Long-baseline experiments: status & future prospects

Chris Marshall, University of Rochester

NNN 2026, Seoul

28 October, 2026



University of Rochester

Fermilab



U.S. DEPARTMENT of ENERGY

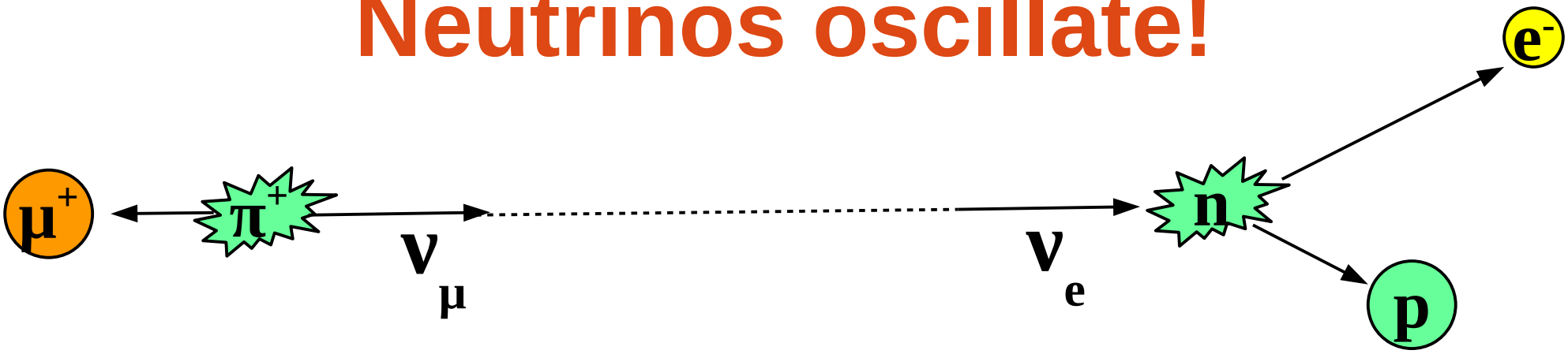
Caveat: who am I?

- I am the physics co-coordinator of DUNE
- I also work on ICARUS and SBN
- I previously worked on Daya Bay and MINERvA
- Opinions expressed in this talk are my own, and are not given on behalf of DUNE

Outline

- **How we got here**: a (very) brief history of long-baseline oscillation experiments
- **Where we are**: what we know from T2K, NOvA, reactor, and atmospheric results
- **Where we're going**: goals for the "next generation"; Hyper-K and DUNE

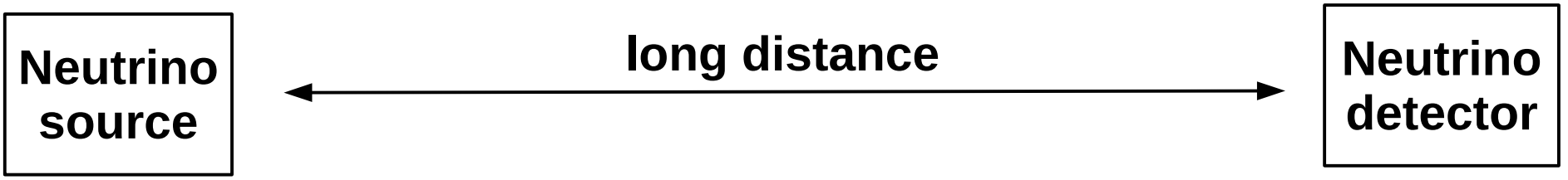
Neutrinos oscillate!



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

- This tells us that:
  - There is **nonzero mixing** between neutrino mass and flavor states
  - The neutrino masses are different, thus there must be **nonzero mass**
- So how can we study this experimentally?

Long-baseline experiments



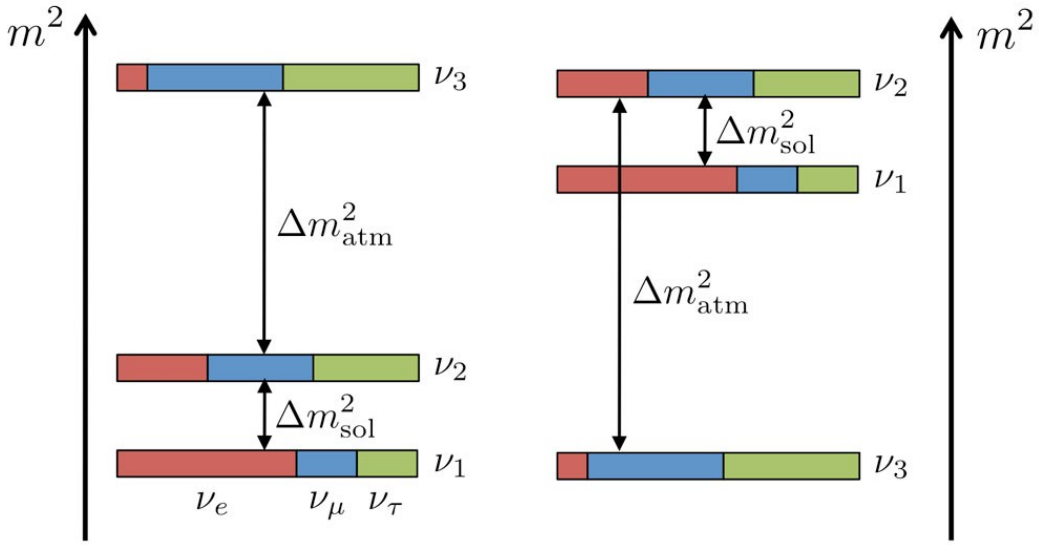
- An ideal source would be:
  - Highly pure in flavor and helicity
  - High intensity
  - Tunable in energy
  - Free
- An ideal detector would be:
  - Very large
  - Able to image interactions with high fidelity
  - Cheap
- So far we have developed **zero** ideal sources and **zero** ideal detectors

MELIORA University of Rochester

Mixing with three neutrinos

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

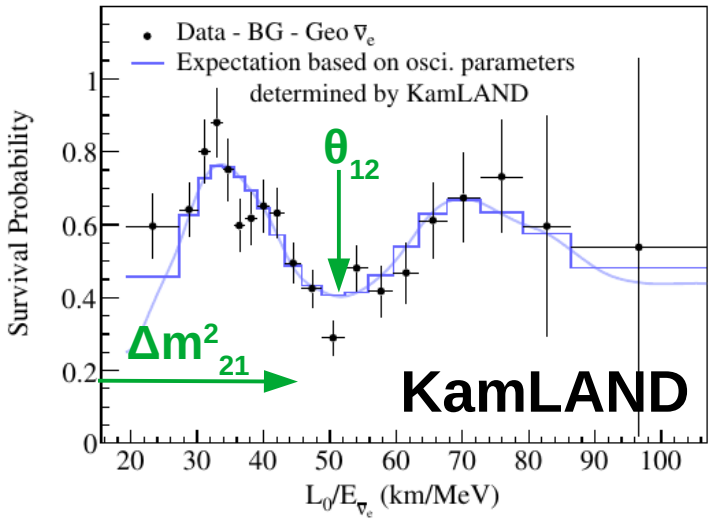
sin() and cos() of mixing angles θ_{23}, θ_{13}, θ_{12}



- Usual approach: assume U_{PMNS} is unitary, parameterize mixing in terms of three mixing angles + a CP-violating phase
- Two independent mass squared splittings
- Experiments have been designed to measure one or two parameters, assuming the model is correct and complete

MELIORA University of Rochester

“First generation” long-baseline reactor experiment

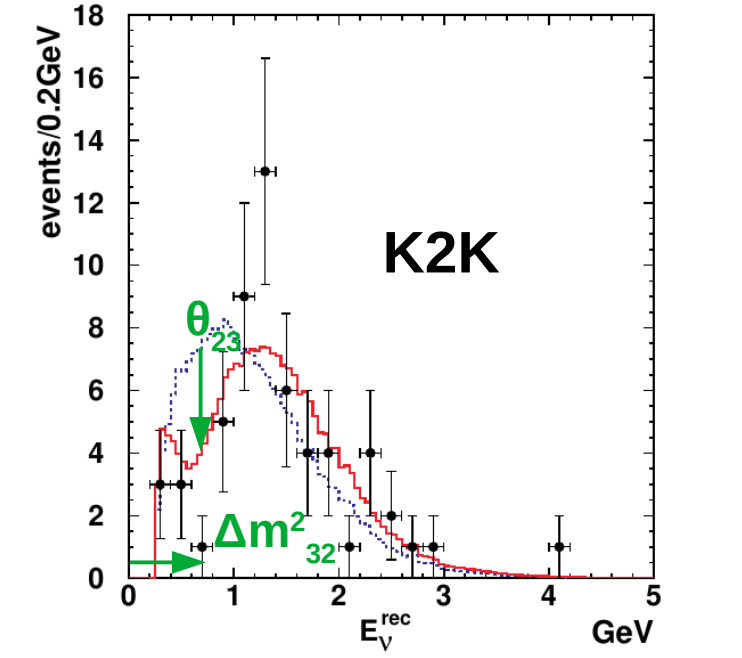


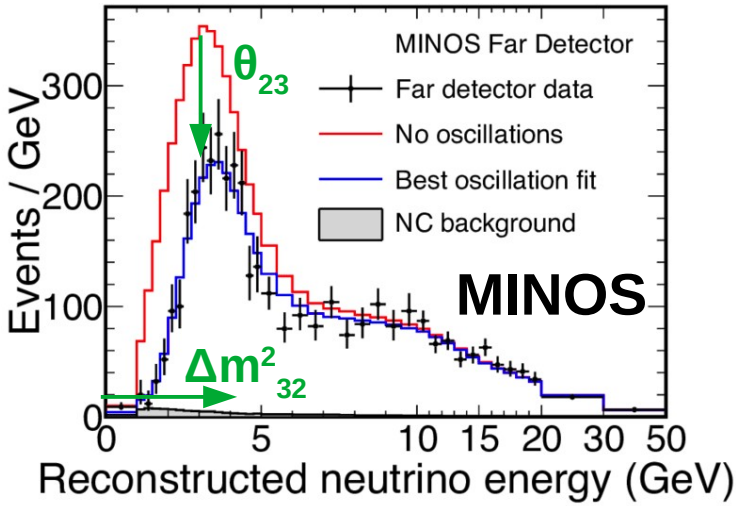


- KamLAND saw a **large $\bar{\nu}_e$ disappearance** with L/E ~ 15000 km/GeV
- This measures θ_{12} and Δm^2_{21}

MELIORA University of Rochester

“First generation” accelerator long-baseline experiments

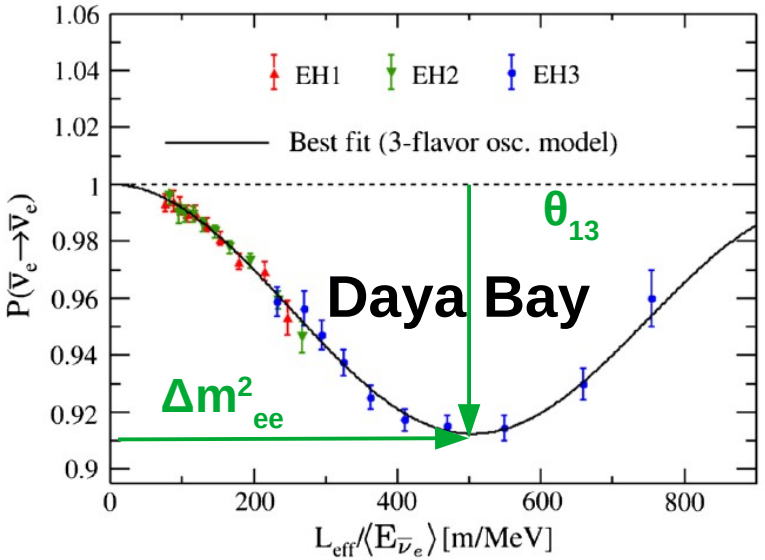


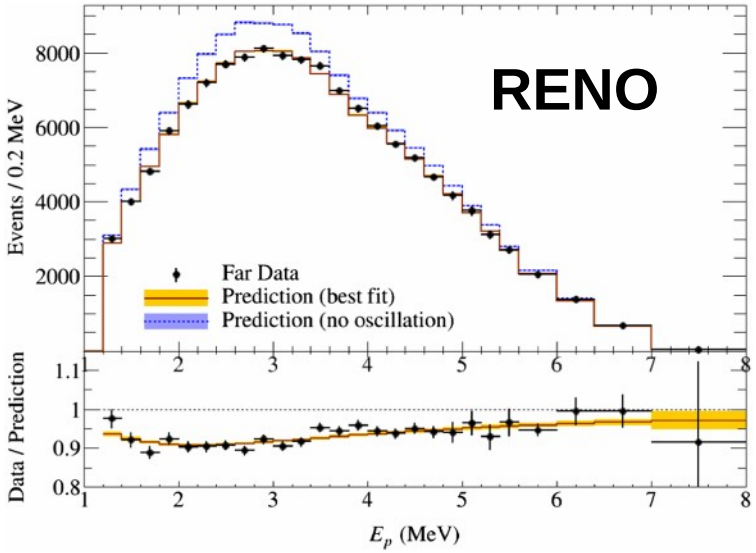


- Super-K saw a large deficit of atmospheric upward-going ν_μ
- First accelerator experiments (K2K, MINOS) saw a **large ν_μ disappearance** with L/E ~ 500 km/GeV
- This measures θ_{23} and Δm^2_{32}

MELIORA University of Rochester

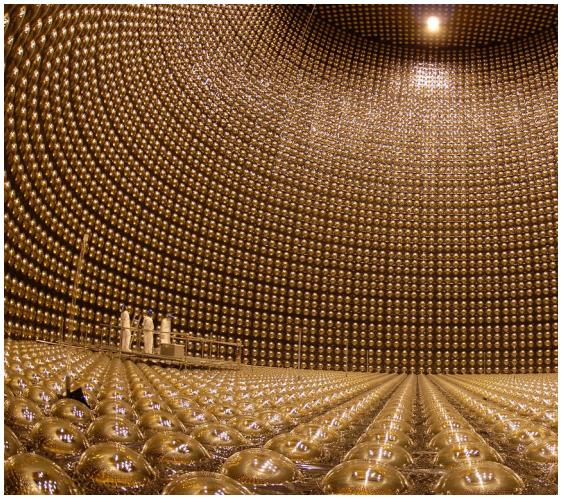
"Second generation" reactor experiments measured θ_{13}

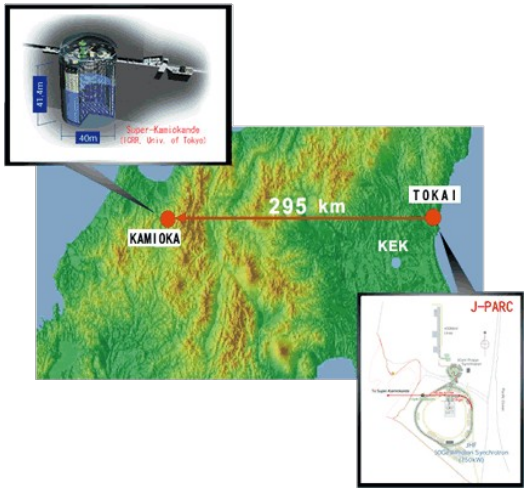




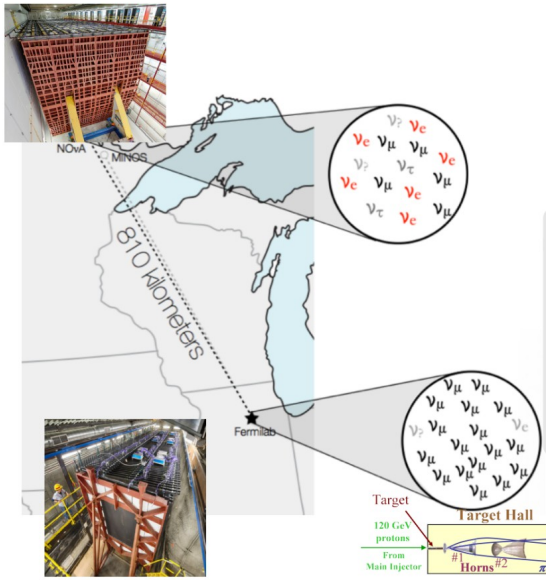
- Daya Bay, RENO, and DoubleChooz see a small (8%) $\bar{\nu}_e$ disappearance with L/E ~ 500 km/GeV
- This measures θ_{13}, Δm^2_{31}
- By this point (2012) all of the mixing angles and |mass^2 splittings| are known!

“Second generation” accelerator LBL experiments: T2K and NOvA





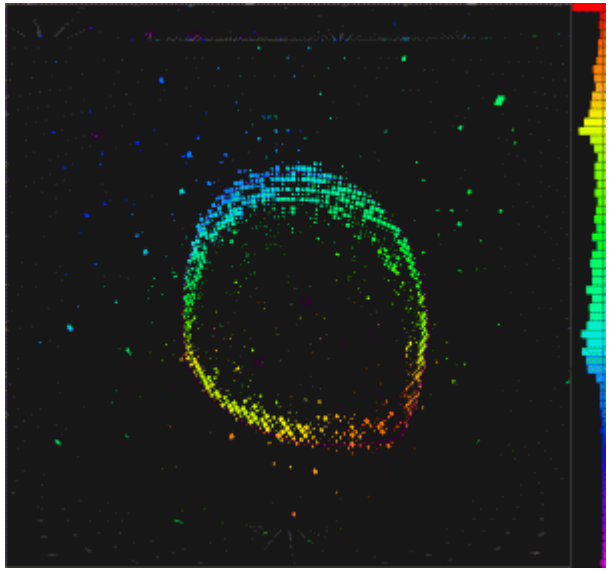


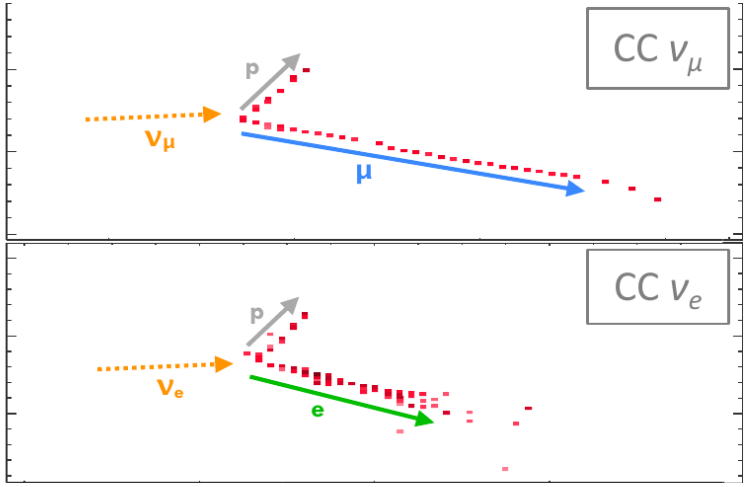


- T2K (Tokai to Kamioka, Japan)
  - 295km baseline
  - Huge water-based far detector (Super-K)
- NOvA
  - 810km baseline
  - Oil+scintillator detectors
- Beams of ν_μ or $\bar{\nu}_\mu$ with narrow energy spectrum, designed to search for ν_e and $\bar{\nu}_e$ appearance
- In principle sensitive to MO and CPV via the **asymmetry** in ν_e and $\bar{\nu}_e$

MELIORA University of Rochester

T2K and NOvA employ different, complementary technologies

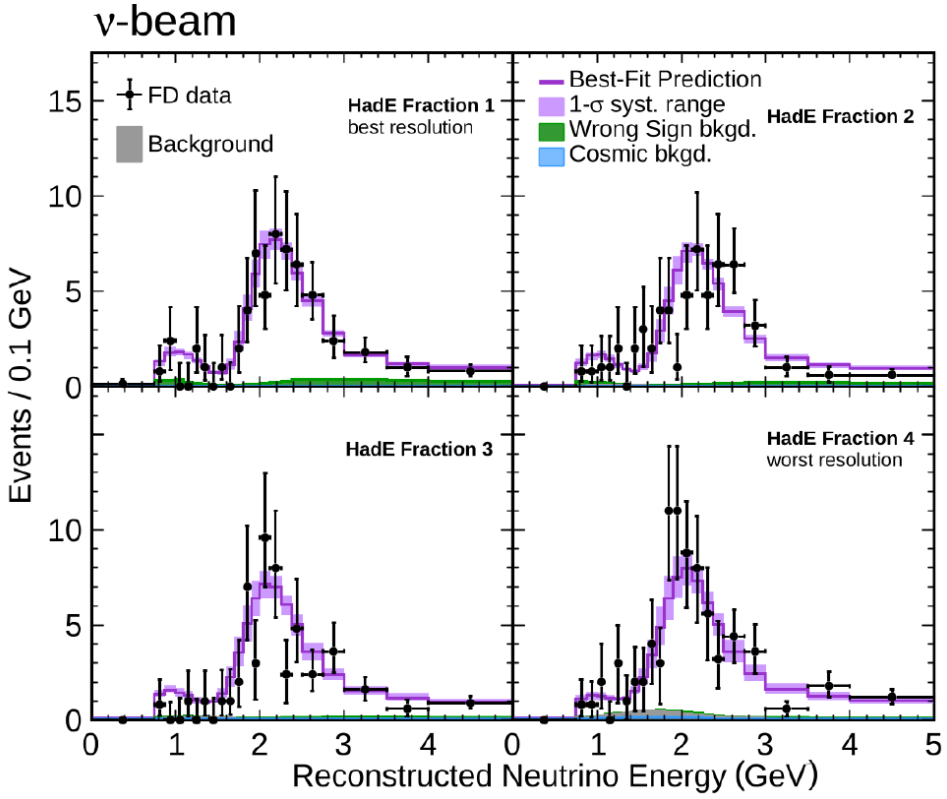


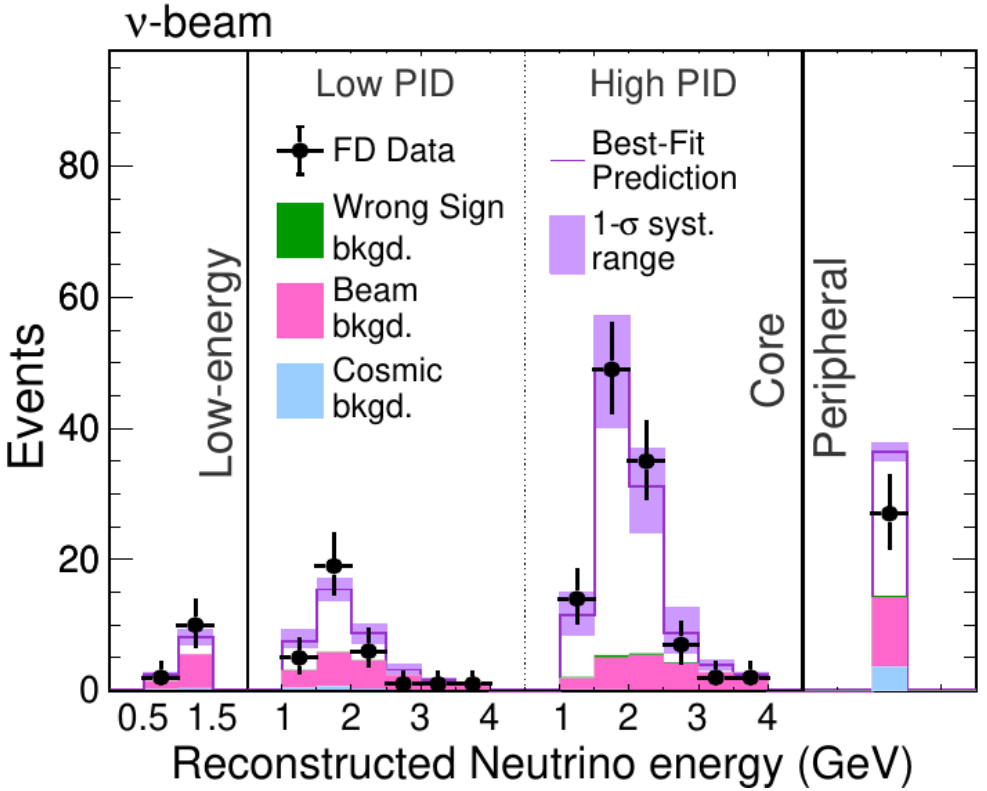


- T2K FD sees rings due to particles above Cherenkov threshold in water
  - Excellent e/μ separation from ring "fuzziness"
  - Reconstruct E_ν from kinematics; most events are CC0π, 1π sample is mostly Δ resonance
- NOvA is segmented scintillator
  - Excellent e/μ separation
  - Reconstruct E_ν calorimetrically
- Detector systematics are uncorrelated

MELIORA University of Rochester

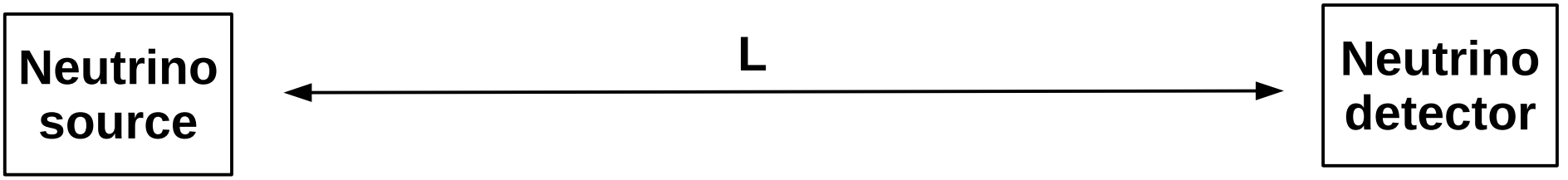
Squeezing as much as possible from FD data (NOvA example)





- ν_μ samples are binned by expected resolution
- ν_e samples separated by PID purity, including low-energy and edge events

Critical role of Near Detectors in accelerator LBL experiments



- Oscillation probability is the ratio of **fluxes**

$$P(\nu_\alpha \to \nu_\beta) = \frac{\Phi_{\nu_\beta}(E_\nu, L)}{\Phi_{\nu_\alpha}(E_\nu, 0)}$$

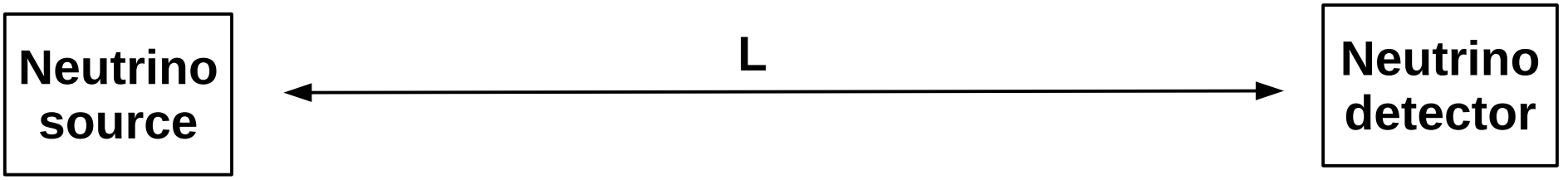
- But detectors measure **event rates**; σ is highly uncertain

$$N(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu)$$

$$N(E_{reco}) = \int \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times \mathbf{D}(E_\nu \to E_{reco}) dE_\nu$$

MELIORA University of Rochester

Critical role of Near Detectors in accelerator LBL experiments



- Near detector constrains flux, cross section, and detector response → uncertainties largely cancel in ratio

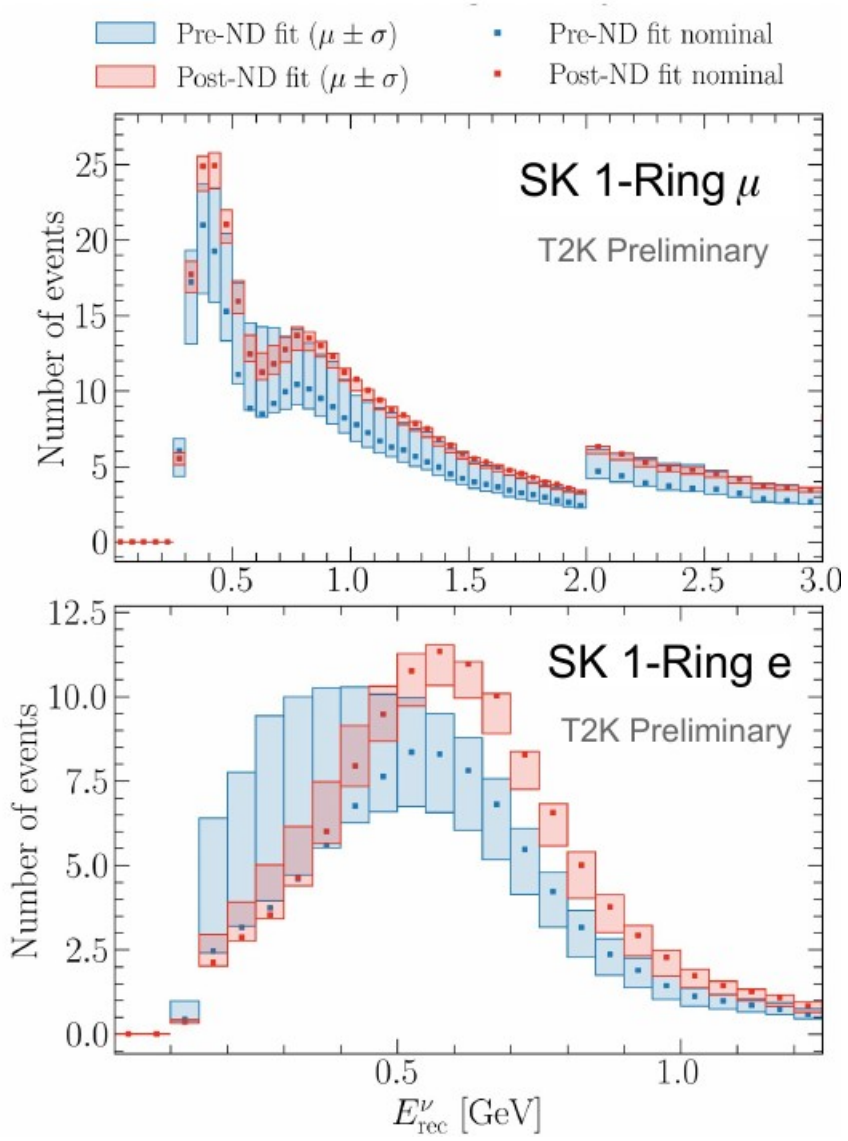
$$P(\nu_\alpha \to \nu_\beta) = \frac{\Phi_{\nu_\beta}(E_\nu, L)}{\Phi_{\nu_\alpha}(E_\nu, 0)}$$

$$N(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu)$$

$$\frac{N^{far}(E_{reco}) = \int \Phi(E_\nu, L) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times \mathbf{D}(E_\nu \to E_{reco}) dE_\nu}{N^{near}(E_{reco}) = \int \Phi(E_\nu, 0) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times \mathbf{D}(E_\nu \to E_{reco}) dE_\nu}$$

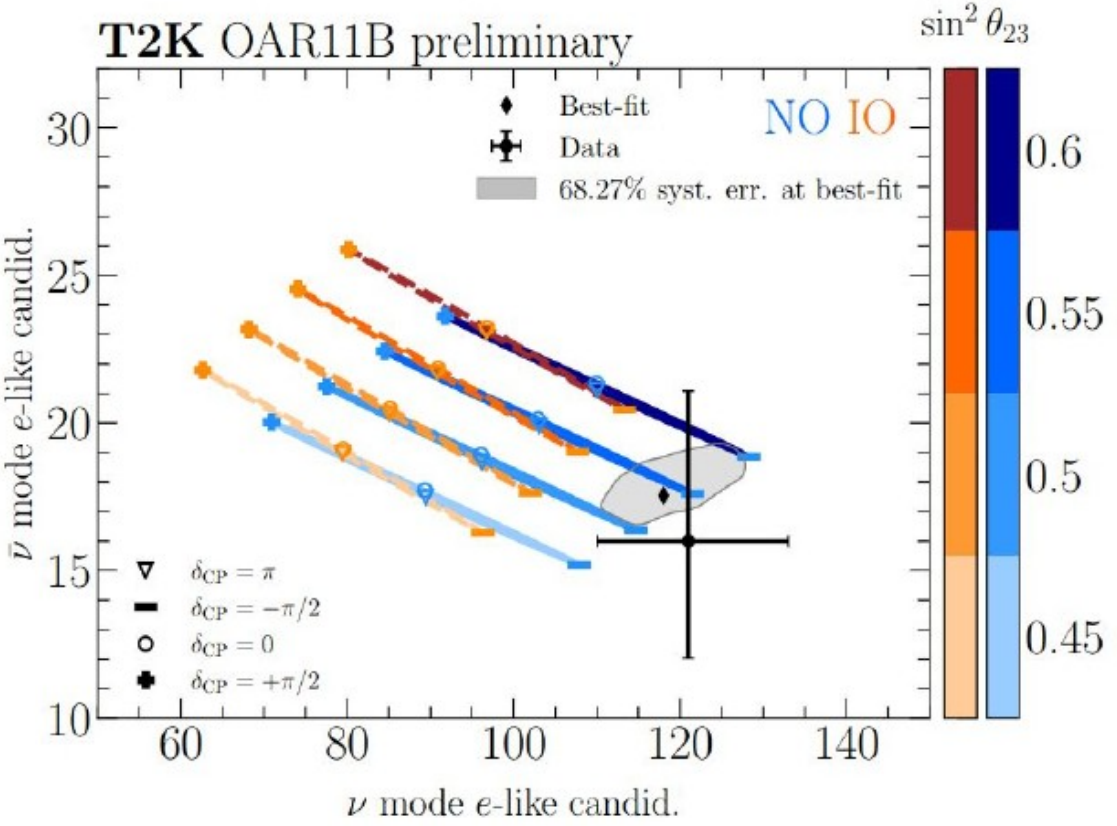
MELIORA University of Rochester

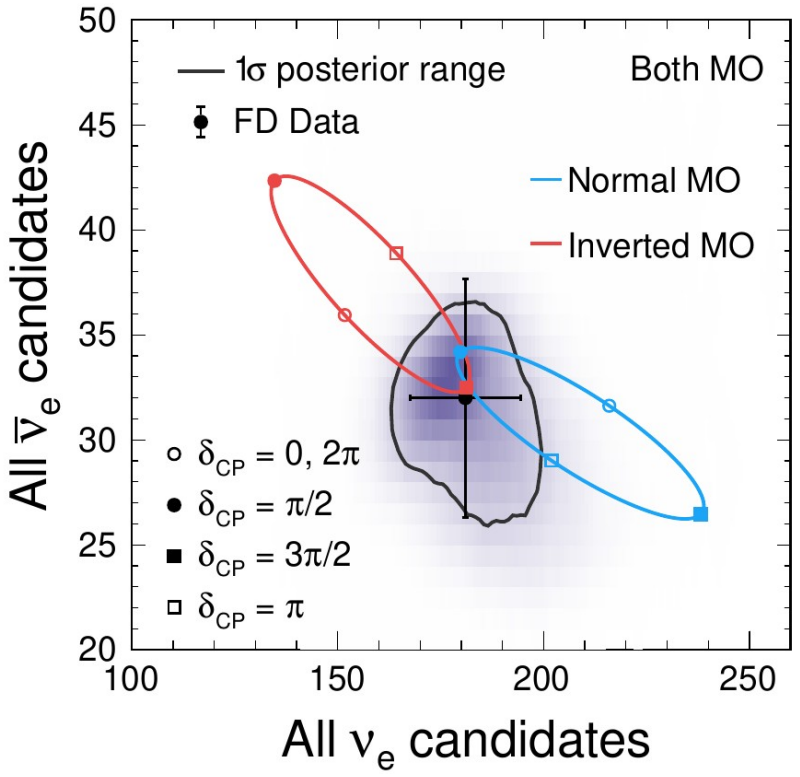
Near Detectors are essential as measurement precision increases



- T2K fits 10 ND280 samples across 4 exclusive selections in neutrino mode
- Reduces uncertainty on the predicted FD event rates in the largest samples
  - 19.2% → 3.7% for 1Rμ
  - 20.3% → 5.7% for 1Re
- Critical for achieving current measurement precision

Data visualization: bi-event plots

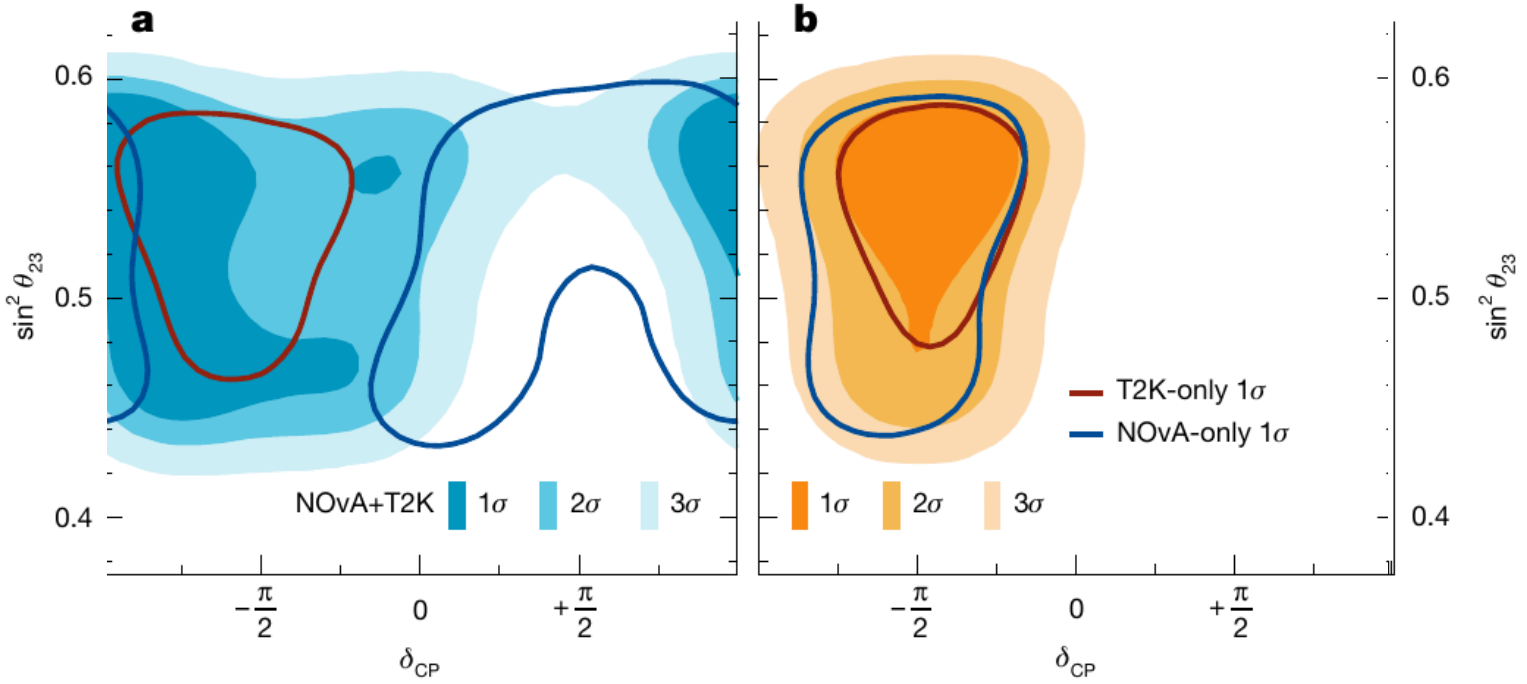




- Count ν_e candidates in neutrino and antineutrino beams
- Compare to expectation for different mass orderings, values of δ_{CP}, θ_{23}

MELIORA University of Rochester

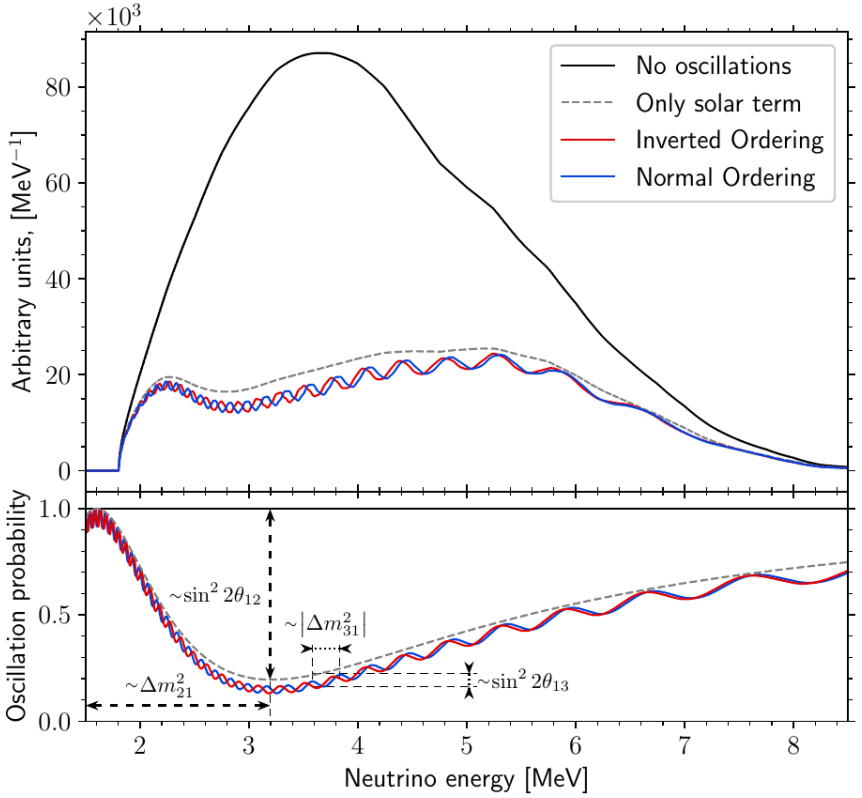
T2K+NOvA results

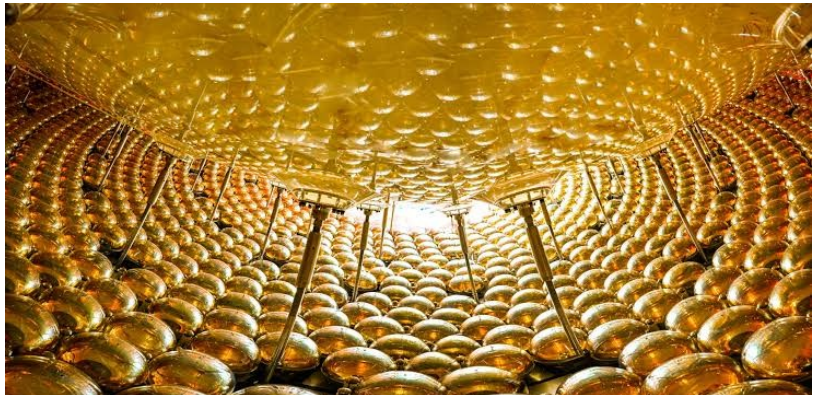


- T2K and NOvA have somewhat different 1σ preferred regions in NO but are not inconsistent
- Data prefer either IO and $\delta_{CP} \sim -\pi/2$ or NO and δ_{CP} somewhere in $\sim(-\pi, -\pi/2)$
- Not precise enough to establish CPV or make definitive statement about mass ordering → need better experiments

MELIORA University of Rochester

“Third generation” reactor: JUNO

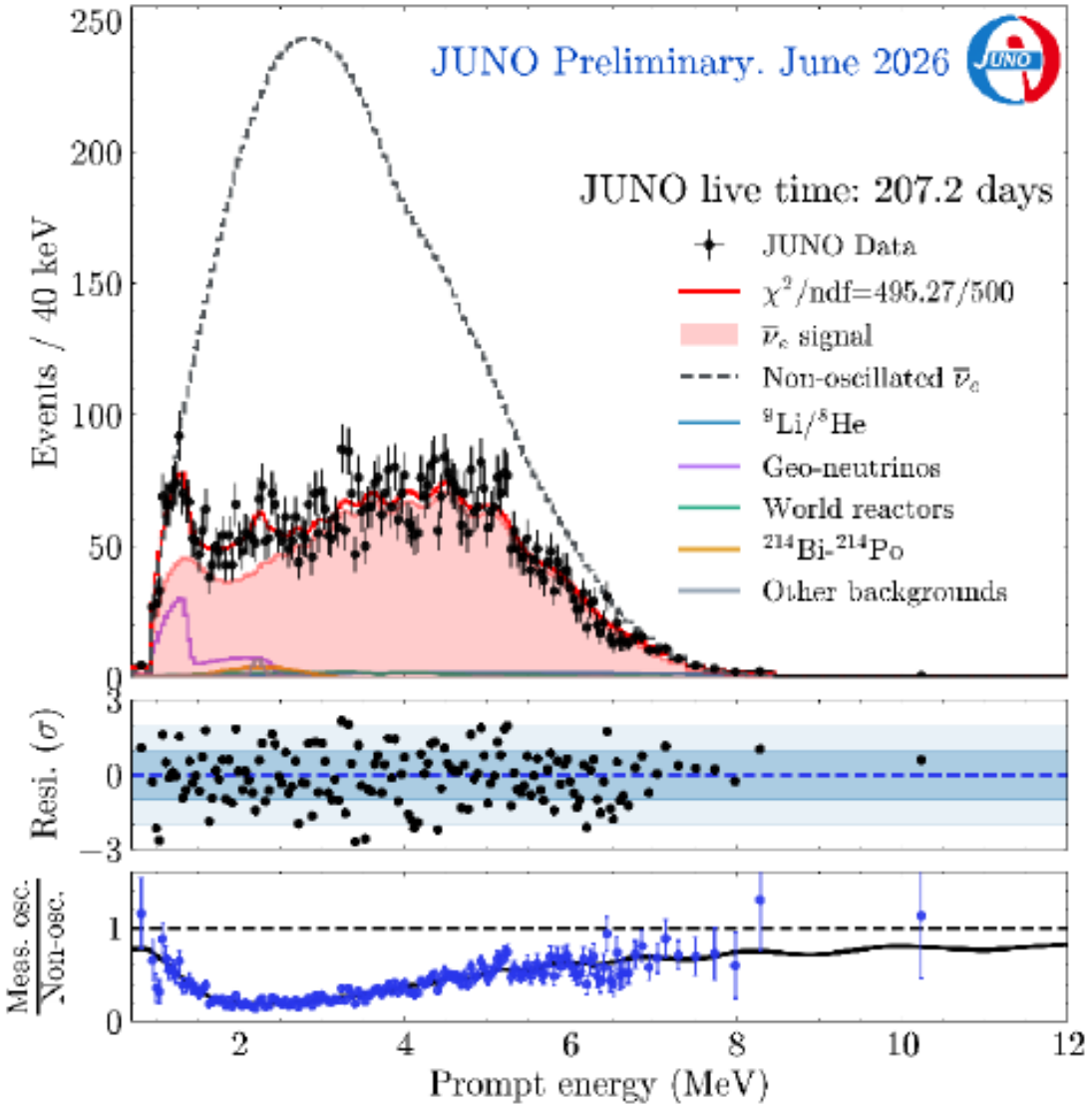




- Super-precise $\bar{\nu}_e$ disappearance over ~50km baseline → first experiment sensitive to 500 km/GeV and 15000 km/GeV at once
- Δm^2_{31} is a **frequency** → incredible precision
- World-leading measurements of Δm^2_{31}, Δm^2_{21}, and θ_{12}
- Mass ordering sensitivity from the “phase of the wiggle”

MELIORA University of Rochester

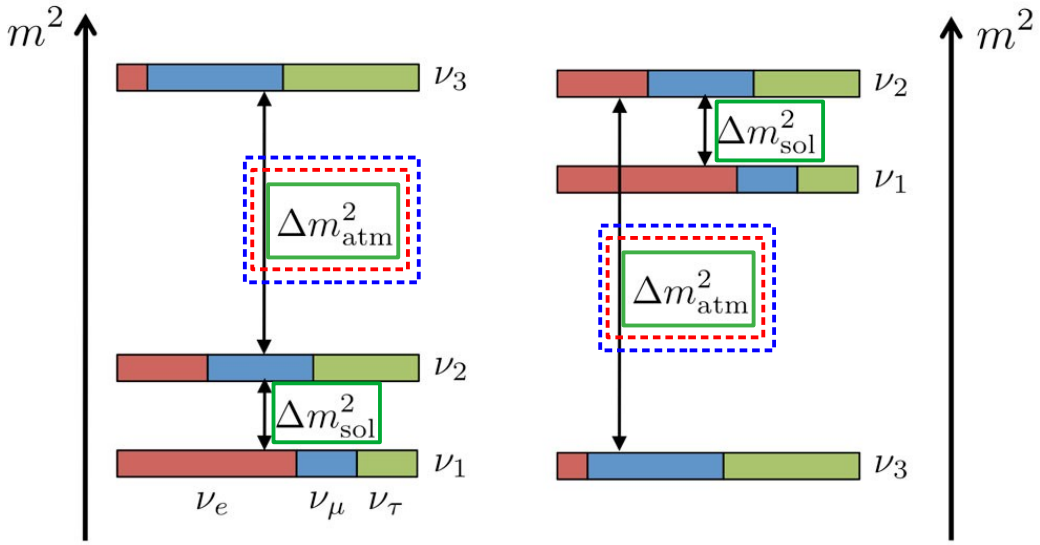
This summer: more new data!



- World-leading measurements already!
  - $\Delta m^2_{31} \rightarrow 1.0\%$
  - $\Delta m^2_{21} \rightarrow 1.06\%$
  - $\theta_{12} \rightarrow 2.1\%$
- Dangerously close to our first sub-percent measurements of neutrino oscillation parameters from a single experiment
- Not yet enough data for standalone mass ordering

Neutrino oscillation: current status

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



mass ordering

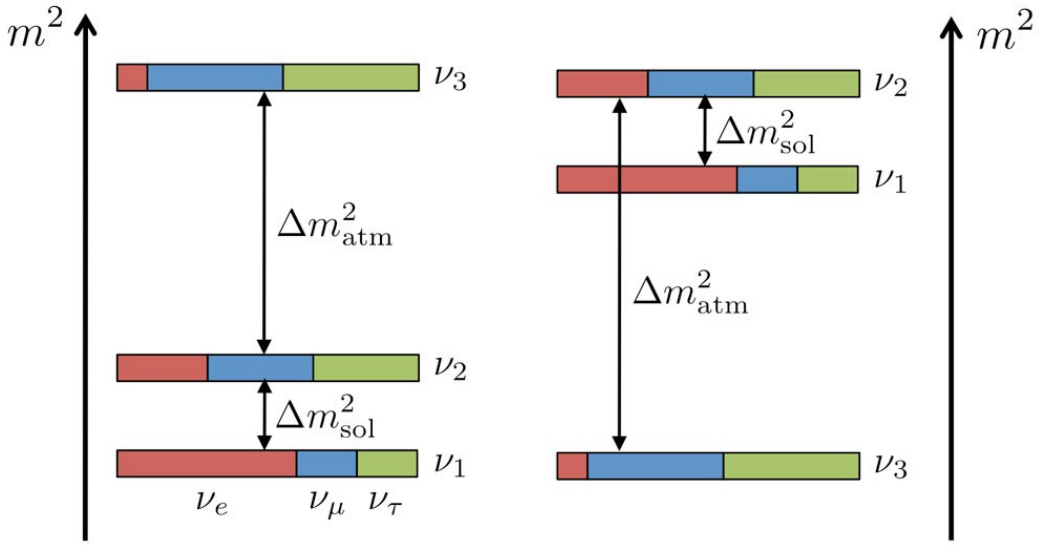
- Current best measurement(s) (solid line) and complementary measurement (dashed):

JUNO
Atmospheric
T2K, NOvA
Daya Bay, RENO

MELIORA University of Rochester

Remaining unknowns

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



mass ordering

- Often said that the goals of the next generation of experiments are
  - Determine the mass ordering
  - Determine if neutrino oscillation violates CP symmetry
- We should do both of these!
  - But I think this is insufficiently ambitious...

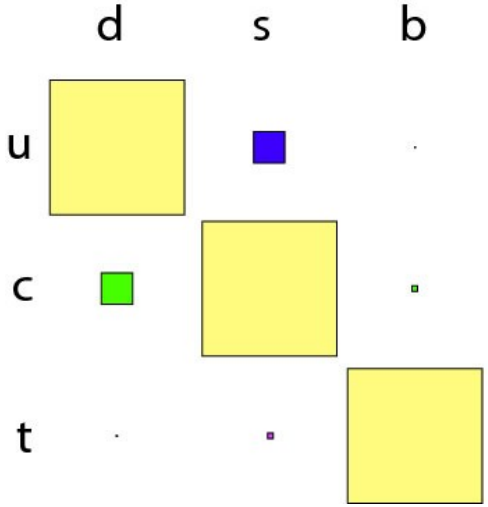
MELIORA University of Rochester

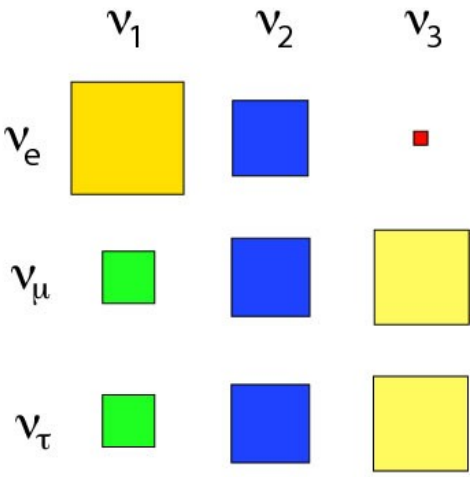
Prepare for surprises: testing the three-flavor paradigm

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

- Is the three-flavor unitary mixing model correct?
- If yes, experiments should:
  - Measure its parameters precisely, including the CP violating phase
- If no, experiments should:
  - Characterize the new physics in neutrino oscillation
  - Is it a matter effect? Additional neutrino species? New interactions?
  - This requires a global program of several experiments

Neutrino oscillation measurements can help inform big questions



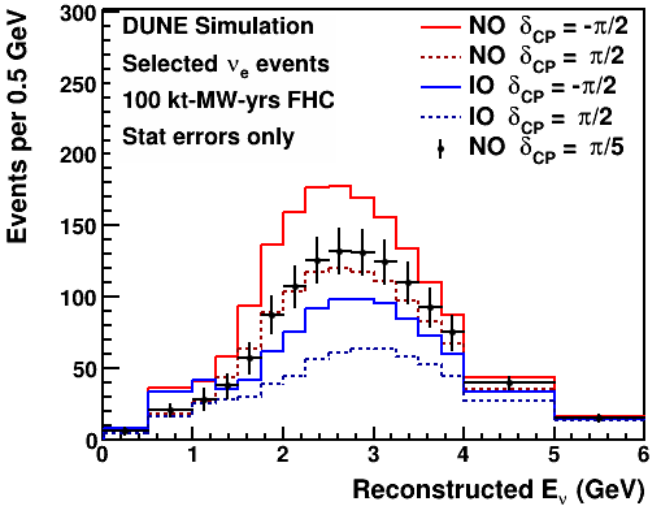


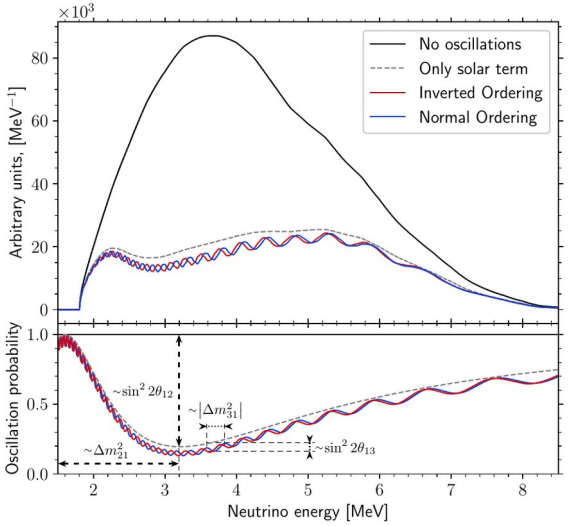
- What is the origin of neutrino mixing?
- Is there an underlying flavor symmetry, and how is it broken?
- Why do neutrinos have mass?
- Is the νSM complete?

This requires not just measuring PMNS parameters, but overconstraining the model

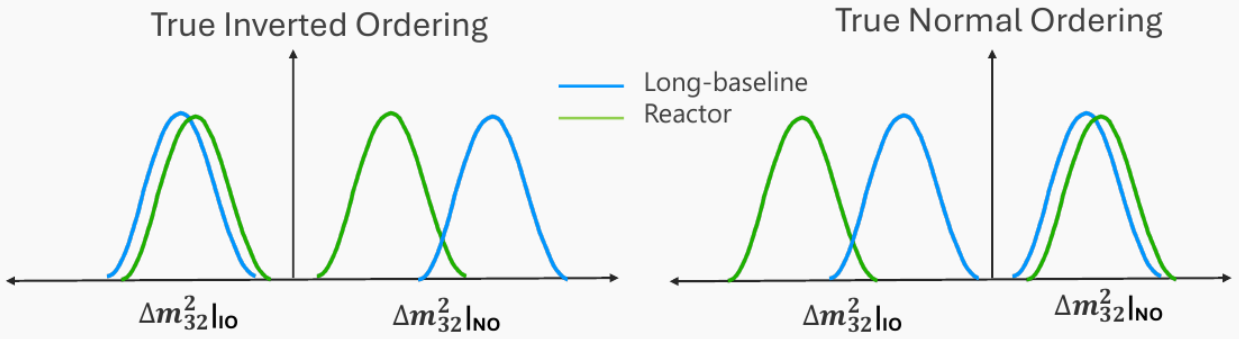
MELIORA University of Rochester

Mass ordering: three approaches





Conceptual Sketch (not to scale)



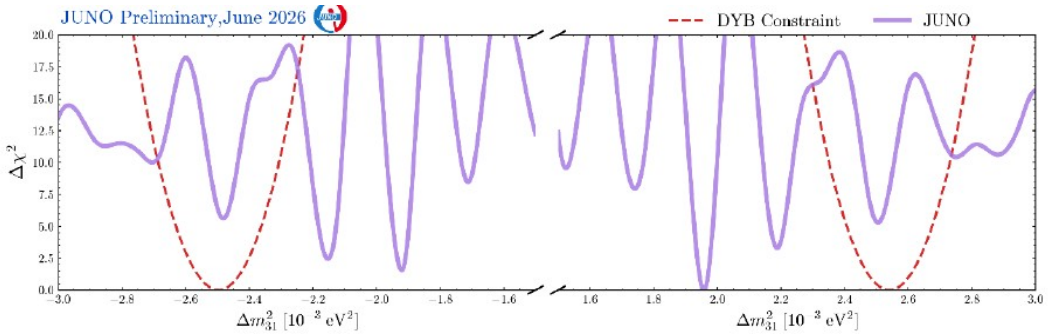
*Nunokawa, Parke and Funchal, PRD 72, 013009 (2005);
Parke and Funchal, PRD 111, 013008 (2025)

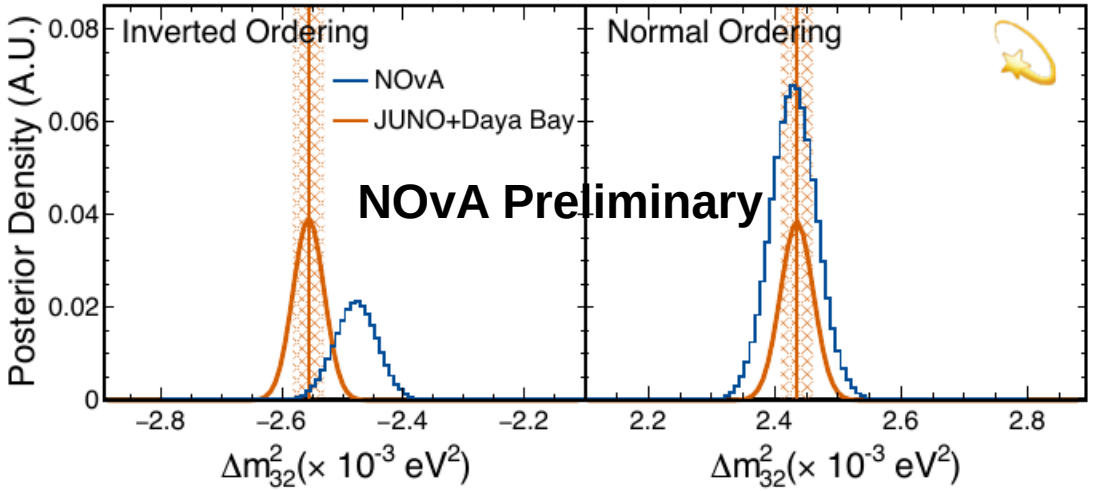
We should pursue all three of these approaches!

- **Earth matter effect**: asymmetry in ν_e and $\bar{\nu}_e$ appearance
- **Wiggle phase**: unique to JUNO, measure fast oscillation over many periods
- **Compare $|\Delta m^2_{\mu\mu}|$ and $|\Delta m^2_{ee}|$**: results should agree assuming the correct ordering

MELIORA University of Rochester

Results from Neutrino26: MO by comparing μμ and ee channels



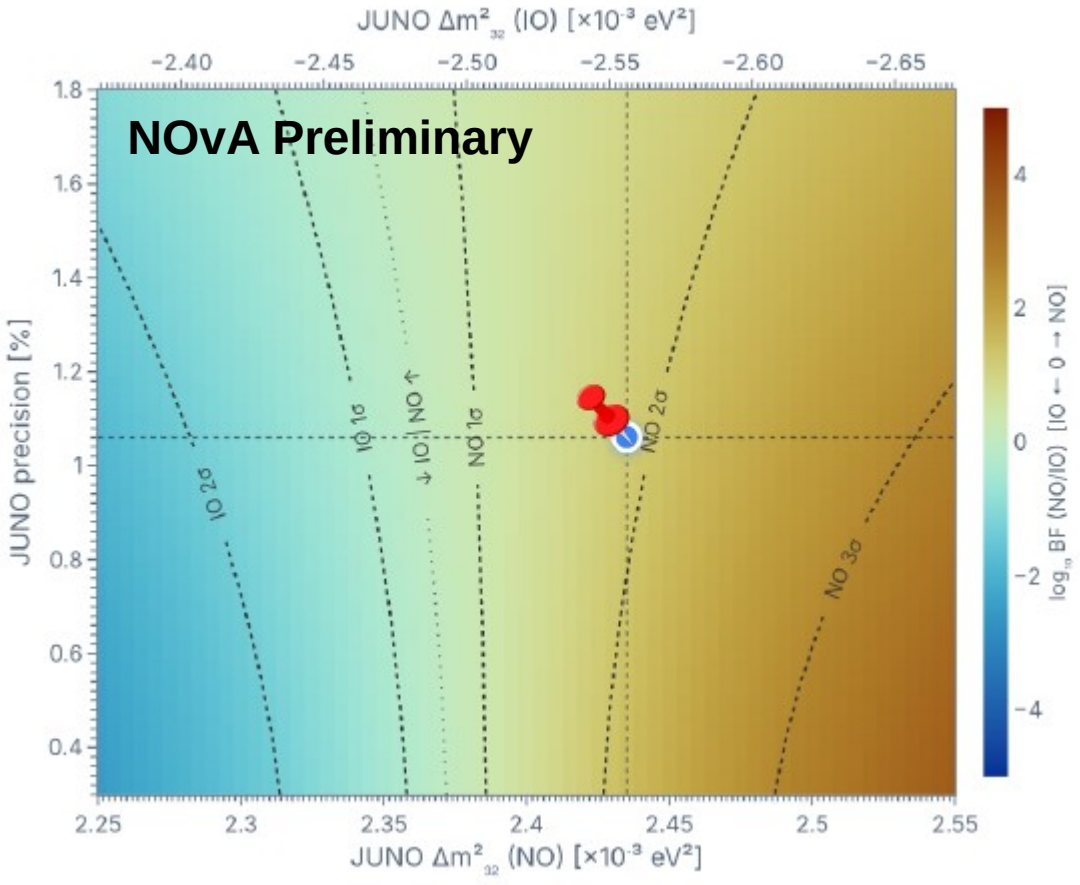


Exp.	JUNO*	NOvA
Δm^2_{32} NO	2.435	2.431
Δm^2_{32} IO	-2.556	-2.479
Precision	1.05%	1.4%

- JUNO(+Daya Bay) measures $|\Delta m^2_{ee}|$ very precisely → compares with NOvA's measurement of $|\Delta m^2_{\mu\mu}|$
- Mild tension is observed assuming inverted ordering → ~2σ preference for NO
- Significance teeters around 2σ depending on which data are included

MELIORA University of Rochester

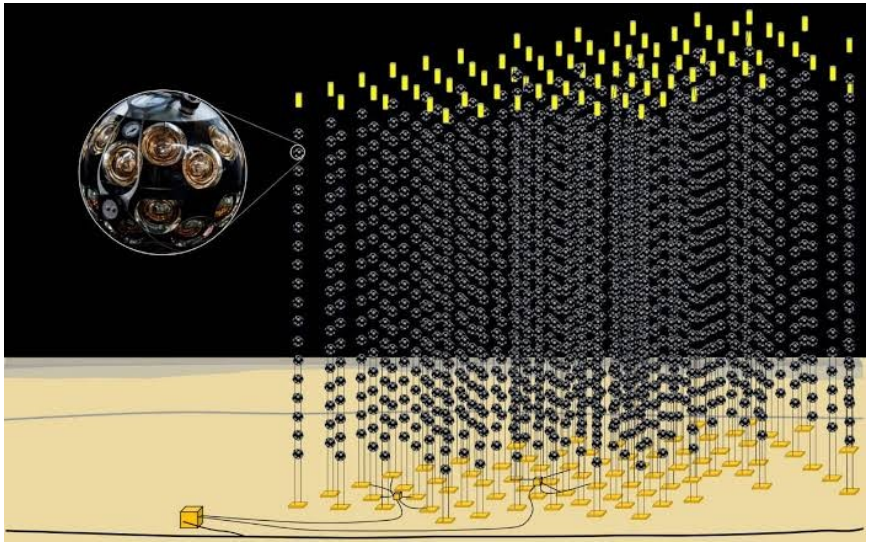
How will this improve with additional JUNO data?

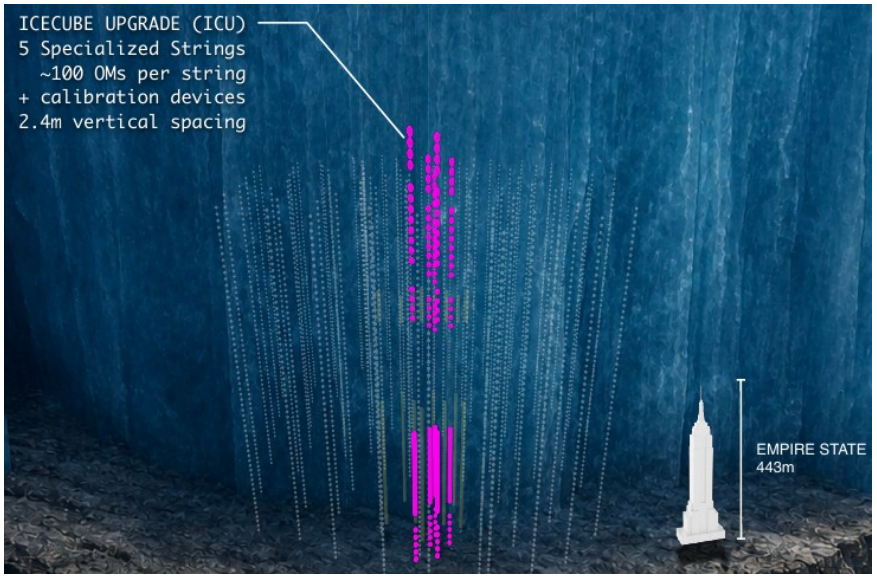


- Significance is limited by JUNO *and NOvA* precision → improving JUNO precision by 2x increases significance by ~0.2σ
- Significance may change **if JUNO central value moves** with additional data → could increase or decrease observed significance
- For this method to get significantly more precise, **need improved LBL/atmospheric measurements** in addition to JUNO

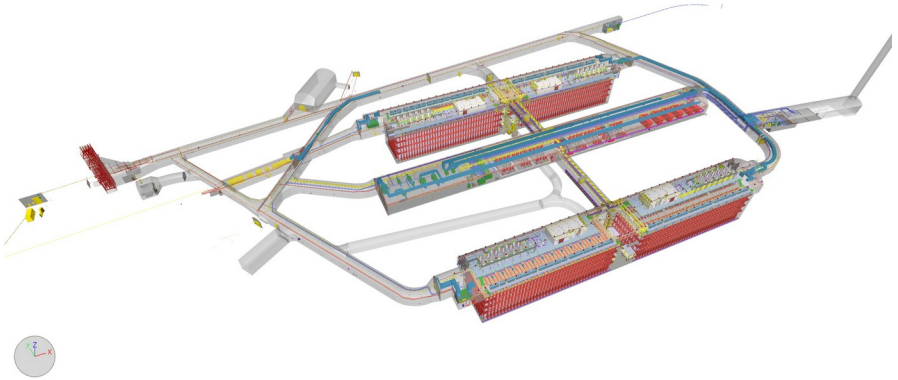
Prospects for oscillations with atmospheric neutrinos

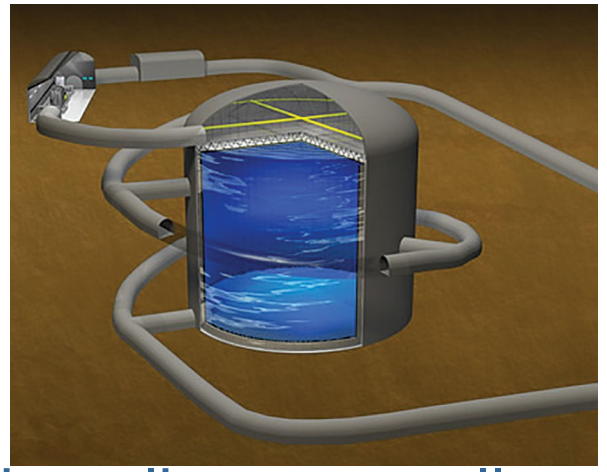
- KM3NeT-ORCA is running (and growing), and sensitive to $|\Delta m^2_{\mu\mu}|$, and separately to MO via Earth's matter effect on $\nu_e+\bar{\nu}_e$ signal
- IceCube has 10 years of data (and a well-deserved Nobel!) + new upgrade → enhanced sensitivity to oscillations
- Currently comparable sensitivity to LBL experiments in $|\Delta m^2_{\mu\mu}|$ and $\sin^2 2\theta_{23}$ and continuing to take more data
- Super-fit of LBL+JUNO+atmo may achieve higher MO significance





The next generation: Hyper-K and DUNE, complementary approaches

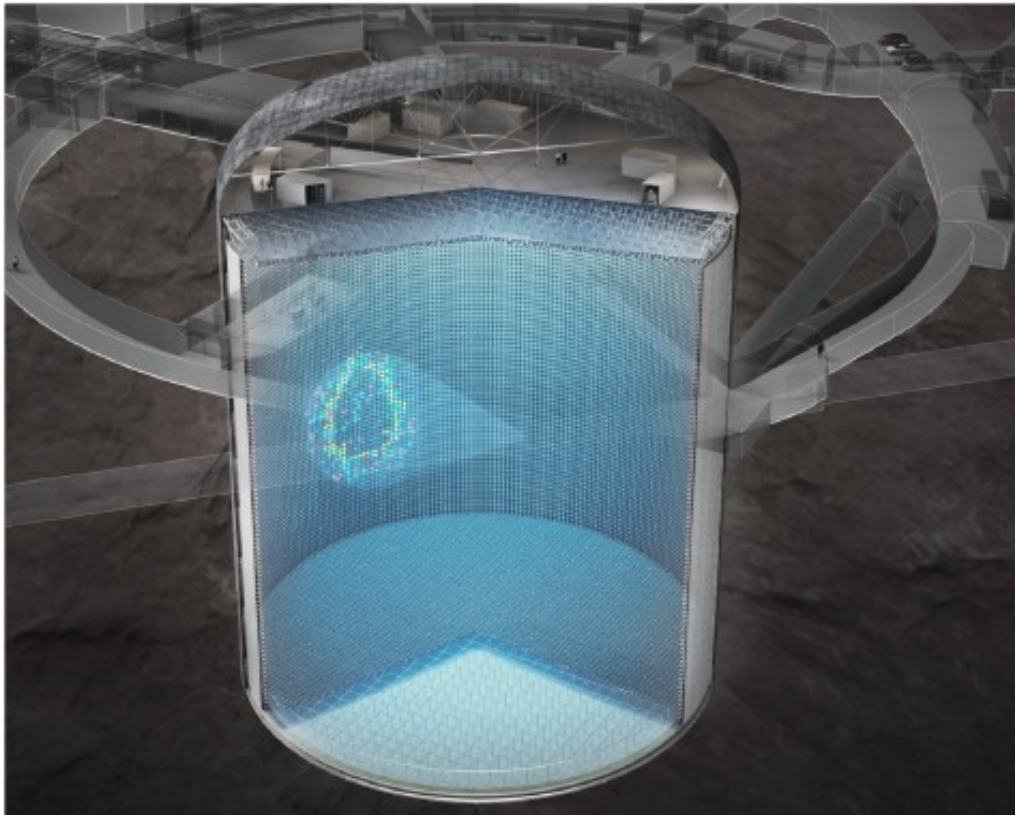




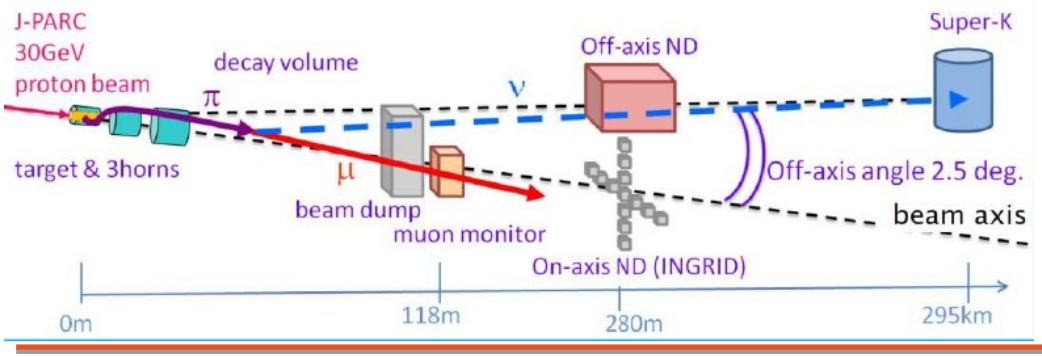
- Very long baseline → large matter effect
- On-axis location & broadband beam
- Reconstruct E_ν calorimetrically over broad range with LArTPC
- Moveable, functionally similar ND to constrain systematics

- Shorter baseline → smaller matter effect
- Off-axis location & narrower beam spectrum
- Reconstruct E_ν from QE kinematics
- Moveable, functionally similar ND to constrain systematics

Hyper-K will greatly expand T2K physics reach



- 8x larger FD + upgraded beamline → much higher statistics
- 20,000 50cm PMTs + 1,000 multi-modules of 3in PMTs → improved photocoverage
- Improved systematic constraints from IWCD

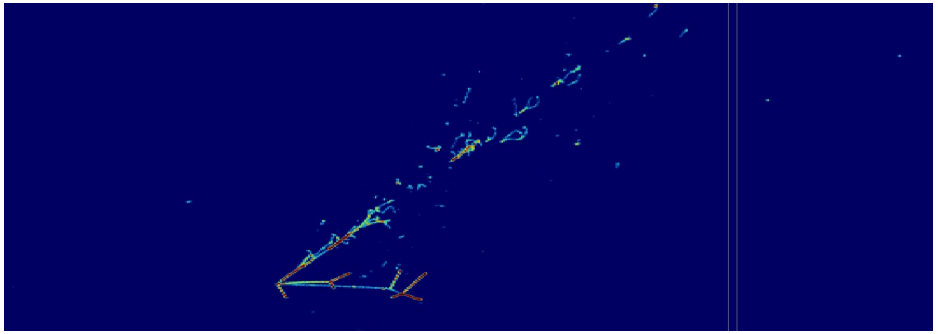


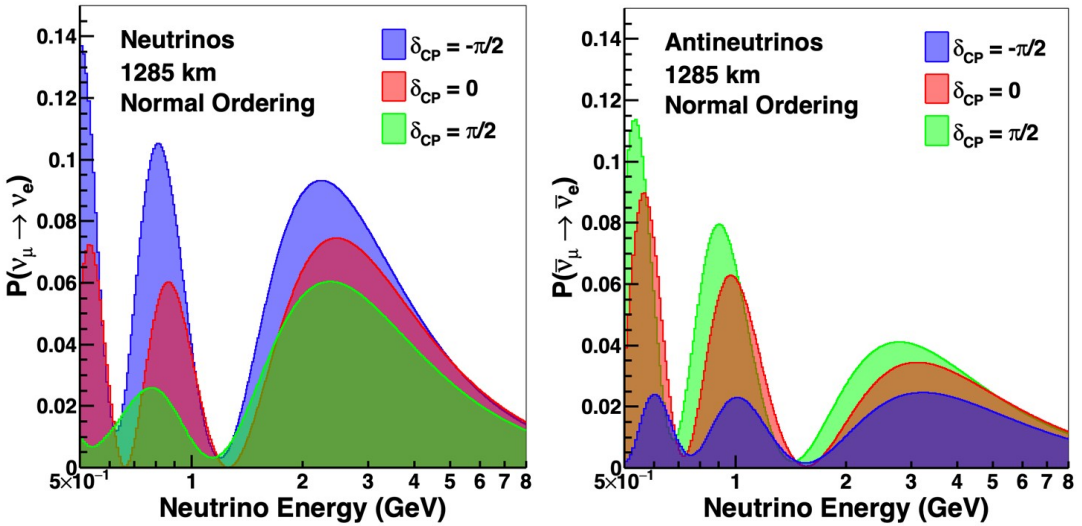


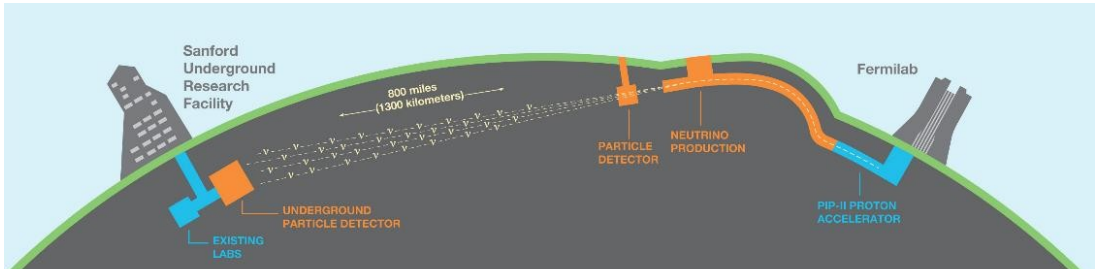


University of Rochester

DUNE: completely measure 3-flavor picture + search for new physics

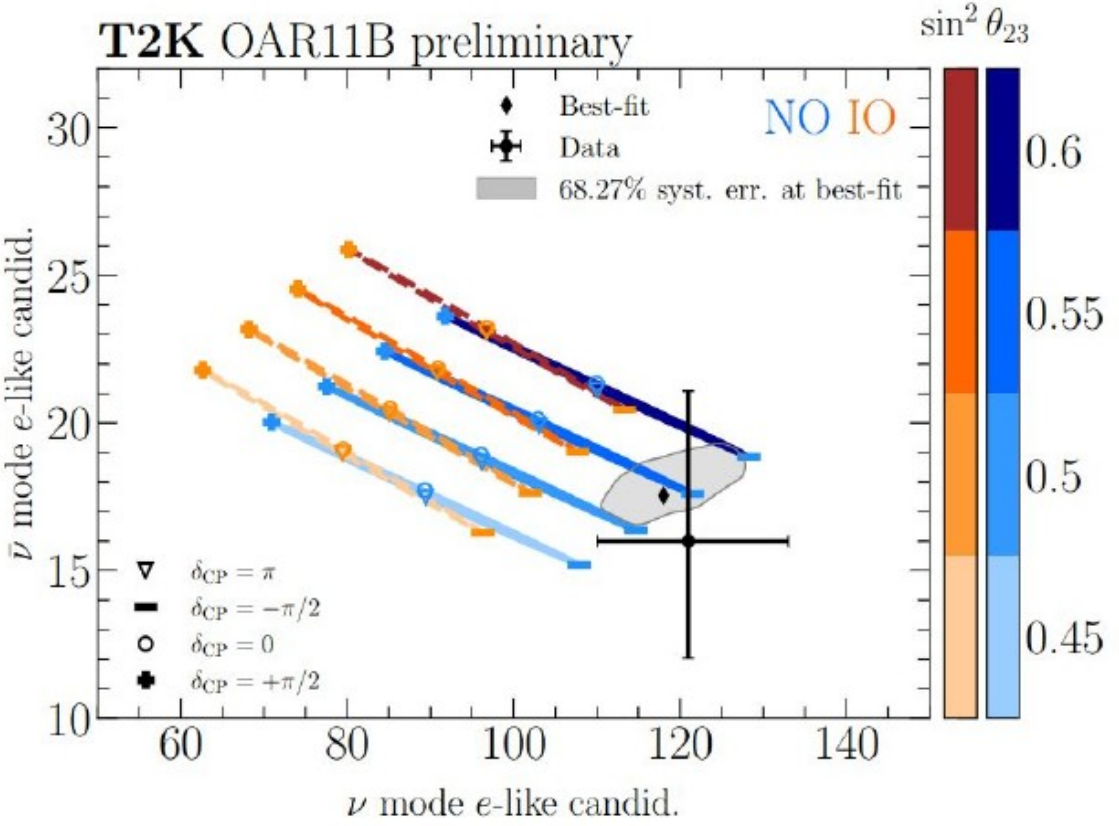


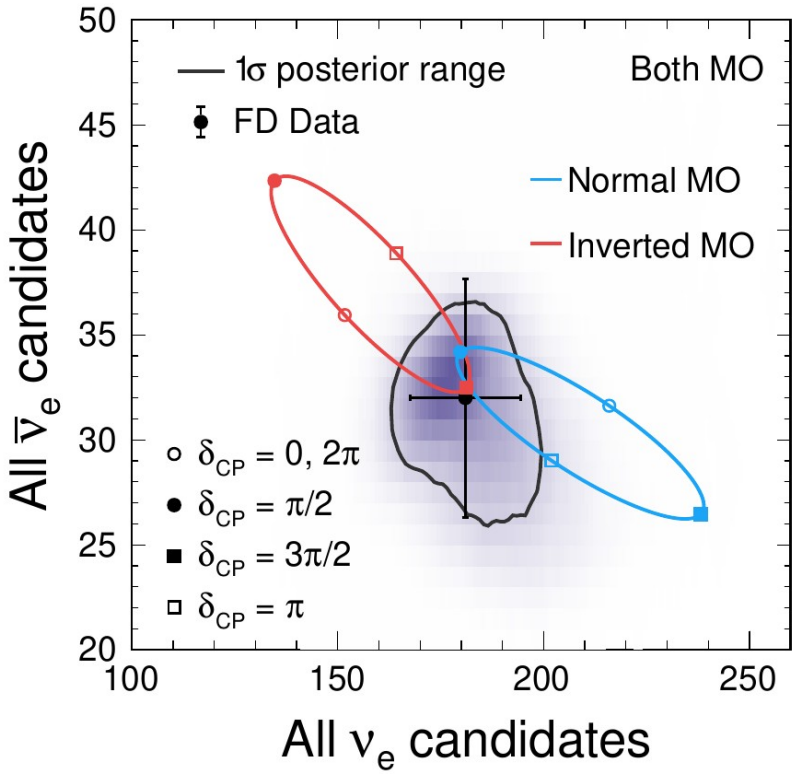




- DUNE has a very different design philosophy from Hyper-K: measure oscillations over >1 full period, long baseline → parameters are not degenerate, **measure everything in one experiment**
- Broader L/E coverage, and more robust to parameter degeneracies
- Different, complementary sensitivity to non-standard oscillation scenarios

Reminder: the present...

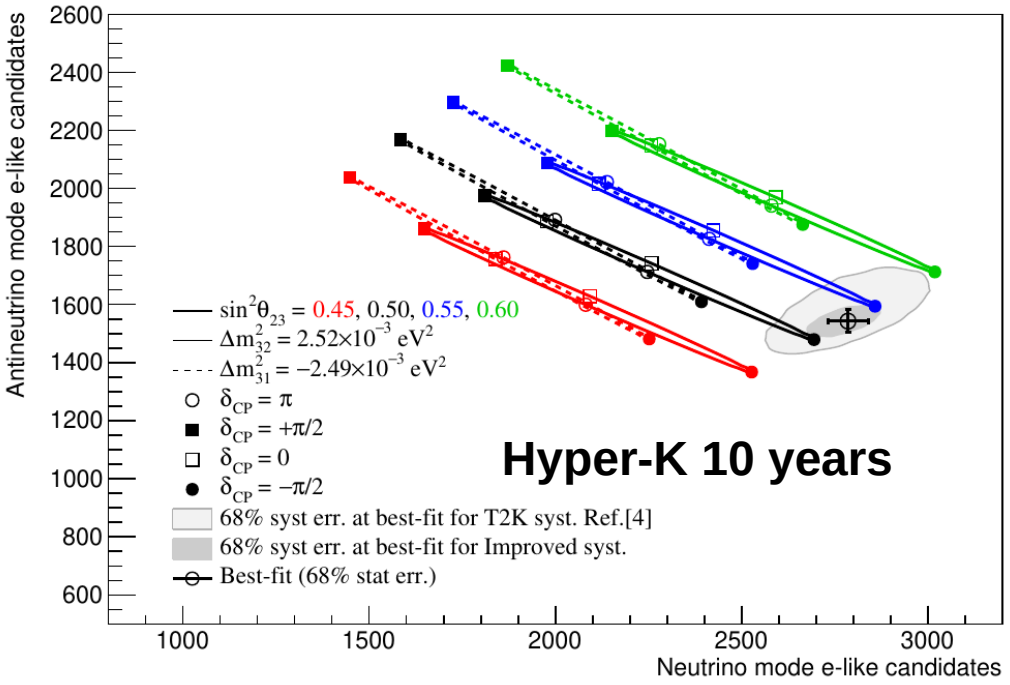


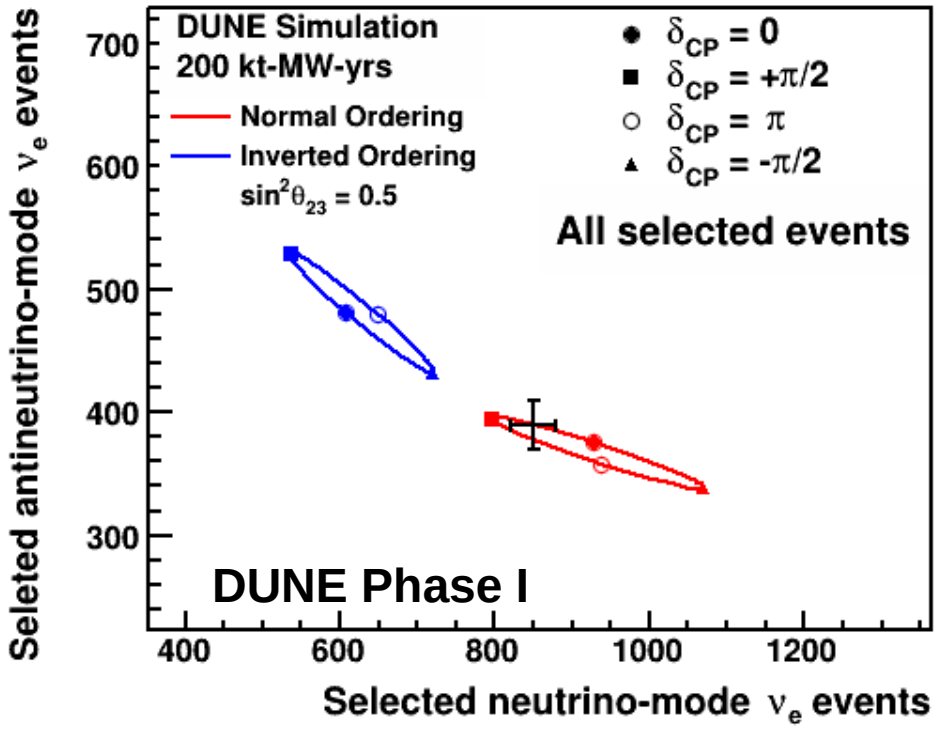


- Large statistical uncertainties → many combinations of parameters are consistent with data
- Degeneracy between MO, δ_{CP}, θ_{23} in both experiments

MELIORA University of Rochester

The near future: Hyper-K and DUNE

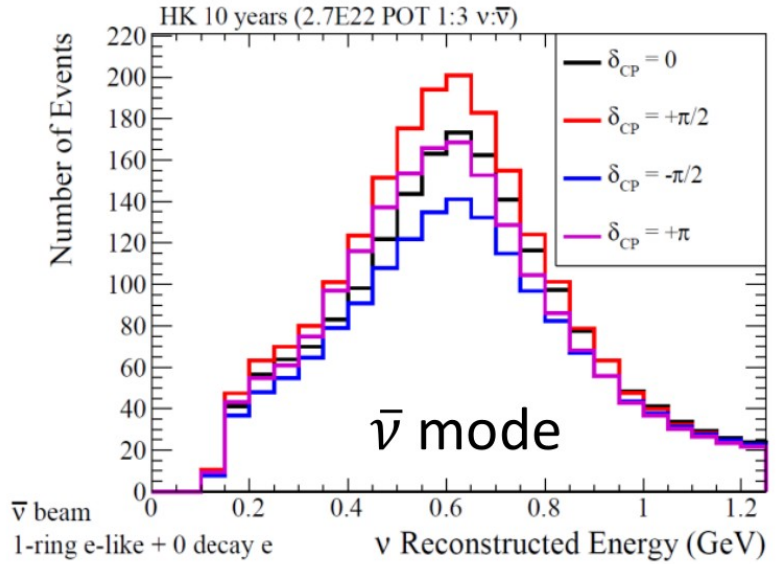


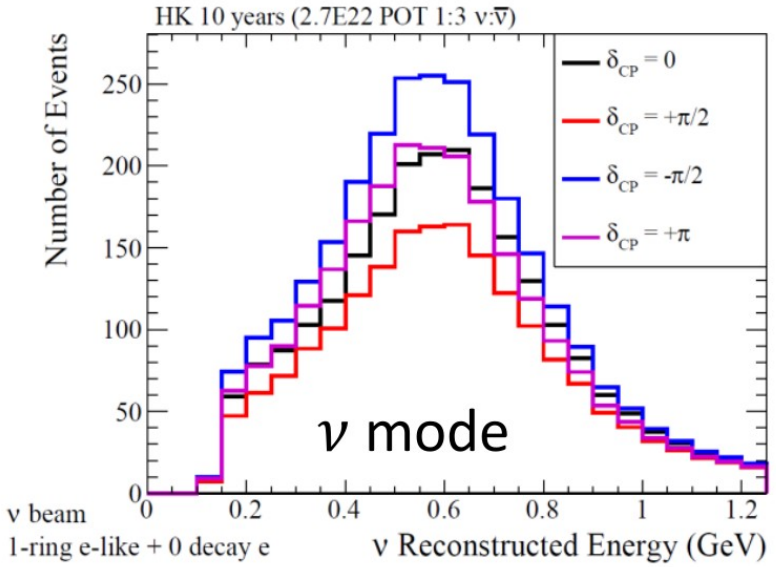


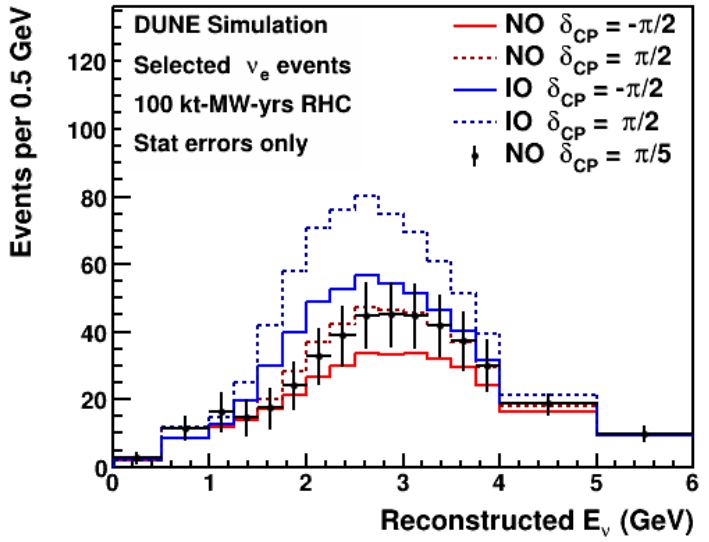
- Hyper-K: Really good at distinguishing CP conserving vs. CP violating values once MO is known
- DUNE: No more overlap, simultaneously separate MO and δ_{CP}, and θ_{23}

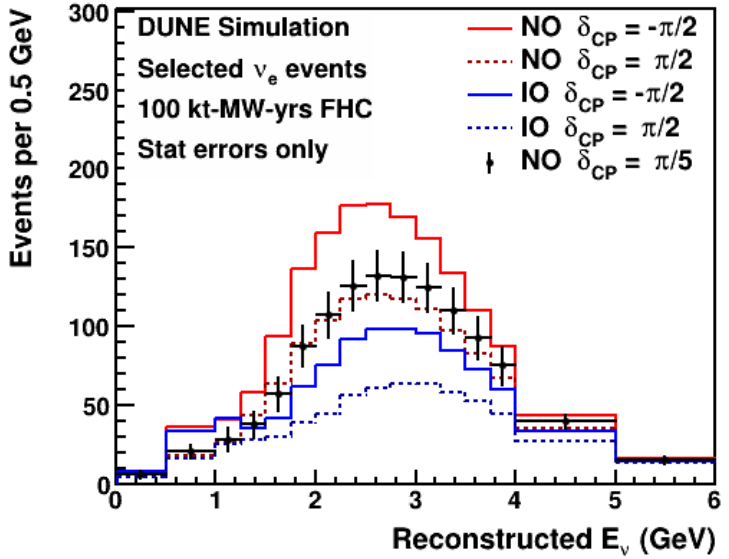
MELIORA University of Rochester

Bi-event plots hide valuable spectral information



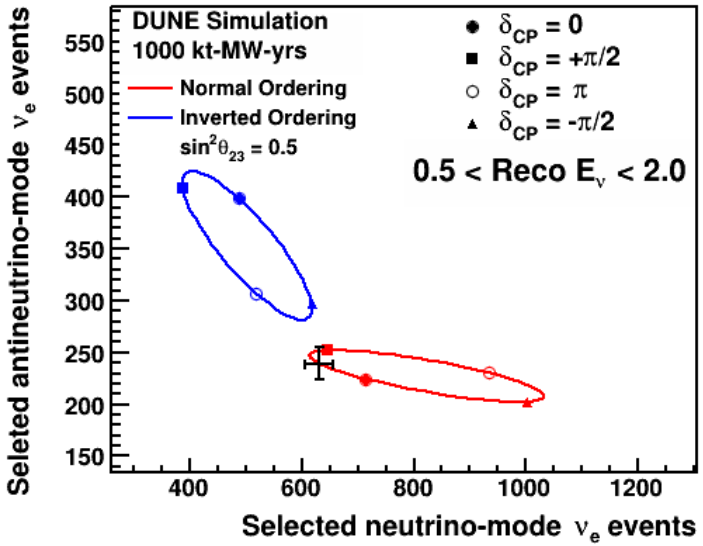


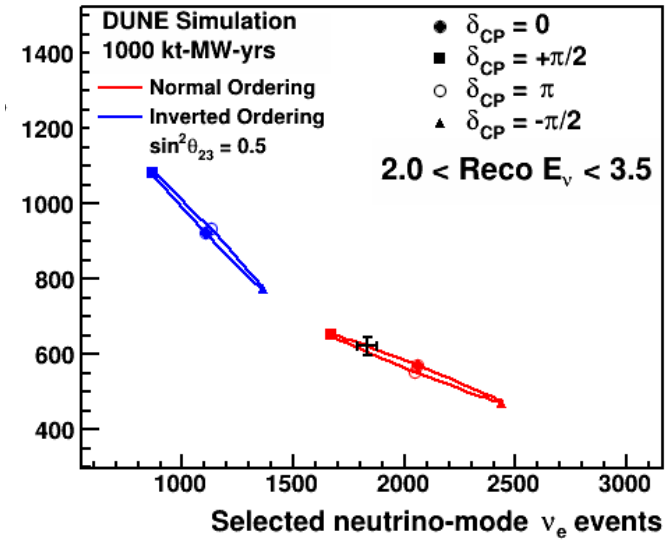


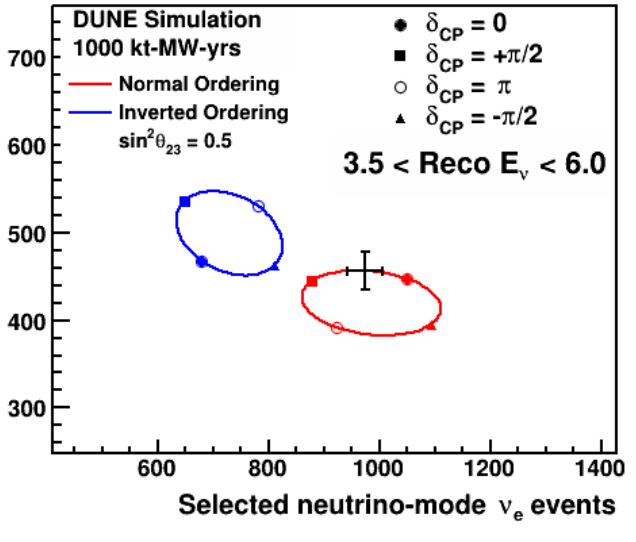


- Different oscillation effects affect shape as well as rate
- Extremely valuable for resolving degeneracies between parameters, especially for DUNE

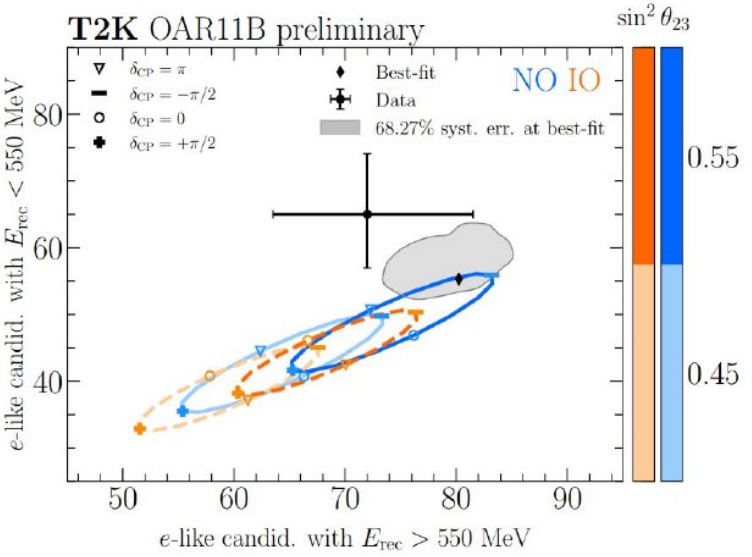
Bi-event plots hide valuable spectral information





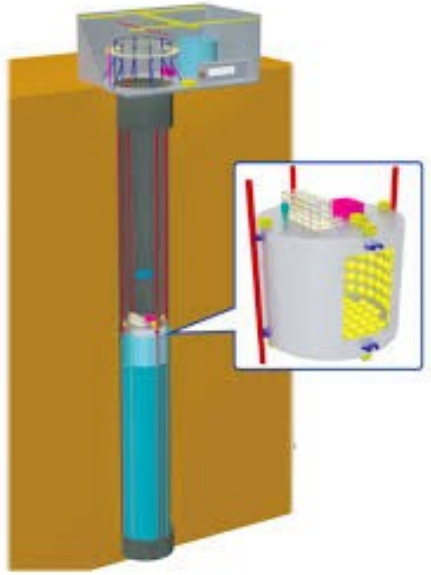


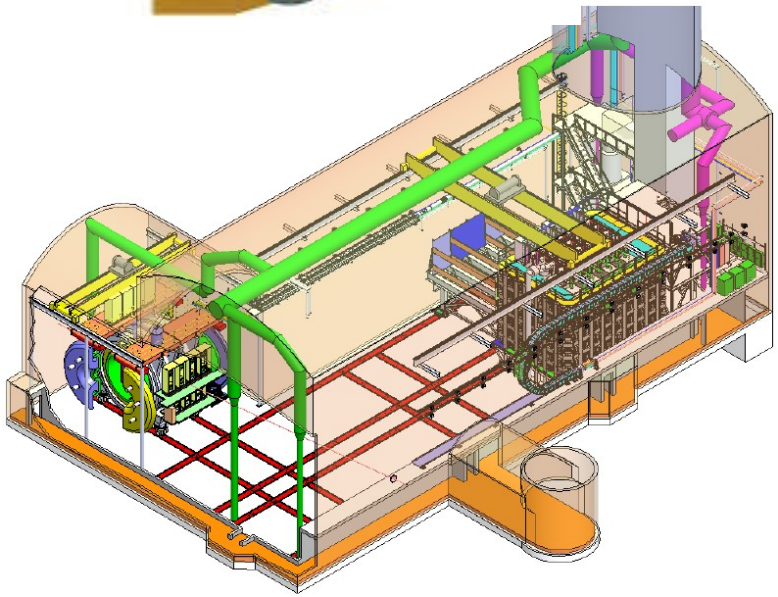
- DUNE can essentially make this plot in slices of L/E → shapes of ellipses change
- Also search for non-SM oscillations as a function of L/E
- Hyper-K can do this too to an extent (beam is narrower) → T2K LE/HE plot for example



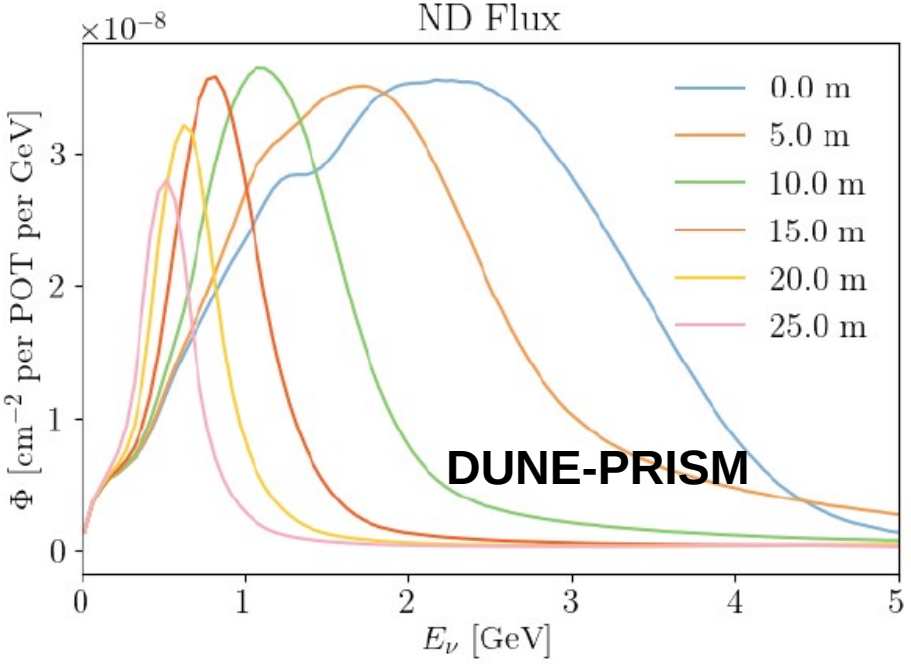
University of Rochester

High precision requires better constraints: moveable NDs





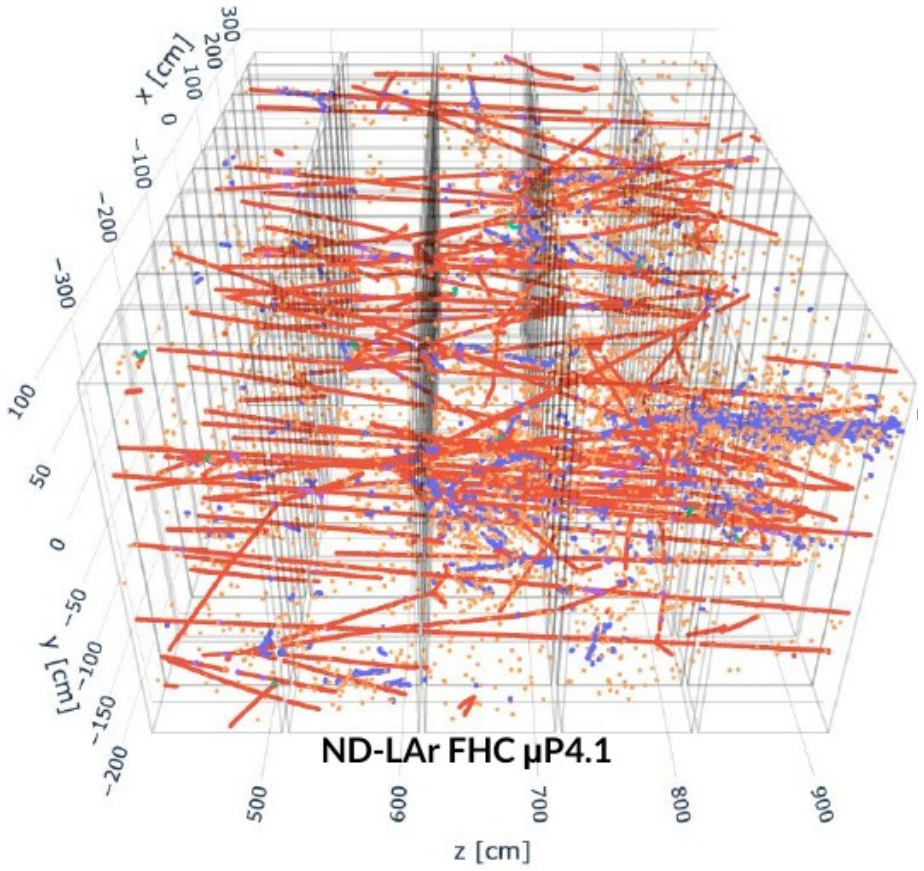
- Key element of both DUNE and Hyper-K is moveable NDs with same technology as FD
- Flux changes with neutrino angle → directly probe **neutrino energy dependence** of cross section
- Crucial because (oscillated) FD flux is different from (unoscillated) ND flux → uncertainties don't fully cancel in the ratio



MELIORA University of Rochester

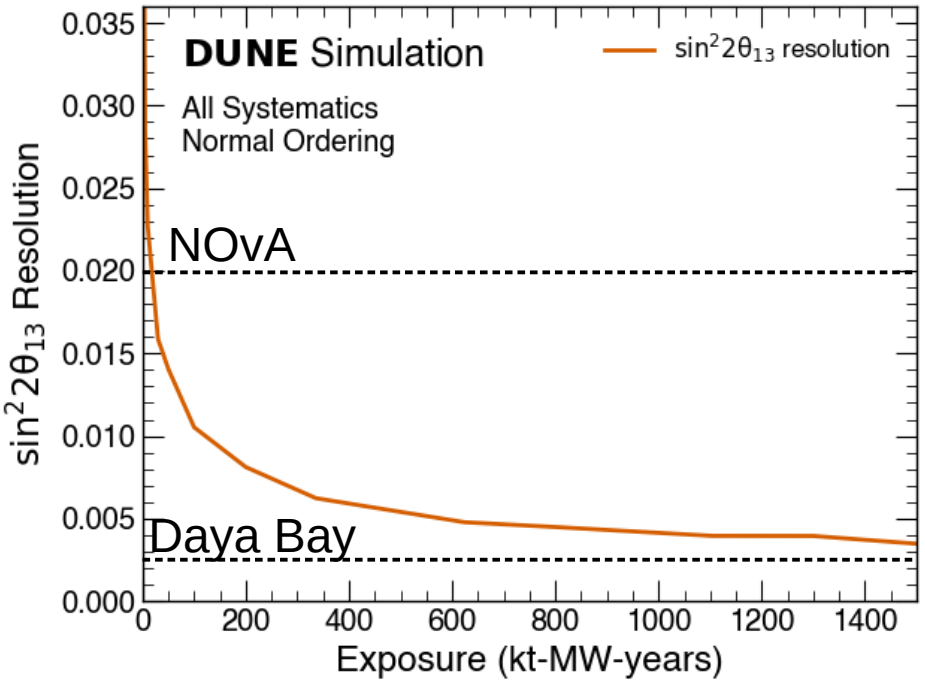
Next Generation, new challenges

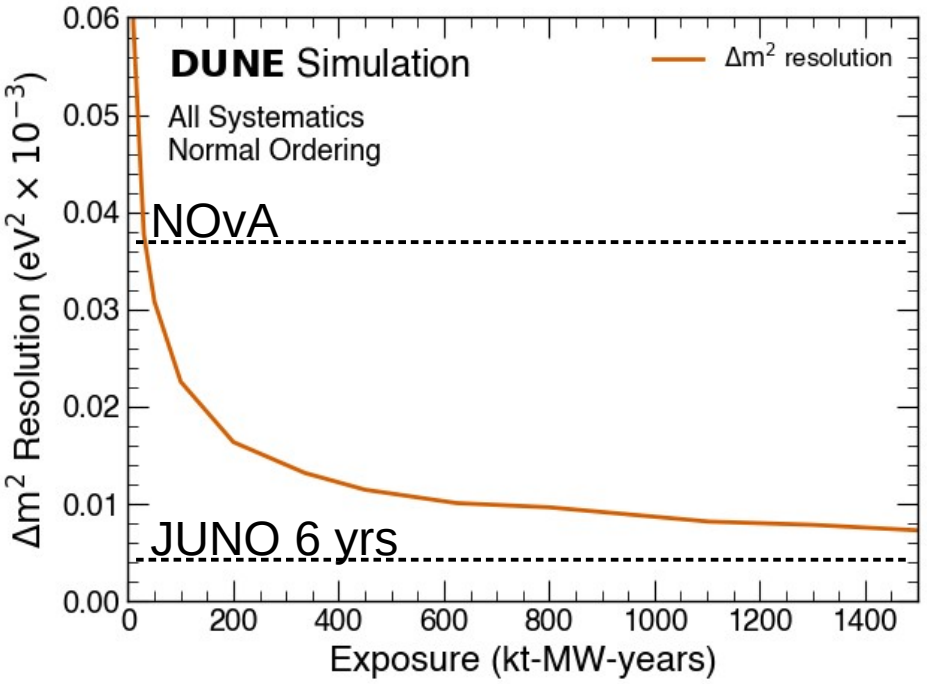
One beam spill at DUNE's ND-LAr (7.5E13 POT)



- DUNE ND-LAr has a new challenge: LBNF is really intense
- To reconstruct individual neutrinos with inherently slow LArTPC requires novel hardware:
  - Pixelated readout to segment charge signals
  - Optical modularity to segment light signals
- And novel software:
  - AI-driven reconstruction techniques not only powerful but likely essential

Over-constraining PMNS & searching for new physics





- θ_{13} from long-baseline and reactor experiments is different PMNS matrix elements, which are equivalent only if unitary is assumed → next generation will approach reactor precision
- Δm^2 with ν_μ and ν_e → measure mass ordering, but also test whether three-mass-state assumption holds

MELIORA University of Rochester

The Next Generation is Now



- JUNO is running
- Atmospheric observatories are running and growing
- Hyper-K and DUNE have moved from excavation to detector construction
- NNN may soon have to revisit its name...

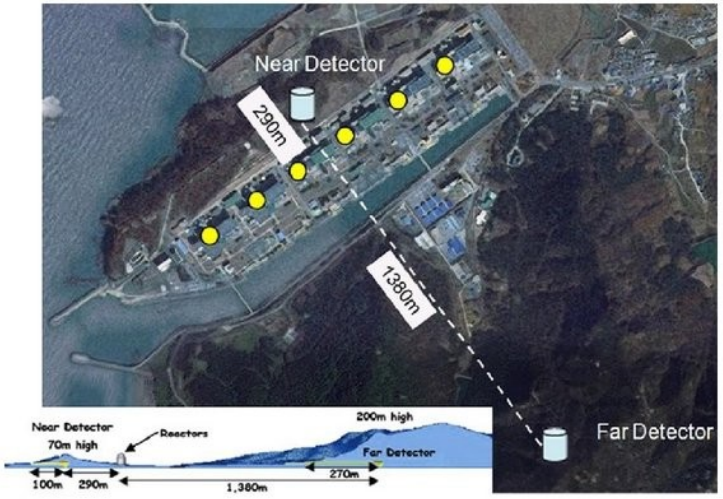
Summary

- Tremendous recent progress & exciting near-term prospects: the future is exciting!
- JUNO is running, DUNE and Hyper-K are well under construction: the Next Generation is here
- Precision is hard: near detectors become increasingly critical
- Be ambitious: let’s stop settling for measurements of model parameters and start searching for new physics in neutrino oscillations

Backup slides

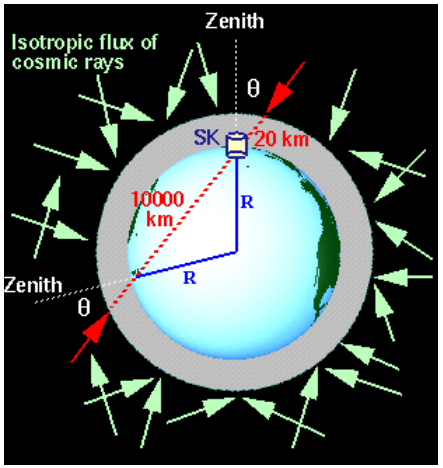
The many long baselines

- long (adj.): extending for a considerable distance
- For this talk I define this to be “long enough to see (SM) neutrino oscillations, but not the Sun”
- For MeV neutrinos, this is O(1 km) and O(50 km)
- For GeV neutrinos, this is O(1000-10000 km)





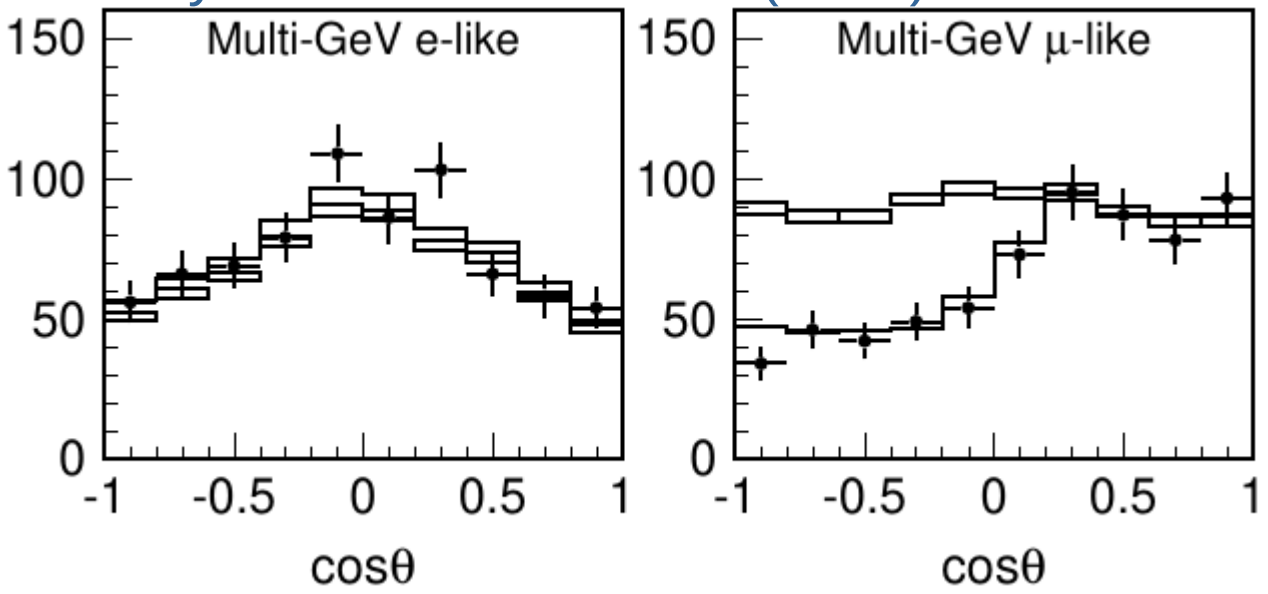


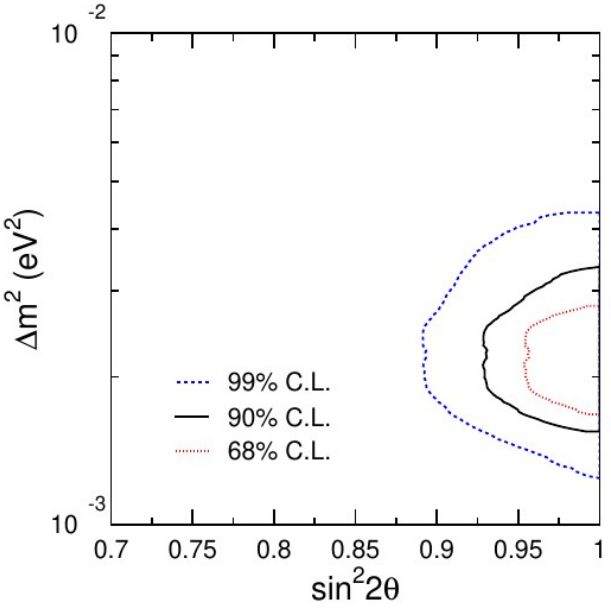


MELIORA University of Rochester

Super-K established oscillation with atmospheric neutrinos

Phys. Rev. D 71 112005 (2005)

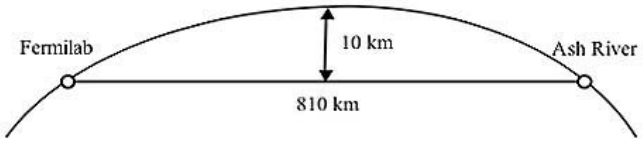


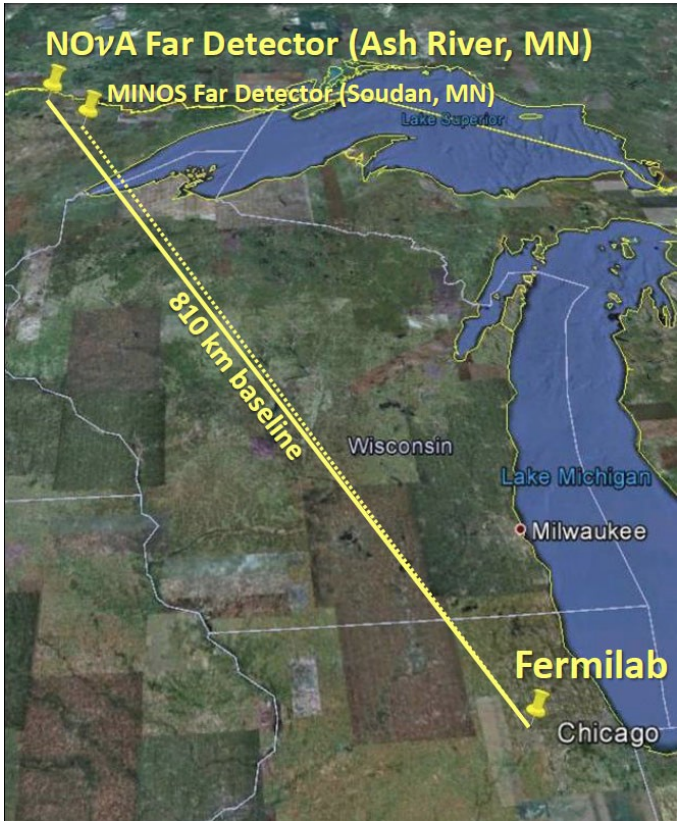


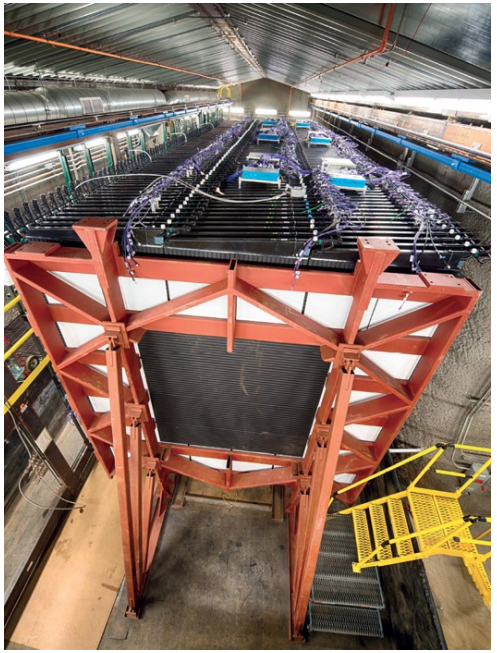
- Super-K determined that θ_{23} is nearly maximal, between 36°-54° at 90% C.L.
- Measured Δm^2_{atm} to be between 1.8-3.1 × 10^{-3} eV^2

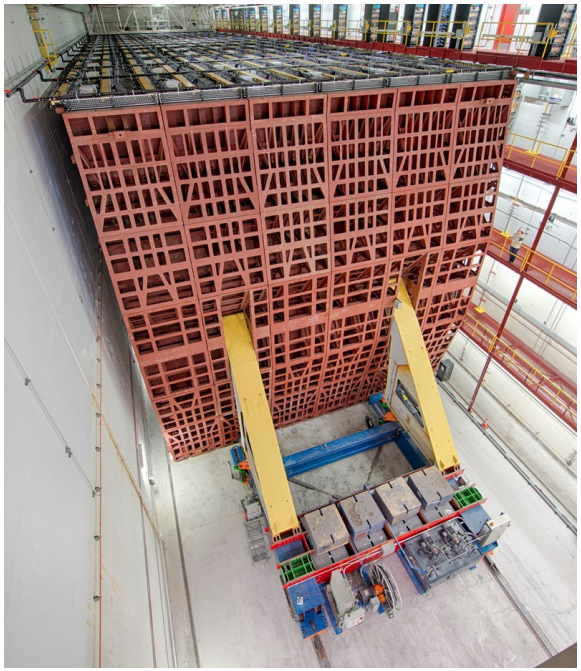
MELIORA University of Rochester

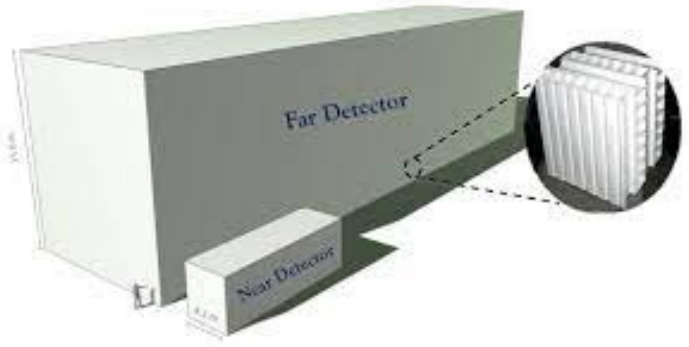
Current experiments: NOvA



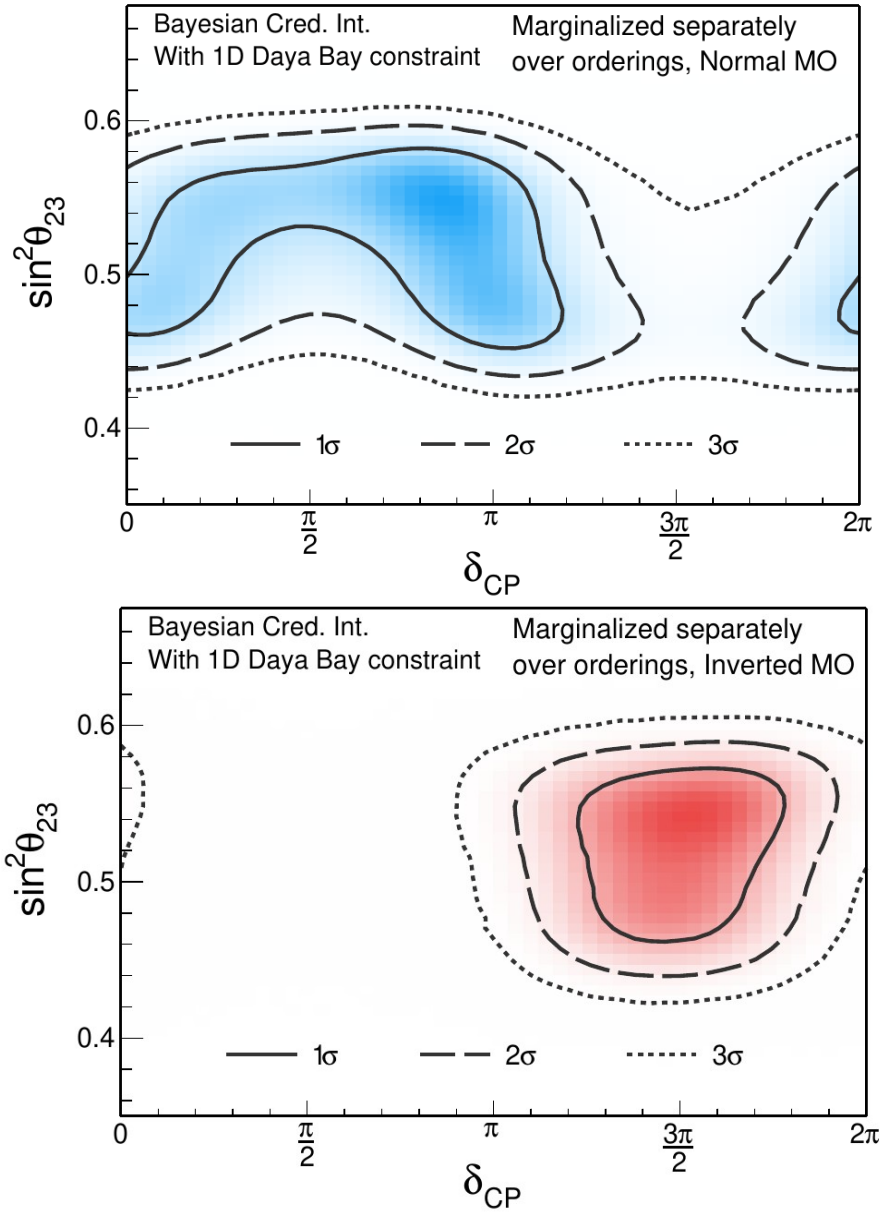








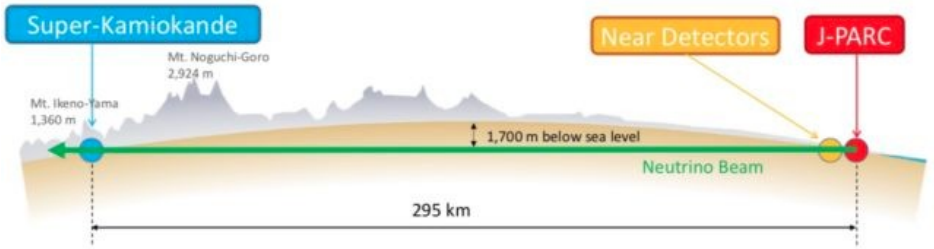
NOvA MO and δ_{CP} results



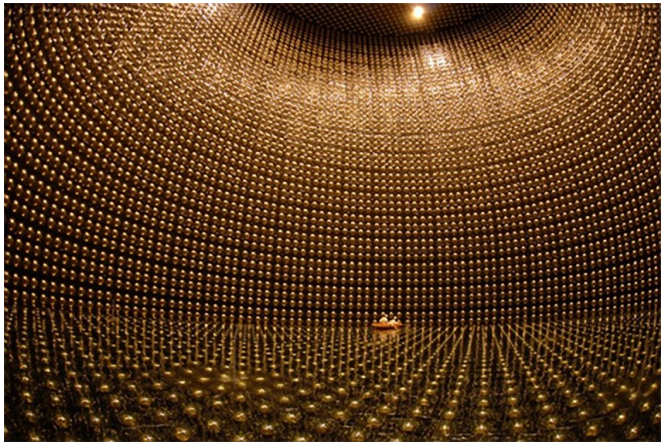
- Data favors either NO and δ_{CP} between (0, π) or IO and $\delta_{CP} \sim -\pi/2$ → essentially asymmetries from CPV and matter effect go in opposite directions
- Almost all values of δ_{CP} are allowed at 1σ in one ordering
- IO and $\delta_{CP} \sim +\pi/2$ is excluded at >3σ

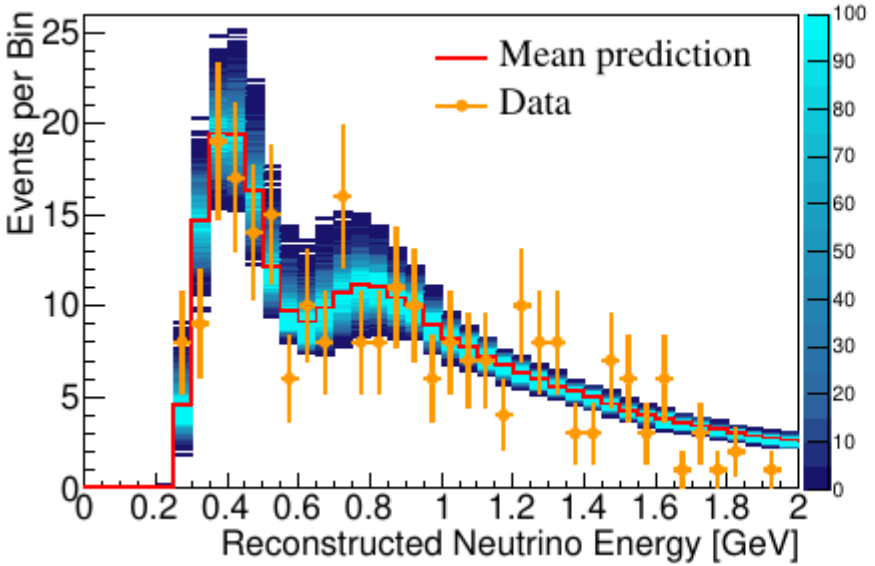
MELIORA University of Rochester

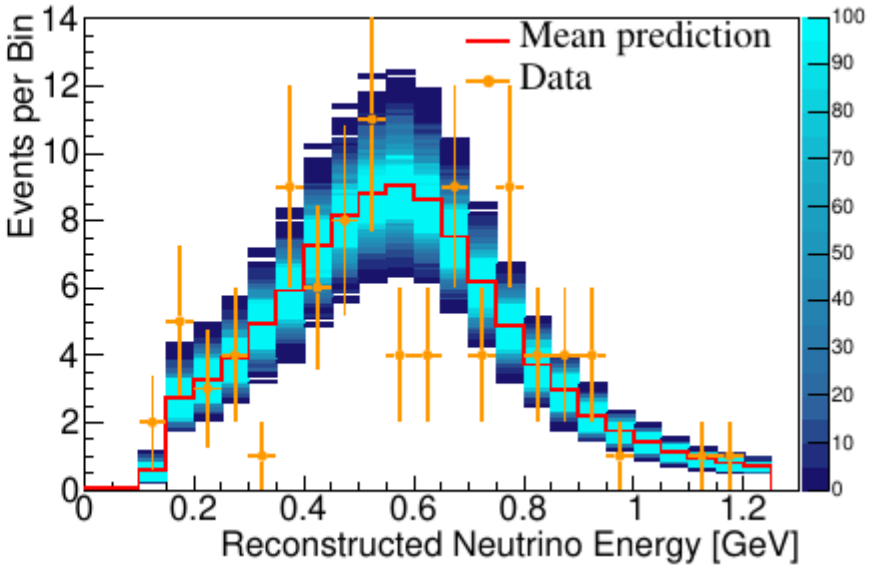
Current experiments: T2K





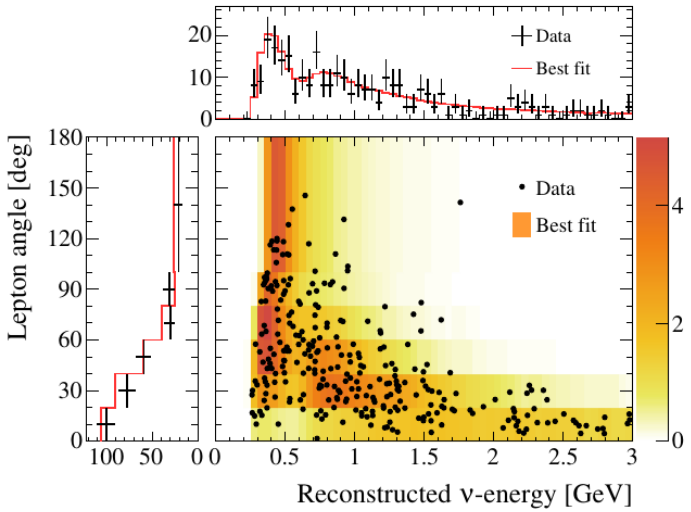


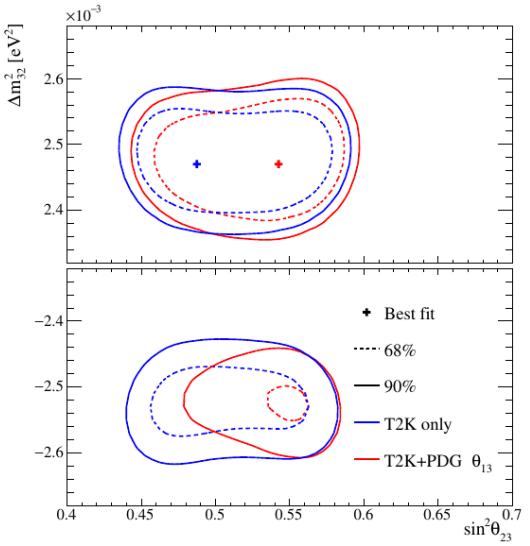


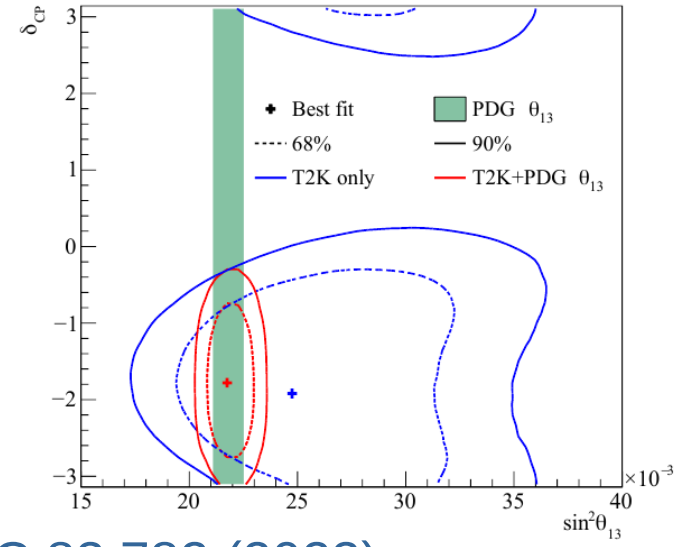


University of Rochester

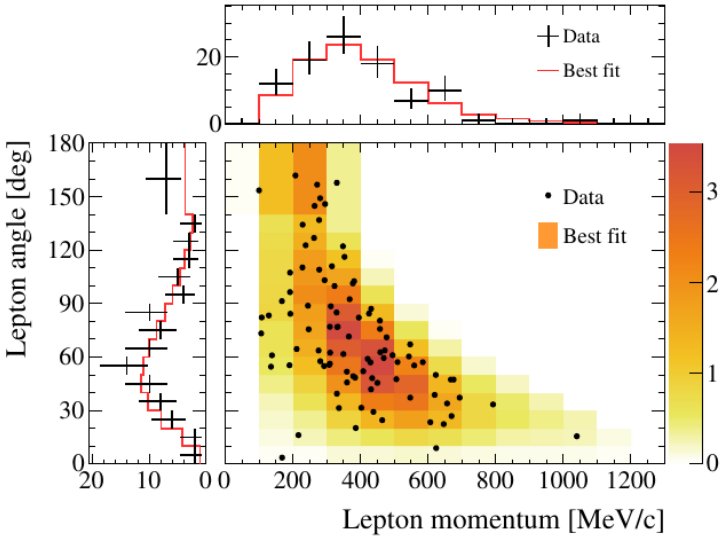
T2K measures $\nu_\mu \rightarrow \nu_\mu$ & $\nu_\mu \rightarrow \nu_e$ with neutrinos and antineutrinos







Eur. Phys. J. C 83:782 (2023)

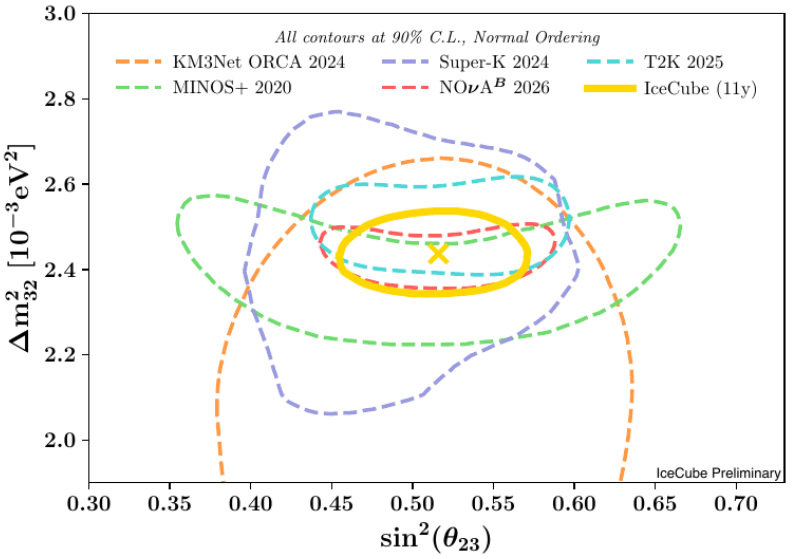


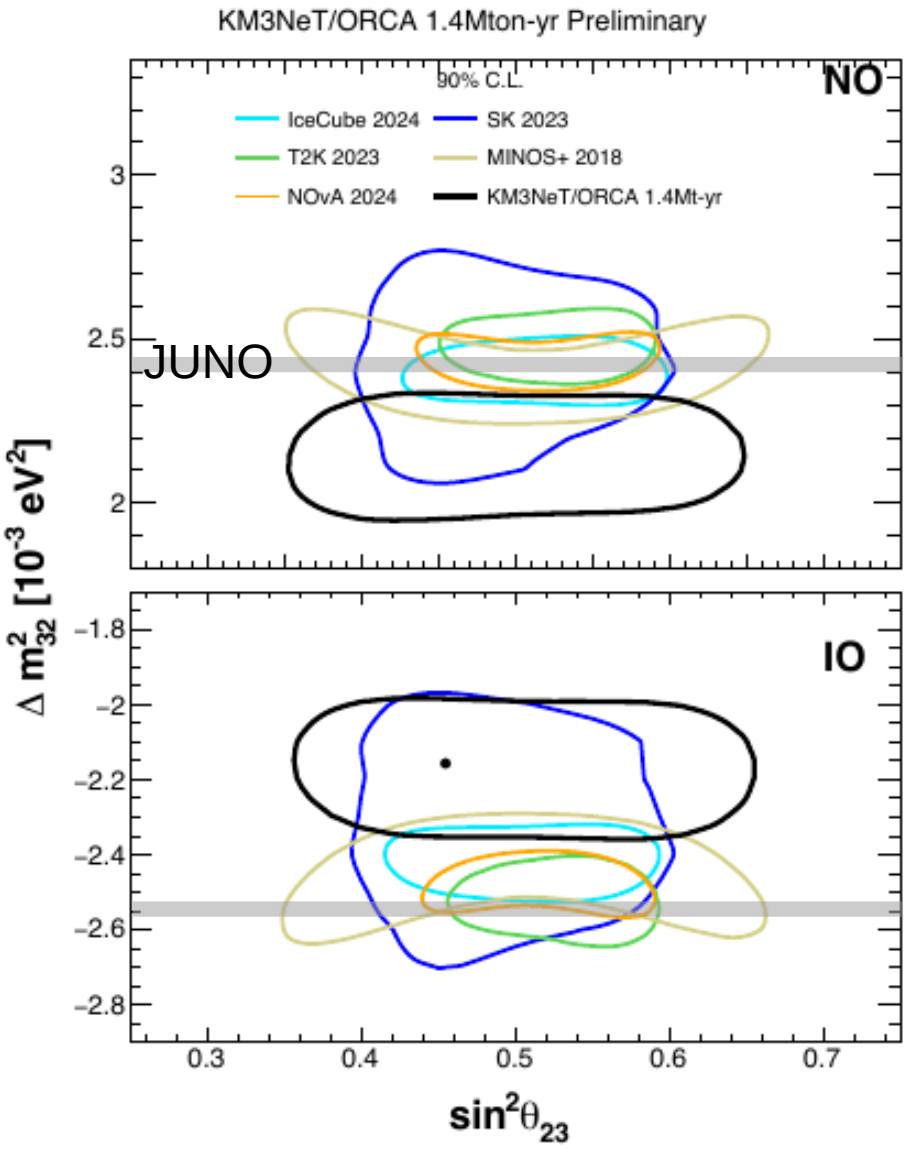
- Improved precision on θ_{23} and Δm^2_{atm}, some sensitivity to θ_{13}
- Weak sensitivity to CP violation, but degenerate with mass ordering

MELIORA University of Rochester

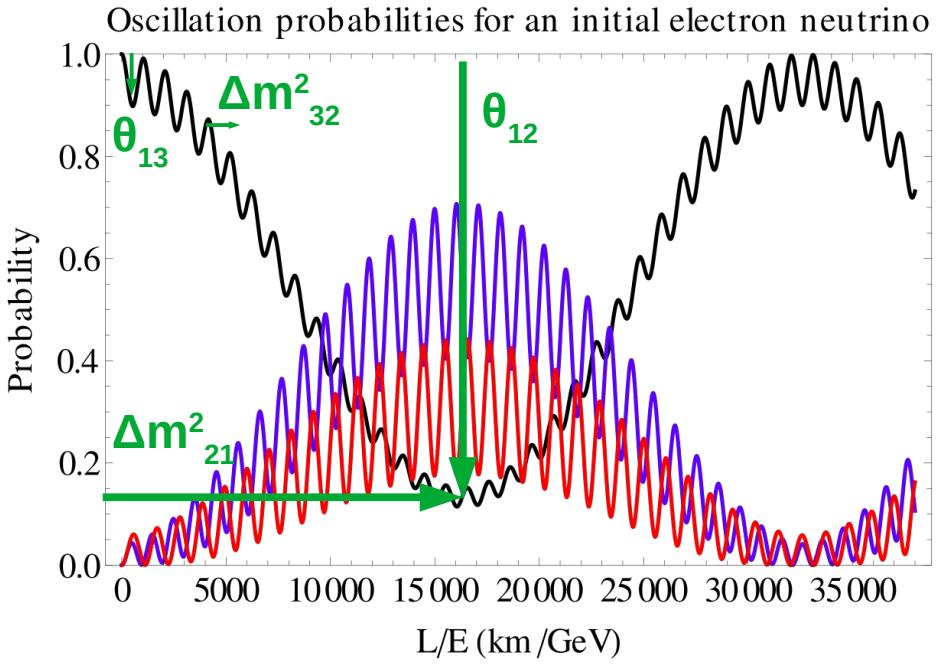
New atmospheric results from Neutrino26

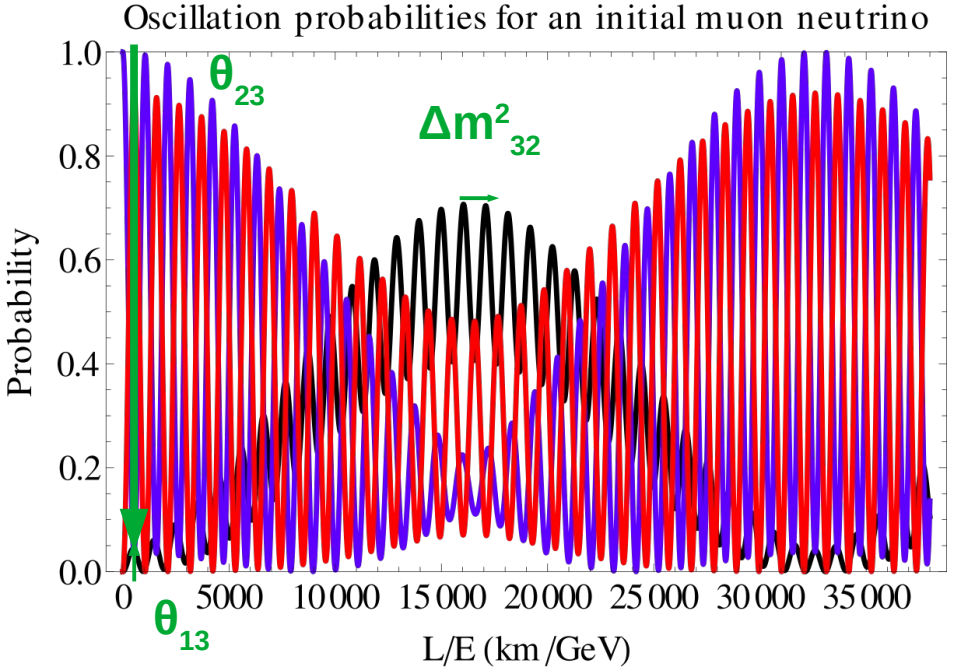
- ORCA prefers very small $|\Delta m^2_{32}|$, mild tension with LBL results
- ORCA is inconsistent with JUNO at >90% CL in both orderings
- IceCube has best resolution of θ_{23}, consistent with maximal





Oscillation probabilities & parameters

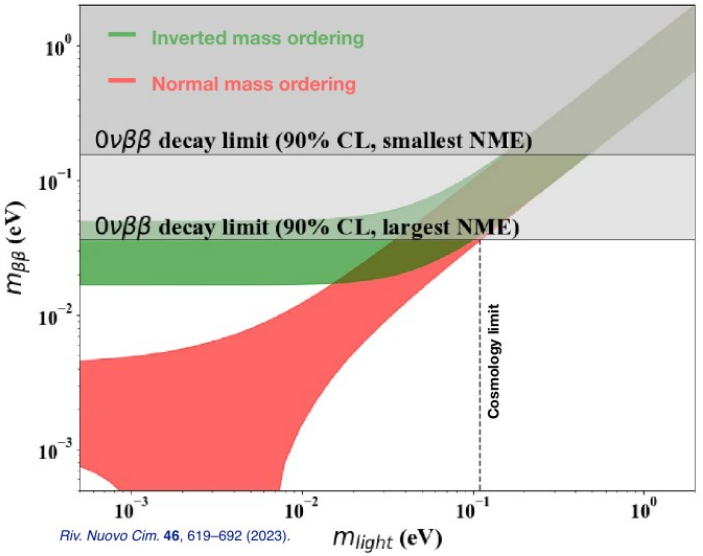


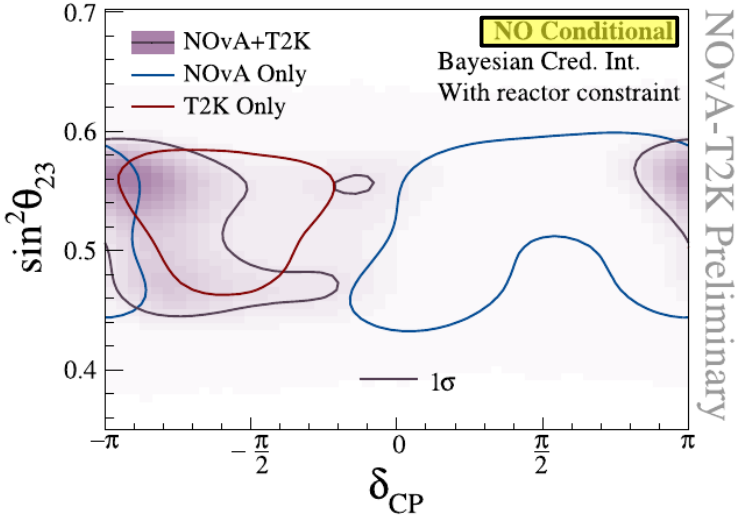


- We know there is a rapid “atmospheric” oscillation and a slow “solar” oscillation
- Mixing angles determine the magnitude of oscillation

MELIORA University of Rochester

Definitive mass ordering determination is critical



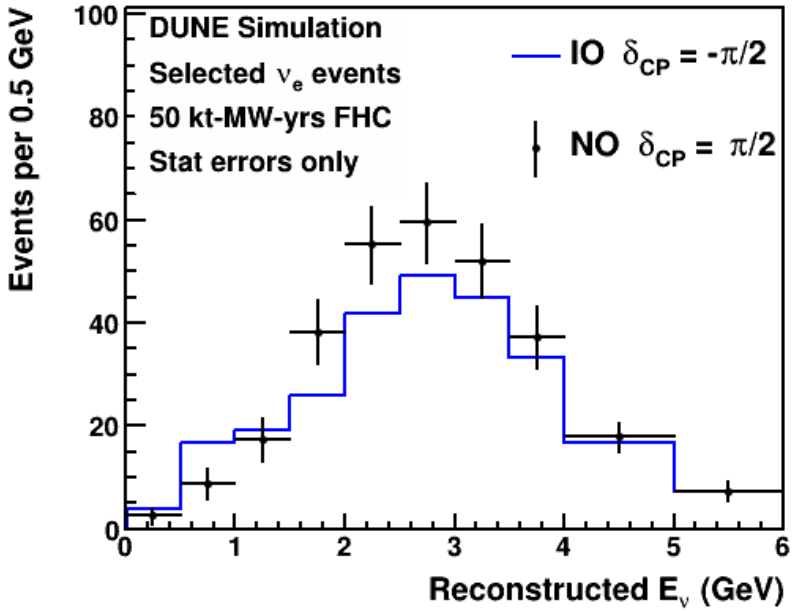


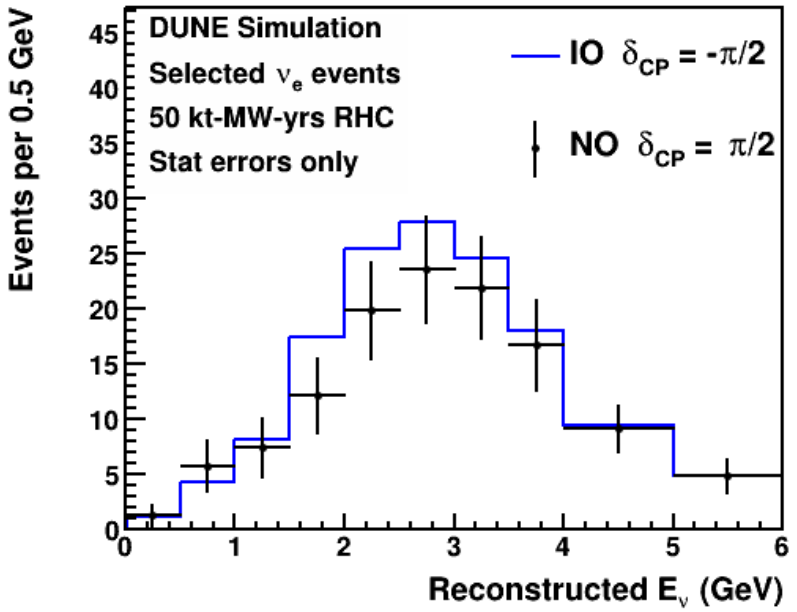
- Mass ordering affects other fields of science → we need a definitive result, and we have to get it right
  - Input to cosmology
  - Informs reach and design of 0νββ
  - Informs reach and design of direct neutrino mass measurements
- Mass ordering is needed to analyze existing and future neutrino oscillation data
- Several qualitatively different ways to measure mass ordering → we should pursue all of them

MELIORA University of Rochester

DUNE infers mass ordering in different way than JUNO, atmos.

- DUNE is the only experiment that measures the mass ordering by separately measuring $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
- Shown here is the worst-case scenario where CPV and matter effect go in opposite directions
- Spectral information is paramount

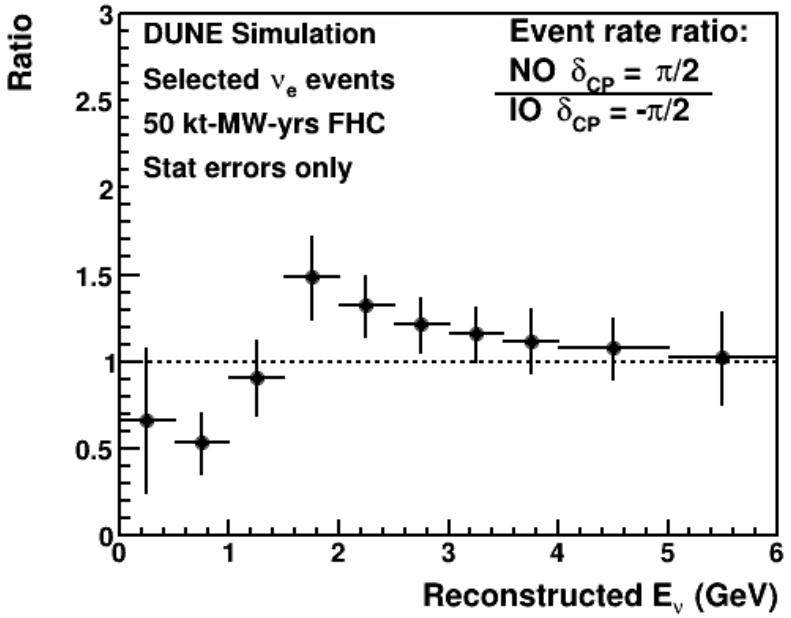


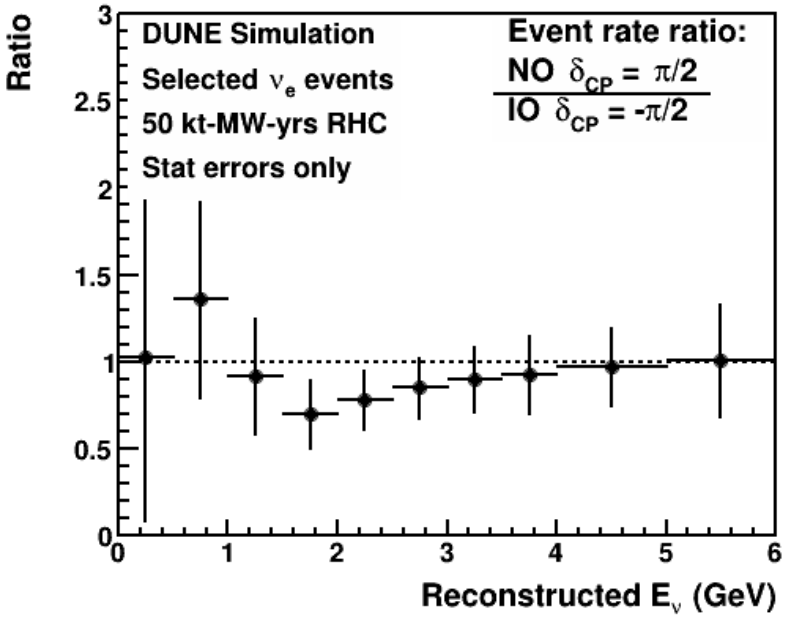


MELIORA University of Rochester

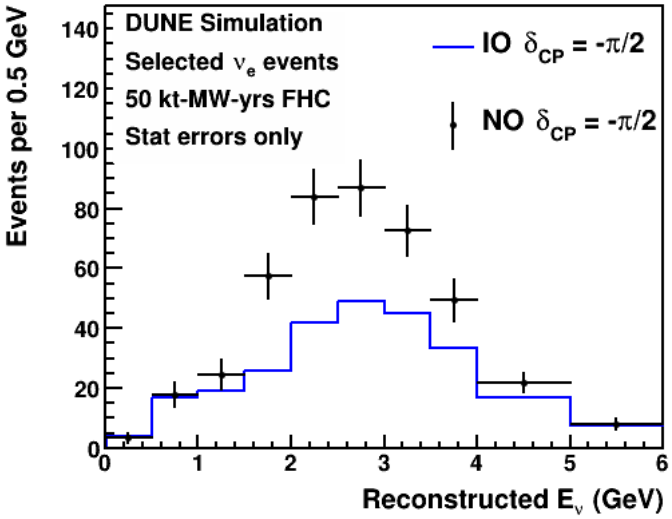
DUNE infers mass ordering in different way than JUNO, atmos.

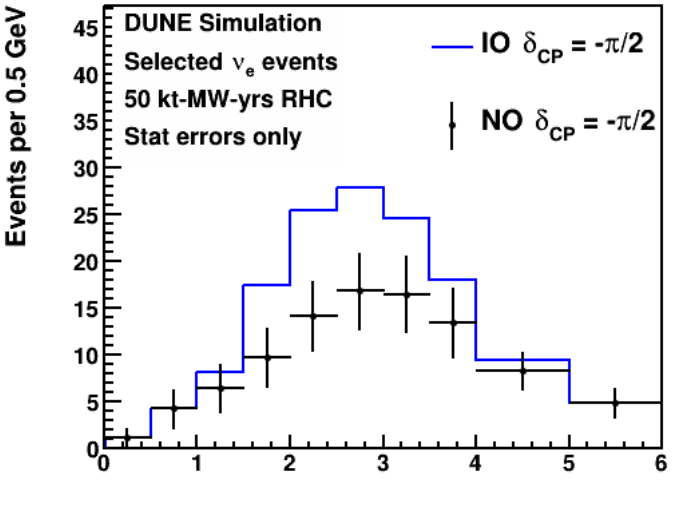
- Same plot as a ratio of NO data / IO prediction in least favorable scenario (error bars for 100 kt-MW-yrs total, about when DUNE exceeds 5σ)
- 40-50% differences in 0.5-2 GeV region, with opposite sign in FHC and RHC

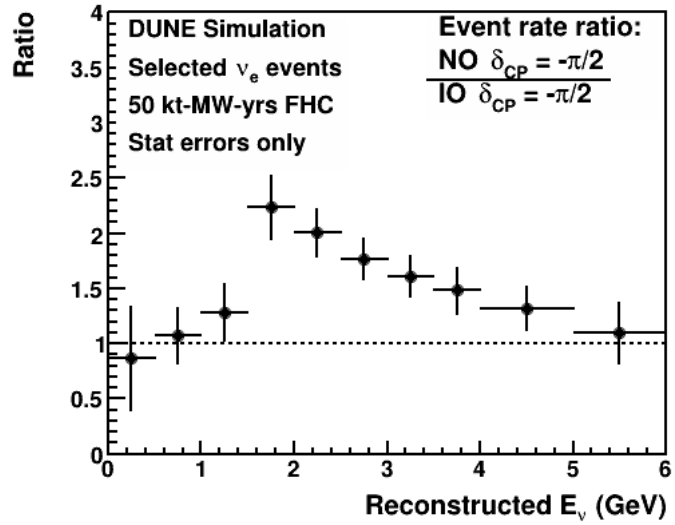


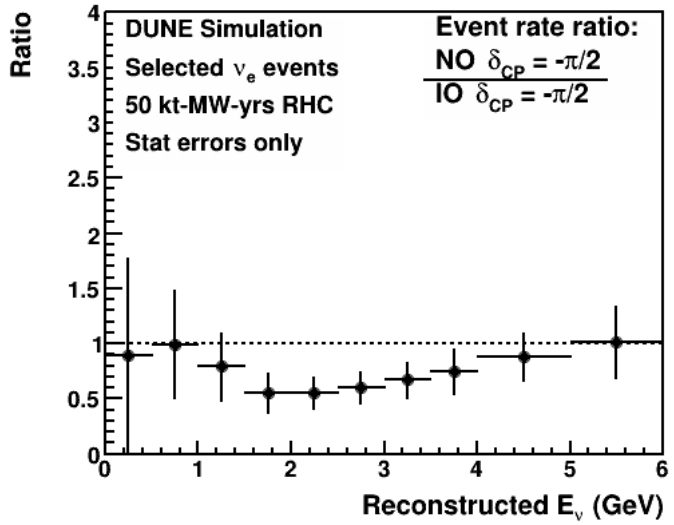


Just for fun, the most favorable scenario for MO discovery



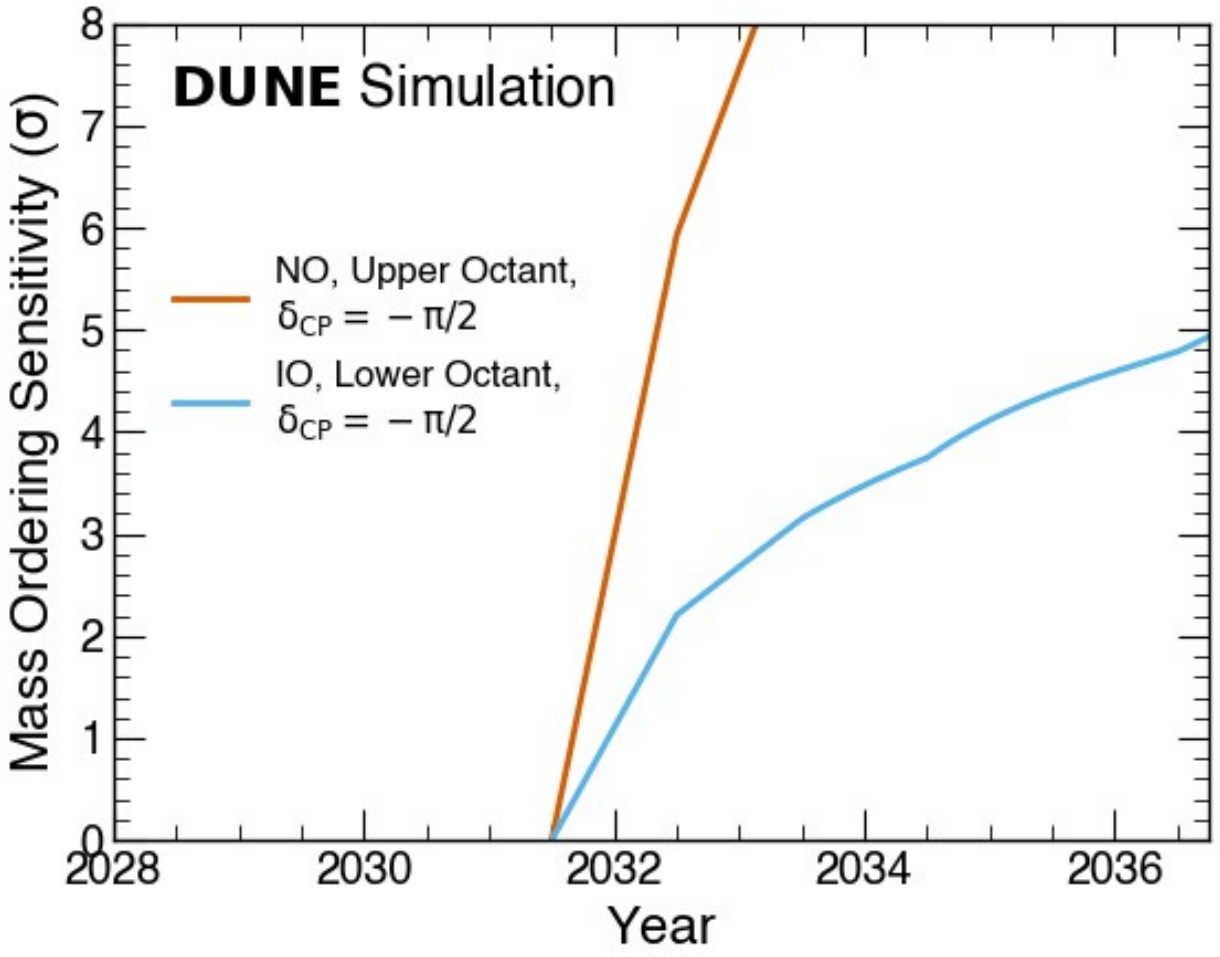






- In easy scenario, NO/IO differences are more than a factor of 2
- DUNE has >5σ significance in ~1 year of Phase I for this scenario

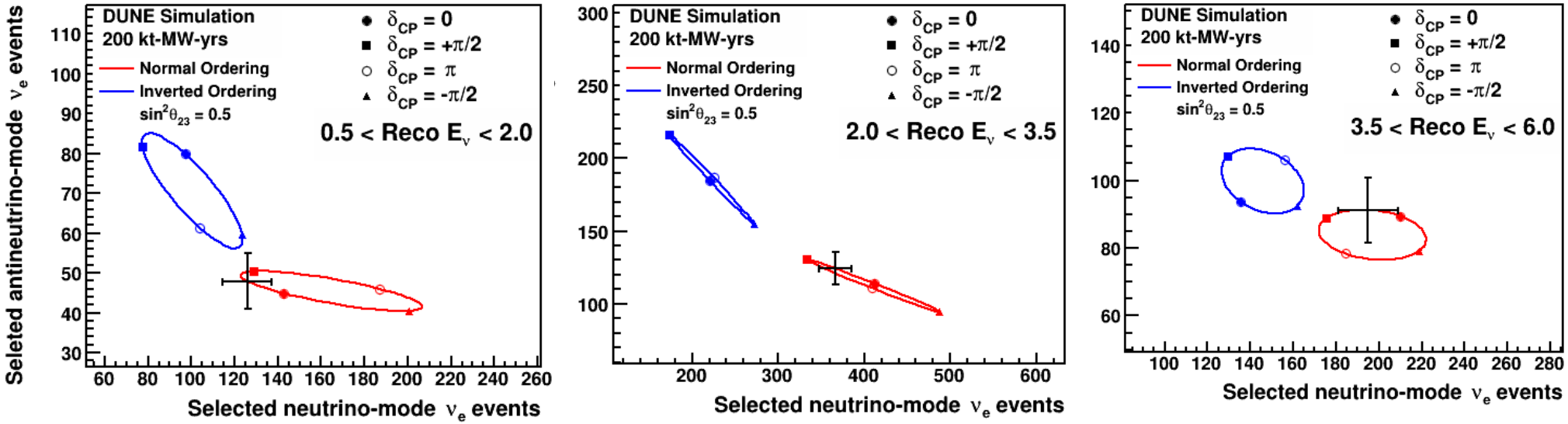
DUNE will determine the neutrino mass ordering no matter what



- DUNE's mass ordering sensitivity depends on true oscillation parameters
- In the "easy" scenario, DUNE surpasses 5σ in <1 year
- But even in the most pessimistic scenario, DUNE reaches >5σ in about 5 years
- Other techniques (e.g. atmospherics) take far longer, or never reach 5σ in unfavorable scenarios

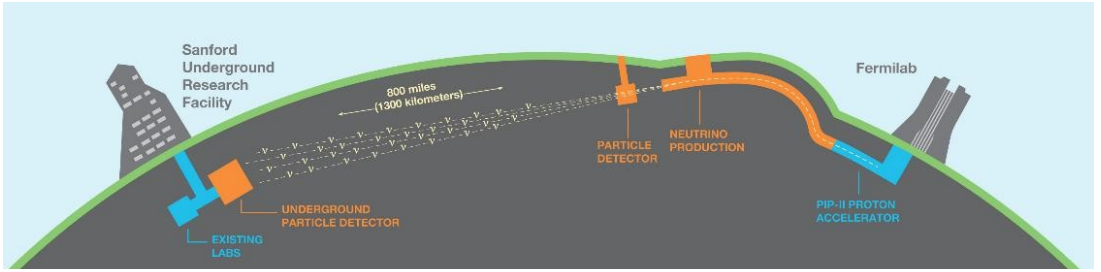
MELIORA University of Rochester

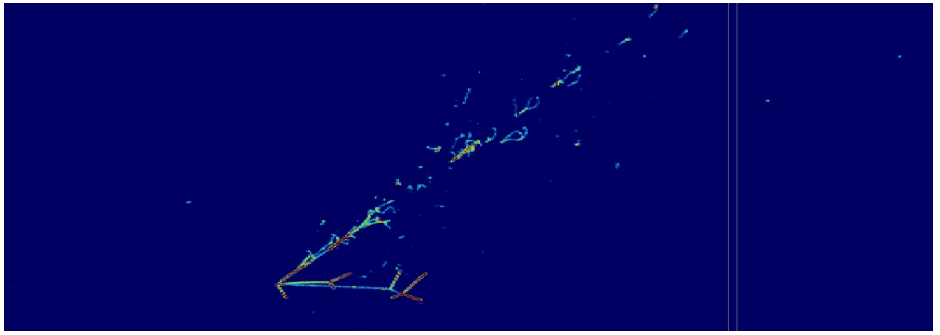
DUNE is sensitive to new physics in neutrino oscillations

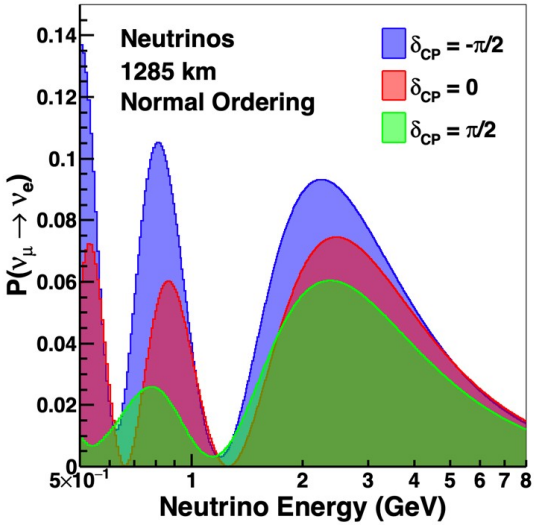


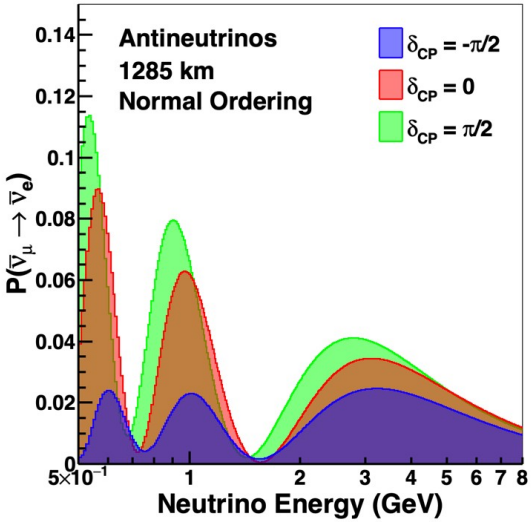
- DUNE can measure oscillation parameters at each bin of L/E
- If 3-flavor PMNS picture is correct, data should prefer the same point in every bin
- It is likely that new physics would distort the result *as a function of L/E* → DUNE has qualitatively unique sensitivity

DUNE's unique physics program has four key ingredients





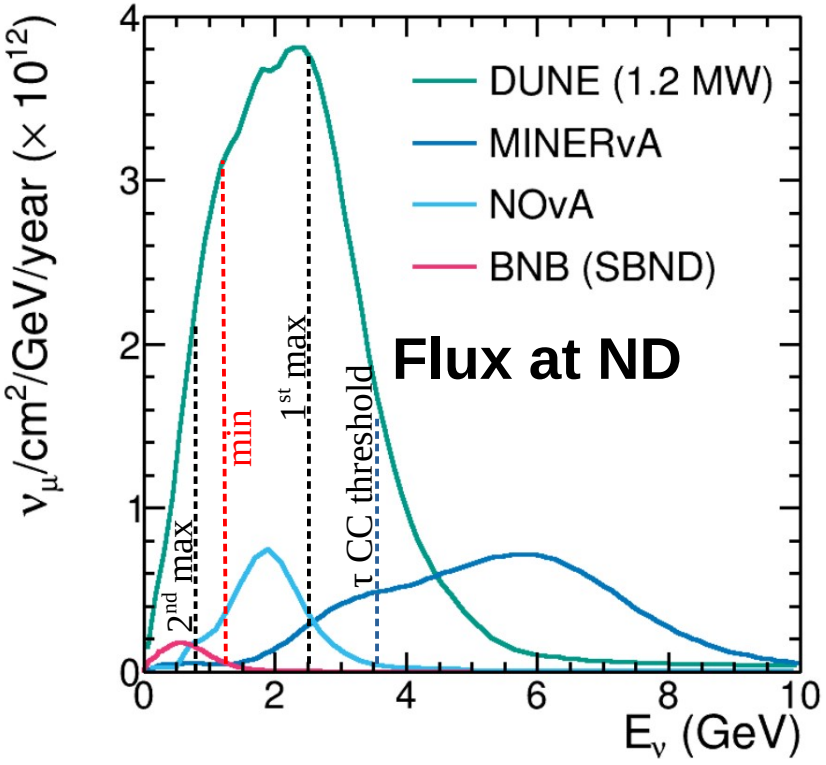




- #1: Wideband neutrino beam
- #2: Very long baseline
- #3: LArTPC technology
- #4: Movable, high-performance Near Detector

MELIORA University of Rochester

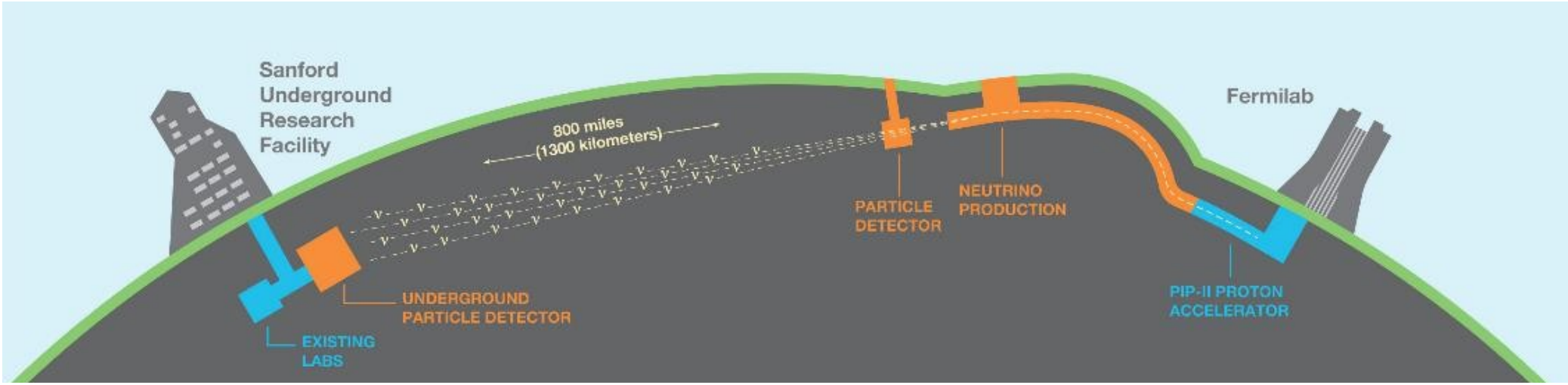
Key ingredient #1: LBNF beamline

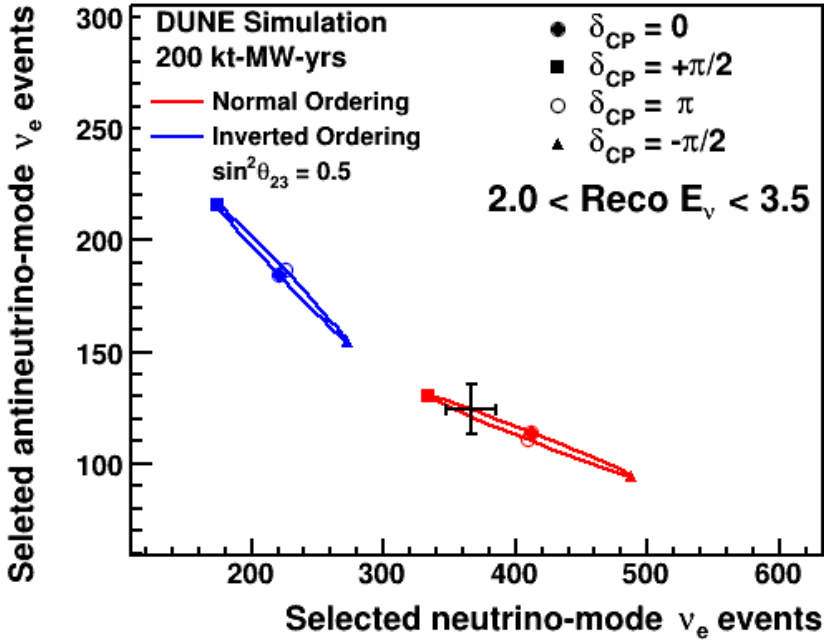


- LBNF's broad spectrum with 120 GeV proton beam has critical advantages:
  - Large flux between the oscillation minimum and maximum, with substantial flux down to the *second* maximum
  - High-energy tail above ν_τ CC threshold → unique three-flavor measurement opportunities
  - Many more neutrinos per POT than is achieved at lower energies

MELIORA University of Rochester

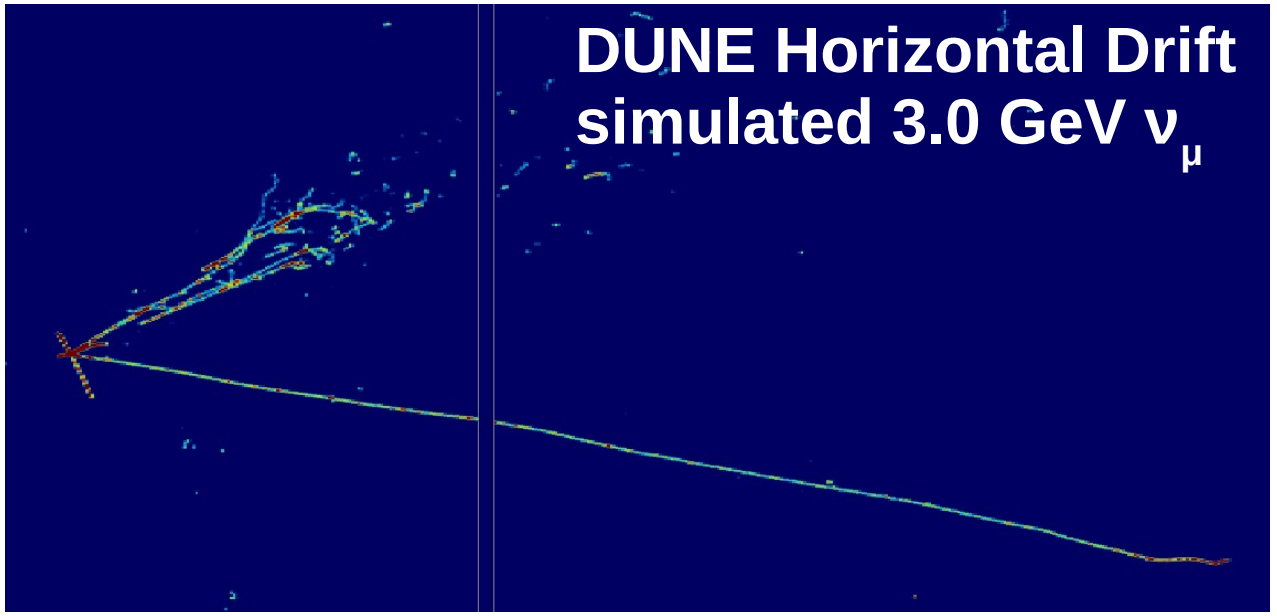
Key ingredient #2: Long baseline

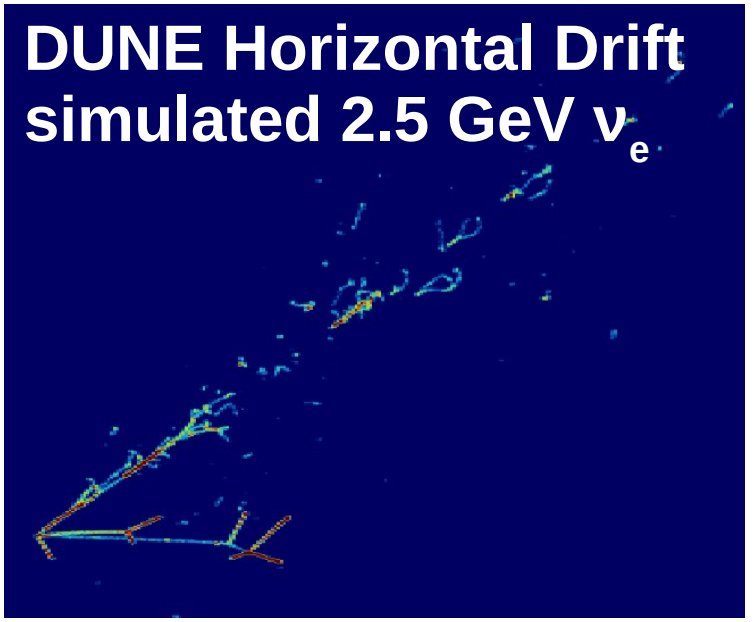




- The lack of degeneracy between CPV and the matter effect is because of DUNE's very long baseline
- Also unique sensitivity to deviations from SM matter effect → new physics

Key ingredient #3: LArTPC technology

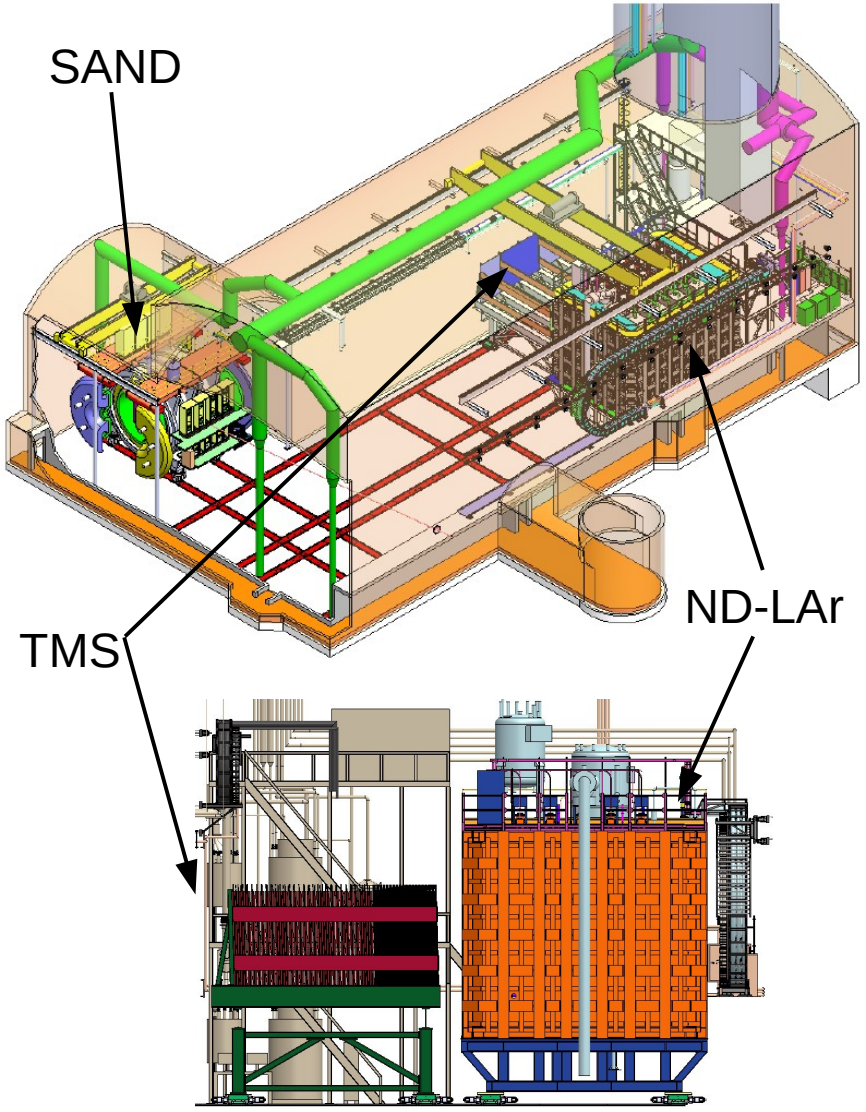




- To take advantage of broad, high-energy beam, we need flavor and energy reconstruction over a broad range of topologies
- LArTPC's low thresholds, exquisite imaging capabilities make it possible to measure oscillations vs. L/E

MELIORA University of Rochester

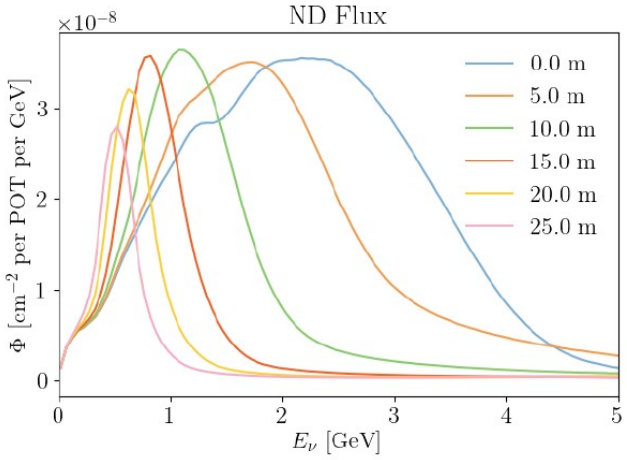
Key ingredient #4: Movable Near Detector



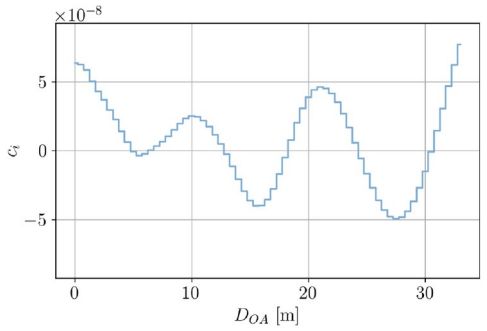
- Two measurement systems:
  - ND-LAr+TMS: LArTPC with a muon catcher (target is same as FD + muon detector → similar to MINOS and NOvA ND)
  - SAND: On-axis magentized low-density tracker and calorimeter
- ND-LAr+TMS moves (PRISM technique)

MELIORA University of Rochester

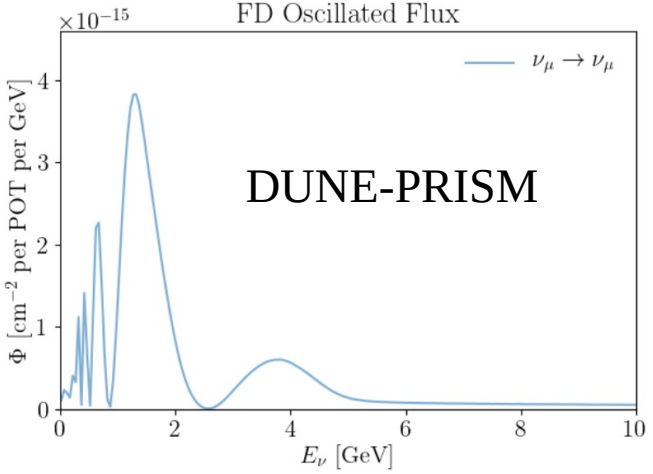
PRISM technique: directly probing neutrino energy dependence

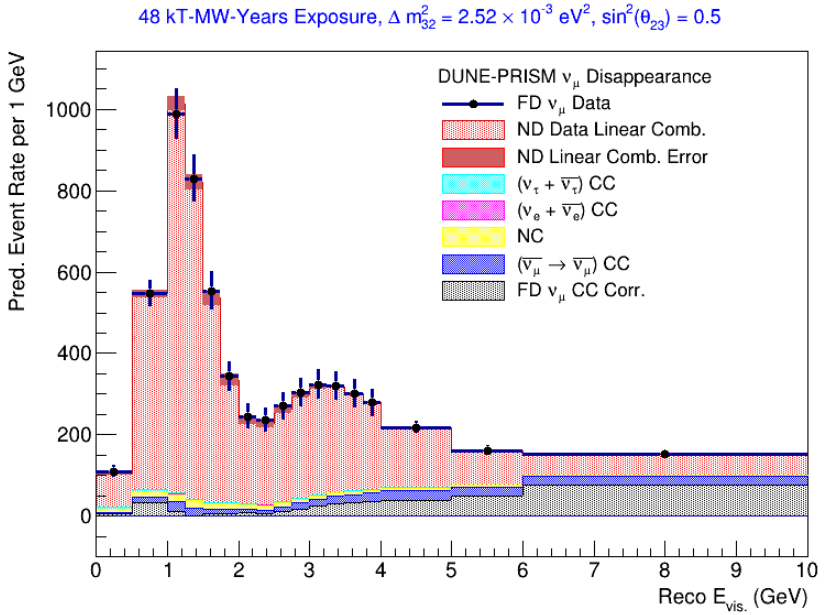


x



→

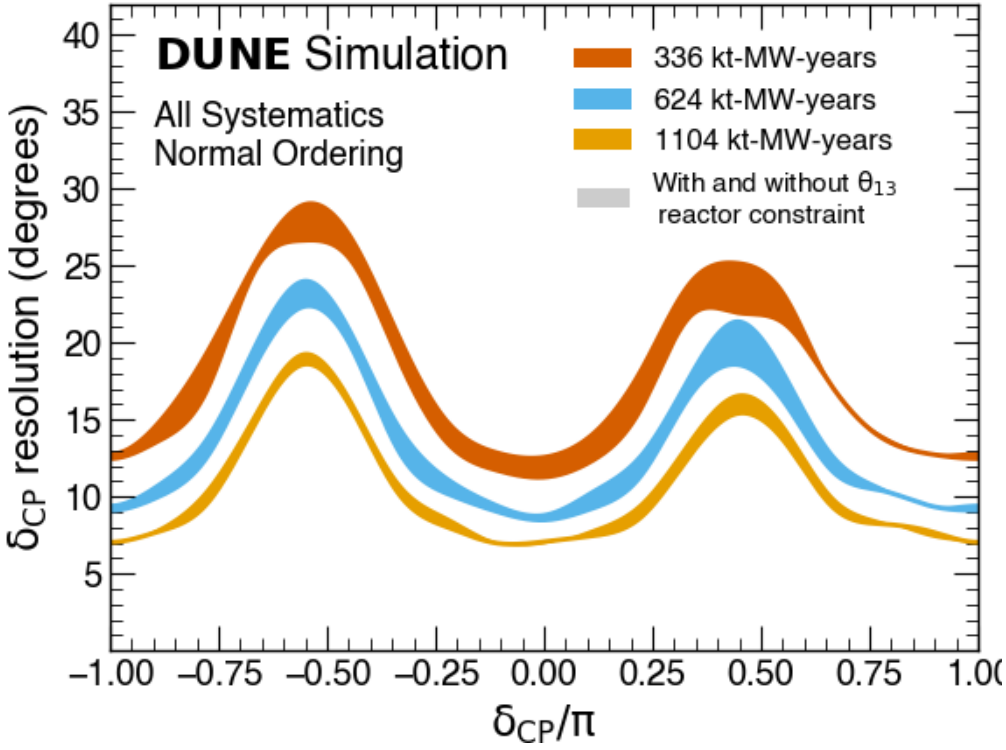


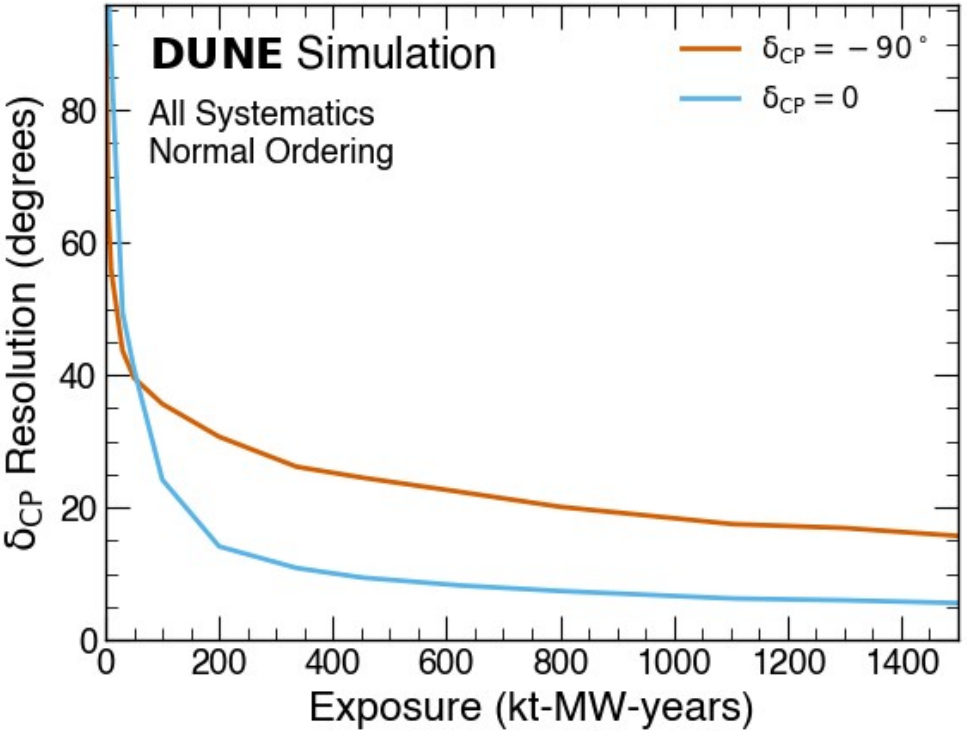


- FD flux ≠ ND flux → uncertainties in **energy dependence** of cross sections, response, etc.
- ND flux changes with angle due to pion decay kinematics
- Take ND data in different fluxes → build linear combination to match FD *oscillated* spectra
- Robust analysis approach with very minimal dependence on interaction modeling

MELIORA University of Rochester

DUNE CP violation sensitivity

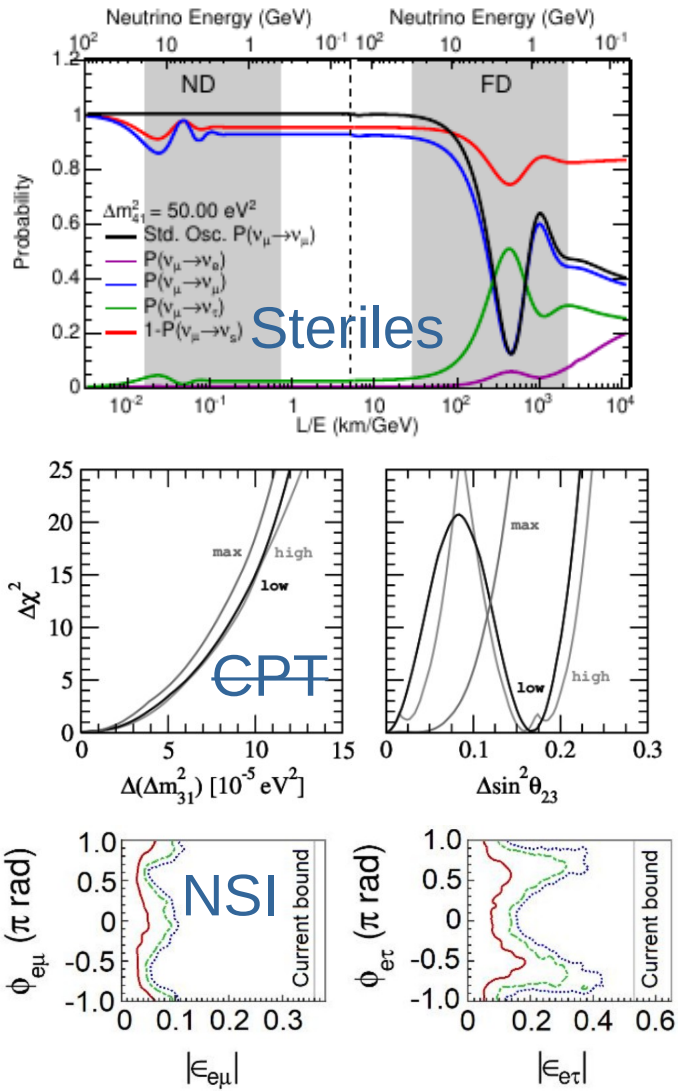




- DUNE has the best ultimate δ_{CP} resolution, especially if CP is violated
- DUNE can resolve degeneracies between different values of δ_{CP} with broad L/E spectrum

MELIORA University of Rochester

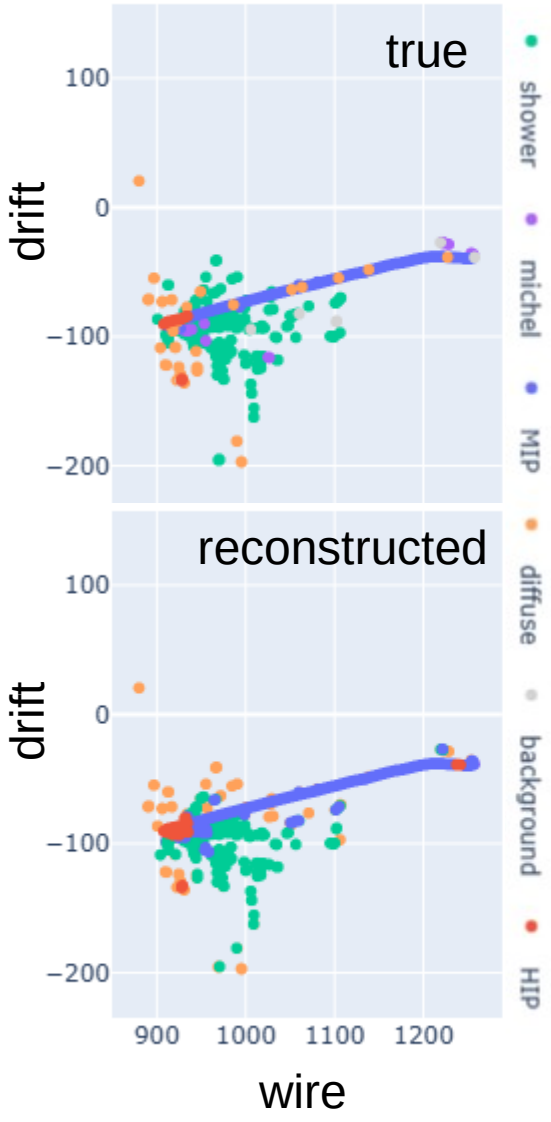
DUNE is sensitive to specific BSM oscillation models



- To search for sterile neutrinos, you want a large range of L/E → wideband beam, two detectors
- To search for CPT violation, you want precise measurements with ν and $\bar{\nu}$ Barenboim, Ternes, and Tortola, Phys. Lett. B780 (2018) 631–637
- To search for non-standard interactions, you want a large matter effect and three-flavor sensitivity de Gouvea and Kelly Nucl. Phys. B908 (2016) 318-365 Coloma, JHEP 03 (2016) 016

MELIORA University of Rochester

ν_τ appearance in DUNE beam



- High-energy proton beam with on-axis detector → DUNE (uniquely) has substantial flux above 3.5 GeV ν_τ CC threshold
- Imaging capability of DUNE makes it possible to reconstruct complex τ final states kinematically
- ML-driven reconstruction based on hierarchical graph network being pursued → opportunities to measure all three neutrino flavors at once

MELIORA University of Rochester