Fermilab Long Baseline Experiments

Kendall Mahn
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for the DUNE, NOvA collaborations

Outline

What do we want to learn with accelerator-based neutrino sources?

What have we learned about neutrinos from NOvA?

What will we learn from DUNE?

- What is novel about DUNE's experimental setup?
- What exciting physics results will DUNE make?
- When can we expect to see first DUNE data?

Neutrino oscillation refresher

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

Flavor states

Mass states

Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS)

If U is unitary, 3 mixing angles (θ_{12} θ_{23} θ_{13}) and one phase (δ_{CP})

U_{ij} , and mass splitting Δm^2_{ij} accessible through ν_α to ν_β oscillation, given energy (E) and baseline (L)

Open questions

Is CP-invariance violated in neutrino oscillations?
- $\delta_{CP} = 0, \pi$?

What is the neutrino mass ordering? (mass hierarchy)
- Is ν_3 the heaviest?

Is ν_3 mostly ν_μ or ν_τ? (θ_{23} "octant")
- $\sin^2(\theta_{23}) > 0.5$, < 0.5, or $\sin^2(\theta_{23}) = 0.5$?
- Is there an underlying symmetry to this matrix?

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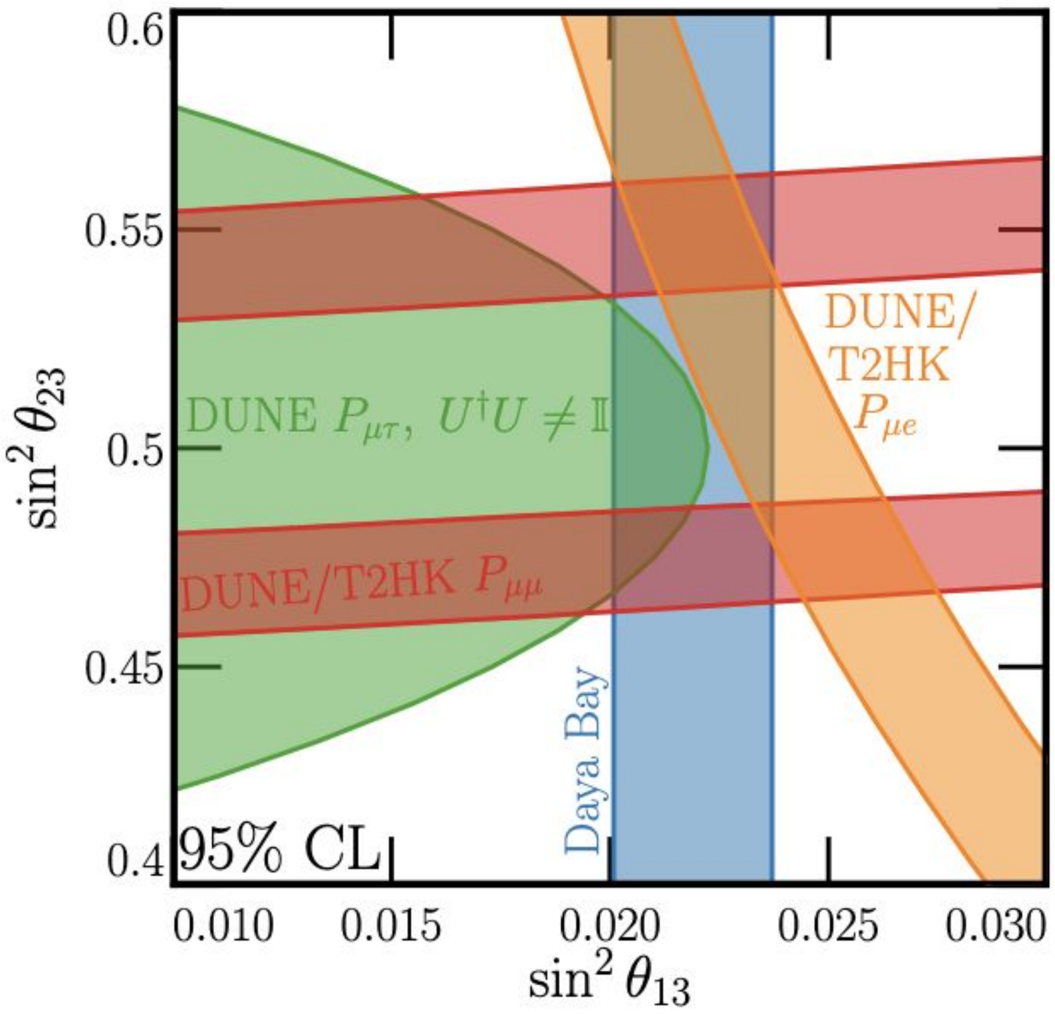
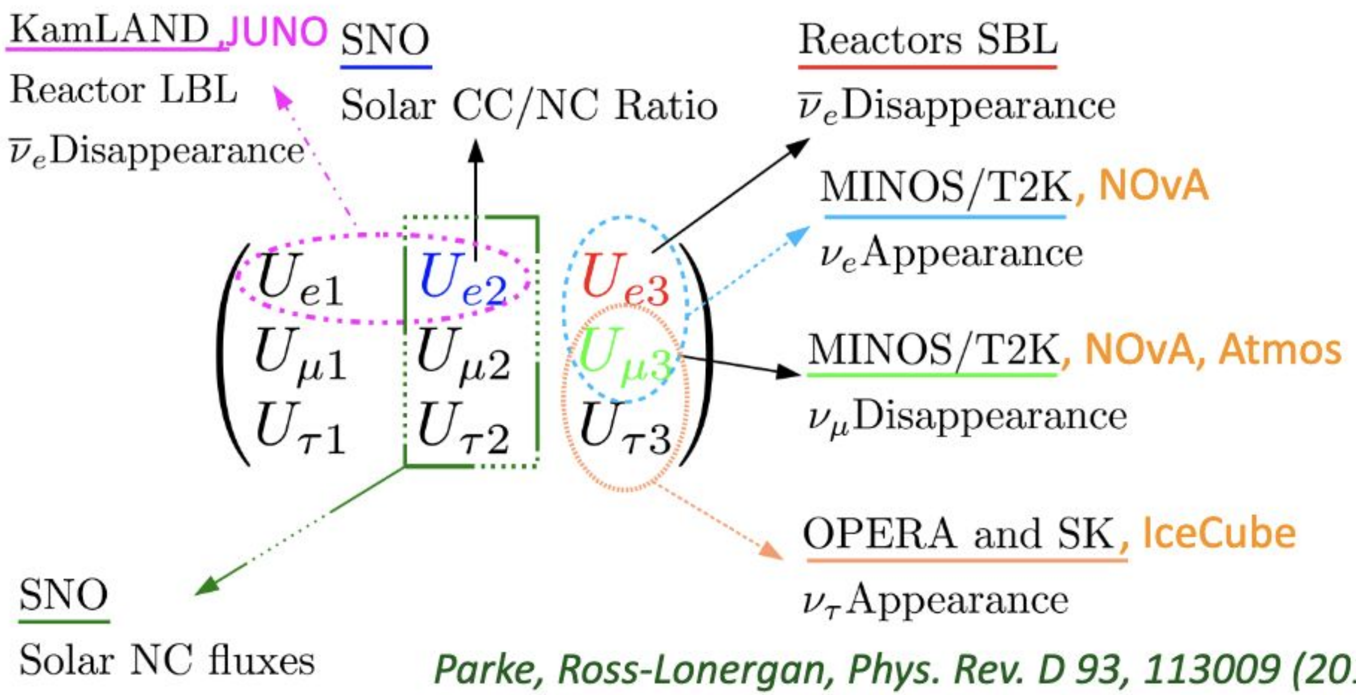
André de Govêa: "*Ultimate Goal:* ***Not Measure Parameters but Test the Formalism*** *(Over-Constrain Parameter Space)*" Snowmass Neutrino Colloquium

- BSM window - *example next page*

Example BSM window





Parke, Ross-Lonergan, Phys. Rev. D 93, 113009 (2016)
Sebastian, Ellis, Kelly, Li, JHEP 68 (2020)

Slide thanks to A. Sousa - “Almost any process involving neutrinos will be affected by the introduced non-unitarity” , see also NPN2025 intro

Open questions

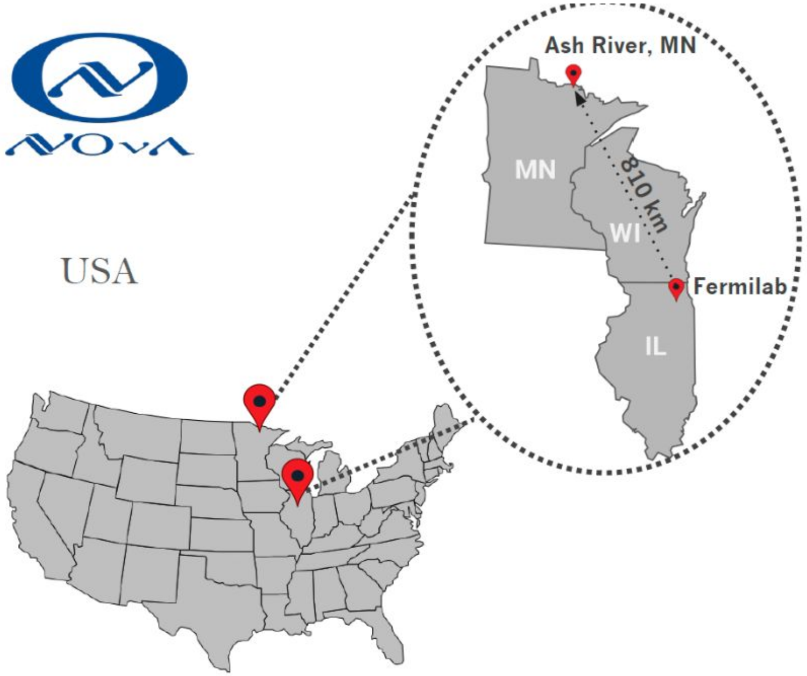
What is the neutrino mass ordering?
(mass hierarchy)

- Is ν_3 the heaviest?

Sensitivity the mass ordering from interactions of ν_e (and electrons) in matter - *complementary to JUNO*

Mass ordering **important to cosmology, and astrophysics, neutrinoless double beta decay**

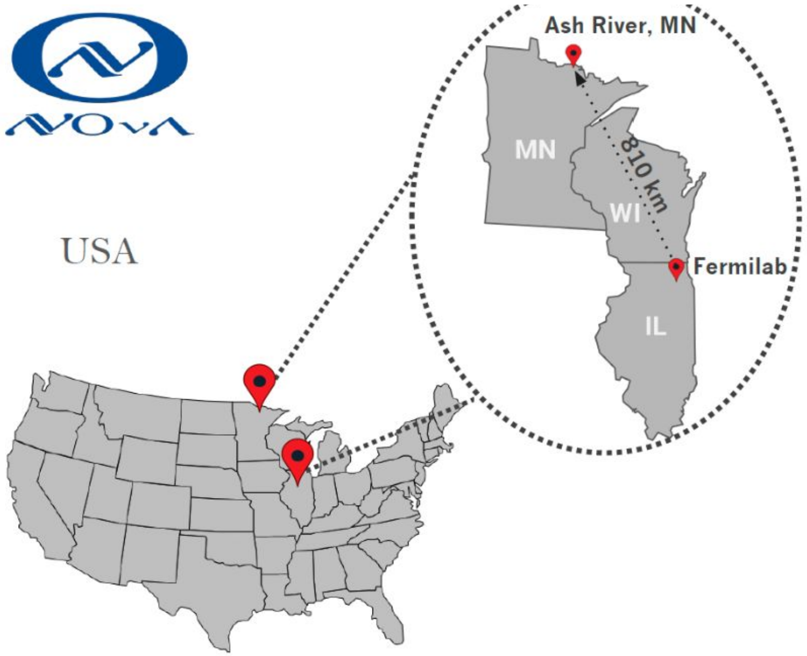
Current long baseline neutrino experiments



The T2K (Tokai-to-Kamioka) and NOvA (NuMI off-axis ν_e appearance) experiments are accelerator based neutrino oscillation experiments

Current long baseline neutrino experiments

	T2K	NOvA
Baseline	295km	810km
Peak neutrino energy	0.6 GeV	2 GeV
CP effect	**32%**	22%
Matter effect	9%	**29%**



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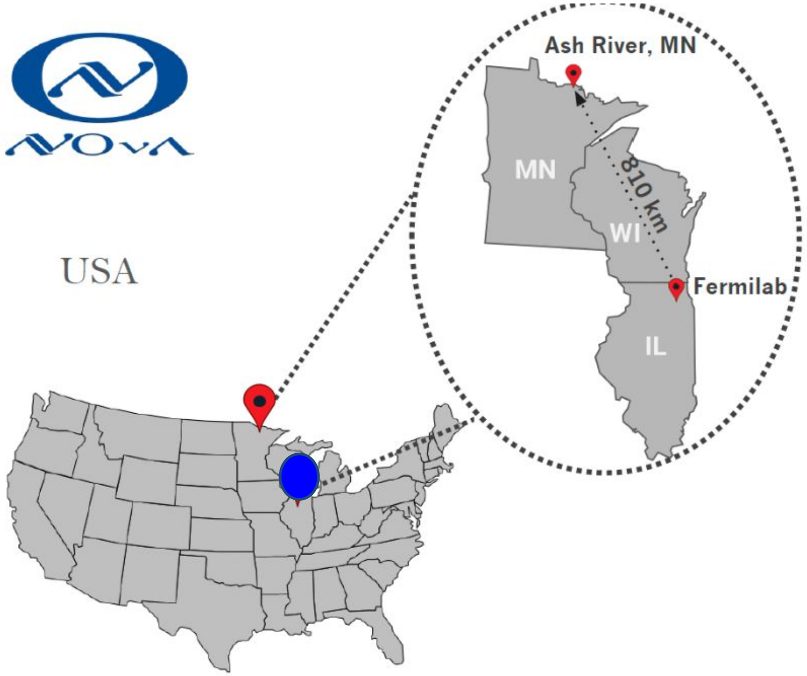
The NuMI Off-Axis Experiment (NOvA)

Key features:

- Accelerator-driven neutrino (or antineutrino beam) - Main Injector (NuMI) at Fermilab



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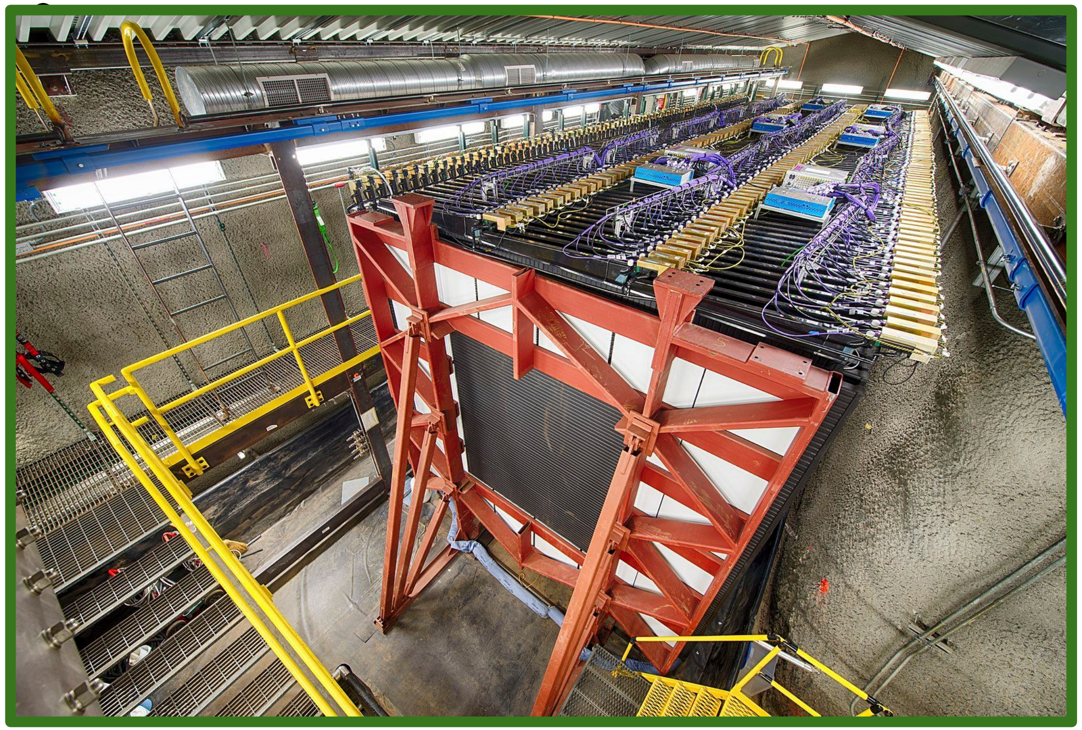
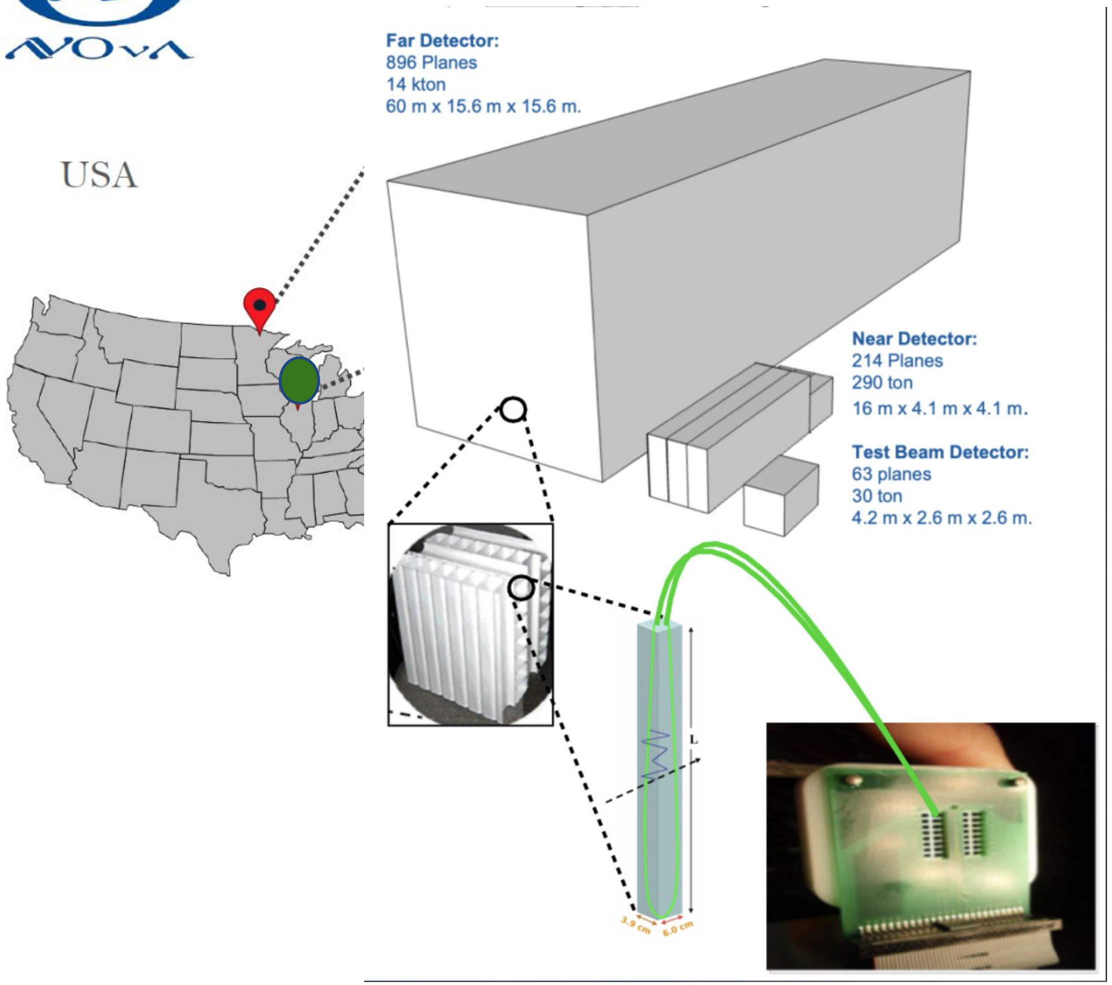
- Detector ‘near’ to the neutrino source
    - NOvA “ND” is off axis



https://doi.org/10.22323/1.390.0188



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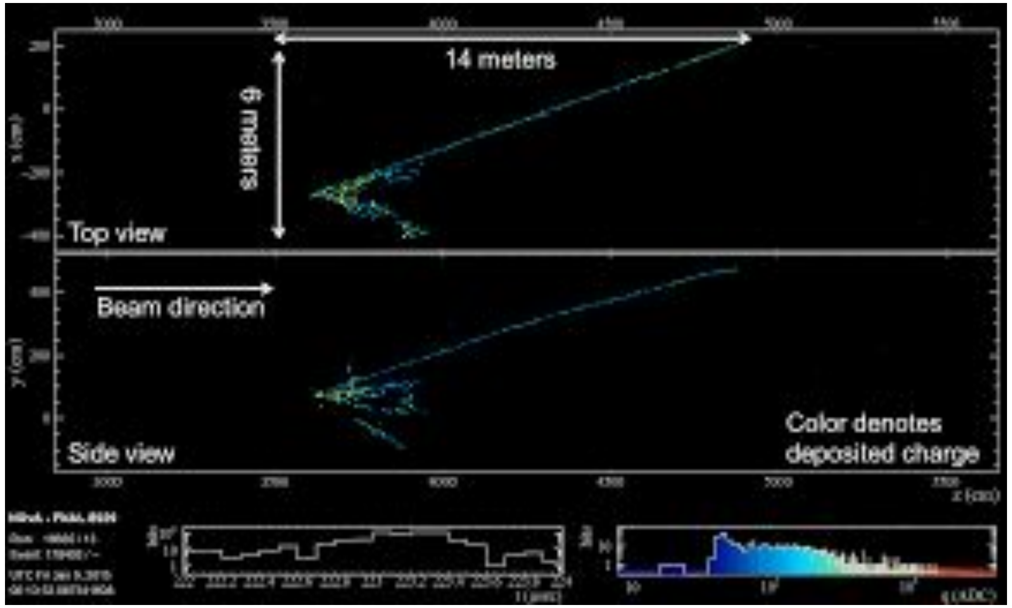
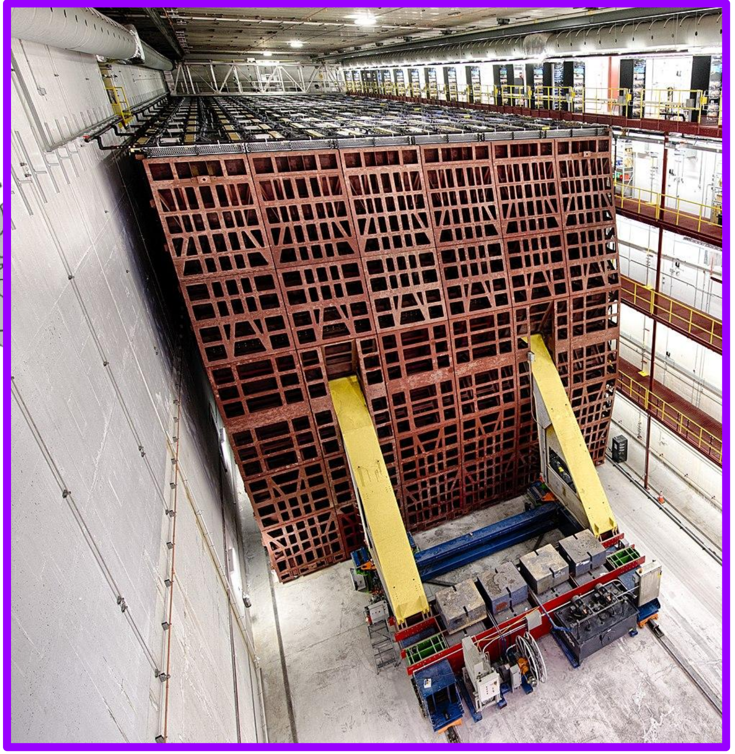
- Detector 'near' to the neutrino source
  - NOvA "ND" is off axis
- 'Far' detector hundreds of kilometers away
  - Enormous liquid scintillator detector





Recent NOvA results - oscillation

Latest NOvA results with 10 years of data in Phys.Rev.Lett. 136 (2026) 1, 011802

Both long-baseline and reactor experiments can measure Δm^2_{31}

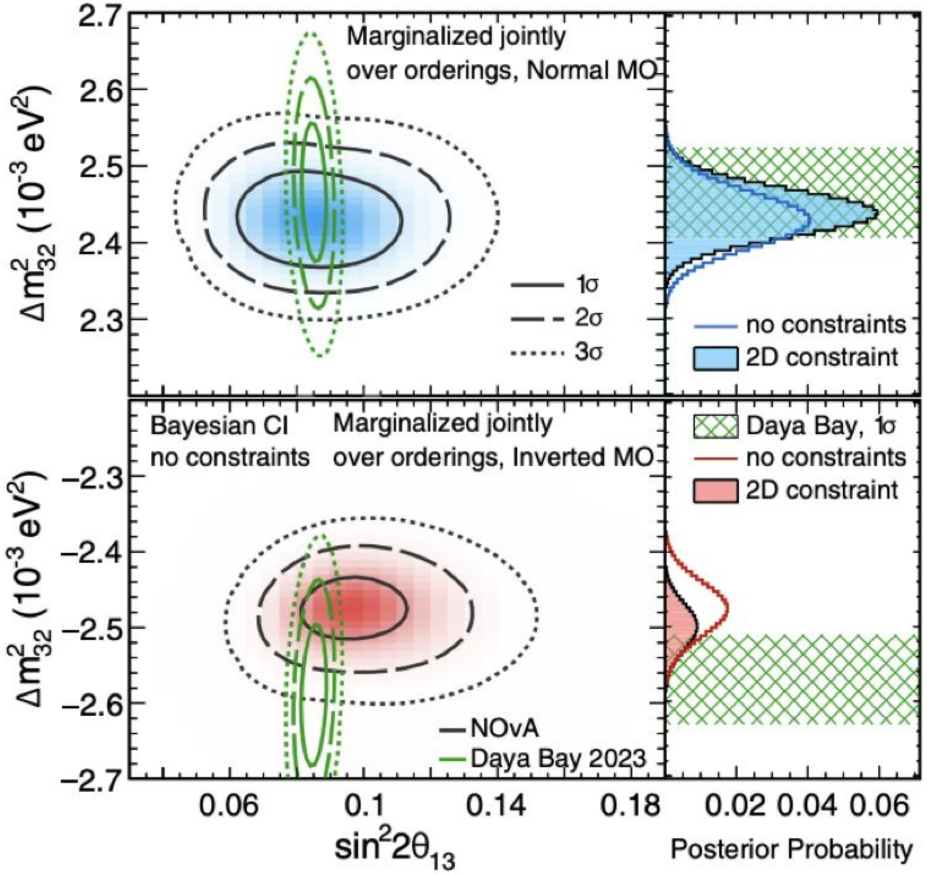
- Reactor through electron antineutrino disappearance
- LBL through muon (anti)neutrino disappearance

In correct ordering, Δm^2 extracted from reactor and LBL measurements should agree.

In incorrect ordering, the values of Δm^2 would disagree.
Parke and Funchal (Phys.Rev.D 111.013008)

Seeing early hints with NOvA+Daya Bay

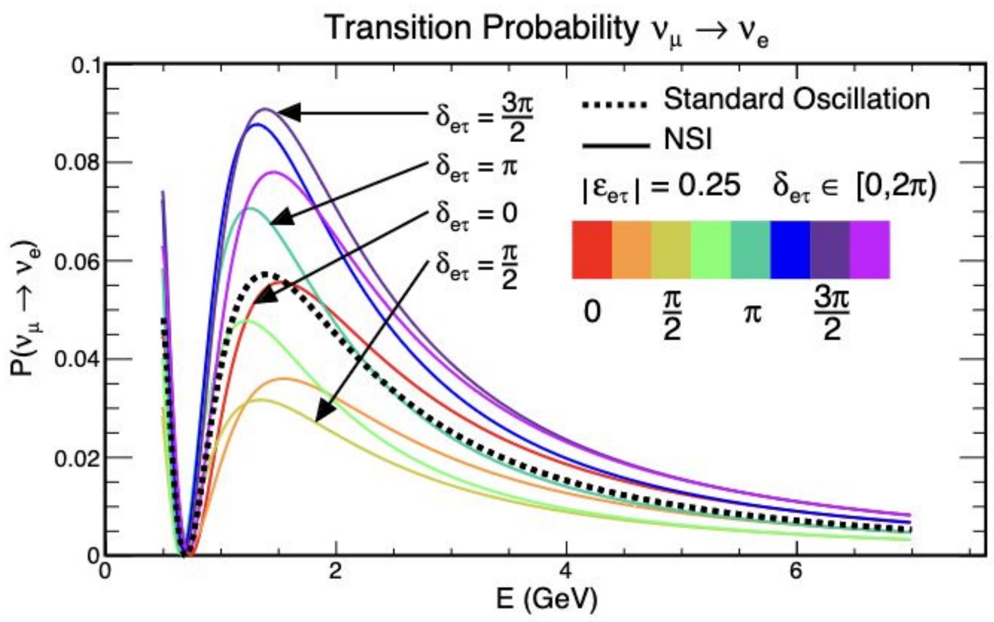
Eagerly waiting the results from JUNO



Phys.Rev.Lett. 136 (2026) 1, 011802

NOvA - non standard interactions

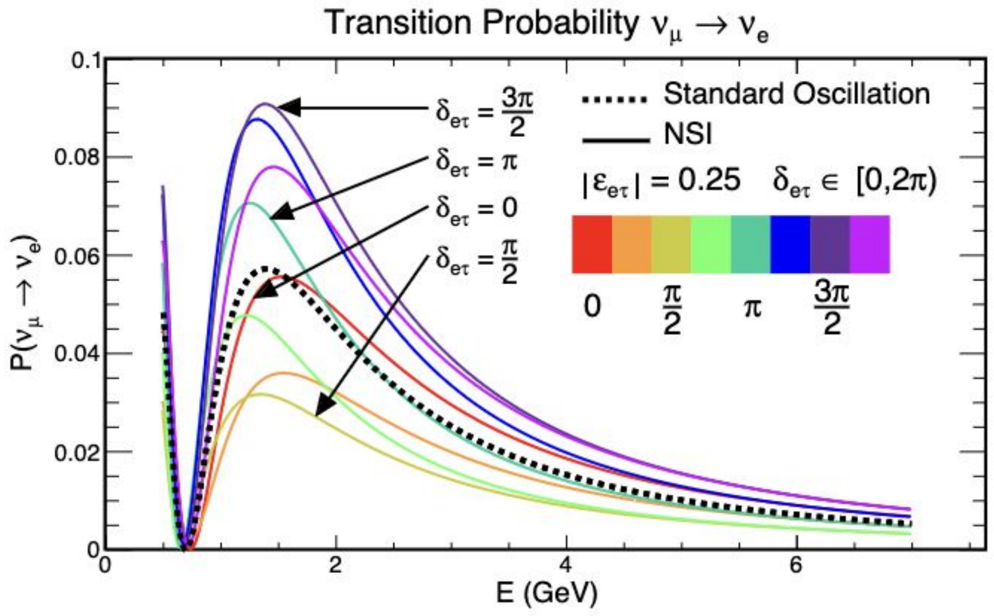
NSI would, like the mass ordering, modify the oscillation probability

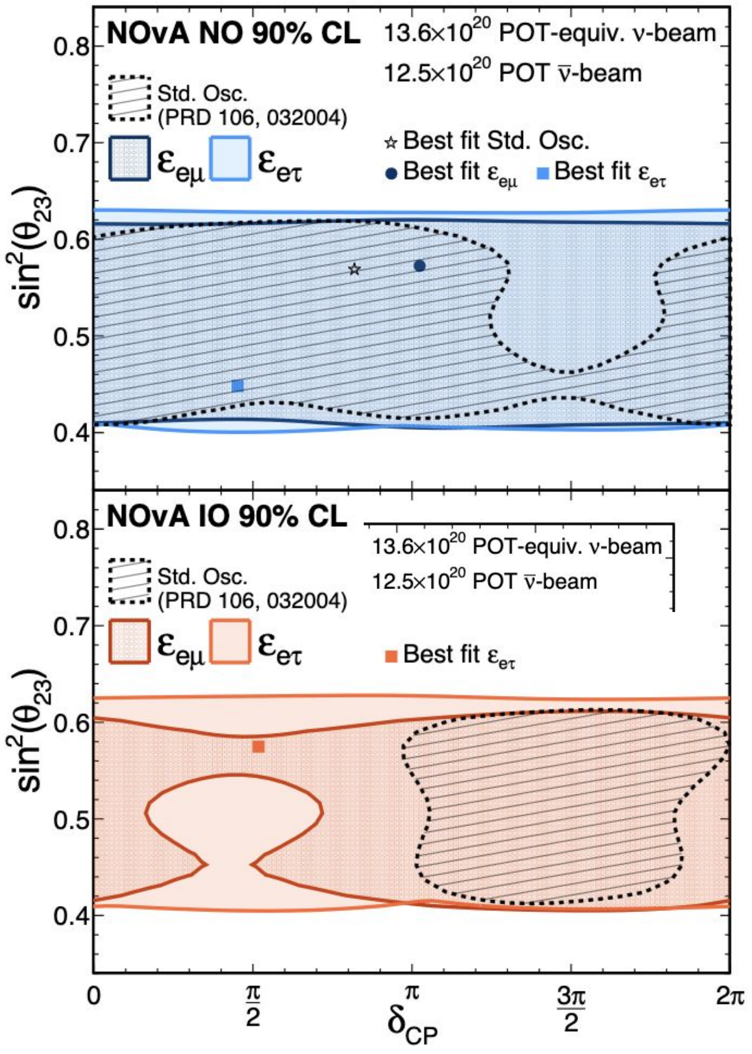


NOvA - non standard interactions

NSI would, like the mass ordering, modify the oscillation probability and the interpretation of (standard) oscillation parameters

- [Phys. Rev. Lett. 133, 201802 (2024)]





Next NOvA plans

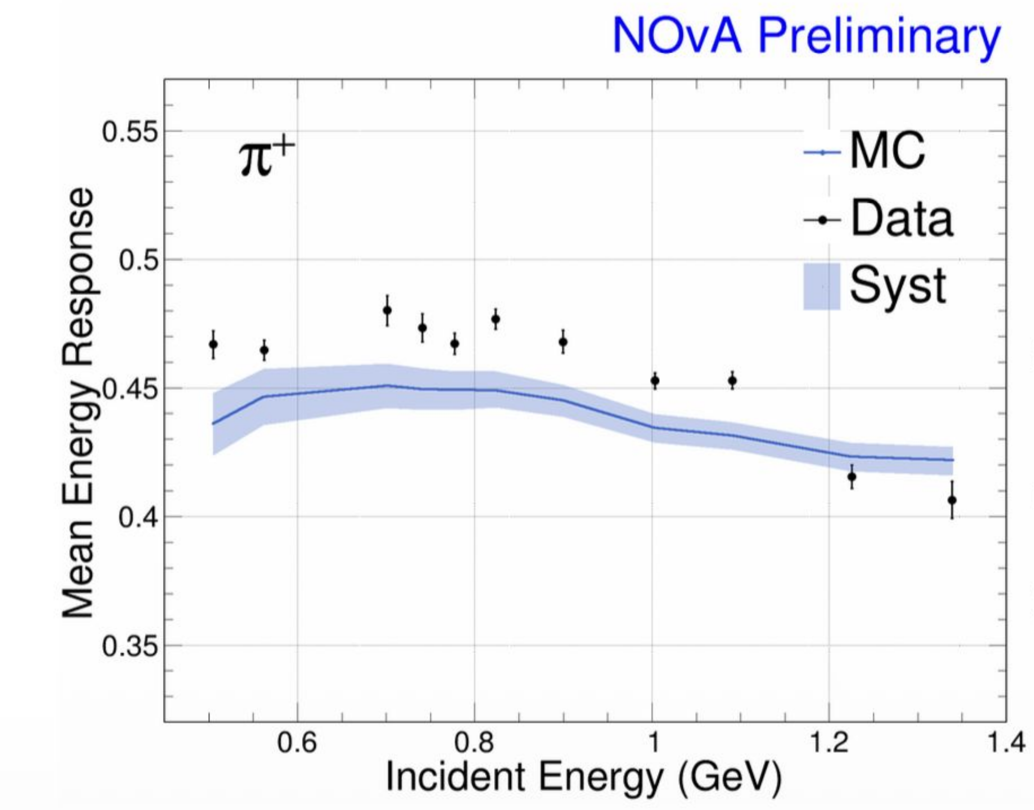
Coordinate push to reduce the statistical and systematic uncertainties to maximise the chances of establishing the neutrino mass ordering jointly with reactor experiments!

To reduce stat uncertainty:

- **Collect more NuMI neutrinos in 2026/2027**
- Updated analysis techniques to leave no neutrino behind

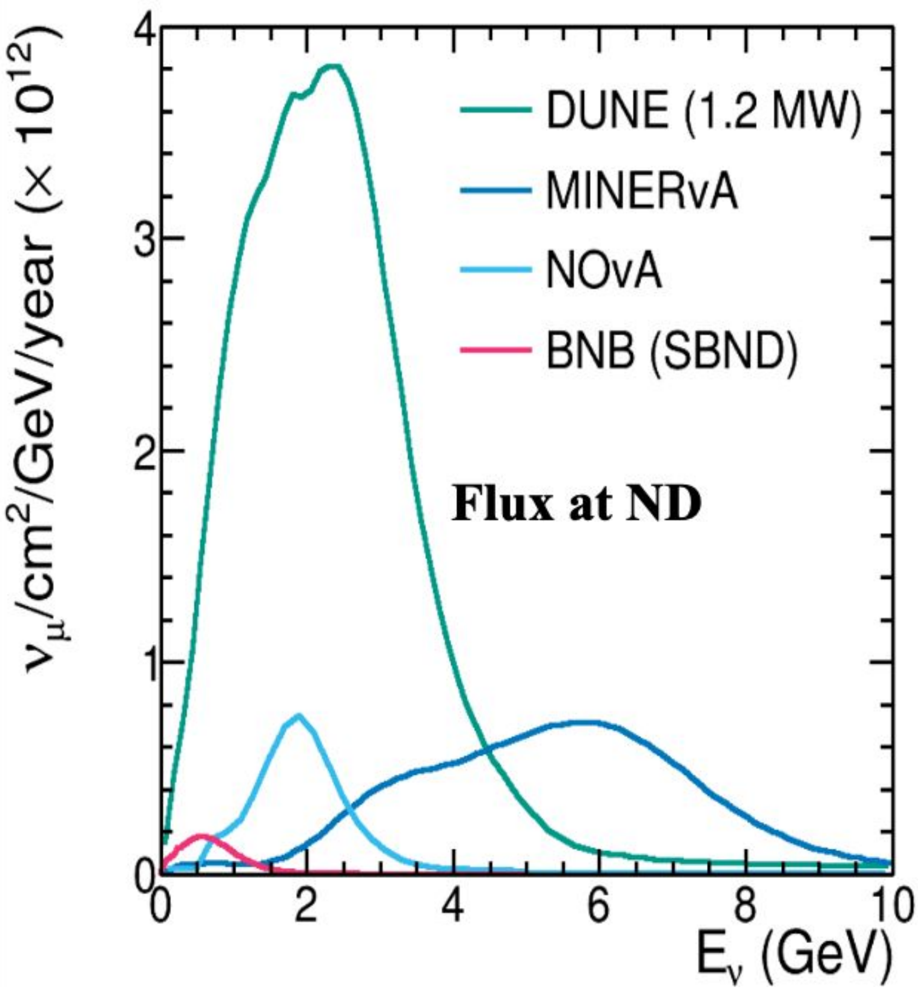
To reduce syst uncertainty:

- **Test Beam and lab measurement to reduce detector response uncertainties**
- Neutrino interaction theoretical work to make more robust uncertainties
- New ML-based energy estimator
- Improved techniques, ND fit

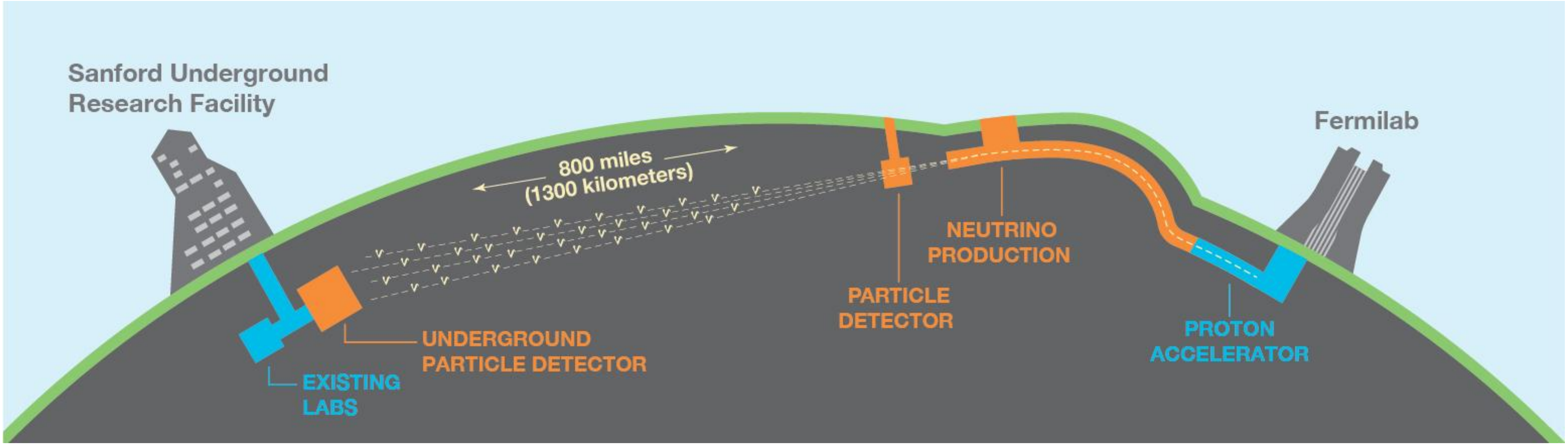


Towards the next generation - NOvA to DUNE

	T2K	NOvA	DUNE
Baseline	295km	810km	1285km
Peak neutrino energy	0.6 GeV	2 GeV	2 GeV



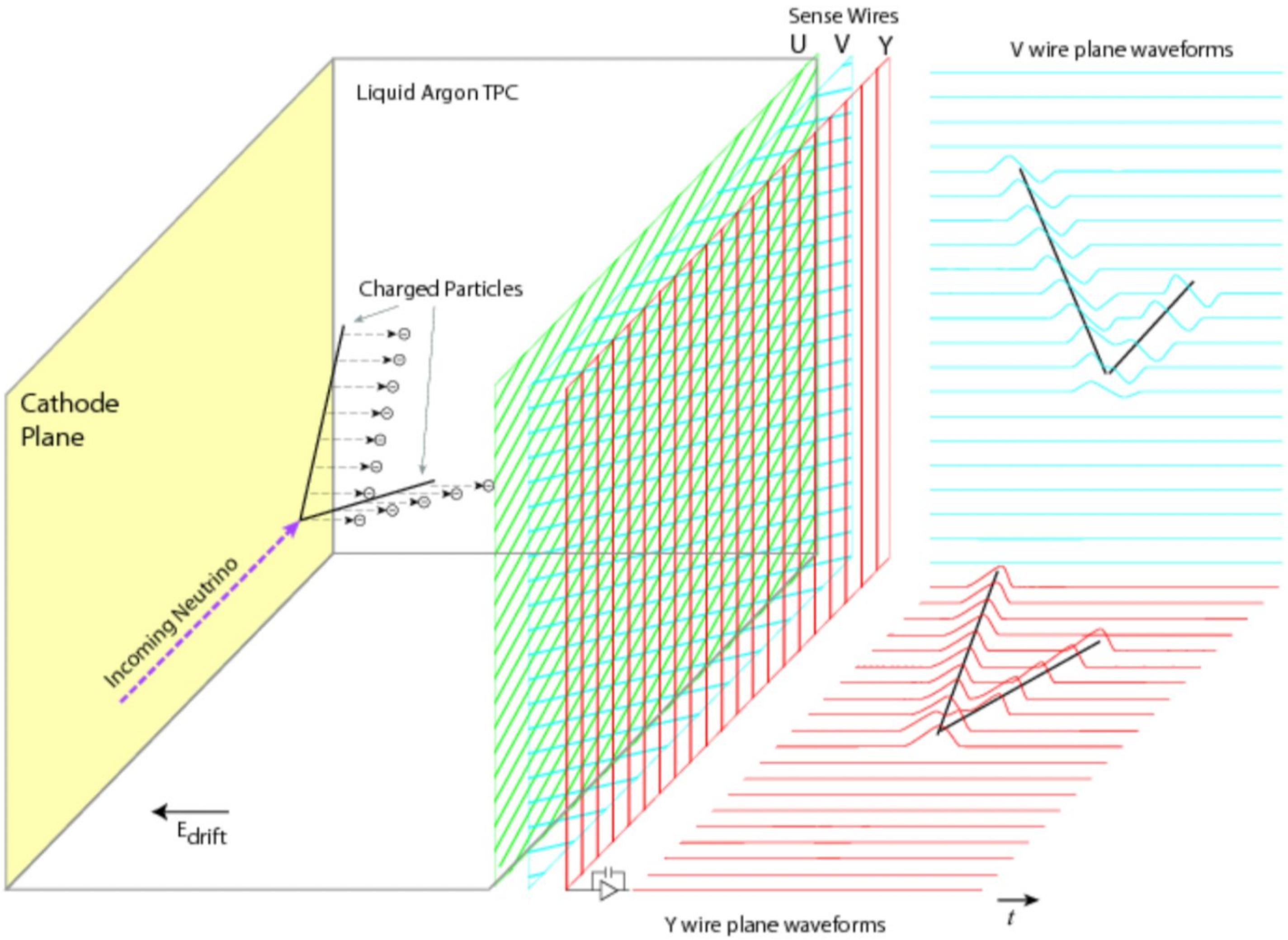
Deep Underground Neutrino Experiment (DUNE)



Key features:

- Accelerator-driven neutrino (or antineutrino beam) - **2.1 MW**
- Detectors 'near' to the neutrino source - **on, off-axis positions** ("PRISM")
- 'Far' detectors hundreds of kilometers away - two **liquid Argon TPCs** initially
  - **1.5km underground** enables supernova, solar neutrino physics

Liquid Ar Technology



credit: B. Yu, y2u.be/lH88L5nVvmY

Liquid Ar Technology

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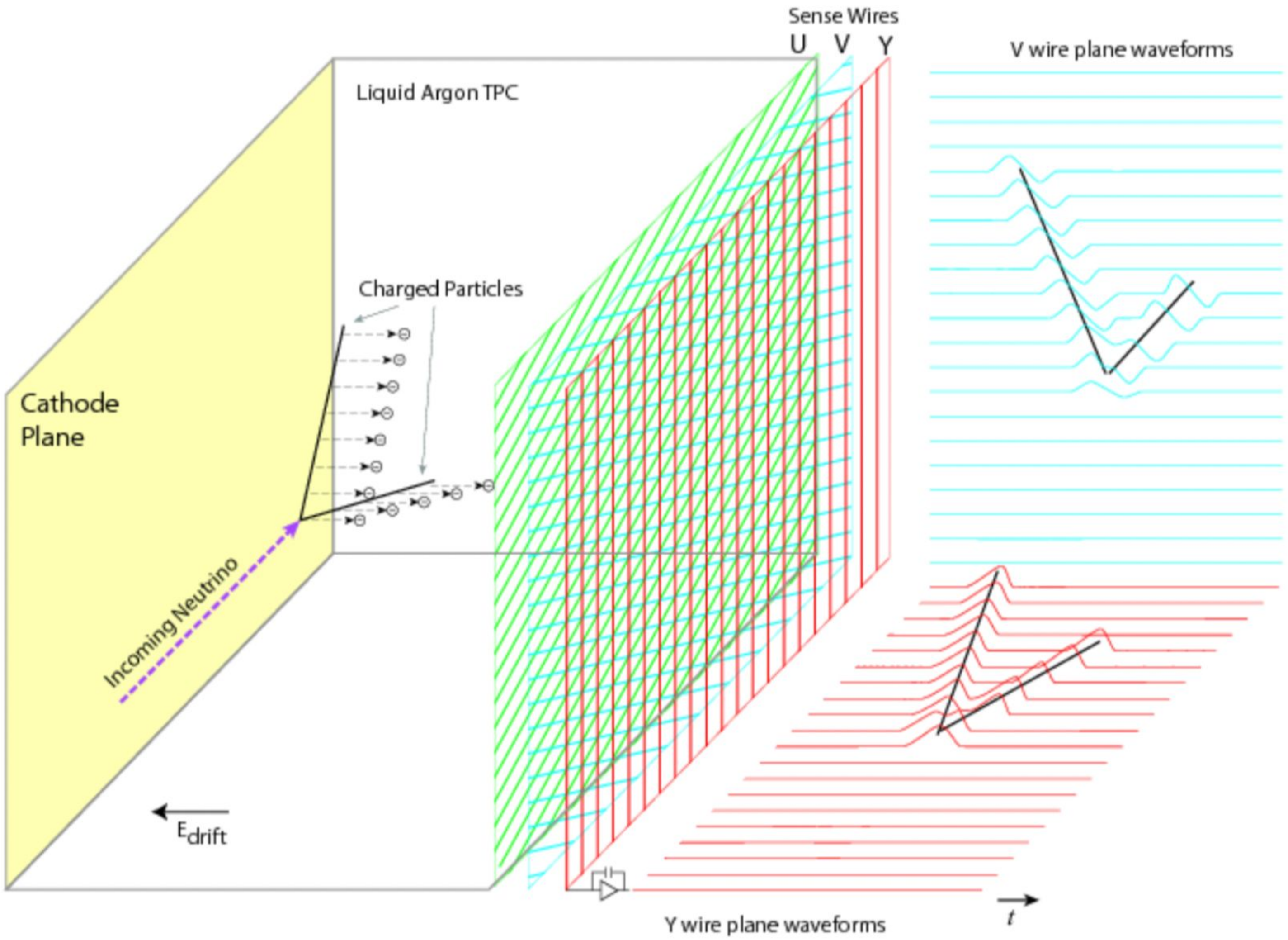
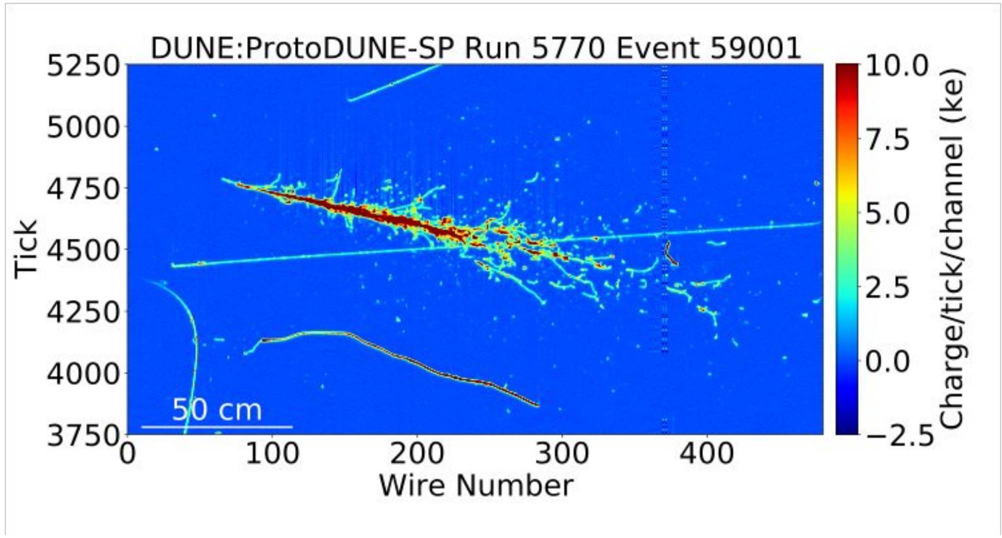
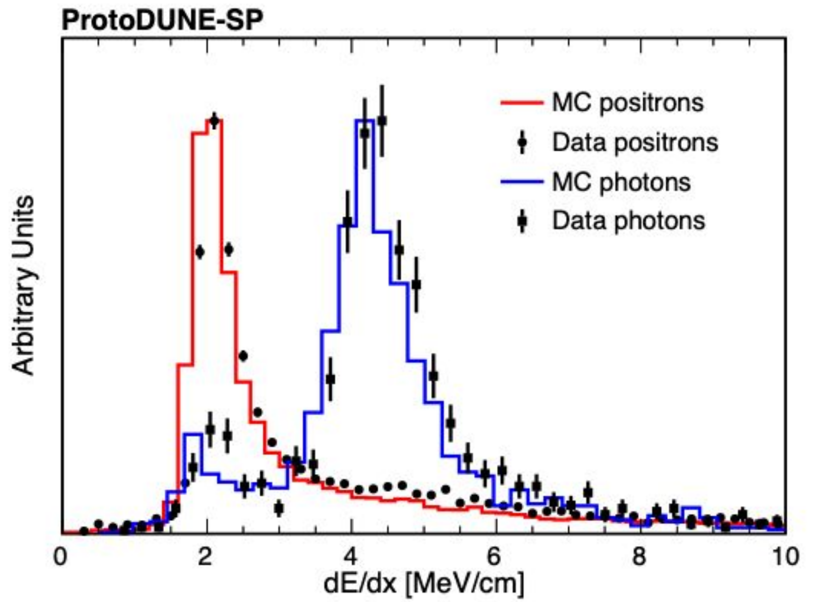






JINST **19** 08 P08005

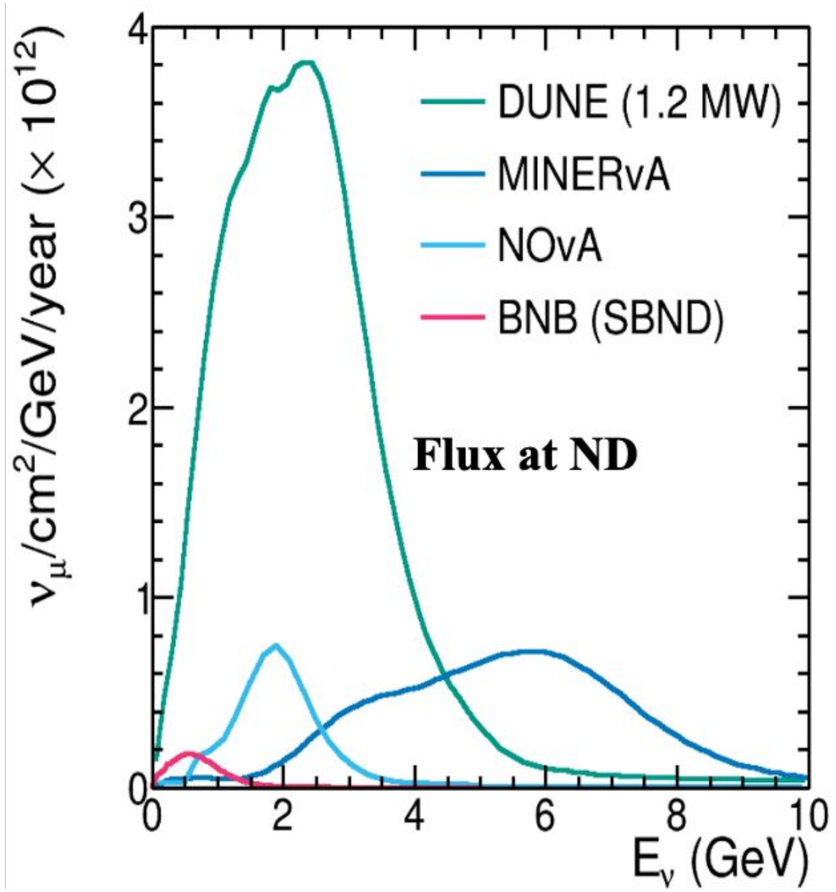
Deep Underground Neutrino Experiment (DUNE)

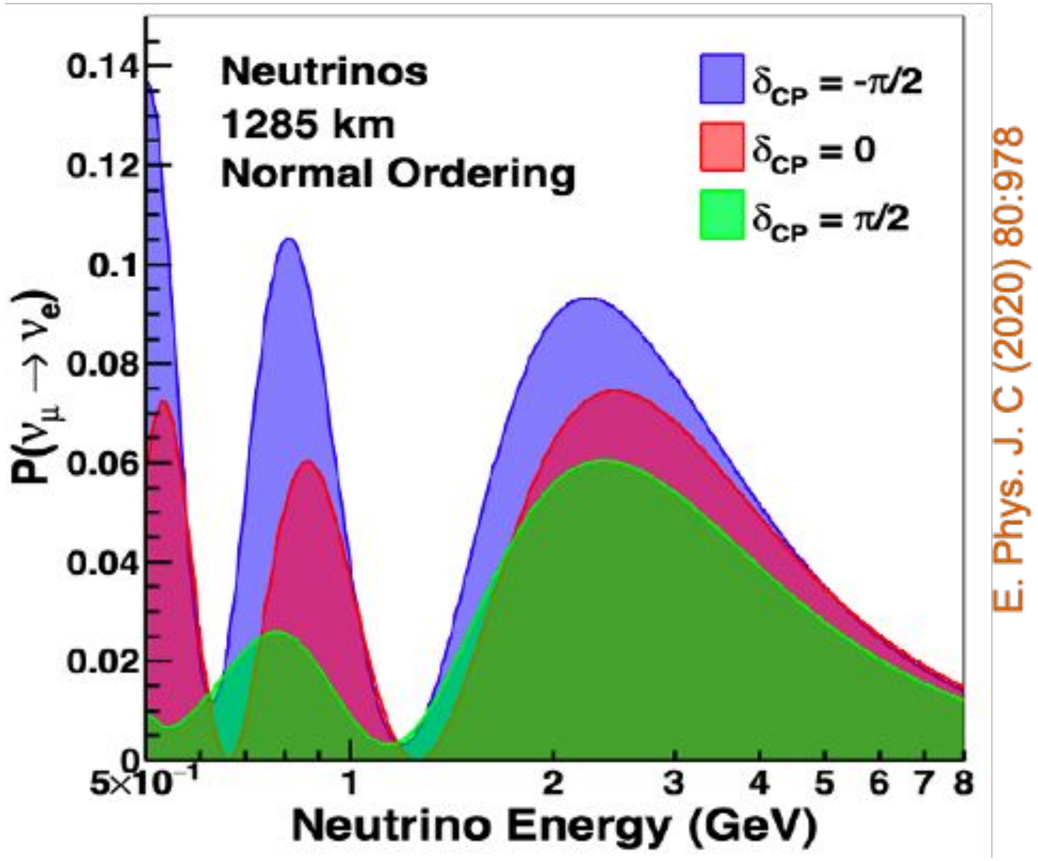
1500+ collaborators

38 countries + CERN

228 institutions

DUNE oscillation reach - conceptual

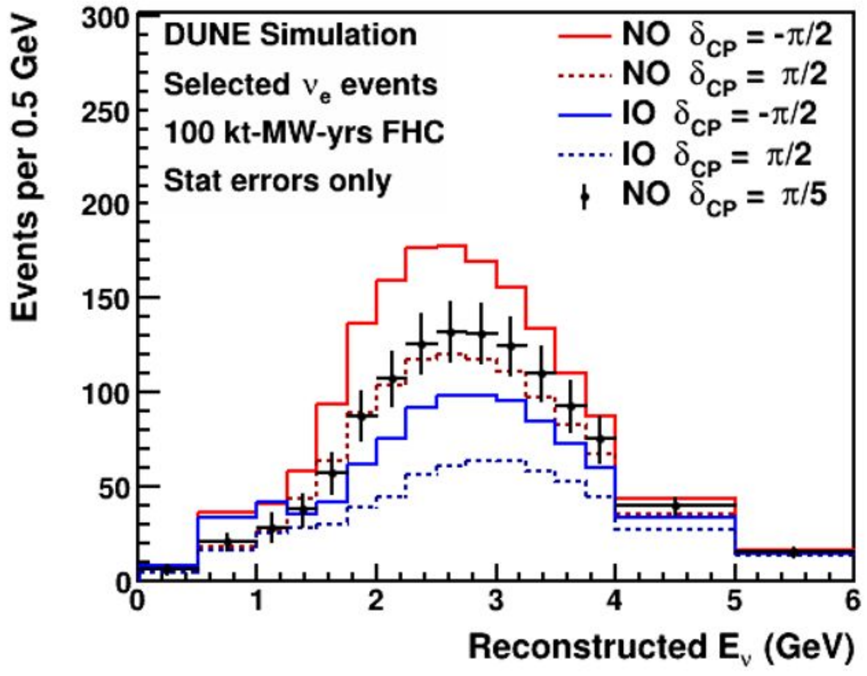


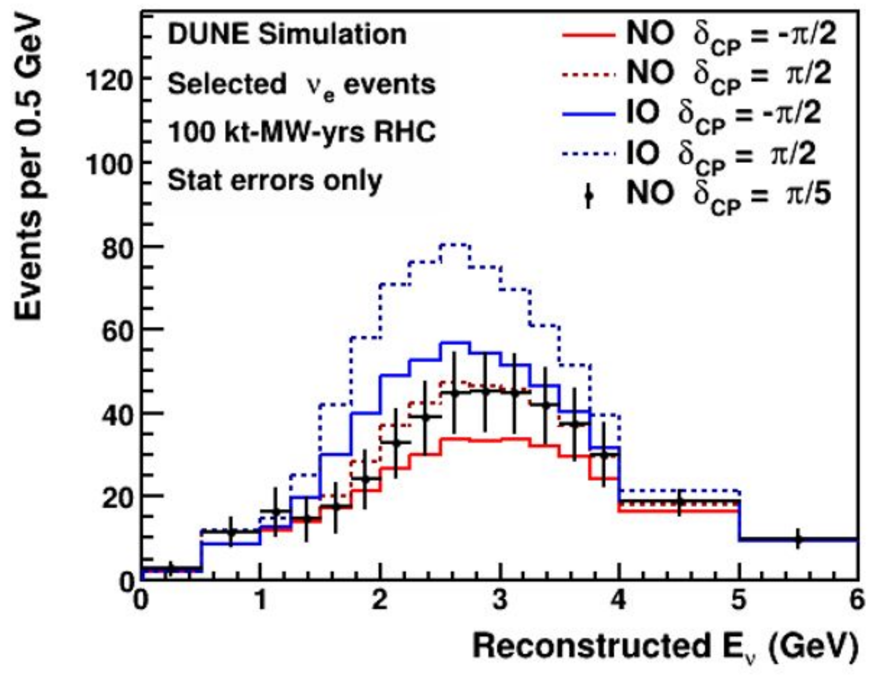


Combination of **wide band beam with 1285km baseline** provides first and second oscillation maxima and **separation of CPV and MO**

DUNE oscillation reach - specific

E. Phys. J. C (2020) 80:978





MO can be determined in 1-3 years (best vs. worst case, regardless of CP value)

This independence may be important to be sensitive to any non 3 flavor effects

- Use wide band spectra to look for any distortions as a function of L/E

DUNE oscillation reach - specific

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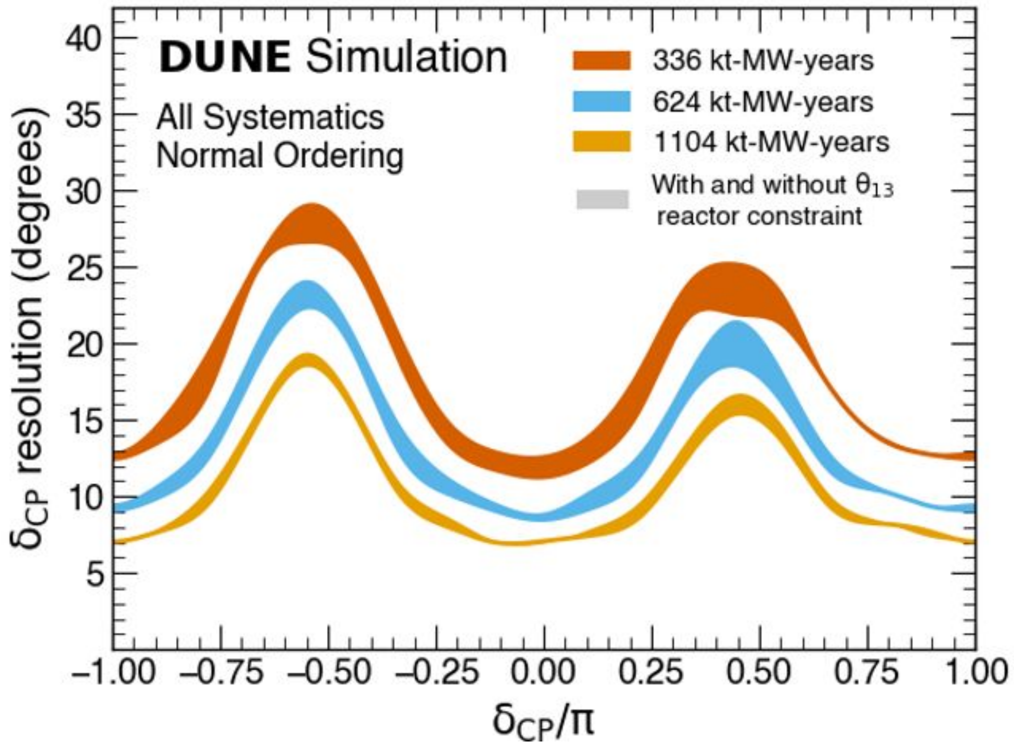
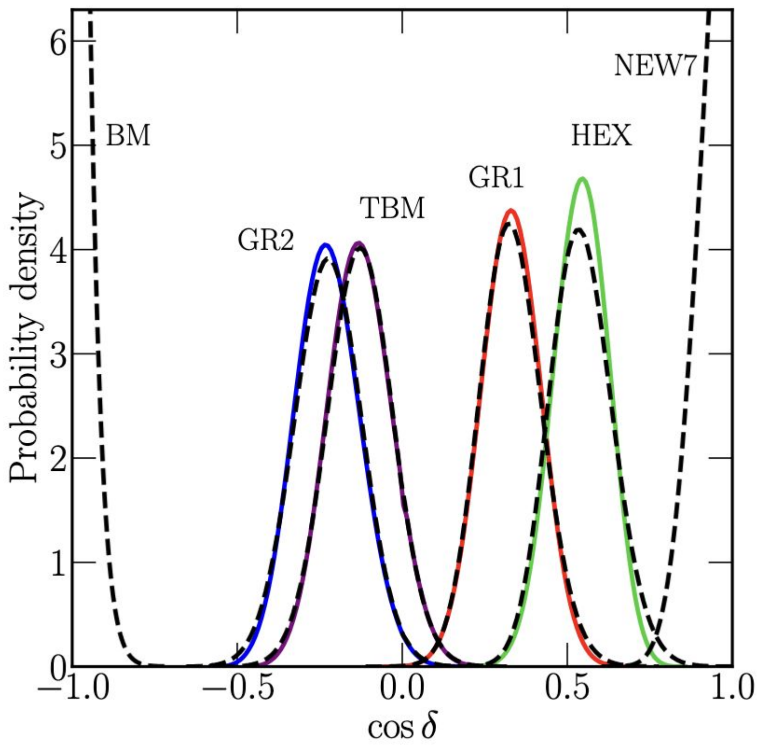




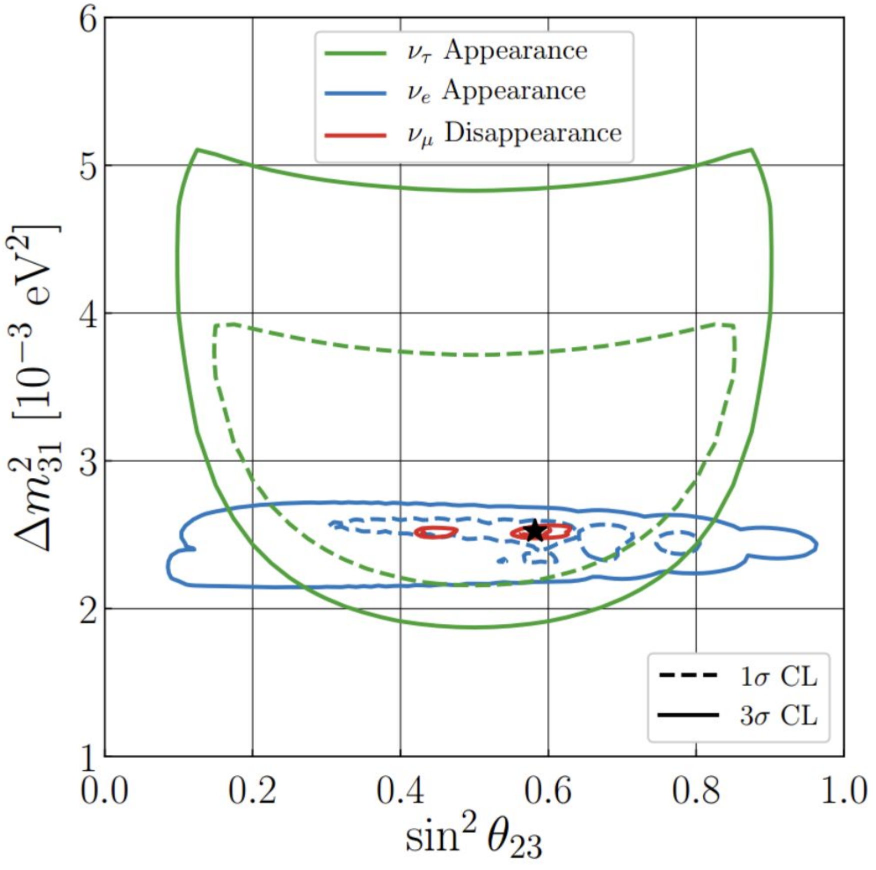
Int.l J. of Mod. Phys. A, 36(30), (2021)

□$_{CP}$ resolution of 6deg at □$_{CP}$=0 - relevant for model separation of various mixing

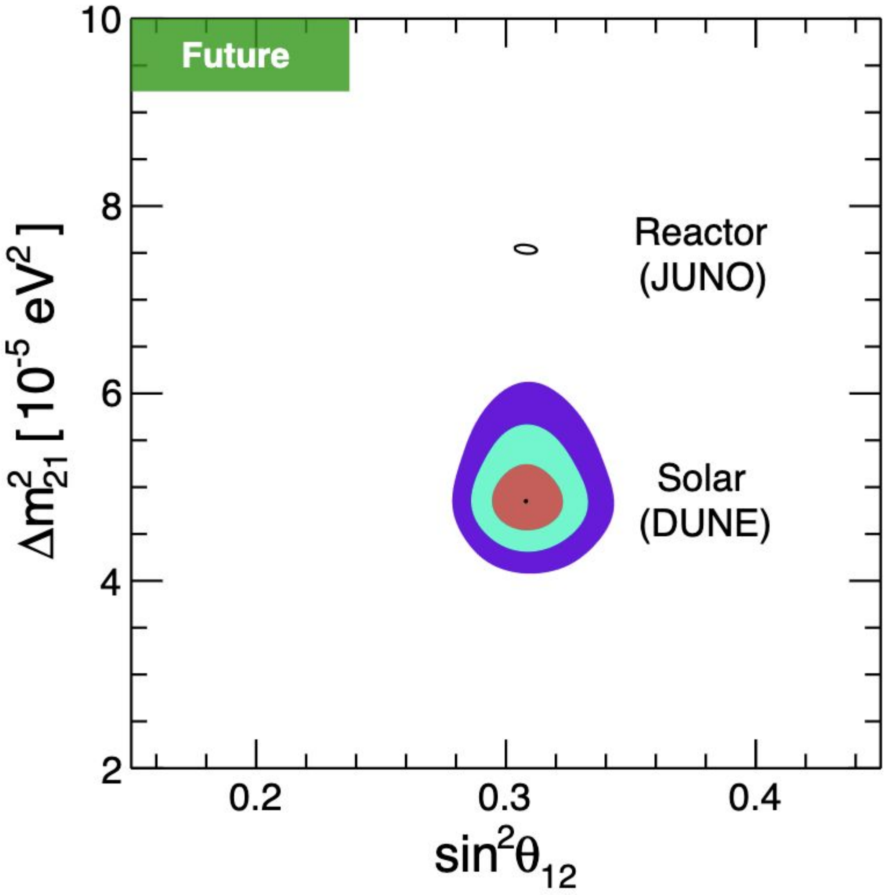
Ability to also resolve octant if θ_{23} is not maximal

Additional 3 flavor probes: solar and tau

J. Phys. G: Nucl. Part. Phys. 49, 11 (2022)



DUNE will produce and measure tau neutrinos

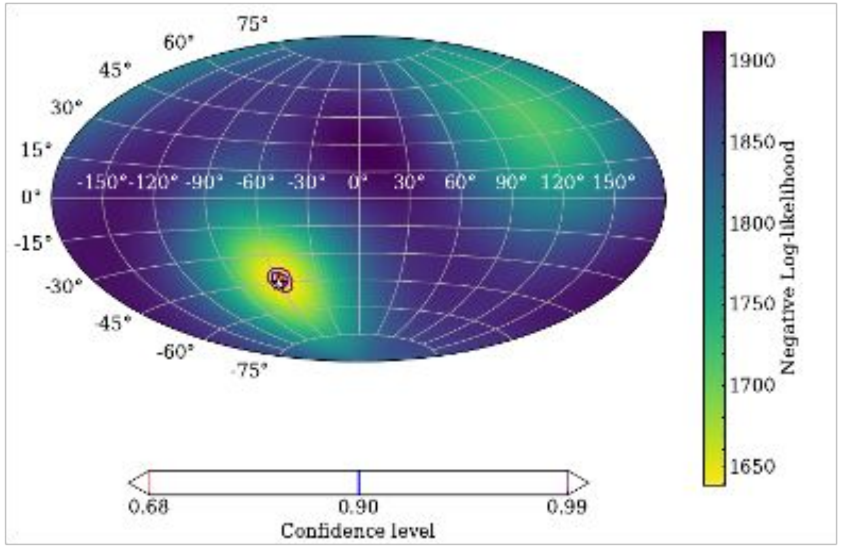


And measure buckets of solar neutrinos

Phys. Rev. Lett. 123, 131803 (2019)

Additional probes: astrophysical sources

Phys. Rev. D 111 (2025) 9, 092006



	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

Neutrinos from core-collapse supernovae

DUNE has unique sensitivity to electron neutrinos

Neutronization burst measurements → mass ordering measurement

Pointing capabilities: ES channel ~5° pointing resolution (40 kt, 10 kpc)

DUNE contributes to BSM landscape

Slides thanks to A. Sousa [@TPC2025](#)

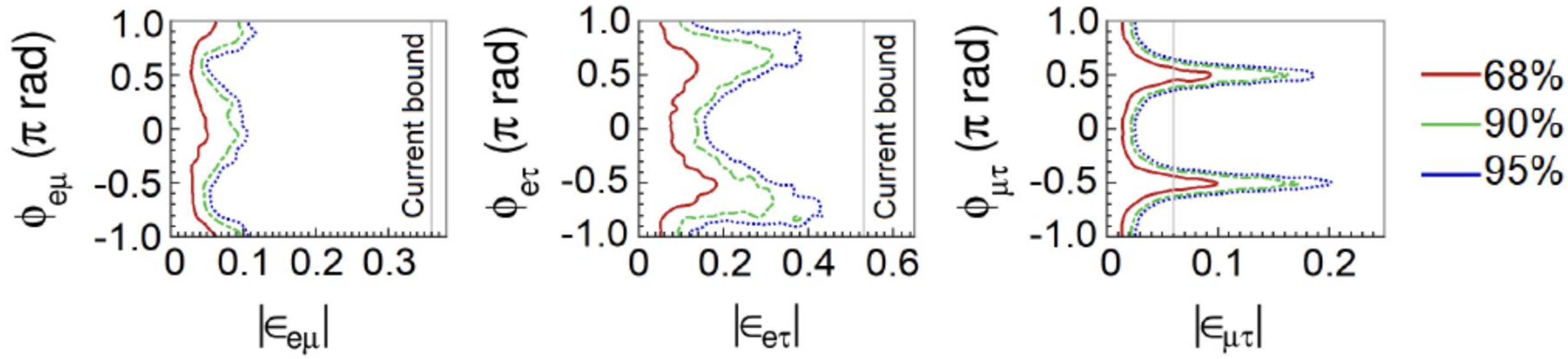
Also see Snowmass NF03 Report, NF02 White Paper, J. Phys. G 51, 120501 (2024)

BSM Scenario	Sources	Signatures	Example Experiments
HNL [1]	Colliders Nuclear decays Fixed target	HNL decay Nuclear decay kinematics HNL decay	ATLAS, CMS, FASER, Belle II, ... KATRIN/TRISTAN, HUNTER ... DUNE ND, SHiP, ICARUS, ...
	Atm. & solar νs	Distorted recoil spectrum HNL decay, double bangs	DUNE, HK, IceCube/DeepCore, ...
	Early Universe	Cosmological parameters ($N_{\rm eff}$)	Simons Observatory, CMB-S4, ...
Non-unitarity [2]	Beam & Atm. νs	Deviations from 3-ν mixing (ND & FD)	DUNE, ESSνSB, HK, ...
LED [2]	Reactor νs Beam νs	Distortion of oscillated spectra (FD & ND)	JUNO, TAO,... DUNE, ...
	Atm. νs	Anomalous matter effects	Icecube, KM3NeT, ...
NSI & light mediators [2, 4]	Reactor & Spallation sources Solar, Beam, Atm & SN νs Beam νs Collider νs	Distortion of CEνNS rate Anomalous matter effects Anomalous appearance, $\nu - e^-$ scattering, tridents Distortion of CC spectrum	COHERENT, CONNIE, CONUS, ... DARWIN, DUNE, T2HKK, HK, IceCube, ... DUNE ND, T2HK ND, IsoDAR, ... FASERν, ...
Long-range forces [2]	Solar & Atm ν UHE Astrophysical nus	Anomalous matter potential Distorted flavor ratios	HK, JUNO, DUNE, ... HE Neutrino Telescopes
ν-DM interact. [2]	Reactor & solar νs Beam ν UHE Astrophysical νs	Distorted oscillated spectra, or time-dependent oscillation params. Distorted flavor ratios & spectra	JUNO, ... DUNE, ... HE & UHE Neutrino Telescopes
ν self interact. [3, 14]	SN νs UHE Astrophysical νs Early Universe Beam & Collider νs	SN extra energy loss, distortion in neutrino spectra Distorted spectra Effects on CMB, BBN, & structure formation Missing energy & p_T in ν scattering	DUNE, HK, JUNO, ... HE & UHE ν telescopes CORE, PICO, CMB-S4 DUNE ND, Forward Physics Facility, ...
ν decay [2]	Reactor & DAR νs Beam νs Atm. νs	Distortion of oscillated spectra	JUNO, IsoDAR, ... DUNE, MOMENT, ESSνSB, HK, ... INO-ICAL, KM3NeT-ORCA, ...
	UHE Astrophysical νs	Distorted flavor ratios & spectra	HE & UHE Neutrino Telescopes
CPT violation [2]	Beam νs Atm. νs	Different ν and $\bar{\nu}$ osc. params.	DUNE, ESSνSB, HK, ... IceCube, DUNE, ...
	UHE Astrophysical νs	Distorted flavor ratios & spectra	HE & UHE Neutrino Telescopes
Lorentz violation [2]	Beam νs Atm. νs	Sidereal modulation of event rate	DUNE, ESSνSB, HK, ... IceCube, DUNE, ...
	UHE Astrophysical νs	Distorted flavor ratios & spectra, velocity dispersion	HE & UHE Neutrino Telescopes
Quantum decoh. [2]	Reactor & DAR νs Beam νs Atm. νs	Distortion of oscillated spectra	JUNO, IsoDAR, ... DUNE, ... KM3NeT, IceCube, HK, ...
	UHE Astrophysical νs	Distorted flavor ratios	HE Neutrino Telescopes
B violation [5]	Detector mass	Nucleon decay, $n - \bar{n}$ oscillations	DUNE, HK, JUNO, ...
Dark Matter [6, 7]	DM annihilation, DM decay Boosted DM, slow-moving DM	Excess of νs from Sun or Earth Scattering, or up-scattering & decay	HK, DUNE, IceCube ...
	Fixed target	Decay Scattering, or up-scattering & decay	DUNE, T2HK, SBN, FASERν, ...
Milli-charged particles [7]	Fixed target Atmosphere	Scattering	DUNE ND, T2HK ND, ... DUNE, HK, JUNO, ...

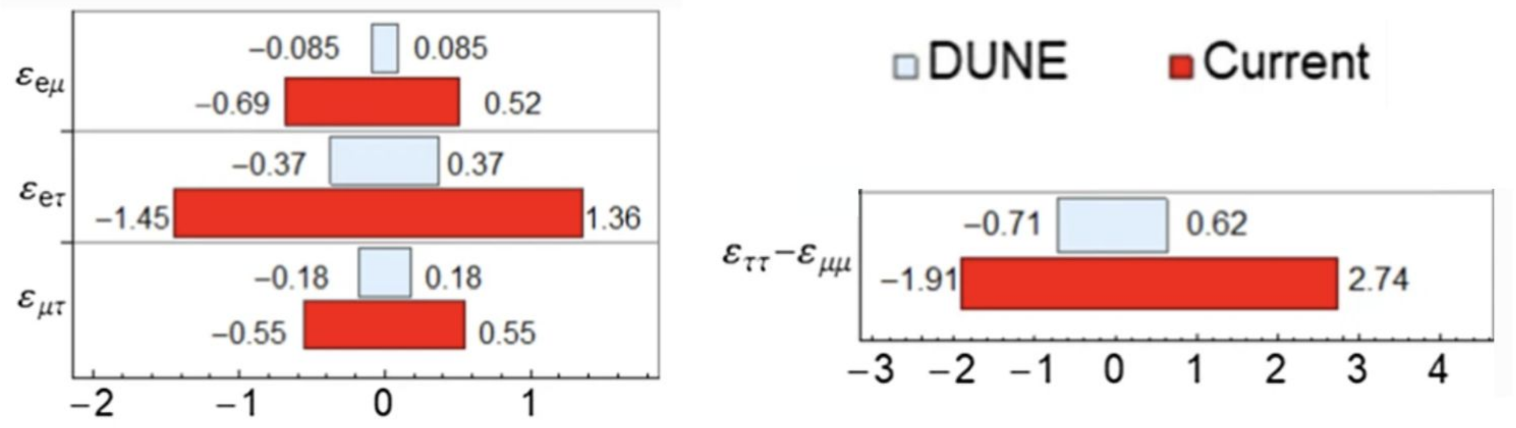
DUNE Non standard interacti ons

- DUNE can improve current constraints on $|\epsilon_{e\mu}|$ and $|\epsilon_{e\tau}|$ by a factor of ~2

DUNE BSM Paper, Eur. Phys. J. C 81, 322 (2021)



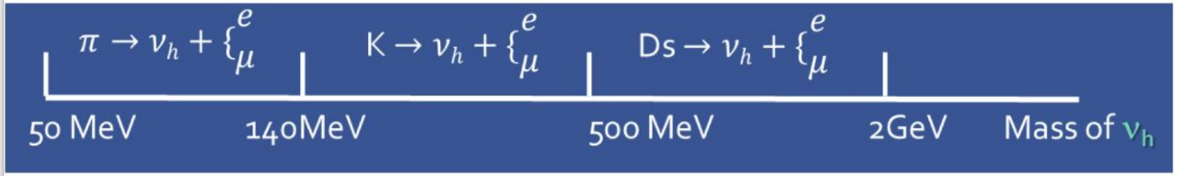
- Allowed regions for an exposure of 300 kt.MW.year. Current bounds from Gonzalez-Garcia, Maltoni, arXiv:1307.3092

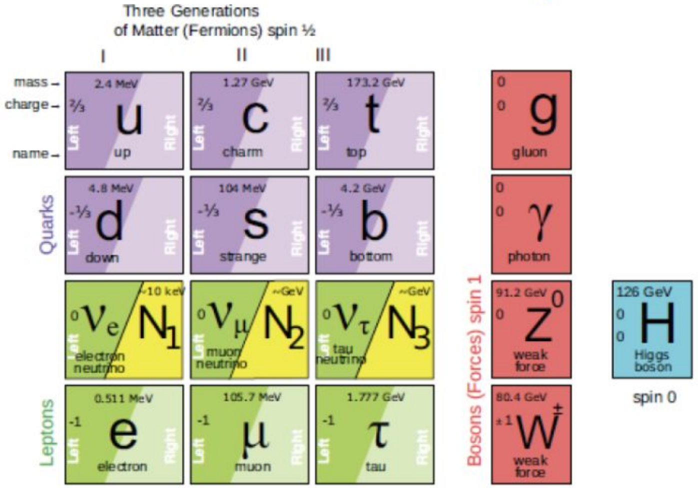


- 90% C.L. 1-dim. DUNE constraints compared with bounds from Gonzalez-Garcia, Maltoni, arXiv:1307.3092

Heavy Neutral Leptons at DUNE

- Right-handed fermion singlet extensions of the SM
- May be created by meson decays in the LBNF beam

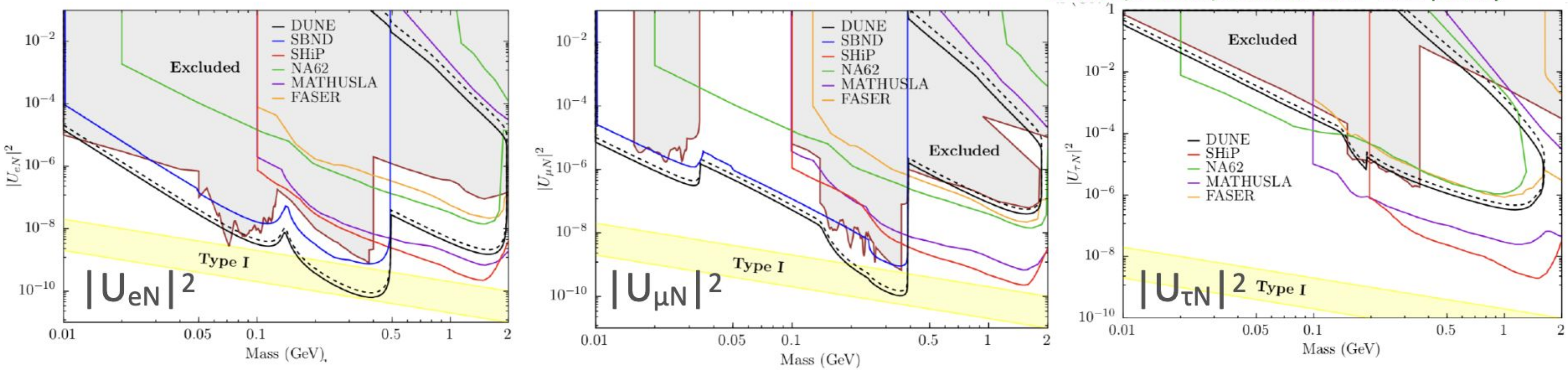




Ballett, Boschi, Pascoli: JHEP 111 (2020)

- Showing DUNE's 90% CL sensitivity to mixing between the active neutrinos and HNLs over a HNL mass range of 10 MeV to 2 GeV

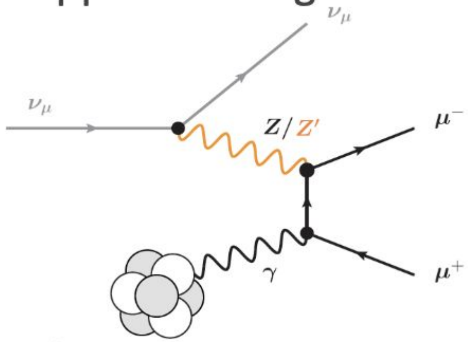
Ballett, Boschi, Pascoli: JHEP 111 (2020)



- DUNE will improve on present experimental limits and be competitive with proposed new efforts to measure HNLs

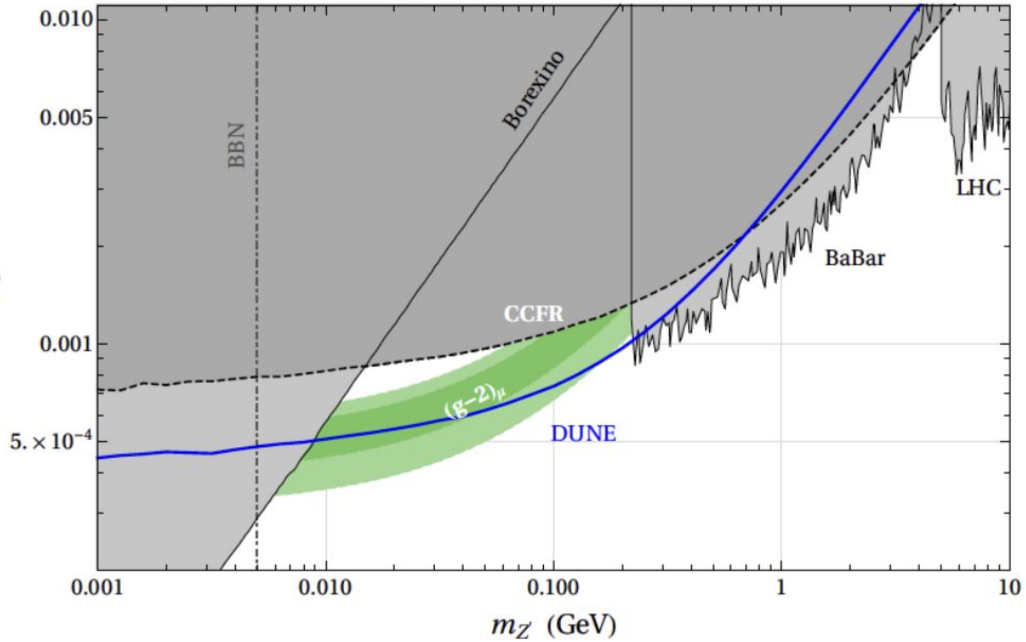
Neutrino tridents in DUNE

- Rare SM process, where ν scatters off Coulomb field of a large Z nucleus, generating a pair of leptons of opposite charge. Has been observed with cross section in good agreement with SM



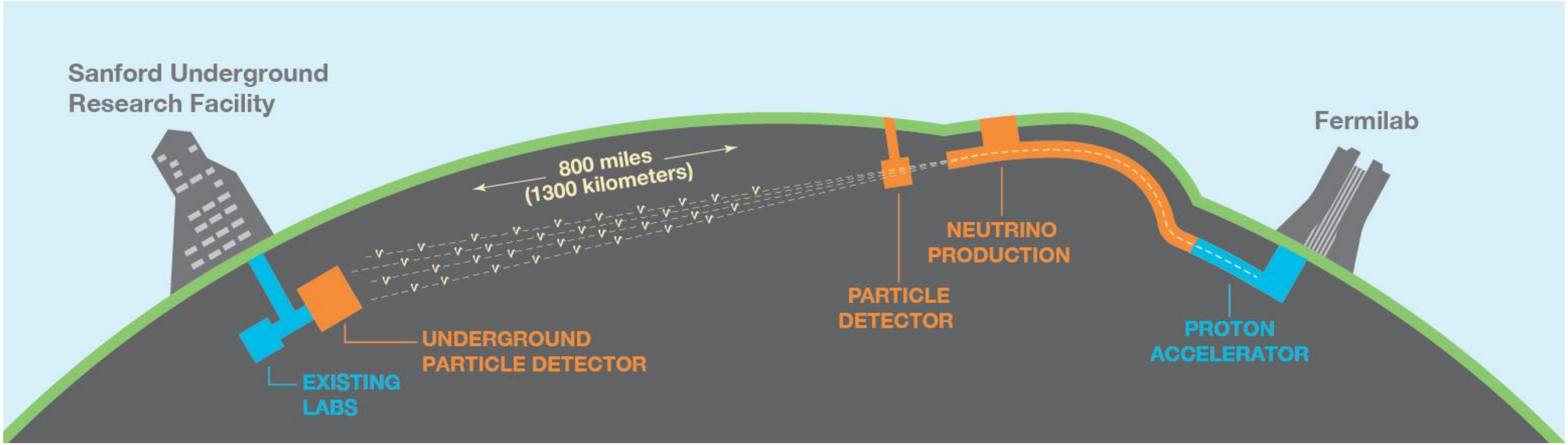
$$\frac{\sigma(\nu_\mu \to \nu_\mu \mu^+ \mu^-)_{\text{exp}}}{\sigma(\nu_\mu \to \nu_\mu \mu^+ \mu^-)_{\text{SM}}} = \begin{cases} 1.58 \pm 0.64 & \text{(CHARM II)} \\ 0.82 \pm 0.28 & \text{(CCFR)} \\ 0.72^{+1.73}_{-0.72} & \text{(NuTeV)} \end{cases}$$

- Departure from SM prediction can be evidence for new physics: DUNE can be sensitive to the existence of new light vector mediators, *e.g.* Z', which might explain the $(g-2)_\mu$ anomaly
- Will be improved further with Machine-learning-based event selection and Phase II ND



*Altmannshofer, Gori, Martín-Albo, Sousa, Wallbank: Phys. Rev. D **100**, 115029 (2019)*

Progress toward building DUNE

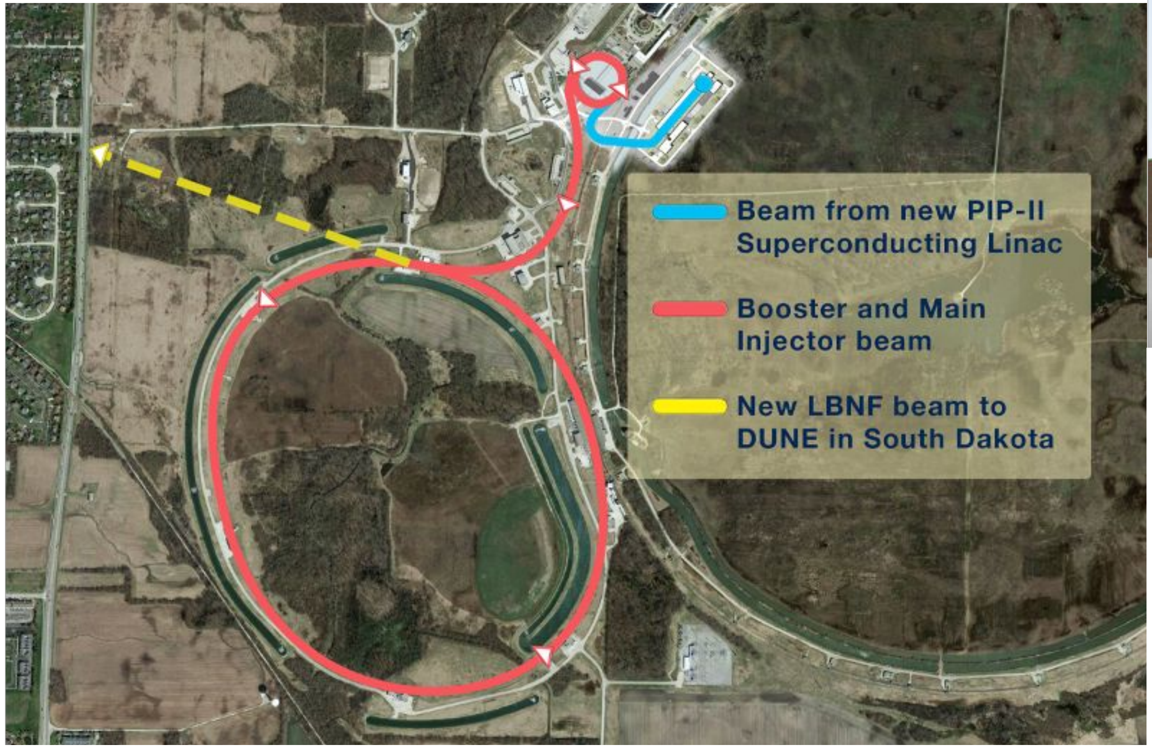


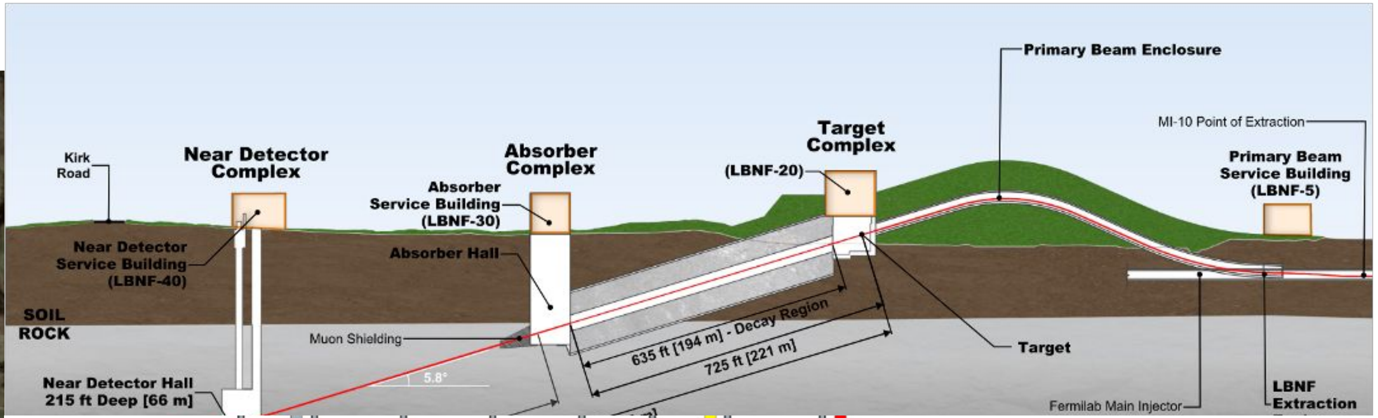
- Beamline construction, near detector prototyping at Fermilab
- Far detector construction at SURF

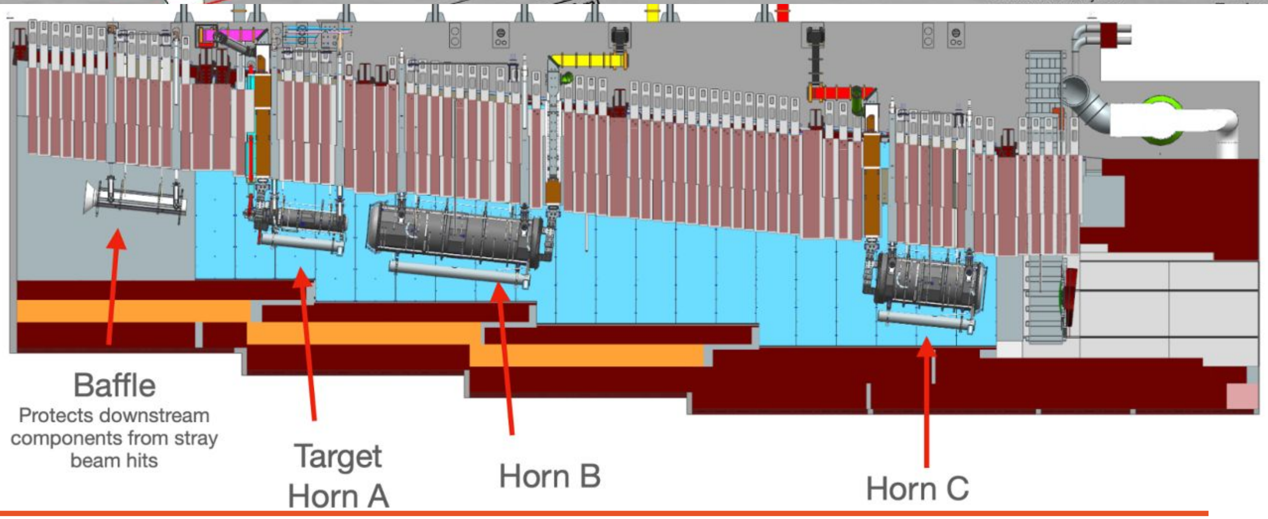
Slides thanks to I. Gil-Botella and L. Fields

Beamline

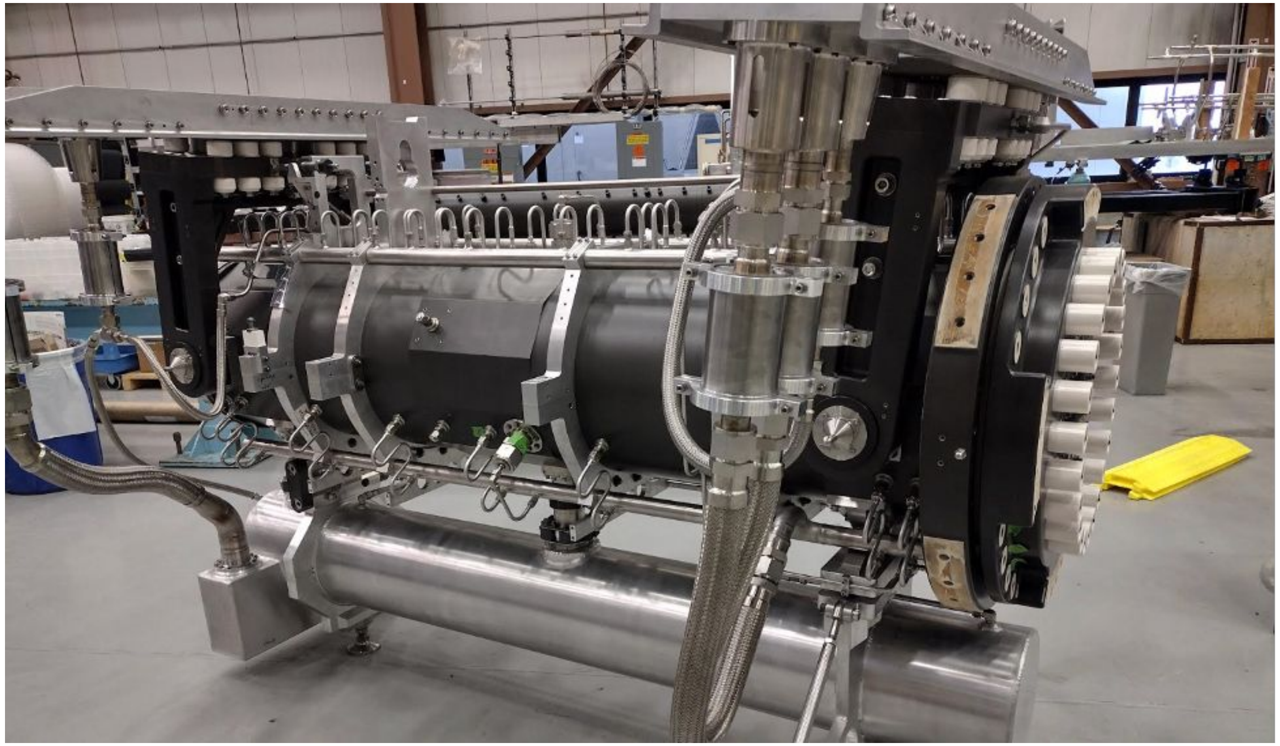
World-leading neutrino beam intensity enabled by PIP-II - beam design phase to complete in 2026
ACE-MIRT upgrade will enable ~2 MW beam by ~doubling frequency of spills







Beamline prototyping



Horn A prototype at Fermilab

Target prototype at RAL (UK)

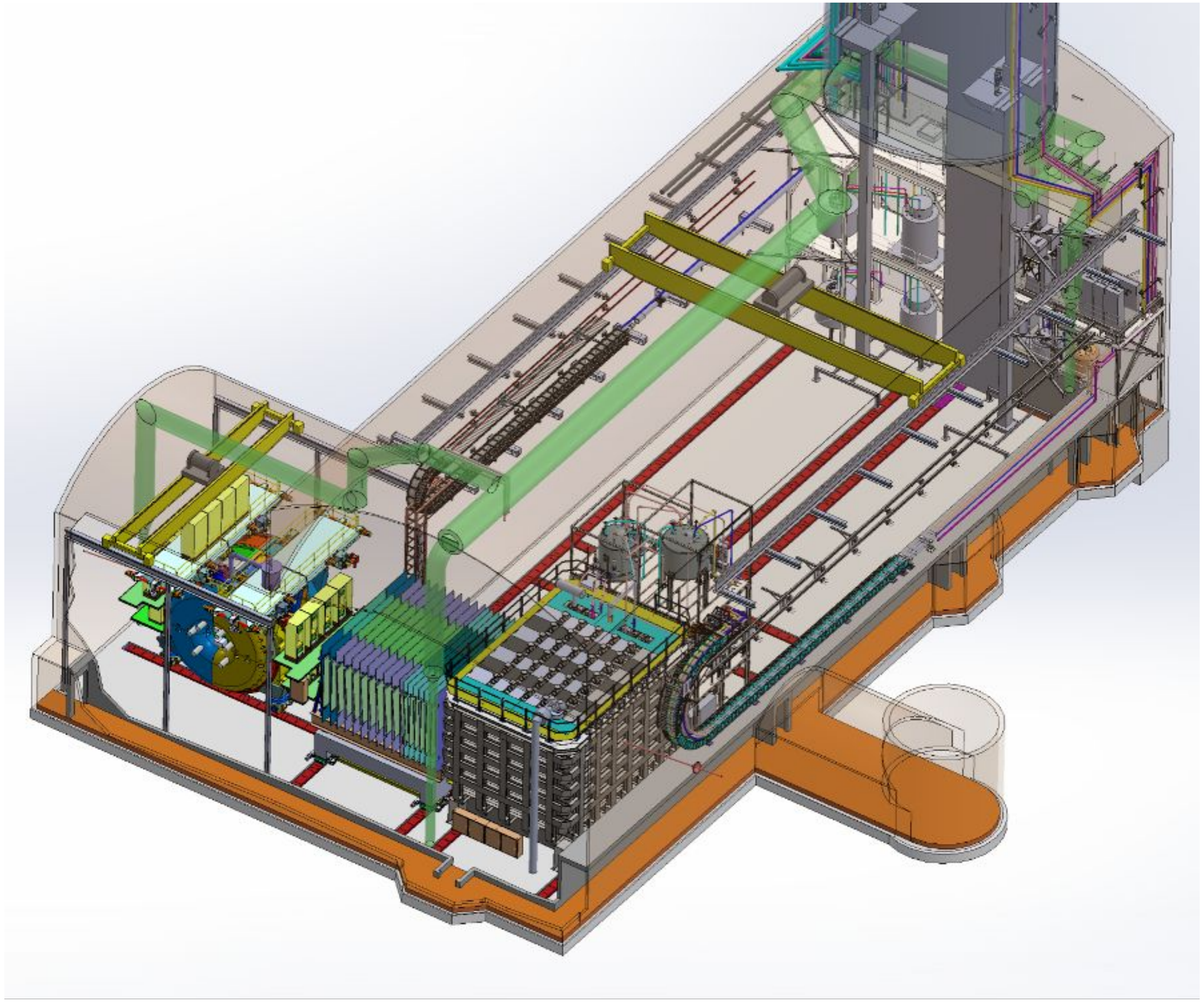
Near Detector

Purpose: enable prediction of Far Detector reconstructed spectra **necessary for systematic uncertainty control in the precision era**

Movable detector system (DUNE-PRISM): LArTPC (**ND-LAr**) with muon spectrometer (**TMS**)

- Constrains energy dependence of neutrino cross sections
- Same target, same technology as FD

On-axis magnetized detector (**SAND**) for beam monitoring and neutrino measurements



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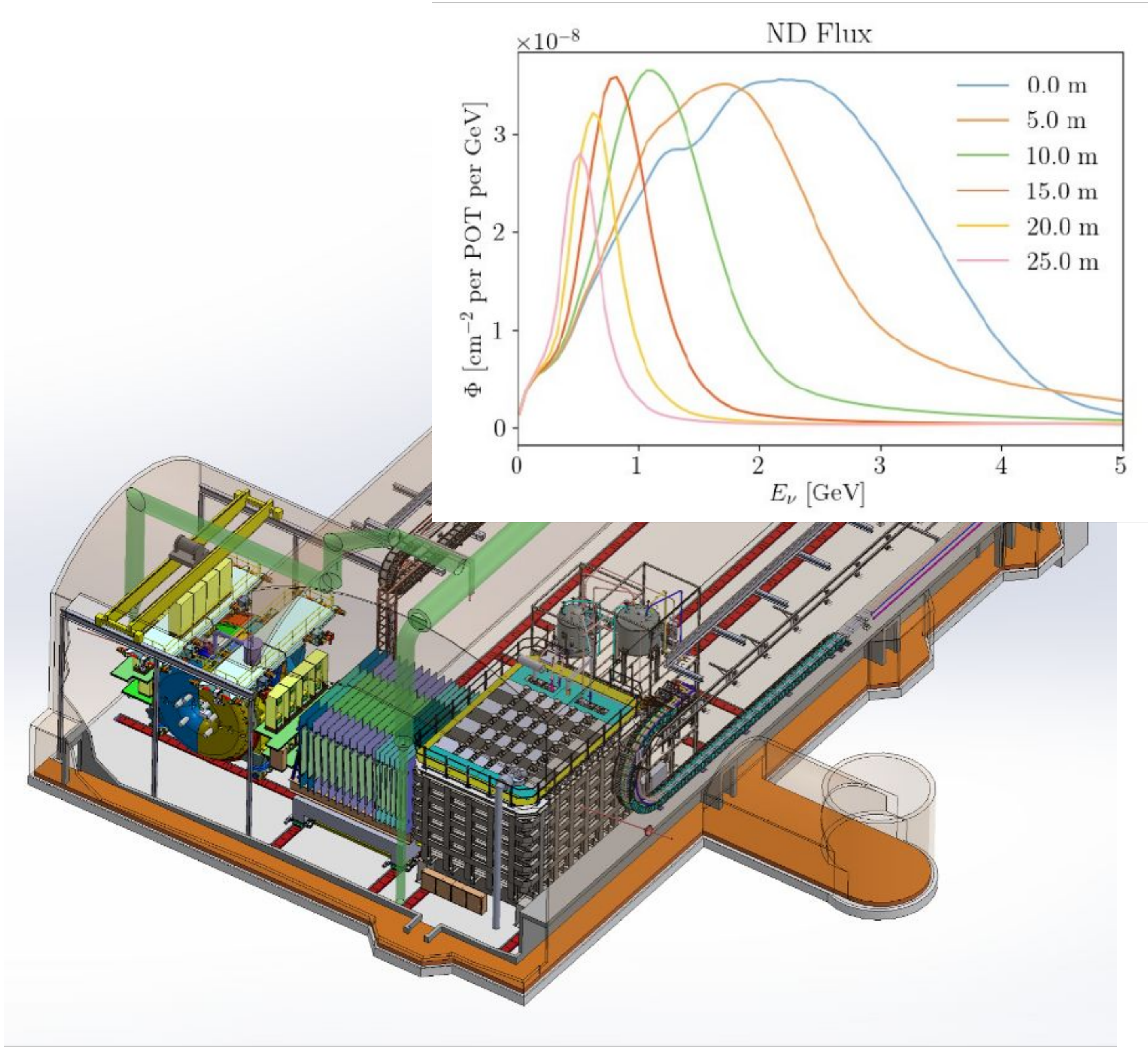

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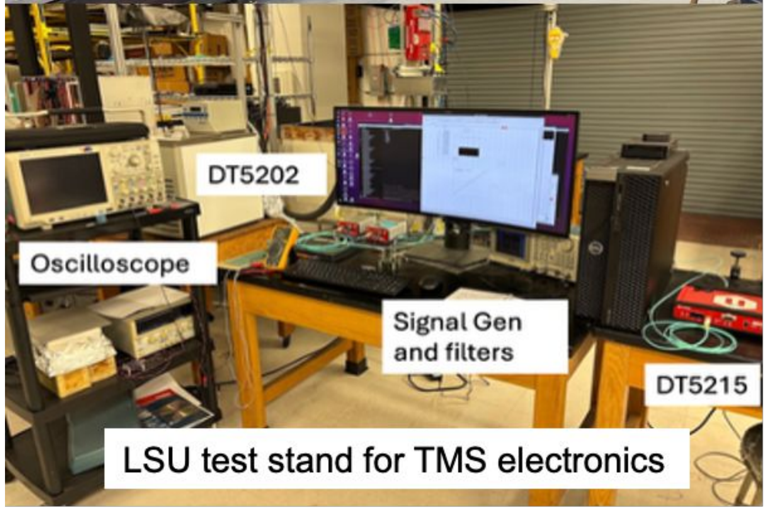
Near Detector progress

DUNE-PRISM testing in Minnesota

SAND integration tests at INFN



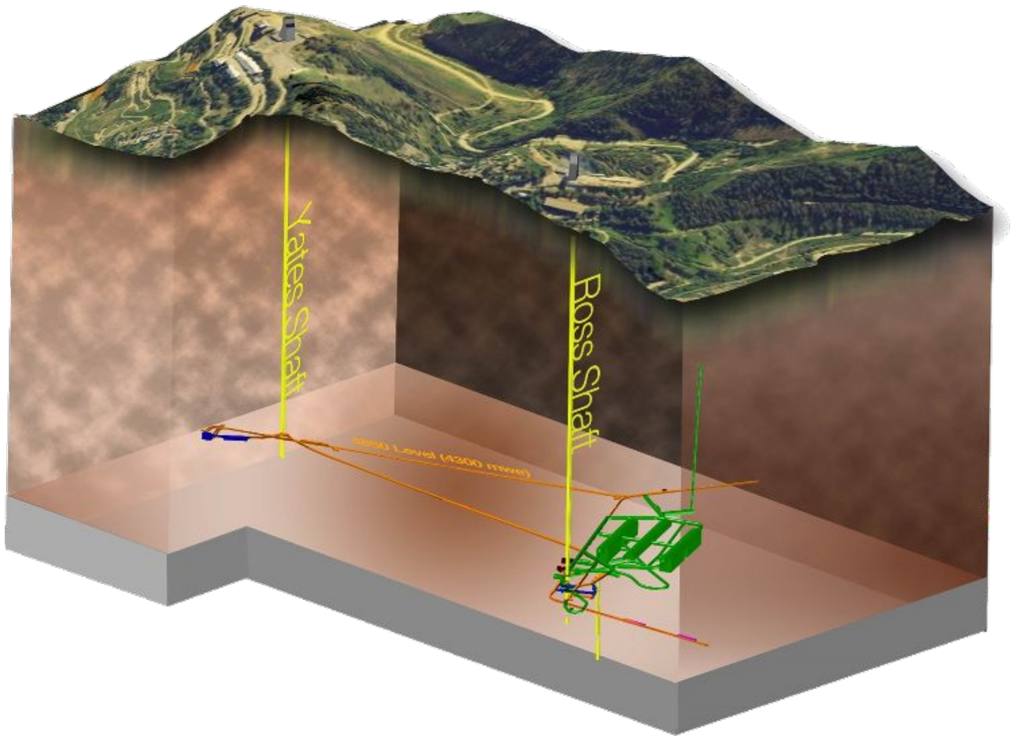
LSU test stand for TMS electronics

Test cryostat arriving at Fermilab

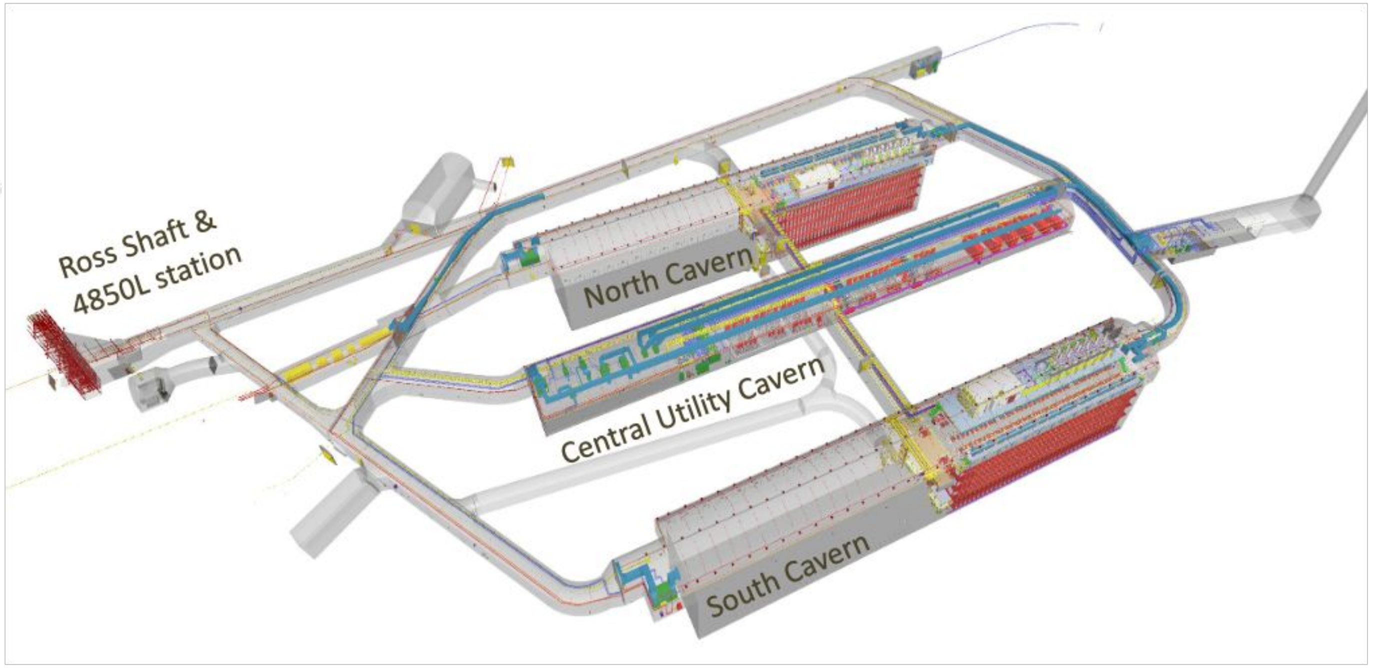
Design is on schedule and nearly complete

- Prototype and test stands have been effective to advance the design

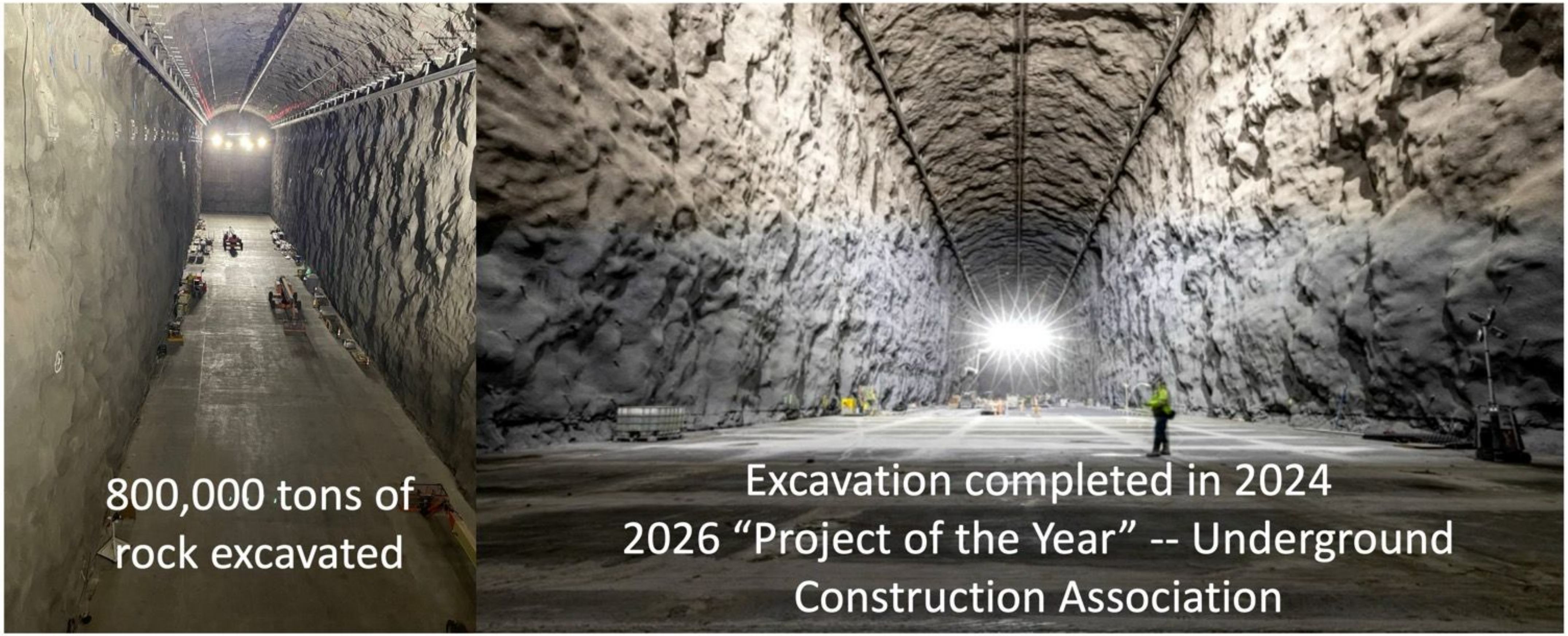
Overview of the underview



Neutrinos from
Fermilab



DUNE cavern

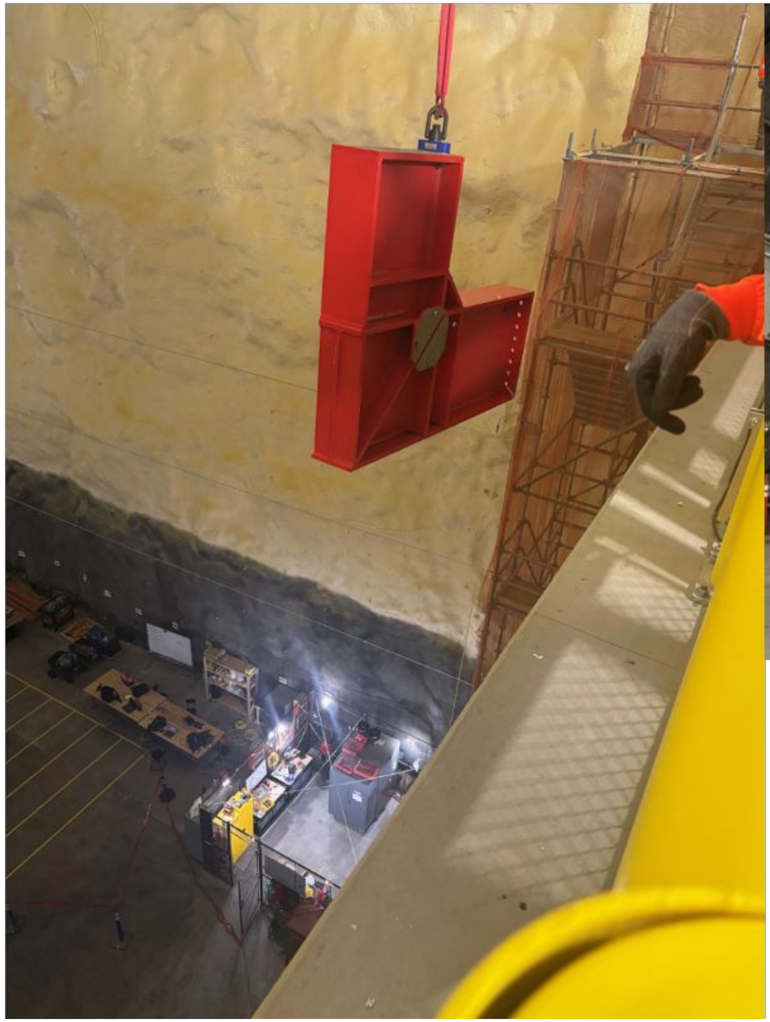


Caverns outfitted with utilities, 'thin sprayed on layer' - Ar pipework to start next year

DUNE support structures

- All warm structure steel has arrived at SURF
- Cold membrane shipments arriving now

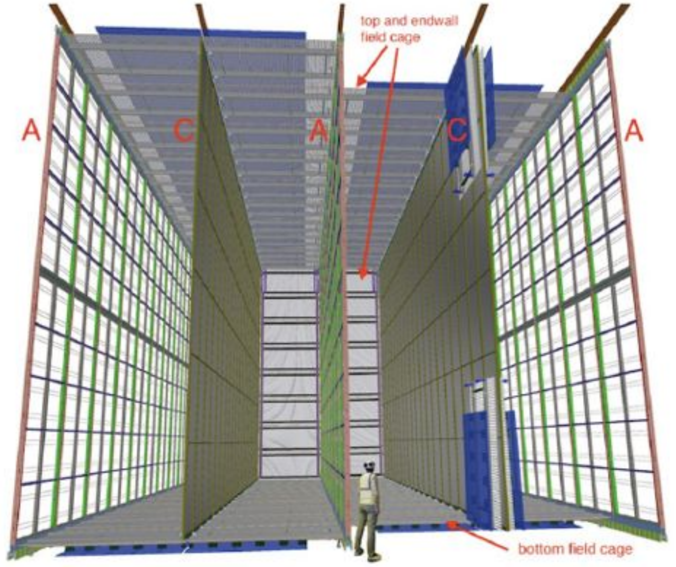
DUNE support structures - going underground



- Successful Far Detector & Cryogenics CD-2/3 DOE Independent Project Review (IPR) – proceed to installation underground!

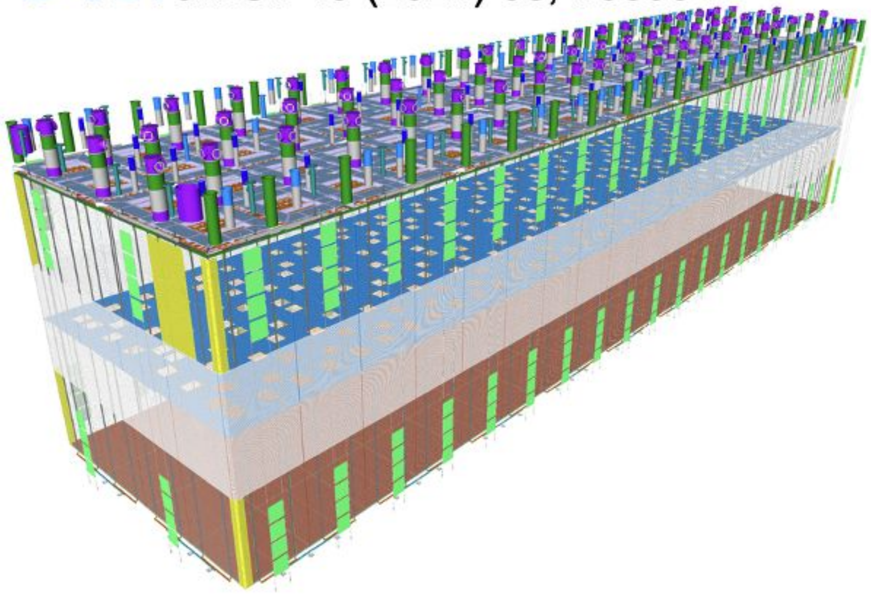
DUNE far detector technologies

FD-HD: JINST 15 (2020) 08, T08010



H 12 m x
W 14 m x
L 58 m

FD-VD: JINST 19 (2024) 08, T08004



H 12 m x
W 14 m x
L 60 m

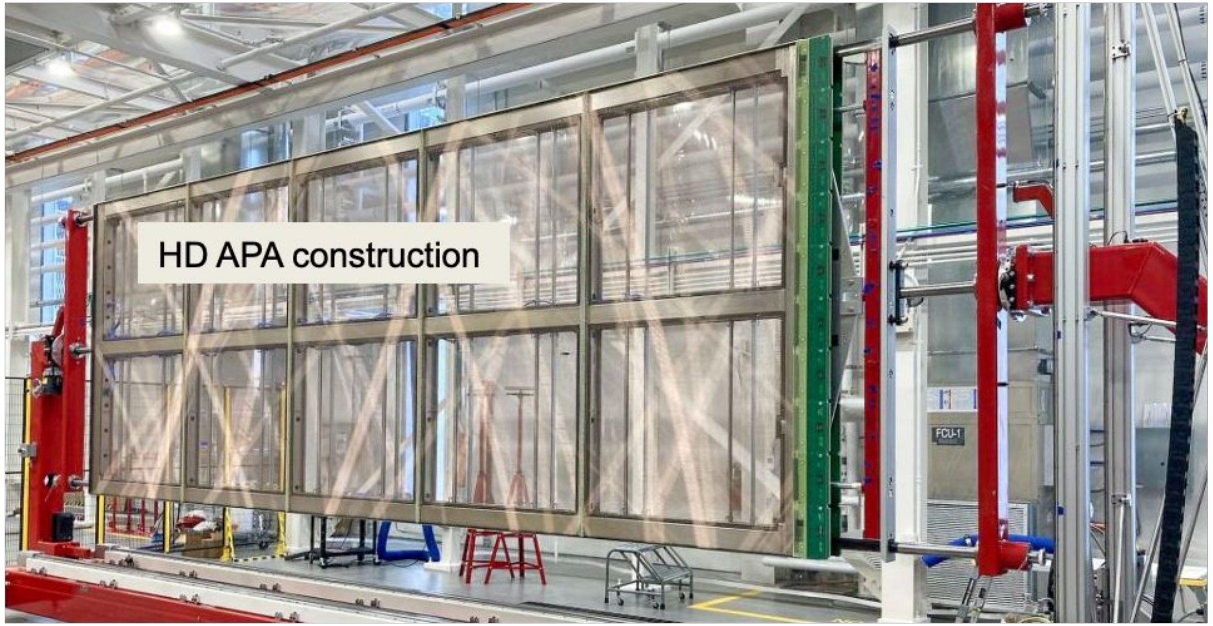
Horizontal drift (FD-HD)

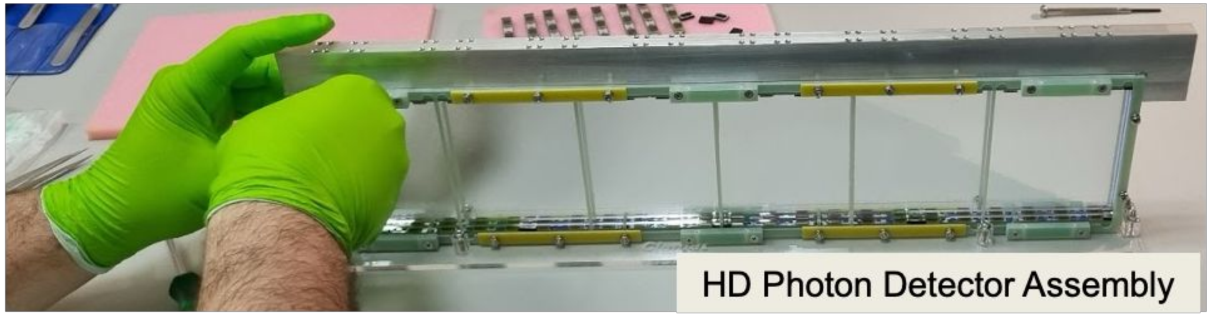
- Four 3.6 m drift regions
- Wire readout plane (APA) technology
- X-ARAPUCA photon detectors integrated in anode planes

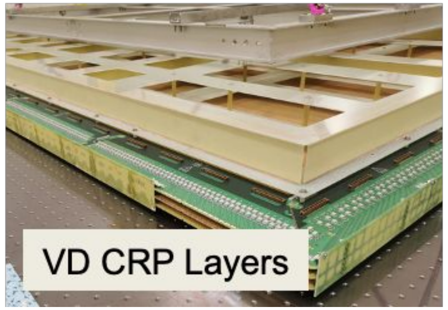
Vertical drift (FD-VD)

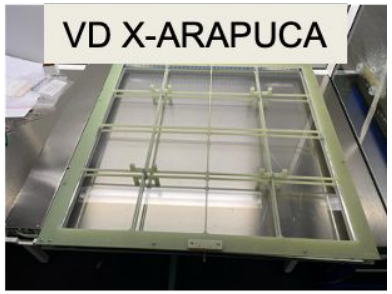
- Two 6.25 m drift regions and central cathode
- Strip-based charge readout plane (CRP) technology
- X-ARAPUCA photon detectors integrated into membrane and cathode planes, with novel power-over-fiber system

Far detector testing and assembly underway









Summary

NOvA plans for an improved Δm^2 measurement for MO determination in comparison to reactors

DUNE's experimental setup makes it highly valuable for precision oscillation physics

- Independant, unambiguous determination of MO via matter effects
- Wide band beam provides sensitivity to □$_{CP}$ and tests of 3 flavor framework
- Intense source and detectors provide a wide array of BSM test opportunities

DUNE is underway

- Far detector cavern excavated, detector construction underway - first data taking planned for early 2030
- Beamline construction underway - first beam planned for 2031

Backup

NPN2026 workshop goals

- This workshop is the sixth in the series New Physics Opportunities at Neutrino Facilities (NPN), which aims to bring together both theorists and experimentalists to actively discuss new physics opportunities at current and future neutrino facilities.
- The primary focus of the NPN 2026 workshop will be on the present status and future directions of accelerator-based neutrino experiments. The workshop aims to provide a platform for detailed discussions on future experimental strategies, facility developments, and the synergies between different accelerator-based neutrino programs, with an emphasis on how they can collectively advance neutrino physics and searches for physics beyond the Standard Model.

Neutrinos: window on new physics

What is the neutrino mass ordering? and absolute mass scale?

Characterize neutrino oscillation:

- Is there new physics in neutrino sector (e.g. charge parity (CP) violation?)
- Are there any symmetries in neutrino mixing?
- Are there non-standard interactions in neutrinos?

What is the mass mechanism?

A NEW ERA OF DISCOVERY
THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

Pathways to Innovation and Discovery in Particle Physics
Report of the 2023 Particle Physics Project Prioritization Panel
Exploring the Quantum Universe

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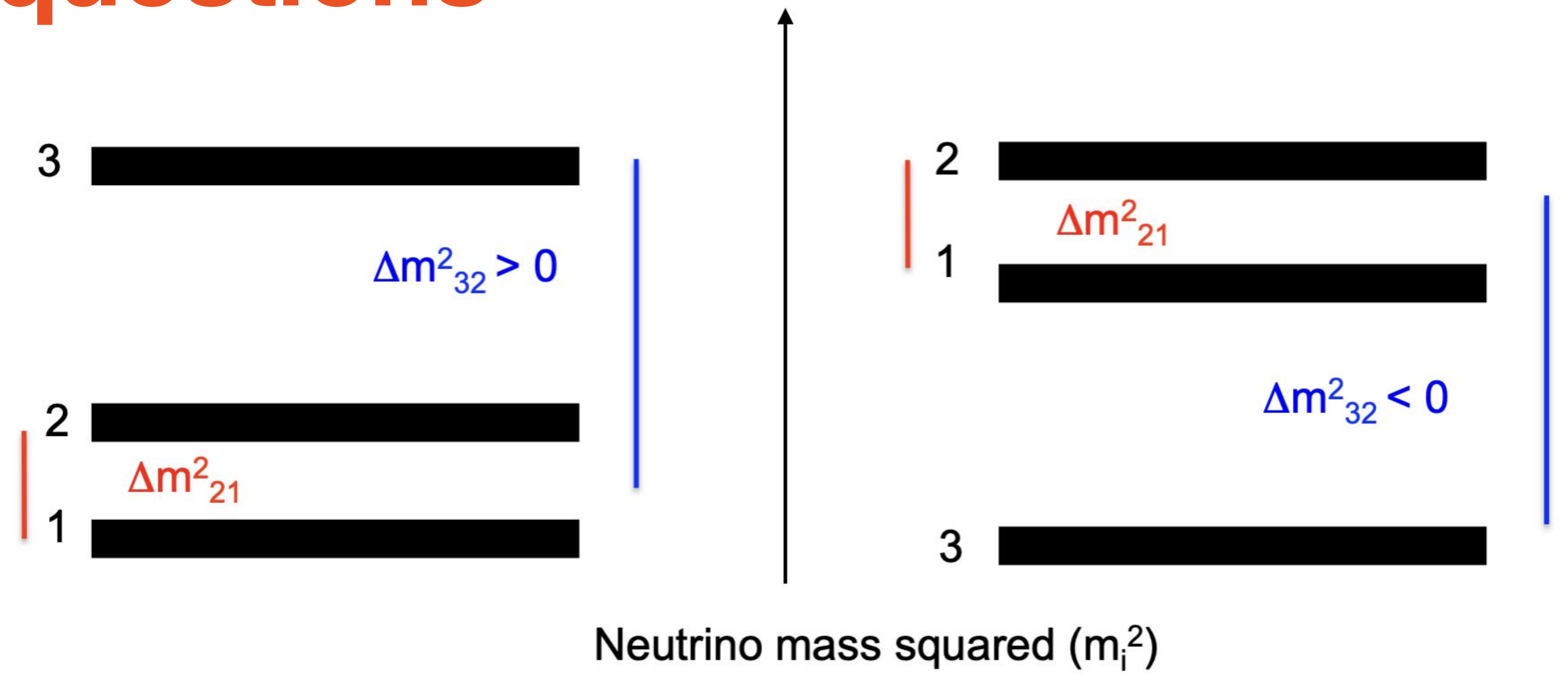
What is the mass mechanism?

Accelerator-based neutrino beams probe oscillation questions and determine the mass ordering

Open questions



What is the neutrino mass ordering?
(mass hierarchy)

- Is ν_3 the heaviest?
- "Normal" mass ordering: $\Delta m^2_{32} > 0$
- "Inverted" mass ordering: $\Delta m^2_{32} < 0$

Neutrino oscillation refresher

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

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) + 2\sum_{i>j}\mathrm{Im}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\left(\frac{2.54\Delta m^2_{ij}L}{E}\right)$$

Probability to oscillate from flavor ν_α to ν_β and depends on:

- U elements (and therefore θ_{23}, δ_{CP}) and mass splitting Δm^2_{32}
- L - ‘Baseline’ - *T2(H)K is 295km, NOvA is 810km, DUNE is 1285km*
- E - neutrino energy

Neutrino oscillation refresher

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

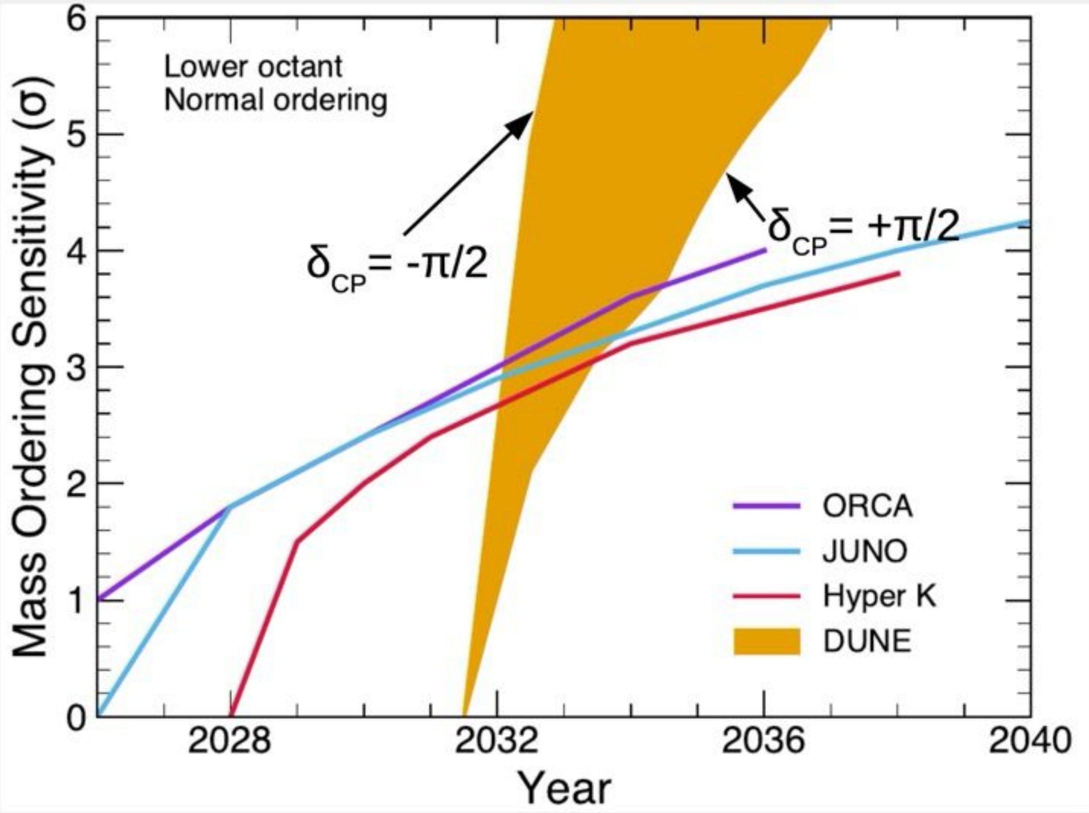
Flavor states Mass states

Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS)

If U is unitary, 3 mixing angles (θ_{12} θ_{23} θ_{13}) and one phase (δ_{CP})

Mass ordering

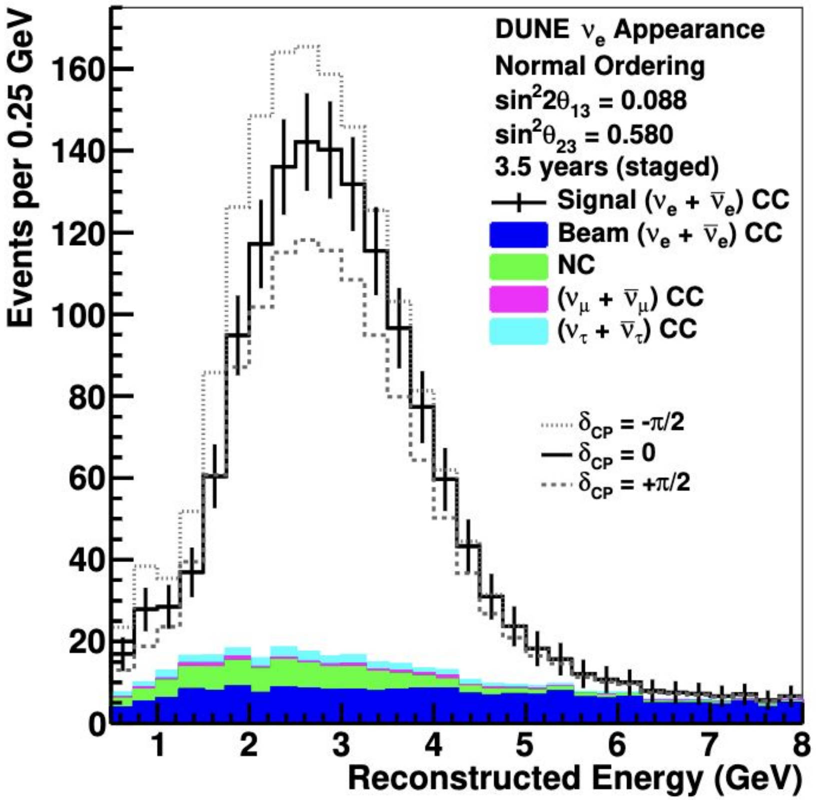
- DUNE is the only experiment that measures the mass ordering by separately measuring $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

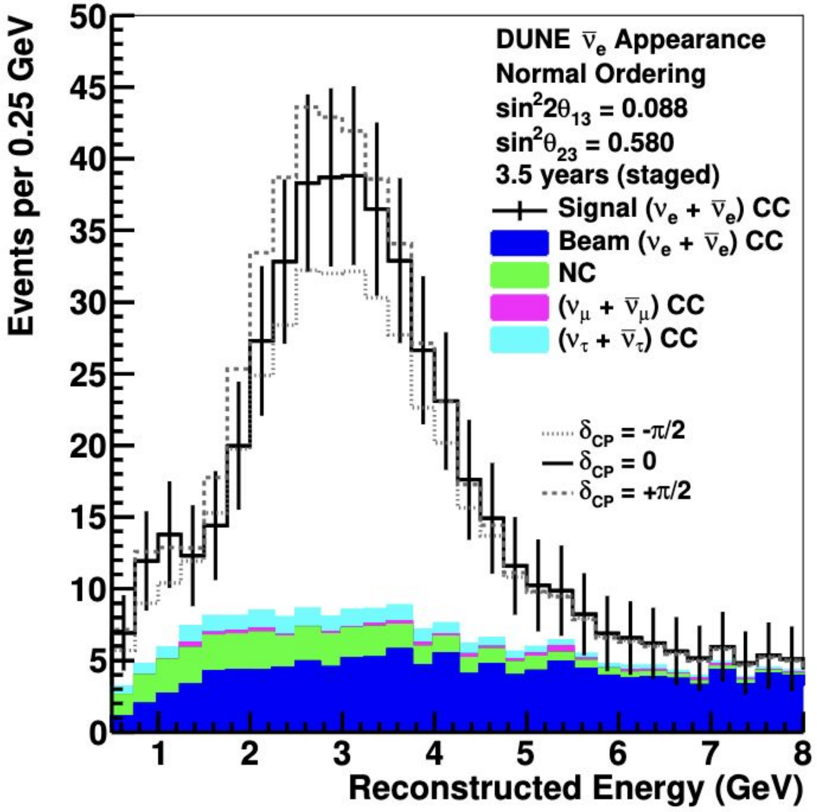


- Existing Super-K atmospheric data (weakly) prefers normal ordering and lower octant
- In this scenario, atmospheric experiments do not reach 5σ for mass ordering discovery
- Despite starting later, **DUNE is the only experiment to reach >5σ**, even in the most pessimistic case

DUNE oscillation reach - details

E. Phys. J. C (2020) 80:978





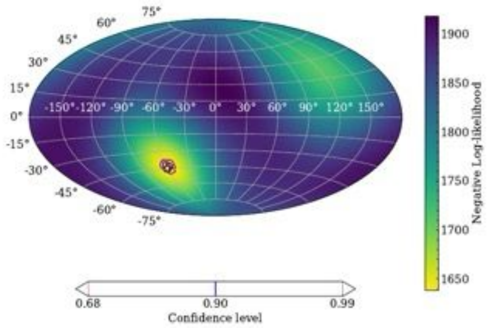
CC inclusive signal - *note modest intrinsic nue and NC backgrounds*

DUNE Physics: Astrophysical Neutrinos

Neutrinos from core-collapse supernovae

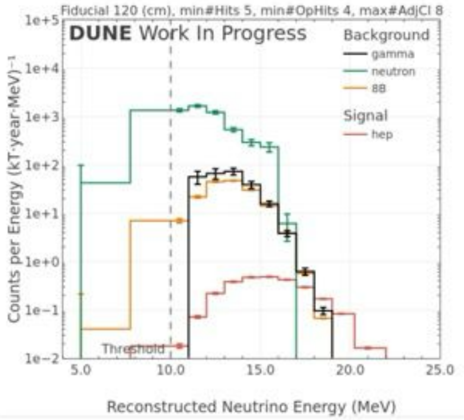
- DUNE has unique sensitivity to electron neutrinos
- **Neutronization** burst measurements → mass ordering measurement
- **Pointing** capabilities: ES channel ~5° pointing resolution (40 kt, 10 kpc)

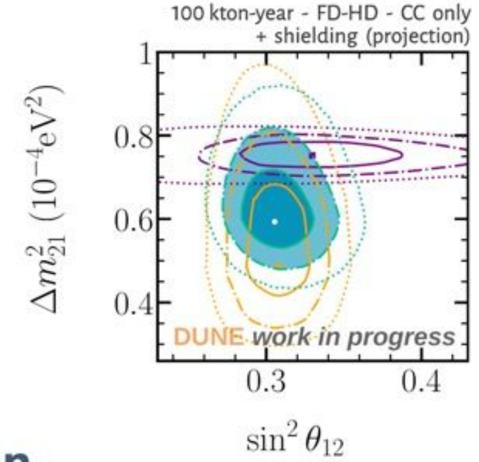
Phys. Rev. D 111 (2025) 9, 092006



	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

[1] Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2] Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)





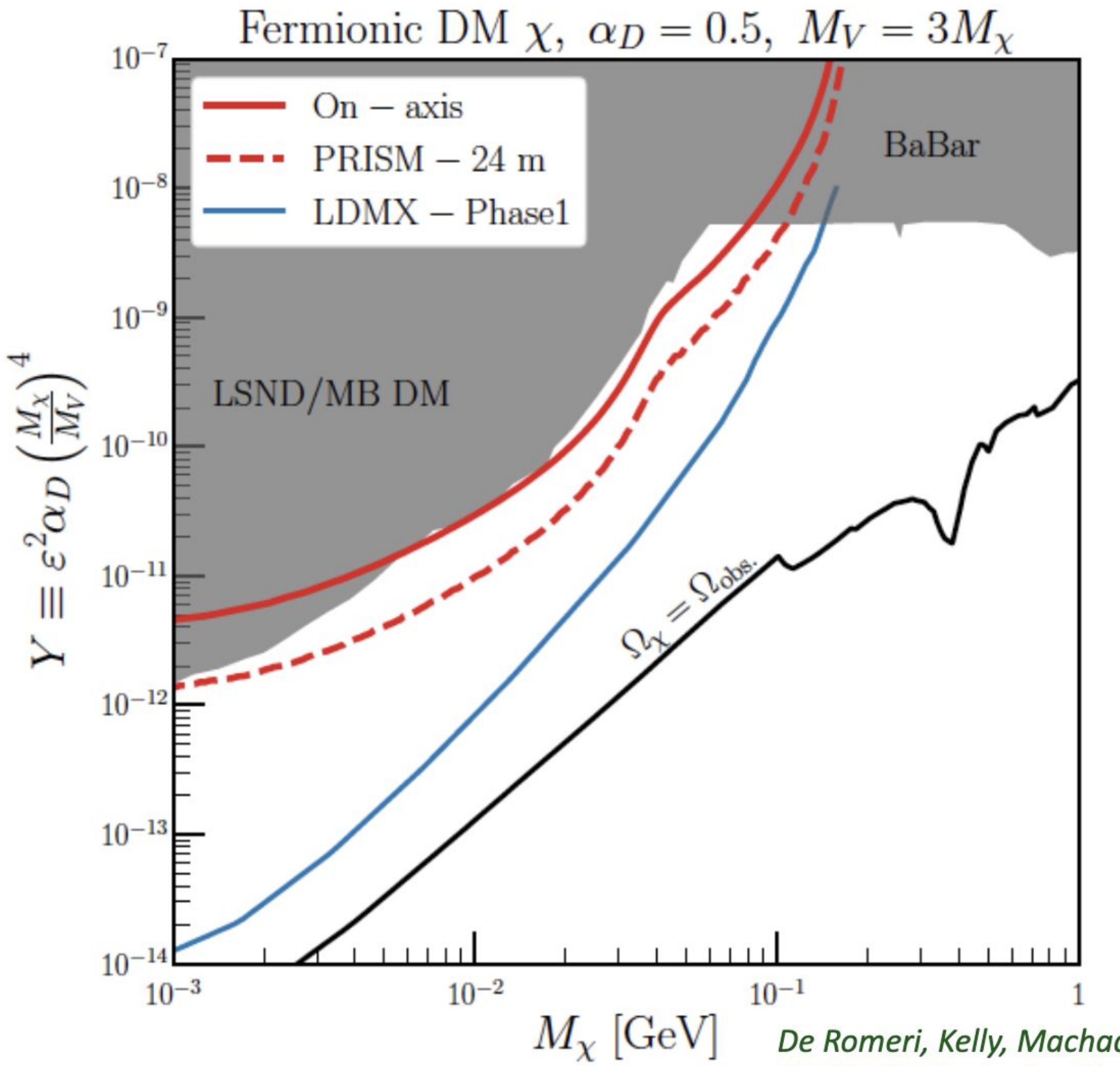
Neutrinos from the Sun

- DUNE has excellent sensitivity to **^{8}B solar neutrinos** above ~10 MeV, and discovery sensitivity to the **hep solar flux**
- DUNE is sensitive to solar oscillation measurements via **day-night asymmetry** induced by matter effects → comparison with JUNO

Building DUNE: Next Steps in Caverns

- "Thin Sprayed-On Layer" (TSL) being applied to caverns now; will be complete in all caverns by October
- Installation of monorail for crane will follow
- Ross shaft Argon pipework will start next year
- Ross shaft headframe improvements underway

Low mass dark matter at DUNE ND



De Romeri, Kelly, Machado, Phys. Rev. D ***100****, 095010 (2019)*
DUNE BSM Paper, Eur. Phys. J. C 81, 322 (2021)

- Showing sensitivity (90% CL) of DUNE for a 7-year (50% neutrino beam, 50% antineutrino) run
- Dashed line shows significant improvements by running off-axis (DUNE-PRISM)