixing angles

Requirement #1: Long baseline

- Existing experiments have degeneracy between mass ordering, δ_{CP}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$
- To resolve, need very long baseline (>1000 km)



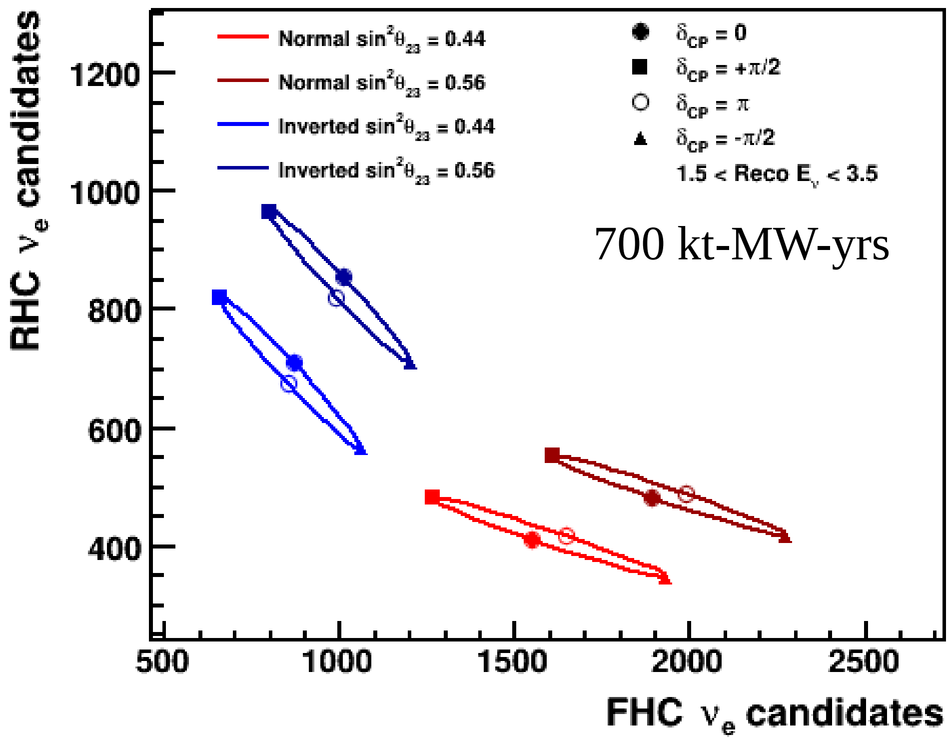
P. Dune, Neutrino2020



A. Himmel, Neutrino2020

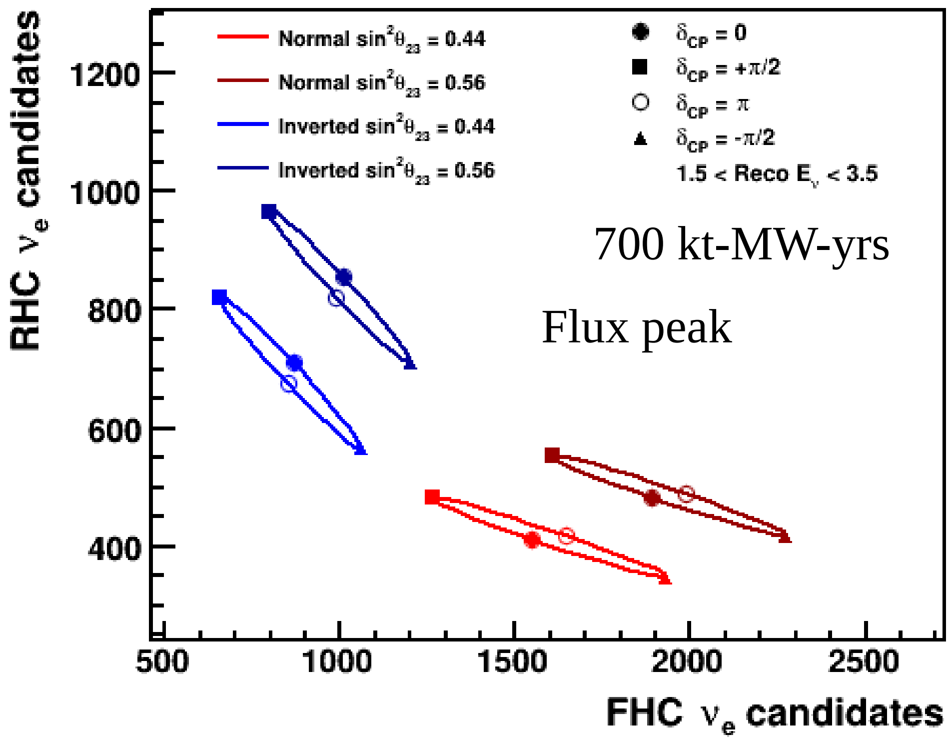
Requirement #1: Long baseline

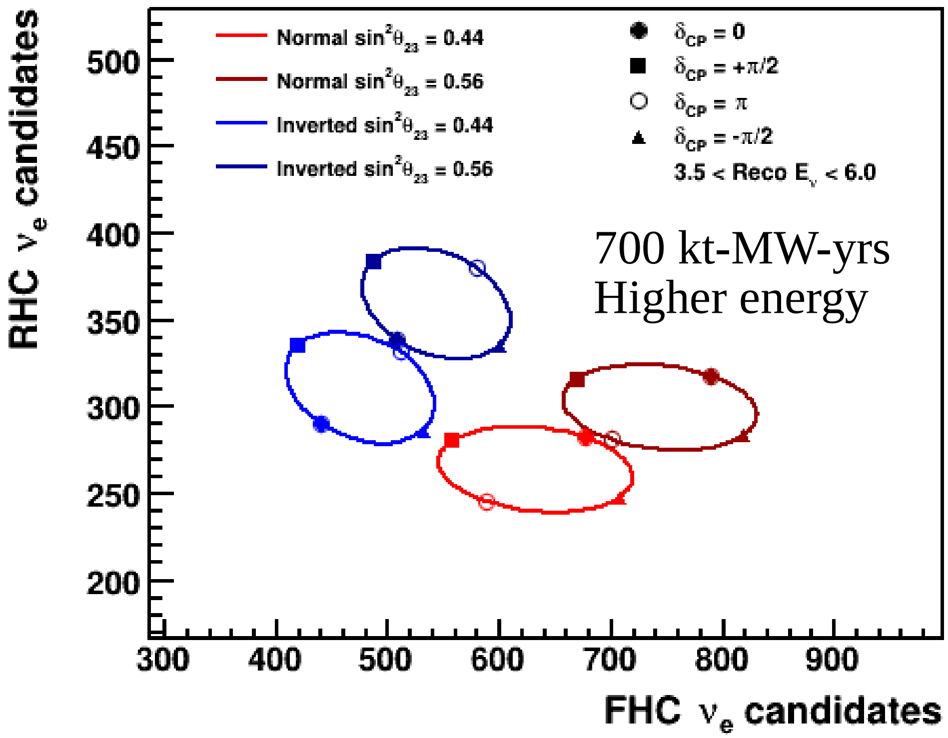
- DUNE's long baseline separates the ellipses for normal and inverted ordering → resolves ambiguity



Requirement #2: Wideband beam

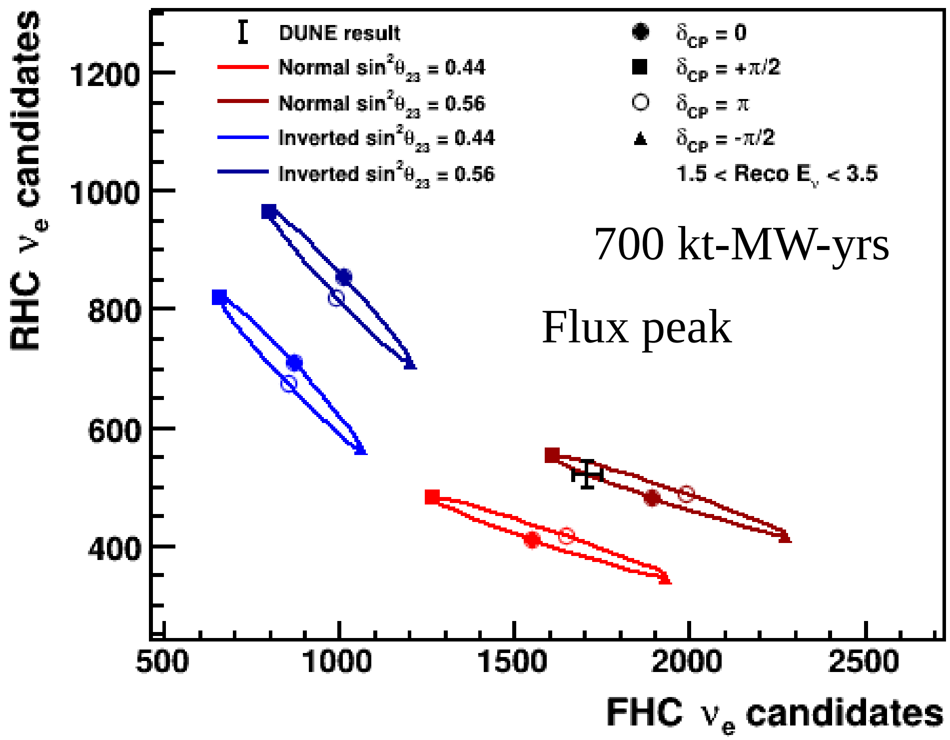
- DUNE's long baseline separates the ellipses for normal and inverted ordering → resolves ambiguity
- Parameters have different energy dependence → measuring oscillations over a full cycle resolves ambiguities

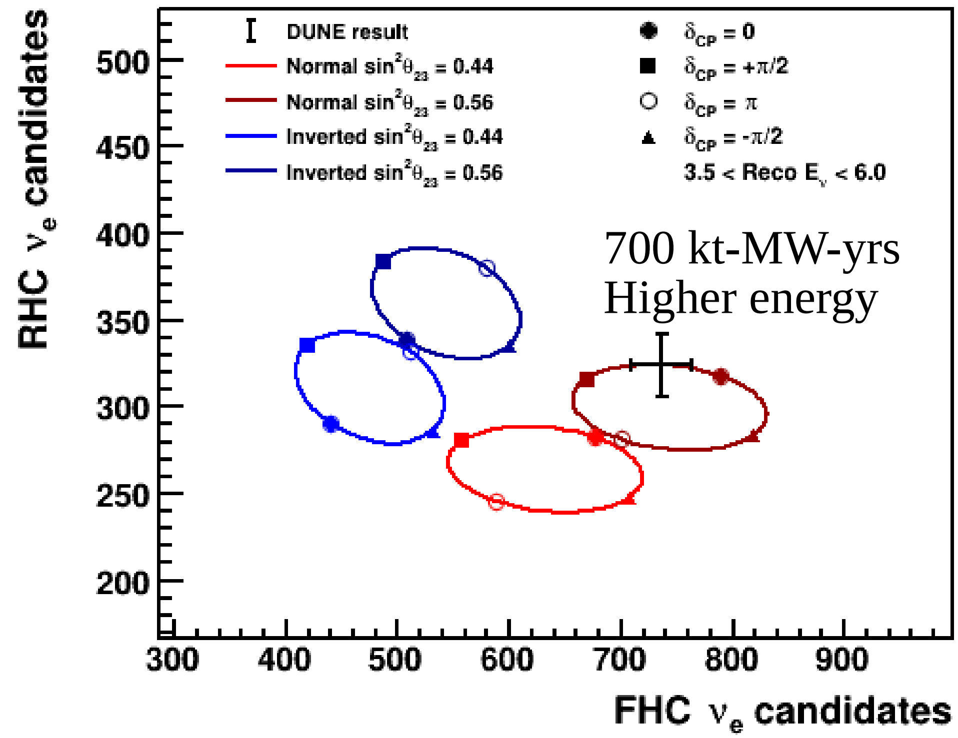




Requirement #3: Intense beam + large far detector

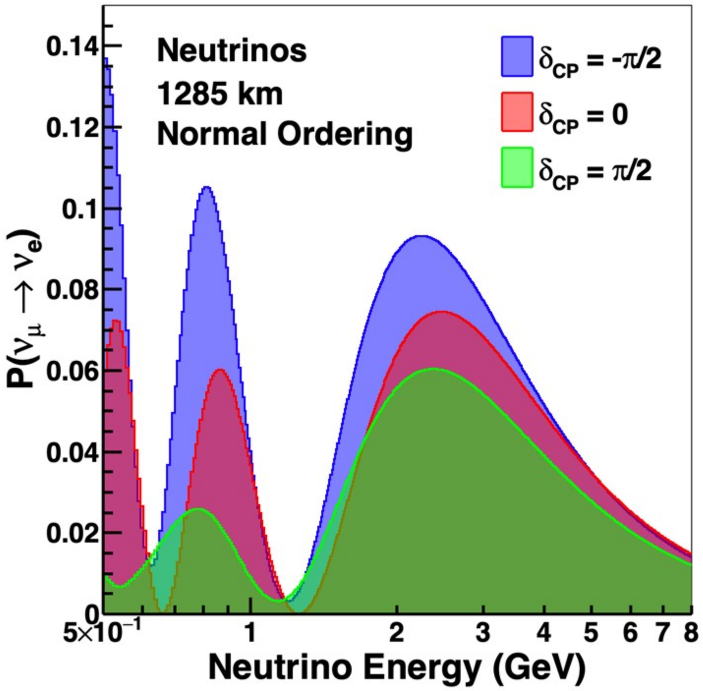
- Product of beam intensity and detector mass gives the statistical precision
- Ultimate statistical uncertainty will be ~few percent

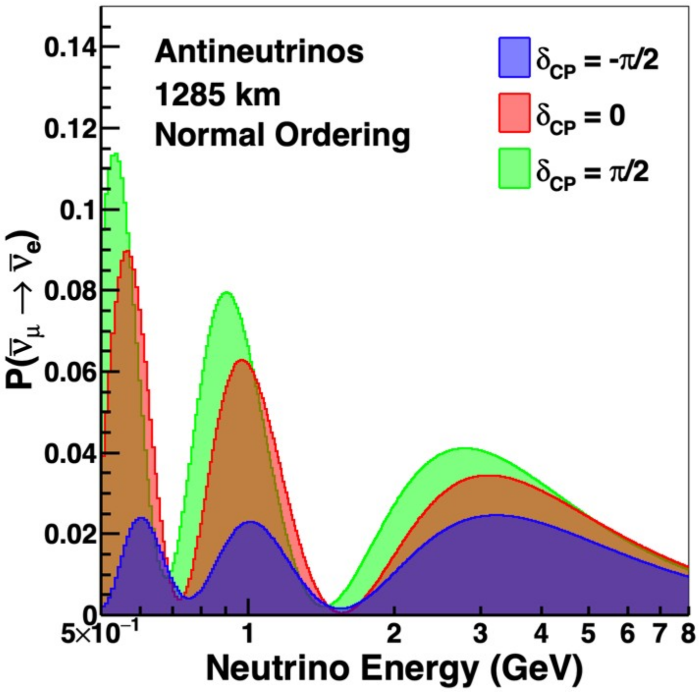




UNIVERSITY of ROCHESTER

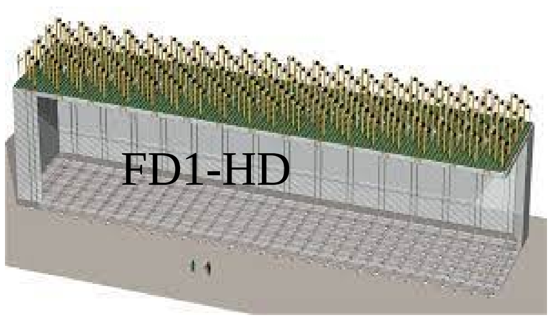
DUNE can measure oscillation probabilities, not just parameters

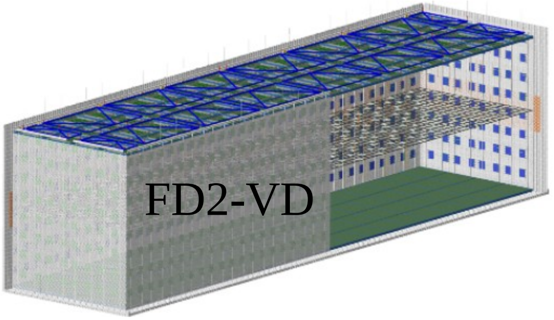


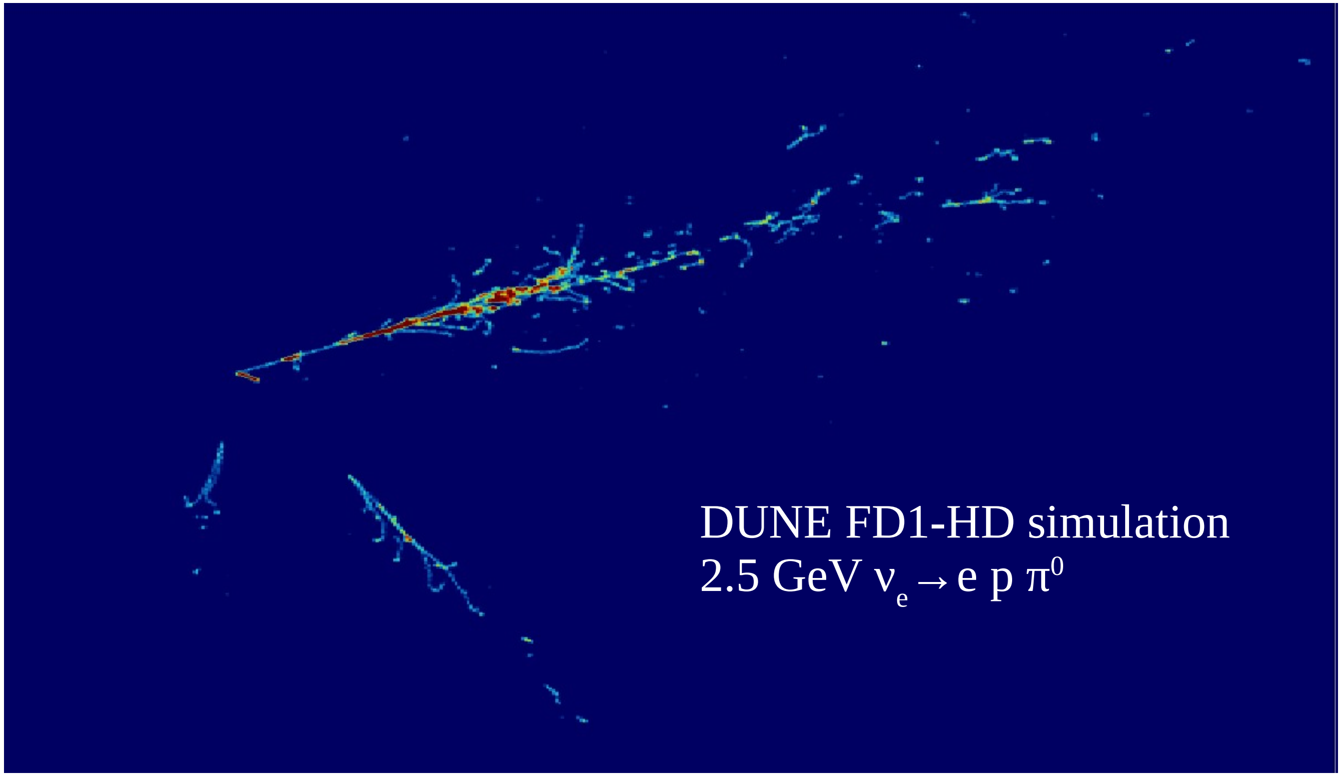


- The wideband beam gives DUNE a unique ability to measure ν_e appearance directly as a function of L/E, over more than a full oscillation period
- Resolves degeneracies in standard parameterization, but also improved sensitivity to effects beyond νSM

Requirement #4: Neutrino energy reconstruction from 0.5-5 GeV

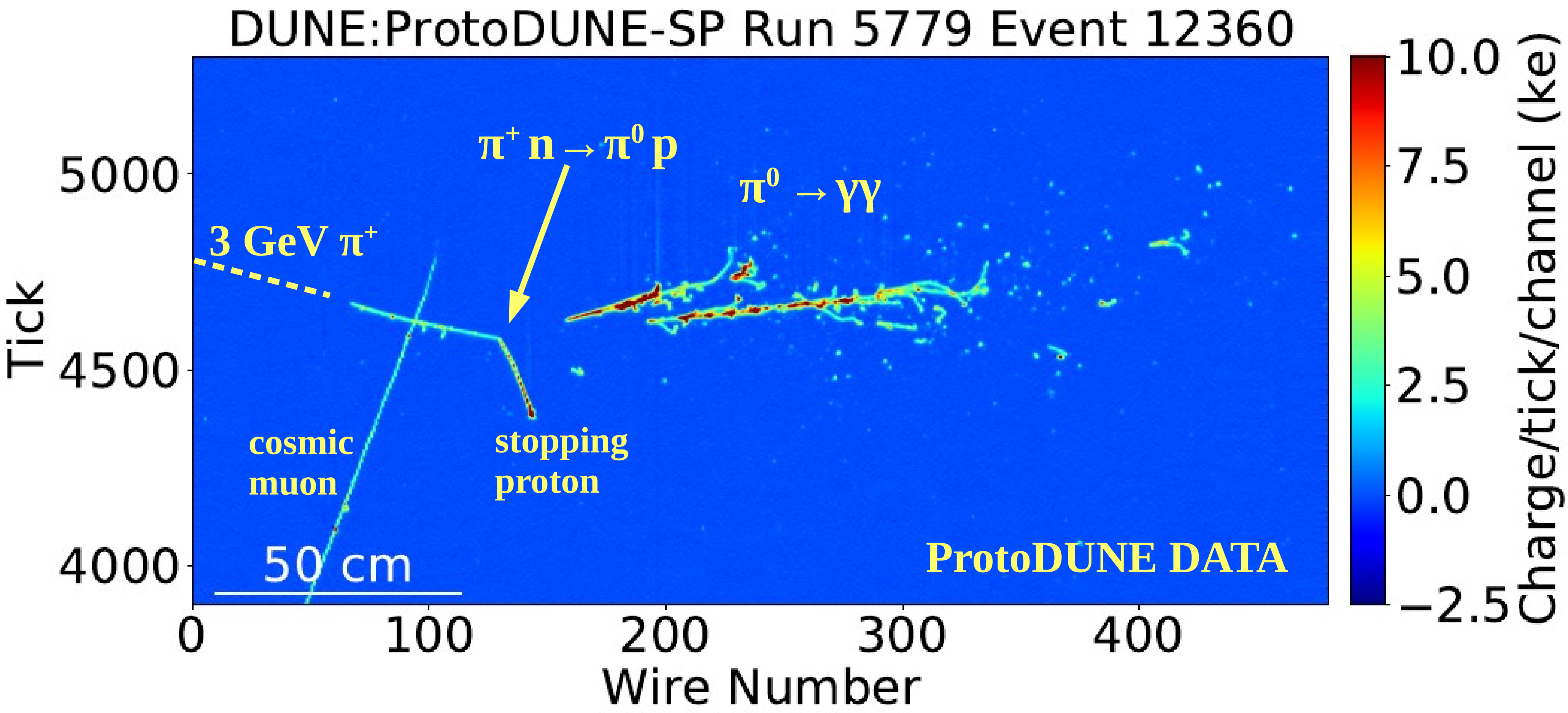






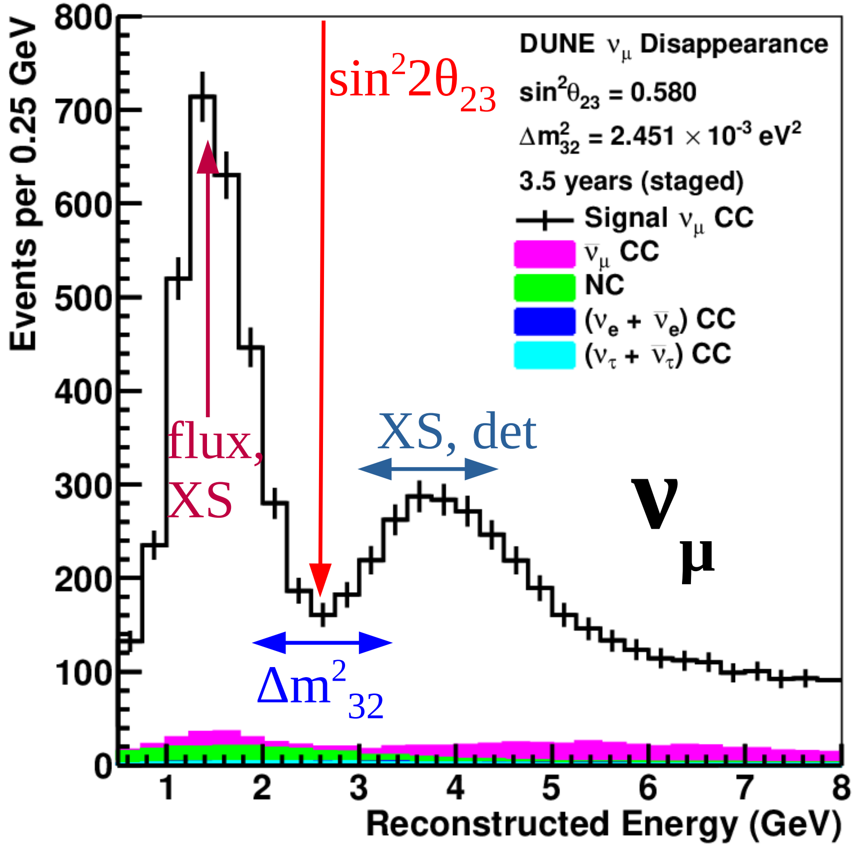
- In order to take advantage of the wideband beam, the far detector must be able to identify flavor and reconstruct neutrino energy over a broad range over energies and interaction topologies
- Exquisite imaging of **LAr TPC** fulfills both requirements, is scalable to very large detector mass, and a dedicated calibration program will provide required resolution

LAr TPC technology and DUNE design is demonstrated



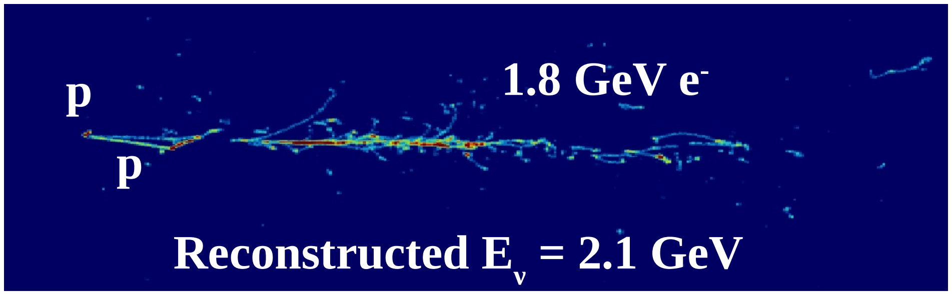
- Successful ProtoDUNE-HD run at CERN Neutrino Platform (data event shown, annotations are my guesses)

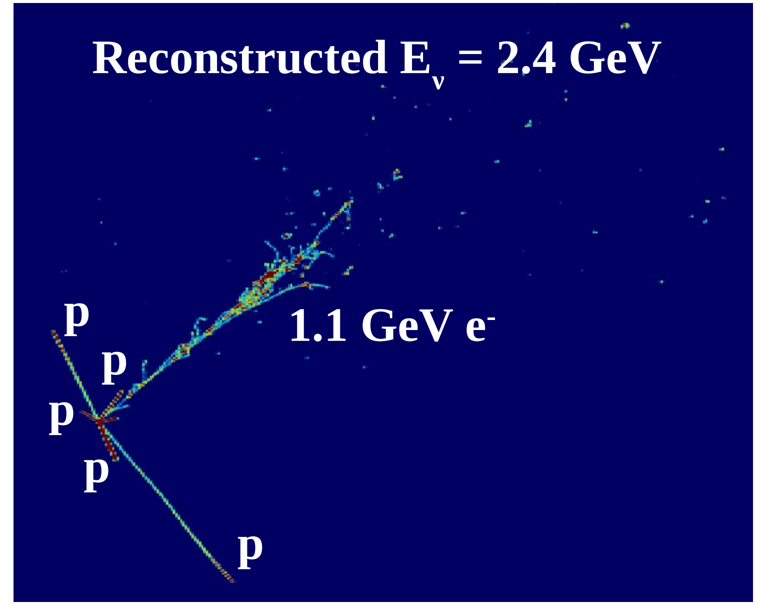
The critical role of the Near Detector at all stages of DUNE

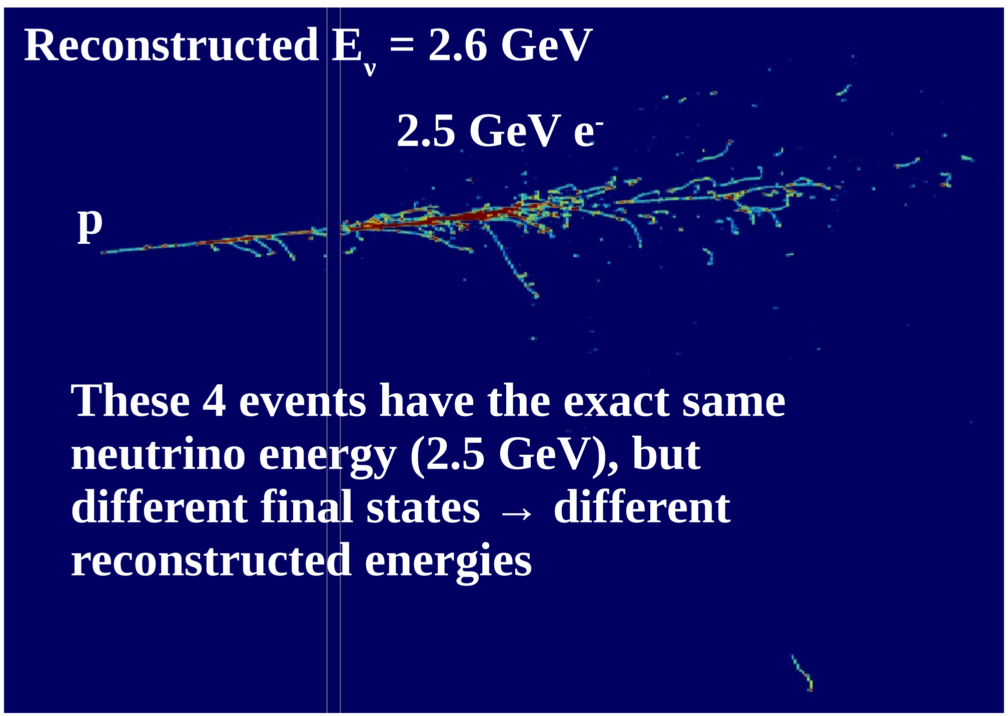


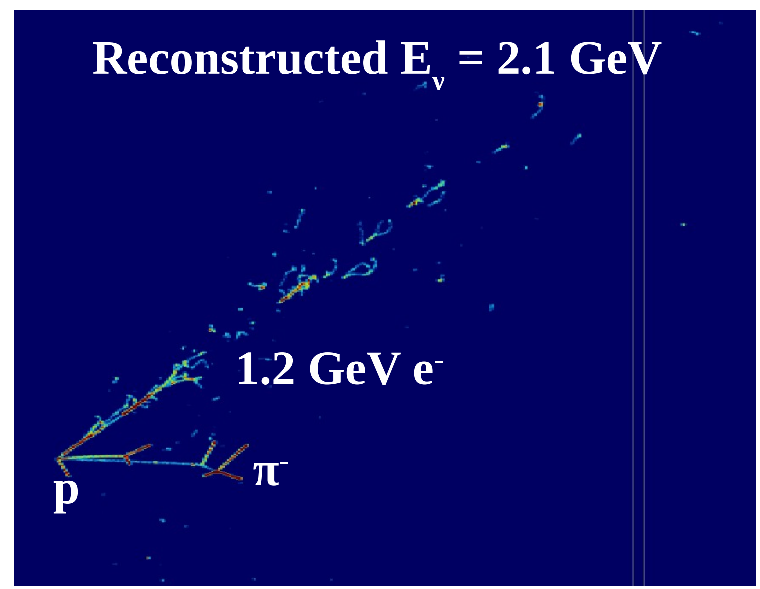
- Observed FD spectra depend on oscillation parameters, but also (strongly) on the flux, ν-Ar cross sections, and LAr TPC detector response
- Cross section uncertainties are large, 10-100% depending on the process
- It is critical to measure *how* neutrinos interact, and what we see in LArTPC

Four ν_es with the same true energy

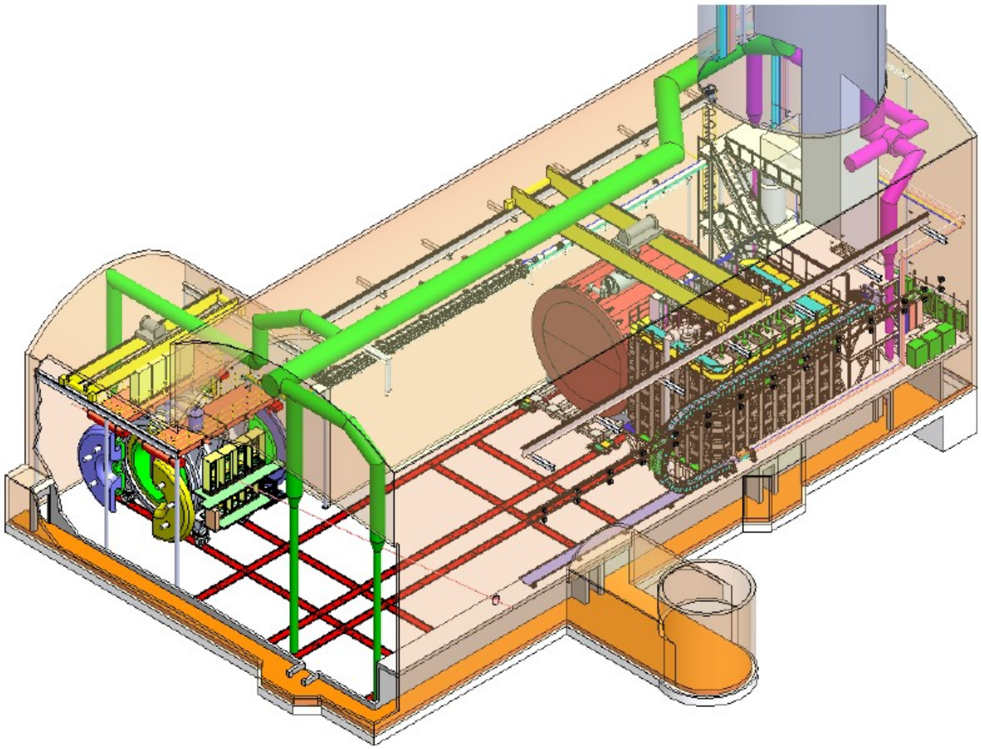


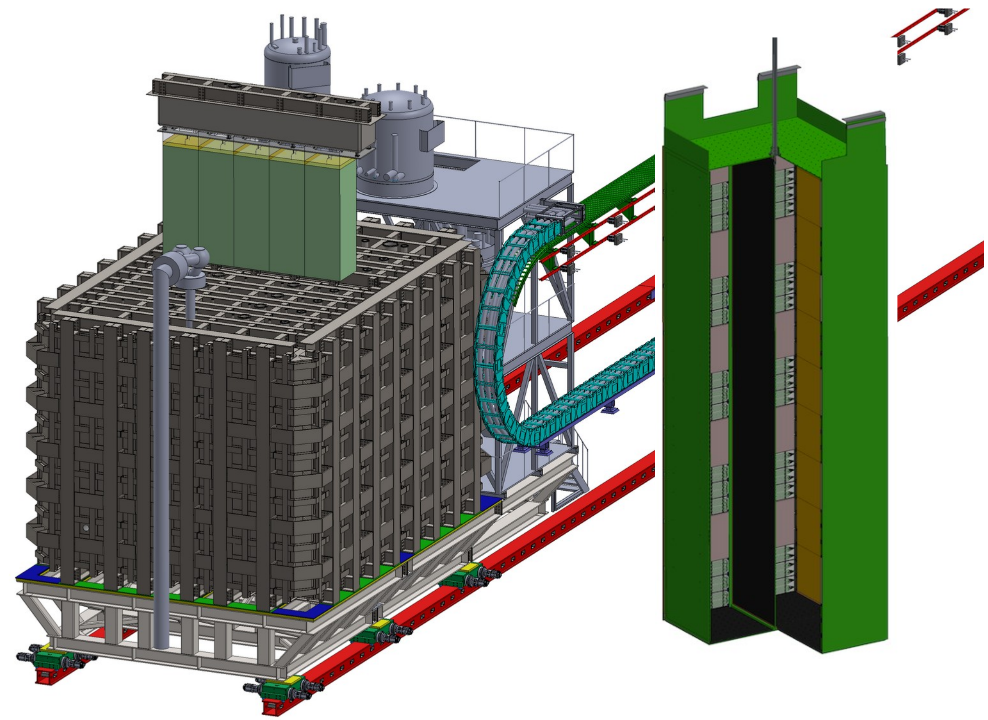






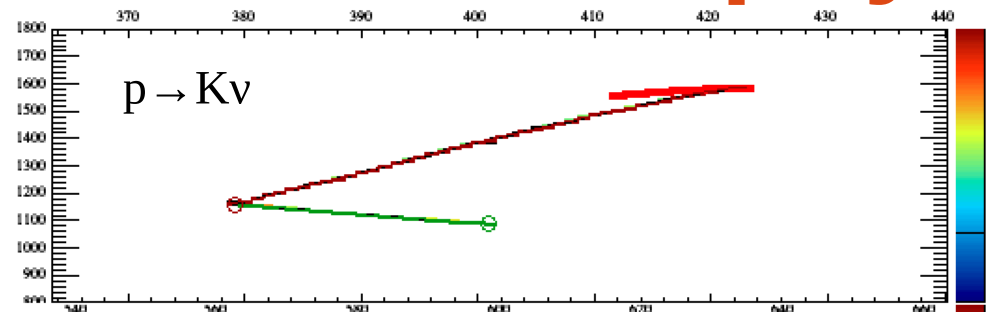
Requirement #5: Precise systematic constraints with ND including LAr TPC

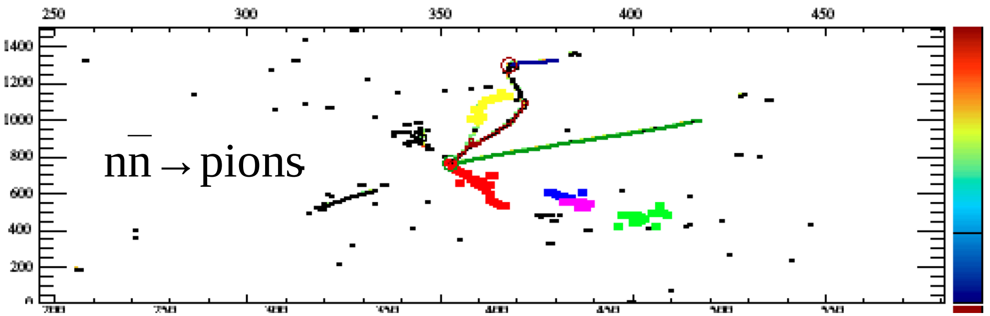


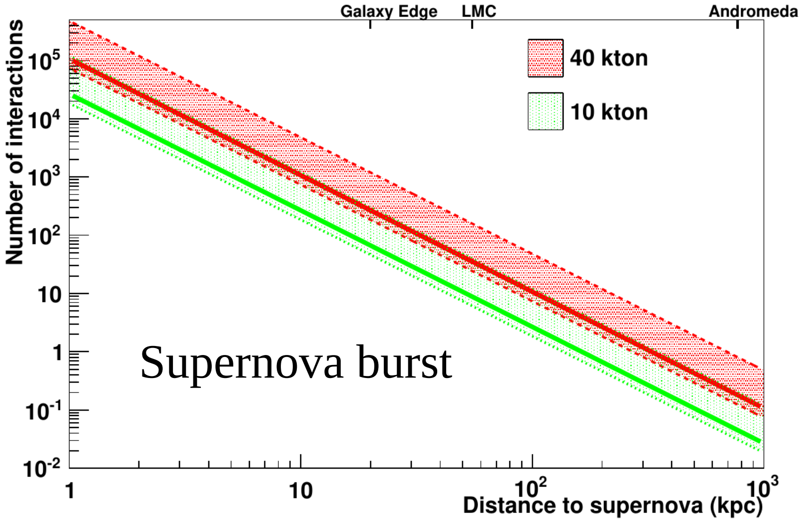


- ND must measure the flux, ν-Ar cross sections, and LAr TPC detector response
- ND-LAr is as similar as possible to FD; differences (modularity, pixelization) are to cope with high event rate & pile-up
- ND-GAr and SAND provide important additional precision constraints on neutrino interaction cross sections and broaden the capability of the ND complex

FD requirements for supernova and BSM physics program



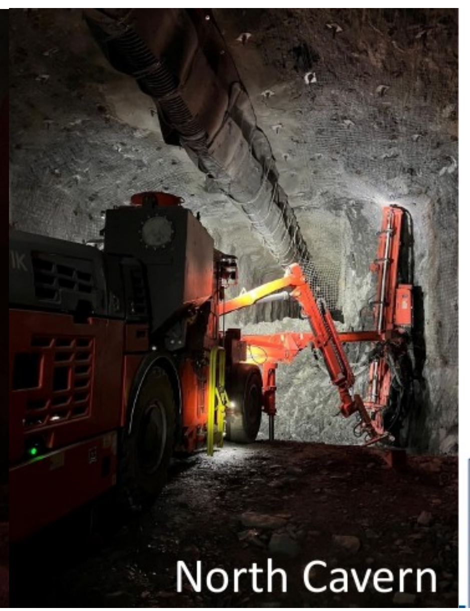


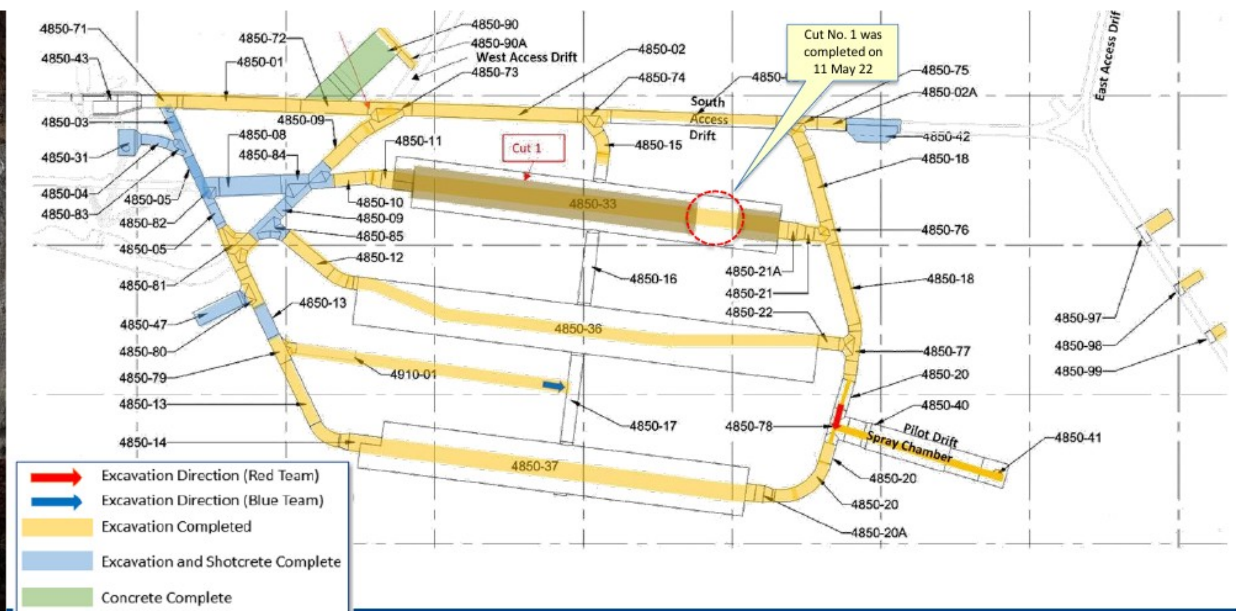


- Deep underground location to reduce cosmogenic backgrounds
- Photon detection for t_0 measurement in non-beam events
- Data acquisition: one of the driving requirements is the ability to read out an entire supernova burst signal (~1 minute)

Far site excavation is well underway at SURF

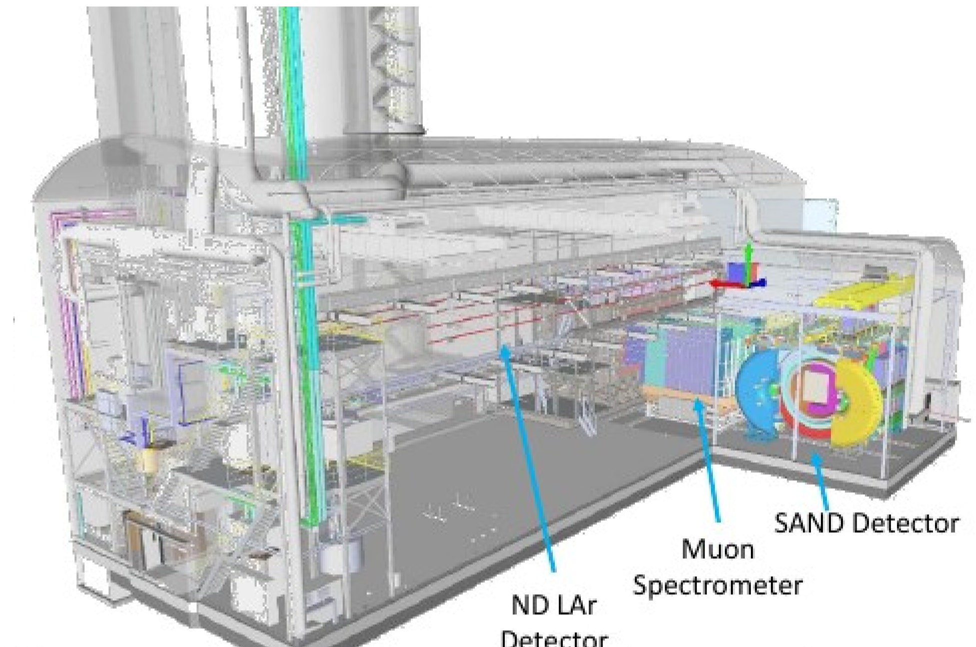
- Excavation is 27% complete by total rock volume
- Yellow shows complete excavation, including first cut of north detector cavern



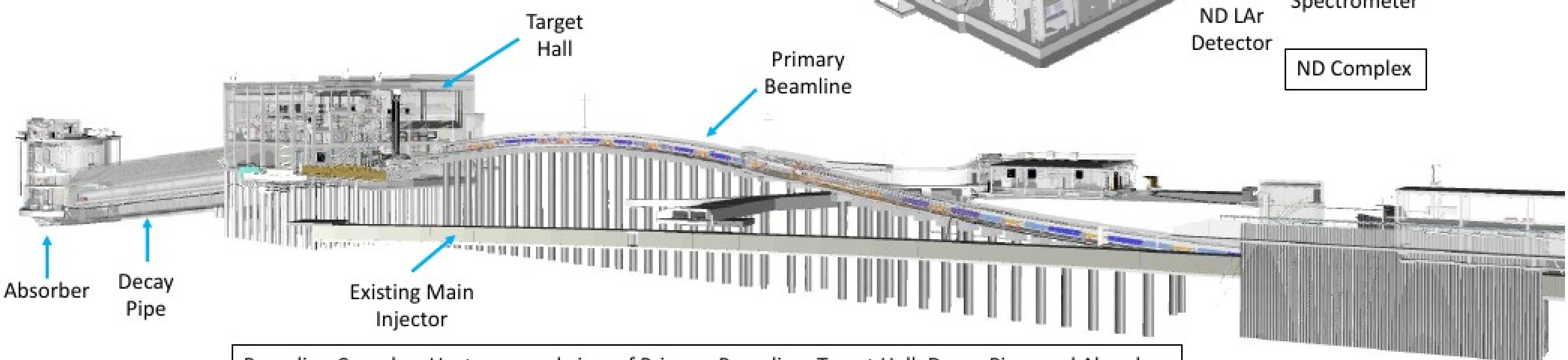


Beamline and Near Detector site at Fermilab: design is 100% complete

- Conventional facilities for the neutrino beamline and the Near Detector underground site have completed their designs



ND Complex



Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

Preparations for APA production are well underway

- “Module-0” APA was tested in CERN cold box
- Plan to install in ProtoDUNE cryostat for a second run in 2022
- APA production at Daresbury (UK) to begin this summer